GANIL

Grand Accélérateur National d'Ions Lourds

Scientific annual report

2022

CONTENTS

01 | INTRODUCTION

1. A few words from the GANIL management

This annual report is an instant picture of GANIL activities, it is also a signature, an open window on the intensive and complex activities that take place in the laboratory for the completion of a rich scientific program led by the user community. 2022 has been an important year for GANIL as it coincides with the 40th anniversary of the first high-energy beam extracted from the CSS2 cyclotron after pre-acceleration in injector and first separated sector cyclotron. GANIL is proud of 40 years of many important discoveries and continuous evolutions to remain at the forefront of the research in nuclear physics, nuclear astrophysics as well as interdisciplinary science based on heavy-ion beams.

Since 2021, GANIL is opening a new chapter with the official entering in operation of the new linear accelerator of SPIRAL2, which demonstrated its performances for the acceleration of light ion beams up to the nominal intensity. In 2022, 40 years after the first beam of 40Ar beam accelerated by the cyclotrons of GANIL at 40 MeV/u, the LINAC has accelerated an 40Ar beam at 7 MeV/u with an excellent transmission, showing that the aimed scientific program of SPIRAL2 has very promising prospects. 2022 was also the year of the formalization of the consortium agreement for the construction phase of the new GANIL injector NEWGAIN, based on a superconducting ECR source, to increase the intensity and diversity of heavy-ion beams at SPIRAL2, strengthening the unique perspectives of the expected scientific outcome.

A complete external review of the DESIR project took place, and confirmed the uniqueness of DESIR assets in terms of beam quality and purity, and gave strong recommendations for a better organisation within the laboratory. The administrative files regarding the modification of GANIL Nuclear Installation for the construction of DESIR were accepted by the Nuclear Safety Authority in 2022, and the building permit request was deposited at the local authorities. The scientific instrumentation of DESIR is developing in partner laboratories. Coinciding with the commissioning of MORA experiment at the accelerator laboratory of University of Jyvaskyla, together with other fruitful activities, GANIL decided to strengthen the links with this University, through a bilateral agreement supporting scientific exchanges, following GANIL spirit to maintain the flame of science and international collaboration alight.

The Super Separator Spectrometer is following-up its installation, and 6 of the 7 Superconducting Multipole Triplets were delivered in 2022, and the electric dipole built in IJCLab was integrated to the beam-line. The clean room to host the laser room for S3-LEB scientific program has been completed. Considerable effort was done to obtain the new derogation for the safety exit while waiting for its construction.

The first experiment campaigns in NFS went very successfully, with the neutron beam characteristics of NFS being exceptional in terms of intensity and signal-to-noise ratio, as demonstrated by the on-line monitoring in intensity, energy, and spatial distribution. In 2022, important milestones were achieved with the creation of a dedicated zone for the storage of actinide targets, for the future scientific program of NFS.

In addition to these important milestones for SPIRAL2, a major project to refurbish and upgrade the complete cyclotron facility, CYREN, was proposed for the continuation and strengthening of the vivid experimental program that is underway at the cyclotron experimental areas, in nuclear and interdisciplinary physics. Technical teams of GANIL are maintaining their efforts of development to continue the delivery of high-quality and high-intensity stable and radioactive ion beams. In particular, in the domain of charge breeding for increasing the energy or intensity of beams, but also in the development of new Target-Ion Source for SPIRAL1, which will deliver beams to the DESIR hall.

Despite severe breakdowns in the cyclotron cooling system, an important experimental program was achieved. Two runs for the cyclotrons, which were extended to compensate the beam-time lost in different repairs, and two for the LINAC were performed, with in total more than 5000 hours of ion and neutron beams delivered to physicists, for the completion of more than 90 different experiments, corresponding to as many collaborations coming on the site of GANIL.

Main pilot beam represents more than 40% of the beam-time, for experiments in nuclear physics and nuclear astrophysics or interdisciplinary physics, mostly radiobiology in D1, and industrial applications. This time is almost doubled for parallel beam time for interdisciplinary research, hosted and managed by CIMAP teams: in IRRSUD and ARIBE, many experiments are devoted to the study of cosmic ices and the formation and evolution of complex molecules in asteroids after irradiation and their implication on the origin of life. In SME beam line, experiments in the field of material irradiation, nanostructuration and innovative materials are performed. The rest of the beam time is devoted to machine study, for the improvement of the accelerator operation, the development of new stable or radioactive ion beams, the SPIRAL2 linear accelerator tuning and different instrumentation and detector tests.

In 2022, the GANIL facility hosted the PARIS array for an extended campaign at the NFS vault and the CSS cyclotron experimental areas. First at the VAMOS magnetic spectrometer where the role of protons and neutrons in nuclear fission was investigated in light-fissioning systems produced by fusion reactions. Secondly, at LISE focal plane, where two experiments used the world premiere tandem mode with ion beams: the exotic beams selected by LISE were sent to two detector setups, ACTAR and the PARIS-EXOGAM combined array, mounted one behind the other for complementary studies of the atomic nuclei.
An extensive campaign was led with the INDRA-FAZIA set-up for the exploration of cluster formation in the low-density matter appearing in supernovae collapse and neutron star mergers.
In NFS, experiments for the study of light-ion production in neutron-induced reactions were performed with the MEDLEY set-up, and the first FALSTAFF campaign was devoted to the evolution of fission properties as a function of the incident neutron energy.
New compression modes of the nucleus were investigated in an innovative experiment with the MONSTER neutron array combined to PARIS.
Activation measurements for nuclear data improvement were performed with the rabbit set-up.

In 2022, the GANIL nuclear physics scientific Community applied to more than 6000 hours of beam-time, and only half of these experiments were approved, showing a strong request on the cyclotron beams. This pressure was also expressed during the GANIL Community Meeting, which gathered more than 150 participants and where inspiring discussions reflected the need for the cyclotron refurbishment for a long-term scientific program.

For the GANIL users, a new program of long-term visiting scientists has been put into place: for preparing an experiment, discussing a project, analyzing results or discussing science, GANIL supports on site stays of external physicists between 2 and 6 months.

The success of the experimental campaigns and the progress of the different GANIL projects is the result of the excellent work and dedication of GANIL teams and their collaborations, for the continuous support of scientific research led by GANIL users. This dedication, acknowledged by all, forms the GANIL spirit, always overcoming the challenges to ensure an optimal operation and upgrade of GANIL accelerators, instrumentation and infrastructure.

2. From design through construction and the evolution of cyclotrons, 40 years retraced.

Seminar given at GANIL on November 21th, 2022

C. Berthe, A.Savalle, G. Duteil, H. Franberg-Delahaye
GANIL, Grand Accélérateur National d'Ions Lourds, CEA-DSM/CNRS-IN2P3, DOD/DIR

Abstract

The first beam of the GANIL facility (Grand Accélérateur National d'Ions Lourds) at Caen was ejected from the second separated sector cyclotron forty years ago (November 19th, 1982). Since then, several evolutions occurred. In 2001, the first exotic beam, produced by the Isotope Separation On-Line method at the SPIRAL1 facility, was delivered to physics. The GANIL team realized an upgrade of this facility in order to extend the range of post-accelerated radioactive ions in years 2013-2017, with first radioactive beams delivered in 2018. In 2019, GANIL became also a LINAC facility, with the first beam accelerated in the SPIRAL2 facility.

From the beginning forty years ago to upgrade of SPIRAL1

November 19th, 1982, 12h30 am, the first beam was seen on the profiler located at the output of the second separated sector cyclotron at GANIL (Figure 1)**. 5 nA were ejected from 150 nA injected ($^{40}Ar^{16+}$), starting from 200 nA $^{40}Ar^{4+}$ ejected of SSC1.**

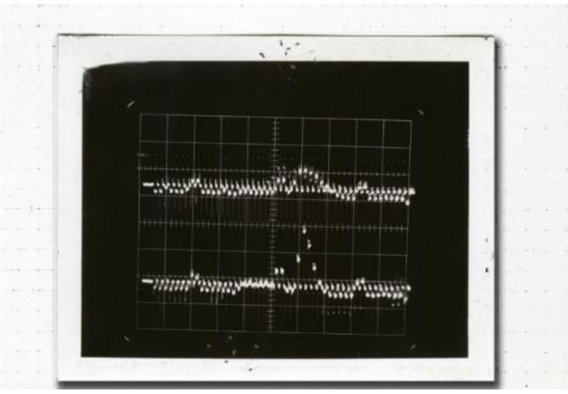


Figure 1: 1st beam profile, SSC2 ejection.

GANIL construction was decided in 1975. The design included two compact cyclotrons as injectors, one for SSC1 and one for SSC2. In the final design, the two injectors may inject the beam into SSC1, and also SSC2 (the two SSCs were identical). There is one rebuncher between the injectors and SSC1, one stripper between SSC1 and SSC2, one low energy spectrometer and a high-energy one, called "Alpha" spectrometer due to its shape. The beam is distributed to experimental areas through a "fishbone" (Figure 2).

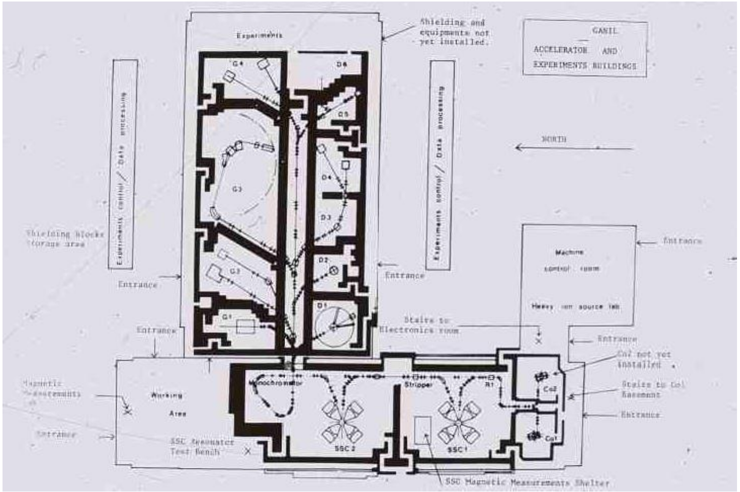


Figure 2: Design of GANIL.

The facility was built in the years 1978 – 1982. In 1983, the first experiment took place in January. That year, Ne, Ar, Kr, and O were accelerated. The O was accelerated at the maximal energy, 95 MeV/nucleon, but the energy was quite low for heavier beams (45 MeV/A for Kr beam).

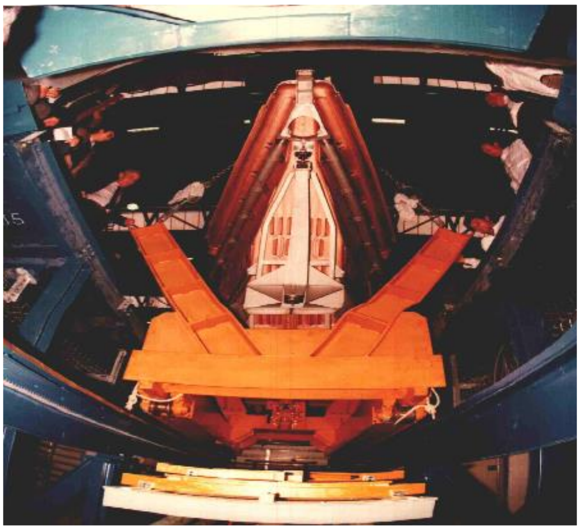


Figure 3: RF cavity ready to be installed in a SSC.

In 1989, the OAE project was achieved [1], increasing the maximal energy for heavy beams. The key point was the stripping efficiency, increased with a higher SSC1 ejection energy (operation of SSC1 with harmonic 5 instead of 7, and new injection radius in SSC2 – 1,2 m instead of 0,825).
Increasing SSC1 energy was facilitated by the new sources, ECR technology replacing the PIG sources, inside the cyclotrons, in 1985. In 1992, the C01 ECR source was installed in a 100 kV platform and a new injection beam line was built, leading to better intensities and higher C01 transmission (up to 65%). However, there were discharges in the accelerator tube and in 2004, we added a solenoid and a dipole inside the platform to have a pre-selection and limit the intensity in the tube.
With high energies and intensity, we could get radioactive beams. The firsts were produced in flight in SISSI [2]. The target was cooled, rotated and designed for 1 KW deposited power. A first superconducting solenoid gave a beam size of 0.2 mm radius, a second gave an angular acceptance of 80 mrad.

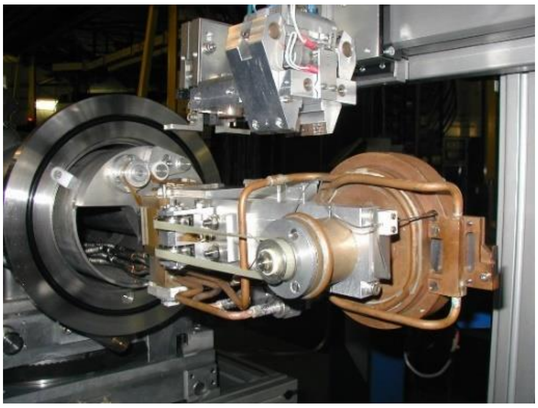


Figure 4: SISSI target

The THI project [3] increased the beam intensity in the years 95 – 2001, up to 5 kW. This was realized with beam loss monitors, a new rebuncher, a new septum for SSC2 deflector, and many hours of beam tests.

In parallel, it was the building and commissioning of SPIRAL1 [4], which consists in a **Isotope Separation On-Line method :** the beam is stopped in a carbon target, to produce secondary elements which diffuse in the target, are ionized in an ion source, and transported to a new cyclotron to be post-accelerated. The cyclotron energy is 1.2 to 25MeV/A using harmonics 2 to 6. In the original project there were two caves for the Target-Ion Sources (Figure 5).

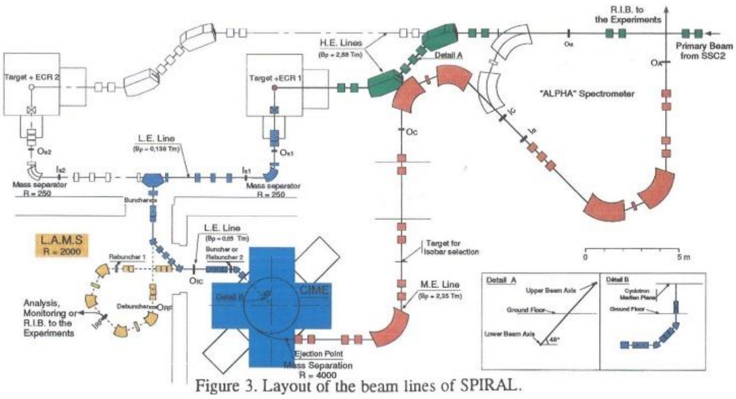


Figure 5: 1st design of SPIRAL1

3 modifications were made to extend the use of GANIL beams: Medium Energy Exit (SME in French) in 1989, Low-energy irradiation beam line south of injectors (IRRSUD) in 2002, and LIRAT which use the low energy beam of SPIRAL1 in 2005. LIRAT consisted in a beam line, an RFQ-cooler and a trap in a platform to study the radioactive beam properties.

In recent years SPIRAL1 was upgraded. It is now possible to use different targets (and no more carbon only), and different ion sources in particular FEBIAD source which is non selective and produces many elements, but is a 1+ source so that a Phoenix charge breeder is needed (Figure 6). However, we use also N+ ECR sources, and in that case the beam must pass through the charge breeder.

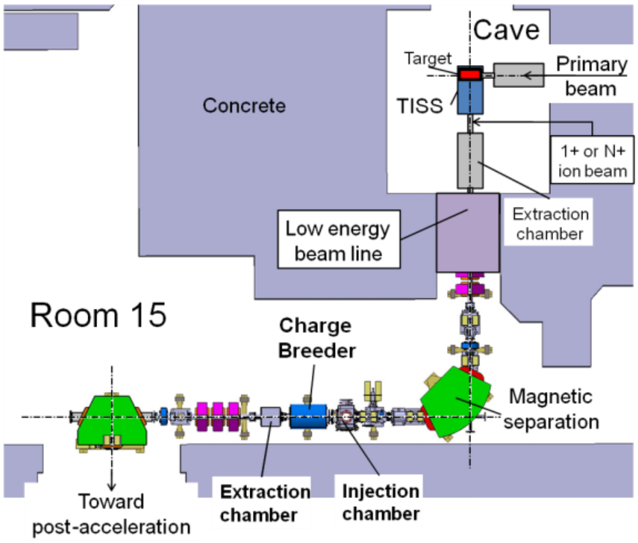


Figure 6: Schematic of the SPIRAL1 upgrade.

The integration of charge breeder and beam line modification was achieved between 2013 and 2016.

In 2017, the charge breeder and beam line commissioning was started. The whole system was validated (performance, beam optics) by the end of 2017. First radioactive beams (^{17}F, ^{38}K) were delivered in 2018-2019.

The mass resolution of CIME cyclotron allows us to purify the beam in many cases for light element (A<20). For heavier masses, stripping foils are generally used.

SPIRAL2

From 2005 to 2019, a large effort was made for the SPIRAL2 project than extending the cyclotron facility. The original project included post-accelerations of fission products in CIME; only the LINAC part with 2 experimental rooms are built today. In 2019, GANIL became also a LINAC facility, with the first beam accelerated in the SPIRAL2 facility.

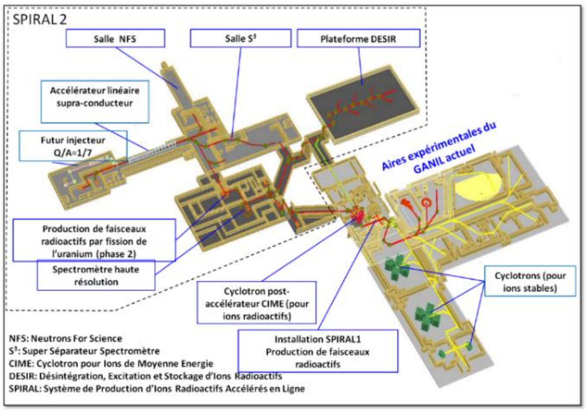


Figure 7: Layout of SPIRAL2

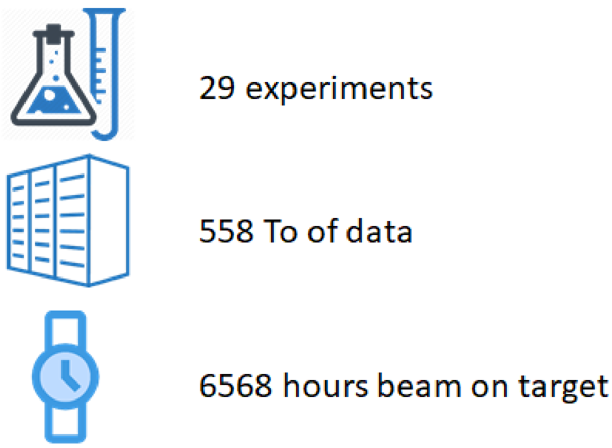
[1] J. Fermé, project « OAE » at GANIL, 11th international conference, Tokyo, 1986.
[2] A. Savalle et al, The SISSI facility at GANIL, EPAC 96, Sitges, Spain, June 96.
[3] E.Baron et al., High intensity heavy ion beams for exotic nuclei production at GANIL, 16th Int. Conf. On Cyclotrons and their Applications.
[4] M. Lieuvin et al., Commissioning of SPIRAL, the GANIL radioactive beam facility, Proc. of the 16th Int. Conf. On Cyclotrons and their Applications. East Lansing, Michigan (2001)

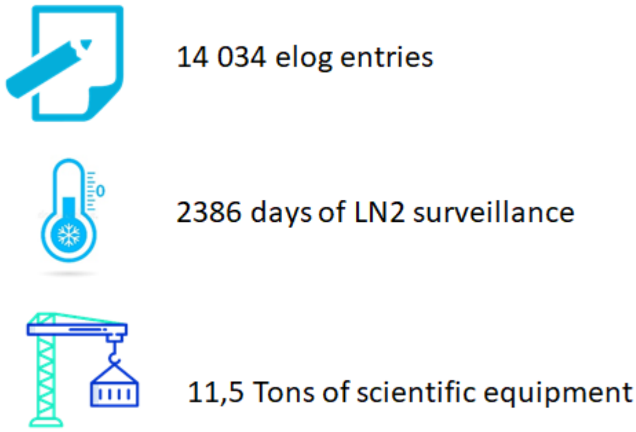
02 | SCIENTIFIC RESEARCH : Internal activities and user experiments

I. Structure, Astrophysics, Reaction and Spectroscopy

1. The golden age of high-resolution Gamma-ray spectroscopy at GANIL

In July 2021, the last experiment using the AGATA European γ-tracking array at GANIL was performed, completing 7 years of an intense scientific campaign between 2014 and 2021. During this campaign, the AGATA array was coupled to a large variety of complementary instruments available at GANIL such as the VAMOS++ magnetic spectrometer [2015-2017; 2021] for the identification of exotic nucleus produced in heavy ions collisions, the NEDA (neutron detector) and DIAMANT (charged particle array) for the spectroscopy of nuclei produced by fusion evaporation (2018) and the MUGAST silicon array for direct reaction using radioactive post-accelerated ions beam from the SPIRAL1 facility [2019-2021]. In total, 29 experiments have been performed and ~500 scientific visitors researcher participated to the data taking at GANIL. Several high level peer-review papers have been published with AGATA data recorded at GANIL (see https://www.agata.org/list_of_publications). One can underline the high resolution spectroscopy of very exotic nuclei such as 96Kr [1], 81Ga [2], 84Ge [3], 207Pb [4], 88Ru[5], 20O[6], 212Po [7], 106-108Sn [8], and 94Ru[9]. In July 2021, the AGATA infrastructures were shut-down at GANIL and the dismounting was achieved by the GANIL technical staff in close collaboration with the AGATA teams. On the 6th of September, 11.5 Tons of scientific material left the facility to reach the LNL facility at Legnaro (Italy) for a new campaign using the stable beams of the TANDEM –ALPI facility and in a near future, the post-accelerated radioactive ions beams of the SPES facility. The 10 years of the AGATA@GANIL project [2012-2021] have been a tremendous effort for the Physics Division who fulfilled with success its objectives. The commitment, including during the pandemic period, of the local staff was acknowledged by the AGATA collaboration at its highest level. The figure shows some key numbers of the AGATA campaign at GANIL





[1] doi: 10.1103/PhysRevLett.118.162501
[2] doi :10.1103/PhysRevC.100.011301
[3] doi: 10.1103/PhysRevLett.121.192502
[4] doi:10.1016/j.physletb.2019.134797
[5] doi:10.1103/PhysRevLett.124.062501
[6] doi:10.1103/PhysRevC.101.021303
[7] doi :10.1103/PhysRevC.104.054316
[8] doi:/10.1016/j.physletb.2020.135474
[9] doi :10.1103/PhysRevLett.129.112501

2. The unified approach to nuclear structure and reactions

The incompleteness of a shell model description of the atomic nucleus was realized very early on. For instance, the inadequacy of perturbation theory for describing resonances was noticed by Fano [1]. The first attempts were to reconcile the shell model with reaction theory by replacing the paradigm of the closed quantum system by the paradigm of the system interacting with its environment of scattering states and decay channels. This gave rise to the shell model embedded in the continuum (SMEC) which provides a unified description of the nuclear structure and reactions and finds a proper framework in non-Hermitian quantum mechanics. SMEC has been recently applied to study the narrow resonances in the continuum of the unbound nucleus ^{15}F [2], the decay of the 21.47 MeV stretched resonance in ^{13}C [3], and near-threshold resonances in ^{11}C and the ^{10}B(p,α)^{7}Be aneutronic reaction cross section [4]. Beta-delayed proton emission from the neutron halo ground state of ^{11}Be raised much attention due to the unusually high decay rate. It was argued that this may be due to the existence of a resonance just above the proton decay threshold [5]. We have used the lenses of real-energy continuum shell model, the SMEC, to describe several observables including the Gamow-Teller rates for the β^--delayed α and proton decays, and argue that, within this model, the large β^-p branching ratio cannot be reconciled with other data, such as the branching ratio $b_r(\beta^-\alpha)$ [6].

[1] U. Fano, Phys. Rev. 124, 1866 (1961)
[2] V. Girard-Alcindor et al., Phys. Rev. C 105, L051301 (2022)
[3] N. Cieplicka-Oryńczak et al., Phys. Lett. B 834, 137938 (2022)
[4] J. Okołowicz, M. Płoszajczak and W. Nazarewicz, Phys. Rev. C 107, L021305 (2023)
[5] J. Okołowicz, M. Płoszajczak and W. Nazarewicz, Phys. Rev. Lett. 124, 042502 (2020)
[6] J. Okołowicz, M. Płoszajczak and W. Nazarewicz, J. Phys. G 49, 10LT01 (2022)

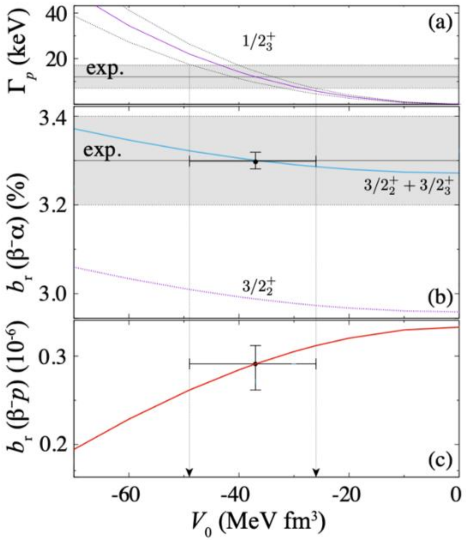


Figure 8 : a) Proton decay width of the $1/2^+_3$ resonance in ^{11}B calculated in SMEC as a function of the continuum coupling strength V_0. (b) The branching ratio for the β delayed α emission from the $1/2^+$ ground state of ^{11}Be to the $3/2_2^+$, and $3/2_3^+$ resonances in ^{11}B. (c) The branching ratio $b_r(\beta p)$.

3. ZDD: A new detection system for the LISE spectrometer

The identification of nuclei after reaction in a target is crucial to filter out only those events that have undergone interaction from the many more that have remained intact. This is particularly important when using composite targets. Indeed, when using a CD2 target, for example, we are generally interested in neutron addition (d, p) or withdrawal (d, t) reactions on deuterium nuclei. These transfer reactrions change the mass of the initial nucleus by one neutron less or more, but keep constant the atomic number. However, there can be also partial fusion reactions with C nuclei of the target, which produce nuclei with a higher atomic charge, slower velocity and greater angular distribution. These nuclei, highly excited during fusion, may then emit protons and tritiums, which need to be eliminated by selecting the atomic number, time-of-flight and angular distribution of the nuclei produced.
To achieve this objective, technical teams of GANIL have designed and built a zero-degree detection system (ZDD) comprising two sets of drift chambers, to determine the angle of the emerging nuclei (from 0 to 7°) from their X and Y positions, an ionization chamber to determine their atomic number, and a plastic scintillator to measure their time of flight. A schematic view of this ensemble is shown Figure 9. All detectors have been equipped with dedicated digital electronics enabling a counting rate of around 10^5 pps. At the rear of the device is a Ge detector to measure gamma rays from nuclei implanted in the scintillator plastic.

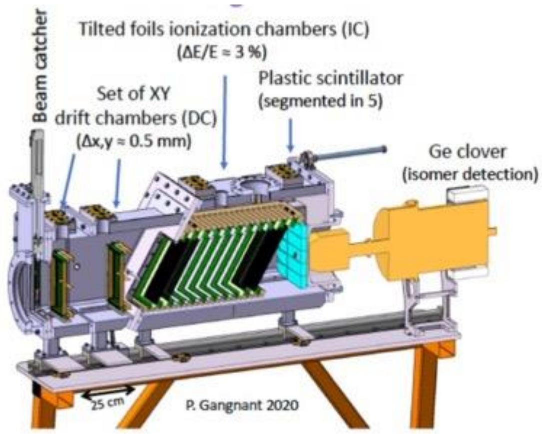


Figure 9

The 2022 experimental campaign at LISE used the ZDD system, which proved to be highly successful. It consisted in studying the excitation of unstable nuclei produced by the LISE spectrometer, either in the active ACTAR target filled with hydrogen, or in a gold target located at the center of the EXOGAM and PARIS gamma-ray detectors (see Figure 10). The ZDD was positioned downstream of the gold target. The first part of the device favors neutron excitations of the nucleus, while the second favors the proton part. In this way, we were able to study the multiple facets of a single nucleus using a device in the form of a TANDEM arrangement of detectors, the only one of its kind in the world. ZDD detection is already the basis of a program of experiments with high scientific potential (e.g. nuclear magicity, nuclei in cluster form, superfluidity, nuclear astrophysics) for at least the next three years on the LISE spectrometer at GANIL.

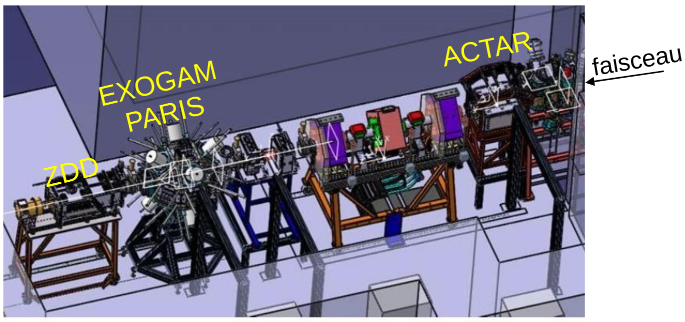


Figure 10

4. ^{22}Na to probe novae explosions

Classical novae are thermonuclear explosions in stellar binary systems, and important sources of the radioactive isotopes of ^{26}Al and ^{22}Na. While gamma rays from the decay of ^{26}Al have been observed throughout the galaxy, ^{22}Na remains untraceable. Its relatively short half-life (2.6 years) could make it possible to unambiguously associate the observation of this isotope, via its gamma line at 1.275 MeV, with its production site (the novae). It could be used to probe the explosion. However, the prediction of such an observation requires a good knowledge of its nucleosynthesis. The ^{22}Na(p,γ)^{23}Mg reaction remains the only source of large uncertainty in the amount of ^{22}Na ejected from the novae. Its rate is dominated by a single resonance on the short-lived key state at 7785 keV in ^{23}Mg.

An experiment was performed at GANIL to measure both the lifetime and the proton branching ratio of the key state. With a beam energy of 4.6 MeV/u, the reaction $^{3}He(^{24}Mg, \alpha)^{23}Mg$ populated the key state. This reaction was tagged with particle detectors, the VAMOS++ spectrometer and the silicon telescope SPIDER, and with AGATA gamma-tracking spectrometer. A combined analysis of particle-particle correlations and velocity difference profiles has been proposed to measure femtosecond nuclear lifetimes. The expected time resolution is 1 fs, which is exceptional. The measured lifetime of the key state is 11(+7-5) fs and the branching ratio is 0.68(17)%.

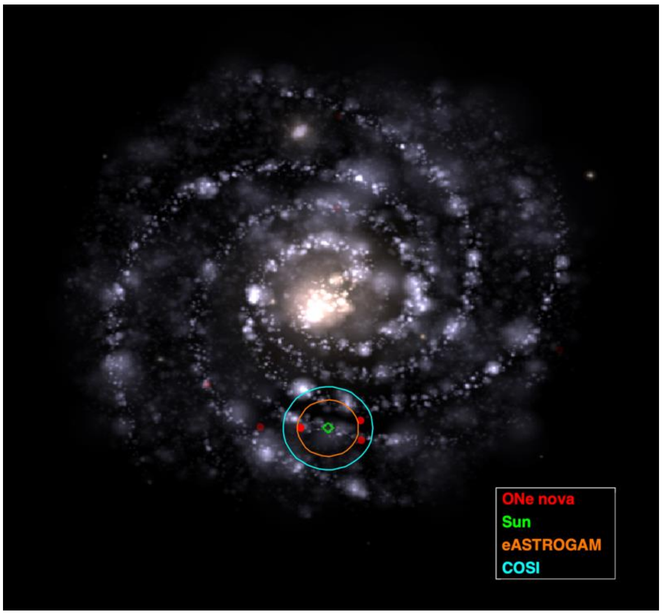


Figure 11 : Our Galaxy, position of the Sun, and detection limits of 22Na with the future gamma-telescopes eASTROGAM and COSI.

The $^{22}Na(p, \gamma)^{23}Mg$ thermonuclear rate has been reevaluated with the statistical Monte Carlo approach and the new data. This new rate was found to be very reliable at maximum nova temperatures, with uncertainties reduced to 40 % (10 %) at T=0.1 GK (0.5 GK). Then, the amount of ^{22}Na ejected during novae was determined precisely using stellar modeling codes. The detectability distances of ^{22}Na from novae have been derived, it is 2.7 and 4.0 kiloparsec for the e-ASTROGAM and COSI gamma-ray telescope respectively, which the reaction rate uncertainty obtained here leads to an uncertainty of 18 %.
This work has been submitted to Nature Communications.

5. ACTAR TPC

E791 Experiment

This experiment aimed at measuring the proton-proton correlations in the decay of ^{48}Ni with ACTAR TPC. Gamow coupled-channels calculations [16] predict a pure $f_{7/2}$ configuration for the two valence protons of the spherical nucleus ^{48}Ni, which would translate into a single component at relatively small angles in the angular correlation plot of the two emitted protons. The purpose of the measurement is to provide experimental information required for a microscopic understanding of this unique emission process by measuring the relative angle of the decay protons.
The ^{48}Ni were produced and selected in the LISE spectrometer using a ^{58}Ni beam impinging on a ^{58}Ni target. ACTAR TPC was used in TPC mode, running with a mix of Ar(90%) and iC_4H_{10}(10%) at 300 and 400 mbar. The main challenge for this experiment was the incoming beam identification: in order to maximize the number of ^{48}Ni reaching the TPC, the momentum slits of LISE were fully opened, hence smearing out the correlation between the energy loss of the ions (measured in Si detectors placed at 0° before the TPC) and their time of flight. The beam trackers CATS were also installed, in order to facilitate the incoming beam identification.
The analysis of the experiment is performed by A. Ortega Moral, PhD student at LP2iB.
Few 2p decays of ^{48}Ni were observed (see Fig.1). However, the production rate of ^{48}Ni nuclei was much lower than expected from previous measurements in the same region of the nuclear chart, hence compromising the original goal of the experiment. Nevertheless, several exotic nuclei undergoing exotic decays (such as beta-2p, beta-3p) were implanted. The study of these decays will permit to refine the theoretical models aiming at describing this region of the nuclear chart.

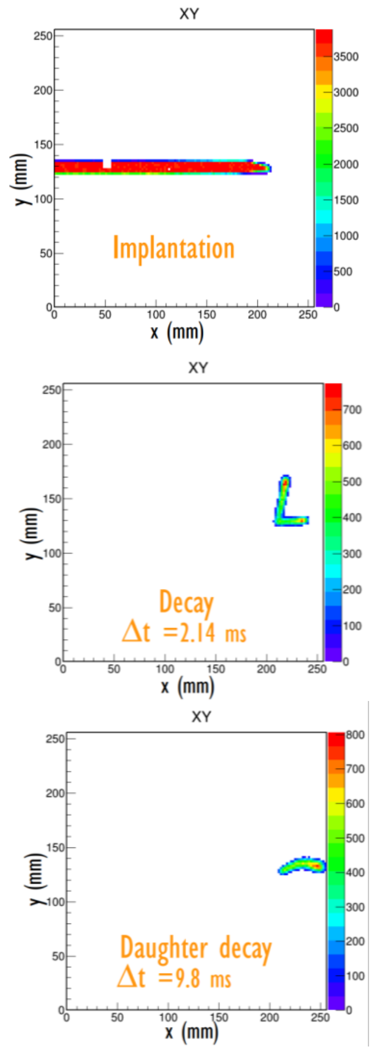
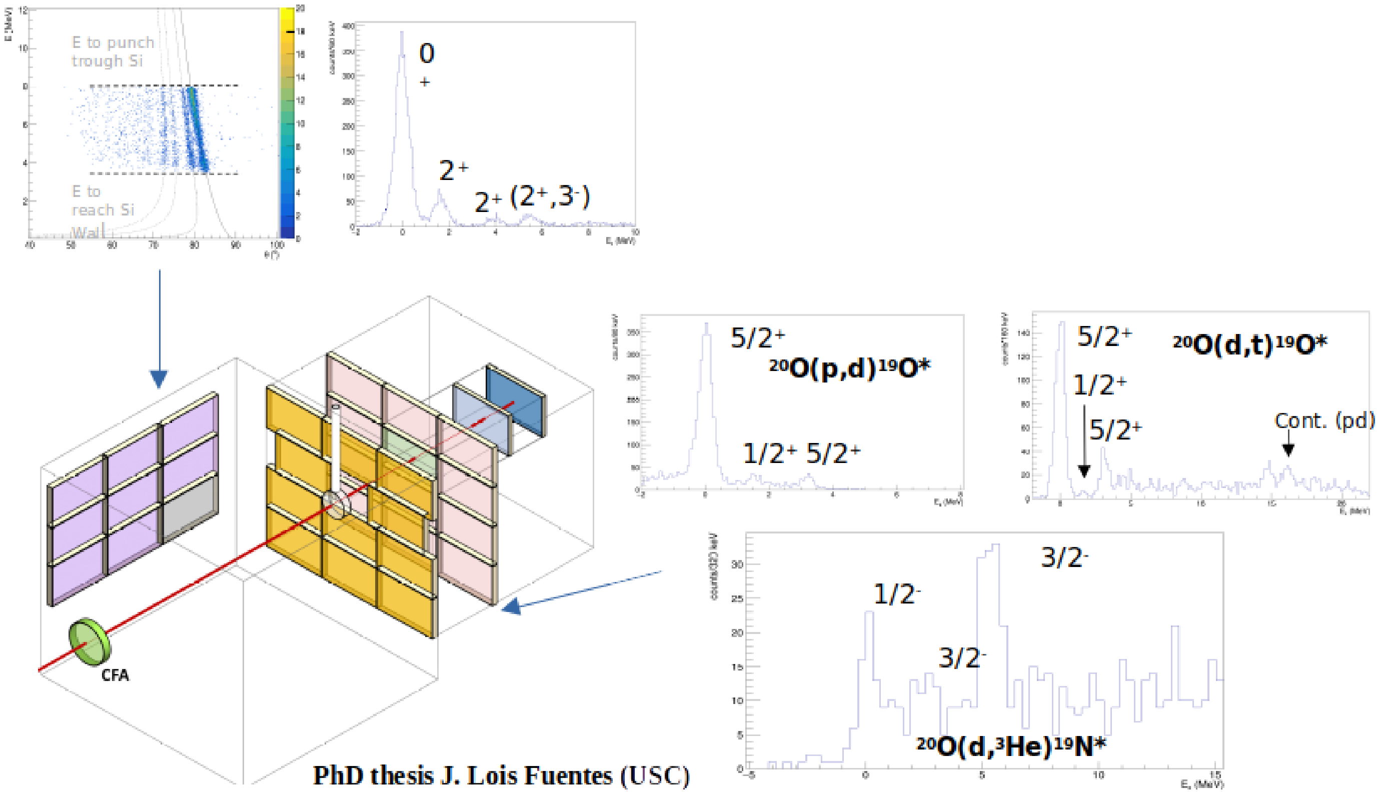


Figure 12 :
Example of typical event recorded. From left to right: ^{48}Ni implantation event, followed by two-proton decay event, and the proton decay from the daughter nucleus ^{46}Fe. Courtesy A. Ortega Moral

E796 Experiment

This experiment aimed at studying the Z=6 proton shell gap through the $^{20}O(d,^{3}He)^{19}N$ reaction with ACTAR TPC. This reaction was used to measure the spin-orbit splitting of the $1p_{1/2}$ and $1p_{3/2}$ orbitals in ^{19}N, which will bring crucial information on the nature of the spin-orbit interaction. In addition, the experiment gives access to the cross-shell states in ^{19}O through the neutron removal reactions $^{20}O(d,^{3}H)^{19}O$ that are important to benchmark modern shell model interactions. The ^{20}O nuclei were produced and selected with the LISE spectrometer before being sent to ACTAR TPC. The active target was filled with a mix of D_2(90%) + iC_4H_{10}(10%) at 950 mbar, hence providing a thick ^{2}H target (equivalent to 11 mg/cm^2 of classic solid CD_2 target). The measurement of the energy of the produced ^{3}He, ^{3}H, etc… was performed with several Si telescopes placed on the front wall of ACTAR (see Figure 13). An additional wall of Si detectors was placed on one of the sides of ACTAR TPC in order to measure the elastic and inelastic scattering of the beam with the target nuclei, proving useful information for the interpretation of the data.
The analysis of the experiment is performed by J. Lois Fuentes, PhD student at the University of Santiago de Compostela (in co-supervision with GANIL). The analysis will permit to measure the spectroscopic factors of the states in ^{19}N populated by the $^{20}O(d,^{3}He)^{19}N$ reaction. Simultaneously, the neutron occupancy of the valence orbitals in ^{20}O were measured through the $^{20}O(d,^{3}H)^{19}O$ and the $^{20}O(p,^{2}H)^{19}O$ reactions

Figure 13 : Scheme of ACTAR TPC with the placement of the Si



detectors used to measure the energy of the recoils, together with reconstructed excitation energy spectra from some of the reaction channels measured during the experiment.

Courtesy J. Lois Fuentes

II. Physics of heavy and superheavy nuclei

1. S^3 Scientific Program and Instrumentation Development

Scientific program and collaboration

In December 2022 a workshop “Physics with SPIRAL2 heavy ion beams” was organized at GANIL. The purpose of the meeting was to bring together the SPIRAL2 community to prepare for the use of Heavy Ions beams delivered by the LINAC accelerator. The workshop was structured around three main axes of exchanges and discussions:

i) accelerator, instrumentation and target development,
ii) scientific program with S^3 beams and
iii) new avenues with heavy NEWGAIN beams.

Dedicated sessions were organized to revise S^3 LoIs submitted in 2018 and to foster new idea and further developments. All those discussions have shown that the scientific program remains at the forefront of science with high scientific impact. S^3 gathers a very strong and diverse community that will require a full synchronization among all teams to identify the starting experimental program for impactful results.

In January 2023, the S^3 commissioning plan was evaluated by the GANIL Scientific Council. Among all recommendations, we can underline that de SC recommended that

i) the GANIL management prioritizes a rapid commissioning of the spectrometer and
ii) the scientific collaboration works out a plan for first exploratory physics runs simultaneously while commissioning the spectrometer and the focal plane detectors.

