IUPAP Report 41

A Worldwide Perspective of Research And Research Facilities in Nuclear Physics by the IUPAP Working Group 9

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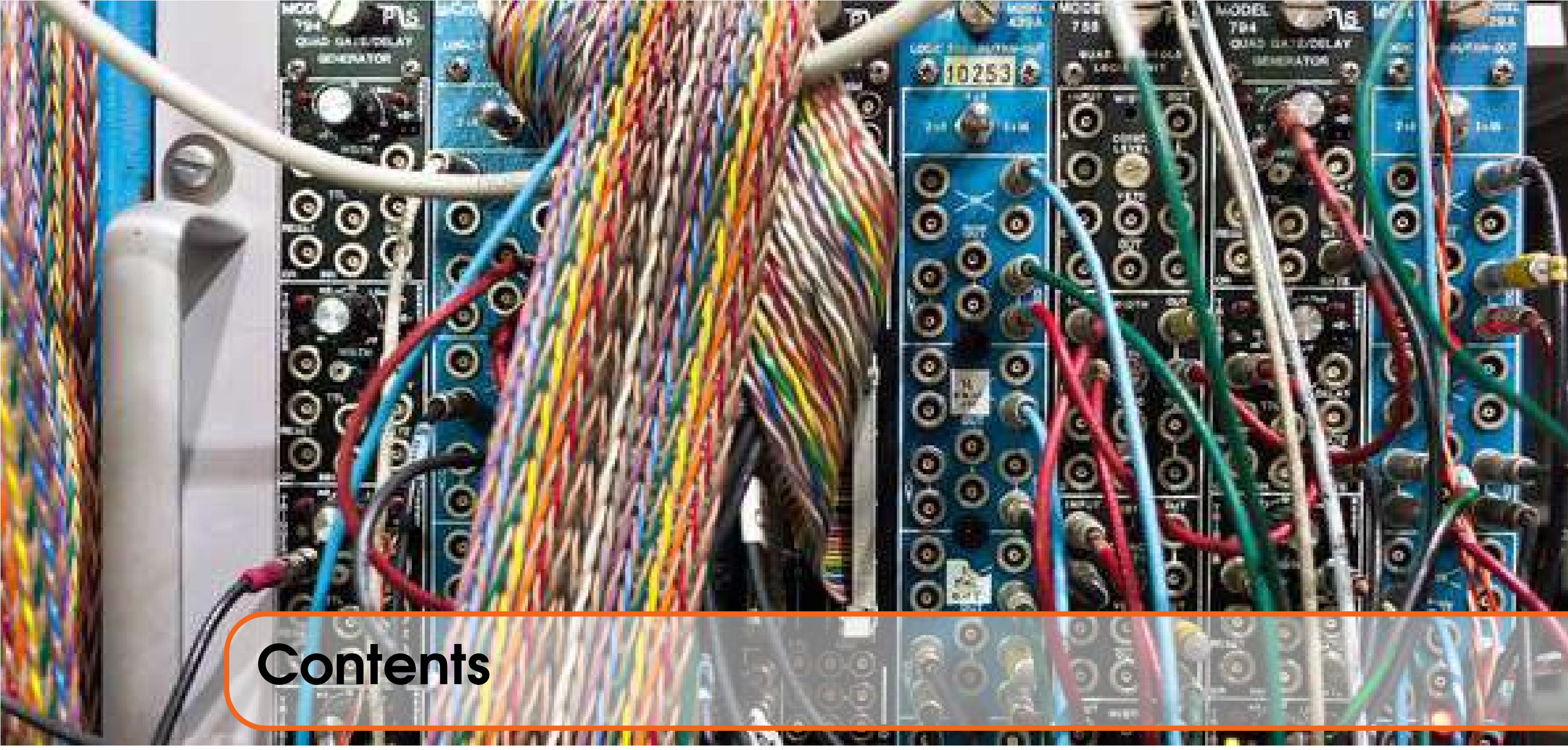

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Preface

At its 2003 Annual General Meeting, Commission C12 of the International Union of Pure and Applied Physics (IUPAP) made a formal decision to establish an ad-hoc Committee on International Cooperation in Nuclear Physics (CICNP). The membership of CICNP included the Chair and Vice-Chair of C12, as well as the Chairs of NSAC and NuPECC and representatives of key laboratories world-wide. Considerable care was also paid to the geographic distribution of members, in order to ensure appropriate representation from the whole nuclear physics community.

The formation of this committee had been a topic of discussion within C12 since 1995 and perhaps even earlier. It was created to facilitate international cooperation within the nuclear physics community following the recommendations of the various committees that preceded it. The objectives of CICNP were:

- To promote international cooperation in the broadest sense with the construction and exploitation of the large nuclear physics facilities - those which are intended for use by a worldwide nuclear physics community.
- To organize meetings on a regular basis, which are open to all wishing to attend, for the exchange of information on future plans for new nuclear physics facilities, be it very large multi-disciplinary facilities or facilities intended to more regional use.
- To stimulate the organization of workshops and/or symposia to discuss the future of nuclear physics and the need for facilities for the various subfields: high energy heavy-ion beam facilities, radioactive- ion beam facilities, multipurpose hadron beam facilities, high energy electron beam facilities.

It was also recognized that there was a need to discuss facilities which are clearly cross-disciplinary, like underground laboratories for particle, nuclear, and nuclear astrophysics. In accomplishing these objectives the committee was to document facilities under construction or being planned in terms of their anticipated performance parameters; to assess these anticipated performance parameters with regard to the requirements of the field; to evaluate the different facilities in terms of their complementarities and to indicate the areas of the field not covered but identified in the current science planning documents, like the NSAC Long Range Plan, the NuPECC Long Range Plan, and similar documents; and to recommend on the need for additional new facilities and for the expeditious use of the current facilities. The first Chair of CICNP, appointed by C12, was Anthony W. Thomas. The creation of this ad-hoc committee was also presented at the IUPAP Council and Chairs Meeting in October, 2003. The IUPAP headquarters welcomed this proposal and suggested that it might become an official Working Group of IUPAP. This led to a formal proposal to that effect, which was approved at the October 2005 General Assembly in South Africa.

The new IUPAP Working Group, WG 9, has the following Mandate (https://WG9.triumf.ca/mandate.html):

1. Provide a description of the landscape of key issues in Nuclear Physics research for the next 10 to 20 years.
2. Produce (maintain) a compendium of facilities existing or under development worldwide.
3. Establish a mapping of these facilities onto the scientific questions identified above.
4. Identify missing components that would have to be developed to provide an optimized comprehensive network of international facilities.
5. Explore mechanisms and opportunities for enhancing international collaboration in nuclear science.
6. Identify R&D projects that could benefit from international joint effort.
7. Serve as a source of expert advice for governmental or inter-governmental organizations in connection with efforts to coordinate and promote nuclear science at the international level.
8. Serve as a forum for the discussion of future directions of nuclear science in the broadest sense.
9. Document the cross disciplinary impact of Nuclear Physics and of nuclear facilities and identify mechanisms for expanding (fostering) cross disciplinary research.

This booklet is the result of the first task which WG 9 has set itself. It is a compendium of those basic nuclear physics facilities world-wide which are considered genuine user facilities by management. As far as it has been possible the information is complete and accurate. However, the very nature of IUPAP means that participation is purely voluntary and in the case of a very small number of countries we have been unable to obtain information. In addition, apart from personal knowledge of the members of the committee it has been necessary to rely on the information provided by the facilities themselves. In spite of the obvious difficulties this is probably the most comprehensive summary of the research facilities available to the international nuclear physics community that has been compiled. It has been supplemented by a brief outline of how these facilities relate to what the committee feels are the major questions facing us in key areas of nuclear science. We very much hope that the nuclear community will find this a useful resource and it will be widely distributed as well as made available on the world-wide web.

This report is the culmination of an enormous amount of work by many people. I would like to thank all of the laboratory representatives who responded to us and helped to ensure the accuracy of the entries. It is also appropriate to acknowledge the efforts of all those members of WG 9 and C12 who worked hard to solicit information, contribute to the overview sections and provide quality assurance on the final document. I would like to particularly thank Walter Henning and Wim van Oers for their tireless efforts to produce a high quality report on schedule. I also would like to thank Gabriele-Elisabeth Körner for her help with obtaining some of the laboratory information in this report. It is a pleasure to acknowledge the enormous amount of work that Susan Brown devoted to the preparation and the presentation of this document.

On behalf of the community I would also like to express appreciation to IUPAP for their support (including a financial contribution to printing costs) of this project.

Anthony W. Thomas (Chair IUPAP WG 9)
July 9, 2007

Updated Versions of IUPAP Report 41 (2018 and 2023)

This updated version IUPAP Report 41 ‘Research Facilities in Nuclear Physics’ was produced in compliance to the mandate of the IUPAP Working Group 9 ‘International Cooperation in Nuclear Physics’, as confirmed by the OECD Global Science Forum. Indeed on a regular scheduled time frame the IUPAP Report 41 was updated, the last one occurring in 2018.

We are aware that the nuclear community considers Report 41 as a useful resource, which is made available on the world-wide web, and this has motivated this new update.

Here we like to remind that this report consists in two parts. The first part discusses in brief the most important science questions to be addressed in the coming ten years in the seven subfields of nuclear physics:

- Nuclear Structure, Nuclear Reactions, Nuclear Astrophysics,
- Hadronic Nuclear Physics,
- QCD and Quark Matter,
- Fundamental Symmetries,
- Applied Nuclear Science,
- Nuclear Power, and
- Nuclear Physics Facilities.

In these years new strategic plannings for Nuclear Science are being prepared in Europe and USA and thus after their publication a revision of this part of the report will be made.

The second part, updated in the past months, is a compendium of those basic nuclear physics facilities world-wide which are considered genuine user facilities by management. As far as it has been possible the information is complete and accurate.

In spite of the obvious difficulties this is probably the most comprehensive summary of the research facilities available to the international nuclear physics community that has been compiled.

We would like to express sincere thanks to all who have contributed to the update of this IUPAP Report 41.

Robert E. Tribble (Chair IUPAP WG 9)
Willem T.H. van Oers (Secretary IUPAP WG 9)
February 2018

Angela Bracco (Chair IUPAP WG 9)
Iris Dillmann (Secretary IUPAP WG 9)
August 2023

Part 1 - Overview

1. Executive Summary

Anthony W. Thomas (University of Adelaide, Australia), February 2018

The IUPAP Working Group on International Cooperation in Nuclear Physics (WG 9) was established in 2003 at the IUPAP General Assembly in Cape Town, with a mandate to examine key issues in Nuclear Physics. Over the last 15 years the work of WG 9 has led to the creation of the Asian Nuclear Physics Association (ANPhA) and of the Association of Latin American Nuclear Physics and Applications (ALAFNA); members of WG 9 served on the OECD Global Science Forum Working Group on Nuclear Science which set out a roadmap for international nuclear science in 2008.

The Working Group also has close connections with NSAC in the United States and NuPECC in Europe and now organises regular meetings with funding agencies from around the world to promote nuclear science. Through these activities the mandate of WG 9 has grown and its aims may now be summarized as:

- to provide a description of the landscape of key issues in Nuclear Physics research for the next 10 to 20 years;
- to produce (maintain) a compendium of facilities existing or under development worldwide;
- to establish a mapping of these facilities onto the scientific questions identified above;
- to identify missing components that would have to be developed to provide an optimized, comprehensive network of international facilities;
- to explore mechanisms and opportunities for enhancing international collaboration in nuclear science;
- to identify R/D projects that could benefit from international joint effort;
- to serve as a source of expert advice for governmental or inter- governmental organisations in connection with efforts to coordinate and promote nuclear science at the international level;
- to serve as a forum for the discussion of future directions of nuclear science in the broadest sense;
- to document the cross-disciplinary impact of Nuclear Physics and of nuclear facilities and to

identify mechanisms for expanding (fostering) cross-disciplinary research.

The purpose of the present document follows closely that of the first IUPAP report on nuclear physics user facilities around the world, IUPAP Report 41. It has been significantly revised and updated and we expect that it will serve as a valuable resource for scientists and administrators. In order to put the impressive array of nuclear physics facilities around the world into perspective, in this introduction we outline the key physics issues that have led to the facilities now operating, under construction or anticipated. In putting these physics issues forward we have drawn heavily on a number of recent reports, including the 2017 NuPECC and the 2015 NSAC Long Range Plans. The NuPECC 2017 Long Range Plan provides a concise, accurate summary of the overall goal of nuclear physics, namely "to unravel the fundamental properties of nuclei from their building blocks, protons and neutrons, and ultimately to determine the emergent complexity in the realm of the strong interaction from the underlying quark and gluon degrees of freedom of Quantum Chromodynamics (QCD)." In order to do this one must explore more deeply the structure of hadrons, the forces between them, the limits of stability of nuclei and the properties of nuclear matter under extreme conditions. Advances in nuclear physics have important consequences for astrophysics, for physics beyond the Standard Model and for a rich bounty of applications in industry and health.

The following sections of this introduction provide background to the key questions which challenge modern nuclear physicists:

1.1 How do the structure of hadrons and their interactions emerge from QCD?

We already know a great deal about non-perturbative QCD but we are still far from a full understanding of the way quarks are confined inside hadrons. On the theoretical side lattice QCD has provided detailed information on the structure of the nucleon and its octet partners but the serious study of excited states is just beginning. We still do not know whether more than three quarks or one quark and one anti-quark can be confined or anything more complicated has a molecular nature. Both effective field theory and sophisticated model building have important roles to play in developing our understanding further. These theoretical ideas are being and will be tested and refined by an impressive array of measurements at new and upgraded facilities, most notably FAIR, JLab, J-PARC and RHIC. The relevant measurements vary from form factor and transition form factor measurements at ever increasing momentum transfer, to deep inelastic scattering (DIS) and semi-inclusive DIS, the latter made much more discriminating by clever new spin dependent measurements.

1.2 What is the structure of nuclear matter?

At the heart of this question is the structure and properties of atomic nuclei, the limits of existence as one moves from stability to proton or neutron driplines, the changes in shell structure, the possible existence of an island of stability at masses above the heaviest nuclei currently known. We do not yet know what role if any the fundamental degrees of freedom of QCD, the quarks and gluons, play in finite nuclei, let alone in the far more dense matter that appears in neutron stars. Amongst the latest facilities designed or built to tackle these issues experimentally we mention specifically EURISOL, FAIR, FRIB, the ISAC facilities at TRIUMF, and RAON in South Korea. Theoretically there has been considerable progress in density functional theory, effective field theory, Green's function Monte Carlo methods and the no-core shell model.

1.3 What are the phases of nuclear matter?

Apart from finite nuclei, which form such an important part of modern nuclear physics, nuclear matter also appears in remarkably different conditions. In a neutron star one may reach densities up to six times the density of nuclear matter, where the composition is currently unknown; it could, for example, be quark matter with the boundaries between hadrons dissolved, or it could be nuclear matter with hyperons or some kind of condensate of kaons or superconducting quark matter. Some insight into this can be obtained in high energy heavy ion collisions, although in that case the matter is not in beta-equilibrium, as it must be in a star. In even higher energy relativistic heavy ion collisions one can form a high temperature quark-gluon plasma with remarkable properties, such a very low viscosity, which need to be further explored. Facilities such as the LHC at CERN (the ALICE experiment), RHIC at Brookhaven National Laboratory, NICA at the Joint Institute for Nuclear Research, and FAIR in Germany are key to exploring this physics.

1.4 What is the role of nuclei in shaping the evolution of the Universe?

Most of the matter that we now take for granted, apart from deuterium, helium and lithium, was formed in stellar processes more than 3 minutes after the Big Bang. Some of these elements were formed as stars aged, others in supernova explosions and perhaps even in processes associated with neutron star mergers, which are so topical given the recent successes of the gravitational wave observatories. Understanding the origin and abundance of the elements is a fundamental objective of nuclear science. This is a field where there are wonderful opportunities for synergy with astronomy and astrophysics. However, the major new rare ion facilities currently operating, such as TRIUMF in Canada, RIKEN in Japan, and FRIB in the US, as well as those under construction around the world, especially FAIR in Germany and RAON in Korea, will be key to unravelling these mysteries.

1.5 What lies beyond the Standard Model?

In spite of its manifold successes, the Standard Model suffers from many problems, not the least being a large number of ad hoc parameters, a huge fine-tuning problem and finally the fact that it describes only 5% of the stuff of the Universe. Nuclear techniques are vital to finding ways to detect dark matter and underground laboratories, where cosmic-ray backgrounds are heavily suppressed, are crucial to the search for it. These laboratories are also vital to efforts to determine the nature of neutrinos, notably through searches for neutrinoless double-beta decay, as well as for numerous applications of nuclear science. Other topics actively being pursued include precision tests of the predictions of the Standard Model, notably involving parity violation and time reversal invariance.

2. Nuclear Structure, Reactions, and Astrophysics

Updated January 2018, by Alexandra Gade (Michigan State University)

2.1 Introduction

Nuclei occupy the center of every atom, constituting 99.9% of its mass. They are the building blocks of the visible matter in the Universe, of the Earth, and of us. The subfield of nuclear structure, reactions, and nuclear astrophysics strives to measure properties of nuclei, explain their existence, formation, and decays; use nuclei to explore physics beyond the Standard Model, and to meet societal needs in areas such as medicine, environment, and material science. The resulting broad research portfolio addresses the nature of the nuclear force that binds protons and neutrons into atomic nuclei as well as emerging dynamical many-body processes such as nuclear reactions or fission.

The ultimate goal of the field is to develop a data-driven, predictive model of atomic nuclei and their interactions grounded in fundamental QCD and electroweak theory with quantified uncertainties. The ability to reliably calculate nuclear properties with the required precision will revolutionize our understanding of the origins of the chemical elements in the Universe and the complex reaction and decay networks that fuel explosive scenarios in the Cosmos.

The importance of atomic nuclei to energy, health, environment, and security means that forefront research in this area plays a critical role in attracting and training the next generation of nuclear scientists needed in research, industry, and medicine. The experimental work is carried out worldwide at major national (user) facilities and smaller, often University-based, laboratories employing a variety of accelerator technologies. While the large facilities continuously push the frontiers of the field, smaller laboratories are typically optimized for specific scientific programs, are engines of detector development and testing, and often allow for a unique hands-on education of students in all areas from acceleration to detection.

The properties of rare isotopes and stable nuclei are interrogated with a powerful arsenal of experimental techniques, such as nuclear spectroscopy following nuclear reactions and decays, high-precision ion- and atom-trapping techniques, and laser spectroscopy, using state-of-the-art equipment ranging from hundreds-of-tons-heavy magnetic spectrographs and scintillator- and solid-state-based radiation detection arrays to table-top laser setups.

Great strides have been made through nuclear spectroscopy in the continuum and for bound states. Penning-trap mass spectrometry has seen a leap in precision and laser-based techniques have broadened their realm of applicability. Experimental breakthroughs are often the result of new equipment developments or advances in accelerator technology, increasing the intensity and the reach for producing certain nuclei. New major rare-isotope facilities are under construction in the US and Europe, while existing, present-generation facilities continue to position the field for the next leap in discovery potential.

In recent years, nuclear theory has championed the development of nuclear many-body approaches whose underlying interactions are developed using chiral effective field theory with roots in the symmetries of QCD. Power counting and renormalization techniques have allowed inclusion of many-body correlations such as three-nucleon forces, which are not necessarily genuine but rather an inherent reflection of truncations in the order-by-order approach. Open-shell systems have now come into reach with such ab-initio type calculations for the first time.

Developments in Lattice QCD started to connect to low-energy nuclear physics with the ultimate goal of anchoring the description of the very lightest nuclei and nucleon-nucleon interactions in QCD. Mean-field and configuration-interaction models have continued as pillars of the field in terms of describing experimental data and concluding on the driving forces of structural change in the exotic regime. The field of nuclear theory has moved to quantified uncertainties, including Bayesian approaches. This enabled meaningful comparisons of data and model calculations where uncertainties in assumptions and input parameters are encoded in theoretical error bars.

Weakly-bound nuclei are a fascinating open quantum system. The particle continuum is at the heart of rare-isotope science and methods to include the effects of weak or no binding near the nucleon driplines continue being incorporated into the various theory frameworks. Computational physics, moving towards exa-scale computing power, has become the third leg of nuclear physics, dramatically and continuously widening the reach of nuclear many-body theory. The field of nuclear reactions has seen novel time-dependent approaches tackling "old" complex many-body processes such as fusion and fission. Reaction theory remains a field with crucial, open theoretical challenges that are a great opportunity for additional, new talent needed in this sub-field.

Due to the complexity of the underlying forces (QCD, QED, and electroweak) in nuclei, there have often been surprises. Progress in the field almost always has had experiment and theory working in close collaboration, informing each other about relevant nuclear properties to be measured or to be calculated for key nuclear systems. Properties of rare isotopes guide approximations, define parameters, and benchmark theoretical approaches. Discoveries continue to surprise, changing the paradigm of the field towards exciting new directions for experiment and theory.

2.2 The nuclear landscape

The territory of nuclear structure, nuclear reactions, and nuclear astrophysics is the various forms of atomic nuclei that can exist. This landscape is illustrated by the chart of nuclei (Fig. 2.1). Only 288 of several thousand nuclei, or isotopes, known to exist are either stable or practically stable (i.e., have half-lives longer than the expected lifetime of the solar system).

By moving away from the region of stable isotopes, by adding nucleons (either neutrons or protons), one enters the regime of short-lived rare isotopes, which are radioactive and decay by emitting β or α particles, or disintegrate through the process of spontaneous fission. The limits of existence are demarcated by the nucleon driplines, beyond which additional nucleons cannot be bound anymore. The proton dripline has been reached for many isotopic chains. However, the

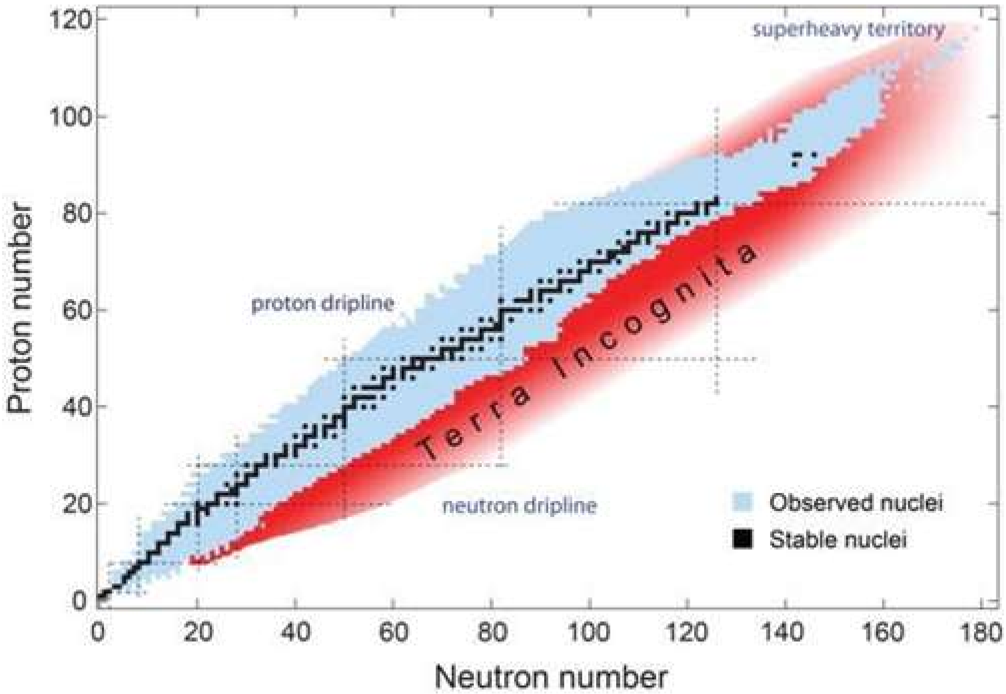


Figure 2.1: The nuclear territory – Black: stable nuclei; blue: nuclei known to exist; red: Nuclei that will still be discovered. The chart of nuclei is bounded by the nucleon driplines where no additional nucleons can be bound. Superheavy nuclei reside at the limit of charge and mass. A vast, unknown, and still uncertain part of the nuclear chart, the Terra Incognita, remains unexplored.

neutron dripline is known only up to oxygen (Z=8). The superheavy nuclide with Z=118, A=294 marks the current upper limit of nuclear charge and mass.

Today, more than 3000 nuclides are known to us, but the number of those which have been well characterized is much less. At present, every year, the discovery of several tens of new isotopes is reported, near or beyond the proton dripline, in the neutron-rich regime, and in superheavy territory. Often, the decay properties of newly discovered isotopes can be studied, such as two-proton emission near the proton dripline or α decay chains for the superheavy elements produced for the first time. Beyond the neutron dripline, multi-neutron decays were studied as messengers of correlations inside such neutron-laden systems.

The limits of atomic number continue to be expanded. Nine new elements have been discovered in the past 30 years. Recently, the International Union of Pure and Applied Chemistry (IUPAC) announced the names for four new elements. Nihonium (Nh), Moscovium (Mc), Tennessine (Ts), and Oganesson (Og), respectively, for elements 113, 115, 117, and 118. Enormous progress has been made in single-atom chemistry, characterizing for example Z=114 Flerovium and Z=112 Copernicium.

As can be seen in Fig. 2.2, most of the isotopes of elements of Z=113 and above were produced in the "hot" fusion of a Calcium-48 beam with actinide targets, the most exotic being Berkelium-249. At present, the pathway to reach beyond Z=118 is not clear. There may be more elements to be found once a means to produce them is realized.

Starting recently, atomic physics techniques have been used to study the heaviest elements: Two experiments have tried to observe X-rays in coincidence with α decays to determine the atomic number, but were not successful. However, recently, laser spectroscopy of Nobelium (Z=102) succeeded, pointing to possible new directions. Based on the chemistry of heavy elements, the high atomic number of superheavy elements is expected to significantly alter their chemistry. There are

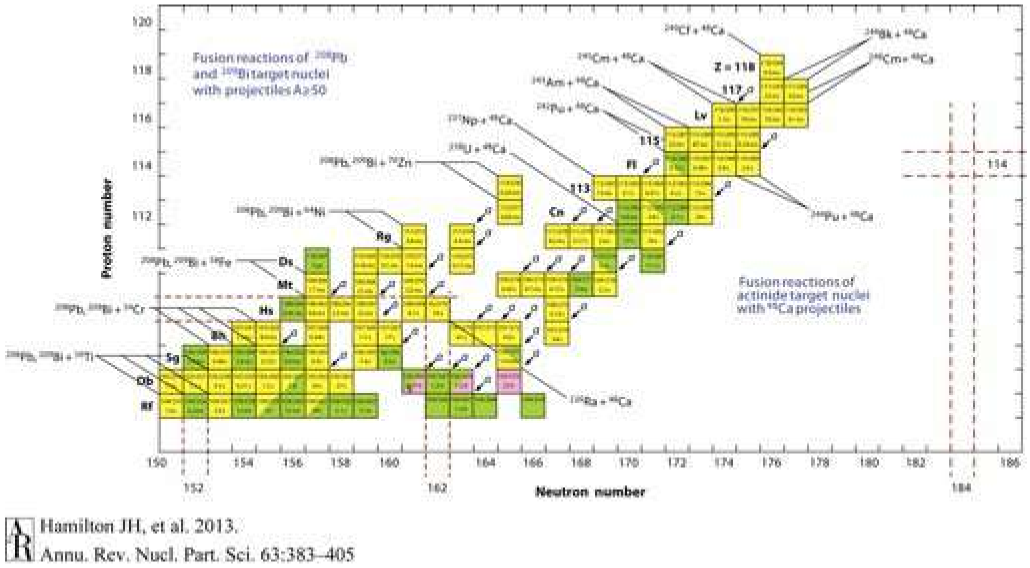


Figure 2.2: Superheavy territory, indicating some of the most recent discoveries, their production reaction, and decay chains.

speculations that beyond element 118 the electrons behave more like a Fermi gas and the chemistry for these heaviest elements will no longer follow a periodic table.

Exciting prospects exist for the expansion and study of the nuclear chart in all directions, with the Superheavy Element Factory operational in Dubna and powerful next-generation rare-isotope beam facilities being completed in the US and Europe.

2.3 Nucleosynthesis in explosive scenarios – multimessenger revolution

Nuclear reactions and decays in stars, stellar explosions, and binary mergers generate energy and are responsible for the ongoing synthesis of the elements in the Universe. They are at the heart of many astrophysical phenomena, such as stars, novae, supernovae, nucleosynthesis in neutron-star collisions, and X-ray bursts. Nuclear physics critically determines the light curves of many objects, the signatures of isotopic and elemental abundances found in their spectra or in the composition of meteorites and presolar grains that originate from them, and the characteristic γ-ray radiation emitted by some of the objects.

Neutron stars, the remnants of supernova explosions of massive stars, are among the strangest inhabitants of the Universe: ultra-compact, $1.5\times$ the mass of our Sun packed into an object with a diameter of merely 20 km, and with a crust that may be home to the most neutron-rich isotopes possible, surrounding an elusive core of unknown composition. The nuclear equation of state, electron capture rates, and the location of the neutron dripline are most important to understand in these extreme objects.

The field of nuclear astrophysics ties together nuclear and particle physics on the microscopic scale with the physics of stars and galaxies in a broad interdisciplinary context closely connected to astronomical observations and large-scale computation and theoretical modeling. One of the grand science challenges of our time is the question for the origin of the heavy elements in the Universe. Given what we know about atomic nuclei, a "rapid" neutron capture process (*r* process) must be one of the major nucleosynthesis processes in nature. It is thought to produce roughly half of the nuclei found in nature beyond the Iron region. While many elements have contributions from multiple processes, there are some that are chiefly produced by an *r* process, such as Xenon, Gold, Platinum, and Uranium.

The possible sites of the *r* process and consequently its conditions and reaction and decay sequences have remained elusive until 2017 where one *r*-process site was reported from a spectacular multimessenger astronomy campaign following the first LIGO/Virgo observation of the gravitational wave signal, GW170817, from a binary neutron-star merger. In addition to the gravitational-wave signal originating from two neutron stars spiraling into each other, a days-long glow, a "kilonova", fueled by the radioactive decay of the synthesized neutron-rich nuclear matter, was left behind, observed and characterized across the electromagnetic spectrum.

An understanding of the radioactive decays of the rare isotopes produced during the merger is crucial to interpret the kilonova signal and connect it to the observed cosmic abundances attributed to an *r* process. This observation has electrified the field of nuclear astrophysics and theoretical modeling of such events. Many decay measurements deep into the *r*-process relevant region have recently been performed at the Japanese rare-isotope facility RIBF at RIKEN Nishina Center.

The gravitational-wave signal from GW170817 has also provided unprecedented information on the size, mass, and deformability of neutron stars, which directly informs the fundamental properties of dense nuclear matter that can, to some extent, be probed in the laboratory through heavy-ion reactions during which nuclear matter is compressed to densities that depend on beam energy. Constraining the equation of state in laboratory experiments, for example, would allow to deduce the energy radiated by the gravitational waves. While it seems certain that these events produce lanthanides, the exact details of the relevant nuclear physics, most of which is yet unknown, will be needed to confirm that these sites are able to produce the heavier elements such as Gold and Uranium.

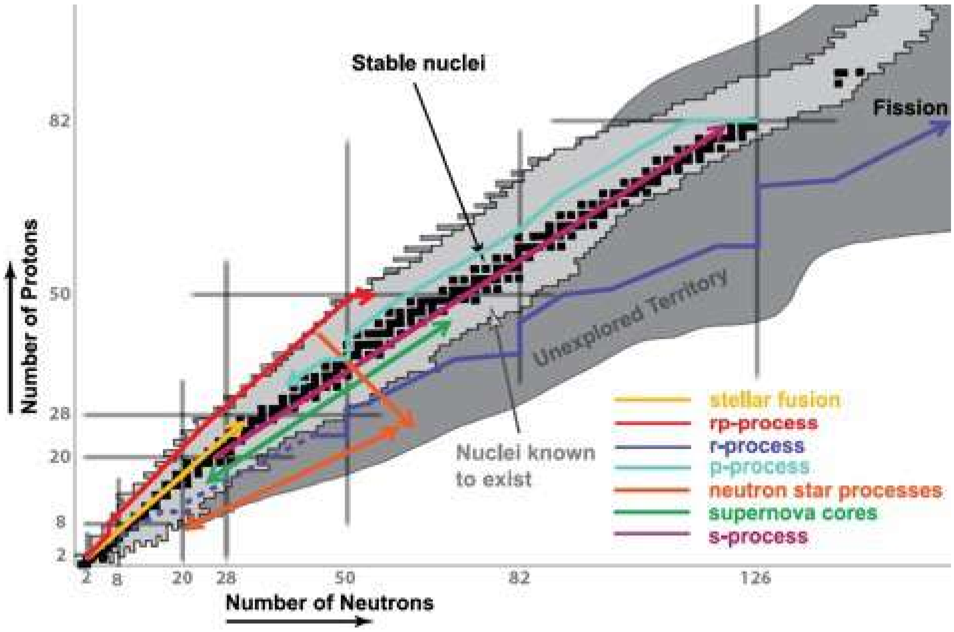


Figure 2.3: Nucleosynthesis processes across the nuclear chart. For most, the reactions and decay properties of rare isotopes are critical to understand the abundance patterns left behind [Figure from F. Timmes].

Studies of other nucleosynthesis paths, such as the "rapid proton capture" (rp) process that fuels X-ray bursts on the surface of accreting neutron stars, are at the verge of a breakthrough with recoil separators existing or under construction at facilities that will be able to deliver high-intensity, low-energy rare-isotope beams to directly measure proton- and α-induced capture reactions along the rp-process path in the relevant energy regime. In the meantime, great strides continue to be made with indirect approaches, often based on transfer reactions that constrain important capture rates when direct measurements are still impossible.

2.4 New paradigms - not your textbook nuclear structure physics

At the heart of the physics of rare isotopes is the study of the particle continuum beyond the nucleon driplines or the nucleon separation energy, the interrogation of changes to the textbook nuclear structure that we know from detailed exploration of stable nuclei and the discovery, and study of new phenomena that are unique to extremely neutron- or proton-laden systems.

As the driplines or nucleon separation energies are approached, weak binding and the proximity of the continuum leads to unique correlations that probe nuclei in the context of open quantum many-body systems. Near the neutron continuum, in addition to studies of the neutron-rich Oxygen isotopes, possibly including the discovery of two-neutron radioactivity, the neutron spectroscopy of discrete unbound states was extended into the region of Neon and Magnesium, where shell evolution is at play and the heaviest neutron halo systems yet were uncovered.

Neutron halos are a hallmark phenomenon of rare-isotope science and their recent identification in the A>30 region was a highlight. For heavier systems, one may not necessarily expect the formation of halos and it is rather suspected that the excess neutrons form a skin around a more symmetric core. While there is evidence for the development of neutron skins, the upcoming next-generation rare-isotope facilities are expected to reach nuclei with skins as thick as 0.5 fm, and after further upgrades even 0.8 fm. Reactions with such exotic systems may be the closest the field can get to study neutron matter in the laboratory.

One of the paradigms of nuclear structure is the shell model of the atomic nucleus, in which the motion of each neutron or proton is governed by a common force generated by all other nucleons. Nucleonic orbits bunch in energy, forming shells – and nuclei having filled nucleonic shells are exceptionally well bound. The numbers of nucleons needed to fill each successive shell are called magic numbers (2, 8, 20, 28, 50, 82, and 126 for stable nuclei). Among the most dramatic discoveries in current rare-isotope research has been the recognition that the traditional magic numbers can break down in the regime of extreme neutron- to-proton ratios and new shell gaps emerge.

Recent progress has been made in the study of shell structure along the traditional magic chains Calcium (Z=20), Nickel (Z=28), Tin (Z=50), and also in regions of rapid shell evolution such as neutron-rich Magnesium, Sulfur, Chromium, Iron, Selenium, and Krypton, for example. New detector arrays in the US and Europe as well as the highest beam intensities in Japan enabled the γ-ray and neutron spectroscopy of some of the most extreme systems of the isotopic chains mentioned above. Advances in mass measurements often allowed a first glimpse even before spectroscopic techniques were in reach, by looking at the evolution of nucleon separation energies, most importantly for the neutron-rich Calcium and Potassium isotopes, in recent years. The next-generation rare-isotope facilities under construction promise an unmatched reach for measurements of nuclear properties that indicate structural evolution and will allow to characterize in an unprecedented way the driving forces that need to be understood for a comprehensive model of atomic nuclei.

2.5 Rare isotopes as laboratory to unravel physics beyond the Standard Model

In spite of the stunning success of the Standard Model of particle physics, it is clear that there must be physics "beyond" it. Collider experiments, at the LHC for example, aspire to probe extensions through the (anticipated) observation of new particles at the highest energy scale. Complementary approaches are afforded through the study of decays mediated by the weak force or through the observation of nuclear properties, such as an electric dipole moment, that break certain symmetries.

Neutrinos are fundamental within the Standard Model. They are the only fermions that do not carry electric or color charge. The only quantum number that can be used to distinguish between neutrino and anti-neutrino is the lepton number. There are many extensions to the Standard Model that do not require lepton number conservation. If the lepton number is violated, the distinction between the neutrino and the anti-neutrino becomes unclear, possibly making neutrinos Majorana fermions that are their own anti-particles. If the rare process of neutrino-less double β decay is observed, it is proven that the neutrino is of Majorana character.

Preparations for ton-scale experiments are ongoing in the world, however, the nuclear matrix elements that govern the decay rate are highly uncertain at present. The nuclear matrix elements need to be known precisely for designing a neutrino-less double β-decay search and – in the event of a positive observation – to deduce the neutrino's effective Majorana mass. The nuclear theory community has initiated concerted efforts to calculate the nuclear matrix elements with quantified uncertainties. Nuclear structure experiments – transfer and charge-exchange reactions – have been performed for the candidate nuclei, providing critical benchmarks for the nuclear structure models that aspire to calculate the neutrino-less double-β-decay matrix elements.

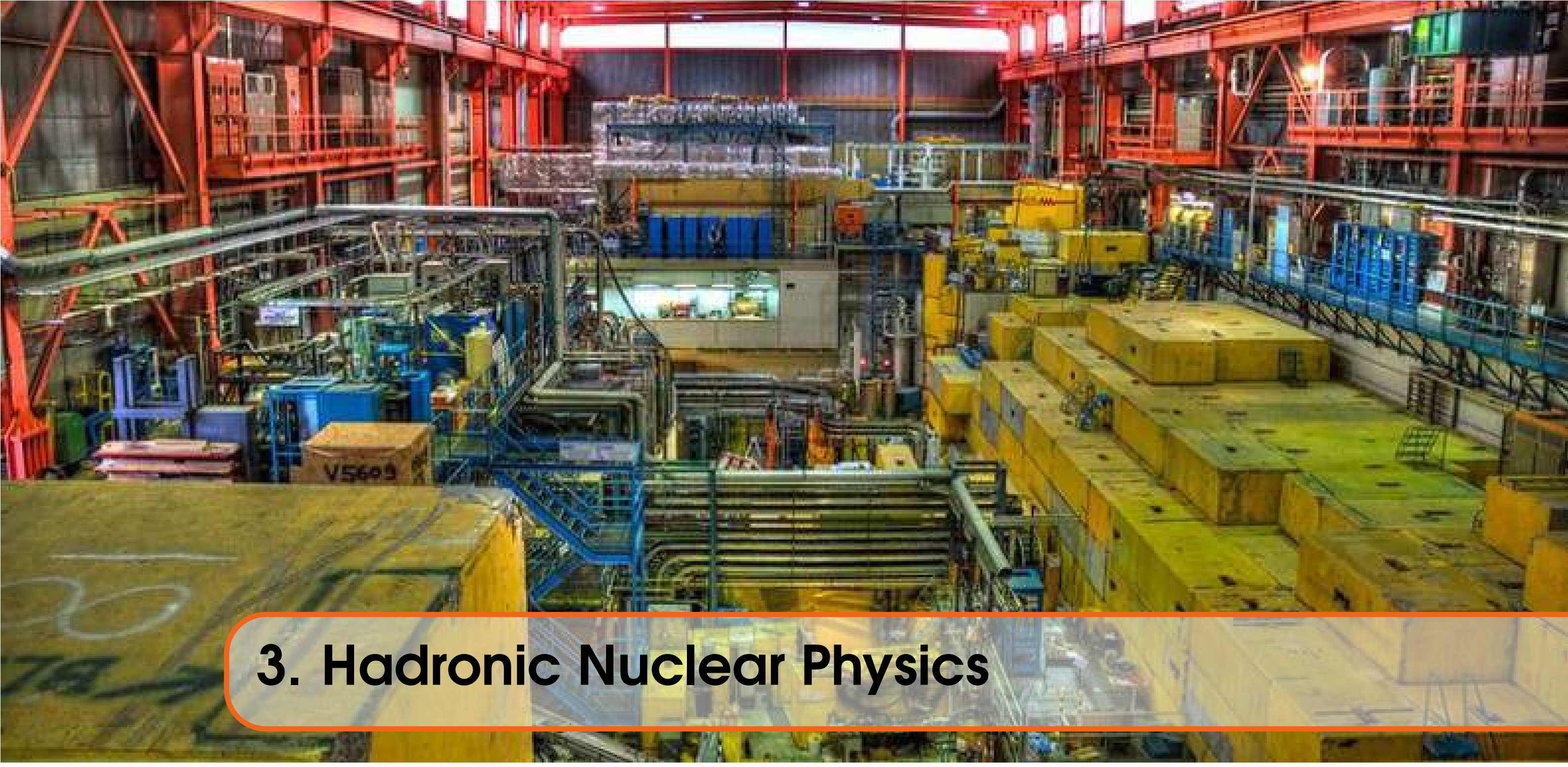
Addressing the apparent matter anti-matter asymmetry in the Universe, measurement of an electric dipole moment (EDM), which would separately violate parity and time-reversal symmetry, is one of the crucial probes of physics beyond the Standard Model, specifically searching for sources of CP violation. Heavy radioactive atoms hold promise as a sensitive system to search for EDMs. The EDM is induced by the interaction of the electrons with the nucleus. An enhancement of order 100–1000 (or more) is possible in nuclei that have pear-like shapes, such as Radium-225.

Recently, experimental progress has been made in the trapping and manipulation of Radium-225 for an EDM measurement and the technical paths to new gains in sensitivity have been identified. One of the mid-term goals of the field is to identify and characterize the best candidates for sensitivity enhancements in atomic EDM searches. Next-generation rare-isotope facilities will provide candidate nuclei at much higher rate, promising orders-of-magnitude increase in sensitivity for EDM searches.

2.6 Relevance

The relevance of nuclear physics spans dimensions from 10^{-15} m (the proton radius) to objects as large as stars – it covers the evolutionary history of the Universe from fractions of a second after the Big Bang to today, 13.8 billion years later. Nuclear physics, through uses of specific isotopes or derived technologies, impacts society in many ways. In addition to nuclear medicine, where certain radioactive isotopes are used therapeutically or for diagnostics, material and environmental science, energy research, or imaging techniques for security directly benefit from nuclear physics.

Recent highlights include measurements of the decay heat of fission fragments of relevance for nuclear reactors. Basic nuclear physics techniques, such as β decay and total absorption measurements have made critical contributions. In the future, rare isotopes useful for a variety of application may be harvested at rare-isotope beam facilities in research quantities. Proof-of-principle experiments have already demonstrated enormous potential with great promise for the future.



3. Hadronic Nuclear Physics

Updated December 4, 2017, by Cédric Lorcé (Ecole polytechnique, Palaiseau)

This is a particularly exciting time for hadronic nuclear physics. While Quantum Chromodynamics (QCD), the fundamental theory of the strong interactions, has been thoroughly tested in the high energy or short distance regime, understanding the low energy or large distance regime remains one of the current key challenges. We are in the middle of a concerted effort to explore the consequences of non-perturbative QCD (the form of QCD applicable for strong binding), exploiting at the same time recent breakthroughs in lattice QCD and new experimental facilities and machine upgrades to test those predictions. In this low energy regime, most of the attention has so far been drawn to the quark content, but a new major facility, the Electron- Ion Collider (EIC), is expected to be built in the next decade in the US to address for the first time in earnest the question of gluonic contributions, essential for completing and refining our modern picture of hadrons.

The first great challenge to be addressed is the question of confinement – that is, why free quarks have never been observed. This is connected in a fundamental way with the nature of the QCD vacuum, a complex medium of quark and gluon condensates and of non-trivial topological structure. A key to unraveling this mystery experimentally is the prediction that within QCD one should find so-called "exotic mesons" (called hybrids and glue balls), in which gluons play more than a binding role, by contributing to the observed quantum numbers in a characteristic way.

The experimental search for these exotic mesons is focused on the GlueX experiment at Jefferson Lab, upgraded to 12 GeV in order to have the necessary energy reach, and in the future on the anti-proton storage ring at the new FAIR facility at GSI, which will allow the high resolution exploration of charmed exotic mesons. These two facilities complement each other in that the latter will explore the nature of confinement in a heavy quark system, where a model invoking a flux-tube picture is perhaps a reasonable starting point, while the former focuses on light, relativistic quarks, for which it is much more difficult to construct a simple physical picture at present. Beside the search for exotic mesons, it has also been proposed to look for the LHCb charmed ‘pentaquark’ using photo-production of J/Ψ at threshold in Hall C at Jefferson Lab. This will shed a new light on

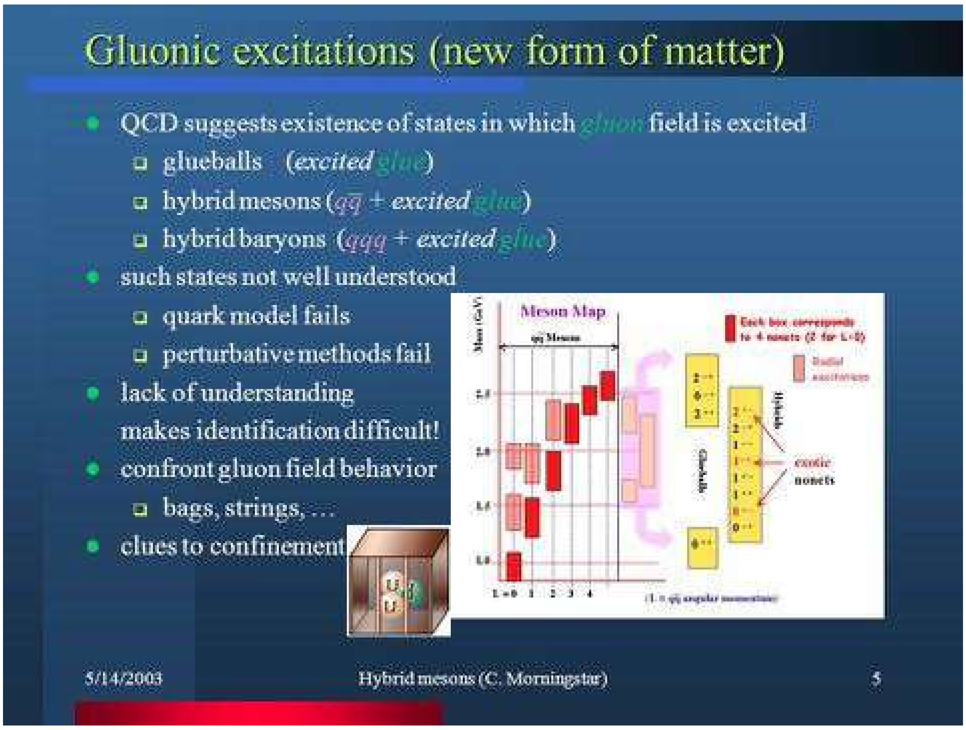


Figure 3.1: Spectrum of mesons (as anticipated by lattice calculations as well as QCD-inspired modeling) in the mass range of 1.5 to 2.7 GeV. Those nonets with J^{PC} quantum numbers that cannot simply be *qq* systems (often called "exotic") are labeled in red on the right.

the existence and properties of this non-standard type of matter, and in turn on the confining force.

Another key question in hadronic physics concerns the origin of the nucleon mass and spin. While the Higgs mechanism generates the mass of most of the elementary particles, the masses of light hadrons (which accounts for more than 99% of all matter around us) find essentially their origin in the strong interactions. The huge mass difference between bound states (like e.g. protons and neutrons) and their constituents (quarks and gluons) suggests that these systems are highly relativistic, and hence carry a significant amount of orbital angular momentum (OAM) already in the lowest state. It has now been fairly well established that about 25-30% of the nucleon spin is attributed to quark spin.

Recently, a compelling evidence for a large and positive gluon spin contribution, though with sizeable uncertainty, has been found using new results from the Relativistic Heavy Ion Collider (RHIC) in the US. The quest is now focused on nailing down the gluon contribution with better precision and the orbital motion. This is a formidable task where semi- inclusive deep inelastic scattering (SIDIS) studies at Jefferson Lab and Drell-Yan processes studied at RHIC and the COMPASS experiment at CERN are currently playing a major role. They are however not sufficient to resolve in particular the gluonic contributions, which is one of the main motivations for building an EIC.

New experimental facilities offer new ways to explore familiar problems – sometimes with surprising results. The ability at Jefferson Lab to separate electric and magnetic form factors of the nucleon, by studying recoil polarization (rather than using the traditional Rosenbluth separation), has led to a dramatic change in the picture of the proton charge distribution. With the 12 GeV upgrade of CEBAF at Jefferson Lab, accurate and reliable measurements of both the electric and magnetic form factors of the proton and neutron can be extended to distance scales a factor of two smaller than currently possible. That is, measurements can be made of structures in the nucleon at

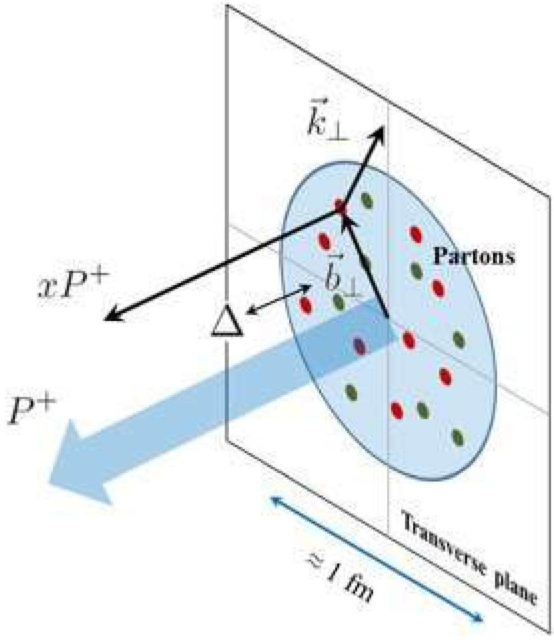


Figure 3.2: Partonic picture of hadrons. Quarks and gluons are characterized by their momentum and/or position relative to their parent hadron

distance scales much smaller than the nucleon itself, thereby probing the inner structure. By adding precision measurements of parity violation one can isolate the individual contributions of the u, d, and s quarks to these form factors – following pioneering work at MIT-Bates, MAMI@Mainz, and Jefferson Lab. Data on nucleon form factors in the time-like region are largely incomplete, but important results have recently been obtained by the BABAR collaboration.

In the last decade, there has been a huge interest in a new set of physical observables, the Generalized Parton Distributions (GPDs), which offer a three-dimensional (or tomographic) view of the internal structure of hadrons and, eventually, nuclei. Moreover, the GPDs also give access to the gravitational form factors which characterize the distribution of mass and pressure forces inside the nucleon. The CLAS 12 detector at Jefferson Lab has been designed to explore the proton GPDs across the entire valence region, while allowing sufficient overlap with the excellent work already done at smaller x at SLAC and reaffirmed in HERA and with Hermes at DESY. A particularly important milestone is the determination of the OAM carried by the u and d valence quarks. This is a key element of the question about how the proton spin is made up as discussed earlier. One may also hope to investigate the GPDs by applying them to the analysis of exclusive antiproton-proton annihilation into two photons at large energy and momentum transfer. It is proposed to measure crossed-channel Compton scattering and the related exclusive annihilation process with various final states (scalar meson, vector meson, or lepton pair) at FAIR.

Another set of new physical observables, the Transverse-Momentum parton Distributions (TMDs), has also recently attracted a considerable amount of attention. They provide complementary three-dimensional pictures of the nucleon, and reveal the importance of initial and final-states interactions. In particular, the so-called T-odd TMDs, like the Sivers and Boer-Mulders functions, are predicted to change sign when extracted from a Drell-Yan process instead of SIDIS. This fundamental feature is currently being tested at Jefferson Lab and COMPASS. TMDs allow one to probe also the transversely polarized quark distributions and hence determine the tensor charge of the nucleon. This is an important quantity as it measures the extent of relativistic effects and enters the analyses of dark matter searches. TMDs have recently been generalized so as to include also the information encoded in the GPDs. In doing so, a direct link with the OAM has been obtained, which greatly helped settling a longstanding controversy about the form of the proper nucleon spin decomposition. It is not clear so far whether generalized TMDs can be extracted from scattering experiments, but several processes have been proposed and are currently under investigation.

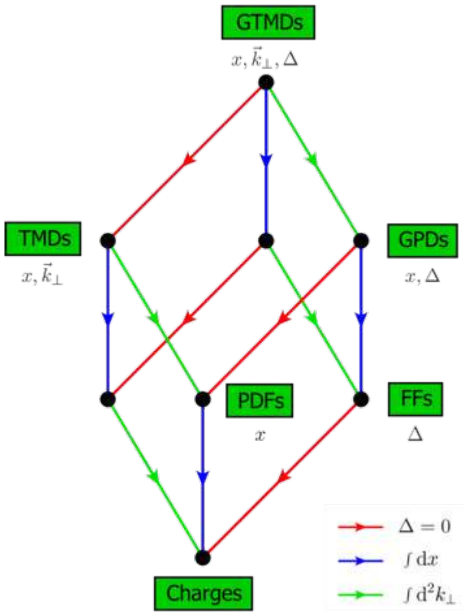


Figure 3.3: Complete set of parton distributions and their interrelations. Δ is the Fourier conjugate variable to position.

A common theme across modern nuclear physics is the effect of a change of energy or baryon density on the QCD vacuum and the hadrons which may live in it. Studies at GSI have already yielded important information on the change of pion properties with baryon density. There are many theoretical predictions of changes of baryon and vector meson masses and other properties with density and temperature which must be tested experimentally. An array of techniques ranging from hadronic atom formation to antiproton annihilation in nuclei to the spin correlation parameters in quasi-elastic electron scattering will be applied to these issues over the next decade. Again the three new hadronic flag-ship facilities, FAIR, J-PARC, and Jefferson Lab with its 12 GeV upgrade, will carry the prime responsibility.

A particularly fundamental question of interest to both the nuclear structure and nuclear astrophysics communities are the origins of phenomena such as the observed 'saturation' of nuclear binding within QCD: that is the total binding energy of nuclei does not simply increase linearly with the number of nucleons, suggesting some kind of screening or reduction in nuclear interactions over the extended size of nuclei. Great progress has been made in understanding the stable nuclei in terms of effective two- and three-body forces, derived either phenomenologically or through modern effective field theory based on the symmetries of QCD. A truly microscopic understanding of the origins of these effective descriptions at the quark and gluon level would allow one to gather more confidence in extending theories to regimes of density or neutron-proton asymmetry – for example at the densities found in the core of neutron stars or in nuclei with highly asymmetric numbers of neutrons and protons.

Some progress has been made in relating the widely used Skyrme force to the quark gluon level description of nuclei and this work needs to be continued. However, most importantly, this consideration points to the experimental challenge of measuring the changes of the properties of hadrons immersed in a nuclear medium, discussed above, especially important.

Last but not least, tremendous progress has been achieved by the Lattice QCD community

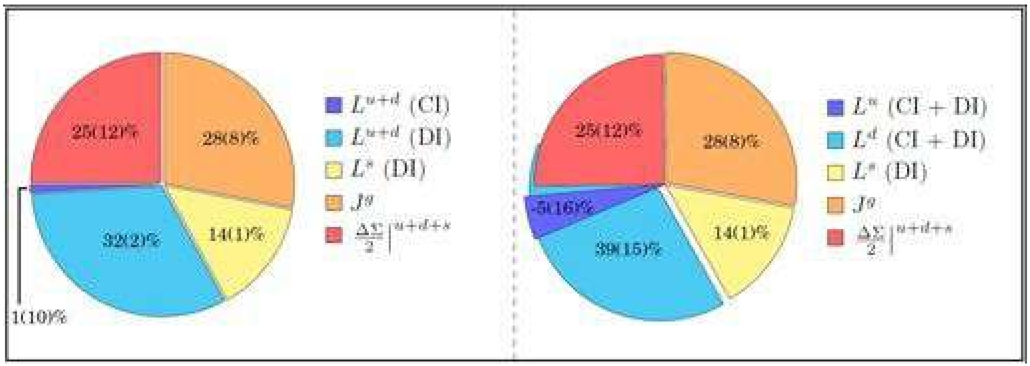
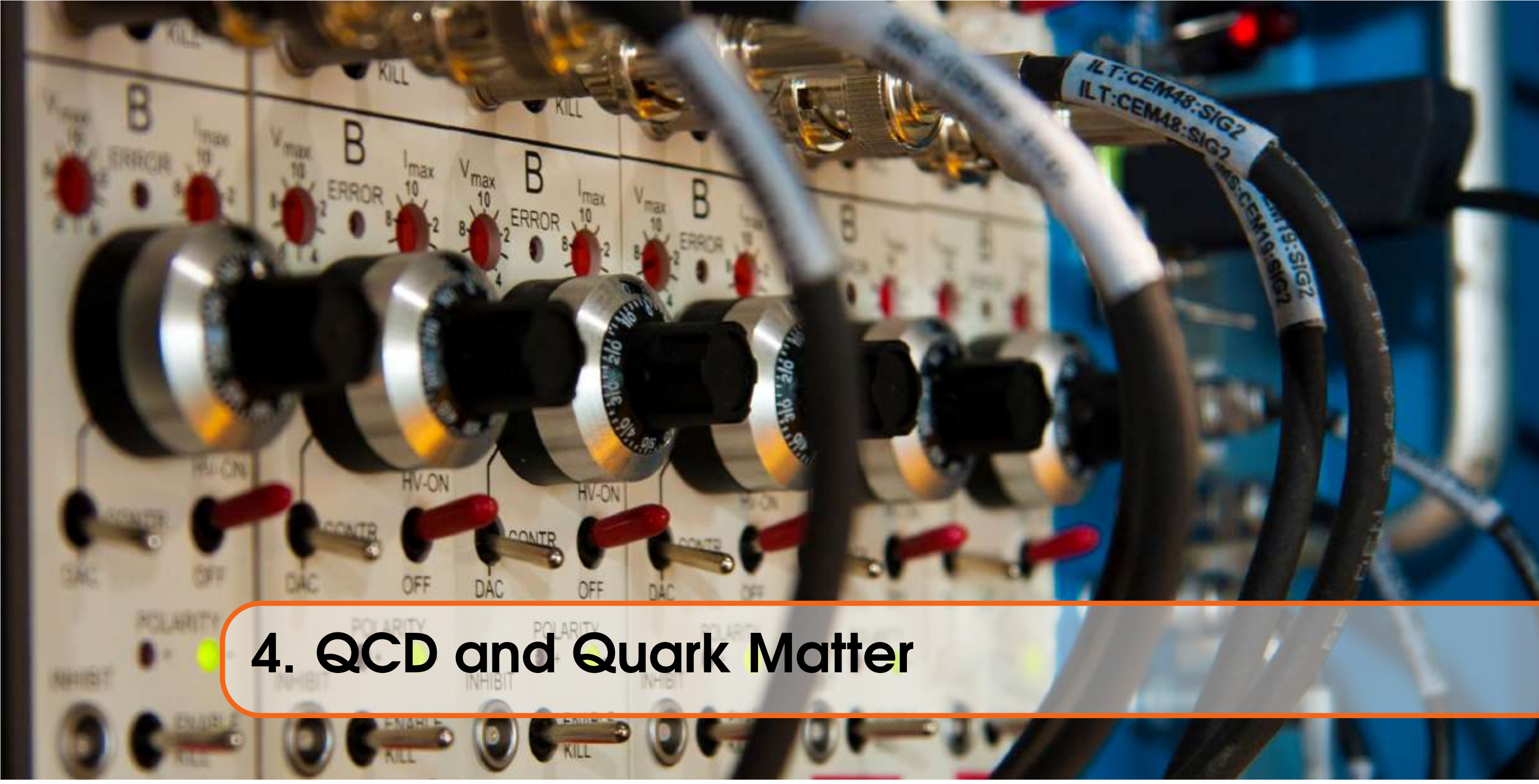


Figure 3.4: Pie charts for the quark and gluon spin and OAM fractions. The left panel shows the quark contributions separately for connected (CI) and disconnected insertions (DI), and the right panel shows the quark contributions for each flavor with CI and DI contributions summed together.

in the last few years. Calculations at the physical pion mass are now available, the so-called disconnected diagrams appear to give significant contributions to the flavor decomposition of angular momentum, and a new technique is currently under investigation allowing one to compute directly the momentum dependence of parton distributions. Effort will be invested in the near future to improve gluon contributions, and in particular the trace anomaly which plays a key role in the nucleon mass budget. No doubt that Lattice QCD will play an ever growing role in the study of the internal structure of hadrons.



4. QCD and Quark Matter

Updated January 15, 2018, by Berndt Mueller (BNL)

The fundamental interactions of nature are described by theoretical models called gauge theories. Quantum Chromodynamics (QCD), the theory of strong interactions, is such a theory, with just a small number of parameters to be determined from experiment. It is, however, difficult to compute the manifestations of QCD in nature except in the high momentum or short distance limit, in which the effective coupling is weak and where the perturbative approach is extremely successful. The spectrum and structure of strongly interacting particles is not calculable in this approach. Tools for understanding this structure include experiment and computer simulations of QCD.

The important questions about QCD that can be accessed with these tools may be formulated as follows:

1. What are the phases of strongly interacting matter and what roles do they play in the cosmos?
2. What is the role of gluons in nucleons and nuclei?
3. What determines the key features of QCD; can they be understood as manifestations of holographic duals described by gravity or string theory?
4. Can the study of QCD vacuum fluctuations at high temperature illuminate other early-universe processes, such as the one responsible for the matter-antimatter asymmetry?
5. How are the unique properties of QCD manifested in unusual properties of strongly interacting matter?

Gauge theories describing other fundamental interactions raise similar questions, and presumably the phase structure of each played its role in the very early development of the Universe. The case of QCD is special, because it can be studied experimentally. Based on the results of lattice gauge theory simulations, the transition from hadrons to a quark-gluon plasma occurs at T≈160 MeV, which is low enough to be studied in the laboratory. (This is not the case for the electroweak gauge theory, where symmetry breaking occurs at T≈100 GeV, out of experimental reach.)

The experimental approach to the study of strongly interacting matter at very high temperatures involves collisions of hadrons at very high energy. The study of the properties of dense, many-body

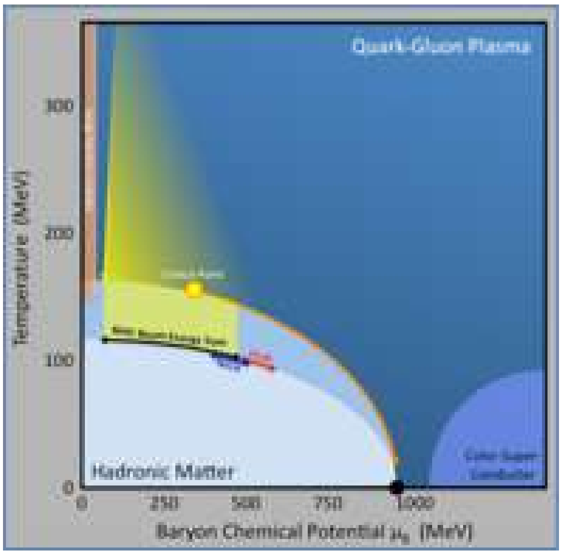


Figure 4.1: Anticipated phase structure of hadronic matter.

systems – implicit in most of the questions above – requires a large volume of high energy density matter. Thus, the fundamental questions about the physical states of strongly interacting matter are addressed in the laboratory by studying heavy ion collisions at relativistic energies.

In order to gain new understanding of QCD from the interaction of relativistic heavy ions, one needs directly comparable data sets from systems of various sizes, different energies and different experimental probes. These ancillary data sets provide "baselines" against which the largest volume, highest temperature, reactions can be compared. Thus a fundamental and systematic study of QCD requires data on nucleus-nucleus, proton-nucleus (or deuteron-nucleus), as well as proton-proton collisions, all at comparable nucleon-nucleon center of mass energies, and preferably in the same detector systems. Hard processes, which can be accurately calculated in proton-proton collisions using perturbative QCD, can then serve as calibrated probes of the medium created in collisions involving nuclear beams.

Addressing many of the questions above also requires data from high energy interactions of hadrons with non-hadronic probes, e.g., deep inelastic scattering (DIS) of leptons from nuclear targets ranging from protons to heavy ions. Addressing the question on the properties of strongly interacting matter also requires the use of spin-polarized beams and/or targets at the highest energies. Fixed target and collider experiments have contributed to the experimental attack on these questions over time. Taking beam energies of 1 GeV or greater, one has:

- fixed target heavy-ion experiments (CERN-SPS, SIS-GSI/FAIR);
- fixed target proton-nucleus studies (Fermilab, J-PARC);
- heavy ion collider experiments (BNL-RHIC, CERN-LHC and in the future NICA);
- fixed target-lepton DIS experiments (CERN, JLab-CEBAF);
- DIS collider experiments (formerly at DESY-HERA – in the future possibly at EIC or LHeC);
- polarized beams (RHIC, future possibilities at eRHIC and JLEIC).

Recent results in this field have primarily come from RHIC at BNL and LHC at CERN. The experiments at RHIC and LHC have produced many new and often unexpected results, which can be summarized as follows: At nucleon-nucleon center of mass energy $\sqrt{s_{NN}} > 100$ GeV, central collisions of heavy nuclei produce a system that reaches a temperature of approximately 300 MeV ($\approx 4\times 10^{12}$ K) and very small baryon chemical potential. This temperature is well in excess of the critical transition temperature predicted by lattice gauge simulations ($T_{crit} \approx 160$ MeV).

A new state of matter is produced under these conditions and observed to have the following properties:

- The matter is an almost "perfect" liquid of quarks and gluons with a shear viscosity-to-entropy density ratio near the quantum limit. This is deduced from the systematics of the collective flow imprinted on the emitted particles, which is well described by nearly inviscid hydrodynamics. Valence quark scaling of the flow indicates that the matter is initially composed of individual quarks, not hadrons. This leads to the conclusion that the produced hot matter is a strongly coupled Quark-Gluon Plasma (sQGP).
- Collective flow effects are also observed for small collision systems at high collision energy, when the number of produced particles is large.
- The matter is opaque to strongly interacting particles (deduced from "jet quenching" measurements) but transparent to real and virtual photons (deduced from direct photon and lepton pair measurements).
- The production of heavy quarkonium states is strongly suppressed when heavy quarks are rare, consistent with partial screening of the color force between heavy quark-antiquark pairs inside the hot matter, but becomes enhanced when heavy quarks are produced abundantly, probably due to final-state recombination.
- Rapidity distributions of produced particles and the suppression of correlated particle production at forward angles in collisions of nucleons with heavy ions are consistent with the existence of a soft gluon component in nuclei called a Color Glass Condensate (CGC).

New questions about the properties of the sQGP have emerged from these discoveries:

1. How close is the shear viscosity-to-entropy density to the quantum bound and how does its value change with temperature?
2. Do heavy quarks (charm, bottom) participate in the collective flow of the sQGP?
3. How small can a droplet of sQGP be and behave collectively as "matter"?
4. Are there quasi-particles in the sQGP that survive at $T > T_{crit}$?
5. What is the color screening length in the sQGP?
6. What are the dominant parton energy-loss mechanisms in sQGP?
7. Is there a critical point in the QCD phase diagram?
8. Is chiral symmetry restored at $T > T_{crit}$?

These and many other questions are under active experimental investigation in a diverse program that includes the study of jets and γ-jet correlations, heavy quarks and quarkonia, low-energy beam scans and proton-heavy ion collisions. A luminosity upgrade for low beam energies using electron cooling will extend the reach of RHIC into the baryon dense region of the QCD phase diagram where there are indications that the critical point may be located. The CERN-LHC heavy ion program continues with upgrades of all detectors planned in 2019-20. A focus of the experiments at the LHC will be hard probes, such as jets, heavy quarks and quarkonia. These processes, which are produced at the early stages of the collision, are sensitive probes of the collision dynamics at both short and long timescales.

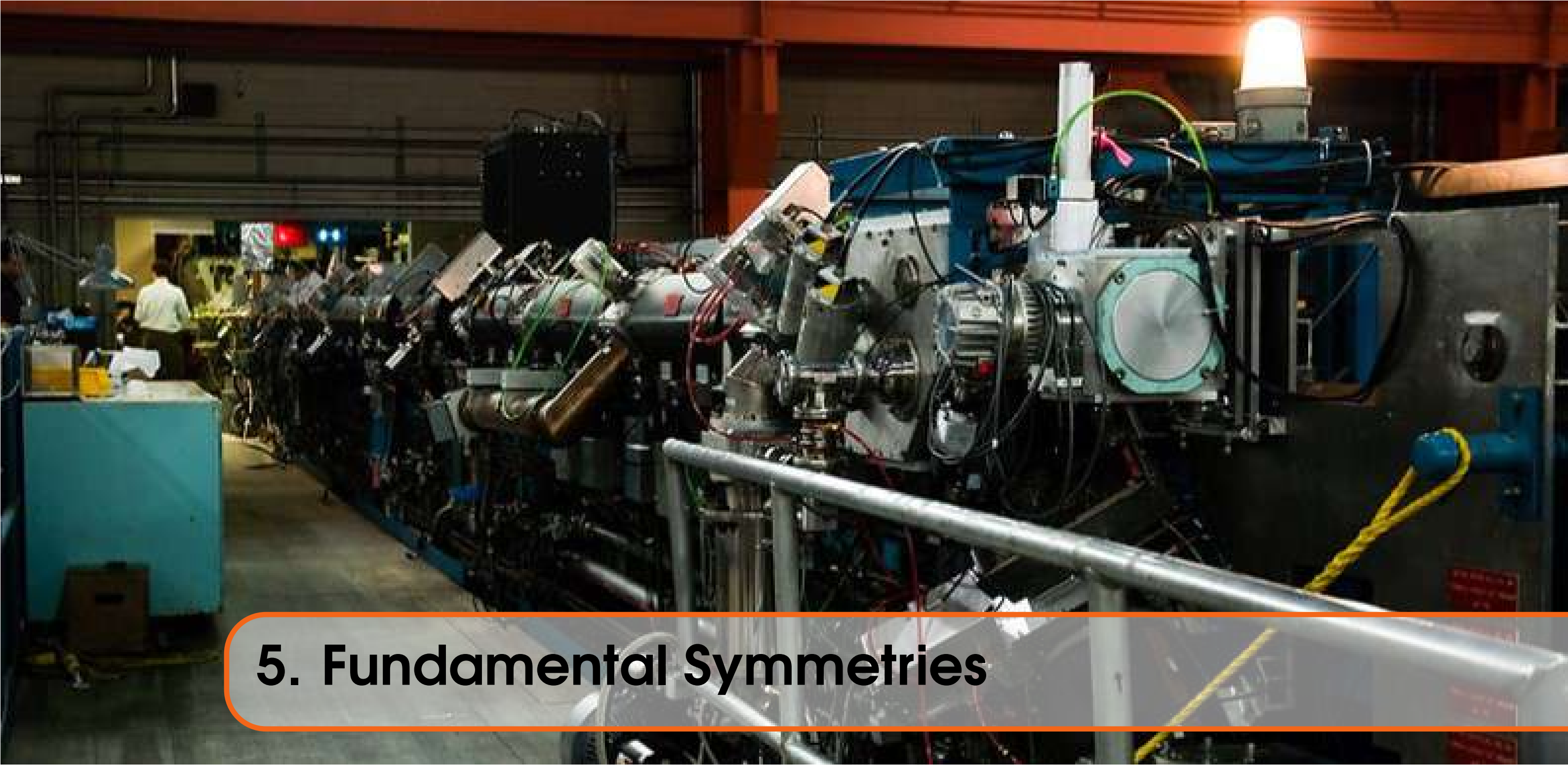
After 2025 complementary studies of the structure of strongly interacting matter are planned at the Facility for Antiproton and Ion Research (GSI-FAIR), where fixed-target ion-ion collisions at lower energies can create nucleus-sized volumes of lower temperature, high baryon density samples of nuclear matter.

Much of our present understanding of the spin structure of strongly interacting matter comes from deep-inelastic scattering measurements of leptons on fixed targets. However, polarized hadron-hadron collisions are directly sensitive to the gluons, and over the last several years significant progress has been made in understanding the role of gluons in the proton's spin. Measurements at RHIC have established that gluons make a substantial contribution to the spin of the proton. Spin asymmetry measurements of W boson production in polarized proton-proton collisions at $\sqrt{s}= 500$ GeV at RHIC provide flavor-separated quark and antiquark helicity distributions.

At high energy, two fundamental aspects of the nucleon partonic structure will remain a focus: One is the nature of the nucleon spin; the other is the nature of the quark and gluon momentum and spatial distributions in the nucleon.

There are plans at BNL and Jefferson Lab to open up a new window on deep inelastic lepton-hadron experiments using electron-ion collisions. At BNL this would involve the addition of an electron ring to one of the existing hadron rings. At Jefferson Lab there are plans to add a figure-eight shaped hadron ring to the existing 12 GeV electron accelerator. Both proposals would make available electron-ion and polarized electron-polarized proton collisions and enable studies of the structure of strongly interacting states of matter using precision (lepton) probes in novel kinematic domains. *[Addendum: The U.S. Department of Energy evaluated proposals from BNL and Jefferson Lab to build an Electron Ion Collider in 2019. Early in 2020, BNL was chosen as the site and now BNL and Jefferson Lab are working together to realize the EIC at BNL.]*

Consideration has also given to adding an electron ring (LHeC) to the CERN-LHC in order to study electron-nucleus collisions at extremely small values of Bjorken-x and high luminosity.



5. Fundamental Symmetries

Updated December 27, 2017 by Jens Erler (UNAM)

With the recent discovery of a particle whose properties are fully consistent with those of the Standard Model (SM) Higgs boson at the LHC, we are about to close a chapter in our quest to understand the fundamentals of the observable universe. The SM, the theory for the strong, electromagnetic (EM) and weak interactions, has to be seen as an overwhelming success, and is in remarkable agreement with the available experimental data (some anomalies aside).

While the details of the SM, such as its particle content and the values of its parameters, are rather ad hoc, its basic structure is dictated by the axioms of quantum mechanics and Lorentz invariance (the independence of physical observables from space rotations and boost transformations) implying an effective field theory (EFT) picture including an ordering principle in terms of mass scales. The fundamental SM Lagrangian arises here as the most general possibility consistent with the assumed SM particles and gauge interactions, and — most importantly — predicts fundamental symmetries such as baryon number (B) and lepton number (L) conservation to leading "renormalizable" order, i.e., up to order four in mass dimension. Various other symmetries are not exact at this level, but their violations are strongly suppressed or are otherwise known to be very small. Thus, high precision tests of fundamental symmetries in particle, nuclear, hadronic and atomic physics serve as indispensable alternatives to the energy frontier, often probing scales not accessible at any existing or planned high-energy collider.

The EFT picture fails dramatically in two respects. The cosmological constant (the unique dimension zero term and possibly the source of the "dark energy" responsible for the accelerated expansion of the universe), and likewise the bilinear (dimension two) Higgs mass term, introduce hierarchies of scales (relative to the Planck scale) which are not understood and moreover are unstable under radiative corrections. It is well possible that at least the problem related to the Higgs may be solved by the discovery of new physics beyond the SM (BSM) with a characteristic scale around a TeV. In this context it is interesting to note that the matter as described within the SM only amounts to 5% of what constitutes the universe. The "dark matter" (about 27%) is possibly a manifestation of TeV scale BSM physics, but may also be associated with very different energy scales. Nuclear physics experiments provide a special quantum context in which selection rules can be used to extract specific components of the new physics with enhanced symmetry violation effects.

For example, one can use the fact that the EM interaction is invariant under space reflections, i.e., under parity transformations (P). With the exception of the tiny θ_{QCD} term, the gauge theory for the strong interaction (QCD) also respects P, so that experiments measuring parity violating (PV) effects in atomic physics or in polarized electron scattering directly probe the weak interaction and new physics. Note, that one generally expects the latter to be chiral and therefore P violating, since this would shield new fermions from receiving ultra-heavy masses, in much the same way as the SM fermions are massless before electroweak (EW) symmetry breaking (at Λ_{EW} = 246 GeV). This strategy is particularly fruitful whenever the SM contribution to a given PV observable is small, which is the case for the left-right polarization asymmetry in both Møller (E158 at SLAC and MOLLER at Jefferson Lab) and e-p scattering (Qweak at Jefferson Lab and P2 in Mainz). These experiments will determine the weak charges (Q_W) of the electron and the proton, respectively, and will not only probe multi-TeV energies, but also test the scale (μ) dependence ("running") of the central EW gauge parameter, the weak mixing angle, $\sin^2\theta_W$, as illustrated in Fig. 5.1.

However, the interpretation of the former is obstructed by nuclear effects and by quark charge symmetry violation effects, which need to be understood independently before electroweak physics can be extracted unambiguously. The *e*DIS data point in Fig. 5.1 is inferred from scattering off deuterons which is easier to treat theoretically and which is dominantly from the recently completed PVDIS experiment at the 6 GeV CEBAF at Jefferson Lab. SoLID is with a future detector to be exposed to the upgraded (12 GeV) beam for a more precise follow-up experiment. LEP 1, SLC, Tevatron, and LHC all refer to weak mixing angle extractions from Z pole asymmetries (for clarity the Tevatron and LHC points are shown shifted horizontally). Another possibility (not shown in the figure) is to map out the sub-Z pole region to about % precision at an electron-ion collider (EIC). Likewise, e-p modes of the LHC (LHeC) and of other possible future circular colliders like the FCC (CERN) or the CEPC/SppC (China) would be able to populate the above-Z pole branch.

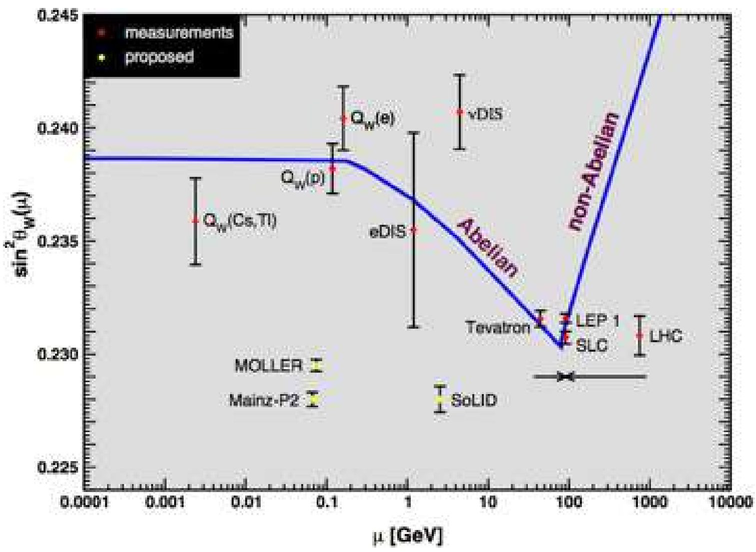


Figure 5.1: Calculated running of the weak mixing angle in the SM, as defined in the modified minimal subtraction scheme. The theoretical uncertainty is below the thickness of the blue curve. Red points with error bars show existing data and yellow points (with arbitrarily chosen ordinates) refer to future experiments. Q_W(Cs,Tl) derives from atomic parity violation, Q_W(p) from Qweak, and Q_W(e) from SLAC-E158, while νDIS and *e*DIS denote deep inelastic neutrino (NuTeV at Fermilab) and electron scattering, respectively.

This class of experiments can also constrain the properties of a dark photon which has been hypothesized as the mediator between a dark sector (possibly responsible for the dark matter) and our visible world. Interestingly, such an object could also affect the anomalous magnetic moment of the muon, g_μ-2, which is known to deviate at the level of almost four standard deviations from the SM. Thus, it is of utmost importance to improve the experimental precision in g_μ-2 which is the goal of new experiments at FNAL and J-PARC, and to reduce the theoretical (hadronic) uncertainties in its SM prediction.

Searches for dark photons and other very weakly coupled new light particles are part of a larger effort to discover the nature of the dark matter. For example, direct detection experiments are in full swing trying to detect the scattering of hypothetical weakly interacting massive particles (WIMPs) with nuclei. And the search for new sub-millimeter range forces is well motivated theoretically and may provide a link to both dark matter and dark energy.

One may also look for new Lorentz structures which are absent in the SM at leading order. The charged current weak interaction takes the form of a specific combination of vector and axial-vector (V-A) terms (as tested in many β decay experiments) and hence exhibits maximal PV. However, the present set of experimental data cannot exclude the presence of scalar, pseudoscalar, tensor or V+A terms at the few percent level. It is then one of the goals of the program of testing fundamental symmetries to tighten these constraints on the Lorentz structure of the weak interaction through semi-leptonic decays (nuclear decay distributions) and purely leptonic decays of muons (such as by the TWIST Collaboration) and taus. Related approaches attempt to test lepton universality to very high precision in decays with l = e or μ (at PSI and TRIUMF) or to study the predicted unitarity of the CKM mixing matrix connecting the mass and interaction eigenstates of quarks.

In particular, there is a worldwide effort to determine the CKM element V_{ud} from neutron decay to high precision to match or surpass the V_{ud} precision from super-allowed Fermi nuclear β-decays. N_{ab} at the SNS, PERC in Munich, as well as PERKEO III and UCNA will improve the constraint on the axial-vector Gamow-Teller transitions, and the existing experimental discrepancies in the neutron lifetime derived from cold neutron beams on the one hand, and ultra-cold neutron storage experiments on the other, need to be resolved.

Much higher energy scales can be probed by electric dipole moments (EDMs). They violate time reversal invariance (T) which in any quantum field theory (QFT) is equivalent to CP invariance – the product of charge conjugation (C) and P. The observed CP violation (CPV) in K and B-meson systems is fully accounted for by the complex phase (δ_{CKM}) appearing in the CKM matrix. However, δ_{CKM} cannot induce effects in EDMs that would be large enough to be detected in any current or planned experiment. As a consequence, if a permanent EDM was observed it would be tantamount to the discovery of a BSM effect with very far-reaching consequences. To understand the deeper origin of the effect it would then be necessary to experimentally probe EDMs in as many systems as possible, including leptons, nucleons, nuclei, diamagnetic and paramagnetic atoms, and molecules.

Since the θ_{QCD} term could induce a nucleon EDM, it would be particularly interesting to isolate a leptonic EDM. The current limit for the electron EDM, d_e, by the ACME Collaboration can be expressed as $|d_e| < e\,\Lambda_{EW}$ (227 PeV)$^{-2}$ (with e being the fundamental electric charge) which sets the sensitivity scale. More than half a dozen experiments worldwide are aiming to strengthen the limit on the very complementary neutron EDM to a similar level and many other systems are being explored. The search for new sources of CPV should be a priority in that the observed baryon-antibaryon asymmetry in the universe (BAU) can only be explained by CPV beyond δ_{CKM}, and also since most BSM scenarios introduce many new complex CPV phases.

Such enormous scales can also be reached in charged lepton flavor violation experiments, including $\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^-e^+$, $K_L \to \mu^\pm e^\mp$, muonium-antimuonium oscillations and μ to e conversion. The complementarity of these processes in the context of different BSM scenarios is well appreciated. Furthermore, the strong suppression of flavor-changing neutral currents in the

SM allows for comparable sensitivities in decays such as $K \to \Pi \nu \bar{\nu}$. Future measurements of the charged (CERN) and neutral (J-PARC) modes will also provide unique constraints on the smaller elements of the CKM matrix.

The BAU also calls B conservation into question. Proton decay experiments already ruled out simple scenarios of Grand Unified Theories of the strong and EW interactions, probing scales in the vicinity of the fundamental Planck scale. The Planck scale itself may come into play should the QFT framework break down, signaled, e.g., by a violation of CPT invariance. The most sensitive tests look for differences in the masses or lifetimes of particles and antiparticles or compare the atomic spectra of hydrogen with antihydrogen as was recently achieved by the ALPHA Collaboration at CERN.

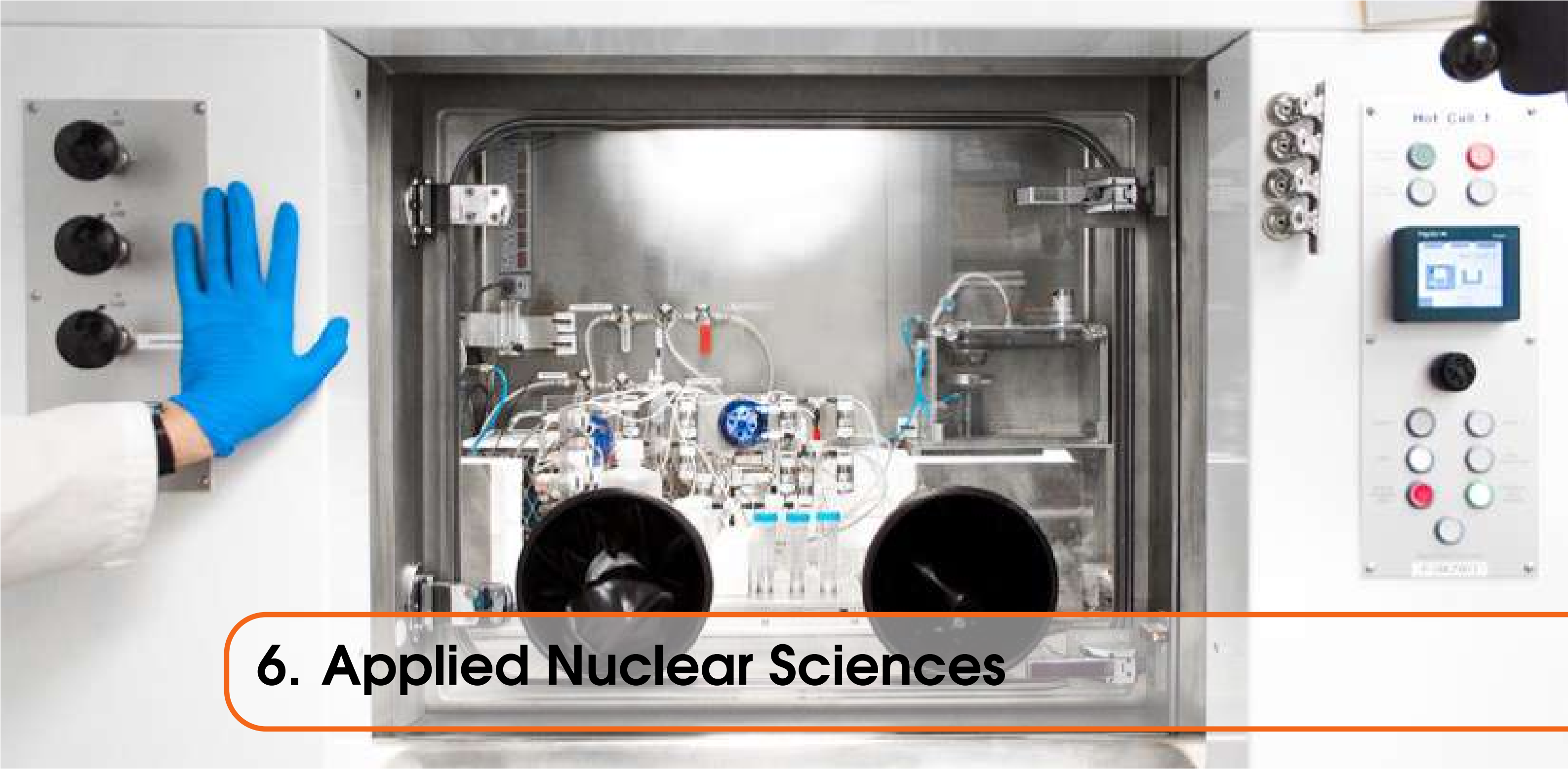
Neutrino mass and mixing are now believed to be at least the major contributor to the phenomenon causing neutrinos to oscillate between flavor eigenstates as observed for solar neutrinos, atmospheric neutrinos, reactor antineutrinos, and accelerator neutrinos. The corresponding Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix is completely analogous to the CKM matrix, except that it allows for two additional complex CPV "Majorana" phases provided the neutrinos are Majorana particles (their own antiparticles). One can incorporate Majorana ν masses within the SM (without introducing new particles) but only if one includes dimension five terms into the EFT of the SM.

In this picture, the neutrino mass scale of order 100 meV or less would be generated by a very large "see-saw scale" roughly of order 10^{14} GeV. Majorana mass terms violate L conservation and would generate ν-less double β decay. This would be a fundamental and new kind of process, and would also determine the absolute ν mass scale (provided that the transition nuclear matrix elements can be evaluated with sufficient accuracy), while ν oscillations are only sensitive to mass-square differences. Currently, the most stringent limit on the lifetime of 5.3×10^{25} years against ν-less double β-decay has been achieved by the GERDA Collaboration.

The more traditional way to determine the absolute ν mass scale is by measurements of β-decay spectra near their kinematically allowed endpoints, such as the new tritium decay experiment KATRIN with a projected sensitivity to ν_e masses down to 200 meV. Moreover, the Project 8 Collaboration demonstrated the viability of a technique for β spectroscopy based on cyclotron radiation which would allow for even greater sensitivity.

On the other hand, should L be a fundamental symmetry of nature one would need to introduce right-handed neutrinos to allow for Dirac masses just as for quarks (but with tiny Yukawa couplings). It is stressed that with the recent extraction of the smallest of the three mixing angles (θ_{13}) the reactor experiments Double Chooz, Daya Bay and RENO have completed the determination of the mixing part of the PMNS matrix. Moreover, θ_{13} is large enough that one can hope to discover a non-trivial value of the CPV Dirac phase (the PMNS analog to δ_{CKM}) by studying the difference between neutrino and the corresponding antineutrino oscillations in experiments based on long baselines. Indeed, first results from the T2K experiment provide a statistically weak indication (at the level of about two standard deviations) for a CPV Dirac phase in the PMNS matrix, joined by an even weaker preference for a ν spectrum with a normal hierarchy, i.e., a spectrum in which the lightest mass eigenstate has the greatest overlap with the electron neutrino and which thus mirrors the quark hierarchy.

Further insight may be gained from experiments studying neutrinos traversing the Earth to isolate matter effects. Some experimental anomalies in the neutrino oscillation sector may be interpreted in terms of "sterile" ν states (extra gauge neutral fermions) calling for further experimental efforts to clarify our understanding.



6. Applied Nuclear Sciences

Updated January 1, 2018, by Marco Durante (TIFPA-INFN)

Over the past five years, applications of nuclear physics continued to grow and to produce benefits for the society. The latest Long Range Plans of the Nuclear Physics European Collaboration Committee (NuPECC, 2017) and of the US Nuclear Science Advisory Committee (NSAC, 2015) identify several specific applications that characterize the broader impact of nuclear sciences in the society. Recent developments in the main applications are summarized below.

6.1 Medical applications

Applications of nuclear physics in medicine are perhaps those with the largest expansion potential in nuclear physics. According to the 2014 NuPECC report "Nuclear Physics in Medicine", medical applications can be further sub-divided into three sectors.

Imaging

Radiography was the first medical application of X-rays and also today represents the most obvious benefit of nuclear physics in medicine. Recent improvements include spectral CT, such as K-edge imaging, based on hybrid pixel detectors; 3- photon cameras (gamma-PET); and ultra-high field MRI. Even if not yet used in clinics, 7T MRI will provide anatomical detail at the submillimeter scale, enhanced contrast mechanisms, outstanding spectroscopy performance, ultra-high resolution functional imaging (fMRI), multinuclear whole-body MRI and functional information. Industrial developments of CT scans are also remarkable, and the most recent devices can scan at 737 mm/s, thus making a chest scan in less than a second and a full body scan in five seconds only.

