GANIL-SPIRAL2 FACILITY - RECENT ACHIEVEMENTS AND UPGRADES

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Abstract

The Grand Accélérateur National d'Ions Lourds (GANIL) is a multi-beam facility, unique in intensity, particle types and simultaneous production. The Système de Production d'Ions Radioactifs en Ligne de 2ème génération (SPIRAL2) facility covering an exceptionally broad intensity range, from nanoamperes to milliamperes further enhances the scientific opportunities of the laboratory. The first proton beams from the LINAC were produced in 2019 and is operational for physics experiments since 2022. The cyclotron operation and the initial operational challenges and lessons learned in the first years of operation of the LINAC and Neutrons For Science (NFS) facilities are presented. The physics program at GANIL-SPIRAL2 is briefly presented. The ongoing upgrades and developments essential to sustain increasingly ambitious pure and applied science programs are also presented.

INTRODUCTION

GANIL-SPIRAL2 [1, 2] is primarily focused on cutting-edge research in nuclear physics, nuclear astrophysics, nuclear data with complementary programs in astrochemistry, material irradiation, nanostructuration, radiobiology and industrial and medical applications.

The field of low-energy nuclear physics is undergoing an important transformation based on results obtained at various facilities in Europe such as GANIL in France, GSI-FAIR in Germany, ISOLDE at CERN, JYFL in Finland and LNL & LNS in Italy and worldwide facilities in Canada, China, Japan, Korea, Russia, USA. These results have further motivated very ambitious efforts worldwide to produce and study nuclei far from stability using Radioactive Ion Beams. In the European roadmap, FAIR and GANIL-SPIRAL2 are classified as ESFRI landmark facilities, with complementary radioactive beams production methods. The FAIR facility will use high-energy stable beams (up to 1 GeV/u) of heavy-ions and will have an unrivalled potential to produce the heaviest exotic nuclei far from stability. The GANIL cyclotron facility delivers high-intensity stable beams up to uranium, as well as exotic nuclei produced via both in-flight fragmentation and the ISOL (Isotope Separation On-Line) method through the SPIRAL1 facility. Radioactive beams from SPIRAL1 can be used directly or re-accelerated while preserving high optical quality. Together with facilities such as SPIRAL2, ISOLDE, and JYFL, and in the future SPES at LNL and ISOL@MYRRHA, GANIL will enable high-precision measurements at low energy that are complementary to those performed with the more energetic beams of FAIR.

GANIL has been operational since 1983, as a cyclotron-based facility. The SPIRAL2 LINAC commissioning started in July 2019 immediately after the authorization. The first test experiments started from Dec 2019 using proton beams and in Dec 2021 with deuteron beams. Three new experimental halls for exploiting stable, neutron and radioactive ion beams are available. The GANIL facility is a multi-beam facility, operating up to 5 simultaneous beams: IRRSUD, SME, CSS high energy, CIME and SPIRAL2, which makes GANIL unique in the world. Complementary atomic physic studies are also conducted in ARIBE.

The paper will briefly summarize the cyclotrons operation and discuss in more detail the LINAC operation. Some new results related to time optimized LINAC tuning and the projects currently underway at GANIL (S^3, DESIR NEWGAIN, CYREN, SAGA) will also be described.

GANIL-SPIRAL2 FACILITY

Figure 1 shows the cyclotrons and SPIRAL2 accelerators along with the associated experimental halls. GANIL construction was decided in 1975 [3]. Between 1983 and 1990, the facility relied on a cascade of three warm cyclotrons ($K_{CO1,2}$=30, K_{CSS1}=400, K_{CSS2}=400). There is a rebuncher between the injectors and the first separated-sectors cyclotron (CSS1) and a stripper between CSS1 and CSS2. A wide spectrum of stable and radioactive ion beams has been delivered since 1983.

The five cyclotrons of GANIL allow the acceleration of ions up to 95 MeV/u for "light" ions and up to 25 MeV/u for uranium. Various techniques have been developed to enhance beam intensities, expand the range of available isotopes, and improve overall beam reliability. A major upgrade occurred in 2001 with the implementation of the "Cyclotron pour Ions de Moyenne Énergie" (CIME), enabling the post-acceleration of radioactive ions produced at the SPIRAL1 facility. In this scheme, the CSS cyclotrons serve as drivers for the production of radioactive species, using stable beams fragmented in a thick carbon target according to the ISOL technique.

