GANIL

GRAND ACCELERATEUR NATIONAL D'IONS LOURDS - CAEN
LABORATOIRE COMMUN IN2P3 (CNRS) - DSM (CEA)

PRODUCTION AND POST ACCELERATION SCHEME FOR SPIRAL

D.Bibet and the SPIRAL group

GANIL, BP 5027, 14021 CAEN Cedex, France

*To be published to the Proceedings of International Workshop
On Production of Radioactive Ions Beams
February 12-17, 2001, PURI (India)*

GANIL S 01 03

SPIRAL
GANIL
Laboratoire commun CEA / DSM - CNRS / IN2P3

PRODUCTION AND POST ACCELERATION SCHEME FOR SPIRAL

D.Bibet and the SPIRAL group

GANIL, BP 5027, 14021 CAEN Cedex, France

Abstract

SPIRAL, the R.I.B facility of GANIL uses heavy ion beams to produce radioactive atoms inside a thick target. Atoms are ionised in a compact permanent magnet ECR ion source. The compact cyclotron CIME accelerates the radioactive ions in an energy range from 1.7 to 25 Mev/u. The cyclotron acts as a mass separator with resolving power of 2500. Plastic scintillator and silicon detectors are used to tune the machine at a very low intensity.

An overview of the facility, stable beam tests results and the R&D program will be presented.

1. SPIRAL OVERVIEW

The primary heavy ion beams accelerated by the GANIL Cyclotrons bombard a production target located in a well-shielded cave beneath ground level in the machine building (figure 1). The radioactive atoms produced by nuclear reactions are released from the high temperature target (≈ 2000 °C), then pass through a transfer tube into an ECRIS source, where there are ionised up to a charge to mass ratio larger than 0.1.

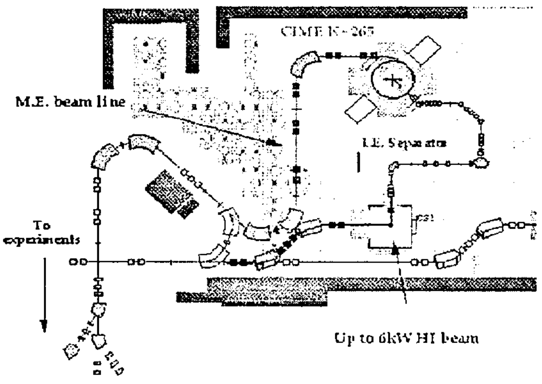


Figure 1 : Spiral layout

After extraction from the ECR with a acceleration voltage up to 36 kV, the low energy RIB will be selected by a relatively low resolution separator (Δm/m = 4*10-3) and injected into the K = 265 compact cyclotron CIME.

The cyclotron accelerates the RIB in an energy range from 1.7 to 25 MeV/u. After acceleration, the RIB will be selected in magnetic rigidity by the modified alpha spectrometer of GANIL and directed to the existing experimental areas.

The mass separation will be performed for the most part by the cyclotron itself, with a resolving power of more than 2500.

Additional separation can be achieved by placing a foil at the object point of the spectrometer in order to select ions having the same Q/A but different mass, or by placing a degrader to select the isobars. However, in this latter case significant losses in RIB intensity will occur.

2. PRODUCTION OF RIB

2.1 Target development

Projectile fragmentation is one of the most important reaction mechanisms coming into play for the production of radioactive nuclei with heavy-ions.

The GANIL facility offers an exented range of heavy-ions with an available energy about 100 MeV/u for the mass up to around sixty. As the projectile rather than the target can be chosen to produce the desired radioactive species, we can use the most resilient and efficient production target for most of the cases.

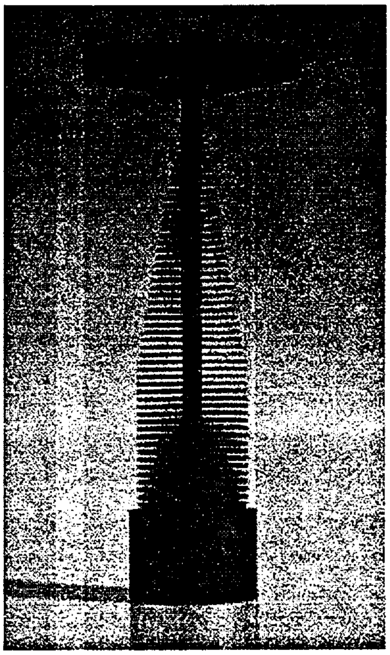


Figure 2 : Argon target

A carbon target has been chosen due to its excellent release properties, its low atomic number for projectile fragmentation the production yield is higher for lighter targets and its high sublimation temperature.

