GANIL FUTURE REPORT TO THE INTERNATIONAL EXPERT COMMITTEE
WORKING GROUP ON "POST-ACCELERATED RADIOACTIVE ION BEAMS"

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EXECUTIVE SUMMARY

In the present report we give an overview the physics at reach based on ISOL post-accelerated Radioactive Ion Beams (RIB) in the energy range between Coulomb and Fermi energies as well as the investigation of three technical options for that purpose, available today, for the future of the GANIL-SPIRAL2 facility at the end of the present decade. **Such an installation would cover a unique and competitive science case at the world level.**
In the following we will summarize the main outcomes of the present report which are described in more details in the respective chapters listed below.

After a short introduction (Sec. I, Context and mission) an overview of the world status of major ISOL post-accelerated facilities (running or planned) is presented in Sec. II, and summarize below:

> **-The full spectrum of ISOL post-accelerated RIB in the energy domain above the Coulomb energy (10 MeV/A) up to Fermi energy and beyond (<100 MeV/A) is not covered by any of the running or projected ISOL RIB facilities in the world (see section II, Table 1).**
>
> **-The investigation of long chains of neutron rich and proton rich nuclei produced by ISOL from light species (C, O, Ne) to medium (Kr, Sn) and up heavy Trans-Actinides with intensities 10^{2-7} pps in the energy range 10-60 MeV/A (Flagship beam ^{132}Sn 10-60 MeV/A10^{7}pps on target) with high purity and beam optics comparable to the best stable beams will be possible and open the way to a rich nuclear structure and reaction research program**.

The physics case is described in section III. The working group has identified three main themes where the ISOL proton and neutron rich post-accelerated RIB in the energy range between 10 to 60 MeV/A and beyond in some options, with masses ranging from the lightest (A<40) to the heaviest (A> 230), will open exciting and unique opportunities.

First, this range in mass and isospin of RIB produced with adequate intensities (10^{2-7} pps) and the chosen energy range will allow the detailed study of very fundamental properties of nuclear matter namely **the Equation of State (EOS) using both very specific nuclear reactions (Inelastic scattering and Charge exchange reactions) and Heavy Ions Collisions (HIC) on long chain of RIB (Z=20,28,50,82), see III.A.**

There exist two main approaches to constrain the parameters of the EoS: heavy ion collisions (HIC) and the measurement of Giant Resonance (GR) properties. These methods are complementary: GRs probe the EoS parameters through excitations close to saturation density through structural information whereas HIC may probe a much larger domain in density. Going far from stability i.e. maximizing isospin asymmetry δ is necessary to constrain the isospin dependence and thus the isovector part of the EoS, of which the parameters are currently poorly determined.
High quality post-accelerated beams at around 50 MeV/A are perfectly suited for studying GR using inelastic scattering reactions and for creating asymmetric nuclear systems at low density in HIC.

A second class of experimental investigations (III.B) will address the structure of “exotic” nuclei and the related nature of the nuclear interaction in the regions around Z=28,50,82 and even higher in Z**, the origin of shell drifts, shapes evolution, Pygmy Dipole Resonances, Pairing in neutron rich matter and neutron stars, Double Beta decay and Double Charge eXchange reactions (DCX). In the mass region between 40<A< 240 nuclear reaction rates at the origin of the formation of the heavy elements in the universe can be measured using indirect methods based on nuclear reactions and detailed spectroscopy.**

Last but not least, a very unique domain of research can be addressed due to the unique high power of the SPIRAL2 HI Driver, to produce via Multi Nucleon transfer and fusion-evaporation processes, Very Heavy Nuclei (VHN) far off stability for which very little is known today.
As discussed in **Sec. III.C**, the structure and spectroscopy of Very Heavy Nuclei (VHN) far off stability (Trans-Lead and Ac) can be investigated in details using the post-accelerated VHN via Coulomb excitation and few nucleons transfer reactions. In addition, the fission process of these VHN, fission barrier and fission fragment distribution will be explored for the first time in this "exotic" region of the mass table.
The Physics case put forward matches very well the expertise in reaction physics developed during the past four decades at GANIL. Therefore, it can be expected that a large fraction of the current GANIL user community will contribute to the exploitation of the new facility. In addition, sophisticated detectors built in view of the now defunct second phase of SPIRAL2 (EXOGAM2, GRIT, ACTAR, FAZIA …) are perfectly suited, if upgraded accordingly, to realize the physics case presented here.

Pre-requisite of these options of ISOL Post-accelerated RIB are described in the introduction of Section IV. We have assumed that the Radioactive Ion Beams (RIB's) are produced as q=1+ ions in a production hall, close to SPIRAL2/DESIR buildings. Such a hall is part of the upgrade plans proposed to the Committee, which was investigated as an initial phase for an ambitious future for GANIL [Del21]. The production building enables to cover wide and diverse regions of the chart of nuclei thanks to different reaction processes using the SPIRAL2 LINAC and/or with an independent Photo-Fission driver. ***We would like to emphasize here that for a minimum additional cost (industrial machine available as a photo-fission driver), the GANIL-SPIRAL2 facility will extensively enlarged its capabilities to produce copiously neutron-rich fission fragments and subsequently its mass coverage of post-accelerated RIB. Last but not least, a dedicated driver for neutron rich fission fragments will permit a very efficient multi beam operations of the future facility.***
The production building includes two types of production cave: one for the production of fission fragments, and another one for products of fusion evaporation, Multi Nucleon Transfer and / or fission fragments stopped in gas cell. These capabilities are developed in detail in a document submitted to the committee in December 2021 [Del21] and summarized in sec. IV.A).

In section IV three technical options for post-acceleration of RI at GANIL in the energy range presented in the physics case are discussed and a preliminary design comparison is presented.

- GANIL-Sector Separated Cyclotrons (SCC) upgrade
- Compact Superconducting Cyclotron
- Superconducting RF LINAC

A. GANIL-Sector Separator Cyclotrons (SSC) upgrade

The present GANIL cyclotron accelerator chain could meet most of RIB post accelerator specifications needed. Downstream the new 1+ production station, we propose to replace the existing ECR ion source and C0 injector by a versatile charge breeder system followed by compact low energy LINAC injector bringing the beam to the desire energies (~1 MeV/A) in order to be post accelerated into the GANIL SSC. This new LINAC injector will improve the beam transmission as compared to the present C0 scheme.
In addition, a full renewal of GANIL SSC RF cavities and related diagnostics is envisaged to insure a few more decades of reliable operation of the new LINAC+SSC accelerator chain.

The main characteristics of the post-accelerator Linac + SSC design option are summarized in the table below:

Parameters	SCC upgrade
Cost of accelerator (Linac+RF)	23 M€
Cost Accelerator building	5 M€
Cost Experimental building	0
Manpower resources	Limited
Max. Output energy: For 132Sn^{26+} For 90Kr^{20+} For Z/A=0.4-0.5	 33 MeV/A 49 MeV/A 80 MeV/A
Energy range (MeV/A)	(discrete energies) [3.5-15] and [24-33-49-80]
Stripping	Required for high energy (SSC2)
Selectivity	Good/very good
Expected Transmission	15% to 50% (with /without stripping)

Table 1

The main advantages and limitations of this option are summarized in the SWOT analysis shown in Sec. IV. B.

The GANIL SSC upgrade will have the clear advantage to make a maximum use of the existing GANIL facility at minimum cost, time duration and human expertise and resources. However, the energy range specifications are not covered for RIB above mass 90, and have discrete values at above 20 MeV/A.
Beam purity and transmission are very good and re-use of experimental building and vaults are possible. Present stable beam operation of existing Ganil, including SPIRAL1, is preserved when the new LINAC and SSC upgrade construction and commissioning is achieved.

B. Superconducting Compact Cyclotron (SCC)

A stand-alone Superconducting Compact Cyclotron could also fulfill the post-acceleration requirements. Together, with an efficient charge breeder system, the SCC will accelerate RIB with a great selectivity and a good efficiency. Additionally, the SCC size (6-7m overall diameter, H= 5m, weight, 700t) can be fitted in existing GANIL infrastructure and/or integrated in the new production hall. Last but not least GANIL expertise and experience in operating large scale cyclotron accelerators is certainly a clear added value for this post-accelerator design option.
This compact and medium cost option would cover the whole needs of physics expressed above.
The design of a K_b=1600 SCC cyclotron has been undertaken these last years for a 400 MeV/A and Q/A=1/2 accelerator for carbon therapy by IBA, the so called C400 project. The design of such magnet for our requirement in term of RIB post-accelerator will be probably with less demanding for maximum final energy of about 100 MeV/A. Nevertheless, a new design has to be undertaken from existing machine in view of the specificities of variable energy, bending and focusing limit needed in our case to accelerate a wide range of Z/A RIB species.

The main characteristics and parameters of the SCC design option are shown below:

	Superconducting Compact Cyclotron
Cost of accelerator	70-80 M€ (based IBA)
Cost Accelerator building	5-10 M€
Cost Experimental building	0
Manpower resources	Very restricted if industrial
Max. Output energy: For $132Sn^{26+}$ For $90Kr^{20+}$ For Z/A=0.4-0.5	 64 MeV/A 79 MeV/A >100 MeV/A
Energy range (MeV/A)	[10-100] MeV/A
Stripping	Not Required
Selectivity	Good
Expected Transmission	10-20% (no stripping)

Table 2

The main advantages and limitations of this option are listed in the SWOT analysis shown in Sec. IV. C

The SCC K1600 is a new post-accelerator which, after a detailed design study, will fulfill the whole range of specifications at the cost of a significant investment but limited human resources and time duration if built by an industrial provider which have large experience in cyclotron construction and commissioning. Implementation can be integrated in the present facility buildings or in the new production hall. Re-use of present experimental building and vaults is possible at the cost of high rigidity upgrades of HE beam and experimental beam line. Stable beam operation of existing Ganil is preserved during construction phase.

C. Superconducting RF LINAC

A more ambitious option for post-accelerated RIB at GANIL-SPIRAL2 for the next decade (beyond 2030) is to build a new superconducting RF LINAC. Recent design and successful commissioning of SPIRAL2 RF SC LINAC demonstrate that the expertise of designing, building and operating such a large accelerator is available at GANIL.

A very efficient charge breeder system should be inserted prior the acceleration, because of the lack of selectivity of such an accelerator in order to limit the injection of parasitic species in the linac.

The large size of such post-accelerator (Length> 100m) limits the choice of its implantation in GANIL premises. It has to be placed close to the production hall building in order to limit the LEBT length. Using the dimensions of the existing SPIRAL2 tunnel and technical corridor width, the post accelerator seems to fit nicely between the existing GANIL and the future DESIR building.
This choice of linac implantation should provide enough room between the production area and the linac injection for the installation of a charge breeder and a mass separation system to be defined.
However, this implementation implies to design and built a new experimental hall nearby.
Although the transmission of the linac itself is around 100% the overall transmission is reduced by the 90% in the Medium Energy Beam Transport line, 95% in the RFQ and 80% in the Low Energy Beam Transport Line. An overall 70% is achievable. It is the best accelerator transmission of the 3 options at the price of the mass selectivity. Additional equipment to improve the selectivity should be studied such a Medium Resolution Mass Separation (MRMS) prior acceleration and will certainly impact the overall transmission efficiency of the whole accelerator chain.

The construction of a superconducting linac is a very mastered technology. All major accelerator projects on the planet use this scheme for the effectiveness of the design. It helps limiting the risk.

The main characteristics and parameters of the Superconducting LINAC are shown below:

	Superconducting LINAC
Cost of accelerator	102 M€
Cost Accelerator building	22 M€
Cost Experimental building	20 M€
Manpower resources	Large
Max. Output energy: For 132Sn^{26+} For 90Kr^{20+} For Z/A=0.4-0.5	 60 MeV/A 75 MeV/A 100 MeV/A
Energy range (MeV/A)	[5-100] MeV/A
Stripping	Required for a minimal selectivity and cost.
Selectivity	Low (constraint on source/stripping)
Expected Transmission	20 % (with stripping)

Table 3

The main advantages and limitations of this option are listed in the SWOT analysis shown in Sec IV.D

The SC RF Linac is also a new post-accelerator. This option will fully cover the design specification in energy range and species but need specific and complex beam selectivity devices before injection.

The modularity of such SC LINAC allow for future energy upgrade if needed at minimal cost. However, the investment cost is quite significant not only because of the SC RF technology itself but also due to the new building dimension to host the accelerator (>100m) and the related need for a new experimental hall nearby to host the instruments (detectors, spectrometers,). Stable beam operation of existing Ganil and SPIRAL1 are preserved during construction phase.

Conclusions

The full spectrum of ISOL post-accelerated RIB in the energy domain above Coulomb energy (~7MeV/A) up to Fermi energy and beyond (<100 MeV/n) is not covered by any of the running or projected RIB facilities in the world (see section II, Table 1).

Investigation of long chain of neutron rich and proton rich nuclei produced by ISOL from light species (C, O, Ne) to medium (Kr, Sn) and up heavy Trans-Actinides with intensities 10^{2-7} pps in the energy range 10-60 MeV/n (Flagship beam ^{132}Sn 10-60 MeV/A, 10^7pps on target) with high purity and beam optics comparable to the best stable beams will be possible and open the way to a rich nuclear structure and reaction research program.

The working group has identified the main research areas where the ISOL proton and neutron rich post-accelerated RIB in the energy range between 10 to 60 MeV/A and beyond in some options, with masses ranging from the lightest (A<40) to the heaviest (A>230), will open rather exciting and unique opportunities.

Regarding the production of a wide range of RI, we have assumed that the Radioactive Ion Beams (RIB's) are produced in q=1+ charge state in a production hall, close to Spiral2/Desir buildings.

Three technical options for post-acceleration of ISOL RIB at Ganil in the energy range presented in the physics case are discussed and preliminary design parameters are listed. SWOT analysis of each options regarding beam specifications, cost, new building construction, and overall advantages and limitations of three technical design options are presented in sec IV.

Summary table showing a comparison of the RIB post accelerator options:

	SCC upgrade with LINAC injector	Superconducting Compact Cyclotron	Superconducting LINAC
Cost of accelerator	23 M€	70-80 M€ (based IBA)	102 M€
Cost Accelerator building	5 M€	5-10 M€	22 M€
Cost Experimental building	0	0	20 M€
Manpower resources	Medium	Very restricted if industrial	Large
Max. Output energy: For 132Sn^{26+} For 90Kr^{20+} For Z/A=0.4-0.5	 33 MeV/A 49 MeV/A 80 MeV/A	 64 MeV/A 79 MeV/A >100 MeV/A	 60 MeV/A 75 MeV/A 100 MeV/A
Energy range (MeV/A)	(discrete energies) [3.5-15] and [24-33-49-80]	[10-100] MeV/A	[5-100] MeV/A
Stripping	Required for high energy (SSC2)	Not Required	Required for a minimal selectivity and cost.
Selectivity	Good/very good	Good	Low (constraint on source/ stripping)
Expected Transmission	15% to 50% (with /without stripping)	10-20% (no stripping)	20 % (with stripping)
Main advantage	lower cost	compact	Upgrade possible flexibility
Main problem	- CSS ageing -33MeV/A max for ^{132}Sn	New Design effort	Manpower cost

Table 4

To conclude, the working group would like to stress that the presented options for post-accelerated ISOL RIB at the GANIL/ SPIRAL2 facility span a rather wide range of technical options, investments costs, human resources allocations, design and construction duration, plus somewhat different coverage of the full energy range, beam purity and transmission efficiency. However, the three options are based on sound and proven accelerator technologies.

These three design options will have in common the advantages to maintain and develop parallel beam operation of the future GANIL facility including the high power, stable beam capabilities at GANIL.

Because of the strategic importance of the choice of one of these options for the future of GANIL, the working group would like to stress that due to the limited time devoted to these pre-design studies **it is necessary to develop a much more detailed investigation of the proposed solutions together with a clear financial and human resource plan in order to reach a viable and well-motivated final decision.**

I. INTRODUCTION (CONTEXT AND MISSION)

The top management of the funding institutions and owners of the Large Scale Accelerator Research Facility Ganil, CEA and CNRS, have sent a mission letter (Sept 2019) to an International Expert Committee (IEC) chaired by Michel SPIRO to collect its advice on the future of the GANIL facility in a wide context, considering in particular GANIL's role and place in fundamental nuclear science as well as in applications and multi-disciplinary aspects both at the European and worldwide level.

In the first round of its mission the IEC has collected and consulted the national Nuclear Physics Community, GANIL users, GANIL scientific members, GANIL management and regional political and academic institutions. During that process, a large number of responses from individual and senior users of the facility have been collected leading to converging views on the future of GANIL.

As a result of that preliminary work, the first guidelines from IEC on scientific goals to be reached were formulated as follows:

- Finalization of the ongoing SPIRAL 2 Phase 1
- Optimization of the multi-user running of the facilities
- More work is needed for Phase 2 Production Hall and Interdisciplinary Hall
- Replacement of CIME and scientific case for 100A MeV re-acceleration
- In principle support to a Phase 3 electron machine (ERL or synchrotron) for scattering of radioactive ions stored in traps which needs to be studied in more details.

Following these contributions two working group were installed to better define at that stage the future opportunities of the GANIL facility and submitted a status report to IEC in December 2020.

Electron probe on exotic nuclei (Valérie Lapoux et al.): The construction of the electron accelerator, either an ERL or a Synchrotron, could be envisaged to start around 2030. By then the production modes of radioactive nuclei as well as the technology of ion traps will have matured in the DESIR hall. Electron detection for elastic and inelastic electron-exotic nucleus scattering needs to be developed.

Interdisciplinary Hall (Gilles De France et al.): This new hall could accommodate, for example, an installation for radiography/tomography or radiobiology measurements and possibly R&D activities concerning the innovative production of radioisotopes. These studies are currently in progress and proposals that are more concrete are expected by the end of the year.

One has to stress that within the e-m working group a rather extensive study on the production modes of exotic nuclei and related target-ion source systems using GANIL SSC HI driver, SPIRAL1 facility, the new SPIRAL2 high power SC LINAC accelerator and the possibility to add an electron driver for producing neutron rich fission products have been investigated [Del21]

During the 2nd meeting of the IEC and after the presentation of the two Working Group conclusions, the IEC decided to implement two additional working groups: one on Post acceleration of exotic beams (S. Gales et al.) and a second one on the Future of cyclotrons for interdisciplinary research (N. Moncoffre et al.).

The physics and accelerator technologies related to post-accelerated RIB were the core of the SPIRAL2-Phase 2 project [Gal07, Eur09] and the present report on the subject will revisit the previous physics case and the relevant accelerator technologies and update them to take into account the evolution of the science case and the related accelerator technologies at running or under construction facilities worldwide.

The aim of the present report is to reformulate the pre-requisite conditions for post- acceleration of RIB as well as the investigation of the technical options available based on accelerator technologies for the future of the GANIL-SPIRAL2 facility at the end of the present decade **covering a unique and competitive science case at the world level.**

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II. WORLD STATUS OF MAJOR ISOL POST-ACCELERATED BEAM FACILITIES

In the beginning of the 90's, Louvain-La-Neuve was the first accelerator facility to introduce in the ISOL concept the so-called "two-step method" for post-acceleration. A driver cyclotron was used to produce in a thick target light exotic beams of mainly noble gas (from He to Ne). After ionization and charge breeding in an ECR ion source, these species were injected and accelerated by a second cyclotron, reaching energies of a few MeV/n in order to mainly investigate reactions of astrophysical interest.