These beams are delivered to different experimental areas hosting a large variety of detectors and spectrometers, which allow detailed studies of nuclear structure and reactions, atomic and material science as well as applications. Among them, the charged particle FAZIA–INDRA array combines the large solid-angle coverage of the INDRA detector with the high isotopic resolution of the FAZIA detector. This unique combination makes FAZIA–INDRA a powerful instrument for studying reaction dynamics, fragment formation, and isospin-dependent properties of nuclear matter.

The GANIL ACTAR TPC detector is a next-generation

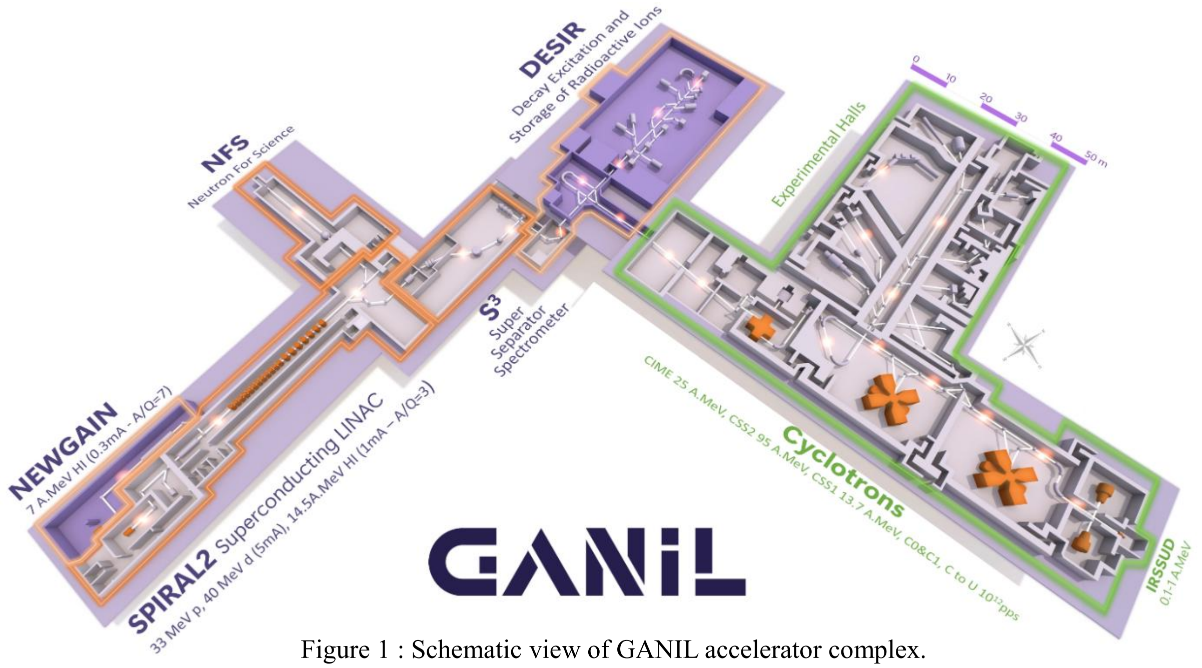

Figure 1 : Schematic view of GANIL accelerator complex.

active-target designed for experiments with very low-intensity radioactive ion beams. It uses a gas volume that acts simultaneously as the reaction target and as a detector, allowing the three-dimensional tracking of charged particles produced in nuclear reactions. ACTAR TPC is particularly suited to studying rare processes and the structure of exotic nuclei near the limits of stability, including resonant reactions, clustering phenomena, exotic decay modes, and nuclear astrophysics reactions.

The LISE spectrometer [4] was the pioneering instrument to demonstrate and exploit the potential of producing nuclei and studying reaction mechanisms very far from stability. The complementary spectrometer VAMOS++ is a high acceptance spectrometer and has the highest A, Z resolution at energies around the Coulomb barrier. It provides new avenues to nuclear structure and reaction studies.

The European AGATA detector is a highly segmented high-purity germanium detector array using γ-ray tracking. When coupled with VAMOS++ and other ancillary detectors including EXOGAM, it allows in-beam and off- beam γ-ray spectroscopy of exotic nuclei produced with stable or radioactive ion beams. AGATA currently at LNL, Italy, will return to GANIL for new campaigns coupled with GRIT in 2029.

