

HIGH INTENSITY BEAMS AT GANIL AND FUTURE OPPORTUNITIES: LINAG

G. Auger, W. Mittig, M.H. Moscatello and
A.C.C. Villari
Ganil, BP 55027, 14076 Caen Cedex 5, France

GANIL R 01 02

Project of a LINear Accelerator at GANIL

HIGH INTENSITY BEAMS AT GANIL AND FUTURE OPPORTUNITIES: LINAG

G. Auger, W. Mittig, M.H. Moscatello and
A.C.C. Villari
Ganil, BP 55027, 14076 Caen Cedex 5, France

I - INTRODUCTION

The systematic and very successful use of high energy fragmentation at GANIL with the first operational high intensity heavy ion accelerator in the 50-100 MeV/nucleon domain, for exploring the structure of nuclei far from stability triggered the question of how to proceed even further in this domain. The study of nuclei far from stability has become one of the major activities at GANIL, and is one of its areas of excellence. In the near future, the possibility of producing and accelerating radioactive beams by the Isol method will be available. For this reason the directors and the scientific council of GANIL decided about four years ago to initiate work on long-range perspectives. The results of the working groups can be found in the minutes of the scientific council, and the physics case has been published recently [ref 1].

In order to add medium-mass nuclei to the ones available with Spiral, a pre-project named Spiral II is now under way. In this project, light-particle (e,p,d,...) induced fission is considered as the method of production of the radioactive ions, with the aim of generating at least 10^{13} fissions/s.

It is clear that the final intensities of RIB's will define the areas of the nuclear chart that will be accessible to experiments. This implies a need for high intensity primary beams and versatile production techniques. Following these scientific needs, GSI has proposed an upgrade of its facility, providing 10^{12} ions/s from p to U at 1.0 GeV. The US project RIA is planning several hundreds of kW of primary beams from protons to U at about 400MeV/nucleon. The ISAC facility at TRIUMF already uses $20\mu\text{A}$ (1.2×10^{14} p/s) of protons at 500MeV for spallation production of ISOL beams, and will be able to use 5 times higher intensities in the future. The UK SIRIUS proposal envisages a high intensity p accelerator for fission and fusion evaporation reactions. RIKEN Japan is starting an energy and intensity upgrade. A European RTD study, EURISOL, is considering different solutions for an eventual European project. The laboratory at Legnaro, Italy, is considering a high intensity low energy proton driver, called SPES. Links to these projects can be found in [ref. 2].

In this context of fast evolution on the European and international level we consider here the possibility of an intensity upgrade of GANIL in its area of excellence, i.e. beams in the energy domain of about 100MeV/nucleon for low to medium mass nuclei ($A < 100$). We evaluated the possibility of producing beams of several hundreds of kilowatts : this is of the order of 1mA, corresponding to

6×10^{15} particles/s for light particles and 3×10^{14} /s for heavier particles. The present accelerator configuration consisting of three cyclotrons in a cascade will not be capable of furnishing such high intensities. At present, the highest beam powers reached are in the 2-6kW domain, or 2×10^{13} particles/s. It is not realistic to expect a very significant increase in such values. With present technologies, only linear accelerators are capable to produce such high intensities. Moreover, recent progress in high intensity ion sources for high charge states are another important feature to be taken into account. **For this reason, we consider the possibility of construction of a very high intensity linear accelerator at GANIL in this energy and mass domain.** Such a possibility would be complementary to the RIKEN, GSI and the RIA projects, optimised in a different mass-energy domain.

The project, as outlined below, can be constructed in various phases, starting at low energy. It would cover a broad range of possibilities of primary and secondary beams. Very high intensity primary beams would be available from below the Coulomb barrier to 100A.MeV from protons to mass 100 nuclei. Even intense heavy beams like U could be accelerated to somewhat lower energy. These beams could be used for the production of intense secondary beams by all reaction mechanisms (fusion, fission, fragmentation, spallation, etc.) and technical methods (recoil spectrometers, ISOL, IGISOL, etc.). Thus, the most advantageous method for a given problem of physics could be chosen.

As indicated by the title of this paper the present work was done as an internal consideration on possibilities of beams at GANIL. It is clear that any project will have to be integrated in an European and international context.

II.- PRODUCTION OF RIB's BY FRAGMENTATION AND ISOL RESPECTIVELY.

To achieve high RIB intensities whilst reaching very far from stability regions, it will be necessary to take advantage of various strategies in the production scheme. Modern next-generation exotic ion beam facilities should therefore consider all available techniques for the production of radioactive elements. Only a multi-beam heavy ion driver offers the possibility of adapting the best production method to the requested radioactive ion beam. This is the major attribute of the present GANIL laboratory, worldwide the unique facility offering both fast radioactive ions from thin target (In-flight) and thick target (ISOL) production methods.

The facility considered in this document represents an intensity upgrade of the present GANIL laboratory, with the same characteristics of the production systems but with a factor of 100-500 higher primary beam intensity. This new facility could provide an upgrade of the RIB final intensity of the same order of magnitude, i.e. 100 – 500 higher.

If one considers an improved separator with characteristics similar to the new A1900, recently commissioned at MSU [ref. 3], the final intensity of in-flight RIB can be increased of another factor 10 to 100 as compared to present devices at GANIL such as SISSI and LISE.

All possible production schemes potentially available in such a facility are shown in figure 1, with two main branches, thin-target (in-flight) and thick-target (ISOL) methods. Primary beams are shown in green, ion beams in blue and neutral particles in black.

In the in-flight method, the primary beam hits a thin target so that the reaction products escape from the target with energies close to that of the beam. Such fragmentation reactions are favourable when high-energy heavy ions hit a suitable target. The fragments are directed forward in a narrow cone at considerable energy, but with a large momentum spread. As much as possible of the beam is accepted into a separator and a particular isotope is selected. The energy from the reaction is usually high enough for many nuclear physics experiments at intermediate energy (see the GANIL reports since 1987).

In the thick target (ISOL) method - like the present SPIRAL - the primary beam hits a thick target. The reaction products are stopped in the target material and diffuse out to the surface. Then they effuse through the target voids and eventually reach the ioniser and are extracted as an ion beam. The beam is then mass analysed and the selected isotope transmitted to the experiment or to a post-accelerator. A variation of the ISOL method is to convert protons or deuterons into neutrons in a converter target. The resulting neutrons interact with a thick production target. The converter and the production target can be one and the same target.

The thin-target and thick-target methods can be combined; the particles from the thin fragmentation target are stopped in a thick target and then pass into the rest of the ISOL. Alternatively the particles can be stopped in a gas catcher and passed into the ion source via a helium gas jet. Another variation is to stop the energetic particles in a gas and then have a helium gas ion guide system or IGISOL (Ion-Guide Isotope Separator On-Line). The particles emerge from the IGISOL as singly charged ions, avoiding the need for a separate ioniser.