The target at GANIL is designed to support a 6KW argon beam. It is made of carbon slices with 0.5 mm thickness (figure 2). The carbon is furnished by Carbonne Lorraine France with a grain size of 4 µm and 8% open porosity. The target is heated at 2000°C by the beam and by an additional ohmic heating. [1]

A special target devoted to the production of helium isotopes has been developed and tested on the SIRA test bench [2]. It is composed of two parts (figure 3). The first part is for production by target fragmentation, the second one by projectile fragmentation. This design and a reduction of the grain size of carbon have increased the production rate of helium-8.

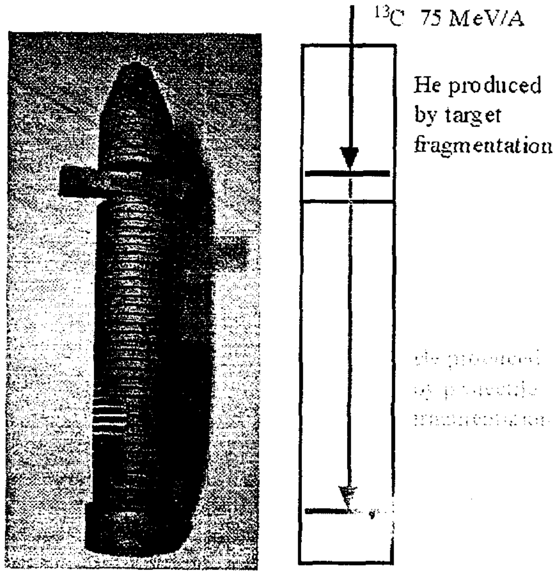


Figure 3 : Helium target

2.2 Ion source development

The use of an ECRIS (Electron Cyclotron Resonance Ion Source) is particularly interesting due to its high plasma density and good confinement, which allow efficient ionisation of almost all elements of the periodic table. Moreover, an ECRIS is well suited to production of highly charged ions, which is an important ingredient for producing accelerated beams over a wide range of energy. The relatively high emittance of an ECRIS (30 - 150 π mm.mrad) can certainly be a problem if one uses "standard" separators, but if the accelerator after the ECRIS is a cyclotron the emittance of this source would not greatly affect the mass resolution.

The development of an ECRIS at GANIL/SPIRAL, for on-line production of radioactive multicharged ion beams of noble gases directly inside the production cave, has resulted in a new ECR type : NANOGAN-III (figure 4).

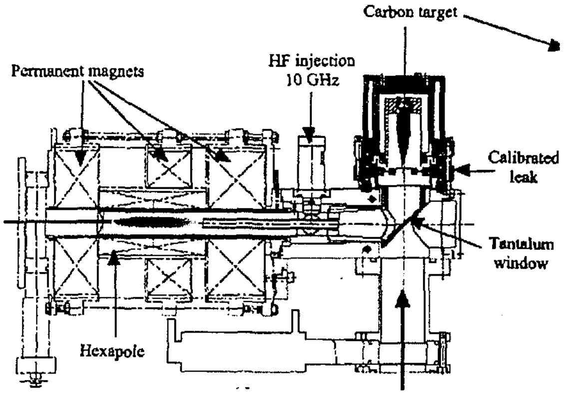


Figure 4 : Target ion-source NANOGAN III

The new model is designed to decrease the cost and the weight compared to the preceding ECR versions. It is a compact permanent magnet source and has been designed for operation with a 10 Ghz transmitter. Its power consumption is 200 W and it is optimised for the 8 + charge state of argon. The ion source is linked to the external carbon target by a cold and short transfer tube giving an efficient production of noble gas elements with a reasonable suppression of condensable contaminants.