SPIRAL2 on the other hand is a new high-power superconducting LINAC (SC LINAC) accelerator [5-7]. It is based on two injectors, one for light ions (*p, d*) and one for heavy ions ($A/Q \leq 3$). The RFQ1 accelerates beams to 0.73 MeV/u, followed by the SC LINAC with 26 cavities and the high energy lines (HEBT). This SC LINAC can accelerate pulsed and Continuous Wave (CW) light and heavy ions up to energies shown in table 1. The SPIRAL2 SC LINAC [6, 8] includes 12 A-type cryomodules, each comprising one low-beta cavity ($\beta = 0.07$, developed by CEA/IRFU [9]) and 7 B-type cryomodules, each housing two higher-beta cavities ($\beta = 0.12$, developed by IJCLab [10]). The choice of cryomodules containing only one or two cavities results from an optimization driven by the physics program, requiring a wide range of beams in terms of energy, intensity, and ion mass. Such a configuration of cryomodules is challenging to operate.

Table 1 : SPIRAL2 SC LINAC Beams

Particles	**H^+**	**D^+**	**Ions**	**NEW-GAIN**
A/Q	1	2	3	7
Max I (mA)	5	5	1	1
Max E (MeV/A)	33	20	15	7
Beam power (kW)	165	200	45	49

The number of cryomodules (19) is comparable to that of the larger and more powerful SNS accelerator in its original construction (23), however, the latter has a much larger number of accelerating gaps. The choice of modern superconducting vs room temperature cavity design is not only linked to higher beam intensities and energies but also to the availability of larger apertures necessary for better control over beam losses.

However, this configuration may introduce an operational risk over time, as the cavities are located in close proximity to the warm focusing sections, which can represent potential sources of contamination that could induce performance degradation. RF and cryogenic performances are therefore carefully monitored, as we have observed limiting field emission for two cavities down from 6.5 MV/m to 5.8 MV/m. No further degradation has been observed since 2022.

Among the main achievements of the 2019-21 commissioning was the SC LINAC design validation by demonstrating long pulse operation with a duty cycle of 10% or more of the nominal beam power. We achieved 16 kW [11] in October 2020, which represents an operation equivalent and validation of the designed power of 165 kW (the operation at 16 kW was limited only by the safety rules of GANIL related to the allowed activation of the beam dump). This demonstration was possible due to a comprehensive analysis of the transverse and longitudinal tuning and the improvement of the LLRF feedback and feedforward systems. Studies were also conducted using alpha beams. The last step of the commissioning was the power ramp-up to 10 kW with a 5 mA deuteron beam transported to the beam dump [12,13], validating the 200 kW deuteron power design. The measured losses, as with the proton 16 kW power ramp-up, were controlled and limited, using transmission monitoring (ACCT, DCCT), BLMs, BPMs and pressure variations in the warm sections. During the two power ramp-ups, the BLM measurements were below the GANIL 1 W/m limits and the operation of SPIRAL2 up to full power was validated from extrapolations [12,13]. SC LINAC tunings with $^{18}O^{6+}$ and $^{40}Ar^{14+}$ beams, at energies of 7 and 14.5 MeV/A, were also successfully carried out in 2022 [14].

The Neutrons for Science (NFS) hall [15], using high-intensity primary proton or deuteron beams from SC LINAC on a Be converter provides the most intense quasi-monoenergetic neutron beams up to 33 MeV and continuous neutron spectra up to 40 MeV, respectively. Various characterizations to better define the beam properties have been performed [16, 17]. The neutron beams are being used for a rich program in applied and fundamental science. Among these are precise measurements related to both fission and fusion reactors [18, 19], nuclear data [20, 21] and material science [22]. In addition these neutron beams have also been used for studies related to activation in radiotherapy accelerators [23]. The proton and alpha-particle beams from LINAC have also been used in the NFS hall, to optimize production isotopes for medical use, like ^{155}Tb [24] and innovative α-emitting ^{211}At isotopes [25]. Detailed studies were also performed of the fission process and of pygmy resonances [26].

To further increase the beam intensity, a NEW GAnil Injector (NEWGAIN project), optimized for lower charge states (A/Q=7) with a superconducting ion source and a new RFQ, is under construction – described later.

SPIRAL2's experimental hall Decay Excitation and Storage of Radioactive Ions (DESIR) [27] will be a new low-energy facility dedicated to precision studies of ground state nuclear properties, such as mass, nuclear shapes, and decay modes, using trapping, decay and laser-spectroscopy techniques. It will receive radioactive beams from both SPIRAL1 and S^3. The construction of the associated building was completed in 2025, and we expect to begin the facility operation in 2028.