With the use of a thin target technique, all the particles are released instantaneously, whereas in the thick-target technique, where all the particles are stopped, there may be considerable delay in the release. This is due to the slow diffusion out of the target and effusion through the target void to the ioniser. In addition, many particles

physically or chemically stick to the surfaces. If the release time is longer than the lifetime of the radioactive particles, they will decay before reaching the ioniser.

The combination of these two complementary techniques allows one to have a complete range of radioactive species available for experiments in a large energy range. The obvious extra advantage of this concept is that the GANIL team has already the know-how for the various production schemes proposed in this document. It is a straightforward upgrade of the present facility.

For a more detailed comparison between produc-

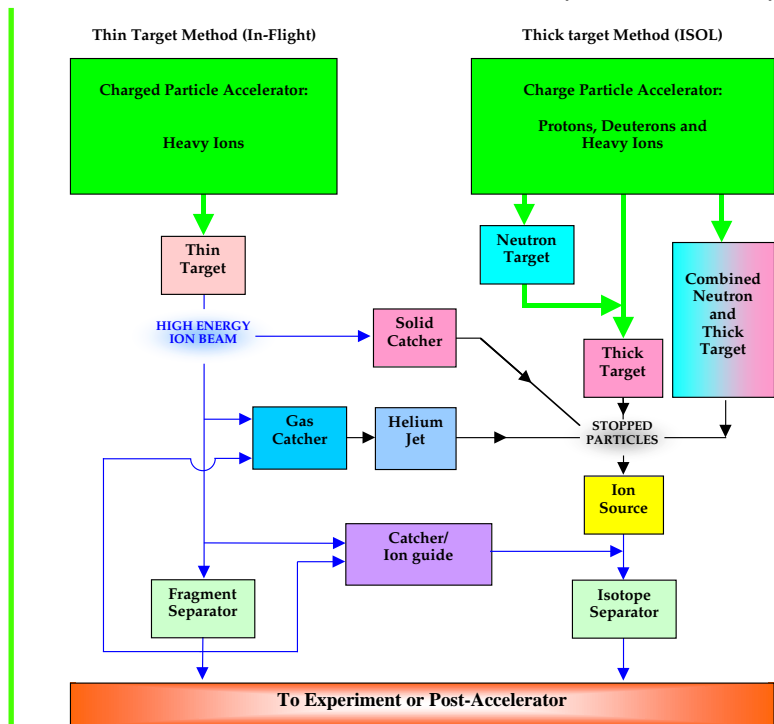


Figure 1. All potential RIB production methods with a heavy ion driver [ref. 4]. GANIL already developed and routinely uses most of the branches shown.

tion methods and yields, see appendix.

II.a THE TARGET FOR THE THIN TARGET METHOD.

A high power rotating target is in operation at SISSI, for a power <2kW but very high power density due to the very strong focussing with a diameter of less than 0.4mm. With a 2cm broad beam, and a radius increased by a factor 5, leading to a target diameter of 0.5m, it should be possible to dissipate powers up to 0.5MW. Calculations done in the context of the R3B collaboration [ref. 5] imply this possibility. In this technology, only solid, high melting point materials can be used as targets. Beryllium is not very well suited due to its toxicity and the relatively low melting point. Therefore the best material is Carbon.

Another possibility is to use a liquid Li target, which also has been constructed at ANL – Argonne National Laboratory, USA [ref. 6] and is presently being considered for IFMIF [ref. 7]. However, the simple target wheel seems to be a more simple and versatile solution, allowing also the use of different target materials in order to make use of different reaction mechanisms for RIB production.

II.b THE TARGET FOR THE THICK TARGET METHOD

The GANIL R&D target-ion source group has developed different solutions for the SPIRAL facility, all using heavy ions as primary beams. The originality of the SPIRAL project lies in the use of an extended range of heavy-ions, up to the maximum available energies. Such an approach differs from the proton (or light-ion) beam technique in that the projectile rather than the target is varied in order to produce the different radioactive species, thereby allowing the use of the most resilient and efficient production target for most cases. In addition, an important work of Parrne [ref. 8] at IPN-Orsay is already being done for developing new solutions specially suited for fission targets. Most of these studies can be extended to higher beam power, provided that radiation hardness is considered as well as the proper dimensional scaling.

In ref. 9, an example of a possible design of a thick target assembly is shown and the target temperature for a $^{20}\text{Ne} - 95\text{A MeV}$ primary beam with 300 kW power on a graphite target is simulated. The authors assumed that 60% of the power is dissipated in a first cooled target and 40% in the second one, used for diffusion of the radioactive species.

A possible target configuration, which matches the requested constraints, corresponds to a parabolic surface shape bombarded by a flat beam profile. In figure 2 we show the temperature profile of a diffusion target which receives 40% of a total beam power of 300 kW. We would like to point out that the temperature distribution around

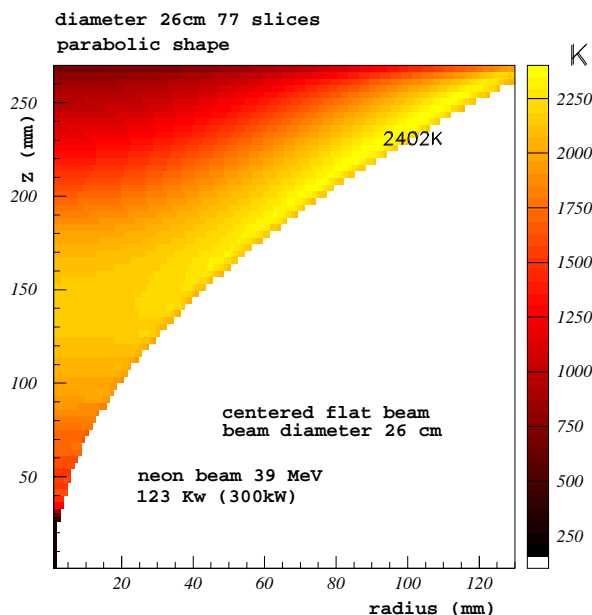


Fig. 2. Target temperature distribution for 40% of 300kW, i.e. 123kW in a parabolic shaped thick hot target.

50 mm of the Bragg peak ranges between 2000 and 2435 K. The diameter of the target is 260mm. A possible implementation of such a target inside a container is proposed in figure 3. The open container geometry around the target should ensure excellent conductivity for the radioactive species. A funnel-shaped structure conducts the radioactive atoms to the ion source.

