ISBN: 978-3-95450-196-0 doi:10.18429/JACoW-ECRIS2018-MOC4

SPIRAL1: A VERSATILE USER FACILITY

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Abstract

SPIRAL1 Upgrade hardware is now almost completed. The FEBIAD 1+ source has been tested for the production of new radioactive isotopes, the SPIRAL1 Charge Breeder (SP1 CB) is in place reproducing nearly the charge breeding efficiencies measured at LPSC laboratory and the infrastructure is operational. The commissioning phase started in the first semester of 2017. It has consisted of a stepwise process to test the upgrade of the SPIRAL1 facility from simple validation (operation of SP1 CB as a standalone source) up to the production of the first 1+/N+ Radioactive Ion Beam (RIB) with the $^{37}K^{9+}$ ion.

This contribution will summarize the different steps completed successfully and especially the measurements performed to validate each of the commissioning stages. These include e.g. ionization efficiency measurements for CB; beam line optics for 1+/N+ and charge breeding tuning. The remaining effort required to ensure the reliability of the complete system for routine RIB operation is also presented. A section will be dedicated to the coupling of SP1 CB to the CIME cyclotron, leading to the delivery of stable beams at unprecedented energies at GANIL.

INTRODUCTION

SPIRAL 1 is in operation since 2001 [1]. Radioactive atoms are produced by fragmentation of heavy ions up to 95MeV/u on a graphite target, and ionized in a multi-charged ECR ion source before post-acceleration in the CIME (Cyclotron d'Ions de Moyenne Energie) cyclotron [2]. This original Target Ion Source System (TISS) [3] was designed to provide mainly gaseous radioactive beams thanks to a cold transfer tube between the target and the ion source, trapping the radioactive condensable elements. The natural extension is to expand the radioactive beam production capability to condensable elements with masses up to 90 a.m.u.; hence, an upgrade of SPIRAL1 has been undertaken. The new configuration is based on the use of the 1+/N+ method developed at LPSC [4]. The aim is to have a larger palette of 1+ TISS devoted to other chemical element families. In this framework, a development of a TISS containing a FEBIAD (Forced Electron Beam Induced Arc Discharge) type ion source [5] is realized and some optimizations are requested to increase the longevity of such a system as well as the global efficiency. Moreover, the charge breeder has been modified to increase its efficiency based on the conclusions of the Emilie collaboration studies [6]. More adjustments have been achieved during the commissioning phase at GANIL to enhance the production of highly charged ions. It started in June 2017 and ended in July 2018. During this period, numerous tests regarding beam optics, charge breeding efficiencies and coupling with the CIME cyclotron have been investigated to validate the whole system. This paper aims to present the outcomes and demonstrate that the SPIRAL1 facility is far beyond a unique 1+/N+ system.

SPIRAL1 CHARGE BREEDER

Figure 1 displays a scheme of the SP1 CB. It is mainly composed of an electrostatic quadrupole triplet aiming to focus the 1+ incoming beam into the SP1 CB injection part, the SP1 CB itself and an extraction system based on a movable grounded electrode connected to an Einzel lens. The SP1 CB is a version of the PHOENIX charge breeder developed at LPSC laboratory and built by the Pantechnik [http://www.pantechnik.com/] Company. During the commissioning, two main changes and one optimization have been done following the tests of this device done at LPSC in 2015. For the beam injection, an inner part of the injection iron plug, which acts as an RF blocker, was previously made of aluminium; it has been replaced by a soft iron piece having the same design to boost the maximum field at injection from 1.19T to 1.38T.

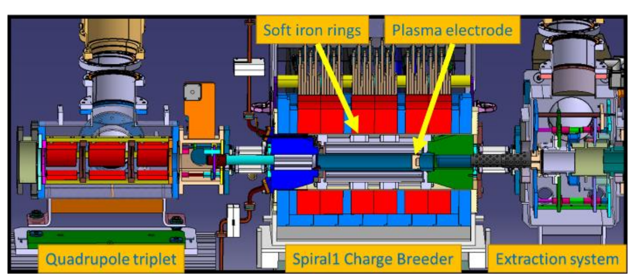

Figure 1: SPIRAL1 Charge Breeder.