The main asset of the DESIR facility is the high purity and optical quality of the secondary beams. A RFQ cooler will reduce the emittance of the ion beams (3 π.mm.mrad, ΔE ~1eV @ 30 keV) before they are sent to a high resolution mass-separator (M/ΔM~20000), recently commissioned [28]. Radioactive ion beams will be further purified (M/ΔM up to 10^7) before delivery to the experimental setups, using a combination of a General Purpose Ion Buncher and Cooler (GPIB, [29]) and a double Penning trap (PIPERADE [30]).

The S^3 Super Separator Spectrometer [31] is a new large-acceptance magnetic separator currently under installation. It is designed to study nuclei produced by fusion-evaporation reactions with extremely small cross sections, using high-intensity heavy-ion beams (Fig. 2). Its primary goal is the study of nuclear structure in superheavy nuclei and neutron-deficient isotopes near the proton drip line, employing a variety of techniques ranging from laser spectroscopy and mass measurement to decay spectroscopy. The spectrometer's optics rely on a two-stage configuration, combining a momentum-achromat section followed by a high-resolution mass-separation stage. S^3 is constructed through national and international collaboration.

The spectrometer relies on a series of large-aperture multipole elements, dominated by seven Superconducting Multipole Triplet (SMT) magnets, based on NbTi Technology. Each SMT integrates dipole, quadrupole, sextupole, and octupole field components within a single compact cryogenic assembly [32]. This multifunctional magnet concept enables strong focusing while simultaneously correcting up to third-order optical aberrations and preserving a large acceptance. The spectrometer is still under assembly due to operational challenges with the SMTs.

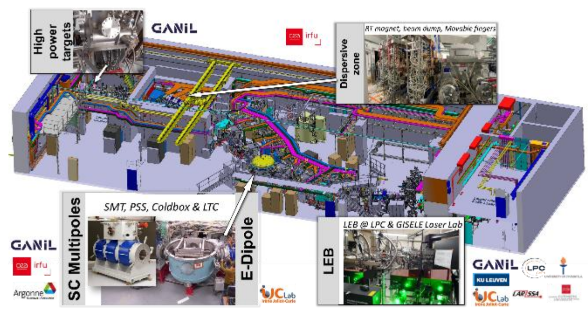

Figure 2 : Super Separator Spectrometer

By combining innovative magnet technology with high-intensity beams and state-of-the-art detection systems, the S^3 spectrometer will significantly extend the capability to explore the limits of nuclear stability and the structure of the heaviest and most exotic nuclei.

Both the cyclotrons complex and the SPIRAL2 facility are connected through the DESIR building.

OPERATIONAL EXPERIENCE

Cyclotrons

From the beginning of operation, the cyclotrons at GANIL have typically delivered approximately 4000 hours of beam per year. Investigations on causes of downtime (Fig. 3) have shown that many issues are related to the aging of the cyclotron systems. In particular, water leaks inside the cyclotrons were identified as a critical concern.

In addition, a short circuit was recently detected in the main coil of the CSS2 cyclotron. This event likely resulted from rainwater damaging the resin protecting the coil. Drying successfully resolved this issue, but it caused significant downtime, impacting the experiments schedule. A dedicated study has been initiated to evaluate possible coil replacement strategies and to estimate the associated maintenance time in case of future problems.

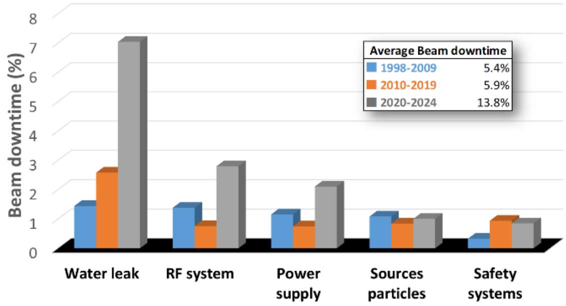

Figure 3 : Distribution of the 5 main reasons for the cyclotron downtime.

SPIRAL2 SC LINAC

Since 2022, SPIRAL2 has been operating for approximately 3 months a year, providing beams not only for physics experiments at NFS, but also for dedicated studies of beam dynamics, diagnostics development, and RF studies. The objective is to optimise the tuning time and increase automation.

During its four years of operation, about 25 physics experiments and industrial applications, as well as 10 machine studies, were successfully conducted. More than 80% of the physics program at the NFS experimental hall was carried out with D^+ beams, with delivered intensities ranging from 9 μA to 47 μA on target, using the Single-Bunch Selector (SBS), after the RFQ, operating at 1 bunch over 100 (as required by experimental conditions). Thus, each remaining bunch contains particles equivalent to a continuous-wave (CW) 188 kW beam at 40 MeV.

