Author(s): Maunoury, Laurent; Dubois, Mickael; Delahaye, Pierre; Annaluru, Arun; Bajeat, Olivier; Frigot, Romain; Hormigos, Stéphane; Jacquot, Bertrand; Jardin, Pascal; Osmond, Benoit; Predrag, Ujic; Retailleau, Blaise-Mael; Savalle, Alain; Toivanen, Ville; Thomas, Jean-Charles; Angot, Julien; Sole, Patrick; Lamy, Thierry; Koivisto, Hannu; Marttinen, Miha; Tarvainen, Olli

Title: Charge breeding at GANIL : Improvements, results, and comparison with the other facilities

Year: 2020

Version: Published version

Review of Scientific Instruments

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Cite as: Rev. Sci. Instrum. **91**, 023315 (2020); https://doi.org/10.1063/1.5128661
Submitted: 20 September 2019 . Accepted: 23 January 2020 . Published Online: 10 February 2020

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COLLECTIONS

Paper published as part of the special topic on Proceedings of the 18th International Conference on Ion Sources
Note: Invited paper, published as part of the Proceedings of the 18th International Conference on Ion Sources, Lanzhou, China, September 2019.

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View Online Export Citation CrossMark

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Note: Invited paper, published as part of the Proceedings of the 18th International Conference on Ion Sources, Lanzhou, China, September 2019.
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ABSTRACT

The 1+/n+ method, based on an ECRIS charge breeder (CB) originally developed at the LPSC laboratory, is now implemented at GANIL for the production of Radioactive Ion Beams (RIBs). Prior to its installation in the middle of the low energy beam line of the SPIRAL1 facility, the 1+/n+ system CB has been modified based on the experiments performed on the CARIBU Facility at Argone National Laboratory. Later, it has been tested at the 1+/n+ LPSC test bench to validate its operation performances. Charge breeding efficiencies as well as charge breeding times have been measured for noble gases and alkali elements. The commissioning phase started at GANIL in the second half-year of 2017. It consisted of a stepwise process to test the upgrade of the SPIRAL1 facility from simple validation [operation of Charge Breeder (CB) as a stand-alone source] up to the production of the first 1+/n+ RIB. Thus, this year, a $^{38m}K/^{38}K$ RIB has been successfully delivered to a physics experiment over a period of 1 week. The yields on the physics target were in the range of ~2–4 × 10^6 pps at 9 MeV/u. The target ion source system (TISS) was made of a FEBIAD ion source connected to a hot graphite target. This is the first time a RIB is accelerated with a cyclotron with the 1+/n+ method. Moreover, a production test with the FEBIAD TISS has confirmed the yields measured previously, which validates the extension of the GANIL/SPIRAL1 catalog for a number of isotopes. In parallel, R&D is being performed on new TISSs (e.g., a fast release one, using surface ionization source). Targets are also a subject of ongoing R&D for yield and release time optimization. This contribution will present the new acceleration scheme of the SPIRAL1 facility, which largely extends the palette of RIBs available for nuclear physicists. It will be compared to the ones used at similar ISOL facilities. This facility is more than a simple ISOL facility, and an overview of the new opportunities offered by the upgraded installation will be also discussed.

I. INTRODUCTION

Since 2001, the SPIRAL1 facility has delivered regularly radioactive ion beams (RIBs) to the nuclear physics community, but it was mainly restricted to radioactive noble gas elements. This limitation was due to the target ion source system (TISS) composed of a hot carbon target connected to an electron cyclotron resonance (ECR) ion source named NANOGANIII. Physicists expect other exotic nuclei (Mg, Cl, Ni, Cr, etc.) to extend their studies such that they can constrain their nuclear models. In the scope of extending the actual RIBs to those based on condensable radioactive species, an upgrade of the facility has been undertaken using the well-known 1+/n+ method developed at LPSC Grenoble.[1] The method chosen to achieve the objectives of the upgrade is the development of new TISSs (Target Ion Source Systems) with a high efficiency,[2–4] while preserving main parts of the existing SPIRAL1 facility: the main building, the TISS handling system, and most parts of the LEBT (Low Energy Beam Transport) beam lines. Nevertheless, two major modifications have been realized: the transformation of the production cave to host new TISSs and the installation of a charge breeder (CB) after the exit of the cave, downstream from the 1+ magnetic mass separator, in the middle of the LEBT. Additionally, the building, the safety access system, the nuclear ventilation system, and the fire protection system have been upgraded to fulfill the safety authority requirements. In 2019, the upgraded facility has delivered, for the first time, a condensable type RIB to the physicists: ~2–4 × 10^6 pps of $^{38m}K^{8+}$ at 9 MeV/u, while delivering successfully standard RIBs (3 realized) of noble gas elements using the previous NANOGANIII TISS. This paper will focus on the SPIRAL1 charge breeder (modifications, performances, on-going R&D) as well as on the ECR type charge breeder projects or operational devices worldwide.