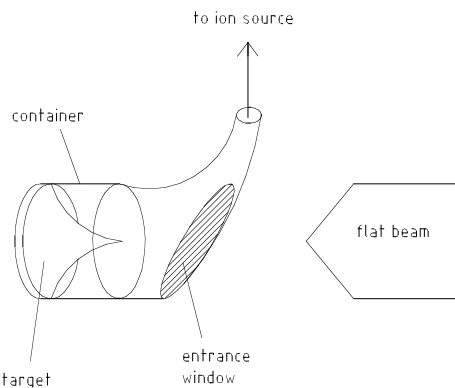


Fig. 3. Target container configuration for high power primary beam.

II.c SUMMARY OF THE PRODUCTION METHODS

To summarise of this short section, we have shown that various possibilities are offered by the use of a multi-beam driver, allowing the optimisation of the production for a large range of radioactive species. The present technologies, developed over many years at several laboratories, are compatible with the full primary beam intensities (of the order of 300 kW) considered in this document. Moreover, the combination of various techniques, most of them only possible in this multi-beam solution, offers a large beam energy range for radioactive ions from the eV level up to 100A MeV.

III. HIGH INTENSITY ION SOURCES

During the last decade, much progress has been made in the production of high charge states at higher intensities. For example, figure 4 shows the evolution of the intensity of O^{6+} beams produced with an ECR ion source. Since 1997 the intensity of O^{6+} (corresponding to $A/q \approx 3$) has reached 1mA.

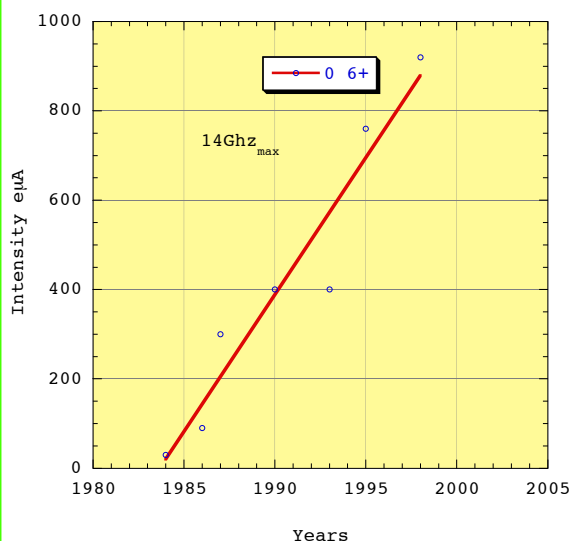


Fig. 4 : Evolution of the intensity of O^{6+} during the last two decades [ref. 11]. The red line correspond to the overall trend.

For heavier nuclei, figure 5 shows the production of different charge states of Ar. At present, the achievable intensity of Ar¹⁴⁺ is approximately equal to 130μA.

An extrapolation (in red, blue and black) in time, permits us to expect an intensity of 1mA for this case by 2005-2010

Supra conducting technologies and new hyperfrequency generators will provide future progress for the maximum frequency and magnetic field in the ECR ion sources, thus important gains of intensities for high charge states is expected in the near future. For example,

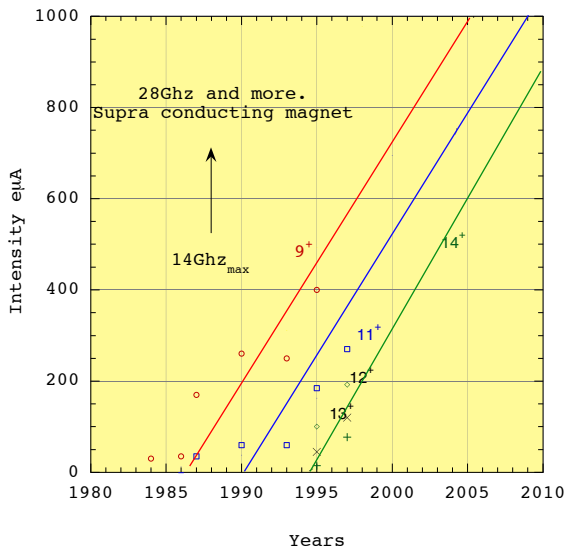


Fig. 5 : Evolution of the intensity of Ar during the last two decades [ref. 10]. The different lines indicate an extrapolation.

recent developments at Catania and Berkeley gave approximately a factor 4 higher intensity for beams of high charge states.

In conclusion, at the moment for the light elements ($Z \leq 20$), ion sources for $A/q=3$ already deliver beams approaching the intensity considered in the present project, i.e. 1mA. Progress in ion source technology should extend this intensity limit to heavier elements. Thus, the project will be optimised for this ratio $A/q=3$. As will be shown below, a broad range of A/q ratio is compatible with the accelerator proposed, thus allowed the acceleration of particles with higher A/q ratio, of course with lower final maximum energy.

IV – A LINEAR ACCELERATOR FOR THE PRODUCTION OF HIGH INTENSITY PRIMARY BEAMS

IV a) PRELIMINARY REMARKS AND ASSUMPTIONS:

The proposed linear accelerator will be optimised for $A/q=3$ ions at 100 A.MeV, as discussed above. Conditions for acceleration of deuterons, protons and lower A/q ions will be determined. The linear accelerator is based on the acceleration of heavy ions without any stripper. This avoids the problem of high power in the stripper targets and directly profits from the progress of heavy ion intensities for high charge-state ion sources.

The heavy ion intensities are assumed to be 1 mA up to 100 A.MeV, 10 mA for protons and 5 mA for deuterons up to an energy limit of 35 MeV and 40 MeV respectively. For higher energies, deuteron and proton intensities will be limited so as to remain below 300 kW power.

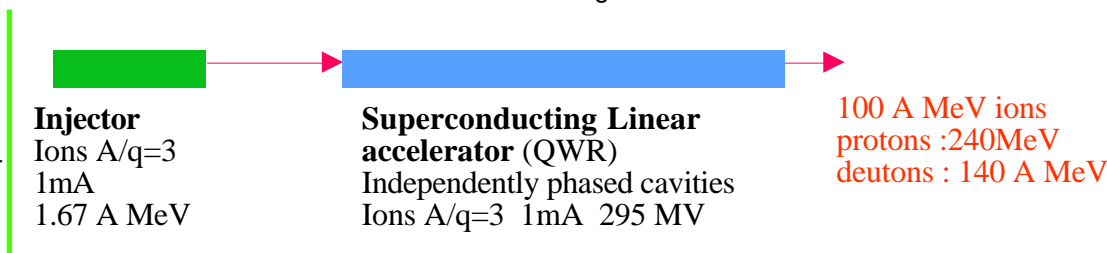
IV b) PRINCIPLE OF THE LINEAR ACCELERATOR.