The ISOL-SPIRAL1 project at GANIL was built on the success of this new ISOL post-accelerated method to produce secondary Radioactive Ion Beams (RIB) at energies between 1 and 15 MeV/n, with excellent purity and optical quality, and intensities up to 10^7 pps. High Power, High Energy HI beams (30-90 MeV/A, few KW) from the C0+SSC Ganil accelerator complex were used to produce and extract from a Carbon target –ECR ion source system more than 15 elements of secondary RIB (from He to Kr isotopes which were further post-accelerated by a new compact cyclotron CIME. The first GANIL-SPIRAL1 beam, ^{18}Ne, was delivered in October 2001. Since 2001 more than 20 publications on beam developments of SPIRAL have been released whereas the results of the SPIRAL experimental physics program have led to about 60 publications in refereed journals during that period [Nav11]. Based on such convincing results, the GANIL scientific council with the help of GANIL experts has developed since mid-2006 a strategy to design and built a new High Power driver based on SC Linac technology SPIRAL2.

Started a few decades before at CERN, the ISOLDE facility [Cat17] is using, since the beginning of the nineties the PS Booster 1,4GeV, 2mA, proton bunches stopped on thick heavy targets to produce by spallation and fission processes a very large number of exotic species. Target heating, effusion and diffusion with appropriate ion sources enables electrostatic extraction and acceleration up to few tens of keV. A subsequent high-resolution mass spectrometer has been used to produce hundreds of new isotopes ranging from ^{11}Li (few ms lifetime) to Fr isotopes. The ISOLDE@CERN facility has acquired with time a unique knowledge in the production and manipulation of RI. More than 1300 isotopes of 70 chemical elements have been used in a wide variety of research fields.

In order to boost the energy of the existing radioactive ion beams of ISOLDE from typically 60 keV to few (2-3) MeV/A, a new concept was proposed whereby the existing singly-charged ion beams from ISOLDE could be accelerated in a universal, fast, efficient and cost-effective way. The concept is based on ion beam cooling and bunching in the buffer gas of a Penning trap, charge-state breeding in an Electron Beam Ion Source (EBIS) [Blu13, Cat17] and post-acceleration in a room-temperature linear accelerator.

Called REX-ISOLDE, this project is operational since 2001 and has already accelerated over 100 isotopes of more than 30 different elements up to 3 MeV/n. More recently, based on REX-ISOLDE success post-accelerated RIB@ISOLDE has been upgraded successfully by putting into operation the HIE-ISOLDE (High Intensity and Energy) upgrade project is operational with a new superconducting linac RF cavities boosting the maximum energy to about 7 MeV/A for ions with mass-to-charge ratios below 4.5, reaching the Coulomb barrier threshold for the full range of nuclei available at ISOLDE.

In Legnaro, Italy INFN-LNL is constructing an ISOL (Isotope Separation On Line) facility delivering neutron rich ion beams up to 10 MeV/u, making use of the linear accelerator ALPI as the secondary accelerator. The facility includes a direct ISOL production target based on UCx. In parallel, an applied physics facility will be developed, with nuclear medicine applications and neutron production.

The SPES project [Spe10] is a national facility, approved, funded and under construction. Commissioning with the first exotic species is expected in 2023. The driver is a commercial cyclotron delivered by the BEST company from Canada, which will send a 40 MeV, 200 μA proton beam onto an UCx target, connected to SIS, PIS and LIS ion sources. The extracted beam is purified through a Low Resolution Mass Separator (LMRS, i.e. a Wien filter and a dispersive dipole), a beam cooler and a High

Resolution Mass Separator (HRMS) and sent to an ECR Charge Breeder to boost the exotic beam charge state. The highly charged exotic beam is further separated in a MRMS (Medium Resolution Mass Separator) and injected into a 100% duty cycle RFQ and into the existing superconducting linac ALPI, which is being refurbished and upgraded to be an efficient exotic beam accelerator. The upgrade of ALPI will give ~ 10 MeV/u energy to $^{132}Sn19^{+}$, taken as the reference ion beam.

The ISAC facility at the TRIUMF [Tri00] laboratory in Vancouver, Canada, using a 500 MeV proton cyclotron as a driver, is a full edged RIB facility. There are 2 post-accelerators, ISAC1 and ISAC2, composed of an RFQ, a DTL followed by a Superconducting LINAC which can accelerate the radioactive ions up to 5 MeV/u and 11 MeV/u respectively. The use of a UCx target and continuous improvement of the RILIS ion source has led to the production of many new elements and a substantial increase of the intensities delivered.

TRIUMF has embarked on the construction of ARIEL, the Advanced Rare Isotope Laboratory, with the goal to significantly expand the Rare Isotope Beam (RIB) program. The main idea is to turn TRIUMF into a multi-user RIB facility in order to increase the output of the various experimental devices and better satisfy the needs of the community. ARIEL will add electron-driven photo-fission of ISOL targets to the current proton induced spallation for the production of the rare isotopes that will be delivered to experiments at the existing ISAC facility. The goal of the ARIEL electron linac is to deliver 50-75 MeV, 10 mA CW electron beam as a driver for photo-fission of actinide targets. Combined with ISAC, ARIEL will support delivery of three simultaneous RIBs, up to two of them accelerated. In addition to the new Superconducting RF electron linac ARIEL will include a beamline to the targets for the electron beams; one new proton beamline from the 500 MeV cyclotron to the targets; two new high power target stations; mass separators and ion transport to the ISAC-I and ISAC-II accelerator complexes; a new building and a tunnel for the proton and electron beamlines.

A very ambitious project, called RAON [Rao16], in the field of “exotic nuclei”, is under construction (2010-2022) in Daejeon (South-Korea). The Rare isotope Accelerator complex for ON-line experiments (RAON), funded at the level of 2B€, is planned as a multi-purpose accelerator facility for providing beams of exotic rare isotopes of various energies. The facility driven by two accelerators: One is a high current proton cyclotron, the other being a high power superconducting linac for accelerating heavy ions up to Uranium. For producing rare isotopes, both the ISOL method and the in-flight fragmentation method are used. The ISOL facility includes a 70 MeV, 1 mA cyclotron, a production target coupled to an ion source, a high resolution mass separator, a charge breeder and an 18 MeV/u superconducting linac as post-accelerator. The in-flight facility includes a front end, a charge stripper, a 200 MeV/u superconducting linac, and a fragment separator. One of the most unique and innovative ideas in RAON is the combined scheme of ISOL + in-flight methods. First beams at RAON are expected in 2022. In a more distant future it is envisaged to post-accelerate rare isotope beams to about 200 MeV/u by using the high energy linac as a post-accelerator, which cannot be done in any other facility.

The table below gives an overview of the present running and/or in construction of Major post-accelerated ISOL beam facilities:

Facility	Location	Driver	Post accelerator	Final Re-Acc RIB energy	Main beams available	Start Date
HIE-ISOLDE	CERN, Geneva	PS booster; 1.4 GeV protons	HIE LINAC	2.7-8 A. MeV	Large variety including fission frag.	Running
SPIRAL	Caen, France	GANIL coupled cyclotrons	CIME cyclotron	2.7-25 A. MeV	He, Ne, Ar, Kr, N, O, F	Running
TRIUMF/ISAC	Vancouver, Canada	500 MeV proton cyclotron	RFQ + SC LINAC	0.2 – 11 A. MeV	Large variety up to Lu	Running
TRIUMF/ARIEL	Vancouver, Canada	Electron Linac 75 MeV 100 kW	RFQ + SC LINAC	0.2 – 11 A. MeV	Fission fragments	2023
SPES	Legnaro, Italy	40 MeV proton cyclotron	ALPI SC LINAC	2-10 A.MeV	Fission fragments and some light nuclei	2023
RAON	Daejeon, Korea	70 MeV proton cyclotron	SC LINAC	< 18 . MeV	KOBRA spectrometer	2023

Table II.1: *Characteristics of major post-accelerated ISOL RIB worldwide.*

As a conclusion from this overview of major post-accelerated ISOL facilities it appears that the full spectrum of post-accelerated RIB in the energy domain above Coulomb energy (10 MeV/n) up to Fermi energy and beyond (<100 MeV/n) is not covered by any of the running or projected RIB facilities in the world.

Despite the fact that major RIB Fragmentation facilities RIKEN(Jp), FAIR(De), FRIB(USA), and others (RAON, China...) will provide RI with energies above 100 MeV/A and produce RIB closer to the drip line, the poor beam qualities as well as the beam losses resulting from the slowing down processes and/or beam cooling, re-acceleration and/or in ring studies will not be competitive with ISOL based post-accelerated RIBs in the energy range mentioned above.

Investigation of long chain of neutron rich and proton rich nuclei produced by ISOL from light species (C, O, Ne) to medium (Kr, Sn) and up heavy Trans-Actinides with intensities 10^{2-7} pps in the energy range 10-60 MeV/n and beyond (Flagship beam ^{132}Sn 10-60 MeV/A, 10^7pps on target)

with high purity and beam optics comparable to the best stable beams will be possible and open the way to a rich nuclear reaction research program as illustrated in the next section.

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[Spe10]: Gianfranco Prete
The LNL radioactive beam facility
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III. PHYSICS WITH ISOL-POST ACCELERATED RIB –KEY QUESTIONS AND POST-ACCELERATOR RIB SPECIFICATIONS

A. The Nuclear Equation of State

Understanding the nuclear equation of state (EoS), that is, the relation between the pressure and the density, temperature, and isospin asymmetry of baryonic matter, is a fundamental issue in nuclear physics. It is also of great importance for modeling astrophysical objects such as core-collapse supernovae and neutron stars.

For nuclear matter (at zero temperature), the EoS is given by the energy per nucleon e(ρ,δ) as a function of the density $\rho=\rho_n+\rho_p$ and the isospin asymmetry $\delta = (\rho_n-\rho_p)/\rho$ (with ρ_n and ρ_p the neutron and proton densities, respectively). Symmetric nuclear matter (δ=0) is the simplest approximation to the bulk matter in atomic nuclei, while pure neutron matter (δ=1) is the simplest approximation to the matter as found in neutron-star cores. The energy per nucleon can be expanded in powers of the isospin asymmetry parameter δ as

$$e(\rho,\delta) = e_{is}(\rho) + e_{iv}(\rho)\delta^2.$$

Both the isoscalar (e_{is}) and the isovector (e_{iv}) part of e(ρ,δ) can be then Taylor expanded in powers of $x = (\rho-\rho_0)/3\rho_0$ around saturation density $\rho=\rho_0$. The general properties of relativistic and non-relativistic nuclear interactions are often characterized in terms of the nuclear empirical parameters, defined as the coefficients of these series expansions:

$$e_{is}(x) = E_{sat} + \frac{1}{2}K_{sat}x^2 + \frac{1}{3!}Q_{sat}x^3 + \frac{1}{4!}Z_{sat}x^4 + \cdots$$
$$e_{iv}(x) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \frac{1}{3!}Q_{sym}x^3 + \frac{1}{4!}Z_{sym}x^4 \ldots$$

The empirical parameters are separated into two channels: the isoscalar channel which defines the saturation energy E_{sat}, the saturation density ρ_0, the incompressibility modulus K_{sat}, the isoscalar skewness Q_{sat}, and the isoscalar kurtosis Z_{sat}; and the isovector channel which defines the symmetry energy E_{sym}, the slope L_{sym}, the isovector incompressibility K_{sym}, the isovector skewness Q_{sym}, and the isovector kurtosis Z_{sym}. It is now commonly accepted that the parameters E_{sat} =-15.8±0.3 MeV, E_{sym}=32±2 MeV, K_{sat}=230±20 MeV and ρ_0=0.155±0.005 fm^{-3} are quite well determined with small error bars. For the higher order parameters such as Q_{sat}, L_{sym}, K_{sym}, Q_{sym}… the error bars are sometimes even larger than the value itself [Mar18].

There exist two main approaches to constrain the empirical parameters: heavy ion collisions (HIC) and the measurement of giant resonance (GR) properties. These methods are complementary: GRs probe the EoS empirical parameters through excitations close to saturation density through structural information whereas HIC may probe a much larger domain in density. Going far from stability i.e. maximizing isospin asymmetry δ is necessary to constrain the isospin dependence and thus the isovector part, e_{iv}, whose parameters are currently poorly determined. High quality post-accelerated beams at around 50A MeV are perfectly suited for studying GR using inelastic scattering reactions and for creating asymmetric nuclear systems at low density in HIC.

Approaching the EOS through Heavy Ion Collisions

An advanced facility with post-accelerated RIB will bring new constraints on the nuclear Equation of State (EoS) by enlarging the study to another dimension: the isospin degree of freedom. In heavy ion collisions the role of neutron-proton asymmetry in the interaction phase of hot fragment production and in their following statistical de-excitation has been investigated so far using only various isotopic combinations of stable beams and targets. Medium-to-high energy radioactive beams can contribute to this field of research by providing tools to explore thermodynamic and transport aspects of nuclear reactions with neutron rich nuclei at intermediate energies (~25-100A MeV). The exploration can provide information on the isospin (N/Z) dependence of the equation of state by studying the in-medium properties of the nuclear interaction, effective mass splitting, mean free path, cluster production…

Interest in the EoS of neutron-rich dense matter was recently reignited by the detection of gravitational wave signals from the merger of two neutron stars (NS) with the LIGO and VIRGO interferometers, heralding a new multi-messenger era for the fields of astronomy, nuclear physics, general relativity and astrophysics. New constraints that help to better understand both macro- and microscopic properties of such compact objects are expected from the analysis of the waveform of the gravitational waves and the subsequent electromagnetic radiation produced by their merger. The understanding of these events requires the knowledge of the EoS over a wide range of densities, temperatures and proton fractions. These astrophysical sites offer rich practical cases for confronting the understanding of the nuclear phase diagram obtained from laboratory investigations of nuclear structure and reactions with new observations. For example, the inhomogeneous matter of the outer layers of neutron stars is expected to play an important role in the understanding of their evolution and dynamics. Light and heavy clusters are supposed to form in three main astrophysical sites: NS mergers, core-collapse supernovae (CCSN) and the NS crust. These clusters affect the neutrino mean free path and, as a consequence, their transport properties. As a result, the cluster composition of sub-saturation neutron-rich matter plays an important role both in the post-bounce dynamics of CCSN and the cooling rates of proto-neutrons stars (pNS).

By essence, the very neutron rich matter involved in the process is far from accessible in terrestrial laboratories. However, such extreme conditions can be to some extent reproduced (at a microscopic level) by heavy ion collisions with radioactive beams. Neutron-rich projectiles at and above Fermi energy are mandatory to produce low-density systems of hot (potentially) exotic clusters and particles to probe the EoS of nuclear matter. The modified properties of fundamental states of light/heavy nuclei in such a medium are important ingredients of models describing the evolution of compact stellar objects.

Recent works in the field of heavy ion collisions have brought new information on cluster production at low density by determining chemical equilibrium constants which describe cluster production rates in a gas of protons and neutrons in equilibrium at finite temperature. With ρ_p and ρ_n the densities of free protons and neutrons and $\rho(A, Z)$ the number density of a cluster species (A, Z), the chemical equilibrium constant $K_c(A, Z)$,

$$K_c(A,Z) = \frac{\rho(A,Z)}{\rho_p^Z \rho_n^{A-Z}}$$

depends only on the temperature and density of the system. Consequently, if such quantities can be extracted experimentally from nuclear data they can be applied in e.g. CCSN simulations to fix the cluster composition.

A method to extract such chemical equilibrium constants proposed by the Texas A&M group [Qin12] has been applied by the INDRA collaboration [Pai20] [Bou20] [Pai20a]. These works have shown how chemical equilibrium constants can be used to constrain the in-medium cluster property modifications by fixing the meson scalar coupling in a phenomenological Relativistic Mean Field (RMF) approach. Due to the limitations of INDRA isotopic identification, so far they are constrained only by a small range of light isotopes of hydrogen and helium (A≤6). Both availability of radioactive ion beams and better experimental devices such as FAZIA, will allow enlarging these studies to an extended range of clusters (A~12) to better constrain the models. Furthermore, beam energies as high as 60A MeV will offer the opportunity to study both multi-fragmentation and vaporization of dilute neutron-rich nuclear matter extending both the range of densities explored as well as the range of clusters of interest compared to previous analyses.

As already discussed in the introduction, the empirical parameters entering the series expansion of the energy per nucleon of nuclear matter are not all well-constrained experimentally, especially for the isovector part (L_{sym}, K_{sym}, Q_{sym}…) Since these parameters are the ones also characterizing the EoS for modelling astrophysical objects [Bur18], nuclear science/experiments are of paramount importance to bring ever more constraints on them. Different observables can be sensitive to different parameters. For example, several different transport models predict that isospin equilibration, which occurs when two nuclei of different N/Z collide, is mostly sensitive to L_{sym}: the smaller the value of L_{sym} (softer equation of state) the faster the rate of isospin diffusion and equilibration. Experimentally, by varying the isotopic composition (N/Z) of projectile and target nuclei, and varying the interaction time (with various beam energies and impact parameters) we can study various extreme conditions (in temperature, isospin and density) similar to those encountered in neutron star crusts for example. Comparison of various experimental data for observables with different isospin sensitivities with predictions for different parametrizations of the EoS in theoretical models (varying the L_{sym} value for example) would bring more constraints.

A better characterization of the properties of this extreme nuclear matter requires the detection and measurement of all reaction products (Z, A, E, velocity vector…) and therefore a 4π device with good granularity and isotopic resolution is necessary. For some years now the INDRA-FAZIA collaboration is engaged in a scientific program on this subject but with beams of stable nuclei, thus reducing the possible range of isospin asymmetries, δ. Radioactive ion beams with large N/Z would bring ever more sensitivity to the experimental analyses and also, hopefully, the capacity to go beyond in constraining higher order parameters of the EoS, such as K_{sym}, Q_{sym}… In this respect, neutron rich radioactive beams in the Fermi-energy domain would open many new perspectives for EoS studies.

Setting aside their astrophysical interest, these nuclear reactions are the main framework for the study of the low-density phase transition of nuclear matter associated with multi-fragmentation [Bor19]. Experimental data indicate that this multi-fragment break-up occurs when nuclear matter is driven, through a compression-expansion cycle, to a low-density region of mechanical (spinodal) instability occurring inside the coexistence region associated with a first order phase transition. Theoretical calculations predict for asymmetric matter (N/Z around 1.5–2.0) the occurrence of a new spinodal region related to chemical instabilities (fluctuations in the proton concentration). In this region, a process known as isospin fractionation is predicted to enrich the liquid phase (fragments) with symmetric matter and the gas phase with neutron rich matter. The idea is to use these radioactive isotopes together with stable beams to produce warm exotic nuclei or nuclear systems, over a wide N/Z range, and then investigate their dynamical and thermodynamic properties. These investigations include the limiting temperatures in excited nuclear systems, the N/Z dependence of nuclear level densities and the symmetry energy term of the EoS. To achieve these goals a post-accelerator reaching bombarding energies as high as 60A MeV is needed.

The availability of low energy exotic beams (~15A MeV) encourages studying the low energy branch of the nuclear matter by producing hot compound nuclei with different N/Z asymmetries. By measuring their temperature as a function of their excitation energy, one can explore the N/Z dependence of the limiting temperature, T_{lim}, i.e. the maximum temperature a nuclear system can sustain before ending its existence and breaking up into its components. Some analyses already report a dependence of the limiting temperature on the mass of the nuclear system. As a combined effect of the Coulomb interaction and of the symmetry energy, one also expects to find lower limiting temperature when moving away from the valley of stability by producing both proton-rich and neutron-rich excited compound nuclei.

The isospin dependence of T_{lim} provides also important links to the isovector part of the nucleon-nucleon effective interaction.

Fusion reactions induced by radioactive beams (~15A MeV) can also provide important information about the N/Z dependence of nuclear level densities. This quantity plays an important role in understanding compound nucleus reactions and in determining thermonuclear rates in astrophysics (nucleosynthesis and supernovae dynamics). The nuclear level density needs to be explored experimentally. In particular, its N/Z dependence is expected to provide unique information about the temperature dependence of the symmetry energy. In order to constrain this parameter, complete data on evaporation of hot asymmetric systems need to be compared to Hauser-Feshbach and Weisskopf calculations.