At extraction, the plasma electrode has been moved closer to the maximum axial field by 10mm to reduce its interaction with the ECR plasma. The two soft iron rings, existing in the early design of the charge breeder, are placed on each side of the hexapole shaping the minimum

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B axial magnetic profile. An optimization of their location allowed optimizing the charge breeding efficiency. The benefit of these modifications can be seen in the Fig. 2. Two charge state distributions of $^{40}Ar^{q+}$ extracted at 20kV are displayed: left side (blue) the charge state distribution as measured during the LPSC test in 2015 and right side (orange) as recorded after the adjustments. It is clear that the highly charged ions are enhanced drastically.

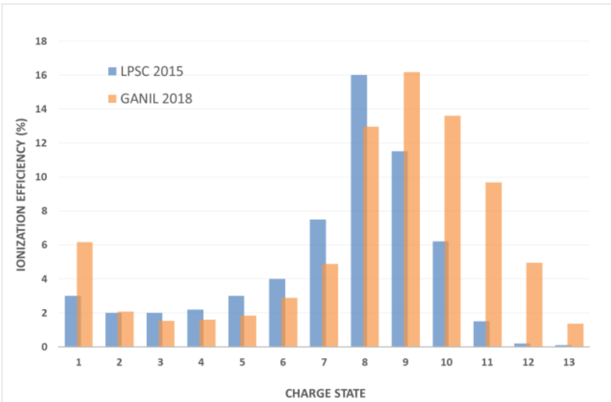

Figure 2: $^{40}Ar^{q+}$ charge state distributions.

MULTIMODE FACILITY

The upgraded SPIRAL1 facility will not use only the 1+/N+ method but other modes will also be available for providing beams to physicists: shooting through modes and SP1 CB as injector.

Figure 3 shows the four possible ways to use the facility. The two first modes (Fig. 3a and 3b) concern the shooting through modes. The SP1 CB is switched off. In the produc-tion cave, either NANOGAN3 TISS or FEBIAD TISS can be used. In the case of the NANOGAN3 TISS, a require-ment in the project was to keep the possibility to use this previous system to provide multi-charged RIB's of gaseous elements especially for their post'acceleration by CIME. For the FEBIAD TISS, the monocharged RIB can be either sent towards a tape station to be qualified (intensity and purity) or sent towards the LPCTrap device [7]. In the fu-ture, this 1+ beam line will connect SPIRAL1 to the SPI-RAL 2 low energy beam facility DESIR (Désintégration, Excitation et Stockage d'Ions radioactifs) [8]. For cleaning up the low energy RIB, a high resolution spectrometer un-der development at CENBG [9] will be installed before de-livering the beam to the new experimental area.

The third mode (Fig. 3c) is the 1+/N+ method. It in-volves the FEBIAD TISS combined with the SP1 CB, which is switched on. The stable or radioactive beam is then transported to the CIME cyclotron to be post-acceler-ated and finally delivered to the GANIL experimental ar-eas.

Finally, a new mode (Fig. 3d) is to use the SP1 CB as an injector since it is by itself an ECR ion source capable to provide highly charged ions on its own. In this mode ions are characterised by their M/Q ratio suitable to be acceler-ated by the CIME cyclotron. Consequently, it opens up a new way to provide stable beams for users in an energy range from few MeV/u up to around 20MeV/u.