In line with those recommendations, a meeting of the S^3 User Collaboration Council is planned in June 2023 to select which setups to be installed at S^3 to perform successful commissioning with a detailed beam time sequences (reactions, measurements, ...).

Finally, the S^3-LEB MoU was signed by all the partners in October 2022. The purpose of this MoU is to specify the role of each Party with respect to planning, funding, constructing and commissioning the S^3-LEB.

S^3-SIRIUS

SIRIUS (Spectroscopy and Identification of Rare Isotopes Using S^3) was delivered to GANIL on march 2021 from Irfu Saclay where the Double-sided Silicon Strip Detector (DSSD) and its instrumentation were developed and tested. The parts of SIRIUS developed at IPHC (Strippy pad Tunnel detector [1-2]) and IJCLab (Tunnel preamplifiers and digitizers [3]) have been installed on SIRIUS to complete the detection setup.

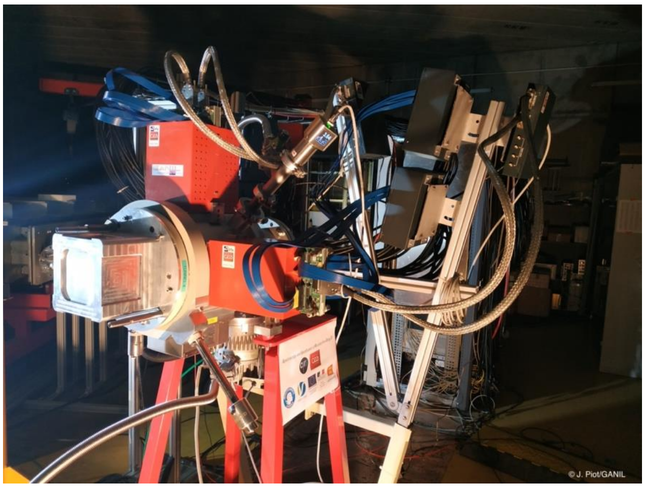


Figure 14 : SIRIUS

The DSSD is operational. The Floating Point Charge Sensitive Preamplifiers (FPCSA) developed by Irfu have been tested with conversion electrons, alpha particles and fission fragments. The gain switching capability of the FPCSA are validated and offer energy resolutions better than the original specifications. Single channel energy resolution for alpha particles is 16.9(6) keV FWHM for the high gain and ~1% FWHM for the low gain after switching.

The Tunnel detector is also operational. All channels have been tested using alpha particles and conversion electrons. The presence of junk events observed in pre-series detectors has been solved thanks to the collaboration between IPHC and the manufacturer. The new detectors show an average energy resolution of 18.3(2) keV FWHM for alpha particles and 13 keV FWHM for conversion electrons.
The time synchronization of the detectors of SIRIUS has been set using the GTS system. The correlation in time of events from different channel has been validated.

The measurement of the time of flight using digitized traces from a silicon detector and the tracker detector was tested on a test bench in fall 2021. This method allowed to obtain a time of flight resolution of 760(349) ps FWHM.

SIRIUS has been funded by the CPIER (Contrat Plan Etat Inter Régional) and the Région Normandie & the European Union through the RIN-Tremplin Grant SoSIRIUS.

[1]H. Faure et al., Proceedings of the 3rd International Conference ANIMMA 2013, http://dx.doi.org/10.1109/ANIMMA.2013.6728085.
[2] P. Brionnet et al, Nuclear Inst. and Methods in Physics Research, A 1015 (2021) 165770
[3] N. Karkour et al, 2016 IEEE Nuclear Science Symposium

S^3-LEB

The S^3 Low Energy Branch (S^3-LEB) is one of the two setups which will be installed at the focal plane of S^3. It will be a source for the production of new and pure radioactive ion beams at low energy as well as a laser spectroscopic tool to measure nuclear hyperfine interactions. It consists of a gas cell in which the reaction products from the S^3 spectrometer will be stopped, neutralized, extracted in a supersonic gas jet as a cold atomic beam and then coupled to a laser system that assures a selective re-ionization of the atoms of interest which are identified by measuring their time of flight. By varying the wavelength of the laser, the hyperfine structure of the atom can be probed and the properties of the nucleus extracted. The laser ions can also be transported to a multi-reflection time of flight mass spectrometer (MR-ToF-MS) for high-precision mass measurements.

The S³-LEB set up is currently under off line commissioning at LPCCaen. The TiSa based laser system was installed in a new laser hut, with two broad band Ti:sa lasers, one double etalon and one single etalon configuration. In-gas cell laser spectroscopy of stable Erbium was successfully performed and the laser ions could be identified thanks to the MR-ToF-MS. Spectral broadening in the gas cell was studied and quantified (see figure below). The transmission efficiency of the ion-guide units was improved for which detailed performance studies of the buncher was performed as well as performance tests in the MR-ToF-MS

In order to perform high resolution laser spectroscopy at S³-LEB, injection locked Ti:sa was installed, aligned and optical path in the gas jet configuration was implemented. Narrowband laser was set up for which the seed external cavity diode laser was aligned for Er RIS first step and seeded. The slave cavity was aligned for lasing at optimal conditions and locking. The line width of the laser was measured for which a scanning Fabry Perot Interferometer set up was implemented. De-Laval nozzle of Mach number M=7 was installed for gas jet. High resolution narrow-band in-gas jet laser spectroscopy of stable Er was performed achieving a spectral resolution <300 MHz. Isotope shift and hyperfine constants measurements were performed. Effects on the spectral resolution with respect to different gas jet conditions are currently being studied.
The first off line results and the in-gas jet laser spectroscopy results with the S³-LEB setup have been published.
(https://doi.org/10.3390/atoms10010021)
(https://doi.org/10.1016/j.nimb.2023.03.020)

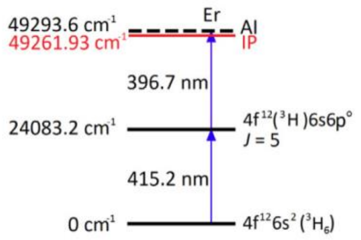


Figure 15 : Resonance ionization scheme of Er

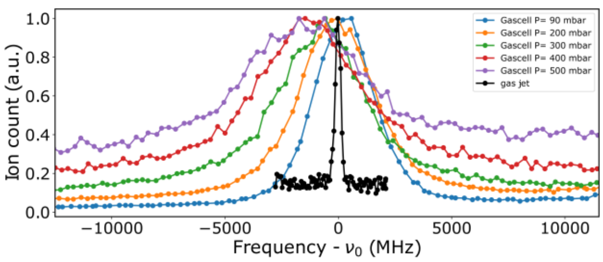


Figure 16 : Resonance ionization spectroscopy of Er in the gas cell for different gas pressures (color) compared to the gas-jet spectroscopy of 170Er (black) for the First Excitation Step transition relative to ν0 = 721,995,050 MHz.

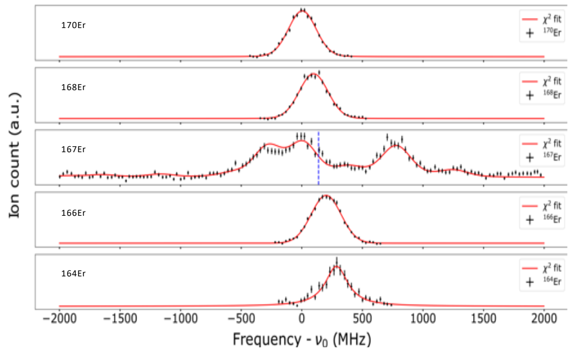


Figure 17 : Laser spectroscopy of stable Er isotopes in the gas jet using the first excitation step relative to ν_0 = 721,995,050 MHz. The measured data points (black) are normalized by the laser powers of both steps and the fit is shown in red. The weighted centroid for ^{167}Er is marked as the blue dashed line

S³-LEB has received funding from the French Research Ministry through the National Research Agency under contract number ANR-13-B505-0013, from the Research Foundation - Flanders (FWO) under the International Research Infrastructure program number I002219N, from the Research Coordination Office – KU Leuven (C14/22/104), from the European Research Council under contract number ERC-2011-AdG-291561-HELIOS, from the FWO and F.R.S.-FNRS under the Excellence of Science (EOS) program (40007501),from the European Union's Horizon 2020 research and innovation program under grant agreement number 654002–ENSAR2–H2020-INFRAIA-2014-2015 and under grant agreement number 861198–LISA–H2020-MSCA-ITN-2019 and from IN2P3-DSM/CEA and GSI under the French-German collaboration agreement number PN1064.

GISELE

The GISELE laser laboratory is dedicated to the development of laser systems and the search for, and investigation of, laser ionisation schemes for various elements [1,2]. This is mainly in preparation for experiments at S³-LEB but also within a wider collaboration with other laser laboratories. The used technique is Resonant Ionisation Spectroscopy (RIS), which is highly element-selective thanks to the unique atomic structure of each element, and can be highly efficient thanks to dedicated (high-power) laser systems and high-efficiency ion detection techniques. The backbone of the lab is formed by multiple pulsed Ti:sapphire lasers pumped by a Nd:Yag laser. Three cavities are standard broadband cavities for high power at fixed frequencies. A fourth cavity is a grating-based system, aimed at having a wide wavelength scanning range. The fifth and newest cavity is an injection-locked laser system, which yields narrow-bandwidth/single-mode laser light ($\Delta\lambda$< 50 MHz) and is dedicated to high-resolution laser spectroscopy. The laser ionisation takes place within an Atomic Beam Unit (ABU), which consists of an oven, extraction electrodes, a TOF region and an MCP detector.
Recently, the first high-resolution spectroscopy results were obtained, in preparation for the first experiments with the S³-Low Energy Branch [3]. Isotope shifts and hyperfine structure constants were measured for stable isotopes of erbium and tin, providing valuable input for future studies of neutron-deficient isotopes of these elements. The erbium isotopes were studied using the $4f^{12}6s^2$ *J=6* ⟶ $4f^{12}6s6p$ *J=5* atomic transition (415 nm) and the tin isotopes by the $5s^25p^2\,{}^3P_0$ ⟶ $5s^25p6s\,{}^3P_1$ atomic transition (286.4 nm), which was also used

as a benchmark of the laser setup. Additionally, the tin isotopes were studied by the $5s^25p6s\ ^3P_1 \rightarrow 5s^25p6p\ ^3P_2$ atomic transition (811.6 nm), for which new isotope shift data was obtained and the corresponding field- and mass-shift factors were extracted. Currently measurements of stable palladium isotopes are under way.

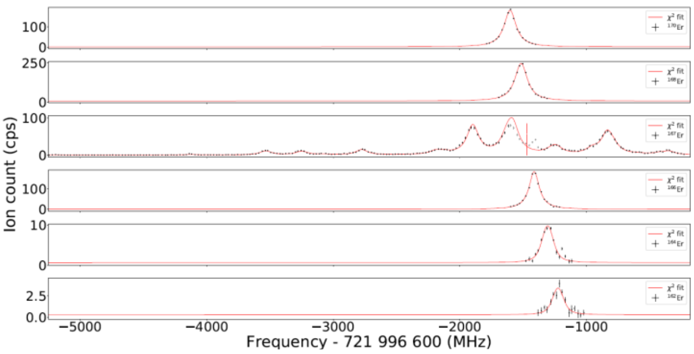


Figure 18 : $^{170-162}$Er RIS scan data shown in black with hyperfine structure fits shown in red

In parallel, several upgrades are ongoing. The current injection-locked laser is the very first version developed at the University of Jyväskylä. Many groups have used the laser since and made upgrades to the design. One of these latest designs is now being put into operation at GISELE and will provide easier and more stable operation for future experiments. A direct diode pumped continuous wave (cw) Ti:sapphire cavity is also being built [4]. Such a cavity has a wide wavelength scanning range, and is to be used as a seed for the injection-locked lasers. It will replace the cw external cavity diode lasers with limited tuning range that currently act as the seed source, while being cheaper than commercially available cw Ti:sapphire lasers.

[1] N. Lecesne et al., Rev. Sci. Instrum. 81.2 (2010) 02A910
[2] J. Romans et al., Atoms 10 (2022) 21
[3] J. Romans et al., Nucl. Instrum. Methods Phys. Res. B 536 (2023) 72-81
[4] V. Sonnenschein et al., Hyperfine Interact. (2020) 241:32

GISELE has received funding from the French Research Ministry through the National Research Agency under contract number BLAN08-1_309740, from the European Union's Horizon 2020 research and innovation program under grant agreement number 654002–ENSAR2–H2020-INFRAIA-2014-2015 and under grant agreement number 861198–LISA–H2020-MSCA-ITN-2019, from IN2P3-DSM/CEA and GSI under the French-German collaboration agreement number PN1064, …

2. Investigation of the properties of ^{252}Fm through prompt γ-ray spectroscopy

^{252}Fm is sitting at the crossing of two deformed shell gaps Z=100 and N=152. The stabilizing effect of these two shells has already been experimentally confirmed using different methods [1-3]. However, no nuclear structure information has been available on ^{252}Fm expect the excitation energy of its first 2^+ state extracted from alpha-decay measurements [4].

In October 2021 a measurement of the prompt gamma-ray transitions of ^{252}Fm was performed at the Fragment Mass Analyser (FMA) [6] at Argonne Tandem Linear Accelerator System (ATLAS) in the USA. Due to its half-life of 25.39 h [Ahmad] the identification of ^{252}Fm could not be done using its alpha-decay. The identification was performed with FMA to separate ^{252}Fm in mass from other isotopes and implanting it in a silicon detector. Gamma-rays emitted at the target position were measured using the germanium array GRETINA [7].

^{252}Fm was successfully produced using the reaction ^{238}U(^{18}O,4n)^{252}Fm. Eleven events were observed through the alpha decay. The measured alpha energy is 7.0±0.5 MeV.

An additional proposal has been submitted to the ANL ATLAS PAC in May 2023, aiming at solving the puzzle of the discovery and assignment of the most neutron-deficient mendelevium isotope ^{244}Md which is presently debated by groups from LBNL, Berkeley, U.S.A. [8] and GSI, Darmstadt, Germany [9].

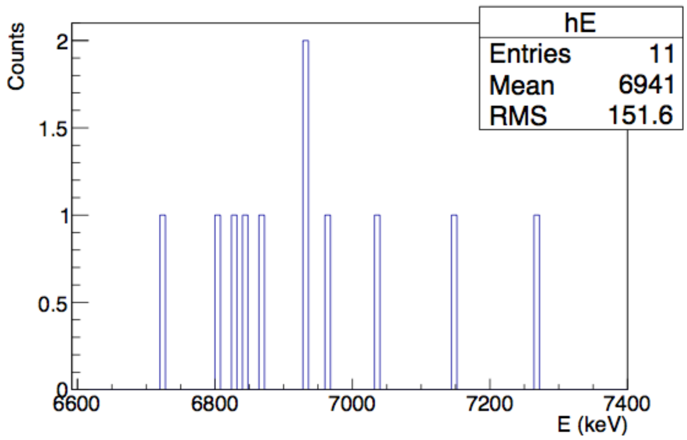


Figure 19 : Alpha spectrum of 252Fm after 26.95h of decay.

[1] P.T. Greenlees et al. Phys. Rev. C. 109 (2012) 012501
[2] R.D. Herzberg et al. Nature Vol 442 (2006) 05069.
[3] M. Dworschak et al. Phys. Rev. C 81 (2010) 064312.
[4] R. Orlandi, Poster Contribution TAN19 Conference.
[5] I. Ahmad et al. Nucl. Phys. A 413 (1984) 423.
[6] C.N. Davids et al. Nucl. Inst. Meth. B 70 (1992) 358.
[7] S. Paschalis et al. Nucl. Inst. Meth. A 709 (2013) 44.
[8] J. L. Pore et al., Phys. Rev. Lett. 124 (2020) 252502.
[9] J. Khuyagbaatar et al., Phys. Rev. Lett. 125 (2020) 142504.

3. Reaction dynamics for the synthesis of super-heavy nuclei and Metrology by Bayesian analysis

One of the main questions in nuclear physics is to find the limits of existence of nuclei which are located at the edges the Segrè chart. The present research programme focuses on the highest masses *A* and atomic numbers *Z*. These so-called super-heavy nuclei (SHN) exist beyond the liquid drop limit of existence defined by a vanishing fission barrier thanks to the quantum mechanical shell effects. They are not present on Earth and should be artificialy synthesized.

Synthesis of these very and super-heavy nuclei by fusion-evaporation reactions is an experimental challenge due to the extremely low cross-sections. Modelling the complete reaction in order to guide the experiments is also a difficult challenge

because models developed for lighter nuclei cannot be simply extrapolated. Fusion reactions are hindered with respect to what is observed with light nuclei because of the very strong Coulomb interaction being enhanced by the large number of positive charges in the fusing system. The dynamical mechanism responsible of the fusion hindrance is still a matter of research [1,2].
The predictive power of the models is low although the origin of the hindrance phenomenon is qualitatively well understood. Quantitative ambiguities are large enough to observe few orders of magnitude differences in the fusion probabilities calculated by different models. A small change of the cross-section could result in many months being required to successfully perform experiments. In such a context, the theoretical researches performed at GANIL on the synthesis of SHN try to find ways to assess the models in order to improve their predictive power. One way is based on uncertainty analysis that is very new in theoretical nuclear physics [3-5]. Standardised methods as well as state-of-the-art data analysis methods such as Bayesian analysis are used. Moreover, a special effort will be put on designing specific experiments dedicated to study the reaction mechanisms that could help to constrain the so-called fusion hindrance.
Bayesian statistical methods are also applied to metrology [5].

[1] David Boilley, Yasuhisa Abe, Bartholomé Cauchois and Caiwan Shen, Journal of Physics G: Nuclear and Particle Physics 46 (2019) 115102 (12pp); Erratum due to a production problem: J. Phys. G: Nucl. Part. Phys. 46 (2019) 129601
[2] Yasuhisa Abe, David Boilley, Quentin Hourdillé, and Caiwan Shen, Progress of Theoretical and Experimental Physics, Volume 2021, Issue 2, February 2021, 021D01
[3] Hongliang Lü, David Boilley, Yasuhisa Abe and Caiwan Shen, Physical Review C94, 034616 (2016)
[4] Bartholomé Cauchois, Hongliang Lü, David Boilley and Guy Royer, Physical Review C98 (2018) 024305
[5] Bartholomé Cauchois and David Boilley, The European Physical Journal A54 (2018) 202

4. MNT as alternative tool to investigate n-rich heavy nuclei

The investigation of the region of the heaviest nuclei is still one of the major challenges in nuclear physics. In particular, the unique feature of those species being stabilized only by quantum mechanics and so-called shell effects, makes them an ideal laboratory to study, and to put constraints on our understanding of the strong nuclear interaction by spectroscopic means [1]. Despite the success accomplished throughout the last two decades in synthesis of new elements culminating in the naming of element 113, 115, 117 and 118, nihonium, moscovium, tennessine and oganesson [2, 3, 4, 5], the perspectives to push the applied reaction scheme of fusion evaporation even further are rather limited.

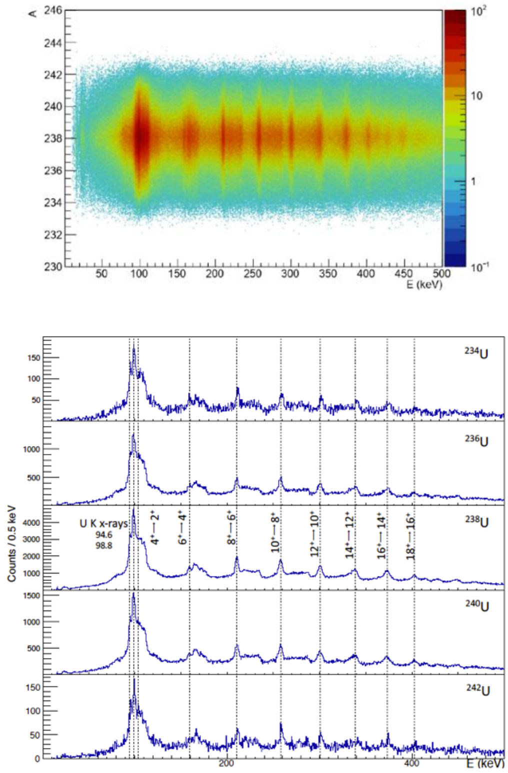


Figure 20 : Preliminary results MNT from the $^{238}U+^{238}U$ experiment at VAMOS. Top: mass vs. photon energy (x-rays and γs detected with AGATA) for uranium-like at 6.765 MeV/A - Bottom : : Photon spectra gated on even-A from 234 to 242. The energies of the measured uranium K x-rays as well as of the rotational band members of ^{238}U are indicated [8]

In particular, neutron-rich actinides and trans-fermium isotopes cannot be produced in complete fusion reactions due to the lack of sufficiently neutron rich projectile-target combinations. An alternative method to produce neutron-rich heavy systems has been proposed by Zagrebaev et al. [6, 7], with the employment of deep-inelastic collisions of heavy nuclei populating n-rich species by Multi-Nucleon Transfer (MNT). Reactions employing ^{238}U as reaction partner are expected to reach into close vicinity of the N=152 sub-shell closure.
The reaction $^{238}U+^{238}U$ was investigated in a recent experiment performed with the combination of the large-acceptance magnetic spectrometer VAMOS, the γ-ray detection array AGATA and the x-ray spectrometer ID-fix [8]. Figure 20 shows first, preliminary results for photon spectra, extracted by gating on even mass values around the elastic channel. More detailed analysis, providing possibly better mass resolution, might reveal the observation of few nucleon transfer reaction channels.
In a collaborative effort with our colleagues from IRFU Saclay (spokesperson B. Sulignano), IJCLab Orsay and IPHC Strasbourg, the MNT reaction $^{136}Xe+^{238}U$ is being investigated in a series of experiments at the (0-degree) gas-filled separator AGFA of the ATLAS facility of ANL, Lemont Il, U.S.A.

[1] D. Ackermann and C. Theisen, Phys. Scr. 92, (2017) 083002.
[2] Y. Oganessian and V. Utyonkov, Nucl. Phys. A 944, (2015) 62.

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[7] V. I. Zagrebaev, Y. T. Oganessian, M. G. Itkis, and W. Greiner, Phys. Rev. C 73, (2006) 031602.
[8] A. Utepov, Ph.D. thesis, GANIL/Université Caen Normandie (2023).

5. Shell closure and rp process studies in the vicinity of ^{78}Ni

Masses are key observable both for the understanding of the solar abundances and the evolution of the nuclear shell structure in exotic nuclei. With this experiment we aim to measure masses in one of the key regions of the nuclear chart, namely the vicinity of the doubly magic nucleus ^{78}Ni.

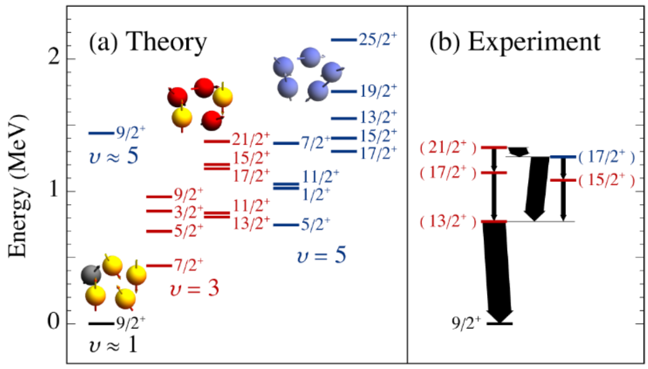
The r-process residual solar abundances are characterized by a three peak structure corresponding to the closed neutron shells of N = 50, 82 and 126. Recent observations of Sr in the kilonova spectrum in the aftermath of GW170817 re-ignited the discussion of the origin of the first r-process peak elements. Precise mass values of exotic nuclei in the vicinity of the closed neutron shell N = 50 are of particular interest for the modelling of the first r-process peak as they affect the calculations of (n, γ), (α, n) reaction rates. Variations in the order of hundreds keV in mass measurements can lead to uncertainties in the calculation of reaction rates of up to an order of magnitude.

Theoretical Shell Model calculations predict a progressive reduction of the Z = 28 shell closure by about 1.2 MeV from ^{68}Ni to ^{78}Ni and an increase of the N = 50 shell closure in ^{78}Ni, thus leading to a preservation of its doubly magic character. These predictions are in agreement with the recent observation at Riken of the 2^+ state at 2.7 MeV. Nevertheless, a second low lying 2^+ state conform with the notion of competing spherical and deformed configurations has been also reported in the same work, and therefore the question of shape coexistence in the region of ^{78}Ni is still open. The mass is a crucial observable that needs to be measured as it can provide an experimental estimation of the gaps and clarify the possible residual interaction into play. From a previous experiment performed in 2017 at IGISOL, the mass of neutron rich ^{74,75}Ni isotopes has been measured and we aim here to go forward into the neutron rich side of the nuclear chart and to measure the mass of the ^{76,77}Ni, hoping to confirm the doubly magic character of ^{78}Ni and to shine light on the presence of shape coexistence in this region.

The first part of the experiment took part in October 2022 where we successfully used for the first time the newly commissioned MR-TOF MS for mass measurements. The second part of the experiment will be held in June 2023 and the MR-TOF MS will be used as a beam purifier in order to remove all contaminants to achieve high precision mass measurements of ^{76,77}Ni with the JYFLTRAP mass spectrometer.

6. Seniority isomers and particle–hole conjugation

Nuclear forces between the nucleons in an atomic nucleus favour the formation of pairs of neutrons or pairs of protons with anti-parallel spins coupled to angular momentum zero (J = 0). This pairing property implies a symmetry with an associated quantum number called seniority (denoted as υ), the number of nucleons not in J = 0 pairs. The concepts of pairing and seniority are particularly useful to understand the structure of semi-magic nuclei, which have either neutrons or protons in the valence shell. Specifically, the symmetry associated with seniority can give rise to nuclear isomers, that is, excited states of the nucleus that are 'reluctant' to decay to lower-lying levels. Seniority conservation can be explained on the basis of a general mechanism, namely a geometric phase associated with particle–hole conjugation, which becomes gauge invariant and therefore observable if the particle–hole conjugation transforms quantum-mechanical states into themselves. This happens if the neutrons or protons half-fill the valence shell. The most pronounced effects of seniority symmetry are therefore expected to occur in mid-shell nuclei.



One such mid-shell nucleus is ^{213}Pb, which in a simple shell-model picture can be described as five neutrons in the $_{1g9/2}$ orbital. The transition probabilities of excited states of ^{213}Pb have been measured at GSI by exploiting the existence of a $21/2^+$ seniority isomer, which was populated in a fragmentation reaction. Results are graphically represented in the figure. On the left are shown all predicted levels, with their assigned seniority υ (black, red or blue for υ = 1, 3 or 5). On the right the observed levels are plotted together with the measured E2 transition probabilities, proportional to the thickness of the arrows. The seniority scheme predicts vanishing E2 transitions between ΔJ = 2 levels with the same seniority (Δυ = 0, straight arrows) and strong ones between Δυ = 2 levels (tilted arrows), in qualitative agreement with the observed strengths. Collaboration: FRS–RISING setup at GSI, Darmstadt, Germany.

[1] J.J. Valiente-Dobón et al., Phys. Lett. B **816** (2021) 136183.

III. Fission and reactions

The FiRe group studies “macroscopic” properties of atomic nuclei that manifest themselves in dissipative reactions and decay processes involving many collective and microscopic degrees of freedom, far beyond the level of single particle excitations: from fusion, deep-inelastic and quasi-fission reactions near the Coulomb barrier to the participant-spectator regime, from fission and particle evaporation to multifragmentation and vaporization. At GANIL most experimental activity in this area is concentrated around the VAMOS++ spectrometer which is revolutionising fission studies, while the multi-detector INDRA, and, most recently, its coupling with the FAZIA array, is at the forefront of research into the nuclear matter equation of state and nuclear symmetry energy.

1. Fission studies at VAMOS

During the fission process, a heavy nucleus splits into lighter fragments due to the competition between the attractive strong nuclear force and electrostatic repulsion. This results in a very large distribution of produced nuclei. The nuclear fission process is driven by a complex interplay between the dynamical evolution of a quantum system composed of a large number of nucleons and the intrinsic nuclear structure of the system at extreme deformations as well as heat flows. The balance between these various aspects decides the characteristics of the emerging fragments. Nevertheless, despite almost 80 years of intense research, fission is still far from being fully understood, and theoretical and experimental knowledge remains incomplete.
Innovative experiments are conducted to widen our knowledge of fission, aiming notably at a complete identification and characterization of the fission fragments and the study of unstable fissioning systems. In particular, pre- and post-neutron evaporation isotopic fission yields are good candidates to investigate the mechanism responsible for the fission fragment production. The experimental access to this production probability (fission yields) requires the measurement of the full distribution of the fission fragments, which is experimentally very challenging.
At GANIL, the inverse kinematics technique is used to produced in-flight fission. Accelerated heavy fissioning systems are excited through nuclear reactions, in particular multi-nucleon transfer reactions, and the produced fission fragments are emitted at forward angles. The VAMOS large-acceptance magnetic spectrometer is used to identify, in mass and atomic number, the full distribution of fragments while a silicon telescope is used to detect the residual recoil emitted in the transfer reaction.
The results for 2022 of the fission@VAMOS program are described below, and cover both studies of actinides and pre-actinides populated in inverse kinematics.

Fission of pre-actinides: ^{178}Hg and asymmetric fission of neutron-deficient pre-actinides

While the importance of structural effects in the nascent fragments is well established in the (trans-)actinide region, the observation of asymmetric fission in several neutron-deficient pre-actinides can be explained by various mechanisms. To deepen our insight into that puzzle, an innovative approach based on inverse kinematics and an enhanced version of the VAMOS++ heavy-ion spectrometer was implemented at GANIL. Fission of ^{178}Hg was induced by fusion of ^{124}Xe and ^{54}Fe. The two fragments were detected in coincidence using VAMOS++ supplemented with a new SEcond Detection arm. For the first time in the pre-actinide region, we achieved access to the pre-neutron mass and total kinetic energy distributions and the simultaneous isotopic identification of one the fission fragments. An article [1] has been published describing the experimental approach, and discussing the pre-neutron observables in the context of an extended asymmetric-fission island located southwest of ^{208}Pb. A comparison with different models was performed, and the lack of agreement either with the data or among the models themselves demonstrates the importance of this new asymmetric-fission island for elaborating the nature of the driving effects in fission.

[1] A. Jinghan et al., Phys. Rev. C **106**, 044607 (2022)

Fission studies of actinides : Experimental evidence of the effect of nuclear shells on fission dissipation and time

In our recent letter [2] we present the first experimental determination of the dissipation energy in fission as a function of the fragment split, for three different fissioning systems. The amount of dissipation was obtained through the measurement of the relative production of fragments with even and odd atomic numbers with respect to different initial fission energies. The results reveal a clear effect of particular nuclear shells on the dissipation and fission dynamics. In addition, the relative production of fragments with even and odd atomic numbers appears as a potential contributor to the long-standing problem of the time scale in fission.

[2] D. Ramos et al. Phys. Rev. C **107**, L021601 (2023)

2. Nuclear EoS & symmetry energy studies with INDRA-VAMOS & INDRA-FAZIA

Experimental study of the ^{40,48}Ca+^{40,48}Ca reactions at 35 MeV/nucleon

In our publication [3] we investigated ^{40,48}Ca+^{40,48}Ca peripheral and semi-peripheral reactions at 35 MeV/nucleon. Data were obtained using the unique coupling of the VAMOS high acceptance spectrometer and the INDRA charged particle multidetector. The spectrometer allowed high-resolution measurement of charge, mass, and velocity of the cold projectile-like fragment (PLF), while the INDRA detector recorded coincident charged particles with nearly 4π acceptance. The measured isotopic composition of the PLF identified in VAMOS and the average light charged particle (LCP) multiplicities are promising observables to study the isospin diffusion. The detection of the PLF in coincidence with LCP allows the reconstruction of the mass, charge, and excitation energy of the associated initial quasi-projectile

nuclei (QP), as well as the extraction of apparent temperatures.
The data analysis, including a reconstruction of the primary QP, is consistent with a strong surface contribution to the symmetry energy term in finite nuclei. The reconstruction of the primary source is therefore mandatory for the study of the symmetry energy term for such reactions.

[3] Q. Fable Phys. Rev. C 106, 024605 (2022)

First results from the INDRA-FAZIA apparatus: isospin diffussion in ^{58,64}Ni+^{58,64}Ni reactions at 32 and 52 MeV/nucleon

The first INDRA-FAZIA experiment, carried out in April-May 2019, aimed to study the dynamical processes of isospin transport. The four reactions ^{64,58}Ni+^{64,58}Ni, at two beam energies, 32MeV/nucleon and 52MeV/nucleon have been investigated, and a signature of isospin diffusion has been obtained by comparing the results of the two asymmetric systems with both the neutron rich and neutron deficient symmetric systems, exploiting the isospin transport ratio technique.
More specifically, the main focus was on the binary output of peripheral to semi-central collisions. Both the neutron content of the quasi-projectile residue and that of the light ejectiles coming from the quasi-projectile evaporation have been exploited to probe the dynamical process of isospin diffusion between projectile and target in asymmetric systems, obtaining coherent indications of the evolution towards isospin equilibration. A stronger relaxation of the original isospin imbalance is achieved for the reaction at the lower bombarding energy: such a finding can be qualitatively justified in terms of the longer timescales for the lower energy case, allowing for a more effective diffusion process. This work has been published in [4].

Lately, the analysis has been extended to the quasi-projectile dynamical breakup exit channel, using the neutron-to-proton ratio of the quasi-projectile reconstructed from the two breakup fragments as isospin observable. We found evidence that the breakup channel generally shows a more pronounced trend towards isospin equilibration with respect to the evaporation channel for the same asymmetric reaction, for both beam energies. We have proposed an interpretation of this new observation based on a longer projectile-target contact time in the breakup case, which could in turn lead to a more pronounced deformation of the interacting system, subsequently inherited by the quasi-projectile and leading to its fission. The contact time information has been extracted from AMD+GEMINI++ simulations of the studied systems and the model calculations seem to support our hypothesis. A second manuscript about these latter results has been recently submitted to Physical Review C.

[4] C. Ciampi et al., Phys. Rev. C 106, 024603 (2022)

INDRA electronics upgrade

The INDRA charged particle multidetector array has been in use since 1993 for the study of nuclear reaction dynamics and the equation of state of nuclear matter. Its 640 detectors grouped into 336 detection modules or ‘telescopes' were originally equipped with custom made electronics based on the VXI standard which was revolutionary for the time thanks to its high degree of integration. After the E789 experiment in 2019 coupling INDRA with FAZIA for the first time it was clear that a change had to be made, not only for the DAQ electronics but also for the low/high voltage supplies. In 2020, at the height of the COVID pandemic, GANIL received 900k€ funding from the Région Normandie for the project GIF (GANIL Innovation Future), of which a third was earmarked for the INDRA electronics upgrade. A beam test in early 2021 validated a DAQ solution based on commercial VME modules developed by Mesytec GmbH & Co. The MDPP-32 is a 32 channel digital pulse processor whose FPGA firmware can be selected depending on the kind of detectors it is connected to: one firmware for charge-sensitive preamplifiers is used for the silicon and ionization chamber detectors of INDRA (the MDPP in this case functions like an ADC), while a different firmware is used for the CsI detectors, providing short and long integration gate signals in order to implement pulse-shape discrimination for identification of light charged particles. Along with the MVLC controller/trigger module, the MDPP modules allow to implement in a single VME crate the full DAQ electronics for INDRA, which used to occupy 4 full bays. At the same time, the low & high voltage supplies have been replaced with a solution from CAEN based on the SY4527 modular setup. All of the power supply and signal cables outside of the vacuum chamber were also replaced. The whole electronics are now housed inside 2 air-conditioned (closed) bays. The first beam test of the new INDRA electronics was the E818 experiment conducted in spring 2022, the second coupling of the INDRA and FAZIA arrays. Preliminary data from this experiment have already shown that with this new digital electronics it is possible to achieve isotopic identification for elements up to Neon (Z=10) in the Si-CsI telescopes of INDRA, whereas previously isotopic identification was only possible for light (Z<5) nuclei using pulse-shape discrimination of the CsI detector signal. This means that the electronics upgrade has not only extended the lifetime of the INDRA multidetector, but also extended the detection possibilities and therefore the physics which can be studied with INDRA in the future.

[5] J.D. Frankland, N. Le Neindre et al., Il Nuovo Cimento C45 (2022) 1

E818: Extending our knowledge of warm nuclear matter in the low density region

Light nuclear clusters such as Hydrogen and Helium isotopes play an important role in warm and low-density nuclear matter that can be found in core-collapse supernovae (CCSN). Clustering affects the CCSN explosion dynamics because it influences the weak interaction rates, and, as a consequence, the dynamic processes that determine the evolution of these violent events.
However, light clusters properties are modified in the matter. Light nuclei in-medium effects have been computed from microscopic quantum-statistical approaches, but the calculations are limited to a relatively small domain of temperatures and densities. A possible phenomenological

solution is the introduction of a density dependent binding energy shift, which should be fixed with the help of experimental constraints from Heavy Ion Collisions, where such clusters are copiously produced, though in a transient configuration.

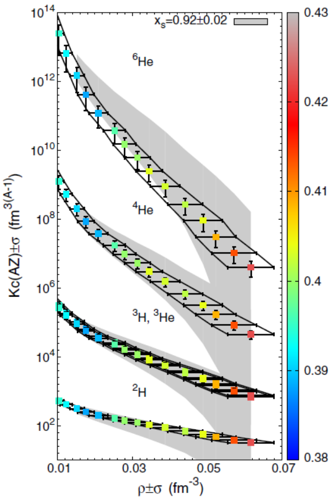


Figure 21 : system 32 A.MeV $^{136}Xe+^{124}Sn$ (INDRA), the equilibrium constants as a function of density. The grey bands are the equilibrium constants from a calculation where we consider homogeneous matter with five light clusters and considering cluster couplings in the range of x_s=0.92 +/-0.02. The color code represents the global proton fraction (Phys. Rev. Lett 125, 012701 (2020)).

A useful observable to pin down the in-medium effects is given by the measurement of chemical constants (K_C) recently extracted from Xe+Sn at 32 A.MeV INDRA data (Figure 21). K_C measurements concern light particles emitted at mid-rapidity (gas of nucleons and clusters in equilibrium). A fit of those data was performed within different versions of the Relativistic Mean Field model. Interestingly, once the in-medium coupling was fixed to reproduce the experimental data (x_s of figure), the different models were shown to produce compatible predictions concerning the location of the Mott dissolution density of the clusters in the dense medium. However, we are still far from a full understanding of the in-medium effects and further efforts are needed.

Concerning E818, K_C will be extracted from total disassembly of the excited projectile data from Ar+Ni and Ni+Ni at 74 A.MeV reactions. The new data sets will complete the one already published using different reaction mechanisms and will extend the analysis to heavier clusters thanks to the improved isotopic resolution of FAZIA and to wider density and temperature ranges as compared to the figure.

Analysis of E818 is in progress (calibration): Ar+Ni data will be available in September 2023 and Ni+Ni data in 2024.

3. Direct reactions in the unified framework of the Gamow shell model

The unified theory of nuclear structure and reactions is essential for the comprehensive description of radioactive nuclei in which bound states, resonances and scattering many-body states are treated equally and within a single theoretical framework. Such a framework has been proposed with the Gamow shell model (GSM), which provides the open quantum system formulation of nuclear shell model [1]. GSM offers the most general treatment of couplings between discrete and scattering states, as it makes use of Slater determinants defined in the Berggren ensemble of single-particle states. For the description of scattering properties and nuclear reactions, it is convenient to formulate GSM in the representation of reaction channels (GSM-CC) [1]. GSM-CC has been applied recently for the description of radiative capture reactions: $^8Li(n,\gamma)^9Li$ [2], $^8B(p,\gamma)^9C$ [3]. The $^8Li(n,\gamma)^9Li$ reaction plays a critical role in several reaction chains leading to the nucleosynthesis of A>12 nuclei. In low metallicity supermassive stars, the hot pp chain can serve as an alternative way to produce the CNO nuclei. In the astrophysical environment of high temperature, the proton capture of ^8B can be faster than its beta decay, thus reaction $^8B(p,\gamma)^9C$ plays an important role in the hot pp chain.

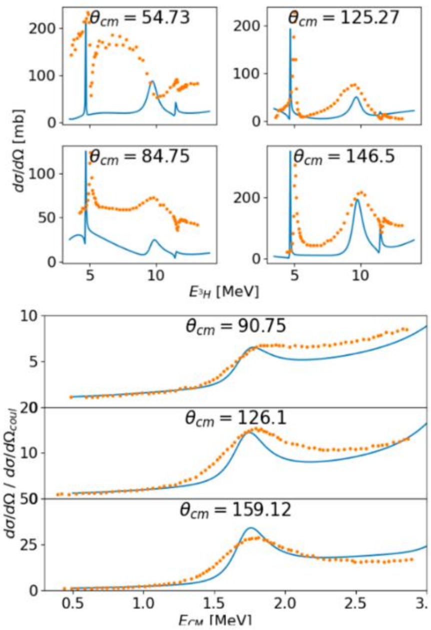


Figure 22 : GSM-CC elastic differential cross sections of the reactions $^4He(^3H,^3H)^4He$ (top) and $^6Li(p,p)^6Li$ (bottom) are compared with experimental data. ^3H bombarding energy is given in the laboratory frame, whereas proton bombarding energy is given in the center-of-mass frame.

Spectra and elastic cross-section for a multi-nucleon projectiles have been studied for 4He(3H,3H)4He, 4He(3He,3He)4He [4], and 40Ca(d,p)41Ca [5] reactions in the coupled channel framework with multi-mass partition reaction channels. The calculations have demonstrated that the spectra and low-energy direct reactions can be studied successfully also in heavier nuclei using the unified framework of the GSM-CC.

