Charge Breeder at GANIL: metal charge-bred elements

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Abstract. The charge breeder of the SPIRAL1 (SP1CB) facility provided this year to physicists new Radioactive Ion Beams (RIB) for experiments and machine development, showing significantly improved performances compared to those obtained during the initial on-line commissioning of the SPIRAL 1 upgraded facility [1]. These improved performances were obtained thanks to thorough studies conducted off-line with 1+ ion beams produced by FEBIAD and ECR ion sources, successfully demonstrating the ability to couple SP1CB with them. In particular, the SP1CB established its capability to efficiently boost condensable elements such as $^{19}F^{n+}$, $^{32}S^{n+}$ and $^{54}Fe^{n+}$, in addition to more standard alkali elements. The charge breeding efficiencies have been investigated varying several parameters: buffer gas, beam transverse emittances etc… The ΔV curves of stable elements as well as radioactive ones were recorded for high charge states. Their trends are discussed in more detail. Finally, as molecular beams provide some advantages compared to atomic ion beams for selecting isobaric species and optimizing transport of the radioactive elements from the hot production target to the SP1CB plasma, one may wonder if the charge-breeding efficiencies could also take advantage of beams in the molecular form. The performances of the 1+/N+ charge-breeding process were investigated using SF_6 molecules broken into SF_x^{1+} ions and compared to regular F^{1+} and S^{1+} ions. This contribution will deal with these topics and latest results will be showed.

1. Introduction

The GANIL charge breeder of the SPIRAL1 facility is now regularly under operation [1-3]. After a commissioning phase at LPSC, the SP1CB has been implemented in the SPIRAL 1 beam lines, and has provided in the last 2 years charge-bred ions mostly from alkali elements (stable and radioactive), establishing its ability to deliver intense post-accelerated RIBs of high quality to nuclear physicists. The 1+ beams were delivered from a Target Ion Source System (TISS) based on a FEBIAD ion source [4] used in surface ionization (SI) mode [2]. Lately, the production of multicharged ions of non-alkali elements has also been investigated. For that purpose, the FEBIAD ion source was used in its more traditional plasma (P) mode to ionize a wide variety of condensable elements. In this mode, the injection of molecular beams was additionally investigated. Here, the production of charge-bred $^{56}Fe^{15+}$ ions thanks to the FEBIAD will be described and two examples of charge-bred $^{32}S^{x+}$ and $^{19}F^{x+}$ beams are presented, that are based on the monocharged molecule SF_x^{1+} produced with the

NANOGANIII TISS [5]. The optimum ΔV values related to the various types of monocharged ion sources and beams used will be discussed in detail. ΔV value is defined later in the text as the voltage difference between the 1+ ion source and the SP1CB: $\Delta V = V_{1+\text{ ion source}} - V_{SP1CB}$

2. SPIRAL1 charge breeder and iron charge-bred ions

The SPIRAL1 facility consists of a production cave where the monocharged ion sources are located [1]. Monocharged ions are transported and mass analyzed prior to their injection into the SP1CB. After the capture and stepwise ionization processes, charge-bred ions are extracted, transported and mass analyzed. M/Q spectra are recorded with a faraday cup downstream from the N+ mass analyzer. Later in the text, outcomes will be showed for two different 1+ ion sources: FEBIAD and NANOGANIII.