Two methods have been successively developed for the SC LINAC tuning [33]. The "advanced method" determines the voltage and phase of each cavity using an improved phase-scan technique designed to reduce phase-measurement uncertainties [13]. The "reference-based method" relies on cavity settings obtained during a prior reference tuning and determines updated parameters from the phase measured on the BPM located upstream of the cavity [34], thereby avoiding the need for cavity detuning/retuning and beam-off measurements.

The tuning time of the SC LINAC that was typically 1–2 days with the advanced method is now approximately 1 to 2 hours using the new reference-based method. Since 2024, the SC LINAC has been tuned using a single calibration, reducing the overall tuning time by nearly 42%, as shown in Fig. 4. This has also improved beam reproducibility and increased reliability [35].

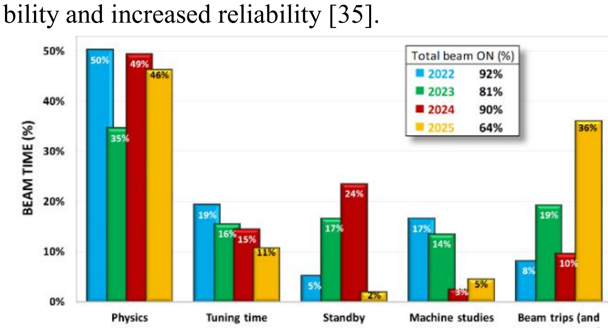

Figure 4 : Availability of SPIRAL2 LINAC.

The availability (including beam time for physics, beam tuning, machine studies, and standby operation) is shown in Fig. 4. It reached high values in the early years of operation, exceeding 90% in 2022 and 2024. In 2023, however, availability was reduced due to the loss of the SC LINAC reference phase and the malfunction of the NFS rotating deuteron-to-neutron converter [35, 36].

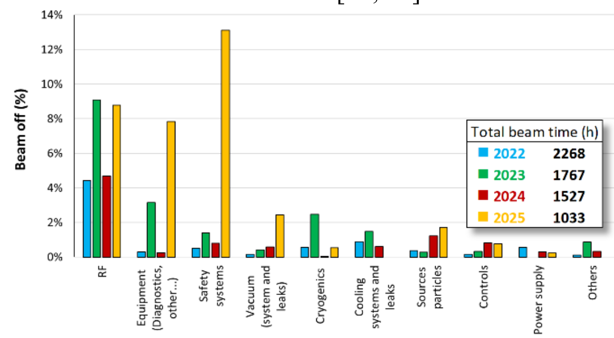

Figure 5 : Breakdown downtime of the LINAC.

In 2025, beam availability was significantly impacted by a single faulty power inverter, an effect amplified by the limited total SC LINAC operating time (Fig. 5). Additional incidents included a failure of the rebuncher tuner system and a beam tuning error that damaged the SBS.

To date, the short cryomodule design has not adversely affected LINAC performances and remains a robust and well-adapted solution. Nevertheless, substantial machine development time has been devoted to implement automatic tuning procedures with cavities switched off [36] (Fig. 6). This capability proved particularly valuable for the eleventh cryomodule (CMA11), the prototype unit equipped with a different RF coupler that developed a vacuum leak during a shutdown period. In 2025 the CMA11 was removed. Its faulty coupler has since been replaced, and the cryomodule is scheduled for reinstallation in the near future and should be available by mid-2026.

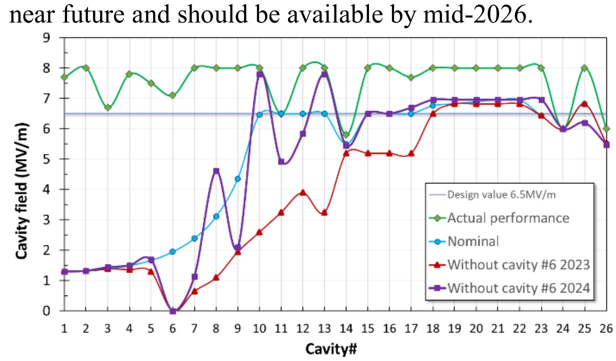

Figure 6 : Cavity field comparison between nominal tuning with all cavities and test tuning without cavity #6.

FUTURE DIRECTIONS

Several new projects are ongoing to further improve the scientific, societal and industrial impact of the facility. Some of these are briefly described below.

