Expert Committee
Vision for the future of GANIL
December 24th, 2021

Maria Jose Garcia Borge (CSIC), Paolo Giubellino (GSI), Ulli Köster (ILL), Hiroyushi Sakurai (RIKEN), Boris Sharkov (JINR), Brad Sherrill (MSU), Michel Spiro (CEA-CNRS, Chair), Johanna Stachel (University of Heidelberg)

Abstract:

This document presents a vision for the future of GANIL that spans the next four decades. Its primary basis is input prepared by the GANIL user community (https://indico.in2p3.fr/event/20534/contributions/) and a summary document "The GANIL contribution synthesis" prepared by a preparatory group (Nicolas Alamanos and Fanny Farget, document attached), which coherently distilled the ideas and proposals. This synthesis document was made available to the committee in June 2020, and was updated in December 2020 (Nicolas Alamanos and Fanny Farget, document attached). Further input came from four working groups charged by the International Expert Committee to develop a vision for the future of GANIL and to explore various aspects of that vision (they are accessible on the same website as for the contributions). This input was submitted to the committee in December 2020 and Spring 2021.

The present document reflects the thoughts and the views of the committee following consideration of the material received.

The vision is composed of a series of modular components, with options that would keep GANIL at the leading edge of nuclear science globally for the decades to come. The vision, as presented in this document, includes discussion of a possible timetable, prioritization for realization of the modules, and the links between the components.

Note:

This report was drafted by a committee of international scientific experts from different scientific fields and the scenarios that emerge reflect their thoughts on the scientific and technological aspects only, without constituting an action plan at this stage.

Michel SPIRO

Paris, le 24 septembre 2019

Objet : Lettre de mission
N/Réf. : CAB-AG/19-201

Cher Collègue,

Comme vous le savez, le paysage européen, pour ce qui concerne la physique nucléaire et les applications associées est en forte évolution avec en particulier la mise en service prochaine de la phase 1 de SPIRAL 2 au GANIL, l'évolution de la construction de FAIR en Allemagne, les développements de ISOLDE au CERN et les importants investissements engagés à JINR en Russie. Sur le plan international également, d'importantes infrastructures de ces domaines de recherche sont en construction ou en projet en Corée du sud et en Chine ainsi qu'aux États-Unis.

Dans ce contexte en forte évolution et compte-tenu de la position et du rôle de notre pays dans le développement des sciences et techniques nucléaires, il nous apparait essentiel d'actualiser notre vision de la place et du rôle futur de notre installation nationale le GANIL. Nous souhaitons démarrer cet exercice en ayant en main une analyse experte et indépendante du positionnement scientifique et technologique du GANIL débouchant sur des voies possibles d'évolution du laboratoire dans son contexte local et régional.

Nous avons souhaité vous confier cette mission et proposons pour cela que vous vous entouriez d'un petit comité composé d'experts de renommée mondiale. Sans que ce soit limitatif, les personnes dont le nom suit ont été pressenties : Johanna Stachel de l'Université de Heidelberg, Hideto En'yo de Riken, Boris Sharkov de JINR et Brad Sherrill de MSU.

... / ...

Nous souhaitons que les points suivants soient abordés :

- Le GANIL dans son environnement local et régional : positionnement disciplinaire (physique fondamentale et applications), lien thématiques et structurels avec les laboratoires voisins, liens avec le milieu industriel régional et national,
- Quel rôle futur pour le GANIL dans la recherche en physique nucléaire fondamentale, dans le contexte européen et à l'international ? Quels partenariats privilégier ?
- Quel rôle futur pour le GANIL dans les applications associées, en France et dans le contexte européen en particulier ?
- Quelles évolutions possibles du positionnement disciplinaire ?

Le secrétariat logistique (missions, frais de réunion, de reproduction) sera assuré par le laboratoire APC. Ces frais seront ensuite remboursés par le GANIL

Au fur et à mesure de votre travail, vous vous assurerez de la bonne articulation de votre prospective scientifique avec la vision générale de l'IRFU et de l'IN2P3.

Nous vous remercions et vous prions de recevoir nos meilleures salutations.

Antoine PETIT
Président directeur-général du CNRS

François JACQ
Administrateur général du CEA

1. Introduction

At the present time, across the globe, nuclear physics and its applications are progressing rapidly. Within this context, the members of the governing board of GANIL, CEA and CNRS are examining the role of GANIL and how it should evolve in the years to come.
The Expert Committee Vision for the future of GANIL has been given the responsibility of analysing the position of GANIL at the national and international level, and to propose an evolution that would maintain its leadership in science. The proposed vision, based on input from its international user community, defines an ambitious plan to maintain a very competitive nuclear science program at GANIL over the next several decades.

