Microscopes for the Physics at the Femtoscale: GANIL-SPIRAL2

Caen, in Normandy, France, is famous as the home of William the Conqueror. Equally well known in the field of nuclear physics is the Grand Accélérateur National d'Ions Lourds (GANIL) laboratory and its major upgrade of the existing infrastructure, Système de Production d'Ions RAdioactifs en Ligne de 2e génération (SPIRAL2) facility. GANIL is primarily focused on cutting edge research in fundamental nuclear physics using ion beams and is supplemented by strong programs in accelerator-based atomic physics, condensed matter physics, radiobiology, and industrial applications. For many decades, GANIL has provided High-intensity stable beams (^{12}C to ^{238}U), beams of short-lived nuclei (Radioactive Ion Beams), produced both by in-flight separation (lifetimes ~ µs) and isotope separation on-line (ISOL) technique (lifetimes ~ ms). The five-cyclotron complex delivers stable beams from energies ~1 MeV to 95 MeV per mass unit with currents up to 10 µA, fragmentation beams up to ~ 50 MeV/A, and reaccelerated beams (SPIRAL1) from 1.2 MeV/A to 25 MeV/A (~40 isotopes). The intensities of the radioactive beams range from a few particles/s to ~10^7 p/s. The new superconducting linear accelerator (LINAC), in addition to very high-intensity light beams, also provides a fourth type of beam, namely neutrons, to the already available arsenal of beams. These numerous types of beams are coupled to versatile detection facilities that allow the exploration of the behavior of nuclei in the phase space of excitation energy, angular momentum, and isospin. The first volume of *Nuclear News* (1991) portrayed the nuclear physics activities at GANIL, followed by the SPIRAL1 project (1995) and interdisciplinary physics (2000). In this article we present the evolution of the facility starting with the cyclotrons, the various associated detectors, and the current status of SPIRAL2. Figures 1 and 2 illustrate the cyclotron and LINAC complexes and their associated experimental halls. These complexes will be connected through a planned future project.

GANIL, a multibeam facility, has been delivering a wide spectrum of stable and radioactive ion beams since 1983. Between 1983 and 1990, the facility relied on a cascade of three warm cyclotrons (K_{C0} = 30, K_{CSS1} = 380, K_{CSS2} = 380). Subsequently, a second injector was added. Various techniques were developed to increase the beam intensities, the number of isotopes, and the reliability of these beams. A major upgrade, in 2001, was the availability of reaccelerated radioactive ions from the SPIRAL1 facility. The cyclotrons serve as the driver for the production of radioactive atoms in a thick carbon target that can be reaccelerated by the new Cyclotron pour Ions de Moyenne Energie (CIME) (K = 265) up to a maximum energy of 25MeV/u (the highest in the world today). A review of the work done using SPIRAL1 beams till 2010 can be found in Ref. [1]. An upgrade, started in 2014, for increasing the number of reaccelerated beams using a Forced Electron Beam Induced Arc Discharge (FEBIAD) ion source coupled with a charge breeder, extends those available with the existing Electron Cyclotron Resonance (ECR) ion source. This, added to the already available secondary beams by using the in-flight method and stable beams, makes GANIL the only facility with this variety of beams. A continuous development of new and more intense stable beams, post-accelerated radioactive beams where GANIL has a niche, is ongoing. In parallel, there has been a continuous evolution in the detection systems, including the addition of various new detectors (discussed below). The functioning of the cyclotrons that has decreased in the last few years as a result of sharing the resources for construction of SPIRAL2, is being ramped up.

Ligne d'Ions Super Epluchés (LISE) Spectrometer

The LISE spectrometer [2] was one of the pioneering instruments to demonstrate the potential of studying nuclei very far from stability. (The use of double fragmentation was also pioneered at GANIL.) The initial use of LISE was to study atomic physics of high charge states using high-velocity ions. Nuclei are produced by fragmentation reactions on a thick target and selected by the doubly achromatic magnetic assembly. Later, a Wien filter and an additional beam-line, LISE2000, were also added. The design of the LISE spectrometer inspired the construction of fragment separator facilities in Asia, Europe, and the United States (the LISE++ simulation code is also widely used). A few of the pioneering highlights include the discovery of the existence of ^{48}Ni, ^{100}Sn, 2p-radioactivity, and the unbound nature of ^{28}O. Recent improvements include the addition