Particle therapy

Radiotherapy with accelerated charged particles, a typical medical application of nuclear physics, is rapidly growing. At the end of 2017, there are 63 centers worldwide for cancer treatment with protons (52 centers) or carbon ions (11 centers). It is estimated that over 200 centers will be active by 2021.

However, despite increasing evidence of clinical efficacy and low toxicity, the method remains controversial. In fact, particle therapy remains much more expensive than X-ray therapy. The success of this therapy in the future will strongly depend on progress in nuclear physics leading to a reduction of the costs – especially the construction of smaller, compact accelerators and beam delivery systems (gantry). Moreover, it will be necessary to improve the benefit of the treatment, i.e. to show that it can provide a decisive advantage also for patients not traditionally elected for particle therapy (i.e. all pediatric patients and adult patients affected by chordomas, chondrosarcomas, bone and soft tissue sarcomas, ocular tumors).

Several comparative clinical trials are ongoing to prove the superiority of charged particles over X-rays for high incidence and mortality tumors, such as pancreas cancer. Results of these trials are necessary to demonstrate that the physical and radiobiological rationale of particle therapy translates into clinical benefit. In recent years, a major breakthrough in cancer therapy has been the success of immunotherapy for treatment of highly lethal cancers, especially melanoma. Excellent results have also been obtained with targeted cancer therapy. The combination of radiotherapy with these new drugs is currently the main topic of interest in oncology, and the role of charged particles in this frame has just started to be tested.

Another rapidly expanding field is that of noncancer diseases. Stereotactic body radiotherapy with X-rays has been successfully applied for the first time to the treatment of ventricular arrhythmia. Pre-clinical studies using carbon ions in a swine model suggest that particle therapy may cure heart arrhythmia with reduced toxicity (Fig. 6.1). This application may largely increase the number of patients who can benefit from particles.

Figure 6.1: Particle therapy for heart disease. An anesthetized pig during an irradiation with high-energy ^{12}C-ions at the GSI Helmholtz Center in Darmstadt (Germany). The beam, coming from the orange window, is directed to the heart of the animal in a feasibility study for cardiac arrhythmia ablation using external, non-invasive, heavy ion beams. Online PET imaging is provided by the detectors on top and bottom (Lehmann et al., Sci. Rep. 6: 38895 (2016)).

Radioisotopes

The use of radionuclides for diagnostic purposes (SPECT and PET) is a mature field in nuclear medicine. The main problem is the shortage of the common isotope $^{99}Mo/^{99m}Tc$ (emitting a 140 keV photon with a half-life of approximately 6 h), the "workhorse" for imaging by gamma cameras and SPECT. New facilities based on fission reactors, cyclotrons, or high intensity linear accelerators are necessary to ensure a regular supply of these important radioisotopes.

Therapeutic applications of the radionuclides have been growing in the past years. The use of ^{131}I for thyroid cancer has been established for many years, but the recent introduction of new vectors (antibodies, peptides, and folates) makes it possible to deliver radionuclides to many common, resistant cancers, and to target micro- metastasis or minimal residual disease following surgery or teletherapy. For targeting single cells, isotopes emitting α-particles or Auger electrons are interesting, because they have short range and high biological effectiveness. A few clinical trials are already ongoing, but the main limitation remains the availability of the exotic isotopes (e.g. ^{117m}Sn for Auger electrons or ^{225}Ac for α-particles).

New interesting applications are those in the new field of theranostics, where radioisotopes are used simultaneously for imaging and treatment. This requires the combination of two, chemically identical (e.g. ^{64}Cu/^{67}Cu) or similar (^{99m}Tc/^{188}Re) isotopes, bound to the same vector; or a single isotope (e.g. ^{117m}Sn) able to destroy the target cells and to be visualized externally.

6.2 Environmental applications

Nuclear physics has greatly contributed to our understanding of climate changes and the impact of anthropogenic activities. Proton–induced X-ray emission (PIXE), Ion Beam Analysis (IBA), and Accelerator Mass Spectrometry (AMS), can accurately measure the composition of the atmospheric aerosol and give to policymakers the knowledge and the tools for a significant reduction in anthropogenic emissions. The new US administration reverted previous environmental policy pulling out of the Paris climate agreement. The development of efficient technologies for elemental and radionuclide analysis to monitor environment changes is therefore becoming more and more relevant. Studies of environmental radioactivity also rapidly evolved in the past few years. Beyond the radioactive waste of nuclear power plants, the focus is now moving toward naturally occurring radioactive materials generated in oil, gas, and mineral production industries, including fracking. Notwithstanding the European efforts in funding large research programs (the EU MELODI platform), large uncertainties remain on the low-dose radiation risk. The discovery of the bystander effect and evidence of late risk of noncancer diseases (especially cardiovascular mortality) may indicate a supralinear risk at low doses. On the other hand, lack of increased morbidities in high-background radiation areas (such as Kerala in India or Ramsar in Iran) suggests a sublinear risk at low doses. Interesting new radiobiological experiments planned in underground particle physics laboratory (INFN Gran Sasso in Italy and SNOLAB in Canada), designed to have zero-background, will help understanding the effect of background environmental radioactivity on living organisms.

6.3 Space radiation

The plans of Space Agencies have recently moved from the International Space Station in Low Earth Orbit (LEO) to manned exploration beyond low-Earth orbit (BLEO), especially to the moon, asteroids, and finally Mars. For exploration in deep space, it is generally acknowledged that exposure to cosmic rays represents the main health hazards for the crew. The recent measurements of the NASA RAD detector on the Mars Science Laboratory during its trip to Mars (11.6.2011 –8.6.2012) indicate that the dose rate in BLEO is about 1.8 mSv/day. This means that in a mission to Mars, crewmembers can absorb a dose close to 1 Sv. This is a very high dose and, even if precise dose limits for BLEO have not been issued bythe Space Agencies, it would not be allowed in any terrestrial activity. Accelerator- based research programs have been established both by NASA (at the Brookhaven National Laboratory in NY) and ESA (at GSI in Darmstadt, Germany, and in the future at the new FAIR facility) to reduce uncertainty on the risk and to develop countermeasures. Passive shielding remains indeed the only practical countermeasure available, but the development of new, highly hydrogenated multi-functional materials is necessary, and tests at high-energy heavy ion accelerators are used to assess the shielding effectiveness (Figure 2). Future mitigation strategies may include active shielding (with superconductive magnets) and radioprotective drugs or dietary supplements.

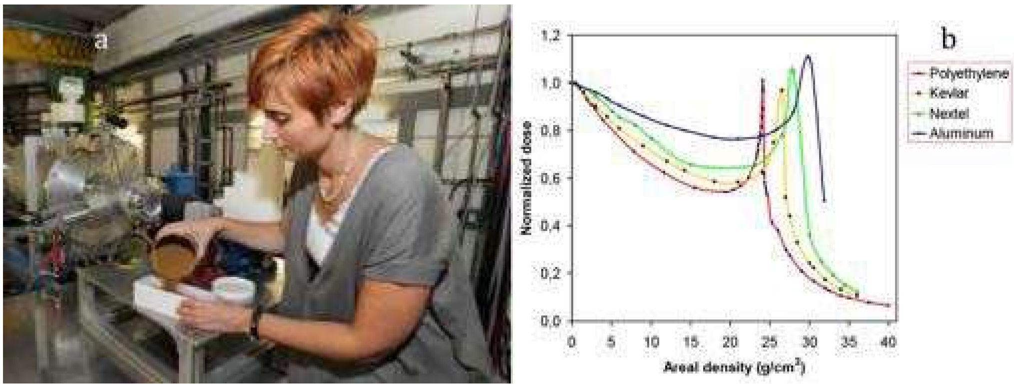


Figure 6.2: Space radiation shielding tests. Accelerator tests of the shielding effectiveness of different space relevant materials. (a) Mars regolith is prepared at the GSI accelerator in Germany. (b) Measured Bragg curves.

6.4 Societal applications

New technical developments have strengthened the position of nuclear techniques compared to other methods for the benefit of the society in many different fields. A few examples are listed below.

Cultural heritage

IBA has been used for decades to analyze art objects. The main strength is its analytical performance, which reaches the trace elemental level, without sampling. Although IBA is considered non-invasive, it has been recently demonstrated that it can induce visible, irreversible changes, depending on the material and on the technique. One of the obvious mitigation strategies is to decrease the beam current and the time of acquisition using more efficient detector systems. The AGLAE Laboratory in the Louvre museum has managed to gain a factor of ten for trace elements analysis with their new detector configuration. Among the new techniques under study, laser-accelerated protons may in the future replace electrostatic accelerators for PIXE, and high-energy monochromatic "-rays are very promising for imaging of large objects. Radiography and tomography using very intense "-ray beams of small bandwidth and high energy will allow high-resolution 2D/3D imaging and in-depth elemental analyses of large objects of various nature and composition.

Archeometry

Radiocarbon dating is the classical method for dating of archaeological specimens. Carbon-14 measurements by AMS allow dating objects from tens of thousands of years ago to the middle of last century with an accuracy of few tenths of years. However, detonation of the atmospheric nuclear bombs during the Cold War years, prior to the Test Ban Treaty in 1963, increased the amount of radio-carbon in the atmosphere significantly, providing a time marker. The so-called “bomb- peak dating” addresses the interesting period of the last sixty years with an accuracy of about two years. Thanks to the improved sensitivity of AMS, it has then be possible to measure the age of the cells within a human body, including human cardiomyocytes, adipocytes, oligodendrocytes and neurons.

The method also finds many applications in forensic science, because it can be sued to date the age of death in corpses, and cultural heritage, helping identifying forgery of modern art works (box 3).

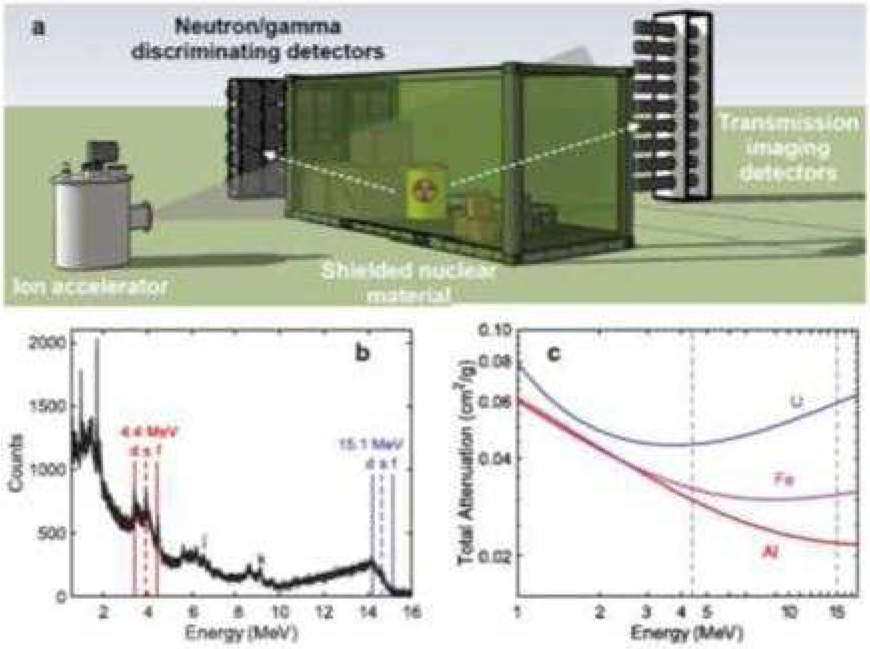


Figure 6.3: Detecting illicit weapon trafficking. (a) Low-energy nuclear reaction imaging relies upon the source of monochromatic photons via a nuclear reaction between an ion accelerated to MeV-scale energy and a target. Gamma rays at discrete energies are produced from nuclear excited states of the product nucleus, with some reactions also producing neutrons. The collimated, penetrating radiation from the nuclear reaction source is used to perform transmission radiography of a shielded object, while neutron/gamma discriminating detectors detect the signature of nuclear fission. (b) Photon spectrum from the $^{11}B(d,n\gamma)^{12}C$ reaction measured with a LaBr scintillation detector. (c) Energy-dependent attenuation for several elements. The 4.438 MeV and 15.1 MeV gamma energies from the $^{11}B(d,n\gamma)^{12}C$ reaction are shown as dashed lines (Rose et al., Sci. Rep. 6:24388, 2016).

The possibility that terrorist organizations will use chemical, biological, radiological or nuclear weapons for future attacks is considered credible and highly probable. Several attempts have been prevented by security services. Nuclear physics can play an important role in prevention of nuclear and radiological terrorism. Screening for illegal transportation of radioactive material is generally performed by radiation portal monitors. For plutonium trafficking, 3He sensors can detect a characteristic neutron emission. However, shielding and background radiation hamper the effectiveness of these detectors. In recent years a large number of new high light-yield scintillator materials have been discovered. In particular, Lanthanum halides provided the starting point for the design and development of several new high performance detector arrays. Muon radiography is also considered a promising technique for searching high-Z materials in trucks. Active methods using small accelerators would be more accurate and sensitive. For instance, a 3 MeV deuteron beam can be used to induce the $^{11}B(d, n\gamma)^{12}C$ reaction, and the different γ-ray peaks provide independent information on the density and the atomic number of the material (Box 4).

6.5 Conclusions

Nuclear physics provided society with a large number of beneficial applications in many completely different fields including medicine, heritage, and security. In the past few years, large efforts have been dedicated to technological improvements, especially in radiation detectors, able to enhance these applications. Future improvements in accelerator design, leading to smaller, compact and cheap particle accelerators, will further boost many applications. In addition, nuclear physicists are recognizing the value of inter-disciplinary research, and very often work closely together with chemists, engineers, biologists, or physicians in all the different steps of the application. Applied nuclear physics is growing as a large and powerful branch of nuclear sciences, bringing benefit to the society and breakthrough research results in other scientific disciplines.

7. Future Nuclear Physics Facilities

Updated January 1, 2018, by Hideto En'yo (RIKEN, Nishina Center for Accelerator based Science)

(This summary is updated from the original manuscript which was published in IUPAP Report 41 in 2013.)

During the last four years, striking updates happened in the world. The mega-science project Nuclotron-based Ion Collider fAcility (NICA) is well on the way of construction as a medium energy heavy-ion and polarized-proton collider at JINR in Dubna. The Chinese Heavy Ion Accelerator Facility (HIAF) project, was approved to be built at Huizhou, Guangdong Province (100km north-east of Hong Kong) as a nascent of the Heavy Ion Research Facility in Lanzhou (HIRFL). Next to HIAF, the China Accelerator Driven Sub-critical System (CIADS) will also be built. In Europe, the scope of the German FAIR project was redefined and a clear project schedule has been drawn up.

In the coming 10 years, together with these “new”comers, SPIRAL2 will take off in France, FRIB in the USA, RAON in Korea, and FAIR in Germany and many other new facilities currently under construction will come online. This is a surprisingly superb situation for the world nuclear physics community and such a situation will bring a quantum jump in the research field of nuclear science.

On the other hand, however, some of these facilities have reached a stage that involves a burden of construction (in terms of budget and human-resources) which is beyond a capacity of a single nation. The price tag for a nuclear physics facility may not be as large as projected for the International Linear Collider (ILC), but the sum of the construction costs for all the nuclear physics facilities (currently running or under construction) in the world is reaching the level of construction costs of the ILC.

Clearly this fact needs to be recognized and efforts must be made to enhance worldwide cooperation while keeping a good balance between domestic, regional (Europe-Africa, Asia-Oceania, and North-South America), and truly international projects. IUPAP WG.9 has recognized its mandate in dealing with such international issues and plans to take a more explicit role on international cooperation for the large-scale nuclear science projects as also requested by the nuclear science funding agency/ government representatives at the Nuclear Science Symposium held at the RIKEN Tokyo Office, August 30-31, 2017. This summary is to provide an overview of the current and future nuclear physics "user" facilities worldwide.

Table 7.1: Subfields of nuclear physics and the main topics to be covered

Subfield	Scientific Headlines
Quark many-body (Hot / Dense QCD)	Quark Gluon Plasma (QGP) Properties of the early universe
Quark many-body (Cold QCD)	QCD Chiral Symmetry Nucleon/meson structure and properties
Nucleon many body systems (Nuclear Structure)	Ultimate Nuclear Picture (including hyper nuclei), Element Genesis and Astrophysics, Super Heavy Element and the Island of Stability
Fundamental Physics	Physics of the Lagrangian, Double beta decays, Neutron EDM, rare decays, etc.
Computation	Ab-initio calculations, Lattice QCD
Application	Nuclear Transformation, Catalyzed Fusion, etc.

Table 7.1 summarizes the subfields of nuclear physics and the main topics to be covered. All the subfields contain prominent scientific topics. This manuscript focused on the facilities which carry out experiments in the first three subfields, namely, "Hot QCD", "Cold QCD", and Nuclear Structure Physics. The latter category requires radioactive (or rare) isotope (RI) beams either from an ISOL (Isotope Separation On-Line) facility or an in-flight projectile fragmentation facility with heavy-ion beams.

Fig. 7.1 gives the list of the large-scale user facilities that are in operation, or under construction at the present, or are being proposed, in each geographical region. One notices that on the American continent, the projects are well distributed probably due to the control exerted by the US government. The mechanism working on the American continent is a two-body interaction, with Canada cleverly covering the subfields not covered by the US.

Europeans are trying a kind of role-sharing by commonly proposing the flagship facilities FAIR and EURISOL together with intermediate steps at distributed facilities in various countries. An especially important role play international inter-governmental organizations such as CERN and JINR offering effective collaboration of countries from around the world. In Asia, there is no such co-operation. Every nation is advancing its own research interests under the (weekly coupled) three nation entity made up by China, Korea and Japan. The recent establishment of ANPhA (Asia Nuclear Physics Association) may be a key to improve the present situation regarding mutual collaborations in Asia. IUPAP WG.9 may then be responsible for furthering applicable worldwide co-operations.

7.1 Hot QCD

This subfield actually started in the late seventies at LBL in the US. In the mid-eighties relativistic heavy-ion programs emerged at the SPS of CERN and the AGS of BNL. Until the very end of the SPS heavy-ion physics program, it was not clear whether the conditions of the Quark Gluon Plasma (QGP) had been reached.

RHIC started operations in 2000 and finally the discovery of a new state of matter (QGP) could be announced. The ALICE experiment at the CERN-LHC started in 2010 and re-discovered this new state of matter. After 30 years of research by increasing the collision energy through five

Subfield		America	Europe	Asia
Quark many-body - Hot QCD -		**RHIC A+A**	**LHC (ALICE)** **GSI (SIS18)** *FAIR (SIS100)* *NICA A+A*	*J-PARC-HI*
Quark many-body systems - Cold QCD -	Hadron beam		**CERN SPS** **GSI (SIS18)** *FAIR (SIS100)*	**J-PARC** **HIRFL**
	Lepton beam	**JLAB-12GeV**	**CERN SPS μ** **MAMI**	**Spring-8** **ELPH**
	Collider	**RHIC p+p**	*NICA p+p*	**(Bess-III)** **(Belle-II)**
		EIC e+A/e+p		*eIC@HIAF*
Nucleon many-body systems	Projectile Fragmentation RI beams	**FRIB**	**GSI** *FAIR*	**RIBF** **HIRFL** *RAON* *HIAF*
	ISOL RI beams	**ISAC** *(ARIEL)*	**HIE-ISOLDE** **SPIRAL2** *SPES*	**BRIF** **RAON** *BRIF2*
	Super Heavy	**High Flux Reactor**	**GSI UNILAC** **Dubna SHE factory**	*Superconducting* *RIKEN RILAC*
Super ISOL			*EURISOL*	*Beijing ISOL*

Figure 7.1: List of large-scale nuclear-physics facilities. The bold characters are for the running facilities, italics for those under construction, and the gray cells for proposed facilities. The electron-positron colliders are also listed in parentheses.

accelerators, convincing demonstrations have finally been obtained regarding the existence of this new state of matter. RHIC and LHC have another 10-15 years of productive research in studying the properties of QGP. It may then very well be that the relativistic heavy-ion colliders are replaced by electron-ion colliders (eIC's). A white paper for such a facility is being presented to the US government and an assessment of the physics with such a facility is currently being made by the US National Academy of Sciences. At CERN there are discussions about a high energy electron-ion collider (LHeC Project).

The history of the "Hot QCD" research has been quite successful not only by reaching in the phase diagram the conditions leading to QGP but also by the healthy growth of international collaborations; researchers got together at accelerators at which one nation alone could not sustain the heavy-ion research program. However, it should be remembered, that none of the facilities for the QGP studies was built from "a green field" by the nuclear physics community (i.e., they were realized by converting an existing accelerator or using an existing tunnel to construct a heavy-ion collider).

What comprises "Dense QCD" is studied at lower-energy heavy-ion collisions, of which FAIR (Facility for Antiproton and Ion Research) at GSI and NICA (Nuclotron based Ion Collider fAcility) at JINR/Dubna are under construction. The FAIR phase-1 scheme is established in 2015 to complete SIS-100 and the experimental facilities by 2025. The first beams at the NICA nuclotron circulated in 2022.

Although the energy regions which FAIR and NICA are targeting are the region once covered by the SPS and low-energy scans at RHIC, no experiments were done with high luminosity. FAIR and NICA will challenge the physics of dense QCD at a much higher interaction rate with advanced experimental technology. NICA will also be a polarized proton collider, so it is indeed a mini-RHIC.

When FAIR will come online, this will be the leading European nuclear physics facility covering "Hot QCD", "Cold QCD", and "Nuclear Structure" with RI beams via projectile fragmentation. It is pity that the original double ring structure of SIS100/SIS300 was postponed. Nevertheless the physics program is well thought out, with an emphasis on those experiments where other facilities cannot compete; consequently no neutrino physics experiments, no hyper-nucleus physics experiments.

7.2 Cold QCD

Until FAIR and NICA become operational, J-PARC's 30 GeV Proton Synchrotron in Japan will continue to be the world's leading facility for "Cold QCD" physics using hadron beams. The beam power is now a stable 40kW for the slow extraction and 400kW for the fast extraction, both reaching one half of the original design goal. Recent discovery of a bound K-pp system is a highlight.

Amongst a handful of lepton-photon beam facilities in the world, Jefferson Laboratory (JLab) in the US is playing the leading role. The CEBAF energy was upgraded from 6 GeV to 12 GeV, and a new experiment started in 2017 at the Hall D using a Bremsstrahlung-photon beam with a new 4π detector. The CLAS spectrometer in Hall B was also largely upgraded and engineering runs started also in 2017. The world's first electron Ion Collider (eIC) is proposed to be built either at BNL by adding an electron ring in the RHIC tunnel or by adding two ion-cooler rings to CEBAF at JLab. The electron-proton colliding luminosity will be 100 times higher than at the former HERA collider. A new regime of QCD, the saturated gluonic field in the nucleon and nucleus will be explored. A similar option is also under consideration at LHC at CERN and HIAF (China). In addition, one should not forget the hadron physics capability of the electron- positron colliders where many new hadronic resonances have been discovered. BES-III and BELLE-II will continue to be frontrunners in exotic hadron searches.

7.3 Nuclear physics with ISOL beams

EURISOL is the future facility with a multi-billion-dollar price tag, carrying the aspirations of the European nuclear physics community. Twenty institutions in Europe signed on to the design report with in addition contributions from twenty other institutions from America and Asia. The Nuclear Physics European Collaboration Committee (NuPECC) has agreed that EURISOL, together with FAIR at GSI are priority goals. Other ongoing projects such as HIE-ISOLDE at CERN, SPIRAL2 at GANIL, and SPES at INFN-Legnaro are now regarded as "intermediate" facilities. This is a very clever and honest approach that satisfies national pride as well as determines the future direction of the projects within the EU.

Although declared as "intermediate", these facilities are anything but minor and are already powerful tools for research. HIE ISOLDE at CERN is a natural extension of the present facility by the addition of a 10 MeV/A post-accelerator. SPES at INFN-Legnaro is a relatively modest 8kW-ISOL project. SPIRAL1 in GANIL is an ISOL facility based on the fragmentation of primary beams from the cyclotrons. SPIRAL2 involves a 200 kW linear accelerator for the production of low-energy radioactive ion beams by means of fusion-evaporation reactions.

In Canada, ARIEL at TRIUMF is under construction which aims at 10^{14} fission/s with the use of a super-conducting electron linac developed in conjunction with the ILC R&D program. These facilities under construction will provide typically $100\times$ more RI compared to current levels. For the far future, EURISOL aims at 10^{16} fissions/s driven by 1 GeV protons of 4 MW beam power.

In Asia, China is considering to build the Beijing ISOL (formerly called Beijing CARIF) facility driven by an existing research reactor. Despite the difference in their drivers, the performance of Beijing ISOL facility is expected to be comparable to EURISOL, i.e., $\approx$100 times more intense than the soon-to-be-ready ISOL facilities mentioned. Although there is no regional consensus in Asia, the Beijing ISOL can be called AsianiSOL (ASOL).

Fig. 7.2 summarizes the ISOL facilities under construction or being planned. While the existing facilities provide 10^{11}-10^{12} fissions/s with a typical ^{132}Sn intensity of 10^6, the European "intermediate" facilities provide 10^{12}-10^{14} fissions/s with ^{132}Sn of 10^8-10^9.

7.4 RI beam with projectile fragmentation

Fig. 7.2 also includes the RI-beam facilities with projectile fragmentation. Compared to the ISOL facilities the projectile fragmentation facilities are superior in producing a wide range of rare RI beams, free from their chemical characteristics and short lifetime. Among these facilities, RIBF at RIKEN currently delivers the most powerful RI beams, typically 3×10^6 of ^{132}Sn per second at an energy of 200 MeV/nucleon.

FRIB at MSU is truly the next generation projectile-fragmentation facility with 200 MeV/A 400 kW LINAC followed by a fragmentation separator. FRIB will be completed by 2022 (partial start slated for 2020). Future options are to double the energy and to add an ISOL facility. The Korean project RISP (Rare Isotope Science Project) was started in 2011 and completed its first phase in 2022. Its second phase for the high-energy section of the superconducting Linac is anticipated to be completed around 2030 for acceletaion of uranium beams up to 200 MeV/A. RISP and FRIB are aiming for a similar level of performance, 10^8/s of ^{132}Sn.

FAIR at GSI is another large facility. Using SIS100 with a U^{28+} 1.5 GeV/A beam, it can improve the RI beam intensity by a factor of 100 to 1000 compared to the present SIS-based facility, making the facility comparable or superior to RIKEN RIBF.

Until Beijing ISOL becomes available China operates two facilities: BRIF2 (Beijing RI Facility) and Heavy Ion Research Facility in Lanzhou (HIRFL), and is starting to build Heavy Ion Accelerator Facility (HIAF) not in Lanzhou but in Guangdong Province (100km north-east of Hong Kong).

7.5 Superheavy element search

On December 30, 2015, IUPAC announced the discovery of the new elements 113, 115, 117, and 118. On November 8, 2016, the 7th row of the periodic table was completed with Nihonium, Moscovium, Tennessine and Oganesson. The future race hunting for the 119th and 120th elements will continue at the SHE factory at Dubna and RIKEN. It should be noted that the future race requires actinide targets which can only be delivered by the High Flux Reactor at ORNL.

7.6 Summary

In summary, one recognizes from Table 2 that the "Hot QCD" and "Cold QCD" facilities are shared efficiently worldwide. Compared to twenty years ago, there are fewer "Cold QCD" facilities because they have been left for collider projects. By having an electron-ion collider in the USA in the future, scientific coverage will be drastically expanded in parallel with more well-balanced regional interests and responsibilities. Assisted by the international competition among the rival facilities in the European, American and Asian continents, RI- beam facilities have become prevalent. Huge advances in this field of physics are expected in the coming 10- 20 years. One may need to consider international amalgamation of research interests when either EURISOL or Beijing ISOL (formerly known as CARIF), both multi-billion dollar projects, is eventually realized.

Type	Facility	Beam		Target (ISOL) or Beam current (Proj. Fragm.)		Post acceleration		Exp. Start
		Beam	Beam Power (kW)	Direct/ Conv/ Proj. Fragm.	Fissions/s Beam pnA	MeV/A	^{132}Sn/s	
ISOL Coming/ Now running	TRIUMF ARIEL	e 30 MeV 10 mA p 500 MeV 100 μA	300 (e) 50 (p)	Direct	$1*10^{14}$	up to 16.5	$2*10^{9}$	2026/27
	HIE ISOLDE	p 1 GeV 2μA	2	D&C	$4*10^{12}$	5-10	$2*10^{8}$	Since 2018
	BRIF	p 100 MeV 200 μA	20	Direct	$1.2*10^{13}$	1.2 – 2.4	$4*10^{5}$	Since 2018
	GANIL SPIRAL2	d 40 MeV 5000 μA	200	Conv	$1*10^{14}$	3-10	$2*10^{9}$	Since 2021
	LNL SPES	p 40 MeV 200 μA	8	Direct	$1*10^{13}$	10	$3*10^{8}$	2024
	RAON/ IRIS	p 70 MeV 700 μA	50	Direct	10^{13}	25	10^{7}	Since 2023
Super-ISOL (planned)	EURISOL	p 1 GeV 5000 μA	4 MW	D&C	$1*10^{15}$	20-150	$4*10^{11}$	?
	Beijing ISOL	Reactor	6 MW	Reactor	$2*10^{15}$	>100	$5*10^{10}$	?
Projectile Fragmentation Coming/ Now running	RAON	U^{79+} 200 MeV	400	PF	8000 pnA	-	10^{8}~10^{9}	~2030
	FAIR	U^{28+} 1.5 GeV	10	PF	50 pnA	-	10^{7}~10^{8}	2026/27
	RIBF	U^{86+} 345 MeV	4	PF	100 pnA	-	$3*10^{6}$	Since 2015
	FRIB	U^{33+} 200 MeV	400	PF	8300 pnA	-	10^{8}~10^{9}	Since 2022

Figure 7.2: Overview of facilities that are under construction or started operation recently (within the last 10 years).

8. Nuclear Power

Updated February 28, 2018, by Nicolas Alamanos and Sylvie Leray (IRFU, DPhN, CEA-Saclay)

Although more slowly than before, the energy demand is continuously increasing due to the growth of the world population and of the standard of living in developing countries and despite the efforts for energy saving and improved energy efficiency [1]. The world's primary energy consumption has increased in 2016 by 1.0% following a ten-year average of 1.8% per year. In the World Energy Outlook 2017 (WEO 2017) [2] the International Energy Agency (IEA) estimates that the global energy needs will expand by 30% between 2017 and 2040, with a population growing from 7.4 billion to more than 9 billion. Two-third of the energy demand growth will come from Asia, in particular China and India.

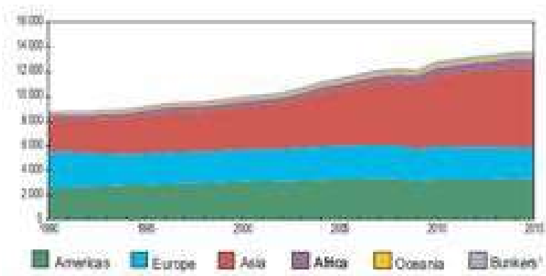


Figure 8.1: World total primary energy supply by geographical region. From [3].

The need for electricity is rising even faster, 2.2% in 2016 following a ten-year average of 2.8% per year [1]. This is driven by the greater use of computers and smart electronic devices in developed countries and by more people getting access to electricity in developing countries. This trend will continue and even intensify with the developments of electric vehicles. In [2], IEA forecasts that electricity will represent 40% of the rise in final consumption to 2040. Again the demand growth will come mainly from Asia. It is for instance estimated that by 2040 the electricity needed for cooling in China will be larger than the total electricity supply of Japan in 2017.

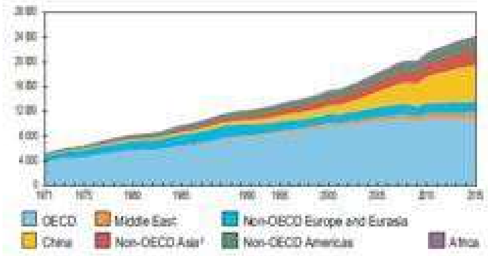


Figure 8.2: World electricity generation from 1971 to 2015 by region (TWh). From [3].

At the same time, concern over the risk of climate change due to CO2 emission is raising. The 2016 Paris Climate Agreement [4] aims at tackling the global climate change risk by limiting the global temperature rise below 2 degrees Celsius above pre-industrial levels. This implies reducing as far as possible the use of fossil fuels and therefore developing all possible alternative options such as energy saving, increasing energy efficiency and developing CO_2-free energy production. Because of the negative image of nuclear power, most of the countries are aiming at reducing their CO_2 emissions by increasing the share of renewable energies, i.e. mainly solar and wind energies since hydro-power deployment is limited by the availability of new sites. IEA foresees that the share of all renewables in total power generation will reach 40% in 2040, solar photovoltaics becoming the largest source of low-carbon capacity, driven mainly by China and India [2]. Fig. 8.3 (from Ref. [2]) shows that already in the period 2010-2016 new power plants were mostly renewables and that the tendency is expected to increase between 2017 and 2040.

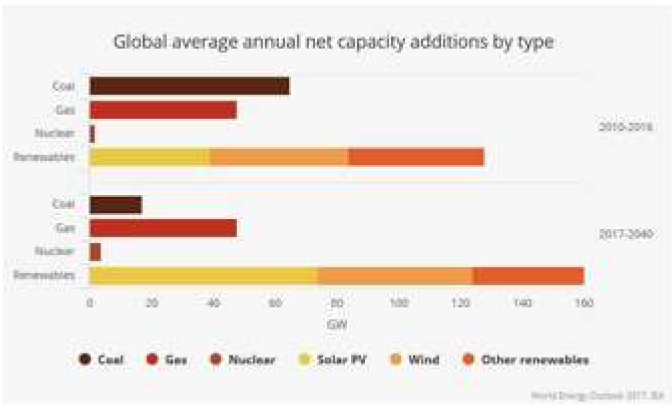


Figure 8.3: Global average annual net capacity additions by type of fuel during the 2010-2016 period and foreseen by IEA between 2017 and 2040. From [2].

However, solar and wind energies have serious drawbacks, the main one being their variability and intermittency in the absence of effective storage solutions. This limits the share of power from renewable source in a grid and implies back-up solutions from other, often fossil fuels, sources and new smart and efficient grid management. The price, which is still much higher than for fossil fuels, is constantly decreasing and may not be an impediment to a rapid growth. A more serious concern is that solar photovoltaics and other renewable technologies are highly dependent on rare earth elements, which carry a risk of possible future supply disruption.

However, since 2013 the tendency has been inverted and nuclear power production is slowly but continuously increasing, driven mainly by China and India. Global nuclear power generation increased by 1.3% in 2016 with China accounting for all of the net growth. Presently, around 11% of the world's electricity is generated by about 450 nuclear power reactors. 58 reactors are under construction, equivalent to 16% of existing capacity, while an additional 150-160 are planned, equivalent to nearly half of existing capacity [5]. 20 of the 58 reactors in construction are in China, 6 in India and in Russia and the number of planned reactors is respectively 39 in China, 19 in India and 26 in Russia [5]. In addition, several new countries are moving towards nuclear energy, building their first reactors like Bangladesh, Belarus and the United Arab Emirates. WEO 2017 estimates that nuclear electricity generation will double by 2040.

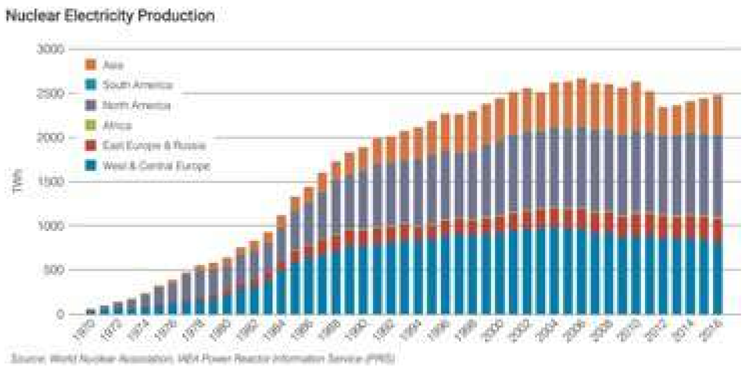


Figure 8.4: Nuclear energy production from 1970 to 2016 by region (TWh). From [5]

Most of the reactors in operation are based on technology developed during the 1950s and later improved (Generation II). They are predominantly water-cooled reactors, either pressurized water (PWR) or boiling water reactors (BWR). The so-called Generation III reactors, which are the reactors presently being built, are using the same technology but their design has been optimized in order to reduce their cost by increasing the availability and lifetime, use more efficiently the fuel by allowing higher burn-up, and have an improved inherent safety.

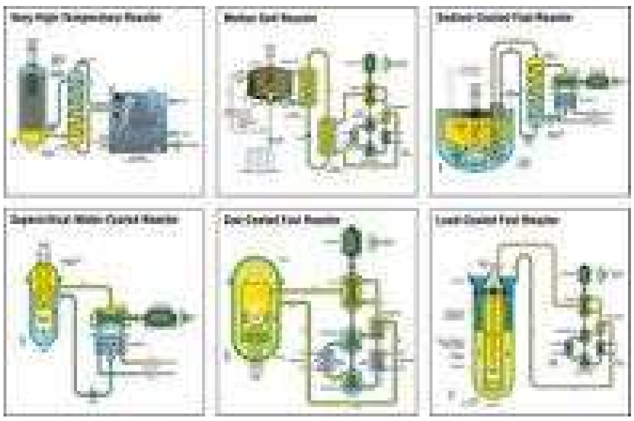


Figure 8.5: The six technologies investigated in GIF. From [6]

A new generation of more innovative reactors is being investigated in the framework of the Generation IV International Forum (GIF) composed of representatives from 14 countries. Technology goals have been defined: Generation IV reactors should provide sustainable energy generation and long-term availability of systems, minimize and manage their nuclear waste, be economically competitive, have high level of safety and reliability, and be proliferation-resistant. Six different systems are studied. They use different coolant, light water for one system, lead-bismuth, sodium or fluoride salt and helium for two of them. Four are fast neutron reactors.

The 2014 GIF Technology Roadmap Update has focused on the most relevant developments for a deployment in the next decade, which are the sodium-cooled fast reactor, the lead-cooled fast reactor and the very high temperature reactor technologies (VHTR) [6]. China is developing a prototype of VHTR, France and Russia are working on advanced sodium-fast reactor designs and a prototype of a lead fast reactor is also expected to be built in Russia.

Like any industrial activity, nuclear energy generation produces wastes but the management of highly radioactive nuclear wastes is a subject of great concern for the public and in fact one of the main reasons, with the fear of accident, why nuclear energy is not well accepted. Although in any case a final deep geologic disposal of remaining long-lived high level wastes will be necessary, the strategy regarding the management of spent fuel varies from one country to another [7]. Some countries, like US, Sweden or Finland, are planning to store directly the spent fuel while other ones, like France, Japan, Russia or China, reprocess the spent fuel to extract plutonium and make MOX fuels that are re-used and the remaining high-level wastes, composed mainly of fission products and minor actinides, are vitrified and intended to be sent to the geological disposal. While reprocessing reduces the amount, volume and radiotoxicity of the high-level waste (HLW) packages to be stored, it generates additional volumes of intermediate wastes during the reprocessing and fuel fabrication processes.

For low (LLW) and intermediate-level (ILW) wastes, near-surface repositories are generally considered and already implemented for in several countries, including Czech Republic, Finland, France, Japan, Netherlands, Spain, Sweden, UK, and USA for LLW and Finland and Sweden for LLW and short-lived ILW. For HLW deep geological sites, the situation varies from, such as Sweden and Finland that have already selected a site and began to build the repository, to countries still in the selection process, for instance, UK and Canada. In France and US, a site has been chosen but the construction not yet started. In parallel to the investigation of disposal solutions, extensive research is being conducted on partitioning and transmutation (P&T) that could lead to reducing the radiotoxicity and volume of the wastes to be finally stored. The idea is to change long-lived isotopes into stable or short-lived ones that could be stored for a limited period.

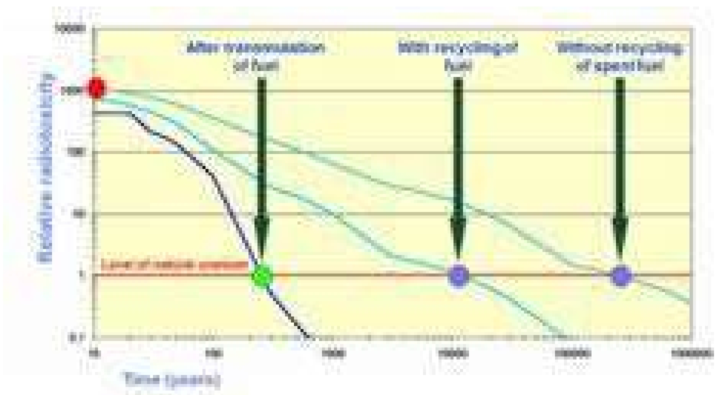


Figure 8.6: Relative radiotoxicity on nuclear waste compared to natural uranium ore as a function of time after unloading from the reactor, for spent fuel without recycling, with Pu recycling and after transmutation of minor actinides. From [8, 9].

It is generally admitted that the transmutation of long-lived fission products is not viable due to the cost and the necessity in most case of isotope separation to avoid creating new undesirable isotopes while transmuting other ones. In contrast, transmuting minor actinides (MA) in addition to plutonium, lead to a significant reduction of the long-term radiotoxicity, as shown in Fig. 6.

In Europe, in particular, the European Commission has been funding many projects concerning new types of reactors, fuels, and material involving minor actinides. A review of the state-of-the-art can be found in the OECD Nuclear Energy Agency (NEA) series of biennial Information Exchange Meetings on Actinide and Fission Product Partitioning and Transmutation [10]. Two different strategies for the transmutation of MA are envisaged: either adding a small amount of MA in a large number of commercial reactors or building a small number of dedicated units able to burn a large amount of MA. Indeed, the addition of MA into fuels degrades the safety parameters, such as the delayed neutron fraction or the Doppler coefficient, and therefore the amount that can be incorporated in a classical reactor is limited but could be counterbalanced by the number of reactors.

Actually, studies of Generation IV reactors also include the investigation of the possibility to burn MA. Transmuting a large amount of MA may be possible in accelerator-driven systems (ADS) in which the operation in a sub-critical mode allows loosening on the safety parameters. There are currently three projects of ADS under studies: MYRRHA [11] in Belgium, C-ADS [12] in China and one in India, the latter being based on thorium fuel. The development of new types of reactors, as generation IV or for the transmutation of MA, implies new types of coolant, moderator (if any), fuel and structure materials, as well as possibly different neutron flux environment. This, together with the requirement for reducing uncertainties, means that there is a need for the measurement of new or more precise nuclear data.

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Part 2 - Individual Laboratories

9. FOREWORD

Nuclear Physics Institutes and Laboratories worldwide which possess an accelerator with an external users group for research in nuclear physics are indicated on the following map (Fig. 9.1) and listed in the following. Figs. **??**, **??**, and **??** list the names of the Nuclear Physics Laboratories, their location, and the chief performance characteristics of the laboratory's accelerator(s).

There are a very large number of medium size and smaller size facilities. It must be recognized that these facilities have a very important role in the education and training of nuclear physicists. In addition these facilities in general serve society at large through various applied nuclear physics programs and in quite a few cases have important programs within nuclear medicine.

If one were to make the arbitrary choice to define truly international user facilities in nuclear physics as those which have a users group of national and international users combined in excess of 300 scientists, one would identify:

- in Japan J-PARC, RCNP, and RIKEN,
- in France GANIL,
- in Germany DESY-HERA, GSI, and COSY,
- in Italy Laboratori Nazionale di Legnaro,
- in Switzerland CERN and PSI,
- in Canada TRIUMF, and
- in the USA, ANL, BNL, JLAB and FRIB.

Other choices are possible and in some contexts perhaps more desirable, but this small group of large facilities would appear in almost any such collection. The individual entries on the Nuclear Physics Laboratories are primarily the responses obtained through a questionnaire that was widely circulated. In a few cases in Europe, entries were taken from the 2012 NuPECC Handbook on International Access to Nuclear Physics Facilities (`www.nupecc.org/pub/hb12/hb2012.pdf`).

As the information was provided on a purely voluntary basis, there are some unavoidable gaps. For example, we had few responses from India. In that case we list below the web pages of several key institutions from which we did not receive information. Additional information on laboratories as defined above and not yet listed would be appreciated. That includes:

- Centre for Advanced Technology (Department of Atomic Energy), Indore [Synchrotron

Radiation Facility, 450 MeV] (www.cat.ernet.in)
- Bhabha Atomic Research Centre (Department of Atomic Energy), Mumbai [Research Reactors] (www.barc.ernet.in)
- Tata Institute for Fundamental Research, Mumbai [Pelletron] (www.tifi.res.in)

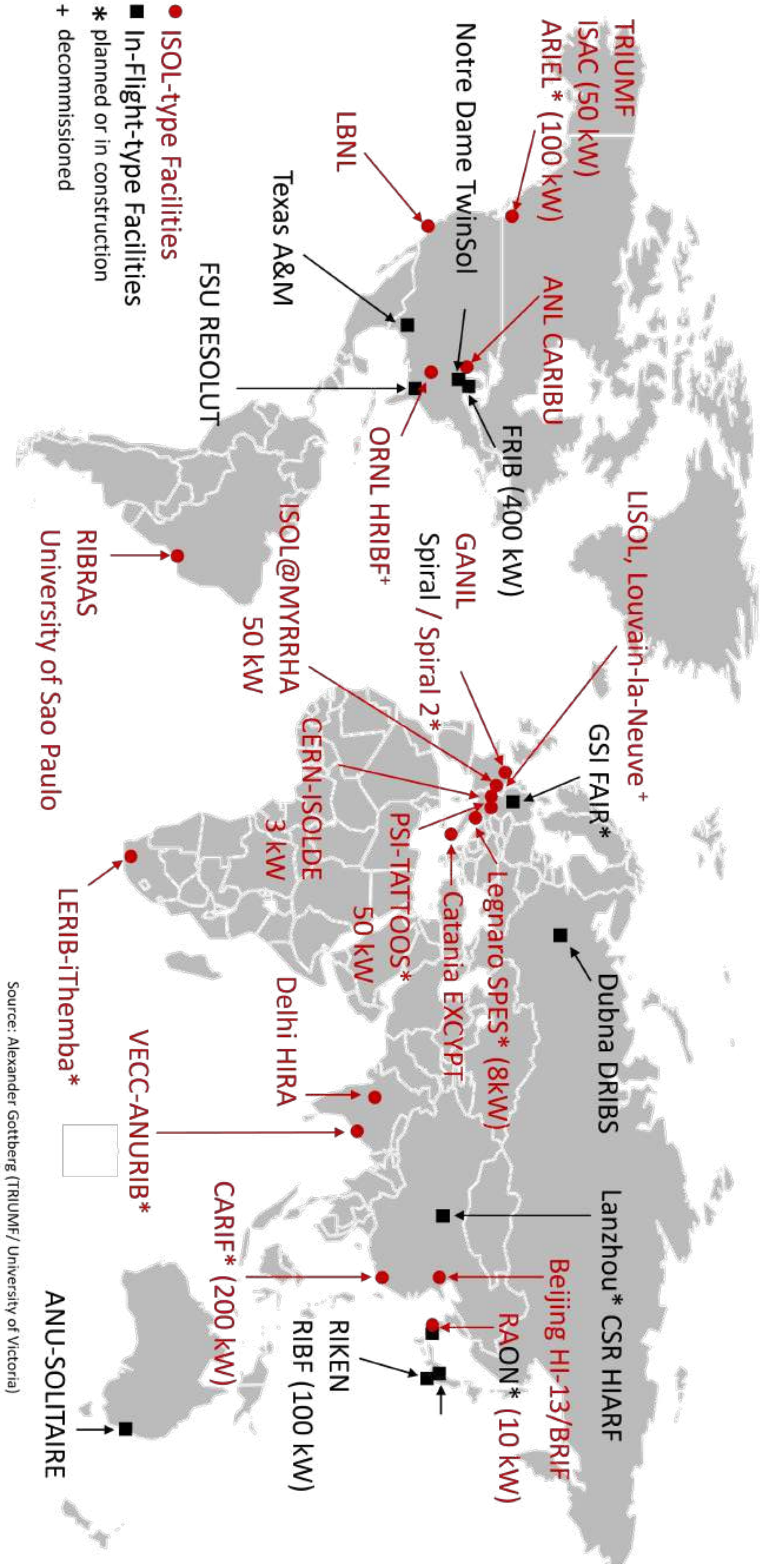

Figure 9.1: Map with the location of major nuclear physics facilities (smaller facilities are not shown here). Courtesy of Alexander Gottberg (TRIUMF/ University of Victoria).

10. LABORATORIES IN AFRICA

iTHEMBA LABORATORY FOR ACCELERATOR BASED SCIENCES

Old Faure Road, Faure, near Cape Town, South Africa
P O Box 722, Somerset West 7129
Telephone: +27 21 843 1000
Facsimile: +27 21 843 3525
www.tlabs.ac.za

Managing Director: Faiçal Azaiez
E-mail: director@tlabs.ac.za

National facility operated by the National Research Foundation (NRF)
which is governed by the NRF Act of 1998.
The South African Government

Scientific Mission and Research Programs

(a) Vision

To be the leading African organisation for research, training and expertise in accelerator-based sciences and technologies.

(b) Mission

To provide state of the art facilities and programs for high quality research, training and services in nuclear sciences and applications for the benefit of the people of South Africa and the continent in general.

Research programs include Subatomic Physics, Accelerator Physics, Materials Research, Accelerator Mass Spectrometry, Radiation Biophysics, and Radioisotope Production and Development.

Characterization of the Facility

Particle accelerators in use

1. The Separated Sector Cyclotron (SSC): A variable energy K=200 Separated Sector Cyclotron with two K=8 injector cyclotrons, two ECR Ion Sources and a polarized ion source. The SSC is currently providing particle beams for basic and applied subatomic research as well as for the production of radioisotopes.
2. An 11-MeV cyclotron is available for the dedicated production of ^{18}F to service the needs of local nuclear medicine facilities for imaging purposes.
3. A 3-MV Tandetron capable of delivering protons (100 μA), alphas (25 μA) and heavy ions ($^{28}Si^{3+}$: 32 eμA) at 3.0 MV terminal voltage. The Tandetron was commissioned in 2017 and is used extensively in materials research for Ion-Beam Analysis (IBA).
4. A 6-MV tandem with a dedicated ion source for Accelerator Mass Spectrometry (AMS). An additional sputter source and a source for α particles are also available.

Figure 10.1: The 3-MV Tandetron accelerator (left) and its micro-probe setup (right).

Figure 10.2: 6-MV Tandem accelerator (left) and the new bending magnet followed by the electrostatic analyser of the AMS facility (right).

Experimental facilities

SSC Laboratory

1. The AFRODITE-plus γ-detector array consisting of 17 50×70mm Clover detectors (Eurogam II type) with BGO escape suppression and an efficiency of 2.8% at 1.33 MeV, 1 TIGRESS-type segmented clover detector, and 8 segmented planar Ge detectors (LEPS).
2. A fast-timing array consisting of 8 50×50 mm $LaBr_3$ detectors for photon detection with good efficiency (∼3%) and excellent timing resolution (∼<400 ps).
3. The ALBA-array consisting of 21 high-efficiency large-volume (89×203mm) $LaBr_3$:Ce detectors. ALBA's efficiencies are calculated to be 19% and 5% at γ-ray energies of 1 and

10 MeV, respectively.

4. A K=600 QDD Magnetic spectrometer with kinematic correction with an Angular Range: 0 – 2° using an external beam stop (inelastic scattering), 3 - 5° with the beam stop located at the entrance to the spectrometer, and > 5° with an external beam stop. The angular acceptance is 50 msr, with a momentum byte of 9% (5% in zero-degree mode). The x and y vertical drift chambers and plastic scintillators in the focal plane ensures an energy resolution of 1/9000 at 200 MeV.
5. Ancillary detectors: The CAKE-array for particle coincidence: 5 x 400 μm thick DSSSD, 16 rings, 8 sectors per DSSSD, θ range: 14 - 166°; solid angle coverage: 26% of 4π; γ coincidence: interchangeable configurations of up to 30 γ-ray detectors including AFRODITE-plus, LEPS, ALBA and fast-timing detectors are now possible with the new frame.
6. A β-decay tape station with a single-spool design and 50 m of 12 mm wide mylar tape.
7. A refurbished Siegbahn-Kleinheinz electron spectrometer from Orsay.
8. A collimated fast neutron beam facility producing quasi-mono-energetic neutrons from p + ^{7}Li/ ^{9}Be in the 30 - 200 MeV energy range. The facility makes provision for measurements at emission angles of 0°, 4°, 8° and 16°.

The Tandetron Laboratory

A nuclear microprobe with cryogenic target station is available with facilities for PIXE, RBS, ERDA, and channelling. The laboratory also has the following complementary equipment available, namely sample preparation, AFM, XRD, and optical characterisation.

The Tandem laboratory

An AMS analysis system with two dedicated detector systems (^{14}C, ^{10}Be, ^{26}Al) is available at the campus in Johannesburg. The Tandem laboratory also offers a nuclear microprobe for ion beam analysis using heavy ion ERDA, and RBS.

Radioisotope Production

The iThemba LABS radioisotopes programme is a world-class effort that has developed over a period of many years. The accelerator facilities allow for the production of a number of important radioisotopes, and the Good Manufacturing Practice (GMP) production capabilities allow for these products to be exported for clinical use. Routine isotope production includes ^{82}Sr, ^{68}Ge/^{68}Ga generators, ^{18}F-FDG, ^{22}Na, ^{123}I, and ^{67}Ga. The ^{123}I and ^{67}Ga that are used as SPECT tracers, and the ^{18}F-FDG that is used for cardiac and neurological applications, are produced solely for 25 local clients.

Human resource at the facility and operation as a user-facility

Table 10.1: Staff at iThemba LABS

Designation	Number of persons
Permanent Staff	253
Short-term contracts	24
Postdoctoral fellows	10
Postgraduate students	200

Special student programs

The training of undergraduate and postgraduate students is consolidated under the Southern African Institute for Nuclear Technology and Sciences (SAINTS). The SAINTS program offers a range of master classes to support students in completing their dissertations in the minimum time.

Program Advisory Committee/ Experiment proposals

iThemba LABS makes use of a PAC to assist in selecting proposals on a year-to-year basis. A call for proposals is sent out once per year. The PAC consists of eight international and domestic committee members.

Table 10.2: User-base of the facility

Group	Number of persons	Participation (%)	Facility usage (%)
International	205	45	30
National	251	55	70

Future plans

The flagship project of iThemba LABS is the establishment of SAIF, the South African Isotope Facility, which is currently under construction. It comprises SAIF Phase 1 (including a new 70 MeV cyclotron and Phase 0 of the Low Energy RIB Facility (LERIB0)), and SAIF Phase 2 for exotic isotope production. SAIF Phase 1 is intended to move radionuclide production from the existing SSC facility, thereby freeing the SSC to increase the available beam time for research.

LERIB0 is based on the front-end target/ion-source similar to the ISOLDE front-end. Beams of 66 MeV protons from the SSC, impinging on a variety of targets to produce radioactive atoms, will allow new techniques of on-line selection and ionization of radioactive isotopes to be developed, particularly for species that have been difficult to extract in a hot cavity setting. SAIF Phase 2 will be based on the usage of a high intensity electron accelerator (Rhodotron) as a driver for rare isotopes, high photons and neutron sources for basic and applied research.

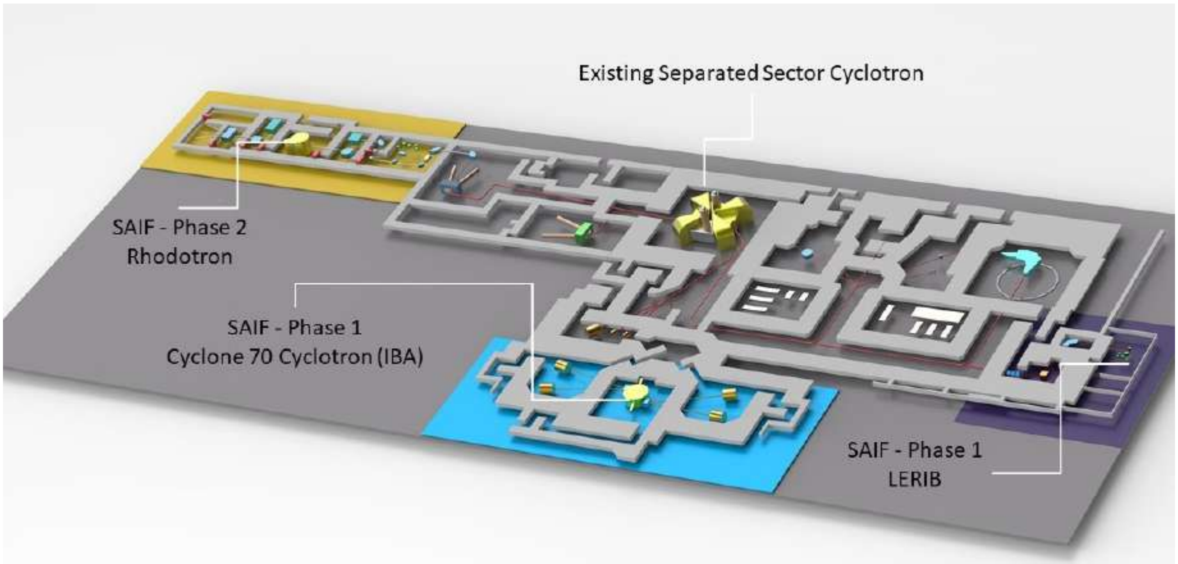

Figure 10.3: Layout of the facilities showing the current SSC and experimental vaults, the locations for the new C70 MeV cyclotron (light blue area) with the four irradiation target systems for radioisotope production, the LERIB0 facility (light purple) using the high-intensity 66 MeV proton beam from the SSC, and phase 2 of SAIF with the Rhodotron (light orange) for rare isotopes production (at low energy and high energy using the SSC accelerator) and for the production of high intensity neutron and photons source.

11. LABORATORIES IN ASIA

BEIJING TANDEM ACCELERATOR, NUCLEAR PHYSICS NATIONAL LABORATORY

DEPARTMENT OF NUCLEAR PHYSICS
CHINA INSTITUTE OF ATOMIC ENERGY(CIAE)
P. O. Box 275(1), Beijing 102413, China
Telephone: (+86)-10-69357880
Facsimile: (+86)-10-69357008

Head of the facility: Weiping Liu
E-mail: wpliu@ciae.ac.cn, wpliu08@gmail.com

Construction: National Committee for Development and Reform
Operation: Ministry of Finance
Funding applicable: National Science Foundation of China (NSFC) and
Ministry of Science and Technology

Scientific Mission and Research Programs

The present research areas of CIAE-DNP are heavy ion physics, nuclear astrophysics, nuclear theory, measurement of nuclear data, application of nuclear physics such as accelerator mass spectroscopy, atomic physics, radiation physics, accelerator technology in the energy range from 2 to 10 A MeV.

The BRIF (Beijing Radioactive Ion Beam Facility) is commissioning and includes a 100 MeV, 200 μA compact proton cyclotron (as a driving machine of unstable nuclei), isotope separator on line (ISOL) and an upgrade to a 14 MeV/q super-conducting linear booster after the existing 15 MV tandem accelerator (for acceleration of stable and unstable nuclei).

Characterization of the facility

1. 150 kV neutron generator.
2. 15 MV tandem accelerator: Stable nuclei (p to U), max. energy: 15 MeV*q; intensity:

up to 2 μA, momentum spread: 30 keV; RIB (A<180): neutron-rich, proton-rich (under construction); 10^{7-12} pps (RIB).
3. Super-conducting linear booster: Stable nuclei (p to U); max. boosted energy: 14 MeV*q, intensity: up to 2 μA; momentum spread: 2%.
4. 400kV underground accelerator (JUNA): Stable nuclei (p, He); max. energy: 450 keV*q; intensity: up to 10 mA; momentum spread: 70 eV.

Brief description of the facility's major experimental instrumentation and its capabilities

The major experimental instrumentation includes: radioactive beam line (GIRAFFE), neutron time of flight spectrometer, Q3D heavy ion spectrometer, accelerator mass spectroscopy, in-beam gamma experimental terminal, ECR platform, irradiative terminal for materials science research, atomic physics terminal, ion source laboratory and public electronic pool.

Nature of user facility

BTANPNL is a National Laboratory of China.

Program Advisory Committee/experiment proposals

BTANPNL has a Science Advisory Committee to evaluate experiment proposals and to advise the research activities.

Number of active users and their origin

There are more than 200 formal users in the last five years.

Percentage of users, and percentage of facility use that come from inside the institution

About 40-50% of users come from outside the institute.

Percentage of users and percentage of facility use from national users

About 90% of users are national users, and they use 90% beam-time of the facility.

Percentage of users and percentage of facility use from outside the country where your facility is located

About 10% of users come from outside of China.

Fraction of the international users outside of geographical region

Up to now the international users are from Asia and North America.

User Group

Most of the users are members of a formal user group and they have had very close collaboration with the institute for a long time.

Number of total laboratory staff

Table 11.1 breaks down the staff at the laboratory in different categories.

Special student programs

Joint summer school every two years together with universities. Student lectures in universities.

Future Plans

The BRIFII project (mainly RFQ-DTL-SC LINAC and experimental facilities) is in progress. In the near future they will provide normal and unstable beams up to 10 MeV/u or 34 MeV/q, with a full spectrum of instruments like a versatile magnet spectrometer, γ-array, decay measurement, large

Table 11.1: Staff at CIAE. *Number includes post-doctoral fellows, graduate students and long term visiting scientists. ** Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent Staff	200
Permanent Staff (Theory)	10
Temporary Staff	50
Temporary Staff (Theory)	10*
Postdoctoral researchers	2
(Resident) Graduate students	100
(Non-resident) Graduate students	10**
Undergraduate students	~50/ year

area and micro-beam radiation stations, et al. The Beijing Isotope-Separation-On-Line Neutron-Rich Beam Facility (BISOL) is planned and listed in national long-range plan, which make use of ISOL and projectile fragmentation techniques. On the one hand, it will separate and accelerate unstable fission fragments (150 MeV/u) induced by thermal neutrons from China Advanced Research Reactor (CARR), and the fission fragments will then bombard the target to produce unstable nuclei far away from β-stability up to neutron drip line with projectile fragmentation method. On the other hand, intense deuteron ion accelerator will yield 1-20 MeV intense fast neutrons up to (1-5)$\times 10^{15}$ n/cm^2/s which can be applied to evaluation of nuclear material. The schematic drawings of current and future facilities are shown in Fig. 11.1.

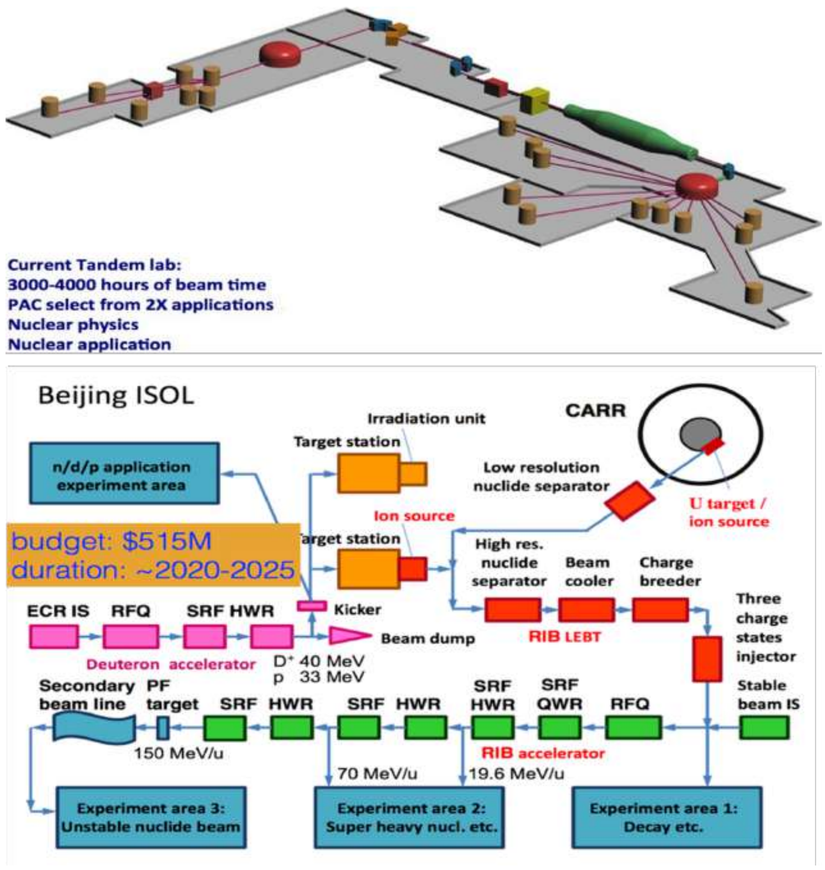

Figure 11.1: Schematic drawing of the current and future facilities in Beijing.

HEAVY ION RESEARCH FACILITY IN LANZHOU (HIRFL), INSTITUTE OF MODERN PHYSICS (IMP), CHINESE ACADEMY OF SCIENCES (CAS)

National Laboratory of China
509 Nanchang Road, 730000 Lanzhou China
Telephone: (+86)-931-4969500/ 4969226
Facsimile: (+86)-931-8272100

Guoqing Xiao
Head of facility: Baowen Wei
Email: mingxie@impcas.ac.cn and caixh@impcas.ac.cn

Funding for construction comes from the National Committee for Development and Reformation of China. Funding for operation comes from the Ministry of Finance of China. Funding from CAS and the National Science Foundation of China (NSFC) are applicable.

Scientific Mission and Research Programs

The research missions of IMP are heavy ion physics, atomic physics, irradiative material science, biology physics, cancer therapy, accelerator physics and technology in the energy range from few eV to 100 A MeV. The heavy ion cooler storage ring facility CSR was finished in 2007 and extended the maximum beam energy to 1000 A MeV. The hadron physics, and high energy density physics will be the missions in near future.

Characterization of the facility

1. 320 kV ECR ion high voltage platform.
2. SFC cyclotron: K=69 and full ion accelerator.
3. SSC cyclotron: K=450 and full ion accelerator.
4. CSRm cooler synchrotron: 12.2 Tm.
5. CSRe cooler storage ring: 9.4 Tm.

Technical facilities

Facility Parameters

Table 11.2: Facility parameters of the CSRm

Ion species	Stable nuclei (p to U)
Max. energy	3.7 GeV/c (p), 1.1 GeV/u ($^{12}C^{6+}$), 520 MeV/u ($^{238}U^{72+}$)
Intensity	10^5—10^{11} pps (stable nuclei)
Momentum spread	$\Delta p/p \sim 10^{-4}$
Experiment mode	External target, Internal target

Table 11.3: Facility parameters of the CSRe

Ion species	Fully stripped heavy ions: p — Ta; H-like, He-like heavy ions: Ta — U; RIB (A<180): neutron-rich, proton-rich
Max. energy	2.2 GeV (p), 750 MeV/u ($^{12}C^{6+}$), 500 MeV/u ($^{238}U^{92+}$)
Intensity	10^{11}—10^{16} pps (stable nuclei, internal target); 10^7—10^{12} pps (RIB, external target)
Momentum spread	$\Delta p/p < 10^{-5}$
Experiment mode	Internal target

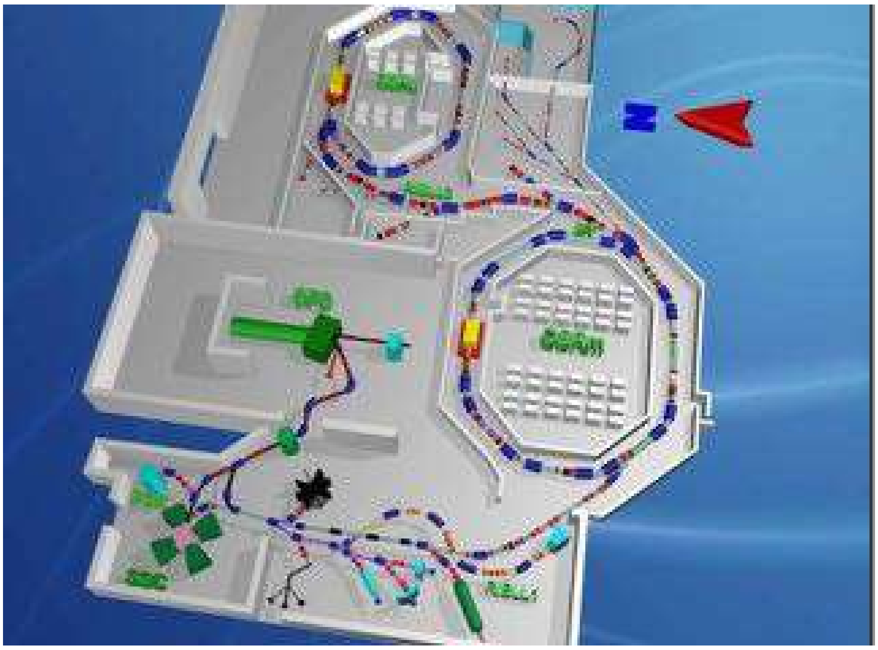

Figure 11.2: Schematics of the facilities in Lanzhou.

Major experimental instrumentation and its capabilities

The major experimental instrumentation includes: radioactive beam line (RIBLL, RIBLL-II), CSRe internal experimental setup with mass, lifetime measurement and laserinstruments, SHE spectrometer, mini 4π charged detector-MUDAL, in-beam γ experimental terminal, ECR platform, 320 kV ECR platform, irradiative terminal for materials science research, irradiative terminal for biology research, cancer therapy terminal, atomic physics terminal, laser laboratory and public NIM pool. The general and some special instruments, detectors and electronics for nuclear physics, atomic physics, materials sciences and biology physics are available.

Nature of user facility

HIRFL is officially a National Laboratory of China.

Program Advisory Committee/experiment proposals

HIRFL has a Science Advisory Committee to adjudicate experiment proposals.

Number of actual, active users of the facility in a given year

There are more than 200 formal users in the last five years.

Percentage of users, and percentage of facility use that come from inside the institution

About 30-40% of users come from outside the institute.

Percentage of users and percentage of facility use from national users

About 90% of the users are national users, and they use 90% of the beam-time of the facility.

Percentage of users and percentage of facility use from outside the country where your facility is located

About 10% of the users come from outside of China and less than 5% of the facility use is from outside of China.

Fraction of international users outside of geographical region

Up to now the international users are from Asia, Europe, and Africa.

User Group

The most of users are formal user group and they have had very close collaboration with the institute for a long time.

Number of total laboratory staff

Table 11.4 breaks down the staff at the laboratory in different categories.

Table 11.4: Staff at IMP Lanzhou. *Number includes post-doctoral fellows, students and the temporary staff of the theoretical centre of the National Lab. ** Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent Staff	400
Permanent Staff (Theory)	<6
Temporary Staff	100
Temporary Staff (Theory)	40*
Postdoctoral researchers	10
(Resident) Graduate students	110
(Non-resident) Graduate students	110**
Undergraduate students	∼50/ year

Future Plans

Facilities for cancer therapy including a booster, high current linear injector and molecular injector for the experimental ring are in planning in the near future. A big facility for high energy density physics is under consideration.

INTER-UNIVERSITY ACCELERATOR CENTRE NEW DELHI

Inter-University Accelerator Centre Aruna Asaf Ali Marg
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Autonomous Inter-University Research Centre of University Grants Commission of India

Program leaders

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Scientific Mission and Research Programs

Inter-University Accelerator Centre (IUAC), an inter-university research institution, was set up by the University Grants Commission of India. The basic objective of the Inter- University Accelerator Centre (IUAC) is to provide front-ranking accelerator-based research facilities for internationally competitive research in multi-disciplinary areas.

The Centre, as the first inter-university research institute within the University system, has been playing a crucial role with its Scientific and Technical staff having dual responsibility of facilitating cutting-edge research for a large user community as well conducting their own research and development to open new vistas of advanced research activities. Emphasis is laid on encouraging group activities and sharing of the facilities at the Centre in synergy with those existing elsewhere. The Centre has designed and commissioned various sophisticated accelerator systems and experimental facilities, in project mode, involving several universities/institutes for research in the areas of Nuclear Physics, Materials Science, Ion-Molecule Collisions, Atomic Physics, Radiation Biology, Radiation Physics, and Accelerator Mass Spectrometry. More than 700 research groups from Universities, Institutes, and Laboratories, from India and abroad, have been using the facilities round the clock, seven days a week, for nearly three decades.

Accelerators at IUAC

- 15 UD Pelletron Accelerator: Capable of accelerating ion beams of all essentially stable nuclei with energies up to 200 MeV depending on the ion species.
- Superconducting Linear Accelerator (SC Linac): Serves as a booster to the 15 UD Pelletron and is designed to accelerate ion beams up to mass 80 above the Coulomb barrier of 5MeV/nucleon for symmetric systems. Typical energy gain from SC Linac is 10 MeV/q.
- Negative Ion Implanter beam Facility (NIIBF): The ion implanter accelerator facility provides varieties of highly stable, collimated negative and singly charged ion beams with variable low energies, 30 to 200KeV, and current intensities, few nA to few μA.

- Positive Ion Beam Facilities: The Low Energy Ion Beam Facility (LEIBF) provides multiply positively charged ion beams at a wide range of energies (a few keV to about a MeV) for experiments in Atomic, Molecular, and material sciences.
- Pelletron Accelerator RBS-AMS Systems (PARAS): Rutherford Backscattering Spectrometry (RBS) facility with 1.7 MV Pelletron accelerator.
- Accelerator Mass Spectrometry And Geochronology Facility: AMS facility based on a dedicated 500kV Ion accelerator.
- Tabletop Ion Accelerators: To inculcate the interest of young faculties and students in the Physical Sciences in education and research we have in-house developed 60 kV Tabletop Ion Accelerator and 30 kV Tabletop Ion Accelerator for Physics students and faculty at the University/College level.

Upcoming Accelerators/Facilities

- High Current Injector Program (HCI): HCI is envisaged to overcome the low current limitation of the Pelletron Accelerator and to provide varieties of ion species like Nobel gases etc. which are not possible with the existing Pelletron Accelerator. It will act as an injector to SC Linac in place of 15 UD Pelletron.
- Free Electron Laser: An upcoming compact THz radiation and electron beam facility
- National Geochronology Facility (NGF): Ministry of Earth Sciences entrusted IUAC with the responsibility to develop National Geochronology Facility (NGF) with financial support. This is a special initiative of the ministry to facilitate the Earth Science community of the country with the much-needed up- to-date modern equipment and resources to carry out cutting-edge research in the field of isotope geochemistry and geochronology in the country.

Brief and compact table with the Major experimental instrumentation and its capabilities

- Gamma Detector Array: For high-spin spectroscopy. It consists of 12 Compton-suppressed HPGe detectors with a 14- element BGO multiplicity detector. It can be augmented with a Recoil-distance device, Mini-orange spectrometer, and a Charged-particle array.
- National Array of Neutron Detectors: The detector array consists of 100 liquid scintillators, each cell having a 5"x5" cylindrical size and type BC501A (Saint Gobain) coupled to a 5" photomultiplier tube. They are all mounted at a fixed flight distance of 175 cm from the target position. The detectors are mounted on a semi- spherical dome (geodesic) structure optimized for the present geometry. The Target is placed in a thin-walled spherical scattering chamber of 100 cm in diameter.
- Heavy Ion Reaction Analyser: Mass spectrometer for reaction products, Mass resolution 1/300, Beam rejection 10^{-12}. has been used for the measurement of sub-barrier fusion and transfer reactions. Used for production of ^{7}Be beam.
- Hybrid Recoil Analyser: Hybrid Recoil mass Analyzer (HYRA) is a dual-mode, dual- stage spectrometer / separator with its first stage capable of operating in a gas- filled mode in normal kinematics (to access heavy nuclei around 200amu mass and beyond) and both stages in vacuum mode in inverse kinematics (to access nuclei around N Z up to 100amu mass and to provide light, secondary beams produced in direct reactions).
- Indian National Gamma Array: It consists of Compton- suppressed Clover detectors with nearly 4π coverage. It has accessories like a plunger for lifetime measurements, a few planar Ge detectors for low energy gamma detection, and a compact charged particle ball. Two-thirds of the array can be coupled to the spectrometer HYRA for recoil tagging.
- General Purpose Scattering Chamber: General Purpose Scattering Chamber is the research facility installed at the 45° beamline in Beam Hall I of IUAC. It is a 1.5 m diameter scattering

chamber equipped with rotating arms and an in-vacuum target transfer system. This facility is being used for both nuclear physics as well as materials science experiments.

- Electrical Transport/ Noise measurements setup, FTIR, Micro- Raman Setup, Photoluminescence Setup, Scanning Electron Microscopy, Scanning Probe Microscopy, Transmission Electron Microscopy, UV-Vis absorption spectrophotometer, X-ray diffractometer, Contact Angle Set-up: Offline facilities for Materials Science studies
- Elastic Recoil Detection Analysis setups, Ionoluminescence Setup, Micro-Raman Setup, Residual Gas Analysis Setup, X- ray diffractometer: For online Materials Science interaction studies with swift heavy ions.
- Single & Two foil Beam-foil spectroscopy: Lifetime measurement of electronic states highly-charged ions.
- Low Energy Multiply charged ion beams: Multiply charged ion beams in the energy range: a few keV to a few MeV. Equipped with two beamlines. Facility for ion implantation, Atomic and Molecular collisions with multiply charged ions, Time of Flight spectrometer, Liquid droplet targets.
- Low-flux irradiation facility, Irradiation in air and vacuum: The heavy ions from the Pelletron are scattered and diffused to give uniform irradiation over an area with a diameter of $\sim$3 cm at a flux of 10^3 - 10^7 /cm^2/s.
- Atom beam sputtering, Ball- milling, Box Furnace, DC Sputter deposition, Thermal evaporation: Setup, Thermal evaporation for electrical contact, ECR plasma-based deposition, RF Sputtering, Tube Furnace: Synthesis facilities for Materials Science
- ASPIRE: The research facility at IUAC provides a dedicated Radiation Biology Beamline equipped with the irradiation system called ASPIRE [Automatic Sample Positioning for Irradiation in Radiation Biology Experiments].

Nature of user facility

IUAC is a user facility of UGC for researchers from Institutions in India and Abroad. National Facility for Space Applications, Geochronology etc.

Program Advisory Committee/experiment proposals

There is an Accelerator Users Committee that adjudicates the experimental proposals.

Percentage of users and percentage of facility use from national users

95% of users and 100% of facility users are from within the country.

Percentage of users and percentage of facility use from outside the country where your facility is located

About 5% of users are from outside India.

User Group

No, there is no registered users group. However, the total number of users is $\sim$700 currently.

Number of total laboratory staff

Table 11.5 breaks down the staff at the laboratory in different categories.

Table 11.5: Staff at IUAC New Delhi. *Number includes post-doctoral and graduate students. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	130 scientists and technicians
Temporary staff	15*
(Non-resident) Graduate students	150**

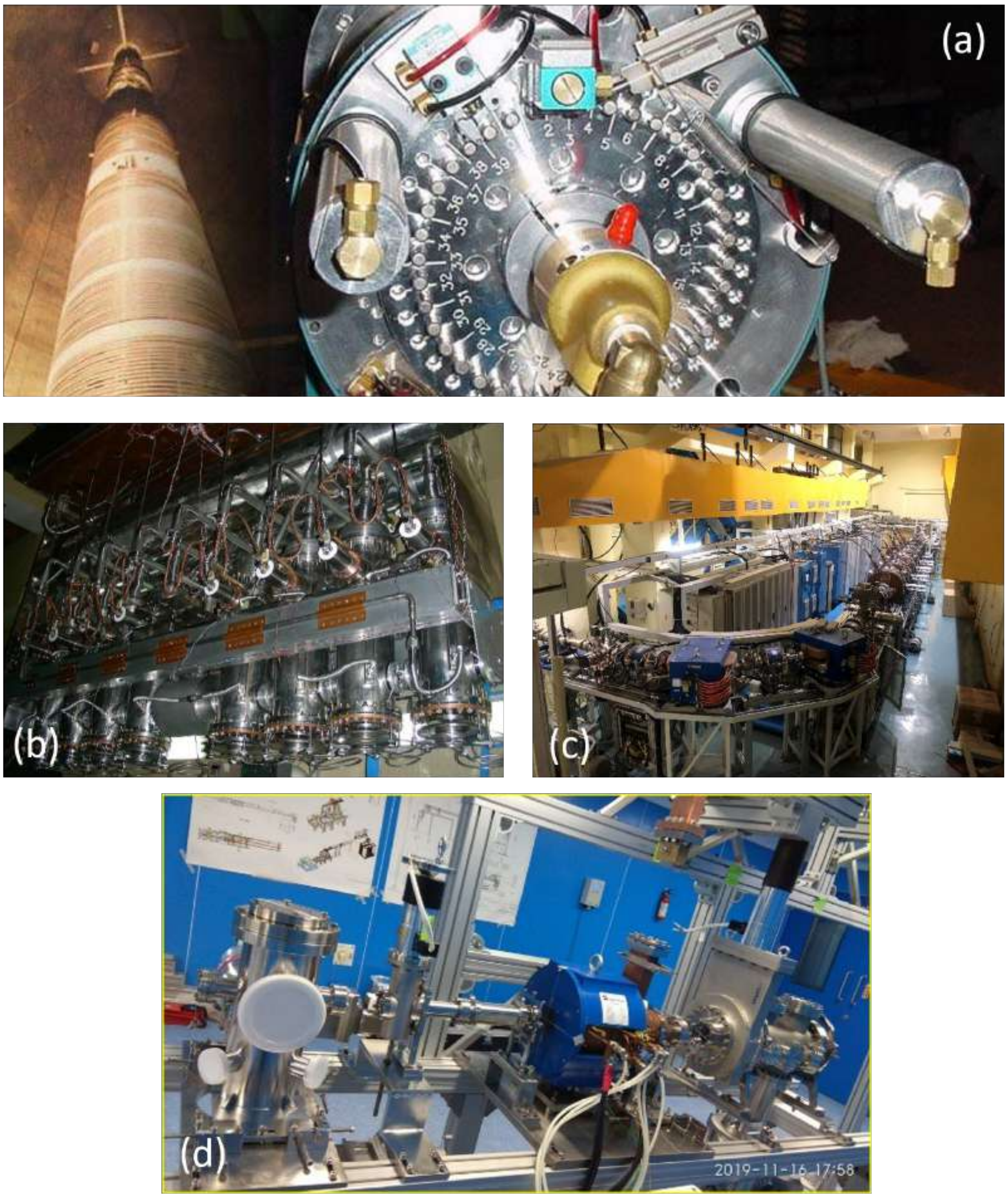

Figure 11.3: Facilities at IUAC: (a) 15 UD Pelletron and SNICS Ion Source; (b) Superconducting Linear Accelerator Module; (c) High Current Injector; (d) Free-electron Laser.

Special student programs

PhD programme in multidisciplinary areas based on accelerators. Three weeks program are held for students at the Master's level, Graduate courses are given for Ph.D. students. One month summer training program for undergraduates students is organized every year.

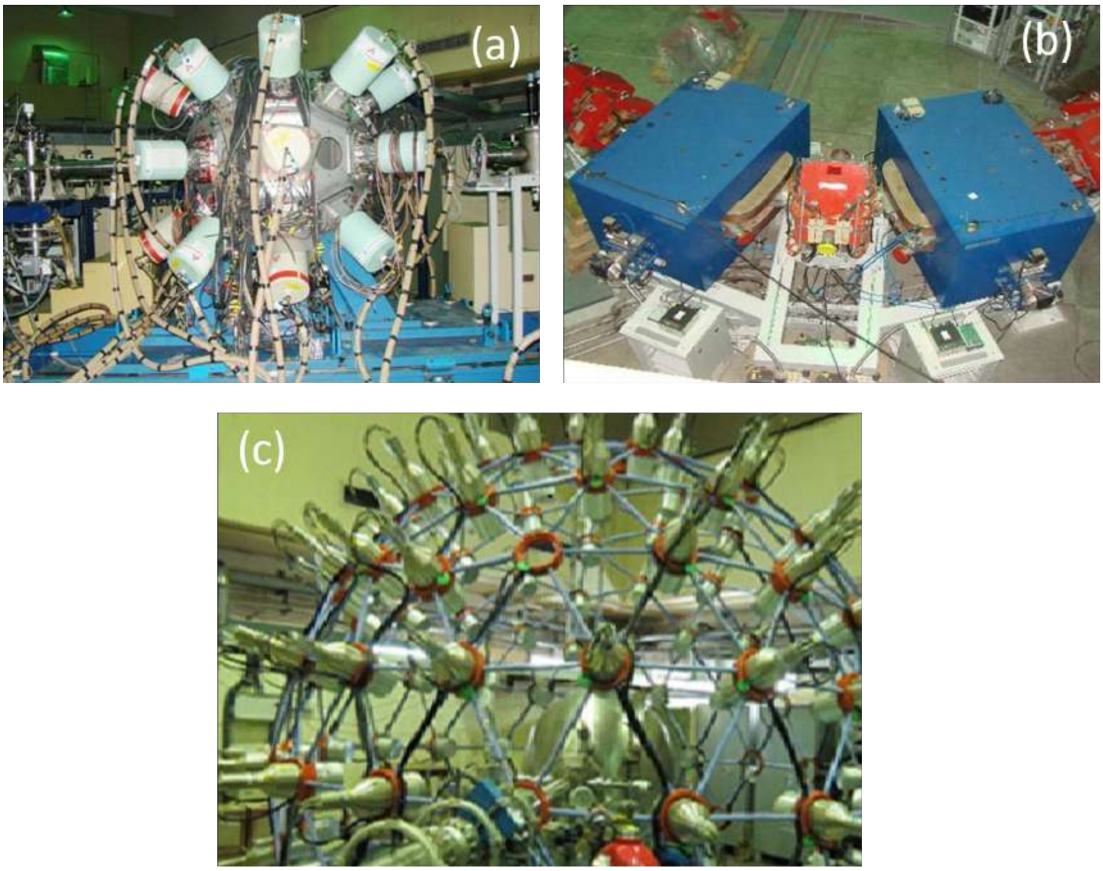

Figure 11.4: Facilities at IUAC: (a) Indian National Gamma Array; (b) Hybrid Recoil Mass Analyser; (c) National Array of Neutron Detectors.

VARIABLE ENERGY CYCLOTRON CENTRE KOLKATA (VECC)

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Telephone: (+91) 33 2337-1230
Facsimile: (+91) 33 2334-6871

Acting Director: Amitava Roy
E-mail : amitav@vecc.gov.in

Funding for the construction and operation comes from the
Department of Atomic Energy, Government of India.

Scientific Mission and Research Programs

The mandates of the Centre are as follows:

- Basic sciences : Experimental and Theoretical research in low and high energy Nuclear Physics using accelerators
- Accelerator based applied research in the field of material science and radiation damage studies
- Societal applications : Cyclotron for Medical Isotope production

VECC Laboratory staff

Table 11.6 breaks down the staff at the laboratory in different categories.

Table 11.6: Staff at VECC. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Total laboratory staff	580
Scientists on staff with doctoral degree	57
Permanent staff (theory)	13
Postdoctoral students (theory)	1
(Resident) Graduate students (theory)	10
Postdoctoral students (experiment)	3
(Resident) Graduate students (experiment)	29
(Non-Resident) Graduate students (experiment)	2*

Special student programs

Vacation programs/projects for undergraduate students (Science and Engineering), are organized of durations ~1-2 months.

Program Advisory Committee/ Experimental proposals

At present the VEC Users' Committee reviews the experimental proposals.

Accelerator facilities

Head of the facility: Dr. Arup Bandyopadhyay.

K 130 224 (88") Variable Energy Cyclotron

This machine is delivering charged particle beam since 1977 and still the work horse of this centre. The following beams as mentioned in the table have been accelerated and delivered to the users. At present the machine is fed alternatively by indigenously developed 14 GHz ECR source for heavy ions and a PIG Ion source for light ions.

K 500 Superconducting Cyclotron

The K = 500 Superconducting cyclotron was built and internal Neon beam was accelerated up to the extraction radius in 2009. The beam extraction process was not successful. The machine was diagnosed to have magnetic field error and the maximum RF voltage for first harmonic operation was also not found to be sustainable. At present a massive repairing work has been undertaken dismantling the major components.

Table 11.7: Ion species and energies.

Ion Species	Charge State	Energy Achieved (MeV)
Proton	1+	20
Helium	2+	80
Nitrogen	5+	105
Oxygen	6+	180
Neon	7+	200
Argon	12+	350

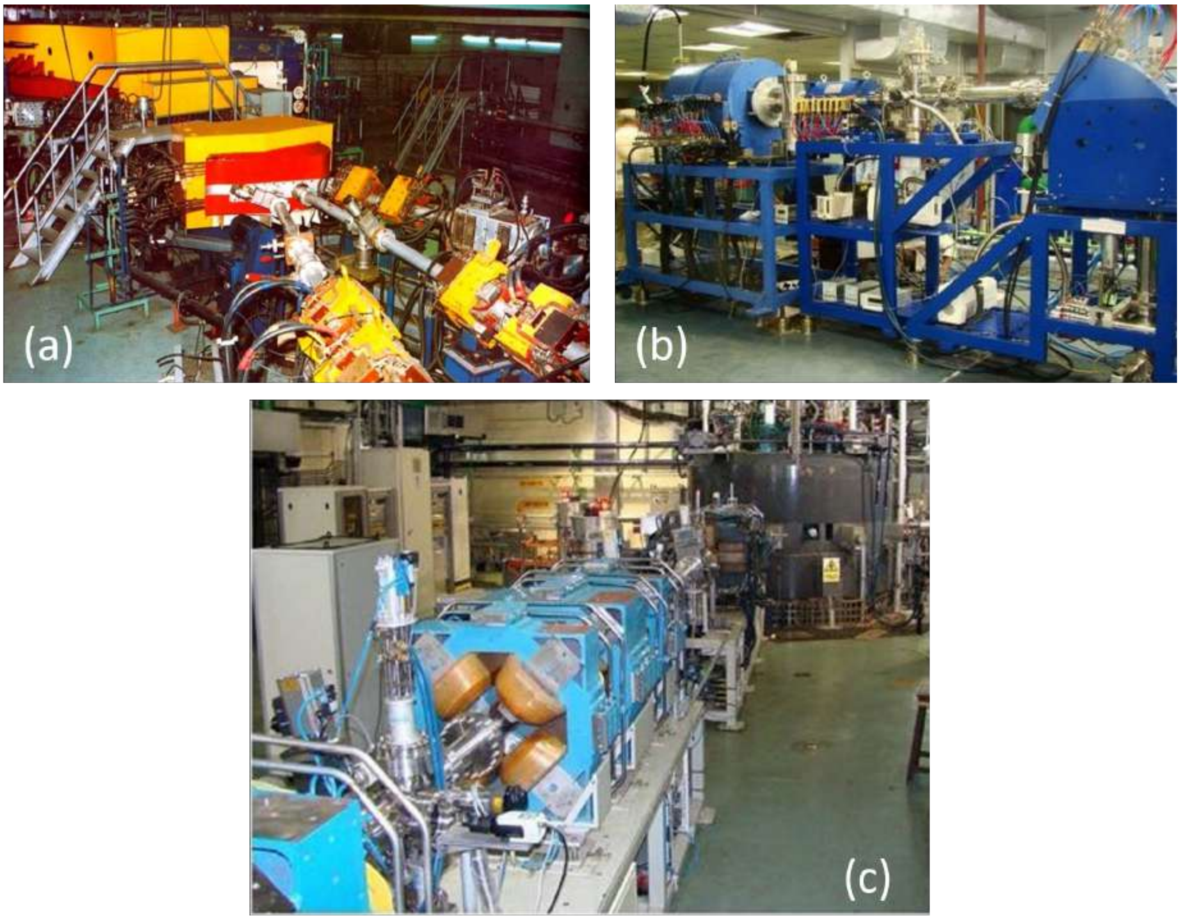

Figure 11.5: Facilities at VECC.

