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PROCEEDINGS

SPIRAL – a new radioactive beam facility

Marcel Lieuvin
and the GANIL staff

Abstract SPIRAL, the Radioactive Beam Facility at GANIL (Caen-France) is in operation since September 2001 and has already accelerated several radioactive beams. The paper presents the machine and the main characteristics of the first beams produced. We describe also the new project which is presently under discussion at GANIL:SPIRAL 2. This new machine will use either an electron or a deuteron linac to produce heavy fission nucleons far from the valley of stability.

Key words accelerator • radioactive ion beams • facility

M. Lieuvin
GANIL (DSM/CEA, IN2P3/CNRS),
Caen, France,
Tel.: +331 44/ 96 45 36, Fax: +331 44/ 96 53 40,
e-mail: mlieuvin@admin.in2p3.fr

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Introduction

The construction of SPIRAL has been described on several occasions [2, 4, 5]. Let us recall that the project was elaborated in 1992 and 1993, accepted in December 1993 and funded from 1994 to 1999 by the IN2P3/CNRS, the DSM/CEA and the Regional Council of Normandy. The construction of the facility was done with the contribution of several nuclear research laboratories, mainly in France but also in Europe. The facility is based on the ISOL technique for production of Radioactive Ion Beams (RIB) with a post acceleration by a new cyclotron: CIME. It was a long and difficult task to obtain the administrative authorisation to run SPIRAL, this was finally done in September 2001, 18 months after the end of the construction. Several radioactive beams have been produced since then, the results are presented below.

Overall characteristics

GANIL produces beams with intensities reaching 6×10^9 to 2×10^{13} pps for ions from ^{238}U to ^{12}C at energies from 24 to 96 MeV/u (THI project) [1]. The GANIL beam is stopped in a target located inside a production cave at the underground level. The radioactive atoms mainly produced by fragmentation of the projectile are released from the target maintained at high temperature (~2300 K), and pass through a transfer tube to be injected into a permanent magnet ECRIS. The radioactive atoms are ionised up to charge over mass ratio (Q/A) ranging from 0.09 to 0.40. After extraction from the source, the low-energy beams (acceleration voltage from 7 kV to 34 kV) are selected by a relatively low resolution separator (dm/m = 4×10^{-3}) and injected into the compact cyclotron CIME (K = 265, Br = 2.344 Tm) (Fig. 1). After acceleration, the radioactive

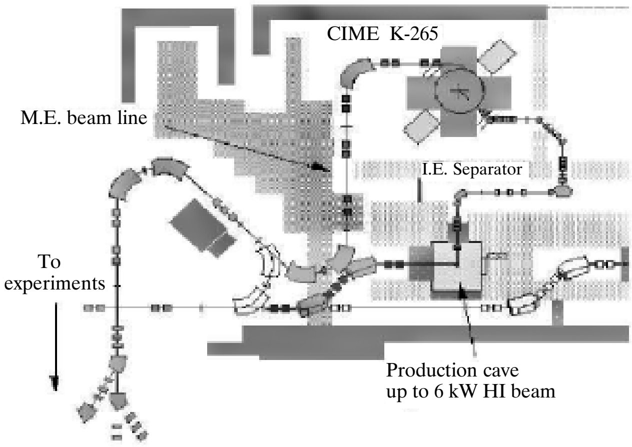

Fig. 1. SPIRAL layout.

ion beam (RIB) pass through the GANIL alpha spectrometer and is directed towards the existing experimental areas. The energy of the radioactive beam extends from 1.7 to 25 MeV/u.

The mass separation is mainly performed by CIME, with a resolving power of more than 2500. Additional separation can be achieved by placing a foil at the object point of the alpha spectrometer in order to select ions having the same Q/A but different masses (this method induces some deterioration of the beam quality).