Over the near term, the evolution of GANIL is based primarily on the SPIRAL2 project, which consisted of two main phases:

i) SPIRAL2-Phase1: High current stable beams produced by the LINAG (LINear Accelerator of GANIL) will be used a) to generate the most intense beams of neutrons at NFS (Neutrons For Science) experimental area and b) for the study of rare events of nuclei far from stability using S^3 (Super Separator Spectrometer) in an independent experimental area. These short lived nuclei produced and separated by S^3, will also be transported to the DESIR (Decay, Excitation and Storage of Radioactive Ions) hall for studying their fundamental properties (upper part of Figure 1).

ii) SPIRAL2-Phase2: the most intense radioactive ion beams (of fission fragments) produced in fission induced by high intensity deuteron beams, from the LINAG, on a uranium carbide target.

The production of these radioactive ion beams requires a dedicated production building, not yet constructed. These beams of fission fragments would be sent to the DESIR hall or post accelerated in the cyclotron facility and sent to existing experimental areas of GANIL.

Today, while the various stages of SPIRAL2-Phase1 projects, including the new injector for heavier ion beams (A/Q=7), appear to be on track, SPIRAL2-Phase2, the core of the original SPIRAL2 project, has been put on hold. The scientific relevance of the SPIRAL2-phase2 was never questioned, however the large total cost of both phases of SPIRAL2, led to a decision, in the beginning of the last decade, of postponing the construction of Phase2, in order to fully secure finances required for the completion of the first phase of SPIRAL2. Subsequently the next steps via building of SPIRAL2-Phase1+ (DESIR) and SPIRAL2-Phase1++ (A/Q=7 injector) was envisaged.

2. SPIRAL2-Phase1

With the newly commissioned LINAG, and the S3 spectrometer, it is possible to produce by fusion-evaporation reactions, exotic neutron-deficient nuclei including nuclei with $N \approx Z$ and also heavy nuclei up to super-heavy elements (Z>104). The experimental possibilities offered by S^3 will be further enhanced with an increase in beam intensities of heavy (A > 40) and very heavy (Xe, Pb, U) nuclei when the (A/Q = 7) injector becomes available (the committee was pleased to hear that funding for this important capability has been secured). A combination of nuclear spectroscopic tools, laser spectroscopy, and ion traps, will open new avenues at GANIL in the field of super-heavy nuclei and exotic nuclei, including measurements with unprecedented precision. Selected exotic beams, produced by S^3 and delivered to the DESIR hall, will provide unique scientific opportunities, some of them not accessible at other facilities, in terms of selection of exotic nuclei and/or beam purity. The DESIR facility is presently in its final design stage, and construction is scheduled to start in 2023. With the start of its radioactive beam program, envisaged before 2030, it will become GANIL's low-energy facility supporting an exciting program up to 2040 at least.

These capabilities, including the ever-expanding versatile opportunities at the cyclotron complex, will give GANIL a solid international standing and visibility over the next decade. With the recent successful commissioning of the LINAG and NFS and the step by step start-up of S^3 and DESIR, a unique and exciting science program will be made possible by the SPIRAL2-Phase1 project. Building upon this solid base, the committee can envision a future for GANIL, at the forefront of nuclear science for the coming decades.