The proposed linear accelerator is a continuous wave (CW) mode machine, to get maximum efficiency in the intensity transmission from the ECR source for heavy ions, with independently phased cavities. It consists of an injector (source+radio-frequency quadrupole) followed by a superconducting linear accelerator based on quarter-wave resonators (QWR).

The choice of a CW machine implies the use of superconducting QWRs. This technology has been developed over many years, and good results have been obtained for the different superconducting cavities tested at Argonne, Legnaro and Jaeri respectively.

A schematic layout of the linear accelerator is shown on figure 6 :

Fig. 6 : Schematic layout of the linear accelerator



IV c) THE HEAVY ION INJECTOR :

We assume that the next generation superconducting ECR ion sources will be able to produce around 1mA $^{36}\text{Ar}^{12+}$ (as the GYROSERSE source, 28 Ghz, LNS-INFN project). The extraction voltage is assumed to be 60 kV: any possibility of increasing this value will be a gain for the RFQ design.

The RFQ has still to be developed. We assume a 5 MV 87.5 MHz RFQ, which will accelerate a $A/q=3$ beam at 1,67 A.MeV. According to specialists [ref. 12], it should present no specific difficulty, as the required beam intensity is quite low as compared with the present highest intensities produced. Nevertheless, calculations must be

done to evaluate more precisely both the RFQ length and its cost.

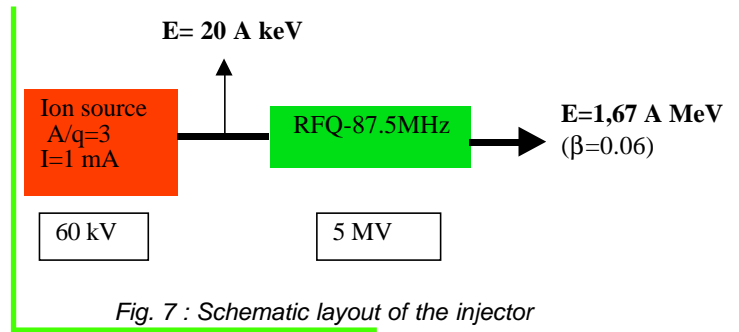


Fig. 7 : Schematic layout of the injector

IV d) THE SUPERCONDUCTING LINEAR ACCELERATOR.

In a cavity optimised for a given β_0 [ref. 13] the energy gain of an ion with a given q/A and a given velocity β is:

$$\Delta W = \frac{q}{A} * E_a L_a \frac{T(\beta)}{T(\beta_0)} \cos \phi_s$$

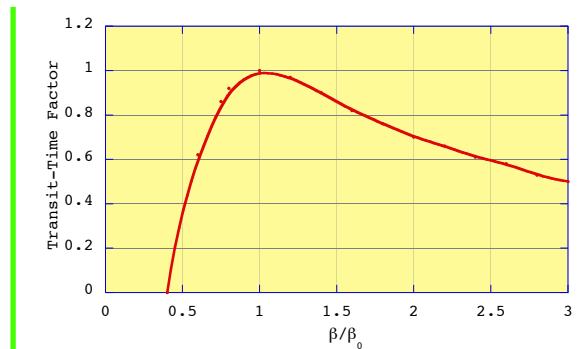


Fig 8 : Transit-time factor for a 2 gap cavity

The transit-time factor $T(\beta)/T(\beta_0)$ is represented on figure 8.

The superconducting linear accelerator will accelerate ions from 1.67 A MeV to 100 A MeV, with a final magnetic rigidity of 4.43 Tm. An optimum scheme could be composed of 4 types of cavities with $\phi_s = 20^\circ$.

Mhz	β
175	0.08
262.5	0.15
350	0.25
350	0.35

The National Laboratory of Legnaro has developed and tested such cavities [ref. 14]. Accelerating fields around 6-7 MV/m have been obtained (with a cryogenic power of 7W per resonator), which corresponds approximately to an acceleration of 1 MV per cavity. With these characteristics we obtain the structure of the accelerator as given in table 1.

Considering the “Legnaro ” scheme, with cryogenic modules containing four cavities and one superconducting solenoid for focusing, the present project results in a total of 76 modules with an approximate total length of 152 meters. The length might be reduced, if the number of solenoids can be decreased above an energy value to be defined . In this case, we could have modules containing 6 or even 8 cavities, instead of 4.

Cavity type	Energy range (A.MeV)	β range	Number of cavities
175 MHz $\beta=0.08$	1.67 à 7	0.06 à 0.12	18
262.5 MHz $b=0,15$	7 à 21	0.12 à 0.21	47
350 MHz $b=0,25$	21 à 63	0.21 à 0.35	140
350 MHz $b=0,35$	63 à 100	0.35 à 0.43	100
TOTAL NUMBER			304

Table.1 : Total number of cavities with the transit-time factor given by figure. 8

Such a machine is very acceptant. With adapted injectors, A/q larger than 3 could also be accelerated in good conditions. The energy diagram of the superconducting linear accelerator is presented in Fig.9.

IV e) IMPLEMENTATIONS.

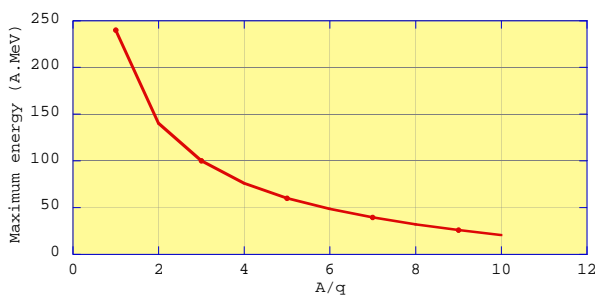


Fig 9 : Maximum energy versus A/q

The whole accelerator requires a building with dimensions of approximately 100m by 25m, similar to the GANIL power supply building. The biological protections need to be calculated. By construction, the beam losses in the superconducting linear accelerator will have to be very low, thus heavy protections are mainly needed at beam dumps.

This building could be implemented in the North-West side of GANIL cyclotron building, with appropriate connections to the existing experimental areas Fig.10 [ref : 22]. Here we show a possible implementation for an intermediate phase, corresponding to 40MeV deuterons. The full project could correspond to a prolongation of this building. Implementation must be optimised with respect to physics program.