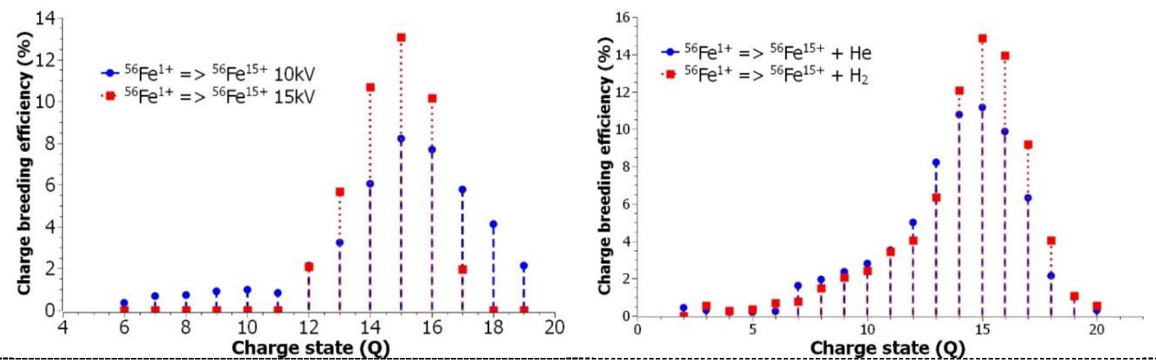

Figure 1. (left) $^{56}Fe^{q+}$ charge state distributions for two extraction voltages and He as the buffer gas; (right) $^{56}Fe^{q+}$ charge state distributions for two buffer gases (He and H_2) at 15kV of extraction voltage.

The FEBIAD ion source can be operated in two different modes: Surface Ionization (SI) or Plasma (P). The source is composed of an anode and a cathode. The cathode produces electrons, which are accelerated by the positive voltage between the cathode and the anode. Ions are produced within the anode volume by electronic impact. As the anode is surrounded by the electrical circuit of the cathode, the heating power also contributes to heat the anode. The SI mode has been found to correspond to 240A heating for the cathode, and a difference of potential of ~ 0V between the cathode and anode. The P mode is ignited by using a higher heating current for the cathode, of 290A and a difference of potential of 140V applied between the cathode and anode. For many years, the SP1CB performances have been evaluated based on noble gases and alkali elements. Thanks to the FEBIAD, it is now possible to produce other type of 1+ ions (P mode); a campaign of experiments has been achieved with the ^{56}Fe element: several hundreds of nA ($^{56}Fe^{1+}$) were extracted, pure from contaminants. For the tests, the SP1CB was tuned with helium as a buffer gas to sustain the plasma, and an optimum value of 15.3V was used. Figure 1 shows the $^{56}Fe^{q+}$ charge states distribution after the SP1CB as a function of the extraction voltage (Fig. 1 left) and buffer gas (Fig. 1 right). The beam losses with 10 kV are up to 40 %, and are reduced to 25 % with 15 kV extraction. By improving also the 1+ beam optics [7], the $^{56}Fe^{15+}$ charge breeding efficiency was increased from 8.2% up to 13.0% while maintaining the total charge breeding efficiency (summed over all charge states) Finally, sustaining the SPICB plasma with H_2 improves significantly the charge breeding efficiencies (Fig. 1 right) of high charge state ions, e.g. $^{56}Fe^{15+}$ from 11.2% to 14.9%. Furthermore, the total charge breeding efficiency increases to 78% with H_2 buffer gas. That behavior has already been established earlier [8, 9], and is confirmed here for a non-alkali element.

3. Charge-bred ions utilizing a monocharged molecular ion beam

The technique of using molecular 1+ beams (AlF, SeCO, SrF, BaF, BF_2) prior to their injection into an EBIS charge breeder has been formerly developed at the REX-EBIS facility (ISOLDE CERN) [10, 11]. Likewise, some preliminary attempts have been made with an ECRIS charge breeder with CO-CO_2 and LaO molecules to produce $C^{2,3+}$ or La^{23+} ion beams [12, 13]. The molecular form enables chemical selectivity (depending on the reactant injected) leading to an improved isobaric selection while speeding up the release from the target and the transport of the radioactive elements to the charge breeder.

3.1. The experimental study

Here, the purpose is to produce S^{q+} and F^{q+} charge-bred ions and to study the behavior and performances of the SP1CB with the injection of molecular 1+ beams of S and F compounds. The NANOGANIII ECRIS provides $^{19}F^{1+}$, $^{32}S^{1+}$, $^{51}SF^{1+}$, $^{70}SF_2^{1+}$ and $^{89}SF_3^{1+}$ ion beams to the SP1CB. Table 1 sums up the NANOGANIII tuning to foster the production of such monocharged beams. The gas injected is sulfur hexafluoride without any buffer gas. 1+ beam transverse emittances are limited with a series of three slits to 40 π.mm.mrad. Hence the 1+ beam is well defined by eliminating beam aberrations. The SP1CB extraction voltage, RF power, $B_{injection}$ current, B_{center} current, $B_{extraction}$ current were set to 20kV, 270W, 1190A, 320A, 655A respectively; helium was injected as buffer gas.

