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OPERATION STATUS OF HIGH INTENSITY ION BEAMS AT GANIL

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Abstract

The Grand Accélérateur National d'Ions Lourds (GANIL, Fig. 1) facility (Caen, France) is dedicated to the acceleration of heavy ion beams for nuclear physics, atomic physics, radiobiology and material irradiation. The production of stable and radioactive ion beams for nuclear physics studies represents the main part of the activity. Two complementary methods are used for exotic beam production: the Isotope Separation On-Line (ISOL, the SPIRAL1 facility) and the In-Flight Separation techniques (IFS). SPIRAL1, the ISOL facility, is running since 2001, producing and post-accelerating radioactive ion beams. The running modes of the accelerators are recalled as well as a review of the operation from 2001 to 2008. A point is done on the way we managed the high intensity ion beam transport issues and constraints which allows the exotic beam production improvement.

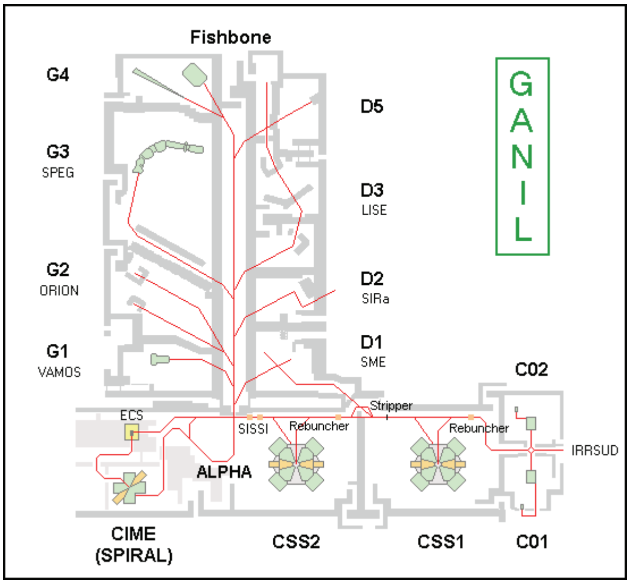


Figure 1: GANIL layout.

RUNNING MODES

Multibeam delivery is possible at GANIL. Using its 5 cyclotrons GANIL-SPIRAL is increasingly a multi-beam facility. Up to four experiments can be run simultaneously in different rooms with stable beams:

- Using the beam of C01 or C02, an irradiation beam line IRRSUD works with 1 MeV/A.
- Using one charge state of the ion distribution downstream CSS1 after the ion stripping, a line uses ion in the range 4-13MeV/A beams, for atomic physics, biology, solid states physics.
- A high-energy experiment.
- An auxiliary experiments sharing the CSS2 beam
- Additionally, the cyclotron CIME (SPIRAL post-accelerator) delivers stable beams for detector tests for example.

During radioactive beam production, no more than three experiments are working simultaneously.

Intense Primary Beams

The facility delivers a wide spectrum of high intensity ion beams ranging from ^{12}C to ^{238}U accelerated up to 95MeV/A as a function of their masses. The acceleration scheme lies on the use of three cyclotrons in line. One compact (C01 or C02, K=30) and two separated sector cyclotrons (CSS1 and CSS2, K=380). Those accelerators and beamlines have been adapted to transport intense ion beams. More than 10 beams are available at a power exceeding 1 kW (Table 1) over 50 stable beams available from the GANIL sources [1]. The beam losses detectors, beam transformers and control system allow the transport of intense stable beams with power exceeding 3 kW in routine operation.