Experimental Facilities (existing and upcoming): Operational with K 130 Cyclotron (Room Temperature)

1. Scattering chamber (100 cm diameter & 200 cm long, horizontal type, to be used with K 500 SCC)

2. Charged particle detector array: Each detector in the forward part of the array (covering angular range $\sim 5^\circ$ - 40°) has been made up of 3 detector elements in telescope configuration. Each detector telescope consists of (i) thin Si-strip 1'E detector (Size: 5cm x 5cm, thickness: 30 – 50 μm, 16 strips, one-sided), followed by (ii) thick Si-strip 1'E/E detector (Size: 5cm x 5cm, thickness: 500 μm – 1mm, 16 strips, double- sided, X-Y directions), and (iii) 4 CsI(Tl) crystals (Size: 2.5cm x 2.5cm, thickness: 4 – 6cm). Backward part of the array consists of $\sim$ 250 Si+CsI telescopes.
3. Neutron multiplicity detector: Neutron multiplicity detector is a large tank of Gd-loaded liquid scintillator, read out using PMTs. The neutron detector is designed in such a way that the charged particle array can be placed within the neutron detector, rendering it possible to and measure simultaneously the neutrons as well as charged particles.
4. Neutron TOF Array: The array will consists of 50 numbers of organic liquid scintillator based neutron detectors, each having 5" diameter and a 5" length. It will be used for fast neutron spectroscopy and neutron angular distribution measurements. The primary motivation of developing the array is to understand some the unresolved issues in nuclear physics having current interest; understanding the dynamics of fission, multifragmentation, investigation of the energy level distributing of nuclei, exotic fragment studies are only a few to name. Currently the mechanical structure of the array is complete and 21 detectors have already been fabricated. The individual detectors have been used for experimental studies using beams from the K130 cyclotron at VECC.
5. High energy gamma detector array: The array consists of 162 BaF2 detectors (each of size: 3.5cm x 3.5cm x 35cm).
6. Gamma Spectroscopy: VECC has commissioned Compton suprresed Clover Detector Array of Six detectors for energy spectroscopy and 1" X 1" CeBr3 array for timing and angular co-relation studies.
7. Ion trap: A Penning Ion Trap has been commissioined. It is used for trapping low energy ions in magnetic field. Typical field required is $\sim$5 T, which is provided by a superconducting solenoid.

Rare Ion Beam (RIB) accelerator and ANURIB Project

Project Leads: Dr. Vaishali Naik and Dr. Arup Bandyopadhyay

The RIB accelerator at VECC is completed up to Linac No. 3 to give 415 keV/u. It is aimed to give 1 MeV/u after Linac No. 5 in 2018 and up to 2 MeV/u with Quarter Wave Resonators (QWR). AT present the facility can be used for Material Science experiments with energy in the range 10 KeV/u to 415 KeV/u. VECC now aims to construct the next generation facility called ANURIB (Advanced National facility for Unstable and Rare Isotope Beams). ANURIB is envisaged as a combined ISOL and fragmentation facility with beam energy from 1.5 keV/A to 100 MeV/A. It will be built around a 50 MeV, 100 kW superconducting electron linac photo-fission driver that VECC is developing in collaboration with TRIUMF laboratory in Canada. The facility will be constructed in stages and initial funding for writing a detailed Technical Design Report on physics and engineering design of components and science plan has been secured. The first part of the 50 MeV Se-linac which is Injector Cryo Module with 10 MeV 2mA has been developed and tested at TRIUMF and would be transported to VECC soon.

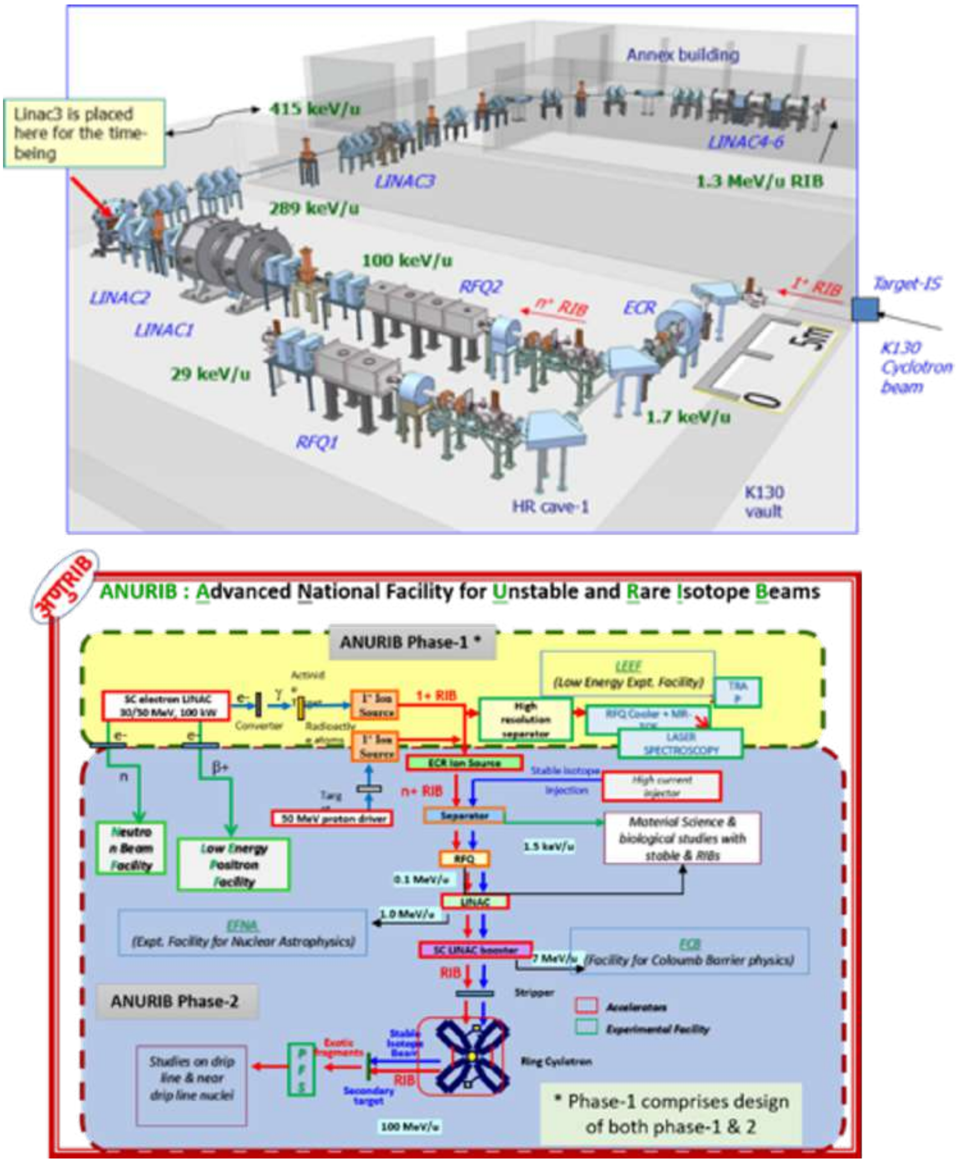

Figure 11.6: RIB facilities at VECC.

PELLETRON LINAC FACILTY MUMBAI

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Head of facility: Prof. R.G. Pillay (TIFR), Dr. A. Saxena (BARC)
E-mail: pillay@tifr.res.in, aloks@barc.gov.in

This is joint facility of BARC (unit of Department of Atomic Energy, Government of India) and TIFR (Automonomous Aided Institution of Dept. of Atomic Energy, Government of India)

Scientific Mission and Research Programs

The research activities at the facility span a variety of problems in nuclear, atomic, condensed matter physics and interdisciplinary areas. A number of application based research programmes such as accelerator mass spectrometry (AMS) and beam induced radiation damage studies in materials have also been taken up. The research work in nuclear physics, which forms the main thrust of activities at this facility, covers areas of nuclear structure studies at high angular momentum and excitation energies and the heavy ion reaction dynamics.

Technical Facilities

The Facility consists of the 14 MV Pelletron accelerator and an indigeneously developed superconducting LINAC booster. The Pelletron acts both as a stand alone machine and as an injector to the LINAC. The LINAC consists of seven modules, each module having a liquid He cryostat which houses four lead coated (2 μm) copper quarter wave resonators. The cavities are designed to operate at 150 MHz with an optimum acceptance at a velocity corresponding to v=0.1. Three different ion sources are available: (i) for negative He ions, (ii) for negative ions of other gaseous elements and (iii) a Cesium sputter ion source for nearly all other elements. An indigenously developed MC-SNICS (Multi-Cathode Source of Negative Ions by Cesium Sputtering) source has been successfully commissioned. A pulsed beam is obtained using a double harmonic drift buncher, built in-house, situated in the low energy injection path of the Pelletron accelerator. The beam bunches have a typical width (FWHM) of 1.5 ns with a separation of 107 ns and has a bunching efficiency of 66 %. The dark beam current between the beam bunches is swept away by a RF parallel plate sweeper, situated at the exit of the Pelletron. In addition, a beam chopper has also been installed to increase the time duration between bunches ($\sim$200 ns - 1.6 μs).

Characterization the facility

Beams available

Beams of ^{6,7}Li, ^{10,11}B, ^{12,13}C,^{14}N,^{16,18}O, ^{19}F, ^{24}Mg, ^{27}Al, ^{28,30}Si, ^{31}P, ^{32,34}S, ^{35,37}Cl are available through Pelletron and Linac upto 8-10 MeV/A, with an intensity of few pnA on target through collimators. Proton beams of upto 24 MeV, $\sim$200 nA are available in the high current irradiation setup. Heavier beams like Iodine, Silver are available through Pelletron. Alpha beam and additional negative ion beams are made available on request.

Major experimental instrumentation and its capabilities

- Clover Detector Array for discrete γ-ray spectroscopy with auxiliary detectors
- 150 cm dia Scattering Chamber for charged particle spectroscopy and fission studies
- BaF_2/$LaBr_3$ array for high energy γ-ray studies with BGO/NaI(Tl) multiplicity filter
- 7.0 T superconducting magnet for hyperfine interaction studies.

Figure 11.7: Inside view of a LINAC cryostat showing four quarter wave resonators.

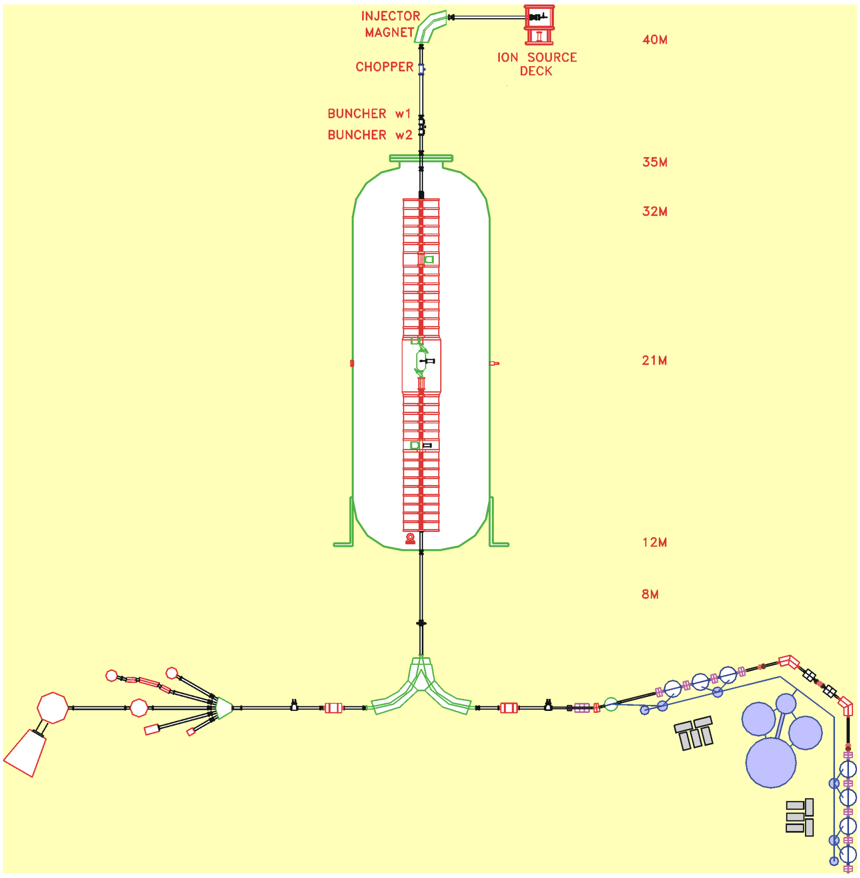

Figure 11.8: Schematic layout of 14MV Pelletron accelerator and LINAC

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- Electron spectrometer and X ray detector set up for atomic physics studies with gas/foil targets

- Irradiation setups
- High current proton and neutron irradiation facility
- Low background offline counting facility

Figure 11.9: Experimental area: User Hall 1 (top) and User Hall 2 (bottom), where both Pelletron and LINAc beams are available.

Nature of user facility

It is a national facility primarily used by TIFR and BARC scientists and open to collaborators from other research institutions/universities.

Program Advisory Committee/experiment proposals

The Pelletron Linac Programme Implementation Committee (PLPIC) screens the experimental proposals and monitors utilization of the accelerator. The Pelletron Linac Facility Committee (PLFC) deals with overall management of the facility.

Number of actual, active users of the facility in a given year

Till date about 50 institutions including universities have used the facility. Typically $\sim$ 60 experiments are carried out every year by different groups.

Percentage of users, and percentage of facility use that come from inside the institution

An estimate of the average percentage of inside users is $\sim$80%.
Percentage of facility use by the inside users $\sim$80%.

Percentage of users and percentage of facility use from national users

Percentage of national users $\sim$95%.
Percentage of facility use by the national users $\sim$99%.

Laboratory Staff

Table 11.8: Staff at BARC and TIFR. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	# of persons (BARC)	# of persons (TIFR)
Total laboratory staff	20	25
Scientists on staff with doctoral degree	30	8
Postdoctoral students	2	4
(Resident) Graduate students (experiment)	8	8
(Non-Resident) Graduate students (experiment)	$\sim$20*	

Special student programs

Summer training programs ($\sim$2 months) are organised by TIFR for undergraduate students. Engineering students do their project works in accelerator instrumentation ($\sim$10 every semester)

Future Plans

The upgrade of HV accelerating tube in the Pelletron is planned to enable operation at a higher voltage and improve the overall performance. It is also proposed to develop low Nb cavities for two linac modules, to enhance the acceptance of the Linac for heavier beams. Efforts are underway for the development of digital LLRF control for the superconducting cavities.

HEAVY ION MEDICAL ACCELERATOR IN CHIBA (HIMAC)

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Telephone: +81-43-206-3205
Facsimile: +81-43-206-4627

Head of facility: Tadashi Kamada, M.D.
E-mail: himac_riyou@qst.go.jp

National Research and Development Agency Government funding

Scientific Mission and Research Programs

National Institute of Radiological Sciences (NIRS) is a Japanese institution dedicated to comprehensive scientific research concerning radiation and health. The primary purpose of HIMAC is clinical trials of cancer treatment using heavy ion beams. During the past 23 years, more than 10,000 patients were treated, being a leading facility of heavy ion beam therapy in the world. Although the primary purpose is clinical trials, HIMAC also supplies various beams to experiments involving basic research beyond medical science, during the nights and on weekends. NIRS was merged into a new organization, National Institutes for Quantum and Radiological Science and Technology (QST), in April, 2016. The policy of open access and fair management remained unchanged.

Characterization of the facility

High-energy heavy ion beams of up to 800 MeV/u are supplied by linear accelerators and two synchrotron rings. Because the two synchrtron rings can work independently, three groups, including linac beams, can share the beam time simultaneously. Therefore, HIMAC offers relatively long beam time for basic research, about 4,800 hours in FY2015.

Technical facilities

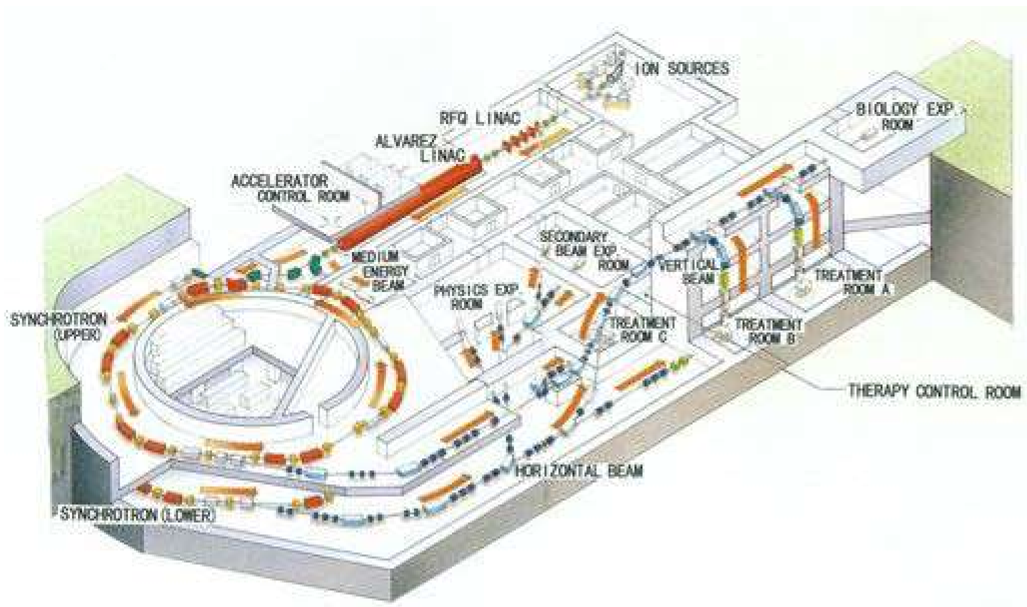

Figure 11.10: Experimental areas at HIMAC.

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Facility parameters

Table 11.9: Typical parameters from the synchrotron rings.

Ion Species	Energy (MeV/u)	Intensity (particles/ s)
He	100–230	$<1.2\times10^{10}$
C	100–430	$<1.8\times10^{9}$
N	100–430	$<1.5\times10^{9}$
O	100–430	$<1.1\times10^{9}$
Ne	100–600	$<7.8\times10^{8}$
Si	100–800	$<4.0\times10^{8}$
Ar	290–650	$<2.4\times10^{8}$
Fe	400–500	$<2.2\times10^{8}$

Beams from an injector linac, 6 MeV/u, are also available.

Brief and compact table with the Major experimental instrumentation and its capabilities

(Caution) In this, and the following descriptions, the clinical treatment part is not included.

Table 11.10: Beam characteristics for different courses.

Course name	Beam characteristics
General Purpose	Thin beams, a few mm in diameter
Secondary Beam Course	Projectile fragmentations
Biology Course	Large uniform field, 10cm in diameter
Medium Energy Course	Beams from an injector, 6 MeV/u

Nature of user facility

Yes, it is. The facility announces calls for proposals periodically.

Program Advisory Committee/experiment proposals

Yes, it has. PAC is composed of scientists from outside of NIRS, nominated by scientific societies and institutions, as well as some requested by NIRS.

Number of actual, active users of the facility in a given year

Most of the outside researchers participating in experiments are registered as "Collaborative Researchers" of NIRS. This number was 639 in FY2015. Other than Collaborative Researchers, a small number of researchers have different titles.

Users inside NIRS are about 138 in the same year. These are statistics based on a participant list concerning each proposal. Thus, the total number of users has been 777.

Percentage of users, and percentage of facility use that come from inside the institution

See the previous answer concerning the number of users. About 18% have come from inside NIRS. No definition or category concerning "Facility Use" exists. As an estimate, 23% of total 127 proposals in 2015 were submitted by researchers within NIRS.

Percentage of users and percentage of facility use from national users

Following the previous paragraph, about 64% of the users and 57% of the proposals come from other institutes in Japan.

Percentage of users and percentage of facility use from outside the country where your facility is located

Foreign users is 18% and 20% of all proposals come from outside Japan.

Fraction of the international users from outside your geographical region

Roughly speaking, about half of the foreign users come from outside southeast Asia, mainly U.S., Canada, and Europe, and some from Russia.

Users Group

: No formal users group exists.

Laboratory Staff

(Caution) Many medical staff members in the hospital are involved in activity related to the facility. Medical staff are, however, excluded when possible in answers to this question or questions hereafter.

Table 11.11: Staff at HIMAC. *Including medical physicists. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Total laboratory staff	13*
Scientists on staff with doctoral degree	7
Postdoctoral researchers	$\sim$3
(Resident) Graduate students	$\sim$10
(Non-Resident) Graduate students	$\sim$10**
Undergraduate students	$\sim$15

Future Plans

A superconducting rotating gantry for cancer treatment is near completed, and the first patient will be treated in 2017.

J-PARC TOKAI

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Facsimile: +81-29-282-5996
URL: j-parc.jp

Director: Naohito Saito
E-mail: director@j-parc.jp

Operation agreement between
High Energy Accelerator Research Organization(KEK) and
Japan Atomic Energy Agency (JAEA)

Scientific Mission and Research Programs

Japan Proton Accelerator Research Complex (J-PARC) covers a broad range of scientific researches. The main subjects in nuclear and particle physics at J-PARC are neutrino physics, strangeness nuclear physics, hadron physics, kaon decay physics, and muon physics. Experiments are performed mainly at Neutrino experimental facility and Hadron experimental facility. In addition, several experiments are also carried out at Material and Life Science Facility (MLF) with pulsed neutron and muon beams. The neutrino experimental facility provides the intense muon- neutrino beam to the huge neutrino detector, Super- Kamiokande, which is located 295km away from J-PARC. The T2K (Tokai-to-Kamioka) experiment measures the neutrino flavor change to search for the new neutrino oscillation, and eventually the hints for the CP-violation in neutrino. At the Hadron experimental facility, various nuclear and particle physics experiments are being carried out using a variety of high-intensity hadron beams. Using kaon beams, strangeness nuclear physics and kaon rare decay measurements are being performed. New beam lines are in preparation to perform hadron experiments using a high momentum beam (High-p) and a muon-electron conversion experiment (COMET).

Using high-intensity muon beams at MLF, muon physics experiments such as g-2 and muon EDM measurements are being planned.

Characterization of the facility

High-intensity proton accelerators produce high-intensity kaon, neutrino, muon, neutron beams, etc. There are three main experimental facilities: Material and Life Science Facility (MLF), Neutrino experimental facility (NEF), and Hadron experimental facility (HEF). Muon and neutron secondary beams are available at MLF, and kaon and other hadron beams are available at HEF.

Table of facility parameters

J-PARC's accelerator complex consists of Linac, Rapid Cycle Synchrotron (RCS), and Main Ring (MR). RCS provides the 3 GeV pulsed proton beam for MLF, and MR provides the 30 GeV proton beam for NEF with fast extraction and for HEF with slow extraction

In the experimental areas, instrumentations are constructed and operated by the users whose proposal on the experiment was approved by the program advisory committee.

Major experimental instrumentation and its capabilities

The following table summarizes beam lines which are under operation or construction for nuclear and particle physics experiments. Note: K1.8 and K1.8BR shared beam line magnets in the upstream part; the beam can be delivered only one of them at a time. Neutrino beam is available at

Table 11.12: JPARC facility parameters

Accelerator Name	Energy	Current (Design) Power	Cycle	Extraction
RCS	3 GeV	400 kW (1 MW)	40 ms	pulsed
MR	30 GeV	475 kW (750 kW) (1.3 MW)	2.48 s ($\sim$1.32 s) (1.16 s)	fast (8 bunches, beam on 4.2 μs)
MR	30 GeV	50 kW (100 kW)	5.2 s	slow (beam on 2 s)

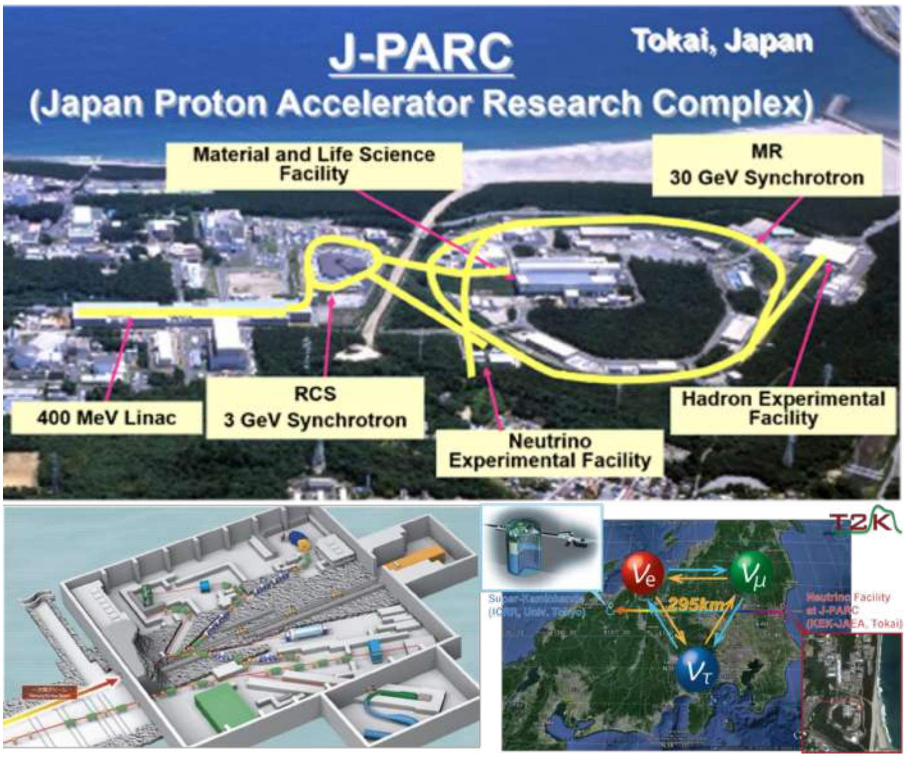

Figure 11.11: Overview of JPARC.

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NEF and other beams are delivered to HEF. New muon beam line (H-Line) is planned at MLF to perform new experiments.

Table 11.13: JPARC facility parameters

Name	Species	Energy	Intensity
ν	ν	0.7GeV (Average)	1.2x10^7 ν/cm^2/10^{21} pot@SK
KL	Neutral K	$\sim$2 GeV/c	$\sim10^6$ Hz
K1.8	$n^{\pm}$, $K^{\pm}$	<2 GeV/c	$\sim10^5$ Hz ($K^{\pm}$)
K1.8BR	$n^{\pm}$, $K^{\pm}$	<1 GeV/c	$\sim10^4$ Hz ($K^{\pm}$)
K1.1BR	$n^{\pm}$, $K^{\pm}$	<1.1 GeV/c	$\sim10^4$ Hz ($K^{\pm}$)
COMET	μ^-, re^-, e^-	20-60 MeV/c	3×10^{11} Hz (μ^-)
High-p	p unseparated	30 GeV <20 GeV/c	$\sim10^{10}$ Hz $\sim10^7$ Hz

Nature of user facility

International user facility

Program Advisory Committee/experiment proposals

There are two Program Advisory Committees. One is for nuclear and particle physics experiments with 30 GeV protons from MR, and the other is for material and life science experiments with 3 GeV protons from RCS.

Number of actual, active users of the facility in a given year

1282 users per year.

Percentage of users, and percentage of facility use that come from inside the institution

7%

Percentage of users and percentage of facility use from national users

32%

Percentage of users and percentage of facility use from outside the country where your facility is located

51%

Fraction of the international users from outside your geographical region

33%

User Group

Hadron Hall User Association for HEF, T2K collaboration for NEF, Neutron and Muon users communities for MLF

Laboratory Staff

Table 11.14: Staff at JPARC. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Total laboratory staff	84
Scientists on staff with doctoral degree	68
Staff (theoretical)	10
Postdoctoral researchers	5
(Resident) Graduate students	10
(Non-Resident) Graduate students	50*
Undergraduate students	10 / year

Special student programs

The Graduate University for Advanced Studies (SOKENDAI) has departments and Ph.D courses in particle physics, nuclear physics, and material and life sciences. KEK staffs can accept and supervise graduate students through it.

Future Plans

New hadron physics experiments and muon experiments will be performed using the new beam line at HEF. The facilities have following upgrade plans:

- New beam lines at MLF
- Increase of main ring power for the neutrino experiment.
- Extension of Hadron Hall and add more beamlines

RESEARCH CENTER FOR NUCLEAR PHYSICS (RCNP), OSAKA UNIVERSITY

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Head of facility: Takashi Nakano
E-mail: director@rcnp.osaka-u.ac.jp

University Institute
Ministry of Education, Culture, Sports, Science and Technology

Scientific Mission and Research Programs

RCNP is a national research center for nuclear physics research both from the experimental and theoretical sides. The aim is to promote and perform world-level research in nuclear and particle physics using advanced accelerators and related facilities to answer basic questions such as “Why are quarks permanently confined in a nucleon?” and “How neutrons and protons constitute nucleus” and “How was the universe born and formed?” The current major experimental activities are: (1) studies of static and dynamic properties of nuclei by using a high resolution proton and heavy-ion beams from the Ring Cyclotron, (2) studies of the quark and gluon properties in a nucleon by using a high-energy polarized photon beam at the Laser-Electron Photon facility at SPring-8, and (3)studies on neutrinos and the dark matter of the universe at Kamioka Double Beta Decay Laboratory.

Characterization of the facility

1. Cyclotron complex (K140 AVF + K400 ring) with relatively light-ions: High energy resolution (1’E/E=4x10^{-5}) with a dispersion matching method between the cyclotron and the magnetic spectrometer.
2. Laser-electron back-scattered photon facility: Polarized γ, 2.4 GeV, 5.0x10^6 cps: polarized γ, 2.9 GeV, 2.0x10^5 cps.

Technical facilities
Table of facility parameters

Table 11.15: JPARC facility parameters

Particle	Max. Energy (MeV)	Intensity (part.μA)
p	400	1
d	200	1
^{3}He	510	0.5
^{4}He	400	0.5
light-heavy ions	100*A*	0.1

Major experimental instrumentation and its capabilities

- Magnetic spectrometer “Grand Raiden”: Q=5.6 msr, δp/p = 5%, p/1’p = 37000, Bρ = 5.5 Tm
- Large Acceptance Spectrometer: Q= 20 msr, δp/p = 20%, p/1’p = 5000, Bρ = 3.2 Tm
- Neutron TOF tunnel: Flight length = 100 m, 1’t = 0.6 ns,
- Projectile fragment separator: Q=1.1 msr, δp/p = 8%, A/1’A = 326, Bρ = 3.2 Tm

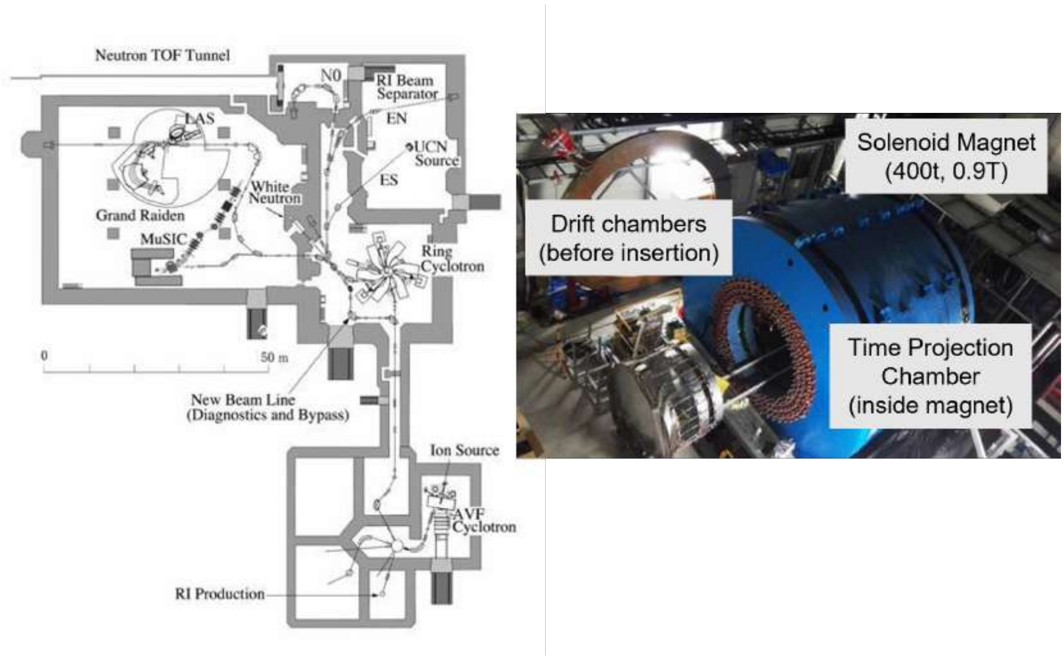

Figure 11.12: (Left) Cyclotron facility at JPARC. (Right) LEPS2 Spectrometer.

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Nature of user facility

National user facility (officially).

Number of actual, active users of the facility in a given year

700 users per year.

Program Advisory Committee/experiment proposals

Percentage of users, and percentage of facility use that come from inside the institution

users 20%, facility use 20%

Percentage of users and percentage of facility use from national users

users 65%, facility use 65%

Users from outside the country where your facility is located

users 15%, facility use 15%

Fraction of the international users from outside your geographical region

Asia, North-America, Africa, Europe, India

User Group

There is a formal users group. The number registered is 300 this year.

Laboratory Staff

See Table 11.16.

Special student programs

Educational experiments for undergraduate students of various universities in Japan.

Table 11.16: Staff at RCNP. *Including medical physicists. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Total laboratory staff	41
Scientists on staff with doctoral degree	79
Permanent staff (theory)	8
Temporary staff (theory)	18
Postdoctoral researchers	13
(Resident) Graduate students	36
(Non-Resident) Graduate students	82*
Undergraduate students	15/ year

Future Plans

Upgrade of the cyclotron facility and a new beamline for hadron spectroscopy at J-PARC are under discussion.

NewSUBARU

SPring-8 site, Hyogo, Japan
NewSUBARU Synchrotron Light Facility
Kouto, Kamigor, Hyogo, 678-1205 JAPAN

Satoshi Hashimoto
E-mail: hashi@lasri.u-hyogo.ac.jp

Facility operated by
Laboratory of Advanced Science and technology for Industry University of Hyogo

Scientific Mission and Research Programs

The aim of the facility of the low-energy γ-ray beam line is to contribute to the science and technology research by means of photo-material reactions, photo-nuclear reactions and electron-positron pair creation. Gamma-ray beam is produced by laser Compton scattering (LCS) with the 0.5 GeV - 1.5 GeV electron beam in the storage ring of NewSUBARU.

A high intensity LCS photon beam isproduced in the energy range of 0.5 MeV to 76 MeV with the γ-ray flux of 10^7 γ-photons/sec. Two γ-ray experimental hutches, Hutch-1 and -2, are installed. Hutch-2 is called GACKO: Gamma Collaboration Hutch of Konan University. LCS γ-ray beams have been used in GACKO for fields of nuclear engineering, nuclear physics, beam physics, nuclear astrophysics, material science, and industrial use.

Figure 11.13: Layout of NewSUBARU synchrotron light facility (left). Gamma-ray beam line is BL01. An electron beam is injected from 1 GeV linac. The electron storage ring (right) is operated with a top-up current of 350 mA. Natural emittance of the electron beam is 37 nm-rad. The circumference of the storage ring is 118.73 m, the RF frequency and number of electron buckets are 500 MHz and 198, respectively.

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Characterization of the facility

MeV LCS γ-ray source in synchrotron light facility.

Table of facility parameters

Beam1: Laser Compton scattering γ-ray beam; Intensity: 10^6-10^9 γ/sec (full spectrum), Energy range: 0.5 - 76 MeV; Linear and circular polarization: $>90\%$.

Beam2: Positron beam; Intensity: 3-5% of the γ-ray (full spectrum); Energy range: 1- 40 MeV; Polarization: the spin of electron and positron are parallel each other and the same with the γ-ray.

Technical facilities

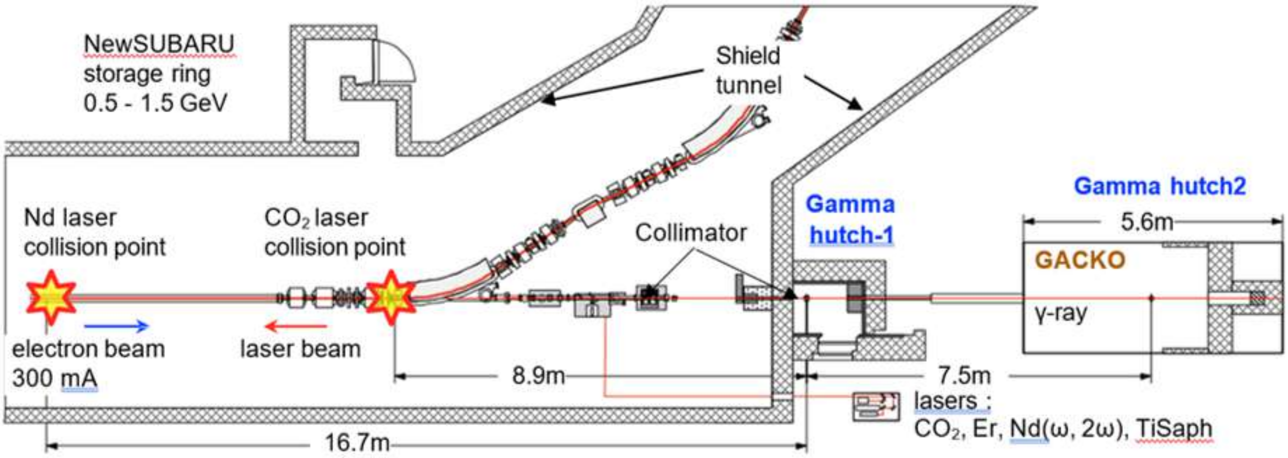

Figure 11.14: A 1/6 of NewSUBARU electron storage ring is shown. Laser injection is made from the outside of the shield tunnel of the storage ring. Electron beam and the laser be collied at two collision points depend on the laser wavelength. LCS-gamma-ray beam propagate to the gamma-ray hutches pass through the vacuum window. Two gamma-ray hutches are arranged in series.

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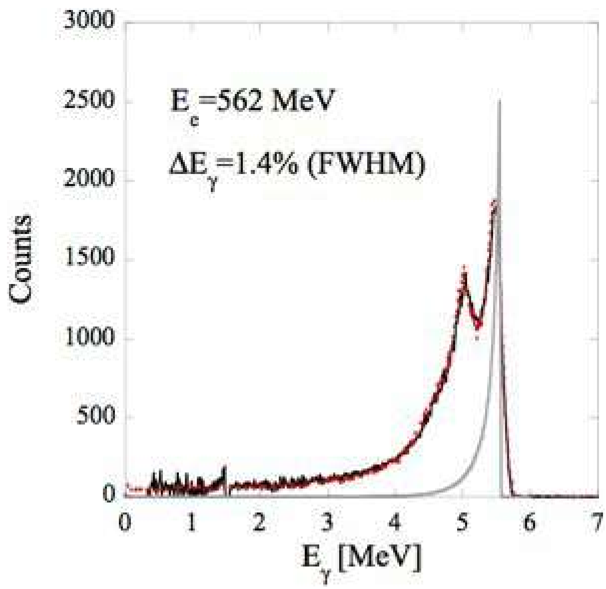

Figure 11.15: This shows a spectra of LCS γ-ray with the Nd:YVO4 laser (wavelength of 1064 nm) scattered with electron beam of 562 MeV measured by a LaBr3 (Ce) detector [Ref]. The LCS γ-ray was collimated with a lead block of 10 cm thick with 2mm diameter hole located at 16.7 m from the collision point. Quasi-monochromatic γ-ray beam with energy spread of 1.4% is obtained. A experimental response function (solid line) of the LaBr3 (Ce) detector along with the simulated response function (dotted line) and energy distribution of the LCS γ-ray beam (grey line). [Ref] Utsunomiya et al. Phys. Rev. C 92, 064323 (2015).

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Major experimental instrumentation

- High purity Ge detectors (45%)
- NaI scintillation detectors (12”×8”, 3”×3” etc.)

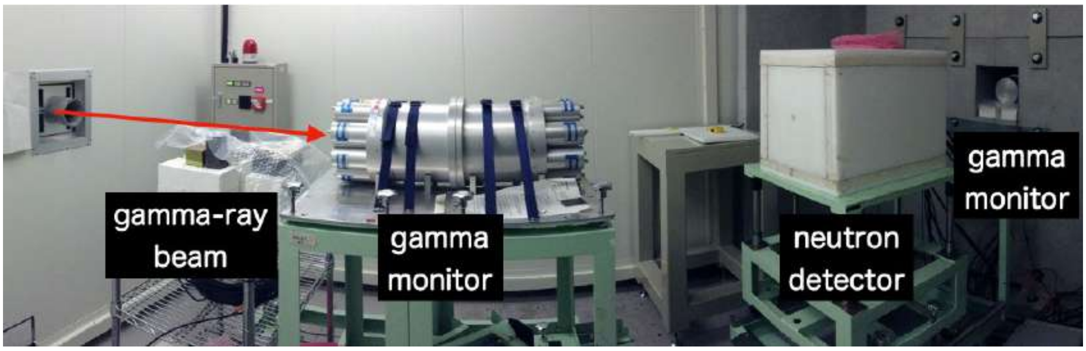

Figure 11.16: Photograph of interior of gamma-ray beam irradiation Hutch-2 (GACK)
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- Neutron detectors (plastic scintillator etc.)
- Electronics devices (NIM modules)

Nature of user facility

Collaborative use (80%), User facility (20%).

Program Advisory Committee/experiment proposals

Yes (Priority for industrial use).

Number of, active users and their origin

10 user groups:

1. Konan University in collaboration with the National Institute for Physics and Nuclear Engineering Horia Hulubei, Romania, and the University of Oslo, Norway, and the Japan Atomic Energy Agency
2. National Institutes for Quantum and Radiological Science and Technology, Japan
3. Research Center for Nuclear Physics, and Institute of Laser Engineering, Osaka University, Japan
4. Institute for Laser Technology, Osaka, Japan
5. Institute of Advanced Energy, Kyoto University, Japan
6. Osaka Prefecture University, Japan
7. Ecole Polytechnique LLR, and CEA, France
8. Linear Accelerator Laboratory, University Paris-sud, France
9. National Institute of Nuclear Physics, University Milano, Italy
10. High Energy Accelerator Research Organization (KEK), Japan

Laboratory Staff

Permanent staff: 3.

Future Plans

New LCS γ-ray beam line is planning at BL04 of NewSUBARU. Rotating laser injection system is considered for changing the γ-ray energy without changing the electron beam energy.

RIBF at RIKEN NISHINA CENTER FOR ACCELERATOR-BASED SCIENCE

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Director: Hiroyoshi Sakurai
E-mail: sakurai@ribf.riken.jp (Hiroyoshi Sakurai, Director)
E-mail: kamigait@riken.jp (Osamu Kamigaito, Accellrator Division Head)
E-mail: UserSupportOffice@ribf.riken.jp (RIBF User Support Office)

RIKEN: National Research and Development Institute under
Japanese Ministry of Education, Culture, Sports, Science and Technology
Dr. Makoto Gonokami (President)

Scientific Mission and Research Programs

RIKEN RI Beam Factory aims at providing exotic nuclei very far from stability as secondary (radioactive isotope - RI) beams. The primary mission is to develop our understanding of nuclear structure and nucleosynthesis in the universe by extending the region of accessible nuclides. It was completed in 2006 and started its full-scale operation in November 2008. In addition to the nuclear physics and nuclear astrophysics, the research programs include the super-heavy element search, nuclear transmutation, plant breeding, RI production, and other related applications.

Technical facilities

Characterization of the facility

Intermediate-energy accelerator complex providing a variety of ions. Fast RI beams are produced by projectile fragmentation and/or in- flight fission.

Table of facility parameters

- Beam species: from hydrogen to uranium including polarized deuteron for primary beams.
- Goal intensities: 1pμA (100 pnA for ^{238}U).
- The beam current achieved so far is 740 pnA for ^{48}Ca, 790 pnA for ^{70}Zn, 170 pnA for ^{124}Xe, and 120 pnA for ^{238}U, respectively.
- Range of energies: typically 345 MeV/u.
- Special properties: A large acceptance fragment separator, BigRIPS, enabling efficient production of fast RI beams.

Lower energy heavy-ion beams from 0.66 MeV/u to 135 MeV/u are also available. Details of available primary and secondary beam intensities can be found respectively at www.nishina.riken.jp/RIBF/accelerator/tecinfo.html, and www.nishina.riken.jp/RIBF/BigRIPS/intensity.html.

Experimental facilities and major instrumentation

Facilities in the low energy branch

- RIPS (RIKEN Projectile Fragment Separator for secondary beams of a few tens MeV/nucleon)
- GARIS II (Gas-filled recoil Separator for search for super-heavy elements)
- CRIB (Low energy secondary beam separator in a few MeV/nucleon, operated by CNS, University of Tokyo)
- KISS (KEK Isotope Separation System WNSC, KEK)

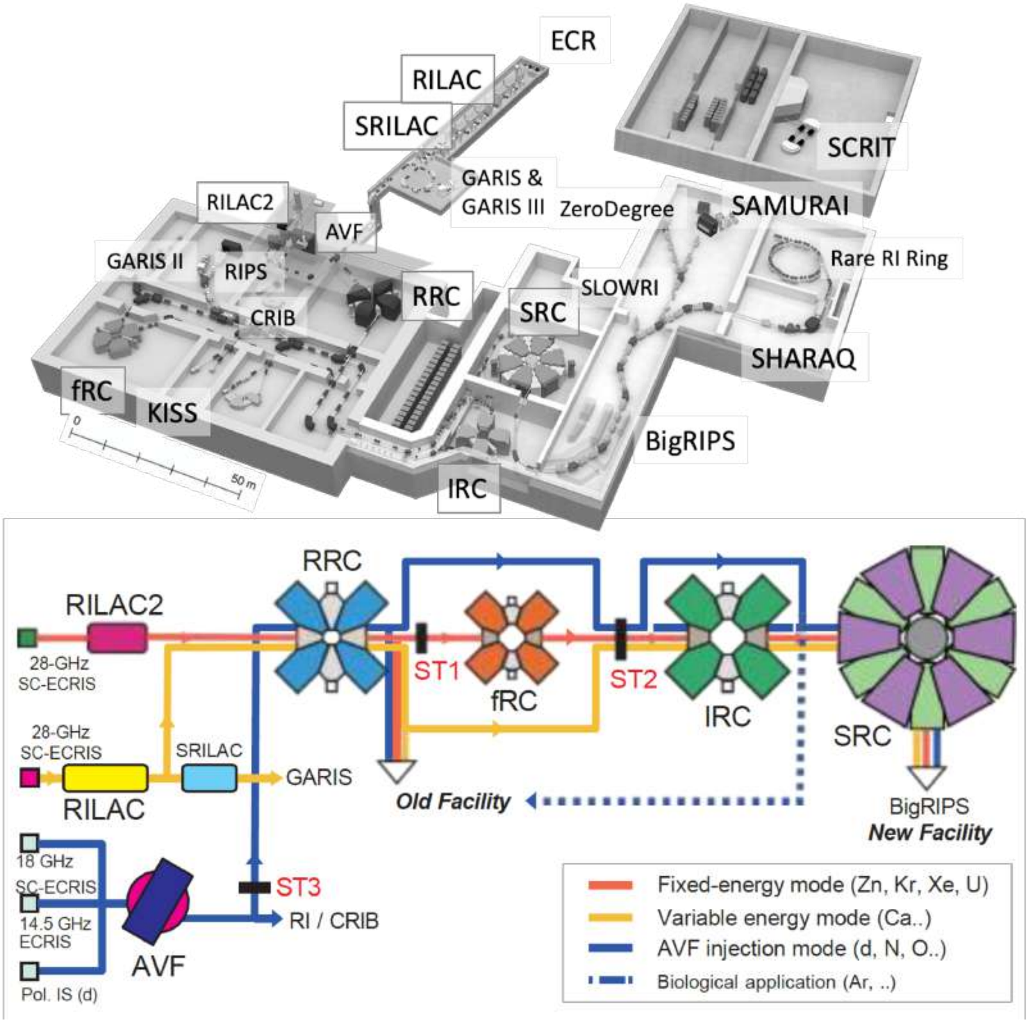

Figure 11.17: Layout of the present facility and RI Beam Facility and acceleration scheme.

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RIBF facilities

- Big-RIPS (Projectile Fragment Separator for secondary beams of 200 MeV/nucleon typical)
- ZDS (Zero Degree Spectrometer)
- SAMURAI (Large Acceptance Spectrograph)
- SHARAQ (High Resolution Spectrograph, operated by CNS, University of Tokyo)
- OEDO (Optimized Energy Degrading Optics for RI beam, operated by CNS, University of Tokyo)

New instrumentation under construction

- SCRIT (Self Confining RI Target for electron scattering)
- Rare-RI Ring(Storage ring for rare RIs)
- SLOWRI (universal low-energy RI-beam facility)

Nature of user facility

RIBF is an user facility. RIBF User Support Office is the official contact for users.

Program Advisory Committee/experiment proposals

Two open program-advisory-committee meetings are held annually with worldwide experts, one for nuclear physics, NP-PAC, and the other for material and lifescience, ML-PAC. Another closed committee is held for industrial applications.

Number of actual, active users of the facility

In FY2020 (from April 2020 to March 2021) 712 users attended the experiments at RIBF.

Percentage of users, and percentage of facility use that come from inside the institution

Users: 44%; Facility use (beam time): 31%.

Percentage of users and percentage of facility use from national users

Users: 99%; Facility use: 98%.

Percentage of users and percentage of facility use from outside the country where your facility is located

1% (Asia 55%, Europe 45%). Note: Note: The international users were much reduced by the difficulty of their travels to Japan due to the Covid-19 epidemic.

User Group

RIBF user's group exists with 743 registered members: ribfuser.riken.jp/RIBF_UG/.

Laboratory Staff

Table 11.17: Staff at RIKEN Nishina Center. *Non-resident graduate students with thesis work primarily done at the facility. **Includes graduate students, postdocs, fixed-term contract, and permanent.

Designation	Number of persons
Permanent staff	72
Temporary staff	61
Permanent staff (theory)	6
Postdoctoral researchers (theory)	5
(Resident) Graduate students (theory)	6
(Non-Resident) Graduate students*	20
External researchers**	6
Undergraduate students	∼80/ year

Special student programs

1) Summer school is organized every summer by CNS, Univ. of Tokyo. at RIKEN Nishina Center. Graduate students and young postdocs from Asia, Europe, and the US are invited.
2) Nishina School is held every summer for Asian undergraduate students. This course includes a laboratory training course. Students from China, Korea, and Hong Kong attend. Currently suspended due to Covid-19.

Future Plans

1) Upgrades of the primary-beam intensity are being planned by introducing a new charge- stripping device enabling the transmission of ions with multiple charge states and other modifications.
2) WNSC (KEK) plans to construct a new facility called KISS-II collecting products of the multi-nucleon-transfer reaction to approach neutron-rich isotopes in the N=126 and actinide regions.

KYUSHU UNIVERSITY TANDEM ACCELERATOR LABORATORY (KUTL)

Tandem Laboratory
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S. Miyahara (Dean of Faculty of Science, Kyushu University)
Head of facility: Kenshi Sagara (Director of KUTL)
E-mail: sagara@nucl.phys.kyushu-u.ac.jp

Institute of Kyushu University
Japanese Government

Scientific Mission and Research Programs

1. Direct measurement of ^{12}C + ^{4}He -> ^{16} O+ γ reaction cross section down to E_{cm} = 0.7 MeV. For this experiment, instruments and methods have been developed such as a blow-in windowless gas target (3 kPa), a recoil mass separator, a chopper for recoils, transform of our tandem accelerator to a small tandem. The experiment will be finished in several years.
2. Anomalous cross section in three-nucleon break- up. Precise and systematic measurements of pd break-up at around 10 MeV have been in progress
3. Accelerator mass spectrometry (AMS) for ^{14}C.

Characterization of the facility

A tandem accelerator with pulsed beam.

Table of facility parameters

Table 11.18: Beams and energies available at KUTL.

Beam	Intensity	Energy
p, d	a few μA	2-18 MeV
C, O	0.1-5 particle μA	3-60 MeV (pulsed)
Si, Ni	50 particle nA	10-70 MeV

Brief and compact list with the Major experimental instrumentation and its capabilities

- Recoil mass separator: 1'0 = ±40mr, E/q= 4MeV, 1'm/m = 200
- Windowless gas target: He10 Torrx3cm, N2 30 Torrx3cm
- Pulsed beam: 3-6 MHz, width = 5-10 ns
- Accel-decel operation: transform the 10 MV tandem to a 1 MV tandem

Technical facilities

Nature of user facility

Users can use the facility. Consult Director K. Sagara (sagara@phys.kyushu-u.ac.jp)

Program Advisory Committee/experiment proposals

Yes. Experiment proposals are discussed and scheduled in the weekly meeting.

Number of active users and their origin

7 staff and 20 graduate students, 6 experimental groups.

Figure 11.18: A recoil mass separator consisting of QQEMDDQQ (upper part) and a windowless gas target (lower part) for astro-nuclear experiments.

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Percentage of users, and percentage of facility use that come from inside the institution

Inside user 70%; Inside use 85%.

Percentage of users and percentage of facility use from national users

100%.

Percentage of users and percentage of facility use from outside the country where your facility is located

0% (foreign users are welcome).

Fraction of the international users from outside your geographical region

None.

User group

Yes. 7 staff and 25 graduate students

Laboratory Staff

Special student programs

Lecture and experiment for undergraduates Graduation thesis experiment for undergraduates. Learning experiment for high school students (2 days in a year).

Table 11.19: Staff at KUTL. *Including medical physicists. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	2
Postdoctoral researchers	1
(Resident) Graduate students	2
(Non-Resident) Graduate students	9
Undergraduate students	5

Future Plans

New upgrade facility is under construction in a new campus. A FFAG synchrotron has been installed, and a small tandem accelerator will be installed. The present tandem accelerator will be shut down around 2013. We will report about our new facility in the next issue.

The present tandem accelerator was designed by A. Isoya in 1970's. The accelerator and ion sources have been often improved for new experimental projects in collaboration with students. Many graduate students from our laboratory have gone to accelerator science and related fields.

TOKAI RESEARCH AND DEVELOPMENT CENTER, TANDEM FACILITY, JAPAN ATOMIC ENERGY AGENCY

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National Institute
Ministry of Education, Culture, Sports
Science and Technology

Scientific Mission and Research Programs

Basic research in fields of nuclear physics, nuclear chemistry, and material science using accelerated heavy-ions as well as radioactive ions.

1. Study of heavy-ion nuclear physics
2. Study of heavy-ion chemistry
3. Study of nuclear fuels and materials
4. Research and development of radioactive nuclear science

Characterization of the facility

(1) Tandem accelerator and superconducting linac with heavy-ion beams.
(2) Tandem accelerator, ISOL, and normal conducting linacs with radioactive-ion beams.

Table of facility parameters

Table 11.20: Tandem and superconducting linac

Beam species	Proton to uranium
Intensities	3 μA (p), 0.5particle μA (others)
Range of energies	20 *A*MeV (A=15) to 5 *A*MeV (A=200)

Table 11.21: Tandem and ISOL + normal conducting linacs

Beam species	Radioactive ions (mainly fission fragments of U)
Intensities	$<$20 particle pA
Range of energies	0.174 *A*MeV to 1.1 *A*MeV
Special properties	ISOL-based radioactive ion beams

Technical facilities

Brief and compact list with the Major experimental instrumentation and its capabilities

Nature of user facility

This facility is an official user facility by Japan Atomic Energy Agency (JAEA), but some part of the facility is maintained by a cooperation of JAEA and High Energy Accelerator Research Organization (KEK).

Figure 11.19: Experimental areas at JAEA Tokai.

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Table 11.22: Tandem and ISOL + normal conducting linacs

Recoil mass separator	Ion-optical configuration: Q-Q-E-D-E-Q-Q Mass resolving power: variable less than 1500 Solid angle acceptance: 10 π mm•mr
Isotope Separator On- Line (ISOL)	Ion-optical configuration: Q-Q-D Mass resolving power: 1200 Available ion-sources: surface and hot-plasma
Gamma-ray detector array (GEMINI-II)	Configuration: 20 Ge-detectors + Compton active shields

Program Advisory Committee/experiment proposals

JAEA-PAC is for the proposals using heavy-ion beams and KEK-PAC is for the ones using radioactive ion beams.

Number of active users and their origin

280.

Percentage of users, and percentage of facility use that come from inside the institution

Users: 90%; Facility: 10%

Percentage of users and percentage of facility use from national users

Users: 80%; Facility: 95%

Percentage of users and percentage of facility use from outside the country where your facility is located

Users: 20%; Facility: 5%

Fraction of the international users from outside your geographical region

Asia: 72%, North-America: 14%, Europe: 14%

User group

None.

Table 11.23: Staff at JAEA Tokai. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	14
Temporary staff	3
Permanent staff (theory)	4
Postdoctoral researchers (experiment)	4
Postdoctoral researchers (theory)	2
(Resident) Graduate students (experiment)	2
(Resident) Graduate students (theory)	1
(Non-Resident) Graduate students	5*

Laboratory Staff

Special student programs

There exist a summer program for under graduate student.

Future Plans

Existing normal conducting linacs will be connected to the superconducting linac to accelerate radioactive ion beams up to 5 to 8 MeV/A as well as to supply an intense heavy-ion beams independent from the tandem beams.

UNIVERSITY OF TSUKUBA TANDEM ACCELERATOR COMPLEX

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Fascimile: +81-29-853-2565

Email: info@tac.tsukuba.ac.jp
Head of the facility: Akira Uedono

University Facility
Government

Scientific Mission and Research Programs

Cross-ministerial Strategic Innovation Promotion Program, Japan.

Characterization of the facility

Electrostatic accelerator facility with two tandems (6 MV Pelletron tandem accelerator and 1 MV Tandetron accelerator;
Lamb-shift polarized ion source
Apparatus utilizing radio-isotopes

Facility parameters

H, D, Polarized H, Polarized D, He, B, C, O, Cl, Au, Bi (Many species)
0.5 MeV – 91 MeV (Depending on the species)

Brief and compact list with the Major experimental instrumentation and its capabilities

Accelerator Mass Spectrometry(AMS), Micro Beam Analysis System, Micro Beam PIXE (μ-PIXE), Rutherford Back Scattering spectrometry System (RBS), IBA system, High-energy Ion Irradiation system, Radiation Effects on Semiconductor Devices for Space Applications, Momentum Analyzer (ESP- 90), Polarized Ion Source.

Nature of user facility

Yes.

Program Advisory Committee/experiment proposals

Yes.

Number of active users and their origin

60.

Percentage of users, and percentage of facility use that come from inside the institution

Users: 90%; Facility use: 70%.

Percentage of users and percentage of facility use from national users

Users: 99%; Facility use: 98%.

Percentage of users and percentage of facility use from outside the country where your facility is located

Users: 1%; Facility use: 2%.

Fraction of the international users from outside your geographical region

Asia; 100

User group
Yes, total number of registered members are 120.

Laboratory Staff

Table 11.24: Staff at Tsukuba Tandem. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	9
Temporary staff	6
Postdoctoral researchers	2
(Resident) Graduate students	30
(Non-Resident) Graduate students	3*

Special student programs
Student labs for high school students. Experiments with the accelerator for undergraduate students.

TOHOKU UNIVERSITY RESEARCH CENTER FOR ELECTRON-PHOTON SCIENCE

Research Center for Electron-Photon Science (ELPH)
Tohoku University
Mikamine 1-2-1, Taihaku, Sendai, Japan
Telephone: +81-22-743-3400
Facsimile: +81-22-743-3401

Director: Hiroyuki Hama E-mail: koho@lns.tohoku.ac.jp

Nationalwide joint-use research center in Electron-Photon Science
Japanese Government (Ministry of Education, Culture, Sports, Science and Technology)

Scientific Mission and Research Programs

Research Center for Electron-Photon Science (ELPH) is a nationalwide joint-use research center in electron-photon science. It was founded to aim at carrying out fundamental researches and applications in nuclear science, and educating students in related fields. ELPH operates two accelerators (Fig. 11.20): a 60 MeV electron linear accelerator and a 1.3 GeV electron booster synchrotron.

The linear accelerator provides an intense pulsed beam and has been used in a wide range of research fields, not only nuclear physis but solid state physics, radiochemistry, biology and so on.

The 1.3 GeV synchrotron (Fig. 11.21) provides two GeV tagged photon beams using internal radiators for quark nuclear physics researches. Recently, a new beam line and two-arm electron spectrometer connected to the 60 MeV linac are under construction to carry out electron scattering for proton under the lowerst-ever momentum transfer in order to determine the proton charge radius.

Technical facilities

The accelerator facilties were severely damaged by the Great East Japan Earthquake occurred in March 11, 2011. After a long-term recovery work, the accelerators were restored, partially renewed, and started operation in the end of 2013.

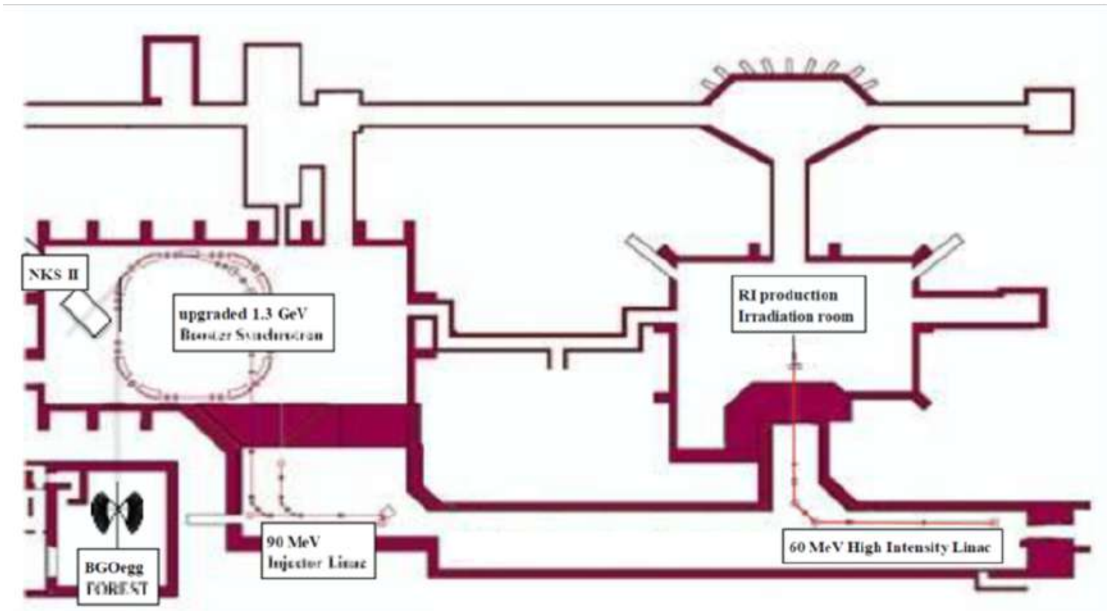

Figure 11.20: ELPH Accelerator Facilities.

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Figure 11.21: 1.3 GeV electron booster synchrotron.
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Characterization of the facility

60 MeV High Intensity Linac: to provide an intense electron beam.
1.3 GeV Booster Electron Synchrotron to produce GeV tagged photon beams.

Facility parameters

1. Electron beam: e^- (and bremsstrahlung), E= 20 - 60 MeV, 180 μA (max), 300 pps
2. (Tagged) photon beams: E= 0.6 – 1.2 GeV, 3 x 10^7 /sec
3. Positron beam: e^+ : E= 100 – 850 MeV, 1 kHz - 1 MHz

Brief and compact list with the Major experimental instrumentation and its capabilities

4π gamma-ray detector system: BGOegg, FOREST
Neutral Kaon Spectrometer : NKS II
Electron Scattering : Two-arm ULQ2 Spectrometers

Nature of user facility

Yes.

Program Advisory Committee/experiment proposals

Yes. Call for proposals : twice a year PAC meetings : twice a year

Number of active users and their origin

Average over these five years (before the earthquake of March 11, 2011):

- Quark Nuclear Physics (including R&D instrument), about 100
- Nuclear Science (including nuclear chemistry) about 50
- Beam Physics (including Coherent Radiation), about 20

Table 11.25: Percentage of users, and percentage of facility use.

Field	Users (%)			Facility use (%)		
Quark Nuclear Physics	45	45	10	45	45	10
Nuclear Science	10	30	60	20	40	40
Beam Physics	70	30	0	70	30	0

User group

Yes. About 150.

Laboratory Staff

Table 11.26: Staff at Tohoku ELPH.

Designation	Number of persons
Permanent staff (scientists)	9
Permanent staff (technical)	5
Temporary staff	7
Postdoctoral researchers	1
(Resident) Graduate students	11

Special student programs

Graduate Program on Physics for the Universe (www.gp-pu.tohoku.ac.jp/english/)

Future Plans

1) Quark Nuclear Physics: construct a new photon beam line at SPring8 (joint work with RCNP and Spring-8).
2) Nuclear physics : construction of a world's first electron scattering facility dedicated for structure studies of short-lived nuclei (joint work with RIKEN RIBF)
3) Accelerator: construct Supercoherent Terahertz Photon Ring.

TOHOKU UNIVERSITY CYCLOTRON AND RADIOISOTOPE CENTER (CYRIC)

6-3 Aoba, Aramaki, Aoba-ku, Sendai,
Miyagi, 980-8578, Japan
Telephone: +81 (0)22 795 7800
Facsimile: +81 (0)22 795 7997

Written by Keizo Ishii E-mail: www-admin@cyric.tohoku.ac.jp or shino@cyric.tohoku.ac.jp

University Institute
Japanese Government

Scientific Mission and Research Programs

CYRIC was established in 1977 as an institution for carrying out research studies in various fields with the cyclotron and radioisotopes, and for training reseachers of Tohoku University for safe treatment of radioisotopes and radiations.

In conformity with the aim of establishment of CYRIC, the cyclotron has been used for studies in various fields of research, such as nuclear physics, nuclear chemistry, solid-state physics and element analysis by PIXE and activation, and for radioisotope production for use in engineering, biology and medicine.

Technical facilities

From 2001, two cyclotrons are working; the first is the new cyclotron (K=110 MeV) which is replaced from the old one (K=50 MeV) for ligh ion beam and the second is the small cyclotron (12 MeV proton) for the production of positoron emitters of PET study.

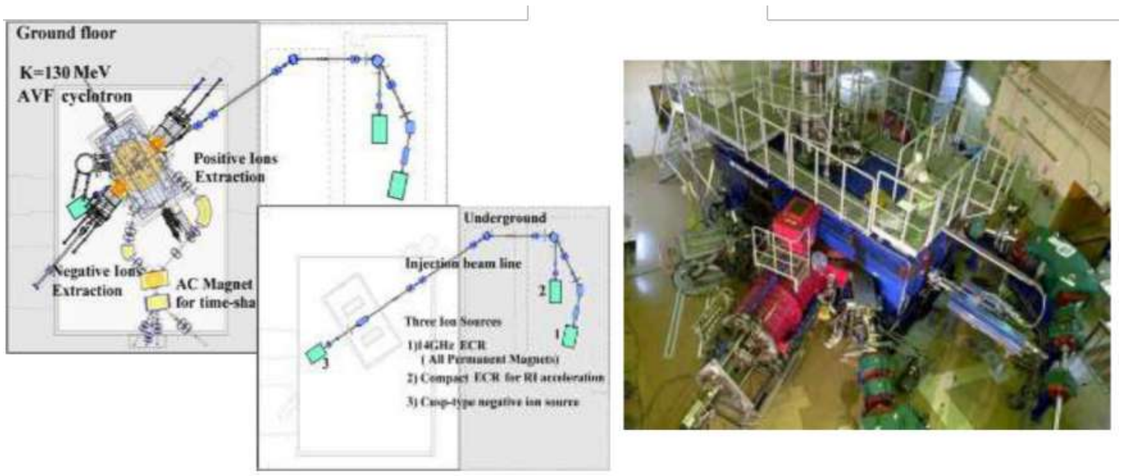

Figure 11.22: Overview of the facilities at CYRIC.

Characterization of the facility

Low-energy cyclotron with light-ion beams

Facility parameters

Beam energies of the new AVF cyclotron(K=110 MeV) and small cyclotron for PET.

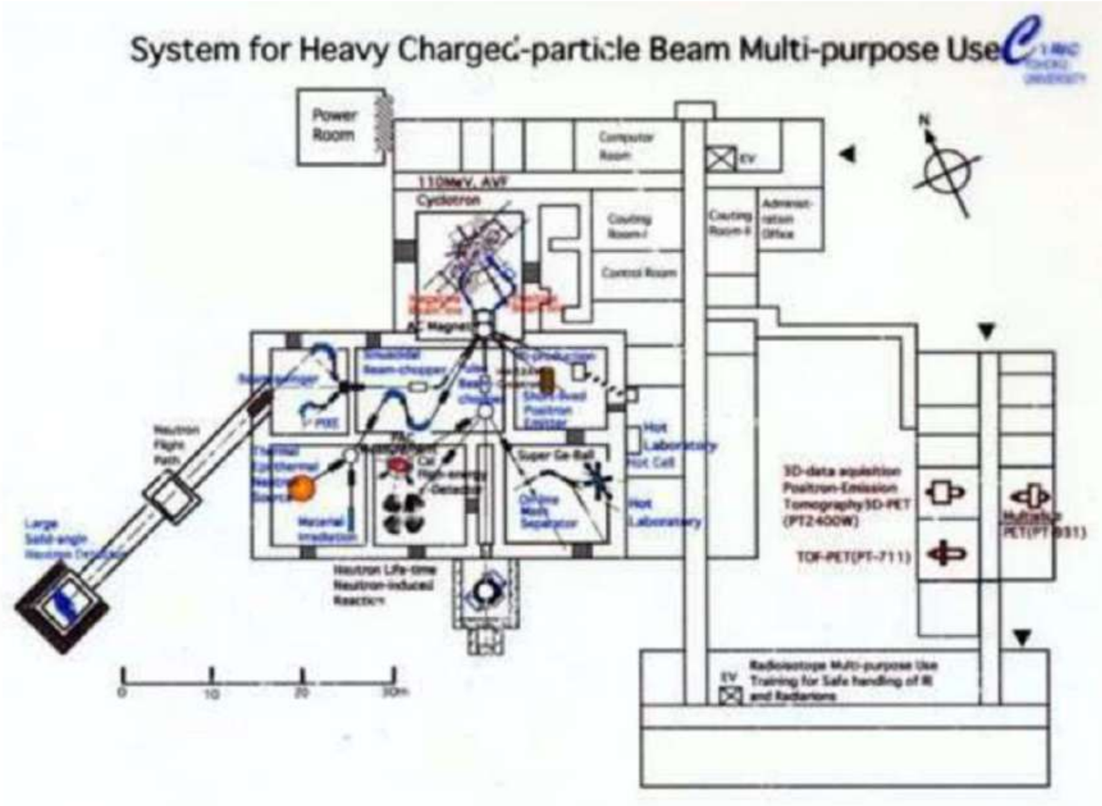

Figure 11.23: Experimental areas at CYRIC.

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Table 11.27: Positive ion acceleration by K=110 cyclotron.

Accelerated species	Energy (MeV)	Beam intensity (μA)
p	10–90	5 μA
d	10–65	5 μA
^{3}He	20–170	5 μA
^{4}He	20–130	5 μA
^{12}C	20–170	1 pμA
^{14}N	20–170	1 pμA
^{16}O	20–170	1 pμA
^{20}Ne	20–170	0.5 pμA
^{32}S	20–170	0.3 pμA
^{40}Ar	20–170	0.3 pμA
^{86}Kr	20–170	0.1 pμA

Table 11.28: Negative ion acceleration by K=110 MeV cyclotron.

Accelerated species	Energy (MeV)	Beam intensity (μA)
p	10–50	40 (present) 300 (goal)
d	10–25	20 (present) 300 (goal)

Table 11.29: Negative ion acceleration by small cyclotron for PET.

Accelerated species	Energy (MeV)	Beam intensity (μA)
p	12	30
d	6	20

Brief and compact list with the Major experimental instrumentation and its capabilities

- Beam Swinger and Large Solid-angle Neutron Detection system for Time-of-Flight Experiments
- On-line Electric and Magnetic Isotope-separator
- High-energy g-ray Detection System
- Neutron-life and Neutron-induced Reaction Analyzing Facility
- High Intensity Thermal and Epi-thermal Neutron Source
- Medical developments of new PET medicines and cancer therapy by proton beam

Nature of user facility

The facility is officially opened for inside-users of university, but is not closed for outside-users' proposals.

Program Advisory Committee/experiment proposals

Yes.

Percentage of users, and percentage of facility use that come from inside the institution

20%: users from institute.
50%: users from Tohoku University.
30%: users from outside university.

Percentage of users and percentage of facility use from national users

95%

Percentage of users and percentage of facility use from outside the country where your facility is located

5%.

Fraction of the international users from outside your geographical region

Asia and Europe

User group

20 groups.

Laboratory Staff

Special student programs

Lectures and site-seeing for high school students and citizens at every summer time (2 days).

Future Plans

a) Nuclear structure study by intense unstable nuclei and beams.
b) Development of intense high energy neutron beams by negative ion acceleration with K=110 MeV cyclotron and the engineering and medical applications by the neutron beam.
c) Fundamental research for cancer therapy by proton beam.

Table 11.30: Staff at CYRIC. *Including graduate students. **In physics, engineering and medical course. ***Non-resident graduate students with thesis work primarily done at the facility.

Designation	**Number of persons**
Permanent staff (scientists)	9
Permanent staff (technical)	4
Temporary staff	26*
Postdoctoral researchers	3
(Resident) Graduate students	25**
(Non-Resident) Graduate students	1-3 / year ***
Undergraduate students	10 year

KAMIOKA OBSERVATORY

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Director: M. Nakahata
E-mail: nakahata@suketto.icrr.u-tokyo.ac.jp

Construction and Operation – Institute for Cosmic Ray Research, The University of Tokyo

Scientific Mission and Research Programs

There are four operating bodies for the underground site in Kamioka:
1) Kamioka Observatory, Institute for Cosmic Ray Research (ICRR), the University of Tokyo;
2) KAGRA Observatory, ICRR, the University of Tokyo;
3) Kamioka Satellite, Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), the University of Tokyo; and
4) Tohoku University Research Center for Neutrino Science.
They are cooperating each other in many aspects such as safety issues.

Kamioka Observatory was established in 1995, initially to house and operate the Super-Kamiokande detector which is a 50,000 tons imaging water Cherenkov detector, mainly to measure neutrinos from the sun, atmosphere and supernova, and to look for proton decay and so on. Kamioka Observatory has expanded its role and now it accepts experiments to use underground spaces by external research institutions.

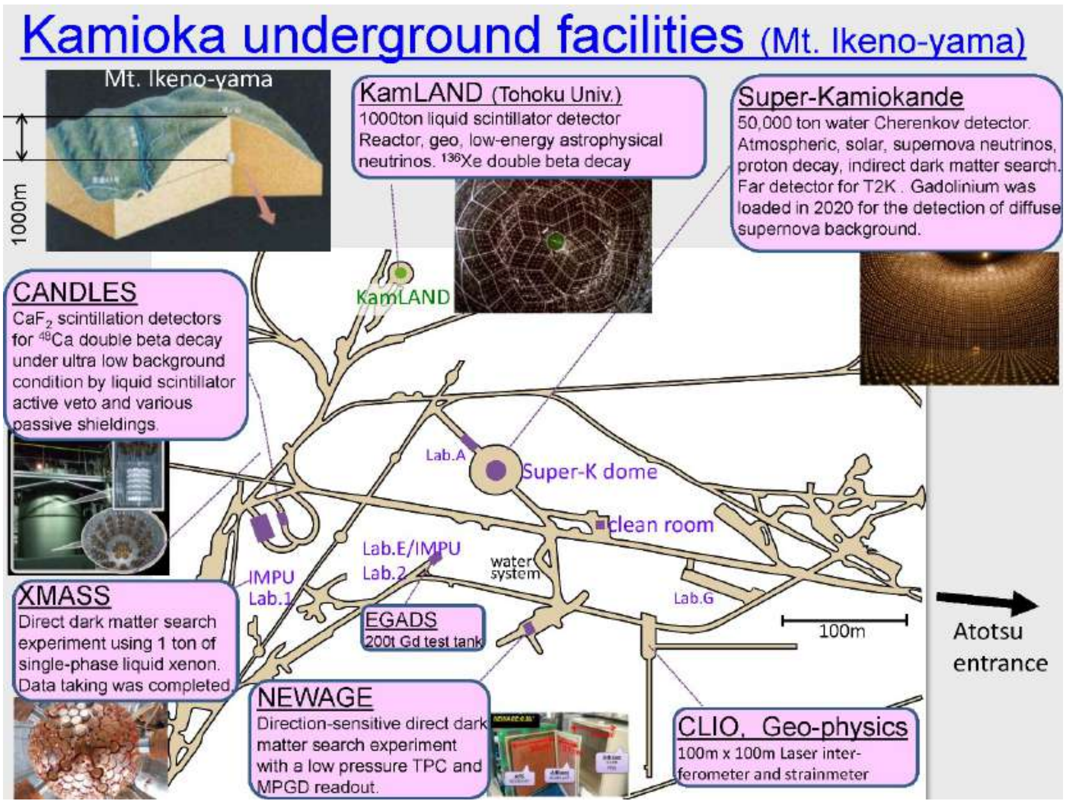

Figure 11.24: The underground facilities are located at 1000 m underground of the Kamioka Mine, Gifu prefecture, about 200 km west of Tokyo.

Figure 11.25: The surface building(upper photo) provides a computer system for offline analyses, meeting rooms and office space for the underground experiments.

Characterization of the facility

Facility parameters

The main facility is the Super-Kamikande detector, 50,000 ton water Cherenkov detector with 42 m in height and 39 m in diameter, at 1000 meter (2700 meter water equivalent) underground of the Kamioka Mine. In addition, several laboratories to accommodate the CANDLES, NEWAGE, EGADS experiments and etc.

Program Advisory Committee/experiment proposals

Yes.

Number of active users and their origin

The Super-Kamiokande collaboration consists of about 200 physicists. They are from institutes in Canada, China, France, Italy, Japan, Korea, Poland, Spain, the U.K., the U.S., and Vietnam. The Super- Kamiokande detector is used as the far detector of the T2K (Tokaito Kamioka) experiment which consists of about 460 physicists. In addition, about 80 physicists mostly from Japanese institutes use underground facilities for other experiments.

IBS RARE ISOTOPE ACCELERATOR COMPLEX FOR ON-LINE EXPERIMENTS

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Telephone: +82-42-878-8701
Facsimile: +81-42-878-8866

Director: Seung-Woo Hong
E-mail: swhong@ibs.re.kr

Government Institution under
the Ministry of Science and ICT
Dr.Do Young Noh (President)

Scientific Mission and Research Programs

IBS RISP (Rare Isotope Science Project) is a project to construct the heavy ion accelerator complex, named RAON (Rare isotope Accelerator complex for ON-line experiments).

RAON consists of the superconducting linear accelerators, RI beams production and sepearation systems based on ISOL and In-Flight methods and advanced experimental facilties. Ions of all elements, from proton to uranium can be accelerated up to 200 MeV/nucleon. RAON will provide world-class high- intensity and high-quality rare isotope beams and produce outstanding research results in the fields of nuclear physics, atomic physics, material science, bio & medical science. RISP was launched in 2011, and its first phase was completed in 2022. Then RISP was converted to a new institute called "Institute for Rare Isotope Sciene".

Technical facilities

Figure 11.26: Aerial view of the RAON (location: Sindong, Daejeon, Korea).

.

Characterization of the facility

The RAON provides ion beams of all stable elements up to uranium with energies up to 200 MeV/nucleon (400 MeV/nucleon upgradable). For production and seperation of RI beams, the ISOL (Isotope Seperation On-Line) and IF (In-Flight) methods are adopted. Especially, the

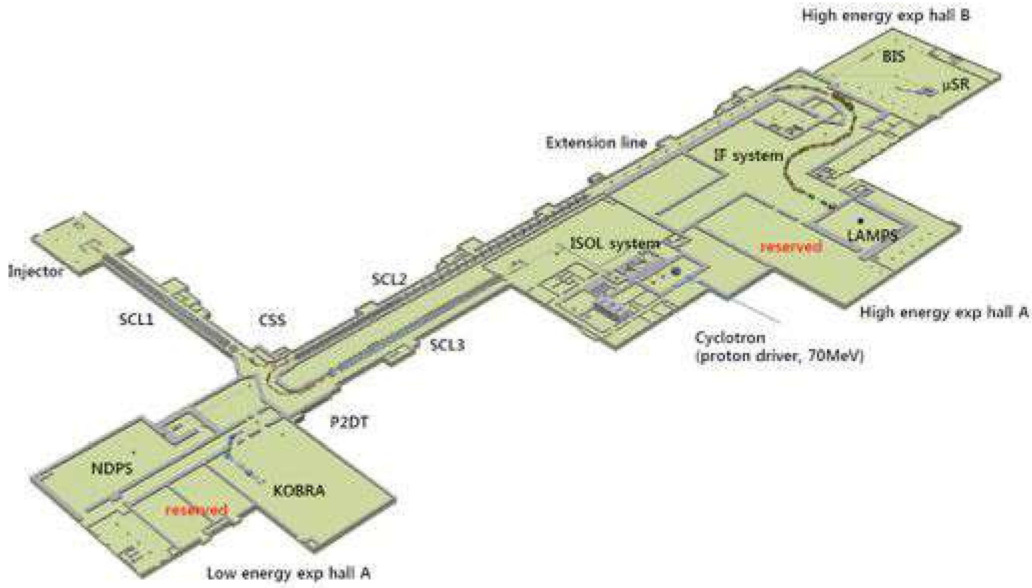

Figure 11.27: Layout of the RAON facility.

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combination of ISOL and IF systems (ISOL → SCL3 → SCL2 → IF, see the figure above) is expected to produce more exotic RI beams to reach the unprecedented area in the nuclear map.

Facility parameters

1. Beam species: from proton to uranium.
2. Goal intensities: 8.3 pμA for ^{238}U at 200 MeV/nucleon (400 kW at maximum).
3. Range of energies: typically up to 200 MeV/nucleon using SCL2 (400 MeV/nucleon upgradable in the future).
4. Lower energy heavy-ion beams from 0.5MeV/nucleon to 18.5MeV/nucleon (output energy of SCL1 and 3) are also available.

The ISOL system will provide intense RI beams by proton-induced uranium fission. A cyclotron is the proton driver for ISOL system (70 MeV, 1 mA at max. for protons).

IF system for high energy RI beam production and separation.

Major experimental instrumentation and its capabilities

New instrumentation under construction:

- KOBRA (KOrea Broad acceptance Recoil spectrometer and Apparatus), main facility for low energy nuclear physics program
- LAMPS (Large Acceptance Multi-Purpose Spectrometer) consists of TPC and neutron array for symmetry energy studies and nuclear structure
- NDPS (Nuclear Data Production System) using fast neutron
- BIS (Beam Irradiation System) for bio- and medical science
- μSR (muon Spin Relaxation) for material science using intense muons
- MMS (Mass Measurement Systems) based on MR-TOF (multi reflection time-of-flight) system for measuring mass of RIs from ISOL

Nature of user facility

RAON is officially a user facility for international science community.

Program Advisory Committee/experiment proposals

A Science Advisory Committee (SAC) with 12 members has been formed, addressing research programs and making advice for experimental facilities. A program Advisory Committee will review and select proposals for experimental programs

User group

Yes. The number of registered users is ≈180 (from the official web site of RAON users organization: http://raonusers.org/)

Laboratory Staff

Table 11.31: Staff at IBS RAON.

Designation	Number of persons
Permanent staff	133
Temporary staff	6
Postdoctoral researchers	3
Graduate students	6

Future Plans

As of spring 2023 the commissioning of the SCL3 (low-energy section of the SC linac) and the ISOL system is done. Experiments with the ISOL and stable ion beams are expected to be carried out in 2024. The high-energy section of the SC linac (SCL2) is anticipated to be completed around 2030. Then the RI beam from projectile fragmentation will be provided to the users together with ISOL beams.

CENTER FOR PROTON THERAPY, NATIONAL CANCER CENTER KOREA

Center for Proton Therapy
National Cancer Center
809 Madu-dong, Ilsan
Goyang, Kyonggi 411-764, Korea
Telephone: +82-31-920-1727
Fascimile: +82-31-920-0149

Heads of facility: Jae-Gahb Park, M.D., Ph.D and Kwan-Ho Cho, MD
Email jwkim@ncc.re.kr

Government supported under the law
Ministry of Health and Welfare

Scientific Mission and Research Programs

The experimental area of the proton therapy facility will be used to perform radiation damage measurements such as for semiconductor and biological objects. The area will also be used to develop the devices for advanced radiation treatments and to test the detector parts to ensure their expected performances. The Research Institute of National Cancer Center will have around 140 staff members composed of mainly biologist and medical doctors for the developments of diagnostics, prevention and treatments of cancer.

Characterization of the facility

Intermediate energy cyclotron, low-energy electron linacs for therapy.

Facility parameters

Proton, 0.1-300 nA, 50-230 MeV.

Major experimental instrumentation and its capabilities

Nozzles to form large-area uniform beams.

Nature of user facility

Therapy facility. Expected users: nuclear, medical physicists and radiation biologists.

Program Advisory Committee/experiment proposals

Not formed yet.

Laboratory Staff

Table 11.32: Staff at the Center for Proton Therapy. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Total staff	3 PhD and 5 MD
Scientists with doctoral degree	4 PhD and 3 MD
Postdoctoral researchers	4
(Non-Resident) Graduate students	2*

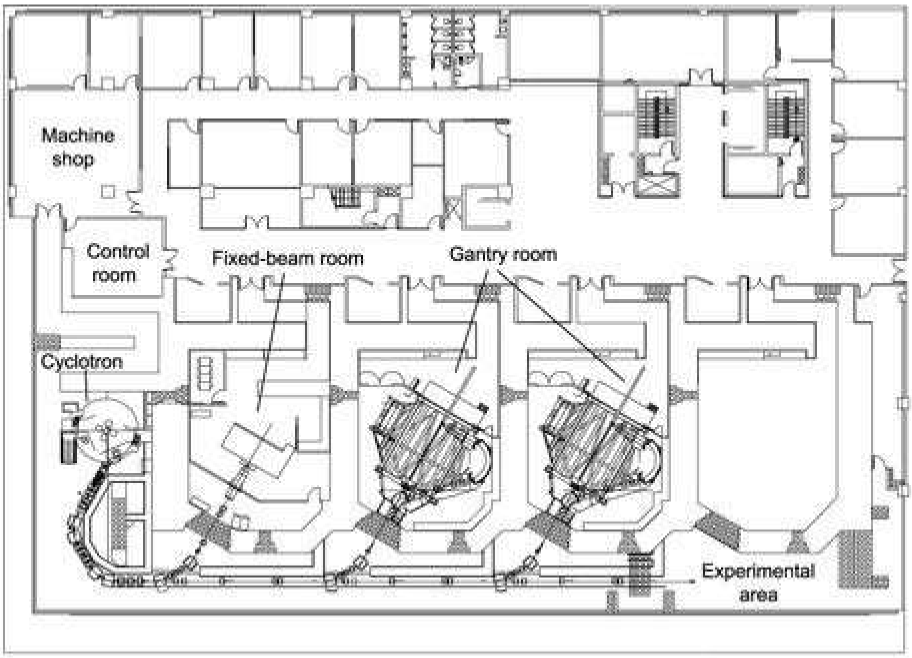

Figure 11.28: Experimental areas at the Center for Proton Therapy.

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Future Plans

Facility will have beams in the end of 2005, and plan to begin treating patients in 2006. The experimental area is expected to be prepared in 2006.

12. LABORATORIES IN AUSTRALIA

ANU HEAVY ION ACCELERATOR FACILITY (HIAF)

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Australian National University
Canberra, A.C.T. 0200 Australia
Telephone: +61-2-6125 2090
Facsimile: +61-2-6125 0748

Director: Prof. Mahananda Dasgupta
Email: Mahananda.Dasgupta@anu.edu.au
Email: director.rspe@anu.edu.au
Facility Operations Managers: Dr Nikolai Lobanov, Dr David Weisser
Web address : https://hiaf.anu.edu.au/

University Institute
Initial Establishment: University Funds and Direct Commonwealth Government Grant
Staffing and Operation: Internal University Funds Instrumentation and development funding:

Internal University Funds and Competitive External Grants, including the Australian Research Council

Scientific Mission and Research Programs

The mission of the Facility is to carry out internationally competitive research in both basic areas of Nuclear Physics and selected applications, to maintain and develop accelerator capabilities for the research community, and to provide a training ground for postgraduate and postdoctoral research in nuclear physics and related areas. The current research programme encompasses

- Fusion and Fission Dynamics with Heavy Ions
- Nuclear Spectroscopy and Nuclear Structure
- Nuclear Reaction Studies

- Nuclear Moments and Hyperfine Fields
- Perturbed Angular Correlations and Hyperfine Interactions Applied to Materials
- Heavy Ion Techniques for Materials Stoicheiometry
- Accelerator Mass Spectrometry – Development and application

Technical facilities

See Figs. 12.1 and 12.2.

Figure 12.1: Aerial view of the Heavy Ion Accelerator Facility within the laboratories of the Research School of Physical Sciences and Engineering.

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Characterization of the facility

Electrostatic Tandem accelerator operating in the 15MV region with the ability to inject into a modular superconducting Linear Accelerator. Producing a broad range of heavy ion beams delivered to ten experimental stations, instrumented for a range of national and international users. Pulsed and chopped beams; Gas and foil stripping and double-stripping operation for heavy beams.

Facility parameters

A broad range of beam species is available, with LINAC beams under development. Beam intensities vary with beam species, from a few particle- nanoamps of the heaviest beams to 100 particle-nA for lighter beams such as ^{12}C and ^{16}O. Flexible, pulsed-beam conditions ranging from nanosecond pulsing to macroscopic chopping in the millisecond and seconds region.

Major experimental instrumentation and its capabilities

- CAESAR Gamma-Ray Array: Nine Compton- suppressed Ge and two LEPS Detectors; Various ancillary devices. Research area: Nuclear Structure; Time- correlated gamma-ray spectroscopy.

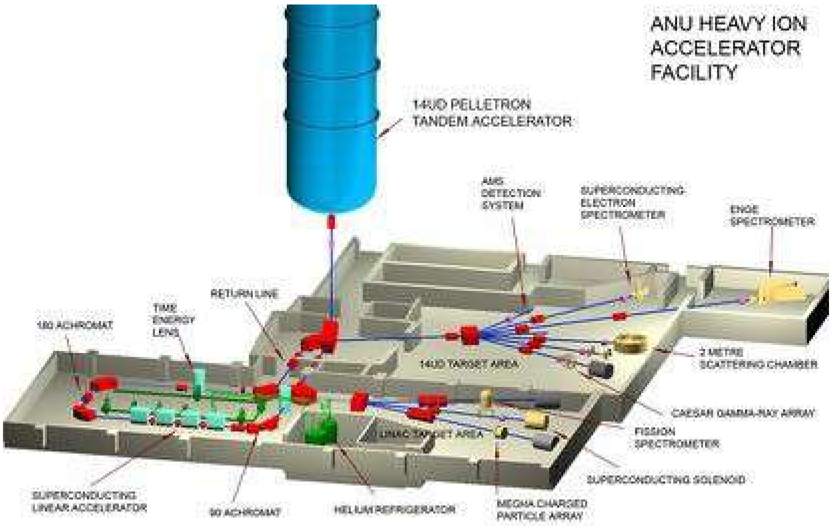

Figure 12.2: ANU Heavy Ion Accelerator Facility: General Layout.