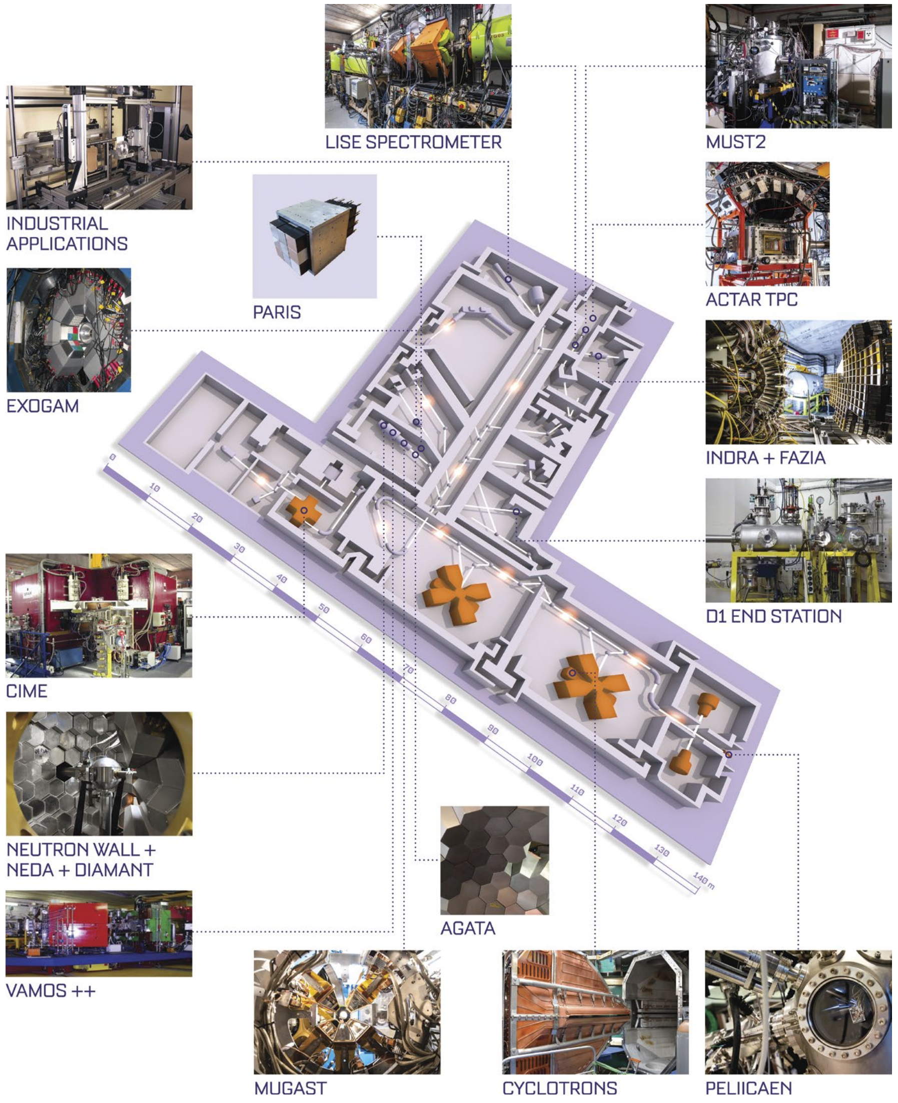

Figure 1. *Cyclotrons and experimental halls.*

of optical components to improve the focusing at the end of the spectrometer and the ongoing implementation of a new zero-degree detector to improve the particle identification. Charged particle detectors like MUr à STrip 2 (MUST2), γ-ray detectors, active targets, and so on are routinely used, in conjunction with the spectrometer, to study evolution of nuclear properties far from the valley of stability. Recent questions addressed include, in N = Z nuclei, proton–neutron pairing in ^{56}Ni, ^{52}Fe using transfer reactions with MUST2 [3], and the signature of a possible alpha cluster state in ^{56}Ni using inelastic α scattering with the active target MAYA. Single particle structure in ^{17}C, mirror symmetry in the unbound ^{12}O nucleus using transfer reactions, and proton radioactivity using ACtive TARget (ACTAR) were also carried out. Two proton correlations in ^{48}Ni and the nature of the Z = 6 shell gap are some of the interesting problems that are currently being addressed.