Table 1: Some of the GANIL High Intensity Beams, the main Limitation Come now from the Target Ability to Withstand the High Power Density

Beams	**Imax [µAe]**	**10^{13} [pps]**	**Emax [MeV/A]**	**Pmax [W]**	**Used with Spiral**
$^{12}C^{6+}$	18	1.9	95	3 200	
$^{13}C^{6+}$	18	2.	80	3 000	X
$^{14}N^{7+}$	15	1.4	95	3 000	
$^{16}O^{8+}$	16	1	95	3 000	X
$^{18}O^{8+}$	17	1	76	3 000	X
$^{20}Ne^{10+}$	17	1	95	3 000	X
$^{22}Ne^{10+}$	17	1	79	3 000	
$^{36}S^{16+}$	6.4	0.25	77.5	1100	X
$^{36}Ar^{18+}$	16	0.55	95	3 000	
$^{40}Ar^{18+}$	17	0.6	77	3 000	
$^{48}Ca^{19+}$	4-5	0.13	60	600-700	X
$^{58}Ni^{26+}$	5	0.12	77	860	
$^{76}Ge^{30+}$	5	0.12	60	760	
$^{78}Kr^{34+}$	7.5	0.14	70	1200	X
$^{124}Xe^{46+}$	2	0.03	53	300	

Secondary Exotic Beams

Exotic beams are produced with two complementary methods. ISOL method with SPIRAL where the primary beam is fragmented in a thick carbon target. The fragments produced are post-accelerated with the cyclotron CIME from 1.2 to 25 MeV/A (Table 2).

Table 2: Radioactive Beam Produced and Post-accelerated from 2001 to 2006. W in [MeV/A]

ions	W	[pps]	ion	W	[pps]
^{18}Ne	7	10^{6}	^{31}Ar	1.45	1.5
^{8}He	15.5	10^{4}	^{6}He	5	3.10^{7}
^{8}He	3.5	10^{5}	^{8}He	15.4	2.10^{4}
^{24}Ne	4.7	2 10^{5}	^{8}He	3.9	8.10^{4}
^{74}Kr	4.6	1.5 10^{4}	^{8}He	3.5	6.10^{5}
^{8}He	15.4	1.5 10^{4}	^{18}Ne	7	10^{6}
^{8}He	15.4	9 10^{3}	^{24}Ne	10	2.10^{5}
^{24}Ne	10	2 10^{5}	^{26}Ne	10	3.10^{3}
^{8}He	15.4	2.5 10^{4}	^{44}Ar	10.8	2.10^{5}
^{15}O	1.2	1.7 10^{7}	^{46}Ar	10.3	2.10^{4}
^{24}Ne	7.9	1.4 10^{5}	^{74}Kr	2.6	1.5.10^{4}
^{33}Ar	6.5	3 10^{3}	^{76}Kr	4.4	6.10^{5}
^{6}He	3.8	2.8 10^{7}	^{75}Kr	5.5	2 10^{5}
^{8}He	15.4	2.5 10^{4}	^{44}Ar	3.8	3 10^{5}
^{35}Ar	0.43	4 10^{7}	^{6}He^{2+}	20	5 10^{6}
^{6}He	2.5	3.7 10^{7}	^{6}He^{1+}	Lirat	2 10^{8}

And by the In flight method with SISSI (Superconducting Intense Source for Secondary Ions) [5] consisting of fragmenting the intense primary beams onto a rotating target. The exotic cocktail beam after the target is purified with the alpha spectrometer and sent to the experimental area.

Since October 1994, SISSI produces secondary radioactive beams. A 0.4mm diameter spot is created on a thick rotating target with a superconducting solenoid with a maximum field of 11 T. A second identical solenoid after the target improves the downstream beam line angular acceptance and thus increases the collection of the secondary exotic ions. The cooling system is provided by a circuit of liquid helium at 4.6 K. The target is a 2000 rpm rotating disk, so that the radiated heat is spread over a much larger area than the beam spot.

In June 2007, the second solenoid quenched and cannot be used. Therefore, a project have been launched to overview all possible solutions to produce secondary beams (alternative solutions, repairing) compatible with the operation schedule and resources. Meanwhile CLIM took over for physicists.

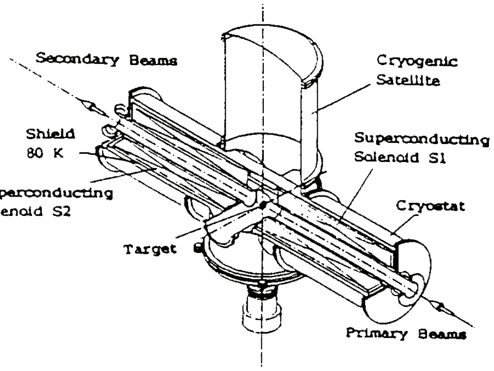


Figure 2: Schematic view of the cryostat of SISSI.