A new system dedicated to the production of condensable elements has also been developed [3]. It consists of an ECRIS with an internal target. This design of mixed coils and permanents magnets makes an hybrid ECRIS call SHyPIE (Source Hybride pour la Production d'Ions Exotiques).

A second direction of research is towards producing radioactive mono-charged ions of any element in the production cave. This development is related to the charge booster project [4].. After selection by the low energy spectrometer, the 1+ ions beam is injected into another ion source for charge multiplication before injection into the accelerator.

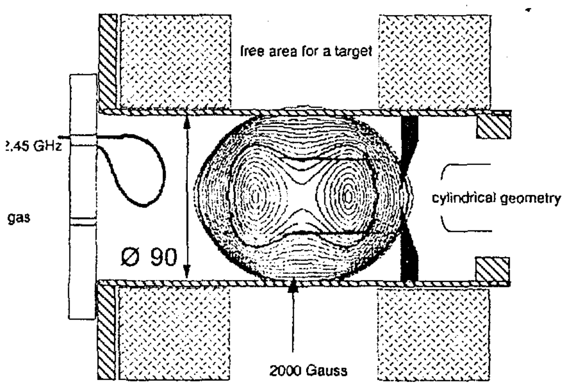


Figure 5 : Target ion-source MONO1000

The MONO1000 ECRIS (figure 5) has been designed in order to be a very simple and low-cost ion source, and in order to easily be refurbished for subsequent use. The magnetic structure is made with only two permanent magnet rings that give a cylindrical symmetry beam. During the first test, a power of 20W at 2.45 Ghz was sufficient to produce 200 µA of Ar 1+. Moreover, the preliminary tests show that the target could be placed inside the chamber, then the transfer time will be reduced, the production efficiency increased, and we can produce any type of element.

The so-called MONOLITHE (figure 6) is dedicated to produce monocharged ions of lithium 11 [5]. The target is split in two parts. The first part is devoted to the production of the radioactive element, and is cooled to remove the beam power; the second part is the diffusion target, heated to over 2000°C for release of the lithium ions.

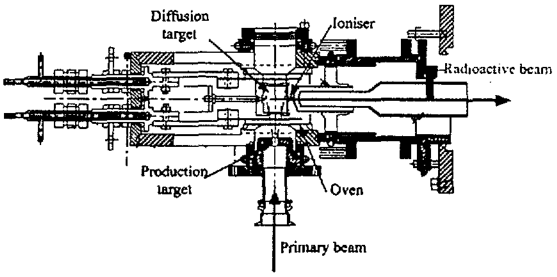


Figure 6 : Target ion-source MONOLYTHE

3. THE POST ACCELERATOR

3.1 Relevant parts for a radioactive beam post accelerator

Here we just want to emphasise the special features of a radioactive ion post acceleration facility and those of the SPIRAL post-accelerator in particular.

- The production system is very compact and allows complete remote removal. As far as is possible, components are made of material resistant to neutron irradiation and with short-lived of activity. In the cave itself, the mechanical assembly is mainly made of aluminium. Ventilation and water cooling system must follow nuclear installation rules. To provide against sparks and to have a reliable production system the high voltage platform has been limited to 36 kV.

- The low energy mass separator must have a large acceptance. It has a mass resolution of 250 for an 80 π.mm.mrad acceptance in both planes. This relatively good mass separation reduces the number of ion species injected into the cyclotron and so minimise the problems related to the tuning of a composite beam and further contamination problems.

- The identification station installed in the injection beam line identifies the radioactive nuclei produced and measures their production rate. The identification method depends on the decay mode of the nucleus, either by direct identification of the γ rays or through observing the half-life of the nucleus [6]. A pulsed magnet allows beam sharing between the measurement station and the cyclotron.

- The choice of a compact cyclotron is based on the main following reasons:

1) The energy range to be covered (≈ 2 to 25 MeV/u) and the charge-to-mass ratio available with an ECRIS ion source are well suited to a compact cyclotron.

2) The cyclotron is a powerful mass analyser and the beam characteristics required by the physicists are easily achieved with this kind of machine.

The beam lines and the cyclotron will be pretuned with a stable "analogue" beam close to the Q/A ratio of the desired radioactive beam. Then we can use either the magnetic field or the RF frequency to shift towards the correct tuning for the radioactive beam [7].