Variable Mode Spectrometer (VAMOS++)

Unlike the LISE spectrometer, mainly designed for fragmentation energies, VAMOS was primarily designed for use with reaccelerated beams from SPIRAL1 and is also used with stable beams (especially in

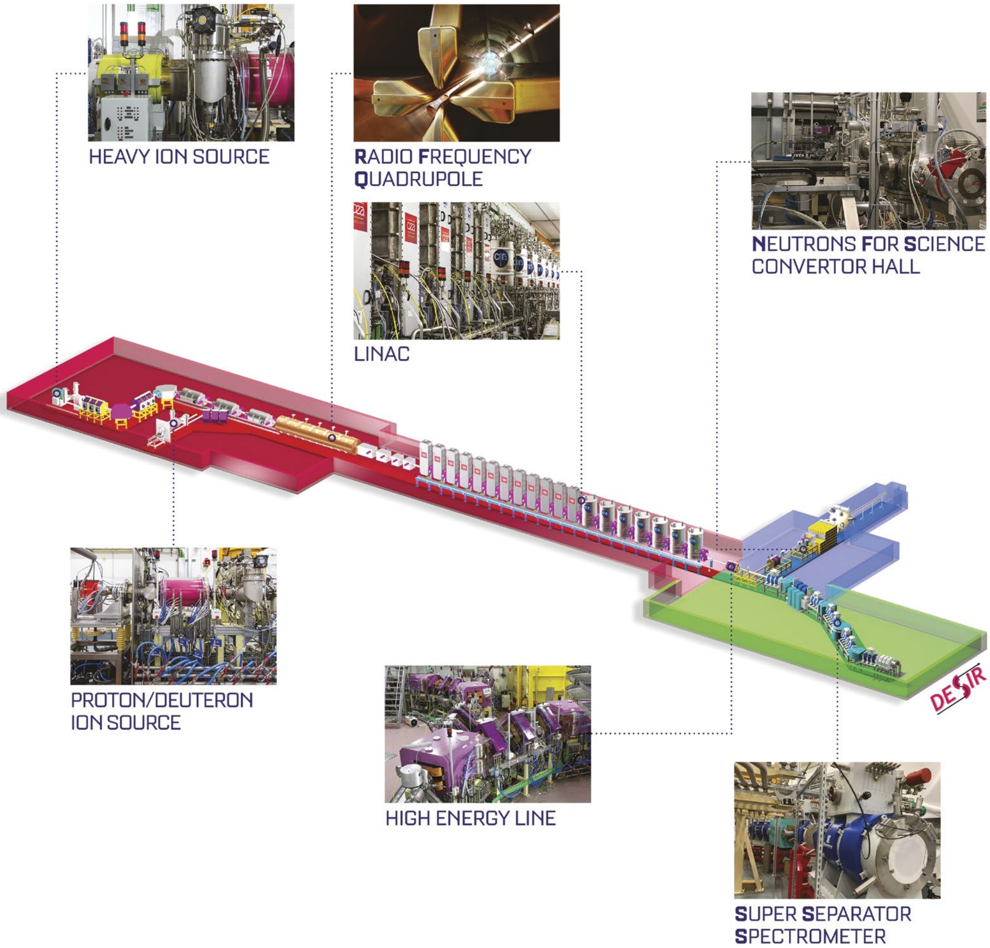

Figure 2. *LINAC and experimental halls.*

inverse kinematics). This spectrometer is a large acceptance magnetic spectrometer, operating since 2001, which consists of three magnetic components: two large aperture quadrupoles followed by a dipole. The detection system of VAMOS, typically consisting of position sensitive multiwire proportional chambers and high-pressure ionization chambers, is used to measure the trajectory, velocity, energy, magnetic rigidity, and the Z for the detected heavy ions. Detailed and extensive studies of the spectrometer and changes in its detection system allowed the maximization of the momentum acceptance (mean value $\Omega \sim 50$ mSr for $\Delta p/p \sim 0.3$) leading to its upgrade (viz., VAMOS++). Presently the resolution of atomic charge and mass are ($\Delta Z/Z \sim 1/70$) and ($\Delta A/A \sim 1/500$), respectively. A new fully digital readout system has also been implemented. VAMOS++ is used in a variety of experiments, coupled to detection systems like large gamma-ray arrays (Advanced Gamma Tracking Array [AGATA], Exotic Gamma-Ray Spectrometer [EXOGAM]), charged particle arrays (TIARA, MUST (MUr a STrip) Gaspard Trace [MUGAST], Identification des Noyaux et Détection à Résolution Accrues [INDRA]), and so on. VAMOS++, with its unique A, Z resolution, has opened up new avenues to study the evolution of nuclear structure for nuclei far from stability, especially using isotopic chains of fission fragments [4] and products from deep inelastic scattering. It is also being used for studying fission dynamics [5] and new nuclei [6]. Ongoing improvements include the Particle-Identification Silicon-Telescope Array (PISTA) near the target and an improved identification of complementary fragment using a second detection arm. Investigations related to the structure of nuclei around the $N = 126$ shell closure, identification of new isotopes for heavy