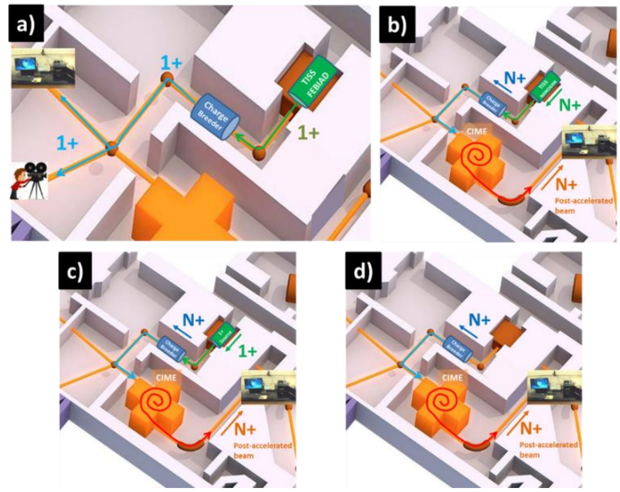

Figure 3: Four modes available at SPIRAL1 facility. a) Shooting through 1+ b) Shooting through N+ c) 1+/N+ d) SP1 CB as injector.

COMMISSIONNING PHASE

The commissioning phase started beginning of June 2017. A major part of the commissioning was dedicated to find out the new optic settings as the beam transport line between the TISS and CIME has been largely reshuffled.

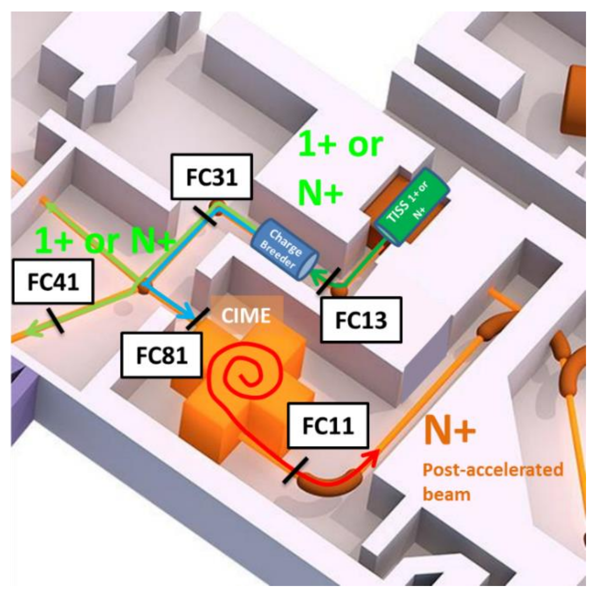

Figure 4: Location of the faraday cups along the SPI-RAL1 facility.

A first study was performed regarding the 1+ beam line between the TISS and the entrance of the SP1 CB (switched off). The goal was to transport 1+ beams from the production cave up to the Faraday cup CF31 (down-stream the SP1 CB, see Fig. 4, with the highest possible transmission. For this goal, an ion gun has been developed

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based on a surface ion source using pellets from the Heat-Wave Labs company [10]. It can deliver stable alkali 1+ beams with an intensity up to several µA over weeks.

Benchmarking the beam characteristics (beam profiles in X and Y at several places and beam currents) using TraceWin code, a set of parameters was found to achieve 79% and 80% transmission for $^{23}Na^{1+}$ and $^{39}K^{1+}$. Doing the same work using the NANOGAN3 TISS but for a mul-ticharged ion beam ($^{40}Ar^{8+}$), the best measured transmis-sion was 62%, lower than those obtained with 1+ ions.

One explanation might come up from the emittance of the beam: In the case of the ion gun (1+ source), the beam emittance is around 30π.mm.mrad instead of, at least, 80π.mm.mrad for the NANOGAN3 (N+ source). The de-celeration tube at the entrance of the SP1 CB complicates the tuning of the beam optics through the charge breeder. It has an inner diameter of 24mm over 80mm length, limiting the size of the beam and the quadrupole triplet produces a strong focusing effect. To overcome this issue, a new de-celeration tube with a larger inner diameter of 48mm will be tested.

To verify the operation of the SP1 CB was conform to expectations, some charge breeding efficiencies were rec-orded, which are presented in Table 1. Even for the K and Ar cases, values are close to the one formerly obtained in 2015 [11]. A larger discrepancy exists for the Na case with a decrease of 47% and 32% for the 7+ and 8 + charge states, respectively. Additional investigation is needed to explain these differences, which are amplified regarding the num-bers obtained recently by the LPSC team [12]: 12.9% charge breeding efficiency for the 8+.

