CYREN PROJECT

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1. INTRODUCTION

1.1 Scientific background

GANIL's cyclotrons deliver ion beams ranging from Carbon to Uranium, with energies covering a range from 0.25 to 95 A.MeV, depending on the type of beam required.
These beams are conducted to experimental areas where dedicated and varied detection systems are installed for the study of nuclear reactions and nuclear structure, as well as radiobiology and innovative techniques for dosimetry and hadrontherapy, the study of materials under irradiation and nanostructuration, molecular collisions and the study of the interstellar medium.
The users of these beams form a community of around a thousand researchers, two-thirds of whom work in nuclear physics and one-third in interdisciplinary physics.
In nuclear physics, researchers also work on other major international infrastructures such as GSI (FAIR), ISOLDE (CERN) and, until now, JINR in Russia and RIBF in Japan. However, GANIL retains a privileged position due to the energy of its beams, which correspond to very complementary experimental conditions and provide access to excitation regimes that are inaccessible elsewhere. In addition, the supply of beams around the world is still fairly limited, and the demand for GANIL's beam time is under pressure from 2 to 3.

In the 1990s, an international scientific committee chaired by Nobel laureate Ben Mottelson recommended upgrading the infrastructure with the SPIRAL1 facility for producing exotic beams. Put into operation in the 2000s, this facility has led to numerous discoveries in nuclear physics and nuclear astrophysics, thanks to the study of states and reactions involved in the processes of stellar nucleosynthesis.

In the 2010s, SPIRAL1's target-source assembly underwent a major upgrade that now enables it to produce certain isotopes at the best rates in the world. This success is due to the very high intensities of the primary beams available, supplied by GANIL's two cyclotrons in cascade. Exploiting the potential of these developments is an asset for GANIL, but it will only be possible if the cyclotrons are able to operate safely.
This need of SPIRAL1 beams is reinforced by the DESIR scientific programme, part of which also relies on the exotic beams of SPIRAL1. DESIR will open up a new field of study at GANIL, with high-resolution measurements of the properties of nuclei in their fundamental or isomeric states: measurements of masses and radii, laser-assisted spectroscopy and spectroscopy using traps. DESIR's unique character is associated with its beam preparation and selection instrumentation, which ensure that the experiments have a level of beam purity unmatched by equivalent facilities.
Thanks to this exceptional resolving power, DESIR will also be the facility of choice for studying possible exotic couplings in the electroweak interaction through precision studies of beta

decay, which can reveal minute deviations from the standard model of particle physics. This programme was recently presented to the GDR Intensity Frontier[1].

The light nuclei produced by fragmentation at LISE enable studies of transfer reactions of interest for nuclear structure and nuclear astrophysics.
One can also mention studies of the equation of state of nuclear matter and clustering in low-density phases, for an understanding of the explosive dynamics of neutron stars. The energy regime provided by GANIL's cyclotrons gives access to very specific density regions corresponding to relaxation and expansion phases following neutron star collisions, whereas the higher-energy experiments at GSI/FAIR or ALICE focus on the collision phase associated to compression.
A vast fission programme is underway with the VAMOS spectrometer. These studies, which began a decade ago associating the VAMOS spectrometer and the technique of inverse kinematics, using heavy ion beams on light targets, have provided access to the complete isotopic yields of fission fragments from nuclei with impact in the nuclear fuel cycle or in nucleosynthesis (fission cycling). These experiments, which are unique in the world, are receiving strong international acknowledgement and theoretical interest for an in-depth understanding of fission mechanism. These much more complete and precise fission yields make it possible to use new techniques for evaluating nuclear data, and to improve estimates of the decay heat of spent fuel and neutron fluxes within reactors. They are of particular interest in a context where new-generation reactors are being considered.