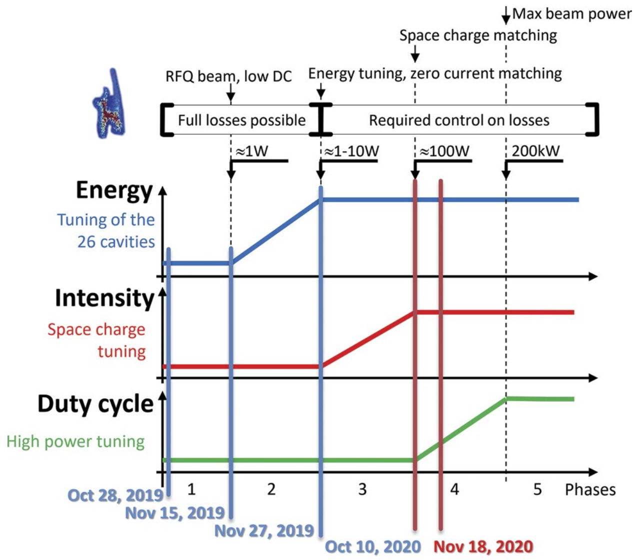

Figure 3. *The major milestones in the increase in proton beam power.*

nuclei, and studies of fission dynamics are underway.

INDRA–Forward Z&A Identification Array (FAZIA)

INDRA [7] is a charged particle array consisting of telescopes combining Si, CsI(Tl), and ionization chambers (564 detectors total), organized in 17 rings having a cylindrical symmetry around the beam axis and covering 90% of 4π. Reaction products can be identified for Z up to 92 with an isotopic resolution for A ≤ 8. FAZIA [8] was developed to have an isotopic resolution up to Z ~ 25, the granularity and signal processing capabilities. Using data from INDRA, the whole low-energy phase diagram of symmetric nuclear matter around the liquid–gas coexistence region has been mapped out, from multifragmentation to vaporization. In addition, many campaigns have greatly advanced the understanding of reaction dynamics in the Fermi energy range, where many-body correlations and fluctuations beyond a simple Mean Field description are essential to explain dissipative phenomena, in-medium effects, and fragment production. With the addition of FAZIA, the density dependence of the nuclear symmetry energy can be addressed through phenomena such as” isospin transport.” The measured velocity dependence of fragment neutron–proton ratios using FAZIA have been used to map out the degree of isospin equilibration in dissipative collisions around the Fermi energy, using INDRA to filter the relevant events. The density and temperature dependence for cluster emission from vaporization events will provide new information about in-medium effects in excited and dilute nuclear matter, as encountered in core-collapse supernovae environments.

MAYA–ACTAR

The low intensity of exotic beams poses an additional challenge for accessing the nuclear structure far from stability. In order to achieve reasonable reaction rates, one can increase the target thickness but with a deterioration in the reconstruction of the reactions kinematics. To overcome these effects, the active-target MAYA detector was developed at GANIL. MAYA is a 1-dimension Time and 2-dimension charge Projection Chamber (TPC) where the gas volume also plays the role of a target. Its segmented cathode allows the three-dimensional mapping of the trajectories and energy estimation of the ions produced in binary reactions within the active volume. These capabilities led to, for example, the discovery of the super-heavy ^{7}H resonance and of its structure [9] measurements of giant resonances in exotic nuclei and studies in inverse-kinematics for fission process. The search of unbound states and the measurement of excitation functions were possible as a wide range of energies could be scanned in a single experiment. Its upgrade, the ACTAR TPC detector, was designed within an international collaboration. Through a higher granularity in spatial and time dimensions, high particle-multiplicity detection, and dedicated digital electronics, ACTAR TPC [10] overcomes the limitations of MAYA. The nucleon–nucleon interaction is being probed at the limits, for example, with experiments on two-proton decay and in unbound systems. The equation of state is systematically studied with soft and giant resonances along isotopic chains. ACTAR TPC will continue its scientific program in the study of fission barriers, nuclear structure, and reactions with exotic systems, including using neutron beams at the Neutrons For Science (NFS) facility.