IMPLEMENTATION

of the first stage (40 MeV deuterons)

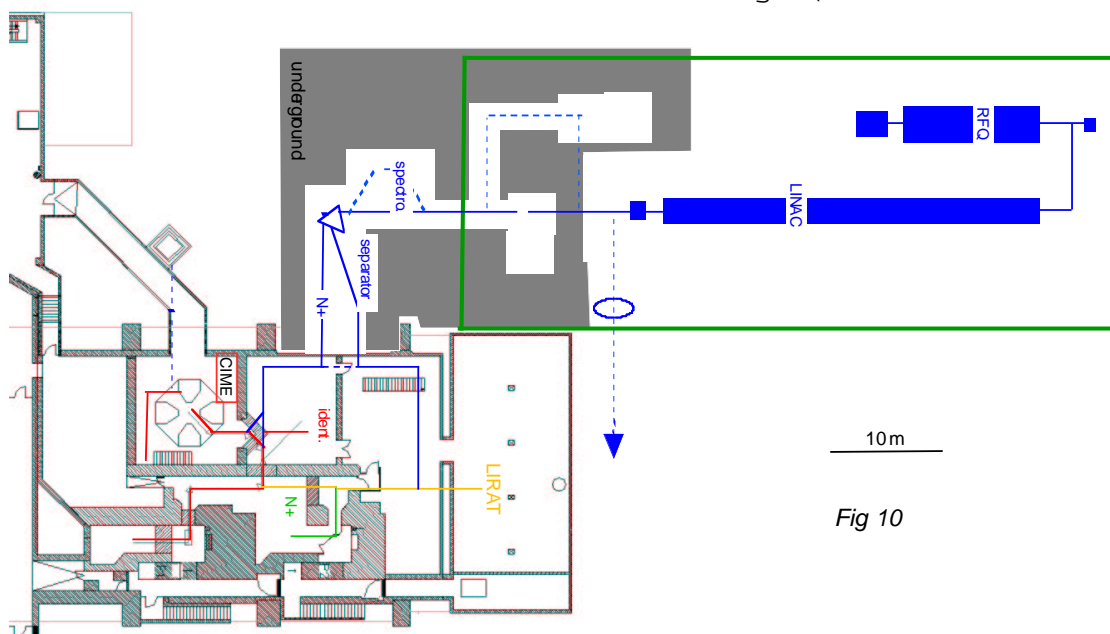


Fig 10

IV f) PRELIMINARY COST ESTIMATION (without buildings, transport lines, and target station):

The cost estimates given below (table 2) are mostly based on Legnaro estimations made for a 100mA accelerator, corrected for the high RF power needed in the present project.

One possible capital investment plan is given in table 3 and 3bis. T0+4 correspond to the first, low energy phase discussed below. The first beam produced at this stage with protons of 35 MeV, deuterons of 40MeV and A/q=3 of 14.5 A MeV could be delivered at T0+4.

EQUIPMENT	COST (M€)
SOURCE	0.76
RFQ	4.57
LINEAR ACCELERATOR	
ONE MODULE <-> 4 MV (4 cavities+1 solenoid)	0,69
76 MODULES	52.44
ADDED COST FOR RF POWER FOR 10mA protons->35 MeV	3.05
ADDED COST FOR RF POWER FOR 1mA->100 A.MeV	6.86
CRYOGENIC PLANT	9.15
CONTROLS (5% total)	3.35
TOTAL with 20% margin	96.2

Table 2

Time in years	T0	T0+4	T0+5	T0+6	T0+7	T0+8	T0+9	T0+10	T0+11	T0+12
Source + RFQ										
Cryogenic plant				3.05			3.05			
accelerator modules			6,33	6,33	6,33	6,33	6,33	6,33	6,33	7,90
Controls						1.83				
Total cost per year			6,33	9.38	6,33	8,16	9.38	6,33	6,33	7,90
Accumulated cost,no margin		19.8	26.13	35,51	41.84	50	59.38	65,71	72,04	79,94

Performances

q/A=1/3 energy (A.MeV)		14,5	24,5	36	45,6	55,8	65,5	76	86,5	99,6
Deuteron energy (A.MeV)		20,3	34,3	50	64,8	78,7	91,9	106,8	121,9	140,1
Proton energy (MeV)		34,6	58,7	96,4	111,5	135	157,4	193,6	209,8	241,3

Time in years	T0	T0+1	T0+2	T0+3	T0+4
RFQ			4.57		
Source		0.38	0.38		
Cryogenic plant		1.52	1.52		
accelerator modules		3.81	3.05	3.05	
Controls		0.76		0.76	
Total cost per year		6.47	9.52	3.81	
Accumulated cost,no margin		6.47	15.99	19.8	

Table 3 and 3 bis

Capital investment (in M€) per year..

Expanded details concerning the first four years are given in lower part of the table.

Total investment without building, beamline, target station	96.2 M€ with 20% margin
Investement for the first phase (see paragraph V)	19.8 M€

Remark-1: An alternative intermediate solution has been considered, using IPHI [ref. 15], in order to accelerate protons up to 35 MeV in a first step. This leads to an intermediate cost of 14.8 M€, instead of 19.8 M€ without IPHI, but the final cost of the whole accelerator would be increased by approximately 4.57 M€.

Remark-2: In the case where the proposed RFQ would present some technical difficulty to be realised, an alternative solution for the accelerator would be to limit the RFQ exit energy to 0.75 A.MeV. (equivalent accelerating voltage: 2.25 MV instead of 5 MV, same frequency) In those conditions, a supplementary type of low β cavities would be necessary for the superconducting linear accelerator, and the following scheme would be obtained (table 4).

Cavity type	Energy range (A.MeV)	β range	Number of cavities
87.5 MHz $\beta=0.05$	0.75 to 3.48	0.048 to 0.086	8
175 MHz $\beta=0.08$	3.48 to 7.20	0.086 to 0.124	12
262.5 MHz $\beta=0,15$	7.20 to 22.55	0.124 to 0.216	48
350 MHz $\beta=0,25$	22.55 to 67.26	0.216 to 0.361	140
350 MHz $\beta=0,35$	67.26 to 99.84	0.361 to 0.433	100
TOTAL NUMBER			308

Table 4.

The total cost of the superconducting cavities should not be affected much, and the RFQ study and construction would be simpler (and safer).

IV g) Flexibility of a linear accelerator.

An independent superconducting cavity linac is flexible, and with a rather simple modification, it can be divided in 2 parts and be used simultaneously as a driver for $A/q=3$, and as a post-accelerator for larger A/q .

Example: driver for $A/q=3$ up to 36.5 A.MeV and post-accelerator for $A/q=6$ up to 24 MeV/A from the original linac defined by: Injector: RFQ with an energy exit =0.75 A.MeV

Cavity type	Energy range (A.MeV)	b range	Number of cavities
175 MHz $\beta=0.08$	0.75 to 7.20	0.048 to 0.124	20
262.5 MHz $\beta=0,15$	7.20 to 22.55	0.124 to 0.216	48
350 MHz $\beta=0,25$	22.55 to 67.26	0.216 to 0.361	140
350 MHz $\beta=0,35$	67.26 to 99.84	0.361 to 0.433	100
TOTAL NUMBER			308

Table 5.