Some of the research carried out at GANIL with cyclotrons beam is contributing to improve the safety of the nuclear industry by testing new waste matrices rich in alpha-emitting actinides (testing of new cements, or studies of multiphase materials with ion beams that simulate the effect of alphas), testing polymers and hybrid materials planned for long-life nuclear waste (study of the radiation-induced formation of complex molecules that would make them water-soluble and labile during storage over long periods).
As far as interdisciplinary physics is concerned, apart from molecular and atomic physics whose activities are mainly carried out at ARIBE, the themes concerned are the study of inorganic and organic materials, astrochemistry and radiobiology. The community of physicists working on these themes is very present at GANIL and the trend is growing. GANIL is part of the EMIR&A research infrastructure and the European networks RADNEXT for component irradiation and CORA-IBER for radiobiology.

In the field of radiobiology, GANIL's beams enable a wide variety of preclinical studies to be carried out using different ions and over an energy range around the Bragg peak corresponding to the maximum linear energy transfer, unlike dedicated infrastructures which are generally proton or very light ion accelerators, and at higher energies. These studies have direct applications for hadrontherapy and space.
The irradiation line dedicated to radiobiology recently received the IBISA [2]label.

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[1] http://gdrintensityfrontier.in2p3.fr/

[2] https://www.ibisa.net/decouvrir-ibisa.html

The particular energy range and diversity of the ions produced also make GANIL's beams (CSS1 and CSS2) unique for materials physics, and for certain technologies such as the production of nanofilters with various applications (purification of blood, water, etc.) or the radiation hardening of electronic components for space and military applications. Recent contacts with the space industry show that demand is set to rise sharply over the next few years, and that GANIL's beams are indispensable, thanks to their variety and unique energy range. Military applications, on the other hand, require a national infrastructure because of their confidentiality.

GANIL's cyclotrons therefore form an essential instrumental ensemble for future research in these different communities, which require beams of varied nature and covering a wide energy range, with more beam time for interdisciplinary physics on a regular basis, varied and high-performance instruments and finally the generalisation of parallel/auxiliary mode operation. All these fields of research require cyclotrons to operate at optimum efficiency.
In addition, the report by the international expert committee on the vision for the future of GANIL, headed by Mr M. SPIRO in 2021, recommends as a first step to consolidate the operation of the cyclotrons through an ambitious renovation programme, so that over the next decade they will be able to produce radioactive ions with SPIRAL1 for DESIR and ion beams for the interdisciplinary physics community.

1.2 Technical background, objectives and scope

Since its creation, GANIL has regularly renovated its equipment, enabling it to continue operating the facility to this day. Over the last ten years or so, renovation operations have been drastically scaled back, due to the redeployment of human and financial resources to the construction of SPIRAL2 and the implementation of the action plan resulting from the first safety review (RXS1).
As a result of this minimalist renovation, often reduced to strictly necessary maintenance, GANIL is now faced with an ageing stock of equipment (some dating back to its construction) that is becoming difficult to maintain and operate, whether for reasons of obsolescence or the volume of human resources that need to be devoted to it.
Against a backdrop of pressure on GANIL's workload, GANIL stakeholders have appointed R. Clédassou (IN2P3) and Ph. Rebourgeard (DRF) to co-lead a working group tasked with analysing GANIL's overall activities and making recommendations. In its report, due in November 2021, this working group recommended, among other things, that an ambitious renovation program for the cyclotron complex be launched as soon as possible.
In addition, the report of the expert committee on GANIL's vision of the future, headed by Mr. SPIRO in 2021, recommends as a first step to consolidate cyclotron operations, so that they can produce radioactive ions for DESIR with SPIRAL1 and ion beams for the interdisciplinary physics community over the next decade.
In March 2022, GANIL launched the CYREN (CYclotrons RENovation) pre-project to establish a renovation program in line with these recommendations, with the following two objectives:

Objective 1: maintain the cyclotron complex in operational condition for 20 years.

Objective 2: to optimize the operating human resources (HR) required once the program has been implemented.

The technical scope of this preliminary CYREN project is limited to the cyclotrons and experimental rooms up to the reaction target, and to the infrastructures, utilities and processes for Safety, Security and Radiation Protection (SSR). Physics detectors and their acquisition systems are excluded.

