POST-ACCELERATION OF HIGH INTENSITY RIB THROUGH THE CIME CYCLOTRON IN THE FRAME OF THE SPIRAL2 PROJECT AT GANIL

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Abstract

The cyclotron CIME is presently used at GANIL for the acceleration of SPIRAL1 radioactive beams. One of the goals of the SPIRAL2 project is to produce, post-accelerate and use in the existing experimental areas much higher intensity secondary beams induced by uranium fission like neutron-rich krypton, xenon, tin isotopes, and many others. Intensity may reach 10^{10} pps. Specific developments are needed for secondary beam diagnostics. Improvement of mass separation is also necessary, and the Vertical Mass Separator (VMS) is specially developed for this purpose.

However, the main concern is related to the high radioactivity linked to RIB high intensity. Safety and radioprotection issues will require modifications of the installation with special care for the maintenance of the cyclotron. The experience of the SPIRAL1 beams, in terms of beam losses and equipment contamination, is especially useful to define the necessary modifications.

INTRODUCTION

The SPIRAL1 facility is now operated since 9 years, so post-acceleration of radioactive beams at GANIL is now routine operation. The SPIRAL2 new facility will extend the possibilities offered to heavier radioactive beams, with much higher intensities, intense beams of neutron-rich exotic nuclei (10^6–10^{10}pps), in the mass range from A=60 to A=140 0. Extracted exotic beam will either be used in a new low energy experimental area called DESIR, or accelerated by means of the existing SPIRAL1 cyclotron (CIME). Post-accelerated beams will then be driven to existing experimental areas (figure 1).

The intense primary stable beams (deuterons, protons, light and heavy ions) will also be used at various energies for neutron-based research, nuclear physics and multi-disciplinary research, in new experimental areas called NFS and S3 0.

In what follows, we give a brief description of the main parts of the new facility, and the status of its construction. Then, in the existing facility, we develop the necessary developments concerning secondary beam diagnostics, and improvement of the mass separation.

Safety and radioprotection aspects are studied in details. Indeed, expected intensities are up to three orders of magnitude higher than with SPIRAL1, while radiological effects may be much more drastic. The experience on SPIRAL1 beams, in terms of beam losses and contamination, is studied in detail in order to decline the necessary modifications.

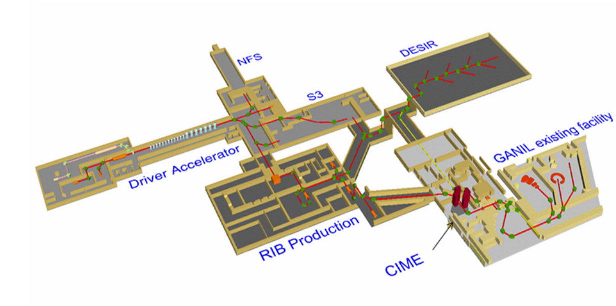

Figure 1: Layout of the SPIRAL2 project, with experimental areas and connexion to existing GANIL

SPIRAL2 DRIVER ACCELERATOR, EXPERIMENTAL AREAS AND PRODUCTION BUILDING

Beams to be Accelerated

Accelerated beams will include protons, deuterons, ions with A/q<3, and optionally ions with A/q<6. As indicated in table 1, a maximum beam power of 200kW is required for deuterons in CW mode.

Table 1: Beam Specifications

beam	P+	D+	ions	ions
Q/A	1	1/2	1/3	1/6
Max. I (mA)	5	5	1	1
Min. output W (MeV/A)	2	2	2	2
Max output W (MeV/A)	33	20	14.5	8
Max. beam power(KW)	165	200	44	48

Injector-1

The Injector-1, dedicated to protons, deuterons and ions of q/A=1/3, is mainly composed of two ECR ion sources with their associated LEBT lines, a warm RFQ and the MEBT line connected to the LINAC.

The 2.45GHz ECR source for deuterons is under test in the CEA/IRFU laboratory at Saclay, with promising results in terms of stability and reliability.

The q/A=1/3 heavy ion ECR source and its analysis beam line are installed at the LPSC laboratory (Grenoble). First beam tests give the expected results in terms of transmission, beam tuning and emittance 0.

Developed by CEA/IRFU team, the RFQ0 is a 4-vane, 88MHz 5-meter copper cavity ensuring bunching of the continuous beam, and acceleration up to 0.75Mev/u.

The first 1-meter RFQ segment is just constructed, and under mechanical and RF tests.