By adding 20 cavities more (10 cavities $\beta=0.08$ and 10 cavities $\beta=0.15$), an appropriate injector for $Q/A=1/6$ giving an energy of 0.75 A.MeV, and some supplementary focusing elements, the following scheme can be obtained (see figure 10):

plementary focusing elements, the following scheme can be obtained (see figure 10):

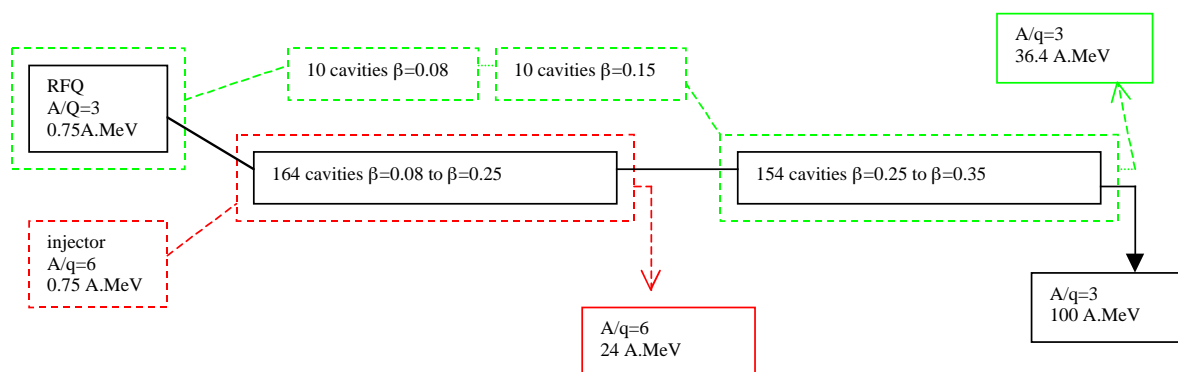


figure 10 : example of simulyaneous use as driver and post accelerator.

V-A possible intermediate construction phase at an acceleration potential of 40MV

V a) General considerations on the production of RIB at low energy using a converter

As has been seen in the preceding section, and as is inherent in the scheme of a linear accelerator, the construction can be divided into sections. After full construction, these sections may serve as beam outputs for different energy domains.

Here we want to consider an intermediate step at an acceleration potential of about 40MV. This corresponds to protons of 35MeV, or deuterons of 40MeV (see above, section IV). Quantitative evaluations of production rates of radioactive ions using a converter have been done in various reports [ref. 8, 16,17,18].

We illustrate the findings by the relation between the beam intensity necessary to produce 10^{13} fissions/s and the incident energy, shown on figure 10. The converter considered is Li, and the production geometry is the one with the use of UCx of [ref. 19]. A proton beam of 10mA and 350kW power, and deuteron beam of 5mA and 200kW at 40MeV, respectively are assumed. In the case of the use of IPHI as an intermediate solution, only protons would be available, (eventually at higher intensity, IPHI being designed for 100mA of protons). At the low energy considered there is a strong quantitative difference between protons and deuterons as projectiles, and Li, Be and C as targets. This is considered in some more detail below.

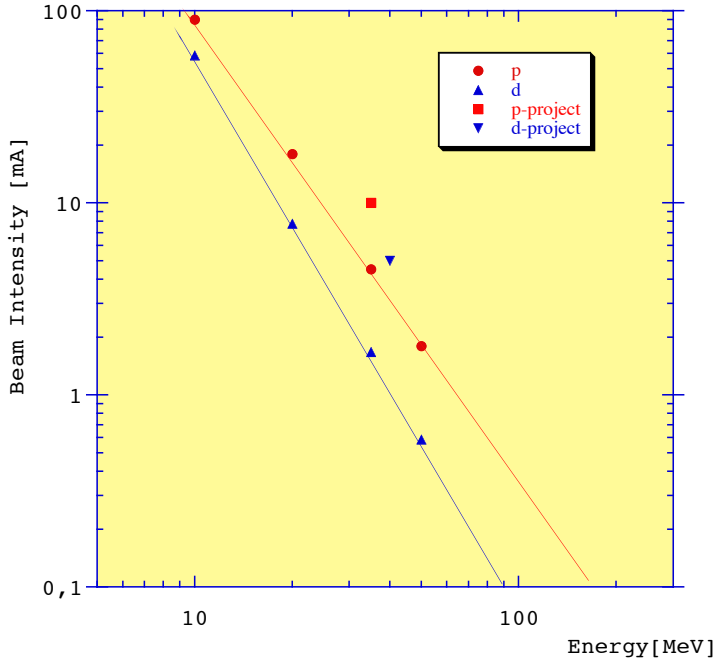


Figure 10: Beam intensity needed to induce 10^{13} fissions/s as a function of energy for protons and deuterons on a Li converter, in the geometry as described by [ref. 19]. Note that yields depend on the geometry and the quantity of fissile material. Here UCx (3kg) and a Li converter were assumed. The energy and the intensity of protons and deuterons are indicated for the first phase of the project.

V b) Protons or deuterons on Li and C converter

At low energy, one way to produce very high fission yields with p or d beams is to use a converter in order to avoid high power dissipation in the target. One important feature is then the neutron production at forward angles, because these are the neutrons that induce the fission. We will limit our discussion here to the energy domain of 30-50MeV. Preceding calculations were done for a Li target; Be can be shown to be more or less equivalent for neutron production, whereas C provides fewer neutrons at forward angles particularly for protons. Table 6 summarises these findings more quantitatively.

	Protons		deuterons	
	0-30deg	4π	0-30deg	4π
${}^7\text{Li}$	0.006	0.027	0.012	0.034
${}^9\text{Be}$	0.005	0.027	0.011	0.037
${}^{12}\text{C}$	0.0003	0.002	0.006	0.012
${}^{13}\text{C}$	0.003	0.019	0.008	0.027

Table 6: Calculated thick target neutron yield in units of neutrons/incident particle. The particle energy is 35MeV. The first column for each beam corresponds to the forward angle domain (0-30deg), the second to the yield over 4π solid angle. [ref. 15 and private communication].

As can be seen from the table 5, there is no very strong target dependence of the neutron yield in the case of a d beam. In the case of protons, ${}^{12}\text{C}$ gives very low yields, and ${}^{13}\text{C}$ should be used.