Table 1: Charge Breeding Efficiencies.

Ion	Charge breed-ing efficiency LPSC 2015	Charge breed-ing efficiency GANIL 2018
$^{23}Na^{7+}$	6%	3.2%
$^{23}Na^{8+}$	5.3%	3.6%
$^{39}K^{9+}$	13.0%	11.6%
$^{40}Ar^{11+}$	12.9%	9.7%
$^{37}K^{9+}$ ($T_{1/2}$ = 1.24s)		5.3%

For the first time at GANIL, a charge breeding effi-ciency of 5.3% has been recorded for one radioactive ion: $^{37}K^{9+}$ with a half-life of 1.24s. As compared to the charge breeding efficiency of the stable isotope, it represents around half of the expected value. As the ^{37}K half-life is long regarding the physics processes involved into the charge breeder, it cannot explain this discrepancy. Never-theless, this measurement lasted only four hours, including preparation with stable ^{40}Ar, which was not enough to op-timize properly such efficiency. More TISS to SP1 CB cou-pling tests should be done in on-line conditions to improve the overall efficiency.

The parameter, which drives the tuning of the com-plete system, is "efficiency". As the yield of radioactive at-oms produced in the hot carbon target are limited espe-cially for the very exotic species having short half-life <100ms, it is mandatory to maximize, for each section of the installation, this parameter. Table 2 shows typical num-bers measured and used to predict what will be the radio-active ion beam intensities available on the physicist target. Two modes are compared: the new 1+/N+ mode and the shooting through N+ mode using the previous NANOGAN3 TISS.

It is clear that the new mode 1+/N+ is, globally, less efficient due to the dissociation of the N0 ⇨ N+ ionization scheme into two separated processes: N0 ⇨ 1+ followed by 1+ ⇨ N+. There is a range (0.31% -1.37%) where the 1+/N+ system is equivalent, in terms of efficiency, to the previous system operating at SPIRAL1. In addition, the global acceleration efficiency of CIME is enhanced (35-42%) for the mode using NANOGAN3 TISS regarding previous values recorded before the upgrade of the SPI-RAL1 facility (around 20%). It might be due to the insert of the SP1 CB, which, thanks to its plasma electrode aper-ture of 6mm, defines better beam characteristics. Coming back to Table 2, the major bottleneck limiting the total effi-ciency of the complete system is the charge breeding effi-ciency and, to a lesser extent, the ionization efficiency of the FEBIAD source, which is currently around 5-10%. As the R&D program is pursued by a part of our group [13], some new discoveries have been done such as the addition of a heavy buffer gas Xe pulling up the ionization effi-ciency to higher values [12]. Concerning the charge breed-ing efficiency, more work will be undertaken on the injec-tion magnetic field profile as it was the major modification done at the LPSC CB leading to the great values obtained [12].

Table 2: Efficiencies Measured Aong the Pathway of the Beam at the SPIRAL1 Facility. See Fig. 4 for the Faraday cups Positions.

Section	1+/N+ mode (FEBIAD)	Shooting through mode N+ (NANOGAN3)
$\varepsilon_{N0 \Rightarrow \text{charged ion}}$	2.5%-50%	5-20%
$\varepsilon_{\text{Beam transport} \Rightarrow \text{FC13}}$	>80%	40-70%
$\varepsilon_{1+/N+}$	5-15%	-
Beam transport FC13 ⇨ FC31	>80%	60-75%
$\varepsilon_{\text{Beam transport FC31} \Rightarrow \text{FC81}}$	70-95%	75%
$\varepsilon_{\text{Beam acceleration FC81} \Rightarrow \text{FC11}}$	15-30%	35-42%
Total	**0.01-1.4%**	**0.3-3.3%**

The new mode "SP1 CB as injector" has been investi-gated during this commissioning phase. It should be men-tioned there that the maximum current accepted by the