Table 1. Settings of the NANOGANIII ion source to produce dedicated monocharged ion beams

	RF power input (W)	Bias disc (V)	Logarithm gas valve voltage (V) (0 = open / 10 = closed)	Intensity (nA)
$\mathbf{^{19}F^{1+}}$	15	450	7.0	1100
$\mathbf{^{32}S^{1+}}$	15	450	8.2	850
$\mathbf{^{51}SF_X^{1+}, ^{70}SF_2^{1+}, ^{89}SF_3^{1+}}$	15	150	7.2	450 - 650

3.2. Sulphur and Fluorine charge-bred ions

Measurements have been done in the same way regarding the SP1CB; only the incoming 1+ ion beam was changed. Figure 2 displays the evolution of the ΔV curves for S^{1+} and three molecular beams of SF_x^{1+}. For all 1+ beams the optimum ΔV values are quite similar, around -20V. The FWHM of the peaks starts at 13V (S^{1+}) to 31.6V (SF_3^{1+}). The right part of the peaks have exactly the same slope (Fig. 2 left). It shows a second hump centered on around 35V and particularly pronounced for S^{1+} and SF^{1+}.

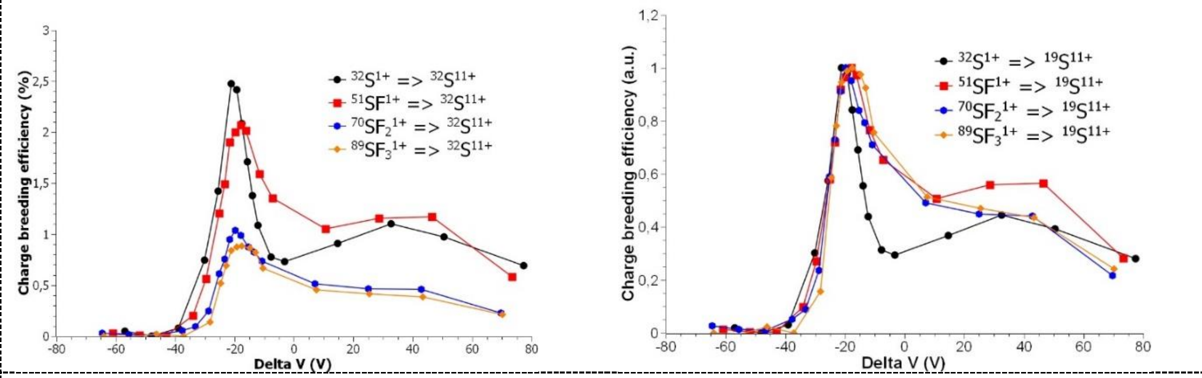

Figure 2. ΔV curves corresponding to S^{11+} charge-bred ions from elemental S or molecules $^{51}SF^{1+}$, $^{70}SF_2^{1+}$ and $^{89}SF_3^{1+}$. The right and left parts are the absolute and normalized data, respectively.

Measurements of F^{q+} (Fig. 3) charge breeding efficiencies were done in the same way as those with S^{q+}.multicharged ions. The behavior is quite different as the optimum ΔV as well as the FWHM of the peaks increase nearly linearly from -19.3V to -9.5V and 9.5V to 29V, respectively. However, while the high ΔV part related to the peaks have the same slope as in the sulfur case (Fig. 3 left), no bump appears at high voltage.