EXOGAM

Various γ-detector arrays used at GANIL range from the Château de cristal (74 BaF2 detector) and more recently the Photon Array for Studies with Radioactive Ions and Stable Beams (PARIS). The high-efficiency EXOGAM, developed for the SPIRAL1 facility, was the first spectrometer of the so-called third generation of large germanium arrays. The Compton-suppressed clovers are electrically segmented to further improve the resolving power for the Doppler correction of γ-rays emitted from moving fragments. EXOGAM has been coupled with many detectors and spectrometers at GANIL and exploited with stable, fragmented, and ISOL [2] beams and has addressed major questions in nuclear structure and nuclear dynamics. More recently, EXOGAM has been equipped with full digital electronics based on the Numériseur pour EXOGAM2 (NUMEXO2) Nuclear Instrumentation Module (NIM) digitizer to improve its performance.

AGATA

AGATA is the state of the art in Germanium technology, consisting of highly segmented HPGe crystals, with fully digital electronics, making use of the advanced technology of Pulse Shape Analysis and Tracking algorithms to achieve the best performance for a γ-detector array. AGATA (a European traveling detector), was commissioned in 2014 at GANIL and exploited along with the VAMOS++ [11] and will now move to Legnaro National Laboratory in Italy. The performances of AGATA allowed a very large gain in resolving power and thus opened new avenues in high-resolution discrete γ-ray spectroscopy at GANIL in addressing the evolution of shell structure [12], deformation, and cluster states in exotic nuclei. A campaign coupling AGATA and VAMOS++ with the MUGAST charged particle array, combined with reaccelerated Radioactive Ion beams (RIB) from the SPIRAL1 are presently addressing questions related to the $\alpha + {}^{15}O$ radiative capture rate, contribution of three body forces in nuclei, and so on.

Neutron Wall and Neutron Detector Array (NEDA)

The Neutron Wall consists of 50 tapered, hexagonal, closely packed liquid scintillators, covering $\sim 1\pi$ at forward angles when placed at the nominal distance. Coupled with the EXOGAM array and a charged particle detector, a range of questions from neutron correlation in Borromean nuclei, to the evidence for a spin-aligned neutron–proton paired phase from the level structure of ^{92}Pd [13] were addressed. The next generation NEDA has hexagonal detectors but not tapered. In the 2018 campaign, 54 (42) detectors of NEDA (Neutron Wall) [14] were coupled to AGATA and an improved DIAMANT detector. Compared to an earlier campaign with EXOGAM, the Neutron Wall electronics operated with analog electronics, whereas with the AGATA campaign the NUMEXO2 fully digital electronics were used for the neutron detectors. The main progress was the much-improved n-γ selectivity and the higher-detection efficiencies. As a result, for example, γ rays depopulating levels at a larger spin (up to a $14\hbar$ compared to $8\hbar$) in ^{92}Pd could be measured. The neutron arrays coupled to EXOGAM and the Global Reaction Array Si array are envisaged to explore dynamics and the structure of halo nuclei, shell evolution, and collectivity in regions far from the valley of stability.

Ligne d'Ions Radioactifs A Très basse énergie (LIRAT)

The LIRAT beam-line is used to transport radioactive ions (up to $A \sim 85$) with energies ≤ 30 keV delivered by the SPIRAL1 target-ion source. These low-energy ions are used to measure, among others, β-ν angular correlations, mirror β-decays, and branching ratio of 0^+ to 0^+ β-decays. The nuclear charge radius of ^{8}He was also addressed using such low energy beams at the Séparateur d'Ions Radioactifs. The presence of a dark decay of neutron and tensor-type interactions in nuclear β-decay are among the topics being investigated.

Interdisciplinary Activities at GANIL

A wide choice of ions and energies gives access to the region at maximum energy deposition and thus allows a variation of the Linear Energy Transfer ranging from electronic to nuclear stopping powers. The very low end of this energy range at GANIL (<500 Kev) is provided by the Accélérateur pour la Recherche avec des Ions de Basse Energie. High-energy ions are used for studies on nano structuration of selective membranes and sensors developments based on topical 2-D materials (graphene, MoS2, etc.). Exploiting time/depth-resolved characterizations to their limit, the sensitivity of functional inorganic materials to dense electronic excitations is also studied. Other topics include understanding atomic diffusion during irradiation, related to lifetime of components used in radiative environment and its study using coupled effects between electronic and nuclear energy losses. Defect engineering and predictions of radiation resistance in material science studies are also performed (e.g., hazardous evolution of polymers relevant to packaging of nuclear materials containing alpha emitters, geopolymer, and ion exchange resins). Measurements to understand the effect of irradiation on ageing and gas emission could be essential for the prediction of their long-term evolution and are also of interest. The role of cosmic rays and stellar wind on ices and silicates for the appearance of molecules in the universe is an open problem, in particular to understand the production and the radio-resistance of newly formed molecules during ice irradiation for understanding the emergence of life. Many experiments done here are devoted to the ion collisions–induced molecular complexification inside carbonated molecules clusters. These measurements, when compared to theoretical calculations, show the special role played by ion collisions in the molecular synthesis in space due to the specific interaction of heavy ions with matter. Avenues using new probes like electronic paramagnetic resonance spectroscopy are being investigated. Possibilities of studying colliding beams, or the possibility of *in-situ* Rutherford Back Scattering (RBS) measurement and dual beam irradiation coupling "low" and "high" energy beams are also being examined. These activities are coordinated by the Center of Research on Ions Materials and Photonics at GANIL.