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CIME cyclotron is around ~80pnA which allows the operation of a wide range of charge states produced by the SP1 CB. Table 3 summarizes the stable beams delivered to physicists for performing physics experiments. The advantages of this operation mode are the following:

- Less cost than using the full GANIL machine
- High versatility especially for delivering beams based on gaseous elements
- Shorter time for tuning the accelerated beam

ONGOING R&D

Obviously, constant R&D is carried on to improve the whole system. It is mainly focused on the two following devices: TISS systems and SP1 CB. Regarding TISS, a R&D has been done to develop a new compact one [14, 15]. In the same hot vacuum vessel, the radioactive atoms are created by fusion-evaporation reactions and ionized through the surface ionisation process. Off-line tests are encouraging and on-line tests are scheduled by spring 2019 at IPNO laboratory to validate the new TISS principle.

Regarding the FEBIAD TISS [13], one of the features for its operation is to have a lifetime of one month including the off line measurements to validate the TISS before installing it inside the production cave. Mostly, R&D targets the protection of insulation against degradation by either the global heat of the system or the carbon vapour coming out from the hot graphite production target.

It is known that the radioactive atoms yields, for specific isotopes, can be enhanced by choosing carefully the material constituting the thick target. Henceforth, R&D related to the development of new targets based on SiC and/or Nb elements are under progress.

Table 3: Stable Beams Produced by the SP1 CB and Accelerated by the CIME Cyclotron.

Element	Charge State	Extraction voltage (kV)	Final energy (MeV)
^{36}Ar	7	15	3.2
^{84}Kr	11	14.3	2
^{84}Kr	17	21.5	5
^{84}Kr	20	28.8	7
^{84}Kr	23	27.2	15
^{129}Xe	22	13.3	2.5
^{129}Xe	22	26.6	5
^{129}Xe	27	32.7	7
^{129}Xe	29	29.5	13

About the SP1 CB, three topics are investigated. First, the exploration of the ECR plasma properties is needed to get more insights of the physics processes underlying the capture as well as the confinement time processes acting on the global yields of the radioactive ion beams [16]. Secondly, it is of prime importance to improve as much as possible the charge breeding efficiency of light elements (A<50 a.m.u.). For this purpose, it is foreseen to study the magnetic field at the injection of the SP1 CB in close collaboration with the LPSC team as they obtained [12] values that are the highest for such a device. Finally, a RF amplifier (TWTA type) with a frequency range from 8 GHz up to 18 GHz will be installed close to the SP1 CB. The aims are three- folds: enhancing the highly charged ion creation especially for the new SP1 CB operation mode described above (SP1 CB as injector), improving the charge breeding efficiency [17] and getting a more stable beam during operation.

CONCLUSION

The upgrade of the SPIRAL1 facility is now over. The infrastructure has been modified to fulfil the safety – security requirements as the radiation area is extended by the use of the charge breeder. Ancillaries for the SP1 CB are installed in the adjacent rooms: RF klystron, power supplies for coils, ΔV platform etc.

The FEBIAD TISS has demonstrated its ability to produce monocharged radioactive ion beams with intensity up to 2 10^6 pps. Ionization efficiency and durability should be improved to match regular operation requirements.

The SP1 CB boosts the monocharged incoming beam with an average charge efficiency beyond 7%. However, this efficiency should be enhanced regarding light elements, which are requested by users. The new optic (setting) has been achieved and well understood for the section upstream the SP1 CB (1+ LEBT) while downstream (N+ LEBT) more investigations are needed using codes like TraceWin to get a better understanding of the parameters found experimentally.

Finally, one can conclude that commissioning phase is over, leaving the way open for the operation phase. A continuous R&D is under progress regarding hot production target materials, new TISSs, SP1 CB and beam optics to improve, at the end, the yields as well as the palette of RIBs available for the users at the SPIRAL1 facility.

ACKNOWLEDGEMENTS

The authors would like to thank all the GANIL technical staff for their support to achieve this upgrade of the SPIRAL1 facility. The authors would like also to give a special thanks to Richard Vondrasek at Argonne National Laboratory for his efficient advices regarding SP1 CB.

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