RIKEN and FAIR in the future deliver much higher beam energies (around and above 100A MeV) suitable for investigating high density dependence (above saturation density) of the symmetry energy by compressing the impinging nuclei during the course of the collision. In this case the behaviour of the symmetry energy term is expected to largely affect the transverse flows measured in collisions of ions with different charge asymmetries. GANIL, with reaccelerated radioactive ions in the energy domain of 15A-60A MeV, would offer a good and almost unique opportunity to access the low density hot clusters and particles mixture phase as well as the production of hot exotic nuclei for thermo-dynamical studies.

Beams: A few examples of interesting accelerated beams that could be delivered at GANIL with the reaccelerated option are indicated in table III.1. For such studies no specific isotopes are required but a large range of isotopes with sufficient intensities, at least 10^6 pps, and covering an energy range from 15A to 60A MeV is mandatory. Since FAZIA is able to identify in mass up to Z~25 only light/medium ion beams (Z~50) are necessary for such physics, since collisions of these nuclei with a target would bring the largest fragment of the multi fragmented event to around such size. Neutron deficient nuclei, as well as light/medium mass nuclei will not be available with the photo-fission method. Such beams would be produced using the fusion/evaporation method (with limitation of life time greater than ~100 ms). This region of proton rich nuclei accelerated in the range of energy (15A-60A MeV) will be only available at GANIL, leading to a uniquely broad range of radioactive ions available at a single facility.

Approaching the EOS through Giant Resonance measurements

Infinite nuclear matter cannot be probed directly in the laboratory, so its properties must me derived through measurements on finite nuclei. Two approaches have been taken. The microscopic approach consists in calculating the GMR properties for different functionals exhibiting different values for the EoS parameters and comparing with the experimental data. In the macroscopic approach, the incompressibility of the nucleus K_A, defined as:

$$K_A = \langle r^2 \rangle \frac{d^2 e}{dr^2}$$

where $<r^2>$ is the root mean square radius, is expanded in a liquid-drop type development:

$$K_A = K_{sat} + K_{surf} A^{\frac{-1}{3}} + K_\tau \left(\frac{N-Z}{A}\right)^2 + K_{Coul} Z^2 A^{\frac{-4}{3}}$$

K_A is linked to the energy of the isoscalar Giant Monopole Resonance (GMR) by

$$E_{GMR} = \hbar \sqrt{\frac{K_A}{m\langle r^2 \rangle}}$$

The measurement of the GMR in stable nuclei has led to the determination of K_{sat}=230±20 MeV [Bla76]. It should be noted, however, that some nuclei such as Sm, Sn and Cd appear softer and seem to indicate a lower value of K_{sat}. The measurement of the GMR along an isotopic chain will then yield K_τ which can be linked to parameters of the isovector part of the equation of state through:

$$K_\tau = K_{sym} - 6L_{sym} - L_{sym}\frac{Q_{sat}}{K_{sat}}$$

Up to now only few systematic experiments along isotopic chains have been performed [Li07] and the error bar on K_τ is large. The availability of post accelerated radioactive beams will allow the extension of the isotopic chains and should lead to more precise values of K_τ over a larger number of elements and therefore, constrain the isovector parameters of the EoS.

Monopole strength is best excited through inelastic scattering of an isoscalar probe such as deuterons or alpha-particles around 50A MeV. The method to measure the GMR in inverse kinematics with radioactive beams has been developed over the past years at GANIL. Very low energy light charged particles need to be detected at small laboratory angles and the incident beam intensity is inherently weak. The solution to these stringent conditions lies in the use of an active target. A pioneering experiment using the active target MAYA on ^{56}Ni took place in 2005 [Mon08] and further work on ^{68}Ni took place in 2010 [Van14]. A first experiment was performed recently with the new device ACTAR which will provide great improvements in angular coverage and resolution. The combination of ACTAR with post-accelerated ISOL beams around the Fermi energy will allow a systematic study of the GMR along several isotopic chains. A typical experiment could be to extend the measurement along the Sn isotopic chain, from $^{112-124}$Sn (Fig. III.1) to ^{136}Sn for which beams of more than 10^4 pps should be available. Good optical properties, such as a small beam spot size and low angular dispersion, inherent to post-accelerated ISOL beams, are of paramount importance to obtain results for unstable nuclei with error bars similar to those in stable nuclei (Fig.III.1).

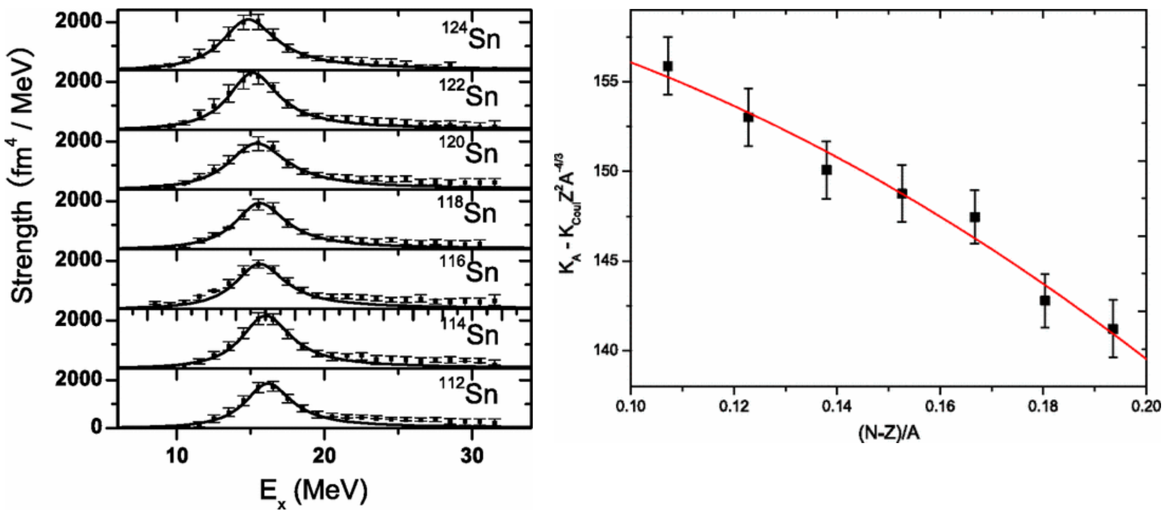


Figure III.1: *Monopole strength distribution (left) and determination of K_τ (right) in Sn isotopes [Li07].*

Recent state of the art calculations using the subtracted second random-phase approximation predict the existence of soft monopole modes in neutron-rich nuclei [Gam19]. The authors link such low-energy compression modes with a compressibility modulus introduced for neutron-rich infinite matter. Indications for such a mode have already been observed in ^{68}Ni [Van14] but no definite proof of the monopole nature could be given. The experiments described above offer the possibility to explore the low energy part of the monopole strength and thus map out the systematics of this elusive mode. This would be a unique opportunity to probe the incompressibility of the neutron-rich matter inaccessible from stable nuclei.

In such experiments, other isoscalar resonances such as the Giant Quadrupole Resonance (ISGQR) and the isoscalar Giant Dipole Resonance (ISGDR) are also measured. The ISGDR can give additional constraints on nuclear matter incompressibility, while the ISGQR can be linked to the effective nucleon mass.
Theoretical works have demonstrated that in heavy nuclei an almost linear empirical correlation exists between the neutron-skin thickness and theoretical predictions for the symmetry energy in terms of various mean-field approaches [Fur02]. This observation has contributed to a revival of an accurate determination of the neutron-skin thickness in neutron-rich nuclei. Excitation of the Antianalog Giant Dipole Resonance (AGDR) observed in (p,n) charge-exchange reactions has been presented as a new tool to measure the neutron-skin [Kra13]. More precisely, the energy difference between the AGDR and the Isobaric Analog State (IAS) in the daughter nucleus is very sensitively related to the corresponding neutron-skin thickness. Studies of the symmetry energy have been performed using AGDR data, and it has been shown that the extracted parameters, the symmetry energy at the saturation density (E_{sym}) and the slope of the symmetry energy (L_{sym}), coincide with those obtained with other methods.

The AGDR can be measured in inverse kinematics using a proton target and measuring the recoiling neutron, for example with liquid or plastic scintillator detectors. The energies of few tens of MeV per nucleon favour isospin-flip rather than spin-flip charge exchange reactions, and so are ideally suited to excite the AGDR.

Beams: GR measurements would be performed along isotopic and isotonic chains. In general comparison with theory will be facilitated by the use of nuclei magic either in protons or neutrons. The minimum usable intensity for experiments to be completed in a reasonable time scale is around 10^4 particles per second. The beams of interest include the n-rich Sn isotopes for which sufficient intensity can be obtained up to ^{136}Sn. The isotonic chains of N=50 and N=82 will also be explored. Zr isotopes are a mainstay of GR studies but are not produced by the standard ISOL method. The possibility of producing n-rich Pb isotopes through multi-nucleon transfer reactions should be explored to evaluate if sufficient intensities could be reached.

B. Nuclear shells and Shapes evolution, Pygmy Dipole Resonance, Pairing in neutron rich matter and neutron stars, Double Charge Exchange and Double beta decay.

The approach based on the study of reactions induced by beams of nuclei away from stability represents a powerful tool to investigate the properties of these nuclei. With respect to facilities such as ISOLDE-CERN, SPES or ARIEL limited to incident energies below 10A MeV, the new facility will allow optimal study of very negative Q-value reactions, further extending the range of possible transfer reaction studies. In addition, the available beam energies are particularly suited for inelastic scattering reactions used to probe collective modes like giant resonances and new modes appearing in neutron-rich nuclei such as the Pygmy Dipole Resonance. Refractory elements can also be post-accelerated, paving the way for nuclear shape studies via Coulomb excitation in a currently inaccessible region. The new high quality post-accelerated beams will allow the observation of nuclear structure phenomena from the unique viewpoint of reactions induced by beams between 10A and 60A MeV. A few specific physics cases are presented below.

Nuclear Shell Evolution

Using transfer reactions, the core physics program envisaged with re-accelerated fission fragments is focused on neutron-rich nuclei around the N=50 and N=82 magic numbers. In the N=50 region, the very recent spectroscopy of ^{78}Ni together with the identification of shape coexistence just below the N=50 shell closure indicate that deformed intruder configurations could play a crucial role in low energy structure properties in this region and towards the limits of the nuclear chart. Quantifying the way collectivity develops nearby ^{78}Ni is crucial since it influences binding energies and the drip-line location with consequences on nucleosynthesis calculations relying on these inputs. To test the microscopic configurations involved, the use of direct nucleon transfer (single or pair transfer) is particularly relevant. In addition to studying intruder configurations, it is mandatory to determine the drift energy of neutron valence orbitals to get more detailed insights in the mechanisms driving the N=50 physics, which can be achieved by a combined study of e.g. (d, p) and (d, t).

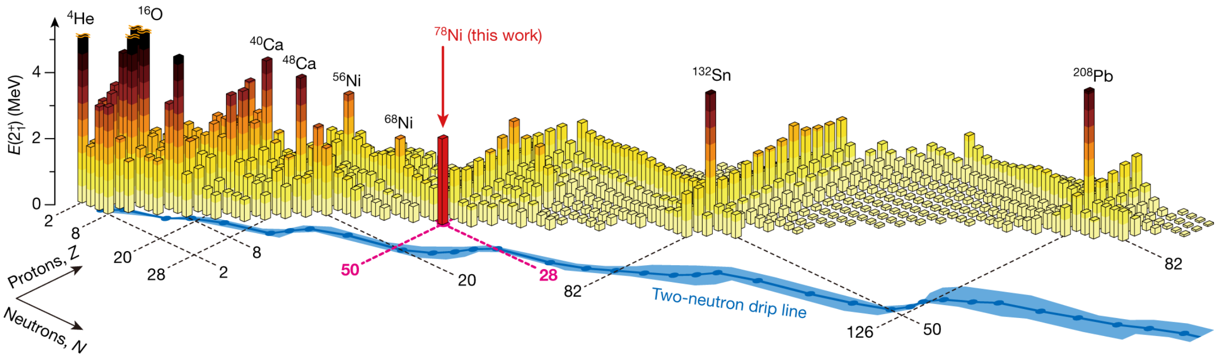


Figure III.2: *Experimental E (2+) as a function of the proton and neutron numbers across the nuclear chart. The magic numbers are also represented with dashed lines. Figure extracted from [Tan19].*

In the region of masses greater than 100, ^{132}Sn is the only other doubly-magic nucleus with the stable ^{208}Pb. It basically represents the core for the study of single-particle excitations and a reference for the description of surrounding nuclei. The vicinity of the r-process path also makes this region of special interest. As in the case of the ^{78}Ni region, the interplay between single-particle states and more collective configurations can be tackled efficiently using transfer reactions. Of critical interest for the r-process is information on the low spin orbitals of N=82 nuclei south of ^{132}Sn which will determine the neutron capture rates in these nuclei. These capture cross-sections can be deduced reliably from the single-particle energies of low angular momentum orbitals and their neutron spectroscopic factors extracted from the one neutron transfer data. The study of these orbitals beyond N=82 in Sn isotopes is also of interest as the question of a new gap at N=90 has been raised.

Concerning the protons shells, an important question to be addressed is the persistence of their structural pattern, hence the related magic numbers, as compared to the case of neutrons. One can tackle this issue by determining proton Fermi surface in *e.g.* the neutron-rich tin region through the combined study of the (^{3}He, d) and (d, ^{3}He) reactions. For the latter reaction, of negative Q-value, beam energies higher than 10A MeV (typically 20A~30A MeV) are needed. The GRIT Silicon array combined with AGATA is well-adapted for (^{3}He, d) reactions using the new version of the HeCTOr ^{3}He cryogenic target under development.

An approach to probe the mechanisms at work in shell structure evolution is the measurement of spin-orbit (SO) splitting, mainly governed by the spin-orbit interaction usually included in the one-body mean field as a surface potential proportional to the derivative of the nuclear density. Recent experimental studies at GANIL on neutron-rich sd-shell nuclei using the (d, p) reaction in inverse kinematics have reported a relatively large reduction of the neutron $2p_{3/2}$-$2p_{1/2}$ SO splitting [Bur14]. This effect was discussed in terms of the SO interaction, as well as by invoking an effect of loose binding [Kay17]. When moving to heavier nuclei, orbitals of higher angular momentum are filled. A well-known tool to investigate high-L orbitals in terms of energy location and occupation, in particular for extracting SO splitting, is alpha-induced one-nucleon transfer reactions such as (α, t) and (α,^{3}He), well-matched for momentum transfers L≳3 [Gal84]. In ref. [Sch04], the energy and spectroscopic factor of the low-lying 7/2+ and 11/2- single-proton states above the Z=50 gap in Sb isotopes, populated using the (α, t) reaction on even-A stable Sn isotopes are investigated. The energy difference of these states, corresponding to the $g_{7/2}$ and $h_{11/2}$ orbitals, is used to infer the evolution of g and h SO splitting with increasing neutron number. A decreasing trend is observed for the energy difference between the two levels with increasing

neutron excess, suggesting a weakening of the SO interaction. Authors also note that existing data suggest a similar trend for the neutron h and i SO partners above the N=82 gap.
Using fission fragment beams at 10A~20A MeV, one could perform (α, t) and (α,^{3}He) transfer measurements using GRIT with its cryogenic He target or ACTAR.

In terms of instruments, the above program will capitalize on the modern detection systems recently constructed or under development. Combined with AGATA or PARIS, the GRIT Silicon-based array will allow high resolution transfer measurements while the ACTAR time projection chamber is well adapted for transfer studies with low intensity beams. The development of a large acceptance spectrometer suited for the energy domain for exclusive measurement would also represent a major asset.

Evolution of nuclear shapes through Coulomb excitation studies

The evolution of nuclear shapes and the occurrence of exotic nuclear shapes is a topic of major interest in contemporary nuclear structure studies. Understanding this evolution is also a prerequisite to better understand the erosion of the nuclear shell structure in nuclei far from stability. Beams of refractory elements (Zr-to-Rh and Hf-to-Ir) can play an important role in these studies, but are currently very rarely available as reaccelerated beams: Only the CARIBU facility at ANL provides limited access to certain Zr, Mo and Ru isotopes on the peak of the ^{252}Cf fission fragment distribution [Doh17]. In the Zr isotopes the most sudden onset of deformation of all known nuclei is observed in ^{100}Zr and the evolution of deformation towards the N=70 harmonic oscillator shell closure at ^{110}Zr [Pau17] still requires elucidation. The neutron-rich Mo and Ru isotopes around N=66 are amongst the best candidates for stable triaxial deformation (similar to the W and Os isotopes discussed in the section on VHE).

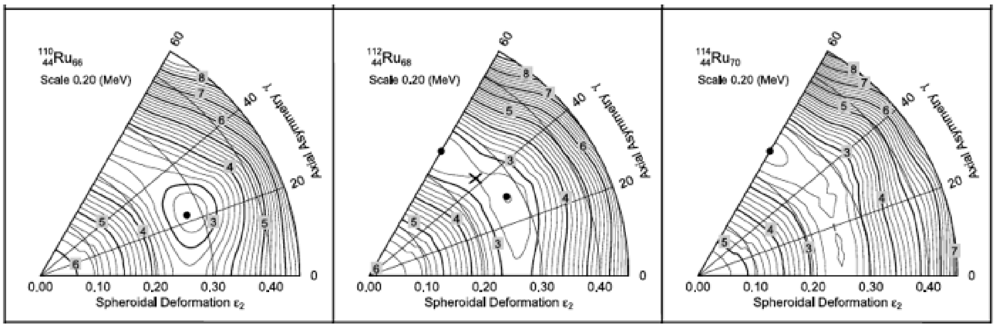
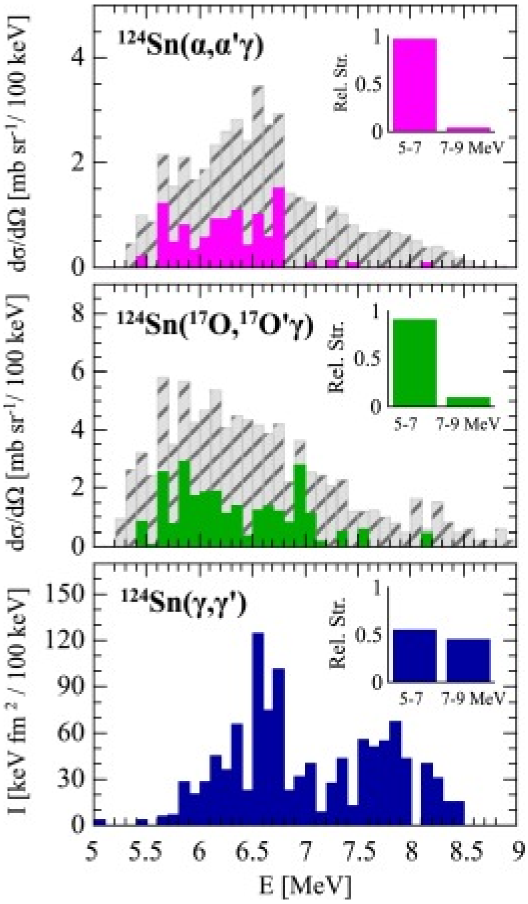


Figure III.3: *Potential energy surfaces of neutron-rich Ru isotopes as obtained by the FRDM model (from [Moe08]) showing pronounced triaxial minima.*

Experimental proof for these theoretical concepts and therefore a further validation of the interactions going into the state-of-the-art beyond mean field models, can only be obtained through low-energy Coulomb excitation experiments, capable of determining complete data sets of electro-magnetic matrix elements of low-lying collective states. A production through fission reactions, the extraction of these refractory elements in a gas catcher and the reacceleration of beams to energies around 4A-5A MeV are mandatory for such studies. In certain cases, high-energy electro-magnetic excitation at energies around 50A MeV may also be applicable to determine the properties of high lying low-spin states. The experiments would be performed using AGATA or EXOGAM for high-resolution gamma spectroscopy and a Si detector array for particle detection to determine particle-gamma angular correlations and cross sections.

