ECRISs AT GANIL TODAY AND TOMORROW

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Abstract

GANIL (Grand accélérateur National d'Ions Lourds) uses ECRISs for producing stable and radioactive ions for more than 20 years. Two ECR4 type ion source (IS) deliver intense multi-charged stable ion beams of gaseous and metallic elements feeding cyclotrons for post acceleration to energies up to 100 A.MeV. A full permanent magnet ECRIS is also employed for producing multi-charged radioactive ion beams in the frame of SPIRAL 1 (Système de Production d'Ions Radioactifs Accélérés en Ligne, part 1). For atomic and material physic experiments, a high performance ECRIS labeled GTS developed at CENG/ Grenoble (France) is currently used to deliver high intensity, high charge state and low energy ion beams. To extend the range of radioactive ion beams available at GANIL, two ISOL (Isotope Separator On Line) projects are underway (SPIRAL1 upgrade and SPIRAL 2). In the frame of these projects, radiation hard singly-charged ECRIS, Q/A=1/3, 1/6 ECRISs, 2.45 GHz deuteron ECRIS and permanent magnet target ion source system (TISS) using an ECRIS are under development in parallel. A review of the main uses, current developments and performances obtained or expected with ECRISs at GANIL are presented. Locations of all the setups mentioned below are indicated in Figure 1.

INTRODUCTION

In 1982, GANIL delivered its first stable ion beam at high energy, using Penning Ion Gauges (PIG) as injectors for cyclotrons. For reasons of short lifespan, the PIG Ion Sources (IS) were frequently replaced (every ~40 hours), reducing the available time for operation. In 1985, a 10 GHz ECRIS named MINIMAFIOS [1] and developed by R. Geller was installed as one of the two injectors. Its advantages were higher lifespan, intensities and stability. Three years later, it was replaced by a 10 GHz CAPRICE [2] ECRIS, allowing an enlargement of the beam range in term of charge states and elements, stretched to metallic elements. In 1991, PIGs are definitely abandoned. The second injector of GANIL is equipped with a 14 GHz ECR4 [3] type IS placed at 100 kV. Its commissioning in 1993 showed an important increase of beam intensities for gas and metallic elements compared to the ones obtained with CAPRICE. A gain of ionization efficiency was also observed using a micro-oven for several metallic elements. Finally, CAPRICE was replaced by an ECR4 IS in 1995.

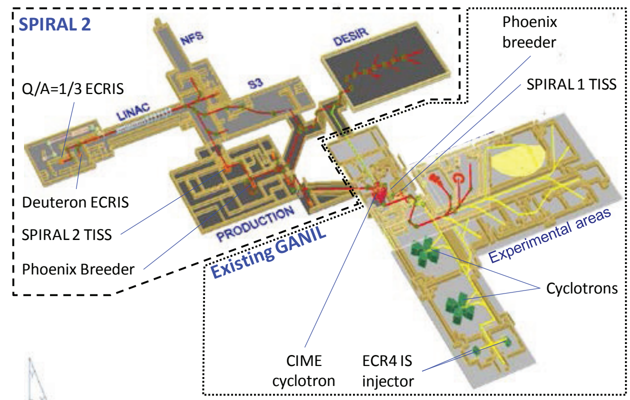

Figure 1: Schematic of the GANIL today and by 2020. Yellow lines: stable ion beams at GANIL. Red lines: SPIRAL 2 ion beam lines.

In 1994, GANIL decided to extend its range of ion beams to radioactive ones using the isotope separator on line (ISOL) method. The studies of SPIRAL 1 facility are undertaken and the first radioactive ion beam is delivered in 2001. Radioactive isotopes are produced in the target and ionized by an original permanent magnet ECRIS (NanoGan III [4]), designed to cope with the numerous constraints inherent to the generation of radioactivity. Ions emerging from the TISS are mass to charge separated and injected in the post-accelerator cyclotron CIME [5] to reach energies up to 25 A.MeV.

The increasing demand of radioactive ion beams encouraged GANIL to extend its range of available beams [6]. In 2006, the construction of a second radioactive ion beam facility (SPIRAL 2) was officially decided at GANIL. Beams of short lived heavy radioactive ions will be produced in flight by the S3 facility [7]. Longer lived isotopes will be produced by ISOL method in the production cave containing a TISS. Two production methods will be used:

- fission of uranium induced by neutrons, these latter being produced in a graphite converter on which a deuteron beam impinges,
- reaction of heavy ions on target material. Two ECRISs are chosen as injectors for the LINAC post-accelerator: an existing 2.45 GHz ECRIS delivering up to 5 mA of deuterons developed at

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IRFU/Saclay/France, and a multi-charged ECRIS being designed at LPSC/Grenoble which should deliver high intensities and heavy ion beams with masses higher than He.