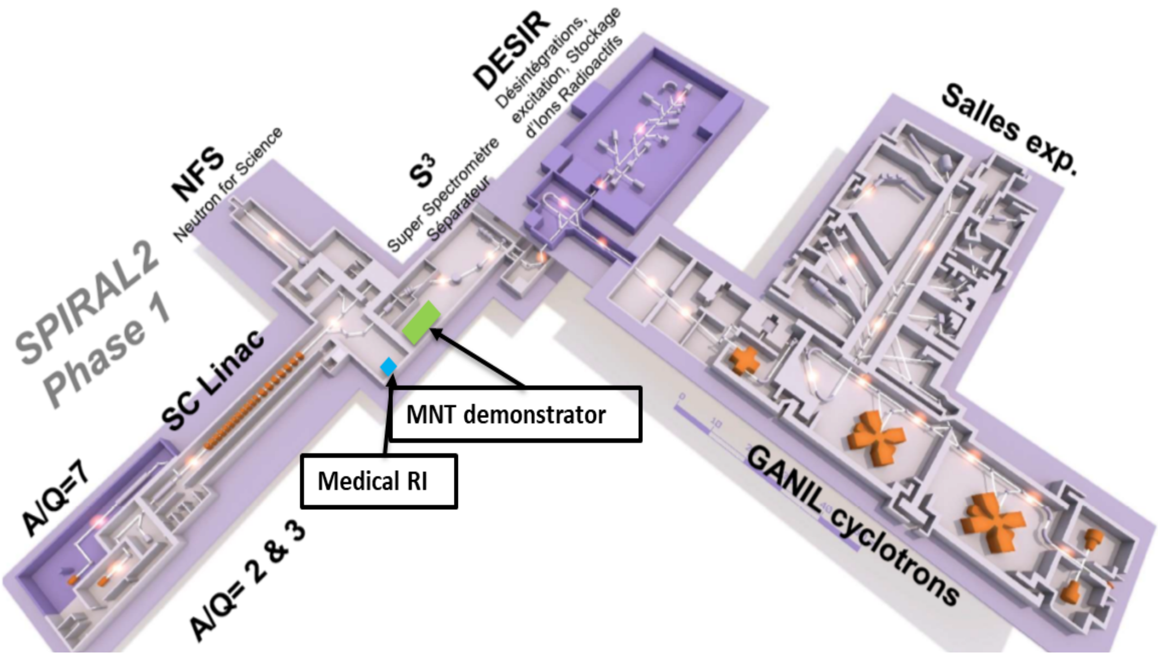
3. Three steps for the future of GANIL

The SPIRAL2-Phase2 project as initially planned is on hold. With this in mind, the future of GANIL for the coming decades could be envisaged to evolve in three steps distributed over distinct time periods.

Step 1: Deployment of SPIRAL2-Phase1: (full implementation in 2030)

Finalization of the construction of the on-going projects, that is: NFS (under exploitation), S3, DESIR and the new injector A/Q=7. The overall budget for this first step is already mostly committed, and its deployment is underway. In addition, the committee recommends a timely installation of a dedicated target station in the LHE2 (High Energy Line) area for production of medical radioisotopes to exploit the most intense high intensity LINAG beams for this important societal application. The committee also recommends a demonstrator gas cell for Multi Nucleon transfer reactions in the S3 hall.

In addition, **the committee considers it very important to operate optimally the existing cyclotrons and the LINAG** and to maintain the capabilities of the existing cyclotron chain. This is necessary to meet the ion beam requirements of the strong interdisciplinary physics community.