Pointing out some of the most significant features of this new installation, one select:

– the radioactive beam production system: it must be compact, remote controlled and reliable. In addition, it must be installed and removed remotely by a robot. The components must be made with materials having an activation as low as possible under the high neutron flux generated by the primary beam;
– in the cave itself, the mechanical assembly is mainly made of aluminium. The cave is equipped with ventilation and water cooling systems following the nuclear safety rules. To avoid electrical breakdowns as far as possible, the extraction voltage has been limited to 34 kV;
– the low energy mass separator must have a large acceptance. It provides a mass resolution of 250 for 80π mm·mrad in both planes. This relatively good mass separation reduces the number of ion species injected into CIME and so minimise the problems related to the tuning of a composite beam and further contamination problems;
– an identification station installed along the injection beam line allows the identification of the radioactive nuclei produced and the measurement of the production rate. The identification method is adapted to the decay mode of the nucleus, it can be either by direct identification of the γ-rays or by measurement of the half-life [3]. A pulsed magnet allows to share the beam between the measurement station and the cyclotron;
– the choice of a compact cyclotron was mainly made for the following reasons:
  1) the energy range to be covered ($\approx$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 separator and the beam characteristics required by the physicists are easily achieved with this kind of machine.

The beam lines and the cyclotron are pretuned with a stable "analogue" beam with a Q/A ratio close to the one of the desired radioactive beam. Then the magnetic field or the radio-frequency (RF) can be used to shift towards the correct tuning for the radioactive beam.

In order to control the tuning of the cyclotron for very low intensity radioactive beams, two radial probes carry an additional diagnostic device. One is equipped with

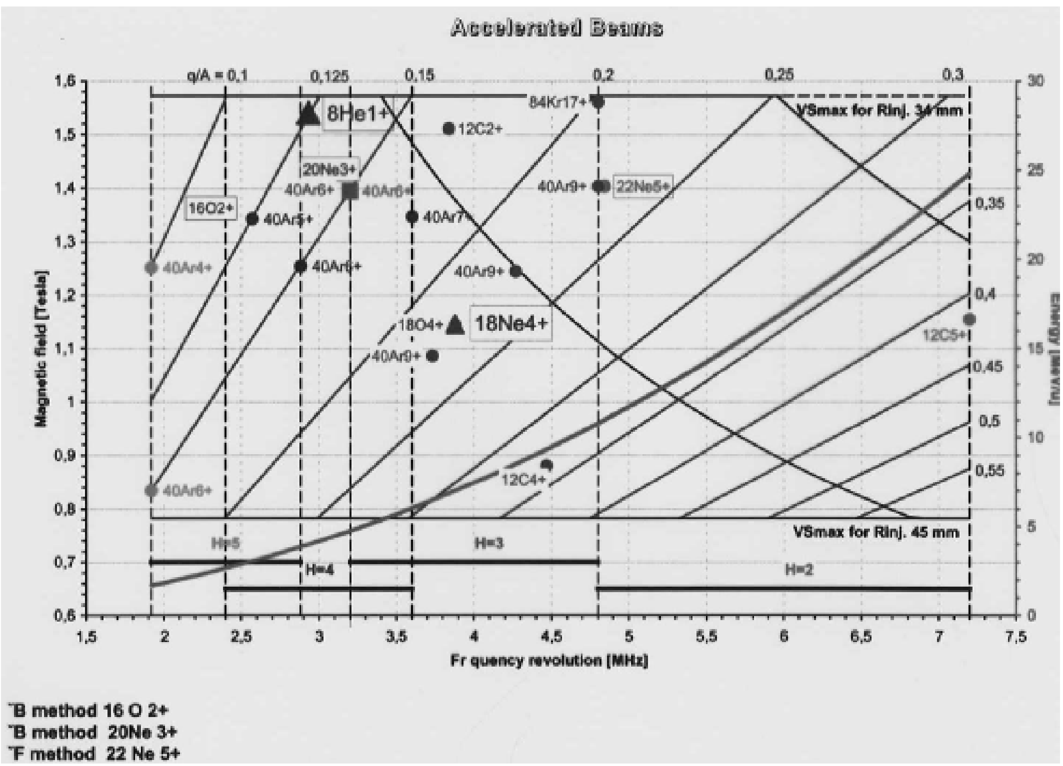

Fig. 2. Working diagram of CIME.