The MEBT line achieves the matching at entrance of the LINAC. It allows also connection of the future Injector-2, dedicated to q/A=1/6 heavy ions, and a very clean fast chopping of the beam bunches for NFS experiments.

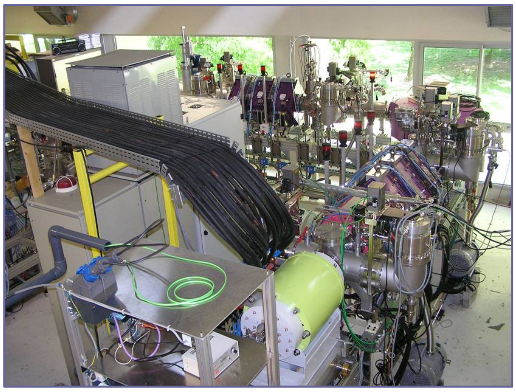

Figure 2: View of ECR source and Spiral2 LEBT1 installed at LPSC (Grenoble) for beam tests

Linac

The LINAC accelerator 0 is composed of 2 families of 88Mhz quarter-wave resonators, developed by the CEA/IRFU and the IN2P3/IPNO teams: 12 resonators with β_0=0.07, and 14 others with β_0=0.12. The transverse focusing is ensured by means of warm quadrupole doublets located between each cryomodule. These warm sections hosts beam diagnostic boxes and vacuum pumps.

All series of β_0=0.07 cavities and corresponding cryomodules shall be delivered at CEA/IRFU by September 2010 and end 2010 respectively. The production of β_0=0.12 cavities was achieved in November 2009, an tested successfully in vertical cryostat during 2010.

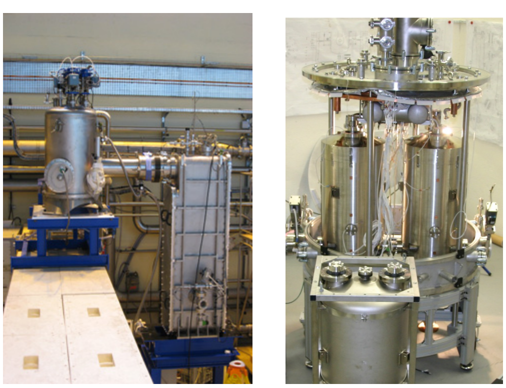

Figure 3: Tests of Crymodule A (Saclay) and assembly of Cryomodule B (Orsay)

HEBT Lines and AEL Experimental Hall

The high energy beam transfer lines transport the accelerated beam either to:

The main beam dump (200 kW) needed for the beam studies, commissioning and tuning.

- The RIB production module, located in the production building.
- The NFS experimental hall, dedicated to neutron-based research.
- The S3 experimental hall (Super Separator Spectrometer, with high mass selectivity).

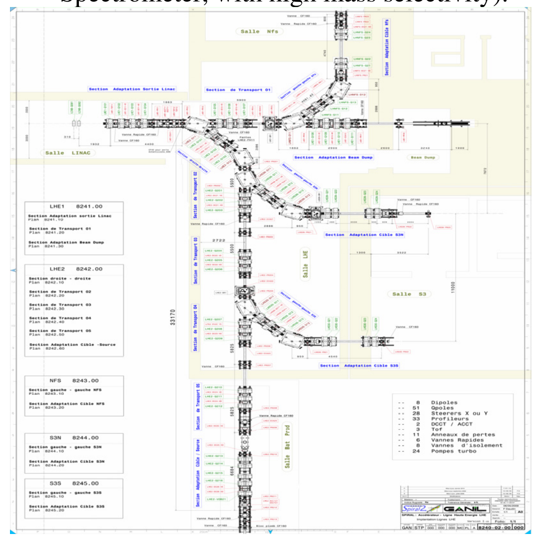

Figure 4: View of the HEBT beam lines

The Letters of Intent (LoI) for the first uses of LINAC beams in NFS or S3 have been already evaluated by the Scientific Advisory Committee (SAC). The associated detectors are in a well advanced phase of design.

Public Enquiry and Start of Construction

The public enquiry, necessary step for the authorization, was launched on June 14th, 2010. The construction of the accelerator building itself should begin by end 2010.