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Table 12.1: ANU HIAF facility parameters

Beam species	Max. energy (single stripping) (MeV)	Max. energy (double stripping) (MeV)	Max. energy (LINAC) (MeV)
^{6,7}Li	60	–	84
^{9}Be	75	–	107
^{10,11}B	90	–	130
^{12,13}C	105	–	140
^{16,17,18}O	120	–	165
^{24,25,26}Mg	150	170	211
^{27}Al	150	180	230
^{28,29,30}Si	165	185	235
^{31}P	165	195	267
^{32,34}S	165	195	278
^{35,37}Cl	180	204	294
^{40}Ca	180	229	320
^{58,64}Ni	195	259	360
^{74}Ge	195	259	409
^{81}Br	195	269	427
^{127}I	210	304	–
^{197}Au	210	323	–

- SUPER-E (Superconducting Electron Spectrometer): Single- detector Lens- mode operation and multiple- detector electron- electron coincidence operation in broad range. Research area: Nuclear Structure; Time- correlated electron spectroscopy; Applications in Nuclear astrophysics.
- SOLENO- GAM: Gamma-ray and electron spectrometer with solenoidal transporter: Transport of residues to focal Plane instrumented with high- resolution electron and gamma detectors. Research area: Nuclear structure; characterisation of isomeric states in neutron-deficient nuclei.

- HYPERION: Gamma-ray correlation table with cryogenic system for sample cooling. Research area: Nuclear structure and Hyperfine interaction applications.
- Two-metre Scattering Chamber: Hybrid detectors for broad-range particle identification. Research area: General applications including elastic recoil Detection analysis (ERDA).
- CUBE spectrometer and Break-up array: Large area position- sensitive Multi-wire detections system; Large Si-strip detector array. Research area: Heavy Ion Reaction dynamics; fission, fusion, incomplete fusion studies.
- SOLITAIRE: Large bore compact superconducting solenoid for residue transport. Multi-wire focal-plane detection system. Research area: Heavy Ion Reaction dynamics; fusion studies cross- sections and heavy element production.
- AMS systems: Wien filter beam selection and gas- hybrid detectors for particle identification; also gas-filled Enge Spectrometer. Research area: High- sensitivity Accelerator Mass Spectrometry; application and development.

Nature of user facility

The facility is informally advertised as a User facility and is available for bona-fide scientific users, either through collaborative programs or as independent groups, at the discretion of the Head. A proportion of the operating time (20agreement between the Australian National University and the Science and Technology Facilities Council of the U.K (the ANU-STFC Agreement). UK Users are formally (publicly) notified about access.

Although operating as a de-Facto National Facility, at this stage, that status is not formally recognised and no direct Facility funding is provided.

Program Advisory Committee/experiment proposals

Allocation of the majority of Accelerator time is through an internal committee for on-going experimental programs. The proportion of accelerator time allocated through the ANU-STFC agreement is approved through a peer-review process, managed by the STFC in the UK with involvement of the Facility Director. A Program Advisory Committee would be a mandatory requirement if designation as a National Facility eventuated.

Number of active users and their origin

The five-year average for the period 2003-2008 inclusive is about 80 per year. This does not include numerous collaborators who do not participate in the on-site running of experiments.

Percentage of users, and percentage of facility use that come from inside the institution

(2003-2008 Period): 36%.

Percentage of users and percentage of facility use from national users

(2003-2008 Period): 18%.

Percentage of users and percentage of facility use from outside the country where your facility is located

(2003-2008 Period): 46%.

Fraction of the international users from outside your geographical region

(2003-2008 Period): 80%

User group

No. A Web registration system is to be implemented.

Table 12.2: Staff at ANU HIAF. *Composed of 8 Academic staff, 3 Scientific Staff at PhD level and 10 General/Technical Staff. **Total currently 19 (Postdoctoral/student/Visiting Fellows). ***Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	21*
Temporary staff	19**
Visiting fellows (theory)	∼2
Postdoctoral researchers	6
(Resident) Graduate students	14
(Non-Resident) Graduate students	∼10***
Undergraduate students	∼8

Laboratory Staff

Special student programs

Annual workshops in Radiation Physics, Applications of Accelerators – duration approximately 1 week each with involvement of about 20-30 undergraduate students, mainly from other Universities.

Annual involvement in summer scholar programs (10-week projects), Industry youth schemes (CSIRO etc.) and Honours undergraduate programs (6-month projects) and various National Youth summer schools.

Master of Nuclear Science Program (coursework) instituted in January 2007.

Future Plans

Mainly incremental upgrades of detector instrumentation (for example, recoil spectrometer for spectroscopy studies).

Recent accelerator improvements funded through the Australian Research Council for include additional Computer Control, improved beam intensities (ion source and pulsing efficiencies) and upgrading of LINAC resonator RF systems and control. AMS facilities have been extended with a dedicated Radio Carbon accelerator system (sited in the Research School of Earth Sciences, commissioned in late 2007).

Under current development and construction is a compact radioactive ion-beam facility designed around a 6.5T superconducting solenoid with active beam tracking and particle identification. The initial aim is production of a tagged He-6 beam using Li-7 induced reactions on Be-9. Future funding would allow expansion of this system.

13. LABORATORIES IN EUROPE

CENTRE DE RESSOURCES DU CYCLOTRON

Chemin du Cyclotron, 2 Bte L7.01.05
1348 Louvain-la-Neuve Belgium
https://uclouvain.be/en/research-institutes/irmp/crc

Director: Nancy Postiau
Telephone : +32 10 47 38 74
E-mail : nancy.postiau@uclouvain.be

Scientific Mission and Research Programs

Radiation damage by light and heavy ions, and by neutrons.
Detector calibration for space missions

Characterization of the facility

Cyclotron CYCLONE 110 for ions from H (10μA, 65 MeV) to Xe (500 nA, 400 MeV).

Nature of user facility

Send a written request to the contact persons.

NUCLEAR PHYSICS INSTITUTE OF THE CZECH ACADEMY OF SCIENCES (NPI)

Husinec - Řež, čp. 130, 250 68 Řež
Telephone: + 420 266173637
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Director: Petr Lukáš
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Scientific Mission and Research Programs

The Nuclear Physics Institute of the CAS (NPI CAS), public research institution of the Czech Academy of Sciences, conducts research in a broad field of nuclear physics, experimental as well as theoretical. At present it employs 290 persons. The Academy is a public body, and NPI CAS is a non-profit institution relying on the state budget and on the national and European science funding systems.

In its technologically innovative activity and laboratory services provided to academic users and industry it is in contractual relationship with other public organizations and business companies. The institute has become the main center of accelerator-based nuclear and atomic physics in the Czech Republic.

Characterization of the facility

Centrum of Accelerators and Nuclear Analytical Methods (CANAM). The CANAM (canam.ujf.cas.cz) is a special unit within the institute incorporating almost all of facilities which deliver ion and neutron beams with various range of particle choice, charge, intensity and energy.

In this report four accelerator facilities are introduced related to nuclear physics research or application: Cyclotron U-120M, Cyclotron TR24, Tandetron 4130MC (3 MV), AMS.

Facilities, major experimental instrumentation and its capabilities

Isochronous cyclotron U-120M

The isochronous cyclotron U-120M (K=40) is a multipurpose multiparticle accelerator which can be tuned according to the type of particles (p, D, $^3He^{2+}$, $^4He^{2+}$) and the use (internal/external beam) in a wide range of energies (1-55 MeV). It is a unique facility operated both in positive (extraction p, D, $^3He^{2+}$, $^4He^{2+}$) and in negative mode (acceleration H^- resp. D^- and subsequent extraction of p, D). Provided accelerated beam currents are from a few nA up to tens of μA.

Table 13.1: NPI Řež facility parameters

Ions		Energy (MeV)	Max. current (μA)
H^+	Internal beam	2 – 37	>200
H^-	External beam	6 – 25	5
H^+/H^-	External beam	6 – 37	50 – 30
D^+	Internal beam	2 – 20	>80
D^+	External beam	12 – 20	5
D^+/D^-	External beam	11 – 20	35 – 20
$^3H^{2+}$	Internal beam	3 – 55	20
$^3H^{2+}$	External beam	18 – 52	2
$^4H^{2+}$ (α)	Internal beam	4 – 40	40
$^4H^{2+}$ (α)	External beam	24 – 38	5

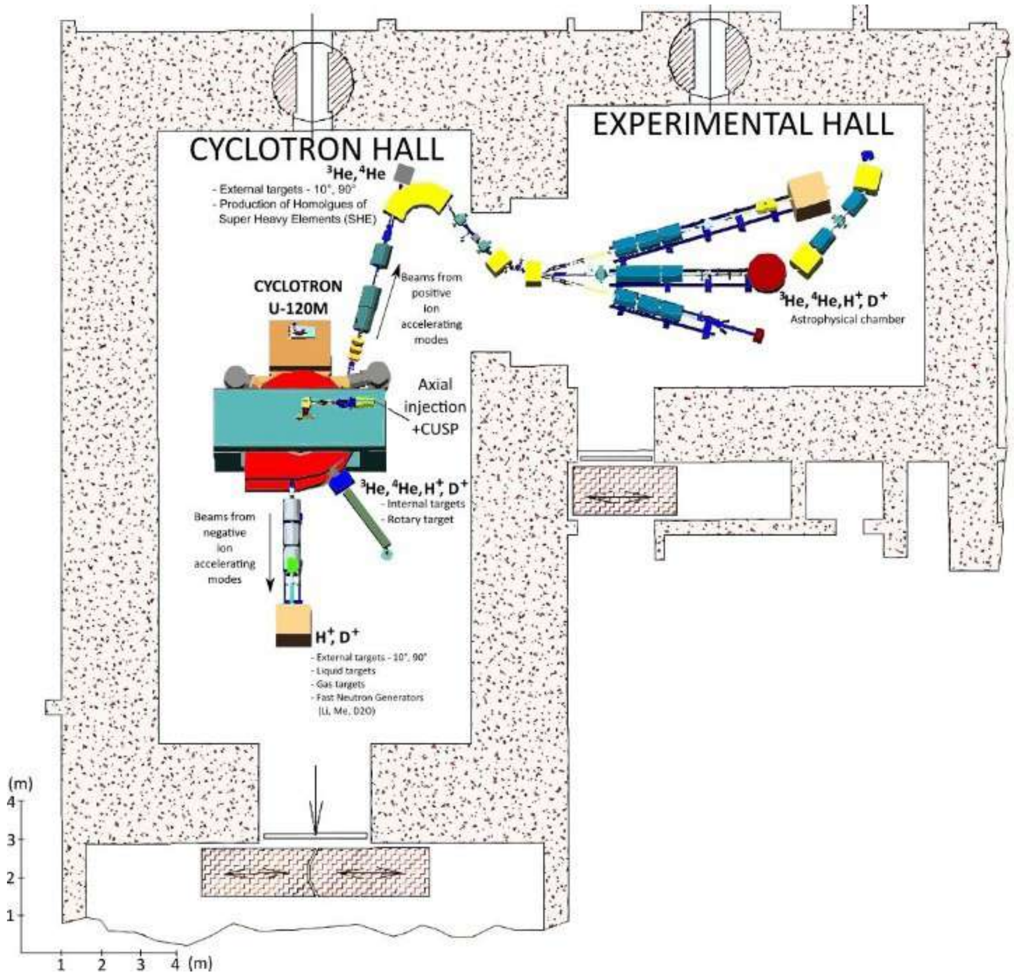

Figure 13.1: Layout of the U-120M Isochronous Cyclotron.

Nuclear astrophysics, fast neutron benchmark tests of activation cross sections, fusion relevant neutronics experiment, measurement of excitation functions and nuclear data, testing of cosmic ray detectors, radiation hardness of electronic components with accelerated ions and fast neutrons, production of fluorescent nanodiamonds, irradiation of biological samples, production of conventional and unconventional radionuclides for preparation and research of radiopharmaceuticals.

Fast neutron generators: High-power-wide spectrum fast neutron sources with p/d+Be reaction (10^{11} n/s/cm^2 up to 33 MeV). Quasi-monoenergetic fast neutron source based on p+Li(C) reaction (10^9 n/s/cm^2, 18 to 33 MeV); Scintillator detector based fast neutron spectrometer. Multi-foil activation technique and gamma-ray spectrometry laboratory. Variety of solid, liquid, gaseous targets and jigs for irradiation samples also in air.

TR-24 cyclotron

The TR-24 cyclotron provides proton beams with energies from 18 MeV to 24 MeV. It is equipped with an axial injection system with an external ion source of the CUSP type, which significantly increases available current of the accelerated beams (up to 300 μA). It is equipped with a short beam line, switching magnet and two target selectors which provides 8 target positions.

Cyclotron based high power fast neutron generation for neutron - irradiation tests of ITER components, fNAA, ADS transmutors, etc., nuclear data validation production of calibration sources, production of conventional and unconventional radionuclides for preparation of radiopharmaceuticals for nuclear medicine.

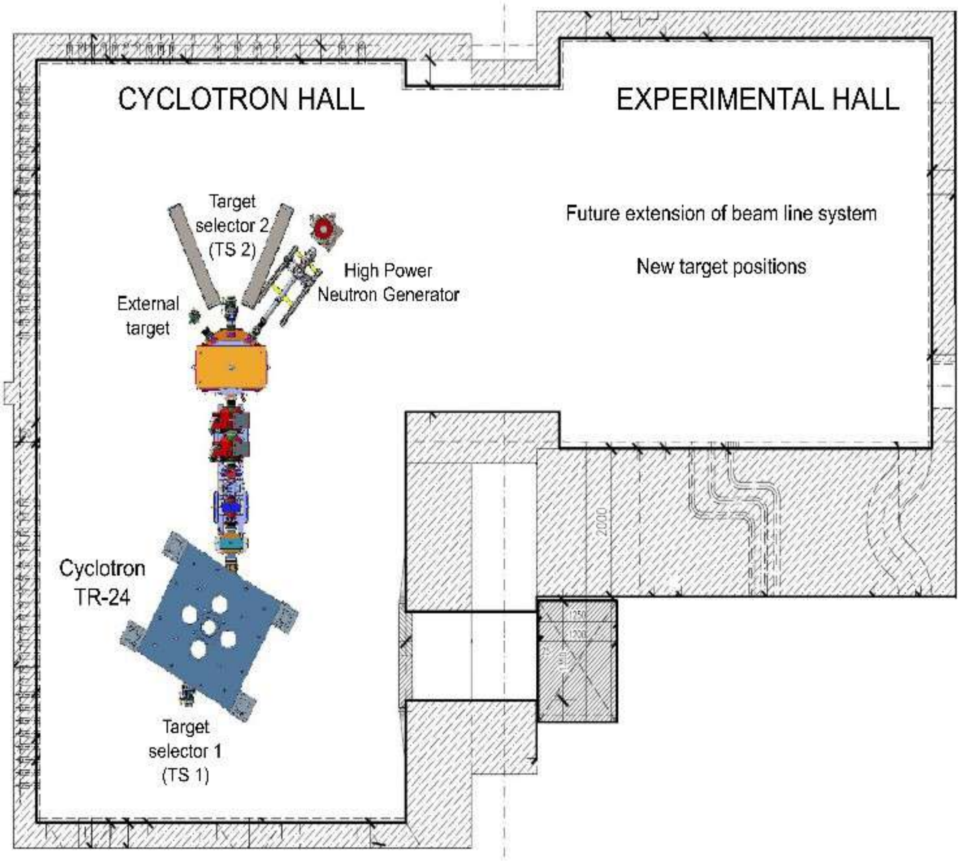

Figure 13.2: Layout of the TR-24 Cyclotron.

High Power Neutron Generator (HPNG), (p+Be target, 24 MeV/300 μA, 7.2 kW, white-spectrum, flux up to 2×10^{12} cm^{-2}s^{-1} in sample at d$\leq$ 20 mm, variable energies E$\leq$ 22 MeV) Scintillator detector based fast neutron spectrometer. Multi-foil activation technique and γ-ray spectrometry laboratory

Variety of solid, liquid and gaseous targets. A commercial production of PET radionuclide ^{18}F and generator ^{81}Rb/^{81m}Kr for lung ventilation studies was implemented on the cyclotron as well.

3 MV Tandetron

The 3 MV Tandetron 4130MC is used in the Laboratory of Tandetron (LT) as a source of ion beams in a broad variety of ion masses, energies, ion currents and fluences. We assembled ion beam analytical methods offering comprehensive non-destructive qualitative and quantitative elemental analyses with high sensitivity and low detection limits, such as: PIXE, RBS, ERDA, PIGE, NRA, PESA. Ion microprobe is for disposal to realize 3D elemental mapping as well as to provide scanning transmission ion microscopy - STIM.

External beams are used for ion beam irradiation as well as ion beam analysis on air. LT offers new structure synthetization by using ion beam implantation, ion beam irradiation, single ion irradiation and ion beam lithography with light and medium heavy ion microbeam. LT systematically partake in the study of synthesizing, structure and properties of advanced materials for micro-electronics, optics, optoelectronics, nanostructures, providing environmental and cultural heritage studies and investigation of materials with exclusive properties (chemical activity, sensing, tuned optical response, bio-compatibility, etc.). Surface structures and systems prepared in cooperation with Czech and foreign institutes by different methods (epitaxial grow, Czochralsky's method, ion implantation, deposition of plasma polymer, CVD, PCVD, magnetron sputtering, etc.) are analyzed

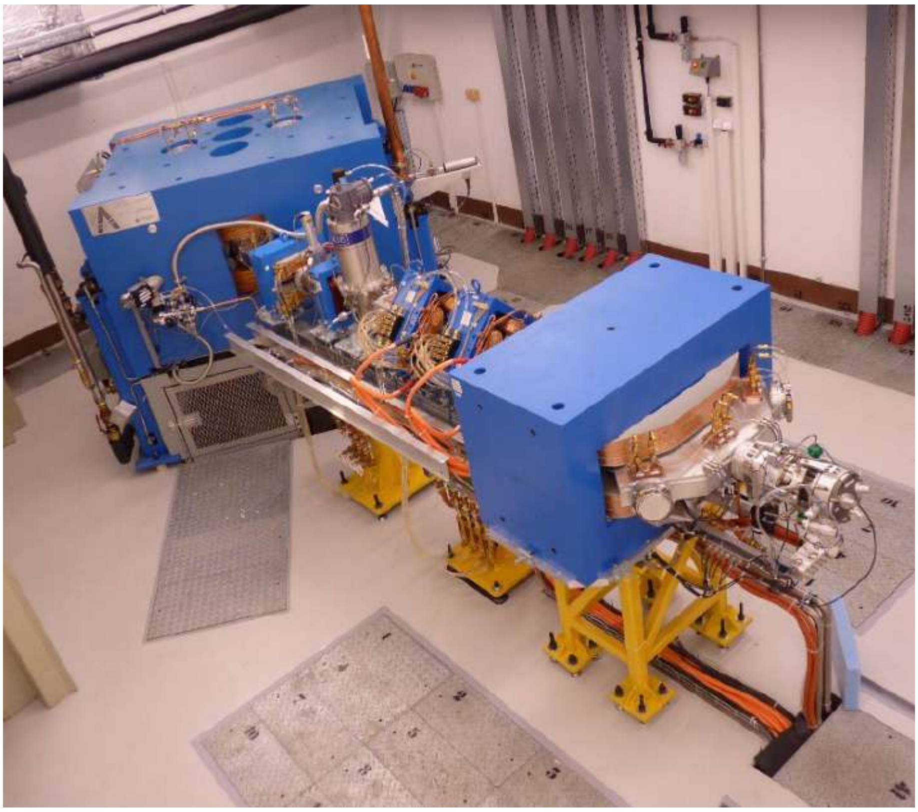

Figure 13.3: Photo of the TR-24 Cyclotron.

in our laboratory with different analytical methods.

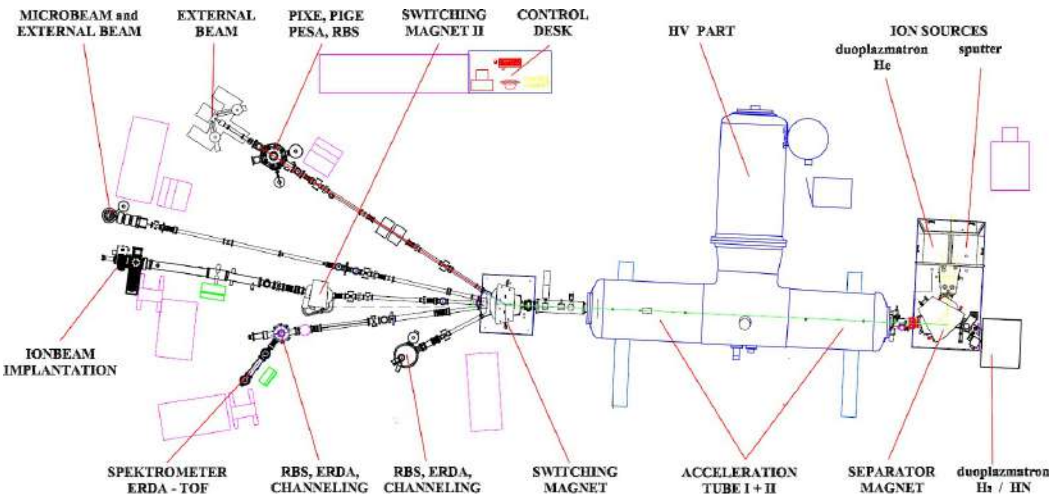

Figure 13.4: Layout of the Tandetron 4130MC.

Ion Implantation / Irradiation: Available ions: typically H, He, Li, O, C, Si, Cu, F, Ag, Au, W are for disposal and others upon the request), we cannot produce noble gasses, lanthanides, radioisotopes

Ion energy: 600 keV - 30 MeV depending on ion charge states

Depth range: less than 500 nm – tens of μm depending on probing ion energy

Ion fluence: 10^7 - 10^{16} cm^{-2}

Incidence ion beam angle: Standard 0°, 7°; others on request Beam current: nA - μA

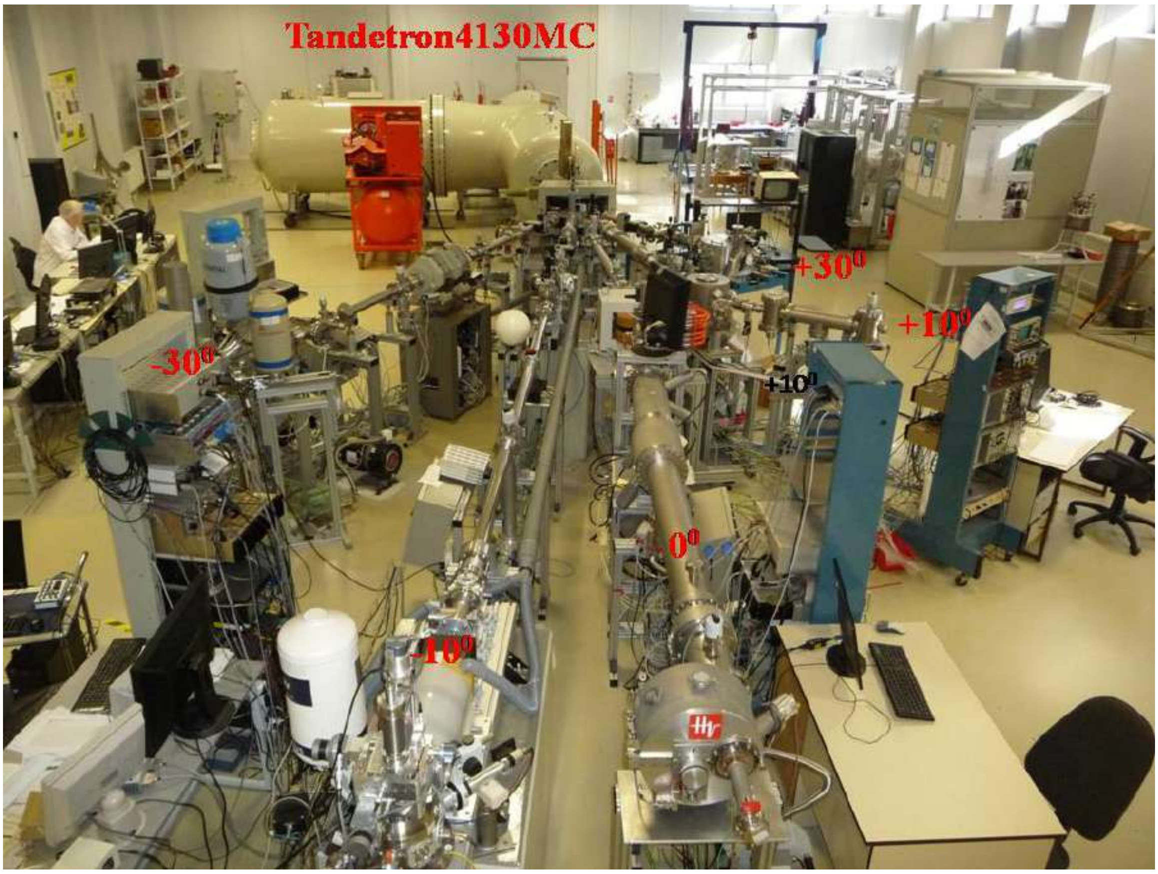

Figure 13.5: Photo of the Tandetron 4130MC with associated beam lines.

Sample size: Small pieces (cm2), up to Ø 580 mm
Temperature: RT, heating stage up to 600°C
Special features: quadrupole mass spectrometry; external beam irradiation of biological samples, volatile samples etc.

Ion Beam Analysis: RBS (B – U elementals depth profiling), RBS and PIXE channeling (single crystalline materials), ERD with He (H, D, T – depth profiling); ERDA TOF (H – S), PIXE (Al-Au); μ-Probe with RBS, PIXE, PIGE (major as well as trace element analysis); STIM (internal morphology), PESA (H),
Depth resolution less than 10 nm (RBS), detection limits about 10^{14} atoms·cm^2 (RBS, ERDA) or in ppm (PIXE, PIGE)

Related main facilities LT is equipped with small deposition and complementary analytics laboratory including
- layer deposition techniques (CVD, two- magnetron sputtering system for various metal and bi-metal coating deposition, spin coating deposition of polymer composite foils with various particles)
- laser source for irradiation, ablation and microstructuring
- analytical methods (optical ellipsometry, optical analysis in UV Vis-NIR range of wavelengths.

AMS facility

A new generation Multi-Isotope Low-Energy Accelerator (MILEA) as an Accelerator Mass Spectrometry system has been operating since the begining of the year 2022. The AMS operates at low terminal voltages energies of up to 300 kV, it enables determination of ^{10}Be, ^{14}C, ^{26}Al, ^{41}Ca, ^{129}I, ^{236}U, ^{239}Pu and other actinides nuclides with limits of detection several order of magnitude lower limits of detection compared with conventional techniques. MILEA provides excellent possibilities of measurement of the above nuclides, because the measured background isotope ratio of $1{\cdot}10^{-15}$ for $^{14}C/^{12}C$ was achieved at routine operations.

Figure 13.6: Photo of the AMS facility MILEA.

ACCELERATOR LABORATORY, UNIVERSITY OF JYVÄSKYLÄ

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University Institute
Various sources of funding: State budget of Finland
University of Jyväskylä, Academy of Finland, European Union Programs

Scientific Mission and Research Programs

The Accelerator Laboratory at the University of Jyväskylä (JYFL) is a national facility with an extensive international programme in education and research on atomic nuclei under extreme conditions as well as related applications. The current research activities include:

- Decay and ground-state properties of exotic nuclei Weak interaction physics
- Structure and spectroscopy of superheavy elements
- Structure and spectroscopy of proton-drip line nuclei
- Accelerator-based materials physics
- Radiation testing for the space industry

Technical facilities

See Figs. 13.7 and 13.8.

Figure 13.7: View of the Department of Physics at the Ylistö campus area.

Characterization of the facility

The accelerator facility consists of three accelerators:

A K=130 AVF cyclotron equipped with two ECR ion sources for heavy ions and a multi-cusp ion source for protons, a K=30 negative ion cyclotron for protons and deuterons and a 1.7 MV Pelletron accelerator.

Reliability of the K=130 MeV cyclotron is reflected in the annual operation time of more than 6000 hours. As the maximum energy for the ion beam from the cyclotron is $E/A = 130(q/A)^2$

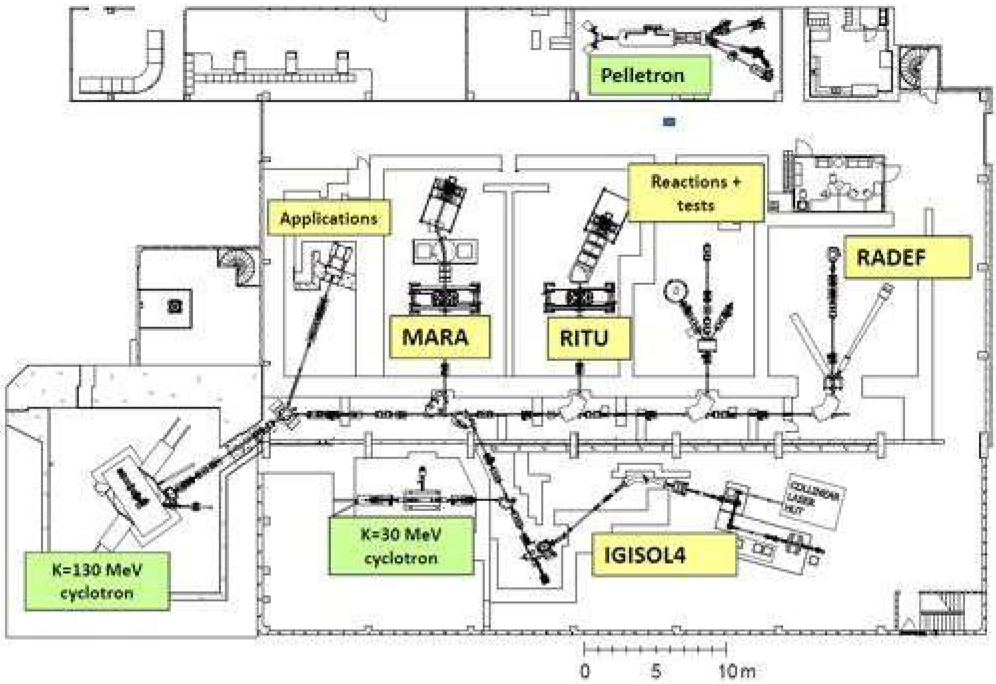

Figure 13.8: Layout of the upgraded JYFL Accelerator Laboratory.

MeV/n, the availability of various beams strongly depends on the performance of the ion sources. Heavy ions are delivered by a 6.4 GHz or a 14 GHz ECR ion source.

The K=30 MeV cyclotron accelerates 18 – 30 MeV protons and 9 – 15 MeV deuterons. It has two beam lines to opposite directions: one for the IGISOL facility and one for applications (e.g. isotope production). The Pelletron accelerator delivers low-energy protons and He ions for ion-beam applications.

Facility parameters

Available beams and intensities from the cyclotron for ions with energies above 5 MeV per nucleon are as follows:

- $>$1 pμA: p, He, B, C, N, O, Ar
- $>$100 pnA: F, Ne, Mg, Al, Si, S, Cl, Ca, Fe, Cr, Ni, Cu, Zn, Kr
- $>$10 pnA: Ti, Mn, Ge, Sr, Zr, Ru, Xe

Intensities for various isotopes depend on the isotopic enrichment of the available material. Metallic beams are extracted from a furnace or a MIVOC chamber. The MIVOC method (based on the use of volatile compound) was developed at JYFL. Negative H ions for high-intensity proton beams up to 50 μA from the cyclotron are produced in the multi-cusp source.

Major experimental instrumentation and its capabilities

- Online isotope separator IGISOL: can separate nuclei far from stability, especially those of refractory elements not available elsewhere.
- Penning Trap JYFLTRAP: consists of a Radiofrequency Quadrupole (RFQ) beam-cooler device and a highprecision Penning trap. It has been used to measure masses of around 200 nuclei with high accuracy.
- Laser Ion Source FURIOUS: currently under development to provide enhanced beam intensity and purity for exotic nuclei from IGISOL.
- Collinear Laser Spectroscopy Line: allows high-sensitivity laser spectroscopy measurements of all elements, using cooled and bunched beams from IGISOL.

- Gas-filled Recoil Separator RITU: is one of the leading instruments in the world for studies of neutron-deficient heavy nuclei.
- Focal Plane Spectrometer GREAT: developed by a group of U.K. institutes and located at the focal plane of RITU. Allows detailed measurement of the decay properties of implanted ions.
- Vacuum-mode Recoil Separator MARA: has been commissioned. It will enable tagging studies of light proton-rich nuclei near the N=Z line.
- Germanium Detector Array JUROGAM2: consists of 24 Compton suppressed Clover- and 15 EUROGAM Phase 1 Ge detectors (efficiency 6% @1.3 MeV) and is used in conjunction with RITU in Recoil-Decay Tagging studies.
- Large Scattering Chamber LSC: is used in Nuclear Reaction studies and Stopping Power measurements.
- Radiation Effects Facility RADEF: is used to study radiation effects in materials and electronics components (mainly for the space industry in collaboration with ESA)
- Beam lines equipped with PIXE, RBS, ToF-ERDA and litopraphy instruments for applied research at Pelletron

Nature of user facility

The JYFL Accelerator Laboratory is considered a user facility. It is one of the Horizon2020 ENSAR2 Access Facilities.

Program Advisory Committee/experiment proposals

The research program at JYFL is overseen by the Program Advisory Committee, consisting of six external members, three local members and a scientific secretary. There are two calls for proposals each year with deadlines of March 15th and September 15th.

Number of active users and their origin

Percentage of users, and percentage of facility use that come from inside the institution

Approximately 15% of the users and 30% of the facility use are from inside the institution.

Percentage of users and percentage of facility use from national users

Approximately 5%.

Percentage of users and percentage of facility use from outside the country where your facility is located

Approximately 80% and 70%, respectively. The number of foreign users during the last 5 years has been on the average 200 per year.

Fraction of the international users from outside your geographical region

Those outside Europa approximately 10%.

User group

The JYFL Accelerator Laboratory does not have a formal users group, but regularly organizes users meetings and workshops to discuss the status and future of research in the laboratory.

Laboratory Staff

Special student programs

The Laboratory has a program of Summer Student Training aimed at undergraduates. An advanced university course of ion-beam and radiation detection methods in organized every second year.

The Laboratory itself is a training site. It has acted as an EU Marie Curie Training site. It regularly runs a Summer School for postgraduate students, and has a program of Summer Student Training aimed at undergraduates.

Table 13.2: Staff at JYFL. *25 senior researchers, 12 post-doc researchers, 25 PhD students, 19 lab. engineers and technicians. **Theory: 1 permanent staff, 2 postdoctoral researchers and 6 graduate students. ***Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Total laboratory staff	81*
Scientists (with doctoral degree)	27
Staff (theory)	9**
Postdoctoral researchers (experiment)	12
(Resident) Graduate students	25
(Non-Resident) Graduate students	∼25***
Undergraduate students	∼10

Future Plans

Commissioning of the new K30 MeV cyclotron will release beam time for tests and long experiments and applications. To hold on to the status as a leading Stable Ion Beam facility, a new ECR ion source has been contructed and will be commissioned in 2017. A new cyclotron control system has been funded and it will be installed in 2017-2019. Commissioning of the upgraded IGISOL facility and the new vacuum-mode separator MARA will open up new possibilities in studies of neutron-rich as well as proton-drip-line nuclei.

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French mix Unity of research University of Lyon/ CNRS (National Centre for Scientific Research
Construction: IPNL (in2p3-CNRS/ University of Lyon)
Operation: IPNL (in2p3-CNRS/ University of Lyon)

Scientific Mission and Research Programs

The main program research made on such facility concerns sputtering and emission from solids under impact of MeV-energy heavy ions and gold clusters. Indeed, under impact of 2 MeV-gold clusters on gold targets, the formation of surface craters is related to very large sputtering yields. The ionised component of such ejected matter consists mainly of large size clusters as shown in time-of-flight experiments.

There are mostly two main researches on the 4 MV accelerator: On one hand, the 4 MV Van de Graaff accelerator is used for research about nuclear waste management: first one, as a particles source for study on effects and damages on matrices after irradiation; Secondly, different ion-beam-analysis methods (such as RBS, PIXE, ERDA and NRA) are powered in order to follow and determine migration of several isotopes which simulate long life radio element inside nuclear waste matrices.

On the other hand, argon ions are used for application of Time-of-Flight Mass Spectrometry to the analysis of environmental samples such as pesticides adsorbed on soils. Besides, facility is uses for ionic implantation and practical for undergraduate and graduate students Finally, our laboratory develops business implantation and analysis services for others labs or firms.

Characterization of the facility

2.5 MV Van de Graaff

Electrostatic van de Graaff 2.5 MV accelerator with gold cluster source.

Table 13.3: IPNL 2.5 MV Van de Graaff parameters.

Accelerated particles	Au_1	Au_5	Au_{13}
Charges	1^+	1^+	1^+
Max. energies (MeV)	2.2	1.5	1.0
Max. intensities	300 nA	100 nA	few pA

4 MV Van de Graaff

4 MV Electrostatic accelerator Van de Graaff used for ionic implantations and ion beam analysis: Nuclear Reaction Analysis, Rutherford Backscattering Spectroscopy, Particles
Induced X-ray Emission, Elastic Recoil Detection Analysis)
3 beams lines dedicated to TOF, RBS+ERDA+PIXE, Ionic Implantations, Extract beam line

Figure 13.9: Van de Graaf 2.5 MV accelerator tube.

Figure 13.10: Bending magnet of the 4MV Van de Graaff accelerator

Table 13.4: IPNL 4 MV Van de Graaff parameters.

Accelerated ions	Protons	Deuterons	^{3}He	^{4}He	^{15}N	Ar
Charges	1^{+}	1^{+}	1^{+}/ 2^{+}	1^{+}/ 2^{+}	1^{+}/ 2^{+}	1^{+}/ 2^{+}/ 3^{+}
Energies (MeV)	3.5	3.5	3.5/ 7	3.5/ 7	3.5/ 7	3.5/ 7/ 9
Intensities	200 nA	100 nA	100/ 20 nA	100/ 20 nA	100/ 20 nA/	50/ 10/ 5 nA

Experimental instrumentation and its capabilities (4 MV VdG)

Instrumentation for ion beam analysis: Nuclear Reaction Analysis, Rutherford Backscattering Spectroscopy, Particles Induced X-ray Emission, Elastic Recoil Detection Analysis.

Nature of user facility

(2.5 MV VdG) No.
(4 MV VdG) Yes, internal.

Program Advisory Committee/experiment proposals

(2.5 MV VdG) No.
(4 MV VdG) Yes.

Number of active users and their origin

(2.5 MV VdG) 2 + national collaboration (in2p3-CNRS labs).
(4 MV VdG) In 2015, there were about 20 active users divided in 2 subjects of research.

Percentage of users, and percentage of facility use that come from inside the institution

(2.5 MV VdG) 100%.
(4 MV VdG) 95%.

Percentage of users and percentage of facility use from national users

(2.5 MV VdG) 66%.
(4 MV VdG) 100%

Percentage of users and percentage of facility use from outside the country where your facility is located

(2.5 MV VdG) 33%.
(4 MV VdG) 0%.

Fraction of the international users from outside your geographical region

(2.5 MV VdG) 0.
(4 MV VdG) 0.

User group

(2.5 MV VdG) Yes (3).
(4 MV VdG) Yes, two formal users group (11 p. and 4 p.).

Laboratory Staff

(2.5 MV VdG) Permanent technical staff: 2; permanent user staff: 1; temporary staff: 1; Number of non-resident graduate students with thesis work primarily done at the facility: 1.
(4 MV VdG) Permanent technical staff: 6; permanent user staff: 9; temporary staff: 7; Number of graduate students resident at the facility: 3.

Special student programs

Practical for under graduate and graduate students.

Future Plans

(4 MV VdG) Replacement by a new one but not funded yet.

SINGLETRON ACCELERATOR AIFIRA FACILITY – LP2I-BORDEAUX

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Scientific Mission and Research Programs

AIFIRA is a small-scale ion beam facility equipped with a single-stage electrostatic accelerator delivering bright beams of light ions (protons, deuterons and helium ions) in the MeV energy range. The facility provides ion beam irradiation, analysis, and imaging techniques to academic research groups and companies. These techniques cover a wide range of applications including materials research, life sciences, environment, geology and geochemistry, archeometry, and applied physics. About 200 days of beam time are allocated each year to internal and external users either coming from local, national, or international teams. AIFIRA is certified as a research platform by its two parent institutions: CNRS/IN2P3 and the university of Bordeaux. Therefore, beamtime allocation is opened to external teams that are accompanied by local experts to prepare, perform and analyze their experiments.

Characterization of the facility

AIFIRA is based on a 3.5 MV Singletron™, provided by HVEE (High Voltage Engineering Europa, the Netherlands). It delivers light ion beams (protons, deuterons and helium) with a high brightness (20 A m^{-2} rad^{-2} eV^{-1}) and energy stability ($\Delta E/E = 10^{-5}$) in 5 beamlines dedicated to specific applications.

Facility parameters

The beamlines are equipped with state of the art instrumentation for ion beam analysis: Nuclear Reaction Analysis (NRA), Rutherford Backscattering Spectroscopy (RBS), Particles Induced X-ray Emission (PIXE), Particles Induced γ-ray Emission (PIGE) And Elastic Recoil Detection Analysis (ERDA)

Major experimental instrumentation and its capabilities

The 5 beamlines are:

- A multi-purpose beamline used for sample analysis at the mm scale (NRA, ERDA, PIXE, PIGE, RBS and C-RBS)
- An external beamline dedicated to ion beam analysis in air for big and/or fragile samples that cannot be inserted in vacuum chambers (PIXE, PIGE)
- A microbeam used for quantitative ion beam imaging at the micrometer scale (PIXE, PIGE, RBS, NRA, ERDA and IBIC)
- A microbeam dedicated to targeted irradiation of living cells with a counted number of particles and with a micrometer accuracy.
- A beamline designed for the production of secondary neutron and γ fields (Nuclear physics and detector calibration)

Figure 13.11: Singletron™ accelerator of the AIFIRA facility.

User group
15 (informal).

Percentage of users, and percentage of facility use that come from inside the institution
5 (50% of beamtime).

Percentage of users and percentage of facility use from national users
15 (100% of beamtime).

Percentage of users and percentage of facility use from outside the country where your facility is located
0 (0%).

Future Plans
Beamlines are being renewed (vacuum systems, remote control, instrumentation). Installation of new silicon drift detectors (SDD) for PIXE analysis is in progress. Development of the IBIC capabilities.

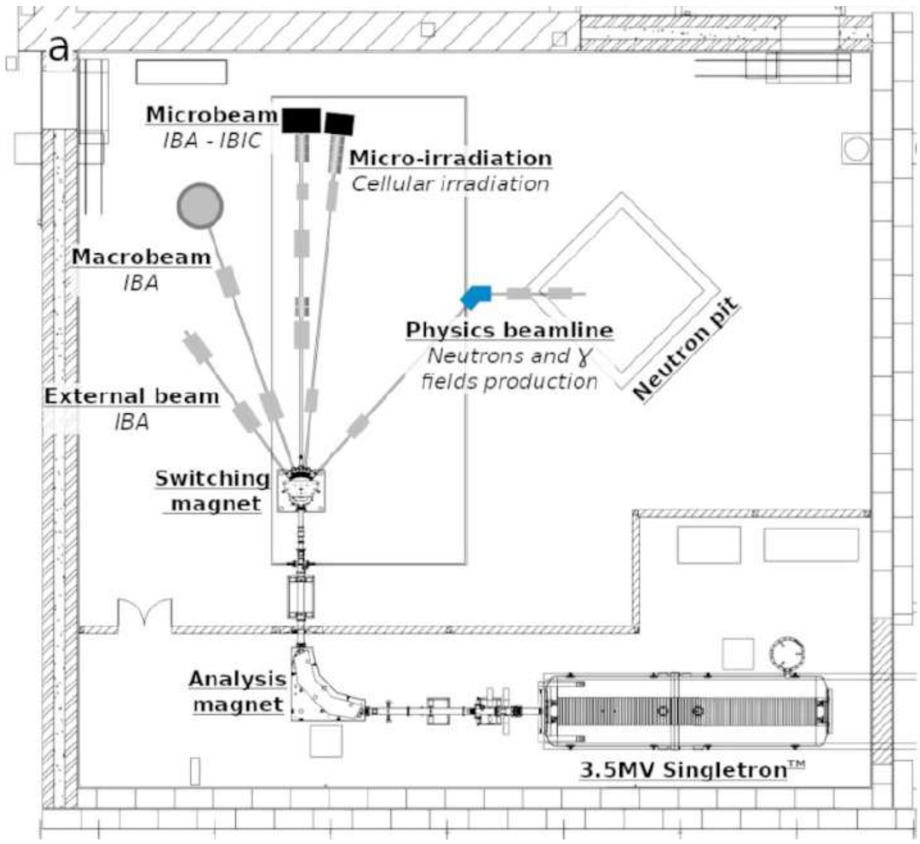

Figure 13.12: Overview of the AIFIRA facility.

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Director: Férid Haddad

Groupement d'Interêt Public (Association of public partners):
CHU de Nantes (public teaching hospital), CNRS/IN2P3 (public research institution in physics), ICO - R. Gauducheau (cancer center),Institut Mines Telecom Atlantique (public engineering school), Ministère de l'enseignement supérieur, de la recherché et de innovation (french government), Inserm (public research institution in medicine), Région des Pays de la Loire (regional government), Nantes Université (Nantes university)

Scientific Mission and Research Programs

The high-energy cyclotron Arronax, located in Nantes, is dedicated to nuclear medicine, radiochemistry and education. The main purpose of this equipment is to produce innovative radionuclides for diagnostic (PET, SPECT) and therapeutic (targeted therapy using radioactive species) applications developed in

research laboratories and hospital-based nuclear medicine departments and to advance knowledge about radiation and matter interactions. The cyclotron was commissioned at the end of 2010 cumulating with a 24h runs at 750 μA. Since then, regular high and low intensity runs over several days are performed. New laboratories and a radiopharmacy are available since 2017 allowing to prepare radio pharmaceuticals under cGMP rules for clinical trials from produced radionuclides.

Technical facilities

Characterization of the facility

High-energy cyclotron with light-ion beams (p,d, He) 8 beamlines with 1 for vertical beam capacity.

Facility parameters

- Protons (H^- acceleration): 30-70 MeV, up to 750 μAe on targets (with 2 beams each at 375 μA in separated target vault).
- Protons (HH^+ acceleration): fixed 17 MeV/n, up to 50 μAe.
- Deuterons : 15-35 MeV, up to 80 μA (dual beam capability).
- Alpha particles: 68 MeV, up to 70μAe and down to a few pA.
- A new pulsing system has been installed and commissioned. This system offers a flexible beam time structure by providing short macro-pulses made up of bunches separated by 32.8 ns. It adjusts the duration of the micro-pulses (>10 μs) and their repetition rate.

Major experimental instrumentation and its capabilities

Faraday cups (<210μA), instrumented 4 sectors collimators are available in all beamlines, single-wire profilers, alumina foils with camera and specific beam dumps with current measurements.

Support on-site EPICS networks for use of diagnostics.

All other dedicated instrumentations at end of beamlines come from users.

Figure 13.13: Cyclotron picture.

Nature of user facility
The main users comes from partners and other French and international institutions. Some industrial companies may also use the beam.

Program Advisory Committee/experiment proposals
The International Scientific Committee meets every year. A Technical advisory committee is also meeting every 2 months and review experimental proposals.

Number of active users per year
30.

Percentage of users, and percentage of facility use that come from inside the institution
50%.

Percentage of users and percentage of facility use from national users
30%.

Percentage of users and percentage of facility use from outside the country where your facility is located
15%

Fraction of the international users from outside your geographical region
5%.

Laboratory Staff
See Table 13.5.

Special student programs
PRISMAP, EU program, leader CERN.

Table 13.5: Staff at GIP Arronax. *Includes permanent staff, postdoctoral researchers, students. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	60
Scientists with doctoral degree	8
Staff (theory)	68*
Postdoctoral researchers	1
(Resident) Graduate students	4
(Non-Resident) Graduate students	6**
Undergraduate students	10

Future Plans

Work in order to access lower energy α beams at higher beam intensities.

THE CYRCE PLATFORM OF THE INSTITUT PLURIDISCIPLINAIRE HUBERT CURIEN (IPHC)

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Scientific Mission and Research Programs

IPHC is a research unit affiliated to the French National Institut for particle and nuclear physics (IN2P3-CNRS) and to the University of Strasbourg. With 400 staff positions, it is one of the largest academical research units in Alsace. IPHC activities are widespread, multidisciplinary, and are structured in 4 scientific departments : subatomic researches (DRS), analytical sciences (DSA), Ecology Physiology and Ethology (DEPE) and Radiobiology, Hadrontherapy and Molecular Imaging (DRHIM).

Characterization of the facility

The Cyrcé platform is built around a TR24 cyclotron (from ACSI, Canada). The technical platform consists of the cyclotron itself, hot chemistry laboratories, an irradiation area, a nuclear medical imaging area for pre clinical application and a small animal house.

Technical facilities

The TR24 cyclotron delivers proton beams from 16 to 25 MeV thanks to movable extraction foils. It is equiped with two extraction ports: one is used for isotope production, the other one is used for irradiation application and sensor qualification.

The Strasbourg TR24 is able to deliver up to 500 μA of proton beam, but 120μA are authorised by the national safety authority in the scope of isotope production. Several isotopes for TEP imaging are regularly produced (F18, Cu64, Zr89), and several will be produced in a near future (Ga68, Cu67).

For irradiation applications, the beam is delivered in a dedicated area where the maximum beam current available is 100 nA and current as low as a few fA may be delivered or even less.

Energy spread at 25 MeV has been assessed at 120 keV.

Facility parameters

The facility is composed of a concrete vault with 2 m thick walls in which isotope production is carried out. Beam is extracted on a beam line inside the vault and directed to a switching magnet located in the experimental hall. The experimental area hosts 2 beam lines for irradiation applications. One is dedicated to sensor testing for the CMS collaboration (https://cms.cern) but can be available for any type of sensors requiring similar beam properties.

Typical beam current used is in the range of 1 to 10fA. Up to 100nA can be used to test for radiation damage. X and Y sensor scanning allows for uniform fluence deposition on sensors under test.

The second beam line is designed for radiobiology where accurate doses may be delivered on biological tisues. Beam currents used for these applications range from tens of pA to tens of nA. In house developed system allows for fast beam switching (cut off in less than 1μs). Dose rate ranging from 1 Gy/s to 1 kGy/s are available.

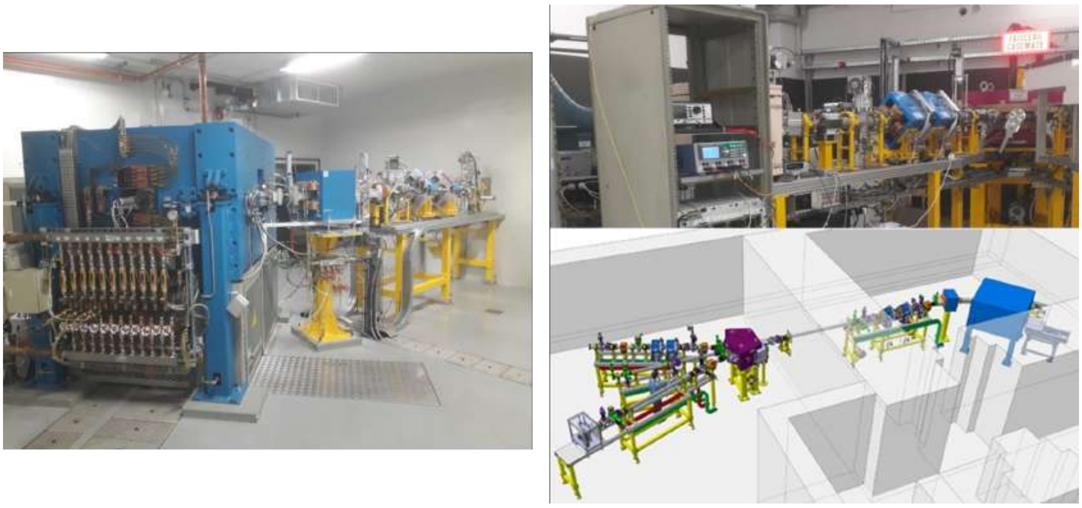

Figure 13.14: Experimental areas at IPHC Strasbourg.

Figure 13.15: View of the radiobiology beamline.

GRAND ACCÉLÉRATEUR NATIONAL D'IONS LOURDS (GANIL)

Boulevard Henri Becquerel– BP 55027 – 14076 Caen cedex 5
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Director: Patricia Roussel-Chomaz
E-mail: patricia.chomaz@ganil.fr
Deputy Director: Fanny Farget

Groupement d'Intérêt Economique (Economic Interest Grouping) - GIE
CEA-DRF (Commissariat à l'Energie Atomique et aux Energies Alternatives - Direction de la Recherche Fondamentale)
CNRS-IN2P3 (Centre National de la Recherche Scientifique – Institut National de Physique Nucléaire et de Physique des Particules)

Scientific Mission and Research Programs

GANIL is a large-scale European facility providing beams of heavy ions from Carbon to Uranium with energies ranging from few keV (∼300 000 m/s) to high energies up to 95 MeV per nucleon (∼120 000 km/s, approximately a third of speed of light). The scientific program is developing along 4 axes:

- Nuclear physics and nuclear astrophysics
- Materials under irradiation and nanostructuration
- Molecular collisions and interstellar medium
- Radiobiology and innovative techniques for hadrontherapy

GANIL is producing rare ion beams (RIB) – exotic nuclei not existing on Earth - using the fragmentation method in LISE Spectrometer and the Isotopes Separation On-Line (ISOL) technique with the SPIRAL1 facility. Exotic nuclei serve as a key in our understanding of the strong nuclear interaction, its influence on the nuclear structure and its evolution with the neutron to proton ratio. They are also of importance for the study of the origin of the chemical elements and the understanding of astrophysical phenomena. The new SPIRAL2 facility started operation in 2019. After commissioning of the LINAC, first experiments are performed in the new NFS experimental hall. SPIRAL2 offers new research prospects thanks to very intense beams of ions and neutrons.

Technical facilities

Acceleration of light and heavy ion beams (Carbon to Uranium) from few keV/nucleon to 95 MeV/nucleon, and production of neutrons. Exotic beams can be produced by ISOL method with the SPIRAL1 facility (up to 25 MeV/nucleon) or In- Flight Separation techniques.

Characterization of the facility

Two separated sector cyclotrons and 3 compact cyclotrons coupled with several experimental areas. One linear accelerator coupled with one experimental area. A second experimental area under construction, and a third starting construction in 2023.

Major experimental instrumentation and its capabilities

Fragment separator (LISE) and a large acceptance spectrometer (VAMOS): These 2 spectrometers can be coupled to different devices available on site: a large solid angle, high efficiency gamma detectors (EXOGAM, AGATA), several modular set-ups for light charged particles (MUGAST, DIAMANT, INDRA, FAZIA, ACTAR), neutrons (NEDA)

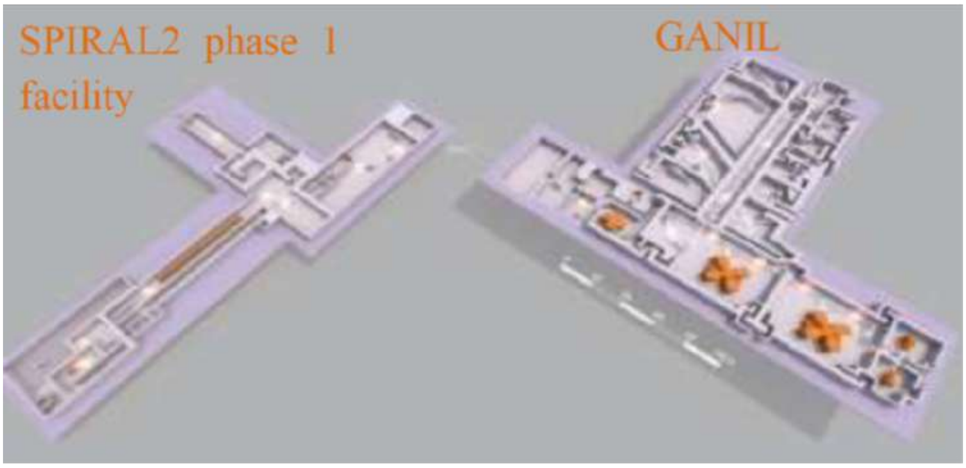

Figure 13.16: Experimental areas at GANIL.

Four beam lines are available for atomic physics, irradiated materials, astrochemistry, radiochemistry and radiobiology, at very low energy (keV/nucleon), medium energy ($\sim$10 MeV/nucleon) and full energy, allowing a broad range of experiments.

Nature of user facility

GANIL is classified as a Research Infrastructure in the roadmap of the French Ministry for High Education, Research and Innovation. SPIRAL2 has been selected as a "landmark" by ESFRI, the European Strategy Forum on Research Infrastructures, corresponding to a strategic instrument to develop the scientific integration of Europe and to strengthen its international outreach.

Program Advisory Committee/experiment proposals

2 PACs: one for Nuclear Physics and one for interdisciplinary research ((materials under irradiation, astrochemistry, radiobiology). Both PAC's are run once or twice a year. Industrial applications have paid access to the ion beams.

Number of active users

Almost 900 scientists registered as GANIL users during a survey performed in 2020. Because of the pandemics, the number of users who came to GANIL in the last couple of years is not representative.

Percentage of users, and percentage of facility use that come from inside the institution

2020: around 6% of users come from inside GANIL.

Percentage of users and percentage of facility use from national users

For 2020, national users represent 36% of the users

Percentage of users and percentage of facility use from outside the country where your facility is located

In 2020, 64% of users come from outside France.

Fraction of the international users from outside your geographical region

13% (outside EU).

Laboratory Staff

See Table 13.6.

Table 13.6: Staff at GANIL (March 2022). *24 permanent experimental scientists. **In addition at the nearby laboratory CIMAP, 24 permanent + 15 students and 8 post-docs working on pluridisciplinary subjects outside nuclear physics and astrophysics.. ***Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	228*
Temporary staff	59
Permanent staff (theory)	4
Postdoctoral researchers (theory)	1
(Resident) Graduate students (theory)	1
Postdoctoral researchers (experiment)	8
(Resident) Graduate students (experiment)	14**
(Non-Resident) Graduate students	60-80***
Undergraduate students	30/ year

Special student programs

Trainings for undergraduate, high school students.
Thesis presentation day for undergraduate

Future Plans

The development focuses of GANIL for the next five years are:

- Ensuring its role of host laboratory for the international nuclear physics and interdisciplinary research using ion beams
- Developing state-of-the-art detectors to perform experiments and open new horizons to nuclear physics
- Providing and accelerating new radioactive ion beams thanks to the completed and upgraded SPIRAL1 facility
- Refurbishing of cyclotrons
- Developing SPIRAL2 facility and Neutrons for science(NFS) new experimental hall
- Commissioning of the Super Separator Spectrometer (S3) (2024-2025)
- Carrying out the future steps of SPIRAL2: DESIR experimental hall, new ion source A/Q=7 (NEWGAIN)
- Implement in a staged approach the recommendations of the International Expert committee ("Spiro report): https://www.ganil-spiral2.eu/wp-content/uploads/2022/03/Expert-Committee-Vision-for-GANIL.pdf

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Scientific Mission and Research Programs

Nuclear Fission. Nuclear structure via neutron- capture of fission reactions. Neutron-induced reaction cross-sections. Fundamental properties of the neutron itself and observables in free neutron decay. Neutron scattering lengths. Applied nuclear research with radionuclides.

Research at the ILL covers many areas of physics, chemistry, biology, materials science, engineering and medicine.

Characterization of the facility

High-Flux 58.4 MW reactor: The most intense source of extracted neutron beams in the world, operating some 40 instruments. Maximum neutron flux in the reactor: 1.5×10^{15} cm^{-2}s^{-1}. In-pile hot source at 2400 K and cold sources at 25 K to adapt the neutron energy spectra.

Facility parameters

Major experimental instrumentation and its capabilities

Five main instruments: Lohengrin (PN1), FIPPS, PF1b, S18 and V4.

The Lohengrin recoil spectrometer for unslowed fission products separates neutron-rich nuclei far from stability. The focal point of the spectrometer can be equipped with ionisation chambers for particle identification, "Clover" detectors for γ-ray spectroscopy, LaBr3(Ce) detectors for fast-timing measurements and Si(Li) detectors for conversion-electron spectroscopy. These detectors are used mostly for studying decays from microsecond isomers or γ decays of refractory beams. Moreover studies of the fission process and applied physics experiments related to reactor applications are performed with this instrument.

The FIPPS instrument uses an intense thermal neutron beam incident on stable, radioactive and/or fissile targets. γ-rays emitted in (n,γ) or (n,f) reactions are registered with an array of 8 "Clover" detectors with anti-Compton shields. Depending on experimental needs these are complemented by additional "Clover" detectors or LaBr3(Ce) detectors for fast- timing measurements respectively. Analysis of $\gamma\gamma$- or $\gamma\gamma\gamma$-coincidences with angular correlation and/or linear polarization measurements provides high precision nuclear structure information, often considered as "complete spectroscopy" in a certain energy range.

The PF1b intense cold neutron beam with polarization option is a multipurpose beam port providing an intense beam of cold neutrons (5 meV average energy) with a capture flux of 2×1010 cm-2s-1, optionally polarized up to 99.7%. This beam is used for detailed studies of the free neutron decay, fission experiments, cross-section measurements and radiobiology experiments with slow neutrons.

The S18 thermal neutron interferometers serves for precision measurements of coherent neutron scattering lengths and fundamental quantum mechanics experiments with neutrons.

The V4 high flux beam tube provides a neutron flux up to 1.5×10^{15} cm^{-2}s^{-1} for production of radionuclides with high specific activity, enabling new applications in medicine and basic science. Radionuclides produced at V4 are e.g. used for neutrino mass experiments (ECHo and HOLMES) or for cross-section measurements at n_TOF@CERN.

Nature of user facility

Proposals for experiments at the ILL are submitted via the “ILL user club” on the ILL’s website (www.ill.fr). Two proposal rounds per year, on 15 February and 15 September.

Program Advisory Committee/experiment proposals

9 different PAC subcommittees each specialised in a particular scientific field (one subcommittee for nuclear and fundamental physics). Each PAC has 8 to 10 external members.

TANDEM FACILITY INSTITUT DE PHYSIQUE NUCLÉAIRE D'ORSAY (ALTO)

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Facsimile: +33- 01 69 15 64 70
E-mail: ibrahim@ipno.in2p3.fr

Head of the facility: Dominique GUILLEMAUD-MUELLER
Head of the Tandem and ALTO facilities (scientific matters): Fadi IBRAHIM
Head of the Tandem and ALTO facilities (technical matters): Saïd ESSABAA

The institution is under the responsibility of the Centre National de la Recherche Scientifique (CNRS)
The University Paris XI Institute under French administrative law, under the responsibility of the French Ministry of Education and Science Research.
The Tandem/ALTO facility, it is under the responsibility of the Institute. It therefore has the same status.

Scientific Mission and Research Programs

The physics fields are: fundamental nuclear physics, nuclear structure, exotic nuclei; nuclear astrophysics; solid physics; atomic physics.

Characterization of the facility

The Tandem is an electrostatic machine (maximum voltage 15 MV). It can speed up an important range of ions, from the protons to the mass agregates, ALTO is a 50 MeV pulsed electron linac, dedicated to the production of neutron rich radioactive beams with a production up to 4×10^{11} fissions per second, on line with a mass separator

Facility parameters

ALTO: neutron rich radioactive beams with production up to 4×10^{11} fissions/sec.

Tandem facility parameters, see Fig. 13.17

Major experimental instrumentation and its capabilities

- Split pole spectrometer
- Parrne separator
- Bacchus spectrometer
- Orsay Segmented Clover Array (OSCAR)

Nature of user facility

Yes.

Program Advisory Committee/experiment proposals

The ALTO Programme Advisory Committee adjudicates experiment proposals twice a year.

Number of active users and their origin

Just with the Tandem facility: 130 active users of the facility. This number will increase with ALTO (end of 2005).

Injected ion species	Injected intensity (μA)	Energy (MeV)	Intensity analysed (pps x 10^{10})
1H	2.5	25	600
2H	1.6	29	113
4He	1.9	36	900
6Li	0.07	50	1.8
7Li	0.09	56	13
9Be	0.0025	62	0.56
11B	0.0042	77	4.3
12C	0.92	69	94
13C	1.8	70	2.6
14C	0.11	72	15
16O	4	90	100
19F	0.2	104	3.3
24Mg	0.06	130	6
27Al	0.18	120	8
28Si	0.14	150	0.063
31P	0.07	155	0.95
32S	0.75	154	29
34S	0.09	130	5.6
35Cl	0.2	154	10
40Ca	0.12	168	37
48Ti	0.014	210	1.2
56Fe	0.0025	99	0.032
58Ni	0.18	182	6.8
81Br	1.5	217	2.2
127I	0.5	297	0.5
197Au	0.2	172	0.045

Figure 13.17: Stable ion species at the tandem.

Percentage of users, and percentage of facility use that come from inside the institution

22%.

Percentage of users and percentage of facility use from national users

42%.

Percentage of users and percentage of facility use from outside the country where your facility is located

34%.

Fraction of the international users from outside your geographical region

2%.

User group

Not for the moment, in progress.

Laboratory Staff

See Table 13.7.

Special student programs

Master experiments: once a year, schools visits (under graduates).

Table 13.7: Staff at ALTO. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	28
Temporary staff	10
Permanent staff (theory)	20
Postdoctoral researchers (theory)	2
(Resident) Graduate students (theory)	6
Postdoctoral researchers (experiment)	10
(Resident) Graduate students (experiment)	42
(Non-Resident) Graduate students	5*
Undergraduate students	10

Future Plans

Construction of 4 low energy lines, in addition with the one already existing. Laser Ion source, high resolution spectrometer.

FORSCHUNGSZENTRUM JÜLICH (FZJ)

NUCLEAR PHYSICS INSTITUTE (IKP)
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Facsimile: + 49 2461 61-8100
E-mail: f.goldenbaum@fz-juelich.de

Prof. Dr. James Ritman (Hadron Structure)
Prof. Dr. Hans Ströher (Hadron Dynamics)
Prof. Dr. Ulf-G. Meißner (Theory)
Prof. Dr. Mei Bai (Accelerator)

Helmholtz Center (HGF e.V.) GmbH (Ltd)
Federal Republic of Germany (90%); State of North Rhine Westphalia (10%)

Scientific Mission and Research Programs

Forschungszentrum Jülich (FZJ) is a multi- disciplinary research center within the framework of the Helmholtz Association. The Institut für Kernphysik (IKP) operates and further develops the Cooler Synchrotron COSY, and makes its beams available to a national and international community - in combination with dedicated detector systems, which have been built and which are operated by international collaborations. The physics program at COSY focusses on the following key topics: Symmetries and symmetry breaking, in particular charge-parity (CP-) and time-reversal (TR-) violations.

The hadron physics program at IKP has been successfully completed by the end of 2015. IKP is also committed to research and development for the FAIR project at Darmstadt as one of its major future activities; several key issues are/will be investigated and tested at COSY:

- High energy electron cooling and stochastic cooling techniques;
- Beam-target interactions using pellet and high- density cluster-jet targets and energy loss compensation techniques;
- Spin-control and manipulation techniques.

In addition, substantial contributions of IKP towards the realization of FAIR include:

- Design, construction and operation of the High Energy Storage Ring (HESR) for antiprotons as the leading laboratory;
- Development and installation of the PANDA detector at HESR as a major institution.

Characterization of the facility

Few-GeV synchrotron for phase-space cooled and polarized proton and deuteron beams, internal and external target stations and (polarized) targets.

As a new project, IKP is pursuing research and development for a charged-particle EDM search (JEDI, Jülich Electric Dipole moment Investigations), which in a first step should lead to a precursor experiment at COSY for protons and deuterons and later to a dedicated precision EDM storage ring.

Facility parameters

Major experimental instrumentation and its capabilities

- TP3: Internal target station, equipped with the -symmetric WASA-forward detector system (for polarimetry)

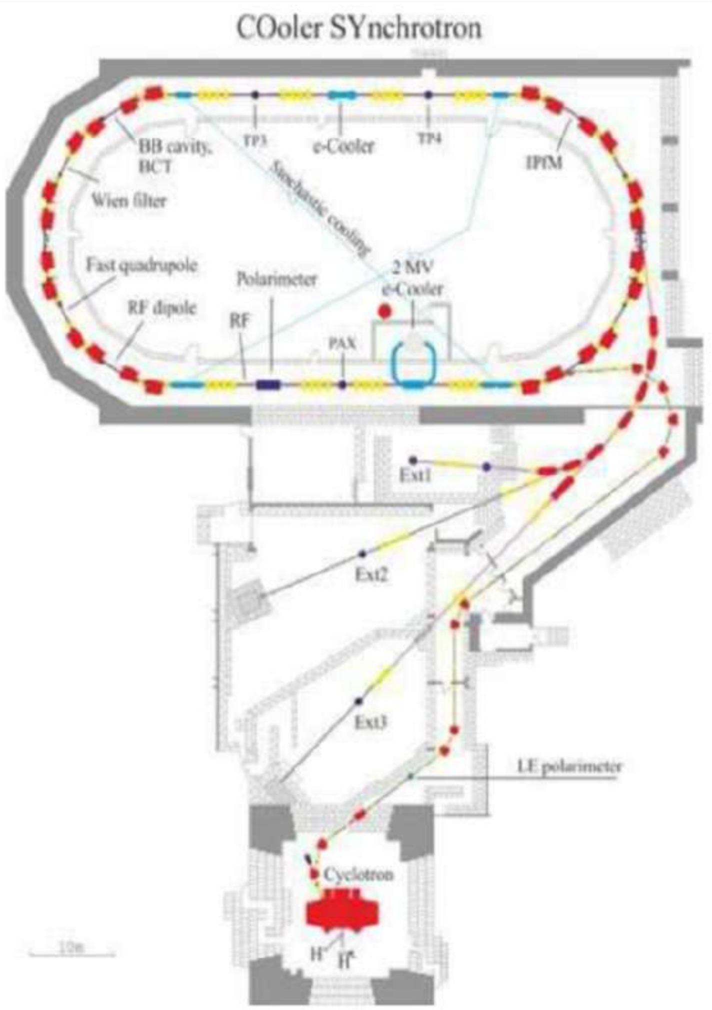

Figure 13.18: Experimental areas at COSY.

Ring length	184 m
Momentum range	0.27 – 3.7 GeV/c
Particle species	p, d (vector and tensor polarized)
Beam intensity	Up to ~10^{11}
Cooling methods	electron, stochastic
Internal experiments	PAX (JEDI), TP3, TP4
External experiments	Ext1, Ext2, Ext3

Figure 13.19: Facility parameters.

- TP4: Internal target station, equipped with a fast ramping superconducting Siberian snake
- Ext1, Ext2, Ext3: 3 external target stations for test setups
- PAX: “Polarized Antiproton Experiment” - Detector system for polarizing (anti-) protons by spin filtering; this target station will be used for JEDI (precursor experiment)

User facility
Yes.

Program Advisory Committee/experiment proposals
Yes.

Number of active users and their origin
~150 / year.

Percentage of users, and percentage of facility use that come from inside the institution
~20%.

Percentage of users and percentage of facility use from national users
~20%.

Percentage of users and percentage of facility use from outside the country where your facility is located
~60%.

Fraction of the international users from outside your geographical region
~10%.

User group
CANU (COSY Acossiation of Networking Universities)

Laboratory Staff

Table 13.8: Staff at FZJ IKP. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	110
Temporary staff	~20
Permanent staff (theory)	7
(Resident) Graduate students (theory)	3
Postdoctoral researchers	~10
(Resident) Graduate students	~20
(Non-Resident) Graduate students	~10*
Undergraduate students	~10

Special student programs
Hadron physics summer school (together with ELSA/ University of Bonn). Lectures and seminars at universities (Aachen, Bochum, Bonn, Cologne, Wuppertal)

Future Plans
High-energy (2 MV) electron cooler commissioning (2014); Siberian snake for longitudinal spin-filtering (PAX) (2017); Precursor charge-particle EDM search (2017 and beyond), which may lead to a dedicated storage ring EDM project involving COSY.

ELECTRON ACCELERATOR (ELSA), UNIVERSITY OF BONN

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Spokesperson: Prof. Dr. Klaus Desch
Phone: +49 228 73 3236
E-mail: desch@uni-bonn.de

Scientific Mission and Research Programs

Photon-induced reactions, Photoproduction of Mesons, Baryon Spectroscopy, In-Medium Properties of Hadrons; Detector physics.

Characterization of the facility

Storage and stretcher ring ELSA with two pulsed linear accelerators and booster synchrotron producing polarised (1 nA) and unpolarised (up to 10 nA) electron beams from 0.5 to 3.2 GeV with high duty factor. Linearly and circularly polarised photons for hadron physics experiments. Testbeam area for detector tests (100 Hz – 100 MHz direct electrons (0.5 – 3.2 GeV).

Major experimental instrumentation and its capabilities

ELSA accelerator with polarised electron source,
Photon taggers with goniometers,
Polarised solid state proton and neutron targets,
Large solid angle spectrometer with Crystal Barrel.
Pixel Beam Telescope for detector tests.

Program Advisory Committee/experiment proposals

Local board of directors.

DARMSTADT LINEAR ACCELERATOR (S-DALINAC)

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Telephone: +49 6151 16-23540
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Director: Norbert Pietralla
E-mail: pietralla@ikp.tu-darmstadt.de
Head of operations: Michaela Arnold

Scientific Mission and Research Programs

Main Fields of Nuclear Research:

- Accelerator science for multifold supercon- ducting Energy-Recovery LINACS (ERLs)
- Photonuclear and electron-induced reactions for the study of elementary nuclear excitations with low multipolarity and at low momentum transfer
- Electric and magnetic giant resonances
- Precision measurements on few-body systems and effective nuclear few-body forces
- Electromagnetic analogues of electroweak nuclear reaction matrix elements

Characterization of the facility

Superconducting recirculating electron accelerator with ERL mode.

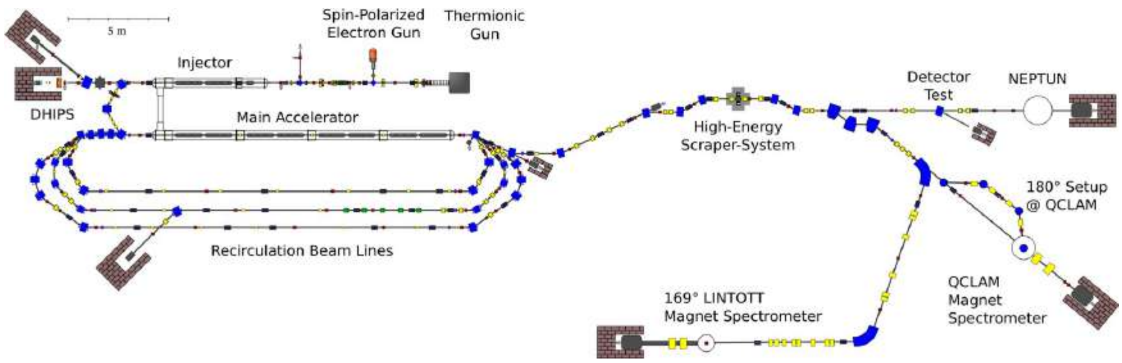

Figure 13.20: Floorplan of the S-DALINAC with its experimental setups.

Facility parameters

Beam: electrons Energy: 2-130 MeV Current: 60 μA (10 MeV), 20 μA (130 MeV) Operation: cw with 3 GHz Energy resolution of beam on target: $< 4\times10^{-4}$.

Technical facilities

The superconducting Darmstadt linear accelerator S-DALINAC (floorplan see Fig. 13.20) provides continuous wave (cw) beams of electrons with a repetition rate of 3 GHz and average currents of 60 μA (injector) or 20 μA (main LINAC). The beam from either of the two sources is prepared in a normal conducting chopper-prebuncher–section. In the superconducting radio-frequency (SRF) injector linac, the bunches can be accelerated up to 10 MeV. Behind the injector linac the beam can be used for nuclear resonance fluorescence experiments at DHIPS (Darmstadt high intensity photon setup) with up to 60 μA. Alternatively, the beam can be further accelerated in the 3 GHz SRF main linac with up to 3 recirculations. A total energy of up to 130 MeV with up to 20 μA beam current is possible. The beam is then extracted to the experimental area with the photon tagger NEPTUN, the LINTOTT spectrometer for high-resolution (e,e') experiments, the QCLAM spectrometer for (e,e'x) coincidence experiments with the capability of measuring at 180° scattering angle and a detector test set-up. The S-DALINAC (see photo below) is used for research in the field of accelerator physics as well. It represents the first superconducting ERL in Germany. In 2021, the first multiturn SRF-ERL with high transmission was demonstrated.

Major experimental instrumentation and its capabilities

Main instrumentation for Nuclear Physics Experiments:

- Nuclear resonance fluorescence facility with three 100% efficient Compton-suppressed Germanium detectors
- Energy loss spectrometer for (e,e') at high resolution in dispersion-matching mode
- Large solid angle magnetic spectrometer of the QCLAM type for single arm (e,e') and coincidence experiments of the form (e,e'x) with x = n, p, γ,...
- Facility for inelastic electron scattering at 180º
- Photon tagger for photon energies of 4 – 30 MeV
- Setup for detector tests

Figure 13.21: View into the S-DALINAC accelerator hall [Photograph by Jan-Christoph Hartung].

Nature of user facility

University research facility, mainly inside users. Outside users are welcome if an in-house group serves as host. Contact director for facility access.

Program Advisory Committee/experiment proposals

No.

Number of active users and their origin

Masters; doctoral students (including scholarship holder); scientific staff: 30; 100; 50.

Percentage of users, and percentage of facility use that come from inside the institution

Mainly inside users (90%).

Percentage of users and percentage of facility use from national users

$\leq$5%.

Percentage of users and percentage of facility use from outside the country where your facility is located

$\leq$5%.

User group

No.

Laboratory Staff

Table 13.9: Staff at S-DALINAC.

Designation	Number of persons
Permanent staff (scientific)	14
Permanent staff (admin-technical)	34
Temporary staff (scientific)	129
Postdoctoral researchers	10
(Resident) (Under-)Graduate students (theory)	35
Postdoctoral researchers (experiment)	30
(Resident) Graduate students	129
Undergraduate students	20

Special student programs

Accelerator school, graduate school HGS- HIRe, Research Training Groups

Future Plans

Electro-fission of transuranium actinides; Highly-repetitive Laser-Compton Back-scattering γ–ray source

GSI HELMHOLTZZENTRUM FÜR SCHWERIONENFORSCHUNG GMBH / FACILITY FOR ANTIPROTON AND ION RESEARCH IN EUROPE (FAIR) GMBH

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Government Institution, legal form: GmbH under German law
GSI: Member of Helmholtz-Association of German Research Centers

Scientific Mission and Research Programs

GSI is located in Darmstadt and maintains two Helmholtz-Institutes in Jena and in Mainz in cooperation with the respective university. GSI's mission is the development, construction and operation of ion beam accelerators for a broad national and international science community and doing research with heavy ions. With the Facility for Antiproton and Ion Research (FAIR) an international accelerator facility is being built next to GSI.

Currently GSI and FAIR are two separate limited liability companies (GmbH), but they operate in close coordination, which is guaranteed also by the fact of shared positions of the top management. The current accelerator facilities are complemented by technically advanced experimental facilities as well as a high-energy (kJ), high power (PW) laser system PHELIX, which altogether offer outstanding opportunities for research in the fields of hadron and nuclear physics, atomic physics, dense plasma research, material science, biophysics and radiation medicine.

During the next years, the major mission of GSI is the construction of FAIR together with national and international partner institutions. As part of those preparations, and with support of the FAIR shareholders, the scientific program "FAIR Phase-0" of GSI/FAIR offers approx. 3 months of beamtime per year for experiments with new and upgraded accelerator and detector components of FAIR. FAIR Phase-0 is planned to run until the start of FAIR.

Characterization of the facility

The GSI/FAIR accelerator complex consists presently of the linear accelerator UNILAC, the heavy-ion synchrotron SIS18 and experiment storage-cooler rings. It can provide highly ionized ion beams of all stable elements from hydrogen up to bare uranium with energies from the Coulomb barrier up to 2 *A*GeV. In addition, secondary beams of unstable nuclei are available. As a further option, secondary pion beams can be delivered at momenta of 0.5 GeV/c to 2.5 GeV/c. Several experiments can be performed in parallel, even using different ions.

The UNILAC, a 120m linear accelerator, provides intense ion beams at energies. The UNILAC serves as an injector to the synchrotron SIS. SIS, the heavy-ion synchrotron with 216m circumference and a maximum bending power of 18 Tm accelerates particles up to 2 *A*GeV. FRS, a 72m Projectile Fragment Separator, provides unstable isotopes of all elements up to uranium.

In the ESR (a 108m circumference experimental storage ring), stable or radioactive ion beams can be stored and cooled. The ion trap facility HITRAP provides cooled highly charged ions as bare nuclei at low temperature (up to U92+), He-like ions or few-electron systems. The CRYRING@ESR provides decelerated exotic ion beams stored at low energy, in the range of about 10 *A*MeV down to a few 100 *A*keV.

The pion-beam facility provides pion-beams in the momentum range of 0.5 to 2.5 GeV/c. The laser PHELIX delivers short or long laser pulses between. Experiments with combined laser and ion beam makes PHELIX unique.

Technical facilities

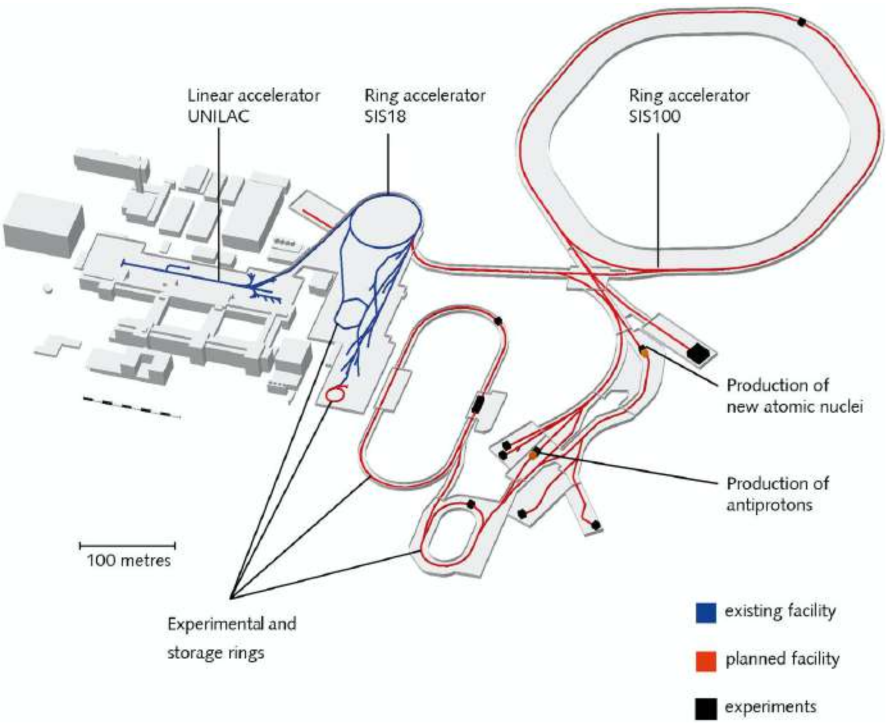

Figure 13.22: Major facilities of GSI and FAIR. (c) GSI

Facility parameters

See Fig. 13.23. The parameters of FAIR will significantly extend these capabilities through adding 3 new accelerator/storage rings (SIS100, CR and HESR), the injector (p-Linac, production targets for new atomic nuclei and antiprotons) and a fragment separator (Super-FRS).

Major experimental instrumentation and its capabilities

See Fig. 13.24. FAIR will add to this by a wealth of instrumentation in the four scientific pillars: APPA, CBM, NUSTAR and PANDA.

Nature of user facility

With the FAIR Phase-0 program, GSI is a user facility for the international science community though with strongly reduced user operation due to the construction of the FAIR facility on the GSI premises.

Program Advisory Committee/experiment proposals

To cover the broad spectrum of research pursued, program advisory committees with international experts have been established for the different fields:

1. The General Program Advisory Committee (G- PAC) addressing the research fields nuclear physics and atomic physics, acting as central PAC.
2. PHELIX and Plasmaphysics Advisory Committee (Phelix Committee)
3. Biophysics and Radio-Biology Program Advisory Committee (Bio-PAC)
4. Materials Research Program Advisory Committee (Mat-PAC)

Facility	Particle	Energy Range	Charge (expl.)	Description
UNILAC - heavy ion linear accelerator	p to U	1.4-11.4 AMeV	p Ar10+ U28+	2 mA 10 mA 4 mA
SIS 18 - Heavy ion synchrotron, magnetic rigidity 18 Tm, cycle rate 1Hz	p to U	10-4500 AMeV (p); heavy ions: 10-1000 AMeV	Ne10+ Ar10+ U73+	2 AGeV, 10^{11} ions/cycle 0.7 AGeV, $3*10^{10}$ ions/cycle 1 AGeV, $2*10^{9}$ ions/cycle; opportunity for electron cooling

Facility	Particle	Energy Range	Charge (expl.)	Description
ESR - heavy ion storage ring, magn.rigidity 10 Tm	p to U	for U up to 560 AMeV (HITRAP: 4 AmeV)		Electron-cooled ions; interaction with internal gas targets
Pion-beam facility	pion-beam	Secondary pion beam; Momentum range: 0.5-2.5 GeV/c		
CRYRING @ESR	p to U	few 100 keV/u; for C 24 MeV/u		Electron cooler, internal target (gas)
Phelix laser	laser beam	high-energy (kJ), high power (PW) laser system ($2x10^{21}$ W/cm^2); pulses 0.5-20 ps or 1-10 ns, with 0.3-2 kJ		

Figure 13.23: Current GSI facility parameters.

Number of active users

Approximately 3.000 scientists are active in the preparation for the FAIR experiments.

Percentage of national and international users

From an analysis of the number of users contributing to the GSI Annual Report over the recent years, one finds:

- Total number of users: ca. 1.300 .
- Internal users: ca. 15% .
- Other national users: ca. 28%.
- International users: ca. 60%.
- Europeans (w/o German users): ca. 32%.
- Outside Europe: ca. 28%.

Laboratory Staff

See Table 13.10.

Table 13.10: Staff at GSI/FAIR. *Incl. graduate students and postdoctoral researchers. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	∼1500
Temporary staff	∼500*
Postdoctoral researchers	∼85
(Resident) Graduate students	∼235
(Non-Resident) Graduate students	∼370**

Special student programs

Most students are enrolled in the Helmholtz Graduate School for Hadron and Ion Research (HGS-HIRe for FAIR), plus other research-field related graduate schools. The International Summer Student Program offers short-term internships for undergraduate students, while longer internships are offered by the program GET_Involved for international students and postdocs. Two- to four-

Name	Instrument	Description
SHIP spectrometer	velocity filter	Separation and detection of super-heavy elements
SHIPTRAP	Penning trap	nuclear structure and atomic physics studies on very heavy nuclei/atoms
TASCA	Transactinide separator and chemistry apparatus	to study single ion chemistry of superheavy ions
M-branch		for materials research with in situ characterization of irradiated samples (SEM, XRD, FTIR, UV-Vis, RGA, etc)
	Heavy-ion microprobe	Precision irradiation experiments with pre-defined number of ions (spatial resolution of ~1 μm) and exposure of boil. material in medium
Stations for irradiating biological samples		scanning biological samples
HADES	High Acceptance Di-Electron-Spectrometer	for studying the properties of vector mesons in high density hadronic matter
FRS – fragment separator	large projectile fragment separator	allowing the production and in-beam separation of nuclei far off stability
R3B	experimental setup for Reactions with Relativistic Radioactive Beams	kinematically complete measurements of break-up reactions of relativistic nuclei; tracking detectors, γ-spectroscopy, neutron detection
Multi-purpose experiment stations (SIS energies) for atomic physics, material sciences and radiation biology research		equipped with, e.g. a charge-state separator/ analyzer foratomic reaction products, a rasterscanner for vertical and horizontal beam deflection (20x20 cm²), irradiation of samples in high-pressure cells

Name	Instrument	Description
ESR	cooler storage ring	equipped with: Schottky and time-of-flight mass spectroscopy; internal gas-jet target and detector system;various X-ray and position sensitive particle detectors; collinear laser spectroscopy system
HITRAP	ion trap	for atomic physics and nuclear structure studies on heavy,highly-charged ions at rest
CRYRING@ESR	Low energy storage ring, electron cooler	Electron cooler, internal target (gas), Schottky detection, particle and radiation detection ports, laser interaction region, extraction of decelerated cooled beams
Two experimental stations for dense plasma research; High energy Proton microscope PRIOR		combined application of intense ion and PHELIX laser beams for plasma generation and diagnosis; Radiographical imaging of dynamic systems, radiography
PHELIX	high power, high energy laser	For plasma physics experiments; in combination with ion beam
Detector test facility		for detector tests; beams of protons, ions, pions and electrons can be provided

Figure 13.24: Experimental instruments at GSI.

week internships are offered for high school and undergraduate students. Further activities for high school students involve International Masterclasses on analysis of experimental data, the series of lectures on modern physics Saturday Morning Physics, or the Girl's-day.

Future Plans

The international FAIR facility will offer relativistic beams of antiprotons as well as of stable and unstable heavy ions combined with sophisticated instrumentation. Energies up to 35 GeV/u are foreseen and an intensity gain compared to the present GSI facility of a factor of 100 for stable and up to 10.000 for rare isotopes. A superconducting synchrotron SIS100 with a circumference of about 1,100 meters and with magnetic rigidities of 100 Tm will be at the heart of the FAIR accelerator facility. Following an upgrade for high intensities, the existing GSI accelerators UNILAC and SIS18 will serve as a injectors.

Attached to the large synchrotron SIS100 will be a complex system of storage-cooler rings and experiment stations including a superconducting nuclear fragment separator (Super FRS) and an antiproton production target. The FAIR design will allow for future upgrade options including the installation of a second accelerator ring in the SIS100 tunnel.

Parallel operation is anticipated to maximize experimental output, in view of intrinsic cycle times of the accelerator and storage-cooler rings. This will allow for a rich and multidisciplinary research program to be conducted covering a broad spectrum of research fields such as: QCD studies with cooled beams of antiprotons; QCD-Matter and QCD-Phase Diagram at highest baryon density; nuclear structure and nuclear astrophysics investigations with nuclei far off stability; precision studies on fundamental interactions and symmetries; high density plasma physics; atomic and material science studies; radio- biological investigations and other application oriented studies. The start of operation of the FAIR facility in its newly constructed halls is scheduled for 2025.

MAINZ MICROTRON (MAMI)
MAINZ ENERGY-RECOVERING SUPERCONDUCTING ACCELERATOR (MESA)

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Collaborative Research Centre (SFB 1044) of German Research Foundation (DFG), Johannes Gutenberg University of Mainz, and Federal State of Rhineland-Palatinate, PRISMA Cluster of Excellence and Centre for Fundamental Physics (German Research Council)

Scientific Mission and Research Programs

Study of the structure of hadrons with electromagnetic probes at low energies and momentum transfers. Search for particles beyond the Standard Model. Precision tests of the Standard Model. Precision studies of light nuclei and hypernuclei. Parity violation experiments.

Characterization of the facility

Cascade of four race track microtrons with c.w. polarized electron beam. Secondary real photon beam.

Facility parameters

Table 13.11: MAMI facility parameters.