In the target, a large variety of elements will be produced. Each of them will be ionized by a specific IS. For gaseous isotopes an ECRIS will be employed. Owing to the dose rate close to the production target, a specific radiation hard ECRIS (named MonoBob [8]) was designed. Technical difficulties have limited their performances to single ionization. Since ion beams must be multi-charged before being injected in the post accelerator CIME, a PHOENIX type charge breeder [9,10] will be inserted between the 1+ ECRIS and CIME. If not post-accelerated, the ions can be directly used by the DESIR [11] facility.

Since 2001, SPIRAL 1 is limited to the production of ions from gaseous elements. The chemical selection was obtained using a cold transfer region connecting the target to the ion source. To offer new radioactive ion beams to physicists while the SPIRAL 2 is being constructed, GANIL decided in 2011 to improve the SPIRAL 1 facility. After transformation, present TISS, surface IS [12] and FEBIAD as developed at ISOLDE [13] will be used in the production cave. As for SPIRAL 2, a PHOENIX type charge breeder will be installed between the singly-charged IS installed in the cave and CIME.

Since 2010, one last ECRIS development is underway to give an alternative solution to the additional stage of charge breeding in case of low charge state (Ar^{8+} for instance) [14]. The final version would consist in a compact, multi-charged and radiation hard ECRIS placed close to the target.

The previous overview shows that at GANIL, ECRISs are used for four different goals:

- highly charged stable ion beams
- high intensity ion beams,
- high ionization efficiency (for stable and radioactive ion beam production)
- high charge breeding efficiency

The range of ECRIS applications is indeed larger than the GANIL use, as the range of existing ECRIS technologies is larger than those employed at GANIL. Nevertheless, GANIL has the chance to be a laboratory where several ECRISs have been designed, constructed and used during years and thus benefits from an important operation feedback. Today, in most cases, due to their complexity, the future ECRISs can no longer be studied and developed in a unique laboratory. Collaborations are more than ever necessary, to go further in the future of ECRISs, as well illustrated by the actual instance of SPIRAL 2.

STABLE BEAM INJECTORS

The cyclotrons of GANIL are fed by stable heavy ion beams produced by two ECRIS: ECR4 type ion sources. The ion masses range from carbon to uranium and the post acceleration energy goes up to 95 A.MeV, depending on the ion mass to charge ratio. Current performances for some metallic beams can be found in reference [15] and on the GANIL web site [16]. More recent results related to I and Cs ion beam production are detailed in ref. [17].

New results for Ti have been obtained using the MIVOC method [18]. The compound (CH3)5C5Ti(CH3) synthesized by the IPHC/Strasbourg team [19] from natural Titanium (48Ti : 75%) has been used for tests. An intensity of 20 (±3) µA for 48Ti10+ was maintained for 4 days, while regulating the temperature of the MIVOC chamber. A consumption of 1.5 mg/h for the MIVOC compound has been deduced, i.e. 0.23 mg/h for 48Ti. The resulting ionization and transport efficiency of Ti for all charge states was of 10%. Corrected from the transport efficiency (33%), the ionization efficiency was close to 30%. The corresponding Ti spectrum is displayed in Figure 2.

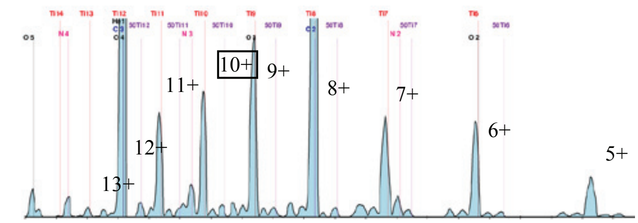

Figure 2. Charge state distribution of Ti. Optimized charge state: 10+ (20 µA). Mixing gaz He. RF power 170 W. Extraction voltage : 74 kV. Total extracted current from the source: 1.9 mA.

SPIRAL 1 ECRIS

Radioactive ion beams are produced by SPIRAL1 using TISSs. High energy ion beam, named "primary beam" coming from previous cyclotrons impinges on a thick carbon target. Helped by the target temperature, radioactive isotopes produced during the collision diffuse out of the carbon up to an ion source (see Figure 3).