[1] N. Michel, M. Płoszajczak, Gamow Shell Model, The Unified Theory of Nuclear Structure and Reactions, Lecture Notes in Physics, Vol. 983, (Springer 2021)
[2] G.X. Dong et al., Phys. Rev. C 105, 064608 (2022)
[3] G.X. Dong et al., arXiv:2212.13172
[4] J.P. Linares Fernandez et al., Acta Phys. Pol. B Proc. Suppl. 16, 4-A22 (2023)
[5] A. Mercenne et al., Phys. Rev. C 107, L011603 (2023)

IV. Fundamental interactions and Dark Sectors

Despite its successes, the Standard Model of particle physics (SM) falls short in explaining several vital aspects of the universe, which is motivating the search for New Physics (NP). One of the SM's major shortcomings is its inability to account for the presence of Dark Matter and Dark Energy, which together make up approximately 95% of the observed universe. The remaining 5% is composed of particles of "normal" matter, whose properties are described by the SM. However, even for these 5%, not everything is fully understood. The SM fails to explain the creation of a matter-antimatter asymmetry and the neutrino masses. Moreover, the SM also lacks an explanation of the gravitational force, making a unified theory of forces necessary. These significant questions require a range of high-energy experiments or precision experiments at particle accelerators or astronomic observatories. The FINDS group at GANIL is conducting precision experiments with radioactive ion beams to address some of these issues. For example, the MORA experiment is searching for a sign of CP violation in nuclear beta decay, which could explain the matter-antimatter imbalance in the Universe. Additionally, the New Jedi and ^{6}He Dark decay experiments are investigating a potential portal to the dark sectors. The measurement of the Ft-values of 0+ to 0+ beta emitters is another approach that contributes to testing the unitarity of the first CKM matrix row via Vud term determination. Deviation from unitarity could indicate the presence of NP, such as a fourth family of quarks or a charged Higgs boson.

The group is also contributing and bringing support to experiments done at GANIL, especially by LPC Caen and LP2IB, to test the SM. During the past three years (2021-2023), the bSTILED experiment, led by O. Naviliat and X. Fléchard, has been undertaking a precise measurement of the beta spectrum shape of ^{6}He. Such a measurement is sensitive to the existence of tensor currents in nuclear beta decay, which could originate from LeptoQuark exchange (LQ). LQs are hypothetical particles that appear in many models of physics beyond the SM. With a goal of sensitivity on the Fierz interference term of a few 10^{-4}, the bSTILED experiment will be able to set limits of the order of a few TeV on the existence of LQs, therefore complementing the measurements done at LHC. The data taking of the bSTILED experiment was done in two steps: one in 2021 collecting a low energy (~10 keV) ^{6}He beam from SPIRAL 1 in the LIRAT beam line, and the second and latest one collecting a high energy (60 MeV/n) ^{6}He beam directly into the YAP scintillator. The first experiment is being analysed and has permitted a remeasurement of the ^{6}He half life with higher accuracy [arXiv:2207.06071].

1. The New JEDI project : Search for a light Dark Boson as a new Force Career

Our universe is mainly composed of dark energy and dark matter, at estimated percentages of 69 % and 26%, respectively. The Standard Model of particle physics fails to describe these hidden sectors of our universe. To date, the real composition of the classical Dark Sectors of our Universe remains a mystery. We still do not have a clear answer to the question "of what is Dark Matter composed?".

In recent decades, an alternative approach to our current understanding of the Universe has been considered through a new theory: The Dark Sectors theory. It is based on the idea that we may also consider an indirect interaction between Ordinary Matter (including stars, planets, interstellar gases…) and Dark Sectors of the Universe. In this theoretical framework, Dark Sectors are defined as hypothetical sets of light particles that interact with ordinary matter with an amplitude a few orders of magnitude less that the electromagnetic interaction, via portals (bosons). Thus, the idea is to verify the existence of a new particle (named Dark Boson) that will act as the messenger of a new fifth force of nature.

Our investigation is further motivated by the recent claim of an anomaly observed in the electron-positron pair decays of an excited state in ^{8}Be, during an experiment of the Hungarian ATOMKI group, which may be interpreted as the signature of a hypothetical dark boson (named X17). However, uncertainties linked to the structure of ^{8}Be and new hypotheses to explain the experimental results are currently debated. The ATOMKI group confirmed latter on the existence of this anomaly on other nuclei such as ^{4}He and ^{12}C. The quantum nature of this hypothetical boson is also unclear at the moment. Independent measurements are needed.
The New JEDI (New Judicious Experiments for Dark sector Investigations) project has been initiated in 2017. It aims to develop a collaboration mainly between the GANIL, IJCLab, University of Minnesota, INFN-LN, NPI, iThemba LABS, IAP, TRIUMP, IP2I and ULB research teams concerning the study of a Dark Boson in the MeV range, on a wider scale. For that purpose, a prototype was defined and built up based on test experiments carried out at the ARAMIS-SCALP facility (Orsay, France) from 2018 to 2020, as well as some GEANT 3 simulations. There is a very dense experimental program. We commissioned successfully this prototype in June 2021 at the tandetron facility located at Rez in Czech Republic.
We realized afterwards some mechanical and detection modifications to complete the first New JEDI setup. The first common scientific objective is to check the existence of the ^{8}Be anomaly. The first experiment on ^{8}Be was realized successfully from June to July 2022 at the ANDROMEDE facility located at Orsay. A PhD student from GANIL is in charge of the fine analysis of these data since December 2022.

Additional details about the project (collaboration list, events, oral contributions, publications…) is available at the New JEDI webpage: https://beyhan-bastin.cnrs.fr/new-jedi/

- Related publication: Lecture Notes on "Investigation of a light Dark Boson existence: The New JEDI project" from B. Bastin, J. Kiener, I. Deloncle, A. Coc, Maxim Pospelov et al., EPJ Web Conf. 275 (2023) 6.

2. Is there a dark decay of neutrons in ^{6}He ?

The existing discrepancy between neutron lifetime measurements in bottle-type and in-flight experiments has been interpreted as a possible sign of the neutron decaying to dark particles [1]. Such a decay could explain the existing discrepancy of 4 standard deviations between the two different methods. If such a neutron decay is possible, then it could also occur in nuclei with sufficiently low neutron binding energy [2]. The ^{6}He nucleus has a two-neutron separation energy lower than the one for a single neutron. The observation of a free neutron from ^{6}He decay would then be a unique signature for dark neutron decay. We report on the results of an experiment performed at GANIL using the neutron detector TETRA and the high intensity and high purity beam of 6He+ of SPIRAL1. The experiment focused on the observation of this hypothesized decay channel, allowing for the first time to set an upper limit on its branching ratio and thus helping clarify the so-called "neutron lifetime anomaly".
The total number of implanted ^{6}He during the experiment is $(1.21 \pm 0.06) \times 10^{13}$ with an average implanted rate at $(1.08 \pm 0.06) \times 10^{8}$ pps within the three seconds of implantation.
The Figure 1 shows the resulting branching ratio values for the dark decay with a 95% confidence level as function of deposited energy thresholds. The value at 150 keV shows a clear sign of Brehmsstrahlung detection in TETRA counters. By taking values for thresholds with energy ≥ 300 keV we can assess an upper limit for this dark decay mode at $Br(\chi) \leq 3.5 \times 10^{-10}$ with a 95% confidence level. This preliminary result tends to exclude the neutron dark decay to explain the 1% neutron lifetime puzzle.

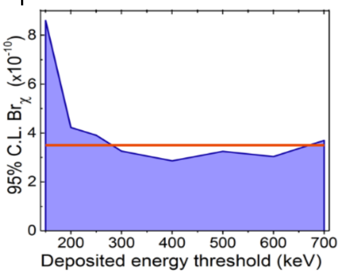


Figure 23 : Maximized branching ratio value for the dark decay with a 95% confidence limit.

[1] B. Fornal and B. Grinstein. Phys. Rev. Lett., 120(191801), 2018.
[2] M. Pfützner and K. Riisager, Phys. Rev. C, 97(042501(R)), 2018.

3. MORA

The Matter's Origin from RadioActivity experiment (MORA) searches for a signature of CP violation in the nuclear beta decay of radioactive nuclei. A large CP violation is actively searched for in high- and low-energy experiments to explain the matter–antimatter imbalance observed in the universe. In nuclear beta decay, the so-called D correlation violates time reversal, and via the CPT theorem, the CP symmetry. MORA aims at achieving a precision measurement of the D correlation in the decays of ^{23}Mg and ^{39}Ca, thanks to a unique combination of ion trapping and laser polarization techniques. A sensitivity of the order of 10^{-4} to a non-zero D correlation will be the aim of first experiments at Jyväskylä, competing with the best experiment realized so far, in neutron decay. Later, a sensitivity of the order of 10^{-5} should be attained with the intense beams of SPIRAL 1 at GANIL, purified and bunched at DESIR with state-of-the-art instrumentation (2027-…).
The MORA apparatus, whose detector and trapping setup is shown in Fig. 1, was installed in the IGISOL hall in Jyväskylä between November 2021 and January 2022. An intense period of offline activity followed, with 3 test beam times in February, May and November 2022. These short beam times permitted to commission the entire device, gradually improving performance. Finally, a capture efficiency of 10% could be achieved for ions delivered from the minibuncher of IGISOL to the MORA trap. A trapping half-life of greater than 5 s could be achieved off-line, while the online data suggest that even longer half-lives could be obtained when using helium cooling in the trap. This exceeds by more than an order of magnitude the trapping half-lives measured with LPCTrap, the ancestor of the MORA trap. Today, the biggest challenge is to reduce the stable $^{23}Na+$ contamination of the beam, which limits the number of $^{23}Mg+$ ions accumulated per bunch in the minibuncher to a few hundred at most. With a laser power of about 150 mW, the proof of principle of the polarization technique in the trap was attempted. Data analysis is complicated due to low statistics and unfavorable signal-to-noise ratio. R&D will be conducted in the course of 2023 to eliminate surface ionized Na+ contamination, before resuming data accumulation for the polarization proof-of-principle and the precision D correlation measurement.

The MORA experiment is supported by the French Agence Nationale de la Recherche (ANR) and Région Normandie. The MORA collaboration consists of GANIL, LPC Caen, IJCLab, JYFL-ACCLAB, KU Leuven, CERN-ISOLDE and IFIC, as partner laboratories.

Figure 24 : MORA detection setup surrounding the ion trap.

Latest publications:

•P. Delahaye, E. Liénard, I. Moore et al., The MORA project, Hyperfine Interact (2019) 240: 63. https://doi.org/10.1007/s10751-019-1611-x
•P. Delahaye, Analytical model of an ion cloud cooled by collisions, Eur. Phys. J. A (2019) 55: 83. https://doi.org/10.1140/epja/i2019-12740-4
•P. Delahaye, G. Ban, M. Benali et al., The open LPC trap for precision measurements in beta decay, Eur. Phys. J. A (2019) 55: 101. https://doi.org/10.1140/epja/i2019-12777-3
•M. Benali, G. Quemener, P. Delahaye et al., Geometry optimisation of a transparent axisymmetric ion trap for the MORA project, Eur. Phys. J. A (2020) 56: 163, https://doi.org/10.1140/epja/s10050-020-00168-y
•N. Goyal, S. Daumas-Tschopp, F. De Oliveira Santos, P. Delahaye, Xavier Fléchard, J. M. Fontbonne, E. Lienard, Luis Miguel Motilla, J. Perronnel, G. Quemener, A. Singh, Detection of recoil ion in the beta decay of laser oriented trapped radioactive isotopes for the MORA Project, INPC 2022 conference proceedings, in revision.
•In preparation: the MORA collaboration, Current Status of the MORA experiment

4. Study of Superallowed 0+ to 0+ Fermi β decays

High-precision measurements of probabilities of superallowed 0^+ to 0^+ Fermi β decays provide demanding and fundamental tests of the standard model description of electroweak interactions. The probability of β decays is associated to the ft value, which is derived from three experimental quantities: the maximum energy release in the decay, the branching ratio and the half-life of the initial state. Following a modification of the ft value by several isospin-symmetry breaking and radiative corrections, the resulting Ft value is used to test the validity of the conserved vector current (CVC) hypothesis, for which the Ft value is expected to be constant for all 0^+ to 0^+ decays independent of the nucleus studied. This CVC test via nuclear physics experiments is much more sensitive than any particle physics tests to date [1] and is currently validated to the $5{\cdot}10^{-4}$ level. Corrected Ft values play an important role in the unitarity test of the Cabibbo-Kobayashi-Maskawa (CKM) matrix through the determination of its leading term Vud. The value of Vud obtained from superallowed 0^+ to 0^+ nuclear β decays is by far the most precise and since Vud plays by far the most dominant role in the unitarity test, its precision must be improved by additional precise measurements.

Among them, heavier and more exotic superallowed Fermi β emitters are expected to be accessible at the DESIR facility of GANIL-SPIRAL2, which should be operational in 2027. They will be produced either at the SPIRAL2-S^3 facility or at the existing SPIRAL1 ISOL facility following the technical developments undergoing within the TULIPE ANR project.

A number of less exotic superallowed Fermi β emitters such as ^{18}Ne and ^{34}Ar are readily available at the SPIRAL1 facility where high-precision lifetime measurements have already been performed [2-6]. Other could be produced at the LISE in–flight fragmentation facility such as ^{10}C and ^{42}Ti, following earlier studies of the superallowed Fermi β decays of ^{38}Ca and ^{30}S [7,8].

^{42}Ti is particularly interesting since its Ft value presents the largest isospin-symmetry breaking correction among all Tz = -1 superallowed Fermi β emitters, which evaluation appears in addition to be very sensitive to the used theoretical framework. Being refractory and short-lived (T1/2~200 ms), it cannot be easily produced at ISOL facilities worldwide, rendering the LISE facility a unique place where to study its superallowed 0^+ to 0^+ Fermi β decay. However, precise lifetime and branching ratio measurements require intense and pure radioactive beams. In order to evaluate the feasibility of such a study, the momentum distribution of n-deficient Sulfur isotopes produced in the fragmentation of a ^{36}S stable beam has been measured at LISE, in order to benchmark the LISE++ simulations performed to evaluated the ^{42}Ti beam characteristics following the fragmentation of a ^{46}Ti stable beam.

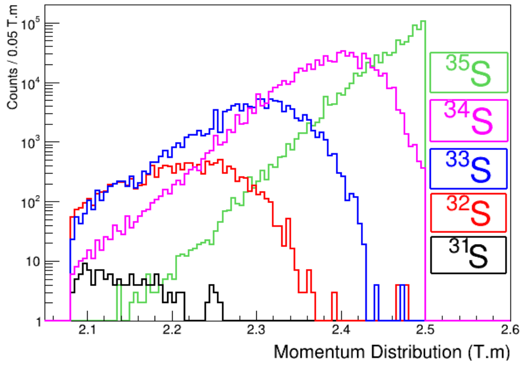


Figure 25 : Momentum distribution scans of n-deficient Sulphur isotopes produced in the fragmentation of a ^{36}S stable beam at LISE.

[1] J.C. Hardy and I.S. Towner, Phys. Rev. C 91, 025501 (2015)
[2] C. Fontbonne et al., Physical Review C 96, 065501 (2017)
[3] J. Grinyer et al., Physical Review C 92 045503 (2015)
[4] J. Grinyer, et al., Physical Review C 91 032501(R) (2015)
[5] G. F. Grinyer et al. Nuclear Instruments and Methods in Physics Research Section A741 18 (2014)
[6] P. Ujić et al., Physical Review Letters 110, 032501 (2013)
[7] B. Blank The European Physical Journal A 51 (2015) 8
[8] e691-2017 experiment, B. Blank et al., “Precision measurement of the beta-decay and branching ratios of 30S”

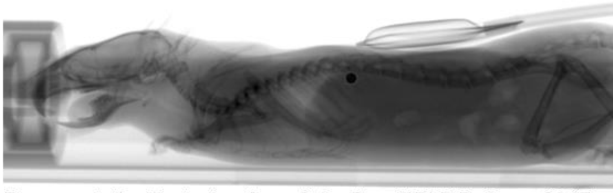
V. Dosimetry, applications and nuclear data

1. Radiotherapy

Respiratory gating in preclinical radiotherapy

Almost 382 000 new cases of cancer were diagnosed in France in 2018 and about half of the patients received a radiotherapy treatment. In this context, the reduction of the side effects and the improvement of the quality of life after the treatments became major issues in research against cancer. Among the areas of research developed at GANIL to develop new treatment modalities, one concerns radiobiology dosimetry to improve the quantification of *in vitro* and *in vivo* experiments.

Two projects were previously performed in the field of external beam radiotherapy at the preclinical scale: preclinical dosimetry based on scintillating fibers and respiratory gating of mobile targets, such as lung tumors.

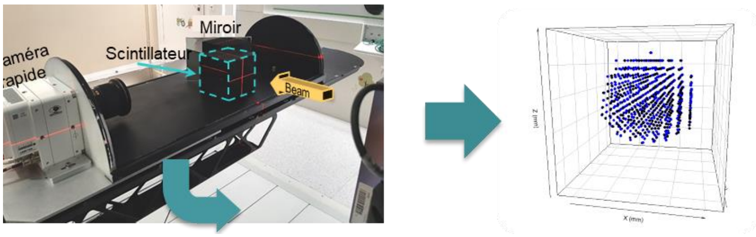


Representative illustration from C. Le Deroff PhD Defense 2017

The Precision X-Ray Company, which develops and sells preclinical irradiators, contacted GANIL to integrate the respiratory gating system developed in collaboration with the CYCERON biology and imaging platform. A Non Disclosure Agreement was signed in November 2022 between GANIL, CYCERON and Precision X-Ray to communicate technical information allowing a possible industrial transfer. This agreement may lead to scientific collaboration on the in vivo evaluation of the respiratory gating system.

Plastic scintillator based dosimetry in proton therapy

A research project was funded by the Normandie Region (RIN PMRT) to extend the use of proton therapy, in particular in the case of treatments requiring small irradiation fields ($< 3\times 3$ cm²), where innovative dosimetry tools are highly desired. In this frame, a new dosimetry system based on a $10 \times 10 \times 10$ cm³ plastic scintillator and an ultra-fast CMOS camera (more than 1000 images per second) was developped. This system can be used for two kinds of dosimetry verifications. The first operating mode concerns the control of the characteristics (energy, position, delivered dose) of the beams delivered by the irradiation system relative to the planned beams characteristics. The second operating mode concerns the 3D reconstruction of the dose distribution produced by a treatment plan.



This project led to two Erasmus Mundus internships (2 students in 2020 and 2 students in 2021) and two M2 internships (in 2020 and 2022). These internships allowed the determination of the optical characteristics of the system and the evaluation of its performance for the control of beams characteristics.

The first measurements in proton beams performed at CYCLHAD provided very promising results for treatment control. These results were presented during the Colloque GANIL in septembre 2021 (https://ganil2021.sciencesconf.org/).

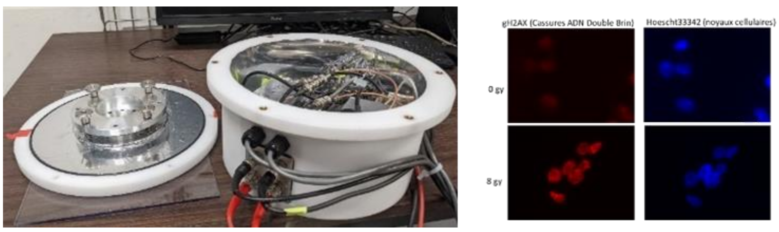
These first results allowed the conception and the realization of a new experimental prototype in 2022. A scientific report was also written for the Normandie region at the end of the RIN project in 2022.

Following this project, a PhD thesis was attributed to this project by the Graduate School and G. Daviau started his PhD thesis in October 2022.

New dosimetry system for alpha emitting radiopharmaceuticals

Targeted Alpha Therapy (TAT) is a very promising treatment modality based on the injection of a radiolabelled molecule (antibodies…) specifically targeting tumor cells. The development of new radiopharmaceuticals and new treatments requires early stage radiobiological assessments (*in vitro* and *in vivo*). Dosimetry methods and tools are much less developed in this field than in other radiotherapy domains, which limit the quantitative interpretation of biological effects.

In this frame, we developed a new dosimetry system for the *in vitro* evaluation of alpha-emitting radiopharmaceuticals. This system, based on silicon detectors and energy spectra measurements is adapted to cell-level evaluations. The development of an experimental prototype was funded in 2020 and 2021 by the ISOTOP 2020 program of the CNRS/MITI (Mission pour les Initiatives Transverses et Interdisciplinaires). A PhD thesis funding CEA/Normandy region was also obtained and A. Doudard started his thesis in September 2020.



New analysis methods were developed and tested at the Centre de Lutte contre le Cancer Baclesse by A. Doudard with ^{223}Ra (Xofigo). A paper was written in 2022 and **published in Medical Physics in January 2023.** (*A. Doudard et al.*

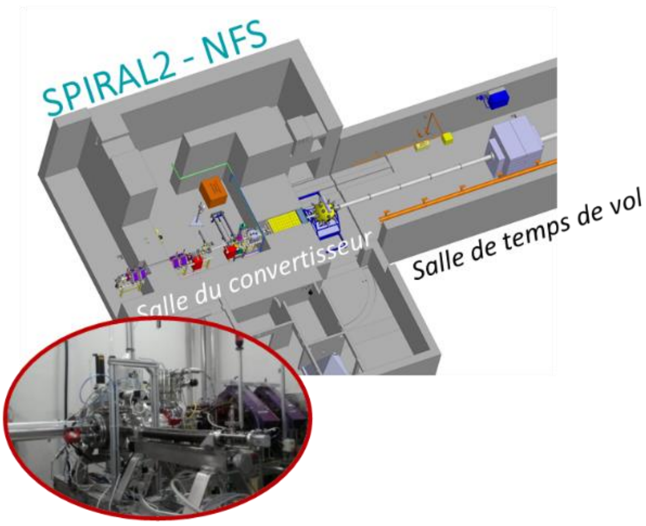
Application of a new spectral deconvolution method for in vitro dosimetry in assessment of targeted alpha therapy. Med. Phys. 2023; https://doi.org/10.1002/mp.16279.). A. Doudard also presented his results in the international conference "New Modalities in Cancer Imaging and Therapy » in October 2022 (https://www.cgo-workshop-vecto.fr/).

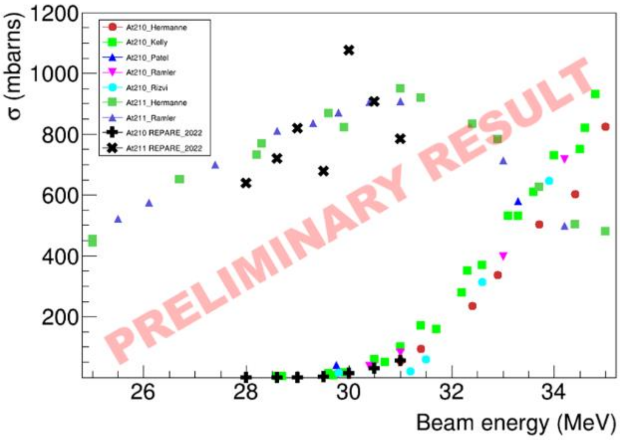
To continue this project we answered two funding calls (INSERM PCSI – 12/2021 and INCa SEQ-RTH 09/2022) to implement an interdisciplinary research program on the alpha-emitting ^{211}At in Caen, from Astatine production (at GANIL) to preclinical studies. Despite positive feedback, these projects were not selected, partly because of the risk related to ^{211}At production at GANIL. This weakness should be overcome in future projects with the first results of the REPARE ANR project including ^{211}At production cross section measurements.

Production of alpha-emitting radio-isotopes for medical applications

A significant part of the REPARE ANR project, led by GANIL, concerns the production of ^{211}At in the SPIRAL2 facility. In this context two deliverables are worked out: ^{210}At and ^{211}At production cross section measurements and the design and manufacturing of a high-power target station. This project is the starting point of a much larger research program, with the study of other medical alpha-emitting isotopes at GANIL and the implementation of interdisciplinary collaboration including all the local actors in radiochemistry, radiopharmacy, radiobiology, medicine…

Concerning the deliverables of REPARE, a **1st experiment was done in September 2022 at NFS**. Bismuth targets were irradiated with alpha particle beams at different energies. These irradiations intended to provide production cross section measurements for ^{210}At and ^{211}At between 28.6 and 31 MeV and optimize beam parameters for ^{211}At production. A preliminary analysis showed a good agreement between our measurements and existing cross section data.





In parallel the REPARE project is also progressing well on the technical part and a high power target station able to sustain up to 10 kW of beam power has been fully designed and mostly built in 2022. It will be tested in beam in July 2023 and hopefully followed by a first ^{211}At synthesis at NFS for a first shipment to ARRONAX.

2. NFS

Start and Commissioning

The Neutrons For Science (NFS) facility is dedicated to the study of neutron-induced reactions. The energy range covered (up to 40MeV) is of major interest for fundamental research and applications. These topics include the need for nuclear data for the next generation of reactors, fusion technology or medical applications.

NFS is composed of a pulsed neutron beam for in-flight measurements and irradiation stations for cross-section measurements and material studies. Continuous and quasi-mono-energetic spectra are available at NFS respectively produced by the interaction of deuteron beam on a thick Be converter and by the $^{7}Li(p,n)$ reaction on a thin Li converter. The flux at NFS is up to 2 orders of magnitude higher than those of other existing time-of-flight facilities in the 1 MeV to 40 MeV range. NFS will be a very powerful tool for physics and fundamental research as well as applications like the transmutation of nuclear waste, design of future fission and fusion reactors, nuclear medicine or test and development of new detectors.

The first proton beam was delivered in December 2019, the first neutrons created in December 2020. After a short characterization phase, the first experiments took place in September 2021.

X. Ledoux, J.C. Foy, J.E. Ducret, A.M. Frelin, D. Ramos, J. Mrazek, E. Simeckova, R. Behal, L. Caceres, V. Glagolev, B. Jacquot, A. Lemasson, J. Pancin, J. Piot, C. Stodel, M. Vandebrouck. First beams at Neutrons For Science. Eur. Phys. J. A. 2021; https://doi.org/10.1140/epja/s10050-021-00565-x

Experiments at NFS

Since the first beams at NFS, 14 experiments were accepted at the PAC between 2020 and 2022. Most of them were realized in 2021 and 2022 or are scheduled in 2023. Two experiments were delayed in 2024, mostly for reason of detectors disponibility.

NUM	Title	Spokesperson	UT Allocated
E799	Excitation functions of short-lived isotopes in proton induced reactions on ^{nat}Fe	E. Simeckova, NPI, Rez	5
E800	**LIONS - Light-Ion Production Studies with Medley at the NFS facility**	A.V. Prokofiev, Uppsala University	17
E802	GARIC - Gas pRoduction In Chromium by neutrons	A.V. Prokofiev, Uppsala University	21
E804	Measurement of fission cross sections standards relative to elastic n-p scattering at neutron energies 1- 40 MeV	D. Tarrio, Uppsala University	31
E807	Study of the (n,xn) and (n,f) reaction for U238	G. Bélier, CEA-DAM	12
E811	Study of the (n,alpha) reactions of interest for nuclear reactors - the SCALP Project	F. R. Lecolley, Ipc Caen	12
E814	**235U Fission fragment study with FALSTAFF at NFS**	D. Doré, CEA/IRFU/DPhN	11
E832	Deuteron activation of natMo - focus on short-lived products	E. Simeckova, NPI, Rez	4
E833	Pygmy dipole resonance in 140Ce using the (n,n'g) reaction at NFS	M. Vandebrouck, CEA Saclay / I. Manea, IJCLAB	23
E835	Measurement of the neutron induced activation in materials	V. Blieanu, CEA Saclay	3
E838	Shedding new light on the structure of 56Ni using (n,3n) reaction at NFS	E. Clément, Ganil	22
E856	Study of neutron induced reactions on 239Pu	G. Bélier, CEA-DAM	42
E858	GARROS - Gas production in iron by neutrons	A. Prokofiev, Uppsala University	22
E859	238U(n, 2ng) and (n, 3ng) reaction cross sections measurements	M. Kerveno, IPHC, Strasbourg	31

1 UT = 8h

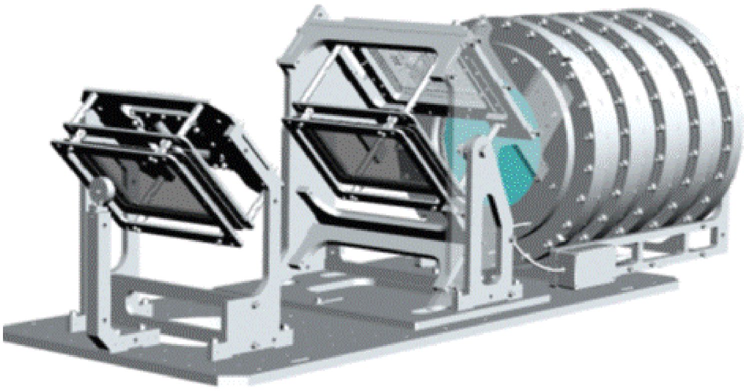
Performed in 2021

Performed in 2022

Scheduled in 2023

3. FALSTAFF

Although discovered more than 80 years ago, fission has not revealed all its secrets. A better description of this process and the improvement of theoretical models require new data. FALSTAFF was built for this purpose. Constraining data will be obtained by studying the correlation between neutron multiplicity and fragment characteristics (nuclear charge, mass and kinetic energy) for actinide neutron-induced fission in the MeV range. This experimental program is particularly rich because it gives access to different aspects of fission such as the fission deformation, the influence of the structure, dissipated energy and the energy sharing between the two fragments. In order to maintain good detection efficiency, the neutron multiplicity is not measured but determined from the difference between the masses of the fragments before and after evaporation. The initial mass of the fragments (before evaporation and determined from the measurement of their speed) and the final mass of the fragments (after evaporation and determined from the measurement of their energy). The charge of the fragments is identified thanks to the measurement of the energy loss. The main difficulty of the experiment comes from the high sensitivity of low-energy heavy fission fragments to energy dispersion in the different thicknesses crossed. The use of FALSTAFF at NFS further allows the study of fast neutron-induced fission by scanning a wide excitation energy range. A first experiment was carried out with a uranium 235 target and future experiments will follow. A second arm will complete the experimental device in order to detect the two fission fragments in coincidence.

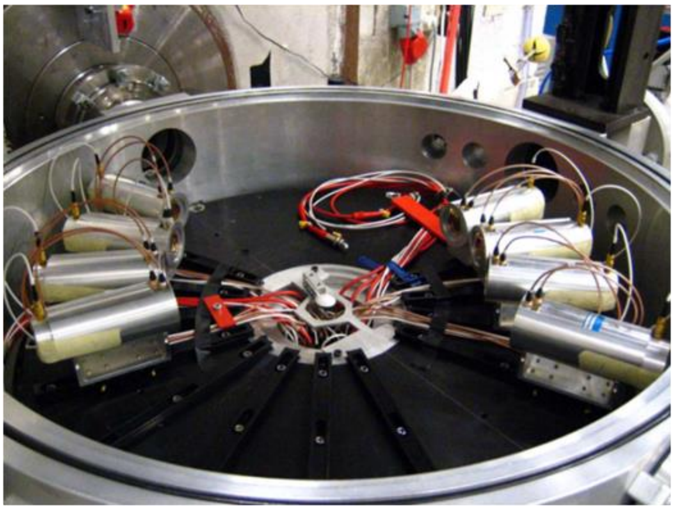


4. MEDLEY

The MEDLEY program is devoted to the measurement of double differential cross-section of light charged particle production in neutron induced reactions. It is a collaborative program between the Uppsala University (Sweden) and Ganil. Since the neutron is uncharged, it is an ideal tool to study nuclear reactions. The neutron beams at NFS allows studying neutron-induced reactions in detail over an energy range where various distinct reaction channels open up and nuclear structure effects gradually wash out with increasing energy of incoming neutrons. At lower excitation energies for a compound nucleus it might be possible to emit at most one particle before the residual nucleus ends up in a state below the separation energies for emission of any further particles. At higher energies, typically above 10 MeV, further particles can be emitted, i.e., multiple particle emission becomes possible. To study the competition between various reaction channels double-differential cross sections are measured for reactions with light ions (p, d, t, 3He and α) in the outgoing channel.

Aside for nuclear reaction model development, the measurements and the resulting data improved evaluated nuclear data are useful for various applications. The C and O data are directly relevant for nuclear medicine and dosimetry. The O and Si data are important to understand radiation effects on electronics and provide input for simulations of, e.g., single event and displacement damage effects when designing new devices. Furthermore, the C data will be useful for detector development, i.e., to understand the response functions of diamond detectors that are used as neutron detectors (e.g., in fusion diagnostics). There are several specific requests on the NEA High Priority Request List.

Medley is designed for detection of charged particles over a wide dynamic range. It consists of eight three-element telescopes mounted inside a 240-mm high cylindrical evacuated chamber with inner diameter of 800 mm. Each telescope consists of two fully depleted ΔE silicon surface barrier detectors (SSBD) and a CsI(Tl) crystal. The back-end part of each crystal is connected to a read-out diode.



5. E832_21– Deuteron activation of natural Molybdenum - focus on short-lived products

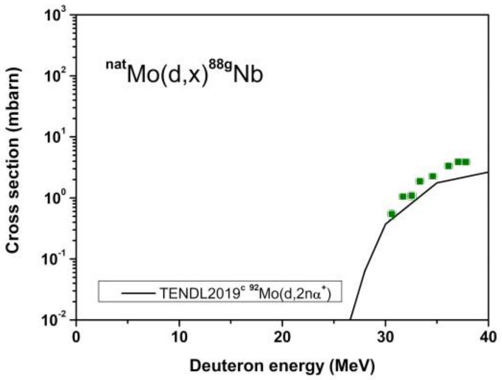
The deuteron-induced reactions at low and medium energies have a great importance in on-going strategic research programs for international large-scale facilities. The activations by deuterons are complex. Due to their low binding energy, multiple different mechanisms (compound nucleus, direct, breakup etc.) are involved. Theoretical models, that do not take into account these mechanisms have a limited predictive power. Theory needs more data with a sufficient quality to be able to extract the relevant information.

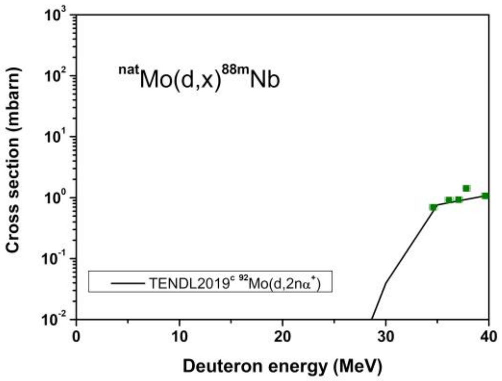
The deuteron interaction with ^{nat}Mo targets populates an extended range of Tc, Mo, Nb, Zr isotopes, many of them unstable with isomers of measurable life-times. Such measurements of both isomers and ground state populations of unstable nuclei, as well as their isomeric ratios, σ^m/σ^g, are extremely important for the theoretical investigation of the moment of inertia, key ingredient of the angular momentum distribution of the level densities.

The E832_21 experiment has been performed in the fall of 2022 by physicists of NPI (Rez). The production excitation function of several isotopes in the d+^{nat}Mo reaction was measured in the 20-40 MeV range. The irradiation station and the pneumatic transfer system, developed at Rez and KIT, were used. New information are expected on ^{91m}Mo, ^{92}Tc, where no data are available due to minute half-lives and on ^{96m}Tc, ^{97m}Tc, ^{101}Mo and ^{101}Tc, where the available data are limited or questionable.

The interpretation capacity of the team comes from the theory group of IFIN-HH, the experimental data at low energies (bellow 20 MeV) and longer half-lives can be complemented by a subsequent experiment at NPI CAS, if needed.

The preliminary data ilustrate the measurement of decay of ^{88}Nb isotope with 15 minutes (ground state) and 8 minutes (isomeric state) half-lives.





VI. CIRIL

This chapter describes some of the experiments that were performed on the beam-lines of the CIRIL platform.

1. Pathways of peptide bond formation and degradation in cyclic dipeptides. ARIBE beam-line

Objectives

The goal is to investigate the processes of peptide bond formation and degradation in the environment provided by homogeneous and hydrated clusters of aminoacids and cyclic dipeptides. Intramolecular reactions of neighbouring groups are efficient opportunities for peptide formation and degradation. These molecular rearrangements, that could have played a role in the origin of life, can be triggered by activating agents or by energetic processes due to particles interactions, like low energy multiply charged ions present in stellar winds. The project, will consider the gas-phase study of the interaction of low-energy ions with homogeneous and hydrated clusters of simple alpha-aminoacids (G, A) and cyclic dipeptides (cAA, cGA, cGG), at the COLIMACON end station of ARIBE.

Summary

The cyclic-Alanine-Alanine (cAA) and cyclic-Glycine-Glicine (cGG) dipeptides considered as isolated species and in cluster have been studied by H+ ion collision at 16keV and mass spectrometry, as well as by ion-ion coincidence experiments. This allows to investigate processes of peptide bond formation and degradation in the environment provided by neighbouring chemical groups as well as among fragment species produced by ion collision. This represents a significant complement in our previous work based on synchrotron radiation photoionisation studies of isolated molecules.

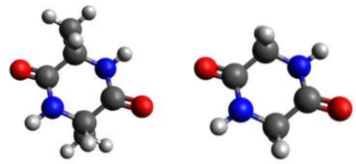


***Figure 1**: The cAA ($C_6H_{10}N_2$, m = 142 Da) and cGG ($C_4H_6N_2$, m = 114 Da) samples.*

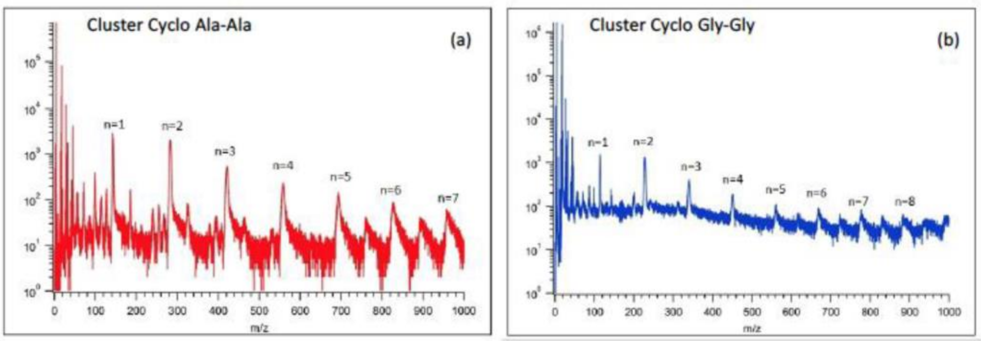


***Figure 3.** The mass spectra of the cAA (left) and cGG (rigth) clusters measured with the COLIMACON apparatus at the ARIBE facility, using H^+ projectiles at 16 keV.*

2. Radiolysis of Complex Organic Molecules (COMs) in the condensed Phase. IRRSUD beam-line

Objectives

Laboratory experiments have shown that complex organic molecules can be formed in space by interaction between radiation and small molecules condensed as tiny ice layers on dust grains in the interstellar clouds. Once formed in space they are further exposed to radiation field, and they can be destroyed by radiolysis. The effects of heavy ion irradiation on ices have been studied within our collaborations since about ten years. In order to contribute to the understanding of radioresistance of organic molecules in space we performed irradiation experiments with solid amorphous and crystalline phase of pyridine as pure and dissolved in water.

Summary

It has been proposed that small nitrogen containing molecules, such as pyridine, can play a role in the first steps leading to formation of large nitrogen containing (polycyclic) aromatic hydrocarbons and of prebiotic molecules such as nucleobases [Soliman et al., 2013, J. Am. Chem. Soc. 135, 155]. We have studied the radioresistance of pure solid amorphous and crystalline pyridine (C5H5N) and pyridine dissolved in water at different concentrations. We have performed eighteen irradiation experiments with the selected combinations of three parameters: i) Temperature of the sample deposition; ii) Temperature of the sample during irradiation; and iii) Concentration of pyridine in the water mixtures. Experiments were performed using IGLIAS (Irradiation de GLaces d'Intérêt AStrophysique) experimental setup of CIMAP mounted at medium energy IRRSUD beamline of the GANIL facility. The mixtures of pyridine and water vapors were prepared in the gas ramp of the IGLIAS and then injected into the vacuum chamber of the setup. Room temperature vapor of the mixture condensed onto the ZnSe substrate mounted on the sample holder. The ZnSe window was pre-cooled to the desired temperature. Subsequently, the samples were irradiated with 61.3 MeV 84Kr15+ ions of the IRRSUD beamline at different temperatures. The destruction of the initial molecule and the appearance of radiolytic products were followed by in-situ infrared absorption spectroscopy as a function of the projectile fluence. The disappearance of the pyridine is characterized by the value of the destruction cross section achieved from the evolution of the pyridine absorption bands under ion irradiation.

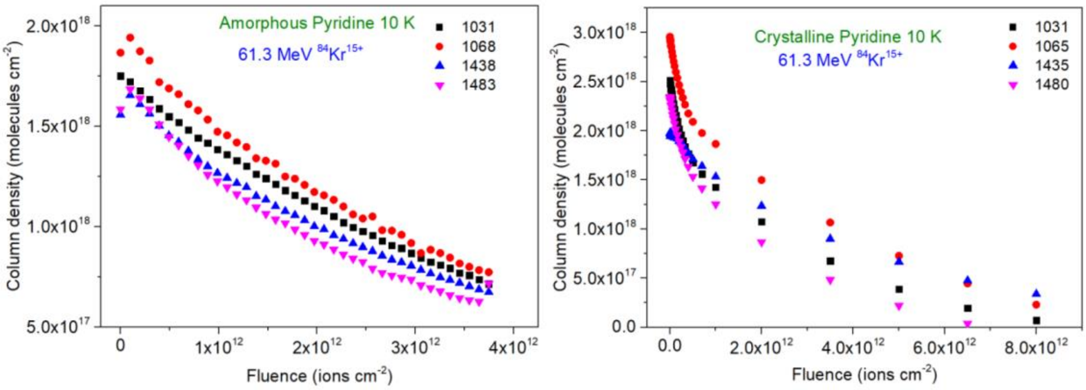


Figure 2: Evolution of the column density of amorphous (left) and crystalline (right) pyridine molecule (calculated for IR absorption peaks at 1031, 1068, 1438, and 1483 cm^{-1}) with projectile fluence during irradiation with 61.3 MeV $^{84}Kr^{15}$ at 10 K.

3. Characterization of radiation damage effects in high-energy neutrino target graphite using low-energy ions. IRRSUD beam-line

Objectives

Next generation high-energy particle beam facilities will require significant advances in accelerator R&D of which high-powered targetry is a major facet. Over time the sustained damage in neutrino targets can lead to a significant decrease in structural integrity and secondary particle production efficiency. As beam facilities with increased proton energy and intensity come online it will be critical to thoroughly understand the processes by which these materials degrade and to be able to predict the extent of damage resulting from new beam designs. Studying the property changes in materials exposed to high-energy proton accelerators is often unrealistic. This is the result of the high residual dose rate of samples, and the requirement for long irradiation sessions on the order of months to reach desired levels of damage. The use of low-energy ion irradiation offers a method to avoid these difficulties by utilizing facilities with short timescale irradiations and no sample activation.