Beam species	e^-
Energy range	180 – 1558 MeV
Maximum current	100 μA
Beam Polarization	80%
Horizontal Emittance	$12 \times 10^{-6}\pi\cdot$ m $\cdot$ rad (1σ)
Vertical Emittance	$1.7 \times 10^{-6}\pi$ m $\cdot$ rad (1σ)
Secondary Beam	tagged photon beam

Major experimental instrumentation and its capabilities

A1 (electron scattering): Setup of three high resolution magnetic spectrometers, one is equipped with a proton polarimeter. Short orbit spectrometer for pion detection. Short orbit, high magnetic field kaon spectrometer. Calorimetric detector for nucleons, time-of-flight walls for neutron detection.

Liquid hydrogen/deuterium/helium target, polarized 3He target. A large scale neutron detector is under construction.

A2 (real photon scattering): Tagged photon beam with unpolarized and polarized photons. Large solid angle detector Crystal Ball. Liquid H2, D2, 3He targets, polarized frozen-spin target.

X1 (X-ray generation): Coherent X-ray generation using transition and undulator radiation and the Smith-Purcell effect. Test beam facility for detector test (max. 855 MeV beam energy).

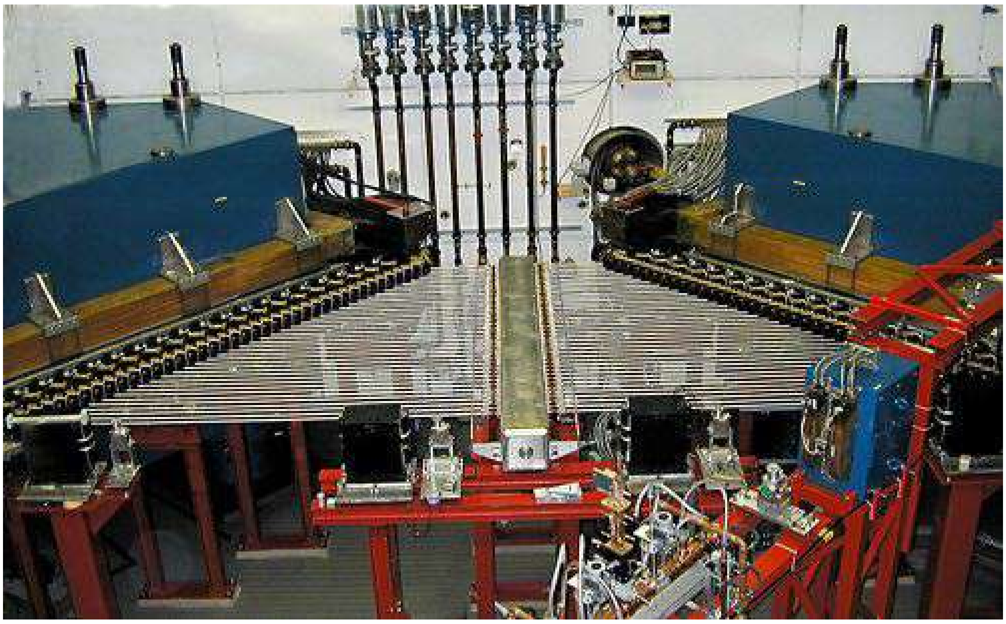

Figure 13.25: Picture of the latest microtron stage MAMI-C. A maximum electron beam energy of 1.604 GeV can be achieved.

Figure 13.26: A1 high resolution spectrometers for electron scattering experiments.

Technical facilities

Nature of user facility

No. All access is through collaborative programs. For access, external scientist should contact the collaborations directly (see instrumentation).

Program Advisory Committee/experiment proposals

Yes. Submission of written proposals, followed by oral presentation to a Program Advisory Committee (1 national and 6 international members, Chair: Prof. Zein-Edine Meziani).

Number of active users and their origin

Average 150 users.

Percentage of users, and percentage of facility use that come from inside the institution

∼50%.

Percentage of users and percentage of facility use from national users

∼50%.

Percentage of users and percentage of facility use from outside the country where your facility is located

∼10%.

Fraction of the international users from outside your geographical region

∼40%.

User group

No.

Laboratory Staff

Table 13.12: Staff at MAMI (as of 2017). *Number includes 8 professors, 20 scientists, and 80 technicians/ administration. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	108*
Temporary staff	115
Permanent staff (theory)	7
Postdoctoral researchers (theory)	10
(Resident) Graduate students (theory)	15
Postdoctoral researchers (experiment)	50
(Resident) Graduate students	65
(Non-Resident) Graduate students	∼15**
Undergraduate students	∼25

Special student programs

Several student programs are organized by the University of Mainz. The facility is integrated in the physics education of the University, e.g. in the context of advanced laboratory courses. High school internships are possible at all stages. Two Research Training Groups (Graduiertenkolleg) of DFG. Annual Student Workshop at Boppard/Rhein.

Future Plans

MESA (Mainz Energy Recovering Superconducting Accelerator) facility (currently under construction, commissioning 2021, parallel operation to MAMI): Two beam modes: extracted beam and energy recovering (ERL) mode with internal gas jet target. Max. electron beam energy/intensity: 155 MeV/150 μA (extracted beam), 105 MeV/1 mA (ERL mode).

Experimental instrumentation for MESA (under construction):
P2 experiment (extracted beam mode): parity violation spectrometer inside large solenoidal magnetic field.
MAGIX experiment (ERL mode): double arm spectrometer setup. GEM detector technology for focal plane instrumentation. Supersonic gas jet target.

TANDEM LABORATORY - CALIBRA RESEARCH INFRASTRUCTURE INST. OF NUCLEAR AND PARTICLE PHYSICS, NCSR "DEMOKRITOS"

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Scientific Mission and Research Programs

The Tandem Accelerator Laboratory (TAL) [1] operates at the Institute for Nuclear and Particle Physics (INPP) of the National Center for Scientific Research "Demokritos" (NCSRD). The INPP is one of the five research institutes of NCSRD. INPP's research activities focus on three main scientific areas: Astroparticle Physics, High Energy Physics, and Nuclear Physics and Applications. All activities combine experiment and theory. The INPP focuses mainly on fundamental research and implements various application programs with significant societal impact. INPP is also active in educational and training activities organized jointly with many Greek Universities.

Characterization of the facility

TAL is a unique Research Infrastructure in Greece, which is currently being fully upgraded with the aim of operating a Cluster of four Accelerators for Ion Beam Research and Applications with the acronym CALIBRA. TAL's total surface is $\approx$2000 sq. meters, half of which are covered by the Tandem accelerator hall and two "target rooms" where the experimental setups are installed. The remaining area is covered by a machine workshop, a target preparation room, an XRF laboratory, the control room, working spaces and offices.

TAL is an open access facility offering yearly at least 2000 hours of beamtime to internal and external users. Roughly 60% of the beamtime refers to ion-beam applications and irradiation services, with the rest being devoted to basic research in nuclear physics and atomic physics with accelerated ions. Good part of the experiments in basic research focus on the study of neutron-induced reactions.

5.5 MV T11/25 Tandem Van de Graaf: It was manufactured by the High Voltage Engineering Corporation (HVEC) and delivered its first beams in 1973. Between 2009 and 2012, the accelerator was significantly refurbished through an EC-funded REGPOT Grant. The accelerator provides currently proton and deuteron beams as well as ions of various elements, from Carbon to Copper. By end of 2022 and thanks to the CALIBRA project presented below, the Tandem accelerator will be completely upgraded with new components including a Pelletron© charging chain, new ion sources, new injection beamline, new voltage stabilizers, new foil and gas strippers, beam profile monitors, and a fully computer-controlled operation system.

PAPAP accelerator: PAPAP stands for "Petit Accellerateur pour l'Astrophysique". It is a 250- keV single-stage accelerator capable of delivering proton and deuteron beams of hundreds of μA (see Fig. 13.27). It was built and initially installed at CSNSM, Orsay, France, with the purpose of investigating nuclear reactions related to solar neutrino problem. When this program was terminated, it was donated to INPP. PAPAP is equipped with a state-of-the-art scattering chamber for material analysis, with sample cooling option down to liquid nitrogen temperatures.

The layout of TAL is shown in Fig. 13.29. Its main areas with the accelerators and the beamlines,

Figure 13.27: The single-stage PAPAP accelerator.

labeled in with circled numbers, are described in Fig. 13.28.

Technical facilities

Major experimental instrumentation and its capabilities

NEOPTOLEMOS Calorimeter: It is a cylindrically- shaped large volume (14"×14") NaI(Tl) detector with a borehole of 32 mm diameter along its axis (see Fig. 13.30). It is used to apply the 4π γ-summing technique [2] in nuclear astrophysics studies of capture reactions, where the cross sections of interest are very small making the use of high-efficient HPGe detectors, even with Anti-Compton shields, impractical. NEOPTOLEMOS has an absolute efficiency better than 50% for a two-fold γ-cascade. It can also be used for depth-profiling measurements.

GASPAR BGO Ball: Loaned by LNL, the Laboratori Nazionali di Legnaro, Padova, Italy, GASPAR stands for “GASP for Astrophysics Research", with “GASP” referring to the GAmma Spectrometer [3] previously operating at LNL. GASPAR is a calorimeter composed of 80 BGO crystals covering 80% of the solid angle (see Fig. 13.31). It is to be used for the study of reactions relevant to nuclear astrophysics. Its advantage over NEOPTOLEMOS is its ability, not only to sum transitions forming a γ- cascade, but also to provide the cascade's multiplicity, which defines the detector's summing efficiency. This way, Monte-Carlo efficiency simulations can be by-passed.

GASPAR has recently been equipped with new digital electronics for signal processing using funds from the CALIBRA project (see below).

ZAPS setup: ZAPS stands for Zero-degree Auger Projectile Spectroscopy. It was installed by the Atomic Physics Groups from the Universities of Crete and Ioannina, Greece, to perform high resolution studies of Auger electrons emitted from projectile ions excited in ion-atom collisions. The components of the beamline hosting ZAPS are shown in panel a) of Fig. 13.32.

The workhorse of the ZAPS setup is the single stage hemispherical deflector analyzer (HDA) combined with a two-dimensional Position Sensitive Detector (PSD) and a four-element injection lens. More details are given in [1] and [4].

IR2 material irradiation setup: It was developed by the Fusion Technology Group of NCSR “Demokritos” for Ion iRradiations of materials with in-situ electrical Resistivity measurements. It

Circled number	Description
1	Ion source electronics Faraday cage
2,3	Duoplasmatron and Sputter sources
4	30-deg. injector magnet
5	Tank; VdG Generator (terminal)
6	90-deg. Analyzing Magnet
7	Poststripper
8	Switching magnet (8 ports)
9	60-deg. beamline: GASPAR 4π BGO-Calorimeter and γ-multiplicity filter for nuclear reaction studies
10	45-deg. beamline: nuclear microprobe
11	32.5-deg. beamline: RBS/Channeling chamber & external micro-PIXE setup
12	15-deg. beamline: NaI calorimeter (14"×14") and HPGe detector array; nuclear astrophysics and depth proling
13	25-deg. beamline: universal scattering chamber for NRA and ion irradiations
14	45-deg. beamline: Zero-degree Auger Projectile Spectrometer (ZAPS) for ion-atom collision studies
15	60-deg. multi-purpose beamline: irradiations with neutrons produced via the d+D or d+T reactions, or material irradiations with ions.
16	PAPAP accelerator

Figure 13.28: Accelerator components and beamlines indicated with circled numbers in Fig. 13.29. (See also Ref. [1])

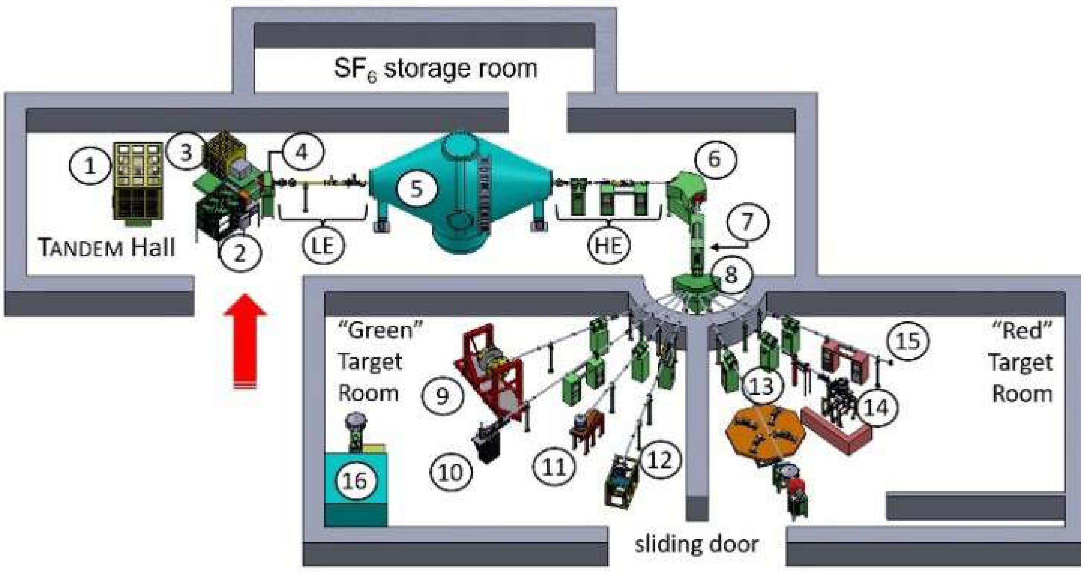

Figure 13.29: Schematic layout of the Tandem-hall and the two target rooms of the laboratory. The main accelerator components and setups are described in Fig. 13.28.

Figure 13.30: The NEOPTOLEMOS Summing Spectrometer.

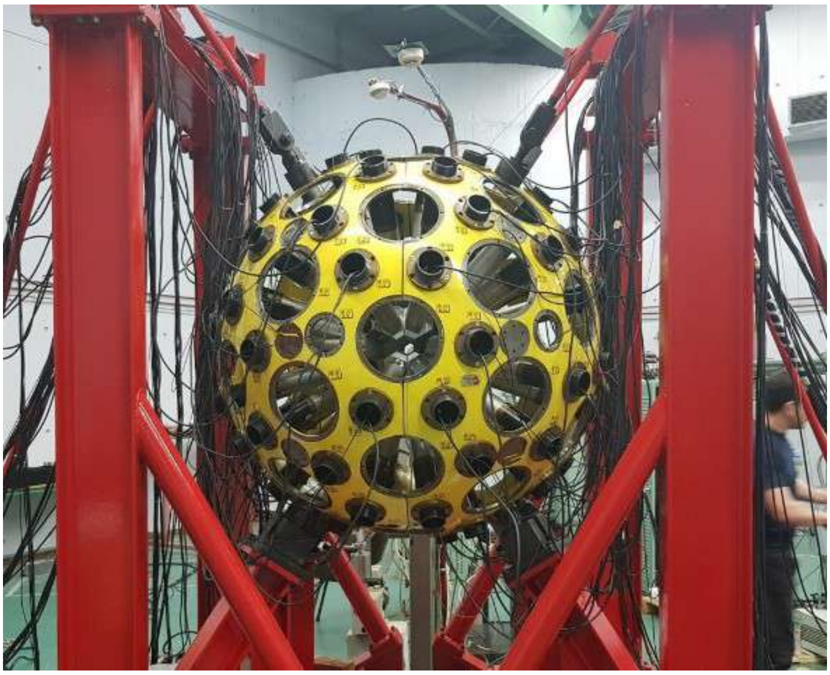

Figure 13.31: The GASPAR BGO Ball.

is used to study radiation damage and recovery in alloys and other fusion relevant materials at well controlled ion fluxes and temperature, from the cryogenic range ($\approx$10 K) up to 700 K by means of a dedicated cryo-cooler. Details are given in [1] and Fig. 13.33.

Nuclear Microprobe: It is a standard micro-beam system purchased by Oxford Microbeams Ltd for the determination of the elemental composition of material surfaces. The arrangement of the different beam defining and focusing elements are shown in Fig. 13.34. The chamber has 22 ports at several angles, where detectors and auxiliary equipment can be attached. It is equipped with a load lock chamber, a microscope just above the chamber entrance with a large focal length and a CCD camera.

External ion beam setup: The setup has an ion-beam exit nozzle covered by a 100-nm-thin

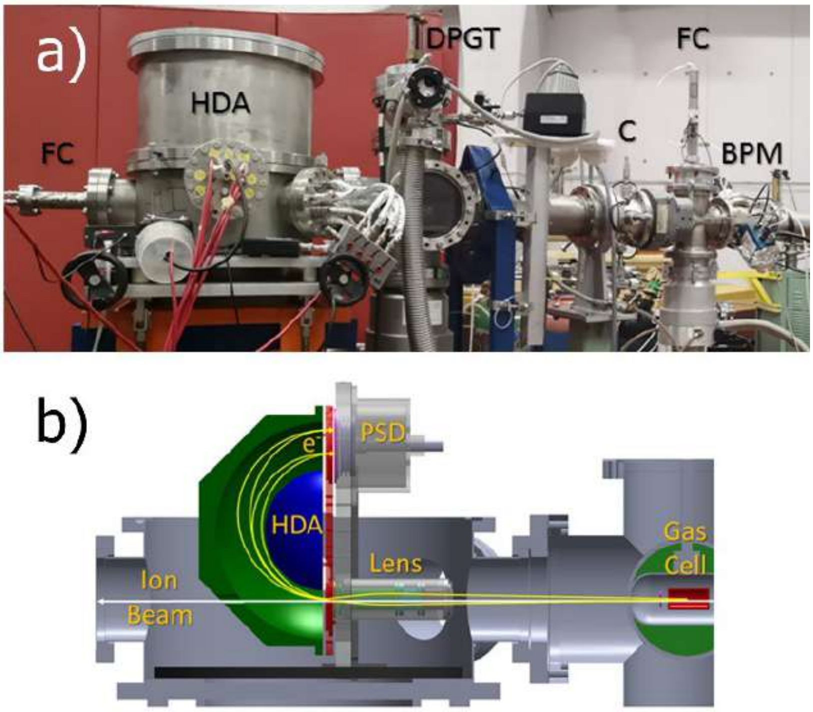

Figure 13.32: The ZAPS beamline.

Si_3N_4 foil. It allows for the detection of X rays with energies down to 1 keV. It is also equipped with a CCD camera, for visual inspection of the sample point under analysis, and lasers for the necessary alignment. The setup was developed to be used with ions heavier than protons.

The setup was recently upgraded to offer fast elemental analysis with a spatial resolution of $\approx$1 mm^2 and examination of large areas on the investigated objects. It is now equipped with state-of-the art Silicon Drift detectors (SDDs) and a fast XYZ motorized stage allowing for the positioning of large objects and scanning over extended areas (several tens of cm^2).

RBS/Channeling setup: RBS and Channeling measurements are performed with the chamber shown in panel a) of Fig. 13.34. It is made of stainless steel and is cylindrically-shaped with a 20-inch diameter. It contains a sample positioning manipulator, which is shown in panel b). A laser (L) mounted outside the chamber is used for the placement of the detectors at the desired scattering angles and for beam alignment. Samples are loaded through a sample loading door (SLD). A glass view port (VP) allows for visual monitoring of the chamber's interior, the sample's translations and rotations and the beam spot's location and shape (see also in [1]).

The laboratory is also equipped with various other instruments including:

- PIXE chamber: Targets are mounted on a rotating disk that can hold up to 16 samples. The disk is manually controlled by an external switch. (See in [1] for details)
- Large-volume universal scattering chamber: It is used for Nuclear Reaction Analysis (NRA), for charged-particle activations as well as for particle-spectroscopy, in general (See also [5]).
- Gas cell: Production of quasi-monochromatic neutrons with the d+D and d+T reactions (see [1] and refs. therein for details).
- HPGe detector array with Anti-Compton Shields: Currently 3 HPGe detectors with 80% rel. efficiency with BGO crystals for Compton background suppression. The array is mounted on a rotating table which can accept at least two more HPGe detectors and their shields.

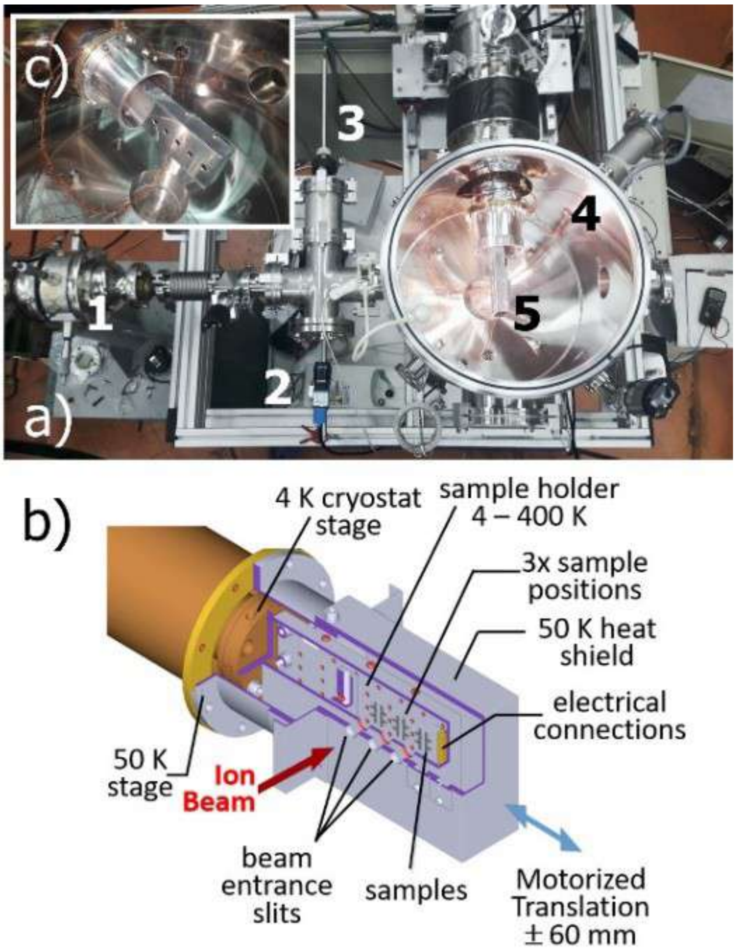

Figure 13.33: The IR2 material irradiation setup. Panel (a) shows: Ta slits (1), CCD camera (2), Faraday cup (3), vacuum chamber (4) and target holder position (5). Panel (b) depicts the individual parts of the target holder that is shown in panel (c).

References

[1] S. Harissopulos et al., Eur. Phys. J. Plus 136, 617 (2021); https://doi.org/10.1140/epjp/s13360-021-01596-5
[2] Sotirios V. Harissopulos, Eur. Phys. J. Plus 133, 332 (2018); https://doi.org/10.1140/epjp/i2018-12185-8
[3] The GASP website: gasp.lnl.infn.it/
[4] The APAPES Home Page apapes.physics.uoc.gr/
[5] V. Foteinou et al., Phys. Rev. C 97, 035806 (2018); https://doi.org/10.1103/PhysRevC.97.035806
[6] CALIBRA Website www.calibra.gr

Program Advisory Committee/experiment proposals

Research proposals can be submitted at any time through the website www.calibra.gr. Beamtime is granted after evaluation by an International Scientific Advisory Committee that meets twice a year. Requests for irradiation and analytical services to state organizations, the private sector, start-ups or funded projects can be addressed by email at any time using calibra@inp.demokritos.gr. Depending on the bulk, nature and necessary duration of the service request, fees may apply.

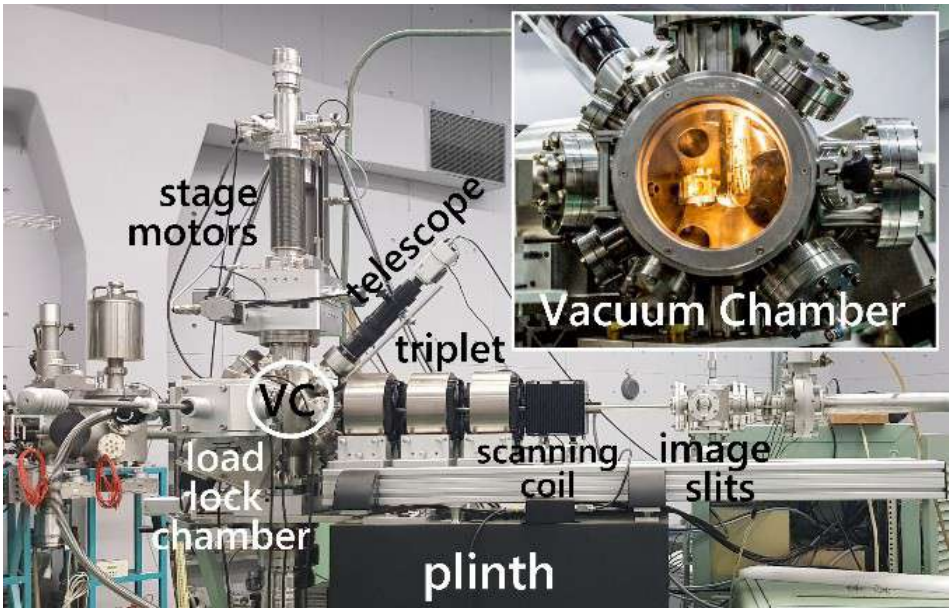

Figure 13.34: (Left) The nuclear microprobe (see also [1]). (Right) : The external ion beam setup.

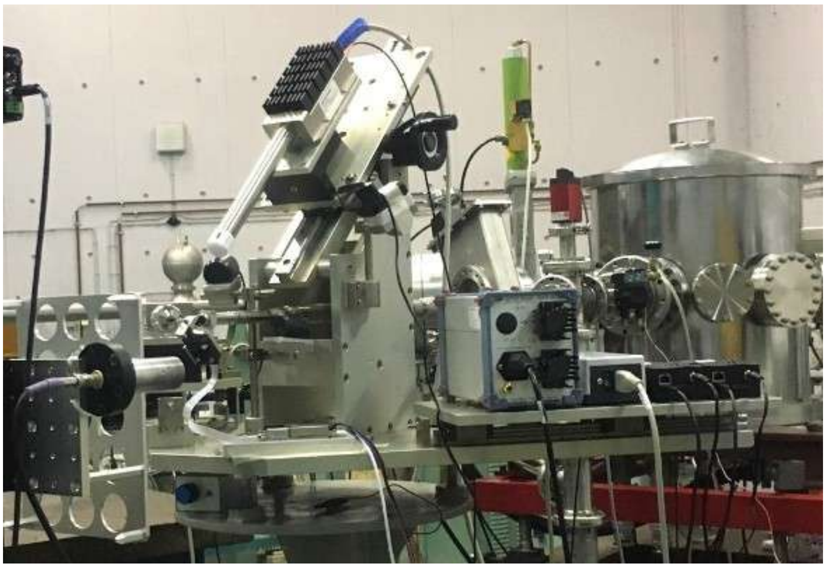

Figure 13.35: The RBS/Channeling chamber and the sample manipulator translations and rotations.

Number of active users and their origin

Well-established user group with 60 users.

Percentage of users, and percentage of facility use that come from inside the institution

15 (25%)

Percentage of users and percentage of facility use from national users

39 (65%)

Percentage of users and percentage of facility use from outside the country where your facility is located

6 (10%)

Laboratory Staff

Table 13.13: Staff at TAL. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	4
Technical staff	3
Postdoctoral researchers	$\sim$4
(Resident) Graduate students	$\sim$4

Future Plans

In 2016, the Tandem laboratory has been included in the National Roadmap for Research infrastructures with the aim to be fully upgraded and establish the CALIBRA Research Infrastructure. CALIBRA stands for "Cluster of Accelerator Laboratories for Ion-Beam Research and Applications" (see in [6] for details). In CALIBRA Phase-1, i.e., by the end of 2022, the existing 5.5 MV Tandem will be completely upgraded as briefly described above. In addition, a 2.5 MV Tandetron for Accelerator Mass Spectrometry, donated by the University of Oxford will be installed. Also, a donated 17 MeV PET Cyclotron, already transferred from Netherlands, will be used to establish a PET radioisotope production laboratory (subject of implementation of CALIBRA's Phase-2).

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Scientific Mission and Research Programs

ATOMKI is one of the research institutes of the Eötvös Loránd Research Network (https://elkh.org/). The Network is a public body and ATOMKI is a public research institution relying on the state budget and on the national and European science funding systems. At present ATOMKI employs 200 persons. In its technologically innovative activity and laboratory services provided to authorities and industry it is in contractual relationship with other public organizations and business firms. The institute was meant to pursue scientific research in certain areas of particle, nuclear and atomic physics and to apply physical methods in other fields.The institute has become the main center of accelerator based sciences in Hungary.

Roughly 80% of the activity goes to basic research. 55% of the research is high energy and nuclear physics, 20% is atomic physics, 20% is environmental physics, 20% material science and 5% is development of techniques and instruments for basic and applied research.

Characterization of the facility

Technical facilities

Atomki Accelerator Center (AAC): The Atomki Accelerator Center is a special unit within the institute incorporating all facilities which deliver ion beams with various range of particle choice, charge, intensity: www.atomki.hu/en/infrastructures/view/1.

In this report these facilities are introduced relating to nuclear physics research or application: Cyclotron (K20), AMS, Tandetron (2 MV).

Isochronous cyclotron (K=20):
For light ions, p, d, ^{3}He, α with intensities of maximum 50 μA. Energies from 3 MeV (p) to 27 MeV for ^{3}He particles. Energy spread of extracted beam: $<3*10^{-3}$ Energy spread of analyzed beam: $<10^{-3}$. External target locations: 8 horizontal, 1 vertical.

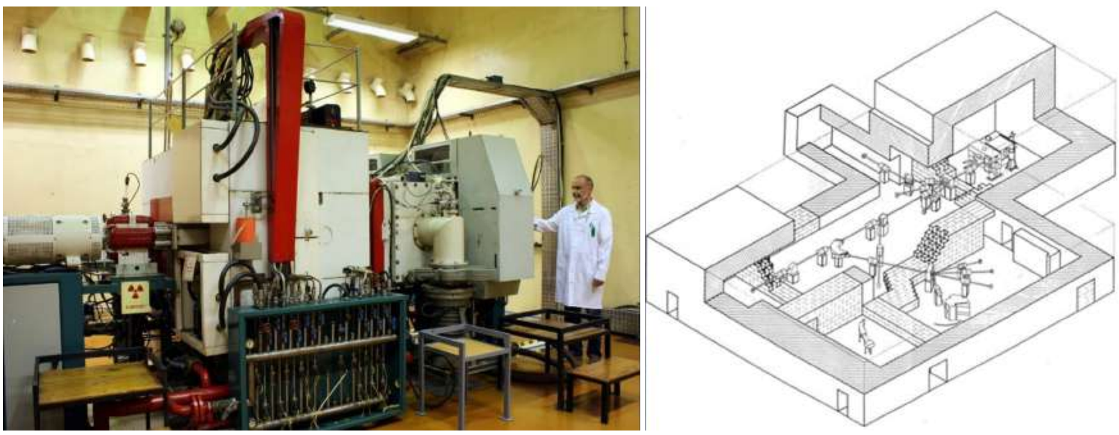

Figure 13.36: Experimental areas at ATOMKI.

Related main facilities: Neutron sources ; B-type radiochemistry laboratory.

Main Instrumentation for Nuclear Physics Experiments: Split-pole magnetic spectrograph. CLOVER-type HPGe detector with BGO anti- Compton shield. Scattering chamber with Si dE-E telescopes. Multidetector array for e+e- spectroscopy. 15-folded $LaBr_3$ array for γ spectroscopy. OBELISK 4π position sensitive, TOF fission detector array. ELENS low-energy neutron spectrometer. Frisch-gridded ionization chambers for (n,f) experiments. Low- pressure, position-sensitive fission detectors (MWPC and GEM counters).

AMS facility:

An accelerator-mass-spectrometry (AMS) facility is operating for ^{14}C measurements and dating from small samples (1–0.01 mg C) at large rate (1 sample an hour) and at large precision (relative error <0.3%).

2 MV Tandetron:

The installation of a 2 MV Tandetron accelerator was completed by HVEE at ATOMKI. The aim of the accelerator is to satisfy the high demand emerged in differentapplications. The machine is a 2.0 MV Medium-Current Plus Tandetron Accelerator System, with main specifications:

- Terminal voltage range: 0.1 – 2.0 MV (max. 2.2)
- Terminal voltage ripple: 25 V RMS
- Terminal voltage stability: ±200 V / hr
- Ion sources: H and He multicusp, cesium sputter for heavy ions
- Beam currents: 200 eμA proton, 40 eμA helium
- Beam energy max (proton): 4 MeV
- 90-degree analysing magnet: 1500 mm radius
- Switching magnet: 9 exit ports

The accelerator provides light ion beams of typically 1-4 MeV to users of atomic physics, nuclear physics, ion beam analysis. The IBA work is performed on various fields ranging from environmental research, through materials science, to biomedical applications.

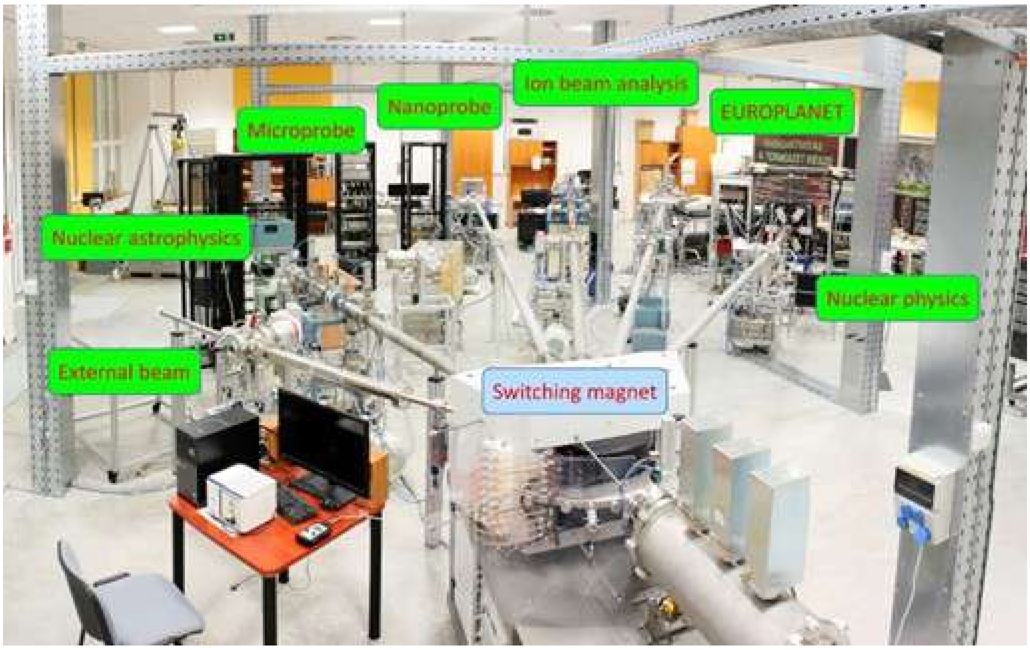

Figure 13.37: Beamlines at ATOMKI.

Major experimental instrumentation and its capabilities

So far seven experimental beamlines have been built. The nuclear physics end station is equipped with an electron-positron pair spectrometer. The nuclear astrophysics end station has various HPGe gamma-ray detectors, and surface barrier Si particle detectors. A scanning nuclear nanoprobe and microprobe include high precision magnetic quadrupole lenses. Detectors: Retractable X-ray detectors with Ultra-Thin Window (UTW) and Be window, particle detection by Si PIPS detectors and PIN diodes, gamma-ray detection by Clover-Ge-BGO detector system. NRA (PIGE/DIGE), external microbeam setup. There is an external milli-beam setup mainly for archaeological and environmental applications.

Nature of user facility

The accelerators and detectors are user facilities.

Program Advisory Committee/experiment proposals

A Program Advisory Committee decides on the experimental proposals: https://www.atomki.hu/en/pac.

Number of active users and their origin

40.

Percentage of users, and percentage of facility use that come from inside the institution

28 (70%)

Percentage of users and percentage of facility use from national users

7 (18%)

Percentage of users and percentage of facility use from outside the country where your facility is located

5 (12%)

Laboratory Staff

Total staff: ∼200; Theoretical staff: 8; Postdoctoral researchers: 3; Graduate students: 4.

Future Plans

In next years the 3rd phase of the Tandetron Laboratory will be realized. Research laboratories and office rooms will be built.

SOREQ APPLIED RESEARCH ACCELERATOR FACILITY (SARAF)

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Scientific Mission and Research Programs

The Soreq Applied Research Accelerator Facility (SARAF), at Soreq Nuclear Research Center, is an Israeli national infrastructure for applied and basic research and training in various areas of nuclear science and engineering. Its high ion current enables generation of high fluxes of fast neutrons, which can be used directly, or be moderated to thermal energies. SARAF was designed to serve as a model for the possible replacement of research reactors by environmentally friendly facilities that do not use fissile materials. Applications at SARAF include: basic neutron-based material, nuclear and particle physics research, radiopharmaceuticals studies, development and production, and non-destructive testing. The construction of the facility, funded by the Israel Atomic Energy Commission (IAEC) and the Israel National R&D Infrastructure Fund (TELEM), began in 2003. SARAF-I operated between 2010 and 2019, and SARAF-II is currently under construction, expected to start delivering beams in 2024.

Characterization of the facility

Major experimental instrumentation and its capabilities

Technical facilities

SARAF-I: The SARAF-I linear accelerator (Fig. 13.38) comprised a 20 keV/u, Electron Cyclotron Resonance (ECR) ion source, a 1.5 MeV/u four-rod Radio-Frequency Quadrupole (RFQ), and a Prototype Superconducting Module (PSM) housing six Half Wave Resonators (HWR). SARAF-I accelerated up to 2 mA continuous wave (CW, 100% duty-factor) protons up to 4 MeV, 10% duty-factor deuterons up to 5.6 MeV, and CW deuterons up to 2.6 MeV. The main high-power irradiation target of SARAF-I was the liquid-lithium target, LiLiT (Fig. 13.39), consisting of a 1.5 mm thick film of liquid lithium jet, force-flown onto a concave thin stainless-steel wall.

LiLiT was used to generate a quasi- Maxwellian neutron flux at epi-thermal energies (10's of keV) and an intensity of 3– 5×10^{10} n/s, by irradiation of 1.9 MeV, 1-2 mA protons on it [2]. A typical neutron spectrum from LiLiT is given in Fig. 13.39. It is a simulation that was benchmarked via experimental data.

Another neutron production target was a solid Lithium Fluoride Thick Target (LiFTiT) (Fig. 13.40), which was irradiated by deuterons to obtain high-energy neutrons.

Neutron-based experiments were mainly performed for measuring Maxwellian averaged cross sections (MACS) of neutron capture on various isotopes that are relevant to the nucleosynthesis s-process [2]. In addition, numerous measurements were performed with direct proton and deuteron beams, mainly cross section measurements via the activation method, and radiation damage studies on various materials.

SARAF-II: This is the extension of SARAF-I to significantly higher energy and current, as detailed in Table 13.41.

SARAF-II will be based on a linear accelerator installed downstream of the ion source and RFQ of SARAF-I, and will include a 5 m long medium energy beam transport (MEBT) and four superconducting modules (Fig. 13.42) [4,5]. The SARAF-II beams will be distributed to several irradiation stations via beam-lines in a target hall, as depicted in Fig. 13.43, and described below.

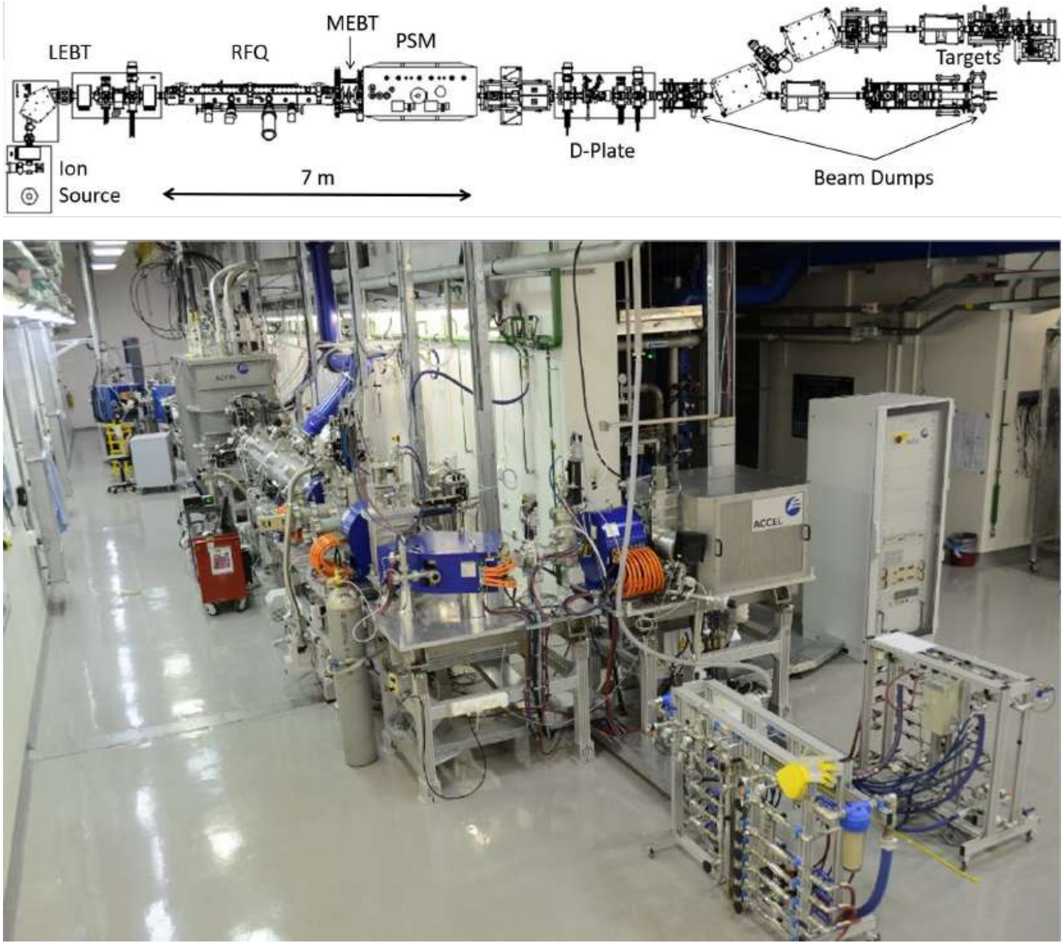

Figure 13.38: Top: Layout of SARAF-I [1]. Bottom: Photo of SARAF-I.

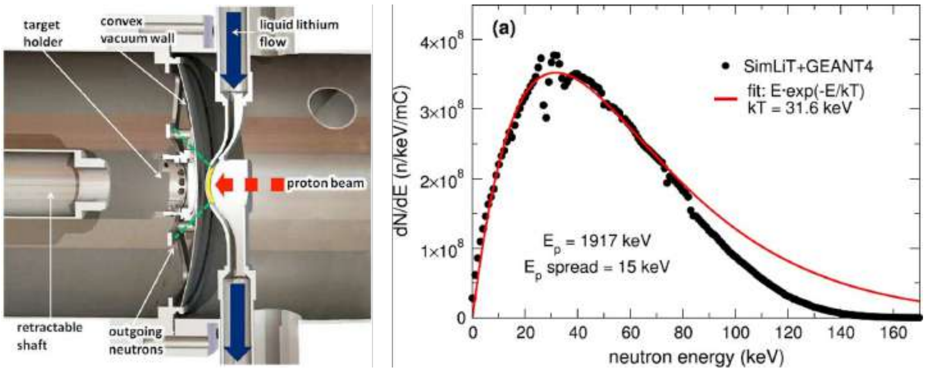

Figure 13.39: (Left) Cross section of LiLiT near the nozzle. The sample to be irradiated by the neutrons is placed at 6 mm from the target [2]. (Right) Typical neutron spectrum from LiLiT [3].

The characteristics of the CW fast neutrons are given in Table 13.44. For SARAF-II high-power targets, we opted for a liquid gallium-indium jet [6], since this compound is liquid at room temperature, it is less hazardous than lithium, and due to its high Z, a 5 mm thick film is enough to contain the 40 MeV deuteron or 35 MeV proton beam. The neutron energy spectrum from GaIn(d,xn) has not been measured, so we estimate it from simulations (see Fig. 13.45).

CW thermal neutrons: The thermal neutron source is designed to enhance and backup the Soreq IRR-1 5 MW research reactor, and as such, will include neutron radiography and diffractometry

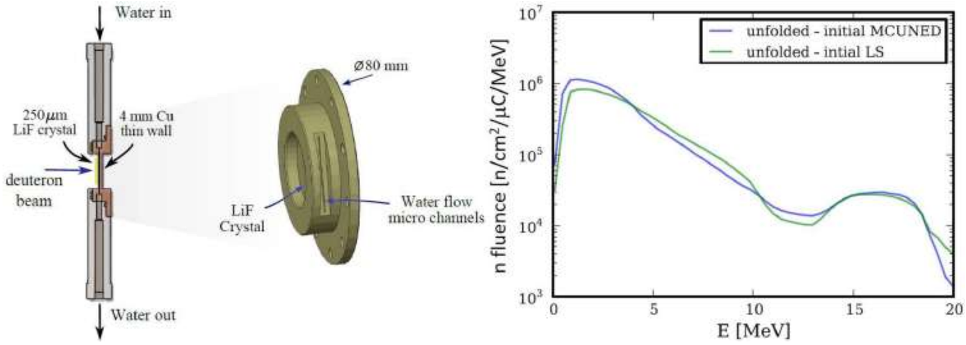

Figure 13.40: (Left) A CAD drawing of LiFTiT. Left: transverse cross section. Right: 3D depiction of the LiF crystal and the copper back [1]. (Right) - Unfolded spectra of LiFTiT by using different initial guess spectra. Spectra are normalized to reflect the neutron spectrum at 6 cm distance from the target [1].

Parameter	Value	Comment
Ion species	Protons/deuterons	$M/q \leq 2$
Energy range	5-40 MeV deuterons 5-35 MeV protons	Variable energy
Current range	0.04-5 mA	CW (and pulsed)
Operation	6000 hours/year	
Maintenance	Hands-on	Low beam loss

Figure 13.41: SARAF-II beam top-level specifications.

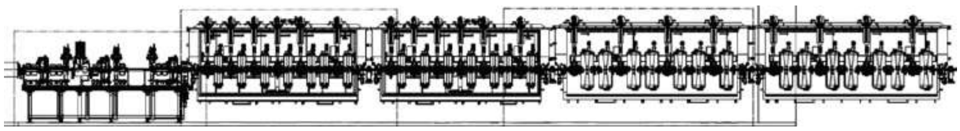

Figure 13.42: Layout of the SARAF-II MEBT and superconducting modules [4]. The ion source and RFQ are to the left of the MEBT, arranged as shown in the Figure before.

stations, as detailed Table 4.

Fast neutrons TOF: In this station we will irradiate solid targets with pulsed ions at various energies, frequencies and pulse lengths, to enable time- of-flight (TOF) applications at a wide range of neutron energies, as detailed in Table 5.

Low power beams: The target area that has been used with SARAF-I will be used also for SARAF-II, but with limited power and neutron rates due to radiation safety constraints. We plan to install there two liquid metal targets, as described in Table 6.

References

[1] I. Mardor et al., Eur. Phys. J. A (2018) 54: 91
[2] M. Paul et al., Eur. Phys. J. A (2019) 55: 44
[3] M. Tessler et al., Phys. Lett. B 751 (2015) 418–422
[4] N. Pichoff et al., Proceedings of IPAC2017, Copenhagen, Denmark, TUPVA052 (2017)
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[6] I. Eliyahu et al., UCANS-8, Paris 2019, www-llb.cea.fr/UCANS8-2019/Eliyahu_poster.pdf

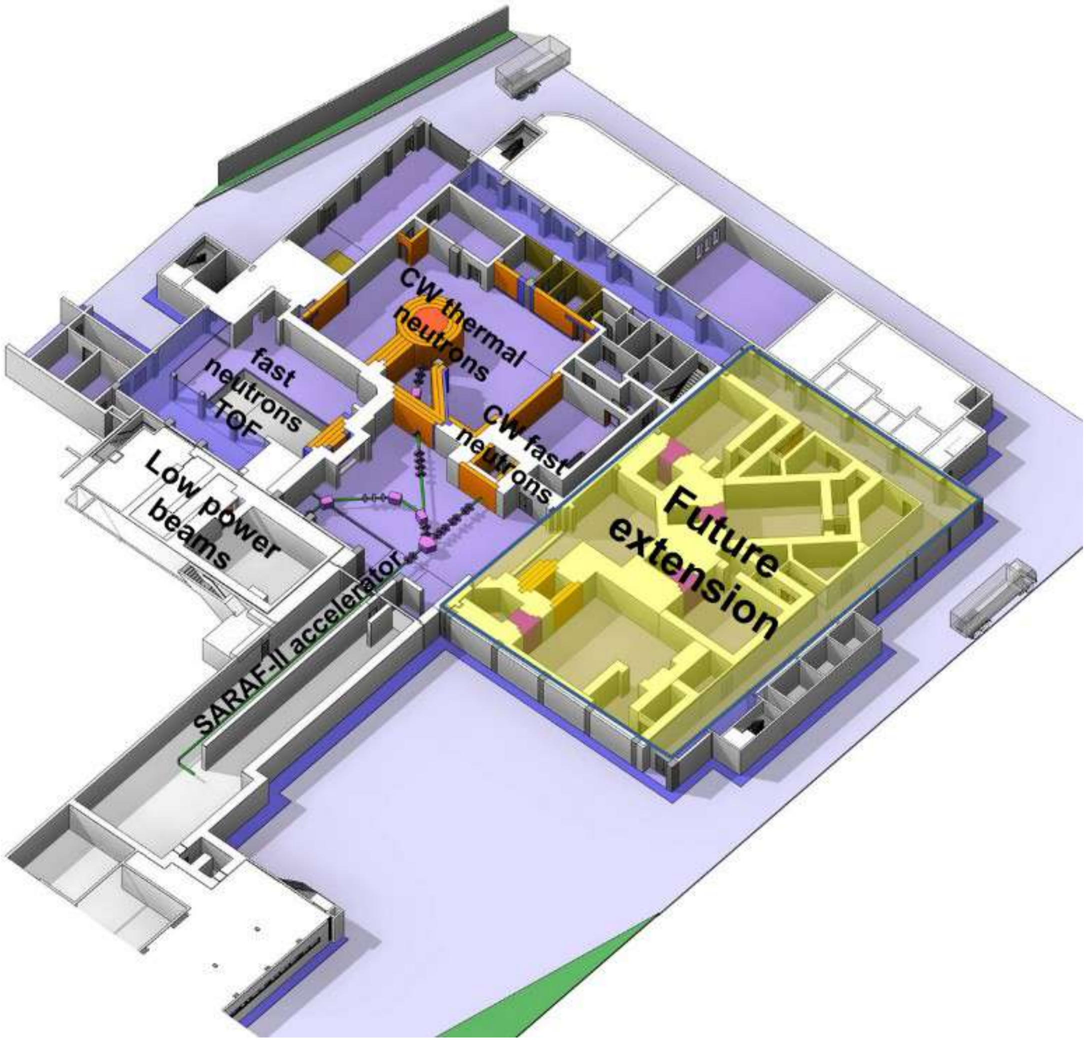

Figure 13.43: Layout of the SARAF-II target hall. The four irradiation areas are described in the text. The yellow-highlighted part is a future extension that is not built yet.

Target	Liquid gallium-indium jet
Beam power	200 kW CW (5 mA · 40 MeV)
Maximal n yield	~1.3×10^{15} n/sec

Figure 13.44: CW fast neutron characteristics.

[7] A. Shor et al., Phys. Rev. Acc. Beams 22, 020403 (2019)

Number of active users and their origin
35 informal users.

Percentage of users, and percentage of facility use that come from inside the institution
12 (34%)

Percentage of users and percentage of facility use from national users
15 (43%)

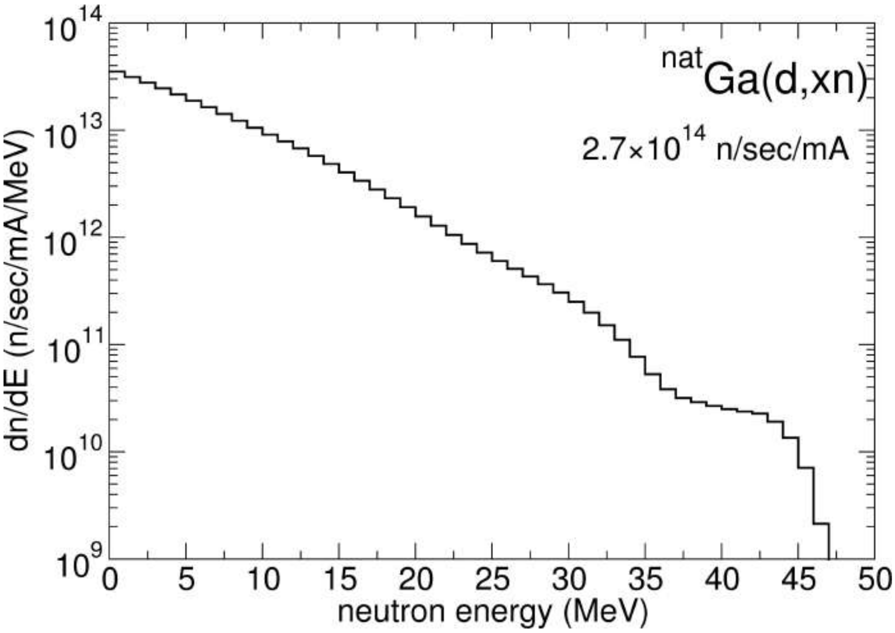

Figure 13.45: Simulated neutron energy spectrum from natGa, the main component (more than 80% of the atoms) of the liquid GaIn target, when irradiated by 40 MeV deuterons. The energy-integrated neutron rate per mA of deuterons is given within the plot. We assume only an S-wave contribution, which is considered the dominant component.

Target	Liquid gallium-indium jet
Moderator	Light water
Reflector	Beryllium and polyethylene
Beam power	200 kW CW (5 mA · 40 MeV)
Thermal camera flux	4×10^5 n/cm^2/sec at L/D=250
Diffractometer	$\sim10^6$ n/cm^2/sec at exit port
Internal irradiation station	Via pneumatic transfer, $\sim10^{12}$ n/cm^2/sec
Development port	$\sim10^6$ n/cm^2/sec at exit port

Figure 13.46: CW fast neutron characteristics.

Percentage of users and percentage of facility use from outside the country where your facility is located

8 (23%)

Laboratory Staff

Theoretical staff: 0; Post-doctoral researchers: 4.

Future Plans

SARAF-II is planned to become operational during 2024. In addition to the target stations described above, we plan to develop also target stations for isotope production and radiation damage studies via ion beams. Furthermore, there are plans to develop fission product generation at the CW fast-neutron station, by irradiation of thin natural actinide targets inside a stopping cell. This could provide 1010 fissions/s, with a separated 132Sn intensity of 106/s. SARAF-II is intended to be

Targets	Solid Li or LiF
Average beam power	Up to 200W (DC~10^{-3}) (5mA· 40MeV)
Beam structure	Down to 1 nsec bunches at 200 kHz [7]
Neutron flight path length	18 m
Epithermal neutrons	
Moderator	Polyethylene
Neutron flux	10^4 n/cm^2/sec 10 m from target
Fast neutrons – 'white' spectrum	
Target thickness	'Thick' target (~25 mm)
Neutron rate at target	~10^{12} n/sec
Fast neutrons – quasi-mono-energetic	
Target thickness	1.5 mm
Ion beam	Protons up to ~30 MeV
Neutron spectrum	Ion beam energy ± 1 MeV (with low energy tail)
Neutron flux	~10^{10} n/sec/sr

Figure 13.47: Pulsed neutrons characteristics.

Liquid lithium jet target (LiLiT 2.0)	
Maximal beam power	10 kW
Target thickness	1.5 mm (for p/d of a few MeV)
Epithermal neutron rate	10^{10} n/sec at 10's keV
Fast neutron rate	10^{12} n/sec at a few MeV
Liquid gallium-indium jet (low power demonstrator)	
Maximal beam power	15 kW
Target thickness	5.0 mm (for p/d up to 35/40 MeV)
Fast neutron rate	3×10^{13} n/sec (spectrum of Fig. 8)

Figure 13.48: Low power neutrons characteristics.

operated as an international user facility, where the beam time will be allocated based on scientific merit by a program advisory committee, and the number of external users is expected to increase significantly. More details about the results of SARAF-I and the plans for SARAF-II can be found in [1] and references therein.

EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS (ECT*)

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Local funding (Fondazione Bruno Kessler), European contracts,
funding through international agencies, EU Horizon funding

Scientific Mission and Research Programs

ECT* is a unique centre in Europe bringing together the scientific community in theoretical nuclear physics and related areas, in the broadest possible sense. It offers an annual schedule of workshops and training programmes and runs a visitor programme. ECT* hosts a research group in nuclear and computational physics, with permanent, postdoctoral and student researchers and is an institutional member of the ESF Committee NuPECC.

Facilities

ECT* is based in two buildings: Villa Tambosi and the Rustico; with two conference rooms (capacities of 40 and 80) and ample desk space for visitors and workshop participants. The ECT* administrative staff finds accommodation for visiting scientists and postdoc researchers in local hotels, apartments and university residences.

Program Advisory Committee

The ECT* Scientific Board is composed of members proposed by the scientific community. Its current composition is U. Wiedemann (chair), A. Arcones, C. Alexandrou, C. Barbieri, A. Corsi, D. Kaplan, D. Lacroix, M. Lewitowicz, B. Pasquini and S. Stringari and V. Braguta (both ex-officio).

Activities

- Workshops and collaboration meetings.
- Doctoral Training Programme and TALENT school.
- Positions for postdocs, PhD students and visiting scientists.
- In-house library, access to Physics Department facilities (via MoU).

Main Fields of Research

Nuclear theory, Quantum Chromodynamics, hadron physics, strongly interacting matter under extreme conditions, nuclear astrophysics, high-energy heavy- ion reactions, hadron therapy, computational physics.

Other Research in related areas: Particle physics, astrophysics, condensed matter physics, quantum information and quantum technology, machine learning.

Number of active users and their origin

800 users per year, from around the world, with the bulk of visitors coming from Europe and the USA.

User group

Users: approx. 800 per year. Associates: approx. 640.

Staff

See Table 13.14.

Table 13.14: Staff at ECT* Trento.

Designation	Number of persons
Permanent staff (Research)	5
Permanent staff (Admin)	4
Fixed term (Director)	1
Postdoctoral researchers	4
(Resident) Graduate students	2

Special student programs

Graduate students are resident at ECT* during the annual Doctoral Training Programme (duration between 3 and 6 weeks, between 15 and 40 students), and the TALENT school (every other year, duration 2 weeks, approximately 30 students).

ECT* is a research centre, with no access to undergraduate student

ISTITUTO NAZIONALE DI FISICA NUCLEARE LABORATORI NAZIONALI DEL GRAN SASSO (INFN-LNGS)

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INFN - Government Institution
President Prof. Antonio Zoccoli

Scientific Mission and Research Programs

The Gran Sasso National Laboratory (LNGS) is one of the four INFN national laboratories. It is the largest underground laboratory in the world for experiments in particle physics, particle astrophysics and nuclear astrophysics. The mission of LNGS is to host experiments that require a low background environment in the field of astroparticle physics, nuclear astrophysics and other disciplines that can profit of its characteristics and of its infrastructures.

LNGS is a worldwide facility with about 1000 scientists, from 29 countries, working at about 20 experiments in their different phases. The scientific leadership of LNGS in many research fields (neutrino physics, dark matter search, rare decays, nuclear astrophysics) is internationally acknowledged.

Characterization of the facility

Both the external as well as the underground structures of the Gran Sasso National Laboratory are located inside the so-called Gran Sasso and Monti della Laga National Park. The headquarters and the support facilities, among which offices, different services, library and canteen, are located in the external building.

The underground facilities are on one side of the 10-kilometer-long highway tunnel that crosses the Gran Sasso massif (towards Rome). The underground complex consists of three experimental halls (each 100 m long, 20 m large and 18 m high) and bypass tunnels, for a total volume of about 180.000 cubic meters. The average 1400 m rock coverage gives a reduction factor of one million in the cosmic ray flux; moreover, the neutron flux is thousand times less than on the surface, thanks to the smallness of the Uranium and Thorium content of the dolomite rocks of the mountain.

While LNGS research activities range from neutrino physics to dark matter, and also to earth physics, biology and fundamental physics in the following focus will be towards the possibilities LNGS offers for Nuclear Physics research.

Major experimental instrumentation and its capabilities

The underground laboratories hosts two electrostatic Singletron® accelerators constructed by High Voltage Engineering: LUNA-400, which can deliver proton and ^{4}He beams with beam energies between 50 and 400 keV, and LUNA-MV, which is expected to get to operation by the end of 2022. During the acceptance tests at the factory of HVEE it has been shown that LUNA-MV can produce intense Proton, Helium and Carbon beams. Their parameters can be found in Table 13.15.

STELLA Low Background Laboratory

Table 13.15: LUNA-400 and LUNA-MV accelerators.

LUNA 400		
Beam	Energy	Intensity
H^+	50-400 keV	$\leq 500\ \mu A$
$^4He^+$	50-400 keV	$\leq 200\ \mu A$

LUNA MV		
Beam	Energy	Intensity
H^+	0.35- 3.5 MeV	$\leq 1000\ \mu A$
$^4He^+$	0.35- 3.5 MeV	$\leq 500\ \mu A$
$^{12,13}C^+$	1- 7 MeV	$\leq 150\ \mu A$
$^{12,13}C^{2+}$	1- 7 MeV	$\leq 100\ e\mu A$

STELLA (SubTerranean Low Level Assay) is operated by the LNGS Service for Special Techniques and allows to perform ultra-low background γ-ray spectroscopy with specially designed high purity Germanium detectors, α spectroscopy with silicon PIPS detectors, and α/β spectroscopy with liquid scintillation counters. The main activities carried out in the facility are γ-ray spectrometry, β and α-particle measurements of materials used in the various experimental activities of the LNGS.

ICP-MS Laboratory
The Service for Chemistry and Chemical Plant operates an inorganic mass spectrometry laboratory equipped with a double focusing spectrometer (High Resolution) and a last generation conventional quadrupole-based mass spectrometer. The facility is mainly dedicated to the screening of radio-pure materials to be used in detectors for rare event physics experiments. A thermal ionization multi-collector instrument is specific for isotopes ratio measurement.

Additive Manufacturing Laboratory
The Mechanics Service of LNGS is equipped with an Additive Manufacturing (AM) Laboratory focused on design of Hi-Res complex devices for both nuclear/astro-particle physics research and industrial technology transfer. The Service is equipped with plastic and metal AM machines (i.e. Selective Laser Melting – SLM) and can perform quality analysis of produced components by means 3D scanner, optical microscope, and automated profilometer. The design for AM is done with dedicated Computer Aided Design (CAD) and finite elements software (i.e. topology optimization, SLM process simulation, etc.).

Program Advisory Committee/experiment proposals

Concerning the accelerator facilities, LNGS has a Program Advisory Committee with 1 national and 2 foreign members.

Number of active users and their origin

45.

Percentage of users, and percentage of facility use that come from inside the institution Percentage of users and percentage of facility use from national users

National users 73%; Facility use by national users 73%.

Percentage of users and percentage of facility use from outside the country where your facility is located

27%.

Fraction of the international users from outside your geographical region

0%

Laboratory Staff

Table 13.16: Staff at the LNGS accelerators. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Total laboratory staff	2
Scientific staff	1
Postdoctoral researchers	35
(Resident) Graduate students	1
(Non-Resident) Graduate students	3*
Undergraduate students	3

Special student programs

No.

Future Plans

Refurbishment and upgrade of the LUNA-400 accelerator.
Increase of the LNGS scientific staff for nuclear astrophysics.
New target station and DAQ available for the accelerator users.

ISTITUTO NAZIONALE DI FISICA NUCLEARE LABORATORI NAZIONALI DEL SUD (INFN-LNS)

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Director: Dott. Santo Gammino
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Designated Contact: Prof. Aurora Tumino
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Government Institution Government funds
President: Prof. Antonio Zoccoli

Scientific Mission and Research Programs

The scientific mission of the LNS is mainly the study of nuclear reactions at low and intermediate energies. Research activity in several multi- disciplinary (i.e. non-nuclear) fields is also strategic. The current research program in nuclear physics is carried out with large detector systems (4π multi- detector systems for the intermediate energy case) and a magnetic spectrometer with large acceptance both in solid angle and in momentum. The LNS are an advanced technological pole for development of different types of instrumentation, acceleration systems and ion sources. The current interdisciplinary research program concerns with studies on Atomic Physics, Solid State Physics, Single Event Effects, Biology and Medicine, Cultural Heritage, Nuclear Waste monitoring, Dosimetry. Importantly, the proton- therapy program started in 2002 as a clinical activity with a beam line (CATANA) dedicated to the treatment of eye melanoma using the 62 MeV proton beam delivered by the cyclotron.

Currently and until 2023 the activity with ion beams is stopped, because of the upgrade of the superconducting cyclotron and of most of the beam lines, in the framework of the POTLNS project. The goal is to increase the beam power up to about 10kW and to develop a new in-flight fragment separator, with improved resolving power compared to the previous.

In addition to the usual activities with the stable beams, there are several ongoing research programs:

- A research program aimed to determine the NUclear Matrix Element of Neutrinoless (NUMEN) double beta decays by measuring heavy ion double charge exchange reactions;
- a research program in the field of astroparticle physics, foreseeing the completion of the KM3NeT/ARCA deep under sea telescope to detect high-energy cosmic neutrinos from point-like sources as well as in a diffuse flux;
- the research project PANDORA, which aims to carry out measurement of β decays in plasmas of astrophysical relevance, and to measure the opacities of plasmas of astrophysical interest (Kilonovae ejecta);
- the research project BCT (Breast Cancer Therapy), which involves the installation and commissioning of an ultra-short pulse power laser (200 TW, 25 fs) for the generation of ion and electron beams aimed at radiobiological and preclinical radiation studies.
- the research project I_LUCE (INFN Laser IndUCEd particle acceleration), which will make available to the community the new laser-driven electron, gamma and ion beams for nuclear and multidisciplinary applications.

Figure 13.49: Aerial view of LNS.

Characterization of the facility

LNS hosts two accelerators, the Tandem MP and the superconducting Cyclotron that can deliver light and heavy-ion beams in the regions of low and medium energy. In June 2020, the accelerators have been turned off to start the upgrade of the entire infrastructure, mainly aimed at the production of high intensity light ion beams (power up to 10 kW) accelerated with the Superconducting Cyclotron.

FRAISE: a facility that will produce tagged secondary radioactive ion beams by in-flight fragmentation of the cyclotron primary beams.

Catana: a beam line dedicated to the treatment of eye melanoma using the 62 MeV proton beam delivered by cyclotron.

Facility parameters

Cyclotron beams can be delivered with timing characteristics: peak width 1 ns FWHM and inter-burst distance 120-150 ns. LNS have two additional separate branches devoted to the realization of an undersea neutrino telescope: one, located at the port of Catania, mostly used for assembling and temporary location of systems and apparata of the infrastructure KM3, the other one, located in Portopalo di Capopassero, is the station for acquisition of data traveling from undersea detectors through an electro-optical cable.

Major experimental instrumentation and its capabilities

- CHIMERA: a 4π charged particle detector, consisting of 1200 (Si + CsI) telescopes. The ancillary FARCOS array is underway with 20 triple telescopes. A plastic scintillator system will be used to detect neutrons.
- MAGNEX: large solid angle and large momentum acceptance spectrometer. In the updated configuration it includes a new focal plane detector and a calorimeter for the detection of γ rays.
- ASTRHO: Array of double-sided silicon strip detectors (DSSSD), each of 48×48 mm2 active area

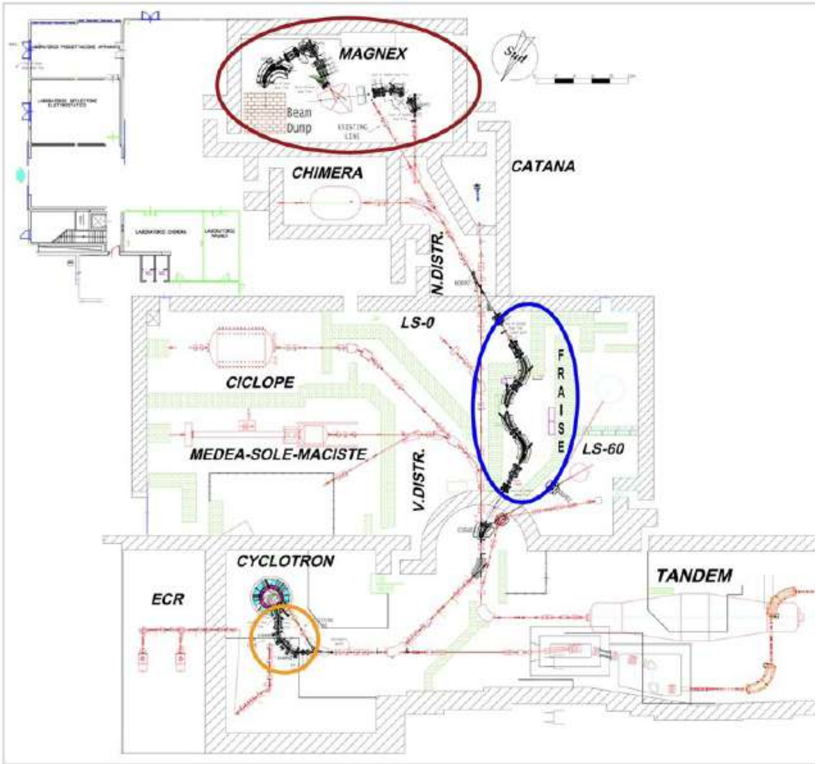

Figure 13.50: Schematic layout of LNS beamlines.

- POLYFEMO: 4π thermalization neutron counter with 12 cylindrical proportional counters filled with 3He, embedded into a polyethylene moderator.
- BaF_2 crystal ball of 180 elements for γ and light particle detection
- CICLOPE to be updated: a cylindrical (4 m diameter, 6 m long) multipurpose scattering chamber designed for intermediate energy experiments.
- CT 2000: a 2m diameter multipurpose scattering chamber especially suitable for low energy experiments.

Nature of user facility

Yes, LNS is a user facility

Program Advisory Committee/experiment proposals

The facility has a Program Advisory Committee which meets at least once per year. The PAC consists of 2 national and 5 foreign members.

Number of active users and their origin

400 (before Covid pandemic). This is the number of people who participated in experiments based on the access cards.

Percentage of users and percentage of facility use from national users

National users 64%, facility used by national users 70%

Percentage of users and percentage of facility use from outside the country where your facility is located

Foreign users 36%, facility use 30%.

Beam	**Energy Range (AMeV)** Tandem	Cyclotron	**Intensity**
Protons	4-28	30-80	<1 pA – 1 μA
Deuterons	2-14	45-80	<1 pA –1 μA
He	-	10-80	<1 pA – 0.3 μA
^{6,7}Li, ^{9}Be, ^{10,11}B	1.5-8	8-55	<1 pA – 0.3 μA
^{12,13}C, ^{14,15}N,	1-8	20-80	<1 pA – 90 μA
^{16,17,18}O, ^{19}F	0.8-8	20-80	<1 pA –80 μA
^{20}Ne, ^{24}Ma		10-62	<1 pA – 85 μA
^{27}Al, ^{32}S,	0.9 – 6.5	10-50	<1 pA – 10 nA
^{34}S, ^{35,37}Cl	0.9 – 6.9		<1 pA – 10 nA
^{36,40}Ar		10-45	<1 pA – 70 μA
^{40,48}Ca	1-4	10-40	<1 pA – 5 nA
^{58,60,62,64}Ni	0.5-3	15-45	<1 pA – 5 nA
^{63,65}Cu	0.7 – 5		<1 pA – 5 nA
^{93}Nb	0.5-1.5	15-40	<1 pA – 5 nA
^{112,116,120,124}Sn	0.3-1.5	15-43.5	<1 pA – 3 nA
^{124,127}Xe, ^{168}Er		10-40	<1 pA – 3 nA
^{197}Au	0.3-1	10-25	<1 pA – 3 nA
^{208}Pb		10-25	<1 pA – 3 nA

Figure 13.51: LNS facility parameters. In red the foreseen intensities after the cyclotron upgrade are indicated.

Fraction of the international users from outside your geographical region

14%.

User group

No.

Laboratory Staff

Special student programs

The Laboratory is involved in many training activities:

- The European Summer School on Experimental Nuclear Astrophysics (biennial), 30 students from all over the world;
- Course on Timing techniques in Nuclear Physics (every year) with an experiment at the tandem accelerator for PhD students, 10 students;
- Thesis proposals day for undergraduate students;
- Open doors for high school students, one week per year (about 3000 students per year).

Table 13.17: Staff at INFN LNS. *All categories. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Total staff*	140
Scientists	21
Scientists (theory)	3
Postdoctoral researchers (theory)	4
(Resident) Graduate students (theory)	4
Postdoctoral researchers (experiment)	16
(Resident) Graduate students (experiment)	∼18/ year
(Non-Resident) Graduate students	∼3**
Undergraduate students	∼16/ year

Future Plans

A growing activity in the accelerator field as well as in collateral activities is in progress, in particular:

- the installation of the new fragment separator FRAISE for production of in-flight high-quality radioactive beams, and the upgrade of the MAGNEX experimental apparatus for the NUMEN experiment;
- the availability of the new NESTOR ion source that will allow to accelerate beams of noble elements with the Tandem MP;
- well established nuclear physics and nuclear astrophysics activity, covering several topics: the equation of state of nuclear matter and the role of symmetry energy, the influence and role of isospin and clustering, the spectroscopy of light nuclei around the neutron dripline, the single and double charge-exchange reactions, the stellar and primordial nucleosynthesis and energetics with indirect methods, such as the Trojan Horse Method and the Asymptotic Normalization Coefficient;
- A second Advanced Ion Source for HAdron therapy (AISHA) is presently under construction for the INSPIRIT project at CNAO, Pavia;
- the installation and commissioning of an ultra-short pulse power laser (200 TW, 25 fs) for the generation of ion and electron beams aimed at radiobiological and preclinical radiation studies (BCT) and I-LUCE with the new laser-driven electron, gamma and ion beams for nuclear and multidisciplinary applications;
- As for the KM3Net/ARCA activity, 10 detection units and two Junction Boxes (the power and optical fiber distribution units) are expected to be deployed from the Capo Passero site next spring, bringing the total number of deepsea strings to around 20. Other strings will be deployed during the marine campaign scheduled for next autumn, thus reaching the completion of just over 1/4 of the first block;
- In the framework of the IDMAR infrastructure (PO- Fesr 2014-2020), by the end of the year 2023, the Cable Termination Frame and the Medium Voltage Converter will be installed on the seabed and connected to the IDMAR cable, making the bottom network for the connection of the first half of the telescope (115 detection units) operational;
- as for the PANDORA activity, 16 HPGe detectors (GALILEO) will be brought from LNL to LNS in the course of 2023 and in the meantime the transfer of know-how and specific expertise on the operation, maintenance and management of germanium detectors, including the setting up of a special laboratory at the LNS already in the design phase, will be carried out. Among the activities to define the next steps: study of expected abundances and constraints in AGB stars for some isotopes of interest for PANDORA; experimental study on the normal

conductive trap of ATOMKI-Debrecen, of magnetic confinement and turbulence in plasma; definition of the analysis algorithm for X imaging and space-resolved spectroscopy.

ISTITUTO NAZIONALE DI FISICA NUCLEARE LABORATORI NAZIONALI DI FRASCATI (INFN-LNF)

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Scientific Mission and Research Programs

The Frascati National Laboratory is the largest and the oldest laboratory of INFN whose peculiarity is the long and consolidated experience in the construction of accelerators. At present two facilities are in operation: the DAΦNE complex, an e^+e^- Φ factory, and the SPARC linear accelerator, a high brightness electron beam able to drive a self- amplified spontaneous free-electron laser (SASE-FEL). Other on site activities regard particle detector development and research with synchrotron light.

Characterization of the facility

- DAΦNE: e^+e^- storage ring, 10-20 MeV c.m. energy, luminosity $5 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$, circumference 97.69 m, maximum current 5 A, number of bunches 1 - 120.
- Beam Test Facility (BTF): e^+/e^- beam line for detector calibration purposes, energy range 25-750 MeV, max repetition rate 50 Hz, intensity $1\text{-}10^{10}$ particles/pulse, pulse duration 1 - 10 ns.
- DAΦNE-Light: four beamlines are operational using, in parasitic and dedicated mode, the intense photon emission of DAΦNE, ultraviolet and soft X-ray region (5-1000 eV).
- SPARC_LAB : facility based on the combination of high brightness electron beams with high intensity ultra-short laser pulse.

Major experimental instrumentation and its capabilities

Main Instrumentation for Particle Physics Experiments: PADME experiment.
Main Fields of Particle Physics Research: Dark Photon searches.
Main Instrumentation for Nuclear Physics Experiments: SIDDHARTA-2 setup.
Main Fields of Nuclear Research:
Low energy K^--nucleus interaction
Kaonic atoms study.
Other Fields of Research:
Research with synchrotron light.
Theoretical physics.
Accelerator physics.
FEL research.
Detector development.

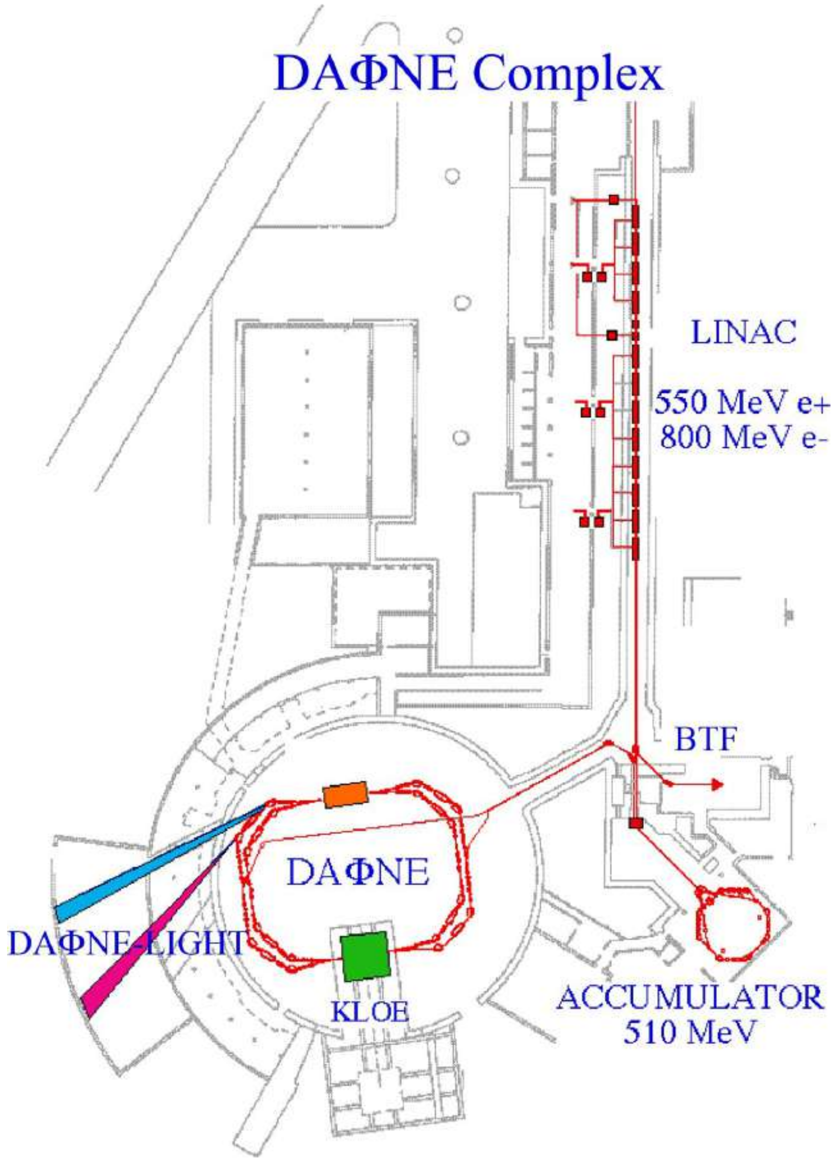

Figure 13.52: Picture of the DAΦNE complex.

Nature of user facility

To apply for beamtime, ask contact persons, or for BTF follow instructions at www.lnf.infn.it/acceleratori/btf/request.html. For DAΦNE-Light instructions are available at https://web2.infn.it/Dafne_Light/index.php/how-to-apply.

Program Advisory Committee/experiment proposals

LNF Scientific Committee has 1 in-house and 8 international members: www.lnf.infn.it/committee/

Special student programs

LNF hosts many initiatives for students, teachers and general public. The program of the fortcoming activities is available here: edu.lnf.infn.it.

Figure 13.53: Beamline at LNF.

Future Plans

In the next years research at DAΦNE will continue for the completion of the SIDDHARTA-2 and of the PADME experiments. Both experiments have collected data in 2020-2021 and are programmed to run up to the end of 2023. A second beam line of the BTF facility has been recently installed and will become operative within 2022.

The SPARC facility will continue experiments on plasma acceleration, for which recently it has obtained the first evidence of FEL lasing induced by an electron beam accelerated by a plasma module. This result is very important since it demonstrates the technical feasibility of the next generation machine which is currently in the design phase, EUPRAXIA@SPARC_LAB. This is part of an ambitious international project, which has been recently approved for insertion in the ESFRI Roadmap. It will become the first photon source available to users, based on plasma acceleration. It is expected to start operations by year 2029.

The KLOE spectrometer will be dismantled and eventually shipped to the USA, at the Fermi National Laboratory, where it will be used as a part of the near detector for the DUNE neutrino experiment.

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Government Institution Funding for construction – INFN
Funding for operation – INFN
Instrumentation & Developments – INFN, grants from the Ministry of University & Research and EU programs

Scientific Mission and Research Programs

The mission of LNL is the research in the fields of nuclear physics and astrophysics, together with the development of technologies relevant to these disciplines. Indeed, experimental activities are continuously supported by intense R&D programs covering accelerator, radiation and particle detector forefront technologies. Moreover, the impact of nuclear methods and techniques on interdisciplinary activities is getting every year stronger. LNL is a European Large Scale Facility providing transnational access to its research infrastructures.

The current main research programs for nuclear physics and astrophysics are:

- Structure of neutron–rich nuclei populated by binary reactions, shell and shape evolution.
- Nuclear structure at high spins, neutron-deficient nuclei and superdeformation.
- Fusion and grazing collisions around and below the Coulomb barrier.
- Fission and quasi–fission dynamics with heavy- ion beams.
- Nuclear structure at high excitation energy (giant resonances).
- Nuclear reactions of astrophysical interest induced by light ions and neutrons.
- Clustering processes in light nuclei.

The main interdisciplinary activities concern:

- Development and production of novel radioiso- topes for medicine and applied physics.
- Production and characterization of targets for precision cross section measurements.
- Elemental microanalysis, using nuclear techni- ques with applications to material, earth and environmental sciences as well as cultural heritage.
- Single ion irradiation of low-D materials for quantum technology applications.
- Development of surface treatments and coatings with application in the fields of detectors, accelerator and industry.
- Study of radiation damage of materials and devices.
- Biophysics, medical physics, microdosimetry.
- Material physics.

In the field of accelerator technologies, the main commitments of LNL are the construction and test of the Drift Tube Linac (DTL) for the European Spallation Source (ESS) in Lund (Sweden) and the conclusion of IFMIF RFQ commissioning in Rokkasho (Japan).

The ISOL facility SPES dedicated to the production and reacceleration of radioactive ion beams (RIB) is presently being completed.

Characterization of the facility

The present basic research facilities operating at LNL are:
The **Tandem-ALPI-PIAVE** complex (TAP), consisting of the XTU Tandem accelerator with a maximum terminal voltage of 15 MV, the super- conducting Linacs ALPI and the SC injector PIAVE, mainly dedicated to nuclear physics and nuclear astrophysics experiments.
Two **Van de Graaff accelerators**, the CN (7 MV) and AN2000 (2 MV), mainly used for applications of nuclear techniques to environment, material science and cultural heritage, detector test and biomedical physics.
The high-current **cyclotron B70** able to produce proton beams with final energies varying from 35 to 70 MeV and maximum intensity of 750 μA. Proton beams are delivered on target systems of several types for the production of radioactive ion beams for fundamental physics, radionuclides of medical interest and neutron sources.
The **ISOL facility SPES**, which will come into operation, at the beginning of 2023 with the first low- energy exotic beams, based on the high intensity cyclotron B70. Fission fragments, produced by the 70 MeV proton beam impinging on a UCx target, are selectively ionized and, after mass analysis, reaccelerated using the Linac ALPI.
The **Material Science Laboratory** for Nuclear Physics, scanning electron microscope (SEM), sputtering systems for solid state and applied physics.
The **Surface Technologies and Superconductivity Service**, dedicated to surface treatments and material coatings, including chemical and cryogenic laboratories, a clean room, a radiofrequency magnetron sputtering system, and instrumentation for thin films characterization.
The **Legnaro-Padova Tier-2 Data Centre** serving mainly the ALICE and CMS LHC experiments together with a Business continuity service for INFN.

Figure 13.54: Aerial photo of the facility.

Facility parameters

See Table 13.56.

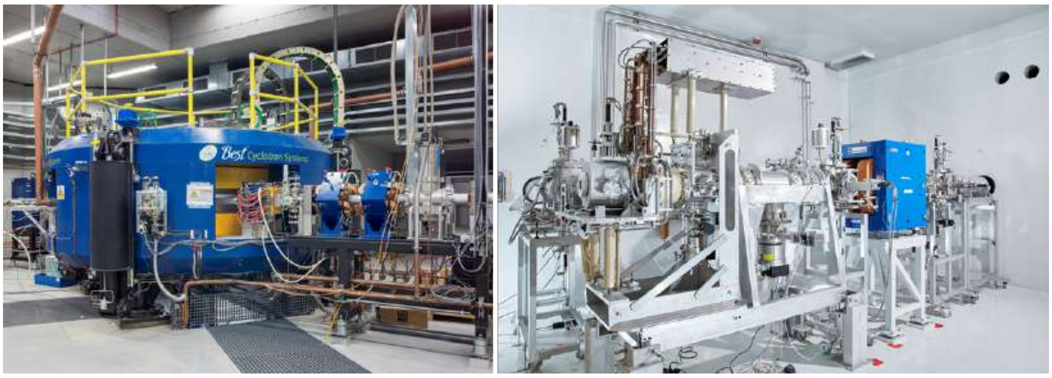

Figure 13.55: The cyclotron B70 (left panel) and the ISOL target of SPES (right panel).

Beam species	Tandem XTU		Tandem+ALPI * PIAVE+ALPI **	
	Energy (MeV)	Current (pnA)	Energy (MeV)	Current (pnA)
$_{1}$H	28.2	25		
$_{7}$Li	56.2	25		
$_{12}$C	98	27	251*	2*
$_{22}$Ne			215**	2**
$_{16}$O	126	5	325*	2*
$_{32}$S	186	5	502*	2*
$_{40}$Ar			389**	10**
$_{48}$Ca	140	2.5	435**	9.2**
$_{58}$Ni	251	1.5	682*	1*
$_{84}$Kr			662.6**	15.4**
$_{82}$Se			510.9*	1.4*
$_{96}$Zr	194.1	1.7	479.5*	0.5*
$_{120}$Sn	210.2	2.8	929**	4.3**
$_{136}$Xe			1182.4**	3.4**
$_{197}$Au	238.2	1.5	1336.5**	3**
$_{206}$Pb			1424.7**	2.2**

Figure 13.56: Table of maximum energy and current for some representative beams available at the TAP accelerator complex.

Major experimental instrumentation and its capabilities

For nuclear physics (Tandem-ALPI-PIAVE accelerator complex):

- PRISMA: large acceptance magnetic spectrometer for heavy ions with ion tracking capabilities, for the study of quasi-elastic processes, nucleon-nucleon correlations and population of neutron-rich nuclei.
- AGATA (at least until 2024): γ-ray spectrometer based on the principle of γ-ray tracking through segmented high-purity germanium crystals, advanced digital electronics, and pulse-shape analysis. The spectrometer is equipped with several complementary detectors for light particles and fragments, LaBr3, and a plunger device.
- GALILEO: γ-ray spectrometer composed of 25 Ge detectors with anti-Compton shields at 90° and forward angles, and 10 triple clusters Ge detectors built using capsules of EUROBALL

mounted at backward angles. The spectrometer is equipped with digital electronics and several complementary detectors for light particles and fragments, LaBr3, and a plunger device.

- GARFIELD: high granularity 4π array for light charged particles and fragments identification equipped with a Ring Counter and digital electronics.
- EXOTIC: in-flight facility for the production of light exotic beams complemented by a set-up for reaction mechanism studies.
- PISOLO: electrostatic deflector followed by a time- of-flight spectrometer for fusion cross section measurements around and below the Coulomb barrier.
- GAMIPE: set-up for g-factor measurements.
- ATS: active target for transfer reactions studies with exotic beams delivered by SPES.

For interdisciplinary and biomedical physics (CN and Tandem accelerators):

- SIRAD: an irradiation facility at Tandem for radiation damage studies equipped with a general- purpose irradiation chamber and an ion electron microscope.
- STARTRACK: detector at Tandem for the measurement of the ionization-cluster-size distributions produced by protons and carbon ions in gas-filled cylindrical volumes.
- BELINA: neutron time-of-flight system at CN used both for the study of nuclear reactions of astrophysical interest and interdisciplinary activities.
- TOTAL-IBA: a facility to perform Ion Beam Analysis at CN comprising simultaneous PIXE, PIGE, prompt NRA and elastic back-scattering.

Instrumentation for applied physics (AN2000 accelerator):

- Scattering chambers dedicated to Ion Beam Analysis with Rutherford Backscattering, Elastic Recoil Detection Analysis, prompt Nuclear Reaction Analysis, RBS-Channeling, in combination with Ion Beam Induced Luminescence (IBIL) and PIXE.
- Micro-beam: beamline equipped with the necessary instrumentation for micro-PIXE analysis with a dedicated HPGe detector. Proton beams with typical size of 2-3 micrometers can be used at rated current of 500 pA. The beam line is also used for rarefied beam (10^2-10^3 protons/s) irradiation of detectors and IBIL and Ion Beam Induced Charge (IBIC) recording.
- LOW ENERGY IRRADIATION: a facility to irradiate with low energy protons (0.4-2.2 MeV) large area spacecraft optoelectronic materials and components. Also usable at CN accelerator for higher energy irradiation.

Nature of user facility

Yes, LNL is a user-oriented facility.

Program Advisory Committee/experiment proposals

All proposals are evaluated on the basis of scientific merit by the LNL Program Advisory Committee (PAC) for the Tandem-PIAVE-ALPI accelerator complex and for the smaller accelerators.

Program Advisory Committee/PAC (current membership): 0 in-house, 2 national, 7 international.

Number of active users and their origin

$\sim$300 (average number per year).

Percentage of users, and percentage of facility use that come from inside the institution

10% users/ 15% facility use .

Percentage of users and percentage of facility use from national users

50% users/ 45% facility use .

Percentage of users and percentage of facility use from outside the country where your facility is located

40% users/ 40% facility use .

Fraction of the international users from outside your geographical region

Outside Europe: $\approx$ 5%.

User group

Yes, https://www.lnl.infn.it/en/user-committee/.

Laboratory Staff

We do not have internal theoretical staff, but we strictly collaborate with Universities, especially University of Padova and Milano.

Table 13.18: Staff at INFN Legnaro. *Incl. graduate students and postdoc researchers. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	127
Temporary staff	∼65*
Postdoctoral researchers	∼35
(Resident) Graduate students	∼25
(Non-Resident) Graduate students	∼20**
Undergraduate students	∼10-15

Special student programs

- Summer student DOE: 1 student per year.
- Stage for Secondary School and University students (yearly held from June to July): about 30-40 students.
- INFN program for teachers: a residential course for high school teachers.
- Didactic laboratory (every year) with an experiment at the Tandem accelerator for university students, 4-6 students.
- Master on “Surface Treatments applied to Innovative Technologies for Industry”: 10 students.