Pygmy Dipole Resonance

The isovector giant dipole resonance (IVGDR), which corresponds to the oscillation of the neutron fluid against the proton fluid, is a broad resonance with mean energy between 12 and 24 MeV and a width in the range of 2.5 to 6 MeV which exhausts almost 100% of the isovector electric dipole strength. Additional E1 strength has been observed at lower energy, near the neutron separation threshold in neutron-rich nuclei. This small-size structure is commonly known as the pygmy dipole resonance (PDR) and can be described as the oscillation of a neutron skin against a symmetric proton/neutron core. The PDR belongs to the new phenomenology specific of nuclei with large neutron to proton ratios. While the halo phenomenon can be considered as a new static property of nuclear ground–states, PDR can be seen as new dynamical modes in neutron-rich nuclei associated with the excess neutrons and appear to represent basic properties of nuclei far from stability. It is expected that the enhancement of the E1 strength close to the neutron separation energy has an impact on the astrophysical r-process by increasing the neutron capture rates [Gor04]. The link between pygmy dipole strength, neutron skin thickness and symmetry energy in asymmetric nuclear matter, which has a strong impact on several neutron-star properties has also been stressed [Pie06, Kli07, Car10].



With the aim of understanding the microscopic nature of the PDR, several experiments have been carried out using various probes like (p,p'γ), (γ,γ'), (α,α'γ), (^{17}O,^{17}O'γ)… and have revealed the complex structure of the PDR: a mixture of isoscalar and isovector characters (see results in ^{124}Sn isotope as an example, Fig.III.4). This behavior has been interpreted with the help of the transition densities: the low-lying part of the PDR has the signature of a neutron skin oscillation, and the neutron contribution at the surface is probed by isoscalar and isovector probes, whereas the higher-lying part of the PDR could correspond to a transition toward the IVDGR [Sav13, Bra19]. In addition, while the IVGDR wave-function is considered as a coherent superposition involving many 1hω particle-hole (1p-1h) configurations, the microscopic structure of PDR might well be very different, including the possibility that only one or two configurations are involved in their wave-function.

Figure III.4: *Comparison of the differential cross sections measured in the ^{124}Sn(^{17}O,^{17}O'γ), ^{124}Sn(α,α'γ) and ^{124}Sn(γ,γ') experiments. Figure extracted from [Pel14].*

The post-accelerated beams at GANIL would make it possible to expand the experimental program to study the structure of the PDR to neutron-rich nuclei which were not previously accessible. First, using inelastic scattering reactions in inverse kinematics at 50A MeV with different probes will allow to give new inputs concerning the isospin character of the PDR states. Alpha inelastic scattering, to probe the isoscalar part of the PDR, can be performed using the active target ACTAR, whereas Coulex and proton inelastic scattering, to probe the proton and neutron contributions to the PDR can be performed using gamma spectroscopy with PARIS-like detectors. Second, by using the (d,p) reaction, one could investigate whether these PDR states involve only transitions corresponding to neutron excitations coupled to the A-1 core in its ground-state. In the case of the PDR observed in ^{132}Sn, from the ground-state of ^{131}Sn being referred as 5/2+, one could excite selectively 1^- states in ^{132}Sn corresponding to the d5/2-p1/2 transition, which contributes importantly to the PDR in [Sar04]. Along with the (d,p) measurement, it is mandatory to obtain (d,t) data in order to infer in detail the structure of the ground-state of the ^{131}Sn nucleus. Detection of the gamma-rays from the decay of the PDR, would provide a strong filter for the possible excitation of the 1^- states. The ^{129,131}Sn(d,p)(d,t) reactions with intense beams at 10A MeV could be investigated with GRIT coupled to the PARIS array which offers high efficiency for high energy gamma-rays. In both cases, this kind of experiment will also benefit from a coupling to a spectrometer. A minimum of 10^5 pps at the entrance of the setup is necessary.

The study of the PDR properties and the transfer reactions around ^{132}Sn discussed previously provide two complementary inputs for inferring neutron capture rates useful for r-process modelisations.

Pairing in neutron-rich matter and neutron stars

Many efforts have been devoted recently to the investigation and clarification of the nature of the pairing interaction in several nuclear systems, from finite atomic nuclei to compact neutron stars. The low-density properties of the pairing interaction as well as its dependence on isospin have important implications on some macroscopic properties of neutron stars. The superfluid properties of the crust of neutron stars have indeed a large influence on the crust thermalization at the formation of a neutron star from a core-collapse supernova or after reheating in low-mass binary dense stars (see Ref. [For10] and refs. therein). Probing the pairing correlations at the surface of nuclei, where the nuclear density is diminishing, and in halo or skin nuclei where the surface is enriched in neutrons, can bring important information in approaching the low-density neutron matter present in neutron stars. For this goal, an explicit isospin dependence of the pairing interaction is necessary and should be explored in addition to its density dependence (surface/volume) [Mar08]. The excitation modes related to the transfer of nucleonic pairs in superfluid nuclei are expected to be strongly sensitive to the specific features of the pairing interaction [Oer01]. It has been recently suggested that the observables related to pairing vibrations could be considered as useful additional constraints in the fitting procedures of the phenomenological interactions which are typically employed to describe pairing within mean field-based approaches, for instance in Skyrme-Hartree-Fock-Bogoliubov (Skyrme-HFB) calculations [Khan09, Mats09]. An exploratory theoretical study [Pll11] has been conducted in which the transition densities calculated in state-of-the-art HFB-QRPA were used to extract two-neutron transfer cross-sections for the ^{124}Sn(p,t) and ^{136}Sn(p,t) reactions at several beam energies. This work concluded that ratios of cross-section $\sigma(GS\rightarrow GS)/\sigma(GS\rightarrow 0^+_2)$ for the ^{136}Sn(p,t) reaction exhibit a clear sensitivity to the surface/volume nature of the pairing interaction. Performing (p,t) reaction experiments induced by neutron-rich Sn isotopes would require incident energies of 15A~30A MeV which the new facility would provide.
A possible setup to be used for such studies would combine the GRIT array with AGATA and the new version of the pure and windowless hydrogen target CHyMENE.

Double charge exchange reactions and double beta decay.

One of the most important fields of study in modern nuclear physics is double beta decay in nuclei. There are a number of nuclei where such decays are energetically allowed. These are usually ground state to ground state transitions. There is presently an intense activity both in experiment and theory to study double beta decays.
The observation of neutrinoless decay would put serious constraints on various gauge models beyond the standard one. It would mean that the lepton number conservation symmetry is broken, that the neutrino is a Majorana particle i.e. its own anti-particle. The expression of the decay rate of the neutrinoless process involves basically two unknowns, the mass of the neutrino and the nuclear transition matrix element. Having determined the nuclear matrix element one will be able to find the mass of the neutrino. In various experiments double beta decays emitting two neutrinos have been observed, however, as of today, neutrinoless double beta decay has not been detected.

The operators that are involved in the beta decay and double beta decay are the Fermi and Gamow-Teller operators. In the case of the neutrinoless process there is essentially a 1/r dependence in the operators and the Fermi transition does contribute, but it is small compared to the Gamow-Teller transition. The nuclear matrix elements for the double beta decays are very small, 1% or less of the total double Gamow-Teller strength (DGT) [Aue89, Aue18].
At present there is no direct way to "calibrate" such complicated nuclear structure calculations involving miniature fractions of the DGT transitions. By studying the stronger DGT transitions and, in particular, the giant DGT states experimentally and theoretically, one may be able to «calibrate" to some extent, the calculations of ββ-decay nuclear matrix elements".
In double charge exchange (DCX) reactions at least two nuclei are involved. This is also the case in the double beta decays. It is therefore natural to look for DCX reactions to provide some information about the various aspects of nuclear structure involving the dynamics of two nucleons.
Only recently [Aue89, Aue18], it was realized that under appropriate conditions DCX reactions are the perfect tool for spectroscopic nuclear structure investigations, being also of high interest for the nuclear structure aspects underlying exotic weak interaction processes. That change of paradigm relies on the observation that under appropriate conditions isovector nucleon-nucleon (NN) interactions will be the driving forces, thus extending the longstanding experience with single charge exchange (SCE) reactions to higher order processes. For obvious reasons, that conjecture can best be explored by peripheral coherent reactions with complex nuclei, leading to éjectiles with particle-stable _Z=±2final states.
There are to date a few attempts to study DCX reactions both at LNS Catania [Cap15] (see Fig.III.5) and RIKEN [Ues15].

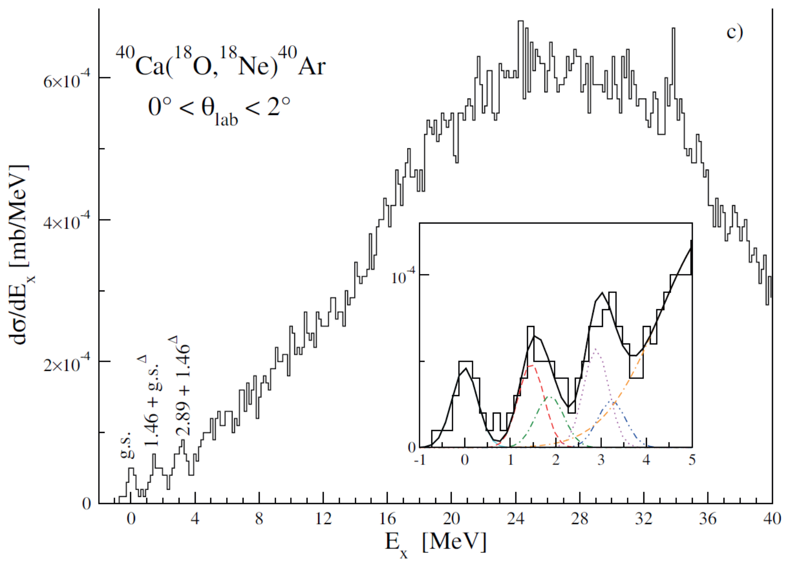


Figure III.5: *Residual energy spectra from the ^{40}Ca (^{18}O, ^{18}Ne)^{40}Ar DCX reaction at 15A.MeV incident energy and forward angle. Taken from ref [Cap15].*

Significant progress in the study of such reactions requires both stable and radioactive intense light beams at Fermi energies and above which may selectively excite DIAS and DGT via DCX reactions like (^{14}C, ^{14}O) and (^{14}O, ^{a} C) in both Z=+/- 2 directions. Such a scientific case fits very well the specifications of the future GANIL facility with its stable high intensity beams and the proposed RIB post –accelerated light mass species associated with a high rigidity and large solid angle magnetic spectrometer.

C. Very Heavy Nuclei far off stability (Trans-Lead and Ac) -MNT and Fusion-Evaporation reactions

Context

Information on the heaviest elements have been obtained mainly using fusion-evaporation and few-nucleon transfer reactions. These techniques have differences and limitations in terms on accessible nuclei and/or excitation energy, angular momentum and in general observables that can be measured. Fusion-evaporation reactions allow studies up to rather high-spins using in-beam spectroscopy but restrict the choice of residual nuclei to be studied because of the limited choice of beam/target combinations. Few-nucleon transfer reactions further limit the range of nuclei to be studied due to the very limited number of targets that can be reasonably used if one avoids highly radioactive targets. These reactions populate rather low spins but the ejectile measurement allows detailed spectroscopy as well as e.g. fission barrier measurement. Obviously, both fusion-evaporation and transfer reactions can be coupled to decay spectroscopy after separation, mass measurement, optics spectroscopy, etc., but again the range of nuclei to be studied is somehow limited. As an example, very few spectroscopic data are available in Odd-Z $_{97}$Bk and $_{99}$Es isotopes; very few high-spin studies have been performed in transuranium nuclei; still very few data related to fission are available in the Au-Fr region and minor actinides, etc.

Multi-nucleon transfer (MNT), fragmentation or spallation reactions have been used in various contexts with again some specific characteristics. Very heavy elements up to the actinide-trans actinide border have been synthesised using MNT reactions [Kra15], and radiochemical technique have been used with rather limited output in terms of spectroscopy. The use of fragmentation reactions at GSI using the FRS has revolutionized the field of fission studied 20 years ago [Sch00]. Recently, MNT reaction have been used at JAEA (Japan) or GANIL [Rod14] to study fission. Spallation reactions using a proton beam on e.g. a U target produces a wide range of actinide nuclei, and is the basis of the REX-ISOLDE facility (up to $_{88}$Ra only).

Multi-nucleon transfer reactions to produce neutron-rich nuclei in the vicinity of N=126 (south-west of ^{208}Pb) have attracted strong interest in recent years, since it was shown that MNT production cross sections can be much larger than for fragmentation reactions [Wat15]. While several so-called N=126 factories are currently envisaged world-wide [Sav20, Hir17] no project so far envisages the reacceleration of these beams for reaction studies.

These MNT reactions together with fusion-evaporation and few nucleons transfer reactions have an extremely high potential if one considers re-accelerating the produced nuclei around the Coulomb barrier for their spectroscopy including Coulex, and detailed fission studies. Rates as low as a few tens of particles per second are of interest for example for Coulex reactions, further examples being developed in the following.

Production rates

The massive production of heavy nuclei from the lead-region up the heaviest actinide has been considered since the birth of the SPIRAL 2 project, revisited again in the context of SPIRAL2 2025 think tank and more recently in the context of the present “International Expert Committee on the Future of GANIL”.
In brief, ions of interest would be produced using fusion-evaporation, (multi-nucleon)-transfer or proton-induced reactions, by making the best use of the energies and intensities available with the LINAG accelerator. The future NEWGAIN A/Q=7 injector is in this respect especially attractive.
Typical production rates are summarized in ***Figure III.6***. Three types of reactions have been considered: fusion-evaporation reactions including inverse-kinematics using Pb or Bi beams, MNT reactions using U beam, and p-induced (up the maximum available energy of 33 MeV). A new target ion-source devoted

to fusion-evaporation and MNT reactions, installed in a dedicated yellow cave is envisaged. All processes leading to the re-acceleration induce obvious losses: extraction from the gas-cell, transport, charge breeding, injection into the accelerator, etc… It is important to note that at this level of the discussion only production rates at the primary target level are considered.

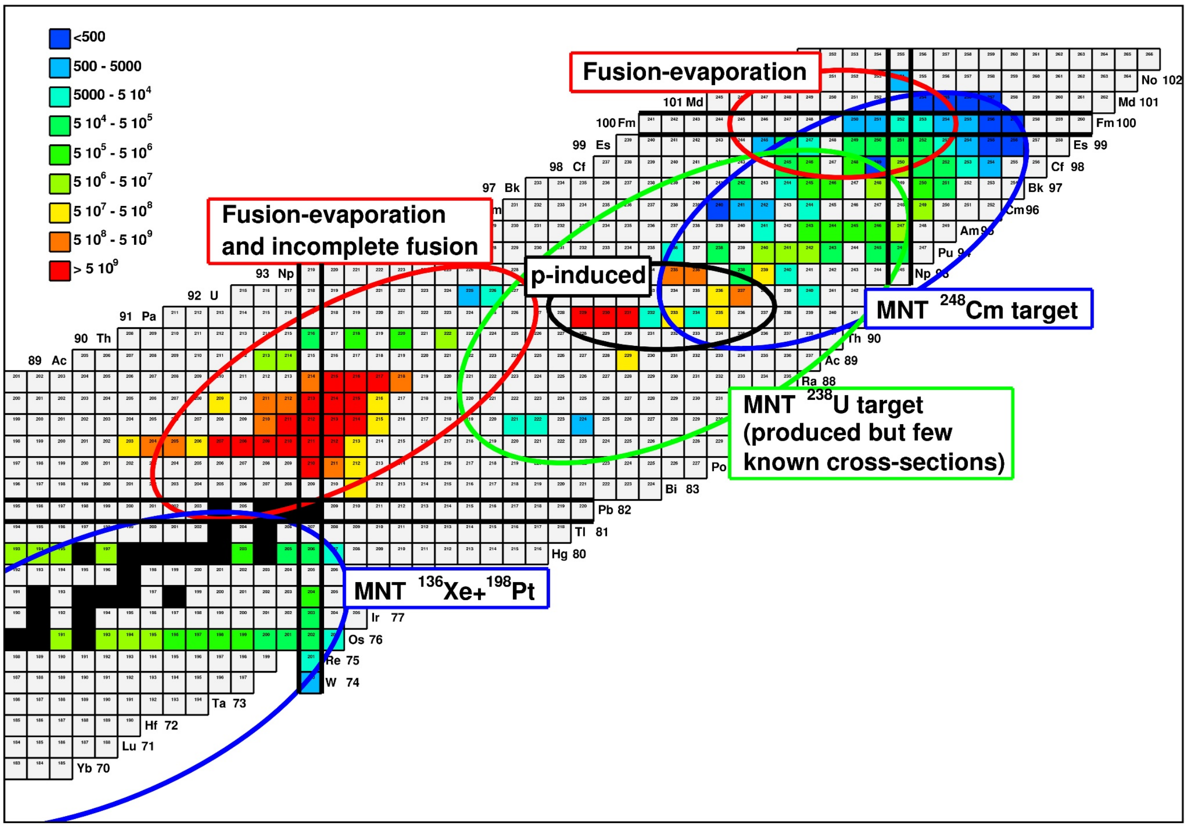


__Figure III.6:__ Estimated production rates at the primary target for very-heavy elements using the LINAG beams. Other nuclei also must be populated, but the cross-sections have either not been measured or are not reported in the literature.

Physics cases

The physics cases presented here have been organized according to their feasibility, given the beam intensities that can be expected. Although being of great interest, we have (provisionally) disregarded the studies of the second or third well, whose feasibility does not seem to be obvious using re-accelerated exotic beams.

Collective properties

Coulomb excitation can be used as tool for spectroscopy or in another powerful manner to deduce electric quadrupole moments. Historically, the second method was employed since the 60s. In a series of 13 experiments, actinide ranging from ^{230}Th to ^{252}Cf were studied using an alpha beam [For71, Bes73]. The inelastically scattered α particles were measured at the focal plane of an Enge split-pole spectrograph, from which the B(E2) was deduced. Still the value measured for ^{248}Cm is adopted in the most recent evaluations.
In a spectroscopic perspective, the Coulomb excitation of ^{232}Th, ^{234,236,238}U, ^{242,244}Pu and ^{248}Cm was performed in the 80s at GSI using a Pb beam, which allows populating high-spin states up to I~30 ħ. This allowed to study the collective properties of these nuclei. The first backbending observed in this

region was done using this Coulex technique, namely in ^{244}Pu [Spe83]: see ***Figure III.7***. The question whether the backbending observed in this region are due to the alignment of a $\pi i_{13/2}$ or $\nu j_{15/2}$ pair is still open 40 years after. Besides yrast bands, negative parity states were observed as well in ^{248}Cm and ^{240}Pu.

It is interesting to note that more than 20 years were needed for the study of the collective properties at high spin of nuclei heavier than ^{248}Cm: this was done in ^{254}No using fusion-evaporation reactions at JYFL and ANL.
There is so far only one transuranium nucleus for which B(E2) has been measured using heavy-ion induced coulex: ^{248}Cm [Pri16].
Given the high atomic number and deformation of the actinide, the coulex cross-section is huge. For Coulomb excitation on a ^{208}Pb target at safe energies, the cross section for exciting the 4^+ collective state is several tens of barn (providing that the nucleus does not fission), such that intensities as low as 100 pps allow the spectroscopy of the first states to be performed. Since the cross-section decreases very quickly as a function of the angular momentum, fission should not be a limiting channel. If, nevertheless, fission was to be dominant, lower beam energies or lower-Z targets could be used.