In order to control the tuning of the cyclotron for the desired radioactive ions two radial probes carry an additional low intensity diagnostic device.(figure7). The radial probe "SDR" in the valley is equipped with a retractable plastic scintillator dedicated to the measurement of the acceleration phase and the phase width of the beam. The probe "SDRSi" in the hill carries a silicon detector (E, ΔE) for identification of accelerated species; it is used to diagnose species prior to extraction [8].

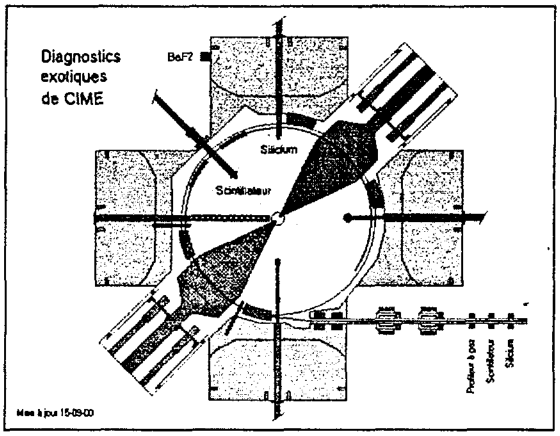


Figure 7 : Low intensity diagnostics of CIME

Downstream of the cyclotron the beam line is also equipped with silicon detectors and a plastic scintillator. A special ionisation chamber for beam profile measurements has been developed to control the beam with only 100 pps from an energy as low as 2 MeV/u.

3.2 Stable beam tests

Waiting for authorisation, from the safety authorities, to accelerate radioactive beams, we obtained quite a few hours of stable beam tests to begin the commissioning of SPIRAL.

The CIME cyclotron has off-centered axial injection. To cover the large energy range required we computed two different central geometries. To run from 5 to 25 MeV/u we use a Muller type inflector. The injection radius is 34 mm and the tip angle of the dee is 60 degrees. The RF harmonic mode is either 2 or 3. At low energy, we use a spiral inflector (Pabot-Belmont type) followed by an electrostatic quadrupole. The RF harmonic is either 4 or 5; injection radius is 45 mm. and the tip angle of the dee is reduced to 40 degrees. In this latter case there is no post in the dee.

Stable ions accelerate for the tests of the machine are plotted on the working diagram of the CIME cyclotron (figure 8). The both central region and the four harmonics mode have been successfully tested. The total transmission -the ratio of the extracted beam current to the analysed current downstream of the ion source- is about 40%, except for the lowest energy 1.7 MeV/u at the lowest extraction voltage of the ion source. The buncher is a saw tooth signal and we can catch about 65% of the CW beam. The extraction transmission is also about 65%, but sometimes with 2 turns.

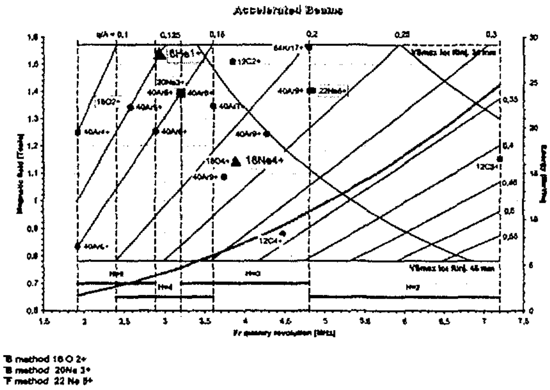


Figure 8 : Working diagram of CIME

At the beginning of the tests, we lost the beam before the extraction radius and we have to put a harmonic one of 10 Gauss to get the beam up to the extraction. After many attempts to found the cause of the lose, we installed an additional radial probe to analyse the off-centering of the trajectories, then we installed four NMR to measure the magnetic field in presence of the vacuum. Finally we discovered a bigger than expected effect of the vacuum on the magnetic gap, witch induces a great unbalance of the magnetic field between the hill sectors. Since we have put spacers, the beam goes to the extraction without correction. Figure 9 shows the turns pattern on RF harmonic 3, with the spacers installed.