Future Plans

The completion of the SPES facility for producing and reaccelerating radioactive ion beams for nuclear physics and astrophysics experiments. This facility is included in the European Road Map prepared by NuPECC and is part of the EURISOL - Distributed Facility (EURISOL-DF).

Development and upgrade of the instrumentation particularly suited for radioactive ion beams.

A new Data Centre for the AGATA DAQ (phase 1), and the upgrading of the Tier-2 Data Centre (phase 2).

Upgrade in energy, beam intensity and ion species of the Tandem-ALPI-PIAVE accelerator complex.

Completion and operation of the laboratories for the development and production of radioisotopes for medicine and applied physics.

Improvement of the infrastructures at AN2000 and CN.

OSLO CYCLOTRON LABORATORY (OCL)

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Initial funding: Norwegian Research Council and University of Oslo
Staffing and Operation: University of Oslo
Instrumentation: Norwegian Research Council and University of Oslo

Scientific Mission and Research Programs

The Oslo Cyclotron Laboratory is the only particle accelerator in Norway dedicated to fundamental research. The research program is focused on nuclear structure physics with special emphasis on studying properties of highly excited nuclei and their effect on nuclear reaction cross sections relevant for astrophysical processes and reactor applications. The cyclotron is furthermore used to produce radioactive isotopes for research and development in medical applications and for irradiations for research projects in radiation biology, material science, and micro-electronics.

Instrumentation and operation of the laboratory is funded by the Department of Physics of the University of Oslo and through research projects funded by the Norwegian Research Council and the European Union. OCL is an open research facility that welcomes users who wish to pursue research projects in collaboration with local researchers from the University of Oslo. The laboratory has a strong emphasis on training of MSc and PhD students.

Characterization of the facility

Technical facilities

The Scanditronix MC-35 cyclotron was installed in 1978 and produced its first beam in 1979. The beam can be delivered to three target stations inside the cyclotron vault and to three additional beam lines in the well-shielded experimental hall after passing through a 90°analyzing magnet (see Fig. 13.57).

Facility parameters

Table 13.19: Beam parameters at OCL.

Particle	Energy (MeV)	Max. intensity (μA)
$^{1}H^{+}$	2–35	50
$^{2}H^{+}$	4–18	50
$^{3}He^{2+}$	6–47	3
$^{4}He^{2+}$	8–35	10

Major experimental instrumentation and its capabilities

- CACTUS detector array of 28 5"x5" NaI(Tl) scintillator detectors
- Oslo Scintillator Array (OSCAR) of 28 3.5"x8" LaBr3(Ce) detectors (under construction, operational Aug. 2017)
- SiRi array of segmented silicon particle detector telescopes and array of parallel-plate avalanche counters for the detection of fission fragments for coupling with CACTUS or OSCAR

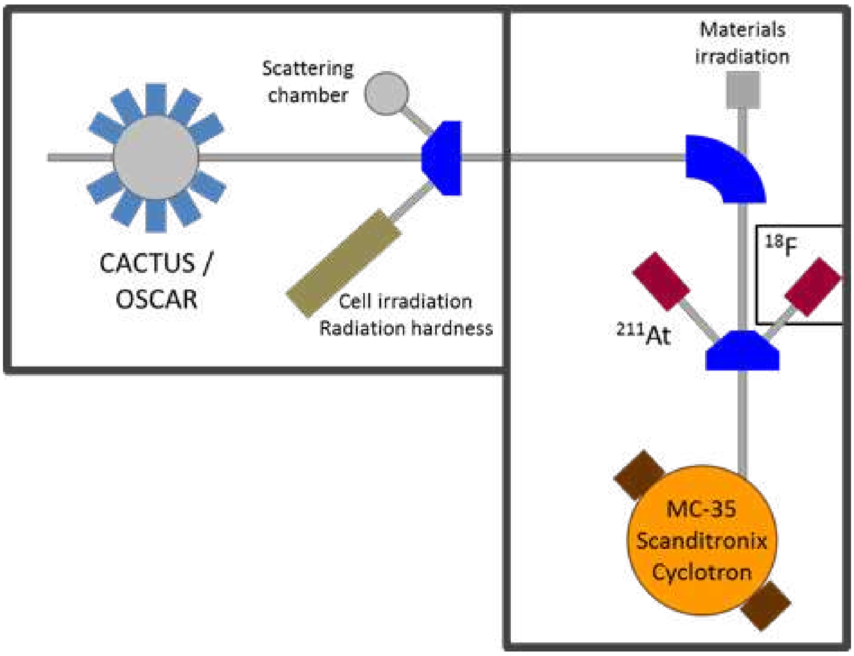

Figure 13.57: Experimental areas at OCL.

- Production targets for medical isotopes such as ^{18}F and ^{211}At
- Beam lines for irradiation of materials and cells equipped with dosimetry equipment
- Class B and C radiochemistry laboratories

Nature of user facility

OCL has an active community of external users from other institutions and welcomes new users. Experiments at OCL generally require collaboration with and support from the local user community.

Program Advisory Committee/experiment proposals

Proposals for experiments are evaluated and beam time is allocated by an internal committee comprising faculty staff of the nuclear physics section of the Department of Physics at the University of Oslo.

Number of active users and their origin

Typically 40.

Percentage of users, and percentage of facility use that come from inside the institution

Users from inside the institution: 70%
Facility use:

- Fundamental nuclear physics: 50%
- R&D for isotope production: 20%
- Radiation biology: 20%
- Material science: 10%

Percentage of users and percentage of facility use from national users

Presently no users from other Norwegian institutions.

Percentage of users and percentage of facility use from outside the country where your facility is located

Foreign users: 30%
Facility use of foreign users: Fundamental nuclear physics: 100%.

Fraction of the international users from outside your geographical region

50%.

User group

No.

Laboratory Staff

Table 13.20: Staff at OCL. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Total staff	9
Scientists	5
Postdoctoral researchers	5
(Resident) Graduate students	7
(Non-Resident) Graduate students	4*
Undergraduate students	~6/ year

Special student programs

Training of students is an important aspect of the laboratory. MSc students have the possibility to obtain beam time to pursue a research project for their MSc thesis. OCL regularly hosts technical students through the IAESTE program.

Future Plans

The commissioning of the OSCAR array is planned for August 2017. This new detector instrument with significantly improved energy and time resolution will widen the scope of nuclear physics research at OCL. A new digital data acquisition system will replace the current analogue electronics.

An internal target for radioisotope production is in the design phase. Replacing the external target station with an internal target is expected to increase the production yield significantly. The radiochemistry laboratory at OCL is being refurbished and new glove boxes are being installed.

Further modernization of the cyclotron control system is planned for the near future.

A new ^{3}He recovery system has been designed and will replace the present recovery system and further reduce the ^{3}He consumption.

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Scientific Mission and Research Programs

IFJ PAN in Krakow, with almost 600 employees and more than 70 PhD students, is the biggest institute of the Polish Academy of Sciences. The institute hosts two cyclotron-based facilities: Cyclotron Center Bronowice with a Proteus-235 proton cyclotron and the AIC-144 homemade proton and alpha-particle cyclotron. The nuclear physics research conducted at these facilities is overseen by the International Advisory Committee, meeting every year.

Characterization of the facility

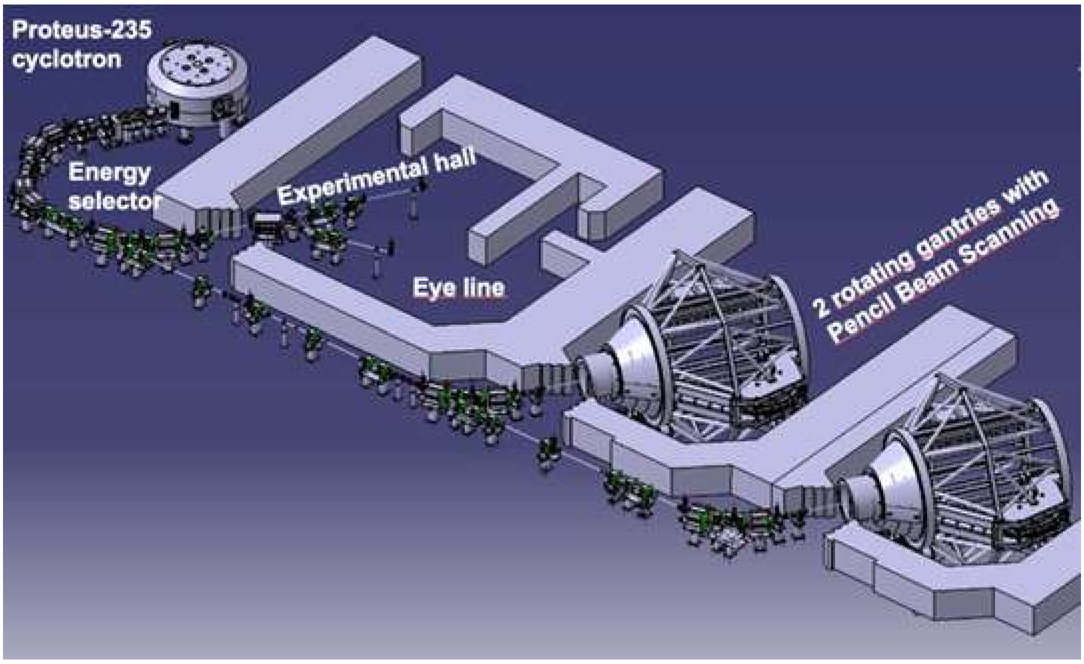

Figure 13.58: Experimental areas at IFJ PAN Krakow.

Technical facilities

The Cyclotron Centre Bronowice (CCB) is a major Polish accelerator facility with a world-class proton radiotherapy centre (the only one in Poland so far) and a modern nuclear physics research laboratory.

The Cyclotron Centre Bronowice houses the technical part, the experimental hall and the medical area. The technical part contains a cyclotron vault together with laboratories for preparations of experiments in physics and biology. The experimental hall is devoted to fundamental research in the field of nuclear physics. The medical area provides the space necessary for the radiation therapy facility, including two scanning gantry therapy units, and for the required diagnostics and preparation of radiotherapy patients.

Facility parameters: Cyclotron Centre Bronowice

The activities of the CCB are focused around the Proteus C-235 cyclotron produced by Ion Beam Applications (IBA) company and installed in 2012. It is an isochronous, 4 sector cyclotron, with PIG hot cathode ion source, maximal proton energy of 230 MeV , beam intensity up to 600 nA and energy spread $\Delta E/E < 0.7\%$. Energy selector enables to reduce the energy down to 70 MeV.

Major experimental instrumentation and its capabilities

The nuclear physics experimental hall hosts 2 detector setups:

a) A big vacuum scattering chamber with high energy particle detectors, KRATTA, and the γ detection system consisting of high-energy γ-ray detectors HECTOR, PARIS and 4 large LaBr3 scintillators. It is used mainly for the investigation of collective, high-energy excitations in nuclei (e.g., giant nuclear resonances) in the yet unexplored regions of excitation energy and spin.

KRATTA (Krakow Triple Telescope Array) is a versatile, low threshold, broad energy range detector system, built to measure the energy, emission angle, and isotopic composition of light charged reaction products. It consists of 38 independent modules which can be arranged in an arbitrary configuration. A single module, covering actively about 4.5 msr of the solid angle at the optimal distance of 40 cm from the target, consists of three identical, 500 mm thick, large area photodiodes, used also for direct detection, and of two CsI(1500 ppm Tl) crystals of 2.5 and 12.5 cm length, respectively. All the signals are digitally processed. The upper energy limit for protons is about 260 MeV.

HECTOR (High Energy gamma-ray deteCTOR) is a high-efficiency array to measure high-energy γ rays in the energy range 2 - 40 MeV with relative full energy peak efficiency (at 15 MeV) of approx. 10%. The array consists of 8 large volume BaF2 scintillators (145 mm diameter and 175 mm length). The energy resolution is 12% for low energy (Co-60) and 10% for high energy (15 MeV) γ rays. Very good time resolution (< 1 ns) allows distinguishing between γ rays and neutron induced events using time of flight method.

PARIS (Photon Arrays for studies with Radioactive and Stable Ion Beams) is the novel detector system to measure medium and high- energy γ rays with good-energy resolution and high-efficiency, based on LaBr3/CeBr3-NaI phoswich detectors, being constructed in the large international collaboration. The PARIS array is coupled to 4 large volume LaBr3 scintillator detectors.

Figure 13.59: Experimental setup.

b) The BINA array (Big Instrument for Nuclear reaction Analysis), a 4π detector system designed for exclusive measurement of elastic scattering and breakup reactions in different configurations of few nucleon systems. It consists of the forward part for precise reconstruction of charged particles momenta (in total around 450 read- out channels), and a backward scintillator ball for registration of particles scattered at higher polar angles (149 channels). The forward part includes two scintillator hodoscopes for energy and energy loss measurement, and Multi Wire Proportional Chamber for reconstruction of particles trajectories. The backward part is built of 149 phoswich scintillator elements forming the detector and, at the same time, vacuum chamber, for cryogenic deuterium target.

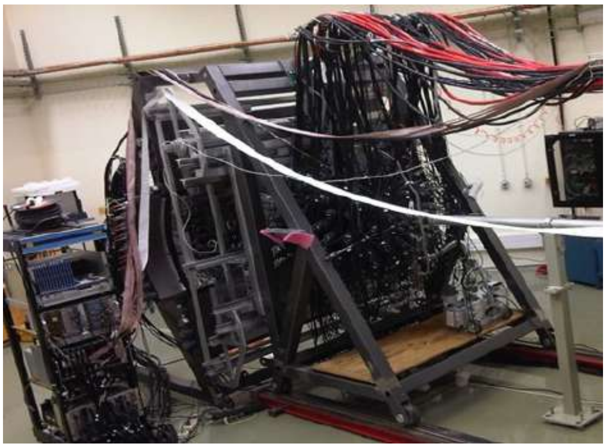

Figure 13.60: BINA.

c) The versatile testing bench for in-beam characterizations of elements of the modern detection systems that are being constructed for the large-scale nuclear physics facilities in Europe (GANIL/SPIRAL2, GSI/FAIR, LNL/SPES).

Treatment Units at CCB Two fully equipped dedicated rotating scanning gantries and eye-treatment horizontal line are used for treating cancer patients. The treatment units are also used for experimental work in the medical physics, radiobiology and testing electronic equipment. The irradiation facilities are equipped with dosimetric instruments such as radiometers, ionization chambers, phantoms, electrometers, alanine, TLDs, GafChromic etc. The irradiation using Pencil Beam Scanning can be performed using large fields up to 30 cm x 40 cm wit hprootn energies up to 226 MeV. The eye-line allows for irradiation with dose rates up to about 1 Gy/s and with th ebeam size not exceeding 40 mm. Parameters of gantries:

Facility parameters: AIC-144 cyclotron

The AIC-144 cyclotron is an isochronous cyclotron designed and constructed at IFJ PAN in the early 90's to accelerate light ions (protons, deuterons and α particles) for research in nuclear physics. The AIC-144 cyclotron is currently operated as a user facility for research and development in radiation physics, dosimetry, medical physics and radiobiology. Parameters of AIC-144 cyclotron are as following: K factor = 60, beam current - up to 80 nA, stability of the beam current $\leq 5\%$.

The cyclotron delivers beams to two irradiation lines located in the target room and in the former eye- therapy room. In their vicinity, several rooms are available for preparing experiments in physics and biology. The users of the facility perform research mainly in the field of radiobiology, proton radiotherapy, detector physics and cosmic industry. The irradiation stations are equipped with dosimetric instruments such as radiometers, ionization chambers, phantoms, electrometers, alanine, TLDs, GafChromic etc.

Eye-line for research at AIC-144 The first eye-line is a high-precision irradiation unit, used in 2011–2016 for treatment of ocular tumors, now fully dedicated to research. The irradiation unit is equipped with a precise dosimetry and positioning setup, which enables to irradiate in pristine Bragg Peak and in Spread Out Bragg Peak (SOBP).

In the experimental room the beam line allows for high-dose (100 kGy) / high dose-rate (20

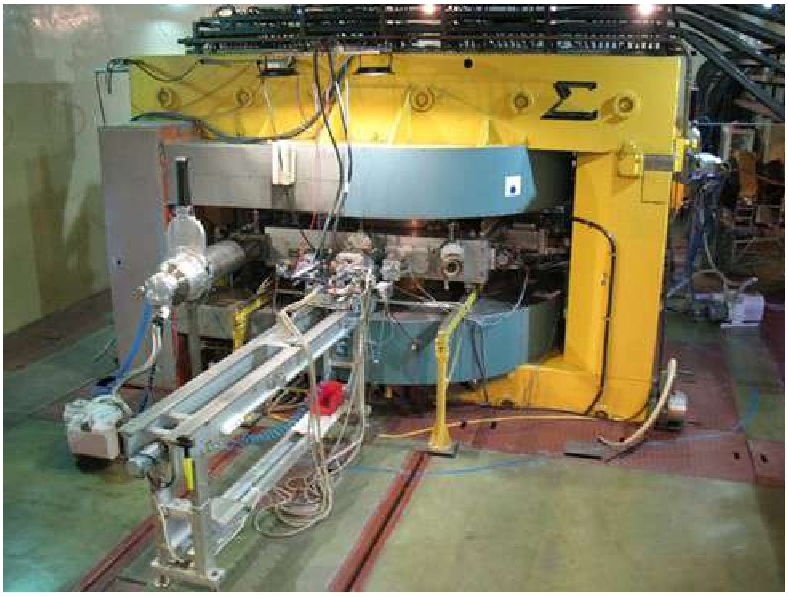

Figure 13.61: AIC-144 cyclotron.

Gy/s) irradiations. Parameters of the irradiation Energy:

- 10- 60 MeV;
- Proton beam current: 2 nA – 100 nA;
- Spot size: $\sim$10 mm (1σ);
- Irradiation field diameter < 12 cm.

Figure 13.62: Experimental irradiation room at AIC-144

HEAVY ION LABORATORY WARSAW

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email: slcj@slcj.uw.edu.pl
www.slcj.uw.edu.pl

Director: Krzysztof Rusek
Scientific Deputy Director: Ludwik Pieńkowski
Head of Accelerators: Jarosław Choiński
PET Project Coordinator: Jerzy Jastrzębski

University Unit
Governmental funds

Scientific Mission and Research Programs

The Heavy Ion Laboratory is a "User Facility" with around 100 national and foreign users per year. The isochronous Kmax=160 cyclotron delivers around 3000 h of heavy ion beams yearly with energies between 2 and 10 MeV/nucleon. The current research program comprises nuclear physics, atomic physics, material sciences, solid state physics, biology, particle detectors development and testing. For more details see Long Range Plan of Polish Nuclear Physics at www.slcj.uw.edu.pl/pnpn/en/52.html.

Actually the Heavy Ion Laboratory is in its transformation phase to become the Warsaw University accelerator centre, operating two cyclotrons. In 2009 a second commercial proton – deuteron cyclotron (E_p = 16.5 MeV) will be installed in the Laboratory building for the production of – and research on the radiopharmaceuticals for the Positron Emission Tomography (PET). Production of long – lived radiopharmaceuticals for other medical and life–science applications is also foreseen.

Characterization of the facility

Medium – energy (2 -10 MeV/nucleon) cyclotron with heavy ion beams;
Low – energy, high current proton – deuteron cyclotron.

Facility parameters

See Table 13.64.

Major experimental instrumentation and its capabilities

For details see: www.slcj.uw.edu.pl/en/96.html.

- GDR multidetector system JANOSIK;
- Gamma - ray, up to 30HPGe multidetector system EAGLE will be comissioned in 2009;
- Two universal scattering chambers CUDAC and SYRENA;
- Charged particle multidetector system ICARE;
- Scandinavian type on-line mass separator IGISOL;
- Irradiation chambers with target water cooling;
- Low background lead shielded HPGe counters;
- Radiochemistry and Quality Control equipment for the radiopharmaceuticals production;

Nature of user facility

The Heavy Ion Laboratory (HIL) was founded jointly by the Ministry of Education and Sciences, Polish Academy of Sciences and Polish Atomic Energy Agency. In the founding agreement the above three authorities enacted HIL to become, from the very beginning a national "User Facility".

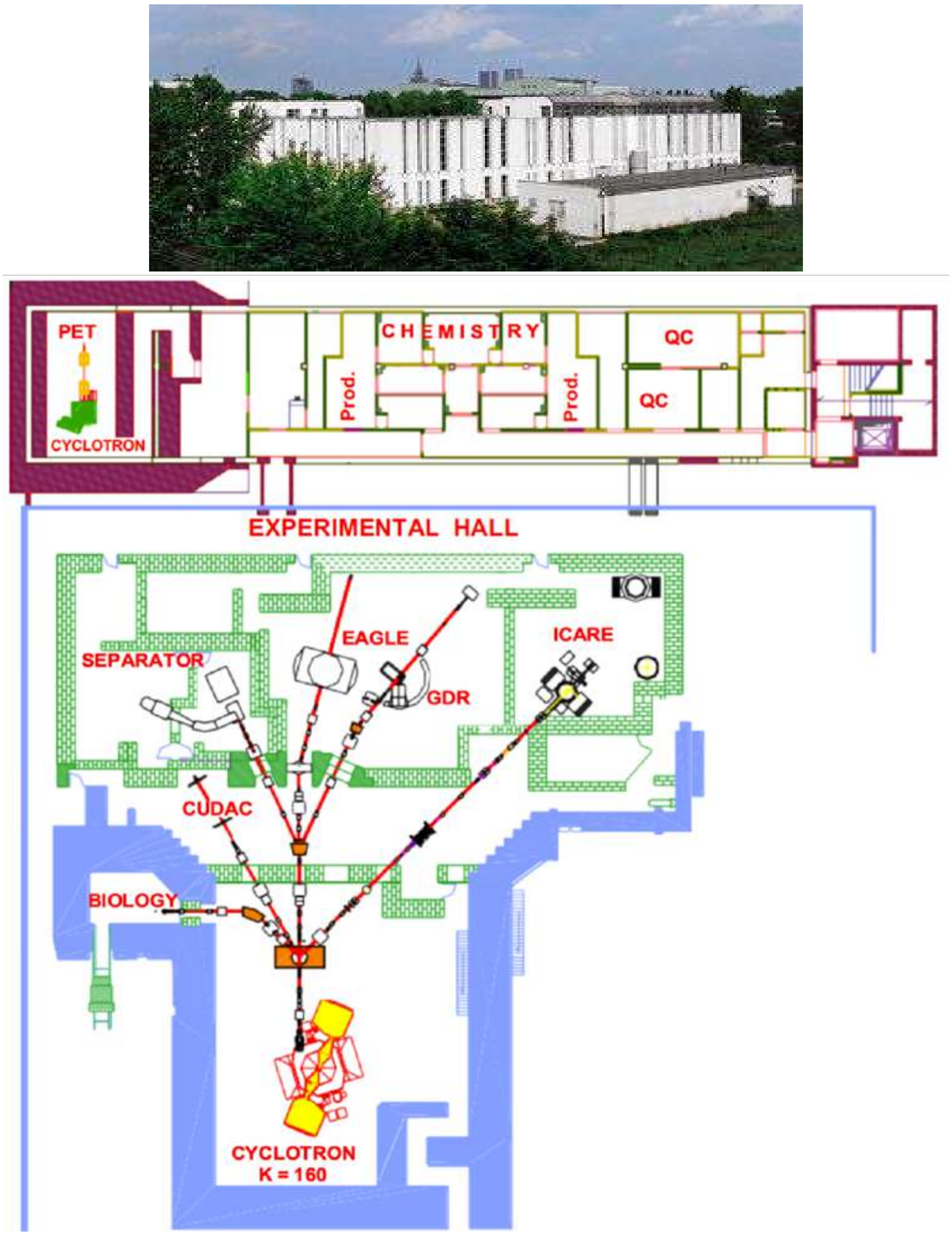

Figure 13.63: (Top) Picture of the HIL Warsaw. (Bottom) Schematics of the beamlines.

Program Advisory Committee/experiment proposals

The K=160 cyclotron beam time is allocated by the Laboratory director on the recommendation of the Program Advisory Committee. The proposals are received twice a year (www.slcj.uw.edu.pl/pac) in a written form and publicly presented. In their ranking PAC considers the scientific value of the proposal, its expected international impact, its contribution to the teaching process and the previous achievements of the proposers.

Number of active users and their origin

About 100 users per year as indicated by the access record.

Percentage of users, and percentage of facility use that come from inside the institution

About 10

Cyclotron	Ion	Energy [MeV]	Extracted current [pnA]
K= 90 - 160	$^{10}B^{+2}$	50	4
	$^{11}B^{+2}$	38 - 55	3 - 4
	$^{12}C^{+2}$	22 - 50	2 - 20
	$^{12}C^{+3}$	89.6- 112	0.8 - 12
	$^{14}N^{+2}$	28 - 50	13 - 143
	$^{14}N^{+3}$	57 - 110	80
	$^{16}O^{+2}$	32	5.7
	$^{16}O^{+3}$	46 - 80	5.7 - 138
	$^{16}O^{+4}$	90	6.5
	$^{19}F^{+3}$	38 - 66	1.3
	$^{20}Ne^{+3}$	50 - 65	11 - 35
	$^{20}Ne^{+4}$	70 - 120	11 - 35
	$^{20}Ne^{+5}$	140 - 190	24 - 40
	$^{22}Ne^{+3}$	44	10
	$^{22}Ne^{+4}$	132	8
	$^{32}S^{+5}$	64- 121.6	0.5 – 1.4
	$^{40}Ar^{+6}$	80 - 132	2.5
	$^{40}Ar^{+7}$	120 - 172	0.9 – 2.3
	$^{40}Ar^{+8}$	195	0.9 – 2
K=16.5	$^{1}H^{+1}$	16.5	> 75 μA
	$^{2}D^{+1}$	8.4	> 60 μA

Figure 13.64: Table of facility parameters at the HIL Warsaw.

Percentage of users and percentage of facility use from national users

About 80

Percentage of users and percentage of facility use from outside the country where your facility is located

About 20

Fraction of the international users from outside your geographical region

No users from outside Europe.

User group

The users group has an elected chair – person, who reports to the Laboratory Scientific Council. The facility users meet 3 times per year on a voluntary basis. No official record of people participating to the users group exists.

Laboratory Staff

Special student programs

An undergraduate Student's Workshop of one week duration is organized in March each year for about 20 participants coming from Physics Faculties of Polish universities. Students, supervised by the Laboratory staff are performing various nuclear physics experiments, including the cyclotron operation.

During Summer up to 7 students from various Physics Faculties take part in one month duration training, participating in experiments, conducted by the Laboratory staff.

Table 13.21: Staff at HIL Warsaw. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	50
Temporary staff	13
Postdoctoral researchers	10
(Resident) Graduate students	5
(Non-Resident) Graduate students	15*
Undergraduate students	20/ year

Future Plans

The Heavy Ion Laboratory is conveniently placed in the heart of the Warsaw University, Polish Academy of Sciences and Academy of Medicine Scientific Campus Ochota. Shortly the intense proton and deuteron beams from a medical cyclotron, equipped with an external beam line will be also available. These beams will be used for the production of PET radioisotopes, subsequently transformed to radiopharmaceuticals using the commercially available chemistry and quality control modules. This 4 Million Euro project is currently financed by the Polish Ministry of Science and Higher Education, Ministry of Health, EC Structural Fund and International Atomic Energy Agency. The Polish Ministry of Health has also financed the PET scanner, located in the neighboring Medical University of Warsaw. Leading the Warsaw PET Consortium, the Laboratory foresees the development of a large interdisciplinary research program including medicine and life sciences, unique at least in this part of Europe.

For the K=160 cyclotron, a new ECR ion source allowing a substantial increase of the accelerated ion species and masses will be installed in 2009.

HIL is an open user facility, serving the needs of scientific community based mainly on evaluation of the merit of proposed programs only. Services provided: target laboratory, mechanical and electronic workshops, library, two conference rooms for 120 and 80 participants, respectively, 12 guest rooms with en-suite facilities and a common kitchen.

HORIA HULUBEI NATIONAL INSTITUTE FOR PHYSICS AND NUCLEAR ENGINEERING (IFIN-HH)

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Scientific secretary: Alexandru Negret
E-mail: negret@nipne.ro

Scientific Mission and Research Programs

IFIN-HH is the largest research institute of Romania, currently employing more than 850 persons. It is a national institute, the activity being supported through scientific projects and commercial contracts. The mission of IFIN-HH is built on four major pillars:

- Basic research,
- Applied research,
- Support of the authorities as a national laboratory,
- Education.

The institute operates an important range of research facilities employed to address all four objectives listed above. It also plays a leading role in the Romanian participation in numerous European and international projects and collaborations, including the national participation to CERN, FAIR and JINR. The structure of IFIN-HH consists of 10 departments and the ELI-NP (Extreme Light Infrastructure – Nuclear Physics) Subunit.

Characterization of the facility

Four facilities are dedicated to nuclear physics research and applications:

- The High Power Laser System (HPLS) operated by the ELI-NP Subunit
- The 9-MV Tandem accelerator operated by DFN (The Nuclear Physics Department)
- The 3-MV Tandetron operated by DFNA (The Applied Nuclear Physics Department)
- The 1-MV Tandetron operated by DFNA.

Major experimental instrumentation and its capabilities

The **High Power Laser System** (Fig. 13.65) of ELI-NP became operational in 2021 and consists of two laser arms capable of producing laser pulses at a power of 0.1, 1 or 10 PW. The facility is capable to provide ultra-short pulses using the Chirped Pulse Amplification method.

Figure 13.65: High Power Laser System experimental area.

Available equipment at HPLS include:

- A high and ultra-high vacuum chambers for 100 TW experiments with one or two laser beams, including different optic stages and diagnostic detectors for secondary radiation sources
- A modular chamber system for 1 PW experiments with one or two laser beams, including different optic elements and diagnostic detectors for secondary radiation sources
- Two vacuum chambers for 10 PW experiments with one or two laser beams, including different optic elements and diagnostic detectors for secondary radiation sources.

The **9-MV Tandem accelerator** operated by DFN is predominantly used for nuclear structure and nuclear reaction studies. It is one of the most reliable small-scale facilities in Europe, accelerating a wide range of ion species from protons to Au, with high intensity and stable operating conditions.

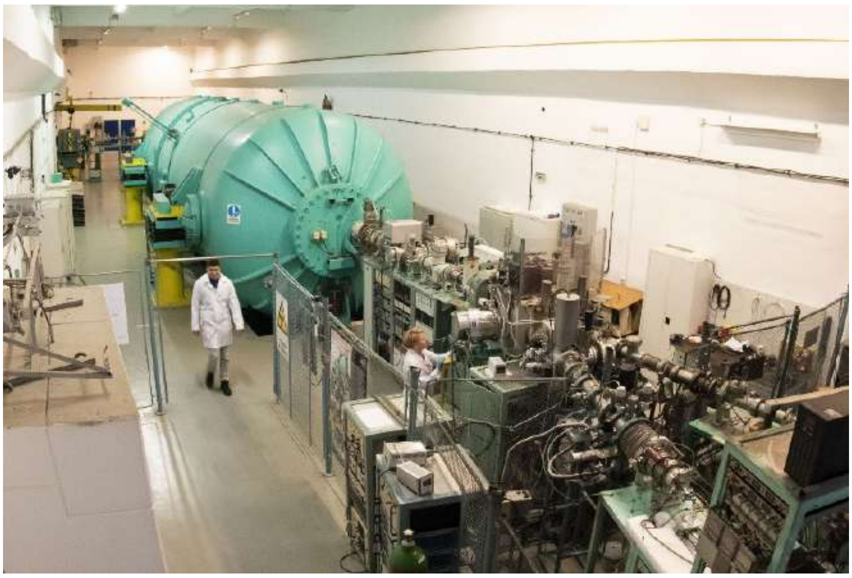

Figure 13.66: The 9-MV Tandem.

The main instrumentation available for experiments include:

- The ROSPHERE spectrometer, a high- efficiency γ array capable of housing up to 25 detectors, HPGe or LaBr3(Ce) scintillators. This combination allows for fast-timing measurements which is one of the most successful specialized segments our lab has to offer. In addition, charged particle and neutron detection capabilities complete the spectroscopic possibilities at IFIN-HH.
- A setup dedicated to nuclear reaction and nuclear astrophysics studies consisting of multi-strip silicon detectors for particle detection with the possibility of radial and longitudinal movement around the target;
- The Neutron Array consisting of 81 BC400 plastic scintillators
- Low-background measurements setup for nuclear reaction cross-section measurements through the activation method.

The **3-MV Tandetron** operated by DFNA is mainly dedicated to applied physics experiments, fully equipped to do ion beam analysis (IBA) and implantation experiments. The first beam-line has all the necessary detectors to perform particle induced X-ray emission (PIXE), particle induced gamma ray emission (PIGE), Rutherford backscattering (RBS) and elastic recoil detection analysis (ERDA). We also have the possibility to do micro-beam analysis using a high performance focusing electrostatic quadrupole lens.

The second beam-line is dedicated to implantation experiments, having the possibility to scan a

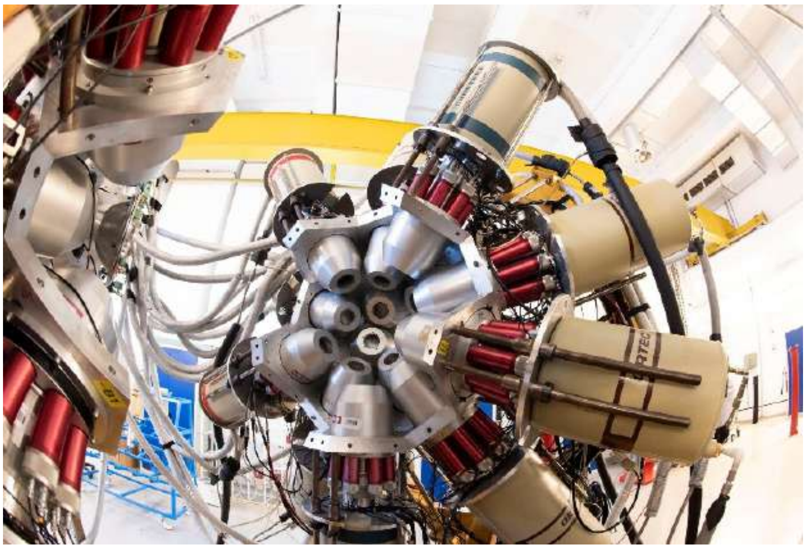

Figure 13.67: The ROSPHERE γ array.

wide sample surface (18x18 cm) with very accurate control of the dose.

The third beam-line is a multipurpose beam-line used mainly for nuclear astrophysics experiments.

Figure 13.68: The 3-MV Tandetron.

The **1-MV Tandetron** of DFNA is exploited for Accelerated Mass Spectrometry (AMS) studies and particularly for ^{14}C dating applications, reaching sensitivities of the order of 10^{-15} for the abundance ratio of the scarce isotope over the abundant isotope. The current applications use the following isotopes: ^{10}Be, ^{14}C, ^{26}Al, ^{41}Ca, and ^{129}I. A chemistry laboratory specialized in sample preparation works together with the 1-MV Tandetron.

Program Advisory Committee/experiment proposals

The HPLS of ELI-NP is currently performing commissioning experiments and a formal user group will be formed as a Proposal Advisory Committee (PAC) will be established in the near future and the first call for proposal by the international user community will be announced in 2022, such that first user experiments are expected to begin in the fall of 2022. Therefore the numbers below do not refer to ELI-NP.

The accelerators of DFN and DFNA operate as user facilities with all experiments being subject to the approval by a PAC: https://tandem.nipne.ro/program_advisory_committee.php

Figure 13.69: The 1-MV Tandetron.

Number of active users and their origin

60 at the 9-MV Tandem, 65 at the 1-MV and 3-MV Tandetrons.

Percentage of users, and percentage of facility use that come from inside the institution

40% at the 9-MV Tandem, 30% at the 1-MV and 3-MV Tandetrons.

Percentage of users and percentage of facility use from national users

5% at the 9-MV Tandem, 60% at the 1-MV and 3-MV Tandetrons.

Percentage of users and percentage of facility use from outside the country where your facility is located

55% at the 9-MV Tandem, 12% at the 1-MV and 3-MV Tandetrons.

Fraction of the international users from outside your geographical region

5% at the 9-MV Tandem, 0 at the 1-MV and 3-MV Tandetrons.

Laboratory Staff

Table 13.22: Staff at IFIN-HH. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	120
Scientists with doctoral degree	65
Postdoctoral researchers	5
(Resident) Graduate students	26
(Non-Resident) Graduate students	9*
Undergraduate students	8/ year

Special student programs

Future Plans

During the next years the second major facility of ELI-NP will be installed and commissioned. It consists of a gamma source that will provide high- brilliance, narrow bandwidth, almost fully polarized γ beams with tuneable energies between 1 and 19.5 MeV. A large variety of experimental setups and multi-detector arrays which cover all possible aspects of photonuclear physics will also be available.

BUDKER INSTITUTE OF NUCLEAR PHYSICS (BINP)

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Head of the facility (ROKK-1M): D.M. Nikolenko
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Director of the Institute: Academician Prof. Pavel V. Logachev

(Legal) form/status of the institution/facility: Member of Russian Academy of Science (Siberian Branch)
Main sources of funding: Federal funding, Russian Foundation of Fundamental Research, BINP budget.
Alexander N. Skrinsky

Scientific Mission and Research Programs

Investigation of the electromagnetic structure of the lightest nuclei in internal target experiments. The current program: Measurement of two-photon exchange contribution in elastic scattering of electrons/positrons on the proton, that is important for the interpretation experiments for proton electromagnetic form factors. Farther studies of the spin-dependent electromagnetic response of few- body nuclei with utilizing of pure polarized internal gas target.

(Deuteron facility) The main direction is the study of electro-nuclear and photo-nuclear reactions in experiments with polarized and unpolarized internal deuterium and hydrogen gas targets. The current research program: measurement of tensor analyzing powers in two- body deuteron photo-disintegration and in coherent and incoherent pion photo-production on deuteron in the photon energy range 400-1500 MeV.

Characterization of the facility

Internal target facility at the electron/positron storage ring VEPP-3.

Facility parameters

- Electron/positron beam energy from 350 MeV to 2 GeV
- Electron/positron beam current 150/50 mA
- Beam lifetime 30000 s
- Beam lifetime with polarized internal target 8000 s
- Beam cross section 0.3 x 0.7 mm
- Bunch repetition 4 MHz (single bunch regime), 8 MHz (two-bunch regime)

Major experimental instrumentation and its capabilities

Atomic Beam Source with superconducting magnets provides polarized deuterium atoms flux 8×10^{16} at/s
Polarized deuterium target thickness: 8×10^{13} at/cm^2
Unpolarized deuterium/hydrogen gas target thickness: up to 10^{16} at/cm2 Non-magnetic particle detector covers the solid angle up to $\sim$1 sr. Detector configuration depends on the reaction under study. Detector is assembled from a set of available elements: tracking system (proportional and drift wire chambers; GEMs), and various scintillators: plastic scintillators of different sizes, CsI and NaI crystals.

Technical facilities

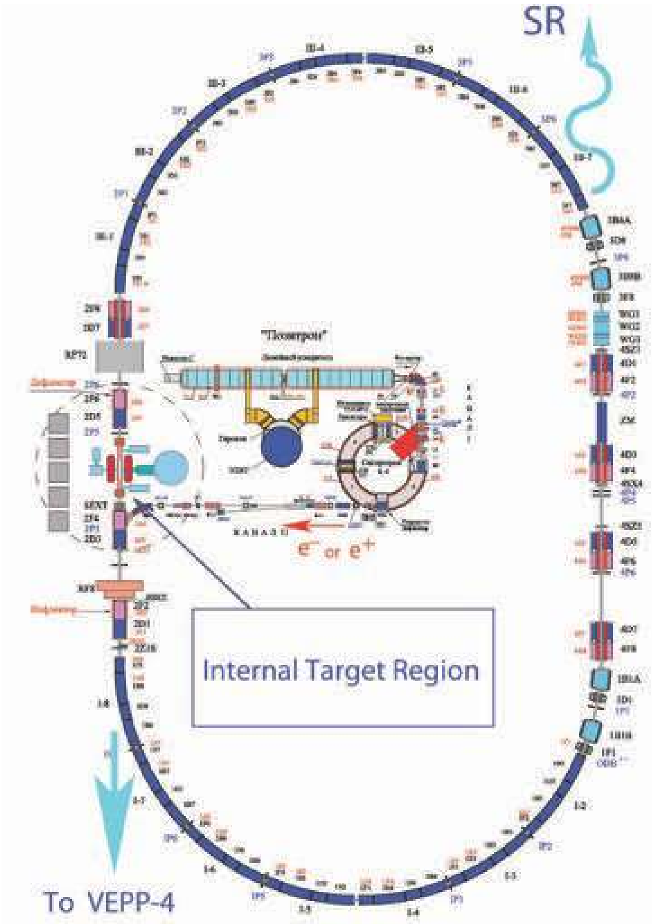

Figure 13.70: Storage ring at the Budker Institute.

Figure 13.71: (Left) View at the Internal Target Area at VEPP-3. (Right) Example of a detector configuration.

Nature of user facility

The facility can be used about 15% time of VEPP-3 (the other time is devoted to the high energy physics and synchrotron radiation experiments).

Program Advisory Committee/experiment proposals

Scientific Council of BINP plays the role of Program Advisory Committee.

Number of active users and their origin

An average over the last four years: 15.
(D facility): About 10 users (plus several students).

Percentage of users, and percentage of facility use that come from inside the institution
60%. (D facility): 70%

Percentage of users and percentage of facility use from national users
79%. (D facility): 85%

Percentage of users and percentage of facility use from outside the country where your facility is located
21%

Fraction of the international users from outside your geographical region
North-America 14%, Europe 7%.

User group
No.

Laboratory Staff

Table 13.23: Staff at the BINP. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Total staff	27
Scientists with doctoral degree	8
Permanent staff (theory)	4
Postdoctoral researchers	4
(Resident) Graduate students	1
(Non-Resident) Graduate students	1**
Undergraduate students	4/ year

Future Plans

The new Injection Complex of BINP will provide more intensive electron/positron beam in VEPP-3 for increasing of luminosity of internal target experiments. The new tagging system with photons energy from hundreds MeV to 1.5 GeV, which is under construction, will provide new possibilities for photonuclear experiments on the VEPP-3.

Construction of a special bypass along the straight section of VEPP-3, containing the Internal Target Facility. Such a bypass would significantly increase the efficiency of the VEPP-3 beam time utilization and enhance the functionality of the facility.

INSTITUTE for HIGH ENERGY PHYSICS (IHEP)

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Director: Dr. Sergey V. Ivanov
Heads of Experimental facilities: Prof. Dr. Alexander Zaitsev
Heads of Accelerators: Dr. Oleg Lebedev
Chief engineer: Alexander Bragin

(Legal) form/status of the institution/facility: Federal State Budgetary Enterprise & State Research Center (functioning under Russian law)

Main sources of funding:
Construction — Federal funding
Operation — Federal funding and, in part, through commercial activities

Scientific Mission and Research Programs

Fundamental research in the field of high energy physics, getting new knowledge about the structure of matter.
Maintaining and developing the national scientific potential and experimental base for research in high energy physics, developing key technologies in accelerator and beam physics and for elementary particle detectors; targeted applied research for high-tech industries.
Educating new generation of researchers, facilitating higher grades of national education and professional training.

Characterization of the facility

Proton (and light-ion) synchrotron. Accelerator Complex U-70 comprising the proton (light-ion) synchrotron U-70 and its injector cascade of booster RCS U-1.5 and two complementary linacs – Alvarez DTL I-100 and RFQ DTL URAL-30

Technical facilities

Synchrotron U-70 yielding 70 GeV protons and/or 34 GeV/u light ions (C).

Facility parameters

Facility's major experimental instrumentation and its capabilities

Facilities for research in fundamental physics:

- «OKA» (IHEP, INR, JINR), kaon decays and interactions;
- «VES» (IHEP), light meson spectroscopy;
- «SVD» (IHEP, JINR, SINP MSU), inclusive reactions;
- «FODS» (IHEP), hard hadron-nuclei interactions;
- «SPIN» (IHEP, JINR), hard hadron-nuclei interactions;
- «HYPERON» (IHEP), mesons in nuclear matter;
- «SPASCHARM» - under construction, (IHEP, JINR), spin physics.

Facilities for R&D and applications:

- «SIGMA» (IHEP), R&D for detector development;

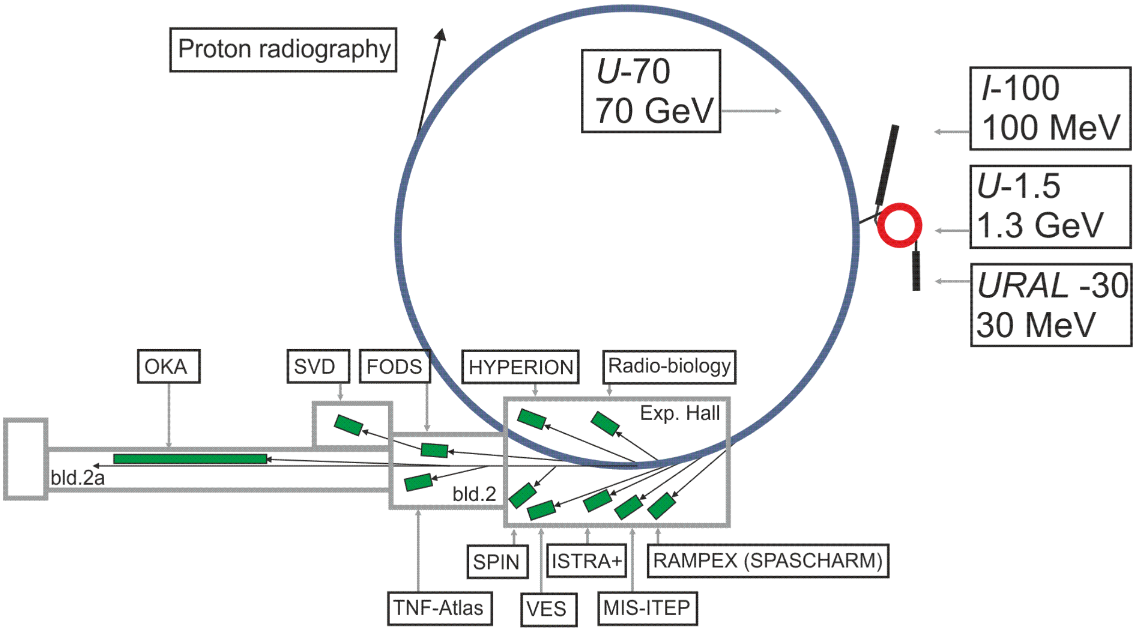

Figure 13.72: Experimental areas at IHEP.

Figure 13.73: Aerial view of IHEP.

- «Channel 4A» (IHEP), R&D for beam optics with crystaldeflectors;
- «Channel 25» (IHEP, . . .), R&D for radiobiology and ray-therapy studies;
- «KMN-ATLAS» (IHEP, MPI,. . . .), R&D for detector development

Program Advisory Committee/experiment proposals

Commission for Experimental Physics, reporting to the IHEP Scientific Board

Number of active users and their origin

180 persons from IHEP (scientific and top engineering staff of experimental physics groups, this number nearly coincides with the number of persons with IHEP affiliation in publications made with the use of the IHEP facilities). 60 persons from other Russian laboratories and 10 users from

Table 1: Specification of synchrotrons

	U-1.5	U-70	
Energy, E	0.030–1.32	1.32–69	GeV
Orbit length, L	99.16	1483.699	m
Curvature radius,)	5.73	194.125	m
Magnet rigidity, B)	0.80–6.87	6.87–233	T⊕m
Compaction factor, (	0.07235	0.011120	
Intensity, N	2–9⊕10^{11}	1.7⊕10^{13}	ppp
Ramping time, t_R	0.030	2.75	s
Cycle period, T	0.060	9.77	s
RF harmonic, h	1	30	
Radio frequency, f_{RF}	0.75–2.75	5.52–6.06	MHz
RF voltage, V_{RF}	6–60	190–300	kV
Lattice period	MFDFM	FODO	
No. of periods	12	60	
No. of super periods	12	12	
Betatron tune (H/V)	3.85/3.80	9.9/9.8	

Figure 13.74: Specifications of the IHEP synchrotrons.

Table 2: Specification of proton linear accelerators

	URAL-30	I-100	
Type	RFQ DTL	Alvarez DTL	
Energy, E	0.1–30 0.	7–100	MeV
Length, L	25.3	79.4	m
Radio frequency, f_{RF}	148.5	148.5	MHz
Pulsed current, I	70	100	mA
Pulse length, t_P	1–10	12–40	μs
Cycle period, T	0.060	1–5	s
Sectioning 5 3 tanks	5	3	tanks

Figure 13.75: Specifications of the IHEP linear accelerators.

abroad (source: list of visitors/experiment participants).

Percentage of users, and percentage of facility use that come from inside the institution

∼70%.

Percentage of users and percentage of facility use from national users

∼95%.

Percentage of users and percentage of facility use from outside the country where your facility is located

∼5%.

Fraction of the international users from outside your geographical region

$\sim$1%

User group

Formal users group exist for the IHEP staff. There are about 200 members of these groups. The situation for outside users is quite different. There are agreements (IHEP – user laboratory) for each activity at the IHEP facilities. The number of users is determined by the user institution or laboratory.

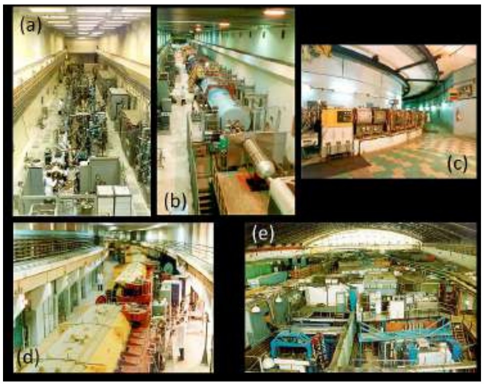

Figure 13.76: IHEP facilities: (a) Proton Linac RFQ DTL URAL-30; (b) Alvarez DTL I-100; (c) Booster RCS U-1.5; (d) U-70 synchrotron; (e) Main experimental hall with beam-lines and detectors.

Laboratory Staff

Table 13.24: Staff at IHEP. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	$\sim$1500
Temporary staff	$\sim$80
Permanent staff (theory)	35
(Resident) Graduate students	$\sim$13
(Non-Resident) Graduate students	$\sim$5/ year*
Undergraduate students	20

Special student programs

Regular courses for students and graduate students (high energy physics – experiment, high energy physics – theory, detectors and experimental methods, accelerator and beam physics, data analysis etc.

Future Plans

Ongoing upgrade of technological systems of the U-70 machine and its injector chain aimed to higher intensity/brightness and improvement of operation(approved, partially funded);
Upgrade of beam lines and detectors at the U-70 machine (approved, partially funded);
Upgrades of the detectors for experiments with light ion beams (in preparation);
Construction of the Center for Ion BeamTherapy (partially approved);
Construction of the AD Pulsed Neutron Source at 1.3 GeV beam from RCPS U-1.5 (partially approved).

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Head of the institution: Prof. Maxiim V. Libanov
Heads of the facility: Prof. Alexander V. Feschenko, Prof. Valery B. Petkov, Prof. Grigory V. Domogatsky

(Legal) form/status of the institution/facility: Institute of the Russian Academy of Sciences
Main sources of funding: Budget from Russian Federation

Scientific Mission and Research Programs

The main aims of INR are development of the experimental base for and fundamental research activities in the field of nuclear physics, elementary particle physics, cosmic-ray physics, and neutrino astrophysics. The Institute comprises the Moscow Meson Factory (MMF) including a high-current linear accelerator of protons and H- ions, the experimental area, the neutron studies complex, and the Troitsk ν- mass installation (the city of Troitsk, Moscow); the Baksan neutrino observatory (BNO, in the Caucasus); the Baikal deep underwater neutrino telescope (detector) Baikal-GVD in Lake Baikal.

- MMF is used for fundamental and applied investigations in nuclear physics, the study of materials, the production of radio nuclides for medicine and industry, the development of proton therapy, and the production of radiopharmaceuticals for medical purpose;
- BNO is used for the study of naturally occurring particle fluxes in the low background area;
- Baikal-GVD is used for the study of the flux of high-energy neutrinos of astrophysical nature and the creation of a telescope with an effective volume of 1 km3 or more.

Characterization of the facility

(MMF) High current proton and neutron beam facility.
(BNO) The main use is a low background facility.
(Baikal-GVD) The primary characteristics of the facility are the low background and large effective volume. At the moment Baikal-GVD is the largest neutrino telescope in the Northern Hemisphere, with effective volume for high energy (over 100 TeV) cascade-like neutrino events close to 0.4 km^3.

Facility parameters

MMF linac:

- Proton energy: 200-500 MeV
- Pulsed current: 15mA
- Frequency: 50 Hz
- Beam species: p, H-

MMF pulsed neutron source: Neutron flux: 10^{13} n/cm^2/sec.
MMF Troitsk-NM Neutrino mass <2.05 eV.

BNO: Low-background laboratories at a depth of 100, 600 and 4800 m.

Baikal-GVD: The main tasks of the Baikal deep-sea neutrino telescope Baikal-GVD are: the study of the flux of high-energy neutrinos of astrophysical nature and the construction of a telescope with an effective volume of 1 km^3 or more. The entire spectrum of work is carried out in close cooperation with the Joint Institute for Nuclear Research (JINR, Dubna) and other partners in the

Figure 13.77: MMF Linac.

Figure 13.78: BNO.

international scientific collaboration "Baikal".

The detector's 8-cluster configuration is shown in Fig. 13.79. The rate of annual increase in the number of active clusters of the telescope from 2016 to 2021 is shown on the right. Each string contains 36 optical detection modules installed at depths from 750 to 1250 m at 15 m intervals. The distance between the strings in the cluster is 60 m, the distance between cluster centers ranges from 200 to 300 m.

Facility's major experimental instrumentation and its capabilities

MMF Linac:

- Pulsed neutron source providing neutron fluxes up to 10^{13}/cm^2/s within the interval from

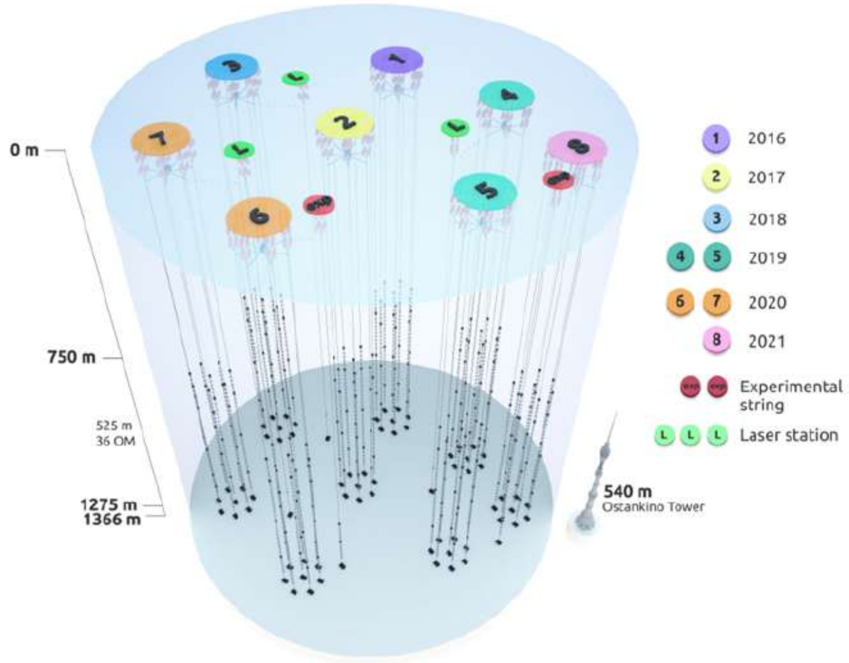

Figure 13.79: Baikal-GVD detector.

thermal energies to tens of MeV;

- 100t Pb Cube – neutron spectrometer with the slowing-down time in lead;
- 50m time-of-flight neutron spectrometer Facility of diffractometers for neutron studies Facility for gamma-ray material studies;
- Facility for radio-nuclides production studies (^{82}Sr, ^{68}Ge, ^{109}Cd, ^{22}Na, etc);
- Facility for studying proton and gamma therapy methods;
- Troitsk-NM facility for neutrino mass measurements in the β decay of tritium (high- resolution β-spectrometer on the basis of a large superconducting magnetic trap).

BNO:

- Baksan Underground Scintillation Telescope (BUST) with a volume of 300 m^3 at a depth of more than 300 m from the surface;
- Gallium-Germanium Detector for solar neutrinos located as deep in the mountain rock as 3600 m and having a target made of 60 tons of metallic gallium and a laboratory for germanium atom extractions;
- Surface installation ANDYRCHI for detecting Extencive Air Showers. ANDYRCHI is located over BUST and covers about $5*10^4$ m^2;
- A set of surface facilities KOVYOR comprising a Large Muon Detector, Scintillation Telescope and Neutron Monitor for studying the penetrating component of cosmic rays and Extensive Air Showers;
- Low-background laboratories at a depth of 100, 600 and 4800 m (3670 m from the mountain surface).

Baikal-GVD: The 8 cluster configuration of Baikal-GVD, comprising 2304 optical modules installed on deep underwater strings, was officially commissioned in March 2021. During the analysis of the data obtained in 2019-2020, the first 10 candidates for high-energy events of astrophysical origin were identified. The Baikal-GVD neutrino telescope participates in the international multi-messenger warning systems to conduct searches and subsequent study of transient astrophysical sources of high-energy neutrinos with the methods of multi-wave and

Figure 13.80: Irradiation facility for radioisotope production at 160-MeV proton beam of INR-linac.

multichannel astronomy. Following the data analysis, the first results of the search for events from neutrinos from the alerts of the IceCube neutrino telescope were published.

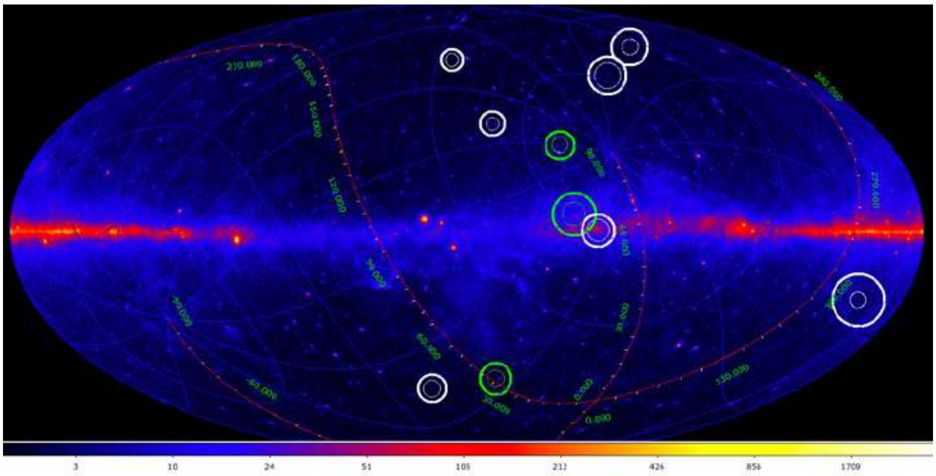

Figure 13.81: Positions of gamma sources and the first ten Baikal- GVD candidates for the astrophysical neutrino events are shown on the celestial sphere. The coordinate grid in the figure corresponds to the equatorial coordinate system. The inner and outer circles around the events correspond to a 50% and 90% probability of registration.

User facility

Yes.

Program Advisory Committee/experiment proposals

Yes.

Number of active users and their origin

15 per year.

Percentage of users, and percentage of facility use that come from inside the institution
80% (estimate)

Percentage of users and percentage of facility use from national users
95%

Percentage of users and percentage of facility use from outside the country where your facility is located
5%

Laboratory Staff

Table 13.25: Staff at INR Trotsk. *Includes permanent, postdoctoral, and graduate student.

Designation	Number of persons
Permanent staff	700
Theoretical staff	70*
Postdoctoral researchers	7
(Resident) Graduate students	5
Undergraduate students	2

Special student programs

Every year the Baksan Youth School for experimental and theoretical physics, School for Students and Young Scientists "Basic Interactions and Cosmology".

Future Plans

MMF: Increasing of proton energy up to 1 GeV with superconducting cavities. Development of diagnostic equipment. Production of various radionuclides (generated at linear accelerator) in a new constructed radiochemical laboratory.

BNO: New artificial neutrino source testing experiment

Baikal-GVD: Enlargement of controlled volume up to 1 km

NUCLOTRON BASED ION COLLIDER FACILITY (NICA) JOINT INSTITUTE FOR NUCLEAR RESEARCH (JINR)

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Academician of RAS Dr. Grigory V. Trubnikov, JINR Director
Heads of Nuclotron-NICA-Related Departments:
Director of Veksler and Baldin Laboratory for High Energy Physics (VBLHEP): Dr. Prof. Adam Kisiel
Leader of VBLHEP Accelerator Division: Dr. Andrey Butenko

JINR is an international intergovernmental research organization. The Supreme governing body of JINR is the Committee of Plenipotentiaries of the governments of 19 Member States.

Scientific Mission and Research Programs

The main fields of JINR's activity are theoretical and experimental studies in elementary particle physics, nuclear physics, and condensed matter physics. A guide to the institute can be found on the web site http://www.jinr.ru . The principal facility for Relativistic Nuclear and Particle Physics is the superconducting ion synchrotron Nuclotron operated by VBLHEP. Ions of all elements, from hydrogen to xenon (to gold in nearest future), can be accelerated up to energies of 4.5-6 AGeV, and secondary beams are available. Internal target station, BM@N (Baryonic Matter at Nuclotron) detector, set of user facilities in dedicated experimental 10000 m2 building are used for relativistic nuclear physics, spin physics, physics of quark flavours and applied researches. During the next years until 2023 the major mission of VBLHEP will be construction of the Nuclotron Based Ion Collider Facility (NICA, http://nica.jinr.ru/ , http://theor0.jinr.ru/twiki-cgi/view/NICA/WebHome). NICA project will support worldleading programmes in relativistic nuclear physics (search for mixed phase, phase transitions and critical phenomena in strongly interacting baryon rich matter) and particle spin physics, radiobiology, applied research and education. The main goal of the project is the study of hot and dense strongly interacting matter in heavy ion collisions (up to Au) at centre-of-mass energies up to 11A GeV. Both colliding and extracted beams will be delivered. The study of spin physics with beams of polarized protons and deuterons is foreseen as well. Applied researches based on particle beams generated at NICA are dedicated to development of novel technologies, environmental problem resolution (like radioactive waste transmutation), energy generation (accelerator driven nuclear reactors), particle beam therapy and others.

Education program is based on the NICA facility for conducting research works and it has the goal to teach and supervise PhD students and young researchers.

Project NICA can serve the wide researcher community in different fields of science and technology where intense and high energy particle beams are required.

Characterization of the facility

The VBLHEP accelerator complex includes a set of ion sources, two linear accelerators – LU-20 and HILac, and two superconducting synchrotrons – Booster and Nuclotron. In 2022/23 it will be complemented by superconducting rings of the NICA collider. The arc source provides light ion beams (p, d, He) at current up to 50 mA. The Source of Polarized Ions (SPI) provides p, d polarized beams at current up to 10 mA. The Laser Ion Source provides a few mA wide spectrum of ion beams up to Fe. The electron string ion source (ESIS Krion) provides the highly charged ion beams up to gold 59+, intensity of gold 31+ is up to 10^9 particle per pulse. LU-20, a 14.5 m Alvarez-type linear accelerator provides ion beams at charge to mass ratio of 0.33 and output energy of 5 A MeV. The LU-20 serves as an injector to the synchrotron Nuclotron. HILac, a 12 m heavy ion linear accelerator provides the ion beams from carbon to gold 31+ at energy of 3.2 AMeV and current up to 10 mA. The HILac serves as an injector to the Booster synchrotron. Nuclotron, the heavy-ion synchrotron with 252 m circumference and a maximum bending power of 45 Tm accelerates particles of p to Xe (Au in future) up to 4.5 - 6 A GeV.

Facility parameters

Table 13.82 summarizes the Nuclotron capabilities achieved to date.

Parameter	Status (November 2016)
Max. magn. field, T	2 (1.8 T routine)
B-field ramp, T/s	0.8 (0.3÷0.6 routine)
Accelerated particles	p-Xe, dt
Max. energy, GeV/u	5.6 (d, ^{12}C), 1.5 ($^{124}Xe^{42+}$, $^{40}Ar^{16+}$)
Intensity, ions/cycle	d $5*10^{10}$ ($2*10^{10}$ routine) dt $8*10^8$ $^{124}Xe^{24+}$ $1*10^4$ ^{12}C $2*10^9$ $^{40}Ar^{18+}$ $2*10^5$ $^7Li^{3+}$ $3*10^9$

Figure 13.82: Nuclotron parameters.

Booster, the heavy-ion synchrotron with 211 m circumference and a maximum bending power of 25 T×m accelerates particles from d+ to Au up to 600 MeV/u. The Booster is located in the yoke of the Dubna synchrophasotron.

Table 13.83 summarized the main parameters of the Booster synchrotron.

Parameter	Status (February 2022)
Max. magn. field, T	1.8 T
B-field ramp, T/s	1.2
Accelerated particles	d+ - $^{197}Au^{31+}$
Max. energy, MeV/u	576
Intensity, ions/cycle	$^4He^{2+}$ $7*10^{10}$ ^{12}C $3*10^9$ ^{56}Fe $3*10^8$

Figure 13.83: Booster parameters.

Technical facilities

The layout of the NICA complex is shown in Fig. 13.84.

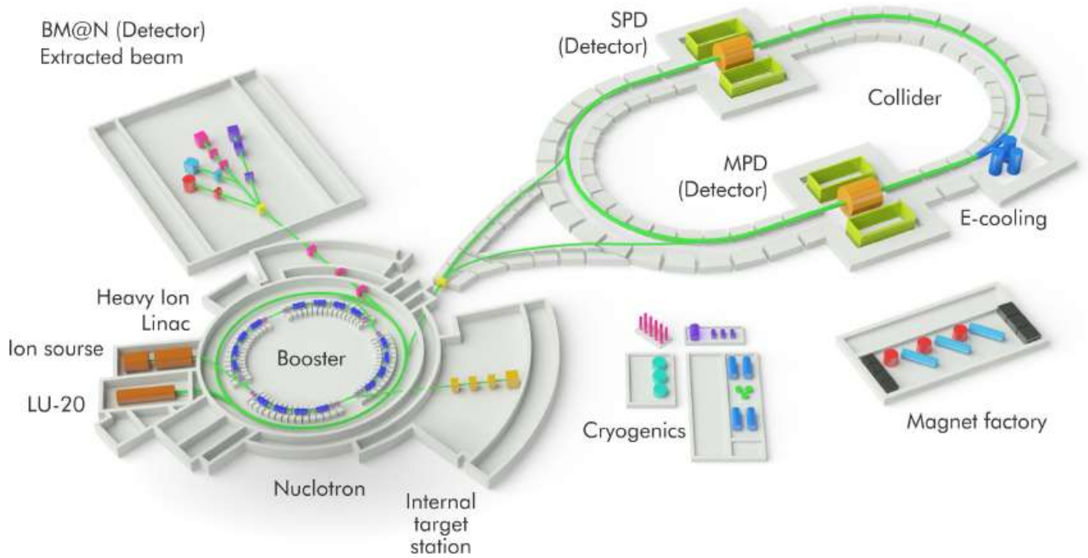

Figure 13.84: Layout of the NICA complex.

Facility's major experimental instrumentation and its capabilities

The instrumentation at Nuclotron consists of internal target station, BM@N detector, user facilities at extracted beams. The internal target station provides an interaction of circulated ion beam wit film or wire targets from hydrogen to tungsten.

BM@N (Baryonic Matter at Nuclotron) is the first experiment at the accelerator complex NICA-Nuclotron. The aim of the experiment is to study interactions of relativistic heavy ion beams with kinetic energy from 1 to 4.5·A GeV with fixed targets. At the Nuclotron energy the nucleon densities in a baryon dominated fireball produced by a collision of two gold nuclei exceed the saturation density by a factor of 3 - 4. The BM@N experiment is well suited for studies of strange mesons and multi-strange hyperons which are produced in nucleus-nucleus collisions close to the kinematic threshold. Heavy- ion collisions are a rich source of strangeness, and the coalescence of Lambda hyperons with nucleons can produce a variety of light hyper-nuclei. The gold ion beam is expected in 2023. The carbon, argon and krypton beams are foreseen in 2022.

The instrumentation at the NICA facility will consist of the experimental set-ups located at the two interaction points at the NICA collider: the MPD (Multi-Purpose Detector) to study heavy-ion collisions and the SPD (Spin Physics Detector) to investigate the spin structure of the nucleon with polarized deuteron and proton beams.

MPD is large solid-angle tracking with a time projection chamber, particle identification with a time-of-flight detector and electromagnetic calorimeter in a solenoidal magnetic field, secondary vertexing with a silicon strip vertex detector. The unique feature of MPD as a collider experiment is the invariant acceptance at different beam energies as compared to fixed-target experiments. MPD is designed to perform a comprehensive scan of the QCD phase diagram with beam species from protons to gold by varying collision system size and c.m.s. collision energy from 4 to 11 GeV per nucleon.

PETERSBURG NUCLEAR PHYSICS INSTITUTE RUSSIAN ACADEMY OF SCIENCE (PNPI)

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V. A. Nazarenko
Heads of the facilities:
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Theoretical Division - Lev N. Lipatov
Neutron Research Dept – Prof. Valery Fedorov

Institute belongs to Russian Academy of Science (RAS)
Main source of funding: Budget of RAS of Science and Education Russian Federation

Scientific Mission and Research Programs

Main research program of HEPD.

- Elementary particle physics (experiments on LHC, Tevatron-USA, Desy-Germany),
- Nuclear Physics (experiments at PNPI, JINR- Dubna, ISOLDE-CERN, GSI- Germany, Cosy-Germany, PSI-Switzerland, K- 130-Jyvaskyla, Finland)
- Solid state physics (MSR-experiments at PNPI and PSI); Radiation physics and Proton therapy at PNPI synchrocyclotron.

All above shown experiments cover as current as well future ones.

Characterization of the facility

The biggest synchrocyclotron in the world with proton energy of 1000 MeV.

Facility parameters

Technical parameters of HEPD facility- synchrocyclotron:

- Energy of extracted protons-1000 MeV,
- Intensity of inner beam-3 mkA,
- Intensity of extracted beam-1 mkA,
- Energy spread of beam 0.1%.

Intensities and energies of second beams:

- Pions +/-(3-10)*10^5 for P=450 MeV/c,
- Muons +/(9-30)*10^4 for P=170 MeV/c,
- Neutrons of E=0.01 eV-200 MeV,
- Total intensity-3*10^{14}/sec,
- Total area: 20000 m^2.

Technical facilities

- Synchrocyclotron on proton energy of 1000 MeV
- Acting atomic reactor
- Building atomic reactor ”PIK”

Facility’s major experimental instrumentation and its capabilities
Nature of user facility

PNPI synchro-cyclotron is considered as a user facility. Foreign members of it are: ISOLDE Collaboration, GANIL (France), (Japan), INFI (Italy), Argonne Lab. (USA), GSI (Germany), LHC

Figure 13.85: Total view of synchrocyclotron.

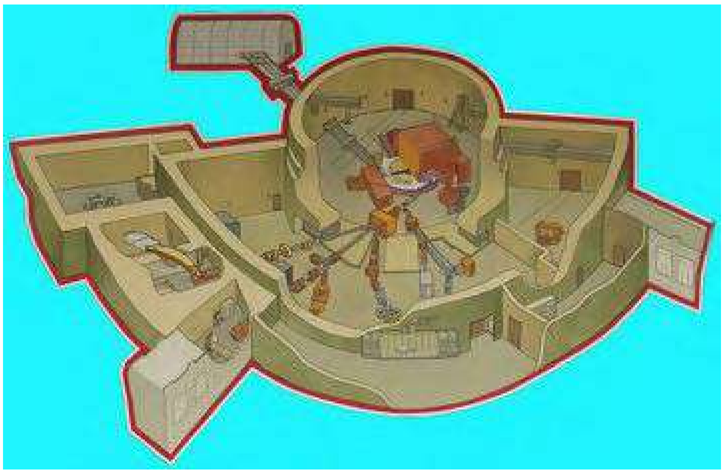

Figure 13.86: Schematic view of accelerator complex.

(CMS, ATLAS, ALICE, LHCb).

RUSSIAN MEMBERS: JINR (Dubna), IETP (Moscow), IHEP (Protvino), NC Kurchatov Institute (Moscow) Minsk State University (Belarussia), St.Petersburg State Technical University, CRIRR (St.Petersburg)

Program Advisory Committee/experiment proposals

Our facility has a Program Advisory Committee with the goal of adjudicating experiment proposals.

Percentage of users and percentage of facility use from national users

The estimated number of national users is 15% of the total number.

Percentage of users and percentage of facility use from outside the country where your facility is located

We estimate a number of users outside the country as 10-15%.

	NAME OF SETUP AND DIRECTION OF ACTIVITY
1	Mass-separator IRIS for the study of short-lived nuclei far from the beta stability region
	Measurements of electromagnetic moments and charge radii of radioactive nuclei
2	Time-of flight neutron spectrometer (GNEIS). Energy of neutrons
	E=0.01 Ev-200 MeV. Full intensity is 3E14/sec.
	Measurements of fission cross sections.
3	MSR facility on muon beam. Investigations on solid state physics using muon spin rotation
4	Two shoulder magnetic spectrometers system (MAP) for measurement of incident and recoil protons with energy 100-1000 MeV.
	Study of nuclear matter density distributions by the method of proton elastic scattering, investigation of nuclear structure by
5	Electromagnetic calorimeter on the basis of CeI
	Investigation of η-meson formation.
6	Experimental variable proton energy facility in the range 200-800 MeV.
	Intensity of 200 MeV proton beam is 3E8 proton/sec. $3 \updownarrow 10^5$ sec^{-1}.
	Measurements of fission cross sections for a number of heavy targets as a function of proton
7	Complex of stereotaxic radiation therapy on 1000 MeV proton beam.
	Treatment of different diseases of head brain. Since 1975 till 2005 1280 patients were treated by this method.

Figure 13.87: Setups at PNPI Gatchina.

Fraction of the international users from outside your geographical region

We estimate a number of users outside the country as 10-15%.

User group

The formal user group is organized now in HEPD facility.

Laboratory Staff

Permanent scientific staff of HEPD consists of 200 physicists and engineers. The number of graduated students in HEPD is on average 12.

CENTRO NACIONAL DE ACELERADORES (CNA) SEVILLA

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Email: cna@us.es
Director: Rafael García Tenorio

Scientific Mission and Research Programs

The National Accelerator Centre (CNA) is a joint centre depending on the University of Seville, the Junta de Andalucía and the High Council of Scientific Research (CSIC). It has the mission of carrying out research in particle accelerators and its multiple applications. CNA is recognized as a Singular Scientific and Technological Facility and it is open for the national and international scientific community to carry out research using its equipment. To do this, 6 different installations are used: a Van de Graaff 3 MV Tandem accelerator, a 18/9 MeV Cyclotron accelerator, an Accelerator 1MV Mass Spectrometer, a PET / CT scanner, a new radiocarbon dating system called MiCaDaS, and a ^{60}Co Irradiator.

The 3MV Tandem accelerator is a versatile tool for materials science and nuclear instrumentation. The cyclotron accelerator is a factory of radiopharmaceuticals and a source for Irradiation. The Accelerator Mass Spectrometry (AMS) system, based on a 1 MV accelerator, finds radionuclides in the environment in tiny fractions. The compact accelerator MICADAS is used for ^{14}C dating. The ^{60}Co irradiator is a source of photons for irradiating aerospace components. The PET-CT scanner is the complement of the Cyclotron for cancer diagnosis.

The application of these 6 infrastructures covers fields as diverse as material sciences, environmental impact, nuclear and particle physics, nuclear instrumentation, medical imaging, biomedical research and preclinical molecular imaging or dating, medical imaging in patients, ^{14}C and irradiation in samples of technological and biological interest, among others.

http://institucionales.us.es/solicitudescna/index.php/en/

Characterization of the facility

In this document we will present the main technical characteristics of the 3 MV Tandem, the Cyclotron and the 1 MV AMS system. A detailed description of the other facilities can be found on http://cna.us.es.

Technical facilities

The Tandem Accelerator, which was installed in 1998 is a Pelletron 3 MV Tandem, model 9SDH-2, by NEC. Negative ions are produced by three ion sources: The Alphatross source is based on radiofrequency techniques and generates negative ions from gases (H, He, N, ...) in conjunction with an Rb charge- exchange channel. The SNICS II is a Cs sputtering source capable of producing tens of μA of negative ions from solid targets. The Duoplasmatron source, with a displaced intermediate (zwischen) electrode, provides modest currents of negative ions (H^-, C^-, O^-) with a high-brightness, which is especially important for microbeam applications. The beam transport system includes elements for focusing (magnetic quadrupoles and electrostatic lens), steering and monitoring (Beam Profile Monitors, Faraday Cups) the beam, a Wien filter and a 90 degree analysing magnet.

Figure 13.88: Picture of the 3 MV Tandem at CNA Sevilla.

The Cyclone 18/9 accelerates protons and deuterons to 18 and 9 MeV, respectively. Seven out of the eight targets are devoted to the production of positron emitters, while in the eighth port an external beamline has been installed to perform experiments in Nuclear Physics. The extracted maximum beam intensities in the internal target ports are 80 μA for protons and 35 μA for deuterons.

In the external beam line of the cyclotron we can do research which requires the use of protons and deuterons with energies above 6 MeV, which is the maximum energy these particles can reach in our 3 MV Tandem. The particle beam passes through a thin window and goes to the air before impacting on the target. A very important detail is the internal coating, with a layer of graphite of few mm of thickness, of the metallic flange that forms the output window, to avoid its activation during the experiments.

A motorized table with step motors, remotely controlled, allows the positioning of the targets with accuracy of 10 μm. Depending on the beam current intensity, this is monitored by different methods: current integrator, ionization chamber, silicon particle detector and radiochromic films. Beam degraders, made of different materials and thicknesses, can be placed, both in vacuum and in air, to irradiate the samples with different energies and beam sizes.

The 1 MV Accelerator Mass Spectrometry (AMS) system is based on a 1 MV Tandetron accelerator. The isotopes of interest are extracted as negative ions from a solid sample in a Cs sputter ion source. They are injected into the 1 MV tandem accelerator through an injection magnet, which separates the mass of interest. Ions are stripped to positive charge states and the molecules dissociated in the stripper channel, which is full of He gas at low pressure. This has shown to provide a much higher transmission for several isotopes than the original Ar specially in the case of the heaviest masses such as ^{129}I and actinides. On the high energy side, the radioisotope of interest is conducted by an analyzing magnet and an electrostatic deflector to a two-anodes gas ionization chamber.

Stable isotopes are measured as an electric current after the magnet by a Faraday cup. Currently ^{10}Be, ^{26}Al, ^{41}Ca, ^{129}I and several actinides can be routinely detected. Isotopic ratios as low as ^{129}I/^{127}I = 10^{-13} or ^{10}Be/^{9}Be = 10^{-14} can be achieved. The limit of detection for actinides is at the levels of 10^{6} atoms per sample.

Figure 13.89: Picture of the Cyclotron at CNA Sevilla.

Figure 13.90: AMS system at CNA Sevilla.

Facility's major experimental instrumentation and its capabilities

At the present time, the 3 MV Tandem accelerator has eight available beamlines or experimental chambers:

1. Nuclear Physics Beam Line: This line includes a high volume vacuum chamber, where nuclear instrumentation (detectors, electronics, etc), that will be used in international Nuclear Physics facilities, can be developed and tested.
2. Microbeam Chamber: In this line it is possible to focus the beam down to size of a few microns using a magnetic quadrupole triplet. The scanning system, synchronized with the data acquisition, allows the formation of maps from different signals with a maximum size

of a few mm2.

3. Multipurpose IBA Chamber: This chamber is equipped with a set of particle, gamma and X-Ray detectors and a large target holder to carry out simultaneously different IBA experiments (RBS, PIXE, NRA and PIGE).
4. Ionoluminescence Chamber: Located behind the multipurpose chamber, this vacuum chamber has black coating walls and is equipped with a heatable sample holder up to 500 oC and a photonic diagnostic system that allows mainly ionoluminescence studies.
5. Irradiation Chamber: This beamline has been designed to allow the irradiation of large areas (up to 16x20 cm2) by raster scanning of the beam through magnetic deflection.
6. Channeling Chamber: This line is dedicated to channeling analysis of single crystalline samples using a 4-axis goniometer. A parallel beam is obtained with a telescopic system formed by two sets of slits. The chamber is equipped with particle, X-Ray and γ-ray detectors.
7. External Beam: This line is mainly used for Cultural heritage studies. The use a magnetic quadrupole doublet, a precision four-jaw object slit and an exit nozzle set with micrometer adjustment, allow to obtain a spatial resolution of about 60 μm.
8. HiSPANoS Line: This is an accelerator based neutron source. Neutrons are produced in a high energy range covering from thermal up to 15 MeV through the reactions p(7Li,n), d(7Li,n), d(D,n), p(9Be,n) and d(9Be,n). A buncher and chopper system and a new experimental line dedicated to neutron time of flight (TOF), produce protons and deuterons pulsed beams with a pulse width of 1-2 ns at the target position at a frequency that can be varied from 32.5 kHz to 2 MHz.

Main Instrumentation for Nuclear Physics Experiments:

- Scanning Ion Microprobe and External beam (based on Oxford Microbeams). IBA chamber (PIXE, PIGE, RBS, NRA, IL, IBIC, channeling). Fast switch for pulsed beams (pulse width 100 ns – continuous).
- Detectors: Charged particles: Si PIPs, DSSSD (40 um) SSSSD (20 um), PAD de 300 μm. SDD for X-rays. Neutron detectors: Li-Glass. Liquid scintillators with pulse shape discrimination, and plastic scintillators. Gamma detectors: LaBr3 and NaI/HPGe
- DAQ & Electronics: Digitizer VME, V751, 8 channels, 10 bit, 2 GS/s, and DT5730, 8 channels, 14 bit, 500 MS/s. Variable voltage sources, CFD, FAN-IN-FAN-OUT, Gate and delay generator, TAC, ...
- Beam monitors, radiochromic films, grafite collimators, aluminium and tungsten foils to be used in the external cyclotron beam.

Facility parameters

Tandem Characteristics:

- Max energy: 6 MeV p, 9 MeV α, 21 MeV (6+ ions)
- Energy resolution $\approx$0.1%
- Max. Intensity: 1 – 40 μA
- Nuclei accelerated: All stable ions
- Minimum energy: 500 keV
- Intensity range: pA to several μA
- Continuous and pulsed beams (ns)
- Max neutron energy: 15 MeV
- Max neutron fluence: 10^{10} n/s

Cyclotron External beam line characteristics:

- Max energy: 18 MeV p, also 9 MeV d
- Energy resolution : 200 keV
- Maximum intensity: 30 μA

- Minimum Energy achieved with degraders: 6 MeV
- Energy resolution at 6 MeV: 500 keV
- Beam spot : 1 mm – 5 cm

Tandetron characteristics:
- Nuclei accelerated: ^{10}Be, ^{26}Al, ^{41}Ca, ^{129}I, ^{236}U, ^{237}Np, ^{239}Np, ^{240}Np
- Terminal voltage range: 0.4 – 1.2 MV
- Terminal voltage ripple: 25 VRMS
- Terminal voltage stability: ±200 V / hr
- Ion source: Cs sputter ion source
- Beam current: 1-2 μA of $^{127}I^-$

Nature of user facility
The accelerators and detectors are user facilities.

Program Advisory Committee/experiment proposals
A Program Advisory Committee decides on the experimental proposals.

Number of active users
96 researchers.

Percentage of users, and percentage of facility use that come from inside the institution
21 (22 %)

Percentage of users and percentage of facility use from national users
46 (48 %)

Percentage of users and percentage of facility use from outside the country where your facility is located
29 (30 %)

Laboratory Staff
6 postdoctoral researchers and 9 graduate students.

CERN/ ISOLDE

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CERN Director General: Prof. Fabiola Gianotti

International Laboratory
Funding contributions from CERN Member States

Scientific Mission and Research Programs

ISOLDE is a radioactive beam facility where isotopes are produced with 1.4-GeV protons at 2 μA on a variety of thick targets (including carbides, oxides, solid metals, molten metals and salts) providing more than 1200 different isotopes and isomers of more than 75 elements. Ion beams are produced in target-ion source units with several different ion sources. These include laser ionization, which is used for around 70% of all cases due to excellent efficiency and selectivity. Isobaric separation is achieved with two alternative online separators (GPS and HRS), which produce beams of 1+ ions at low energies (30-60 keV). For re-accelerated beams, the ions are cooled and bunched in a Penning trap, before being bred to higher charge states in an electron- beam ion source. The ions are then accelerated to 3.1 MeV/u by normal-conducting cavities of the REX-ISOLDE Linac. The recent HIE-ISOLDE upgrade has added four cryomodules, each with

five superconducting cavities, that can accelerate beams up to around 10 MeV/u. The mission is to use radioactive ion beams to address a broad range of scientific questions. The focus is on nuclear physics, in particular the structure and reactions of exotic nuclei, via measurements of ground-state nuclear properties such as electromagnetic moments, masses, and charge radii; measurements of radioactive decay properties; and studies of reactions with post- accelerated beams such as Coulomb excitation, inelastic scattering and nucleon transfer. This is complemented by activities in atomic physics, nuclear astrophysics, and fundamental physics. Techniques such as emission channeling, perturbed angular correlations, βNMR and Mössbauer spectroscopy are also used to pursue research in condensed-matter physics and material science, biophysics and medicine.

Characterization of the facility

An ISOL radioactive beam facility delivering ion beams at low energy (30-60 keV) or reaccelerated up to 10 MeV/u.

Facility parameters

Detailed information is available at www.cern.ch/isolde .

- Primary beam: Protons: 1.4 GeV, $< 2\ \mu$A
- Delivered species: >1000 isotopes of 75 elements
- Beam energy: Low energy: 30-60 keV; High energy: around 10 MeV/u
- Intensity: From <1 up to 10^{13} ions/s

Facility's major experimental instrumentation and its capabilities

The facility can host travelling equipment on general purpose low- and high-energy beam lines, along with more permanent devices listed below:

- GLM: Beam line for implantations subsequently used for offline emission channeling, Mössbauer spectroscopy, and studies.

Figure 13.91: The CERN/ ISOLDE facility.

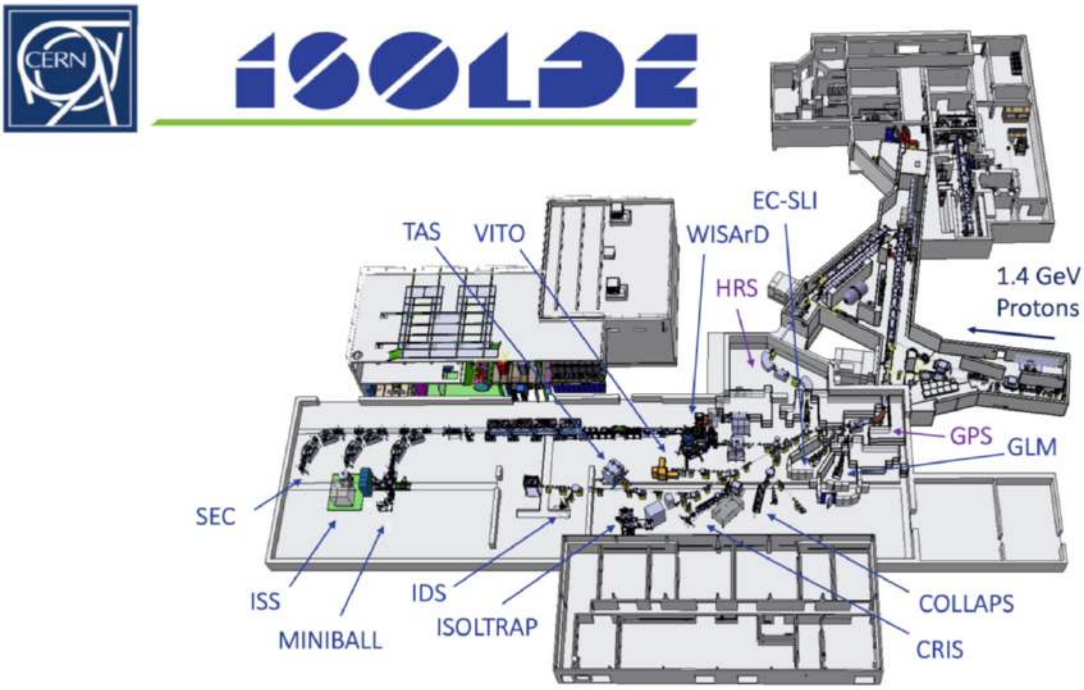

Figure 13.92: The ISOLDE facility showing the two mass separators and major instrumentation (see table below).

- EC-SLI: Online setup for emission channeling with short-lived isotopes.
- COLLAPS: Collinear laser spectroscopy.
- CRIS: Collinear resonant ionisation spectroscopy.
- ISOLTRAP: High-resolution Penning trap mass spectroscopy.
- ISOLDE DECAY STATION (IDS): Tape station system with facilities for fast-timing measurement of excited states lifetimes, proton and α emission, γ-ray spectroscopy, and neutron time-of-flight spectroscopy.
- TAS-LUCRETIA: Total absorption γ-ray spectrometer
- MIRACLS: Multi-reflection time-of-flight spectrometer for collinear laser spectroscopy.
- WISArD: Weak-interaction experiment focusing on $\beta\nu$ angular correlations.
- MINIBALL: High-resolution detector array for γ-ray spectroscopy following Coulomb excitation and transfer reactions.

- ISS: Solenoidal spectrometer for binary reaction studies.
- SEC: Large versatile scattering chamber for reaction experiments.

Nature of user facility

ISOLDE is a CERN user facility.

Program Advisory Committee/experiment proposals

The ISOLDE and Neutron-Time-of-Flight Experiments Committee (INTC) undertakes peer review of proposals 3 times per year and makes recommendations to CERN Research Board.

Number of active users and their origin

About 450 users coming every year to participate in around 50 experiments.

Percentage of users, and percentage of facility use that come from inside the institution

About 2% of registered users are from CERN.

Fraction of the international users from outside your geographical region

Around 20% from outside Europe.

User group

Representatives of ISOLDE member countries form the ISOLDE Collaboration Committee which meets three times a year. An annual ISOLDE Workshop and Users Meeting is held each winter.

Laboratory Staff

See Table 13.26.

Table 13.26: Staff at CERN/ ISOLDE. *One physicist, plus technical, operations, and user support – supplemented as required by technical experts from CERN Accelerator and Technology Sector. **CERN fellows. ***Non-resident graduate students with thesis work primarily done at the facility, with around 10-15 Ph.D. theses/year.

Designation	Number of persons
Permanent staff	15*
Temporary staff	3
Postdoctoral researchers	6-8**
(Resident) Graduate students	12-15
(Non-Resident) Graduate students	>50***
Undergraduate students	10-15

Special student programs

CERN Summer Student Programme; CERN Doctoral Student Programme; and CERN public engagement programs.