RIB Production and Transport

The general layout of the RIB production and beam transport scheme is presented below:

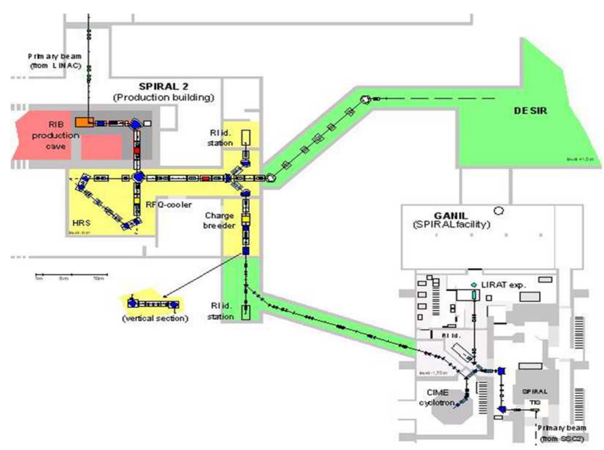

Figure 5: General layout for the RIB section

The main Target-Ion-Source (TIS) contains a rotating carbon converter for the production of neutrons using the 5mA 20A.MeV deuteron primary beam. The neutron flux produces fission reactions in a uranium carbide target. The carbon converter target is developed, in the frame of a collaboration with the LNFN/LNL laboratory. A first version is developed for a 50 kW beam power 0.

The uranium carbide target will be a high-density one ($11 g/cm^3$) for a yield of 5.10^{13}fissions/s 0. The ionisation scheme uses four types of 1+ ion sources: ECR, FEBIAD, surface ionisation, and laser ion source.

The beam analysis line enables to select the mass of interest. Despite the use, as often as possible, of selective sources, the beam of interest will often be polluted by isobars. A selection tool is being developed, in two steps: a RFQ-cooler, developed by LPC-CAEN, to decrease the emittance to 1 π mm.mrad 0, and a High Resolution Separator (HRS), developed by CENBG 0.

Next, the 1+ transfer line, from the ion sources either to the identification station,, to the low-energy experimental area DESIR or to the charge booster, will privilege electrostatic components.

The charge booster, needed to inject the RIB into the CIME cyclotron, is of Phoenix type and developed by the LPSC laboratory 0.

The n+ beam line will transport the beam towards the CIME cyclotron, inside the existing GANIL hall.

Safety Aspects

The cave housing the production module and the 1+ analysis line will be a radiological red zone (Equivalent Dose Rate> 100 mSv/h), due to activation and to fission products. Thus, disconnection, maintenance, and TIS reconnection will be realized by a robot and master-slave manipulators.

The HRS and booster are both in a “yellow zone”, accessible after decreasing of radioactivity (the access will be possible when the EDR is <2 mSv/h).

The safety requirements imply also to confine the radioactive beams. The mechanical design of the beam lines is based on independent modules with double valves, so that it will be possible to extract a module without loss of confinement. The whole vacuum system will be connected to a gas storage system, in order to release gas after a suitable radioactivity decrease period and gas analysis verifications.

Production Building

The production building, which will host the RIB production cave and the RIB transport lines, will be of nuclear type. It will contain hot cells, for the production cave (including production module, and analysis beam line), for maintenance operation on the production modules, and for nuclear waste.

Use of Radioactive Beams

The SAC will evaluate the LoI for the radioactive beams in January 2011. First requests indicate the interest of the community in SPIRAL2 beams at low energy in DESIR (40% of requests), as well as in post-accelerated beams.

ACCELERATION OF THE RIBs IN THE CIME CYCLOTRON AND USE OF THE EXISTING EXPERIMENTAL AREAS

Acceleration of RIBs in CIME Cyclotron

SPIRAL2 beams include potentially all ion isotopes from ^{6}He to ^{238}U, with two production maxima (in case of UCx fragmentation) around A=90 and A=130.

For light beams, the CIME energy range is 1.2 MeV.A (F_{RF} = 9.6 MHz, h= 6)-24 MeV.A (F_{RF} = 14.4 MHz, h= 2). For heavy ions, the maximal energy depends on the charge/mass (q/A) ratio. Examples are $^{91}Kr^{17+}$ at 9.3 MeV.A, $^{132}Sn^{20+}$ at 6.1 MeV.A.

Gas profilers will no more be convenient for heavy masses (A>100) and low energy (E<3 MeV.A), due to the thickness of the window). R&D is launched to determine how to extend the energy range of these diagnostics or to develop new ones. Preliminary, encouraging results are detailed in 0.