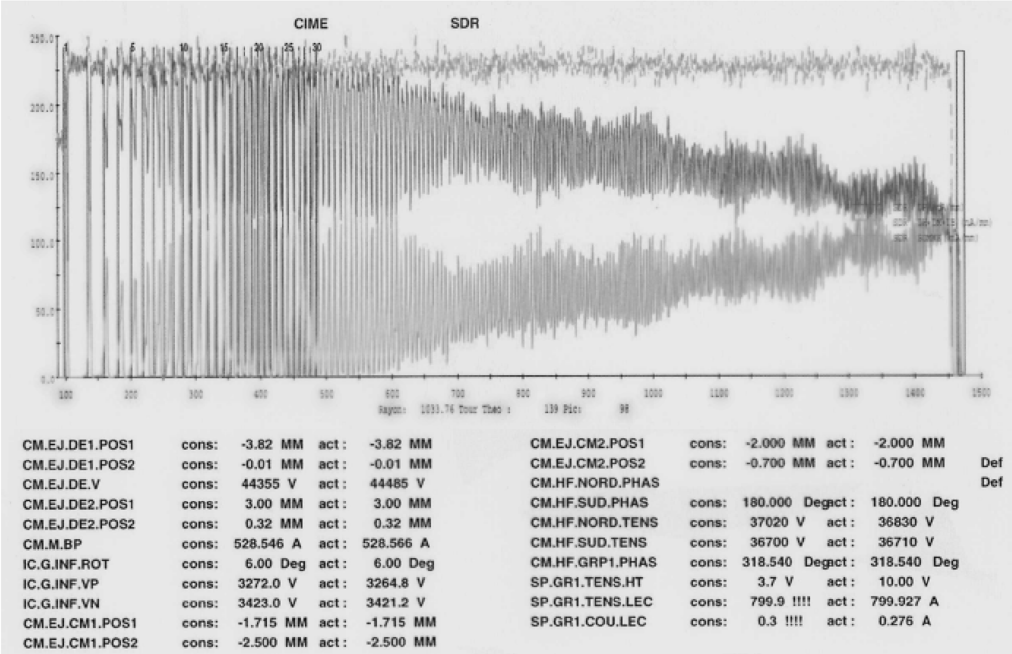

Fig. 3. Turn pattern on harmonic 3.

a retractable plastic scintillator dedicated to the measurement of the phase and phase width of the beam. The second one carries a silicon detector (E, ΔE) for a complete identification of the accelerated species. After acceleration, the beam line is also equipped with silicon detectors and a plastic scintillator. A special ionisation chamber for beam profile measurements has been developed. Profiles of beams with intensities as low as 100 pps at 2 MeV/u can be measured.

Tests with stable ions

Before getting the authorisation to produce a first RIB, we had more than one year to perform the commissioning of CIME with stable beams.

The CIME cyclotron has an off-centred axial injection and two different central geometries to cover the large energy range required.

From 5 to 25 MeV/u we use:

- a Muller type inflector, injection radius: 34 mm;
- angle of the tip of the dees: 60 degrees;
- RF harmonic mode 2 or 3.

At energies between 1.7 and 5 MeV, we use:

- a spiral inflector (Belmont–Pabot type) followed by an electrostatic quadrupole, injection radius is 45 mm;
- angle of the dee tips reduced to 40 degrees (no posts in the dees);
- RF harmonic mode 4 or 5.

The working diagram of the cyclotron printed below shows the stable beams produced along this commissioning period (Fig. 2). Both the central geometries and the four harmonics mode were successfully tested. The total transmission of the cyclotron was of the order of 40 to 50% for most of the beams with the exception of the lowest energy: 1.7 MeV/u which implies a very low extraction voltage at the source. The buncher uses a saw tooth signal and can catch about 65% of the CW beam. The extraction transmission is also about 65%, but sometimes with 2 turns.

At the beginning of the tests, the beam was lost before the extraction radius. It was necessary to add a 10 gauss first harmonic to keep the beam centred up to the extraction.

In order to understand this difficulty, an additional radial probe was installed to analyse the off-centring of the trajectories as well as four NMR probes able to measure the field under vacuum.

These equipments have shown an unexpected effect of the vacuum on the magnetic field due to a non-symmetric deformation of the magnet. Additional spacers have allowed to correct this defect and to obtain a complete acceleration without first harmonic correction. Figure 3 shows the turns pattern on RF harmonic 3, with the spacers installed.