Summary

The IRRSUD beamline experiment at 300°C planned to irradiate POCO ZXF-5Q and Toyo-Tanso IG-430 graphite to 0.1, 0.3, 0.6 and 0.9 DPA at 300°C with and without pre-implanted helium content. These conditions span the damage ranges of many current and future FNAL targets while examining irradiation effects near the temperature where annealing is expected to play a significant role. Diffraction patterns of graphite irradiated at 100°C has shown that significant amorphization has already occurred at the level of 0.6 DPA, so the range of planned damage levels aims to investigate material property changes to see at what damage level this occurs at for a temperature of 300°C. Due to lower than expected flux the targeted 0.1 DPA specimens only reached 0.07 DPA, the 0.30 DPA specimens reached the targeted damage level, and the 0.6 DPA specimens were not irradiated at all. Irradiation induced hardening was probed using nanoindentation experiments, while crystal lattice spacing changes were observed using GIXRD measurements. Future work will measure crystal lattice changes using TEM techniques. Results from ongoing PIE work will be compared to data at a range of damage levels obtained at an irradiation temperature of 100°C, and future experiments plan to complete the 300°C irradiation, irradiations to similar damage levels up to 500°C are also planned for future experiments.

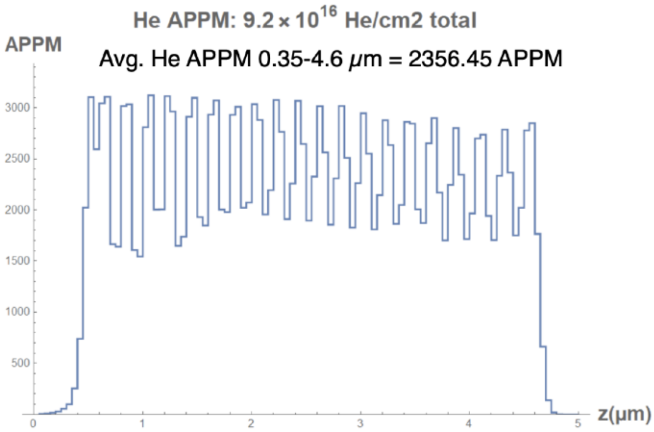


Figure 1: Achieved helium concentration from MIBL pre-implantation for samples that will eventually be irradiated to 0.9 DPA at 500 C

4. Early warning sensors for monitoring trace of heavy metal ions in water. IRASME beam-line

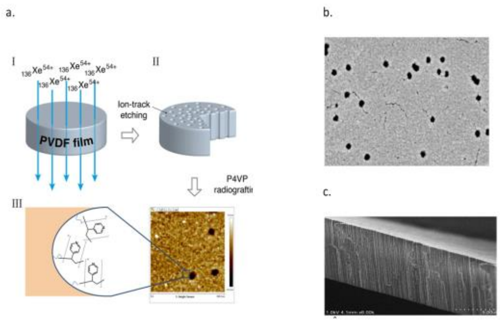
Objectives

The need for water quality monitoring, in environment and health context, required by European and national regulations, is increasing. The trend is for real-time, on-site and in situ analyses. Quality standards are now in the very low µg/L (ppb) or ng/L range. The objective of getting on-site information requires fast, portable, low-cost, environmentally friendly and sensitive instruments. However, very few options are available. Functionalized nanoporous polymer electrodes based on ion-track-etching techniques meet these requirements (Fig. 1). The proposed nanoporous polyvinylidene difluoride (PVDF) electrodes mix not only the gold electrode nanostructuration but also the functionalization inside of the etched ion-tracks to collect and preconcentrate metal ions by passive adsorption. Once the ion is trapped by complexation inside the porosity, the detection is done electrochemically (Fig 2). The functionalization is radically induced taking opportunity of SHI-matter interaction leading to residual radicals, still present inside etched-tracks in PVDF.

Summary

The monitoring of several metal ions, notably Se(IV), As(III) and Cr(VI), is becoming an urgent issue in case of soil leachates and oil production waters. It pushes for radiografting of novel functionalities (aromatic amines, thiols, Cu doped EDTA-like complexes) inside track-etched PVDF membranes to explore and enlarge ion detection possibilities. As the sensitivity is proportional to nanopore density, the objective of the present experiment was to irradiate PVDF membranes at various fluence (e.g. various nanopore densities), prior to etching and subsequent grafting.

The experiment was performed under He atmosphere in presence of the "Tromblon". Unfortunately, we have suffered various difficulties due to slits leaking at D1 entrance and the resulting vacuum degradation. For the machine preservation, the beam was shut down for the D1 cave until the return of an appropriate vacuum level for safe machine operation. Therefore, only 50% of the time was used.



I: Irradiation ⇨ II : Révélation chimique ⇨ III : Fonctionalisation

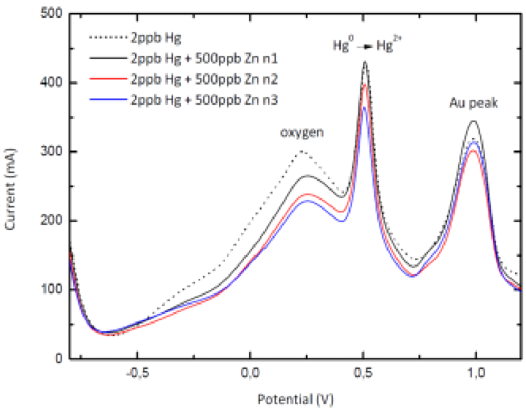


Figure 2. Square-wave ASV response of 2ppb Hg(II) aqueous solutions with and without high Zn salt content (PVDF-g-P4VP membrane-electrodes; 10 MeV/mau Kr^{36+} at 10^9 cm^{-2}; 0.1M HNO_3 electrolyte 4h of adsorption, 50s of electrodeposition)

5. KRAS Inhibitors treatment in Association with X vs hadrons Radiations in non small cell lung cancer

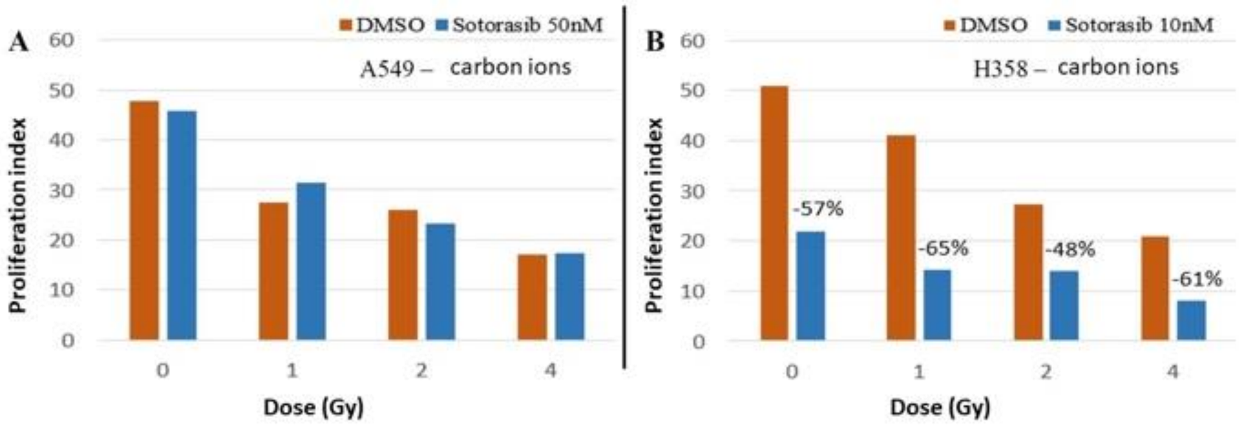
Objectives

Locally advanced inoperable lung cancer is currently treated with radiotherapy and chemotherapy with limited efficacy. Resistance to treatment is linked to mutations in cancer. The KRAS mutation is common in lung cancer and confers resistance to radiation therapy and chemotherapy. Sotorasib is a new treatment targeting one of the mutations in KRAS (KRAS G12C mutation) that provides interesting responses in patients with metastatic lung cancer. It could be interesting to use these treatments targeting the KRAS G12C mutation in locally advanced inoperable forms in order to improve the antitumor efficacy of radiotherapy and chemotherapy. Studies on cell models are needed to know the effectiveness of this combination before clinical trials in humans and a personalized treatment. This project aims to study the effectiveness of a combination of treatment combining Sotorasib with the usual treatments: chemotherapy with platinum salts and irradiation in cell models of lung cancer. We wish to (i) assess radio-sensitivity of such treatment on two cell lines carrying the KRAS G12C mutation and one line carrying another KRAS mutation as a control line and to (ii) establish the impact of such treatment on the cancer stem cell subpopulation, described to be more resistant.

Summary

The objective of this project is to evaluate the efficacy of the tyrosine kinase inhibitor Sotorasib (targeting the KRAS G12C mutation) in combination with carbon ions irradiation in KRAS G12C mutated lung cancer cell lines (H358). Carbon ions appear to have a significant impact on proliferation. Indeed, for the A549 line (control cell, with no KRAS G12C mutation), proliferation seems to decrease from a dose of 1 Gy (A). Proliferation does not seem to decrease at 2 Gy, but seems to relapse at 4 Gy. When the inhibitor is added, no impact on the proliferation index is observed. This cell line displays the same decrease at 1, 2 and 4 Gy as in the control condition, and the proliferation indices are very close.

For the H358 line (B), irradiation also causes a reduction in cell proliferation. It seems that there is a greater reduction at 2 Gy than at 1 Gy, which was not the case for the A549. With the addition of the inhibitor, a reduction in cell proliferation is observed (between 48 and 65% depending on the dose). As with X-rays, this reduction does not seem to be greater with increasing dose.



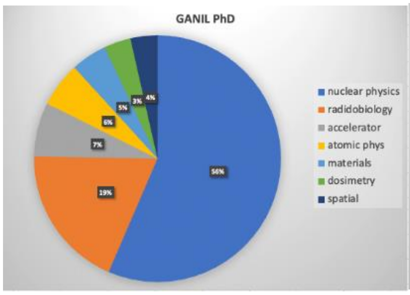
VII. GANIL Users

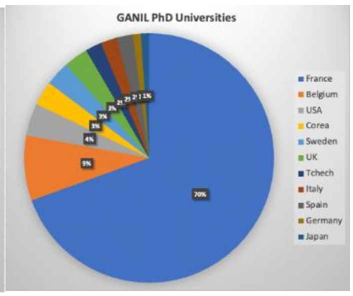
In 2022, the GANIL User Community counts about 1000 members; 75% of them are European, among which half is French, and 10% from Asia, and 10% from America.
In 2022 around 280 scientists came to GANIL performing experiments. Users came for half from French laboratories and Universities, and distributed mainly in Europe, due to the difficult international situation and the restrictive travel conditions.
The distribution of the Countries of their University or Research Centers is shown in the Figure 26.

An incomplete survey revealed that among the GANIL users, one counts about 80 PhD students. 75% of them are French, the rest is distributed mostly in Europe, and few in the US and Korea. The fields of research are predominantly Nuclear physics, Accelerators and Radiobiology.

More than 150 users attended the GANIL Community Meeting, in September 2022, where many ideas generated lively discussions within the various collaborations, in relation to the cyclotrons refurbishment project CYREN. In particular, the possibility of a new injector for the cyclotrons was considered as a promising option. There was also a claim for a strong and urgent need from the users for new SPIRAL1 beams.

Priority list of exotic beams exists and the need for a stronger interaction between the users and the beam developers was pointed out.
The place of interdisciplinary is growing in the scientific perimeter of GANIL with very prolific and diverse projects and results, pressing for more beam-time.
The progress on DESIR and S^3 projects resulting from an impressive work was acknowledged. Discussions arose on the organization that will need to be put in place on the beam-sharing between S^3, NFS and a possible beam-sharing system that would be necessary to satisfy both communities. The need of an efficient target laboratory, the use of actinide targets was also strongly pointed for both experimental programs of S^3 and NFS.





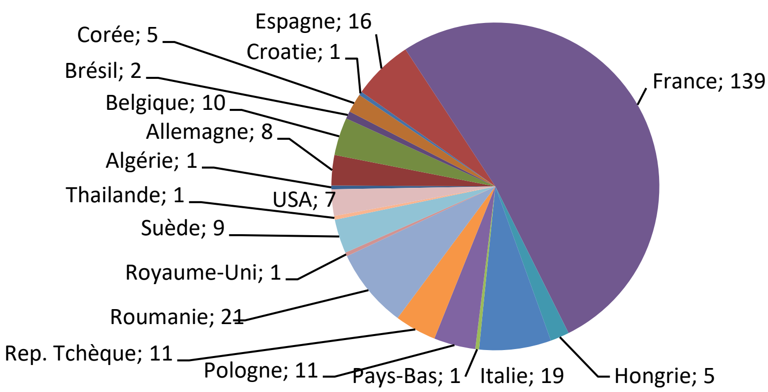


Figure 26 : GANIL users coming for experiments in 2022

VIII. Communication and outreach

1. Conference

During the EPOPEA Science and Innovation evening on October 10th, a GANIL researcher presented science of GANIL, with a focus on the Neutron for science installation.

2. Public meeting for exchanges and information

The GANIL local information commission organized on November 16th its annual public information meeting in the presence of many students.

3. Demonstrations

On the occasion of the science festival, organized by the Ministry of Research and Higher Education, GANIL presented a scientific stand in the Caen science village from 14th to 16th of October.

GANIL participated in FENO, the festival of Norman excellence, organized by the Normandy Region. For 3 days, researchers, engineers and technicians presented GANIL's activities through scientific demonstrations and games. FENO welcomed 45,000 visitors from 21st to 23rd of October.

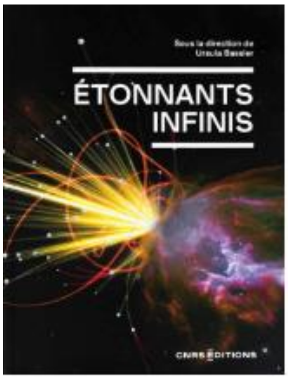
4. Visits

Hervé Morin, President of the Normandy Region and Julie Barenton-Guillas, Vice-President in charge of higher education, research innovation and digital, came to GANIL on February 24th to meet the new management team and see the progress of the SPIRAL2 facility, officially in operation since December 2021.

The prefect and sub-prefect in charge of the recovery plan have visited GANIL on October 3rd. This visit gave an opportunity to present the DESIR project and the planned schedule for the public inquiry that will have to be performed before obtaining the permit for construction.

On the occasion of the signature of the France 2030 regional convention on December 13th, Bruno Bonnell, Secretary General for France 2030 investment visited GANIL. He was accompanied by Hervé Morin, the President of the Normandy Région and Pierre-André Durand, the Prefect. The Signature took place at the GANIL guest house.

5. Publication



In thirty short chapters abundantly illustrated and written by IN2P3 researchers, the book "Amazing infinities" reports on what we already know as well as what we are still looking for. Two GANIL researchers, Antoine Lemasson and Olivier Sorlin, contributed to this work.

Légende : Etonnants infinis, collective work under the direction of Ursula Bassler

03 | OPERATION, TECHNOLOGICAL RESEARCH AND DEVELOPMENT

I. Executive Summary of accelerator and experimental areas operation

Since 2019, operation at GANIL concerns the LINAC as well as the cyclotrons.
The first beam was ejected from CSS2 forty years ago, SPIRAL1 first radioactive beam is 22 years old (see “from design through construction and evolution of the cyclotrons”, this report). The LINAC is still in commissioning phase, preparing for S^3, but also operating for experiments in NFS (Neutrons For Science), with 5 experiments and 2 tests performed in 2022.
The time available for physics in NFS is increasing to 1140 hours, while 1810 hours are preserved for beam time in cyclotrons experimental areas, despite a worrying increase of failure rate of the cyclotrons facility.
D3 and G1 are the most requested experimental areas with the cyclotrons beam.

1. GANIL operation status

From the first experiment in 1983, the time available for physics with cyclotrons is around 110 000 hours, with a peak in 2005 (more than 4000 hours physics time), and a decrease since 10 years due to the construction and operation of SPIRAL2 (Figure 27).

Since 2019 yet, LINAC operation is to be added to cyclotron operation (Figure 28). Total physics beam time is close to 3000 hours in 2022, in addition to the auxiliary beam-time delivered to SME (410 hours), IRRSUD (1130 hours) and ARIBE (600 hours) operation. This correspond to a total available beam-time for experiments of more than 5000 hours. During next years, the parallel operation of cyclotrons and LINAC will be considered to increase available time for experiments.

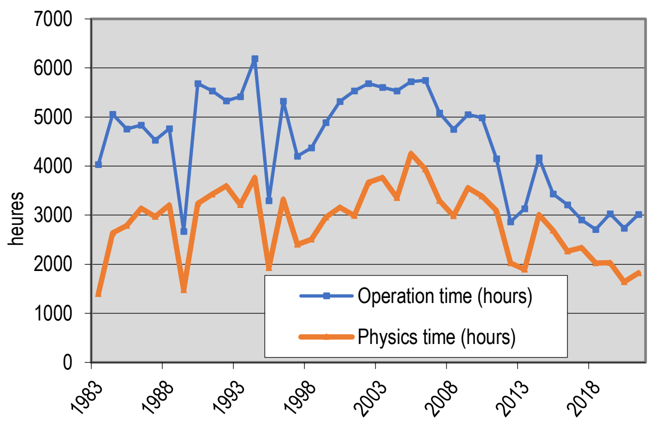


Figure 27: Beam time available for physics since 1983.

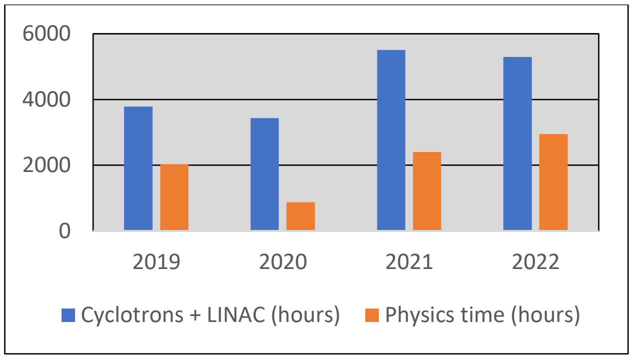


Figure 28: Beam time available for physics (Cyclotrons + LINAC).

2. 2022 cyclotrons operation

The accelerator failure rate is at a high level, and is increasing these last years (Figure 29).
The rise of the failure rate is mainly due to water leak inside the machine, and particularly on the RF cooling circuits.
Considering this evolution and the high-level demand (there is a factor 2 more demands at the PAC – Physics Advisory Committee - than time available for cyclotrons) a major renovation plan of the cyclotron facility is needed. This is the CYREN (Cyclotron Renovation) project. The objective is to operate the facility 20 years more.

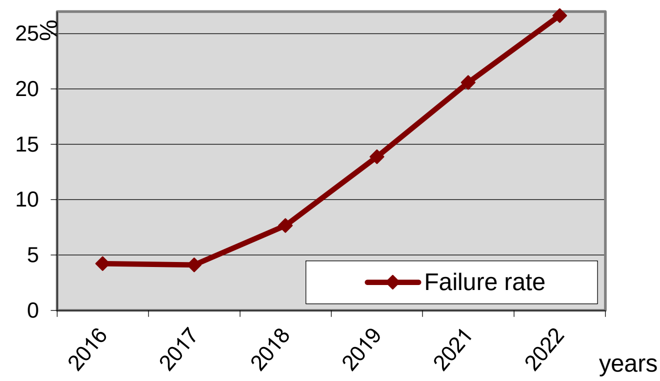


Figure 29: cyclotrons failure rate since 2016

The accelerator tuning rate is at 10%, to be compared to 16% in 2021. A part of this decrease is associated to the number of different beams tuned (1 per week in 2022 1,2 per week in 2021).
The most requested experimental halls are (Figure 30): G1 (fusion reactions or fission studies with CSS1 beams and SPIRAL1), LISE (D3/D4/D6) (fragmentation of CSS2 beams and SPIRAL1), D5 (Indra-Fazia), G4 (industrial applications), and D1 (interdisciplinary physics).

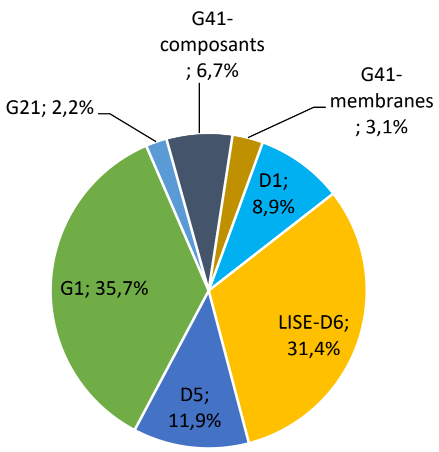


Figure 30: Experimental areas beam distribution in 2022

The main part of the machine studies (2% in 2022) is related to developments for radioactive beams at SPIRAL1 (see Radioactive Beam Developments in this report). This 2% rate is quite low and should be increased to improve the cyclotrons secondary beam diversity.

3. 2022 LINAC Operation

With NFS the only experimental room in operation, the LINAC schedule is shared between physics, improvement of the tuning methods and tools, and beam development for S^3.

D+ (5 times), H+, 4He2+ have been tuned for NFS in 2022, as well as 2 new beams with q/A=1/3: ^{18}O6+ and ^{40}Ar14+, this second one being extrapolated from the ^{18}O6+ tuning. These two beams are representative (q/A and energy) of the beams required for S^3.

Machine studies are related to tests of new tuning methods, beam diagnostics, RF tests, Machine learning…

The failure rate is quite low (9,4%), after major troubles in 2021 (31%, with in particular a major breakdown of a RF cavity) (Figure 31). It should be expected that the conception problems are behind us and that the failure rate will stabilized around 10%. This low failure rates gives confidence in the beam developments for S^3 and in the developments for NFS experimental programme.

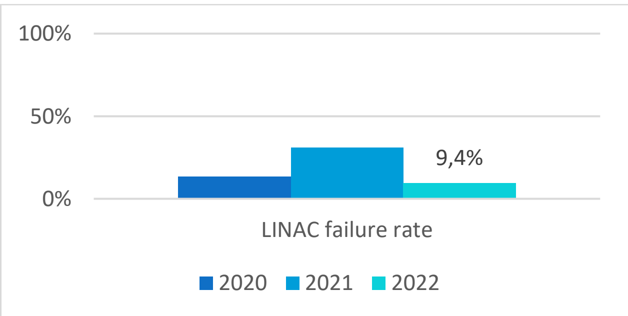


Figure 31: failure rate (LINAC and NFS)

II. Target Ion Sources

1. ECR ion sources production on Cyclotron and SPIRAL2 facilities

Assessment of produced beams at cyclotron and Linac injectors

Two ECR ion sources provide beams to cyclotron facility. These ion sources are working simultanously to provide beams for high-energy experiments and for low-energy beam line (IRRSUD).

In 2022, twelve types of ions have been produced, representing more than 4000 hours of beam used for accelerator tuning and physics experiments.

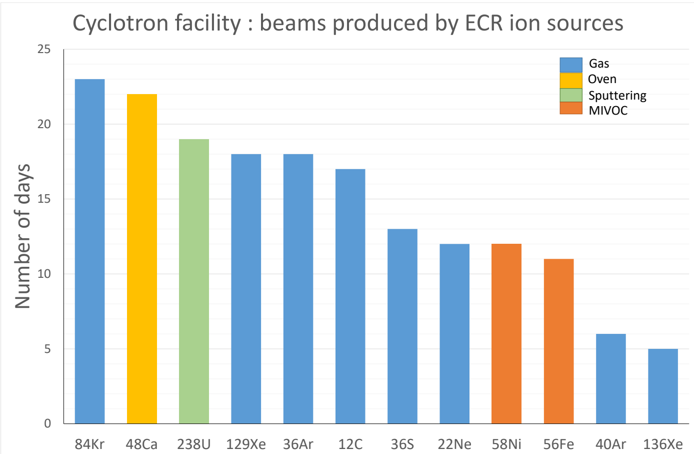


Figure 32 : Beams produced by ECR injectors on cyclotron facility in 2022

During this period, different techniques have been used to inject isotopes into the ion-source plasma chamber. Gaseous injection is the most efficient and stable technique. But for some metallic beams, the evaporation technique needs to be adapted depending on physical properties of the sample.

To improve ECR beam quality, improvements are always in progress. In 2022, a new system has been used for MIVOC technique to produce ^{58}Ni beam, in collaboration with IPHC, Strasbourg.

This technique is based on the use of specific compound that becomes volatile under vaccum. Because of the complex molecule $(C_{10}H_{10})_2{}^{58}Ni$, the main parameter to increase intensity is the conductance between the compound and the plasma chamber.

A new system has been developped to optimise the conductance by increasing the diameter of the transfer tube and design, and also improving the insulation of the polarized tube, which was a parameter that regulary failed on the previous system.

Moreover, a temperature regulation of the sample has been optimized to reduce the influence of the accelerator hall temperature evolution on vapor flux production, which improves the stability of the beam extracted from the ion source.

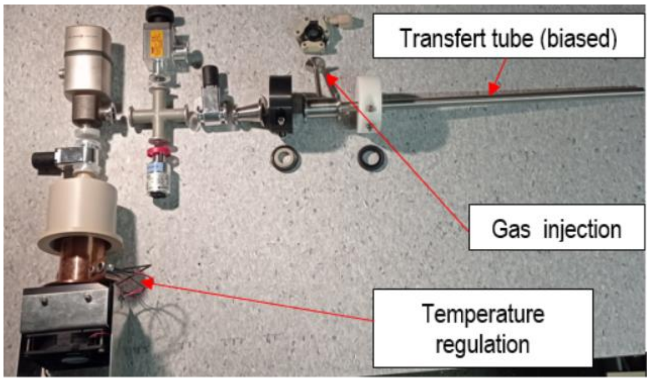


Figure 33 : New design for M/VOC injection

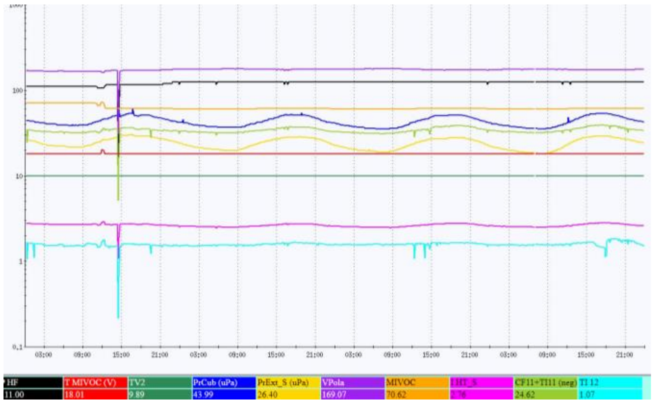


Figure 34 : Stability during 4 days : blue ligne is intensity used by physic expermients

The online results showed that 20µAe of $^{58}Ni^{11+}$ was delivered during long term operation, with a real improvement in stability. This design is now routinely used when MIVOC technique is to be used.

2. SPIRAL2 injectors : first year with light and heavy beams.

Light ion source (H+,D+) :

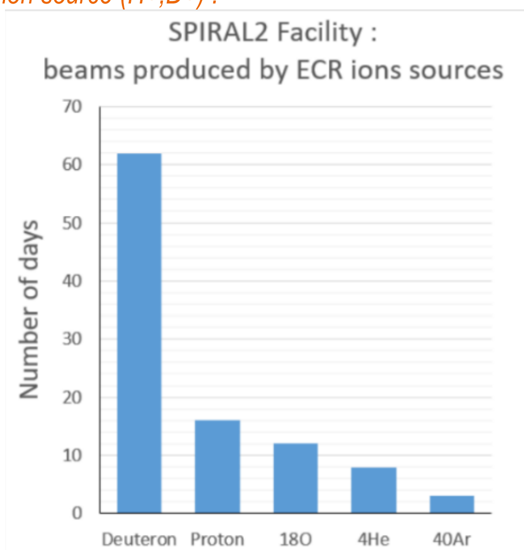


Figure 35 : Beams produced by ECR injectors on SPIRAL2 facilty in 2022

In 2022, the main beams produced with SPIRAL2 Linac have been produced by the Light Ion Source, dedicated to proton or deuteron beam. An intensity of 8mA is usually produced at the extraction of the source during several days.

After 3 years of operation, an inspection of the 40kV extraction system has been made, as electrical discharges were observed during the last runs. It was observed that the insulators had metallic deposits, which favored the appearance of electrical discharges between the electrodes. The whole extraction system was therefore cleaned and reinstalled after a precise alignment of the different electrodes.

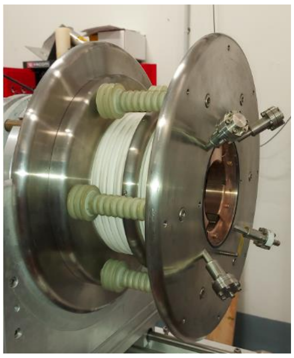
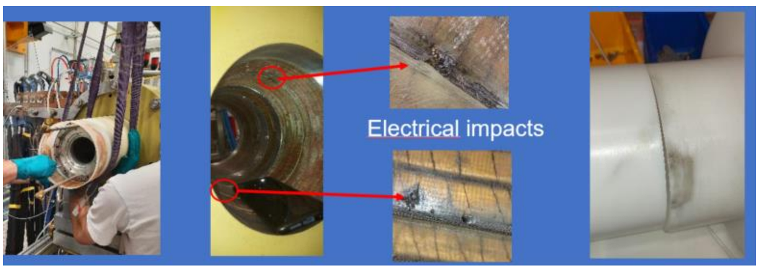


Figure 36 : Photo of extraction system

Heavy-ion source : Phoenix V3

On heavy-ion injector, ^{18}O and ^{40}Ar have been produced and accelerated by LINAC for commissionning of Q/A=1/3 beam for the first time in 2022. To produce these beams, an extraction of 60kV of the Phoenix V3-18GHz ECR Ion source is needed.

Important work for ion source insulation improvement has been performed during 2021-2022. Indeed, since the beginning of the PhoenixV3 commissioning, many power supplies dysfunctions were observed when 60kV extraction voltage was applied. It was decided during summer 2022 to completely dismantle the source in order to diagnose insulators and find the cause of the electrical faults. Observations revealed a weakness in the insulation system. In addition, the electrical discharges had the effect of degrading the epoxy insulation of the coils, which was the origin of the disjunctions of the magnetic field power supplies.



A stainless steel coating was installed inside the source to protect the coils, and a Kapton coating was added between the coils and the insulator. In addition, spare insulators were used to restart in the best possible conditions. Due to this upgrade, we were able to produce, for the first time, ^{18}O and ^{40}Ar beams extracted at 60kV, energy required to inject ions into the RFQ.

Theses beams have been used and accelerated by LINAC for commissionning of Q/A=1/3 beam for the first time in 2022. The intensities than we obtained at the extraction of the ion source were 700e.µA for $^{18}O^{6+}$ and 100e.µA for $^{40}Ar^{14+}$.

Finally, at the end of 2022, a first test of ^{40}Ca beam with an extraction voltage of 60kV was carried out, which is the first beam in a long list of metal beams that we need to develop and optimize. To inject the calcium into the plasma chamber, we used the Large Capacity Oven classically used on GANIL ion sources. We obtained over 20e.µA of $^{40}Ca^{16+}$ (which is the charge state required for the ^{48}Ca beam) and 45e.µA of $^{40}Ca^{14+}$ with a ^{40}Ca consumption around 0.7mg/h. These initial results are encouraging, but this is just the beginning of an exciting adventure.

3. SPIRAL1 : Radioactive ion beam developement

SPIRAL1 is a facility dedicated to the production and acceleration of radioactive ion beams (RIBs). It produces RIBs though the ISOL technique, that is, radioactive isotopes are produced and stopped in a thick target and are then transported in atomic form towards an ion source, where they are ionized before being accelerated and separated. SPIRAL1 is a modular installation compatible with multiple primary beams and, since its upgrade, with multiple targets and sources. Started in the 2010's, this upgrade aimed at extending the RIB offer by allowing to use other target materials than graphite (up to Nb) and by making the facility compatible with other types of sources capable of ionizing condensable elements. Today, graphite remains the only target material used in SPIRAL1 although some early studies of new target materials have already started and should resume at the end of 2023. Two new sources have been developed:

- MonoNaKe, a surface ion source dedicated to the production of K and Na ions, also capable of producing Li ions.
- FEBIAD, a universal electron-impact hot source capable of ionizing any element that enters the source. It is limited only by the sticking time of the most refractory or the most chemically reactive isotopes, which may decay before they reach the source.

Since both of these sources generate only 1+ ions, they also require a charge breeder to increase the charge state for post-acceleration. The SPIRAL1 Charge Breeder (SP1CB) is an ECR-type breeder that can also be used as a standalone stable-gas ion source.

ECS FEBIAD

The FEBIAD ion source has reached a reliable design in 2022, with good and repeatable performances. Online tests on FEBIAD sources are being performed every year since 2021 to probe its capabilities and limitations. Two development studies took place in 2022 with a FEBIAD source. The goal of the first one, with a primary beam of 36Ar, was to compare the production rates of the latest design to those of an early design of the FEBIAD. The results showed that the production rates were better for Ar isotopes (by a factor up to 2) but lower

for short-lived condensable elements like Al, showing that the target ion source system (TISS) was more efficient but colder than previously. It was later demonstrated online that the beam heating, which was higher in 2013, plays an important role in the diffusion out of the target.
The second, with a primary beam of 84Kr, allowed exploring new possible beams, as it was the heaviest element ever sent in a FEBIAD TISS in SPIRAL1. Despite the very low power of the primary 84Kr beam, we observed over 30 isotopes that had never been produced in SPIRAL1, including isotopes of Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb and Kr. Following the machine studies, we performed a 2-weeks long endurance test on the FEBIAD-TISS with source heating at nominal value, during which we observed an excellent stability of the source performances.

By extrapolating measured rates to the best primary beams, we estimate that around 40 of the isotopes observed in 2022 could be produced at a "post-accelerable rate" (expected rate after post-acceleration >1*10^4 pps). The list of the recently produced beam will be added on the ganil website (https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/available-beams/).

The conclusions of the 2022 FEBIAD experiments is that the latest design is more reliable and has a higher ionization efficiency, but the FEBIAD TISS was operated at lower temperature than during the 2013 experiment. Given its remarkable resilience, it should now be operated at higher target and source heating power.

ECS MonoNaKe

MonoNaKe is a target ion source system (TISS) initially designed to produce Mono-charged radioactive alkali ions of Na and K by fragmentation and surface ionization. The TISS is made of a "Christmas tree" like graphite target whose container is coupled to a 4 mm in diameter ionizing tube made of graphite (Figure 37).

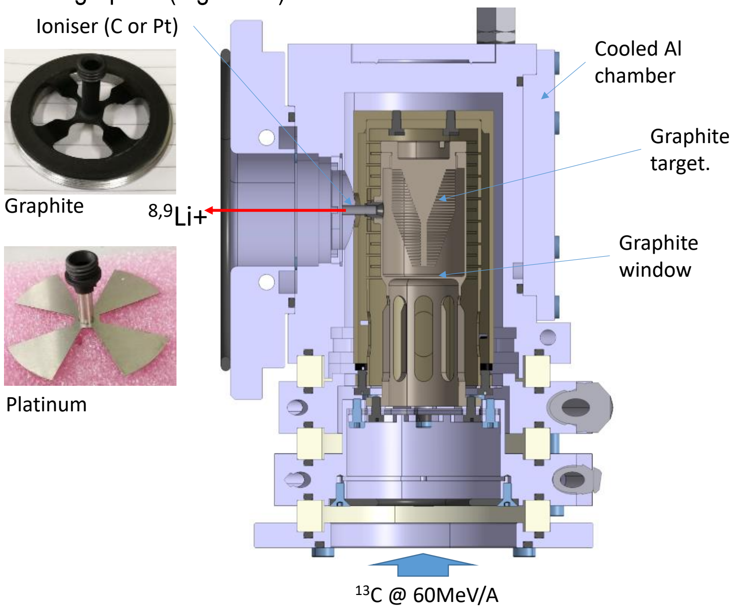


Figure 37 : Cross section of the MonoNaKe TISS and graphite and platinum ionisers.

The use of graphite allows the whole system to sustain a temperature close to 1700°C for 2 weeks. It demonstrated in 2007 its ability to produce $^8Li^+$ with a total atom-to-ion transformation (AIT) efficiency close to 5% but it has never been used for physics experiment. A recent demand for a $^8Li^+$ beam has led to reconsider the design of the ionizer to ensure the requested intensity. Due to its particular physicochemical characteristics, platinum was chosen to replace the graphite of the ionizing tube, which should allow increasing the ionization efficiency of Li by one order of magnitude. A French company overcame the challenge of welding edge-to-edge two 0.2 mm platinum foils to build the ioniser. During the qualification tests, the tube was heated to a temperature higher than 1500°C, close to the Pt fusion point and no damage was observed.
Bibliographic data and experimental results performed on the SPIRAL1 test bench motivated an on-line study, which was performed in May 2023.
Despite a relatively low rate (2.2×10^4 pps compared to ~10^9 pps produced in the target), three important results were obtained:

1. A rough set of beam parameters is now available that can be used as a starting point in the future to significantly improve the transport efficiency and the $^8Li^+$ rate.
2. The extraction of the beam at the exit of the TISS seems to have a very important influence on the downstream transport efficiency. An improvement of the extraction is already under study and will be tested off-line by winter 2023-2024.
3. No indication of aging of the Pt ioniser was observed during off-line (after dismantling) and on-line tests

If the efficiency of the platinum ioniser is confirmed for atoms having a first ionisation potential lower than 6 eV, the working region of MonoNaKe could be extended to alkaline-earth and to a few lanthanide elements.

TULIP ECS project

The TULIP project, funded by ANR, aims at producing short-lived neutron-deficient metallic ions. It consists of two important phases: the proof of principle through the production of rubidium ions and the production of metallic ions in the region of ^{100}Sn.
Its principle consists of producing radioactive ion beams with a relatively low-energy stable ion beams (~5 MeV/u) sent on thin (some µm thick) and large (40 mm in diameter) targets (Figure 38). Recoils produced by fusion-evaporation reactions continue their flight through a 2 µm thick window and are stopped in a graphite catcher. The window, the catcher and a ring of graphite form a cavity, which includes an exit hole. In order to favor the production of short-lived ions, the cavity is heated, equipped with an inner electric field. The design of the different components, geometry, size, recoil range, were optimized to minimize the atom-to-ion transformation (AIT) time.

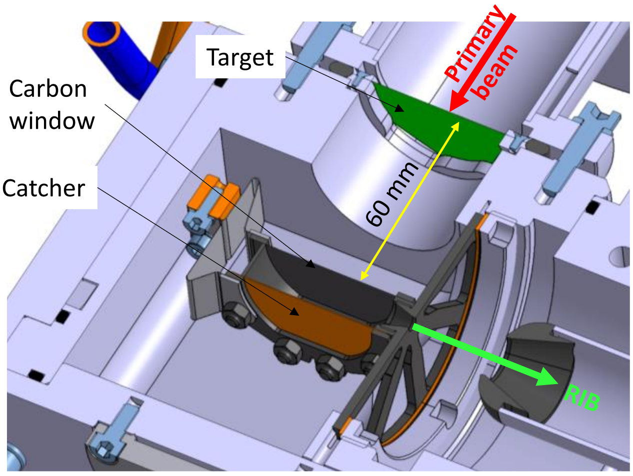


Figure 38 : Cross-section of the TULIP TISS for alkali ion production.

A first on-line test was performed in March 2022 to produce neutron-deficient isotopes of Rb using a primary beam of ^{22}Ne @ 4.5 MeV/u and a ^{nat}Ni target. Exceptionally short atom-to-ion transformation (AIT) times (<1 ms) were observed but the AIT efficiency was lower than expected. More developments are underway.

To move towards the production of metallic elements, an original TISS called SPEED, is based on the alkali version of TULIP cavity, equipped with an electron emitter to ionize the atoms effusing in the cavity. The first tests showed an AIT efficiency of a few percent for noble gases and AIT times of a few milliseconds. This development is the subject of PhD, to be defended in 2023.

Presently, the SPEED system needs further improvements to reach an ionization efficiency comparable to the one offered by a FEBIAD. A study to couple a FEBIAD to the TULIP cavity has thus been launched in parallel, appearing to be a more straight-forward solution since the FEBIAD has recently proven to be performing very well and to be reliable.

The damages observed in the thin production target, observed during the first on-line TULIP test has motivated the study of a rotating target, able to sustain a higher primary beam intensity for a higher production rate while limiting its operation temperature. It will also allow the use of more materials with lower fusion temperatures to be used, for an extension of the variety of nuclei produced with TULIP.

The charge breeder

SPIRAL1 Charge Breeder (SP1CB) has been fitted with a new travelling wave tube (TWT) RF amplifier with a variable frequency in 2021. The objective was to use it in combination to the existing Klystron amplifier to enable double-frequency heating to increase the mean charge state at the exit of SP1CB. By injecting gas (Ne, Ar, Kr) in the breeder (*i.e.* using it as a source), we indeed observed that the mean charge state after SP1CB was increased by around 10-15%. This was also observed for Rb in 1+/N+ mode. Charge breeding is important to increase the energy of the ion beams. However, some experiments of nuclear astrophysics need low-energy ion beams, for which it is of importance to improve the production of low charge states.

During tests with SP1CB, we discovered a new heating mode, allowing high charge breeding efficiencies for low charge states. The following figures illustrate the control we can have on the charge-state distribution after the charge breeder using multiple heating modes.

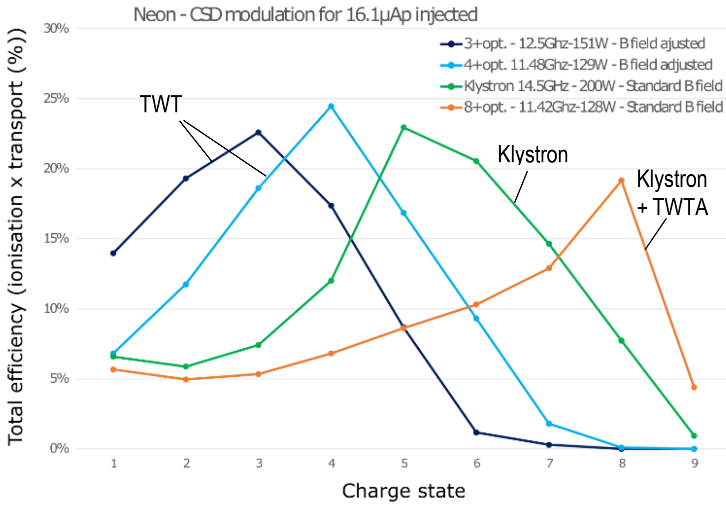


Figure 39 : Charge state distributions of Ne obtained with the variable frequency alone (TWTA), the fixed frequency amplifier (Klystron) and both frequencies at once (Klystron+TWTA).