2. METHODOLOGIES

2.1 Identifying needs

An initial survey of renovation needs was carried out in 2021 by the Operations and Development Division (DOD), the summary of which was formalized in a white paper that provided valuable input for the CYREN preliminary project. With regard to infrastructures, easements and SSR processes, the inventory of needs was carried out within the framework of CYREN in 2 steps.

Step 1: systematic inventory of the various types of equipment according to predefined criteria (state of disrepair, reliability feedback, maintainability/evolutivity, impact on operation in the event of breakdown) and identification of the need for preventive action.

Step 2: for each type of equipment requiring preventive action, identification of possible solutions to be implemented, with assessment of the associated human and financial resources.
For each of the technical issues addressed (detailed in paragraph 4), this 2-stage analysis was carried out by a working group led by the project manager, and formalized in an analysis grid. This 2-step methodology was also deployed to complement the analysis of certain themes addressed in the DOD white paper.

2.2 Synthesis and definition of scenarios

All the technical solutions identified were compiled in a summary file and each solution was assigned to one of the following scenarios:
Optimised scenario:
This is the scenario which, for GANIL, best meets the two objectives set: maintenance in operational conditions for 20 years with optimised HR. This scenario includes, in particular, the construction of a new HF cavity to replace one of the four cavities and to have a spare and the renovation of the cyclotron control system to a stage that prepares for its convergence with the one of SPIRAL2.

Two degraded scenarios:
In these scenarios, equipment renovation is only partial. Some equipment whose failure is not considered critical for operations (limited downtime in the event of a breakdown) is not treated. For other equipment, only part is refurbished and the replaced equipment constitutes a stock of spares for the non-refurbished part of the fleet. In these scenarios, all the critical points are secured and the objective of maintaining equipment in operational condition for 20 years is met. On the other hand, the HR required for this maintenance is not optimised

insofar as refurbished and ageing equipment coexist. As these two scenarios do not meet the two major objectives, they are not presented in the rest of this document.

2.3 GANIL management committee (CODIR) recommendations

The GANIL management committee recommended in June 2022 to take into account the treatment of the three other HF cavities for the CSS (new or renovation) and the complete convergence of the cyclotron and SPIRAL2 control systems.
Regarding this last point, GANIL argued that the complete convergence (i.e; one single control command for both accelerators) would represent a significant financial and manpower effort for a little operating benefit. This topic is therefore excluded from the renovation programme, and a simple stage that prepares for its convergence with the one of SPIRAL2 is considered.

3. CONTENTS OF THE PLANNED RENOVATION PROGRAMME

The following paragraphs provide a summary of the planned refurbishment measures by technical theme

3.1 Infrastructure and utilities

3.1.1 Electrical distribution

The 90 kV delivery substation comprises two lines and two 10 MVA transformers, providing a redundant power supply for the site. The substation's management system (controls, safety management) is outdated and needs to be upgraded. It constitutes a regular failure mode for the original installation and SPIRAL2.
The harmonic filter in the original installation, which is currently out of order, needs to be replaced. Without the reactive energy compensation it provides, operation with just one of the 90 kV 10 MVA transformers is not possible with both installations in operation, thus depriving GANIL of its redundant power supply.
The 20 kV HV cells and the 20 kV - 400V transformers supplying the cyclotrons are also included in the renovation programme.

3.1.2 Refrigeration systems

The refurbishment programme covers the following sub-systems:

Water treatment: this produces decarbonated and demineralised water for both facilities. It is outdated from the outset and is a regular failure mode for both facilities.

Aero-refrigerating towers (TAR) and primary circuit: the TARs need renovation (repair of civil engineering defects, complete overhaul of the waterproofing, change of packaging, etc.). The primary circuit, made of steel, is subject to corrosion in the presence of decarbonated water and should be replaced with stainless steel piping.

Secondary circuits: replacement of heat exchangers and expansion vessels.
A technical and economic study is planned to define the best technical solution for renovation, in particular for water treatment, for which osmosis treatment could judiciously replace decarbonation treatment.