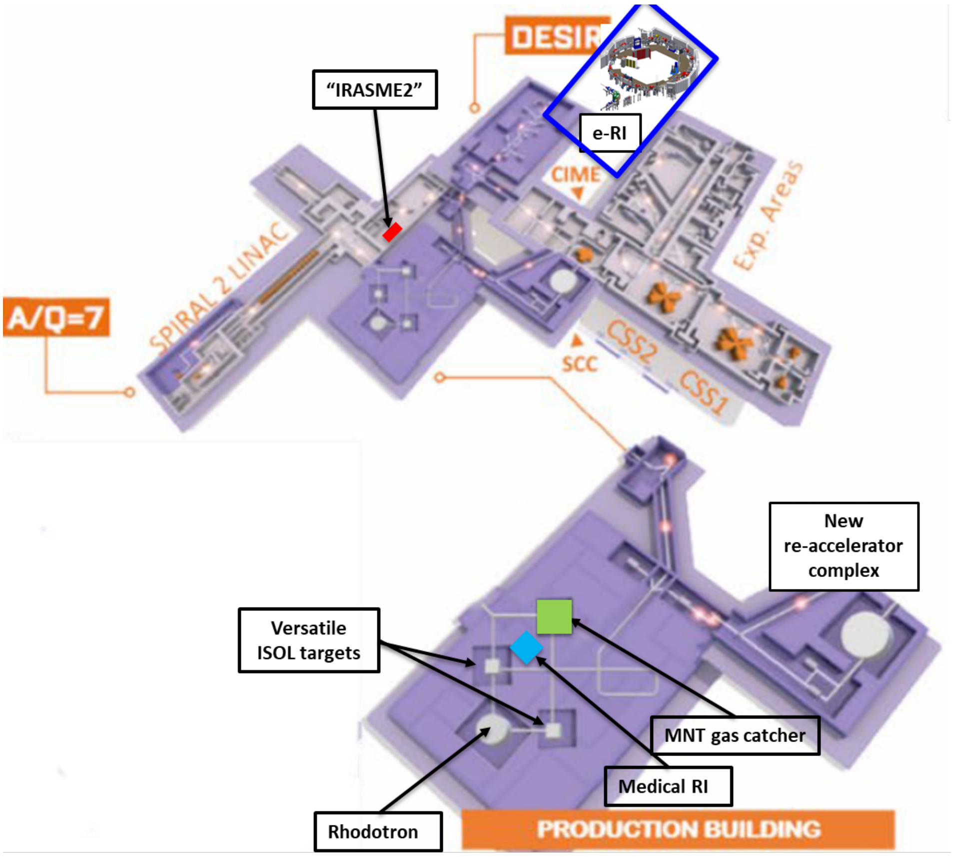


Fig. 1 Upper panel: Schematic view of the SPIRAL2-Phase1 project together with the current GANIL facility. The high-intensity linear accelerator LINAG, NFS, S3, DESIR and rare-isotope production experimental areas are shown. DESIR will receive low-energy SPIRAL1 (from the existing GANIL cyclotrons) and S^3 beams. A dedicated target for medical radioisotopes should be installed in the LHE2 area and a gas-cell demonstrator for multi-nucleon transfer reactions can be placed in the S^3 hall.

Lower panel: An expanded view of various new projects that are proposed and strongly supported by GANIL's scientific community that are shown in the upper part of the lower panel. The production building, lowest part of the figure, will be a revised version of SPIRAL2-Phase2, and will house the fission and multi-nucleon transfer targets for nuclear physics, as well as other targets for production of medical radioisotopes or secondary neutrons respectively. See text for more details.

GANIL is currently in the top five nuclear physics facilities in the world and is expected to continue so with Step 1 until at least the middle of the next decade.

Step 2: (implementation until 2035)

- **Refurbishment/replacement of CIME with a new re-accelerator complex, to reaccelerate exotic nuclei with high beam quality (intensity, emittance and purity) from the energy domain starting from the Coulomb barrier up to the Fermi energy and beyond. This unexplored energy domain coupled with the wide array of reaccelerated beams of nuclei far from stability will provide a deeper insight into the many facets of the nuclear system.**

It should be pointed out that none of the exotic-nuclei facilities (running or planned) in the world, i.e. ISOLDE at CERN, SPES in Italy or FRIB at MSU in the USA is targeting energies of exotic nuclei beams that are accessible by the proposed scheme at GANIL. The project RAON in Korea (under construction) aims to reaccelerate exotic nuclei up to, for example, 17.5 MeV/nucleon. In contrast, the GANIL project, aiming to re-accelerating radioactive beams to energies of the order of ~100 MeV/nucleon will be unique in this global effort, with the promises of major impact in the field.

- **Construction of the production building for production of neutron-rich exotic nuclei: a revised Phase 2 version that would include different production mechanisms,**
  i) from fission of a uranium carbide target, induced by LINAG beams
  ii) from photo-fission by an electron driver
  iii) from multi-nucleon transfer reactions using a gas-cell catcher.

The second possibility will allow to simultaneously exploit the LINAG beams at S^3 or for interdisciplinary applications, and the fission products for post-acceleration. For this option the construction of a new electron accelerator for photofission (for example based on an IBA Rhodotron®) could be considered.
The same production building should also house the target stations for production of medical radioisotopes or slow neutron beams respectively. The space freed in the S^3 experimental hall after the movement of the Multi Nucleon Transfer demonstrator moves to the production building, could accommodate an "IRASME2" beamline thus providing LINAG beams also to the materials science community (paper on possible interdisciplinary activities using LINAG beams, attached).
With Step 2, it will be possible to investigate long chains of neutron-rich and neutron-deficient nuclei produced by the ISOL method up to heavy trans-actinides with intensities of 10^2-10^7 particles per second to be studied at DESIR or reaccelerated in the energy range 10-60 MeV/nucleon (this includes flagship beams such as ^{132}Sn at 10^7 pps on target) with high purity and beam quality comparable to the best stable beams. These capabilities, enforced by the state-of the art GANIL spectrometers and instrumentation, will open new paths for nuclear structure and reaction research. These steps will give GANIL a worldwide leading and unique programme beyond the next two decades.