Figure 4 shows one identification measurement using the silicon detector. Several beams with Q/M values differing only by a few 10^{-4} are accelerated simultaneously. During this test the silicon detector stands at a radius near the extraction, an RF shift allows to get the desired species at the extraction radius.

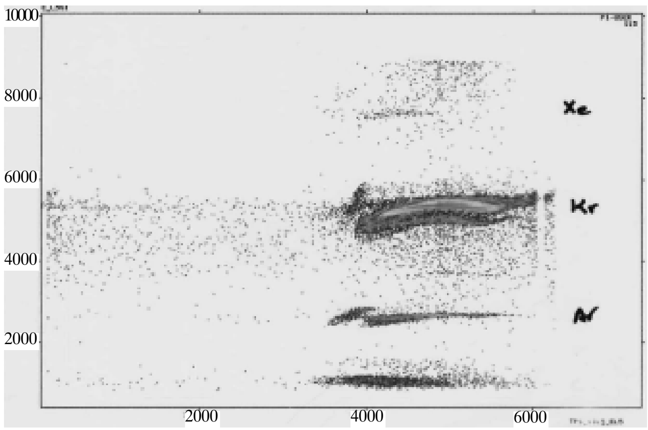

Fig. 4. Beam identification with the silicon detector.

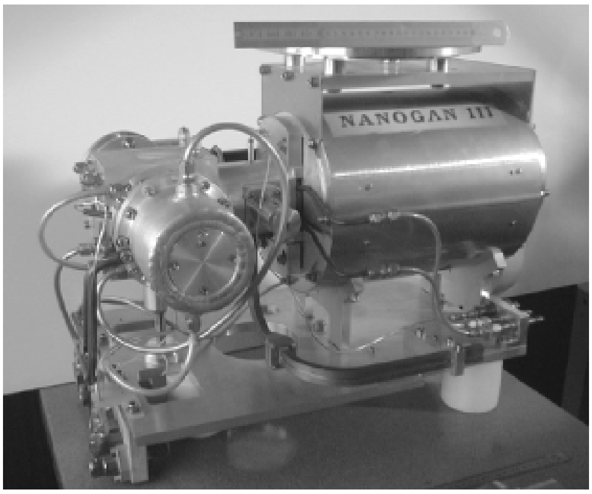

Fig. 5. The target and source assembly.

Production of radioactive ion species

After extensive tests on SIRa, the test stand installed since 1993 in one of the GANIL beam lines [3, 6, 7], the RIB production method chosen is based on an external carbon target linked to the ECR NANOGAN-III source by a short and cold transfer tube (Fig. 5).

This allows efficient production of noble gas elements with reasonable suppression of condensable contaminants. As an example, the overall efficiency of the system for the production of $^{35}Ar^{8+}$ is better than 10%. The ionisation efficiency – all charge states – of Ar ions has been measured to be better than 95% when NANOGAN-III is tuned in order to maximise the 8+ charge state.

The carbon target has been chosen due to its excellent release properties and its high sublimation temperature. This target guarantees the production of noble gases with reasonable yields and can be used with high power primary beams. This requirement has necessitated a special target design, which can withstand high power load while keeping fast release properties. From the production point of view, the target temperature should be as high and as uniform as possible, in order to minimise the delay time between production and release. The temperature profile is related to the properties of the Bragg peak, which is particularly pronounced in the case of heavy ions. Therefore, a special conical design, which distributes uniformly the power density over the target volume has been developed.

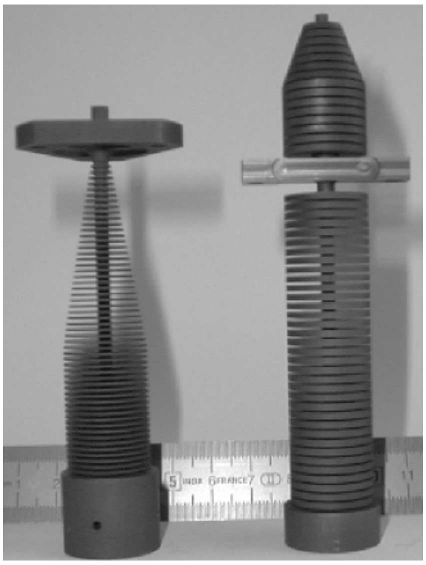

Fig. 6. Carbon targets for Ne/Ar (left) and for He production (right).