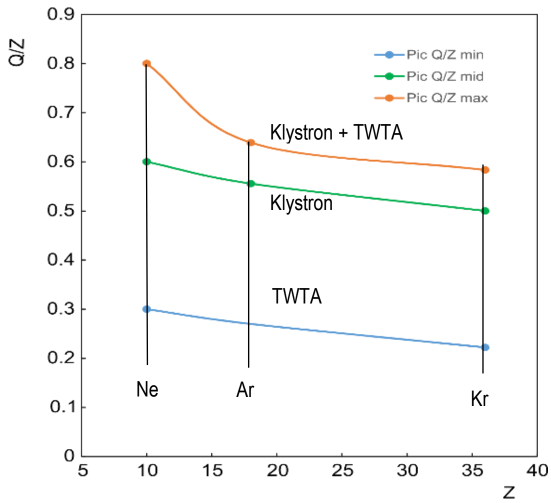


Figure 40 : Mean charge state as a function of the Z of the injected gas for different heating modes.

III. Physics of Accelerators

1. First heavy-ion beams in LINAC

The SPIRAL2 Superconducting linac commissioning was carried out between 2019 and 2021 at the same time as the transition to operation with first tests performed in NFS. H^+, D^+ and $^4He^{2+}$ beams were successfully tuned and sent through all accelerator components up to SAFARI beam-dump at their nominal energy of 33 MeV for H^+ and 20 MeV/u for D^+ and $^4He^{2+}$ with ~100% linac transmission. Figure 41 shows the transmission evolution during power ramp-up with H^+ and D^+ beams up to 100% chopper duty cycle.

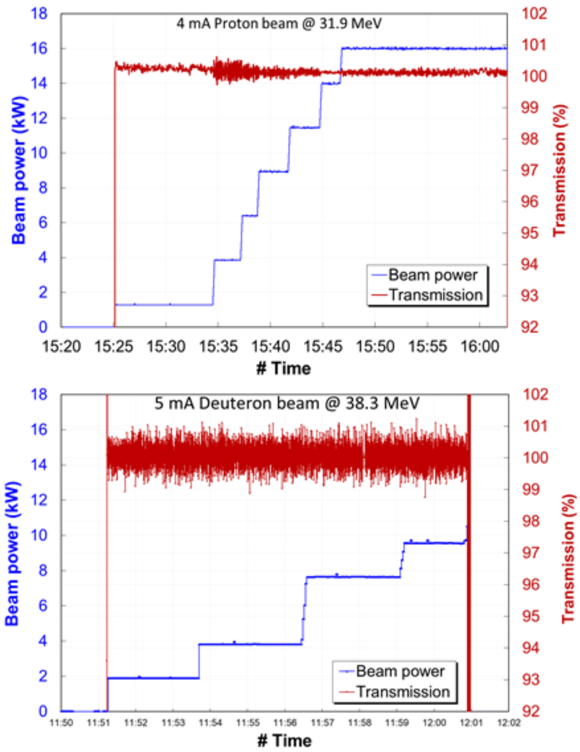


Figure 41.Evolution of the transmission (red) and beam power (blue) during the power ramp up to 100% DC with: 4 mA H^+ beam (top) and 5 mA D^+ beam (bottom).

2. BEAMS for S³ commisioning

The heavy ion beams $^{18}O^{6+,7+}$ and $^{40}Ar^{14+}$ were tuned and accelerated in 2022 as part of the preparation for the Super Separator Spectrometer (S³) commissioning. Table 1 shows the beam parameters tuned in 2022. The transmissions for $^{18}O^{6+}$ and $^{40}Ar^{14+}$ beams were higher than 99% while for $^{18}O^{7+}$ it was higher than 98%.

Parameter	$^{18}O^{6+}$	$^{18}O^{7+}$	$^{40}Ar^{14+}$
Max E (MeV/u)	7	7	7
Max I (µA)	50	78	80
Transmission (%)	99	98	99
Beam power (kW)	1	0.6	1.2

Table 1: Accelerated heavy ions in SPIRAL2.

The $^{18}O^{6+,7+}$ and $^{40}Ar^{14+}$ tunings were performed to obtain a final energy of 7 MeV/u, a value higher than that required for physics experiments at this time. To obtain this energy lower than the nominal energy (14.5 MeV/u), the cavities downstream cavity number 15 were switched off and detuned, while the last cavity (number 26) was used in rebuncher mode to reduce the energy spread. The $^{18}O^{6+}$ beam was accelerated to 7 MeV/u, then the parameters corresponding to acceleration of $^{18}O^{7+}$ and $^{40}Ar^{14+}$ beams up to the same energy were extrapolated.

To qualify the tuning, a power ramp up to 1 kW with a $^{18}O^{6+}$ beam at 7 MeV/u was performed. The strategy in this case was to accelerate the beam with a peak current of 50 µA through the linac and increase the pulse length up to 100% duty cycle. Figure 42 shows the evolution of the duty cycle and average current.

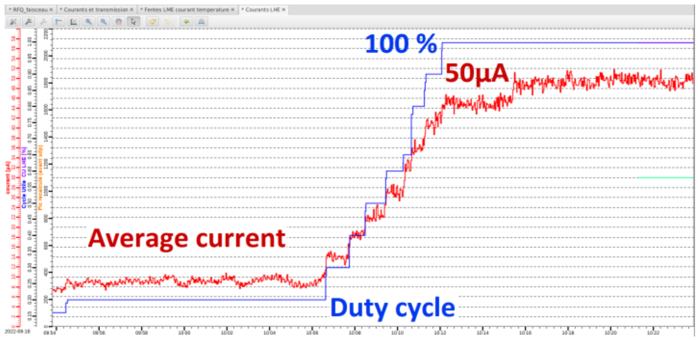


Figure 42. Power ramp up of 50 µA $^{18}O^{6+}$ beam: Duty cycle (blue) and average current (red).

A 78 µA $^{18}O^{7+}$ beam was then accelerated up to 7 MeV/u as expected with 1‰ duty cycle. Without transport optimisation of the MEBT and the LINAC after the switch, the measured transmission was 95%. The same process was repeated to switch from $^{18}O^{6+}$ to $^{18}O^{7+}$ with an energy of 0.73 MeV/u (no acceleration in linac), confirming the results obtained in the first study.

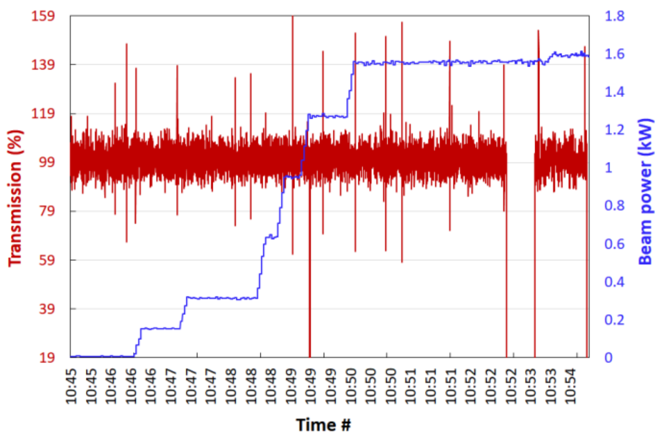


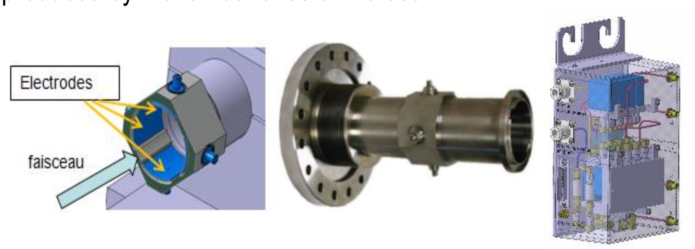
Figure 43. Power ramp up of 80 µA 40Ar14 Beam: transmission (red) and beam power (blue).

Finally, a 80 µA $^{40}Ar^{14+}$ beam was accelerated to 7 MeV/u. A power of 1.6 kW was achieved with a 100% duty cycle, and a maximum transmission higher than 99%. Figure 43 shows the evolution of the transmission and beam power during the power ramp up, the large variations in transmission are due to electronic noise. The intensity for heavy ion beams was ≤600µA. Further studies to characterise beam losses at low energies will be carried out in 2023.

IV. Equipments for beam acceleration, transport and diagnostics

1. Development and installation of new Radio Frequency distribution electronics and Beam Profiler Monitor calibration systems

The Beam Position Monitors (BPM) are beam diagnostics installed in the quadrupoles of the hot sections of the SPIRAL2 LINAC. Twenty BPMs and their instrumentation chain measure the following characteristics: beam position, ellipticity (a characteristic of the transverse shape), and beam phase. The four electrodes of a BPM capture the electric field produced by the ion bunches of the beam.



Each BPM electronics is synchronized with reference RF signals at the accelerator frequency (h1 = 88.0525 MHz) and its double frequency (h2 = 176.105 MHz). New RF distribution electronics and BPM calibration systems were designed and installed in 2022.

Two RF distribution electronic racks are used in the SPIRAL2 BPM system, one for LINAC part A (LINA) and another for part B (LINB). A spare rack is provided in case of failure, making a total of three racks. The phase deviations among the 16 h1 signals and between the three racks must be limited, as with the h2 signals. The requirement of having interchangeable racks imposes strong constraints on the phase disparities, which we did not have with the existing two racks.

Each BPM electronics consists of four measurement channels, one per electrode. The four measurement channels must have very close gains and phase offsets to meet the specified requirements. The quality of the measurements depends on these gain and phase deviations between channels. To compensate for existing disparities on the analog cards, we perform digital gain and phase corrections. These corrections are determined through calibrations.
An important achievement in the year 2022 has been the automation of the calibration process for the full BPM ensemble, which has been reduced from two weeks to three days!
This impressive result was achieved thanks to the Calbox, its graphical interface, and the design of a dedicated rack.
The calibration results show that the front-end distribution signals have a maximum deviation of 0.03 dB in amplitude, 0.5° at h1, and 1° at h2, values that meet the BPM specifications.

A new calibration campaign is planned for 2023 to compare the corrections with the previous ones, assess the drift of the electronics, and compare the achieved results.

2. Development of LBE2 fluorescence profilers

Two secondary emission (EMS) profilers (Figure 44) are currently installed to measure the position and profile of the proton/deuteron beam in the LBE2 line of SPIRAL2. These profilers are not suitable for the high-power beams in this line as they do not allow for more than 10 seconds of measurements without degrading their wires. This limitation makes it difficult to adjust the transport and alignment of the beam in the LBE2, and has led to the replacement of profilers during the commissioning phase of the accelerator.

Figure 44 : SPIRAL2 type EMS profiler

aperture	84 mm
wire diameter	150 µm
Type	modulated steps 17 wires with a step of 1 mm 10 wires with a step of 2 mm 20 wires with a step of 3 mm
Intensité max.	Faisceau continu : <200 µA Faisceau pulsé : <5 mA pulses de 20ms / s

Table 1 : LBE profilers specification

The Fluorescence Profil Monitor (FPM) does not have this power constraint and allows for continuous measurement of the continuous beams in the LBE2 line. The principle of this type of profiler lies in visualizing the trace left by the beam interacting with the residual gas present in the vacuum chamber, in the form of fluorescence in the visible spectrum. This type of profiler only works with high-intensity beams, typically Deuterons and Protons from the SPIRAL2 source.
In the LBE2 line, the vacuum is between 10E-5 and 10E-6 mbar. By passing through it, the beam produces photons that can be visualized by a high-definition industrial camera with very high sensitivity. Figure 45 shows an image obtained with an 8mA Deuteron beam after 6 seconds of exposure. The distribution of particles is then obtained using real-time digital image processing (Figure 46).

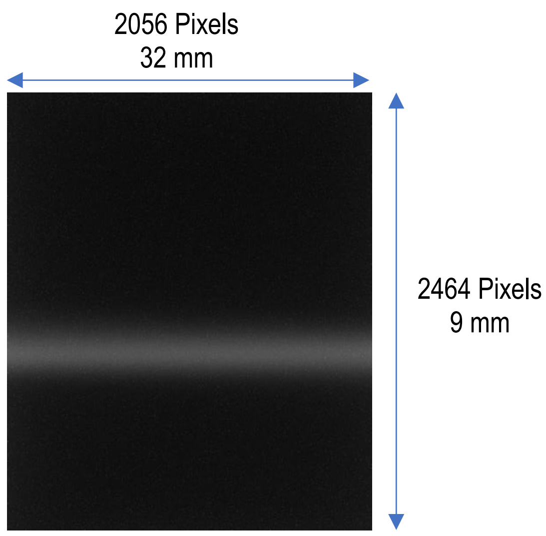


Figure 45 : : the beam as recorded by the camera

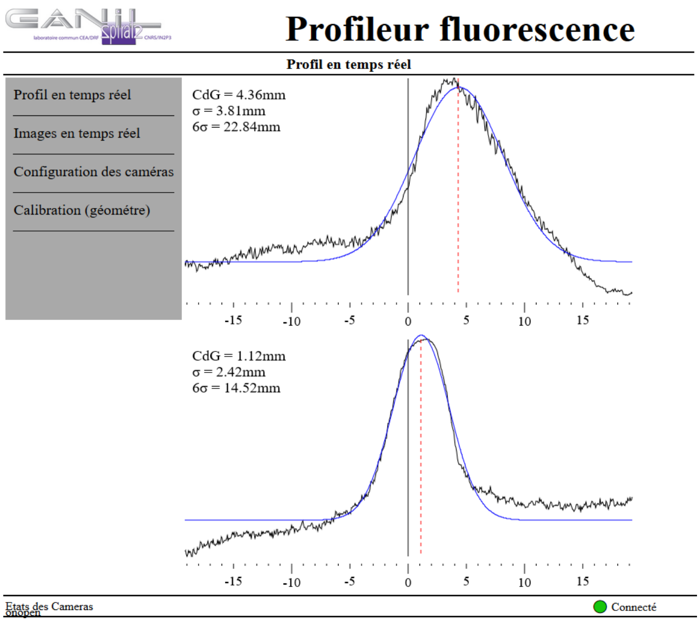


Figure 46 : proposed interface, with real time processing

A feasibility study was conducted in 2021, involving the installation of a camera and a window at the LBE2-EMIT location, along with offline image processing. Currently, the project is in the development phase, with the objective of installing 2 profilers for machine studies in 2023 and fully qualifying all 4 profilers in 2024.
The cameras are capable of providing a higher resolution than the wires, thanks to continuous image processing performed by a Linux mini PC near the beamline.
The next major step will be to test the first version of the monitoring program during a machine study run of SPIRAL2. Adjusting parameters such as exposure time and image transfer rate is planned during the validation phase with the beam. Following that, in 2024-2025, the fabrication of a new vacuum chamber and the installation of LBE2-PR13 will take place. In parallel, it will be necessary to develop a graphical interface for operation.

3. SPIRAL2 single bunch selector reliability improvement

Introduction

The SPIRAL2 single bunch selector (SBS) is a travelling wave (TW) kicker, based on two meander shaped striplines ("meanderlines") so that the HV pulse travels at the same speed as the beam in the Medium Energy Beam Transfer: $\beta = v/c = 0.039$.
The design is based on a CERN/Linac 4 chopper, and adapted to the needs of SPIRAL2

The commissioning phase of SPIRAL2 proved that the initial design of the system was not robust enough: 2.5 kV pulsers were not sufficient and not reliable for long term operation at maximum voltage (±2.5 kV) and repetition rate 0,8 MHz, whereas the SBS is mandatory for beam profile measurement for most of the experiments at SPIRAL2/NFS based on proton and deuteron beams.

Spare Controller Board

New additional controller board has been designed, manufactured and is under test, to be compatible with the different upgrades and to provide a spare unit.
It contains several enhancements, such as

- A 0-10V output for pulse amplitude control instead of a motorized potentiometer.
- An interlock input for the new protection electronics
- a new trigger input, with led signalling
- A new pulser "enable" command

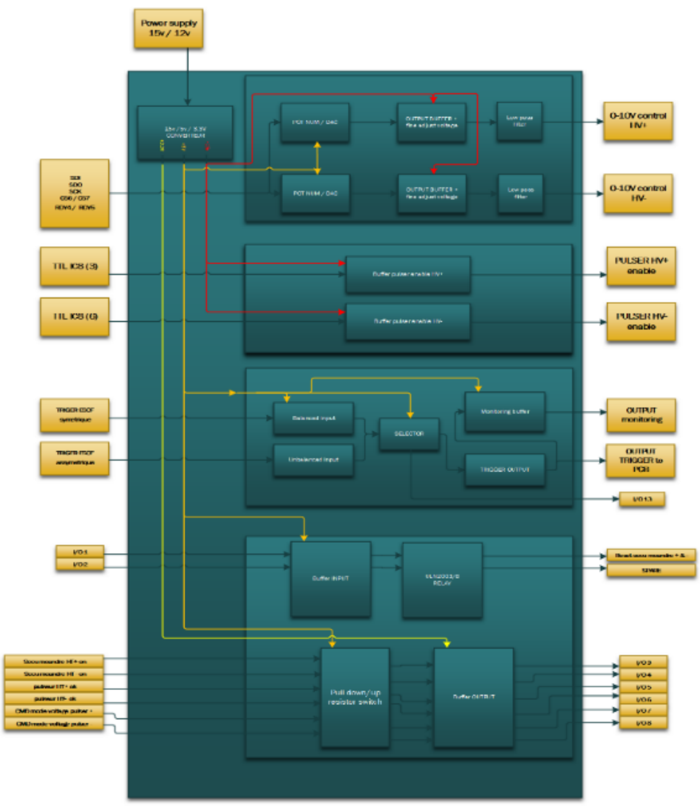


Figure 47 : block diagram of the new SBS controller

New PULSERS

New 3 kV pulsers have been ordered from the FID company and have been intensively tested before their installation. Their operating voltage is limited to 2.8 kV by the control software and no troubles occurred during the last run. The pulsers have also been protected against load mismatching by an extremely fast electronic system which verifies that each pulse reaches the matching load and disables the pulses if not.

Remote interface IMPROVEMENT

The local control system is now able to show the signals generated by the pulsers, via retrieval of data of an oscilloscope. This enable to check the proper synchronization of the pulses.

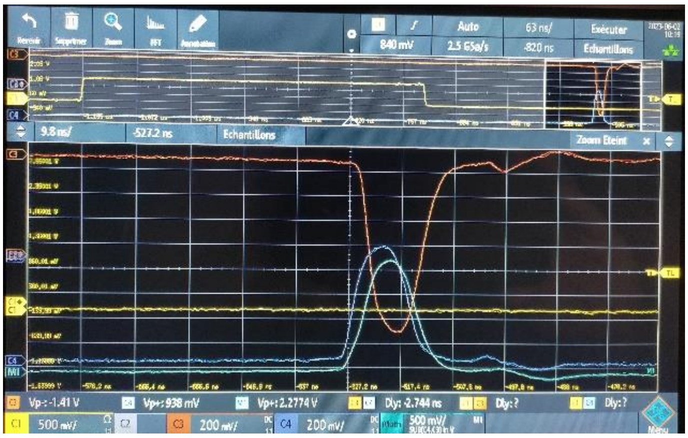


Figure 48 : Print screen of oscilloscope and measurement

Alarms due to a wrong behaviour of the system, are notified to the operators now and threshold can be configurated from the GUI .This renders the system safer.

4. Qualification Progress of Superconducting Magnet Triplets for the S³ project

Summary of the recent tests on SMT

In June of 2022, the Superconducting Multipole Triplet (SMT) n°5 "AMPERE" underwent its most recent round of testing. These Superconducting magnets are based on the so-called Meissner effect, whereby the magnetic field is expelled from the coil at extremely low temperatures.

Throughout our testing process, several quenches and undesired dumps were observed.

Upon analyzing the results of the tests, we have identified two primary concerns.

The first one relates to the Cryogenic System (CryoS), which triggers a dump when the current reaches approximately 70 A. The second issue is associated with Quadrupole 3, which can cause a quench or a dump at a significantly higher current level, above 250 A. Based on our analysis, we believe that the lack of cryogenic liquid was a contributing factor to numerous dump/quench events observed during testing.

Regarding the second dump/quench, many different improvements were implemented to determine the root cause, and many different tests have been performed, to interpret with high attention the results to propose improvements to the system, in accordance to the genuine willingness of the team to conquer these challenges and rectify the shortcomings.

The detected quench during the tests of the quadrupole for SMT "Einstein" observed previously at a current value of 75 A, has been remedied by changing one High-Temperature Superconducting (HTS) delaminated lead (cf. Figure 49). Several hypotheses were put in place but the explanation of this quench is still under investigation with the manufacturer.

Figure 49 : The picture shows the $YBa_2Cu_3O_{7-x}$ (YBCO) coated HTS leads experiencing degradation as they become unsoldered and separated from the copper bar.

Iron yokes & effect

A significant decision was made in 2022 to temporarily remove the blue iron yoke shells from the SMT's cryostats as shown in Figure 2. This decision was the consequence of the almond shape of the cryostat that prevented the blue yokes to be aligned better than 200 µm, inducing an additional magnetic force that drags the cold mass position at high current values. At current value larger than 250A, the strong magnetic force is being guided by the iron yokes, and the force exerted by the eight tie rods is not sufficient to stabilize the position of the cold mass in its position. Thus, we observed a significant displacement of the cold mass, by approximately 2 mm.

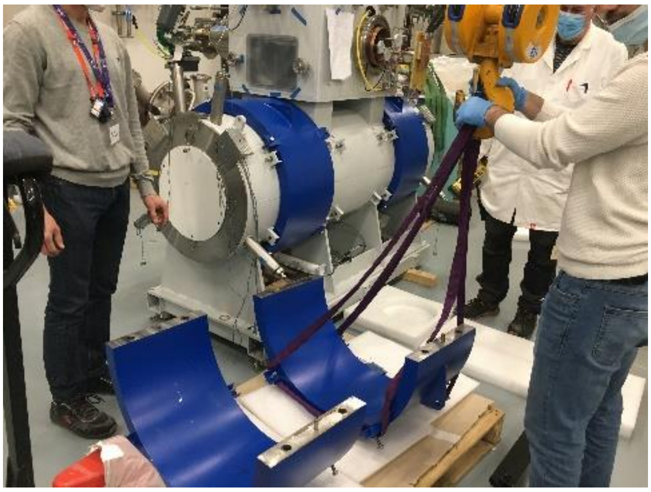


Figure 50 : A picture while removing one of the three iron shells for SMT n°5 AMPERE.

Furthermore, based on an analysis conducted using ion optic modeling software (LISE++), this misalignment of the cold mass center axis by 2 mm may result in a transmission loss of 12%. Subsequently, an analysis of the theoretical field map estimates that the removal of the iron yokes will only result in a reduction of 7.41% in the expected field integral.

During the latest tests for SMT n°5 “Ampere” without the iron yokes, preliminary alignment measurements were performed consecutively and have proven that the cold mass position is stable while increasing the current up to a certain value.

5. Qualification Progress of the Power Supply System for S³ Project.

PSS description

The PSSs (Figure 51) are custom Power Supply Systems used to power the Superconducting Multipole Triplets (SMT) of the S³ (Super Separator Spectrometer) experimental room. These 7 PSS consist each of 8 power supplies (PS), a magnet safety system (MSS) and a computer made control system. There are 8 PS for the 11 magnets of a SMT, therefore a wired electrical cabinet has been added to adapt the loads configuration.

Each PSS has three 465A/5V PS for the Quadrupoles, one 100A/5V PS for one of the 2 dipoles and four 365A/5V for the 3 Octupoles and/or 3 Hexapoles. Fast contactors and power resistors are used to discharge the energy stored in the loads if a quench is detected. The MSS consists of eight fast voltage acquisition cards that transmit to a NI CompactRIO FPGA controller signals to launch the dump in case of quench detection.

Figure 51 : a PSS

Compliance tests: Specific Functions tested and validated in 2022.

The general compliance tests were done in 2020/2021. The PSS have additional specific functionalities due to their particular topology which were tested in 2021/2022.

Before using the PSS, the load configuration must be confirmed by an automatic check that consists of supplying each load with a current ramp to validate the PS versus load connection.

One of the primary functions of the PSS is to protect the SMT magnets from a quench with a fast and reliable detection and disconnection. This is the role of the MSS with rapid data voltage acquisition of the coils and currents leads of each SMT load. The protective function is ensured by a fast current discharge if a resistive effect is measured. The complete calibration and check of the MSS has been performed in 2021/2022 for the 2 SMT tests benches planned for the SMTs of S³.

Figure 52 : PSS n° 4 and n°5 ready for SMTs qualification

Two PSS are now fully installed and operated in the S³ room (Figure 52).

They serve as tests benches for the qualification of each SMT before their final installation and their commissioning on the beam line of the spectrometer. The remaining 5 PSS will be started and commissioned with their respective SMTs in 2023/2024.

VI. Vacuum and Cryogeny

1. Improvements to the SPIRAL2 cryogenic system

The SPIRAL2 cryogenic system is designed to cool down superconducting cavities to 4.3 K using liquid helium. The helium cooling system is able to provide 1.1 kW of cooling power at 4.3 K plus 3 kW at about 50 K. The cryogenic plant and the distribution system (cold valves boxes) are in nominal operation since 2019.
Based on these years of operation, feedback has driven several improvement studies, some of which have been implemented during 2022.

Thermo-acoustic oscillations (TAO) compensations

Thermo-acoustic oscillations, also known as Taconis oscillations, are a resonant phenomenon driven by large thermal gradients in cryogenic system. When conditions get resonant, it builds into strong pressure oscillations with potentially high heat loads, which, at worst, may preclude the cryogenic systems operation.
On SPIRAL2, such a phenomenon was identified late in 2017 in each cold valve boxes of the LINAC. The pressure oscillation generated by the TAO was strong enough to prevent the use of the superconducting cavities.
A temporary solution was developed and fully tested: a short circuit between the return line and the helium bath of the cryomodule was added, to prevent the pressure oscillation. This solution restored the stability of the cryogenic system but a relaxation phenomenon was observed: a helium gas flow that occurred roughly every 30 minutes caused some pressure stability perturbations. Moreover, the compensation system perturbed the helium level sensors in part of their measuring range. Therefore, a new TAO compensation system was developed. It is a RLC resonator that aims to compensate and damp the resonance. This new system was tested during the 2022 accelerator run and performed satisfactorily.
Work related to TAO monitoring is still ongoing. G2CA is implementing a dedicated monitoring system based on fast, piezoelectric (IEPE - Integrated Electronics Piezo-Electric) pressure sensors. The system, once operational, will be able to detect any TAO oscillation and provide on-line users the frequency and the amplitude of the resonance.

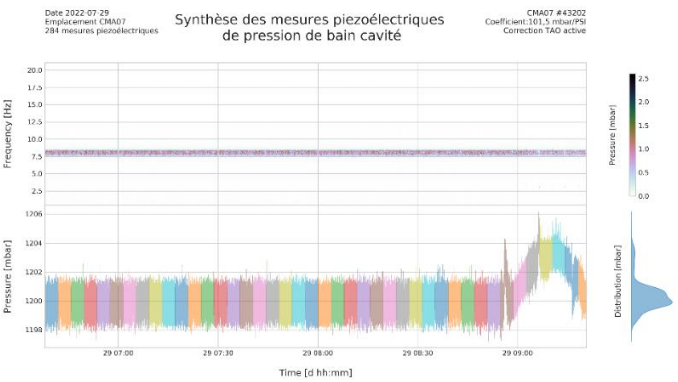


Figure 53 : An example for the TAO survey and detection (case of cavity CMA07)

2. Heat load observers

The development of numerical model of the cryogenic system is an ongoing project started in 2017 as a collaboration with CEA DSBT Grenoble. Using MatLab and the SimCryogenics library developed by DSBT, it was possible to build an accurate model of the cryomodules.
This same model is also used as a soft sensor. Based on the helium parameters (level, pressure) and the valves conditions, the software is able to compute the heat load on the cryogenic system. This feature, implemented in the cryogenics PLCs, has been tested during 2022. It helped to pinpoint a powerful field emission phenomenon on cavity #14 during the 2022 run, and thus proved its usefulness. Developments are still ongoing in order to enhance the precision and the speed of the soft sensor.

3. On-line leaks monitoring

The helium refrigerator is a closed circuit machine: the cryoplant recovers and recycles helium, and the losses are limited to leaks. We nevertheless observed freezing at some points of the LINAC, which indicate cold gas leaks through closed valves. These valves leakages are difficult to observe during operation, as the LINAC is not accessible. Therefore, additional monitoring has been installed on all warm outlets of each cold valves boxes. When temperature gets too low, the thermal switches generate an alarm signal to the cryogenics operators through the cryogenics control system, for future investigation of the potential leaks when tunnel access becomes possible.

4. Analyzer manifold upgrade

Helium purity is critical for operation of such helium cooling system; all elements except helium are solid at 4 K and such impurities may severely damage the turbines that provide most of the cooling power, or clog the heat exchangers. Therefore, an analyzer device tracks impurities down to ppm levels. These impurities concentration are measured at various locations of the cryogenic installation through a set of valves, check valves, pressure regulator and safety valves grouped in a so-called “analyzer manifold”. This manifold need to be fully upgraded because of several components failures and poor initial design. The upgrade was an opportunity to add several more analysis locations, based on the operation feedback. This work was performed with support from the G2CA team, who updated the user interface panel used to drive this manifold.
The new manifold is now fully operational, except for some of the new, low pressure analysis locations which require some more work to be fully operational.

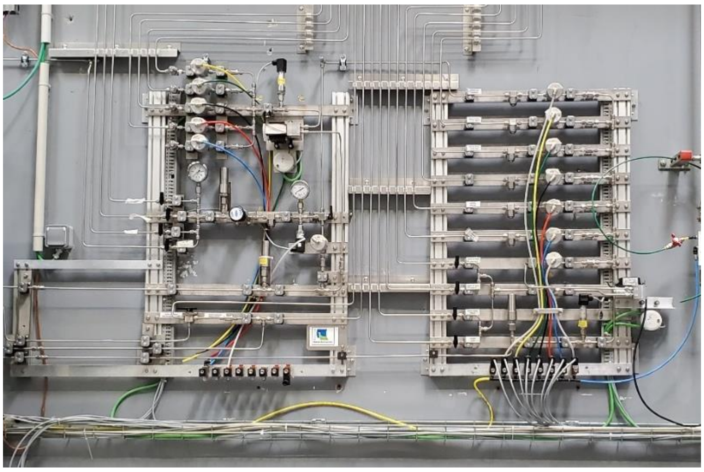


Figure 54 : The new manifold analyzer implemented in 2022

5. Development of a calibrated flow-injection system for the qualification of vacuum systems

To qualify vacuum systems, a calibrated flow-injection system has been developed

Objectives

To qualify a vacuum system, the minimum pressure achieved, the pumping speed or the outgassing flow need to be evaluated.

Most of the time, the way to realize this evaluation is to inject a "calibrated leak" from special bottles of gas equipped with a specific conductance, providing fixed value of flow. However, these bottles are expensive and the production of a fixed flow limits them to particular configurations. That is why the vacuum and cryogenics group developed a gas injection system in order to have a bench capable of injecting an adjustable gas flow, useable with different gases and compatible with ultra-high vacuum pumping installations. Last but not the least constraint: this bench must be mobile and usable in most of the GANIL facility. This development was developed within the framework of a professional training program (Licence professionnelle TechViMat)

Software

To control the bench, a program has been developed with Labview (see Figure 55). This program and its man-machine interface allows for a simple and stable use of the bench.

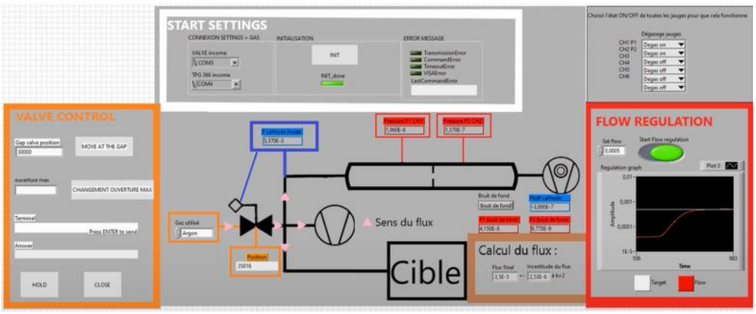


Figure 55 :view of interface

Results

Actually this bench can produce a flow between 5.10^{-3} mbar.l/s and 5.10^{-6} mbar.l/s with nitrogen with an uncertainty of 15%. All system can be used in major part of accelerator and measures were already done to check simulations.

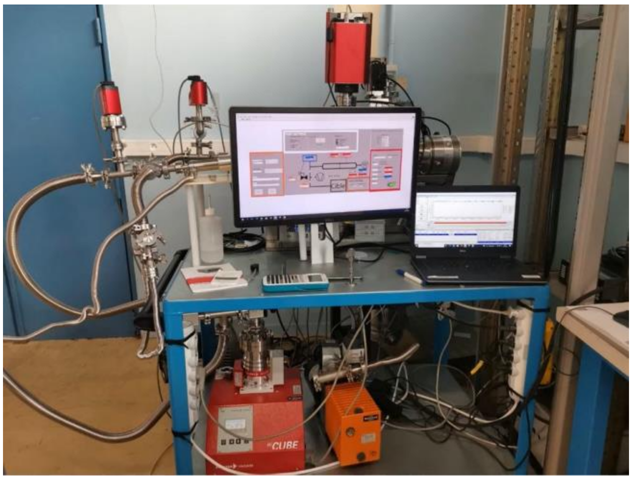


Figure 56 : injection bench

VII. Automats and Command Control

1. New technology for the synoptic of LISE

Context

The LISE synoptic provides a general view of the beam line status in rooms D3, D4 and D6. Initially, it was made up of LEDs driven by an old-generation Programmable Logic Controller. The experimental areas are brought to evolve according to the experiments. In particular, scalable and modular aspect are important criteria.

Software presentation

The choice fell on the new Siemens WinCC unified supervisor. This is based on native web technologies such as HTML5, SVG, and JavaScript. The application runs on a dedicated server directly integrated into GANIL's IT architecture. The connection to the application is made by a web browser (web client) from any computer station, both from a Windows and Linux environment.
One of the main advantage of this technology is to be able to access the synoptic easily from the outside (up to 10 simultaneous connections). This technology will be deployed on future GANIL supervisions.

Programming

The creation of a global library grouping together the different types of equipment (quadrupoles, dipoles, insertions, valves, Faraday cups, etc.) makes it possible to move them, according to their state. This library can then be used for future projects. In order to make the synoptic more ergonomic, a color code has been defined to quickly differentiate between the different possible states of the equipments.

Commissioning

With the close collaboration of the technical group in charge of LISE operation (GGOI) and physicists, tests wree carried out and validated the functional aspect of the synoptic. This was deployed in the southern acquisition on two 55-inch screens.

2. Development of a new "Autofill" system.

Context

Figure 58: Exogam detectors.

EXOGAM detection clusters require liquid nitrogen cooling in order to use the semiconducting properties of Germanium. The automatic filling system called "autofill" is designed to keep the EXOGAM clusters at low temperature.

The liquid nitrogen supply is provided by a tank associated with the AUTOFILL cabinets.

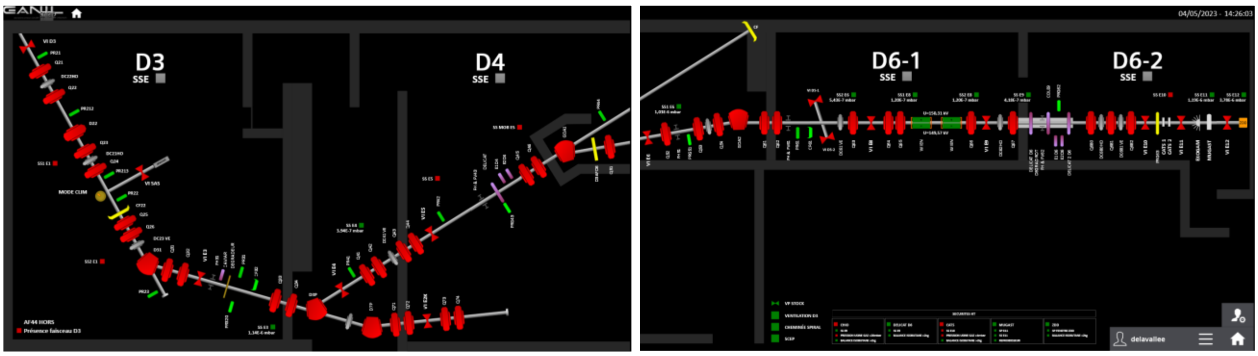


Figure 57: New LISE synoptic. Red : off/out/closed, Green : on/in/open, Yellow : inserted. Purple: detectors

Hardware presentation

Figure 59: Autofill cabinet and tank.

The Autofill system is made up of a nitrogen tank with a capacity allowing several filling of the detectors. This tank is associated with a mobile cabinet containing the automation, the high and low voltage power supplies, the valves and the temperature sensors detecting the filling of the detectors. An extension cabinet can be added to increase the capacity of the Autofill from 8 to 16 detectors lanes.
The choice of the programmable controller was made on the latest generation of SIEMENS PLCs (S7-1500) associated with a Wincc Unified touch panel, which was used for the first time at GANIL and will be deployed for future projects.
The equipments allowing the cooling of the detectors as well as the detection of the filling have been developed at GANIL.

Programming

The realization of the PLC program and the Human machine interface are made under the TIA PORTAL software. The implementation of the AUTOFILL under WinCC Unified allows the dynamization of the equipment that can be controlled from the touch panel.
The development of the touch panel was carried out with the constraint of providing the essential information for monitoring the filling of the detectors and the operation of the tank in a minimum number of views. Additional views for adjustment and maintenance allow to adjust and follow the evolution of the detectors.

Commissioning

The Autofill has been developed by a G2CA/GGOI team with the close collaboration of the technical group in charge of Detectors DELPH. Tests validated the functional aspect of the autofill system. The Autofill has been used with success for the first time in the LISE experiment room.

3. Prototyping S^3 software application responsible for management of experience parameters. Features and technologies.

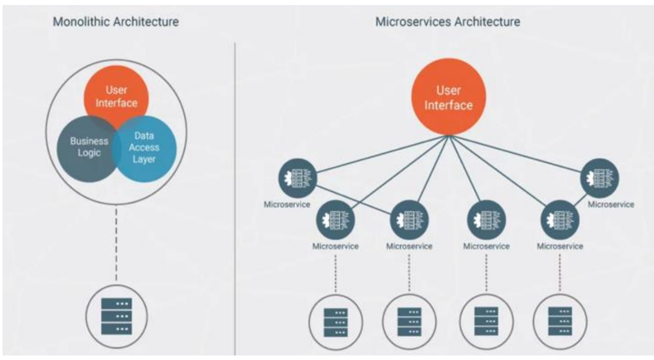
Context

S^3 room is mainly composed of magnetic elements (quadrupoles, dipoles, electrostatic deflector …). For a given experience, the values of magnetic fields for each of those elements may differ depending on the beam characteristics and the optic configuration. First, physicists need to calculate those values and then to transmit them to the differents electronic devices controlling the magnetic elements.
The main objectives of the S^3 parameters application are :

- Facilitate complex calculations of those parameters using the concept of optic configurations and to transmit them in one shot to the chosen equipments
- Store in a database the values of all the parameters of a given experience and be able to reload them easily in a future experience
- Read in one shot all the on-line values of a set of equipments and compare them to values stored in database
- Manage the energy, optic and beam characteristics changes

Software presentation

S^3 parameters application is based on microservices architecture and web technologies. The idea is to define independent software components (microservices) that are responsible of a given feature. The application can then use a given microservice for a given feature. Main advantage of this type of architecture is that every microservice can be tested and developed independently. Team working is much more possible. Application is accessible through a simple web browser on different devices (laptop, digital tablet, smartphone) from any location (in GANIL or outside GANIL) with a secure connection.



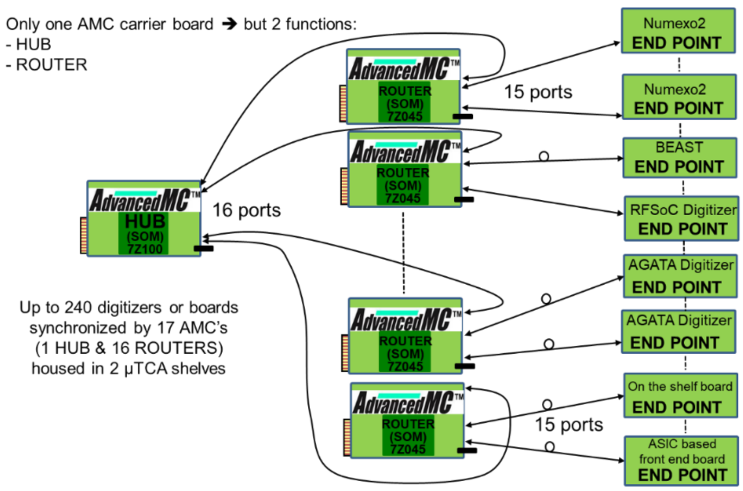
Commissioning

The application is still in development phase. In this phase, tests are performed to validate the software architecture. For instance, the access from the web application through the web services to the various equipments of S^3 and the parameters stored in the database is presently under test.
Next step is to validate all features of the application with technical groups in charge of S^3 and physicists.

VIII. Acquisition and Data Policy

1. SMART

SMART stands for "**S**fp and **M**icrotca for **A**dvanced **R**emote **T**rigger", and 2022 is the first key year for the SMART project in terms of results. This ongoing R&D program led by the GANIL group for acquisition techniques (GTA) aims to provide a new timestamping system to our digitizers and other electronic modules involved in data acquisition.
The second element of this apparatus (trigger part) is to keep only relevant information concerning the physics experiment in order to reduce the volume of data stored on disks and to facilitate data analysis. The architecture, built in conformance with MicroTCA standard, uses a tree configuration with a single HUB board and up to 16 ROUTERS to reach 240 digitizers called END POINTS (see figure below). These modules exchanging data at 4 and 2 Gbit/s are linked by high performances copper cables, or optical fibbers for distance that can exceed 100 meters. The first level of proof of concept validates the synchronous distribution of a 100 MHz clock to each END POINT and a timestamping system where each watch in every END POINT is able to tag data buffers on 48 bits/10 ns.
Extra tests are still in progress and the second step is the validation of trigger processing. In parallel, autumn 2022 has been dedicated to initiate the SMART project phase 2 in order to increase the number of controlled END POINTS by a factor of two, from 240 to 480 mainly for AGATA detector requirements.