3.1.2 Heating- Ventilation- Air conditioning

The renovation programme includes the replacement of certain unit heaters and extraction fans.

3.1.3 Buildings

The two main renovation operations involve re-roofing the Machine Building (BAM) and the Energy Building (BEN) to ensure their watertightness.
The problem of equipment storage, which has been omnipresent at GANIL for several years, has been reinforced by the renovation programme, which generates a need to store spare equipment, some of which has large dimensions, such as an HF cavity. The renovation programme therefore includes the construction of a storage building with three times the capacity of the existing building. This capacity is an initial estimate, which will need to be backed up by a precise inventory of all requirements.

3.1.4 Computing infrastructure

In addition to replacing workstations and servers whose warranties are due to expire, the renovation programme includes an upgrade of the network architecture to take account of the new requirements generated by the renovation of equipment, in particular power supplies.

3.2 Safety / security / radiation protection systems

3.2.1 Radiation protection equipment

The refurbishment programme includes the replacement of the remaining 60 SAPHYMO beacons, which are original.
The operational dosimetry system is becoming obsolete. The current dosimeters are no longer on the market and the new generation is not compatible with our reading terminals. Replacing this system is also part of the renovation programme.
Finally, it is planned to purchase replacement gamma spectroscopy equipment to ensure continuity of service for the SPR measurement laboratory, particularly for monitoring releases.

3.2.2 Access Management Unit (UGA)

This system was commissioned in 2013. Due to obsolescence, the renovation operations identified correspond to the single passage detection system in the SAS and supervision (currently in Panorama E2 V6).

3.2.3 Fire safety system

The current Siemens fire safety system is reaching the end of its useful life and a study is currently underway to replace it, with the support of a CEA expert. This subject is included in the renovation programme

3.3 Cyclotron and experiment room equipment

3.3.1 Power supplies and magnets

The refurbishment programme covers the 360 remaining power supplies that are between 30 and 40 years old.
Power supplies for SPIRAL1, IRRSUD and VAMOS, which are more recent, have therefore been excluded.
For the 115 low-power power supplies (<1kW) and the 225 medium-power power supplies (<60KW), the chosen solution is to purchase catalogue power supplies controlled by an interface already developed by GANIL.
For the 20 high-power power supplies, the chosen strategy is to manufacture new power supplies to specifications imposing the technical solution for the sake of standardisation and technical control.
The NMR probe magnetic measurement system is no longer supported by the manufacturer METROLAB and the new system is not compatible with the old one. A complete replacement is planned.

3.3.2 HF cavities and systems

For the past twenty years or so, the accelerator HF cavities in the two CSSs have been subject to leaks from their cooling circuits, resulting in major repairs (around 10 days of downtime). Until now, the leaks have always been more or less easily accessible for repair. In order to prevent the risk of shutdown following a leak that cannot be repaired, **the optimised scenario provides for the manufacture and installation of a new cavity and the conservation of the replaced cavity as a spare.**

The feasibility of such an operation was studied as part of the preliminary project.

Sourcing of manufacturers capable of producing such an object was started on the basis of references supplied by PSI laboratory and with the help of IBA.
To date, three manufacturers have been contacted: SATIL (France), Research Instrument (Germany) and SDMS (France). SATIL is not in a position to provide all the necessary services, RI considers the project to be very risky and has shown no interest, although it has not completely closed the door. SDMS is capable of carrying out the work; the plans for the cavities have been sent to SDMS for an assessment of costs and timescales. **The cost of a new cavity is estimated at 5.7M€ (+/- 300k€), with a two-year lead time.**

The transport of a cavity into a cyclotron casemate (as well as its removal) is envisaged using a crane, with an opening in the roof of the machine building. The technical feasibility was validated by a specialist lifting company after a site visit. The operation is estimated to cost 350 k€ and take 3 months to complete.