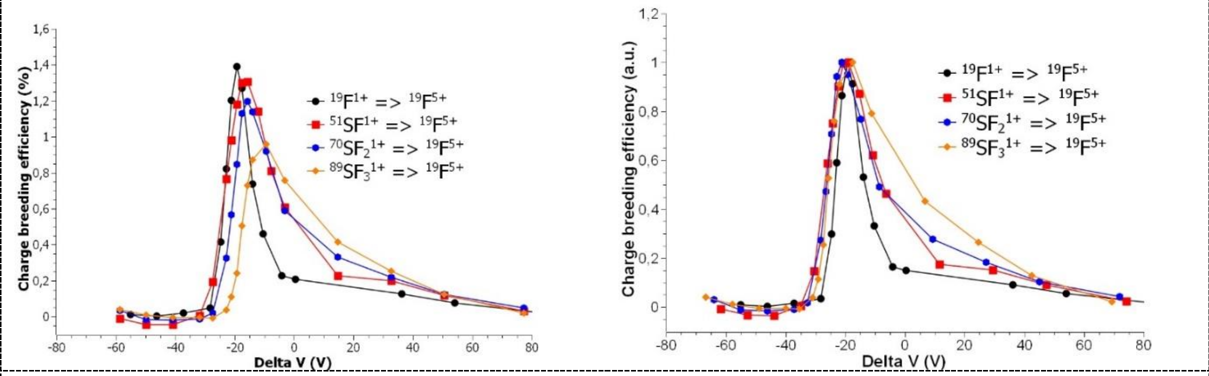

Figure 3. ΔV curves corresponding to the F^{5+} charge-bred ions from elemental F or molecules $^{51}SF^{1+}$, $^{70}SF_2^{1+}$ and $^{89}SF_3^{1+}$. The right and left parts are the absolute and normalized data, respectively.

3.3. Discussion

The charge breeding efficiencies are quite low with the maximum of ~2.5% and ~1.4% for S^{11+} and F^{5+}, respectively. A value of 5.5% was obtained for S^{1+}/S^{9+} but it was too close of a large contaminant peak to allow measuring methodically the ΔV curve. One explanation might be the large emittance combined with a large energy spread (4.8eV [7]) of the 1+ beam which are disadvantageous for achieving high charge breeding efficiencies [14]. The charge breeding efficiencies of single elements (S^{1+}, F^{1+}) are close to that of the simplest molecule SF^{1+}. With the increasing number of covalent bounds of the molecule to break (more F atoms), the charge breeding efficiency drops and even collapses for S^{11+}. Likewise (see the right part of Fig. 2 and 3), the slopes of the low energy part are really steep and equal for both cases. On the high ΔV side, the behavior are significantly different for S^{11+} and F^{5+}, which does not exhibit a hump. The subsequent open questions are: Does another process than coulomb collisions exists to slow down and capture 1+ ions? Why the ionization $F^{1+} \rightarrow F^{5+}$ appears in comparison so suppressed for these ΔV values? Are the molecules possibly more volatile than the atomic ions, and can be recycled from the plasma chamber wall? Finally one may wonder how the internal energy of the SF_x^{1+} could possibly play a role in their capture by the ECR plasma.

4. ΔV curves of the SP1CB versus monocharged ion sources

Figure 4 displays the ΔV curves for SP1CB using He as buffer gas coupled with the NANOGANIII ion source and the FEBIAD ion source in P or SI mode. The black curve corresponds to the FEBIAD SI mode for radioactive $^{47}K^{10+}$ ($T_{1/2}$=17.5s). The optimum ΔV value is 4V for a FWHM of 11V. A similar ΔV curve was published in the reference [8] (Fig. 7) for stable $^{39}K^{9+}$ with an optimum ΔV value and a FWHM of -5.5V and 7V, respectively. These results have been obtained using a thermal ion gun and can therefore be considered as a reference since this method minimizes the energy spread and allows a precise knowledge of 1+ incoming ion energy maximizing the charge breeding efficiency. Thus if that case is considered as the reference, the optimum energy of the 1+ ion is equal to 5.5. The optimum energy measured with the FEBIAD in SI mode is equal to 7eV corrected of the additional 3V applied on the anode which is close to this nominal value. The blue ΔV curves where obtained using the NANOGANIII ion source providing S^{1+}/F^{1+} ions. The mean ΔV value is -20.2V for an average FWHM of 18.7V. NANOGANIII is an ECR type ion source with the plasma potential speeding up the 1+ ions. Therefore, the ΔV value is negative to slow 1+ ions down to 5.5eV (our reference) leading to a plasma potential value of 20.2V+5.5V=25.7V which is a typical value for ECR sources. Finally, the red ΔV curve was recorded with the charge distribution obtained for $^{56}Fe^{15+}$ ions using FEBIAD in P mode. The mean ΔV value is 15.3V for an average FWHM of 12V. With the same argument as developped for NANOGAN, the plasma potential of the FEBIAD should be of the order of -9.8V. In fact, the Figure 3 taken from the reference [15] reproduced in Fig. 4 (right) shows the electrostatic field distribution inside the anode of two different types of FEBIAD ion sources. It is clear from the picture that 1+ ions are extracted within an electrostatic field lower than the one applied. From our measurement, a value of -9.8V can be deduced, which is really close to the one calculated and displayed in the Fig. 4 (right) picture (VADIS "active" volume).