Table 1. RIBs tested at SIRa and predicted at SPIRAL with 2 kW of primary beam on target.

Beam	Charge state	Intensity (I) before acceleration (pps)	SPIRAL energy min./max. (A MeV)
^{6}He (0.8 s)	1+	1.0×10^{9}	2.7/7.2
	2+	8.0×10^{7}	6.8/22.8
^{8}He (0.12 s)	1+	3.0×10^{6}	2.7/4.0
	2+	3.6×10^{5}	3.8/16.3
^{17}Ne (0.11 s)	+(3–6)	1.5×10^{5}	2.7/24.3
^{18}Ne (1.7 s)	+(3–6)	1.5×10^{7}	2.7/22.9
^{19}Ne (17 s)	+(3–6)	2.5×10^{8}	2.7/21.6
^{23}Ne (37 s)	+(3–6)	6.0×10^{7}	2.7/17.7
^{24}Ne (3.4 m)	+(3–6)	2.0×10^{7}	2.7/16.4
^{25}Ne (0.61 s)	+(3–6)	5.0×10^{5}	2.7/15.1
^{32}Ar (98 ms)	+(6–8)	2.3×10^{3}	2.7/16.4
	9+	1.1×10^{3}	4.8/19.2
^{33}Ar (0.17 s)	+(6–8)	1.7×10^{5}	2.7/15.4
	9+	8.0×10^{4}	4.6/18.6
^{34}Ar (0.84 s)	+(6–8)	1.2×10^{7}	2.7/14.5
	9+	6.0×10^{6}	4.3/18.0
^{35}Ar (1.78 s)	+(6–8)	3.0×10^{8}	2.7/13.7
	9+	1.5×10^{8}	4.0/17.3
^{74}Kr (11 m)	+(15–16)	1.0×10^{5}	2.7/12.3
^{75}Kr (4 m)	+(15–16)	7.0×10^{5}	2.7/11.9
^{76}Kr (14.8 h)	+(15–16)	3.0×10^{6}	2.7/11.6
^{77}Kr (74 m)	+(15–16)	2.0×10^{7}	2.7/11.3

A specific target divided into two parts due to the long range of He in carbon, was developed for the ^{6,8}He production (Fig. 6). The ^{13}C primary beam only heats the first part (production target), while the second one (diffusion target) stops the fragmentation products, and is heated by an electric current through the axis.

The radioactive beams which were produced at SIRa are now available at SPIRAL. They are listed in Table 1 (with a primary beam power limited at 2 kW). The list is no limiting.

First radioactive ion beams

The first SPIRAL beam has been delivered for physics by the end of last September. The ^{18}Ne (1.67 s half-live) isotope has been produced through the projectile fragmentation of ^{20}Ne primary beam at 95 A MeV on a carbon target. The aim of this experiment was the spectroscopy of the exotic ^{19}Na nucleus, very little is known about this nucleus which has $N = 8$ magic number and is unbound at its ground level.

For this first experiment, a maximum primary beam intensity of 0.18 pμA was used, in order to limit the irradiation of the production ensemble. The radioactive atoms released from the carbon target – heated only at 1800°C – were ionised by NANOGAN-III ECR ion source to the 4+ charge state. The beam was accelerated up to the energy of 7 A MeV. The maximum beam intensity of ^{18}Ne achieved during this first run was of 2×10^6 particles per second at the experimental area. The beam was contaminated by 15% of ^{18}O and a very small amount (<1%) of ^{18}F. The beam was finally purified from the contaminants by a stripping foil placed in the entrance of the LISE spectrometer.

The overall efficiency of the production and acceleration amounts to about 3%.

This figure results of the following factors:
- more than 90% of the produced atoms diffuse out of the target and arrive in the ECR ion source;
- 15% of these atoms are extracted in the charge state 4+;
- the transmission of the low energy separator, corresponding to the first half of the injection line of CIME was of the order of 50% (this low value was due to a misalignment, and was further improved thanks to a magnetic steerer);
- the transmission of the cyclotron CIME, everything included, was also 50%.