The replaced cavity will be a stored for eventual future replacement, but to do so it must be kept in specific conditions (nitrogen inerting).
The extension of the optimised scenario involves replacing all four cavities. The cost of manufacturing the 3 additional cavities is estimated by SDMS at 4M€ per unit, with a delivery rate of one cavity per year.
This complete scenario could be subject to cost and time optimisation: once the first new cavity has been installed, subsequent cavities could certainly be renovated, retaining certain parts. The various technical options for renovation can only be defined in partnership with an expert industrial and have not been evaluated at this preliminary design stage.

GANIL plans to call on technical assistance to draw up the technical specifications, analyse the bids, select the manufacturer, monitor the project and carry out acceptance tests and inspections.

In addition to the cavities, spare components for the microwave transmitters (klystrons) and HF amplifiers (tetrode tubes) must be supplied before they become obsolete. The PLCs the HF systems are also part of the refurbishment programme.

3.3.3 Command and control

In terms of maintaining operational conditions, the renovation of the cyclotron control command system, known as Ganiciel, is necessary due to the obsolescence of certain VME cards and the cessation of support for the MOTIF/XRT graphics technology used in the 45 Human Machine Interface (HMI) applications.

The development of the Ganiciel was initiated in 1990 and put into operation in 1993 in a minimal configuration that was subsequently enhanced over the years with new control and adjustment Human-Machine-Interfaces. The legacy of these successive patches is today a software architecture in which graphics functions are mixed with others related to equipment control or algorithms.
The renovation strategy is built in 3 stages.

The first stage involves a complete refactoring of the existing code in order to separate the various functionalities.
The second stage involves migrating the graphics functions to Web technologies, transferring the equipment control and algorithmic functions to the 'ADA servers' layer of the software package, and virtualising 8 of the 31 VME chassis. The communications protocols are then managed at ADA server level and no longer by VME boards, and the VME I/O boards are replaced by Ethercat-connected terminal blocks.
The third stage consists of finalising the virtualisation and removal of the remaining VME racks, with the exception of the 9 that contain boards developed by GANIL specifically for the equipment they manage.

The work to be carried out for these 3 stages is estimated at 12 FTE. To carry out this work, GANIL plans to use a software engineering contract with a monitoring ratio of one third to ensure that the code developed by the service provider is appropriated and to carry out the qualification tests.

3.3.4 Programmable Logic Controllers (PLC)

GANIL has several generations of PLCs. The renovation programme concerns the replacement of the S5 series PLCs for which the manufacturer no longer sells spare parts. This represents around thirty PLCs to be renovated including the renovation of the equipment they control. The first PLCs to be refurbished will be those used for vacuum systems (some operations already started in 2023). The renovated equipment will be kept as spares until the S5 series has been replaced.

3.3.5 Vacuum systems

Vacuum systems are typically pieces of equipment that have been regularly renovated for several years in accordance with an established programme. The refurbishment programme incorporates this established programme up to 2026.

3.3.6 Diagnostics and beam equipment

The main operation included in the refurbishment programme concerns the replacement of around 200 motor control cards that have become obsolete.

3.3.7 Production targets

The remote manipulator for the CLIM target at LISE needs to be made mechanically reliable, and its control system also needs to be upgraded at the same time.

3.3.8 Ion sources

The ion sources themselves do not require renovation or replacement. However, the environment of the source located on the high-voltage platform of the C02 injector needs to be renovated (electrical engineering, instrumentation, automation).
However, a preliminary study has been carried out into the benefits of installing a more efficient PHOENIX V3 type source on the C02 injector. This preliminary study shows **a potential gain in intensity of 2 to 15 depending on the beams**, by modifying the injection line in the C02 cyclotron. However, at this stage of the study, the possibility of injecting these beams into C02 and the feasibility of installing a new inflector have not been demonstrated and could require modification of the C02 HF cavity. The study should therefore be continued as part of a dedicated preliminary project.
The opportunity to install a more efficient C02 source is therefore not included in the renovation programme. However, the environment of the C02 source and its power supplies will be renovated, taking into account a sizing compatible with a PHOENIX V3 source.