Irradiation and hardening of electronic components for space are performed using high-energy heavy ions. These studies include the Single Event Effect to improve the architectures and define testing standards used in space. Dedicated equipment for irradiation of polymeric films allows for industrial production with various ion tracks densities and ultimately very fine and uniform filters.

Double differential cross-section for charged particles with 95 MeV/A ^{12}C beams on various elements that are relevant to hadron therapy is also investigated. At the Laboratoire de Radiobiologie avec des Ions Accélérés, various aspects related to the understanding of the biological effects related to direct and indirect (bystander) impact by carbon beams in cancer treatment are studied. The topics range from understanding differential cellular responses of radioresistant tumors to conventional radio and hadron therapy and explorations of the fundamental mechanisms of communication between irradiated and normal cells.

Status SPIRAL2

From the activities at the cyclotrons we now move to the new state-of-art LINAC and its experimental halls.

SPIRAL2 was approved in 2005, with the building construction starting in 2011. In 2006, along with the Facility for Antiproton and Ion Research in Germany, it was recognized as a European Strategy Forum on Research Infrastructures (ESFRI) facility and presently is a landmark ESFRI facility. The project was planned in two phases: the construction of a LINAC for very-high-intensity stable beams, and the associated experimental halls and the infrastructure for the re-acceleration (by CIME) of very intense short-lived fission fragments (10^{13} ff/sec), produced using deuteron beams on a uranium target (the latter is currently on hold). SPIRAL2 is a result of strong French (Commissariat à l'Energie Atomique et aux énergies alternatives–Centre National de la Recherche Scientifique [CEA-CNRS]) and international collaborations. Its new superconducting LINAC and the NFS facility are now in a very advanced final stage of commissioning. SPIRAL2 will allow the exploration of the yet unknown properties of exotic nuclei near the limits of the periodic table of elements, by creating short-lived isotopes and measuring ground-state properties (such as the mass of the nuclei) with a high level of precision—a level equivalent to being able to measure a pea being added to the weight of an Airbus A380. The facility also provides beams of energetic neutrons that will open new avenues of research with both short- and long-term impact. It will help uncover yet unknown properties of the fission process, provide accurate and precise data necessary to better understand current and next-generation energy sources, delve into measurements necessary for more efficient production of isotopes for radioisotope therapy, and much more.

LINAC

Figure 2 shows the schematic layout of the LINAC accelerator along with its two existing experimental halls.

The LINAC at GANIL has been designed for different particles over a large range of ions, energies, and intensities (Table 1), unlike other large projects like LINAC4, Spallation Neutron Source (SNS), or European Spallation Source (ESS). This diversity of beams and energies required the design of a new compact multicryostat structure for the superconducting LINAC. At 200 kW in continuous-wave mode, the beam power is high enough to make a hole in the vacuum chamber in less than 35 µsecs! The operation of high beam intensities, like 5mA, causes space-charge effects that need to be controlled to avoid a beam halo, which could activate components of the accelerator. The injector was successfully commissioned with 5 mA proton, 2 mA α particles, 0.8 mA oxygen, and 25 µA argon beams with transmission of ~100% through the Radio-Frequency Quadruple (RFQ). In parallel, components of the LINAC were installed and cryomodules cooled