2. BEAST for SMART

A new firmware has been developed for BEAST module (Back End Adaptor for Synchronization by Timestamping). This module was originally built as a gateway between GTS and CENTRUM protocol used for coupling at GANIL 20 years ago. As SMART protocol is replacing the GTS, this upgrade gives the opportunity to switch rapidly from one coupling system to another with the same hardware. At the same time, these modules are also the first END POINTS used in the validation of the SMART concept.

3. Trigger Processor

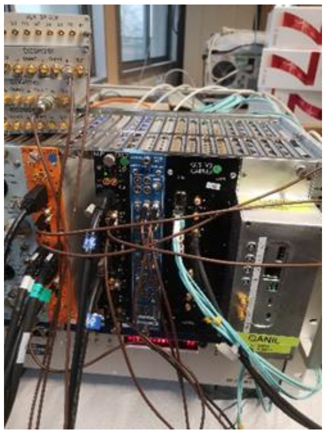


Figure 60 : Ganil Trigger Processor card on the right

The GTS Trigger Processor module is a nuclear physics trigger module based on the Xillinx Virtex-7 VC707 development board. It allows managing 8 partitions supporting individually up to 256 channels

Several tests were done in 2022 to finalize the trigger Processor development. The Trigger Processor was used with success for the AGATA campaign in LNL, Italy. The project closing meeting was organized in march and some fixes have been made. A git repository was created by developers to facilitate user access to the documentation and to the firmware and software upgrades.

4. Negma

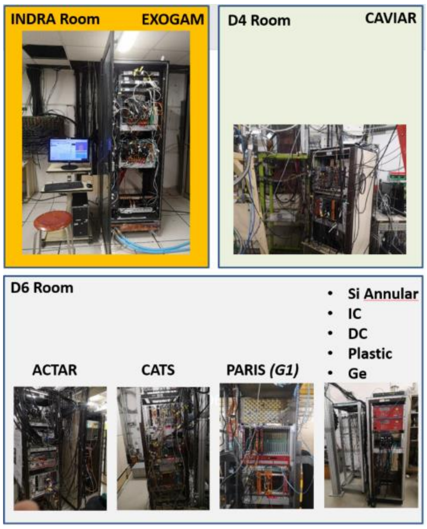
NEGMA is standing for "New Generation of Multi-function ADCs". It is based on a new Xilinx Evaluation kit ZCU216 to study the possibility of using the new generation of RFSOC-FPGA ADCs for nuclear physics. As a first step a firmware was written and a software developed for one channel to evaluate the performance of the system and to implement some usual algorithms for the proof of concept.

Figure 61 : Negma developpement card based on RFSOC-FPGA ADCs

5. Ubuntu 22 migration

Data acquisition software ran on operating system (OS) linux Centos7 since 2015. An up-to-date version of the operation system became crucial and it was chosen to move to Unbuntu 22.04. New OS means new compiler and new libraries. Each element software of acquisition needed a migration. So for GRU and RC, the most of the works was the update of code lines to be compliant to new compiler gcc11. An other issue to solve was the incompatible version of gsoap, the GANIL main protocol of communication between all entities of acquisition software. The Narval software needed a redefinition of context and upgrade of its looger Chainsaw with a specific version.

6. Lise 2022



The LISE2022 campaign has been a new and a big challenge for GANIL acquisition system. LISE2022 was based on several data acquisition systems assembled : ACTAR, CATS, EXOGAM, PARIS, ZDD, CAVIAR. It was a large challenge in terms of cabling and timing to allow all of them to work together. In particular, there was not enough place in D6 room and we had to split the system into several parts that added more complexity on cabling and on the GTS tree system (clock & time stamp). The successful experiment provided a lot of feedbacks to prepare new and more complex experimental configurations.

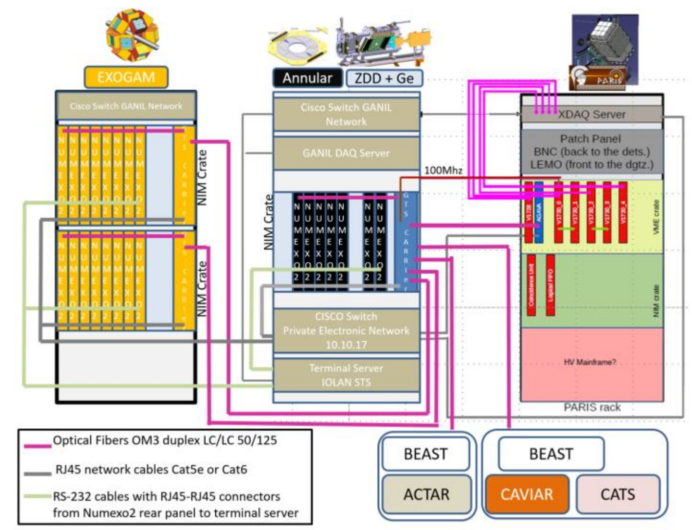


Figure 62 : Data Acquisition systems fo LISE 2022 Experiment

7. Data Policy, Data Management Plan

As a public research infrastructure, GANIL is required to respect the European open science policy and to make scientific research and the data it produces accessible to the general public. To facilitate this, GANIL relies on two documents, the Data Policy and the Data Management Plan. The first, the 'Data Policy', defines a certain number of rules that the experimenters hosted at GANIL are requested to respect.

In particular, all data acquired at GANIL must be stored on the servers available at GANIL.

The DMP, Data Management Plan, is intended to be more precise insofar as it applies to define the entire life cycle of experience data, from their production to their storage to their use by the laboratories and their publication. This document lists the metadata associated with a dataset; some of these metadata are mandatory in order to provide the minimum information to find the data. This includes the detectors used, the intensity of the beam or any other element that can help to contextualize the data taking to then facilitate their interpretation and the resulting conclusions. Once produced, this data is hosted on GANIL storage infrastructure on highly available servers. These servers are able to withstand the loss of several disks or servers without causing any loss of data. In operation about 8 months a year, the experiments carried out at GANIL generate about 1 petabyte of data. This amount of data corresponds to more than 200 days of HD video on these servers or to the digitization of the United States Library of Congress 55 times.

After a period of 1 year, the data produced is considered "cold". It is expected that, after a year, the raw data has already undergone pre-processing to remove "less relevant" information and no longer requires the same access or availability performance. The data is then transferred to capacitive servers for long-term archiving at the in2p3 computing center in Lyon. To do this, GANIL takes advantage of the RENATER network.

In accordance with the open science policy after a 3-year embargo period, the data produced at GANIL are made accessible to the public.

X. Realizations in Mechanics

This chapter describes some of the achievements of the Mechanics group of GANIL.

1. Cyclotron magnet cooling circuit Renovation

The cooling copper circuits of the cyclotrons date from the 1980s, therefore water leaks regularly appear on these circuits, in particular those of the RF cavities. These leaks generate machine downtimes, which have an impact on the scientific output.
In this context, it was decided to renovate the cooling circuit of the MSE3 magnet of the CSS2 cavity. This operation is a heavy operation, including opening and closing of the cavity, disassembly/assembly of the MSE3, and manufacturing of a new magnet cooling circuit.

Figure 63 : MSE3 Magnet inside CSS2

Figure 64 : CSS2 cavity opened

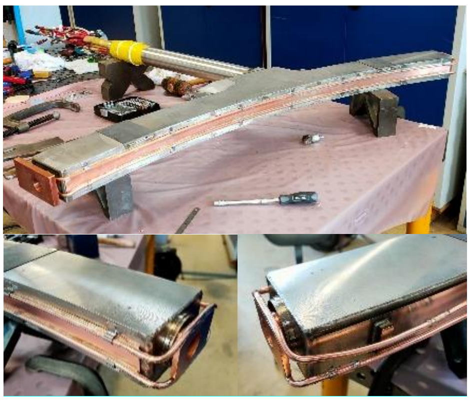


Figure 65 : MSE3 Renovation

2. REPARE Project

A high power irradiation station has been designed in the context of the REPARE project, which aims at producing up to 100 GBq of ^{211}At in 8 hours of beam time using the very high beam intensity available at the GANIL SPIRAL2 facility. The solid target station is conceived to dissipate up to 10 kW of beam power. This station includes :

- A cooling system combining direct water-cooling and target rotation, tested offline and demonstrated to be very efficient ;
- A dedicated current measurement method and beam synchronization with wheel rotation ;
- A reliable extraction system ensuring an easy and safe manipulation of the target rackets.

Detailed fluidic simulation calculations have been performed during the design process to ensure efficient cooling. Several offline tests, focused on the absence of water leak during rotation, cooling efficiency, beam current reading and racket extraction mechanism, have been conducted to confirm calculations and main functionalities.
The REPARE irradiation station is currently assembled. The cooling efficiency, current measurements and beam synchronization will be tested under realistic conditions with beam in 2023. The first ^{211}At production run might be planned in fall 2023 providing the tests are all successful.

This work is supported by the French Research National Agency under the contract ANR-19-CE31-0013-01.

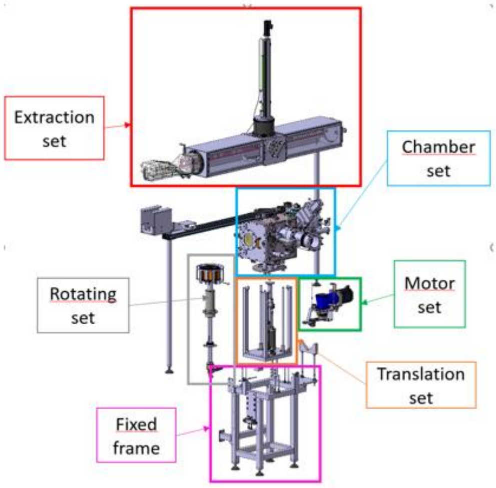


Figure 66 : High Power Irradiation Station

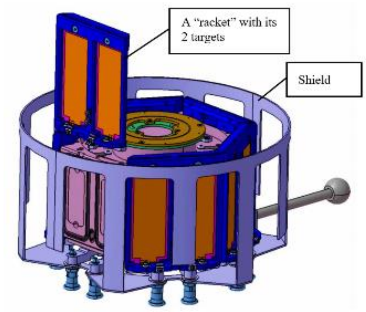


Figure 67 : Rotating Target

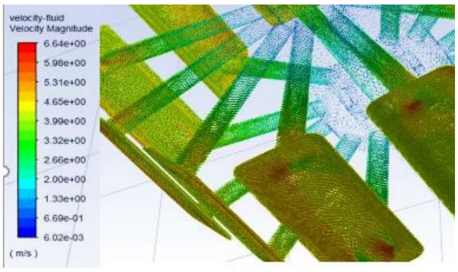


Figure 68 : Cooling Calculation

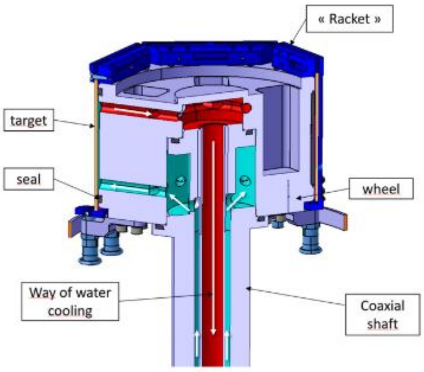


Figure 69 : Cooling System

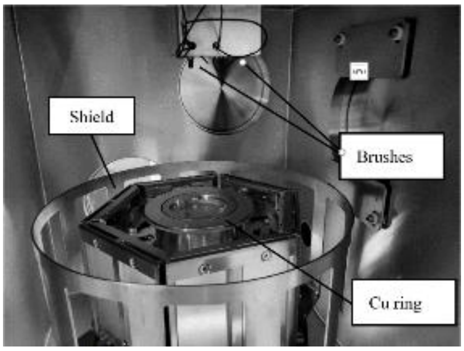


Figure 70 : Inside chamber

3. PISTA

The replacement of the VAMOS SPIDER detector by 8 PISTA modules will enable an identification of the nuclear transfer reaction with a very high precision. Considering the volume of the equipment, it was necessary to design a new VAMOS target chamber, using EXOGAM target loaders and guaranteeing the use of the multiwire detector 160mm downstream of the target.

The PISTA detectors are composed of couples of trapezoidal E- ΔE silicon, integrated in printed circuits with H&V tracks connected to the electronics by capton cables.

The supporting structure of PISTA is composed of an angularly adjustable part, on which is mounted an octagonal crown equipped with 8 curves rails, and allowing the alignment of the PISTA detectors. This structure is then mounted in the new target chamber.

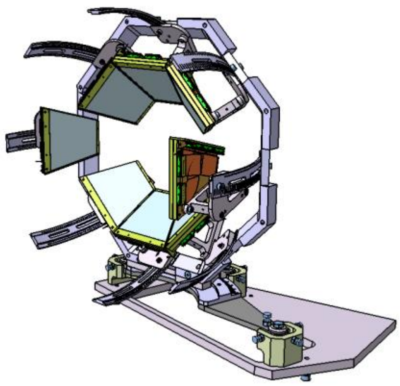


Figure 71 : Design of the supporting Structure

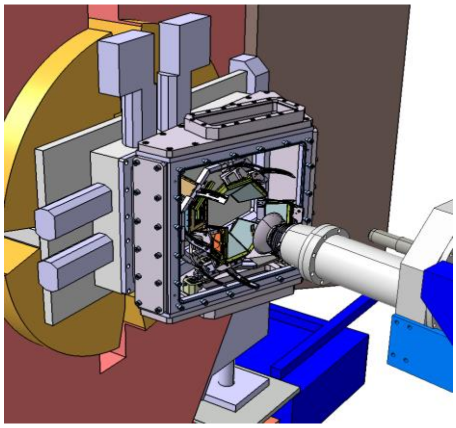


Figure 72 : Manufacturing of the supporting Structure

Figure 73 : Integration in the new target chamber

4. LINAC Pepper Pots for S^3 Beam

To enable the tuning of the SPIRAL2 LINAC tuning in S^3 spectrometer, it was necessary to design and manufacture a new pepper pot for beam intensity reduction. The objective of this equipment is to reduce the beam intensity with different factors : 1/100, 1/1000, 1/2000 and 1/12000. Mechanical design was conducted to lead to this design with 2 parallel sheets with Ø 0.025 mm holes.

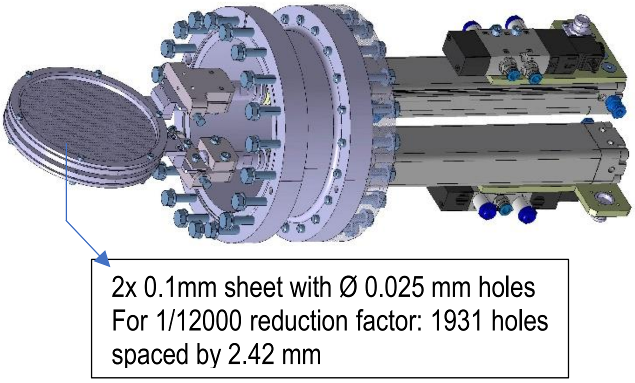


Figure 74 : Pepper Post design

5. NFS fixed Converter

For the production of neutrons, the NFS installation is equipped with a rotating converter designed by IRFU. In case of breakdown of this system, a fixed converter with cooled thick beryllium and a power deposit of 1.5kW was designed, allowing to produce intense neutron beams and to conduct experiments. Mechanical study was then conducted with the IRFU collaboration for thermal calculations.

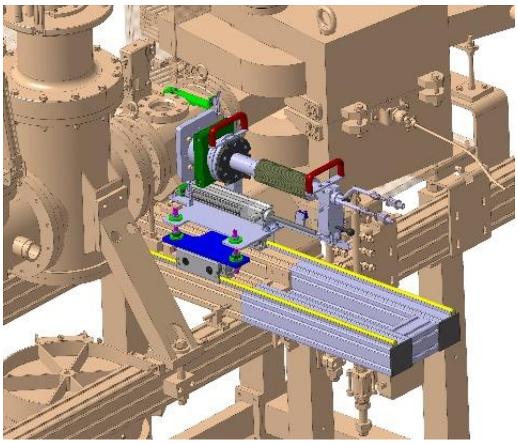


Figure 75 : Environment Fixed Converter

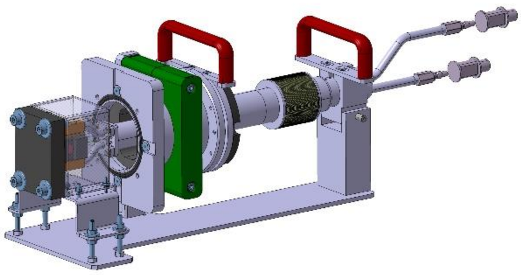


Figure 76 : Fixed converter design with its lead shield

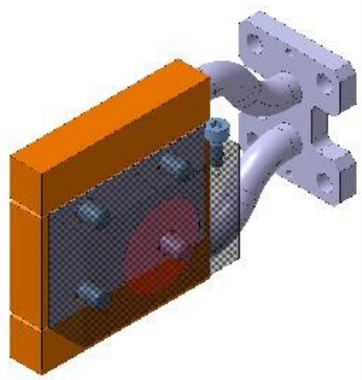


Figure 77 : Cooled fixed converter head

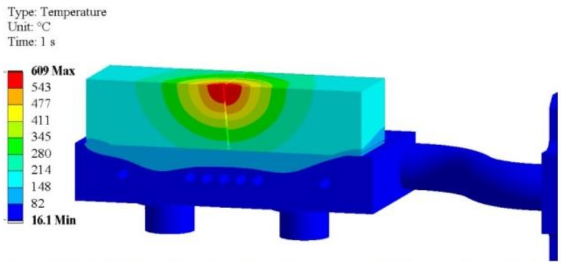


Figure 78 : Cooled fixed-converter head thermal calculations

XII. Detection and laser for physics

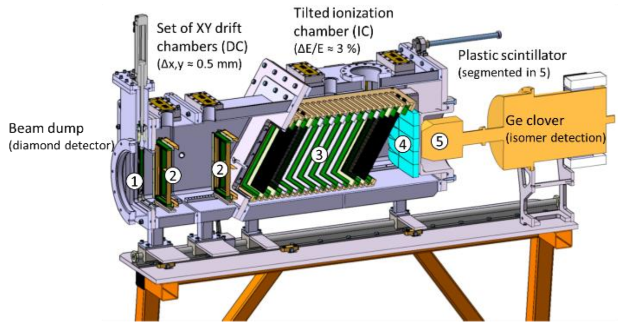
This chapter collects some of the realizations performed by the Detection and Laser for Physics group, in support to the experimental program.

1. LISE Specific detection 2022

ZDD project summary

The scientific program at LISE involves reactions with radioactive beams of intensities of 10^3-10^7 pps. These studies require to have detection system for identification of beam-like reaction products at angles ±4° (aproximatelly ±100 mrad) after a secondary target located in D6.2 hall.

ZDD (Zero Degree Detector) detection system provides identification of medium mass ion residues up to A ≈ 70 and determines their emission angles with measuring their energy loss ∆E in a tilted ionisation chamber, their vertical and horizontal position (X,Y) with a Drift chamber, and their total energy E_{tot} in a plastic/PM wall at intensities higher than 10^5 pps.



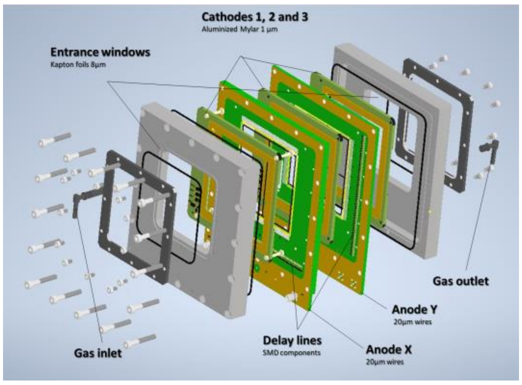
ZDD status

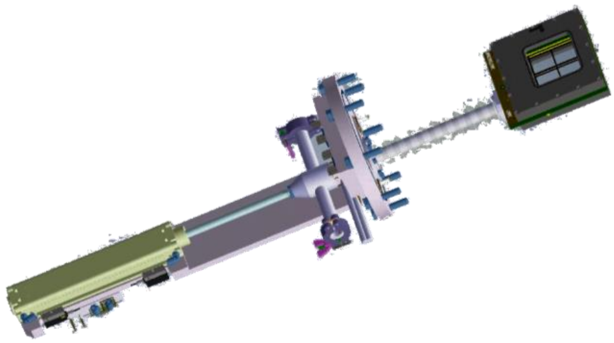
Conception and Design has been made in 2021. Assembly and integration for Lise 2022 campaign has been achieved and first exploitation has been realized in experiment E823_21 and E798_19.

DeLiCAT

New tracker DeLiCAT (DElay LIne CATs) for spectrometer LISE has been developed with the aim to replace existing CAVIAR tracking detector. The new detector has the same principle of operation with an active area 70 × 70 mm² with delay line signal readout. The detector consists of two sections with X and Y anode wires plans, operated with pure isobutane gas at about 8 mbar pressure. It can perform measurements of time and X-Y position for LISE beams. Using delay line readout reduces required number of electronic channels. New detector uses the same mechanical insertion flange than CATS detector. These solutions allow creating more cost-effective and standardized version of LISE trackers with improved performance.

Conception and Design has been made at the end of the year 2022. Assembly, test in exploitation are planned for 2023 Lise campaign.





2. R&D on gas recycling for ACTAR-TPC

Recent advance in active target detectors in which the detection gas can also serve as a target for nuclear reactions allows for a boost in exploring the unbound nuclei near the drift lines and the exotic associated nuclear phenomena. In experiments with low intensity radioactive ion beams, this detection technique that is based on a gas filled ionization detector can fulfill the requirement of thick target to get high reaction yield without deteriorating the energy resolution. ACTAR-TPC at GANIL has been working since 5 years and is used to reconstruct a 3-D mapping of the decay or reaction products from two dimensional projection of the tracks and electron drift time.

Some of the most common gases used in active target detectors are isobutane (iC4H10), hydrogen (H2), helium (He) or a mixture of gases to achieve better ionization gain factor, like CF4 mixed with He, methane (CH4) mixed with argon (Ar), etc... Gas purity is a key factor in ensuring optimum detector performance and it is thus important to pay attention to the molecular impurities that normally accumulate in the detector volume because of small air leaks or material outgassing.

Usually the detection chamber is continuously supplied with fresh gas and the used gas is released to atmosphere. Concerning the operational cost, open loop gas circulation is not possible in the case of using expensive gases like xenon (Xe), ^{3}He or ^{3}H. In addition, some experiments demand the use of greenhouse gases (GHG) like CF4, SF6 or C_3F_8 to achieve the physics interest, gases which cannot be released in the atmosphere. The 'closed loop' method permits a recycling by sending the released gas through a filtering system and a re-injection into the detection chamber. However, the quality of the recycled gas after cleaning must be satisfactory in order to keep constant the functioning point of the detector.

A new study, funded by Normandy region over 2022 and 2023, aims to investigate the effect of gas recycling on detector performances and try to stabilize the detector response over time ensuring a constant quality of the recycled gas. A wire chamber detector (Mayaito) was set-up in 2022 and coupled with a gas regulation system working in open or closed loop to perform this R&D topic. After the identification of various factors like temperature, electronics stability…the system is ready to be studied in a closed loop in 2023.

3. New detection systems for Spiral2 experimental areas

SIRIUS and S^3 diagbox in pre-commissioning phase

The multi-detector SIRIUS has been built since 2015, by a collaboration between IJCLab, IRFU, IPHC and GANIL. The full system has been installed in 2021 at GANIL in G3 area, for first tests. In 2022, The system has moved in G2 for two beam tests, one for Diagbox in LEB configuration and one for SED (Secondary electron detector) used in both configuration SIRIUS or LEB. SED, which has been developed at GANIL, is now completely characterized and ready to be used.
All the servitudes has been installed and are functional.

FALSTAFF in NFS for first exploitation

FALSTAFF detector is a collaboration between IRFU, LPCC and GANIL, to study fission fragment distribution at NFS. After an installation in G3 in 2021 for a first test in GANIL, it has been moved in G1 and coupled with VAMOS at the second arm place and commissionned during 2022 VAMOS experiment E826_21. At the end of the year, the system was moved to NFS for its first experiment E814_20. We were in charge of all the system integration and exploitation and also the maintenance of the ionization chamber and the two SED detectors, built at GANIL in 2021.

4. New Tracker CATS'UP

Project Summary

Beam detector system, CATS (Chambre A Trajectoires de Saclay), are used for more than 20 years to provide event-by-event particle tracking in experiments with radioactive beams at GANIL. It consists of two low pressure multiwire proportional chambers with one plane of anode wires placed between two cathode planes (active area: 70×70 mm2), segmented into 28 vertical and horizontal strips (2.54 mm wide). The anode wires deliver a time signal allowing a time-of-flight measurement with an accuracy around 300ps. The cathode strips are individually read out and the position of incoming particles is reconstructed using a charge centroid finding algorithm with a spatial resolution of 400 µm with a counting rate of 3.10^5 particles per second.

The front-end and back-end electronics are old and more and more difficult to maintain at the good level and the detector maintenance is very time consuming. That's why an upgrade of the electronics is planned, together with the project of improving also the detector design.

Project Status

Project has begun in 2020. In 2022, a second prototype detector with some improvement on gap homogeneity and better links on strips was built. In this prototype, the X and Y cathodes have similar design and all connections, strips and high voltages, are done without any soldering operations.
The prototype is equipped with new electronics, developed by LP2IB. The first prototype with new current preamplifier and SAM readout system, based on GET chip and commercial Z-board, has been tested. Some adjustments and precise characterisation are still to be done in 2023.

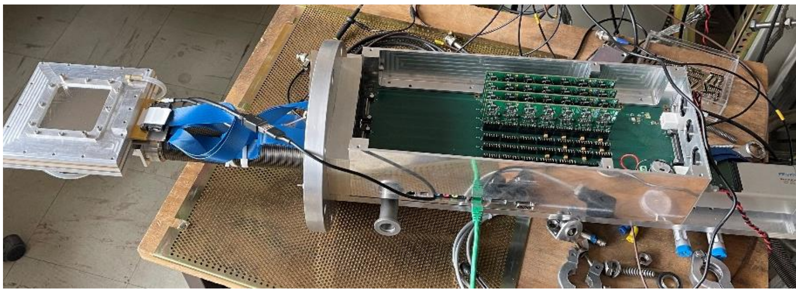
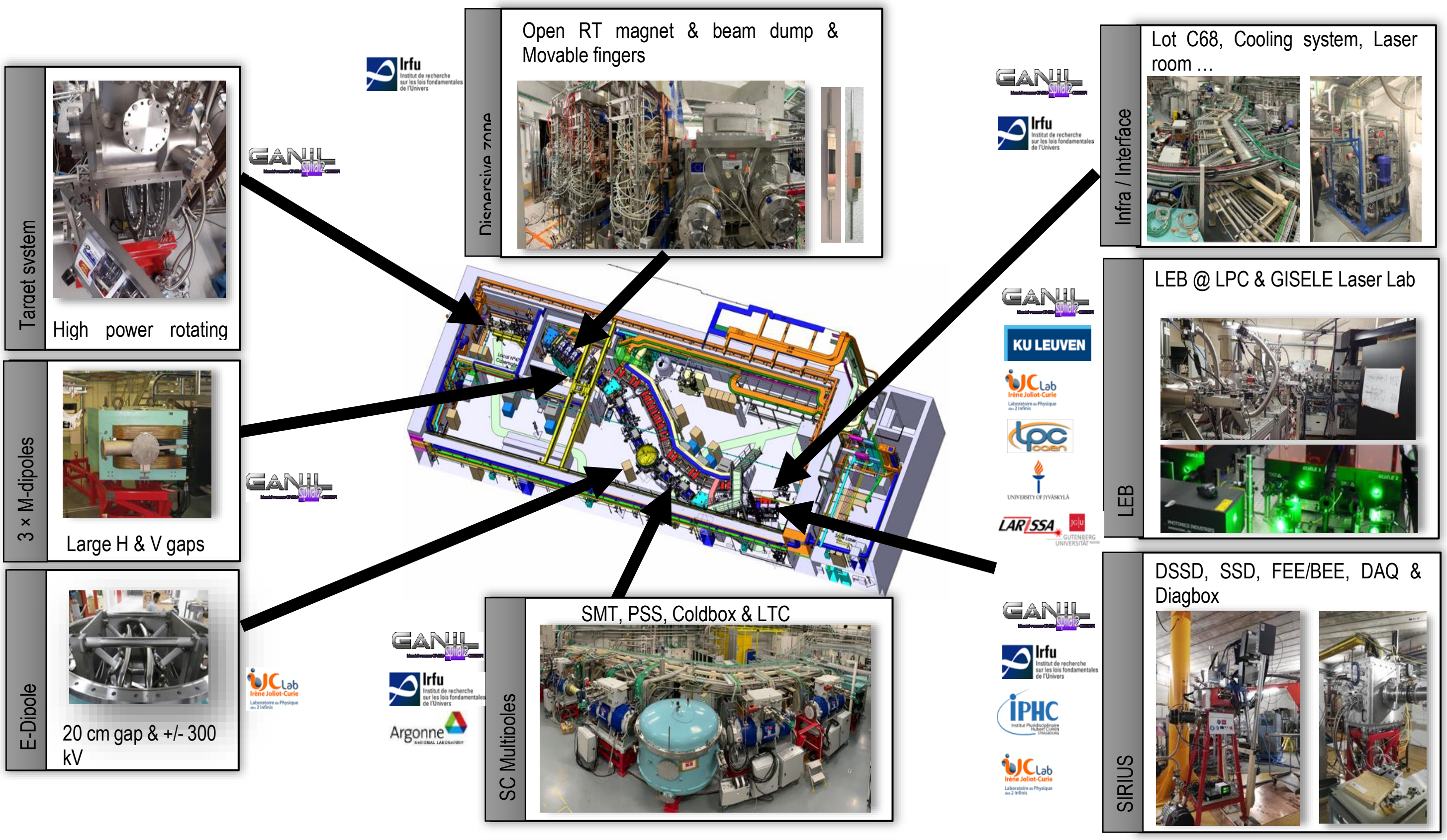


Figure 79 : CATS'UP on new vacuum thruster with all electronics (FE and BE) integrated

XIV. Report on SPIRAL2 scientific projects



- High selectivity > 10^{13} - High efficiency 50% - In flight mass separation > 1/450
- Versatility & unique instrumentation (SIRIUS – LEB)

Figure 80 :: Main equipment and detection of the Super Separator Spectrometer (S^3)

1. The Super Separator Spectrometer (S^3) for the very high intensity beams of SPIRAL2

The Super Separator Spectrometer S^3 is, with the NFS (Neutrons For Science) facility and DESIR experimental hall, a major experimental system developed for SPIRAL2. It is designed for very low cross section experiments at low (<15MeV/u) energy. It will receive the very high intensity (more than 1pμA) stable ion beams accelerated by the superconducting LINAC accelerator of SPIRAL2. S^3 will be notably used for the study of rare nuclei produced by fusion evaporation reactions, such as superheavy elements and neutron-deficient isotopes. Such experiments require a high transmission of the products of interest but also a separation of these nuclei from unwanted species. Hence S^3 must have a large acceptance but also a high selection power including physical mass resolution. These properties are reached with the use of seven large aperture superconducting quadrupole triplets which include sextupolar and octupolar corrections in a two-stage separator (momentum achromat followed by a mass spectrometer) that can be coupled to the SIRIUS implantation-decay spectroscopy station [2] or to a gas cell with laser ionization to provide very pure beams for low energy experiments [3]. S^3 is now in the installation and tests phases as show as shown in Figure 80.

In the following we will report on the last scientific objectives of S^3 as well as the current status of the facility and its different elements: target station, magnets, electric dipole, detection set-up, and a low energy branch.

Spectrometer and infrastructure

The Spectrometer is in its final construction/installation stage (85% completed). This process requires a large variety of skills from the GANIL technical groups and associated laboratories (Irfu, IJCLab). The spectrometer is based on highly advanced technological equipment: Superconducting Multipole Triplets, Electric Dipole, Target Station, Beam Dump, Diagnostics, Vacuum System, Cryogenic system, PLC and Control Command, …) and required complex infrastructure (Cabling - 80km cables and 4600 connectors, Clean Laser Room, Security Systems etc…).

To fulfill the specific constraints relating to a Basic Nuclear Installation “INB”, and to ensure the quality follow-up of the installation, a quality assurance plan is deployed.

The main technical achievements in 2022 are:

Infrastructure:

- Lot C68: All cable trays and electrical panels installed, cable connections on cabinets and part of S³ equipment's ongoing (100% of the 80 km cables in place and most of the 4600 connectors done)
- Laser room: Clean room in its final stage of construction (80% completed)
- Beam dump cooling system qualified in 2022
- Cryogenic transfer line: all sections of the cryogenic line have been installed and will be tested in 2023

Separator-spectrometer:

- Electric Dipole: integration in the beam line completed (Ti electrodes, HV feedthroughs) and connection to the power supplies expected in 2023
- Vacuum tests of most of the sections done
- 6 over the 7 Super Conducting Multipole Triplets (SMT) delivered
- Cryogenics cold box turbine crashed in 2022 that prevented to perform the qualification test of the SMT5 and SMT6.
- Beam dump: 2 chambers, 9 translation mechanisms, 5 fingers, shielding parts have been studied, tested and validated at Saclay. Some equipment is already been installed at S³. The dump plates and the cooling pipes assembly final architecture was frozen in 2022.

Figure 81 : Upstream Beam Line Installation

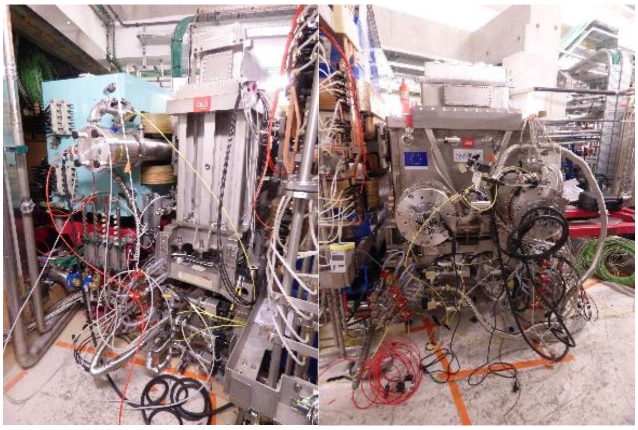


Figure 82 : Upstream and downstream Beam Dump installation

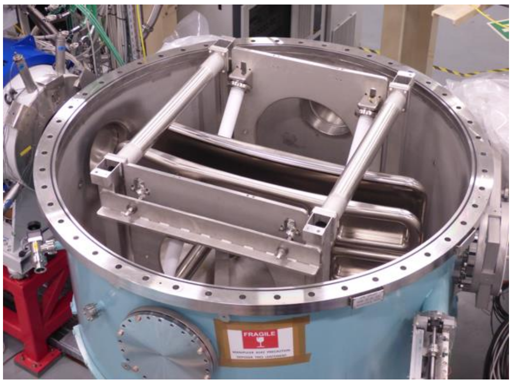


Figure 83 : Electric dipole installation

Figure 84 : Clean laser room

S³ has received funding from the French Research Ministry through the National Research Agency EQUIPEX (EQUIPment of EXcellence) under contract number ANR-10EQPX- 46, from the FEDER (Fonds Européen de Développement Economique et Régional) under contract number FEDER 0111251 – 21E03702, from the CPER (Contrat Plan Etat Région) under contract number 15P04209, from the U.S. Department of Energy, Office of Nuclear Physics under contract number DE-AC02-06CH11357 and from the E.C. FP7-INFRASTRUCTURES 2007 SPIRAL2 Preparatory Phase under grant agreement number 212692.

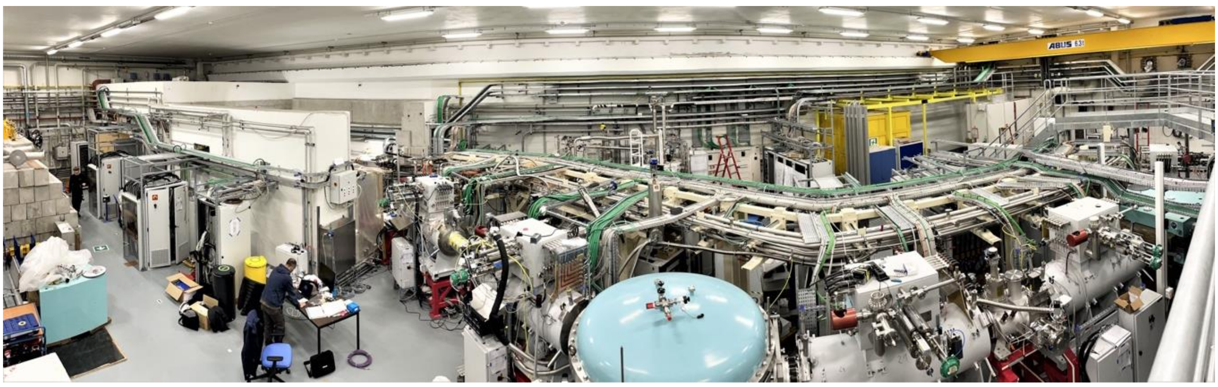


Figure 85 : S³ experimental area

2. DESIR

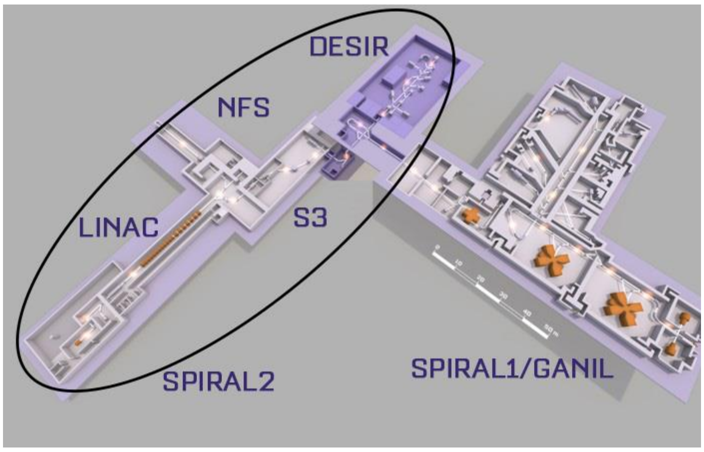
Presentation

DESIR (Disintegration, Excitation and Storage of Radioactive Ions) will be the new "low-energy" experiment room for GANIL and SPIRAL2. It will receive radioactive beams produced by SPIRAL1 and S^3 . The experiments carried out there will enhance our understanding of the fundamental rules governing the structure of atomic nuclei.
These experiments will be based on the following three pillars of ultra-low energy analysis: the study of radioactive decay modes, laser excitation and storage in traps.

- Radioactive decay studies can be used to determine the lifetime and structure of nuclei. These parameters are key to understanding the synthesis of chemical elements in stars.
- Laser excitation provides information on the shape, magnetism and quantum properties of nuclei.
- By storing ions in electromagnetic and optical traps, we can manipulate them to determine their mass or study their decay with precision.

DESIR facility

The DESIR facility is part of the SPIRAL2 framework project, and aims to create a third experimental hall for experiments on radioactive nuclei produced by the GANIL facility at very low energies. As such, it is positioned at the interface of the SPIRAL2 and SPIRAL1 beam lines.



The DESIR hall is a partially underground building with a surface area of 1,330 m2 and a height of 10 meters. The hall will accommodate 20 to 30 nuclear physics and interdisciplinary experiments using very low-energy radioactive beams. The two beam production sites (SPIRAL1 and SPIRAL2/S^3) will enable DESIR users to study a wide range of atomic nuclei with very varied characteristics, in a perfectly adapted environment. This diversity and the purity of the available beams will be the main features of this facility.

The DESIR facility will make ultra-pure samples of exotic nuclei available to its users, thanks to several in-line ion beam separation and purification devices designed mainly at LPC Caen and LP2i Bordeaux. More than 100 meters of transport lines, designed at IJCLab Orsay, will carry the beams to DESIR and its experimental facilities, and identification devices such as the one developed at the IPHC in Strasbourg will enable them to be qualified before use. At the same time, other conventional radiological monitoring and safety systems will ensure the safety of personnel and the protection of the environment, while enabling them to act permanently as close as possible to their devices.

The DESIR collaboration is made up of around one hundred French and European researchers, engineers and technical staff. These people are currently contributing to the design and construction of DESIR, as well as to the development of the experimental devices that will be used in DESIR.

Administrative authorizations

The Dossier d'Autorisation de Modification (DAM) for INB 113 for the construction of the DESIR facility was transmitted, in its second version, on March 22, 2022 to the Ministry of Ecological Transition -(and more particularly to the Mission de la sûreté nucléaire et de la radioprotection, MSNR) and to the Autorité de Sûreté Nucléaire (ASN). This version includes the response to the requests for additional information issued by the MSNR in 2021, following the ASN's pre-investigation of its first version, as well as a translation of the commitments made in parallel by RXS2 (Réexamen de Sûreté n°2) for INB 113, notably concerning the evolution of the platform for calculating the radiological impact. A new appraisal schedule running from March to October 2022 has been drawn up by the MSNR, ASN and IRSN, with a view to issuing a reasoned opinion on the DAM DESIR dossier by December 2022. Clearly on the critical path of the SPIRAL2-DESIR project, this new schedule consequently pushed back to spring 2023 the conduct of the Public Enquiry essential for obtaining the building permit (scheduled for May 2023) and promulgation of the modification authorization decree (scheduled for December 2023).
During 2022, the ASN (mainly on the regulatory aspects of the dossier) and IRSN (mainly on the technical aspects of the dossier) investigated the DAM dossier at a steady pace, with numerous constructive interactions (question/answer process formalized by letter + technical meetings on specific topics). No less than a dozen letters were exchanged during this period, including around a hundred questions requiring duly justified answers. The complementary nature of the project team and GANIL's CSQ ensured that responses were always received within the deadlines set by the authorities, even

during the summer vacations. Although some of the questions raised required further study and analysis of subjects that had not been sufficiently investigated beforehand, a formal opinion that the file was admissible was formalized at the end of November 2022.
During this period, the transparency of our exchanges with the authority and the Ministry of Economic Transition enabled us to prepare in the most efficient way possible the steps to be taken in the process of obtaining both the decree and the building permit. The Prefect of Calvados organized the prefectural phase of the administrative authorization process, i.e. the examination of the building permit application. At the same time, MSNR established the timing for the referral of the project to the French Environmental Authority (AE), in anticipation of its examination of the risk assessment and environmental impact study files, with the referral being made as soon as the ASN's reasoned opinion was received. In the end, at the very beginning of December 2022, our file was referred to the Environnemental Authorities and the application for a building permit was submitted to the Epron town hall.