CYREN

For more than 40 years, the GANIL facility has provided stable and radioactive ion beams for fundamental, applied, and industrial research using the five cyclotrons. Since 2010, however, maintenance and refurbishment of the cyclotrons had been reduced to a minimum, mainly due to the construction of the SPIRAL2 facility and the implementation of additional compliance measures required by the French nuclear safety agency. As a consequence, beam availability has progressively decreased over the years.

To address this situation, an ambitious renovation program, CYclotrons RENovation (CYREN) [37], was launched in 2024 to ensure the facility's continued operation for at least the next 20 years. The project encompasses the modernisation of the cyclotrons complex, with special emphasis on addressing water leaks in various equipment, such as the RF cavities, as well as improvements to the associated beam lines, experimental halls, and building infrastructure. It also include renovation of technical utilities, safety, security, and radiation-protection systems. Addressing these issues will require the partial disassembly of the cavities and beam lines, including modification of the control system. The program require careful planning of maintenance to minimise the impact on the physics programmes.

NEWGAIN

The NEW GAnil Injector (NEWGAIN) project, currently in the construction phase [38], aims to install a second injector for the SPIRAL2 facility. It is designed to accelerate heavy ions with a mass-to-charge ratio (A/Q) between 3 and 7, enabling unprecedented beam intensities, particularly for uranium beams. The project officially begun the construction phase in May 2023.

The injector includes several key components: a high-performance superconducting ECR ion source, ASTERICS [39], developed in collaboration with the Laboratoire de Physique Subatomique et de Cosmologie (LPSC Grenoble), and a heavy-ion RFQ designed by CEA Paris-Saclay [40] to minimize beam losses in the low-energy section. The beam transport lines will also allow interconnection with the existing Phoenix V3 ion source, providing operational flexibility during commissioning and operation.

ASTERICS is an ambitious superconducting ion-source development targeting beam intensities of about 13 pμA for intermediate-mass ions up to xenon and 10 pμA for U^{34+}. First acceleration is provided by a 7 m long RFQ. Three RFQ modules have already been manufactured and are currently undergoing qualification tests [41].

During Phase 1, the injector will be installed at GANIL using the Phoenix V3 source, while the ASTERICS source will be installed and commissioned in parallel at LPSC Grenoble. A significant milestone was reached in May 2025 with the installation of a new vacuum chamber in the dipole magnet shared by NEWGAIN and SPIRAL2. The next major step concerns civil engineering work, including the drilling of an emergency exit. First beam production with the NEWGAIN injector is expected around 2029.

SAGA

The recently founded Space Applications at GANIL Accelerators (SAGA) project is a strategic initiative aimed at broadening the range of technological applications accessible at GANIL. SAGA promotes the development of new experimental programs in fields such as space radiation effects and material science. By enabling these new activities, SAGA strengthens GANIL's multidisciplinary role and expands its user community to include researchers from applied physics and engineering.

SAGA involves the adaptation of beam lines and experimental areas to accommodate a wider range of irradiation conditions, beam species, and energies required by these new applications [42]. Dedicated instrumentation and irradiation setups are being developed to support experiments requiring high beam stability, precise dosimetry, or controlled irradiation environments.

Through this diversification strategy, SAGA will allow the optimisation of the accelerator infrastructure use. An optimised organisation structure, required for parallel operation, will be implemented with the objective of allowing 2000 hours of industrial applications out of about 10000 hours of beam time per year by 2031.

Longer-term Recommendations

In 2022, an international expert committee recommended the construction at GANIL of a high-intensity facility for radioisotope production using fission and multi-nucleon transfer reactions, followed by post-acceleration up to 100 MeV/u [43]. An electron-ion scattering facility was also suggested. Several different scenarios to meet identified scientific objectives are being considered.

CONCLUSION

With the completed commissioning and early operation of the SPIRAL2 facility, GANIL has demonstrated beam delivery over a wide range of particles, energies and intensities. Operational experience has highlighted both the strong performance of the superconducting LINAC and the challenges associated with system complexity and aging cyclotron infrastructure. Significant progress has been achieved in LINAC tuning strategies, beam reproducibility, and reliability, while ongoing efforts address remaining limitations.

At the same time, major upgrade projects—including S^3, DESIR, NEWGAIN, and CYREN—will considerably extend the scientific reach and operational capabilities of the GANIL facility. The SAGA project further strengthens this evolution by promoting diversification toward applied and interdisciplinary research.

Together, these developments position GANIL as a unique multi-beam facility, capable of addressing both fundamental nuclear physics and a broad spectrum of emerging scientific and industrial applications in the coming decade.

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