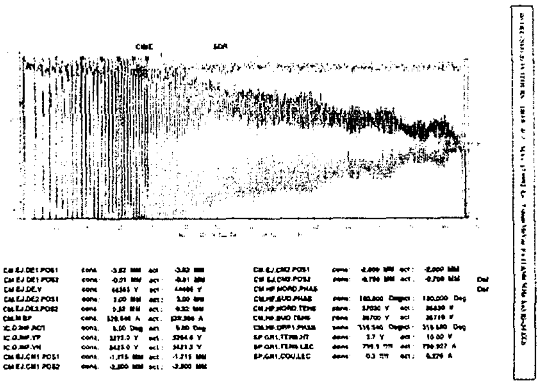


Figure 9 : Turn pattern on harmonic 3

Figure 10 shows the results of the silicon tests to identify several beams with the same Q/M, injected at the same time in the cyclotron. The difference of mass Δm/m between them is only a few 10-4. During this test the silicon detector stands at a radius near the extraction, and we shift the RF frequency in order to get the different species at the extraction radius.

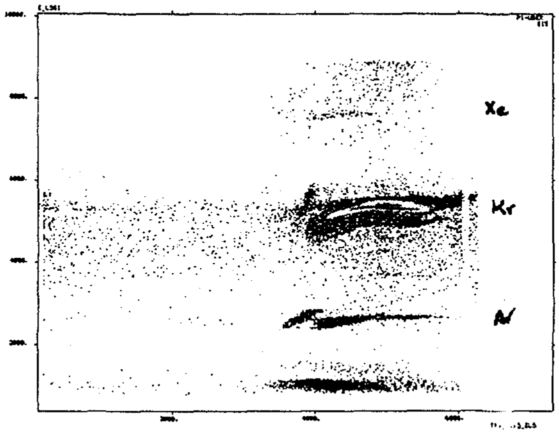


Figure 10 : Silicon tests

4. BASIC STUDIES FOR SPIRAL PHASE II

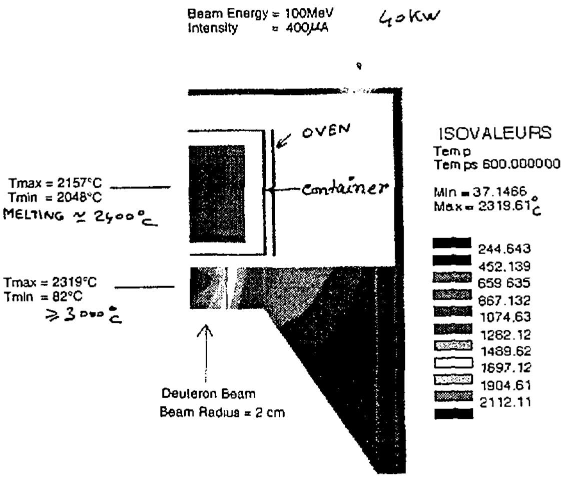
The present SPIRAL project , which is about to deliver its first beams in a few months, will produce and accelerate nuclei by fragmentation of the projectiles delivered by the GANIL cyclotrons. For the reason that this primary beam is less intense and energetic as its atomic number increases, it is planned to add a complementary equipment based on fission of heavy elements in order to produce and accelerate usable intensities of neutron-rich beams.

A working group extending to the French community was created in October 2000 whose tasks are :

- to investigate the research domains that can be reached with exotic beams issued from fission at a rate of about 10^{13}/s.
- to compare the advantages and drawbacks of a 80-100 MeV, 500 µA deuteron accelerator and of a 45 MeV, 500 µA electron linac which would use the photofission process.
- to evaluate the present possibilities for realising a target-source ensemble capable of withstanding 25 to 50 kW and to produce singly-charged ions
- and to study the installation of such a new driver, with the setting up of the beam lines to inject the exotic species into either CIME or the GANIL cyclotrons used as post-accelerators.

The study of the production of neutron-rich isotopes through fast neutron induced fission by deuterons had started already almost three years ago as a European R & D program with several components :

- measurements of cross-sections, mass distribution, isotopic distributions
- development of a model for calculating these cross-sections
- neutron production induced by deuterons in light and heavy targets (with or without converter). Figure 11 gives the production of RIB by converter method.
- measurements of yields and release times of the gaseous products
- singly charged ion sources
- safety aspects.