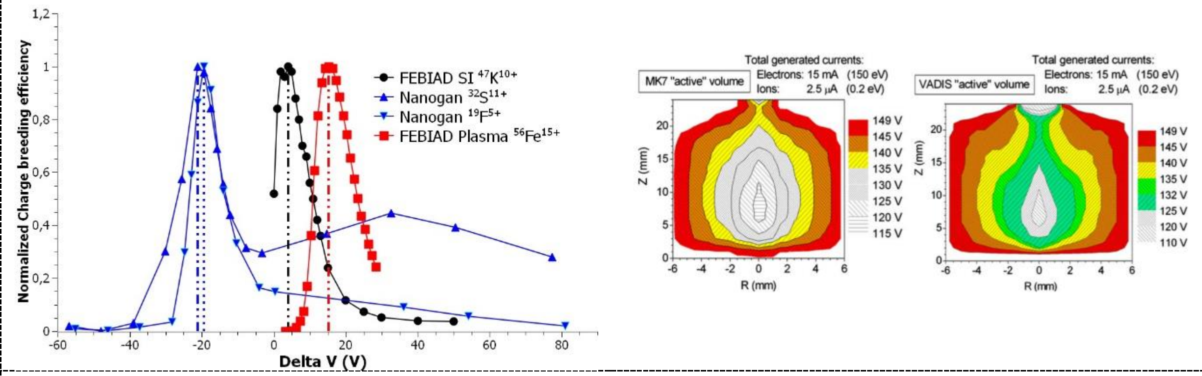

Figure 4. (left) ΔV curves for charge-bred ions for different monocharged ion sources and (right) electrostatic field distribution inside the anode of two FEBIAD types (MK7 and VADIS) [15].

5. Conclusion and outlooks

Each year the operation of SPIRAL1 leads to a better control and understanding of the 1+/N+ technique applied to the RIB production: FEBIAD TISS in the surface ionization mode, charge breeding performances, 1+ as well as N+ beam optics and optimum ΔV values have been investigated. In this article, the capability of SPIRAL1 facility to provide charge-bred ions of non-alkali ions, as well as the operation of the FEBIAD source in the plasma mode has been established with $^{56}Fe^{15+}$ reaching a charge breeding efficiency of 15%. The method of molecules as carriers for the radioactive atoms has been investigated with SF_x^{1+} molecular ions produced with NANOGANIII. The performances of the SP1CB appears to be very similar with atomic and molecular beams. The peculiarities observed (second hump, slopes in the high energy parts and slight shift of the optimum ΔV) in the ΔV scans might give new insights on the 1+ ion capture by an ECR plasma. For the future, hydride compounds would be the way to follow up. Last results obtained during a radioactive run in 2021 proved that the global TISS efficiency is similar to produce either $^{42}Cl^{1+}$ ($T_{1/2}$=6.8s) or $(H^{42}Cl)^{1+}$. Furthermore, with these two examples, on-line as well as off-line measurements showed evidence of the high potential of hydride molecules [16, 17]. Subsequently, next experiments to be performed with the SP1CB would be the charge breeding test of C^{q+} (physicists plan to perform experiment with ^{10}C $T_{1/2}$=19.29s) ions using CH_x^{1+} and CF_x^{1+} molecular ions from CH_4 and CF_4, respectively.

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