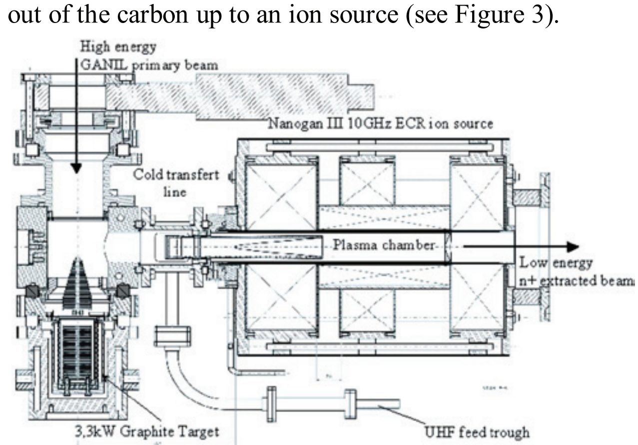

Figure 3: SPIRAL1 TISS

This source must cope with several requirements, *i.e.* mainly injection parameters of the post-accelerator cyclotron CIME and hostile neighborhood around the production target. That induces multi-charged ionization (typically $^{40}Ar^{8+}$), reliability, simplicity, radiation hardness and low cost. A simple permanent magnet ECR ion source was designed and is now used since 1998. According to the initial requirements of the SPIRAL1

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project, to the ECR principle and to the primary ion masses used, mainly radioactive ions from gases are produced, from He to Kr [20].

SPIRAL 2 PROJECT

The SPIRAL 2 project [21] is based on a multi-beam driver in order to allow both ISOL and low-energy in-flight techniques to produce Radioactive Ion beam (RIB). A superconducting light/heavy-ion LINAC with an acceleration potential of about 40 MV capable of accelerating 5 mA deuterons up to 40 MeV and 1 mA heavy ions up to 14.5 MeV/u is used to bombard both thick and thin targets. These beams could be used for the production of intense RIB by several reaction mechanisms (fusion, fission, transfer, etc.) and technical methods (ISOL, gas catchers, recoil spectrometers, etc.). The production of high intensity RIB of neutron-rich nuclei will be based on fission of uranium target induced by neutrons, obtained from a deuteron beam impinging on a graphite converter (up to 10^{14} fissions/s) or by a direct irradiation with a deuteron, ^{3}He or ^{4}He beam.

The atom-to-ion transformation will take place into the TISS. Owing to the large variety of radioactive atoms produced in the target, four different singly-charged ion source types are considered and are presently under development: Surface ion-source [22], FEBIAD IS, Laser IS [23] and ECRIS. Only this latter is presented in this paper.

Production of Primary Q/A=1/3 Ion Beam

As shown in the paper [24] of T. Thuillier, several beam intensities requested by the SPIRAL 2 project cannot be produced today by the most performing ECRISs, even if some of them already fit with the specifications (see Table 1).

Table 1: Non exhaustive list of ion intensities expected at the exit of the Q/A=1/3 ECRIS of SPIRAL 2.

Ion	SPIRAL 2 specifications	PHOENIX V2	Other ECRIS	Reference
$^{18}O^{6+}$	1000	1300	2850 ($^{16}O^{6+}$)	VENUS [25]
$^{40}Ar^{14+}$	420	50	514	VENUS [25]
$^{36}S^{12+}$	240	55	-	-
$^{48}Ca^{16+}$	160	16	70	SECRAL [26]
$^{58}Ni^{19+}$	57	19	50	SUSI [27]

Reaching the expected intensities needs to develop a new ECRIS. Regarding the requirement level, a large volume 28 GHz superconducting (SC) ECRIS seems to be the most adapted. Such a SC ECRIS has not been included in the SPIRAL 2 construction budget. Thus, the commissioning of the linear accelerator will be made by 2014 with the existing room temperature ECRIS PHOENIX V2 developed at LPSC/Grenoble/ France. It is presently under tests to produce Ar^{14+}, Ca^{16+} and Ni^{19+} beams. Its installation on SPIRAL 2 should take place by spring 2014. A new SC ECRIS would be developed if funding were granted.

Production of Primary Deuteron Beam

The 2.45 GHz ECRIS [28] developed at Saclay has already demonstrated its capability to respect the SPIRAL 2 specifications, *i.e.* to deliver more than 5 mA of deuteron at 40 kV of extraction voltage. The source and the low energy beam line with a part of their services will move at GANIL to be installed by the end of 2012.