Future Plans

A 30-kV MR-TOF device is being developed to enhance beam purity. This will enable the PUMA experiment at ISOLDE, where trapped antiprotons will interact with radioactive ion beams. A project has started to demonstrate the feasibility of a novel design for a compact superconducting recoil separator. A new laboratory will soon be operational to produce nanomaterial based primary targets, improving target yields and lifetimes. Parallel delivery of beams from both HRS and GPS separators to end users is currently being developed. Work is underway to investigate the possibility to renovate and upgrade the beam dumps for the primary beam to facilitate delivery of 2-GeV protons and enhance the yield of spallation products and lighter mass fragments, particularly for exotic proton-rich species. In the longer term, the ISOLDE Collaboration has begun to develop plans for a significant future expansion of the facility to fully Exploit the Potential of ISOLDE at CERN (EPIC). Within EPIC, additional target stations to enhance the capacity of ISOLDE are being considered along with improvements to capability via beam purity and quality. Plans include improvements to post-acceleration and a new target hall to give space for new experimental installations.

CERN/ ALICE

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ALICE Management Board Spokesperson: Marco Van Leeuwen
CERN Director General: Prof. Fabiola Gianotti
Director for Research and Computing: J. Mnich
Director for Accelerators and Technology: M. Lamont

International Laboratory
Funding contributions from CERN Member States

Scientific Mission and Research Programs

Besides proton-proton collisions, aimed at exploring particle physics at the TeV scale, both proton-nucleus and nucleus-nucleus collisions are a significant part of the experimental program. With heavy-ions at a center-of-mass energy of 5.5 TeV per nucleon pair, the LHC carries the study of nuclear matter under extreme conditions and of the quark-gluon plasma into a new and unexplored energy domain.

The Large Hadron Collider (LHC) came into operation in 2009. The accelerator complex is typically operated for four-year running periods, interspersed with Long Shutdowns of 2-3 years each. Run 3 started in 2022, with a centre-of-mass energy of 13.6 TeV for pp collisions and 5.36 TeV per nucleon pair for Pb-Pb collisions. The ALICE detector underwent a major upgrade in Long Shutdown 2 (2019-2021) with a substantially improved pointing resolution and continuous readout for Pb-Pb interaction rates of up to 50 kHz. Besides proton-proton collisions, aimed at exploring particle physics at the TeV scale, and Pb-Pb collisions, proton-Pb collisions are planned also in Run 3 and 4. Short exploratory runs with other species have taken place in the past and are planned for the future.

Characterization of the facility

High energy proton-proton collider, relativistic heavy-ion collider.

Facility parameters

The LHC and the injector complex have undergone several upgrades to increase the heavy-ion luminosity in Run 3 (2022-2025). The expected peak luminosity for Pb-Pb collisions is 6×10^{27} $cm^{-2}s^{-1}$ at a collision energy of 5.36 TeV per nucleon pair. The centre-of-mass energy for pp collisions is 13.6 TeV with an instantaneous luminosity up to about 2.4×10^{34} $cm^{-2}s^{-1}$ in Run 3 (2022-2025). Beams with intermediate mass ion species can be collided at energies and luminosities between these values.

Facility's major experimental instrumentation and its capabilities

There are four large experiments at the LHC, which all participate in the heavy-ion program: ALICE is the general purpose experiment optimised for heavy-ion physics, while ATLAS and CMS are general-purpose particle physics experiments, and LHCb was optimised for b-physics and CP violation measurements.

Nature of user facility

Facility with general purpose detectors that are operated by large collaborations.

Program Advisory Committee/experiment proposals

Large Hadron Collider Committee (LHCC, 12 CERN + 21 international members)

Number of active users and their origin

ca. 2000 users working primarily with heavy ions, ca . 12000 working primarily in particle physics

Fraction of the international users from outside your geographical region

ca 30%

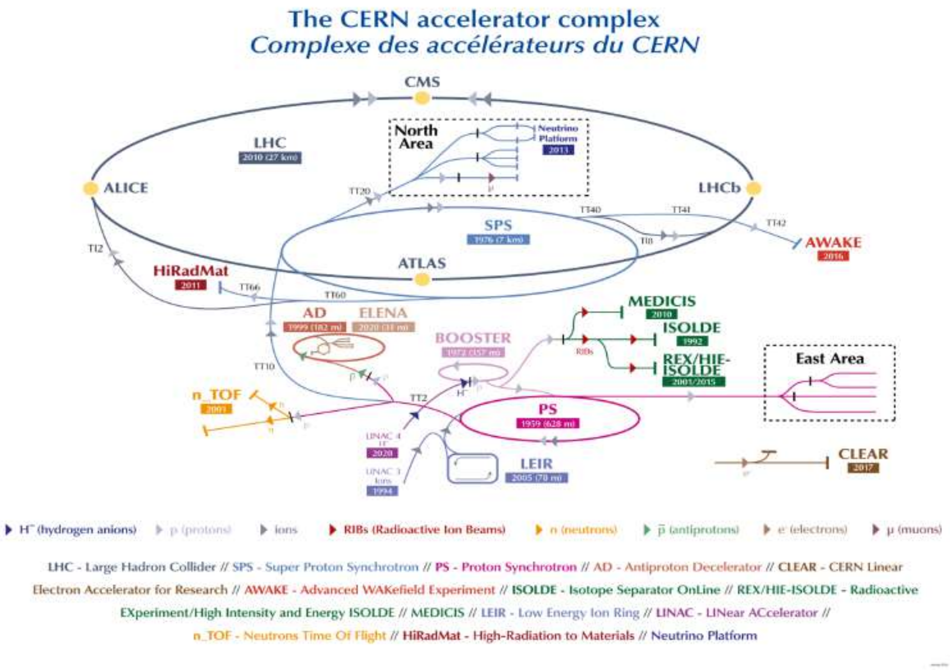

Figure 13.93: Accelerator complex at CERN (Image: CERN).

Figure 13.94: Beam View of the ALICE Detector (Photo: CERN).

PAUL SCHERRER INSTITUT (PSI)

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Scientific Mission and Research Programs

Precision physics with low-energy muons, pions and UCN.

Main fields of research: Materials science, life sciences, energy research. Muon spin spectroscopy with seven μSR instruments at the Swiss Muon Source SmuS. Radiation hardness tests of materials and electronic components and circuits with high intensity proton, neutron, electron, pion and photon beams. Neutron scattering and imaging with 16 instruments at the spallation neutron source SINQ. X-ray experiments at the 2.4 GeV electron synchrotron (Swiss Light Source SLS) with 16 beamlines and the free electron laser SwissFEL (5.8 GeV electron linac) with two photon beamlines.

Center for proton therapy treatment of cancer and related research with a dedicated 250 MeV cyclotron, 3 patient gantries (2 for treatment) and the OPTIS2 facility for treatment of ocular tumors. Production of radionuclides at SINQ and at the IP2 facility for radiopharmaceutical research.

Characterization of the facility

High Intensity Proton Accelerator facility HIPA with isochronous ring cyclotron running at 50.6 MHz frequency and delivering 2.4 mA proton current at 590 MeV. Secondary beams of $\pi^{\pm}$, $\mu^{\pm}$, and neutrons.

Facility's major experimental instrumentation and its capabilities

Several highest intensity, low-energy pion, muon and ultracold neutron (UCN) beamlines.

Program Advisory Committee/experiment proposals

Submission of proposals. Information on procedures for nuclear and particle physics available at https://www.psi.ch/ltp. Presentation in an open users meeting. PAC meets once per year. PAC committee consists of 1 in-house, 2 national, and 10 international members.

Future Plans

Light source upgrade SLS2.0 with a diffraction- limited storage ring (2024).

14. LABORATORIES IN NORTH AMERICA

SNOLAB

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Executive Director: Dr. Jodi Cooley

University Institute
Construction – Canada Foundation for Innovation, Ontario Innovation Trust, Northern Ontario Heritage Fund, FEDNor
Operation – Canada Foundation for Innovation, Ontario Ministry of Colleges and Universities

Scientific Mission and Research Programs

SNOLAB is located on the traditional territory of the Robinson-Huron Treaty of 1850, shared by the Indigenous people of the surrounding Atikameksheng Anishnawbek First Nation as part of the larger Anishinabek Nation. We acknowledge those who came before us and honour those who are the caretakers of this land and the waters.

SNOLAB is Canada's deep underground research laboratory. Located 2 kilometres below the Earth's surface in the Vale Creighton nickel mine near Sudbury, Ontario, Canada, it is one of the deepest, cleanest underground laboratories in the world. SNOLAB capitalizes on Canada's scientific strengths to facilitate world-class research, train highly qualified personnel, and inspire the next generation of leaders in science and innovation.

The scientific community has an increasing need for SNOLAB's unique combination of capabilities. Very deep, ultra-clean facilities and the in-house expertise and specialized technical and project management support allow researchers to build underground experiments. SNOLAB's depth provides an ideal low-radiation background environment for the study of extremely rare physical interactions. These capabilities are in demand by the Canadian and international particle physics communities, who have prioritized research into neutrinos and dark matter that require experiments to be extremely sensitive and more advanced than ever before.

Other fields can also take advantage of SNOLAB's deep underground facilities, and it has supported experiments in genomics, bioinformatics, and mining engineering. Further opportunities in life sciences, nuclear security, and quantum technology will emerge over the term of this plan. SNOLAB will expand its activities in these areas, while focusing on astroparticle and particle physics as the central science disciplines. The great depth at which SNOLAB is located is required to shield these sensitive detection systems from the ubiquitous cosmic radiations that bombard the surface of the planet. By placing 2km (6000m water equivalent) of rock between the detectors and the surface these cosmic rays are sufficiently attenuated, by a factor of 50 million down to one cosmic ray muon every day per 4m2, that the rare and exquisite signals from the science of interest can be separated from the signatures from other backgrounds.

Opportunities for SNOLAB will emerge over the term of this plan in nuclear security, quantum computing, biology, and geology. Detection of very small levels of radioisotopes can provide crucial information about nuclear events, thereby aiding national security interests. Specifically, SNOLAB will enable projects that support nuclear non-proliferation, including the Comprehensive Nuclear Test Ban Treaty (CTBT). Canada's involvement in the rapidly growing quantum technology industry is expanding. Research and testing on superconducting quantum devices in a low radiation environment will provide valuable insights to advance the technology, and such an environment may be required to operate the technology. SNOLAB will continue supporting programs in life sciences, including experiments on the impact of low radiation environments on cellular mutation and repair processes and experiments on the impact of deep underground environments on metabolism.

Our vision is to be the leading international laboratory in deep underground science, hosting the world's most advanced experiments that provide insight into the nature of the universe.

Our mission is to

- Enable world-class underground science performed by national and international collaborative research teams, supporting projects from concept to completion;
- Spearhead research and development that maximizes the potential scientific and societal impact from underground projects;
- Catalyze scientific collaboration and knowledge exchange through workshops, local engagements, and professional outreach;
- Promote innovation through transfer of arising technologies; and
- Inspire the next generation of scientists, innovators, and leaders through strong public and educational outreach and formative training opportunities.

Characterization of the facility

Underground laboratory.

Technical facilities

The facility includes a surface building which houses offices, conference rooms, IT systems, cleanrooms, electronics labs, warehousing and change rooms. The underground facility is located at a depth of 2070 m and comprises 5000 m^2 of clean room facility, at better than Class2000, including three large detector cavities. In addition to the required health and safety systems and user support services, support infrastructure for experiments within the underground laboratory include HVAC, electrical power, ultra-pure water, compressed air, radiological source control, radio-assay capability, chemistry lab, I.T. and networking, and materials handling and transportation. The very specific requirements of developing and operating experiments in an underground laboratory are supported by a staff of 140 people covering business processes, engineering design, construction, installation, technical support and operations. The SNOLAB scientific research group connects to the experiments and provides expert and local support, as well as undertaking research in its own right as full members of the research collaborations.

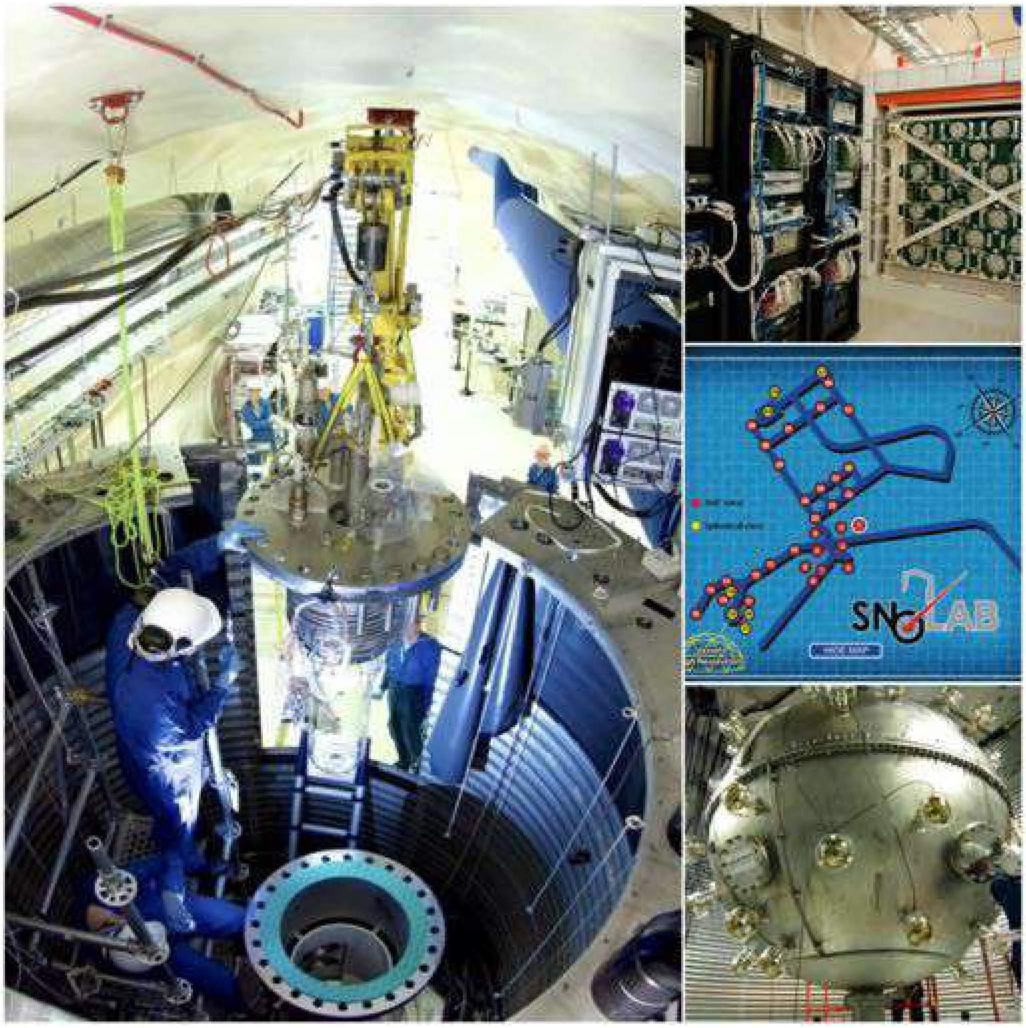

Figure 14.1: The SNOLAB underground facilities are located at the 6800 foot level of the Vale Creighton Mine and include the original SNO cavern.

Facility parameters

- Underground clean room area / volume: 5000 m^2 / 37000 m^3
- Rock overburden: 2070 m
- Muon flux: 3×10^{-6} m^{-2} s^{-1}
- Thermal neutron flux: $4.7\times$ 10^{-2} m^{-2} s^{-1}
- Fast neutron flux: 4.6×10^{-2} m^{-2} s^{-1}
- Ambient air radon level (Bq m): 130 Bq m

Program Advisory Committee/experiment proposals

All Experiment LOI's are submitted to SNOLAB to be reviewed by the Experiment Advisory Committee.

Figure 14.2: The surface building provides clean room space, change facilities, meeting rooms and office space for the underground experiments.

Number of active users and their origin

Currently about 1100 people use the SNOLAB facility (includes faculty, RA's, students and engineers) from 164 Institutions worldwide.

Percentage of users, and percentage of facility use that come from inside the institution

5% internal, including researchers, technicians, engineers and researchers.

Percentage of users and percentage of facility use from national users

About 17% of the users (PI, Research Scientists) are from Canada. About 30% of the HQP are from Canada.

Percentage of users and percentage of facility use from outside the country where your facility is located

About 83% of the users are from outside Canada

Fraction of the international users from outside your geographical region

52% of users are from North America.

Laboratory Staff

Number of non-resident graduate students with thesis work primarily done at the facility: 101 MSc and 233 PhD total so far.
Involvement of undergraduate students in research (approximate average number at a given time): 63 in 2022.

TRIUMF

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Executive director and CEO: Nigel Smith
E-mail: director@triumf.ca

TRIUMF INC. is a joint venture owned by a consortium of Canadian universities
Funded by the Canadian Federal Government under a contribution administered by the National Research Council of Canada (NRC).
Experimental program supported by the relevant Science Research Councils
(Peer reviewed: Natural Science and Engineering Council NSERC, Canadian Institute for Health Research CIHR, etc.)

Scientific Mission and Research Programs

TRIUMF is Canada's national laboratory for particle and nuclear physics and accelerator-based science. It is owned and operated as a joint venture by a consortium of (presently 21) Canadian universities via a contribution through the National Research Council Canada with building capital funds provided by the Government of British Columbia. Its mission is to serve as Canada's particle accelerator centre; to advance isotope science and technology, both fundamental and applied; to collaborate across communities and disciplines, from nuclear and particle physics to the life and material sciences; to discover and innovate, inspire and educate, creating knowledge and opportunity for all.

TRIUMF was founded in 1968 by Simon Fraser University, the University of British Columbia (UBC), and the University of Victoria to meet research needs that no single university could provide. The University of Alberta joined the TRIUMF consortium almost immediately. There are currently (June 2023) 21 full members from across Canada in the consortium that governs TRIUMF.

Since its inception as a local university facility, TRIUMF has evolved into a national laboratory while still maintaining strong ties to the research programs of the Canadian universities. The science program has expanded from nuclear physics to include particle physics, molecular and materials science, accelerator physics, and nuclear medicine. TRIUMF provides research infrastructure and tools that are too large and complex for a single university to build, operate, or maintain.

Since its opening in 1969, the laboratory has received more than $1 billion of federal investment and $40 million from the Province of British Columbia. The provincial contributions fund the buildings, which are owned by UBC and located on an 11-acre site in the south campus of UBC.

There are over 550 scientists, students, engineers, and staff performing research on the TRIUMF site. It attracts over 600 national and international researchers every year and provides advanced research facilities and opportunities to over 200 students and post-doctoral fellows each year. In addition to the onsite program, TRIUMF serves as a key broker for Canada in global research in particle, nuclear, and accelerator physics.

Characterization of the facility

- Intermediate energy proton (H^-) Cyclotron (500 MeV), four independent extracted beams: 150 μA, 100 μA, 60 μAs and 10 μA.
- ISAC-I facility: Low-energy beams or via RFQ linac, Drift Tube Linac for acceleration of stable and radioactive beams up to 1.8 MeV/u.

- ISAC-II facility: Superconducting Linac for for acceleration of stable and radioactive beams up to 16 MeV/u.
- Four low-energy H^- cyclotrons: two high intensity machines (1 to 2 mA) 30 MeV and two 50 μA at 42 MeV and 13 MeV dedicated to isotope production for life sciences and medical applications.

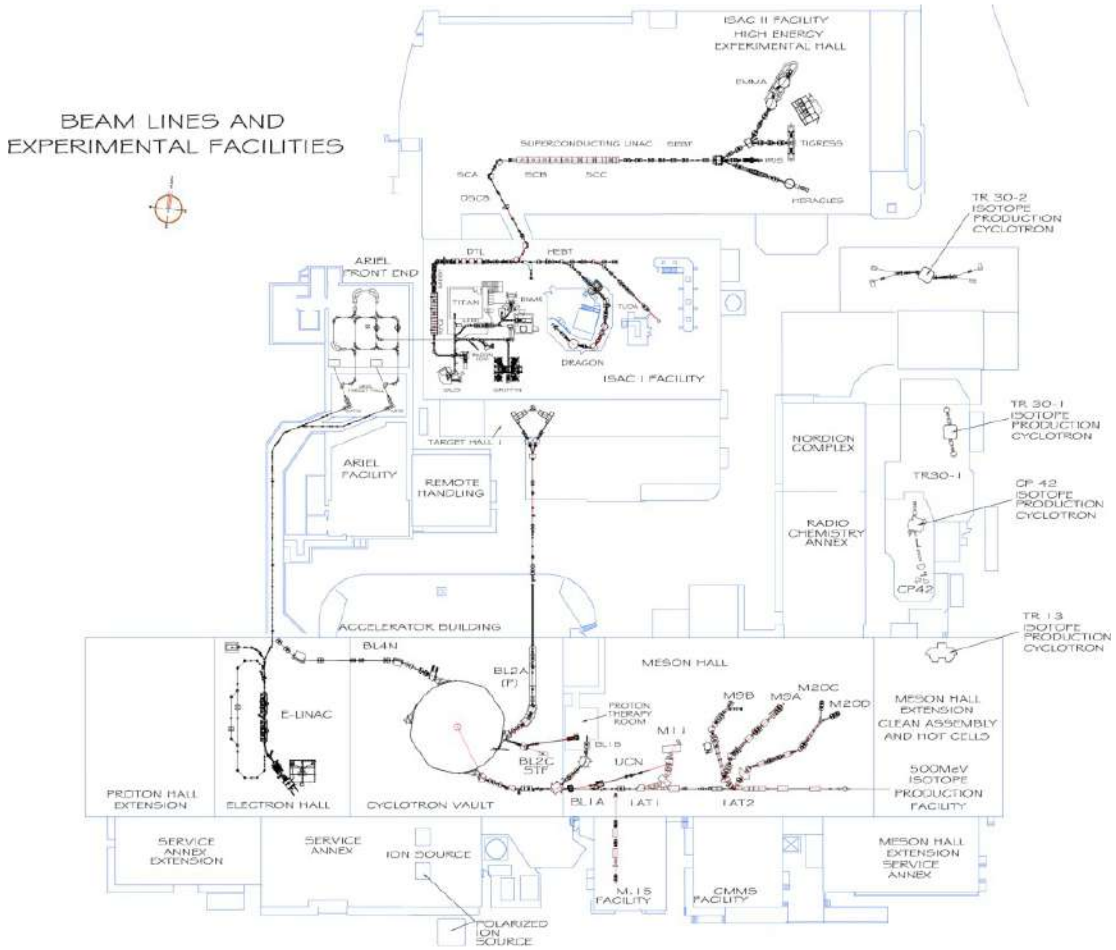

Figure 14.3: Beam lines and experimental facilities at TRIUMF.

Technical facilities

Facility parameters

- Protons: 60-100 MeV and 200 -500 MeV 150 μA
- Muons: up to 150 MeV/c 10^7/sec
- Radioactive beams from ISOL facility ISAC: up to 6.0 MeV/u, mainly A<150, up to 10^8/sec (isotope dependent)

Facility's major experimental instrumentation and its capabilities

The following instrumentation is available at the ISAC facilities:

- TRINAT: Neutral atom trap
- GRIFFIN: 16 Large volume Germanium Clover detector array
- Polarizer: polarized low energy ion beams (currently ^{8}Li, ^{11}Li, Na, Mg)
- βNMR/ βNQR: Depth controlled magnetic characterization of surfaces and interfaces
- Laser- spectroscopy: Collinear laser spectroscopy beamline
- TITAN: Penning trap for mass measurement and in-trap decay spectroscopy

- Francium: Francium atom trapping facility
- OSAKA: Polarized beta-decay spectroscopy
- DRAGON: low energy recoil spectrometer and windowless gas target for radiative capture reactions for nuclear astrophysics
- TUDA: Segmented silicon detector array for low energy charged particle reactions in nuclear astrophysics
- TIGRESS: 12 Large volume segmented Germanium Clover detector array.
- DESCANT: Neutron detector array for TIGRESS and GRIFFIN
- IRIS: Solid hydrogen target reaction station
- EMMA: Electromagnetic recoil spectrometer for ISAC II

In addition: μSR spectrometers for condensed matter research.
Radiochemistry facilities for life science tracers development.
Large Clean rooms for detector development and construction.

Nature of user facility

Yes, by the funding agency.

Program Advisory Committee/experiment proposals

TRIUMF has four EECs (Experiment Evaluation Committees): Subatomic Physics, Molecular and Materials Science, Particle Physics, and Life Sciences. More information can be found at https://www.triumf.ca/research-program/planning-experiments/experiment-approval/about-eec-lspec-committees.

The first two meet twice a year and the last meets once a year. The laboratory is also advised by a Policy and Planning Advisory Committee composed of leading Canadian researchers in relevant subject areas that provide strategic advice on overall program direction.

Number of active users and their origin

Over 640 scientific visitors per year.

Percentage of users, and percentage of facility use that come from inside the institution

It is estimated that more than 75% of the users come from outside the institution.

Percentage of users and percentage of facility use from national users

On average 35% Canadian users

Percentage of users and percentage of facility use from outside the country where your facility is located

On average 65% of the visitors come from outside Canada.

Fraction of the international users from outside your geographical region

Australia & New Zealand: 2 users (0.3%).
Europe: 99 users (15%).
Asia: 113 users (18%).
USA/Mexico: 226 users (35%).

User group

The elected TRIUMF User Executive Committee represents the TRIUMF User Group with currently around 300 registered members: www.triumf.ca/triumf-users-group.

Laboratory Staff

The formal FTE staff complement of TRIUMF is about 400; including undergraduate students, graduate students, postdoctoral fellows, and temporary workers, the total is over 550 (see Table 14.1).

Table 14.1: Staff at TRIUMF. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Staff	∼400
Theory staff	11
Postdoctoral researchers	∼56
(Resident) Graduate students	∼56
(Non-Resident) Graduate students	∼29*
Undergraduate students	∼100/ year

Special student programs

High School: Research fellowships (2/y); Undergraduate students: Summer research fellowships (5/y); summer research awards and Coop term (100/y); Graduate students: Summer Institute: (40 students each summer); Journal clubs.

Future Plans

Facility upgrades include

- the Advanced Rare IsotopE Laboratory (ARIEL): 50 MeV, 10 mA electron linac for photon-induced production of rare isotopes; additional proton beamline for rare isotope production with 50 kW, 500 MeV protron beam.
- Ultra Cold Neutron facility: Spallation target with 40 μA, UCN production target (commissioning); nEDM experiment; Second UCN port for various experiments.

TANDEM VAN DE GRAAFF ACCELERATOR, INSTITUTO NACIONAL DE INVESTIGACIONES NUCLEARES (ININ)

Tandem Van de Graaff Accelerator,
Departamento de Acceleradores y Estudio de Materiales,
Gerencia de Ciencias Ambientales, Dirección de Investigación Científica,
Instituto Nacional de Investigaciones Nucleares,
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General Director of ININ: Dr. Javier C. Palacios Hernández
Director of Scientific Research: Dra. Verónica E. Badillo Almaraz
Manager of Environmental Science: Dra. Claudia E. Gutiérrez Wing
Head of the department: Dra. Paulina Amador Valenzuela
E-mail: paulina.amador@inin.gob.mx
URL: https://www.gob.mx/inin/acciones-y-programas/acelerador-tandem-van-de-graaff-73303

National Institute
Main sources of funding: Budget from the Institute (Secretary of Energy)
and Federal grants for research projects (Conacyt-Mexico)

Scientific Mission and Research Programs

The Tandem Van de Graaff accelerator at ININ still is the accelerator that is able to produce the highest operational voltage in Mexico. The mission of the laboratory is forefront research in nuclear physics and ion beam analysis.

The major research programs are dedicated to the study of nuclear reactions, mainly to measure experimental cross sections for fusion, elastic and inelastic scattering, using heavy ion beams. Ton beam analysis is another activity of great importance implemented for the determination of elemental composition by using techniques such as PIXE, PIGE, RBS, ERDA and NRA. The principal applications of these ion beam analysis techniques are focused on atmospheric particles pollutants, soils and geological samples, water and materials science.

Characterization of the facility

6 MV nominal voltage Tandem Van de Graaff accelerator with a SNICS II ion source. For the research programs of the department the maximum operated voltage required is 3.5 MV and the minimum being 1.0 MV. The commissioning year was 1968. The facility has an injector, an analyzing and a switching magnet with a total of seven experimental ports (five of them currently in use) and uses carbon as foil stripper.

Facility parameters

Under special conditions and if budget is approved, the facility is able to produce beams of heavier ions. Beryllium beam is produced using a molecular cathode. The facility is the only one in the country with the permit from the corresponding national regulatory commission to produce deuterium.

Facility's major experimental instrumentation and its capabilities

1. Scattering chambers (some of them designed and manufactured at ININ),
2. Charged particle detectors,

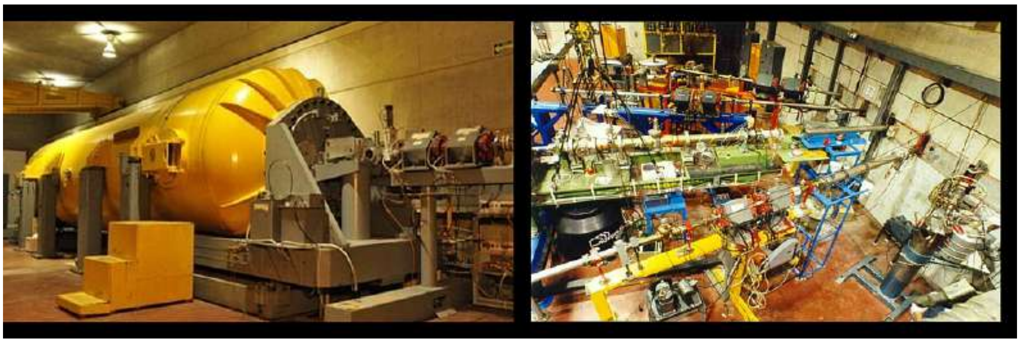

Figure 14.4: View of the Tandem Van de Graaff accelerator tank and experimental setups.

Beam	Ion charges	Analyzed currents (nA)	Range of energies (MeV)
H, D	1+	40 – 600	2 – 7
Li	2+, 3+	2 – 8	3 – 14
Be	3+, 4+		4 – 17.4
B	3+, 4+, 5+	5 – 40	4 – 21
C	3+, 4+, 5+	15 – 200	4 – 21
O	4+, 5+, 7+	50 – 150	5 – 28
N	2+, 3+, 5+	2 – 10	3 – 21

Figure 14.5: Beam species at ININ.

3. Gamma and X ray detectors,
4. Capability for neutron beams production dedicated for spectroscopy by using the D(d,n)^{3}He and ^{9}Be(D,n)^{10}B nuclear reactions, with typical neutron yields of 10^8 and 10^{10} n/sec, respectively. The facility is the only one in the country with the permit from the corresponding national regulatory commission to produce neutrons using these nuclear reactions.
5. Capability for external beam, beamline dedicated to perform ion beam analysis (at atmospheric pressure) in big samples and to prevent structural damage, in anthropological samples, for example.

Nature of user facility

The main purpose of the Tandem Van de Graaff facility is to provide the beamtime required for experiments of scientists of the department that have projects approved with either external or internal funds. In general, beamtime is not offered to external users. However, scientists from outside the Institute could use the facility if they are associated (under a collaboration) with scientists of the department.

Program Advisory Committee/experiment proposals

Beamtime is granted by a program advisory committee formed by the scientists, technicians, operator of the facility as well as the head of the department.

Number of active users

Number of active users is 9 per year.

Percentage of users, and percentage of facility use that come from inside the institution

In a typical year a total of 1000 hours of beamtime is offered at the facility, 75% is for basic research, 15% for applications and 10% for education. 95% of the users are from inside the department/ institution.

Percentage of users and percentage of facility use from national users

Approximately 4% of users are from outside the Institute (national universities) and are in collaboration with researchers from the department.

Percentage of users and percentage of facility use from outside the country where your facility is located

About 1% of users (in the past five years) are from outside the country, but they are in direct collaboration with researchers from the department.

Fraction of the international users from outside your geographical region

In the past five years there has been one international user (in direct collaboration with researches from the department) from Europe.

User group

No.

Laboratory Staff

See Table 14.2.

Table 14.2: Staff at ININ. *Includes 6 with a doctoral degree. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent laboratory staff	13*
Theoretical staff	1
Postdoctoral researchers	2
(Resident) Graduate students	2
(Non-Resident) Graduate students	2**
Undergraduate students	3/ year

Special student programs

Every two years, some activities of the Mexican Summer School of Nuclear Physics (organized by the nuclear physics division of the Mexican Physics Society) are held at the Tandem Van de Graaff Facility. As part of the "Summer of Scientific Research Program" (organized by the Mexican Academy of Sciences) students (undergraduate and graduate) around the country can collaborate in a short project with researchers of the facility, the duration is a couple of months.

Guided visits for groups of students from universities.

Future Plans

Planning to finish the experimental line intended for experiments using Time of Flight for astrophysical experiments

LABORATORY OF PELLETRON ACCELERATOR, INSTITUTO DE FISICA, UNAM

Main University Campus of UNAM
Laboratory of Pelletron Accelerator
Instituto de Fisica, UNAM Circuito de la Investigación Científica s/n Ciudad Universitaria
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Telephone: +52 55 56225043 / 56225005
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Head of the facility: Dr. José Luis Ruvalcaba Sil
E-mail: sil@fisica.unam.mx
Director Instituto de Fisica, UNAM: Dr. Arturo Menchaca Rocha
E-mail: karim@fisica.unam.mx

Research laboratory of an institute of the national university
Three main sources of funding:
i) Federal grants for research projects (CONACyT-Mexico).
ii) University grants for short term research projects (UNAM).
iii) Budget from the institute.

Scientific Mission and Research Programs

The Pelletron laboratory is one of the most important laboratories of the National University of Mexico (UNAM), Mexico and of the Latin American countries. The main activity of the laboratory is research focused on three subjects: i) Fundamental physics on phenomena related to interaction between ion beams and matter. ii) Ion beam analysis of materials and its applications. iii) Ion beam modifications of materials.

There is no other laboratory in Mexico with these three features. The research topics are determined and described in detail in the development program of the institute (IFUNAM, http://www.fisica.unam.mx/plan2003.pdf). The main research topics are:

1. Nuclear Reactions in Astrophysics
2. Thermoluminiscence properties of irradiated materials.
3. Atomic and molecular physics.
4. Development of analytical methods based on ion beam accelerators
5. Interdisciplinary applications of ion beam analysis (materials science, archaeology and arts, geology and soils, food, odontological materials, biomaterials, etc.).
6. Pollution and environmental studies.
7. Biological and medical tissues studies by ion beam analysis
8. Applications of ion beam dosimetry.
9. New materials and modification of surface properties by ion beam implantation and ion beam mixing.

Future research projects must fit the research frame of the institute. The revision of the program of research is carried out every three years or less, if necessary.

Under the actual research program it is considered the development of the following devices in the next future to complete and improve the researches:
a) A microbeam facility for materials characterization (biological, medical, nanomaterials, national heritage).
b) A WDX spectrometer for the study of ionization processes and X-ray emission by heavy ions and for analytical purposes.

Characterization of the facility

Low-Medium Energy Tandem Pelletron Accelerator (3 MV) for ion beam analysis and ion beam implantation.

Facility parameters

See Table 14.6.

Beam species	Ion source	Ion charges	Intensities*	Range of energies	Remarks
H	SNICS	1^+	1nA-1mA	1-6 MeV	No radioactive beams are used; it is not allowed to produce neutrons and deuterons by nuclear reactions.
He	Alphatross	$1^+, 2^+$	1nA-300 nA	1-12 MeV	
C, Si	SNICS	$2^+, 3^+, 4^+$	1nA-5mA	1-18 MeV	
N, O	SNICS	$2^+, 3^+$	1nA-500 nA	1-12 MeV	
Cu, Au	SNICS	$2^+, 3^+, 4^+$	1nA-3mA	1-18 MeV	
Ag	SNICS	$2^+, 3^+$	1nA-0.5mA	1-18 MeV	

Figure 14.6: The parameters for the most used ions at UNAM (*The intensity depends on the ion charge).

Facility's major experimental instrumentation and its capabilities

Note: Fundamental physics measurements are carried out also in the analytical beam lines.

Technical facilities

The main instrument of the laboratory is a 3 MV Tandem Pelletron Accelerator with four fully operational ion beam lines. It is possible to produce ions from H to Au or even heavier (except noble gas from Ar). The maximum energy of the beam depends on ion charge and ion production cross sections. Two kinds of ion sources are available: A ion sputtering source for solids (SNICS) and a plasma radiofrequency (RF) source for gases (Alphatross).

One beam line is used mainly for measurements of astrophysical reactions and light isotopes separation while two beam lines may be used for ion beam analysis in vacuum or for non-vacuum measurements by an external beam set-up at the air atmosphere. The main analytical techniques are PIXE, RBS (including channeling) and PIGE but ERDA, PESA, XRF and NRA may also be carried out. Finally, one line is used for ion beam implantation and the modification of the surface properties of materials. Measurements on basics processes of interaction of heavy and light ion beams with materials may be done on most of the ion beam lines (e.g. ionization cross sections by heavy ions).

Low, medium and high vacuum equipment, high performance electronics devices, detectors of radiation (X-rays, Gamma rays, particles, UV and visible light), computers for the accelerator control and data acquisition are associated with the accelerator and represent a valuable part of the laboratory.

3 MV Tandem Pelletron Accelerator, Instituto de Fisica, UNAM, Mexico							
	Main Purpose	Fully Oper.	Most used ion beams	Remarks	Type and number of detectors	Most used methods of analysis	Main topics of research
Beam lines	Ion beam interaction's phenomena	3*	H, He, C, N, O, F				Ionizations, Scattering and nuclear reactions cross sections, mainly
	Ion beam analysis	2	H, He, C, Si	+ one external beam	X-rays (4) Gamma-rays (2), Particles (8)	PIXE, RBS, RBS-channeling PIGE, PESA, ERDA.	Atmospheric pollution, odontological and biological studies, food analysis, national heritage studies (Archaeology and arts), soils and geology samples.
	Ion beam implantation	1	H, He, Si, C, Ti, Cu, Ag, Au	Max. area of irradiation: 10x10 cm			Nanomaterials, New surface properties (metals, polymers, semiconductors, biomaterials).

Figure 14.7: Experimental areas at UNAM.

Figure 14.8: Experimental areas at UNAM.

Nature of user facility

Since the use of the laboratory require a high degree of specialization on ion beam accelerators, radiation production and management and its detection, the research staff of the Experimental Physics Department of the Instituto de Fisica represents the main official user of the facility. All the experiments are approved or rejected by a scientific committee who determine the research feasibility and if the experiments keep under the radiological security regulations for this laboratory.

Scientifics and research people from other institutes of the UNAM or other universities of the country may use the facility if they are associated to a member of the staff of the facility, mainly by a research project approved by the scientific committee of the laboratory. They may be considered also as external users when they have access to the laboratory by an external service, by short terms contracts for a specific use (analysis or irradiation). Non-university institutions and industry are always considered as external users.

Program Advisory Committee/experiment proposals

The facility has a scientific committee who determine the feasibility of a research and if the experiments accomplish the radiological security regulations for this laboratory. The research topics and scientific applications are mainly determined by the frame- program of development and research of the institute.

Number of active users and their origin

Regular users from the research departments of the institute per month (average of the last three years): 14 research scientists.

Percentage of users, and percentage of facility use that come from inside the institution

85%. Facility use: 85%.

Percentage of users and percentage of facility use from national users

Users from other institutes and universities: 10%. Facility use: 10% . External users: 5%. Facility use: 5%

Percentage of users and percentage of facility use from outside the country where your facility is located

Foreign users: 2%. Facility use: 5%

Fraction of the international users from outside your geographical region

One. The group GAMMAI (Group of Analysis and Modification of Materials by Ion Beams) is in charge of the management of the Pelletron accelerator laboratory. It is composed by 8 research scientists and 4 technicians.

Laboratory Staff

See Table 14.3.

Table 14.3: Staff at UNAM. *5 research scientists and 2 technicians. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	7*
Temporary staff	4 PhD students
Postdoctoral researchers	0
(Resident) Graduate students	6
(Non-Resident) Graduate students	12**
Undergraduate students	15

Special student programs

Summer programs (between one and two months) organized by the Mexican Academy of Science and the UNAM program of science for young students (high school and university). Open laboratory days (One full day for university students, one for high school and secondary students). Guided visits for students (around 15 per year).

Future Plans

Under the actual research program it is considered the development of the following developments in the next future:
a) A micro-beam facility for materials characterization (biological and medical tissues, studies on nanomaterials, samples related to national heritage). The expected spatial resolution of the

experimental set-up is 1 μm.
b) A WDX spectrometer for the study of ionization processes and X-ray emission by heavy ions and for analytical purposes.
c) A new chamber for ion beam implantation. The main new features of this device concern to in situ characterization and the control of the sample temperature.

7-MV ACCELERATOR, UNIVERSITY OF KENTUCKY

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Head of the facility: Prof. Steven W. Yates
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Chair Department of Physics and Astronomy: Prof. Bradley Plaster
http://www.pa.uky.edu/accelerator

Construction: Commonwealth of Kentucky
Operation: University of Kentucky
Nuclear Structure and Neutron-Induced Reactions (Sponsored by the U. S. National Science Foundation and Department of Energy, Office of Science, Office of Nuclear Physics)

Scientific Mission and Research Programs

The primary mission is to carry out basic research in nuclear science, with a special emphasis on neutron- induced reactions. An equally important goal is to provide high-quality education for students in nuclear physics and nuclear chemistry. A secondary missionis to search for applications, which contribute to national security or energy independence. Current research is focused primarily on examining the structure of complex nuclei and on the determination of neutron scattering cross sections of importance for advanced reactor and other applications.

Future research will likely focus on acquiring data which contributes to our understanding of fundamental symmetries and current questions in nuclear physics, with a strong emphasis on nuclear structure.

Characterization of the facility

The single-ended electrostatic accelerator is housed in a cylinder tower adjacent to the Chemistry-Physics Building. Only light ions are accelerated, all with nanosecond pulsed/bunched beams. Pulse widths: protons – 0.8 ns; deuterons and He ions – 1.3 ns. Sub-nanosecond pulsing is available through post- acceleration bunching.

Facility parameters

Accelerated energies:

- protons – 0.4 MeV to 7.0 MeV
- deuterons – 0.4 MeV to 7.0 MeV
- $^{3}He^{+}$ ions – 1 MeV to 7.0 MeV
- $^{4}He^{+}$ ions – 1 MeV to 7.0 MeV

All beams are available as nanosecond-pulsed beams or continuous beams. Pulsed beams have average intensities of 1 to 5 microamps, and continuous beams can be up to 30 microamps.

Facility's major experimental instrumentation and its capabilities
Technical facilities

Please see http://www.pa.uky.edu/accelerator/ and associated links.

Nature of user facility

Unofficially, several groups visit each year to collaborate on experiments, because of our special capabilities in neutron-induced and neutron- producing reaction studies. Commercial firms can purchase beam time.

Program Advisory Committee/experiment proposals

Arrangements are made to accommodate users by contacting Prof. Steven W. Yates.

Number of active users and their origin

Over the last few years, several research teams have visited to carry out experiments of their own design. University of Dallas, Prof. S. F. Hicks and undergraduate students; U. S. Naval Academy, Prof. J. R. Vanhoy and undergraduate students; University of Guelph, Prof. P. E. Garrett, graduate students and postdoctoral scholars; Georgia Institute of Technology, Prof. J. L. Wood ; Mississippi State University, Prof. Benjamin P. Crider and graduate students.

Percentage of users, and percentage of facility use that come from inside the institution

Inside users: 50%

Percentage of users and percentage of facility use from national users

National users (including Canada) 45%

Percentage of users and percentage of facility use from outside the country where your facility is located

5% outside the U.S.

Fraction of the international users from outside your geographical region

All are from Europe and Canada.

User group

No formal user group exists.

Laboratory Staff

Table 14.4: Staff at Accelerator Facility at U Kentucky. *Total laboratory staff (2 with doctoral degree). **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	3*
Theoretical staff	1
Postdoctoral researchers	2
(Resident) Graduate students	0
Undergraduate students	$\sim$2/ year

Special student programs

Graduate students from the University of the Western Cape in Cape Town, South Africa.

Future Plans

There are no expansion plans; the last major accelerator upgrade was in 1990.

CYCLOTRON AT LAWRENCE BERKELEY NATIONAL LABORATORY (LBNL)

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Telephone: +1-510-486-5088

Head of the facility: Dr. Larry Phair
E-mail: LWPhair@lbl.gov

Department of Energy Office of Science for Nuclear Physics

Scientific Mission and Research Programs

Part of the Nuclear Science Division, the 88-Inch Cyclotron supports ongoing research programs in nuclear structure, astrophysics, heavy element studies, and technology R&D by Lawrence Berkeley National Laboratory (Berkeley Lab) and UC Berkeley. Major instrumentation at the 88-Inch Cyclotron include the Berkeley Gas-filled Separator (BGS), and the superconducting VENUS ion source, one of the most powerful Electron Cyclotron Resonance (ECR) ion sources in the world.

Characterization of the facility

The 88-Inch Cyclotron accelerates both light and heavy ions to low energies.

Facility parameters

See Table 14.9.

Ion	Energy range	Max intensity	Primary uses
protons	1-60 AMeV	20000 nA	Radiation effects testing, nuclear science
Deuterons	1-32.5 AMeV	20000 nA	Neutron production, nuclear science
^{3}He	1-45 AMeV	20000 nA	Nuclear science
^{4}He	1-32.5 AMeV	20000 nA	Nuclear science, isotope production, radiation effects testing
Ions A = 7-40	1-32.5 AMeV for q/A=1/2	10000 nA	Nuclear science, radiation biology
Ions A = 40-180	Maximum energy depends on q/A (> Coulomb barrier)	3000 nA	Nuclear science
Heavy Ion Cocktails (A = 3-209)	4.5, 10, 16, 20 AMeV	1E7 ions/cm^2/sec	Radiation effects testing

Figure 14.9: Facility parameters at the 88 inch cyclotron.

Technical facilities

The 88-Inch Cyclotron at Lawrence Berkeley National Laboratory (LBNL) is a variable energy, high-current, multi-particle cyclotron capable of accelerating ions ranging from protons to uranium at energies approaching and exceeding the Coulomb barrier. Maximum currents on the order of 10 particle μA, with a maximum beam power of 2 kW, can be extracted from the machine for use in experiments in 8 experimental “caves”. Beam currents up to the mA level could also be developed through the use of internal ion sources and targets. These beams are used in conjunction with the Berkeley Gas-filled Separator (BGS) and the FIONA ion trap, a key facility for superheavy element research. In addition to single-isotope beams, the cyclotron's Berkeley Accelerator Space Effects (BASE) Facility can produce mixed-ion "cocktail" beams for use in single event effects (SEE) studies. The cyclotron can also produce high-intensity pulsed, neutron beams via thick target deuteron breakup whose energy can be determined via time-of- flight.

Facility's major experimental instrumentation and its capabilities

- Berkeley Gas-Filled Separator (BGS): A He-filled separator which has high efficiency for normal kinematic experiments for heavy element physics and chemistry. The BGS provides rejection of beam-like and fission fragment nuclides formed in heavy-ion reactions in excess 1×10^{12} for use in heavy-element research. The back end of the BGS can accommodate an array of pixelated Micron "W2" Si detectors and three "Clover" HPGe detectors for use in alpha- and gamma-decay spectroscopy of evaporation product nuclides. Alternatively, the back end of the BGS can be coupled to the FIONA ion trap that can isolate a single charge-to-mass ratio fragment.
- Berkeley Accelerator Space Effects (BASE) Facility: Radiation effects testing. Heavy ions used at the BASE Facility are accelerated in the form of "cocktails," named because of the fact that numerous heavy ions with the same mass-to-charge ratio are injected into the cyclotron, which accelerates the ions while acting as a precision mass separator. The cyclotron frequency is used to select only the desired ion, a process that takes about 3 minutes.
- Neutron Beamlines: Pulsed, high intensity neutron beams based on thick target deuteron break-up are available with a broad spectral range (50 keV to 62 MeV), centered at roughly half the beam energy. Samples can be placed as little as 5 centimeters away. Low intensity neutron beams are also available for spectroscopy measurements.

Nature of user facility

The Cyclotron is supported to run a local program in nuclear science and a national program for radiation effects testing using the BASE Facility.

Program Advisory Committee/experiment proposals

No.

Number of active users

300

Percentage of users, and percentage of facility use that come from inside the institution

20% of users; 60% of facility use

Percentage of users and percentage of facility use from national users

0% of users (not a national user facility)

Percentage of users and percentage of facility use from outside the country where your facility is located

5% users; 1% of facility use

Fraction of the international users from outside your geographical region

100%

User group

No.

Laboratory Staff

See Table 14.5.

Table 14.5: Staff at the LBNL 88 inch cyclotron. *11 with a doctoral degree. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	33*
Postdoctoral researchers	4
(Resident) Graduate students	10
(Non-Resident) Graduate students	2**
Undergraduate students	5/ year

Special student programs

We provide research experiences to undergraduate students through DOE programs such as SULI and CCI. In addition we are collaborating with the UCB Physics Department on ways to get their undergraduates more hands-on research experience.

We provide research experiences to high school students through the LBNL summer high school program

Future Plans

1) The MARS ion source will be built and coupled to the Cyclotron, providing higher energies and intensities of heavy ion beams.
2) Monoenergetic neutron beams using thin targets.

ATLAS (THE ARGONNE TANDEM LINAC ACCELERATOR SYSTEM) ARGONNE NATIONAL LABORATORY (ANL)

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Laboratory Director: Dr. Paul Kearns
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ATLAS Scientific Director: Dr. Guy Savard
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Department of Energy, Office of Science, Nuclear Physics Department of Energy Office of Nuclear Physics SC-26

Scientific Mission and Research Programs

The mission of the ATLAS facility at Argonne is to enable research of the highest quality by its users and staff, especially probing the properties of atomic nuclei, through utilizing the capabilities of the accelerator and research equipment in a safe and efficient manner, with the associated responsibility of research and development in accelerator science and in the techniques that are required to accomplish its scientific goals. The major scientific goals of the ATLAS research program are: (a) understanding of the stability and structure of nuclei as many-body systems built of protons and neutrons bound by the strong force, (b) exploring the origin of the chemical elements and their role in shaping the reactions that occur in the cataclysmic events of the cosmos, (c) understanding of the dynamics governing interactions between nuclei at energies in the vicinity of the Coulomb barrier, and (d) testing with high accuracy the fundamental symmetries of nature by taking advantage of nuclei with specific properties.

To reach these goals, major research topics included:

1. The development of beams of short-lived isotopes and their subsequent use for measurements of astrophysics interest and for nuclear structure and reaction studies;
2. The production and characterization of nuclear structure away from the valley of stability including nuclei at the very limits of stability, i.e., nuclei at and beyond the proton drip-line, on the neutron-rich side of the valley of stability, and in the region with $Z>100$;
3. The study of the nature of nuclear excitations as a function of mass, proton or neutron excess, spin and temperature; with emphasis on characteristics such as nuclear shapes, the interplay between degrees of freedom, changes in shell structure;
4. The use of traps for high-precision mass measurements for astrophysics and for searches of physics beyond the standard description of the weak interaction.

Smaller scale, complementary efforts exploit the exceptional and often unique capabilities of ATLAS: for example, the irradiation of samples for materials research, developing accelerator mass spectrometry techniques for applications in environmental studies, oceanography, astrophysics, fundamental interactions, and any other area of basic science where they apply, and accelerator research experiments.

Characterization of the facility

Superconducting Heavy-ion Linac.

Facility parameters

ATLAS can provide beams of all stable elements from protons to uranium, and a selection of radioactive beams produced through either in-flight production for light beams close to stability or with the CARIBU facility for neutron-rich, mid-mass isotopes.

The ATLAS superconducting linac has been upgraded to allow high heavy-ion beam intensity, essentially limited by ion source performance, at Coulomb barrier energies. The maximum beam intensity can exceed 10 pµA and maximum values for various types of source feed material are given in Table 14.10.

Type of Material	I pµA	Examples
Gases	10-55	Ne, Ar, Kr, Xe, O, N, …
Non-refractory Metals and Non-metals Tboil< 1500°C	1.0-11	Si, S, Ni, Fe, Ce, Ca, U…
Refractory Metals Tboil > 1500°C	~1	Mo, Ti, Zr, V, Pt, Ir …
Low Boiling Point Heavy Metals	0.6 – 2.5	Au, Pb, Bi, …

Figure 14.10: Maximum currents available at ATLAS for various types of source feed material.

The intensities for ions lighter than 12C are restricted by administrative constraints based on radiation safety considerations. When needed, isotopically enriched material is used at no direct cost to the user. The consumption rate varies with the element. For 48Ca, for example, for a beam of 250 pnA on target, the consumption rate is typically 0.15 mg/h.

The maximum beam energy available depends on the charge-to-mass ratio of the species extracted from the ECR ion sources. The maximum energy that can be attained at ATLAS, with or without stripping, for the various stable isotopes available is shown in Figure 2. The intensity available after stripping is typically 20

The in-flight and batch-mode produced radioactive beams are typically light beams, up to A 50, one or two neutrons away from stability. Typical beams that have been used in the past are presented in Table 14.11.

Beams of mid-mass, neutron-rich isotopes are available at low or Coulomb barrier energy via the CARIBU upgrade of ATLAS. These isotopes are obtained through 252Cf fission and converted into a beam by a gas catcher system. Yields for a thin 1 Ci 252Cf source are given in Figure 3. Reaccelerated CARIBU beams have essentially the same properties as stable beams accelerated through ATLAS. The reacceleration requires increasing the charge state of the radioactive ions which is done through an EBIS charge breeder. This introduces a macro-structure on the beam with typically 20 pulses per second of 1 ms duration each.

Facility's major experimental instrumentation and its capabilities

- Fragment Mass Analyzer (FMA): Recoil separator for reaction products. The focal plane instrumentation includes a large variety of detectors (Si DSSD, PPAC, ionization chamber, tape transport, etc).
- Gammasphere: The national gamma-ray facility of 110 Compton-suppressed Ge detectors. The facility, now operating with digital electronics, can be used in conjunction with the FMA, AGFA, or independently on a separate beam line.
- HELIOS (Helical Orbit Spectrometer): A superconducting solenoidal spectrometer with uniform axial field for 'inverse kinematics' nuclear structure studies.

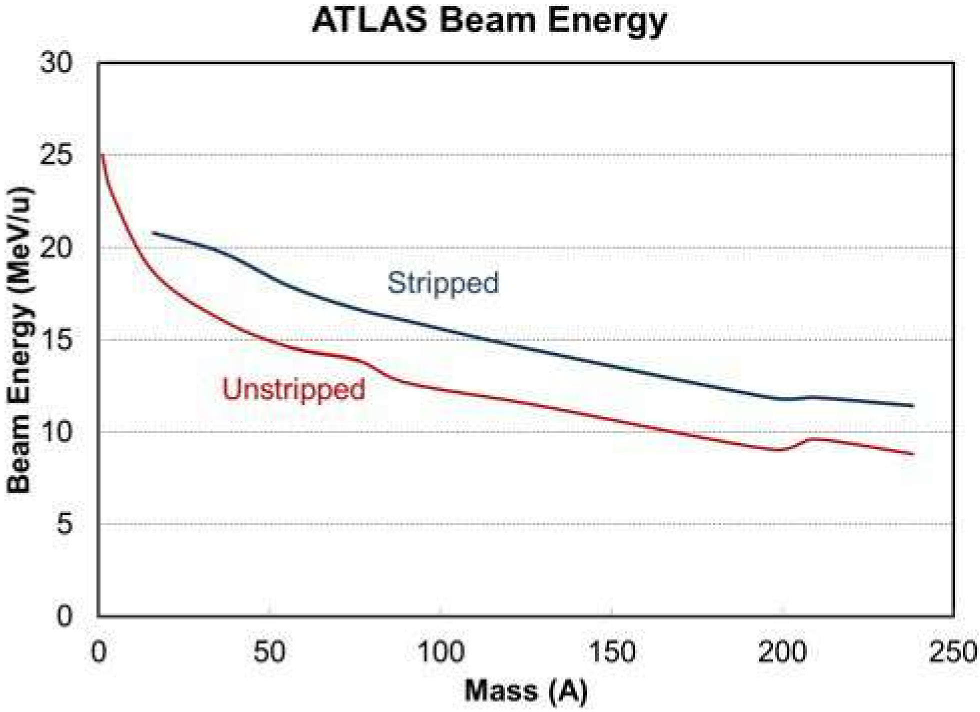

Figure 14.11: Maximum beam energy from ATLAS as a function of ion mass for two stripping assumptions. In general stripped beams will have approximately 20% of the intensity of unstripped beams.

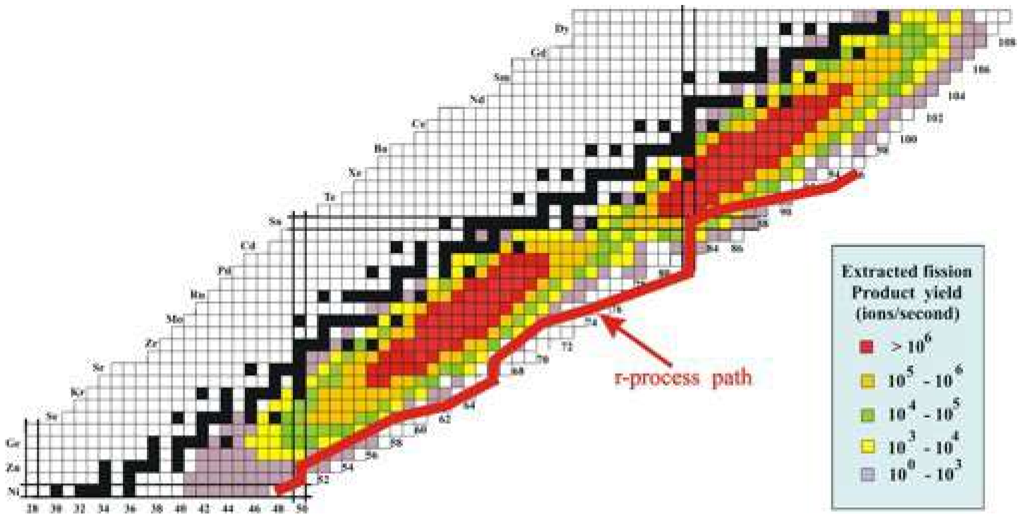

Figure 14.12: Fission yield distribution for a thin 1 Ci 252Cf source in ions/s. Stopped beam total efficiency to target is approximately 40%. For accelerated beams with ATLAS, total efficiency to target, including charge breeding efficiency, is approximately 5%.

- Area II Split pole spectrograph: Dedicated for use with the Penning trap systems below .
- Split pole spectrograph: Used primarily in astrophysics, AMS Measurements.
- In-flight RIB production target: System of cooled gas cells or solid targets combined with a large bore superconducting solenoid and a resonator, used for the production of rare isotope beams for astrophysics and nuclear structure research.
- Canadian Penning Trap (CPT): An instrument for high-precision mass measurement that includes a gas catcher system to slow down reaction products and transform them into slow

Ion	Half-Life	Reaction	Intensity (ions/sec/pnA)	Opening Angle (degrees)	Production Energy (MeV)	Max. Rate (ions/sec)
6He	0.807 sec	d(^{7}Li,^{6}He)^{3}He	150	19	75	1 x 10^4
8Li	0.838 sec	d(^{7}Li,^{8}Li)p	2000	11	71	1.5 x 10^5
8B	0.770 sec	3He(^{6}Li,^{8}B)n	10	13	27	
10C	19.29 sec	p(^{10}B,^{10}C)n	540	4.5	120	5 x 10^4
11C	20.385 min	p(^{11}B,^{11}C)n	2300	4.5	105	2 x 10^5
14O	70.606 sec	p(^{14}N,^{14}O)n	1200	2.9	170	1 x 10^5
15C	2.45 sec	d(14C,15C)p	24000	5.4	96	2 x 10^6
16N	7.13 sec	d(^{15}N,^{16}N)p	30000	5.4	70	3 x 10^6
17F	64.49 sec	d(^{16}O,^{17}F)n p(^{17}O,^{17}F)n	20000 20000	4.5 1.7	~90	2 x 10^6
19O	26.9sec	d(^{18}O·^{19}O)p	10000	4.7	145	2 x 10^5
21Na	22.48 sec	d(^{20}Ne,^{21}Na)n p(^{21}Ne,^{21}Ne)n	4000 8000	4.0 2.6	113	2 x 10^6
25Al	7.183 sec	d(^{24}Mg,^{25}Al)n p(^{25}Mg,^{25}Al)n	1000 2000	3.7 2.2	204 180	4 x 10^5
37K	1.226 sec	d(^{36}Ar,^{37}K)n	1200	2.2	280	1 x 10^5
18F	109.77 min	batch.				6 x 10^6
44Ti	59 yr	batch				2 x 10^6
56Ni 56Co	6.10 day 77.12 day	batch				5 x 10^4 2 x 10^5

Figure 14.13: Energy and production rates for in-flight and batch-mode produced radioactive beams at ATLAS. In some cases, the allowed maximum radiation may limit primary beam current.

moving 1+ ions, an RFQ-based transport system, a storage trap and a high-precision Penning trap.

- Advanced Penning Trap (APT) system: High-field isobar separator system with very high mass resolution based on a linear Penning trap, injecting either an RF quadrupole trap for weak interaction studies or a general purpose station for beta-decay investigations.
- Argonne Gas Filled Analyser (AGFA): High-acceptance gas filled separator for fusion and deep-inelastic reaction products
- General purpose scattering chamber
- Large array of double-sided Si strip detectors: Includes annular and rectangular counters and associated electronics.
- X-array: An array of detectors for decay spectroscopy including Ge "clover" detectors, and Si detectors for electron spectroscopy.
- General-purpose beam lines: Two fully instrumented beam lines for equipment brought in by outside users.

Technical facilities

Nature of user facility

DOE Designated National User Facility

Program Advisory Committee/experiment proposals

Yes, PAC meets on average twice a year.

Number of active users and their origin

Typically 200-250 users are present at ATLAS for an experiment each year. Including users on approved proposals, the number of users is typically 390 - 420 each year.

Percentage of users, and percentage of facility use that come from inside the institution

20% of the users are internal, 36% of beam time (2016 numbers)

Percentage of users and percentage of facility use from national users

39% of users, 30% of beam time (2012 numbers)

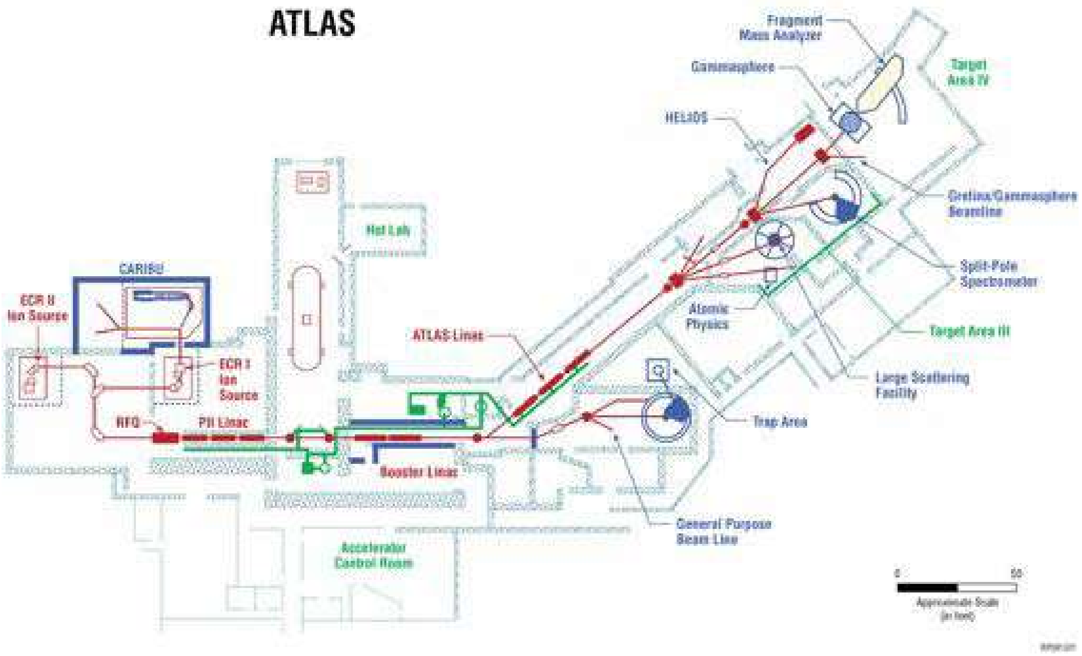

Figure 14.14: ATLAS Floor Plan.

Percentage of users and percentage of facility use from outside the country where your facility is located

41% of users, 34% of beam time (2012 numbers)

Fraction of the international users from outside your geographical region

90.1%

User group

Yes, 548 active user appointments, group represented by an executive committee.

Laboratory Staff

Table 14.6: Staff at the ANL Physics Division. *Plus 8 active emeritus staff. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	120*
Permanent staff (Theory)	4
Postdoctoral researchers	16
Postdoctoral researchers (Theory)	2
(Resident) Graduate students	8
(Non-resident) Graduate students	20**
Undergraduate students	30-40/year

Special student programs

Graduate Programs, Laboratory-Graduate Research Appointments, Guest Graduate Appointments, Thesis-Parts Appointments, Research Aide Appointments, International Student Exchange Program, Cooperative Education, Undergraduate Programs, Fall Science Undergraduate Laboratory

Internships, Spring Science Undergraduate Laboratory Internships, Summer Science Undergraduate Laboratory Internships, Community College Student Internships, Pre-college Program, Pre-Service Teacher (PST) Program, Research Aide Appointments, Cooperative Education, Symposium for Undergraduates in Science, Engineering, & Mathematics, Faculty and Student Team (FAST) Fellowships

Future Plans

New initiatives: AIRIS, a new recoil separator to increase the intensity and purity of the in-flight produced radioactive beams. AIRIS will consist of a high power production target followed by a magnetic chicane and a superconducting RF rebuncher to focus and select the isotopes of interest. It will be located in the main beamline, right after the superconducting linac so that the separated radioactive beams can be transported to a large number of experimental areas.

AMUU, the ATLAS Multi-User Upgrade, will take advantage of the pulse structure of the reaccelerated CARIBU beams which only fill the linac for about 3% of the time to inject stable beams in the linac for the remaining 97% of the time so that two independent experiments can be performed at the same time, increasing significantly the available beamtime. Design studies for AMUU have been completed and a full proposal is being prepared for submission to DOE.

CENTER FOR EXPERIMENTAL NUCLEAR PHYSICS AND ASTROPHYSICS (CENPA), UNIVERSITY OF WASHINGTON

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President, University of Washington: Ana Mari Cauce
Director, CENPA: David W. Hertzog
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Associate Director, CENPA: Gary Holman

University Center of Excellence,
Department of Energy Office of Science for Nuclear Physics

Scientific Mission and Research Programs

The University of Washington is a major research university situated on a beautiful campus in Seattle in the Pacific Northwest. The UW – “U-Dub” – receives the second largest amount of federal research funding of all US universities. Seven UW scientists have won Nobel Prizes, including physicists Hans Dehmelt in 1989 and David Thouless in 2016. CENPA played a major role in the work leading to the 2015 Nobel Prize to Arthur McDonald.

Nuclear Physics at UW

The UW is a unique center for nuclear physics. It is home to the national Institute for Nuclear Theory (INT), and to the Center for Experimental Nuclear Physics and Astrophysics (CENPA), one of DOE’s Centers of Excellence. In addition, a leading nuclear theory group exists within the Department ofPhysics. The Department of Physics, INT, and the Astronomy Department share a spacious building, which encourages collaboration. CENPA has its own laboratories including an FN tandem accelerator in the North Physics Laboratory across campus.

The focus of CENPA is experimental study of the fundamental symmetries of nature and the properties of neutrinos. CENPA physicists played a major role in the SNO experiment that resolved the solar neutrino problem, showing it was caused by neutrino oscillations and mass, research recognized by the

2015 Nobel and Breakthrough Prizes. How large the mass is will be addressed by 2 projects that study the tritium decay endpoint. KATRIN in Germany is running now and producing results Project 8 is a next-generation idea based on cyclotron resonance emission spectroscopy (CRES) that is hosted at CENPA. The LEGEND project will search for neutrinoless double beta decay, which would signal that neutrinos and antineutrinos are the same particle. CENPA physicists are spearheading high-precision measurements involving muons. Most notably, the Muon (g-2) Experiment at Fermilab is sensitively testing the Standard Model. The MuSun experiment at the Paul Scherrer Institute will determine a central parameter in the theory of fundamental astrophysics processes. CENPA has developed the most intense source of radioactive 6He atoms in the world. A new effort using the CRES technique is being developed to measure the beta decay spectrum and search for new physics. Delicate torsion balances continue to be used to explore dark matter, axions, general relativity, and extra dimensions. The world’s most sensitive direct microwave search for axions, ADMX, is in progress at CENPA.

Characterization of the facility

The facility is an infrastructure center for designing and building complicated experiments that operate in a variety of venues. A precision machine shop and modern electronics shop exist for preparation of major components of collaborative off-site experiments (see website for more details).

The accelerator part of the facility is an FN tandem Van de Graaff that can also be operated with a terminal ion source for low energy helium or hydrogen isotope beams. Energies from 100 keV to 5 MeV with currents of tens of μA are available for those isotopes. Operating as a tandem, the usual range of ion beams with terminal voltage up to 9 MV are available. A ^{8}B radioactive beam of 10 ions/second has been developed. CENPA is not a DOE user facility, but outside users can run experiments collaboratively and/or by various arrangements. Experimental proposals are evaluated by the Director and Associate Director in consultation with the faculty.

Besides the students and postdocs, we have a 12 technical staff (engineers and technicians) and 2 administrative. In summer several Research Experience for Undergraduates (REU) students work at CENPA. REU is an NSF-sponsored program.

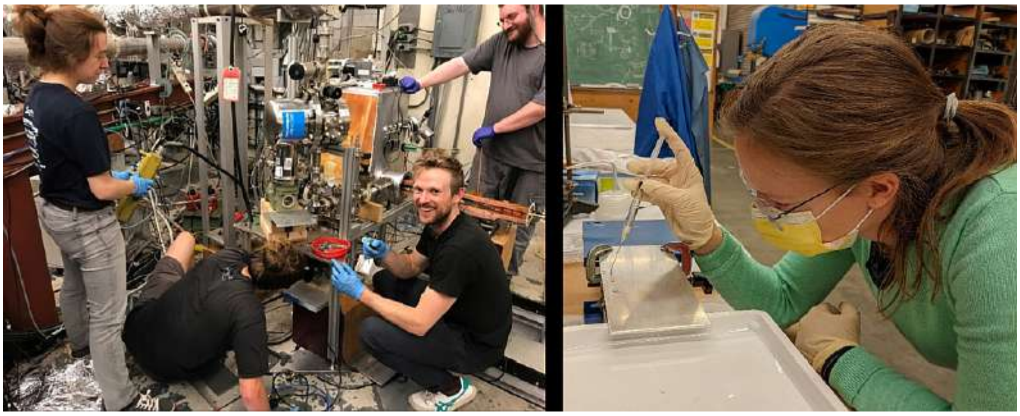

Figure 14.15: Left: Graduate students adjusting ^{6}He beta decay apparatus in preparation for an upcoming run. Right: Postdoctoral Scholar Claessens preparing a new in-beam detector for the Muon g-2 experiment.

CYCLOTRON INSTITUTE AT TEXAS A&M UNIVERSITY

Cyclotron Institute, Texas A&M University
College Station, TX 77843, USA
Telephone: +1 979 845-1411
Facsimile: +1 979 845-1899

Head of the facility: Sherry J. Yennello
E-mail: yennello@tamu.edu
President Texas A&M University: M. Katherine Banks

University Facility (Department of Energy University Laboratory)
Construction: Department of Energy Office of Science for Nuclear Physics
Operations: Texas A&M University

Scientific Mission and Research Programs

The Cyclotron Institute is jointly operated by the U.S. Department of Energy and the State of Texas to carry out a program of basic research in nuclear science. Institute programs include measurements of reaction rates for nuclear astrophysics, studies of heavy-ion reactions at low and intermediate energies, determination of the properties of giant resonances in nuclei and -decay studies of fundamental weak interaction parameters and production of medically relevant isotopes. In addition, the Institute provides beam time to government and commercial agencies that test electronics components for space radiation effects and produce medical isotopes.

Characterization of the facility

The Cyclotron Institute operates a low to medium energy superconducting cyclotron, the K500 and a lower energy conventional cyclotron, the K150. Both cyclotrons are available for experiments. Each cyclotron is injected by a dedicated ECR ion source, while the 150 is also injected by a negative hydrogen/deuterium source. The K150 cyclotron is used to produce secondary beams. The secondaries are stopped in ion-guide gas stoppers and transferred to a charge-breeding ECR source where highly-charged ions are produced. Following the charge-breeding ECR source, the ions are injected into the K500 cyclotron and accelerated.

Technical facilities

Institute staff constructed, and now operate, a K150 (88”) cyclotron, a K500 superconducting cyclotron, and associated advanced ECR sources. A large complement of state-of-the-art detectors and spectrometers are also available for nuclear physics research. The facility layout is shown in Fig. 14.16.

Facility parameters

Fig. 14.17 shows the range of beams and beam energies which have been extracted from the K500 cyclotron. Over 55 different beam species have been run at varying energies. The maximum energy run to date is 70 MeV/A for light ions. U beams have been run at 12 MeV/A. Intensities up to 1 particle μamp have been achieved for extracted heavy-ion beams. Figure 3 shows the range of beams and beam energies extracted from the K150 cyclotron. In Table 14.19, the available beam types, energies, and maximum intensities are summarized by groups for each cyclotron.

Facility’s major experimental instrumentation and its capabilities

See Table 14.20.

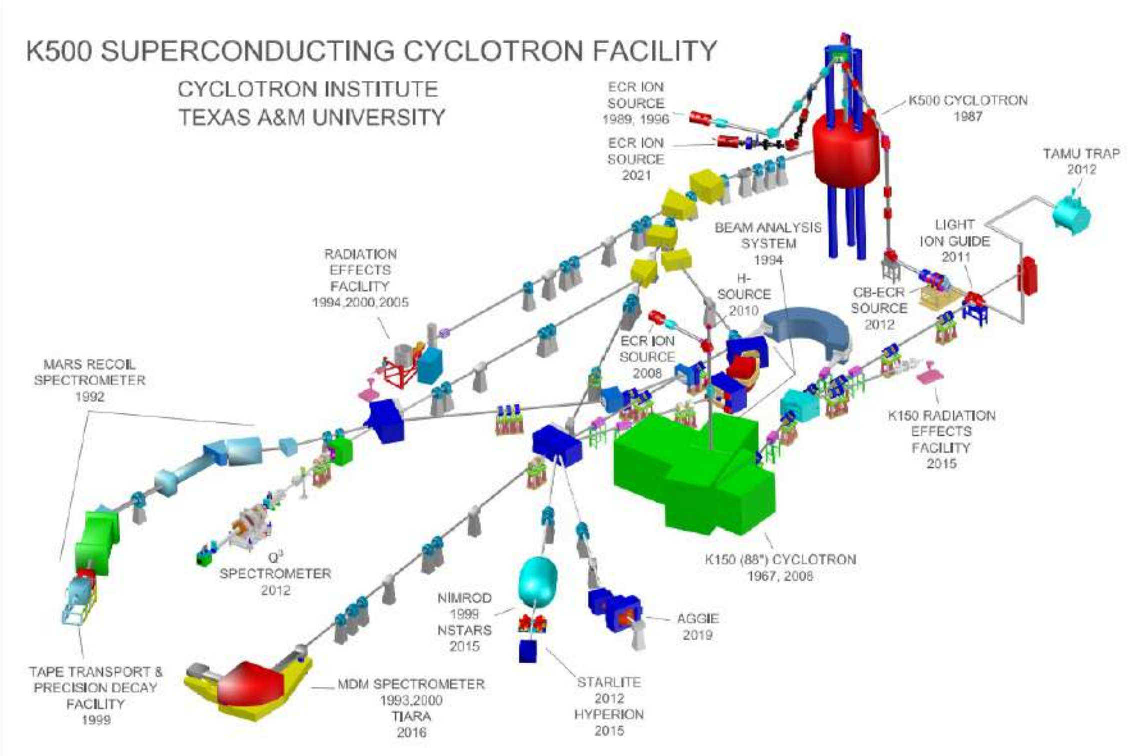

Figure 14.16: Full laboratory layout at the Texas A&M cyclotron.

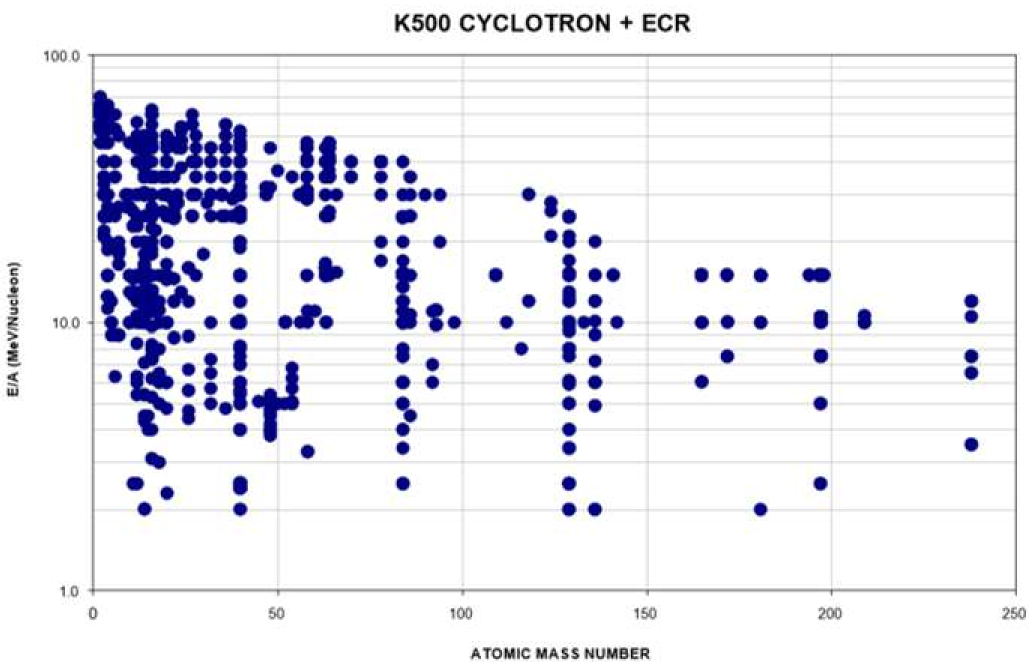

Figure 14.17: Available beams from the K500.

User facility

No.

Program Advisory Committee/experiment proposals

No.

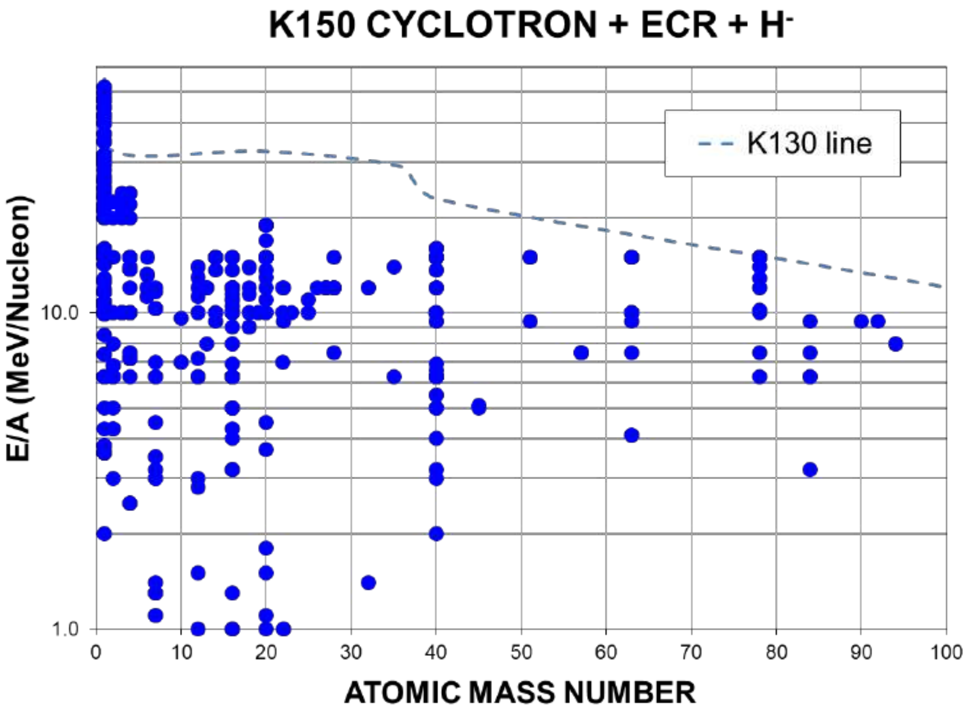

Figure 14.18: Available beams from the K150.

K500 Beams	Energy range (MeV/u)	Max. Intensities (pnA)
D	53 – 70	1000
He	12-30, 53-70	1000
Li	4 – 70	475
Be, B, C, N, O	2 – 70	300
F, Ne, Na, Mg	2 – 60	200
Si, P, S, Ar	2 – 60	180
Ca, Cr	2 – 50	180
Fe, Ni, Cu, Zn	2 – 47	100
Kr, Ag	2 – 40	120
Sn, Xe, Pr	2 – 25	50
Ta, Au, U	2 – 15	10

K150 Beams	Energy range (MeV/u)	Max. Intensities (pnA)
P	4 - 50	20,000
He	3 – 24	15,000
Li	1 – 24	1500
C, N, O	1 – 24	1000
Ne	1 – 20	1000
Ar	1 – 20	400
Cu	1 – 15	10
Kr	1 – 15	1

Figure 14.19: Table of available beams.

Number of active users and their origin

Over past couple of years, in-house users average approximately 45, external users (excluding radiation effects) average approximately 35, and radiation effects users number more than 200. Of

Device	Description	Parameters	Primary Uses
MARS	Recoil Spectrometer	$\Delta\Omega$ = 9msr; K* = 160; $\Delta m/m$ = 1/300	Secondary beam production
MDM	Magnetic spectrometer	$\Delta\Omega$ = 8msr; K* = 400; $\Delta E/E$ = 1/4500	Elastic, inelastic and transfer reaction studies
TAMU Trap	Superconducting Solenoid	Actively shielded 7T magnet with a 210mm diameter bore	Penning trap for beta-decay studies and mass measurements
NIMROD	Neutron and charged particle detector	4π detector for neutron and charged particle multiplicities	Heavy-ion reaction mechanism and equation of state studies
AGGIE	Gas-Filled Recoil Separator	Theoretical max. Bρ = 2.4 T m, ±50 mrad acceptance in x and y, optional recoil transfer chamber	Fusion-evaporation reactions and online chemistry
TexAT	Versatile active-target TPC with ancillary Si+CsI forward wall	245 x 224 x 130 mm^3 active volume; Gases: (deuterated) methane, isobutane, He:CO_2, CO_2, or P5/P10	Thick-target inverse kinematics with RIBs, beta-delayed charged-particle spectroscopy, transfer/fusion studies
DAPPER	Detector Array for Photons, Protons, and Exotic Residues	High efficiency gamma energy, gamma multiplicity; charged particle coincidence for E*	Transfer reactions relevant to stockpile stewardship, nuclear forensics, and nuclear astrophysics
FAUST	Charged particle detector; good energy and position resolution	E Resolution: 1%. Position Resolution: <200um. 1.6<theta<45.5 degrees	Nuclear dynamics and thermodynamic, reaction mechanism studies, multi-particle correlations, nuclear equation of state

Figure 14.20: Major experimental equipment.

the external users, about 60% are from outside the US in a typical year.

Percentage of users, and percentage of facility use that come from inside the institution

Approximately 9600 hours of beam time are provided each year. About 44% of this is used for radiation effects testing and the remaining 56% is used for basic research. Outside users (nearly always) collaborate with Institute faculty and staff.

Percentage of users and percentage of facility use from national users

Percentage of users and percentage of facility use from outside the country where your facility is located

In a typical year, nearly all the users from outside of the US come from Europe.

User group

No.

Laboratory Staff

See Table 14.7

Special student programs

We operate a summer program for 12 undergraduate students as a National Science Foundation REU site for nuclear science. We also host 7 undergraduate students from minority-serving institutions for research internships supported by the Department of Energy.

Table 14.7: Staff at the Cyclotron Institute at Texas A&M. *xxx. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
T/TT Faculty (experiment)	7
T/TT Faculty (theory)	4
Research Faculty (Theory)	3
Other permanent staff	59
Postdoctoral researchers	7 (3 in theory)
(Resident) Graduate students	39 (11 in theory)

INSTITUTE FOR NUCLEAR THEORY (INT) SEATTLE

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http://www.int.washington.edu

Director: David B. Kaplan
Telephone: +1 206 685 3546
E-mail: dbkaplan@uw.edu

US Department of Energy, local funding (University of Washington), other grants

Scientific Mission and Research Programs

The INT hosts scientific visitor programs of four weeks or longer in duration, as well as shorter topical workshops lasting 2-5 days. Subjects of these meetings range over all of nuclear theory, broadly defined, often with interdisciplinary connections to other branches of physics. The INT also hosts summer schools and administers the National Nuclear Physics Summer School. The INT has a permanent research staff of four Senior Fellows, as well as a couple of five-year Fellows and a variable number of post-docs. An administrative staff helps with organization of INT visitor programs, with meeting the IT needs of visitors, and with maintaining the INT web page, on which INT seminars are archived.

Characterization of the facility

The INT is located within the Physics and Astronomy building at the University of Washington, and physically consists of over 20 desks for visitors, mostly two desks per office. Visitors have internet access and printing capability.

Rooms of various sizes are available for seminars, informal discussions and larger conferences.

Main fields of research

Nuclear structure and dynamics, QCD and hadron physics, lattice field theory, relativistic heavy ion collisions, nuclear matter under extreme conditions, nuclear astrophysics, precision tests of physics beyond the Standard Model, and interdisciplinary connections to nuclear physics.

Related Areas: Particle physics, astrophysics, condensed matter physics, many-body atomic physics, mesoscopic physics, computer science.

Program Advisory Committee/experiment proposals

National Advisory Committee Membership is typically nine people, with three rotating off each year. New members approved by the DOE.

Number of active users and their origin

Approximately 400 users per year, from various international origins.

User group

Users: approximately 400 per year. Accumulated email list includes over 2000 past visitors to the INT.

Laboratory Staff

See Table 14.8

Table 14.8: Staff at the INT Seattle (status 2013). *One director and 3 senior fellows. **Temporary: two 5-year Fellows, 4 post-docs, 4 graduate students. ***Typically 35-60 graduate students participate in INT summer schools, when hosted. A few graduate students attend INT programs and workshops each year, usually with their thesis advisers.

Designation	**Number of persons**
Permanent staff	4*
Temporary staff	10 **
Administrative staff	5
(Non-Resident) Graduate students	$\sim$35-60***
Undergraduate students	$\sim$1

FACILITY FOR RARE ISOTOPE BEAMS (FRIB)

Facility for Rare Isotope Beams, Michigan State University
640 S. Shaw Lane
East Lansing, MI 48824-1321 USA
Telephone: +1 517-355-9671
Fax: +1 517-353-5967

Head of the facility:
Director FRIB: Thomas Glasmacher
E-mail: glasmacher@frib.msu.edu

Higher Education Institution (State University)
U.S. Department of Energy Office of Science

Scientific Mission and Research Programs

The mission of the Facility for Rare Isotope Beams (FRIB) is to provide forefront research opportunities with rare isotope beams.

FRIB is funded as a user facility by the U.S. Department of Energy Office of Science (DOE-SC), supporting the mission of the DOE-SC Office of Nuclear Physics. A broad research program is made possible by the large range of primary and secondary (rare isotope) beams provided by the facility. In its first year of operations, FRIB delivered more than 200 rare isotope beams for experiments—including beams of previously undiscovered isotopes. The major research thrust is to determine the nature and properties of atomic nuclei, especially those near the limits of nuclear stability. Other major activities are related to nuclear properties that influence stellar evolution, explosive phenomena in the cosmos (e.g. supernovae and x-ray bursts), and the synthesis of the heavy elements; and research and development in accelerator and instrumentation physics. An important part of the FRIB program is the training of members of the next generation of scientists.

Characterization of the facility

FRIB's 400-kW superconducting radio-frequency linear accelerator (linac) provides stable ions, used to create intense radioactive beams separated by physical means, beams stopped in and extracted from a gas cell for use at very low energies or reacceleration with a 3-6 MeV/u superconducting linear accelerator.

Technical facilities

FRIB's technical facilities (Fig. 14.21) include the superconducting heavy-ion linear accelerator, the superconducting fragment separator (ARIS) and subsequent beam lines, the various experimental vaults, the gas stopping and low energy beam area, the linac-based ReAccelerator (ReA) facility, the cryoplants, shops and assembly areas.

Facility parameters

A list of available primary beams and a beam list for stand-alone operation at ReA3, ReA6, or the stopped beam area (both stable and radioactive) can be found at https://frib.msu.edu/users/beams/index.html. Over 200 rare isotope beams produced by fragmentation of the primary beams were used in experiments at FRIB during its first year of operations.

Facility's major experimental instrumentation and its capabilities

1. For production and separation of radioactive ion beams: 3-stage ARIS fragment separator.

2. For the high-resolution, large-acceptance analysis of reaction residues: S800 spectrograph, Sweeper Magnet.
3. For charged- particle detection over large solid angle: High Resolution silicon strip detector Array (HiRA); Active Target Time Projection Chamber (AT-TPC).
4. For neutron detection: Modular Neutron Array and Large Multi-Institutional Scintillator Array (MoNA- LISA); Neutron Walls; Neutron Emission Ratio Observer (NERO); Low-Energy Neutron Detector Array (LENDA).
5. For γ-ray detection: Segmented Germanium Array (SeGA); high-efficiency CsI Array (CAESAR); Summing NaI detector (SuN)
6. For decay studies: FRIB Decay Station initiator (FDSi), Beta Counting System (BCS); The Proton Detector and GADGET system – A cylindrical gas volume designed to detect weak, low-energy, β-delayed protons and α particles
7. For stopped production and beam manipulation and studies: Room Temperature Gas Catcher (RTGC); Advanced Cryogenic Gas Stopper (ACGS); Cyclotron Gas Stopper
8. For studies with stopped beams: Low Energy Beam and Ion Trap (LEBIT) facility; Single Ion Penning Trap (SIPT) mass spectrometer; BEam COoler and LAser spectroscopy (BECOLA) facility for collinear laser spectroscopy; Positron Polarimeter (POSPOL) for fundamental interaction studies
9. For excited-state lifetime measurements: Triple plunger for exotic beams (TRIPLEX)
10. A superconducting reaccelerator (ReA) for the post-acceleration of rare isotopes delivered from the gas stoppers and charge bred in an EBIT (maximum energy depends on mass-to-charge ratio – 6 MeV/u for Uranium)
11. Separator for Capture Reactions (SECAR) – A separator for the measurement of reaction rates on proton-rich unstable nuclei in the astrophysical rapid proton capture process
12. SOLARIS – large-bore solenoid spectrometer for reaction experiments with reaccelerated beams with the AT-TPC or with a silicon detector array
13. Other major experimental equipment that has been hosted by FRIB: Gamma-ray energy tracking array (GRETINA); Array for Nuclear Astrophysics Studies with Exotic Nuclei (ANASEN); Versatile Array of Neutron Detectors at Low Energy (VANDLE); CloverShare.

Nature of user facility

User facility funded by the U.S. Department of Energy Office of Science.

Program Advisory Committee/experiment proposals

Yes.

Number of active users and their origin

601 in FY22 As of July 2023, FRIB has delivered more than 200 rare isotope beams to experiments and supported 506 participants, including 94 students, across 41 experiments, 39 countries, and 136 institutions.

Percentage of users and percentage of facility use from national users

Percentage of users: 75% [from FY22]. FRIB began running user experiments in May 2022. As of July 2023, 75% of user experiments had U.S.-based spokespersons.