Another issue is the separation of the different isobars inside the cyclotron. The RIBs produced in SPIRAL2 will have higher masses, and thus will have much lower differences in $\Delta m/m$ implying very small differences in phase position at extraction (Table 2).

Table 2: Possible pollutant, mass separation and phase difference at the CIME extraction for different beams

beam	Possible pollutant	d(q/m)/ (q/m)	Phase shift at ejection (φ)
$^{15}O^{4+}$	$^{15}N^{4+}$	$1.9\ 10^{-4}$	48°
$^{132}Sn^{20+}$	$^{132}Xe^{20+}$	$1.0\ 10^{-4}$	35°
$^{140}Cs^{21+}$	$^{140}Ba^{21+}$	$4.8\ 10^{-5}$	16°

Using additional separation systems will thus be necessary. For this purpose, a vertical mass separator located inside the cyclotron has been developed at GANIL 0 and a prototype was tested in various configurations. The pollutants were simulated by applying a shift of the cyclotron magnetic field ($\Delta B/B = 10^{-4}$ for a pollutant with $\Delta m/m = 10^{-4}$ for example).

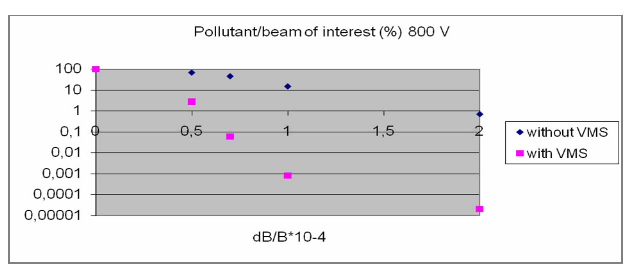

Figure 6: ratio pollutant/beam of interest in function of $\Delta m/m$

In the best case, it is possible to obtain a significant decrease of the intensity of the pollutant even when $\Delta m/m$ approaches a few 10^{-5}, and to divide this intensity by a factor 10^3 when $\Delta m/m = 10^{-4}$ (figure 6).

The final device is under construction. We hope to separate ^{132}Sn from ^{132}Xe, or ^{140}Cs from ^{140}Ba, or at least, to achieve a significant decrease of the pollutant intensity.

Safety Issues

The CIME cyclotron was constructed in the frame of the SPIRAL1 project, for the production of rather light ions (up to krypton) and of very short-lived elements. Thus, the problematic of radioactivity and contamination deposited inside the low-energy beam lines or in the cyclotron centre was not considered at that time.

With the SPIRAL2 project, producing beams with an important radiological impact (such as Sn beams which decays to Iodine), we must now consider the Equivalent Dose Rates (EDR) due this deposition, and also the risks of contamination. Release of radioactivity is to be avoided in case of accident leading to loss of confinement.

Hopefully, higher energy implanted atoms should be much less released than at low energy or not at all.

Experience with the SPIRAL1 Operation

In order to get a better knowledge about the way the radioactivity is deposited in the low-energy beam lines, the CIME cyclotron (figure 7), and the experimental areas, several beam tests have been realized.

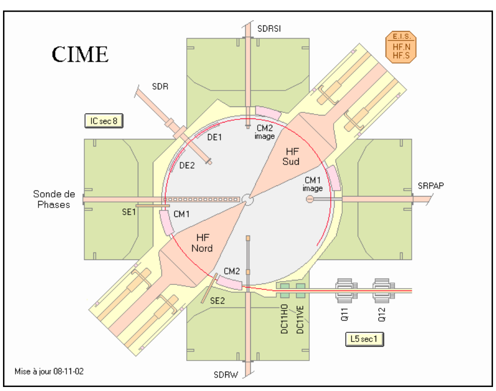

Figure 7: CIME cyclotron

First, a ^{76}Kr beam was accelerated and stopped on a tantalum plate mounted in the ejection beam line. The half-live is 14.8 hours ($^{76}Kr \rightarrow ^{76}Br$) and 16.2 hours ($^{76}Br \rightarrow ^{76}Se$).The average intensity was 2.10^7 pps before acceleration, and 5.10^6 pps after acceleration.