Step 3: (implementation until 2040)

Construction of an electron accelerator (for example an Energy Recovery Linac (ERL) or latest generation synchrotron) to offer a new probe of exotic nuclei: electron-scattering on radioactive ions (e-RI). Scattering experiments with electrons on exotic nuclei will provide model independent information on the charge densities, electromagnetic transition densities, and magnetic current distributions for nuclei far from stability[1]. This program will complement the studies made by direct reactions using the new re-acceleration complex. It would give a rich and unique flagship programme beyond the middle of this century. Feasibility studies and prototyping of such a machine could be soon initiated given a strong interest shown by an external collaboration.
The overall vision is shown schematically in the lower part of Figure 1 (layout) and time wise in Figure 2.

4. Rationale

These intellectually exciting and highly innovative projects should keep GANIL at the forefront of nuclear science over a very long period. They build on the core competencies at GANIL and its main asset: expertise in the production and study of exotic nuclei.

1 Many sophisticated state-of-the-art nuclear physics models (e.g., ab-initio, beyond mean-field) predict these distributions for nuclei far from stability and need to be confronted with experiment results.

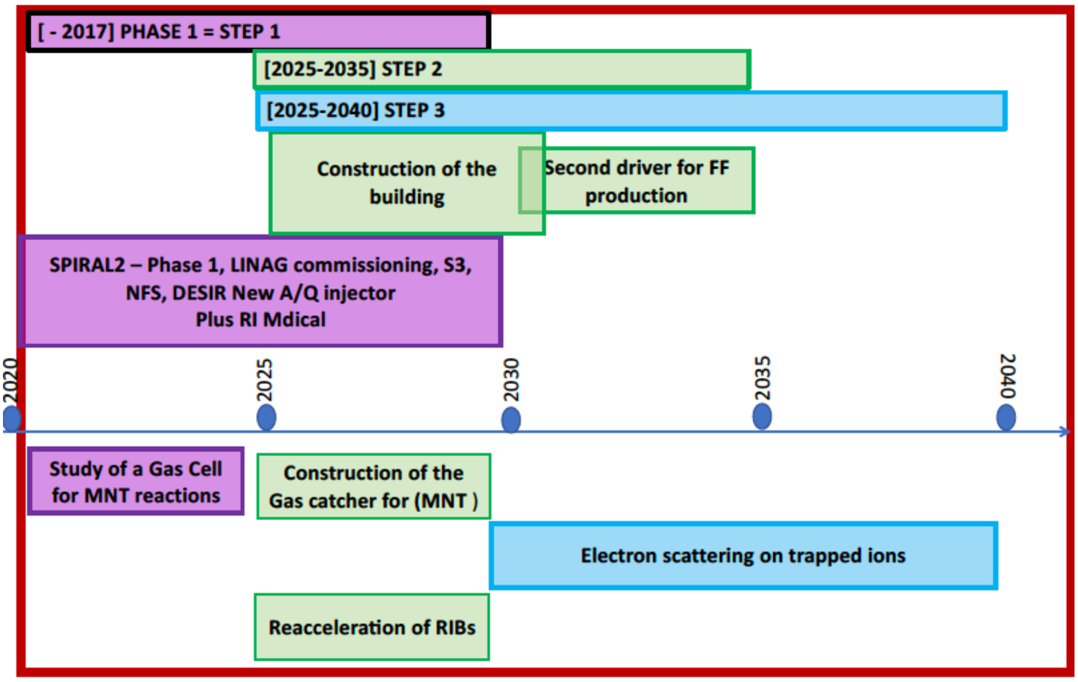


Fig. 2 Graphic timeline of the various GANIL projects.

Step1 (violet): SPIRAL2-Phase1 (- 2030) including a demonstrator gas catcher for multinucleon transfer reactions in the S^3 hall and production of medical radioisotopes in the LHE2 area,
Step2 (green): Revisited SPIRAL2-Phase2 (2025-2035) including the production building, Reacceleration, and an "IRASME2" beam line for materials science with ion beams (2025-2030), **later complemented by a Driver for Photo-fission** (2030-2035),
Step3 (blue): Building of the **Electron-accelerator** (2030-2040) required for **scattering on Radioactive Ions**.