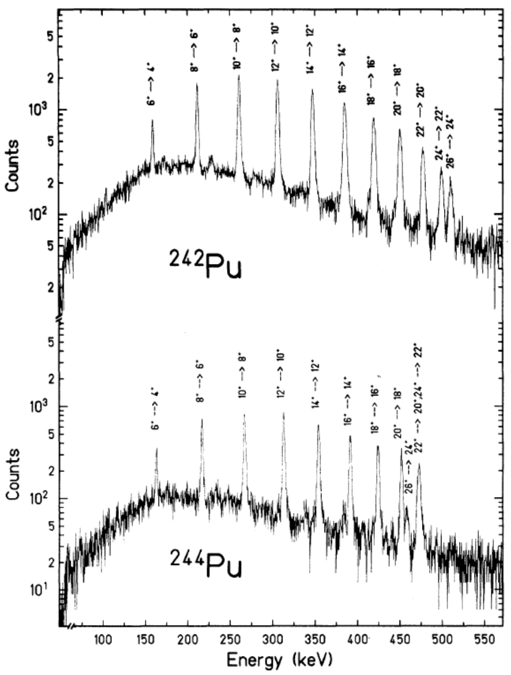


Figure III.7: *Coulomb excitation of ^{242,244}Pu using a Pb beam, GSI [Spe83].*

Our proposal is therefore dual:

- Measure B(E2) for transuranium nuclei up to Fm and possibly 254No. 252Fm is especially interesting because doubly magic deformed.
- Use Coulomb excitation as a tool for medium to high spin spectroscopy in the heaviest nuclei, not only in even-even nuclei. In this way, we can fill the almost blank region between Cm and Fm were almost no medium to high spin states are known. In the even Z 97Bk and 99Es nuclei, there is simply nothing known. Spectroscopy along and near the N=152 line could be performed down to 246Pu were limited data are available.

Similar experiments can also be envisaged for neutron-rich W and Os isotopes, where the current knowledge is limited to isotopes close to stability and a few low-spin states (see ***Figure III.8***). These isotopes are the best candidates for static triaxial nuclear shapes amongst all known nuclei, but the knowledge of electro-magnetic matrix elements is primordial to prove this hypothesis. Finally, the N=126 isotopes ^{204}Pt and possibly ^{202}Os, may come into reach to search for an island of inversion below ^{208}Pb using high-energy electromagnetic excitation to locate their first excited states.

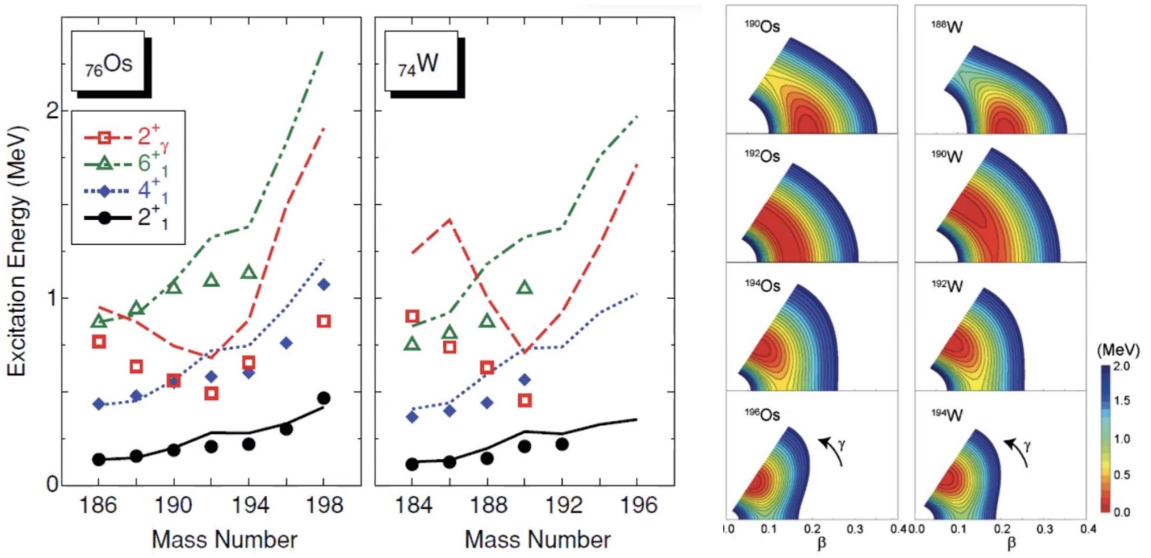


***Figure III.8:** Excited states in neutron-rich Os and W isotopes (left) compared to beyond-mean-field calculations showing the importance of triaxial degrees of freedom around N=116 (right) [Nom11].*

The requested beam energy is typically below the barrier "safe coulex" with intensities larger than ~100 pps for the spectroscopy, and larger than ~10^3 pps for B(E2) measurement, while experiments at higher energy typically require > 10 pps.

<u>Spectroscopy using direct reactions</u>

One-nucleon transfer reactions are powerful to perform detailed spectroscopy. Indeed, the detection of the energy and angular distribution of the ejectile provide the excitation energy and spin of the populated stated. Complemented with gamma and electron spectroscopy, it provides even more details on the level scheme. This technique was widely used up to the 1970s using e.g. (α,t), (d,p) or (d,t) reactions and a spectrograph to detect the ejectile (see e.g. ***Figure III.9***). These experiments have in particular been crucial to study the properties of [521]1/2$^-$ down sloping orbital from the spherical $f_{5/2}$ shell, which closes the presumed Z=114 shell gap [Ahm77]. Compared to coulex or fusion-evaporation reactions, the technique does not allow the access high-spin collective states, but it is particularly suited to probe the occupancy of the proton and neutron orbitals near the Fermi surface.

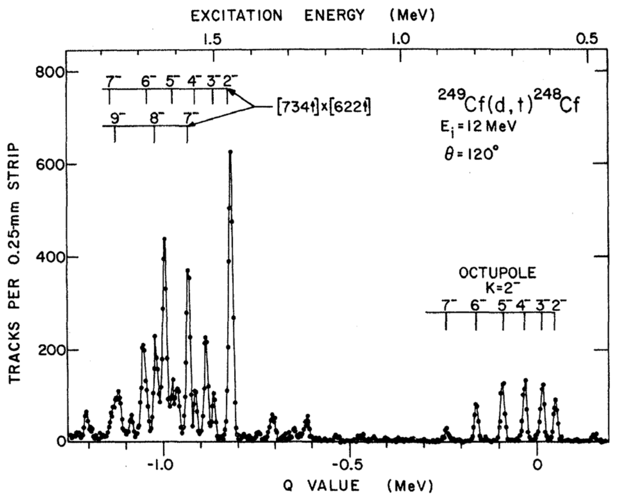


***Figure III.9:** example of spectroscopy using the direct reaction $^{249}Cf(d,t)^{248}Cf$ [Yat75]*

A limitation of this technique is due to the limited target availability. Therefore, using inverse kinematics reactions would make it possible to renew this technique to obtain detailed spectroscopic information. However, in inverse kinematics an expected limitation arises from the energy resolution one can achieve for the light particle. Reaching a few keV resolution is not straightforward and deserves detailed investigations. The detection of gamma rays and if possible, conversion electrons is especially important in that case.

Obviously, the technique is particularly adapted to spherical nuclei, whereas the coulex is not appropriate. This is e.g. the case for *N*=126 neutron-deficient nuclei which can be well produced using fusion-evaporation reactions in inverse kinematic (paragraph "Productions rates" above).
The requested beam energy is typically 7 MeV/A with intensities larger than ~10^3 – 10^4 pps.

Fission

Theoretically, fission is one of the most complex phenomenon in nuclear physics to describe, since it involves nuclear structure and dynamical process during which the nucleus explores several degrees of freedom. It is also known that the structure of the fission fragments plays a role on their distribution (strong shell effects in the vicinity of ^{132}Sn). Therefore, its modelisation is still associated with large uncertainties. Any uncertainty has dramatic effect on the observables. As an example, changing the fission barrier height by 1 MeV corresponds to a lifetime difference of up to several orders of magnitude. For a recent review of fission experimental studies, see [And18].

Fission barrier distribution

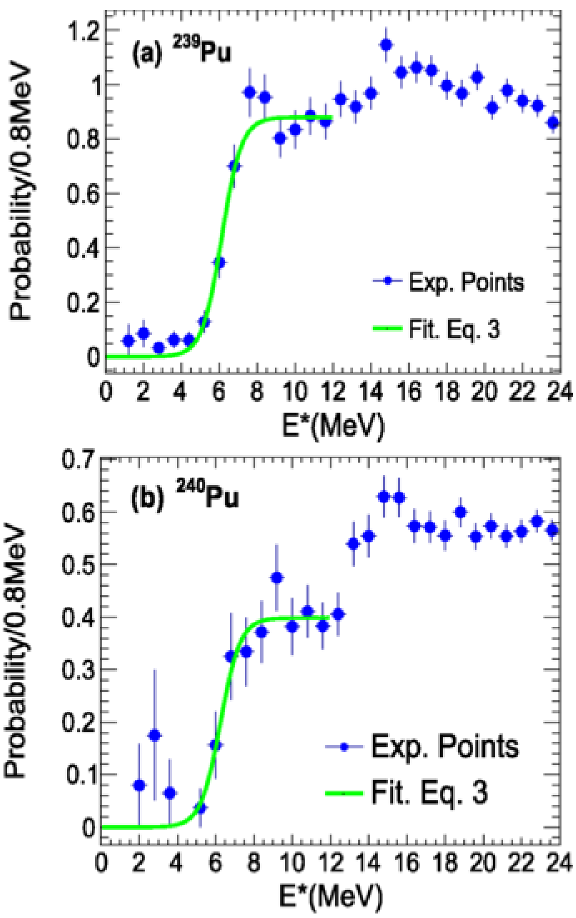


Figure III.10: *Fission probability as a function of excitation energy for ^{239,240}Pu using MNT reactions [Kea19].*

The fission barrier height is one of the most crucial quantity that governs the heavy nuclei stability, and in the particular in SHN where the macrosocopic liquid drop barrier vanishes. It is also a key ingredient in r-process abundances calculations [Gor15], and obviously a key measurement for nuclear data.
The basis of the method consists to measure the fission probability P_f as a function of the excitation energy $E^*$of the fissioning nucleus, which can be approximated as $P_f(E^*) = P/\{1 + \exp[2\pi(B_f - E^*)/\hbar\omega]\}$, where B_f is the fission barrier height, and $\hbar\omega$ its curvature.
To avoid biases due to the reaction mechanism, the most direct way to measure a fission barrier is to use a (n,f) reaction. This is obviously not always possible, therefore "surrogate" direct reactions have been use since the 70's (see e.g. [Gav76] using the (^{3}He,df) or (^{3}He,pf) reactions). More recently, the technique has been extended to multi-nucleon transfer reactions at GANIL [Rod14] or JAEA [Kea19], see ***Figure III.10***.Our proposal is to extend the technique using re-accelerated exotic ions and direct reactions. Although produced at modest intensities, the low number of open channels compared to MNT reactions will partially compensate for this deficit. There is of course great interest in doing these measurements for actinides, but also for lighter nuclei in the neutron-deficient Pb region (Au-Fr) for which there are few data.

The statistics needed is at the order of 100 fission events per energy bin. The required beam energy is about 7-10 MeV/A with beam intensities of at least 10^4 pps.

The ongoing PISTA upgrade of SPIDER lead by GANIL and CEA/DAM collaboration will provide excitation energy resolution of ~700 keV for transfer reaction (compared to 2 MeV today with spider) and would certainly improve the sensitivity for such kind of measurements. This will give information similar to that obtained at JAEA, but for other exotic channels. Using VAMOS may allow to measure at the same time the fission fragment distribution (see next paragraph). ACTAR is another option to be investigated.

Fission fragments distribution

While the fission probability is to a first approximation related to the barrier height, the fission fragment distribution is more sensitive to fission dynamics. The distribution is sensitive to the potential energy surface that the nucleus explores up to the scission point. Multimodal fission modes result from a complex energy surface. Their study as a function of the excitation energy of the fission system allows to probe this surface. The dynamics up to the scission combined with nuclear structure also play a role in the final fragment distribution: nuclear dissipation, collective modes, pairing correlations, shell effects in the final fragments, etc.

Fission fragment distribution measurements has been revolutionized at the end of the 20th century at GSI by [Sch00]: see ***Figure III.11***. The fissionning nuclei were produced using the fragmentation of a U primary beam at ~1 GeV/A, then Coulomb excited on a heavy target. The technique has recently been revisited at GANIL, but using MNT reaction induced by a U beam on a C target [Rod14]. One of the fission fragment was fully identified in mass and charge using VAMOS. It is important to note that in both case (GSI and GANIL), the inverse kinematics leads to a large fragment velocity which enables their full identification. Experiments using a similar technique are also performed at JAEA but in direct kinematics (see e.g. [Leg16]), with however only pre-neutron fragment mass measurement. Indeed, the a full (A, Z) distribution is a very powerful and sensitive observable to both neutron and proton shell effects.

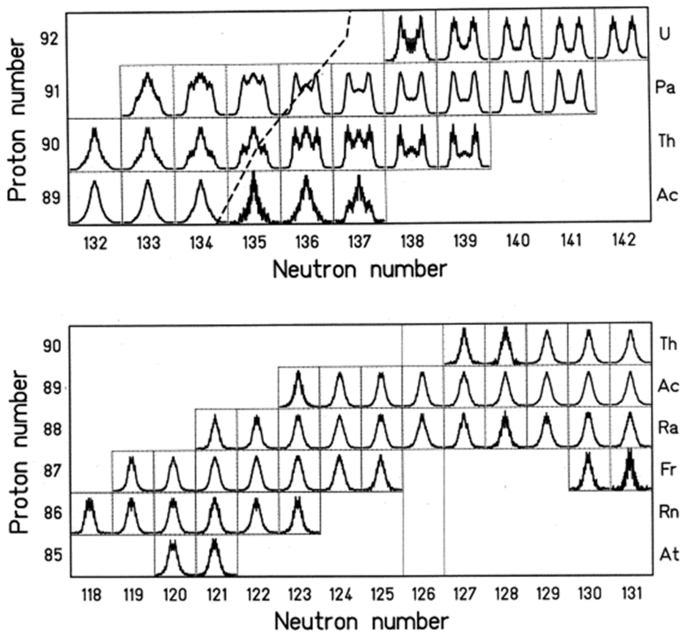


Figure III.11: *Fission fragment distribution obtained at GSI [Sch00].*

Our proposal is to perform similar experiments using few nucleons transfer reactions. Like for fission barrier measurements, this will allow to open few channels and to obtain the excitation energy of the fission system with a good accuracy.

The statistics needed is at the order of 1000 fission per fissionning system per E* interval (few bins needed). The beam energy is 7-10 MeV/u and the beam intensity need to be carefully estimated (preliminary guess = $10^6 – 10^7$ pps range).
Beams: The proposed facility is expected to provide a uniquely wide range of post-accelerated beams through several methods: projectile fragmentation (SPIRAL1), photo-fission (Rhodotron), n-induced fission (LINAG), Fusion (LINAG), Multi-nucleon transfer (LINAG). The beam energies would range from the barrier (~5A MeV) to the Fermi energy (~50A MeV) compared to other ISOL facilities limited to 10A-12A MeV or even the future RAON expected to reach 18A MeV in its initial implementation. Competition in some cases could come from slowed-down beams from in-flight facilities such as RIKEN or FAIR but with much worse beam characteristics such as emittance, energy and time resolution, strongly limiting the scope and quality of the obtainable data.

The following table summarizes a few examples of flagship beams necessary to carry out the physics program described above in Sections III.A,IIIB and III.C. It is not intended to reflect the very broad possibilities of the facility.

Flagship Beams

Element	Mass(es)	Beam energy range (A MeV)	Minimum intensity (pps)	Physics Topic
C	14	25-60	10^7	DCX
O	14,18	25-50	10^7	DCX
Ne	18	25-60	10^7	DCX
Ni	52-56 & 66-74	25-70	10^6	EoS, HIC
Kr	72-76 & 88-94	25-70	10^6	EoS, HIC
Zn	80,81	10	10^4	Shell evol
Ge	82,83	10	10^4	Shell evol
Sn (Z=50) Ge Ga Zn	106-110 &126-136 82Ge (N=50) 81Ga (N=50) 80Zn (N=50)	50	10^4	Giant resonances, Pygmy dipole resonance
Sn	126,128,130,132,134	10-30	10^4	Shell evol, nn pairing
Sn	106-110 &126-132	25-70	10^6	EoS, HIC
Os	190-194	~4.5	1000	Triaxiality
Pt	202	50	100	N=126 shell closure
Minor actinide (Z=93-100)	240-250	4-15	100	Spectroscopy, fission barrier and fission fragments distribution.

Table III.1

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IV. GANIL RIB POST-ACCELERATOR DESIGN COMPARISON

A. Introduction

In this report, a few options to post accelerate ISOL Radioactive Ion Beams (RIB) at GANIL Facility around 2030 are presented.
We assume in the following that the Radioactive Ion Beams (RIB's) are produced in q=1+ in a production hall, close to Spiral2/Desir buildings. Such a hall is part of the upgrade plans proposed to the Committee, which was investigated as an initial phase for an ambitious future for GANIL [Del21]. Such a future arguably includes the reacceleration of RIBs to Fermi energies, as developed in this document.
The production building enables to cover wide and diverse regions of the chart of nuclei thanks to different reaction processes using the SPIRAL2 LINAC and/or with an independent Photo-fission driver. These capabilities are summarized in the table below (extracted from a document submitted to the committee in December 2021 developing in more details the concepts proposed in [Del21], and Table1).
The production building includes two types of production cave: one for the production of fission fragments, and another one for products of fusion evaporation, Multi Nucleon Transfer and / or fission fragments stopped in gas cell (***Table IV.1***). Depending on the configuration of the post-accelerator, beams produced by fragmentation at SPIRAL 1 could additionally be available.