Deuteron beam (energy 100MeV, 350µA intensity) + Converter (Carbon) + Diffusion Target (UCx, 360 g U)
$\longrightarrow$ 6 x 10^{12} fission/s (LAHET).

Figure 11 : Production of RIB by converter method Systus simulation

The driver could be a commercial compact, fixed energy cyclotron.

As for the photo-fission process, the radioactive beam production was proposed both by W. Diamond and Y. Oganessian. The Dubna physicists measured a variety of parameters (yields, etc.) with a modest 25 MeV, 20 µA microtron. The results raised the interest in the competition with the deuteron accelerator. If this photofission solution were retained, then an existing cryogenic electron linac could be moved from Saclay to GANIL and rejuvenated.

A first document should be ready to be submitted in the spring of this year, so that a go-ahead permission could be given to prepare a detailed proposal. The aim is to have such a complementary machine by the year 2005.

5. THE THI PROJECT

5.1. Goals of the project

The production of exotic nuclei at GANIL is presently performed by fragmentation of the projectile in the target of SISSI ; it will be soon completed by the ISOL method, with subsequent acceleration of the rare isotope beams by the cyclotron CIME. Both devices require high intensity primary beams. The THI project, described in details in the proceeding of the International Conferences on Cyclotron [9,10], consists of a series of actions undertaken on the GANIL accelerators components in view of increasing the present intensities of light ion beams (up to atomic numbers Z ≈~40). The aim is to go from 400 watts, which is considered as a safe value for the beam power if no special precaution is taken, up to a maximum value of 6 kW, a limit imposed both by the thermal properties of the targets and the need for a "reasonable " amount of additional shielding. Examples of goal figures are given in table I.

Projectile	Present intensity for 400 watts	Expected intensity	Beam power
	(pps)	(pps)	(kW)
^{12}C	2.2 10^{12}	2.0 10^{13}	3.7
^{16}O	1.6 10^{12}	2.0 10^{13}	4.9
^{20}Ne	1.3 10^{12}	2.0 10^{13}	6.1
^{36}Ar	7.7 10^{11}	1.1 10^{13}	6.0

Table 1 : The beam power is given for 95 MeV/n beams.

The series of adaptations required by this upgrading in terms of protection of the components and control of the beam behaviour is described below, along with the results of the beam tests and the proposed strategy to overcome some limitations.

5.2. the accelerator implementation

5.2.1. Ion source and platform

For the ion species obtained from gaseous elements, the GANIL ECR4 ion source delivers enough intensity to reach the output goals, provided beam losses are minimised in the cyclotrons and beam lines. However, efforts are to be spent in order to get stability over days, especially when the total current drained from the source brings an excessive loading of the 90 kV accelerating tube of the insulated platform. As for ions from condensable materials, developments are worked on, especially through the MIVOC method, and beams of ^{58}Ni (700 W) and ^{36}S (1 kW) have been already used by the experimenters.

5.2.2. Protection against beam losses

The vacuum chambers of all the dipoles of the beam lines have been thermally shielded either by carbon or tungsten sheets, or water-cooled copper sheets. In addition, each entrance and output of these dipoles is equipped with an electrically insulated collimator made of carbon ; when operating at high intensity, any change in the beam direction or transverse dimensions leading to an amount of loss larger than a pre-determined level triggers a reduction of the intensity through a fast response electronic module. Identically, the electrostatic and magnetic injection and extraction elements of the two SSCs have frontal insulated and water-cooled electrodes that are used in the same manner.

Below this "safety" level however, the intensity lost on any of these sensors can be measured on a logarithmic scale and therefore be minimised.

A complementary and more global system protects portions of the accelerator as a whole : the difference between input and output currents of each SSC is measured by a differential current transformer so that below a given transmission efficiency, the intensity reduction is triggered [11]. Downstream from SSC1, beam lines are protected in the same way.

5.2.3 Reducing the losses in the cyclotrons

As indicated above, the loss sensors located in the SSCs are equipped with a logarithmic converter. At each step of the intensity increase, several readjustments are made, for example correction of the beam direction, change of the RF voltage and phase of bunchers and rebunchers , etc . The most important loss takes place at the entrance of the electrostatic deflector of SSC2, of which both the septum and the high voltage electrode are protected by a detector/shield sensor .