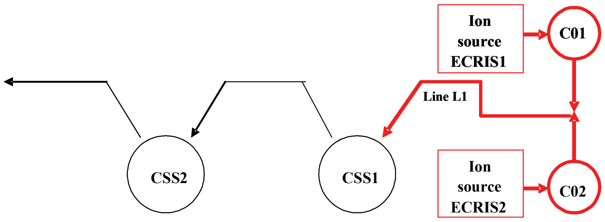
HIGH INTENSITY BEAM TRANSPORT

In 1995, a High Intensity Transport safety system (THI) was studied and validated in 1998 in order to allow sending a several kilowatt beam into the experimental rooms. The system protects equipment against the beam power loss. The safety regulation rules allow the GANIL to accelerate beam to a maximum of 2·10^{13} ions per second or 6 kW out of CSS2. Within those limits, uncooled or unshielded elements may melt very rapidly and must be protected by a safety system.

The machine tuning uses three modes to increase beam power transportation.

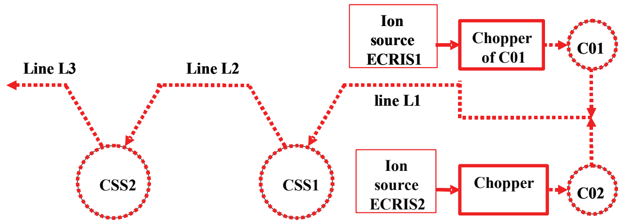
Injector Mode

This mode allows the acceleration of an ion beam with a maximum beam power < 400 W up to the injection of CSS1.



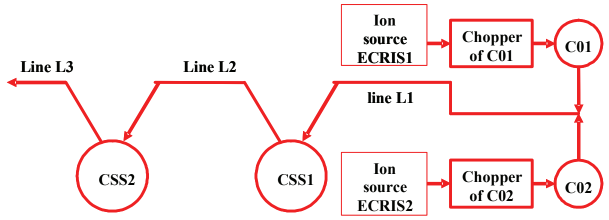
Tuning Mode

By using of a chopper to reduce the mean beam intensity (equipment protection) and keeping the crest intensity identical (space charge limitation) a 400 W beam can be tuned overall the machine.



Watching mode

The high power beam (up to 6 kW) is reached in this mode by reducing the chopping rate and monitoring the safety system controls beam losses presented in [3] and [4].



A 26 µAe (5 kW) for ^{36}Ar at 95 MeV/A has been successfully accelerated.

2001-2008 SPIRAL STATUS

For the production and acceleration of radioactive ions with the ISOL method, the stable heavy ion beams of GANIL are sent into a target and source assembly. The radioactive atoms produced by nuclear reactions are released from the target, kept at high temperature, into an ECR source. After ionisation and extraction from the source (extraction voltage < 34 kV), the multi-charged radioactive ions are accelerated up to a maximum energy of 25 MeV/A by the compact cyclotron CIME (K=265). The first SPIRAL beam delivered to the physics was ^{18}Ne in October 2001. Since, more than 30 radioactive beams were produced in 8500 hours of SPIRAL operation over 23600 hours of total beamtime delivered to nuclear physics experiments.

Fig. 3 shows the time repartition between SPIRAL and GANIL beams over 8 years.

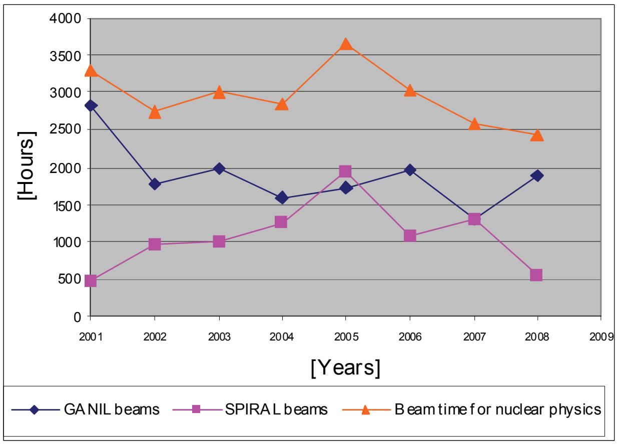


Figure 3: Beamtime shared over the years between GANIL beam (out of CSS) and SPIRAL1 beams (out of CIME).