Ion Beams Production from Gaseous Isotopes.

In order to ionize gaseous isotopes (of He, O, Kr or Xe…) coming from the target of SPIRAL 2, the design of a new radiation hard ECR source of singly-charged ions has started in 2002. The startup design is based on a previous ECRIS named MONO1000 [29] which presented several interesting features for ISOL use: simple mechanical arrangement, small, low cost, reduced weight and thus simplified retreatment process. Its ionization efficiency was high enough (~80% for Ar or for heavier noble gases) and the source presented a large aperture between the magnetic rings which allows connecting the target very close to the plasma chamber, which is important to succeed in producing short lived isotopes.

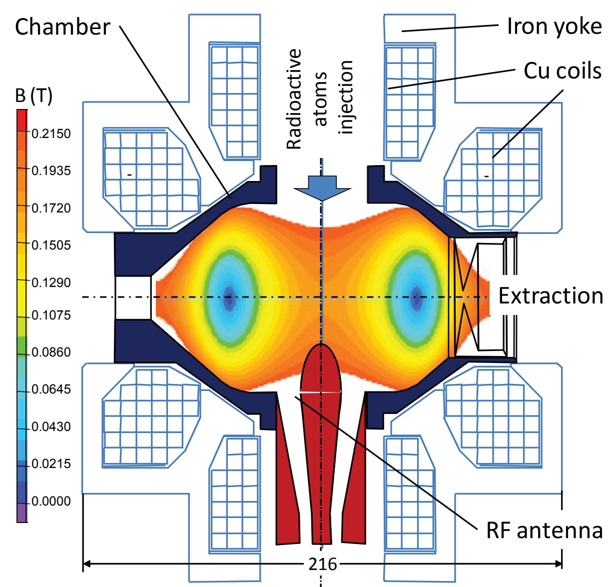

Figure 4: Schematic of the SPIRAL 2 singly-charged ECRIS.

To cope with the constraint of hostile environment around the target of SPIRAL 2, and of the installation of the TISS under vacuum, we attempted to reproduce the magnetic field and performances of Mono1000 by using only radiation hard components and low out-gassing materials. The final solution (MONOBOB) mainly consists in a magnetic structure where each permanent magnet ring was replaced by two coils insulated by glass fiber, and in a simple chamber free of O-rings. The

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2.45 GHz power is injected via an RF antenna which can deeply penetrate the chamber owing to the particular shape of the magnetic field. Cross section of the source is given Figure 4.

The current extracted from the source is generally lower than 1 mA and the ionization efficiency in the singly-charge state ranges from 40% to 100% for noble gases ranging from Ar to Xe. Extraction configuration must be improved, being for Xe close to 40% (at 14 kV).

SPIRAL1 UPGRADE

To reinforce the choice of ion beams to those made from condensable elements and with masses up to Xe, an upgrade of SPIRAL 1 has been undertaken [30]. Beams and technical options considered during the prospective phase [31] have been sorted out. A schematic of the ongoing upgrade is presented in Figure 5. Surface ionization, FEBIAD or new multi-charged ECR ion sources will be installed in the production cave after its modification. Out of the cave and after mass separation, an ECR Phoenix Booster type will be installed on the present low energy beam line to increase the charge of the radioactive ions from 1+ to N+ for post-acceleration.

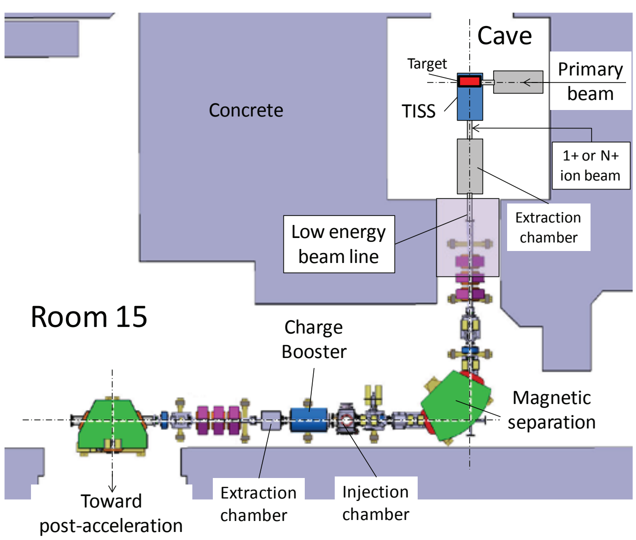

Figure 5: Schematic of the SPIRAL 1 upgrade.