In order to reduce the width of the last turn at extraction of SSC2, a new rebuncher (R2) was designed [12] and put in operation with great success.

5.2.4. Radiation and safety problems

These problems mostly concern the high energy section : upstream from the injection into SSC2, the beam energy is at most 13.6 MeV/n, which does not raise any severe radiation or activation problem. For beamline L3 at energies up to 95 MeV/n , we have now sufficient knowledge about the neutron spectra produced by heavy ion impact and of the attenuation coefficients in concrete : the thickness of the shielding around SSC2 and SISSI has been modified according to the expected intensities.

There are two places in the accelerator where losses are inevitable :

1) the charge state separator located after the stripper where all undesired charge states are lost in the vacuum chambers; these chambers are shielded with carbon plates and the activation level stays at reasonable values.

2) when SISSI is in operation, the downstream focusing and bending elements are tuned for the magnetic rigidity of the secondary beam, while the primary one, although slowed down by the target, is defocused and lost in the first two bending magnets which have been equipped with water-cooled, removable shields or on water-cooled ring-shaped collimators which can be recessed in a lead envelope by an actuator when not in use. The SISSI target is removable by a robot.

Concerning the extraction elements of SSC2, none of them should suffer a permanent loss, thanks to the detection system mentioned above . The only exception is the electrostatic deflector where a small fraction is permanently lost ; hopefully, a fast disconnection device was designed right from the beginning of the construction so that the whole set can be lift up by a crane and evacuated.

5.2.5. Stripper

In order to increase the carbon stripper lifetime without defocusing the beam, the whole foil-holder was made to rotate at 0.01 rpm in a plane perpendicular to the beam so as to use a larger area of the carbon foil. In the rotation, the phase of the bunch at SSC2 injection is only slightly affected by foil inhomogeneities (± 0.16 RF degrees) and this excursion can easily be compensated by a feedback action on the bias voltage applied to the stripper.

5.2.6. Supervision

Supervision already exists concerning an eventual trip of any current supply. However, in order to prevent the effect of a feedback loop failure, the voltage across the load is measured in addition to the output current. While the beam is still on, this double check is especially useful for all the power supplies of the correcting and harmonic coils (45 per cyclotron) which are located in the same room as the SSCs.

5.3.Tuning method

Several methods are possible to step-by-step tune the accelerator for high intensity, while protecting the secondary emission beam profile monitors (when they are in the beam, the average intensity has to be reduced by a factor of 500) and other fragile elements. A combination of pepper-pot and chopper was chosen. The beam is tuned at low intensity with these two devices and, once the BPMs are removed, the pepper-pot is also removed and the intensity is step by step increased by varying the repetition rate of the chopper.

This combination is not quite satisfactory, particularly because the tuning is sensitive to the peak intensity : a new chopper has to be designed so as to avoid using the pepper-pot.

5.4. results and perspectives

5.4.1. Beam tests and routine operation

The first test beam was $_{36}$Ar $^{10+/18+}$ accelerated at 95 MeV/u. The intensity extracted from the ion source at 80 kV and in a 60 x 60 π mm mrad emittance is of the order of 5x10 ^{13} pps, which should be sufficient to reach 1.1x10 ^{13} pps at SSC2 output, corresponding to a power of 6 kW. The tests led to the following results [13] :

1) a 2 kW (3.6x10^{12} pps) beam could be extracted from SSC2 and maintained for more than 30 hours. As a matter of fact, it is important to carry a constant heat load inside the production target of SPIRAL in order to maintain its temperature as constant as possible (on the contrary, an interruption of the beam in the SISSI target is of less importance, all ions exiting of this thin target under the effect of their kinetic energy).

2) in spite of several attempts, the goal of a 6 kW (1x10^{13} pps) extracted beam could not be reached, some limit standing in the vicinity of 2.7 to 2.8 kW. The most important limiting factor is the amount of beam lost in SSC2 and in particular in the extraction process.

A second test was performed with a $_{13}$C$^{3+/6+}$ at 75 MeV/n. In a first 13 hours period, a 1.3x10^{13} pps (2kW) beam was extracted from SSC2. Then, the ultimate goal of 2x10^{13} pps (3 kW) was reached for several hours[14].