Production cave	Beams	Reaction mechanism	When
Gas cell/ production cave with **A/q=7 driver**	Light to heavy (N=126) neutron rich beams, with intensities up to 10^6 pps Neutron deficient heavy (A>200) ion beams, with intensities up to 10^8 pps Refractory fission fragments with intensities up to ~10^7 pps	Multi-nucleon transfer Fusion evaporation in inverse kinematics or using intense proton beams (not possible at S3) Fusion fission reactions	* After completion of the NEWGain A/q=7 injector > 2027 * ideally in the production building >2030
Fission fragments from **LINAC**	70<A<150 with intensities up to ~10^9 pps	Fusion reactions Light particle induced fission (p,d,3He,4He)	Production building >2030
Fission fragments from **Rhodotron**		Photo-fission à la ALTO	Production building >2030

Table IV.1

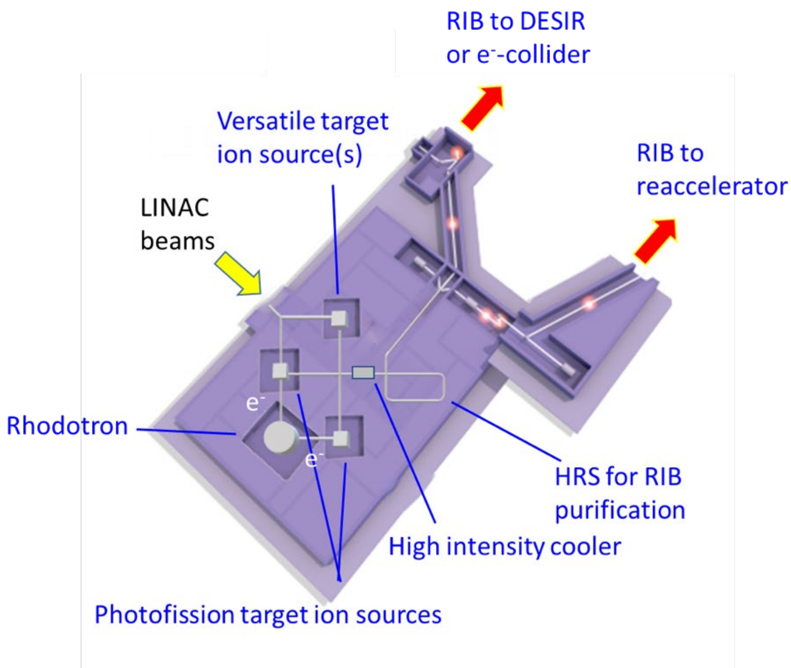

Figure IV.1: *sketch of the production building as proposed in [Del2].*

The beam should be post accelerated after a charge breeding (ECR breeder or EBIS breeder)

- The post accelerator should deliver a wide range of light, medium and heavy weight beams up to U in the energy range between 10 to 60 MeV/A (bench mark RIB ^{132}Sn up about 60 MeV/A)
- $1/7 < Q/A < 1/2$
- Beam isotopic Purity as high as possible
- The intensity at the exit of the Post-accelerated RIB could be as low as 10^2 pps and up to few $10^{12\text{-}13}$pps (stable beam operation: for accelerator tuning and physics needs)

We have investigated three solutions for the RIB post-accelerator:

1. GANIL-CSS upgrade
2. Compact superconducting cyclotron
3. LINAC

B. GANIL Sector Separator Cyclotrons: SSC upgrade

The present GANIL accelerator chain could meet most of RIB post accelerator specifications discussed above, providing the design and installation of a new injector. In addition, the LINAC + SCCs combination may provide a RIB post accelerator system with optimum re-use of the existing accelerators and buildings of the present GANIL facility and therefore minimizing the financial investment. Since the present C0 injectors are not optimum (20% transmission) we propose to replace the existing C0 injector by a small low energy LINAC injector.

Therefore, this proposal relies on the replacement of a C0 injectors with a new RFQ injector and subsequent DTL cavities up to 0.2-1 MeV/A for RIB with Q/A between 2 and 7. ***Figure IV.2*** shows the long low- energy beam line (100m) used to transport the 1+ RIB produced by the target-ion source system located in the production building to the new low energy injector LINAC.

Then the charge of the RIB is boosted (1+to N+) in an EBIS or ECRIS located on a platform. The N+ beams are accelerated in 15 m long LINAC (RFQ 200 KeV/A, Rebuncher + cavities). About 3.5 MV acceleration in few resonators would be sufficient to reach the injection energy in the GANIL SSC1. In the presented sketch of implantation (***Figure IV.3***) the existing C01 injector will be dismantled.

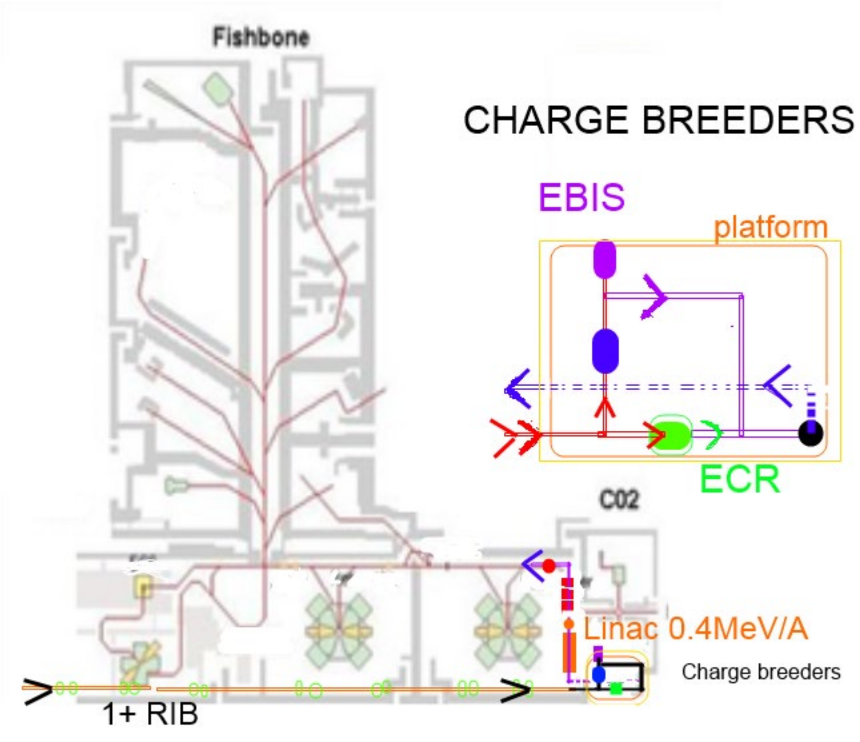

Figure IV.2: *Sketch of the implantation of a new CSS injector system.*

The advantages

- Main accelerator and beam line already in operation in the present GANIL facility (some renovation of RF system of SSC's may be needed)
- Most of beam lines can be conserved
- Optimal mass selectivity and very good beam purity (SSC acceleration provide high mass resolution+ stripping)
- High charge state is not required from ECR charge breeder
- Upgrade cost is minimized, re-use of existing CSS's, fish bone and experimental halls (although the experimental halls may be modified to host new equipment's). Excellent local expertise of the existing accelerator complex and related upgrade leading to an efficient use of human resources.
- The existing GANIL SSC accelerator complex can be kept for stable ion acceleration as well.
- Preserve the parallel multi user advantage of the present GANIL facility
- Synergy with the new RFQ injector of the "Newgain" project (Q/A=1/7 new SPIRAL2 injector)
- The typical transmission 15% (including stripping) for the highest energy. For the [3-15] MeV/A range up to 50% transmission could be obtained since a stripping is not needed (the SSC1selectivity will be sufficient for many experiments).

The drawbacks

- Discrete energies available
- SSC2 bending limitation K=380 MeV=>Limitation of RIB maximum energies at 34 MeV/A for ^{132}Sn and at 49 MeV/A for ^{90}Kr while up to 80 MeV/A can be obtained for Q/A=0.4.
- HE beamline: Bρ max limit 2,88 T.m
- Not suited for fast energy changes (fast means less than few hours)
- Aging installation

Technical aspects

Replacing the C0 compact cyclotron injector

Considering the rather low intensities of the produced RIB, it is rather clear that losses in the accelerator chain have to be minimized. Therefore, in order to boost the beam transmission (x4) it is strongly advisable to replace C0 injector by new small LINAC injector (RFQ+3 DTL).
This sole modification is however not sufficient to reach the benchmark beam energy of 60 MeV/A for Sn isotopes.

Replacing CSS2

To boost the final energy to E>60 MeV/A, one would need the replace SSC's and the beam lines downstream SSC2 in order to increase the maximum magnetic rigidity Bro up to 4 T.m. Then a solution could be found by building a new SCC machine (Rinj=1.5m, Rext=4.0m, K=800, H=3, 4 sectors) and replacing as well the alpha spectrometer and the beam line distributions toward 2 rooms.
Note that for 75 MeV/A for the $^{132}Sn^{44+}$, the maximal magnetic rigidity is Bρ = 3.9 T.m which overpass the present GANIL limit Bρ max=2,88T.m.
This option is quite attractive in terms of performance for the new RIB post-accelerator, but due to the relative high cost of this type of upgrade as well as the production and commissioning time of the new accelerator complex, the working group has decided at this step to put the focus on a less costly alternative both on financial and human resources.
We have investigated the low-cost and maximum re-use option, which consider only the replacement of the injector of the SCC1+SSC2 cyclotron chain. This alternative proposal consists of the addition of 2 charge breeders (EBIS and ECRIS boosters) to reach in an optimum way- the Q/A ratio of RI to be injected in a new LINAC injector.

Refurbishment/renovation of SCC's and of the two RF cavities

After 40 years' operation SCC RF cavities are one of the main concerns for a longer operation of the GANIL accelerator facility. This replacement has to be envisaged in the coming years (5-10 y) to guarantee a longer lifetime of the present GANIL facility. A significant investment in the construction of 4 new CSS RF cavities is requested. In addition, this investment would permit to maintain operational the existing GANIL heavy ion driver for stable ions and the associated experimental halls fully operational for many more decades.

In this SCC option, the main limit in energy is not connected to RF (the limit is connected to extraction radius of SSC2 & B max giving Bρ max = 2.9 T.m).
The New RF cavities will not boost the maximal energy. If the cavities are rebuilt one could consider a shift of the SCCRF cavity to be more adapted to a higher frequency RFQ (40-88 MHz) and stripping of heavy RIB. The energy gain in SSC2 is small, because of the harmonics H_{css2}=2, inducing 5-10% beam losses. However, the ratio H_{css1}/H_{css2} is constrained by the average stripping ratio Q2/Q1 (#2-2.5) and the compatibility of radii: RinjCSS2 F_{CSS2}/H_{CSS2}= $Rextr_{CSS1}$ F_{CSS1}/H_{CSS1}. Hence, any SSC frequency modification would have an influence on harmonics, injection/extraction radii, and RF Dee aperture. A

Possible choice could be [14-28] MHz, Hcss1=10, Hcss2=4, dee aperture $18° < \alpha_{CSS} < 28°$, keeping the same (injection) radii.
The first evaluations conclude that the arguments to shift the CSS frequency range to [14-28] MHz are not so strong, though it would reduce the harmonics of the LINAC, it would require a new RF design. Hence, if new RF cavities will be built, the original frequency range [7-13.45] MHz is the best operational choice. A reduction of the Dee aperture could be considered to increase the SCC2 energy gain per turn and ease the SSC2 extraction (α_{CSS2}=34°=> α_{CSS2}=26-30°).
The fixed frequency of the LINAC (here 50 MHz) should be chosen carefully since there are only four possibilities: any Bρ limitation will reduce the final energy: here the selection of $^{90}Kr^{32+}$ to get 49.5MeV/A as the reference beam, reduce the maximal final energy of $^{132}Sn^{25+/40+}$ from 35 to 33.5 MeV/A (F_{CSS2}=8.333 MHz). For High energy neutron rich RIBs only 3 CSS2 energy are available (24, 33.2, 49.1MeV/A).

Design parameters

The injector LINAC, especially the frequency choice, has to be studied in such way to fit the cyclotron possibilities. The fixed frequency of the LINAC, which correspond to a standard design restrict the available energies. A possibility of small variation of the RFQ+LINAC (F=F0±5%) frequency could help to ease the cyclotron operation and meet better the physics need (see RILAC1 design at Riken, or HMI RFQ) [11,12,13,14,15].
In the ***Figure IV.3***, taking an injector LINAC at F=50 MHz, we have 4 possibilities for the SSC frequency: F_{css}=50/7, 50/6, 50/5, 50/4. In blue, the intrinsic possibilities of C0+SSC1+SSC2. Operating range of a fixed frequency LINAC+SSC1+SSC2: 4 energies available (24, 33, 49, 80) MeV/A. But 80 MeV/A is possible only for light ions or proton rich ions. Operating range of SSC1 is enlarged with the LINAC up to 14.7 MeV/A with 8 energies between 3.6, and 14.7 MeV/A. Transmission is expected to be multiplied by a factor 3.

	SCC upgrade with LINAC injector
Cost of accelerator	23 M€
Cost Accelerator building	5 M€
Cost Experimental building	0
Manpower resources	Medium
Max. Output energy: For 132Sn^{26+} For 90Kr^{20+} For Z/A=0.4-0.5	 33 MeV/A 49 MeV/A 80 MeV/A
Energy range (MeV/A)	(discrete energies) [3.5-15] and [24-33-49-80]
Stripping	Required for high energy (SSC2)
Selectivity	Good/very good
Expected Transmission	15% to 50% (with /without stripping)
Main advantage	lower cost
Main problem	- CSS ageing -33MeV/A max for ^{132}Sn

Table IV.2: *Parameters of the Linac+ SSC Option.*

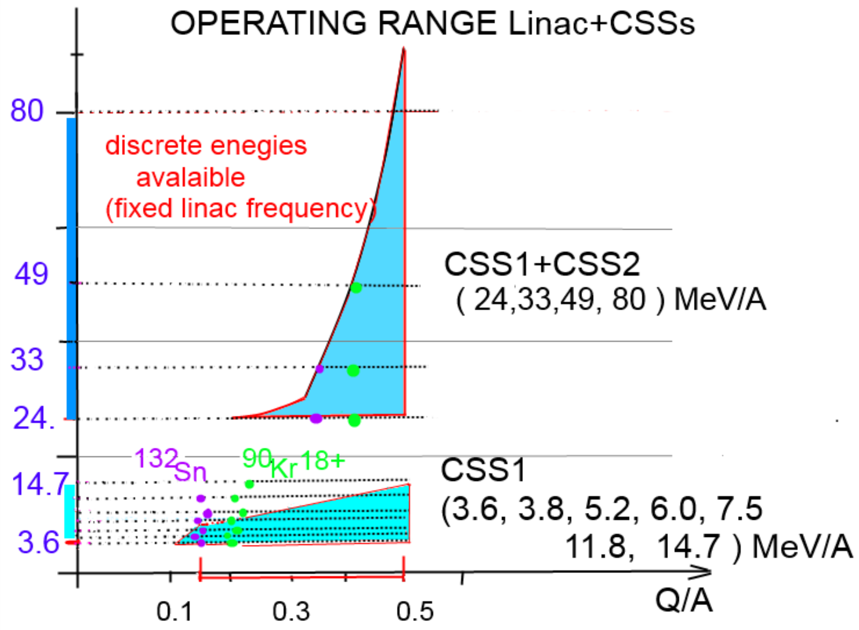

Figure IV.3: Working diagram of the LINAC+SSC accelerator complex

SWOT summary

LINAC+CSS	
S	W
Optimizes the GANIL existing accelerator chain and the investment	Emax not reached for Sn and A>130 E max~33 MeV/A
Re-use of existing acceleration chain	A=250 Emax~25 MeV/A but for A=50Emax=80 MeV/A; A= 90 E max=50 MeV/A
reusable and/or upgradable physics areas	Energy range from 10 to 80MeV/A discrete values
Low additional Human Resources	Minimal renovation of RF cavities
Local team has proven experience in accelerator and equipment/settings	new gallery to install LINAC 1MeV/A injector
High Purity secondary re-accelerated RIB	Partial sub-contracting needed for upgrade (RF, lines,building)
Conservative and proven design (RIKEN)	upgrade of expts areas to host new physics instruments needed
upgrade that keeps the existing GANIL HI Driver operational	
O	T
Uses NEWGAIN project design for the 1MeV/n new LINAC injector	SSC aging conditions (RF, seals, coils…)
Interdisciplinary parallel beam and experimental areas (SME+AIRES)	Long-term (>15 years) sustainability of existing SCC to be investigated in detail.
Multi Users operation	
SPIRAL1 RIB post -accelerated RIB possible in stand alone operation	

C. Superconducting compact cyclotron (SCC)

A stand-alone superconducting cyclotron (SSC) could also fulfill the post-acceleration requirements (60 MeV/A ^{132}Sn). In this configuration, where there are no stripping losses, the overall transmission could still be competitive, despite the relatively low transmission of superconducting cyclotrons.
However, even assuming a reasonable charge state out of the source (such as $^{132}Sn^{25+}$ for example), such a superconducting cyclotron would require a high value of the bending capability of the magnet, i.e. K_b=1600 MeV, which is above of the existing MSU K1200 cyclotron, the largest superconducting compact cyclotron ever built. The design of a K_b=1600 cyclotron has been undertaken these last years for 400 MeV/A and Q/A=1/2 dedicated to carbon ion therapy SCC by IBA, the so called C400 project. The design of such magnet for our requirement in term of RIB post-accelerator will be probably with less demanding for maximum final energy of about 100 MeV/A compared to the C400, since vertical focusing can be achieved with a smaller flutter and spiral angle. Nevertheless, as presented in ***Table IV.3***, a new design has to be studied in view of the specificities of variable energy and bending limit needed to accelerate a wide range of Z/A RIB species.

Name	K_b*	K_f*	R_{extr} [m]	<B> [T]	Nb sectors	RF dee, harmonics	Total weight [tons]
NSCL K1200	1200	400	1.03	3.0-5.3	3	3, H=1	250
LNS Catania	800	200	1,0	2.2-4.8	3	3, H=2	
AGOR KVI	600	200	0,9	1.7-4.05	3	3, H=2,3,4	400
C400 project	1600	400	1.87	3.4	4	2, H=4	700

Table IV.3: *Worldwide existing superconducting cyclotrons. *K_b and K_f correspond respectively to the bending limit K_b and the focusing limit K_f for the maximum energies $E/A_{Max} < Kb\ (Q/A)^2$; $E/A_{Max} < Kf\ (Q/A)$.*

Table IV.4 below shows the first design parameters envisaged for the GANIL superconducting cyclotron K1600 post-accelerator. Bending limit $^{132}Sn^{25+}$ E= 57,65 MeV/A –Focusing limit $^{12}C^{6+}$ =150 MeV/A

Name	K_b*	K_f*	R_{extr} [m]	<B> [T]	Nb sectors	RF dee, harmonics	Total weight [tons]
GANIL SC Cyclo	1600	300	1.15	3-5	3 or 4	3 or 2, H=2, 3, 4	700

Table IV.4: *First parameters GANIL Superconducting compact cyclotron*

In fig.IV.4 a possible implantation of this K1600 SCC is shown inside the new production with an injection low –energy beam line from the 1+-N+ booster system following the target ion-source ensembles.
One may also look at the implantation of this new machine in place of the CIME post-accelerator cyclotron. However, this option needs to be investigated in detail in terms of civil engineering, size and utilities constraints. In addition, it is not clear at this stage if the K1600 SCC low energy will allow medium and heavy ion RIB at energy below the Coulomb barrier (7 MeV/A).

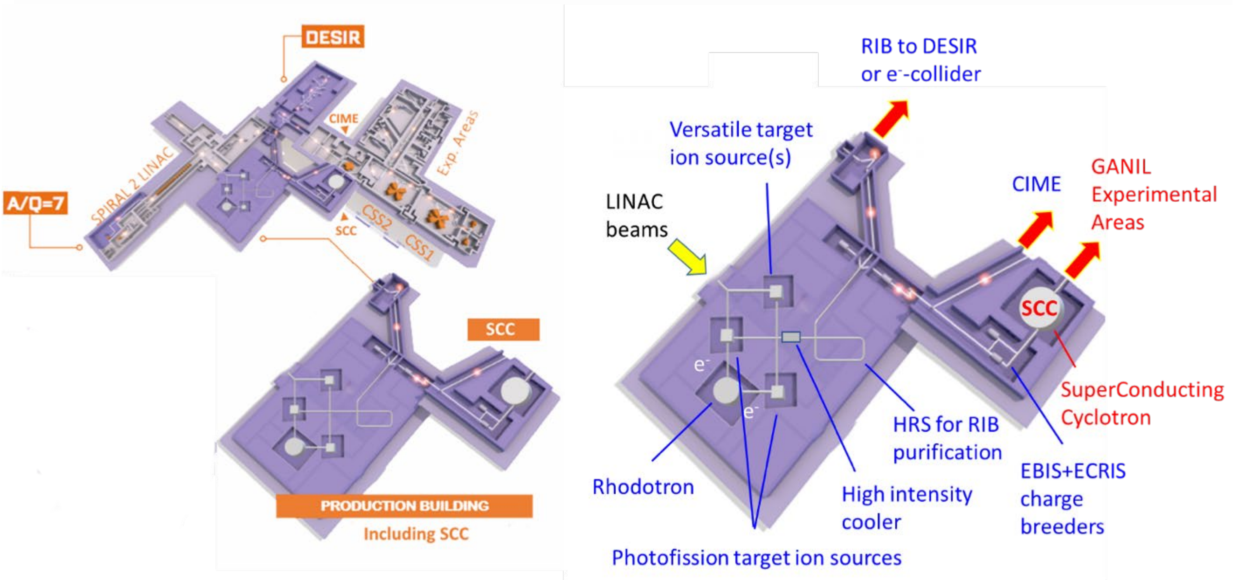

Figure IV.4: *Possible location for the SCC in the production building, enabling the use of the existing experimental areas, and a parallel use of CIME for energies lower than 10 MeV/A.*

Technical considerations and recommendations

To assess whether a compact superconducting K1600 cyclotron is a viable option for the post acceleration of secondary, radioactive beams a number of issues have to be considered:

Mass separation

The beams from 1+ to N+ charge breeding schemes are not very pure and are most likely dominated by stable species originating from the walls of the source and the extraction system. This implies that the post-accelerator should have a very good mass separation. The AGOR cyclotron demonstrated that beams with a relative $\Delta(Q/A)$ of 10^{-4} can be separated very well without special measures, i.e. the contaminant is suppressed by a factor 10^6. In a K1600 cyclotron the number of turns (actually RF periods) needed for acceleration will be significantly larger than in AGOR so an even better mass separation should be feasible. By proper shaping of the magnetic field (field bump or dip to increase the number of turns) even further improvement is feasible.