Two main methods may be considered for converters stopping high-power (<1MW) low-energy beams:

-A windowless liquid Li target. Such a target has been constructed at Argonne,[ref. 20] for MW power dissipation. For much higher power, (i.e.10MW), such targets are part of the IFMIF project [ref. 7]. In our context of much lower power dissipation (350kW and 200kW for protons and deuterons respectively) costs and security constraints would have to be evaluated.

-A fast rotating target. This target is very similar to that of the thin target production method involving heavy ions, as discussed in section II.a. It is shown that it should be possible to dissipate powers up to 0.5MW in such type of targets. In the case of converters, C seems to be the most resilient material. ${}^{13}\text{C}$ could be considered as target material, because only a limited quantity is necessary, of the order of 0.5kg in the geometry considered. If natural C is used, this strongly favours the use of deuterons in this energy domain.

These considerations show that there is no technical impossibility concerning the high power target-converter, for protons as well as for deuterons. However, optimisation of yield and cost-effectiveness may result in a preference for one of the beams.

With the intensities cited above and in the converter-production ion source geometry considered, fission rates of the order of 10^{13} to 10^{14} /s could be reached with a heat production limited to the fission energy, this is 0.3 to 3kW. In the converter-target geometry of the RTD project report SPIRAL II of M.G. Saint Laurent et al [Ref : 18], with a C converter and 360g of UCx material, 4.5mA of 40MeV deuterons would be necessary to produce 10^{13} fissions/s, well within the range of projected intensities.

Note that in the prospect of higher energies as future evolution, the range increases with E^2 . Thus production luminosity will increase by roughly 1 to 2 orders of magnitude going from this intermediate stage to the final projected energy.

Vc) Direct target method

Fission induced directly by deuterons, without converter, may be advantageous, because it requires only small quantities of target material. With the fission cross-section induced by protons or deuterons of 1.5mb [ref. 21] and the useful range of about 2g/cm², this results in 1×10^{13} fissions/s for a beam of 0.33mA, corresponding to 12kW. In this case, the target material mass could be as low as 10g. However 12kW of heat would have to be removed from the target-ion source.

Vd) Use for near Coulomb Barrier Physics.

This intermediate construction step with a 40MV acceleration potential, leads for $A/q=3$ to 14.5 A MeV, an energy sufficient for all near-barrier physics. This would allow users to do fusion-evaporation physics, like high spin physics. Remember that beam intensities of 1mA would be available with appropriate ion sources. This would permit research in the domain of low cross-section phenomena, such as formation of super heavy elements. The very high intensity would allow the production of rare fusion-evaporation products in thin targets. Coupled to with an appropriate separator, this could provide a mean of producing secondary beams for decay properties and reaction studies.

V e) Cost estimation and time schedule of the 40MV intermediate phase.

Table 7 gives an estimation of a time and cost schedule of this intermediate phase. T_0 is the time of decision of construction and founding. The first beam can be expected 4 years later. The cost includes building and target ion source station, without margin.

Time in years	T0	T0+1	T0+2	T0+3	T0+4	Total
Accelerator (see Table 3bis)	Technical study	6.47	9.52	3.81		19.8
Target/Source	Technical study	Technical study	3.04	3.04		6.08*
Bulding	Technical study	3.35				3.35*
Beam lines	Technical study	1.07	1.07	1.22		3.36*
Radioprotection	Technical study	Technical study	0.61	0.61		1.22*
Miscellaneous		0.3	0.3	0.3		0.9
Total cost per year		11.19	14.54	8.98		
Accumulated cost,no margin	0.3	11.49	26.03	35.01		

Table 7 : Total cost estimates including building, target/source, beam lines, etc.

* : Values from [ref. 21].

VI. Conclusion.

We have shown that modern linear accelerator techniques together with high intensity ion sources delivering high charge states, can provide an outstanding opportunity for GANIL to upgrade its research facilities in its domain of excellence. The linear accelerator proposed in this document would be able deliver beams of several hundreds of kilowatts from protons (6×10^{16} particles/s) up to heavy ions with $A=100$ (2×10^{14} particles/s).

The final project would provide an increase of more than 2 orders of magnitude over the present primary beam intensities. For secondary beams, obtained by the thin target method (fragmentation), together with a modern fragment separator, this would result in an increase of 3 to 4 orders of magnitude for fragmentation products. For secondary beams obtained by the thick target method (ISOL) or a combination of these two methods, the intensity would be increased more than two orders of magnitude. Moreover, all techniques already developed and presently applied at GANIL could be directly used in the new facility, provided the correct scaling would be done.

An intermediate stage of moderate size would provide the exploitation of the accelerator from the 4th year of construction. This initial stage would provide the following opportunities:

a) Production of fission products by protons or deuterons; three methods could be used, probably in a complementary way:

- Production of fission fragments by fast neutrons from a converter, decoupling the primary beam from the source of fission products. Up to about 10^{13} fissions/s

could be obtained with small quantities of UCx(360g), For bigger target volumes up to about 10^{14} fission/s could be expected.

- Production of fission fragments by direct bombardment of fissile material by protons or deuterons. This can produce about 1.10^{13} fission/s for a 12kW power dissipation, a number very similar to that for photo-fission.

- Production of fission fragments by neutrons from a converter hitting a thin target in a He gas using IGISOL techniques. Very fast extraction would be possible for all chemical elements.

b) The physics domain from below the Coulomb barrier up to several times the barrier (14.5 A MeV) could be covered. The high intensity would give access to domains of very low cross-sections, such as the production of super heavy elements.

c) The very high intensity would allow the production of rare fusion-evaporation products in thin targets. Coupled to an appropriate separator, this could provide a mean of producing secondary beams for decay properties and reaction studies.

The realisation of such a project would provide a versatile instrument covering a broad range of physics in a large energy range. It offers the possibility of a construction in complementary parts. The overall cost of such project is naturally quite high. It will have to be integrated in the European and International context.

Acknowledgment : The authors thanks for fruitful discussions with A.Chabert (GANIL), and J.M.Lagniel (SEA-CEA)



Annexe

I- Comparative study between a high energy proton and a light and heavy ion driver for Isol beams

For this comparative study, data from the NSAC task force on Radioactive Ion Beam are available on the web site of the task force [22] and has been collected by Paul Schmor (Triumf) from different sources/specialists over the world. In this document are considered thick target method (ISOL) yield using the following accelerators:

- 1- 1 GeV proton accelerator with 100 μ A of beam intensity, corresponding to a maximum of 100kW beam power, called HE proton.
- 2- 100 A MeV light and heavy ion accelerator with maximum intensity corresponding to the same 100kW of beam power, called Heavy ion.