The main thrusts for producing exotic nuclei foreseen at GANIL are:

- the ISOL method, already in operation but requiring additional R&D effort (SPIRAL1); [Option 1]
- in-beam method based on fusion or multi-nucleon transfer reactions using S^3 or in a dedicated gas-cell plus quadrupole mass filter located in the S^3 hall [Option 2] or in the production building; [Option 2+]
- the ISOL method based on fission of a uranium carbide target induced by LINAG beams or based on a new electron accelerator for photofission (SPIRAL2-Revised Phase2) in the production building; [Option 3]

The exotic beams produced by these 3 methods may be sent to the DESIR hall without reacceleration or could be reaccelerated using the CIME **or, better,** a new re-acceleration system, to the existing experimental halls of GANIL with their state-of-the art equipment. Low-energy beams (not reaccelerated) may be used in traps for electron-nucleus scattering experiments, offering an electromagnetic probe for the structure of exotic nuclei.
A judgement of their scientific relevance, considering the envisioned reacceleration or electron scattering schemes, is given in Table 1.

	SPIRAL 1 (Cyclotrons of GANIL) Option 1	SPIRAL 1 plus LINAG plus S3, DESIR, A/Q=7 (Phase 1 = Step 1) Option 1 + Option 2	Phase 1 or Step 1 plus Production building of fission products and Multi nucleon transfer for exotic nuclei Option 1 + Option 2 + Option 3
Absence of the high energy reacceleration nor electron scattering	not competitive in international context	will soon face international competition	unique but rather specific scientific opportunities
with new reacceleration	unique, but insufficient	Unique	unique, with new wide scientific opportunities
with electron scattering experiments	not worthwhile	important and unique	flagship and unique with a new and a wide user community

Table 1. The main production methods of RIB at GANIL and their scientific relevance, in the case of the absence of a new project and in the case of the acceptance of one or two of the envisioned new projects that is reacceleration of exotic nuclei and electron scattering.

Studies with beams of exotic nuclei produced by the SPIRAL1 (cyclotrons of GANIL) and/or by SPIRAL2-Phase1 projects without any further evolution of the facility will not be internationally competitive in the long run. It is clear that the currently operating facilities such as RIBF-RIKEN, HIE-ISOLDE and ISAC2-TRIUMF and those coming on line in the next few years like FRIB, RAON and FAIR will diminish markedly the competitiveness of the existing GANIL facility. Thus it is essential to **plan an exotic nuclei factory in a new production building, based on fission fragments and/or multi nucleon transfer products, subsequently reaccelerated to the energy domain from above Coulomb energy up to Fermi energy and beyond. The full vision is completed by a high luminosity electron accelerator (L>10^{29} $cm^{-2}s^{-1}$) for scattering on trapped exotic nuclei.**

The energy, intensity and beam quality targeted by the above ideas (reacceleration and electron scattering), will not be covered in the near future by any of the running or projected RIB facilities in the world.

While they could stand on their own, the scientific relevance and impact of re-acceleration of exotic nuclei and electron-scattering experiments would greatly benefit from the availability of nuclei produced by fission **in a Revised Phase 2 Production Building**. The accelerated beams would then become available in the current GANIL experimental halls and coupled with a unique ensemble of state-of-the-art spectrometers (VAMOS++, LISE...), and instrumentation (FAZIA, PARIS, GRIT, EXOGAM, AGATA…) that will lead to a world leading facility.

Today, the intensities of light ion beams provided by the LINAG are the highest in the world and this also open new opportunities for additional interdisciplinary applications, e.g. the production of radionuclides for emerging applications in medicine. These opportunities should be exploited in a timely manner, in parallel to the nuclear physics program outlined above. The long term future of the materials science community at GANIL would be further strengthened with access to LINAG beams via an “IRASME2” beam line in the S3 hall.

The successful execution of any of the presented upgrade options will require an adequate level of research, engineering and technical staff during the design, construction and exploitation phases. The foundations should therefore be laid by an appropriate recruitment strategy at GANIL and the supporting French laboratories. Additional key competences and support from international partners will be required and are best obtained via collaborations of mutual benefit.

5. Conclusions

With the existing capabilities and the currently launched projects (SPIRAL2-Phase1) GANIL is, for the next 10 -15 years, a world-class fundamental research laboratory in low energy nuclear physics, atomic physics, material science, radiobiology, and applications to related fields. GANIL provides unique expertise and capabilities and is a world-class facility for researchers worldwide. The quality of the radioactive ion beams at GANIL, with the corresponding equipment will yield direct nuclear reaction and scattering data that will rival results from the best stable beam facilities, something that is difficult or impossible to achieve elsewhere.