As mentioned in 5.2.1., beams of ^{58}Ni (700 W) and ^{36}S (1 kW) are considered now as routine operation.

5.4.2. Current improvements

In both cases mentioned above (Ar and C beams), it was difficult to overcome a 95 % transmission efficiency through SSC2 with these intensities, with the consequence of a loss in the extraction system. Computer simulations, somewhat linked to experimental observation, seems to substantiate the idea that this deterioration of the beam qualities (like a widening of the turn at extraction) is due to longitudinal space charge effects. These simulations are currently pursued and have been extended to the injector cyclotron, where part of the origin of the phenomenon may lie.

In the meantime, a watercooled shield capable of withstanding a 600 W power was installed upstream from the electrostatic deflector of SSC2, then allowing up to a 10 % loss if no other cure were found.

Other improvements are underway. They deal in particular with correcting the instabilities of the beam and of the beam diagnostics :

- the instabilities of the (low frequency) differential current transformers trigger the safety interlock system too frequently because they are too noise sensitive. A new type of current transformer operating at the cyclotron RF frequency has been developed and should cure the problem.
- a new chopper, capable of reducing the intensity by a factor as low as 500 must be developed in order to suppress the obligation to operate a first tuning of the cyclotrons with a pepper-pot which deeply modifies the space charge effects.
- a complete modification of the ion source platform is under study : in order to minimise the accelerating tube load, a charge state selection will be installed between the source and this tube.

As soon as the administrative authorisations are delivered by the Safety Authorities, beam tests of line L4 linking the α spectrometer to the production target of SPIRAL will be undertaken, first at low intensity to check all the alignment, focusing and wobbling functions, along with the beam loss detection system. Then, a 2 kW , 95 MeV/n $_{20}$Ne beam test will be reiterated, followed by the full-scale test on the target and subsequent production and acceleration of $_{18}$Ne.

References

[1] A.C.C. Villari, Nucl. Instr. Meth. Phys. Res. B126 (1997) 35.

[2] F.Landre-Pellemoine et al., Recent results at the SIRA test bench: Diffusion properties of carbon graphite and B4C targets, GANIL, report P 00 29

[3] N.Lecesne et al., Radioactive Ion Beam Production Tests for SPIRAL, GANIL report S 96 03

[4] N Chauvin, La transformation d'état de charge 1+ → n+ pour l' accélération des ions radioactifs. Thesis, Grenoble, ISN 00 76

[5] A.C.C Villari et al., Ion source developments for RNM production at SPIRAL/GANIL, GANIL, report P00 28

[6] S. Kandri-Roody, et al, Proceedings of the International Conference on Cyclotrons and their Applications, Caen, France, 359, (1998)

[7] L. Boy et al., Tuning methods for the SPIRAL facility, GANIL, report S 97 02

[8] B.Laune et al., Proceedings of the International Conference on Cyclotrons and their Applications, Caen, France, 163, (1998)

[9] E. Baron and the GANIL Staff - Upgrading the GANIL facilities for high-intensity heavy ion beams ((T.H.I. Project). Proceedings of the 14th Int. Conf. on Cyclotrons and their Applications. Cape Town , South Africa (1995), p 39. Ed : J.C. Cornell. Publisher : World Scientific.

[10] Experience with high intensity operation of the GANIL facility. E. Baron, J.L. Baelde, C. Berthe, D. Bibet, A. Chabert, C. Jamet, P. Gudewicz, F. Loyer, M-H. Moscatello, E. Petit, C. Ricaud, A. Savalle and G. Sénécal. GANIL Report A 98 02. Proceedings of the 15th International Conference on Cyclotrons and their Applications (CYCLOTRONS'98), Caen 1998, pp 39-44. Editors : E. Baron et M. Lieuvin. Publisher : IOP.

[11] C. Jamet et E. Petit.- Same reference as [2]

[12] M. Di Giacomo. - Same reference as [2]

[13] Ganil high intensities : how to go higher. E. Baron. Les Nouvelles du GANIL 65, July 1999, pp15-17

[14] THI : Goal reached with a carbon beam, and some results of beam tests and theoretical studies related to longitudinal space charge effects. E. Baron. Les Nouvelles du GANIL 66, November 1999, pp 13-15