Beam process

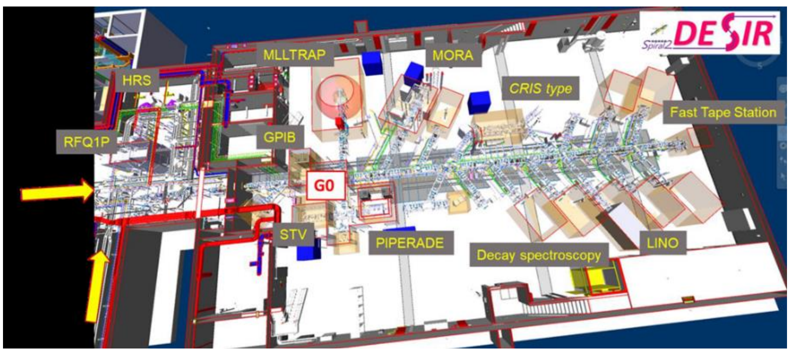
Installation of the LP2iB junction line demonstrator was completed in spring 2022, and developments during the year focused on the development of the various automation systems managing the vacuum and interfacing the optical and interceptive equipment. At the same time, standardized control applications based on those developed for the HRS spectrometer, which are currently being finalized, were developed for the lines.
At GANIL, the assembly of section 2 of the same transfer line continued intermittently, dictated by the need for human resources to operate the accelerators and experimental areas of the GANIL and SPIRAL2 facilities, as well as for the installation of the S^3 spectrometer and various other renovation/improvement projects underway at INB 113.

Figure 86 : Picture of the current assembly of the transport line for ion beams from the SPIRAL facility

Experimental qualification of the High Resolution Spectrometer HRS, with a mass resolution targeted of the order of M/DeltaM = 20000 in order to separate certain isobars, begun in 2019 at LP2I Bordeaux, has also continued. DESIR's HRS was recently equipped with an arbitrary signal generator, mounted on the high-voltage platform. The assembly of a first 45° mobile deflector was carried out in order to check that all the parts were correctly matching.
The entire GPIB control system was transferred to EPICS. Voltage probes based on the Rogowski coil principle have been produced for use in measuring GPIB RF voltages over an extended range. A test bench has been set up at LP2i Bordeaux to characterize the beam diagnostics used to commission the GPIB and PIPERADE devices, and which will equip the 3 keV beam transport line (L3K) between the GPIB and PIPERADE.
The development program for the RFQ-cooler associated with this spectrometer was relaunched at the end of November at LPC Caen.

Experimental process

The development program for the **MLLTrap** cryogenic trap at the IJCLab will take shape in 2022 with, on the one hand, the design and construction of its upstream RFQ-cooler and, on the other hand, the finalization of the installation of the upstream beam transport line (line evacuated at the end of the year).
The LPCTrap development program officially became the **MORA** program (@DESIR). The trap, technically developed jointly by the LPCC and GANIL, was installed in the Finnish laboratory at Jyväkylä to enable it to be commissioned, fine-tuned and finally run its first campaign. The results obtained were extremely encouraging, but clearly highlighted the importance of the intense radioactive beam purification program that DESIR has set itself as its main objective in terms of beam handling.
In 2022, the **PIPERADE** cryogenic trap development program focused on the activation of its two resonant trapping zones and the transition process from one to the other. The study of a tool specifically adapted to these delicate adjustments, an imager, was studied for commissioning at PIPERADE in early 2023 at LP2I Bordeaux.
More generally, the layout and phasing of the experimental devices in the experiment hall has evolved significantly over the year (see next figure). Operating scenarios have been drawn up to enable the physical and functional breakdown of the various high-voltage platforms required on the GPIB reference, and to specify the timing system requirements for beam delivery operations in the hall.



3. NEWGAIN

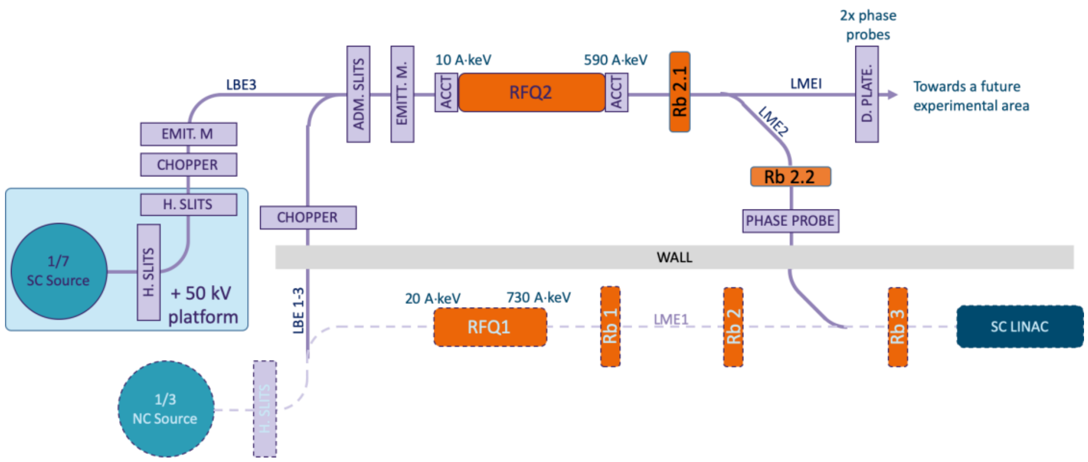


Figure 87:Schematic diagram of the new injector

The NEWGAIN project (NEW GAnil INjector) aims to construct a second injector A/q=7, so as to produce very intense heavy-ion beams up to uranium, well beyond the performance of the existing injector of the SPIRAL2 linear accelerator. With the addition of this new injector, the SPIRAL2 LINAC will deliver, within its energy range of operation, the most intense beams in the world over a large variety of ions (ranging from protons to uranium).
The second injector is designed to be fully compatible with the existing facility and to further enhance its 'multi-user' capabilities. It is composed of the following:

- A high-performance superconducting ion source (1/7 SC Source)
- A first low energy beam transport line (LBE3) connecting the superconducting ion source to the Radio-Frequency Quadrupole (RFQ2).
- A second low energy beam transport line (LBE1.3) connecting the existing ion source PHOENIX V3 (A/q=3) to the RFQ2
- An RFQ2 that will accelerate heavy ions up to the injection energy for the superconducting LINAC
- A medium energy beam line (LME2) connecting the RFQ2 to the LINAC, with a possibility to send the medium energy beam (via LMEI) to a future experimental area (to be defined).

A schematic diagram of the new injector is presented in Figure 87.

The NEWGAIN project preliminary design phase started on May 7th 2020, and the detailed design phase started in June 2021.
The project is organized through a broad national collaboration, involving a large number of French laboratories from CEA/DRF/IRFU and CNRS/IN2P3.
The production and validation of the consortium agreement for the Equipex (funding of 13,7M€ out of 20M€ for equipment for the Construction phase) was completed in September 2022, and the consortium agreement signed by all partners was submitted to the ANR in December 2022.
In 2022, studies have progressed, with all integration constraints taken into account on an ongoing basis. The final result of the injector integration is shown in Figure 88. All aspects relating to equipment installation, maintenance operations and security conditions have been taken into account.

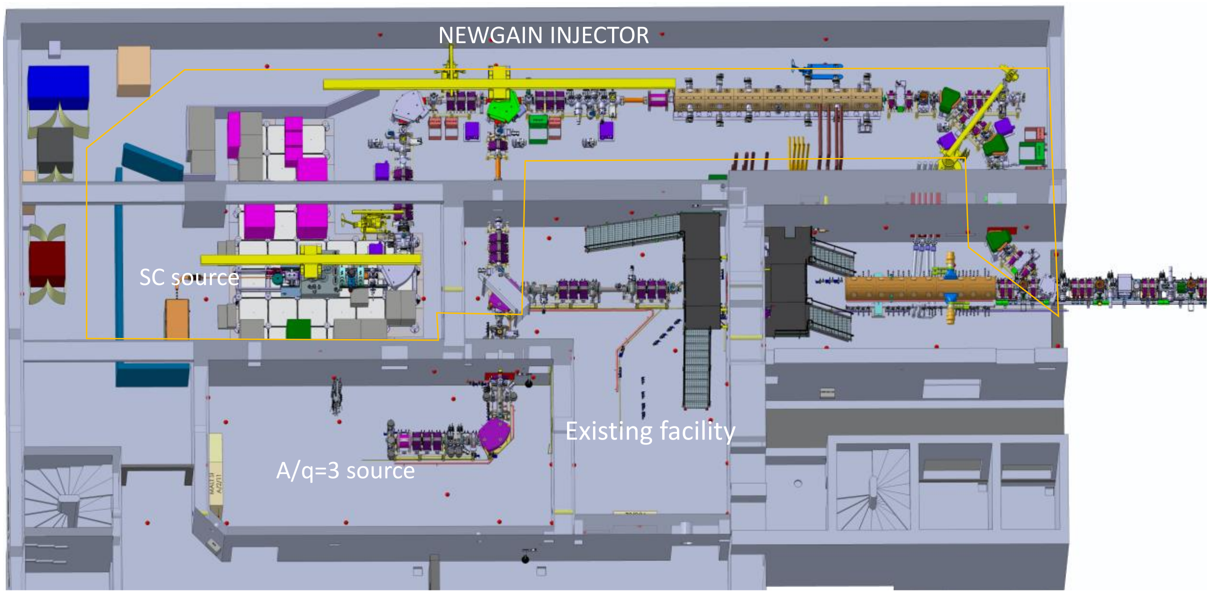


Figure 88 : View of the injector integrated inside the existing cave and with the existing beam lines

One of the most critical points in terms of integration is the connection with the existing MEBT line, as the space left free for the addition of the dipole and its ancillaries is extremely limited, as shown in Figure 89.

The general technical specifications have been defined with the whole project team, with the aim of taking them strictly into account during the detailed design of each piece of equipment.

The final choice for the beam diagnostics has been done, the vacuum system has been defined, and the technical specifications for each sub-system have been written, in order to be ready to launch the calls for tenders in 2023, the vacuum components being the first equipment to be ordered.
The power supplies for the beam line magnets have been defined. The prototype of a combiner cavity for the RF system test bench was manufactured at GANIL and the first RF tests could start before the end of 2022.

Some specific development for the control system started (example: emittancemeter) and the general technical specifications for the control system were sent to the whole project team, in particular to the collaborating partner laboratories that will develop some parts of the control system.
Xrays measurements have been performed with the existing SPIRAL2 rebunchers, in order to define the various operation modes for the future new rebunchers, radioprotection calculation have been performed to validate the wall crossing fillings, and the preliminary safety studies have been started.
The technical specifications have been drawn up for project management assistance in the design and implementation of building works (emergency exit, wall crossings) and infrastructure modifications.
The validation process by the future exploitation group, of the technical choices having an impact on the injector operation, was launched in autumn 2022. The Ion source-High voltage platform will be reviewed in 2023, the study of this part of the project being in a less advanced stage.

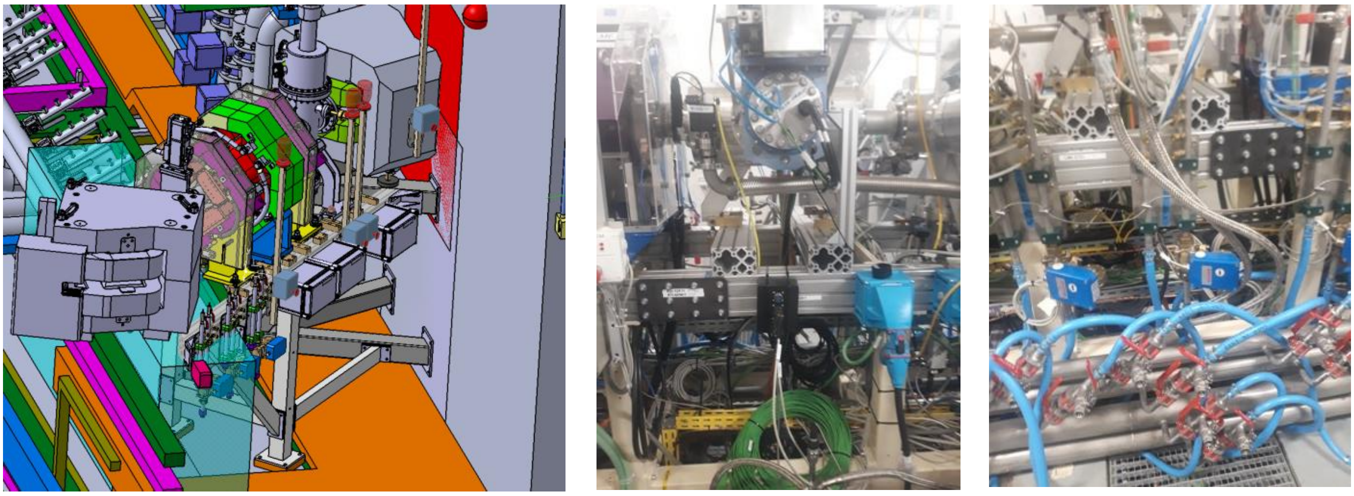
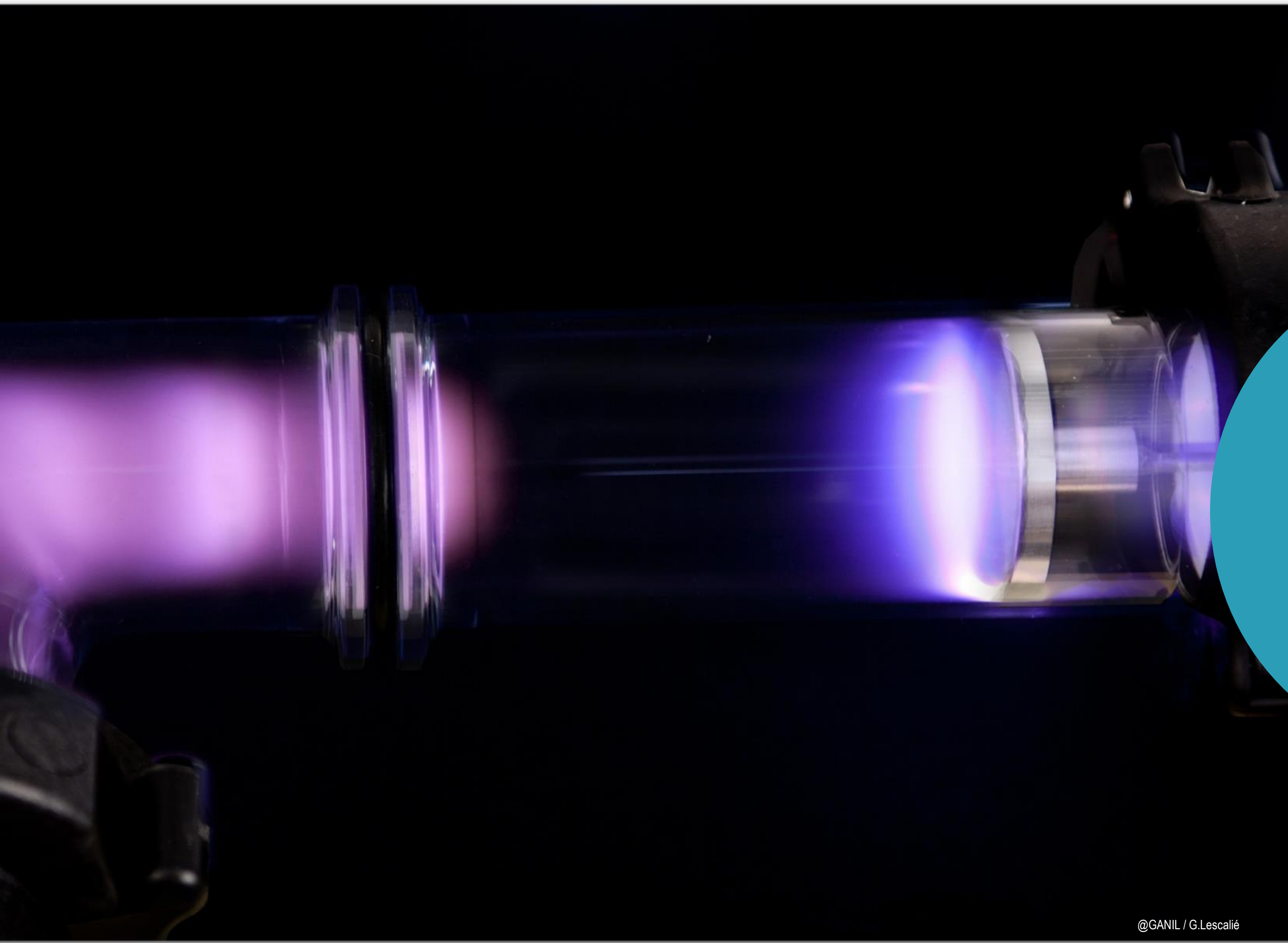


Figure 89 : 3D view and photos of the injector connection zone in the existing MEBT line

04 | SUPPORT ACTIVITIES



I. Environemental report

1. Radioactive releases

The nuclear facility GANIL is under supervision of the french Nuclear Safety Authority (ASN) which gave in 2015 the authorisation to atmospheric radioactive emission for the GANIL and for SPIRAL2 with limits for each facility (see table below). The ASN defined also the methods to monitor and measure the released radioactivities. GANIL carries on-going monitoring in both chimneys and each month, provides the quantity of radioactivity released to the Authority.

GANIL	Tritium (Bq)	Noble gas (Bq)	Iodines (Bq)	Other β and γ emitters (Bq)
Annual limit for GANIL	2.10E+09	3.27E+10	1.94E+08	9.70E+12
Release in 2022	9.220E+07	4.462E+09	2.450E+05	4.903E+11
% release in percentage of the annual limit in 2022	4.39%	13.65%	0.13%	5.06%

SPIRAL2	Tritium (Bq)	Noble gas (Bq)	Iodines (Bq)	Other β and γ emitters (Bq)
Annual limit for SPIRAL2	6.50E+09	2.20E+12	5.00E+05	1.40E+12
Release in 2022	2.599E+08	3.620E+10	1.153E+05	4.689E+11
% release in percentage of the annual limit in 2022	4.00%	1.65%	23.06%	33.49%

The annual limits were respected all along the year and the relases were largely below thoses limits.

The dosimetry of the population around the GANIL due to those releases in 2022 was estimated below 1 µSv.

2. Environmental monitoring

The radiological monitoring of GANIL's environment is defined by the regulation and the french Nulear Safety Authority (ASN). Certified laboratories analyse each month 80 to 90 samples of air, water, plants and milk and once a year, some soil samples and agricultural products. GANIL has two air monitoring stations. On-going irradiation monitoring are carried on with detectors in those stations and dosimeters around the site and in towns near GANIL. All the radiological values are available on the official website for the radiological environmental monitoring in France: https://www.mesure-radioactivite.fr (available in English).

All the results are under the detection limits except a few rainwater measurements of global beta emitters staying nevertheless inside natural level standards.
The activity and releases of GANIL's facility did not involve any increased level of radioacitivty in its near environment.

Non radioactive releases

The main risk concerns the cooling towers of GANIL's and SPIRAL2's facilities releasing steam. The monthly water analysis showed the absence of legionella bacteria in water.

GANIL's activities does not induce specific non radioactive release in the atmosphere. The sole releases are due to the heating system burning gas and the burning of diesel for the periodic tests of electric generators needed for safety. The quality of the effluent are controlled regulary and meet the standard values.
GANIL's facility took a few years ago some measures to restrict the release of perfluorocarbon gas used in detectors. The release of those gases were of 13 kg in 2022 which is equivalent to 85 tons equivalent carbon dioxide. GANIL will continue to study how to reduce the release of such gases.

Liquid effluents

Wastewater are transferred to the public sewerage system (19 000 m^3). An accredited laboratory analyses the quality of wastewater with radiological and chemical tests 4 times per year. In 2022, all measured parameters were under the limits required by the Nulear Safety Authority and the local public department for water.
No effluents containing tritium were transferred to the public sewerage system in 2022.

Wastes

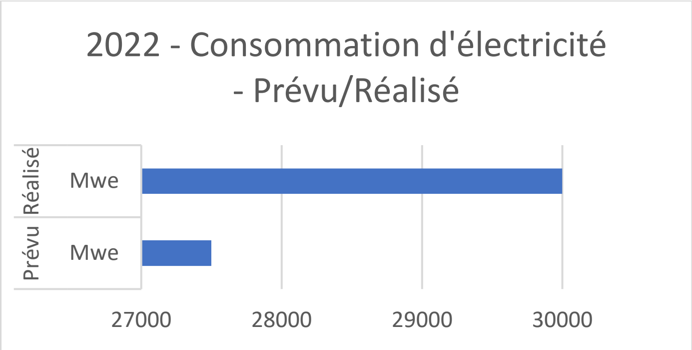
Dangerous wastes were produced in larger amount than usual on GANIL site in 2022 in comparison of the precedent years due to cleaning of old chemical products (from cooling systems, machining,…). Dangerous wastes are now followed up using the new official website plateform “Trackdéchets”.
Due to renovation works of ADI project, the quantity of non-recycled waste were high in 2022 (36 tons), twice than usual.
In 2022, a new building was put into operation to store the radioactive wastes. About 10 tons of very low level activity waste are waiting for sorting or transportation to the French National Agency for Nuclear Waste (ANDRA).

II. Energy Consumption

GANIL consumption of electricity, gas and water is correlated to its experimental program. Depending on the configuration and infrastructure used for experiments, energy and water consumption levels may therefore vary considerably.

Electricity consumption 2022

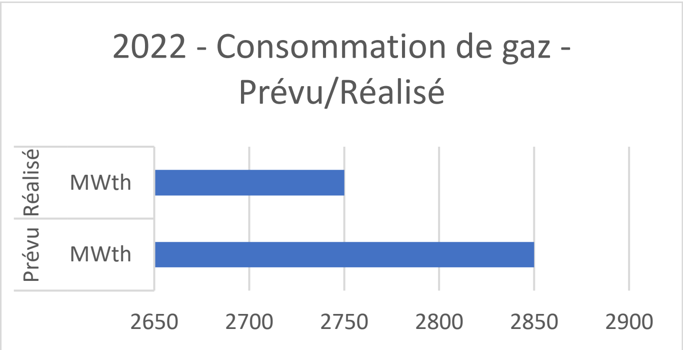
In 2022, forecast consumption, based on feedback from previous years, was estimated at 27.5 Gwe; actual consumption in 2022 was 30 Gwe.



Power consumption was around 10% higher than expected, despite a slightly reduced operating schedule. The main causes were operating contingencies and higher temperatures.

2022 gas consumption

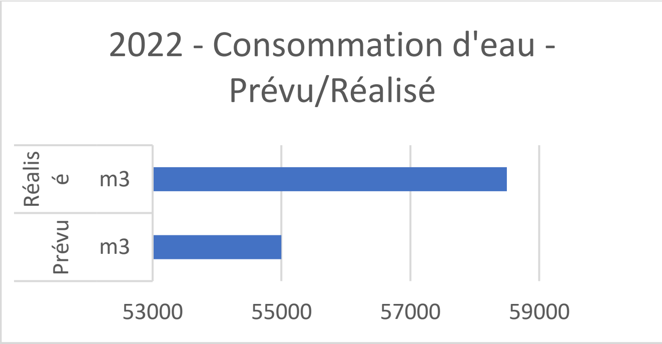
Heating of the buildings is the main origin of gas consumption. It depends mostly on winter temperatures.



Consumption was around 5% lower than expected, given the higher seasonal temperatures.

2022 water consumption

Consumption was about 6% higher than expected, although the duration of the operating schedule was slightly reduced. The main causes were operating contingencies and higher seasonal temperatures.



Sobriety plan

In 2022, in response to government requests, GANIL has embarked on a sobriety initiative by setting up a working group - GT Sobriété - to define a sobriety plan to reduce its energy consumption, its carbon footprint and, more generally, its environmental footprint.

A 10% reduction in energy consumption by 2024 compared with 2019 is expected. In accordance with the tertiary sector decree, the sobriety plan identifies actions that will enable the company to achieve the following targets for tertiary sector buildings:

- 40% reduction by 2030
- 50% reduction by 2040
- 60% reduction by 2050

The sobriety plan aims to implement short-, medium- and long-term actions:

- Short term: installation of energy meters, photovoltaic panels, a communication plan to promote low electricity consumption, changes to heating and air-conditioning settings, etc.
- Medium-term: deployment of initial actions (see short-term), regulatory and improvement energy audits, renewal of the energy audit, etc.
- Long term: work to improve the energy efficiency of tertiary buildings, installation of a photovoltaic panel plant on campus, introduction of smart building management, recovery of energy dissipated by various processes, etc.

III. Radiological report

The Service for Radio Protection, SPR, is responsible for the tasks entrusted to the Employer's Radiation Protection Advisor (CRP), whose role is to assist the employer in the prevention of risks of exposure to radioactivity.
The SPR service manages radiation protection issues related to projects, as well as those linked to the operation of an INB and its protective equipment, some of which is classified as EIP.
The data presented below show the radiation protection balance for personnel in 2022.

The following table shows the integrated doses (external exposure) for GANIL staff and some physicists from foreign laboratories visiting the GANIL site.

Catégories	Nombre total de personnes	Répartition par classe de dose (mSv)			Dose collective (H.mSv)
		< SD(3)	SD< dose <2	>2	
CEA (1)	122	85	37	0	4,56
CNRS (1)	189	136	53	0	10,26
Physiciens extérieurs (2)	56	52	4	0	2,27
TOTAL	**367**	**273**	**94**	**0**	**17,09**

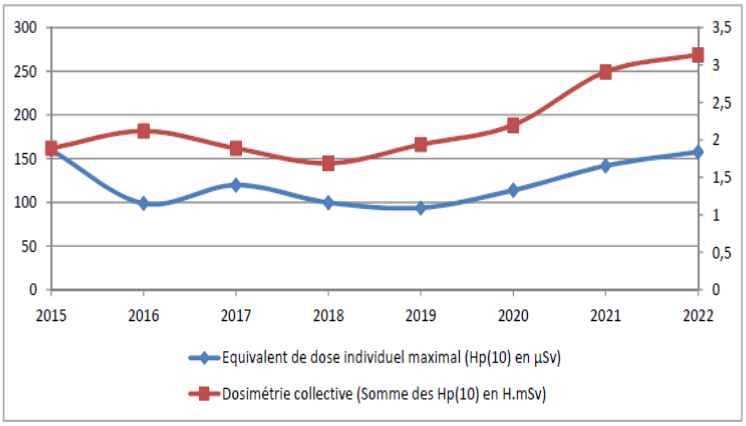
(1): this workforce includes interns, supervised fixed-term contracts and CIMAP agents working on the site (2): foreign experimenters and all non-CEA or CNRS contracts

In 2022, 367 people were monitored by GANIL for remote dosimetry service. The number of staff whose dose is between the detection threshold (0.05 mSv) and the 2 mSv limit has increased. This is due to the greater number of interventions on SPIRAL 2, as the SPIRAL2 facility shows slightly higher doses than GANIL cyclotrons.

	Dose Hp(10) (µSv)	0 à 20	20 à 50	50 à 100	100 à 150	150 à 200	200 à 250	250 à 350	350 à 550	550 à 1000
Nombre d'agents	GANIL	227	29	8	1	1	0	0	0	0
	CIMAP	37	0	0	0	0	0	0	0	0
	Expérimentateurs extérieurs	189	2	0	0	0	0	0	0	0
	Entreprises extérieures	212	0	0	0	0	0	0	0	0
	TOTAUX	665	31	8	1	1	0	0	0	0

Tableau 1 : monitoring by operational dosimetry

In 2022, 665 people were monitored by operational dosimetry. The cumulative dose equivalents recorded show that the facility operation is not irradiating, as very low doses are reccorded. The distribution is more or less the same as over the last 5 years.
Collectively, the slight increase observed can be explained by greater operation of the SPIRAL2 facility. This is in addition to the results for the original facility. Collective dosimetry measured showed a slight increase. It is 3.14 H.mSv



Tendance sur les 8 dernières années

In 2022, deferred and operational dosimetry will generally remain at very low levels.The values for collective deferred dosimetry (7.7 H.mSv) and collective operational dosimetry (3.14 H.mSv) are low with respect to the facility's annual collective dose target.
The difference between deferred and operational dosimetry monitoring is explained by deferred dosimeters not returned or returned late.
As a reminder, GANIL's dose constraints are :
- effective dose over a sliding 12-month period ≤ 2 mSv for exposed personnel
- daily effective dose ≤ 50 µSv.
- annual collective dose ≤ 10 H.mSv.
These constraints were therefore respected during the year 2022.

In 2022 various actions were carried out by the Radioprotection Service:
- Training :
  - 1 triennial radiation protection refresher course for 21 GANIL staff.
  - Training sessions for new visitors are held every other Tuesday, i.e. 27 sessions for 232 people, including 128 external participants.
  - 4 training sessions for personnel working in the actinides zone at Spiral 2, for 16 people.

IV. Safety and Security report

On its campus, GANIL has a Basic Nuclear Facility (INB 113) housing the particle accelerators and associated experimental areas, an establishment open to the public (ERP, the guest house), a non-INB building used mainly for offices, and non-INB utilities subject to ICPE (Installations Classées pour la Protection de l'Environnement) regulations.
The SSRE group manages issues relating to these themes for all facilities, whether or not they are part of the INB.
Below are the main indicators and issues dealt with in 2022;
Conventional Safety

Data on accidents at work show a slight drop compared with previous years. The number of occupational accidents reported in 2022 was 1, with a frequency rate (Tf) of 0.24 and a severity rate (Tg) of 0.02. These results are due to systematic safety visits to the experiment rooms and awareness-raising sessions.
Each new experimental setup underwent a safety inspection before the start of the experiment. In addition, the safety service has set up awareness sessions on the wearing of Individual Protection Equipment.

In 2022, National Nuclear Safety Authority carried out three inspections at GANIL, focusing on radiation protection of workers, static and dynamic containment, and project management. Three significant events were reported, concerning the failure of some CO_2 fire extinguishers to meet their re-test dates, the failure of fire dampers and the loss of the first containment barrier of the NFS converter vacuum vessel.

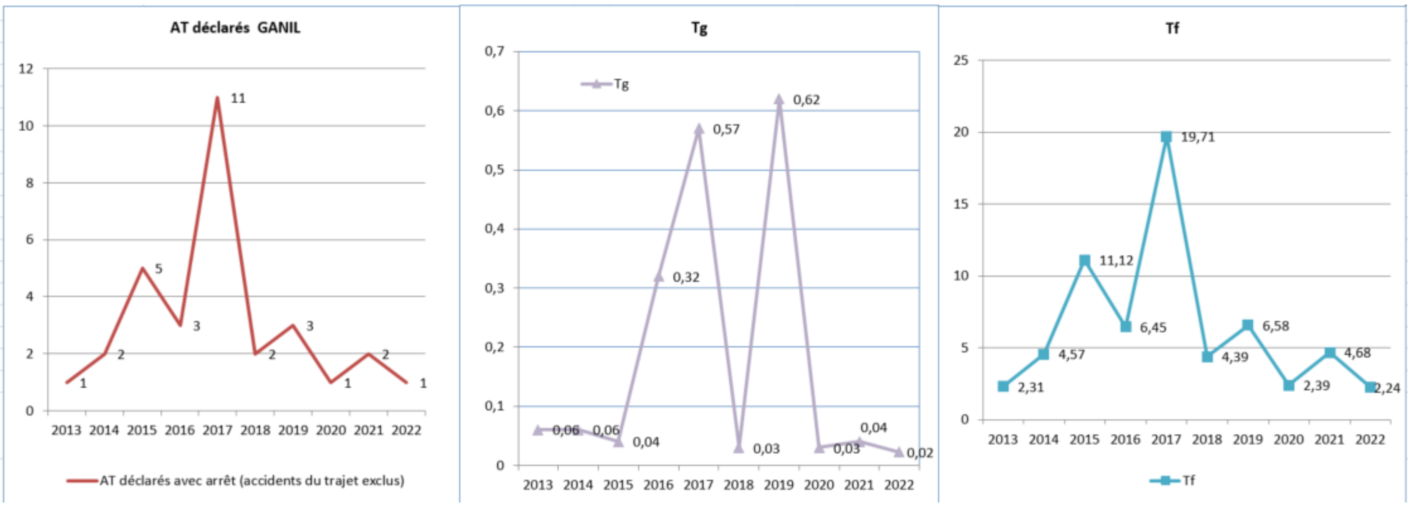


Figure 90 : Data on accidents at work

V. Report on infrastructure projects

1. RXS1 : First Safety Reassessment of the 113th French Basic Nuclear facility

In accordance with the French Environment Code, GANIL, which operates a nuclear safety facility, INB 113, must carry out a safety reassessment every 10 years to check that its facilities comply with the regulations, and to ensure the level of safety. The French nuclear safety authority (ASN) conducted the first reassessment of INB 113 (113th French Basic Nuclear facility) between 2011 and 2015. This investigation resulted in an action plan based on the conclusions of the investigation and GANIL's commitments to the ASN. This plan covers a series of actions for the 5 cyclotron accelerators and associated experimental rooms, with a timetable extending to 2023 and representing an investment cost of 12 million euros.

The main points of this action plan are set out below:

- Commissioning of a new waste storage area to improve containment and separate waste types (solid, liquid, low-level activated, very low-level activated, etc.):
  - Authorisation for commissioning in 2021 and nominal operation in 2022, as shown in Figure 94
  - Installation of the waste sorting, characterisation and repackaging area completed

Figure 91 : New waste storage area

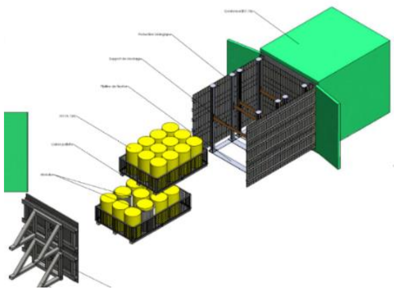


Figure 92 : Container number 2 - Biological protection + ATEX

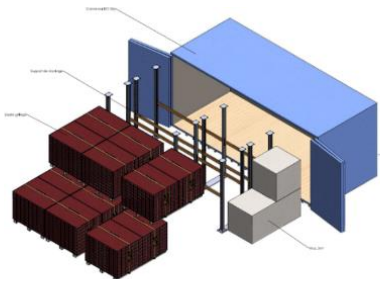


Figure 93 : Containers number 7 & 8

Figure 94 : Waste storage area and waste sorting, characterisation and reconditioning room

- Studies and implementation of measures to improve smoke extraction and reinforce the fire stability of the original facility's structures (cyclotrons and experimental rooms)

- This latest project, known as ADI (Improving Fire Protection), started in 2021, with commissioning expected in 2023. It involves carrying out the following works as shown in Figure 95:
  - flocking of metal structures
  - installation of 2-hour fire-stop partitions
  - caulking hoppers and wall penetrations
  - installation of smoke curtains
  - smoke extraction systems
  - civil engineering to recover extinguishing effluents

Figure 95 : Smoke extraction and ventilation systems, fire compartmentation of premises, flocking of metal structures and 700m3 fire water collection tank.

Almost all the work will have been completed by 2022, and 2023 will see all the reservations removed, and the new facilities handed over and brought into service.

2. RXS2 : Second Safety Reassessment of the 113th French Basic Nuclear facility

The report concluding the second reassessment under the French Environment Code was submitted to the French Nuclear Safety Authority (ASN) in 2021. Investigation by the ASN is scheduled for 2023.

The various analyses carried out as part of the second safety reassessment show that a large number of operating reference documents (procedures, operating methods, instructions, forms, etc.) need to be revised in order to incorporate regulatory requirements, the reorganisation of the laboratory in 2019 and certain process improvements (periodic inspections, waste management, organisation of radiation protection, etc.).

In particular, several new Activities of Importance for Protection have been identified:
- assessing the radiological consequences for the environment and for personnel,
- monitoring and accounting for radioactive effluent discharges,
- environmental monitoring.

However, despite the improvements that need to be made, experience feedback and analyses relating to environmental compliance show that staff dosimetry and the impact of normal operation of the INB are very low.
This finding is consistent with the conclusions of the first safety reassessment, which gave rise to numerous major modifications (LED, Maco, ADI projects, refurbishment of the wastewater network, etc.).

The studies for the second reassessment resulted in a list of around 200 actions spread over a 5-year action plan. The first list of actions (~26) was therefore triggered in 2022 and will be completed by mid-2023.

In addition, in order to limit the impact on internal human resources, an assistance service has been defined in 2022 in order to launch a consultation and start this service in 2023.

3. CYREN (CYclotrons RENovation) : Refurbishment of the GANIL cyclotrons facility

GANIL cyclotrons are used not only in the domain of nuclear physics and astrophysics but also for interdisciplinary ion beam physics like radiobiology, dosimetry, hadrontherapy, study of irradiated materials, nanostructuration, molecular collisions, or applications related to space industry (tests of radiation hardness of electronic components). In the near future, they will also be particularly essential to address the DESIR scientific program based on the exotic beams produced by the SPIRAL1 facility.
However, the cyclotron breakdown rate has increased over the last 5 years from about 5% before 2017 to 26% in 2022, due to the concentration of the laboratory's human resources on new SPIRAL2 projects over the last 10 years, turning away from cyclotron maintenance programs. Curative maintenance work has therefore increased and become too important.
GANIL cyclotrons are 40 years old and a renovation plan of this 'historic' part of the facility is required to maintain and reinforce the scientific programs for the next decades.

In this context, in 2022, the **CYREN** (CYclotrons RENovation) project is considered, with two objectives of the project
- **Purpose n°1** : keep the facility in operational conditions for at least 20 years (Maintenance in Operating Conditions (MOC))
- **Purpose n°2** : optimize manpower needed for maintenance and operation after refurbishment

The technical scope of the project is broken down into 3 parts:
- Cyclotrons and experimental caves
- Infrastructures and utilities
- Safety / Security / Radioprotection Systems :

The main topic for the cyclotrons is the radio-frequency cavities for the 2 separated sector cyclotrons (SSC) as shown in Figure 96. The major risk is an internal leak in the cooling circuit, which would be impossible to repair as it would be unreachable.
The risk analysis defined 2 different scenarios (reference and high), one where only one new cavity is manufactured and an old one becomes a spare, the other where all 4 cavities are changed.

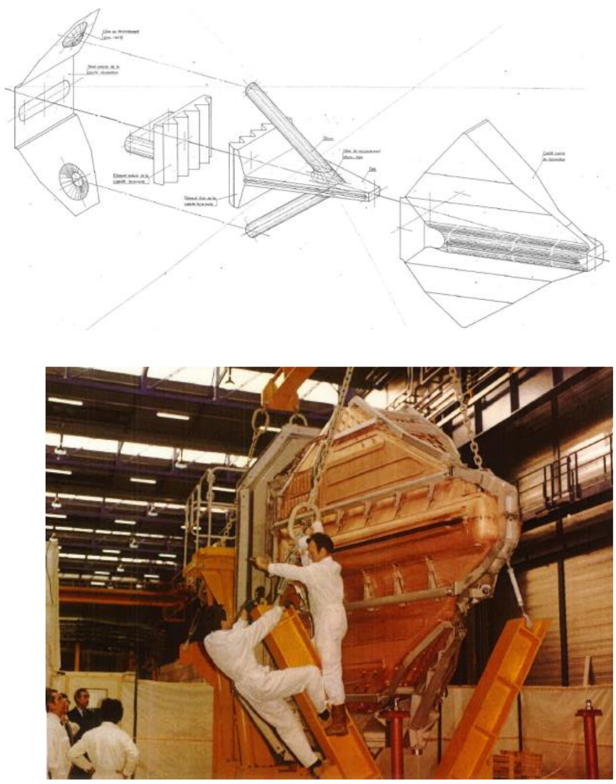


Figure 96 : Exploded view of a SSC cavity with its variable-frequency tuning system (6 to 14MHz) and 1982 photograph of a cavity delivery

Very few companies are able to manufacture such an SSC RF cavity. The manufacturing delay is 2 years for the first cavity then 1 cavity per year. The RF charaterization of the new cavity is estimated to 8 months.

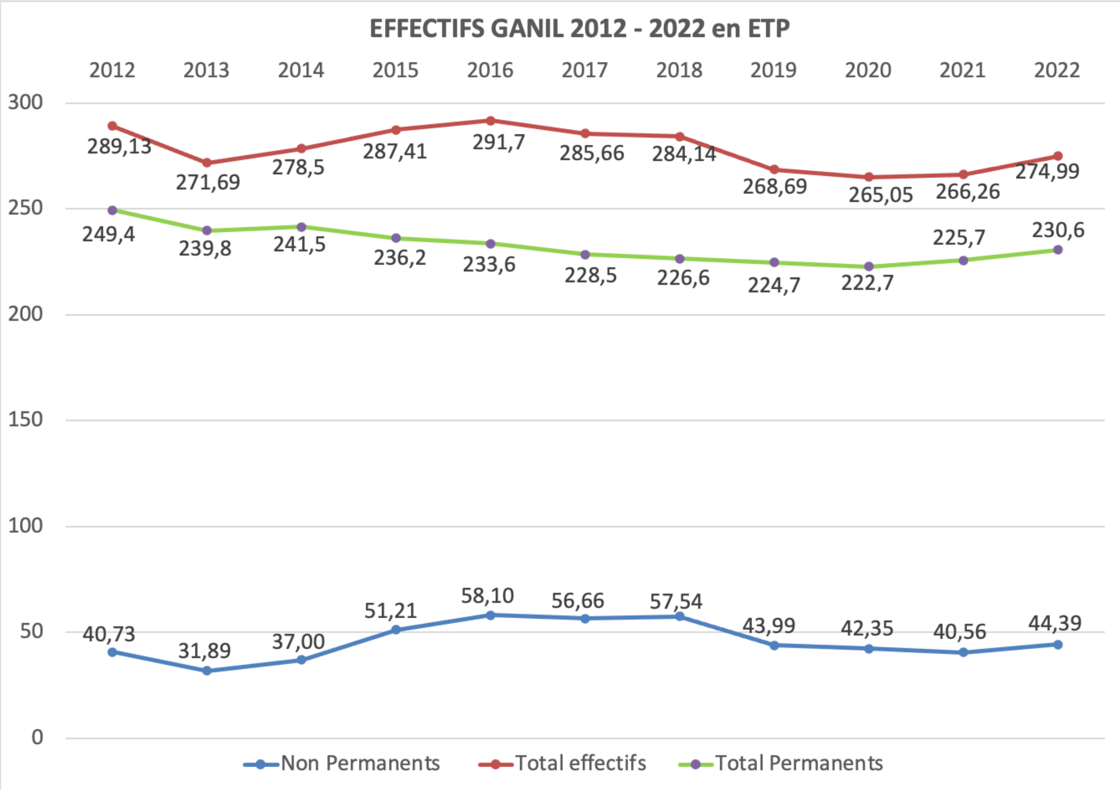
In addition, and as a minimum, we need a vacuum chamber to store the replacement cavity, with nitrogen inerting to prevent corrosion, and a new storage building adapted to the 8 m-high assembly.
Removing or installing a new cavity in the current accelerator building will not be possible without moving 200 concrete blocks and dismantling the beam transport lines. The chosen option will be to make an opening in the roof of the accelerator building so that a big crane can be used to move it.