Over the same period, the experience allowed reducing and optimizing the tuning time (Fig. 4) and meanwhile the number of tuned beams increased (Fig. 5).

A list of the radioactive beams [2] delivered is reported in Table 2.

More generally, the GANIL cyclotron delivers beam around 4000 hours a year (Fig. 6). The reduced time in 2008 is due to a shortened machine schedule of 4.5 weeks to allow technical staff to concentrate on SPIRAL2 construction.

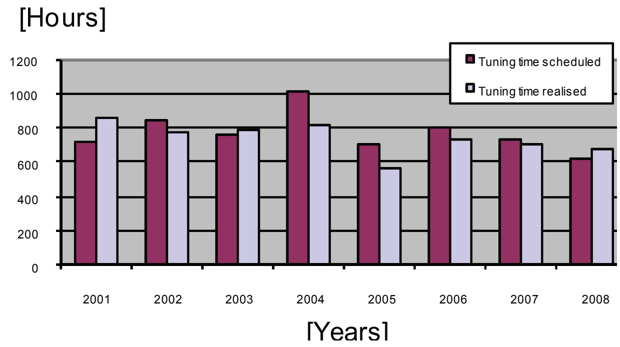


Figure 4: Tuning time.

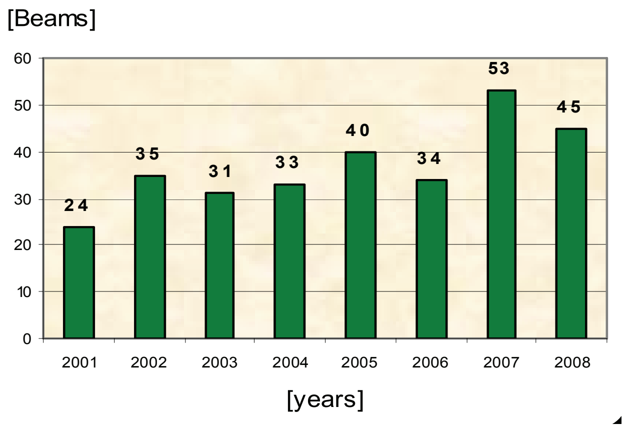


Figure 5: Number of beams tuned between 2001 and 2008.

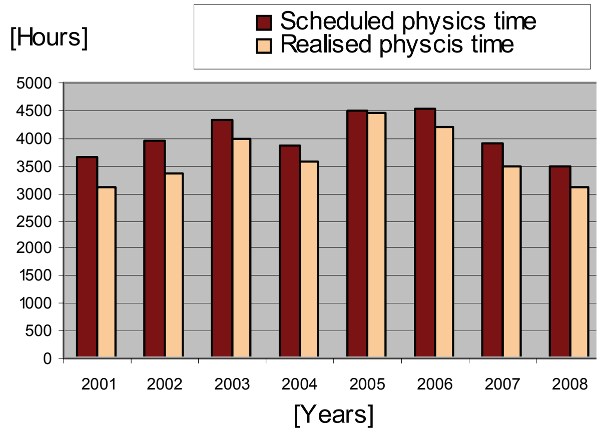


Figure 6: Schedule and realized machine running time.

FORSEEN MACHINE DEVELOPMENTS

The SPIRAL2 machine [7] will increase the capability of the GANIL. It is foreseen to some extend to use at the same time the new SPIRAL2 beams and the existing ones. Therefore, a GANIL 2015 committee was created to identify the strength and weakness of the actual facility for the close future [8]. One of the main recommendations of this committee is to extend the radioactive ion beam variety available from the SPIRAL1 facility. As the highest priority, the study of the modification needed for the insertion of a charge breeder out of the cave of SPIRAL1 is pointed out. Additionally, detailed studies to allow the high intensity beams of SPIRAL2 into specifically identified caves have to be carried out with very specific constraints from the radioactive beams. In the following is reviewed the evolutions machine-side to take into account the committee recommendations.