Owing to the stringent regulation requirements the TISSs need to conform, the present TISS working in the cave will only be slightly transformed : The ECRIS will not be modified. Only the target and RF injection system will be improved to increase the global atom-to-ion transformation efficiency.

The booster that will be used on SPIRAL 1 is a commercial version of the Phoenix booster designed by LPSC Grenoble [32]. It has been first tested on-line at CERN [33] and is also under operation at TRIUMF [34]. Moreover, the breeding principle has been successfully tested at ANL [35]. Valuable feedback provides benefits to the design of our charge breeder [36] (see Figure 6): the vacuum system has been reinforced in the injection chamber to reach a very low pressure, important for getting a high 1+ to N+ transformation efficiency, narrowing the charge state distribution and to limit the presence of contaminants. The 1+ optical system has been studied to ensure an easy tuning of the beam injection with many degrees of freedom (vertical and horizontal steering, electrostatic lenses). A translational freedom of the coaxial injection tube along the booster axis has also been added to optimize the electric field shape near the plasma and thus the capture conditions. The possibility to make the 1+ and existing N+ beams going through the booster when it is off has been taken into account. This function is essential when the beam delivered by the TISS is directly used, *i.e.* without charge breeding, either for post-acceleration or in the experimental beam line LIRAT [37] (Ligne d'Ions Radioactifs A Très basse énergie). In this case, the coils of the booster are used to transport the singly-charged ion beam through the apertures of the booster electrodes. The beam can be adapted for injecting it inside the cyclotron by tuning of the beam line after the booster.

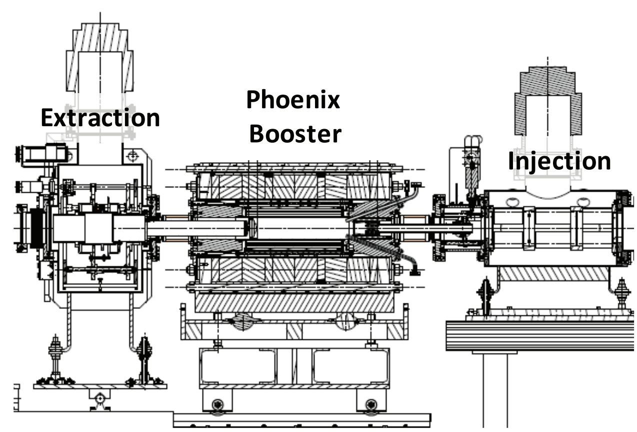

Figure 6: Injection, charge breeder and extraction for SPIRAL 1.

The singly charged ions coming from the cave will cover the range from He^{+} to Xe^{+}, with post-accelerated energies ranging from ~25 A.MeV to ~7 A. MeV respectively, depending on the isotopes considered. The breeding efficiency is generally better for ion masses higher than ~30. Beyond mass higher than ~100, the transport between the TISS and the booster must be made at lower extraction voltage, due to the limit of the magnetic rigidity of the mass separator, which limits the transport efficiency. Thus the preferential mass range of SPIRAL 1 upgrade goes from ~30 to ~100.

The transformation had to be managed in a frame of very strict safety rules, leading to a stopping period of operation of 1.5 years from 2014 to beginning of 2015. The installation of the booster should be achieved by June 2014 and new beams should be available by spring 2015.

MULTIGAN

As previously demonstrated [38], the large and direct aperture performed between a two magnetic rings ECRIS permits a direct view between the target cavity and the plasma, making possible the production of radioactive ions from condensable elements. Years ago, this possibility incited us to transform a full permanent

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magnet singly-charged ECRIS [29] into a full coil singly-charged ECRIS to sustain the dose rate present around a TISS.

Producing multi-charged ions needs to restart the process: first, testing with permanent magnets if an arrangement as simple as for MONO1000 but with a reinforced magnetic field could cope with magnetic features requested for a multi-charged ionization. An ECRIS [14] has been built and is presently under test on a bench of the Pantechnik company. Preliminary results have showed the production of Ar^{4+} and Xe^{6+} but with a low intensity. Depending on the results, especially the ionization efficiencies, a version might be developed and adapted to be tested on SPIRAL1 for producing medium charge state condensable ions of short half-life (<100ms). In a second step, and if the results are encouraging, we will attempt to reproduce the magnetic structure with coils only.

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