Percentage of users and percentage of facility use from outside the country where your facility is located

Percentage of users: 25% [from FY22] As of July 2023, 25% of user experiments had internationally-based spokespersons.

User group

1843 registered users as of 26 June 2023.

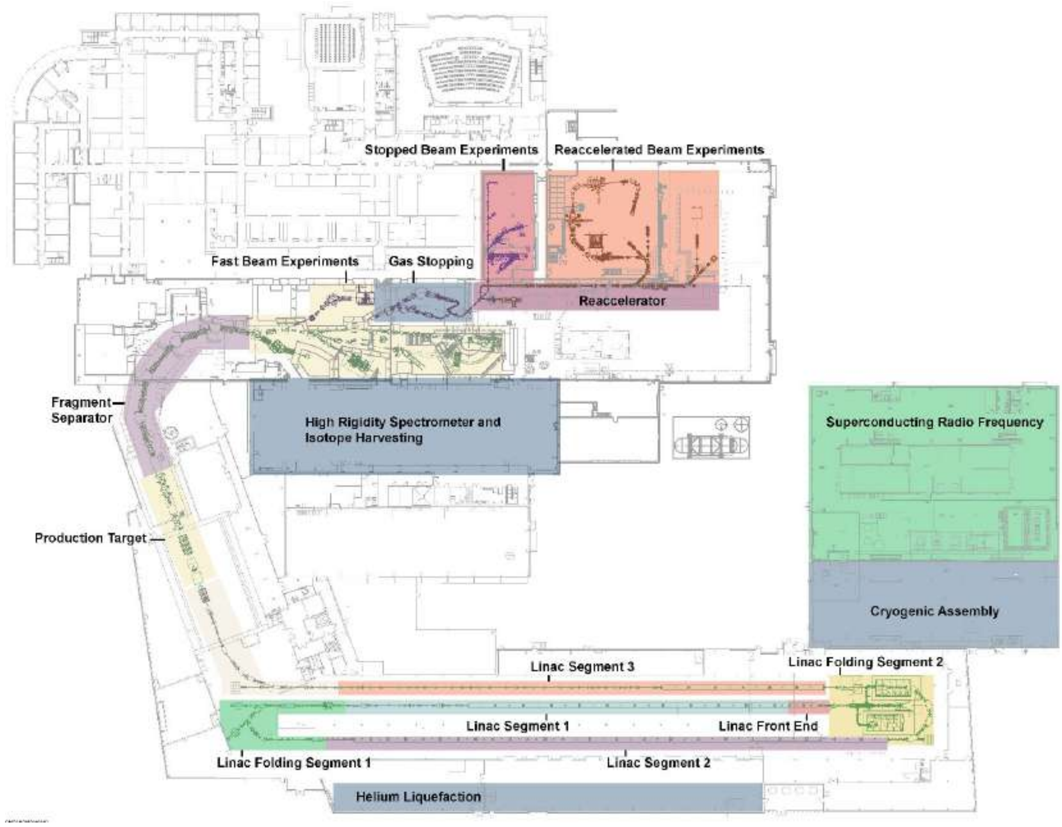

Figure 14.21: FRIB facility layout.

Laboratory Staff

See Table 14.9.

Table 14.9: Staff at FRIB (as of July 2023).

Designation	Number of persons
Total laboratory staff	477
Staff scientists with doctoral degree	51
Faculty	47
Postdoctoral researchers	29
Graduate students	140
Undergraduate students	119

Special student programs

Graduates:

FRIB Theory Alliance summer schools; Exotic Beams Summer School **Undergraduates:**

INSIGHT: Institute for Nuclear Science to Inspire the next Generation of a Highly Trained workforce; REU: Research Experience for Undergraduates; CEU: Conference Experience for Undergraduates; Professional Assistant Program; Honors College Seminar; Directors Research Scholar program; Nuclear Science Summer School; SROP: Summer Research Opportunities Program; PING: Physicists Inspiring the Next Generation program **High school and others:** PING: Physicists Inspiring the Next Generation program ; PAN: Physics of the Atomic Nuclei; Mini-PAN: One-day version of PAN; MST: Mathematics, Science, and Technology camp; Catch-a-Cosmic-Ray event; FRIB Open House (about 4,000 visitors); MSU Science Festival

Future Plans

A number of science-driven upgrades are in progress to enhance FRIB's discovery potential. Isotope harvesting will allow for extraction of rare isotopes during routine operation of the FRIB nuclear physics mission – without interfering with FRIB's primary users. The harvested rare isotopes have a role in multiple fields of study, such as medicine, biochemistry, materials science, horticulture, and astrophysics.

The High Rigidity Spectrometer (HRS) will have a significant benefit for FRIB's scientific program, extending the scientific reach to neutron-rich isotopes by a combined production-rate and luminosity increase of up to a factor of more than 100. The project is underway, and a user community of over 500 scientists supports HRS.

The FRIB400 energy upgrade will double FRIB's beam energy to 400 MeV/nucleon and expand the scientific impact by increasing the yield of many rare isotopes tenfold. The science community laid out the opportunities in the FRIB400 whitepaper (https://frib.msu.edu/frib400paper), endorsed by the community.

The FRIB Single Event Effects (FSEE) Facility (https://frib.msu.edu/fsee) uses energetic and penetrating heavy-ion beams to measure the response of electronic components to such ions. This simulates in a few minutes the effect of cosmic rays on electronics over decades. FSEE facility will provide up to 2,000 hours/year to users.

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST) NEUTRON PHYSICS GROUP

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Head of Group: Jeffrey S. Nico
E-mail: jnico@nist.gov

US Government, Dept. of Commerce, National Institute of Standards and Technology, Radiation Physics Division, Neutron Physics Group

Scientific Mission and Research Programs

The NIST Neutron Physics Group provides a location for internal and external users to conduct both fundamental and applied physics experiments with thermal and cold neutrons at the NIST Center for Neutron Research (NCNR). The research program includes studies of the weak interaction, neutron instrumentation, neutron interferometry, neutron imaging, and neutron metrology and dosimetry. Past and current experiments in fundamental physics include measurements of the neutron lifetime, a search for time reversal violation in polarized neutron decay, study of nucleon-nucleon interactions via parity-violating spin-rotation of polarized neutrons, a search for the radiative decay mode of the neutron, and precision measurements of neutron scattering lengths. Instrumentation development is focused on the polarized He-3 neutron spin filters for neutron scattering and fundamental neutron physics. The neutron imaging program includes studies of fuel cells, energy storage devices, structural materials, and geological samples. In neutron interferometry, there is work in quantum materials, nuclear physics, Pendellösung interference, and quantum information science

Characterization of the facility

Thermal and cold neutron beam lines at a research neutron source.

Facility parameters

- NG-6 cold, polychromatic beam line: neutron fluence rate (no filters); 2.3×10^9 cm^{-2} s^{-1} with 6 cm diameter beam
- NG-6M monochromatic beam line: wavelength = 0.496 nm; typical available fluence rate = 6.5×10^5 cm^{-2} s^{-1}; pyrolytic graphite crystal size = 5.1 cm by 5.1 cm
- NG-6U monochromatic beam line: wavelength = 0.89 nm; capture fluence rate = 4.7×10^6 cm^{-1}; potassium-intercalated graphite monochromator
- NG-7 Neutron Interferometer and Optics Facility: wavelengths - 0.2 nm - 0.48 nm; fluence rate $\approx 2\times10^5$ cm^{-2} s^{-1} beam size = 2 mm by 8 mm; phase stability - 0.25 degrees/day; contrast - 90%
- NG-C Fundamental Physics, polychromatic beamline; capture fluence rate = $8\ \times10^9$ cm^{-2} s^{-1}; beam size 11 cm by 11 cm

Facility's major experimental instrumentation and its capabilities

There is a major user-based program in thermal neutron imaging at the BT-2 beamline. In addition to the neutron beam lines, there are laboratories for spin- exchange optical pumping of ^{3}He-based neutron spin filters for use in neutron scattering.

Technical facilities

A diagram of the beam layout at the NCNR is shown below. The Neutron Physics Group operates the NG-6 Cold Neutron Imaging Instrument; the NG-6M, NG-6A, and NG-6U monochromatic beam lines that split off NG-6; two beamlines at the NG-7 Neutron Interferometer and Optics Facility; the NG-C high flux beamline; and the BT-2 Neutron Imaging Facility.

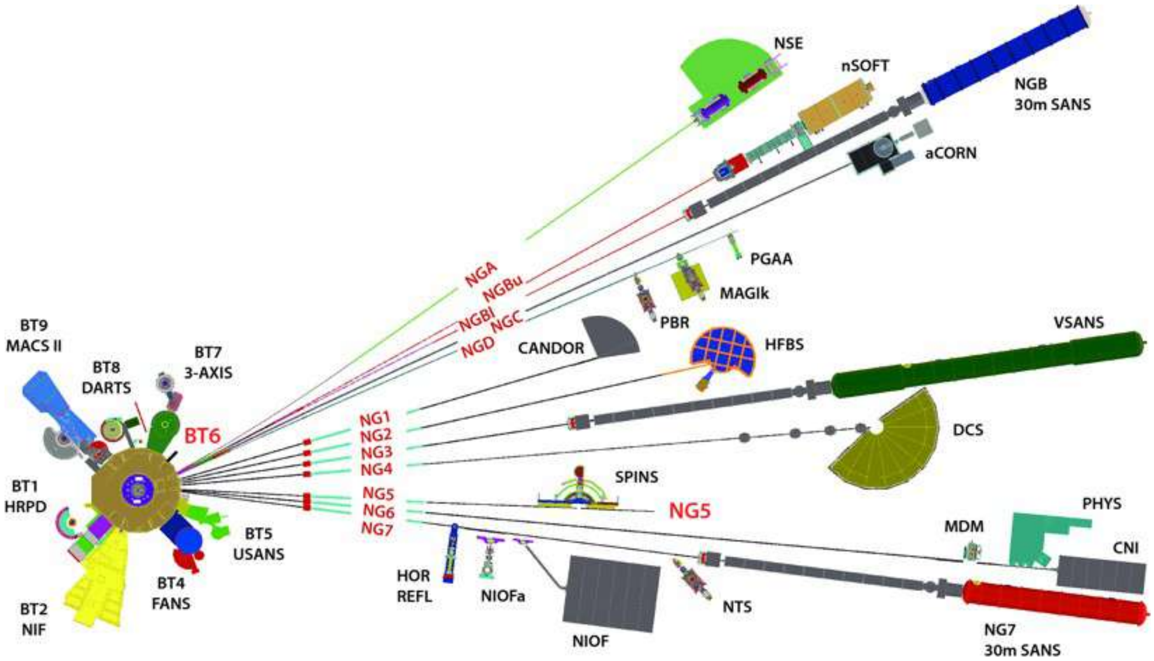

Figure 14.22: Beamlines at NIST.

Nature of user facility

Some neutron beamlines are operated as user facilities by the NIST Center for Neutron Research as well as the Neutron Physics group.

Program Advisory Committee/experiment proposals

Two beamlines accept experimental proposals through the NCNR Beam Time Allocation Committees.

Number of active users and their origin

This number varies depending on many conditions, but a typical year has about 30 people.

Percentage of users, and percentage of facility use that come from inside the institution

Percentage of users from inside the institution is zero because we define "users" to be from the outside. Percentage of facility use from inside the institution is about 50%.

Percentage of users and percentage of facility use from national users

80% (users); 40% (facility use)

Percentage of users and percentage of facility use from outside the country where your facility is located

20% (users); 10% (facility use)

Fraction of the international users from outside your geographical region

100%

User group

No.

Laboratory Staff

Table 14.10: Staff at NIST (Nuclear Physics Group). *Non-resident graduate students with thesis work primarily done at the facility.

Designation	**Number of persons**
Permanent staff	10
Temporary staff	9
Postdoctoral researchers	4
(Resident) Graduate students	2
(Non-Resident) Graduate students	2*
Undergraduate students	1/ year

Special student programs

Summer Undergraduate Research Program sponsored by NIST, the National Science Foundation, and the students' institution,

NUCLEAR SCIENCE LABORATORY (NSL)/ INSTITUTE FOR STRUCTURE AND NUCLEAR ASTROPHYSICS (ISNAP), UNIVERSITY OF NOTRE DAME

ISNAP or Nuclear Structure Laboratory, Department of Physics
124 Nieuwland Science Hall, University of Notre Dame
Notre Dame, IN 46556, USA
Telephone: +1 574-631-9012
Facsimile: +! 574-631-5952
E-mail: nsladmin@nd.edu

Head of the facility: Prof. Dan Bardayan
danbardayan@nd.edu
President: Rev. John Jenkins, CSC

University Institute
Construction: University of Notre Dame
Operation: National Science Foundation

Scientific Mission and Research Programs

A major program at the NSL is to use the unique set of experimental tools and techniques available to address open questions in stellar astrophysics. Extremely high-intensities of stable beams at low energies are required to measure some of the weakest cross sections, and these measurements cannot be made at radioactive or heavy-ion beam facilities. The NSL provides a unique experimental environment for this important aspect of the field. The focus of the present activities is on the understanding of nucleosynthesis in the early stars, the source of neutrons for the production of heavy elements, the origin of seed materials for nuclear processes in explosive stellar events, and the flux of neutrinos in our sun and other main sequence stars. A number of key reactions for neutrino and neutron production in quiescent and explosive stellar environments have been investigated. New theoretical tools have been developed for deriving reliable reaction rates and for investigating the impact of the nuclear reactions on nucleosynthesis, energy production and time scale of dynamic stellar environments. Studies of critical nuclear structure parameters (e.g., masses, onset of deformation, and incompressibility) have been performed to extract information critical to understanding the nucleosynthesis aspects of core collapse supernovae associated with the p- and r-process and the origin of long-lived galactic X-ray sources.

Beyond interests in nuclear astrophysics, the nuclear structure effort has focused on the study of nuclear clusters with broad overlap to questions in nuclear astrophysics, the investigation of collective modes and nuclear incompressibility, and on novel modes of quantal rotation using techniques in γ-ray spectroscopy. The growing fundamental symmetries program has focused on the half-life measurements of mirror transitions to improve the precision of ft-values that can be used to determine the Vud element of the CKM matrix and ultimately test the Standard Model.

The development of the St. Benedict ion trapping system will further expand this program by allowing for beta-neutrino angular correlation measurements in mirror transitions. Strong efforts have been made to develop a program in nuclear physics and accelerator applications, often in collaboration with other university groups and institutions. This includes the use of AMS techniques for the detection of long-lived isotopes as well as the application of Particle Induced X-ray Emission (PIXE), X-Ray Fluorescence (XRF) and Raman spectroscopy as analytical tools to probe archaeological, forensic, and biological samples.

Characterization of the facility

Low-energy accelerators with light to medium ions with high intensity.

Technical facilities

The NSL is a mid-sized nuclear physics laboratory. The NSL operates three low-energy accelerators on campus for nuclear physics research:

- 10MV FN Pelletron Tandem accelerator for DC or pulsed ion beams.
- 5MV 5U single ended 5U Pelletron accelerator for high intensity ion beams.
- 3MV 9S Pelletron Tandem accelerator for nuclear application research.

Facility's major experimental instrumentation and its capabilities

The JN accelerator has been moved to the SURF underground lab and comprises the CASPAR facility. The local accelerators serve a total of fourteen target stations, five for the 5U Pelletron in two target halls, seven for the FN Tandem distributed over three target halls, and two for the 9S in a single target hall. A new target hall was built with support of the University and is primarily dedicated to experiments with radioactive beams from the TwinSol facility and for housing the 9S accelerator.

The 5U machine provides heavy ion beams in various charge states up to A=40 for inverse kinematics experiments using the St. GEORGE recoil separator with the HIPPO gas-jet target. Light ion beams (H, He) are used for the windowless re-circulating gas target RHINO, and for a solid beam-stop target system. The 3MV tandem is equipped with two beam-lines and target stations funded through university support.

The FN Tandem accelerator is the driver for the TwinSol dual superconducting solenoid separator that provides intense radioactive beams reaching A=41 for radioactive beam experiments. The Tandem is also central for the

AMS facility with the gas-filled Browne-Buechner Spectrometer as the last station for isobar separation. In addition, the tandem serves four target stations for basic nuclear physics experiments, including a large scale scattering chamber, a neutron time of flight beam-line, a station for the measurement of conversion electrons, and an activation beamline primarily used for AMS cross section measurements. These beam-lines are also used to host external user experiments. Finally, one additional beamline is reserved for hosting the Enge spectrometer, which is currently undergoing installation.

The 9S tandem serves two dedicated target stations for applied physics experiments, one for radiochemistry measurements operated independently by the Radiation Laboratory (a DOE-BES funded facility), and one PIXE material analysis station.

Nature of user facility

Officially we are not a user facility but we have a large number of users from all over the world.

Program Advisory Committee/experiment proposals

The laboratory personnel meet once a week and make decisions on proposed experiments. The proposers typically give a brief 10-15min presentation to discuss why the experiment needs to be performed and the associated technical requirements. The group then decides if there are competitive proposals, if the experiment is doable, and if the experiment is interesting. Then we attempt to find the best solution with regards to the schedule and competing resources.

Number of active users and their origin

40 approximately in a given year (pre-Covid).

Percentage of users, and percentage of facility use that come from inside the institution

There are two major inside users: Radiation Laboratory Personnel (DOE funded laboratory on the campus of Notre Dame) and individual scientists from the Physics Dept. here at Notre Dame.

Percentage of users and percentage of facility use from national users
50%

Percentage of users and percentage of facility use from outside the country where your facility is located
50%

Fraction of the international users from outside your geographical region
50%

Laboratory Staff

Table 14.11: Staff at the Nuclear Structure Laboratory. *Tenured faculty, research faculty, faculty emeriti and staff. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	29*
Permanent staff with doctoral degree	21
Postdoctoral researchers	1
(Resident) Graduate students	31
(Non-Resident) Graduate students	10**
Undergraduate students	20/ year

Special student programs
Research Experiences for Undergraduates (REU –summer program);
Research Experiences for Teachers (RET – summerprogram for High School Teachers);
Local High School students doing projects with faculty (academic year);
Quarknet network of High School Teachers (year-round + special programs in the summer).

Future Plans
A neutron source is being developed for nuclear astrophysics and applied measurements.

An Enge split-pole spectrometer is being installed for studies of structure of exotic nuclei of astrophysical interest.

The St. Benedict ion trapping facility will be used for fundamental symmetry studies of β-decay.

A new electron-conversion spectrometer (fIREBall) will be used to study the nature of 0+ states.

The exotic beam facility TwinSol is being augmented with a third solenoid and will be called TriSol. The upgrade will greatly increase the quality of the exotic beams available. A new silicon detector array is being designed to facilitate use of the first TwinSol solenoid as a solenoid spectrometer for the studies of rare decays from exotic nuclei.

The FN accelerator is transitioning to the use of SF6 as an insulating gas, which will ensure its continued operation at high voltages.

RELATIVISTIC HEAVY ION COLLIDER (RHIC), BROOKHAVEN NATIONAL LABORATORY (BNL)

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Director, Brookhaven National Laboratory: Dr. Doon Gibbs
Heads of the facilities:
Nuclear and Particle Physics, Associate Laboratory Director [RHIC] – Dr. Haiyan Gao
Collider-Accelerator Department Chair [RHIC] – Dr. Wolfram Fischer

BNL is operated by Brookhaven Science Associates for Department of Energy Office of Science, Office of Nuclear Physics

Scientific Mission and Research Programs

Brookhaven National Laboratory is a multi-program U.S. Department of Energy laboratory with scientific programs in Particle Physics; Nuclear Physics; Basic Energy Sciences; Life Sciences; and Applied Sciences. A guide to the laboratory can be found on the web site www.bnl.gov. The principal facility for Nuclear and Particle Physics (NPP) is the Relativistic Heavy Ion Collider (RHIC). Operation began in 2000 and will continue until 2025. Large parts of RHIC will then be used to construct the Electron-Ion Collider. RHIC can collide light and heavy ions from protons to uranium, including combinations of different ion species. Gold beams reach energies up to 100 GeV/nucleon and polarized protons up to 255 GeV. Two detectors, STAR (large solid-angle detector optimized for particle identification and extended tracking and calorimetry in the forward direction) and sPHENIX (state-of-the-art large acceptance detector for high-rate measurements of jets and heavy flavor), are used to study reaction products from ion-ion or proton-proton collisions. The primary scientific mission of RHIC is to explore the unique quantum many-body phenomena exhibited by matter governed by Quantum Chromodynamics (QCD) under extreme conditions analogous to those attained in the first microseconds of the universe following the BigBang. A secondary mission is to quantify the contributions of gluons and sea quarks and antiquarks to the overall spin of a proton. Major discoveries to date include the transition at very high temperatures from ordinary nuclear matter to quark-gluon matter that behaves as a nearly viscous-free liquid, and observation that gluon spin contribution to the proton spin is non negligible. The layout of RHIC on the BNL site and an illustration of its two principal detectors are shown in Figure 1. Table 1 summarizes the collider's capabilities achieved to date.

Characterization of the facility

Relativistic heavy ion collider; polarized proton collider.

Facility parameters

For exemplary tables on RHIC performance, see Table 14.24.

Facility's major experimental instrumentation and its capabilities

RHIC Facility: The present instrumentation at RHIC consists of two collider detectors designed to provide complementary capabilities from measurements of high energy collisions of heavy nuclei and of spin- polarized protons. Each detector occupies one of the six beam-crossing regions in the RHIC ring.

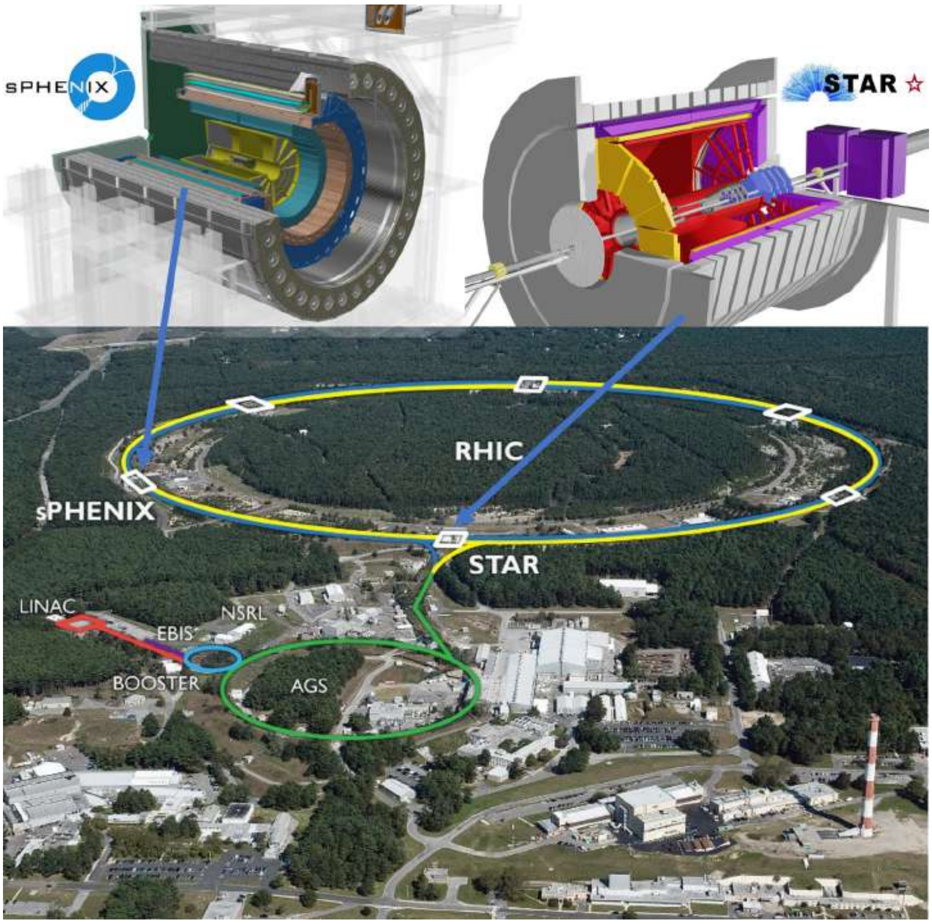

Figure 14.23: Layout of RHIC and illustration of its two principal detectors, STAR and sPHENIX.

Mode	Beam energy [GeV/nucleon]	No of bunches	Ions/bunch [10^9]	* [m]	RMS emittance [μm]	Peak luminosity [$cm^{-2}s^{-1}$]	Avg. store luminosity [$cm^{-2}s^{-1}$]	Luminosity per week
U+U	96.4	111	0.3	0.7	2.2→0.4	$8.8 x 10^{26}$	$5.6 x 10^{26}$	0.2 nb^{-1}
Au+Au	100	111	2.0	0.7	2.0→0.7	$155 x 10^{26}$	$87 x 10^{26}$	3.0 nb^{-1}
Ru+Ru§	100	111	1.0	0.7	1.2→0.9	$38 x 10^{26}$	$21 x 10^{26}$	0.5 nb^{-1}
Zr+Zr§	100	111	1.0	0.7	1.15→0.9	$48 x 10^{26}$	$22 x 10^{26}$	0.5 nb^{-1}
Cu+Au	100	111	4.0/1.3	0.7	4.1→1.2	$120 x 10^{26}$	$100 x 10^{26}$	3.5 nb^{-1}
Cu+Cu	100	37	4.5	0.9	2.5→5.0	$2 x 10^{28}$	$0.8 x 10^{28}$	2.4 nb^{-1}
h+Au	104/100	111	45/1.3	1.0	2.0→3.0/1.5	$17 x 10^{28}$	$10 x 10^{28}$	33 nb^{-1}
d+Au	101/99	111	130/1.9	0.7	2.4→2.2	$85 x 10^{28}$	$50 x 10^{28}$	125 nb^{-1}
p +Au	103/97	111	225/1.6	0.85/0.7	2.7→3.2/3.0→1.3	$88 x 10^{28}$	$45 x 10^{28}$	140 nb^{-1}
p +Al	103/98	111	240/11	0.85/0.7	2.4→3.7/2.2→1.7	$760 x 10^{28}$	$380 x 10^{28}$	1.2 pb^{-1}
p +p *	100	111	225	0.85	2.8→4.0	$115 x 10^{30}$	$63 x 10^{30}$	25 pb^{-1}
p +p *	255	111	185	0.65	3.1→3.9	$245 x 10^{30}$	$160 x 10^{30}$	60 pb^{-1}

§At the request of STAR, luminosities for Ru+Ru and Zr+Zr were leveled at $21.5 x 10^{26}$ $cm^{-2}s^{-1}$ using a variable vertical separation. The potential peak luminosity with centered beams exceeds the leveled luminosity by a factor of 4.
*Blue and Yellow ring intensity- and time-averaged polarization of $P = 55\%$ in stores at 100 GeV in Run-15 and $P = 55\%$ at 255 GeV in Run-17 as measured by the H-jet.

Figure 14.24: Achieved beam parameters and luminosities for all ion combinations at the highest energy, and for polarized protons at 100 and 255 GeV. RHIC has also operated extensively at lower energies.

sPHENIX Detector – state-of-the-art large acceptance detector for high-rate measurements of jets and heavy flavor.

STAR Detector – large solid-angle detector optimized for particle identification and extended tracking and calorimetry in the forward direction.

Nature of user facility

DOE Designated National User Facility

Program Advisory Committee/experiment proposals

Yes, see https://www.bnl.gov/npp/pac.php

Number of active users and their origin

RHIC has been designated as a User Facility by the U.S. Department of Energy and has a Program Advisory Committee. At present there are 917 users registered in the Users' Office. Of these, 10% are BNL staff; 45% are from other U.S. institutions; and 45% from outside the U.S. Of the non-U.S. users, 34% are from Asia; 10% from Europe; less than 1% from South America; and 55% from North America.

User group

The RHIC/AGS Users' Group (www.rhicuec.org) also includes users from the NASA Space Radiation Laboratory (NSRL), a facility that principally makes use of one of the RHIC injectors to study the effects of heavy ion beams on biological materials and electronics.

Laboratory Staff

Table 14.12: Staff at BNL. *122 permanent staff with doctoral degrees plus 6 temporary. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff (experiment)	503*
Permanent staff (theory)	6
Postdoctoral researchers (experiment)	∼78
Postdoctoral researchers (theory)	1
Graduate students	∼325
Undergraduate students	∼93

Future Plans

The Electron-Ion Collider (EIC) to be built at BNL will add an 18-GeV polarized electron ring to the facility and provide high-energy, high-luminosity electron-nucleus and polarized electron-proton collisions, with at least one new detector in a dedicated collision region. The capabilities of variable center-of-

mass energy, high luminosity, and polarizations provided by the EIC will extend deep inelastic scattering measurements of the partonic structure ofthenucleons and nuclei. These measurements will provide precision insight into the region where the constituents are completely dominated by self- interacting gluons. This extended reach will enable tests of QCD and predicted universal behavior in cold matter characterized by very high, possibly saturated, densities of gluons. The EIC will provide three-dimensional imaging of the internal structureof the nucleons and nuclei and allow for a full decomposition of the proton spin, therefore answering the question where the proton spin comes from. With the EIC, physicists will discover how the nucleon mass is dynamically generated by the interactions of quarks and gluons inside.

SANFORD UNDERGROUND RESEARCH FACILITY (SURF)

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Managed and operated by the South Dakota Science and Technology Authority under a Cooperative Agreement for the US Department of Energy, Office of High Energy Physics, with initial construction support mainly from South Dakota state and private funds

Scientific Mission and Research Programs

SURF is an international facility dedicated to compelling multidisciplinary underground scientific research, including physics, biology, geology and engineering. The unique underground environment at SURF allows researchers to explore a host of important questions regarding the origin of life and its diversity, mechanisms associated with geologic processes as well as a number of engineering topics such as mining innovations and technology developments. A deep underground laboratory is also where some of the most fundamental topics in physics can be investigated, including the nature of dark matter, the properties of neutrinos and topics related to nuclear astrophysics such as the synthesis of atomic elements within stars. SURF's mission is to advance world-class science and inspire learning across generations.

Characterization of the facility

SURF property comprises approximately 1 km^2 (223 acres) on the surface and more than 31 km2 (7700 acres) underground. In total, the facility consists of more than 600 km of tunnels extending to over 2450 meters below ground; two main shafts provide redundancy in terms of safe access and some services such as power and network. Of the 29 underground elevations that are currently accessible, the following have been identified as key levels for science activities: 300L (130 m, 350 mwe), 800L (280 m, 770 mwe), 1700L (550 m, 1500 mwe), 2000L (620 m, 1700 mwe), 4100L (1280 m, 3700 mwe), 4550L (1430 m, 4100 mwe) and 4850L (1490 m, 4300 mwe), which is the main level with the most infrastructure. In particular, the 4850L provides research facilities with an ultra-low background environment, field rock with very low levels of U and Th, and reduced-activity concrete and assayed construction materials. In particular, at the 4850L Davis Campus the muon flux has been measured to be 5.3×10^{-5}/m^2/s (107 reduction in cosmic rays) and the thermal neutron flux has been measured to be 1.7×10^{-2} /m^2/s. Low background radioassay (gamma-ray counting) facilities are available with U and Th sensitivities on the order of 0.1 μBq/kg (1 ppt) for a two-week counting time. Production of electroformed copper is also performed at the facility (average U, Th decay chain $\sim$ 0.1 μBq/kg).

Facility parameters

See Table 14.25.

Underground lab area (m^2) / volume (m^3)	1938 / 7777
Overburden (m / mwe)	1490 / 4300
Muon flux (m^{-2} s^{-1})	5.3 X 10^{-5}
Neutron flux (m^{-2} s^{-1})	1.7 X 10^{-2}
Radon level (Bq m^{-3})	300

Figure 14.25: Table of facility parameters (4850L)

Facility's major experimental instrumentation and its capabilities

SURF owns 1.5M liters of xenon gas (further purified by the LZ collaboration to remove Kr to ppq levels). For monitoring radon concentrations, SURF owns 2 AlphaGUARD instruments (PQ2000 Pro and DF2000, including an AlphaPM progeny monitor), 2 other AlphaGUARD units are on loan from LBNL. Particle counters are used to determine cleanliness class in key laboratory areas, and SURF owns five MetOne particle counters: 2 BT-637S models and 3 GT-521S models. Bulk storage for liquid nitrogen is available at SURF as well as vehicles for transporting it to various laboratories. SURF holds an NRC Broad Scope license for radioactive materials, with various gamma-ray and neutron survey instruments and a liquid scintillator counting system (Perkins Elmer Model 4910).

Technical facilities

Two well-furnished underground research campuses are located the 4850-foot level of the facility. The Davis Campus (near the Yates Shaft) has a footprint of 1018 m^2 / 4633 m^3 (3017 m^2 / 11,354 m^3 total) and includes a stainless-steel tank that can be used for shielding (7.6 m diameter, 6.4 m high). The Ross Campus (near the Ross Shaft) has a footprint of 920 m^2 / 3144 m^3 (2653 m^2 / 8805 m^3 total). Laboratories provide cleanroom spaces (as low as class 100 with appropriate protocols), redundant utilities, HVAC, access and professional support staff including environment, safety and health, engineering, and scientific support staff. Long-term underground radon data have been collected at various locations, and recent average concentrations are 300 Bq/m3 for the 4850L Davis and Ross Campuses, with low baselines around 150 Bq/m3. A vacuum-swing adsorption radon reduction system is available at the Davis Campus, providing a 770x Rn reduction at the system output (0.1 Bq/m^3 at 150 m^3/hr airflow) and approximately 250x Rn reduction inside Davis Cavern tank. On the surface, the principal facility that directly serves science needs is the Surface Laboratory, which provides approximately 210 m^2 of lab space (265 m^2 total). The Surface Laboratory facility includes two cleanrooms (total of more than 90 m^2), one of which is served by a commercial radon-reduction system capable of a measured reduction of 2200x at the output and 770x inside the cleanroom (averaging <0.5 Bq/m^3). A new surface maintenance and support facility opened in 2021 that replaces the shipping and receiving warehouse located at the Ross Complex, consolidates maintenance capabilities and resources, provides office space as well as offering some staging space for research groups. The new facility was funded by a $6.5M state investment and has a total footprint of 2415 m^2.

Nature of user facility

SURF hosts experiments with collaborators from a number of national and international institutions and laboratories. SURF is submitting an application in 2022 to become a DOE Office of Science Designated National User Facility.

Program Advisory Committee/experiment proposals

All SURF experiment proposals receive internal SURF review. Groups requesting significant SURF resources or significant changes to the capacities and/or capabilities of the facility may be subject to external review and evaluation. Facility resources requested by some proposals are

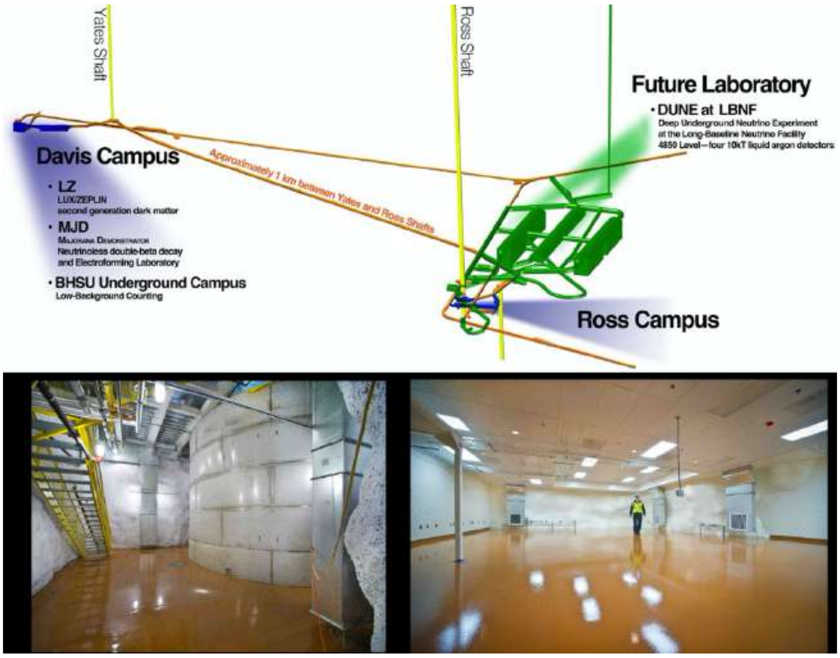

Figure 14.26: The SURF 4850 level highlighting existing campuses (blue shading), as well as LBNF/DUNE caverns currently under construction (green shading). Pictures of space at the Davis Campus are also shown.

allocated by the Laboratory Director based on merit review. To evaluate experiment proposals, SURF established an external Science Program Advisory Committee in 2021 consisting of domestic and international scientific experts covering the full range of SURF science. Peer review is intended to be commensurate with the resources requested.

Number of active users and their origin

Annual users at SURF can be represented as follows: pre-pandemic average (FY18-19) = 239, pandemic average (FY20-21) = 172. Approximately 330 individual researchers are currently active at SURF (see User group section).

Percentage of users, and percentage of facility use that come from inside the institution

3% of SURF users are internal, including staff scientists, engineers and technicians.

Percentage of users and percentage of facility use from national users

88% of SURF users are from U.S. institutions.

Percentage of users and percentage of facility use from outside the country where your facility is located

12% of SURF users are from non-U.S. institutions.

Fraction of the international users from outside your geographical region

12% of SURF users are from institutions that are outside North America (most from Europe, some from Asia).

User group

The SURF User Association includes approximately 330 members based on onsite activities from a total pool of roughly 550 experiment collaborators (currently not including the DUNE experiment, which currently comprises a total of 1500 members). The User Association has an executive committee and a formal charter. The User Association charter was recently updated to expand membership to include the global underground science community, and a corresponding registration process is being developed and is expected to be launched in 2022.

Laboratory Staff

Table 14.13: Staff at SURF. *Including 3 scientists with a doctoral degree. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	180*
Postdoctoral researchers	0
(Resident) Graduate students	1
(Non-Resident) Graduate students	~75**
Undergraduate students	~10-15/ year

Special student programs

Davis-Bahcall scholar program, generally accepting 8 scholars per year (http://www.doe.sd.gov/scholarships/DAVIS-BAHCALL.aspx.
Dave Bozied, Chris Bauer Engineering and Jack Headley STEM summer internships, accepting up to 9 students per year: (http://www.sanfordlab.org/careers/dave-bozied-and-chris-bauer-internships).
Related programs: BHSU REU (http://www.bhsu.edu/research/reu), BHSU QuarkNet (http://www.bhsu.edu/Academics/Natural-Sciences/Physics/QuarkNet/About) both with research conducted at SURF.

Future Plans

Construction for the Long Baseline Neutrino Facility (LBNF)/Deep Underground Neutrino Experiment (DUNE) is underway at SURF. The excavation phase for two large caverns (each 150m L × 20m W × 28m H) and a utility cavern (190m L × 20m W × 11m H) started April 2021 and is expected to last approximately 3 years. For additional space, SURF engaged with a design firm to conduct a feasibility study for caverns that could be excavated on a non-interference basis with LBNF/DUNE.

Several 4850L locations are being considered for laboratories with a cross-section of 20 m wide × 24 m high and up to 100 m in length. Current 4850L expansion designs are expected to accommodate future generation dark matter experiments (50-100 tons, e.g., DARWIN) and neutrinoless double beta- decay projects (100 tons). Other experiments could also take advantage of the LBNF neutrino beam, such as the Theia water-based liquid scintillator project. There is significant opportunity for expansion to meet the needs of a wide range of research disciplines into the future. Several disciplines would benefit from a deep site, including extremophile biology and geothermal projects, but most significantly, physics experiments that are particularly sensitive to cosmogenic backgrounds. In particular, neutrinoless double-beta decay experiments continue to analyze existing data and develop analysis tools that may allow next- generation measurements to be made at such sites as SURF's 4850L. The cosmic-ray muon flux on the 7400L (6500 mwe) is expected to be 25x lower than the 4850L and would provide a superior advantage in ensuring cosmogenic backgrounds are negligible.

JOHN D. FOX SUPERCONDUCTING LINEAR ACCELERATOR LABORATORY

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University Institute
U.S. National Science Foundation
Florida State University

Scientific Mission and Research Programs

The mission of the laboratory is forefront research in nuclear physics, nuclear astrophysics and the education of graduate students. The major research programs are the study of nuclear reactions induced by radioactive beams, the structure of nuclei at high angular momentum, the structure of nuclei far from stability using both stable and radioactive beams, and reactions of importance in astrophysics.

Characterization of the facility

9 MV tandem Van de Graaff accelerator injecting into a 8 MV superconducting LINAC.

Facility parameters

See Table 14.14.

Table 14.14: FSU accelerator beam energies and intensities.

Particle	Intensity (pnA)	Max. energy (A MeV)
p	300	8.7
^{3}He	100	12.2
^{4}He	100	10.0
^{6,7}Li	100	9.1
^{12}C	150	8.3
^{14}C	40	7.1
^{16}O	150	7.8
^{28}Si	80	6.4
^{32}S	40	5.6
^{35}Cl	30	5.0

Facility's major experimental instrumentation and its capabilities

1. In-flight radioactive beam line RESOLUT
2. Dedicated ^{14}C ion source
3. Gamma detection array with digital electronics
4. Split-pole magnetic spectrometer (2017)
5. Scattering chambers, charged particle detectors
6. Neutron detector array

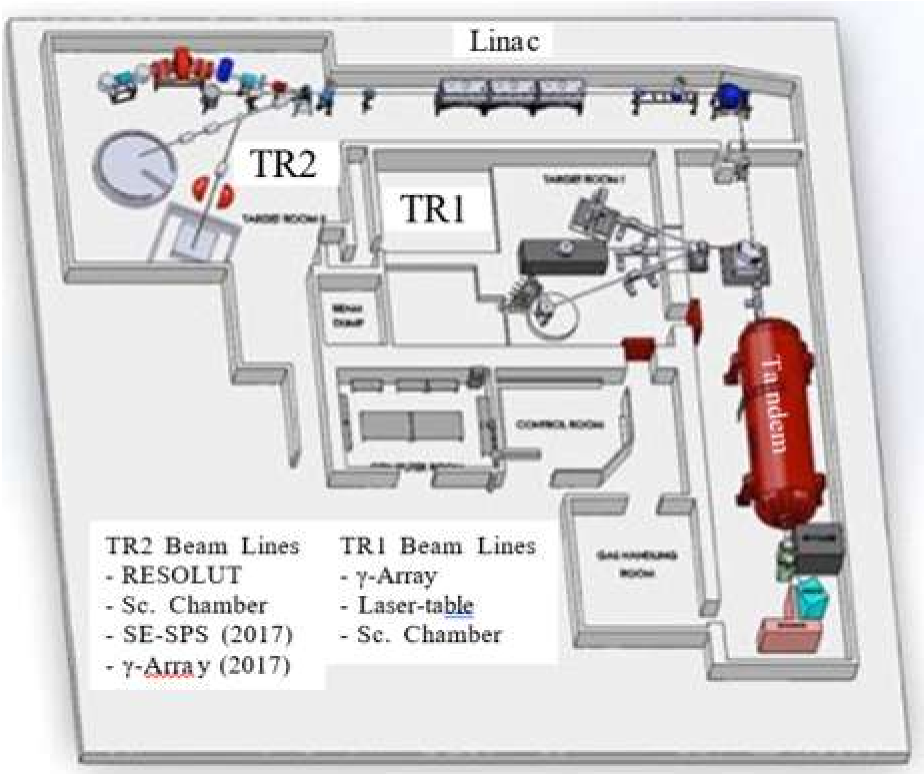

Figure 14.27: Accelerator laboratory at Florida State University.

Nature of user facility

Not a user facility.

Program Advisory Committee/experiment proposals

No PAC – collaborations can be discussed.

Number of active users and their origin

Number of active users averaged over the last 5 years is 25 per year, including faculty, postdocs, and graduate students.

Percentage of users, and percentage of facility use that come from inside the institution

Estimated at 80% averaged over last 5 years

Percentage of users and percentage of facility use from national users

10%.

Percentage of users and percentage of facility use from outside the country where your facility is located

10%.

Fraction of the international users from outside your geographical region

100%.

User group

Founding Member of ARUNA, the Association for Research with University Nuclear Accelerators.

Table 14.15: Staff at the FSU accelerator. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Faculty (experiment)	6
Research Faculty (experiment)	2
Technical staff	7
Faculty (theory)	2
Postdoctoral researchers	3
(Resident) Graduate students	14
(Non-Resident) Graduate students	4*
Undergraduate students	$\sim$9/ year

Laboratory Staff

Special student programs

Summer Junior Fellows program for high school students.

Future Plans

High-resolution high-acceptance Super-Enge Split Pole Sectrograph (2017). Planning to add superconducting resonators to increase the maximum energy and mass of beams.

THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY (JEFFERSON LAB)

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Jefferson Lab is a user facility managed and operated by Jefferson Science Associates, LLC (JSA) for the U.S. Department of Energy.
Department of Energy Office of Science for Nuclear Physics
Work for Others funded by the U.S. Department of Energy

Scientific Mission and Research Programs

The Department of Energy's Thomas Jefferson National Accelerator Facility, or Jefferson Lab (JLab), is a nuclear physics research laboratory built to explore the fundamental nature of confined states of quarks and gluons, including the nucleons that comprise the mass of the visible universe. The Continuous Electron Beam Accelerator Facility (CEBAF), (originally designed to deliver up to 6 GeV, with high current up to 200 µA), today delivers polarized beams up to 12 GeV, with high current up to 90 µA. Its continuous wave electron beams and associated experimental equipment offer unique research capabilities to its international user community. Jefferson Lab is also a world-leader in the development of the superconducting radio-frequency (SRF) technology utilized for CEBAF. This technology is the basis for an increasing array of applications at JLab, at other DOE labs, and in the international scientific community. It has facilitated the development of JLab's Free Electron Laser (FEL) and Energy Recovery Linac (ERL), and enabled JLab to contribute to the construction of SNS at Oak Ridge and LCLS-II at SLAC.

Characterization of the facility

Jefferson Lab features a continuous wave recirculating electron accelerator providing beams from 0.05 up to 12 GeV, 100 picoamps to 90 micro amps. CEBAF can provide beams simultaneously to four experimental halls each with complementary experimental equipment. The FEL has been renamed the Low Energy Recirculator Facility (LERF) which enables new capabilities such as medical isotope research.

Facility parameters

Continuous Electron Beam Accelerator Facility (CEBAF) parameters:

- Energy: up to 12 GeV
- Current: nA to 90 µA
- Polarization: > 80%
- Relative Energy Spread and Stability: $\sim 10^{-4}$
- Pulse Structure: 250 MHz to 1500 MHz
- Beam Power: up to 1 MW
- Controlled Helicity Correlated Properties: $< 10^{-6}$ level
- Four experimental end-stations (halls)

Figure 14.28: Aerial photo of the Jefferson Lab accelerator site

Low Energy Recirculator Facility (LERF) parameters: Electron beam parameters

- Energy range: 50-170 MeV
- Current: up to 8 mA
- Charge: up to 270 pC Laser parameters
- Wavelength range: 1-4 microns/0.3-1 micron
- Micropulse energy: up to 300 μJ, 20 μJ, 2 μJ
- Pulse length: $\sim$0.1-2 ps FWHM nominal
- PRF: 74.85 MHz ÷ 2x down to 4.68 MHz

Facility's major experimental instrumentation and its capabilities

CEBAF (Superconducting Radio Frequency Accelerator): Electron beam energies up to 12 GeV, with beam currents ranging from 100 picoamps to 90 microamps, continuous-wave electron accelerator. Simultaneous beams to up to four experimentalHalls with polarization exceeding 80%.

Hall A: Two high-resolution magnetic spectrometers, Super Bigbite Spectrometer, MOLLER experiment

Hall B: Large acceptance detector built around a superconducting toroidal magnet in the forward part and a superconducting solenoid in the central part, enabling the detection of multiparticle final states.

Hall C: Two general-purpose spectrometers (both of high momentum resolution) and experiment-specific equipment.

Hall D: GlueX spectrometer system, including superconducting solenoidal magnet for detecting multiparticle decays of exotic mesons.

Superconducting Radio Frequency Technology Facility: Superconducting accelerator cavity fabrication, surface treatment, cryomodule assembly and test,and research facilities.

LERF: The Energy Recovery Linac (ERL) Free Electron Laser driver was designed to provide 10 kW/1 kW of laser light with sub-picosecond pulse length, and transform-limited bandwidth. It can also be used as an accelerator test facility for studying advanced ERL concepts, and testing out new diagnostics and instrumentation.

Computational and Data Science: JLab operates large clusters of computers for Lattice Quantum Chromodynamics (LQCD) calculations as part of the Nuclear and Particle Physics LQCD Computing Initiative (NPPLCI) established by the DOE Office of Science. These clusters include over 30,000 cores and include 320 GPUs. JLab also develops and utilizes data science techniques such as artificial intelligence and machine learning to enhance current detector capabilities and to design new detector and accelerator systems.

Applied Research Center: In collaboration with local colleges/universities and the City of Newport News, share cooperative R&D laboratories in lasers, plasmas and materials.

Figure 14.29: Experimental Equipment at JLab

Nature of user facility

DOE Designated National User Facility

Program Advisory Committee/experiment proposals

Yes.

Number of active users and their origin

Jefferson Lab has some 3200 registered users with nearly 1500 actively involved in experiments.

Percentage of users, and percentage of facility use that come from inside the institution

As a user facility, very little of the research at Jefferson Lab is conducted by scientists in-house; and would estimate JLab staff to be almost 10% of its user community.

Percentage of users and percentage of facility use from national users

65%.

Percentage of users and percentage of facility use from outside the country where your facility is located

35%.

Figure 14.30: SRF cryomodule assembly at Jefferson Lab.

Fraction of the international users from outside your geographical region

31% are from outside North America.

User group

The Jefferson Lab Users Organization has some 1700 active users, and its work is coordinated by the Jefferson Lab User Organization Board of Directors (JLUO BOD). The Chair of the JLUO BOD represents the users with the Program Advisory Committee and JSA, and with the Laboratory Director.

Laboratory Staff

See Table 14.16.

Table 14.16: Staff at Jlab. *Including 178 scientists with a doctoral degree. **6 Laboratory scientists plus 9 in joint positions with local universities. ***20 employed by laboratory directly, 7 employed at universities and reimbursed by the Lab; 21 employed/paid by the user community. ****Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff (experiment)	744*
Permanent staff (theory)	15**
Postdoctoral researchers (experiment)	48***
Postdoctoral researchers (theory)	9
(Resident) Graduate students (experiment)	∼80
(Resident) Graduate students (theory)	10
(Non-Resident) Graduate students	∼100****
Undergraduate students	∼37/ year

Special student programs

Jefferson Lab's programs involve more than 13,000 students each year; they include:

- Hampton University Graduate Student Program (HUGS)
- Becoming Enthusiastic About Math and Science (BEAMS)
- Science Lectures for High School and Middle School Students (Science Series Lectures)
- Virginia Regional Science Bowls (High School and Middle School)
- Cooperating Hampton Roads Organizations for Minorities (CHROME)
- The Department of Energy's Science Undergraduate Laboratory Internships (SULI)
- Jefferson Lab Science Activities for Teachers Program
- Jefferson Lab High School Summer Honors Program
- Graduate Student Seminar Series
- Summer Detector and Computer Lecture Program
- Jefferson Lab Mentorship Program
- Virginia Summer Residential Governor's Mentorship in Engineering
- Research Experience for Undergraduates with Old Dominion University
- Community College Internship Program
- SURA/JLab Thesis Prize Program
- SURA Fellowship at JLab Program (for Graduate Students)

Future Plans

Jefferson Lab is operating the upgraded CEBAF facility in order to provide new insights into the structure of the nucleon, the transition between hadronic and quark/gluon descriptions of matter, and the nature of quark confinement. The facility has unique capabilities world-wide for exploring non-pertubative QCD and hadron and nuclear structure in the valence region. CEBAF will continue to provide unique capabilities to the international scientific community as the premier high luminosity fixed target electron scattering facility. This capability will be significantly enhanced with the implementation of the proposed Solenoidal Large Intensity Device, SoLID. Other options for CEBAF upgrades under consideration are polarized and unpolarized positron beams, and a cost-effective energy upgrade to 24 GeV using Fixed Field Alternating gradient (FFA) technology for the recirculating arcs. JLab is also partnering with Brookhaven National Lab to construct the future Electron Ion Collider facility.

TRIANGLE UNIVERSITIES NUCLEAR LABORATORY (TUNL)

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Telephone: +1 919-660-2600

Director: Prof. Robert V. F. Janssens
Email: rvfj@email.unc.edu

Four-University Facility (Duke University, North Carolina Central University, North Carolina State University, and the University of North Carolina at Chapel Hill)
U.S. Department of Energy

Scientific Mission and Research Programs

The Triangle Universities Nuclear Laboratory (TUNL) is a U.S. Department of Energy Center of Excellence consisting of a consortium of four major universities within the North Carolina Research Triangle area: Duke University, North Carolina Central University, North Carolina State University and the University of North Carolina at Chapel Hill. Three particle-beam accelerator facilities are operated by TUNL: (1) the High Intensity Gamma-ray Source (HIGS), (2) the Laboratory for Experimental Nuclear Astrophysics (LENA), and (3) the tandem laboratory.

The facilities are used to study the structure of nuclear matter and to measure nuclear reaction rates important for astrophysics. The capabilities of these facilities enable nuclear structure studies over a wide range of nuclear phenomena from low-energy QCD to nuclear structure, and from reaction dynamics of few- nucleon systems to collective excitations in heavy nuclei. In addition, these facilities are also used for research relevant to national nuclear security, homeland security and the environment.

Characterization of the facility

Accelerator facility.

Facility's major experimental instrumentation and its capabilities

The High Intensity Gamma-Ray Source (HIGS): The γ-ray beams at HIGS are produced by Compton backscattering of photons from electron bunches circulating inside the optical cavity of a storage-ring based Free Electron Laser (FEL). The electron-accelerator drivers consist of a 180-MeV linac pre-injector, a booster injector with a 180 MeV to 1.2 GeV energy range, and a race-track shaped storage ring that has an energy range of 250 MeV to 1.2 GeV. The circumference of the storage ring is about 108 m. The FEL consists of electromagnetic undulators that are installed in one of the straight sections of the storage ring. These form the active elements of an optical klystron with an optical resonator length of 53.7 m (mirror-to-mirror distance). The high intensity of this source, about 1000 γ's/s/keV, is mostly a result of the combination of high intra-cavity optical power and the high average beam current in the storage ring (about 100 mA). The layout of the facility is found in Figure 14.31.

The γ-ray beams at HIGS are nearly mono- energetic and highly polarized (linear or circular). The beam energy is tunable by adjusting the electron energy and magnetic field strength in the undulators.

The γ-ray beam energy range is from 2 to 130 MeV. The energy spread of the γ-ray beam is selectable to about 1% (FWHM) by collimation. The γ-ray beam specifications and information about the HIGS facility are available on the TUNL web site: https://www.tunl.duke.edu.

- HINDA (HIγS NaI Detector Array with NaI shields)

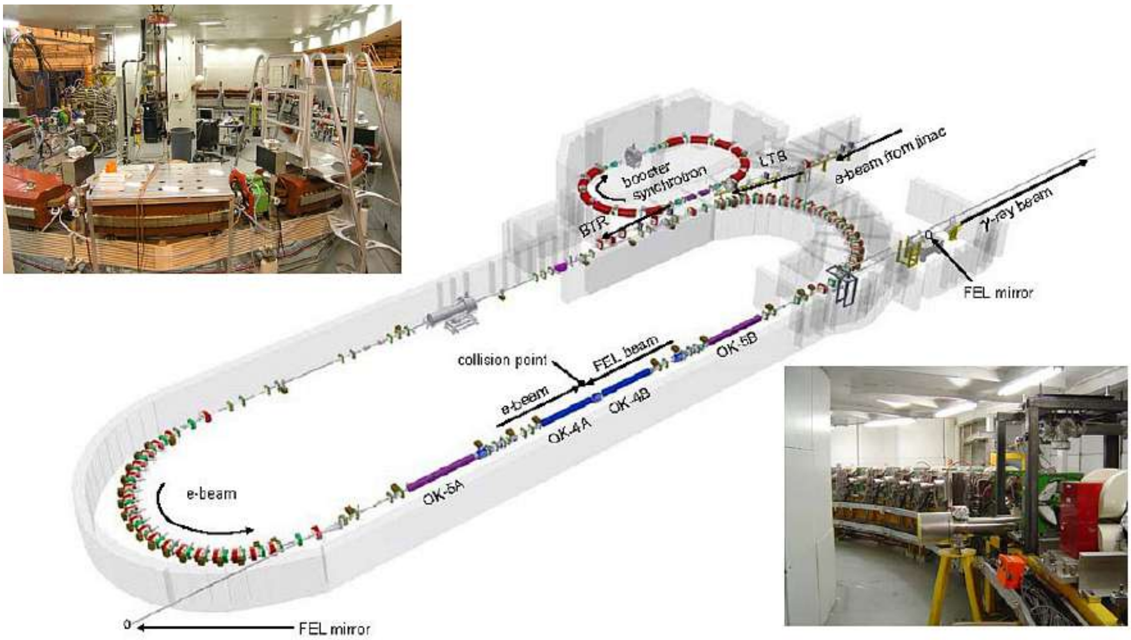


Figure 14.31: Layout of the HIGS accelerator systems with photographs of the booster (upper left) and a section of the electron storage ring (lower right).

- Cryogenic Targets (hydrogen/deuterium, ^{3,4}He)
- Clover array of high resolution γ-ray detectors (HPGe, Cerium Bromide and Lanthanum Bromide)
- Liquid scintillator arrays for fast neutron detection
- ^{3}He counters for slow neutron detection

The Laboratory for Experimental Nuclear Astrophysics (LENA): LENA is a light-ion low-energy accelerator facility dedicated to nuclear astrophysics experiments. The floor diagram of the laboratory is shown in Figure 2. The laboratory has two low- energy electrostatic accelerators that are capable of delivering high-current charged particle beams to target. One is an Electron Cyclotron Resonance (ECR) source on a 200-kV isolated potentialplatform (230 keV total energy) and the other one is a 2-MV Singletron accelerator. The ECR source can produce pulsed and DC proton beams with currents of up to 20 mA on target. The Singletron can deliver beam currents up to 2 mA DC as well as pulsed beams (0.15 – 4 MHz with pulse widths of 2 – 20 ns). Both accelerators are fully computer-controlled. The standard y-ray detectors at LENA include a large-volume HPGe detector surrounded by a NaI annulus which incorporates active and passive shielding. The combination of HPGe + NaI permits coincidence / anti-coincidence,Q-value, and multiplicity cuts to be applied, which often enables measurements of low- yield cross-sections with a quality that is competitive with underground laboratories. There is also a large solid-angle segmented, position-sensitive NaI annulus as well as other scintillators. For more information, visit: https://tunl.duke.edu/nuclear-astrophyics .

- HPGe detector with NaI shield
- Scattering chamber for charged-particle induced reactions

The Tandem Laboratory: The main accelerator in this laboratory is an FN tandem Van de Graaff that has a maximum terminal voltage of 10 MV. The floor layout of the tandem accelerator laboratory is shown in Figure 3. Negative ions can be injected into the tandem from three sources:

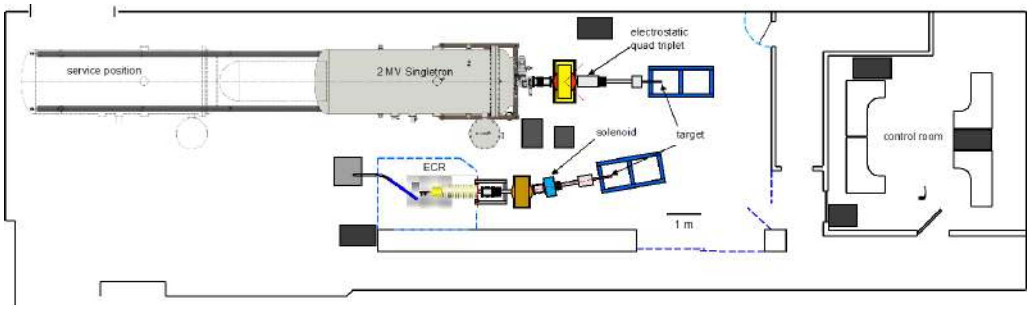


Figure 14.32: Layout of LENA

(1) a direct extraction negative ion source, which provides beams of unpolarized H- and D- ions, (2) an atomic beam polarized ion source, providing beams of polarized H- and D- ions, and (3) a helium- ion source, which produces beams of 4He and 3He ions. All beams can be pulsed with a repetition rate up to 5 MHz. After acceleration, momentum analyzed beam can be delivered to any one of 7 beam lines. The main target-room equipment includes general-purpose charged-particle scattering chambers, a neutron time-of-flight (TOF) spectrometer system, and an Enge split-pole magnetic spectrometer. A special feature of the facility is the production of secondary beams of fast neutrons that are nearly mono-energetic and can be unpolarized or polarized. The shielded neutron detectors in the TOF spectrometer enable neutron scattering measurements using an unshielded source. Measurements of neutron-induced reactions that require the use of an array of neutron detectors can be carried out in the shielded neutron source area, which produces a collimated neutron beam.

The beam parameters for the tandem are summarized in Table 14.17.

Table 14.17: Summary of beam parameters of the TUNL FN tandem.

Parameter	Value
E_{max}(p,d)	20 MeV
Pulse width (FWHM)	1.1 ns
Pulse rep. rate	DC to 5 MHz
I_{max} on target (DC)	5 μA (unpolarized)
	2 μA (polarized)
Beams	p, d, ^{3,4}He
ΔE	<500 eV

- Neutron time-of-flight spectrometer
- Scattering chamber for charged-particle reactions
- Enge split-pole spectrometer
- HPGe clover detectors
- Assortment of liquid scintillators for fast neutron detection
- High-pressure gas scintillators, e.g., ^{4}He and ^{3}He

Facility parameters

HIGS:

- 1.2-GeV Storage-ring Free Electron Laser
- Gamma-ray produced by Compton-back Scattering at E_γ = 2 – 130 MeV (up to 10^3 γ/s/eV)
- Nearly mono-energetic γ-ray beam (linear and circular polarization)
- Two target areas on a single beam line

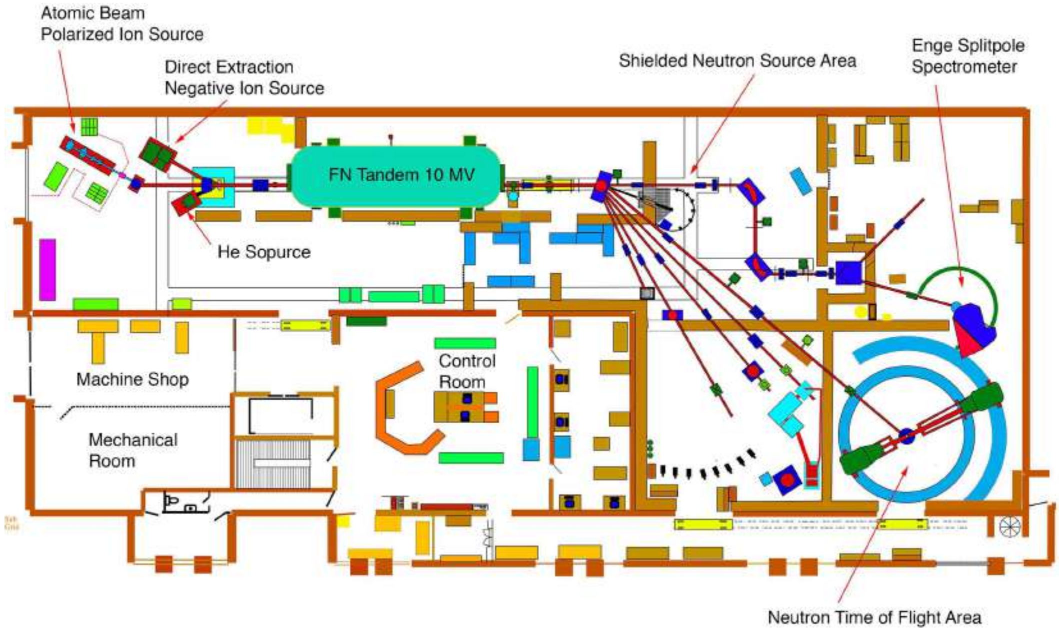


Figure 14.33: Layout of tandem laboratory.

LENA:
- 200-keV ECR ion source
- 2-MV Singletron accelerator
- Light-ion beams (p, d, α)
- One target area

Tandem Lab:
- Tandem Van de Graaff (V_{max} = 10 MV)
- CW or pulsed (f$\sim$ 5 MHz) light-ion beams (p, d, α)
- Fast mono-energetic neutron beams (CW or pulsed)
- Multiple target areas and beam lines
- Collimated neutron beam

Nature of user facility

Not a user facility.

Program Advisory Committee/experiment proposals

Yes for HIGS.

Number of active users and their origin

100 users for HIGS, 10 for LENA, 50 for the Tandem Lab.

Percentage of users, and percentage of facility use that come from inside the institution

40%/ 60% for HIGS; 100%/ 100% for LENA; 80%/ 70% for Tandem Lab.

Percentage of users and percentage of facility use from national users

45%/ 60% for HIGS; 100%/ 100% for LENA; 95%/ 95% for Tandem Lab.

Percentage of users and percentage of facility use from outside the country where your facility is located

55%/ 40% for HIGS; 0%/ 0% for LENA; 5%/ 5% for Tandem Lab.

Fraction of the international users from outside your geographical region
45% Europe and Asia for HIGS; 0% for LENA; 60% Europe for Tandem Lab.

User group
No.

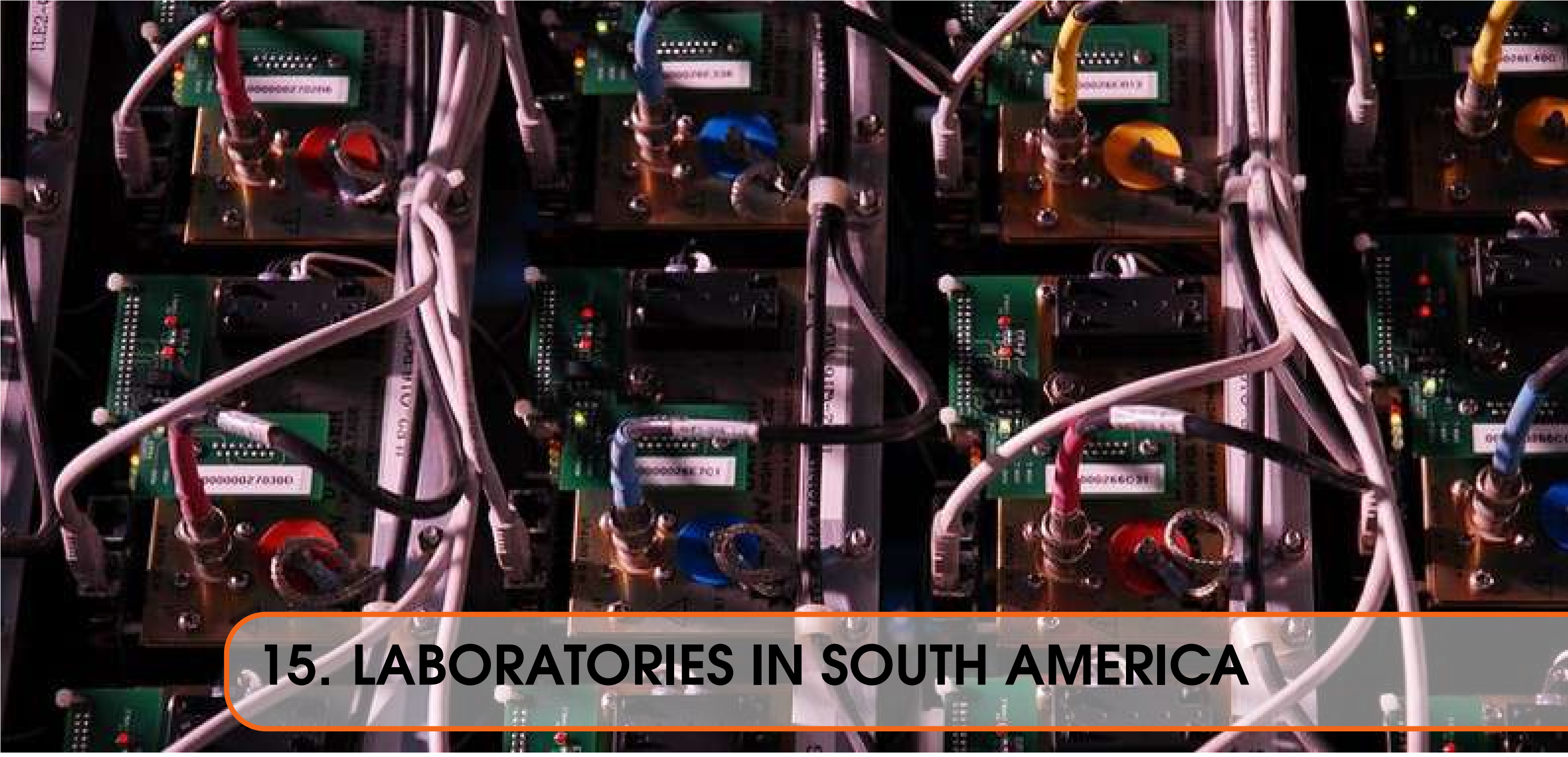
Laboratory Staff
See Table 14.18.

Table 14.18: Staff at TUNL. *Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	18.5 FTE
Postdoctoral researchers	8
(Resident) Graduate students	25
(Non-Resident) Graduate students	10*
Undergraduate students	11/ year

Special student programs
NSF/ REU (Research experience for undergraduates).

Future Plans
HIGS: Energy and intensity upgrade. LENA: Detector upgrade. Tandem lab: Heavy-ion beams.



15. LABORATORIES IN SOUTH AMERICA

TANDAR LABORATORY, COMISIÓN NACIONAL DE ENERGÍA ATÓMICA

Av. General Paz 1499, San Martín
Prov. de Buenos Aires B1650KNA, Argentina
Telephone: (54-11) 67 72-70 73
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www.tandar.cnea.gov.ar/

Heads of the facility:
Ing. Andrés Fernández Salares
Ing. Carlos A. Miguez
Email: alurrald@tandar.cnea.gov.ar
Dr. Adriana Cristina Serquis (President of CNEA)

Governmental agency
Government budget (CNEA)
Funding agencies (mainly CONICET and ANPCYT)

Scientific Mission and Research Programs

The main experimental and theoretical research lines are related to Nuclear Physics and its applications. In the field of the low-energy nuclear physics nuclear reactions: elastic scattering angular distribution measurements, offline measurements of fusion and transfer cross sections and breakup reactions and their influence on fusion reactions involving weaklybound nuclei. A result of basic research activities has been the application of various experimental nuclear physics techniques to other fields of knowledge: biomedicine, environment, material science, nuclear astrophysics.

Accelerator Mass Spectrometry have been performed on 1OBe samples of geological interest and a dedicated line equipped with a Wien velocity filter and 6.7 m time-of- flight system was commissioned for the measurement of actinides contents. Radiation damage on solar cells and single events effects on electronic devices are now very active line of research and applications.

A heavy-ion microbeam facility for the study of biological (mainly environmental remediaton) and physical problems with high spatial resolution is also routinely used. A high intensity low-energy proton accelerator for accelerator-based Boron Neutron Capture Therapy (BNCT) is being developed.

Characterization of the facility

The main instrumental tool for research is a nominal 20 UD electrostatic tandem accelerator (see Figs. 15.1 and 15.2).

Facility parameters

An example of frequently used beams are: protons, lithium, beryllium, carbon, oxygen, fluorine, sulphur, nickel, iodine, gold, uranium with typical on-target intensities in the range of 1 to 100 particle- nA and energies of a few MeV/nucleon.

Figure 15.1: Sketch of the Tandar accelerator building

Facility's major experimental instrumentation and its capabilities

- Microbeam facility (beam spots of about 1 μm2) with high resolution X-ray detection.
- QDD magnetic spectrometer.
- External beam facility with on-line dose determination. Vertical proton beam for biological cell irradiation.
- Line for Accelerator Mass Spectrometry (AMS) equipped with Wien velocity filter, 6.7 m Time of Flight (start and stop microchannel plates followed by a solid-state detector).
- 30-inch diameter multipurpose scattering chamber. Irradiation chamber of 31-inch diameter, with an irradiation area of 3.2-inch diameter for simulation of outer-spaceenvironmental conditions (EDRA line).

Nature of user facility

Unofficially, user facility.

Figure 15.2: Inside the tandem

Program Advisory Committee/experiment proposals

No.

Number of active users

42

Percentage of users, and percentage of facility use that come from inside the institution

80% / 90%.

Percentage of users and percentage of facility use from national users

80% / 90%.

Percentage of users and percentage of facility use from outside the country where your facility is located

20% / 30%.

User group

40 registered members in the users group.

Laboratory Staff

See Table 15.1.

Table 15.1: Staff at Tandar directly related with nuclear- physics research and/or the TANDAR accelerator facility. *Including 13 scientists with a doctoral degree. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	40*
Permanent staff (theory)	1
Postdoctoral researchers	1
(Resident) Graduate students	2
(Non-Resident) Graduate students	2**
Undergraduate students	2/ year

Special student programs

An extension course for senior high-school students is carried out yearly (once a week; from April to November).

CENTER FOR ACCELERATOR MASS SPECTROMETRY AT THE NATIONAL ATOMIC ENERGY COMMISSION (CNEA) BUENOS AIRES

National Atomic Energy Commission (CNEA)
Ezeiza, Buenos Aires, Argentina
Telephone: (54) 011 4125 8595

Head of the facility: Eng. Sebastian Consorti
Email: sebaconsorti@cnea.gob.ar

Scientific Mission and Research Programs

The mission of the laboratory is applied AMS technique for archeology, astrophysics, geology and environmental science.

The major research programs are the measurement of ^{14}C for bio-based materials certification and for radiocarbon dating.

Characterization of the facility

8 MV tandem Van de Graaff accelerator.

Facility's major experimental instrumentation and its capabilities

- Telescope detector for isotope identification.
- Scattering chambers, charged particle detectors.
- Graphitization line for ^{14}C sample preparation.

Laboratory Staff

1 engineer, 3 physicists, 1 chemical and 1 technical staff.

Future Plans

Planning to add a Time of Flight detector to measure ^{129}I.

Planning to add a Gas Filled Magnet to measure ^{60}Fe and ^{53}Mn for astrophysics applications.

LABORATÓRIO ABERTO DE FÍSICA NUCLEAR – LAFN UNIVERSIDADE DE SÃO PAULO

Departamento de Fisica Nuclear-IFUSP
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http://portal.if.usp.br/fnc/pt-br; http://portal.if.usp.br/fnc/node/368

Prof. Alexandre Suaide – Head of the Nuclear Physics Department
Rubens Lichtenthäler Filho - Director of LAFN (from June 2019 up to 2023)

The LAFN (Open Laboratory for Nuclear Physics) is part of the Nuclear Physics Department of the Institute of Physics, University of São Paulo, a public university funded by the Government of the State of São Paulo.
Operation (including salaries) is funded by the University.
Maintenance and upgrades are funded by several state agencies, such as FAPESP (State of São Paulo), MCT, Capes, CNPq and FINEP.

Scientific Mission and Research Programs

The LAFN is a low energy nuclear physics laboratory at the University of São Paulo, dedicated to the advancement of basic and applied nuclear physics. A large part of the research programs involves graduate students from USP. Research is developed in several topics of Nuclear Structure and Reactions (light and heavy ions) and Applied Nuclear Physics.

Characterization of the facility

The accelerator is a NEC 8UD (8 MV) Pelletron Tandem electrostatic accelerator.

Facility parameters

- Stable Beams: p, d, ^{6,7}Li, ^{10,11}B, ^{12,13}C, ^{16,17,18}O, ^{19}F, ^{28,29,30}Si, ^{35,37}Cl, ^{63,65}Cu and ^{107,109}Ag.
- Intensities on target: from 0.2 to 200 pnA, depending on the ion species.
- Energies: 16 MeV (p) to 80 MeV (Si)
- Radioactive ion beams delivered by RIBRAS (Radioactive Ion Beams Brasil) facility: ^{8}Li (10^6 pps, E<32 MeV); ^{6}He (10^5 pps, E<28 MeV); ^{7}Be (10^5 pps, E<31 MeV); ^{8}B (10^4 pps, E<35 MeV).

Facility's major experimental instrumentation and its capabilities

RIBRAS: Two 6.5 T superconducting solenoids for selection and focusing of secondary radioactive ion beams (Fig. 15.4).

A neutron wall: neutron detector (2 m x 2 m, position sensitive scintilators).

The Saci-Perere: Gamma-ray spectrometer consisting of four HPGe with Compton suppressors and 4π charged particle telescope system (Fig. 15.5) and a new scintillator system with two detectors with 9 x 5 cm^3 LYSO(Ce) crystal pixels each, with SiPM readout, capable of operation under high magnetic fields and intense neutron radiation (such as the RIBRAS environment).

The 30B: General purpose scattering chamber (about 50 cm radius) for nuclear reactions

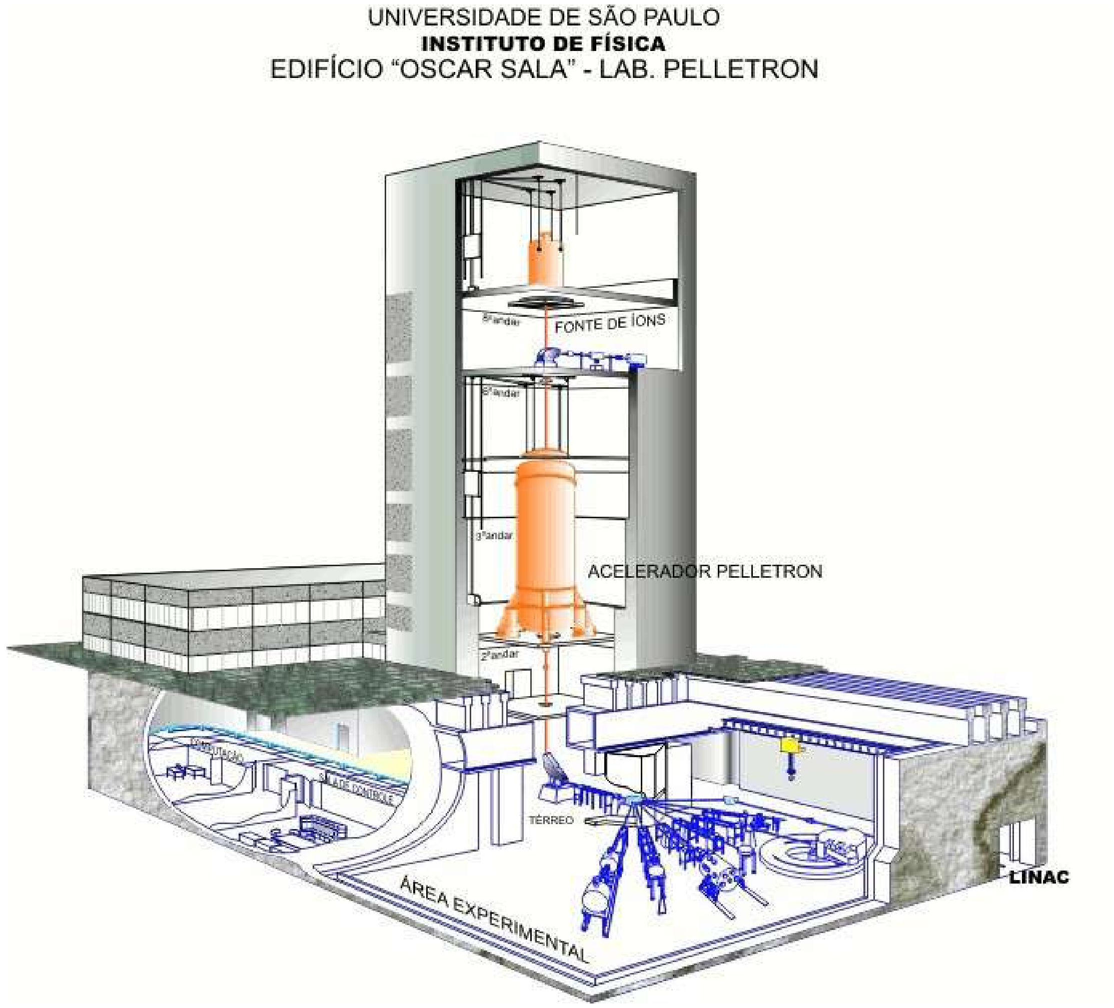

Figure 15.3: The 8 UD Pelletron Tandem accelerator.

mechanism and applied nuclear physics studies.

The Enge split-pole: Magnetic spectrograph used to study transfer reactions.

The 0 degree: New beam line for the study of the effects of radiation in electronic devices (Fig. 15.6). Allows homogeneous irradiation in a 2.3 cm^2 beam spot area, controlling the intensity of beam from 10^7 to 10^2 particles/cm^2.

Technical facilities

Its major facility is the 8 MV Pelletron Tandem Accelerator (Fig. 15.3), with several peripherals. In the experimental hall are installed the RIBRAS two- solenoid radioactive beam system, an Enge split-pole spectrograph for the study of transfer reactions, a multipurpose scattering chamber for nuclear reactions mechanisms and applied nuclear physics, a γ-ray spectrometer for nuclear structure and reaction studies, and a new beam line for irradiation of electronic devices.

Nature of user facility

The facility is open for users from all Institutions.

Figure 15.4: The RIBRAS (Radioactive Ion Beams in Brasil) facility.

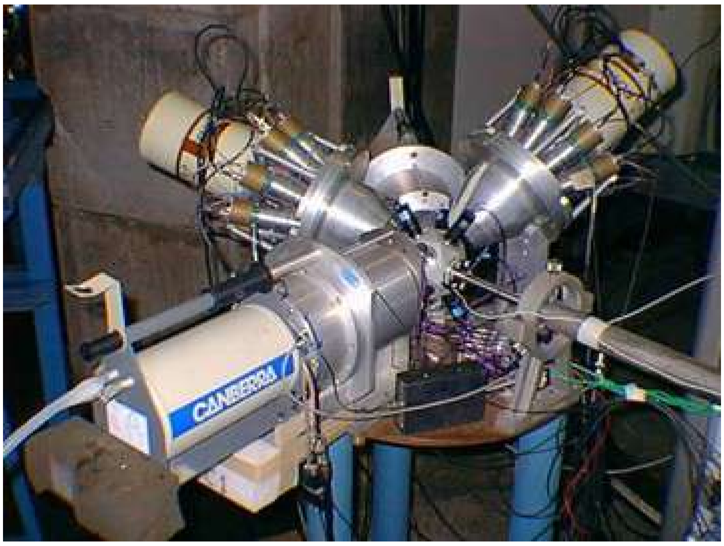

Figure 15.5: The SACI-PERERE gamma-ray spectrometer.

Program Advisory Committee/experiment proposals

The PAC consists of five members with at least one from outside the University and meets once a year. About 200 days/year are distributed, 5 days/week, 24h/day. Last PAC meeting had 226 days approved, 141 of which with high priority.

Number of active users and their origin

Presently there are 122 registered users. More than 70% of which are active.

User group

Yes. All users are included in the Users Group.

Percentage of users, and percentage of facility use that come from inside the institution

About 50% of the users are from the home institution. All experiments involve the participation of home institution researchers.

Figure 15.6: The 0 degree beamline composed of three scattering chambers for studies of the effects of radiation in electronic devices.

Percentage of users and percentage of facility use from national users

National users are about 80%.

Fraction of the international users from outside your geographical region

About 10% of the users come from outside South America.

Laboratory Staff

See Table 15.2.

Table 15.2: Staff at LAFN. *Including 7 scientists with a doctoral degree. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	22*
Permanent staff (theory)	1
Postdoctoral researchers (last 5 years)	9
(Resident) Graduate students (last 5 years)	24
(Non-Resident) Graduate students	8**
Undergraduate students (last 5 years)	22

Special student programs

The staff members of the facility also participate actively in the organization of Biennial Nuclear Physics Summer Schools (theoretical and experimental) with participation of several students from Brazil and South America.

Future Plans

Improve the national program to study tolerant electronic devices to be used in harsh environment, such as the space. Enhance the studies of reaction mechanisms using particle-time of flight and particle- gamma coincidence techniques. New strip detector telescopes are installed in the 30B line and will be installed at RIBRAS. A new acquisition system based on digitizers is being installed. The neutron wall is operational,but its electronics will be renewed with digitizers and VME acquisition using FPGA devices. Neutron-charged-particle and gammas coincidences will be measured to determine exclusive break-up with radioactive beam.

VAN DE GRAAFF LABORATORY, CATHOLIC UNIVERSITY RIO DE JANEIRO

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Head of the facility: Prof. Marcelo Maia da Costa
Pe. Josafá C. de Siqieira, S.J. (Rector)

University Laboratory - Department of Physics
Private

Scientific Mission and Research Programs

The Laboratory started in the 70´s as a Nuclear Physics Lab. In the 80´s the activities were directed towards applications such as Material Science (RBS, PIXE), Environment Analysis and Atomic Physics research. In the 90´s, the lines on Atomic Collisions in gases and Surface Physics and Analysis were included.

Nowadays, Astrophysics (FTIR), Nanotechnology and Biological Material Analysis are the current areas.

Characterization of the facility

The accelerator is a 4 MeV single-end Van de Graaff.

Facility parameters

Proton to argon beams.

Technical facilities

Radiofrequency ion source. Analyzing magnet: ME = 40

Facility's major experimental instrumentation and its capabilities

Several TOF systems for ion detection. (identification, angular and energy distributions); RBS , PIXE, FTIR systems.

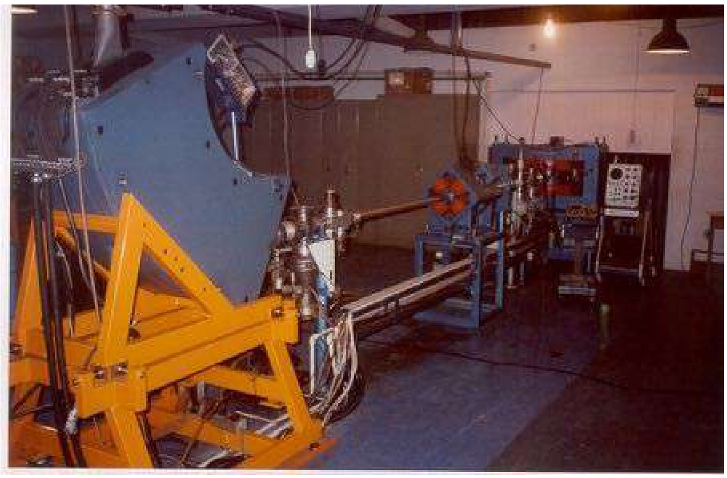

Figure 15.7: 90° magnet

Nature of user facility

It is operated by the staff members, very often with external cooperation.

Program Advisory Committee/experiment proposals

No.

Number of active users and their origin

About 5 groups a year. Each group has typically few persons and has the beam for 5 days per week. It is possible to operate by night and week ends, but the accelerator is now used only during the day time.

Percentage of users, and percentage of facility use that come from inside the institution

80%.

Percentage of users and percentage of facility use from national users

100%. Of course, foreign professors come as visiting researchers.

Percentage of users and percentage of facility use from outside the country where your facility is located

–

Fraction of the international users from outside your geographical region

Visiting professors come from US or Europe.

User group

2 groups of 3 permanent persons.

Laboratory Staff

Table 15.3: Staff at the Van de Graaff laboratory. *Plus 10 scientists with a doctoral degree. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Faculty (professors)	5*
Postdoctoral researchers	2
(Resident) Graduate students	7
(Non-Resident) Graduate students	1–2**
Undergraduate students	∼3/ year

VAN DE GRAAFF ACCELERATOR LABORATORY, UNIVERSITY OF CHILE

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Nunca, Santiago 6850240, Chile
Telephone: + (56) 22 978 7276/7281
Facsimile: + (56) 2 271 2973
http://www.fisica.ciencias.uchile.cl/nuclear

Head of the facility: Dr. Jose Roberto Morales
Dean Faculty of Sciences: Prof. Raul G. E. Morales-Segura

University Owned Facility

Scientific Mission and Research Programs

This is the only charged particle accelerator operating in the Chilean university system. The principal features of its scientific mission are: to perform research in basic and applied nuclear physics; b) to provide training to undergraduate and graduate students in experimental nuclear physics and related areas. The current research programs are:

1. Applications of accelerator-based IBA methods to multidisciplinary studies like elemental characterization of airborne particulate matter from urban and remote sites, elemental composition of archaeological materials, bioaccumulation of metals in tissues, and others.
2. Measurement of nuclear reaction cross sections of medical and astrophysical interest.
3. Measurement of stopping power in a variety of metallic foils.

Characterization of the facility

Single-end Van de Graaff accelerator, High Voltage Engineering KN3750. 3.75 MV maximum. RF ion source. Operates at 30 psi SF_6. Beam switching magnet with nine exits.

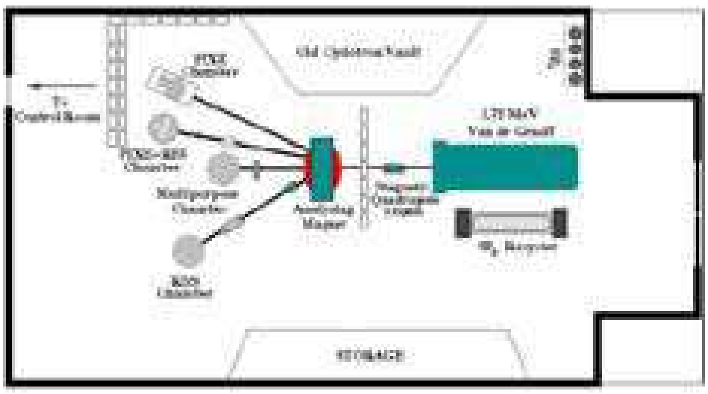

Figure 15.8: Layout of the Van de Graaff facility.

Facility parameters

Single charge ions of protons, deuterons, alpha, Xe, Ne. Variable energy in the range from 300 keV to 3500 keV. Beam intensities from less than one nanoamp. to tens of microamps.

Facility's major experimental instrumentation and its capabilities

Four dedicated irradiation chambers:

1. PIXE chamber. Manual and remote control of target position. Thin and thick targets.
2. ORTEC scattering chamber for RBS and stopping power measurements.

Figure 15.9: Beam lines of the of the Van de Graaff facility.

3. CINEL-Strumenti Scientifici chamber for simultaneous PIXE and RBS. Remote controlled target positions.
4. Multipurpose chamber for ion implantation and nuclear reaction measurements
5. X-ray and gamma spectroscopic systems; HPGe, HPSi, Si(Li), Na(Tl), and surface barriers detectors; CAMAC multiparametric data acquisition system.

Nature of user facility

From the university system.

Program Advisory Committee/experiment proposals

There is a Users Advisory Committee.

Number of active users and their origin

6 in nuclear physics and applications; 2 (plus students) in thin films and material science.

Percentage of users, and percentage of facility use that come from inside the institution

90% users from the institution; 100% use from inside.

Percentage of users and percentage of facility use from national users

10% users from other national institution; 5% use by users from other national institution.

Percentage of users and percentage of facility use from outside the country where your facility is located

None at present.

Fraction of the international users from outside your geographical region

None at present.

User group

Nuclear and IBA applications: 6; Material Science and thin films: 2 (plus students); Technical developments: 2 (one from other national institution)

Laboratory Staff

See Table 15.4.

Table 15.4: Staff at the Van de Graaff laboratory. *Plus 1 part-time. Including 3 scientists with a doctoral degree. **Non-resident graduate students with thesis work primarily done at the facility.

Designation	Number of persons
Permanent staff	7*
Postdoctoral researchers	1
(Resident) Graduate students	1
(Non-Resident) Graduate students	2**
Undergraduate students	∼20/ year

Special student programs

2 internships during one month in summer student vacation period.

Future Plans

Development of oxygen, nitrogen, argon and krypton beams. Get a new ion source

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