Most of the ions produced in SPIRAL are gases (He, O, Ne, Xe, etc.). The 1+/N+ ion source actually used cannot extract other species with an acceptable yield. Therefore, a modification of the couple target-source should be studied. Moreover, any modification of the existing irradiation cave implies a safety report inducing a time delay in the construction. It has been decided to study new sources that fit in the existing environment (plugs, power supply connections, remote handling, etc.). In addition, it becomes obvious that the choice of the source type will be done between two types:

- Compact 1+/N+ : Alkali source
- 1+ source in the cave and a charge breeder (N+) outside of the cave.

Compact 1+/N: Alkali Source

In the framework of the production of radioactive ion beams by the isotope separator on-line (ISOL) method, a new system has been developed at GANIL/SPIRAL to produce multi-charged alkali ions. The principle, referred to as the “direct 1+/N+ method”, consists of a surface ionization source associated with a multi-charged electron-cyclotron-resonance ion source without an intermediate mass separator [6]. This new system has been tested on line using a ^{48}Ca primary beam at 60.3 MeV/A. The experimental evidence of the direct 1+/N+ process has been obtained for a potential difference between the two sources of 11 V, and with a 1+/N+ charge breeding efficiency of 0.04% for $^{47}K^{5+}$. This value is significantly lower than the value of 6% obtained for stable K ions with the standard 1+/N+ method.

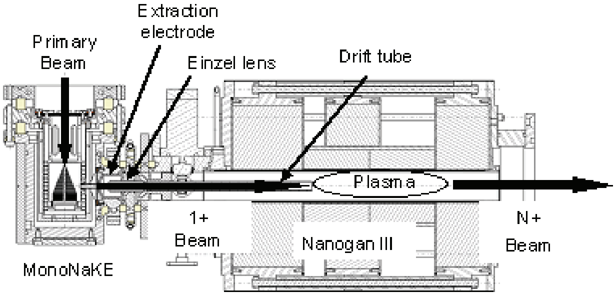


Figure 7: surface ionization source associated with a multi-charged electron-cyclotron-resonance ion source.

Charge Breeding for SPIRAL1

Another possibility to create new ion species and accelerate them through CIME cyclotron is to implement a 1+ source in the irradiation cave. The atom produced during the fragmentation of the primary in the carbon target of SPIRAL is ionized only once by an ion source. The final higher charge state necessary to accelerate it through the cyclotron is done via a so-called charge breeder outside the cave. The interest of such a solution is that the reduced source dimension compared to ECR source is kept compatible with the cave mechanical constraints due to their compactness.

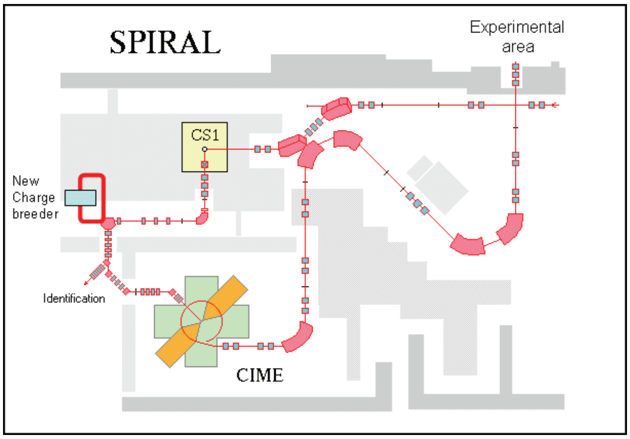


Figure 8: Possible SPIRAL1 low energy beam modifications to insert a new charge-breeder.

Intensity Increase (primary and secondary Beams)

The increase of the ion beam intensities is still possible for the primary stable beams and the exotics beams as well. We recall the safety regulation limitations: $2{\cdot}10^{13}$ ions per second or 6 kW out of CSS2 and $5{\cdot}10^{11}$ ions per second out of CIME. It appears that already few beams reach or are close to reach these limits, mostly light ion species (Table 1). Nevertheless, significant improvements are possible for heavy ions. A GANIL Test Source (GTS) exists and is under commissioning until the middle of 2010. Its installation on a machine platform is technically possible and will be decided then. The Table 3 recalls the gains expected along the acceleration chain by increasing the production at the source.