4. PLANNING

The planning of the work to be carried out as part of this renovation is based on the fact that changing a cavity stops the production of high- and medium-energy beams for at least 15 months. It has been carried out by minimising cyclotron shutdowns and scheduling the work associated to renovation during the 2^{nd} half of each year between 2024 and 2028 for the optimized scenario and between 2024 and 2031 for the complete scenario.
The planning for the renovation of the three other HF cavities, including the associated necessary shutdowns until 2031, will be consolidated in the project phase when the technical options will be chosen (not available yet at this pre project stage).

5. SUMMARY OF COSTS AND HUMAN RESOURCES

The work carried out as part of the CYREN preliminary project has made it possible to highlight the operations that need to be carried out over the next few years in order to maintain GANIL's cyclotrons and its experimental rooms in operational condition for 20 years, the scientific interest of which for the nuclear physics and interdisciplinary physics community is recalled in the report of the group of experts led by Michel SPIRO and in the introduction to this document.
The proposed renovation programme is an ambitious one, as its aim is to emerge as quickly as possible from a situation in which the maintenance effort required of the teams increases with the age of the equipment, some of which is as old as GANIL.
Independently of this ambition, it is important to emphasise that the low level of maintenance practised in recent years is not sustainable in the long term and that to maintain the cyclotrons in operational conditions, the regular upgrading of equipment must return at least to the level practised before the construction of SPIRAL2.
The summary table below shows, for each refurbishment item, the breakdown of costs and human ressources between the refurbishment costs, which must be included in GANIL's operating budget, the costs of the CYREN project and the cost of the HF cavities project.
For each renovation item, the costs are presented excluding uncertainty.

Topic	rejuvenating	renovation	cavities	TotalCYREN budget	FTE (Human Ressources GANIL)	Skills
Buildings/logistical support	525	1700		2225	1,3	buildings/support
encumbrances	3236	420		3656	2,9	encumbrances
Computing Infrastructure	223	75		298	0,9	Computing infrastructure
Equipment for safety and radioprotection	2162	991		3153	2	Safety and radioprotectio
Power supplies/Magnets	2008	2172		4180	11	power supplies/ magnets
PLC	270	0		270	11	PLC
Cavities and HF systems	777	305	19310	20392	15	HF
Command control	1000	330		1330	5	Command Control
Diagnostics	223	152		375	2,7	Diagnostics
Targets-Ion sources	65	0		65	0,9	Target-Ion Sources
Vaccuum	450	140		590	1,6	Vaccuum
Contracts					4,8	Contracts
Mechanics					3,4	Mechanics
Total	**10939**	**6285**	**19310**	**36534**	**62,5**	Without margins
Margins on uncertainties	1123	348	1069	2540		
vagaries on uncertainties	496	176	542	1214		
vagaries on project	2188	1257	3862	7307		
TOTAL (k€)	14746	8066	24783	47595	80 FTE	TOTAL FTE with with 30% margin for uncertainty

The §4 mentions operations spread over 5 years for the optimised scenario and 8 years for the complete scenario. This is the result of an "as soon as possible" scheduling of actions, taking into account the technical constraints, the desire to limit the unavailability of the cyclotrons for the scientific community and the other projects that GANIL must carry out in parallel.
Expenditure profiles can be spread over longer periods

6. CONCLUSIONS

The cost of such a complete refurbishment programme is 47.6M€. These amounts should be set against the value of the accelerator complex, currently estimated at over €500m.
As far as human ressources are i concerned, the needs of the CYREN project have been anticipated and provision has been made for 10 FTEs for 2024, with a consequent reinforcement in terms of fixed-term contracts (5 FTEs). The analysis of the skills gaps remains to be consolidated. The assessment of CYREN's needs, heightened by uncertainties, indicates that this provision is not sufficient and needs to be reinforced from 2024 for at least 3 years. This should be done in coherence with a potential spread of expenditure profiles, as mentioned above.
Recourse to technical assistance has been considered in areas such as HF cavities, command control and refrigeration, with the implementation of project management contracts being planned.