Table 1. *Beam specifications.*

Particles	H^+	D^+	Heavy ions
A/Q	1	2	3
Max. I (mA)	5	5	1
Min. energy (MeV/A)	0.75	0.75	0.75
Max. energy (MeV/A)	33	20	14.5
Max. beam power (kW)	165	200	45

to liquid-helium temperatures with the required mechanical stability to operate the 26 superconducting cavities at their design specifications. A major additional prerequisite was that a large number of safety systems needed to be certified and put into operation. Following a very rigorous six-year authorization process by the French nuclear-safety authority, the commissioning of cryomodules with Radio Frequency (RF) power and beam through the LINAC started in July 2019. The key commissioning steps included: conditioning of the RF couplers at 300°K and 4°K, demonstration of the cavity performance at 6.5 and 8 MV/m. The first beam was injected into the LINAC in late October 2019, and within a month all the cavities were tuned to accelerate a low-intensity proton beam (200 µA) to its designed energy (33 MeV). A first test at the NFS facility was made in December 2019 (see below). After a phased and detailed study of the response of the various subsystems, the beam dynamics, in September 2020, at a high peak ~5 mA current with a suitable time structure and a net beam power of ~150 W, were demonstrated. This was the required crucial step in demonstrating control over the losses for very high-beam intensities. Subsequently, a 16 kW proton beam, a major milestone, was obtained at the end of November 2020. Figure 3 illustrates these major milestones. Additionally, helium beams are also being used to further characterize the beam transmission. 40 MeV deuterium beams will be used for PAC-approved experiments in autumn 2021 at NFS. It should be noted that the maximum power permitted at NFS is 2 kW (40 MeV deuteron beam with a mean current of 50 µA).

NFS Facility

The first proton beams at the NFS facility [15], in December 2019, were used for the irradiation of various targets like Cu, Fe at three beam energies, including the maximum energy of 33 MeV. This first test at NFS was led by the team from Nuclear Physics Institute (NPI), Rez (Czech Republic). Figure 4 shows the irradiation chamber used. It is connected to a “fast rabbit” system to transport the irradiated target to a counting station. Precise measurements of such cross-sections are necessary to improve codes for operation of nuclear reactors.

Quasi-Mono-Energetic Neutron Beams

Interaction of a proton beam with thin targets (converters) of lithium/beryllium was used to produce the first quasi-mono-energetic neutrons in September 2020. The energy spectrum and flux of neutrons produced at zero degrees were measured using a plastic scintillator. The neutron energies (1–30 MeV) were determined from the measured time flight of the neutrons between the production target and the detector with a suitable time structure of the proton beam. The quasi-mono-energetic spectrum of the neutrons produced by protons interacting with thin targets of lithium and beryllium is shown in Figure 5.

Continuous Neutron Spectra

A thick, rotating, beryllium converter (CEA, Irfu), designed for 2 kW power dissipation, composed of an 8-mm-thick disk, rotating at 2,000 rpm was used to produce the continuous neutron energy spectrum. Power dissipation tests were performed, where the evolution of the temperature in different parts of the converter was measured as a function of the dissipated beam power. The measured temperatures agree with simulated values up to the maximum beam power of 1.35 kW used. The neutron energy spectrum measured by the time-of-flight method is shown in Figure 5. The measured spectrum is in good agreement with Ref. [16]. In November 2020, a first test experiment using a "white" neutron spectrum on two targets (CH_2 and C) was performed to measure the angular distribution of light charged particles using the (Si-Si-CsI) telescopes of the MEDLEY setup (University of Uppsala) with the NUMEXO2 digital readout system using electronic modules developed at GANIL. Figure 6 shows a typical 2-D plot of ($\Delta E1$–$\Delta E2$), the energy losses in the two detectors ($\Delta E1$–$\Delta E2$).

Next steps

The immediate steps at SPIRAL2 are to attain the design goal of full power allowed at NFS (2kW) with the deuteron beams for the start of the PAC-approved physics program in 2021. This year we also envisage having a simultaneous operation of both accelerators. Slightly longer term, work on the infrastructure is steadily proceeding on assembling the various available components of the Super Separator Spectrometer (S^3) as they are being received. Simultaneously, work on the S^3-Low Energy Branch (LEB) is progressing well. The start of commissioning of S^3 is expected mid-2023. The Decay, Excitation, and Storage of Radioactive Ions experimental hall will be a bridge, receiving exotic beams both from S^3 and SPIRAL1