Table 3: Expected Intensity and Energy Gains by Implementing the GTS Source

Gains	**Low energies**	**Middle energies (<13MeV/A)**	**High energies**
Intensities			
Light Ions	1 to 2	1 to 2	1 to 2
Heavy Ions	2 to 4	2 to 4	2 to 4
Very heavy Ions	10	10	10
Max Energies			
Light Ions	1 MeV/A for all ions	13.6 MeV/A for all ions	No gain
Heavy Ions			Possible gain
Very heavy Ions			

From the exotic beams point of view, the production is limited by the power that the carbon target can handle. Two target types exist: one for the ^{6,8}He production that

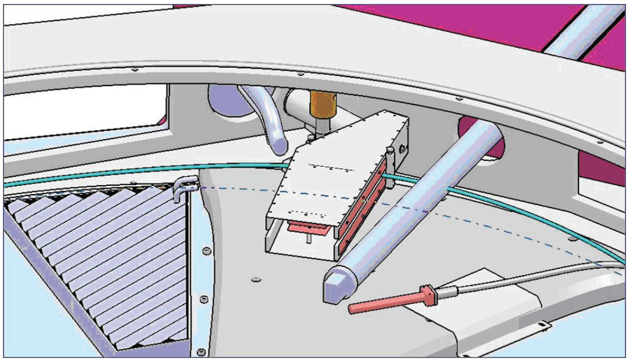


Figure 9: Electrostatic vertical deflector used to purify exotic beam from pollutant beam.

can handle 3kW beams and another limited to 1.5 kW for other ion species. The safety limitation to 6 kW beam shows a potential improvement of the production from 2 to 4. Nevertheless, preliminary study shows the increase of the target dimensions for higher power might reduce the diffusion of the created beam in the kernel target. The gain seems not to be linear with the power deposited. A working group is constituted to investigate this option.

Increase Beam Purity out of CIME

Even with a selective ECR source, the exotic ion beams created on SPIRAL1 might be polluted by ions with a ratio mass over charge close to the ion of interest and then be accelerated by the cyclotron CIME. The condition to eliminate an undesired ion corresponds at first order to:

$$\left[\frac{M_2}{Q_2}-\frac{M_1}{Q_1}\right]\bigg/\frac{M_1}{Q_1}>\frac{1}{2\pi\ H\ N_{turn}} \qquad (1)$$

where N_{turn} is the number of turns. Hence the mass resolution of a cyclotron is defined as $R = 1/2\pi\ H\ N_{turn}$.

Depending on the harmonic, the mass resolution of CIME can reach $2\cdot10^{-4}$. But even with this resolution beam tail may exit. The intensity of such beams does not need to be necessarily high to penalize the physics experiment. A elegant solution is to insert an electrostatic vertical deflector around the 10 last trajectory paths of the beam in the cyclotron. The amplitude of the sinusoidal electric wave between the deflector plates will be zero for the beam of interest (isochronous) and increase with the mass/charge ratio difference. The efficiency of such a device is measured and is able to reduce by a factor 10 beams $3\cdot10^{-4}$ far. This device will improve purity of the beam sent to the physics.

CONCLUSIONS

The first beam of GANIL was sent to an experimental room in 1983. Since then, the variety and intensity of the ion beams available always increased. Progresses in the source domain make possible to potentially transport of kW beams. The cyclotrons and the beam lines had to be upgraded to handle such a new constraint. In 2001, the first exotic beam of SPIRAL1 was produced with the existing cyclotron used as a driver. The exotic ion production was then depending on the target power resistance and the increase of the primary beam power. This leads to the developments of 3 kW target of SPIRAL1 and meanwhile increases the primary beam power within the safety rules (<6 kW).

The variety of the ion species is now the main concern at GANIL. The actual selective ECR ion source should be replaced by an alternative ion in order to access to metallic beams.

The great care given to the maintenance of the 25 year old machine allows us to still expect to increase its performances and be competitive until the SPIRAL2 arrival and afterwards.

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