The present design of the carbon target allows to increase the primary beam intensity up to 1 pμA, which corresponds to 10^7 particles per second of ^{18}Ne.

The excellent stability and reproducibility of the whole production and acceleration system should be pointed out. During the experiment one could easily change the tuning of the cyclotron from ^{18}O – the stable "analogue" beam – to ^{18}Ne within some 15 minutes.

The intensity of ^{18}F accelerated at the same energy (7 A MeV) was also measured at the end of the run, simply by a small change on the CIME magnetic field. We measured an intensity of 2×10^5 particles per second with the same primary beam intensity (i.e. 0.18 pμA). It is expected that, at the maximum intensity and using a primary beam of ^{19}F, the final ^{18}F intensity would be of the order of 10^7 particles per second.

Since then, beams of ^{8}He at 15.4 A MeV and 3.5 A MeV and ^{76}Kr at 7.3 A MeV were also produced for experiments. The intensities achieved using a primary beam power of respectively 1.4 kW and 500 W are in perfect agreement with the expected ones. The intensities for ^{8}He at higher and lower energies, corresponding to the charge states of 2+ and 1+, were of 1.4×10^4 pps and 4×10^4 pps. For ^{76}Kr, the intensity obtained was of 1×10^6 pps.

A vacuum leak problem in the zone close to the target during the ^{8}He runs necessitated a small change in the design of the window support.

A new target for He production with the capability to withstand a beam power up to 3 kW (the maximum allowed intensity for ^{13}C primary beam) will be in operation this autumn (2002). The maximum operation intensity of 6 kW in the production target for Ne, Ar and Kr primary beams should be achieved in 2003.

Table 2 shows the first RIBs produced and the comparison with the predicted intensities (for the same primary beam intensities).

Table 2. First radioactive beams at SPIRAL.

Ion	Primary beam (pps)	I (pps) and E	I predict.
^{18}Ne (4+)	^{20}Ne 1.2×10^{11}	2×10^6 7 A MeV	1×10^6
^{8}He (2+)	^{13}C 9.7×10^{11}	1.4×10^4 15.4 A MeV	2×10^4
^{8}He (1+)	^{13}C 7.5×10^{11}	4×10^5 3.5 A MeV	2×10^5
^{76}Kr (11+)	^{78}Kr 4.4×10^{10}	1×10^6 4.3 A MeV	1×10^6

Future projects at GANIL

SPIRAL, as it is now, can produce only radioactive ions obtained by fragmentation of the stable heavy ions accelerated by GANIL. Of course, this limits considerably the number of radioactive species which can be produced.

A project named SPIRAL II was since the beginning foreseen to extend the number of available species.

In this project, fission induced by light particles (e, p, d, etc.) is proposed to produce the radioactive ions, with an aim of 10^{13} fissions/s at least.

Since 2001, two proposals are studied simultaneously:
- the electron option where electrons, accelerated up to 45 MeV by a super-conducting linear accelerator produce high energy photons by bremmstrahlung, the photons themselves inducing the fission of the atoms of the uranium target;
- the deuteron option where the fission of uranium is obtained by the neutrons produced by 40 MeV deuterons stopped in a converter or in the target itself.

After a careful analysis of the two options, the deuteron one was finally preferred, in spite of a higher cost, as it opens more possibilities for the future.

In the present design, the project named LINAG phase 1 is mainly composed of a deuteron source (possibly a copy of SILHI, the high intensity proton source of the 5 MeV accelerator French project) followed by a RFQ with an output energy of 0.75 MeV/u and a superconducting linear accelerator made with independently phased quarter wave resonators (QWR). The deuteron beam (5 mA and 40 MeV) is directed toward a heavily shielded production target were the neutrons produce the uranium fission.

Conclusions

SPIRAL is in operation since September 2001. The first radioactive beams produced have shown that the machine and the concept are sound. The intensities obtained are in good agreement with the ones predicted. In the meantime, progress were made on the production of the primary beams and the limit of 6 kW CW was now reached for several species. The demand of beam time for experiments using radioactive ions exceeds the possibilities of the machine by a factor 3 or more.

New developments are on the way, they will allow GANIL to continue to play a major role in nuclear physics and astrophysics research in Europe.

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