Transmission

The transmission of compact superconducting cyclotrons is clearly less than that of linear accelerators and separated sector cyclotrons. When accelerating with a chain of separated sector cyclotrons as is done at GANIL and RIKEN stripping is needed at an intermediate energy. Depending on the energy at which the stripping has to be performed (not a really free parameter) this will lead to significant intensity losses. The **extraction efficiency** of compact superconducting cyclotrons varies very significantly. For the Texas A&M and MSU machines extraction efficiencies of up to 70 % have been reported. For the AGOR cyclotron, which has a fully active extraction system (no iron bars etc.) the extraction efficiency is typically better than 70 % and for certain beams values close to 100 % have been obtained. On the other hand, the extraction efficiency of the Catania cyclotron is generally less than 50 %. From the operating experience of the AGOR cyclotron it is clear that proper tuning of the extraction parameters requires an extensive set of beam diagnostics along the extraction path and also during the final phase of acceleration where the beam passes the $Q_r = 1$ resonance to create sufficient turn separation by exciting a precession motion. In addition, high quality field mapping and beam dynamics calculation tools are needed.

The **injection efficiency** of the different machines also varies substantially. For the Texas A&M K500 cyclotron values of around 15 % are routinely achieved, while the LNS cyclotron reaches values up to 30 %. For the AGOR cyclotron typical values are around 10 %, maximum achieved values around 15 %. Injection efficiency is affected by a number of parameters in which these cyclotrons differ:

- The Texas A&M cyclotron uses a 1st + 2nd harmonic buncher. This allows to create a sawtooth bunching voltage of which the first three harmonics are close to those of a perfect sawtooth. They have observed very significant charge exchange losses in the injection line, which may be mitigated by improving the vacuum in the beam line.
- In the LNS cyclotron additional getter pumps have been installed in the axial hole of the cyclotron, which had a clear beneficial effect on the injection efficiency.
- The AGOR cyclotron has a single frequency buncher and pumping in the axial hole of the cyclotron is far from optimal, which together may explain the lower injection efficiencies achieved.

Based on the operating experience of the three machines it is safe to conclude that by improving the bunching and the vacuum of in particular the last part of the injection beam line in the cyclotron axial hole it should be possible to reach injection efficiencies of 30 % or better.
The transmission of the acceleration region need not be a factor that limits transmission, provide sufficient pumping of the acceleration chamber can be achieved. In the existing superconducting cyclotrons cryogenic pumps have been mounted in the RF cavities and transmissions are then essentially 100 %. In cyclotron based on the IBA C400 machine, which has two accelerating cavities, the possibilities to obtain a sufficiently high pumping speed in the acceleration chamber are even better.

The conclusion is that an overall transmission of at least 20-25 %(0,3x0,7-0,8) should be achievable.
Ion source beams

The apparent emittance of beams extracted from ECR ion sources is rather large due to the fact that the beam is extracted in a region with a relative strong magnetic field. This causes further degradation of the beam quality due to higher order term in the transfer function of the ion optical elements of the injection beam line because the apertures of these elements are not sufficiently large in comparison to the beam size while also the length - aperture ratio is unfavorable. It is therefore important to minimize the length of the injection beam line between the ion source and the injection point. The beam intensity extracted from ECR sources for injection into cyclotrons is generally space charge limited, i.e. more current could be obtained by increasing the extraction voltage of the source. The maximum energy of the injected ions is, however, constrained by the maximum electric field strength in the inflector and in the central part of the RF cavities that can be applied reliably. It is therefore worthwhile to consider whether an accel-decel scheme to increase the effective extraction voltage of the ion source is feasible.

As a function of the charge state out of the ion source, here are few figures of the energies reachable by a Kb=1600 cyclotron:

- $^{132}Sn^{22+}$Bending limit = Kb $(Q/A)^2$ =44 MeV/A
- $^{132}Sn^{26+}$Bending limit = 62 MeV/A
- $^{132}Sn^{32+}$Bending limit = 94 MeV/A (Bρ=5.72Tm)

The advantages

• Cyclotron size (6-7m overall diameter) can be fitted in existing GANIL infrastructure or in a new production hall (Fig.IV.4)
• Good selectivity (a stripping at high energy could help to increase it)
• Industrial manufacturer can be envisaged (synergy with IBA C400) saving in design and construction time

The drawbacks

• High charge states are required at the source
• New complex and detailed design
• Energy range limited: low energy limit (<10 MeV/A) to be studied: [10-100] MeV/A at the exit
• Not suited to achieving rapid energy changes (at least several hours)
• Transmission: 10% to 25% (MSU K500 15%, AGORK600 10-20%, LNS K800 30%.

K1600 SCC Parameters

	Superconducting Compact Cyclotron
Cost of accelerator	70-80 M€ (based IBA)
Cost Accelerator building	5-10 M€
Cost Experimental building	0
Manpower resources	Very restricted if industrial
Max. Output energy: For 132Sn^{26+} For 90Kr^{20+} For Z/A=0.4-0.5	 64 MeV/A 79 MeV/A >100 MeV/A
Energy range (MeV/A)	[10-100] MeV/A
Stripping	Not Required
Selectivity	Good
Expected Transmission	10-20% (no stripping)
Main advantage	compact
Main problem	New Design effort

Table IV.5

In the fig IV.5, below, a preliminary working diagram is shown derived from the C400 design.

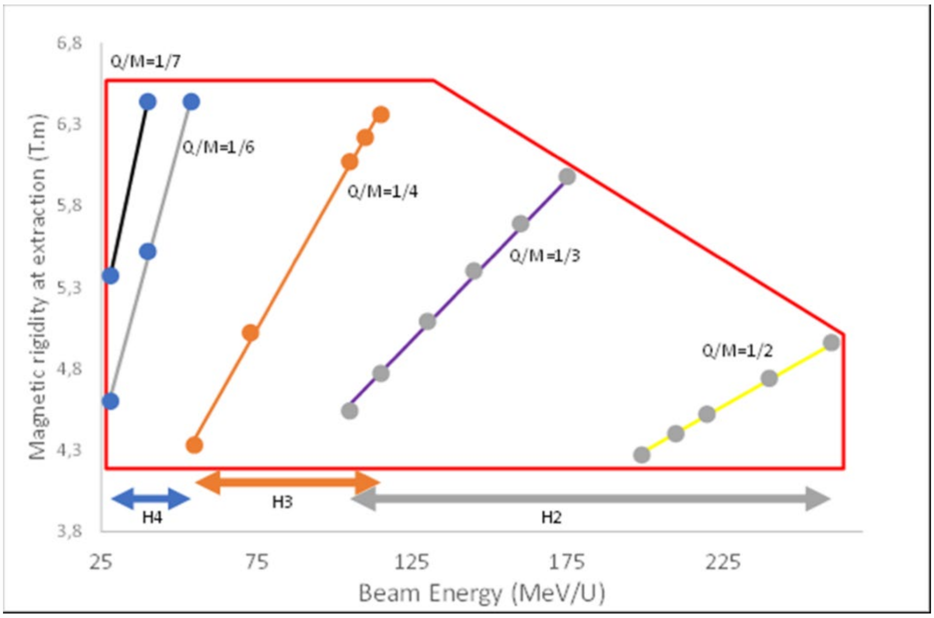

***Figure IV.5:** Working diagram of the superconductiong cyclotron solution*

SWOT summary

Super Conduction Compact Cyclotron (C400 type)	
S	W
High purity of RIB, mass separation	IBA C400 design study to be adapted to variable energy.
Compactness = Limited new vault construction to host SCC	RIB Transmisison from ECR axial injection + acceleration limited 10%-20 %.
Fixed design (E/A, Q/A)	132Sn26+Emax=64MeV/A ; Kr 90 MeV/n; Ar > 120 MeV/A if KB=1600 Kf=300
Existing local Cryogenic Competence	High Beam rigidity Br~ 5-T.m
Limited manpower for operation	Alpha and HE transfer lines to be rebuilt and/or adapted to high rigidity
O	T
Existing industrial provider to design and built such SCC	New design / adaptation of the C400 - Time duration to reach a new TDR
The new machine fits into existing buildings	Limited transmission for weak RIB prodcution
Strong industrial involvement possible	Modification of HE transport and to experimental areas
New SCC May be located in place of CIME cyclotron (to be studied)	

Pre-Design discussion with industrial provider

Preliminary exchanges with IBA show that GANIL design from a C400 basis in which some elements of Cyclone70 (p 70 MeV Aronnax) were included is possible. IBA consultation have led to the main comments and required evolutions from the existing IBA C400 design are:

- **The superconducting coil system (flexibility of isochronism)**: We are leaning towards a magnet of symmetry 4. We are comfortable with this geometry, which allows two acceleration cavities, a valley dedicated to extraction and a valley possibly dedicated to instrumentation. These last two valleys would allow an efficient pumping and thus a good vacuum level. If we consider a "compact" magnet having more or less the size and field of the C400, we would expect without too much problem 40 MeV/u for the species at low q/m (1/7), Species with higher q/m ratio would be higher in energy per nucleon but the flexibility of the magnet remains to be studied. The magnet would therefore be similar in size but very different from the C400: less spiral, with an adjusted gap coil, different penetrations in the cryostat, etc.
- The pole coils (idem, for isochronism)
- **The RF system**: The reference orbital frequency of ~7.5 MHz (for Q/m=1/7 and the field strength of the C400). This means that we would have an effective acceleration mode around 30 MHz on Harmonic 4. The faster species (Q/m more favorable) would be on lower orbital harmonics. The RF system will therefore have to be flexible. The CSS could thus be equipped with two independent cavities, which would also open the way to accelerations on odd harmonics. Thus, in addition to the cavities, there would be external resonators to allow these harmonic changes.
- **A central region** exchangeable via an axial extraction system of the latter.

It is a large project but it remains competitive with the other solutions proposed. However, some options may have to be define that could impact the overall cost (70-80 M€). For example:

- For the C400, as there is no cryo-plant on site, we will opt for a cooling and condensation system of Helium. At GANIL, the management of cryogenic fluids may be centralized for the lab.
- On the C400, the cryo-coolers has been changed to pulse tubes. This also has a cost but a positive impact on maintenance time.
- What are the exact requirements in terms of documentation/certification of the machine?

D. Superconducting LINAC

Description

The superconducting linac is composed of

- Charge breeder and selectivity type "Medium Resolution Magnetic Spectrometer"
- a Low Energy Beam Transport line (LEBT)
- A RFQ room temperature cavity
- A Medium Energy Beam Transport line (MEBT)
- A superconducting post accelerator composed of 3 cavity families

We assume that a pre-selectivity of secondary radioactive ions is managed before the 1+-N+ charge booster. This selection is not part of the LINAC study. The charge booster will have to be carefully selected in order to limit the production of parasitic species.

The localization of the post accelerator can be optimized in order to limit the LEBT length and to avoid any existing building disassembly. Using the existing SPIRAL2 tunnel and technical corridor width, the post accelerator seems to fit nicely between the existing GANIL and the future DESIR building (***Figure IV.6***)

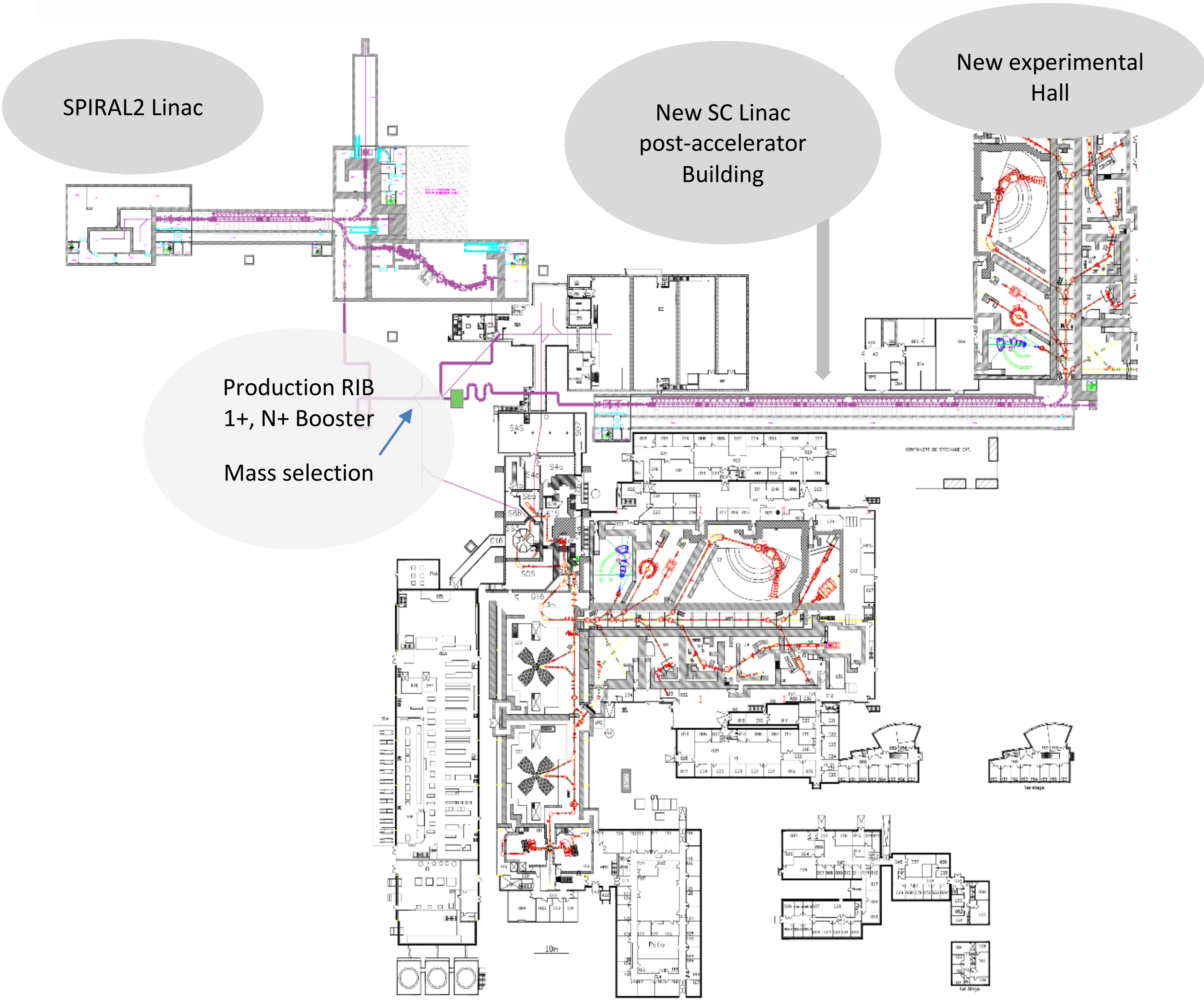

Figure IV.6: *Superconducting linac post acceleration installed in the present GANIL installation.*

This choice of linac implantation should provide enough room between the production area and the linac injection for the installation of a charge breeder and a mass separation system to be defined.
In such a configuration, the re-use of the existing experimental hall will suffer from 3 disadvantages:

- Long High Energy Transport lines
- Necessity to inverse the room distribution.
- Such an inversion will also forbid the use of the existing cyclotrons complex.

It is therefore preferable to optimize new experimental hall, which permit parallel operation of all existing GANIL accelerator. Those new halls can easily be optimized for the new physic domain provided by the post accelerator.

Transmission and selectivity

Transmission of a linear accelerator should consider all its individual components. The linac itself shows around 100% transmission, but it is necessary to consider 90% in the Medium Energy Beam Transport line, 95% in the RFQ and 80% in the Low Energy Beam Transport Line. An overall 70% is achievable.
The stripping and associated selection beam line add two benefits: the selectivity and a better acceleration efficiency in the linac, resulting in a significant cost reduction. The stripping by itself reduce the transmission to a number that depend of the particle mass, and its energy. A numerical example gives a 30% efficiency for ^{132}Sn at 15MeV/A.
The selectivity is a subject by itself, in direct relation with physic requirements, which will also reduce the overall transmission of the post acceleration. It is necessary to include a second step of selection between the charge booster and the linac injection with a device similar to the SPES Medium Resolution Mass Separation (MRMS), with a resolution to be carefully optimized. The SPES separation provide a theoretical mass selection of 1/5000. Like any high-performance system, it is most likely that the day to day operation of such a system will show real performance closer to 1/1000, which looks close to the required performance.
The transmission of a realistic post-acceleration, from the booster to the experimental hall, is therefore probably below 10%, and as low as the physic will required for the adequate separation.

The advantages

The construction of a superconducting linac is a very mastered technology. All major accelerator projects on the planet use this scheme for the effectiveness of the design. It helps limiting the risk.
The newly commissioned SPIRAL2 LINAC will provide a nice synergy for this new post-accelerator. One of the major highlights is the re-use of the Quarter Wave Resonators (QWR) cavity type. The low energy cryo-modules are used in this post-accelerator design as well as the SPIRAL2 high energy QWR cavities. A new extension of SPIRAL2, project named NewGain, includes an injector optimized for the A/Q=7 acceleration. The ongoing work for this NewGain RFQ will benefits to the post-accelerator project.
As all ongoing projects uses superconducting linac, a dynamic community, communication and development will highly be beneficial for this post accelerator development.
The linac post accelerator can be later upgraded at demand to reach higher final energy like 100 or 150 MeV/A.

The drawbacks

The building size: The LINAC is a long structure and requires a relatively large building. The design, as of today, is based on the SPIRAL2 tunnel and technical corridor width. The required utilities multiply the building size.
Low selectivity. The nice acceptance of a linac accelerator is also its major drawback since even the parasitic particle are accelerated to the experiments. It is required to add a separation that we can optimize at low energy, and this system has a cost. The stripping help to optimize the cost of the machine, reducing the length of the LINAC and associated building, at the price of transmission reduction. The Multiple charge state transport in the LINAC should not be considered.

It is not realistic to rely on an industrial manufacturer for such specific project.
A new experimental hall needs to be included.
The global cost is high, but also with less surprises since the design re-use of known objects.

Cost estimation

The cost is estimated using the following assumptions:
The accelerator building is estimated to be 3500m², with the cost estimate of 3300€/m². Total of 12M€.