The maximum intensity on different targets has been limited, in some cases, according to present knowledge on chemical properties, heat resistance and the maximum expected heavy ion intensities within the next 5 years. The final RIB intensities of a hypothetical final project can be taken directly from this table, multiplying the RIB yield by the hypothetical maximum intensity available in the future. In the case of heavy ions, the present proposed facility would be able to accelerate up to 300 kW, instead of 100kW. Therefore, the final intensities of the proposed facility will be a factor 3 higher than the numbers we quote from the reference [23].

Five cases can be taken as typical examples of these tables. The final yields take into account diffusion, effusion and ionisation to 1^+ charge state.

1- Production of ^{11}Li :

With 1GeV protons on UC target of 1000cm^3 volume, the production yield is 3.7×10^6 pps.

With ^{18}O on a two step target (Li + C), of 4cm^3 volume, the production yield would be of 1.4×10^8 pps.

The heavy ion driver has an advantage of a factor 30 for this short lived isotope.

2- Production of ^{37}K :

With 1GeV protons on CaO target with 1000cm^3 volume, the production yield would be of 2.4×10^{12} pps.

With 0.2GeV protons on CaO target with 900cm^3 volume, the production yield would be of 1.1×10^{13} pps.

The heavy ion driver used for the acceleration of protons has an advantage of a factor 4.

3- Production of ^{52}Ni :

With 1GeV protons on ZrO_2 target with 1000cm^3 volume, the production yield would be of 8.3×10^{-2} pps.

With ^{58}Ni on a two step target + gas catcher (Li + He), the production yield would be of 5.4×10^3 pps. The gain in favour of a heavy ion driver (a factor 10^4) is clear for this short lived isotope, mainly due to the fast extraction in the gas catcher. An efficiency of 6% was assumed for the gas catcher.

4- Production of ^{132}Sn :

With 1GeV protons on UC target with 820cm^3 volume, the production yield would be of 2.2×10^{10} pps. With 0.2GeV deuterons on a W converter followed by a UC target of 180cm^3 volume, the production yield would be of 1.4×10^{11} pps. The heavy ion driver used for the acceleration of deuterons has an advantage of a factor 6.

5- Production of ^{227}Fr :

With 1GeV protons on ThC target with 820cm^3 volume, the production yield would be of 7.6×10^{10} pps. With 0.44GeV ^3He on ThC target with 360cm^3 volume, the production yield would be of 7.2×10^{10} pps. The yields are similar in this case.

A more general analysis of this table leads to the following qualitative conclusions :

HE protons are favoured in the region close to the stability and heavy ions far from stability. This is mainly due to the use of different techniques. With heavy ions the problems of beam power deposition and the release out of the target can be de-coupled, minimising losses for nuclei of short lifetimes. For the HE protons, the larger range results in higher in-target production of radioactive nuclei, providing higher final yields for long lifetimes.

Heavy ions are clearly advantageous if one takes into account the fact that the heavy ion driver can be used not only for thick target (ISOL), but also for thin target (In-Flight) method. The thin target method allows to have energetic RIB in the energy range of 20 to 100 A MeV without re-acceleration. The method is extremely fast (less than $1\mu\text{s}$), allowing to produce beams very far from stability, with very short lifetimes. In addition, there is no chemical selectivity.

II - Comparison with the project of GSI.

The projected maximum primary beam intensity of GSI is 1.0×10^{12} pps from protons to Uranium at 1.0A GeV.

Supposing a spectrometer with large angular acceptance, and a given momentum acceptance, the yield increases approximatively proportional to the range. This would give a factor 40 higher yield per incident particle. In the solution proposed in the present document, the primary beam intensity is of the order of 10^{15} pps for ^{18}O and 3×10^{14} for ^{40}Ar . The final RIB intensity of the present proposed facility is more than one order of magnitude higher than the future GSI project in the mass region $A < 100$. Moreover, the energy region covered by both accelerators is different. The GSI project is not yet funded.

III - Comparison with RIKEN factory.

The primary beam intensity of the RIKEN RI beam factory is, at least, one order of magnitude smaller than the one of the present proposed facility. No thick target production method is proposed at RIKEN, therefore, no low energy high quality beam would be available. The first phase of the RIKEN RI beam factory is under construction.

References :

- | | |
|---|---|
| <p>1 : Long term plans in the study of atomic nuclei. Hors série nouvelles du GANIL</p> <p>2. http://www.ganil.fr/eurisol</p> <p>3 : http://www.nscl.msu.edu</p> <p>4 : adapted from R. Bennett and A.C.C. Villari, FINA report (2001)</p> <p>5 : R3B research project, see e.g the report by A. de Vimes</p> <p>6 : http://www.lanl.gov</p> <p>7: http://insdell.tokai.jaeri.go.jp/IFMIFHOME/ifmif_home_e.html</p> <p>8 : C.Lau, Thesis, IPN Orsay, Note IPNO T000-08</p> <p>9 : L. Maunoury et al. , preprint Ganil (Ganil S 01 02)</p> <p>10 : 12th ECRIS conference (1995)</p> <p>11 : C.Barué, private communication.</p> <p>12 : Discussion with J-M Lagniel et B.Aune from SEA-</p> | <p>DAPNIA-CEA</p> <p>13 : Rapport GANIL R 92 04- A.Chabert</p> <p>14 : A.Facco Presentation at Eurisol meeting held in Legnaro on 27th February-</p> <p>15 : http://cern.web.cern.ch/CERN/Divisions/PS/Linac96/Proceedings/Monday/MOP58/Paper.html</p> <p>16 : D.Ridikas Thesis, Caen 1999 GANIL – T 99 04</p> <p>17 : D.Ridikas and W.Mittig, GANIL P 98 22.</p> <p>18 : M.G.Saint Laurent, report on the RTD Spiral2, 2001</p> <p>19 : D.Ridikas, A.C.C.Villari, and W.Mittig, report to the scientific council of GANIL, 2000</p> <p>20 : http://srfsrv.jlab.org/isol/ISOLTaskForceReport.pdf</p> <p>21 : J.P.C.Stevenson et al.,Phys.Rev.111(1958)886</p> <p>22 : F.Loyer (private communication)</p> <p>23 : http://srfsrv.jlab.org/ISOL</p> |
|---|---|

IV - Comparison with RIA.

Beam intensities proposed for RIA are similar to those in the present document. The factor 4 higher energy in the RIA project is compensated to a good part by the factor 3 higher beam intensity in the present project. The high energy U-like fragmentation, which could be covered in the RIA approach, would not be accessed in the present project. The projectile fragmentation of very heavy ions would be covered, in Europe, by the GSI new project for the thin target method. RIA is not yet funded.