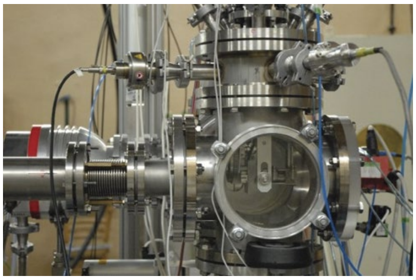

Figure 4. *The NFS irradiation station (built by NPI, Rez).*

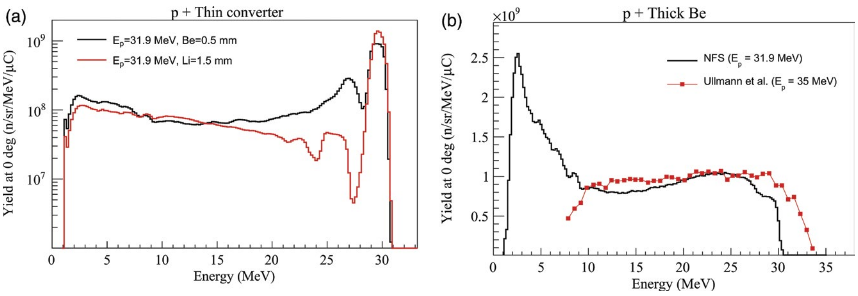

Figure 5. *(Left) Quasi-mono-energetic spectrum of neutrons produced at 0° using a 31.9 MeV proton beam with thin lithium and beryllium converters. (Right) Energy spectrum of neutrons of a 31.9MeV proton beam with a thick beryllium converter (courtesy of X. Ledoux and D. Ramos).*

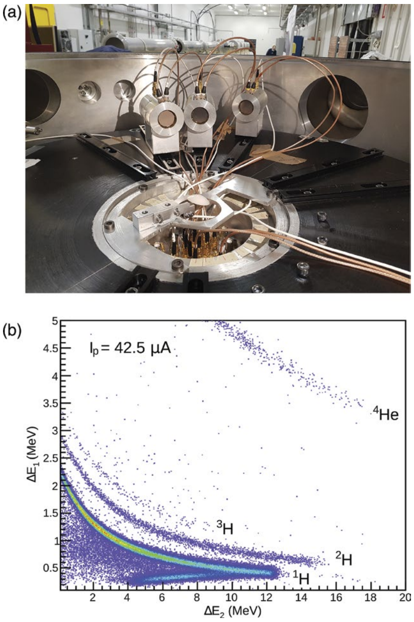

Figure 6. *(a) MEDLEY setup. (b) Energy loss identification matrix ($\Delta E1$–$\Delta E2$) for charged particles emitted by a CH_2 target irradiated by a quasi-mono-energetic neutron beam.*

and is expected to start experiments in 2026. In parallel, a continuous improvement in the facility is planned, starting with the integration of a new A/Q = 7 injector to further sustainably increase the intensity of heavy ion beams at the LINAC. With the startup of this major upgrade at GANIL, plans for the next-generation facility and the future of GANIL are being studied by an international committee of experts. With its present state of the art facilities and their continuous evolution, GANIL–SPIRAL2 will allow us to explore the key questions related to, namely, understanding of how regular and simple patterns emerge in the intrinsic structure of complex many body nuclei and identify the degrees of freedom that govern the dynamics of their collisions. These explorations for understanding the physics of infinitely small systems under controlled conditions also have an impact on understanding the physics of infinitely large systems.

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References

1. A Navin et al., *J. Phys. G: Nucl. Part. Phys.* 38 (2011) 024004.
2. R. Anne et al., *NIM* A 257 (1987) 215; R. Anne and A. C. Mueller, *NIM* B 70 (1992) 276.
3. B. Le Crom et al. (submitted to *Phys Lett.* B).
4. A. Navin et al., *Phys. Lett.* B 728 (2014) 136.
5. D. Ramos et al., *Phys. Rev. Lett.* 123 (2019) 92503.
6. Y. Watanabe et al., *Phys. Rev. Lett.* 115 (2015) 172503.
7. J. Pouthas et al., *NIM* A 357 (1995) 418; J. Pouthas et al., *NIM* A 369 (1996) 222.
8. R. Bougault et al., *EPJ* A 50 (2014) 47.
9. M. Caamano et al., *Phys. Rev. Lett.* 99 (2007) 062502; M. Caamano et al. (submitted to *Nature Physics*).
10. B. Mauss et al., *NIM* A 940 (2019) 498.
11. J. Ljungvall et al., *NIM* B 955 (2020) 163297.
12. J. Dudouet et al., *Phys. Rev. Lett.* 118 (2017) 162501.
13. B. Cederwall et al., *Nature* 469 (2011) 68.
14. J. J. Valiente-Dobon et al., *NIM* B 927 (2019) 81.
15. X. Ledoux et al., *EPJ Web of Conf.* 146 (2017) 03003.
16. L. Ullmann et al., *Med. Phys.* 8 (1981) 396.

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