In addition, GANIL is classified as a landmark on the ESFRI list of European Very Large Research Infrastructures, **complementary to FAIR that will operate at much higher energies.**

The vision for the future of GANIL presented here is compelling. It provides a path for the long term future of the Laboratory and a path for continued leadership in fundamental nuclear science, interdisciplinary research and applied science answering societal issues.

Reacceleration to energies from the Coulomb barrier up to more than one order of magnitude higher (~100 MeV/nucleon) of a wide variety of beams (produced with the help of the existing facility, SPIRAL2-Phase1, and with a dedicated Production Building) would further attract a large community to GANIL to study frontiers of Nuclear Physics. Such a facility would be a basis to provide the nation with the necessary competence and experts in nuclear physics and nuclear engineering for decades to come.

Electron scattering experiments at high luminosity with trapped exotic nuclei would bring new insight and enable flagship experiments with results to enter textbooks in Nuclear Physics. Interdisciplinary spin-off applications, which are made feasible by such a facility, should be maximally exploited, with appropriate installations and with maintenance or rejuvenation of the GANIL injector cyclotrons.

The projects presented in this document, which are unique on the international scene, **lay out a vision to keep GANIL at the forefront of nuclear science globally for many decades to come**. The options presented are ambitious, demanding commitment of significant financial and human resources, and can only be realized within the framework of a strong national and international participation of universities and laboratories.

List of acronyms

CSIC: Consejo Superior de Investigaciones Científicas

https://www.csic.es/en

GSI: Gesellschaft für SchwerIonenForschung

https://www.gsi.de/en/start/news

FAIR: Facility for Anti-proton and Ion Research

https://fair-center.eu/

RIKEN

https://www.riken.jp/en/research/labs/rnc/

JINR: Joint Institute for Nuclear Research

http://www.jinr.ru/main-en/

NSCL: National SuperConducting Laboratory

https://nscl.msu.edu/directory/sherrill.html

ILL: Institut Laue Langevin

https://www.ill.eu/fr/

GANIL: Grand Accélérateur National d'Ions Lourds

https://www.ganil-spiral2.eu/

SPIRAL: Système de production d'ions radioactifs accélérés en ligne

LINAG: LINear Accelerator of GANIL

S3: Super Separator Spectrometer

https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/experimental-areas/s3/

DESIR : Désintégration, Excitation et Stockage d'Ions Radioactifs

https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/experimental-areas/desir/

NFS: Neutrons for Science

https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/experimental-areas/nfs/

LHE: Ligne Haute énergie --- High Energy Line

CIME : Cyclotron d'Injection de Moyenne énergie

ERL: Energy Recovery Linac

RI: Radioactive Ion

RIB: Radioactive Ion Beam

ISOL: Isotope Separation On-Line

RIBF-RIKEN: Rare Ion Beam Factory

https://www.nishina.riken.jp/ribf/

FRIB: Facility for Rare Isotope Beam

https://frib.msu.edu/

RAON: Rare isotope Accelerator complex for ON-line experiments within the Rare Isotope Science Project (RISP)

https://www.ibs.re.kr/eng/sub01_05.do

ISOLDE: Isotope Separator On-Line DEvice

https://isolde.web.cern.ch/

SPES: Selective Production of Exotic Species

https://web.infn.it/spes/

HIE-ISOLDE: High Intensity and Energy ISOLDE

https://hie-isolde-project.web.cern.ch/hie-isolde-project/

VAMOS : Variable Mode Spectrometer

https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/experimental-areas/g1-vamos/

LISE : Ligne d'Ions Super Epluchés

https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/experimental-areas/d3-d6/

FAZIA: Four-pi A and Z Identification Array

http://fazia.in2p3.fr/?lang=en

PARIS: Photon Array for studies with Radioactive Ion and Stable beams

http://paris.ifj.edu.pl/articles.php?lng=en&pg=15

GRIT: Granularity, Resolution, Identification, Transparency

http://grit.in2p3.fr/

EXOGAM: EXOtic nuclei GAMma detection

https://www.ganil-spiral2.eu/scientists/ganil-spiral-2-facilities/instrumentation/exogam/

AGATA: Advanced Gamma Tracking Array

https://www.agata.org/

IRASME: Ligne d'irradiation à moyenne énergie du GANIL. GANIL medium energy irradiation line