After 3 days of production, the beam was stopped and the cyclotron opened. EDR was measured along the beam line and inside the cyclotron. Superficial contamination was also investigated, leading to the following results:

- An EDR of 1 mSv/hour was measured at the contact of the tantalum plate. No superficial contamination was found; ions were implanted in the plate.
- An EDR of 1 mSv/hour was also measured at the contact of the inflector (entrance side), with a superficial contamination of 10 000 Bq. This corresponds to about 30% losses on inflector, with 10% superficial contamination.
- Losses were also present on the septum plate of the first exit deflector (about 15%), in the cavity extremities, and at the entrance of the second magnetic channel.
- Some losses (a few %) were also measured in the injection beam line. EDR measurements showed that the cryogenic pumps located at proximity of these beam losses were contaminated.

These results indicate the losses, thus the radiation levels to be considered in case of maintenance of specific elements. Superficial contamination must be taken into account in particular at injection (losses at low energy). Some contamination of the pumps is also to be considered in the low energy line.

During other beam tests, .the contamination of the vacuum pumps, in injection beam line as well as in ejection one, has been quantitatively determined. Beam "losses" were simulated by detuning and gamma spectrometry used to measure the contamination trapped by a cryogenic trap.

At low energy, the contamination corresponds to 10 to 20 percents of the beam losses nearby. At medium energy (> 1 MeV.A), this contamination is very low (<1%).

Consequence for the SPIRAL2 Operation and Necessary Modifications

Maintenance

Using the preceding measurements, and extrapolating to ^{132}Sn, representative of SPIRAL2, the different maintenance operations have been studied.

As an example, the EDR at 30 cm of the inflector would be around 2 mSv/hour a few days after the beam stop. Total maintenance operation lasts about 20 minutes while the operation at close proximity of the inflector lasts about 5 minutes. The total integrated dose for the operator is about 200 µSv per operation.

Considering the frequency of each maintenance operation, the annual collective dose related to SPIRAL2 beams in the existing facility is estimated to 10 man.mSv. This means that operation is possible with some optimisations, including use of spares for inflectors, deflectors, and improvement of mechanics in order to ease mounting and dismounting, and to reduce the operation time close to the equipment.

Figure 8: maintenance of the inflector

Modifications of the CIME Casemate

A particular attention will be necessary to avoid contamination of the cyclotron hall during operation maintenance. Nevertheless, taking into account an accidental contamination, a confinement will anyway be necessary. The walls will have to be sealed, and a nuclear ventilation will complete the confinement.

This study is still preliminary and the modifications are quite important (preliminary cost ~2 M€).

Vacuum

In the SPIRAL2 facility, up to the CIME cyclotron, the contamination of the pumps justifies the connection of these pumps to the storage of gases.

After ejection, the contamination of the "vacuum" gases is reduced, so that their storage is not necessary. However, they have to be collected and analyzed before release. Thus, the vacuum system has to be modified, with in particular the use of hermetic primary pumps.

Experimental Areas

The SPIRAL2 radioactive beams will be mainly used in the G1 and G2 experimental areas (figure 9). These two rooms are largely used today for SPIRAL1 beams, with in particular the gamma detector EXOGAM, and the VAMOS spectrometer in G1.

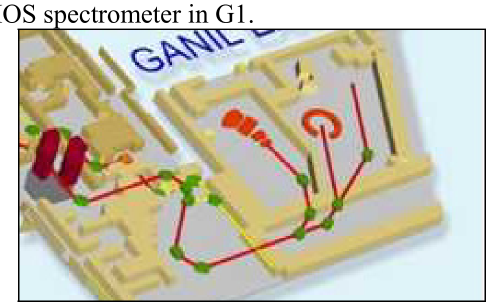

Figure 9: Cyclotron CIME connected to G1 & G2 experimental halls

The challenge of using the high intensity radioactive beams in the experimental areas is related to the high activity (up to 10^{10} Bq) close to a gamma detector. One would have to take care of:

- The incident beam (it has to be stopped away from the detector with a shielding).
- Interactions of the incident beam with residual gas resulting to halo and other causes of losses.
- Rutherford scattering on target.

A project is launched in order to modify the beam lines and experimental equipment in these two rooms. The other experimental areas will be treated in a second time.

CONCLUSION

The major SPIRAL2 accelerator components are in their phase of technical tests and/or construction, while the accelerator building is completely defined. The detailed design solution of the RIB process equipments and the production building, compatible with the safety constraints, is underway.

The necessary modifications of the existing GANIL facility have been identified, but are still to be fully validated.

At the beginning of SPIRAL2 operation with the cyclotron CIME,, the beam intensity will probably be reduced to check the hypothesis in terms of radioprotections, safety, and detection.

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