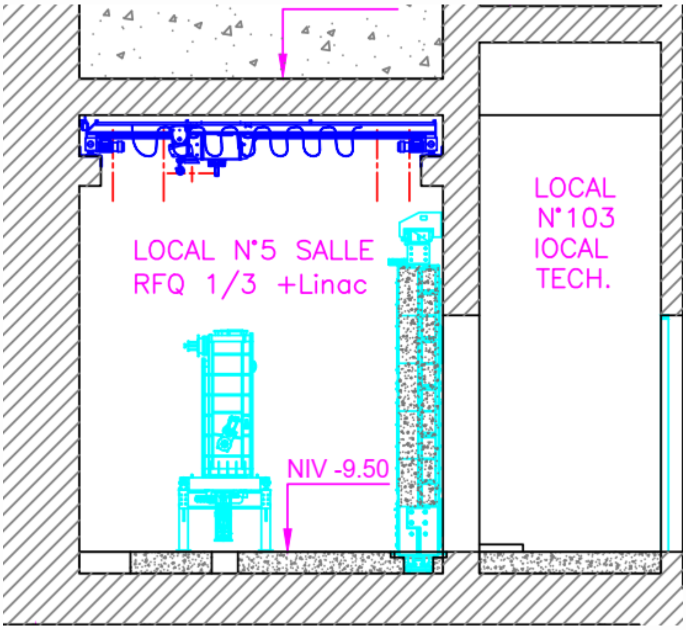

Figure IV.7: *SPIRAL2 tunnel cross section, which serve as reference for this preliminary design.*

The new experimental halls, without the instruments, are estimated to be 80×50m about the size of the new DESIR hall. We assume a total of 12M€.
All the building will require a dedicated system engineer, to be estimate, rounded at 10M€.
The SPIRAL2 accelerator cost was 33M€. It includes the source, RFQ, lines, superconducting accelerator, the helium factory, magnets, diagnostics and all associated utilities. The superconducting linac alone costed 12M€. The post-accelerator breakdown is therefore the following:

- Superconducting linac, including helium factory (12x4): 48 M€
- Lines, diagnostics, utilities, etc… : 25 M€
- Cabling etc…: 10 M€
- RFQ: 5 M€
- Booster: 1 M€
- Medium resolution Magnetic Spectrometer: 2 M€ (SPES = 1.5 M€)
- Contingencies: 8 M€

The superconducting project is estimated to be 130M€ including the buildings.

Parameters

	Superconducting LINAC
Cost of accelerator	102 M€
Cost Accelerator building	22 M€
Cost Experimental building	20 M€
Manpower resources	Large
Max. Output energy: For 132Sn^{26+} For 90Kr^{20+} For Z/A=0.4-0.5	 60 MeV/A 75 MeV/A 100 MeV/A
Energy range (MeV/A)	[5-100] MeV/A
Stripping	Required for a minimal selectivity and cost.
Selectivity	Low (constraint on source/ stripping)
Expected Transmission	20 % (with stripping)
Main advantage	Upgrade possible flexibility
Main problem	Manpower cost

Table IV.6

SWOT summary

LINAC Supra	
S	W
Versatility of available beams	High cost and large new civil engineering building construction
transmission during acceleration very good	New building for new experimental areas . Cannot connect with existing facility
Ambitious goal for 2030	Additional HR needed for operation (RF, cryogenics, SC Cells,..)
Maximum Energy Specifications for all RIB reached	Complex and costly upstream purification system of post-accelerated RIB
	Detailed study to be undertaken needed to asses RIB Purity on target
O	T
Experience gained on SC LINAG of SPIRAL2	Existing HR not available for operation of a new SC Linac post-accelrator
NEWGAIN injector synergy	
New accelerator facility with new SC RF Linac Long term future of GANIL	
may replace the present C0+SSC chain	

V. SUMMARY AND CONCLUSIONS

The full spectrum of ISOL post-accelerated RI in the energy domain above Coulomb energy (~7MeV/A) up to Fermi energy and beyond (<100 MeV/n) is not covered by any of the running or projected RIB facilities in the world (see section II, Table 1).
Investigation of long chain of neutron rich and proton rich nuclei produced by ISOL from light species (C, O, Ne) to medium (Kr, Sn) and up heavy Trans-Actinides with intensities from 10*2 up to 10*7 pps in the energy range 10-60 MeV/n (Flagship beam ^{132}Sn 10-60 MeV/A, 10^7pps on target) with high purity and beam optics comparable to the best stable beams will be possible and open the way to a rich nuclear structure and reaction research program.
The working group has identified the main research areas where the ISOL proton and neutron rich post-accelerated RIB in the energy range between 10 to 60 MeV/A and beyond in some options, with masses ranging from the lightest (A<40) to the heaviest (A> 230), will open rather exciting and unique opportunities.
Regarding the production of a wide range of RI, we have assumed that the Radioactive Ion Beams (RIB's) are produced in q=1+ charge state in a production hall, close to Spiral2/Desir buildings.

Three technical options for post-acceleration of ISOL RIB at Ganil in the energy range presented in the physics case are discussed and preliminary Design parameters are listed. SWOT analysis of each options regarding beam specifications, cost, new building construction, and overall advantages and limitations of three technical design options were presented.
We present here a table showing a comparison of various RIB post accelerator options in the GANIL/SPIRAL2 context.

	SCC upgrade with LINAC injector	Superconducting Compact Cyclotron	Superconducting LINAC
Cost of accelerator	23 M€	70-80 M€ (based IBA)	102 M€
Cost Accelerator building	5 M€	5-10 M€	22 M€
Cost Experimental building	0	0	20 M€
Manpower resources	Medium	Very restricted if industrial	Large
Max. Output energy: For 132Sn^{26+} For 90Kr^{20+} For Z/A=0.4-0.5	 33 MeV/A 49 MeV/A 80 MeV/A	 64 MeV/A 79 MeV/A >100 MeV/A	 60 MeV/A 75 MeV/A 100 MeV/A
Energy range (MeV/A)	(discrete energies) [3.5-15] and [24-33-49-80]	[10-100] MeV/A	[5-100] MeV/A
Stripping	Required for high energy (SSC2)	Not Required	Required for a minimal selectivity and cost.
Selectivity	Good/very good	Good	Low (constraint on source/ stripping)
Expected Transmission	15% to 50% (with /without stripping)	10-20% (no stripping)	20 % (with stripping)
Main advantage	lower cost	compact	Upgrade possible flexibility
Main problem	- CSS ageing -33MeV/A max for ^{132}Sn	New Design effort	Manpower cost

Table V.1

To conclude, the working group would like to stress that the presented options for post-accelerated ISOL RIB at the GANIL/ SPIRAL2 facility span a rather wide range of technical options, investments costs, human resources allocations, design and construction duration, plus somewhat different coverage of the full energy range, beam purity and transmission efficiency. However, the three options are based on sound and proven accelerator technologies.
These 3 design options will have in common the advantages to maintain and develop parallel beam operation of the future GANIL facility including the high power, stable beam capabilities at GANIL.

The Linac plus existing GANIL C0+ SCC accelerator chain will have the clear advantage to make a maximum use of the existing GANIL facility at minimum cost, time duration and human expertise and resources. However, the energy range specifications are not covered for RIB above mass 90, and have discrete values at above 20 MeV/A.
Beam purity and transmission are very good and re-use of experimental building and vaults are possible. Present stable beam operation of existing Ganil, including SPIRAL1, is preserved when the new LINAC and SCC upgrade construction and commissioning is achieved.

The SCC K1600 is a new post-accelerator which, after a detailed design study, will fulfill the whole range of specifications at the cost of a significant investment but limited human resources and time duration if built by an industrial provider which have large experience in cyclotron construction and commissioning. Implementation can be integrated in the present facility buildings or in the new production hall. Re-use of present experimental building and vaults is possible at the cost of high rigidities upgrade of HE beam and experimental beam lin. Stable beam operation of existing Ganil, preserved during construction phase.

The SC RF Linac is also a new post-accelerator which will benefit from the SPIRAL2 LINAG construction and commissioning. This option will fully cover the design specifications in energy range and species but need specific and complex beam selectivity devices before injection.
The modularity of such SC LINAC allow for future energy upgrade if needed at minimal cost. However, the investment cost is quite significant not only because of the SC RF technology itself but also due to the new building dimension to host the accelerator (>100m) and the related need for a new experimental hall nearby to host the instruments (detectors, spectrometers,). Stable beam operation of existing Ganil and SPIRAL1 are preserved during construction phase.

Because of the strategic importance of the choice of one of these options for the future of GANIL, the working group would like to stress that due to the limited time devoted to these pre-design studies **it is necessary to develop a much more detailed investigation of the proposed solutions together with a clear financial and human resource plan in order to reach a viable and well-motivated final decision.**

VI. ANNEXES

A. High energy beamline considerations

Any post accelerator providing a beam of ^{132}Sn@60MeV/A overpass the Bρ limitation of GANIL experimental Area.
A stripping a High Energy could help to fit the maximal limit by reducing the maximum energy to 55 MeV/A. However, the heavier Isotopes (Z>45) will not be fully stripped at this energy and more than 50% of the particles would be lost.

- For SSC version, we do not overpass GANIL design Bending limit, the intrinsic limitation of SSC will not require up-grading the high energy beam lines.
- For the LINAC or Superconducting cyclotron SCC reaching 60MeV/A, the use of GANIL existing LHE beam line (fishbone L3…) will restrict the energy (at 55 MeV/A for ^{132}Sn case) and reduce the effective transmission by a factor 2.
- For the LINAC = $^{132}Sn^{25/45+}$ @60 MeV/A; Bρ=3.3 T.m

With a stripping of Sn beam at 55 MeV/A to get $^{132}Sn^{50+}$, 50% of the beam are lost, but the maximal Bρ=2.88 T.m

- For the Superconducting cyclotron = $^{132}Sn^{32+}$ (EBIS source) @60 MeV/A; Bρ=4.67 Tm (stripping at final energy to be considered).

It is clear that a modification of GANIL LHE beam line should be studied in connection with the post accelerator chosen.

B. Pre-buncher at variable frequency for SSC upgrade

The coupling of LINAC to variable frequency machine is a delicate design effort, which could require variable frequency RFQ+DTL, like it has been done at ISL Berlin (variable frequency) and at RIKEN RILAC1 (variable frequency LINAC). We suggest instead to use a fixed frequency and low energy LINAC but using **a pre-buncher at variable frequency**. This technical option relies on the recent work accomplish at RIKEN with their new injector RILAC2 [f_{LINAC} 36.5 MHz] injecting in the SSC cyclotron cascade used at F=18.25 (h_{LINAC}=2): The main trick is to use a subharmonic buncher, to fit the cyclotron frequency. By varying the harmonic h_{LINAC} it is possible to find out several solutions leading to the acceleration at different SSC's frequencies.

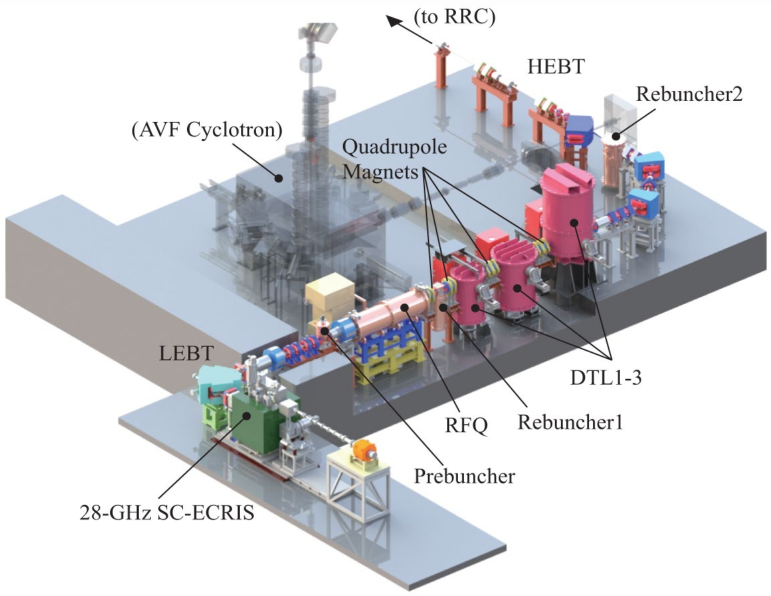

Figure VI.1: *RILAC 2: An example of LINAC injector for a cyclotron chain: q/A=1/7: A=238 Q=35+.*

C. Charge Breeding (1/N+) schemes and selectivity problems

An efficient Post acceleration schemes require charge states with q/A of the order of 1/4-1/5, the highest charge is economically favorable since it reduces the length and size of the post accelerator. Two technologies (ECRIS-CB and EBIS-CB) have been developed and studied during the last twenty years. ECRIS-CB is based on the regular ECR ion source machine using a magnetic confined plasma while the EBIS is built on intense electron focused by a superconducting solenoid. These two complementary technologies provide different beam qualities, operation modes and different technical limitations.
Table VI.I displays a comparison of both technology parameters regarding requirements for post-accelerators.

R&D ECRIS Charge Breeder

Although less efficient and having a lower control on the Q/A to produce, the promise of the second RF frequency heating will lead to an enhancement of the charge breeding efficiency as well as a better control of the Q/A. That R&D is actually under progress at GANIL.
The contamination by stable ions as well as the requirement of a buffer gaz (He) is a major problem of the ECRIS Charge Breeders. The interaction of the plasma with the plasma chamber produces numerous stable contaminants ranging from tens of μA (air gases: O, N, C, Ar, Ne) to pA (isotopes of chamber, wave-guide material etc.). The buffer gas required for the operation give pollution of hundreds of μA. R&D is under progress to moderate that process by the use of liners (new material); ultra-cold gas line; coating source wall or specific cleaning process. Though many tests have been realized (ANL) or are under progress (LPSC - INFN-LNL – GANIL collaboration) to reduce the contamination, many problems are still unsolved. Such a breeder would be very tricky to use in combination with a LINAC as a post accelerator without employing a Medium Resolution Separator (MRS) of, at least, 1/1000 of resolution power.

R&D EBIS Charge Breeder

An EBIS-CB is a pulsed machine allowing easily getting the Q/A needed for an experiment and it is able to ionize species fast. Due to the lack of interaction with the vessel walls, the RIB are often pure after a small magnetic spectrometer. However, very short extracted beam pulses width (0.1 ms) introduce high instantaneous rates on the experimenter's detectors.
Various schemes have been developed for lengthening the extracted beam pulse. At REX-EBIS, the trap electrodes and extraction barrier can be ramped linearly, producing a beam pulse > 1ms. At MSU@ReA-EBIT, even better result has been obtained with 4 ms pulse width: it represents for a 50 ms cycle, however, an increase of the peak intensity (x12) on any detectors (pile-up, dead time…).
To deliver RIB in pseudo CW mode, there are two ways already explored, one of which is already under operation. The debuncher mode will allow to "re-create" a type of continuous beam (CW) but, even if the proof of principle has been demonstrated, it necessitates more R&D to use it regularly under operation. The "slow extraction" mode (in operation mode at REX-ISOLDE) corresponds to a smooth high voltage ramp of inner EBIS electrodes to have a continuous leak of ions; the cooling-bunching process occurs in parallel of the charge breeding one: at MSU, they can hence produce beams with 1000ms charge breeding and 900ms extraction but with a larger energy spread.

Comparison ECR/EBIS

	ECR Charge Breeder (GANIL, formerly at CARIBU@ANL, Triumph, SPES under progress)	EBIS Charge Breeder (ISOLDE, recently TRIUMF, recently CARIBU@ANL, Rea3@NSCL, EBIS-CB@RAON)
Efficiency (stable-radioactive ions)		
M < 70	Max 24 %	Max 35 %
70< M < 130	Max 15%	Max 20%
M > 130	Max 13%	Max 12%
Q/A		
M < 70	1/4 – 1/3	1/5 – 1/2
70< M < 130	1/5 - 1/4 ($^{132}Sn^{25+}$ realistic)	1/4 - 1/3: (132Sn33+ realistic)
M > 130	~1/7	up to 1/4
Contamination	High contamination due to the interactions of the plasma with the plasma wall chamber	Few contaminants <pA
Charge breeding time	~10–20 ms per charge 4ms for ($^{39}K^{3+}$) / 450 ms ($^{85}Rb^{15-20+}$)	4ms ($^{9}Li^{2+}$) - 700 ms ($^{224}Ra^{51+}$) Cooling- bunching in parallel of charge breeding processes included (~50% / 50%). (94 ms for $^{87}Rb^{20+}$)
Maximum injected beam	10^{12}pps	10^{10}pps
Mode of operation	CW or pulsed	Pulsed (cycle 1Hz to 50Hz)
Admittance Output emittance @ at 30 keV	< 40 π mm.mrad for 50% efficiency ~100 π.mm.mrad	10 π.mm.mrad for 50% efficiency ~20 π.mm.mrad
Conclusion	Adapted to a system having a very good selectivity downstream the charge breeder. Adjusted to deliver high intense stable beam to users	Pile up for experiment to be considered. Very high charge state and good transmission; intrinsically more selective, but require beam preparation upstream (cooler buncher for accumulation)

Table VI.1

More or less, these two technologies can match together as they have advantages for one balancing disadvantages for the other.
We propose the following scheme getting additional benefits of both. The 1+ RIB has already a small transverse emittance thanks to HRS (High Resolution Separator) well adapted for being injected into either the EBIS-CB or the ECRIS-CB. Now, the EBIS-CB has its own buncher and the charge bred output ions are analyzed by the Nier-type spectrometer (combination of electrostatic and magnetic elements) selecting only one charge state. Concerning the ECRIS-CB, the 1+ RIB is directly sent to its injection side and hence charge bred, extracted, cooled down to get a small transverse emittance before being mass analyzed thanks to a magnetic dipole. In the case of using a LINAC as post-accelerator, a

MRS (with R above 1000) must be developed and installed prior to inject the RIB in it. If the post-accelerator is a cyclotron, that MRS is no more requested.

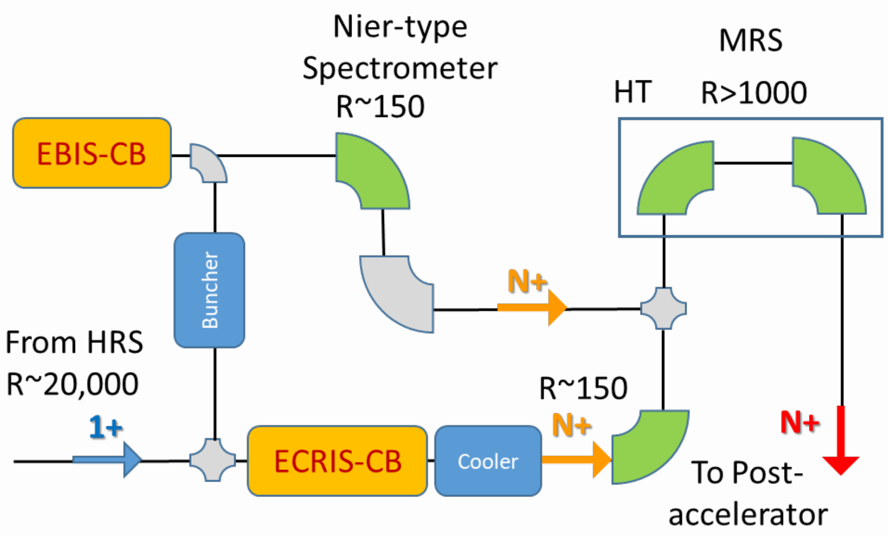

Figure VI.2: Ion sources disposition

There are two options available to upgrade that scheme:

- Adjunction of a MR-ToF-MS between the buncher and the EBIS-CB in order to reach mass resolution in the range of 100000
- Setting in a “Debuncher” just after the Nier-type spectrometer for CW operation

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