A request for exceptional funding has been sent to the French Ministry of Higher Education and Research, with the aim of obtaining an exceptional budget in 2023.

VI. Report on employment

In 2022, permanent staff of GANIL has increased by 5 new members, despite an important number of 12 leaves for retirement.

In addition to the permanent staff of GANIL, in 2022, 17 short-term contract staff were recruited, in addition to 8 post-doctoral contracts, 15 PhD fellow, and 5 apprenticeship fellows, in total 45 temporary positions.
The evolution of permanent and non-permanent staff is depicted in the following figure:



VII. Financial report

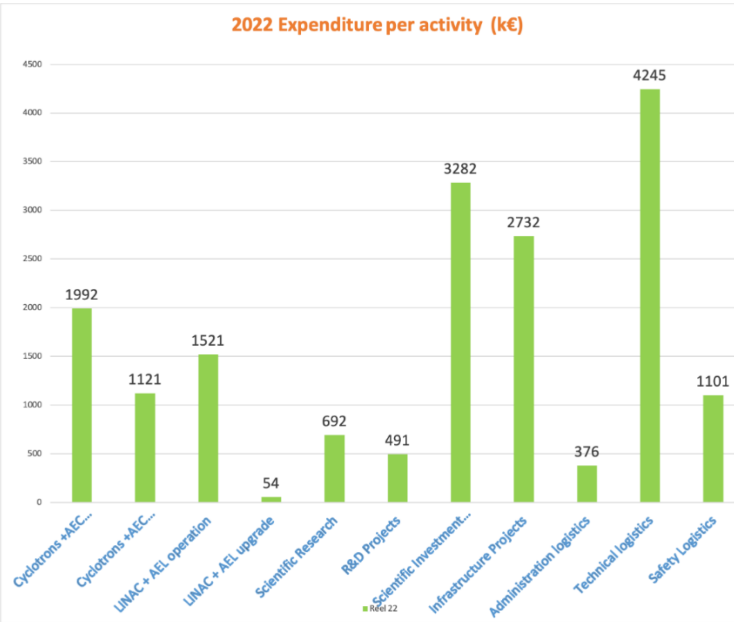
1. Expenditures

In 2022, the expenditures have reached an amount of 17,6M€ divided into :

- Current expenditures : 11,6M€
- Safety reassessment : 2,7M€
- SPIRAL2 : 3,3 M€

Breakdown of expenditures per activity :

This chart shows the implemention of expenditures between running costs (Cyclotrons and LINAC), upgrades of the facilities, projects and site costs (logistics).



2. Ressources 2022

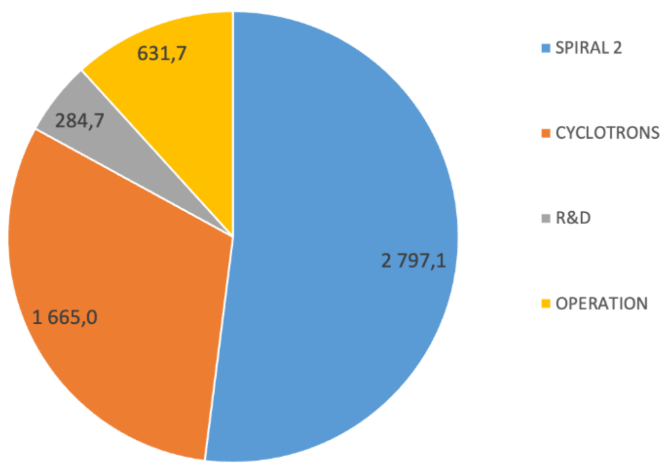
The funding of the laboratory includes subsidies from the GANIL members (11,6M€ allocated in 2022 and 5,6M€ of carry-forward) and from external resources from State, Region, Europe, and others partners.

External resources reached a level of 5,4M€ and were distributed as follows:

- Normandie Region: 1,2M€
- Europe: 1,6M€
- Ministry of Research: 0,2M€
- National Research Agency: 1,2M€
- Other: 0,6M€

Their use is distributed as depicted in the following picture:

Distribution of Ressources per activity (k€)



VIII. Training report

Numerous training courses are provided each year to maintain GANIL staff at a high level of competence and accreditation. The total annual cost of training is over 150 k€, reflecting the high standards and qualifications required for GANIL staff.

The following Figures show the origin of the training budget, and the distribution of the budget among the different specialities.

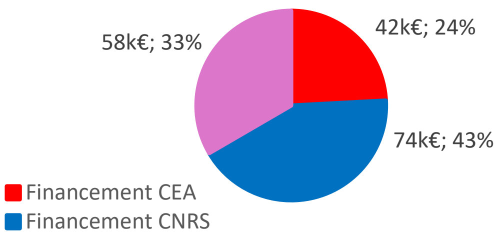


Figure 97 : Distribution per origin

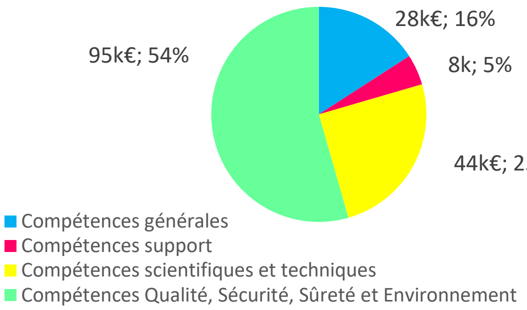


Figure 98 : Répartition du budget par compétence

GANIL funding covers fire training for all GANIL staff, training for employees with status other than CEA or CNRS, and language training for CEA employees that cannot be covered by the unit's CEA budget.

Finaly, the following Figure displays the distribution of teached hours among the different specialities.

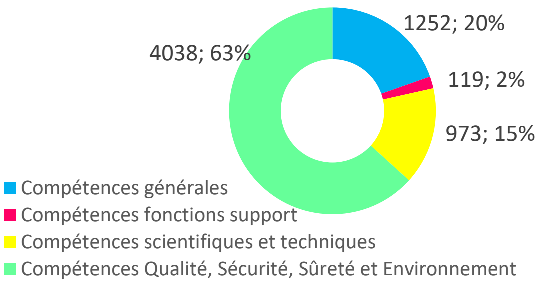
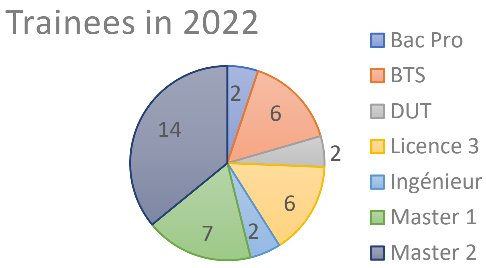


Figure 99 : Breakdown of teaching hours per different specialities

Ganil contributes to the national effort in education and higher education, welcoming numerous interns, work-study students and doctoral fellows every year.
To raise its profile as an employer, in 2022 Ganil decided to take part in job fairs in the Calvados department, starting with the "OSER" forum at Caen University. This enabled us to establish a personal dialogue with students and young graduates, and to raise awareness of Ganil's professions.



In 2022, GANIL hosted 12 apprenticeship fellows and 39 trainees:

- 5 % Professional School,
- 20,5 % Technical Diploma,
- 15,5 % Licence,
- 5 % engineer school,
- 18 % Master 1,
- 36 % Master 2.

GANIL staff is also involved in maintening and developping high level of skills and knowledge, and contributes yearly to more than 400 hours of different teaching in Schools, Universities, Engineering Schools and Technical Studies.
Once a year, GANIL organizes the PhD days, addressed to master students. In 2022, more than 90 students from masters of Strasbourg, Orsay, Bordeaux and Nantes came to visit GANIL.

In 2022, GANIL hosted more than 800 visitors from schools, high-schools, and general public. The visits include an introductory seminar on GANIL and its science and a tour of the facility.

IX. Activities in Technological Transfer

Régional

A sector of excellence, Normandie Energies supports the region's economic development and ecological transition by bringing together all of Normandy's energy players.

An association that supports innovative technology start-up projects at 3 sites in Normandy: Caen, Le Havre and Rouen.

National

For 30 years, this network has brought together professionals involved in developing public research. Its 180 members are all those who produce public research and have a mission to promote it: research organisations, universities, university teaching hospitals, grandes écoles.

Network of IR development officers

Network of IR valorisation officers specialising in matter sciences and engineering

Network of IN2P3 development officers

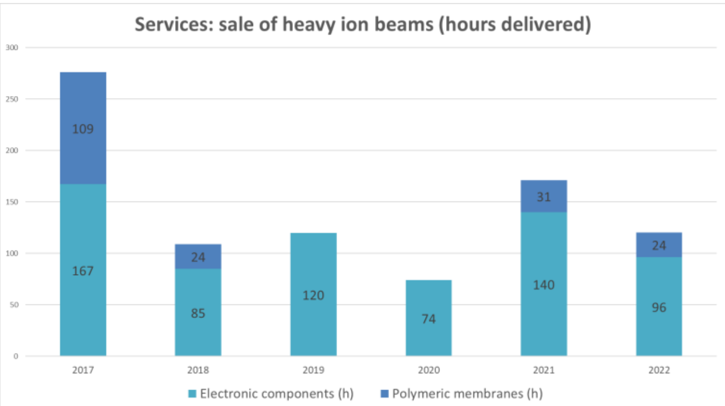
CEA Valorisation Network

European

RADiation facility Network for the EXploration of effects for indusTry and research

GANIL is participating to Regional, National and European Networks.

Industrial applications using stable ion beams focus today on microporous membrane production by irradiating polymer films with heavy ions, and on the tests of electronic components to study their behavior and resistance under irradiation. This second type of application is presently undergoing a strong rise of activity due to the development of "new space" activities. Companies dealing with the aerospace industry have developed programs of component certification with the use of GANIL beams. A sample irradiation device was constructed based on specifications defined by CNES (Centre National Etudes Spatiales) and was jointly financed by CNES and GANIL, including detection and control system. The beam time dedicated to these various applications is billed to the user at an hourly rate.



GANIL is present at conferences such as RADECS (Radiation and its effect on Systems and Components) and at national meetings (RDV CARNOT) that foster links between academics and industrial partners.

With its scientific and technological expertise, GANIL also acts as a relay enhancing the transfer of its employee skills to industrial companies and their applications.

Technology transfers available in 2022 :
Beam profile monitor with regional company : PANTECHNIK Boost Your Physics

Patent on mechanical structure for specific aluminium vacuum pipes with national company : stirweld

Different R & D contracts are in construction in 2022. They are related to various domains that reflect the variety of techniques and scientific specialties of GANIL:

- Dosimetry for medical applications with US company : PRECISION X-RAY IRRADIATION
- New types of adaptable gloveboxes for radioactive sample manipulation with national company : IDEALEX RADIOPROTECTION
- State-of-the art instrumentation for the automation of intelligent electrovalves with national company : VELAN

In more upstream research, connection to industrial partners exist in the fields of:

- Artificial intelligence for monitoring complex and multi-parameters systems as accelerators.
- Conception and production of innovative radio-isotopes for medical care.

Finally, GANIL is involved in training industrialists in technical areas of expertise, in collaboration with CNRS Entreprise. A vacuum training session was given to the company : FREWITT

05 | ANNEXES

I. Publication list

1. Articles

Observation of a correlated free four-neutron system

M. Duer, T. Aumann, R. Gernhäuser, V. Panin, S. Paschalis, D. M. Rossi, N. L. Achouri, D. Ahn, H. Baba, C. A. Bertulani, M. Böhmer, K. Boretzky, C. Caesar, N. Chiga, A. Corsi, D. Cortina-Gil, C. A. Douma, F. Dufter, Z. Elekes, J. Feng, B. Fernández-Domínguez, U. Forsberg, N. Fukuda, I. Gasparic, Z. Ge, J. M. Gheller, J. Gibelin, A. Gillibert, K. I. Hahn, Z. Halász, M. N. Harakeh, A. Hirayama, M. Holl, N. Inabe, T. Isobe, J. Kahlbow, N. Kalantar-Nayestanaki, D. Kim, S. Kim, T. Kobayashi, Y. Kondo, D. Körper, P. Koseoglou, Y. Kubota, I. Kuti, P. J. Li, C. Lehr, S. Lindberg, Y. Liu, F. M. Marqués, S. Masuoka, M. Matsumoto, J. Mayer, K. Miki, B. Monteagudo, T. Nakamura, T. Nilsson, A. Obertelli, N. A. Orr, H. Otsu, S. Y. Park, M. Parlog, P. M. Potlog, S. Reichert, A. Revel, A. T. Saito, M. Sasano, H. Scheit, F. Schindler, S. Shimoura, H. Simon, L. Stuhl, H. Suzuki, D. Symochko, H. Takeda, J. Tanaka, Y. Togano, T. Tomai, H. T. Törnqvist, J. Tscheuschner, T. Uesaka, V. Wagner, H. Yamada, B. Yang, L. Yang, Z. H. Yang, M. Yasuda, K. Yoneda, L. Zanetti, J. Zenihiro, M. V. Zhukov

Nature 606, 678-682 (2022).

An experimental view on shape coexistence in nuclei

Paul Garrett, Magda Zielinska, Emmanuel Clément

Prog. Part. Nucl. Phys. 124, 103931 (2022).

Evidence of Partial Seniority Conservation in the $\pi g_{9/2}$ Shell for the N=50 Isotones

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Impact of Nuclear Deformation and Pairing on the Charge Radii of Palladium Isotopes

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L. Lalanne, O. Sorlin, A. Poves, M. Assié, F. Hammache, S. Koyama, F. Flavigny, V. Girard-Alcindor, A. Lemasson, A. Matta, T. Roger, D. Beaumel, Y. Blumenfeld, B.A. Brown, F. de Oliveira Santos, F. Delaunay, N. de Séréville, S. Franchoo, J. Gibelin, J. Guillot, O. Kamalou, N. Kitamura, V. Lapoux, B. Mauss, P. Morfouace, M. Niikura, J. Pancin, T.Y. Saito, D. Suzuki, C. Stodel, J.C. Thomas

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Accreting neutron stars from the nuclear energy-density functional theory. II. Equation of state and global properties

A. F. Fantina, J. L. Zdunik, N. Chamel, J. M. Pearson, L. Suleiman, S. Goriely

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Chemical reactions in H2O:CO interstellar ice analogues promoted by energetic heavy-ion irradiation

A.L.F. de~Barros, C. Mejia, E. Seperuelo~Duarte, A. Domaracka, P. Boduch, H. Rothard, E.F. da~Silveira

Monthly Notices Of The Royal Astronomical Society 511, 2491-2504 (2022).

On the synthesis of N-O bearing species in astrophysical ices - an infrared spectroscopic study using heavy-ion irradiation of solid N2:CO samples

A. Bergantini, A.L.F de~Barros, A. Domaracka, H. Rothard, P. Boduch, E.F. da~Silveira

Monthly Notices Of The Royal Astronomical Society 511, 31-41 (2022).

Swift heavy ions irradiation of water ice at different temperatures: hydrogen peroxide and ozone synthesis and sputtering yield

C. Mejia, A.L.F. de Barros, H. Rothard, P. Boduch, E.F. da Silveira

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Mass measurements towards doubly magic ^{78}Ni: Hydrodynamics versus nuclear mass contribution in core-collapse supernovae

S. Giraud, L. Canete, B. Bastin, A. Kankainen, A.F. Fantina, F. Gulminelli, P. Ascher, T. Eronen, V. Girard-Alcindor, A. Jokinen, A. Khanam, I.D. Moore, D.A. Nesterenko, F. de Oliveira Santos, H. Penttilä, C. Petrone, I. Pohjalainen, A. De Roubin, V.A. Rubchenya, M. Vilen, J. Äystö

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Mirror symmetry at mass A = 54: E4 effective charges near doubly magic ^{56}Ni

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Phys. Lett. B 834, 137398 (2022).

The β-decay of ^{70}Kr into ^{70}Br: Restoration of the pseudo-SU(4) symmetry

A. Vitéz-Sveiczer, A. Algora, I, A. Morales., B. Rubio, G, G. Kiss., P. Sarriguren, P. Van Isacker, G. De Angelis, F. Recchia, S. Nishimura, J. Agramunt, V. Guadilla, A. Montaner-Pizá, A, S.E. Orrigo., A. Horváth, D. Napoli, S. Lenzi, A. Boso, H, V. Phong., J. Wu, P.-A. Söderström, T. Sumikama, H. Suzuki, H. Takeda, S, D. Ahn., H. Baba, P. Doornebal, N. Fukuda, N. Inabe, T. Isobe, T. Kubo, S. Kubono, H. Sakurai, Y. Shimizu, C. Sidong, B. Blank, P. Ascher, M. Gerbaux, T. Goigoux, J. Giovinazzo, S. Grévy, T. Kurtukián Nieto, C. Magron, W. Gelletly, Zs. Dombrádi, Y. Fujita, M. Tanaka, P. Aguilera, F. Molina, J. Eberth, F. Diel, D. Lubos, C. Borcea, E. Ganioglu, D. Nishimura, H. Oikawa, Y. Takei, S. Yagi, W. Korten, G. De France, P. Davies, J. Liu, J. Lee, T. Lokotko, I. Kojouharov, N. Kurz, H. Shaffner, A. Petrovici

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Controlling the diversity of ion-induced fragmentation pathways by N-methylation of amino acids

Dario Barreiro-Lage, Chiara Nicolafrancesco, Jaroslav Kocisek, Alberto Luna, Janina Kopyra, Manuel Alcami, A. Bernd Huber, Fernando Martin, Alicja Domaracka, Patrick Rousseau, Sergio Diaz-Tendero

Physical Chemistry Chemical Physics 24, 941-954 (2022).

First results of a new quadrupole minimum-B permanent magnet electron cyclotron resonance ion source

T. Kalvas, V. Toivanen, S.T. Kosonen, H. Koivisto, O. Tarvainen, L. Maunoury

Plasma Sources Science and Technology 31, 12LT02 (2022).

The capture of injected 1+ ions in charge breeder electron cyclotron resonance ion source plasma

O. Tarvainen, J. Angot, T. Thuillier, M. Migliore, L. Maunoury, P. Chauveau

Plasma Sources Science and Technology 31, 125003 (2022).

^{178}Hg and asymmetric fission of neutron-deficient pre-actinides

A. Jhingan, C. Schmitt, A. Lemasson, S. Biswas, Y. H. Kim, D. Ramos, A. N. Andreyev, D. Curien, M. Ciemala, E. Clément, O. Dorvaux, B. De Canditiis, F. Didierjean, G. Duchêne, J. Dudouet, J. Frankland, G. Frémont, J. Goupil, B. Jacquot, C. Raison, D. Ralet, B.M. Retailleau, L. Stuttgé, I. Tsekhanovich, A.V. Andreev, S. Goriely, S. Hilaire, J.F. Lemaître, P. Möller, K.H. Schmidt

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M. Holl, S. Lindberg, A. Heinz, Y. Kondo, T. Nakamura, A, J. Tostevin., H. Wang, T. Nilsson, L, N. Achouri., Al, H. Falou, L. Atar, T. Aumann, H. Baba, K. Boretzky, C. Caesar, D. Calvet, H. Chae, N. Chiga, A. Corsi, L, H. Crawford., F. Delaunay, A. Delbart, Q. Deshayes, P. Diaz Fernández, Z. Dombrádi, A, C. Douma., Z. Elekes, P. Fallon, I. Gasparic, J.-M. Gheller, J. Gibelin, A. Gillibert, N, M. Harakeh., A. Hirayama, R,

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A. Bronis, P, F. Heßberger., S. Antalic, B. Andel, D. Ackermann, S. Heinz, S. Hofmann, J. Khuyagbaatar, B. Kindler, I. Kojouharov, P. Kuusiniemi, M. Leino, B. Lommel, R. Mann, K. Nishio, G, A. Popeko., B. Streicher, B. Sulignano, J. Uusitalo, M. Venhart, V, A. Yeremin.
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S. Nandi, G. Mukherjee, A. Dhal, R. Banik, Soumik Bhattacharya, S. Basu, Shabir Dar, S. Bhattacharyya, C. Bhattacharya, S. Kundu, D. Paul, S. Rajbanshi, S. Chatterjee, S. Das, S. Samanta, R. Raut, S, S. Ghugre., H. Pai, Sajad Ali, S. Biswas, A. Goswami
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D.A. Nesterenko, K. Blaum, P. Delahaye, S. Eliseev, T. Eronen, P. Filianin, Z. Ge, M. Hukkanen, A. Kankainen, Yu.N. Novikov, A.V. Popov, A. Raggio, M. Stryjczyk, V. Virtanen
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Experimental study of the ^{30}Si(^{3}He,d)^{31}P reaction and thermonuclear reaction rate of ^{30}Si(p,γ)^{31}P
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Q. Fable, A. Chbihi, M. Boisjoli, J.D. Frankland, A. Le Fèvre, N. Le Neindre, P. Marini, G. Verde, G. Ademard, L. Bardelli, C. Bhattacharya, S. Bhattacharya, E. Bonnet, B. Borderie, R. Bougault, G. Casini, M. Commara, R. Dayras, J.E. Ducret, F. Farget, E. Galichet, T. Génard, F. Gramegna, D. Gruyer, M. Henri, S. Kundu, J. Lemarié, O. Lopez, J. Lukasik, L. Manduci, J. Moisan, G. Mukherjee, P. Napolitani, A. Olmi, M. Pârlog, S. Piantelli, G. Poggi, A. Rebillard-Soulié, R. Roy, B. Sorgunlu, S. Velardita, E. Vient, M. Vigilante, J.P. Wieleczko
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First results from the INDRA-FAZIA apparatus on isospin diffusion in ^{58,64}Ni+^{58,64}Ni systems at Fermi energies
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A. Chatillon, J. Taïeb, A. Heinz, H. Alvarez-Pol, L. Audouin, Y. Ayyad, G. Bélier, J. Benlliure, G. Boutoux, M. Caamano, E. Casarejos, D. Cortina-Gil, A. Ebran, F. Farget, B. Fernandez-Dominguez, T. Gorbinet, L. Grente, H.T. Johansson, B. Jurado, A. Kelic-Heil, N. Kurz, B. Laurent, J.F. Martin,

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J.M. Boillos, D. Cortina-Gil, J. Benlliure, J.L. Rodriguez-Sanchez, H. Alvarez-Pol, L. Atar, T. Aumann, V. V. Avdeichikov, S. Beceiro-Novo, D. Bemmerer, C. A. Bertulani, K. Boretzky, M. J. G. Borge, M. Caamano, C. Caesar, E. Casarejos, W. Catford, J. Cederkall, M. Chartier, L. Chulkov, E. Cravo, R.N.P. Crespo, I. Dillmann, P. Diaz Fernandez, Z. Elekes, J. Enders, O. Ershova, A. Estrade, F. Farinon, L.M. Fraile, M. Freer, D. Galaviz Redondo, H. Geissel, R. Gernhäuser, P. Golubev, K. Göbel, J. Hagdahl, T. Heftrich, M. Heil, M. Heine, A. Heinz, A. Henriques, M. Holl, A. Hufnagel, A. Ignatov, H.T. Johansson, B. Jonson, J. Kahlbow, N. Kalantar-Nayestanaki, R. Kanungo, A. Kelic-Heil, A. Knyazev, T. Kröll, N. Kurz, M. Labiche, C. Langer, T. Le Bleis, R. Lemmon, S. Lindberg, J.F.D.C. Machado, J. Marganiec, A. Movsesyan, E. Nacher, M.A. Najafi, T. Nilsson, C. Nociforo, V. Panin, S. Paschalis, A. Perea, M. Petri, S. Pietri, R. Plag, R. Reifarth, G. Ribeiro, C. Rigollet, D.M. Rossi, M. Röder, D. Savran, H. Scheit, H. Simon, O. Sorlin, I. J. Syndikus, J.T. Taylor, O. Tengblad, R. Thies, Y. Togano, M. Vandebrouck, P.J.F. Velho, V. Volkov, A. Wagner, F. Wamers, H. Weick, C. Wheldon, G.L. Wilson, J.S. Winfield, P. Woods, D. Yakorev, M. Zhukov, A. Zilges, Zuber K.
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Elena Litvinova, Yinu Zhang
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B. Borderie, S. Piantelli, J.D, Frankland, N. Le Neindre
Proceedings from *International Workshop on Multi-facets of EoS and Clustering (IWM-EC 2021)*, 23-26 November 2021. Caen, France, (2022).

New Metallic Stable Ion Beams for GANIL
Frederic Lemagnen, Christophe Barue, Mickael Dubois, Romain Frigot, Nicolas Lechartier, Vincent Metayer, Benoit Osmond
Proceedings from *ECRIS 2020 - 24rd International Workshop on ECR Ion Source*, East Lansing, United States, (2022).

Organic chemistry on the surface of jovian icy satellites: formation of complex refractory organic matter by implantation of sulfur ions into water-alkanes ices
Alexis Bouquet, Grégoire Danger, Laura Tenelanda-Osorio, Philippe Boduch, Hermann Rothard, Julien Maillard, Isabelle Schmitz-Afonso, Carlos Afonso, Philippe Schmitt-Kopplin, Fabrice Duvernay, Cintia Pires da Costa, Lawry Honold
Proceedings from *Europlanet Science Congress 2022*, Granada, Spain 18 – 23 September 2022 , (2022).

Properties of pasta phases in catalyzed neutron stars
H. Dinh Thi, A. F. Fantina, Gulminelli, F.
Proceedings from *International Workshop on Multi-facets of EoS and Clustering (IWM-EC 2021)*, 23-26 November 2021. Caen, France, (2022).

Proton partial widths evaluation through the ^{30}Si{^{3}He,d)^{31}P transfer reaction for understanding abundance anomalies in Globular Clusters
Djamila-Sarah Harrouz, Nicolas De Séréville, Philip Adsley, Faïrouz Hammache, Richard Longland, Beyhan Bastin,

Thomas Faestermann, Ralf Hertenberger, Marco La Cognata, Livio Lamia, Anne Meyer, Sara Palmerini, Rosario Gianluca Pizzone, Stefano Romano, Aurora Tumino, Hans-Friedrich Wirth

Proceedings from *16th International Symposium on Nuclei in the Cosmos*, Chengdu, China, (2022).

Radioactive and Stable Ion Beam production at GANIL

M. Dubois, O. Bajeat, C. Barué, V. Bosquet, P. Chauveau, S. Damoy, R. Frigot, S. Hormigos, P. Jardin, N. Lechartier, F. Lemagnen, L. Maunoury, V. Métayer, B. Osmond

Proceedings from *19th International Conference on Ion Sources*, Online, Canada, (2022).

Role of the 1+ beam optics upstream the SPIRAL1 charge breeder

Laurent Maunoury, Samuel Damoy, Mickael Dubois, Romain Frigot, Stéphane Hormigos, Bertrand Jacquot, Omar Kamalou

Proceedings from *ECRIS 2020 - 24rd International Workshop on ECR Ion Source*, East Lansing, United States, (2022).

Seismic Analysis for Safety Requirements of SPIRAL2 Accelerator

Cécile Barthe-Dejean, Franck Lutton, Matthieu Michel

Proceedings from *31st Linear Accelerator Conference - LINAC22*, Liverpool, United Kingdom, 28 August-2 September 2022, (2022).

Spectroscopy of ^{17}C Above the Neutron Separation Energy

Sunji Kim, Jongwon Hwang, Yoshiteru Satou, Nigel A. Orr, Takashi Nakamura, Yosuke Kondo, Julien Gibelin, Lynda, N. Achouri, Thomas Aumann, Hidetada Baba, Franck Delaunay, Pieter Doornenbal, Naoki Fukuda, Naohito Inabe, Tadaaki Isobe, Daisuke Kameda, Daiki Kanno, Nobuyuki Kobayashi, Toshio Kobayashi, Toshiyuki Kubo, Sylvain Leblond, Jenny Lee, Miguel, F. Marqués, Ryogo Minakata, Tohru Motobayashi, Daichi Murai, Tetsuya Murakami, Kotomi Muto, Tomohiro Nakashima, Noritsugu Nakatsuka, Alahari Navin, Seijiro Nishi, Shun Ogoshi, Hideaki Otsu, Hiromi Sato, Yohei Shimizu, Hiroshi Suzuki, Kento Takahashi, Hiroyuki Takeda, Satoshi Takeuchi, Ryuki Tanaka, Yasuhiro Togano, Adam G. Tuff, Marine Vandebrouck, Ken-ichiro Yoneda

Proceedings from *8th Asia-Pacific conference on Few-Body problems in Physics*, Kanazawa, Japan, 1-5 March 2021, (2022).

SPIRAL2 Final Commissioning Results

Angie Orduz, Pierre-Emmanuel Bernaudin, Marco Di Giacomo, Robin Ferdinand, Bertrand Jacquot, Omar Kamalou, Jean-Michel Lagniel, Guillaume Normand, Alain Savalle, Didier Uriot

Proceedings from *31st Linear Accelerator Conference - LINAC22*, Liverpool, United Kingdom, 28 August-2 September 2022, (2022).

Study of the symmetry energy from ^{48,40}Ca + ^{48,40}Ca collisions at 35 AMeV

Q. Fable, A. Chbihi

Proceedings from *International Workshop on Multi-facets of EoS and Clustering (IWM-EC 2021)*, 23-26 November 2021. Caen, France, (2022).

Superconducting Cavity and RF Control Loop Model for the SPIRAL2 Linac

Frédéric Bouly, Marco Di Giacomo, Jean-François Leyge, Mereke Tontayeva

Proceedings from *31st Linear Accelerator Conference - LINAC22*, Liverpool, United Kingdom, 28 August-2 September 2022, (2022).

The New GANIL Beams: Commissioning of SPIRAL 2 Accelerator and Resent Developments

Hanna Franberg Delahaye

Proceedings from *15th Int. Conf. on Heavy Ion Acc. Technology, HIAT2022*, Darmstadt, Germany, 27 June – 1 July 2022, (2022).

Three Years of Operation of the SPIRAL2 LINAC: Cryogenics and Superconducting RF Feedback

Pierre-Emmanuel Bernaudin, Muhammad Aburas, Marco Di Giacomo, Adnan Ghribi, Philippe Robillard, Laurent Valentin

Proceedings from *31st Linear Accelerator Conference - LINAC22*, Liverpool, United Kingdom, 28 August-2 September 2022, (2022).

Three Years of Operation of the SPIRAL2 SC LINAC- RF Feedback

Marco Di Giacomo, Muhammad Aburas, Pierre-Emmanuel Bernaudin, Frédéric Bouly, Olivier Delahaye, Arnaud Dubosq, Adnan Ghribi, Jean-Michel Lagniel, Jean-François Leyge, Guillaume Normand, Angie Orduz, Frank Pillon, Samuel Sube, Laurent Valentin

Proceedings from *31st Linear Accelerator Conference - LINAC22*, Liverpool, United Kingdom, 28 August-2 September 2022, (2022).

Unitary limit in heavy nuclei

Panagiotis E. Georgoudis

Proceedings from *29th Symposium of the Hellenic Nuclear Physics Society (HNPS2021)*, Athens, Greece, 24-25 September 2021., (2022).

II. Conference list

In 2022 GANIL hosted or organized different workshops and schools:

- ISOL France, 9-11 mars 2022, 50 participants
- Russbach School on Astrophysics, March 13-19, 2022, 42 participants
- Journées techniques « La mécanique dans le nucléaire », 31 mai 2022, 24 participants
- GANIL Community Meeting, October 17-21, 2022, Caen, 152 participants
- LISE workshop, March 28-30, 2022, 91 participants
- NFS workshop, April 13-14, 2022, 102 participants
- LISA Summer School, “Structure of Complex Atoms”, September 4-9, 2022, Bagnoles de l’Orne
- Physics with SPIRAL2 Heavy-Ion Beams, December 12-16, 2022, 103 participants

III. Committees

1. Members of the Program Advisory Committee (PAC)

Mandate – March 2019 to March 2023
DE OLIVEIRA François,GANIL, Caen, France
JUNGHANS Arnd,HZDR, Dresden, Germany
LACROIX Denis,IPN Orsay, France
OBERTELLI Alexandre,Institut für Kernphysik TU Darmstadt, Germany
RIDIKAS Danas,IAEA, Vienna, Austria

Mandate – February 2022 to February 2026
ASAI Masato,JAEA, Ibaraki, Japan
GAUDEFROY Laurent,CEA DAM, Bruyères-le-Châtel, France
LEIFELS Yvonne,GSI, Darmstadt, Germany
MORO Antonio, University Sevilla, Sevilla, Italy
OBERSTEDT Stephan, JRC Geel, Geel, Belgium
PETRI Marina, University York, Heslington, United Kingdom
TUMINO Aurora, University Kore, Enna, Italy

2. Members of the Scientific council members

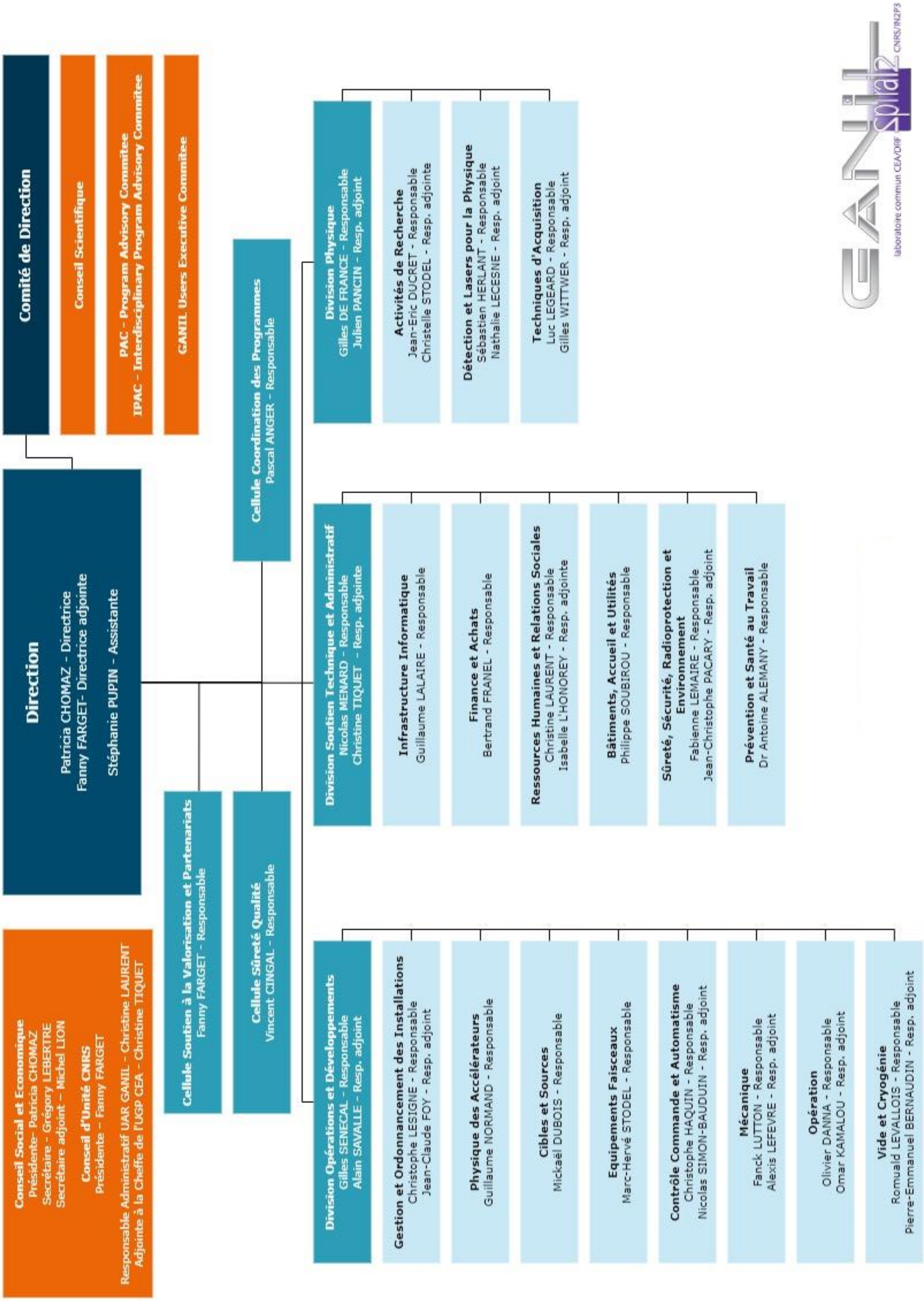
Ani Aprahamian, Univ Notre Dame, USA
Amine Cassimi, CIMAP, France
Anna Corsi, Irfu/DPhN, France
Anne-Marie Frelin, GANIL, France
Jerome Giovinazzo, CENBG, France
Fabiana Gramegna, LNL INFN, Italy
Ferid Haddad, ARRONAX, France
Rituparna Kanungo, Triumf, Canada
Michal Kowal NCBJ, Varsovie, Poland
Alain Letourneau, Irfu/DPhN, France
Nathalie Moncoffre, IP2IL EMIR&A, France
Iain Moore, Jyfl, Finland
Jaromir Mrazek, NPI, Czech Republic
R.G. Pillay, TIFR Mumbai, India
Christoph Scheidenberger, GSI Darmstadt, Germany
Bob Tribble, TAMU, USA (Chairperson)
David Verney, IJCLab, France

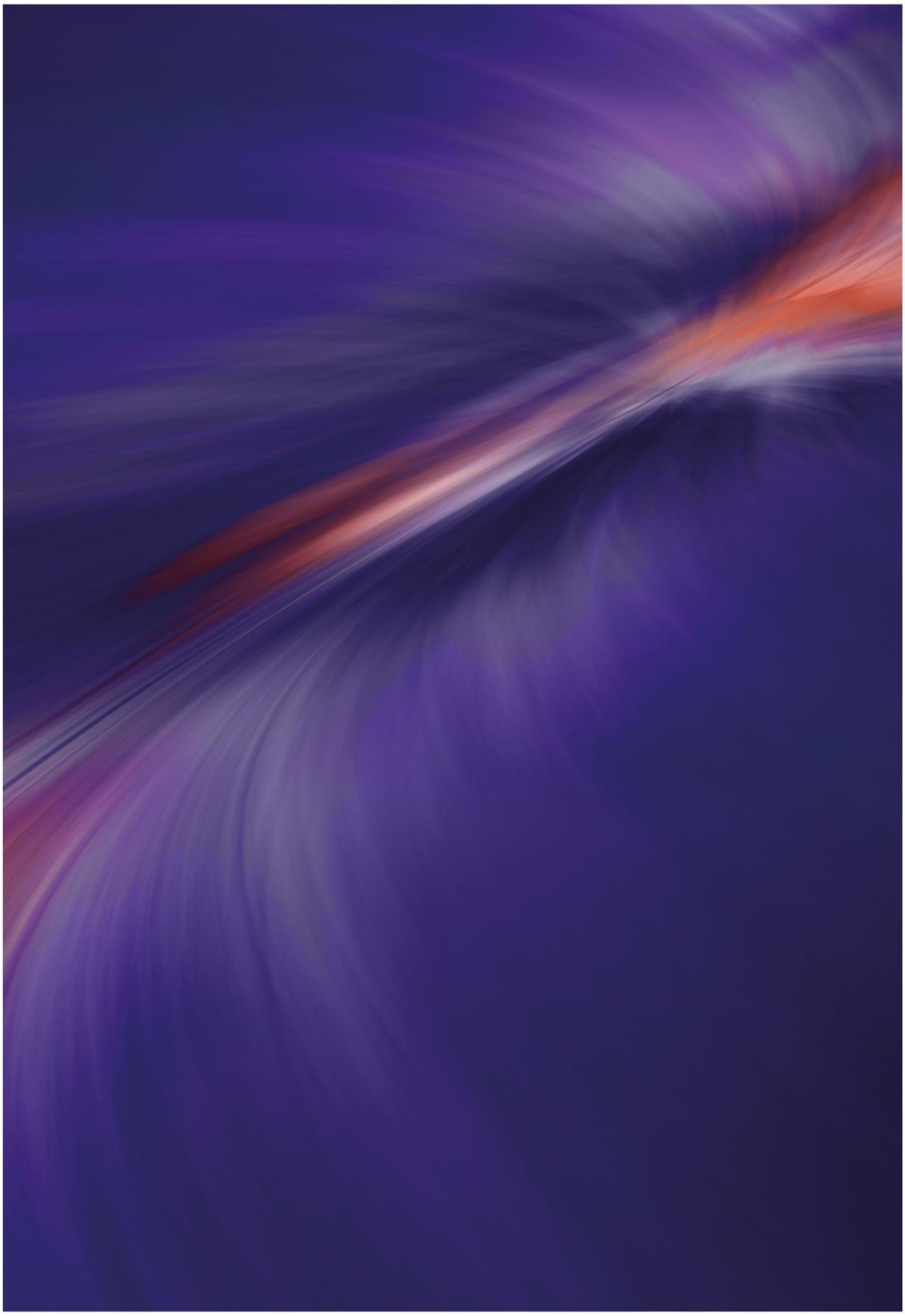
Ex-officio members:
Chairperson GANIL PAC
Chairperson GANIL GUEC
Chairperson Interdisciplinary PAC

3. Members of the GANIL Users Executive Committee (GUEC)

Silvia Leoni (Chair), University of Milano and INFN, Italy
Emmanuel Clément, GANIL, France
Maria Colonna, INFN LNS Catane, Italy
Andreas Görgen, University of Oslo, Norway
Antoine Lemasson, GANIL, France
Adam Maj, IFJ PAN Krakox, Poland
Marika Schleberger, Univ. of Duisburg-Essen, Germany
Marlene Assie, IPN Orsay, France

IV. Organisation Chart





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