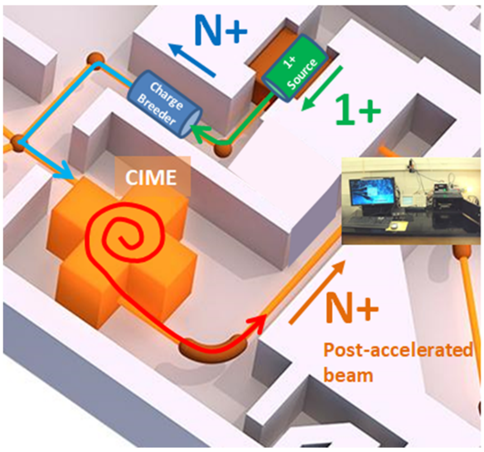

FIG. 1. Layout of the facility in the 1+/n+ mode.

FIG. 2. Photo of the SP1 charge breeder installed in the middle of the LEBT.

II. UPGRADED SPIRAL1

The new facility layout is displayed in Fig. 1. The Isotopic Separator On Line (ISOL) production method is combined with the 1+/n+ method to produce RIBs within an energy range from a few MeV/u up to 20 MeV/u. The key points for the success of such RIB production methods are being efficient, being fast, and being clean; this philosophy should be applied to all the main devices of the facility: TISS, charge breeder, LEBT, and post-accelerator. The new FEBIAD (Forced Electron Beam Induced Arc Discharge) TISS is represented in green. It is the combination of the hot carbon target designed for the NANOGANIII TISS[5] connected via a sliding transfer tube to a VADIS (Versatile Arc Discharge Ion Source)[6] type FEBIAD mono-charged ion source. The hot body of the ion source allows the beam formation based on a large range of condensable elements; an early test in 2013[7] demonstrated the ability of the ion source to deliver beams fulfilling requirements in terms of RIB production for future Physics programs: $^{21,25,26}Na$, ^{23}Mg, $^{25,28,29}Al$, $^{29,30}P$, $^{31,32,33}Cl$, ^{37}K, etc. This ion source can be operated in two modes: plasma mode or surface ionization mode; in the surface ionization mode, alkali elements are ionized efficiently, thanks to the hot temperature of the ion source body. In plasma mode, the power supplies of the cathode and anode are switched on to create and accelerate electrons generating the plasma within the anode body. Figure 2 displays an image of the SPIRAL1 Charge Breeder

TABLE I. Production yields of RIBs achieved in 2019 (bold numbers are final yields used by physicists).

Target ion source system	Experiment number	Radioactive ion beam	$T_{1/2}$ (s)	Primary beam	Power on target (W)	Yield before upgrade on physicist target (pps)	Yield after upgrade on physicist target (maximum pps)
(Shooting through) NANOGANIII	E745	$^{14}O^{4+}$ at 7.5 Mev/u	70, 6	$^{16}O^{5/8+}$ 95 MeV/u	≈1300	1.0 × 10^5	**2.7 × 10^5**
	E786S	$^{46}Ar^{9+}$ at 10 Mev/u	7, 8	$^{48}Ca^{10/19+}$ 95 MeV/u	≈600	2.0 × 10^4	**7.0 × 10^4**
	E768S	$^{15}O^{3+}$ at 4 Mev/u, 7 Mev/u	122, 2	$^{16}O^{5/8+}$ 95 MeV/u	≈1400	1.8 × 10^7[a]	**2.0 × 10^7**
(1+/n+) FEBIAD	E737	$^{38m}K^{8+}$ at 9 Mev/u 5.0 × 10^5[b]	0, 9	$^{40}Ca^{9/20+}$ 95 MeV/u	≈800	0	**8.0 × 10^5**[c] **4.1 × 10^6**[d]

[a] In 1+ state.
[b] Requested yield.
[c] Isomeric.
[d] Isomeric + ground state.

(SP1-CB) in the middle of the LEBT (also indicated in blue in Fig. 1).

During Spring 2019, two runs of RIBs have been taking place. The "shooting through" mode (no plasma present in the charge breeder) and the new "1+/n+" mode of operation have been employed.[8] Table I sums up the obtained results. Three experiments have been successfully carried out with the previous NanoganIII TISS ($^{14}O^{4+}$, $^{15}O^{3+}$, and $^{46}Ar^{9+}$), where the multicharged RIBs were transported through the SP1-CB. The yields on the physicist target are slightly higher after the upgrade of the SPIRAL1 facility compared with the ones recorded with the former facility. There are two possible reasons for this observation: first, the plasma electrode aperture of the NANOGANIII TISS has been shrunk from 7 mm down to 5 mm, leading to an emittance decrease, and second, the multicharged RIBs must currently go through the plasma electrode of the SP1-CB, which has an aperture diameter of 6.0 mm. Henceforth, this defines a good quality source term for transporting the low energy RIBs up to the injection section of the CIME (Cyclotron à Ions de Moyenne Énergie) cyclotron leading to higher transmission efficiency during the post-acceleration. The last row in Table I represents the characteristics for the production of the ^{38m}K beam done for the first time with the 1+/n+ method and the upgraded facility. The requested yield on the physicist target was 5.0×10^5 pps, and it has been successfully provided at 8.0×10^5 pps; taking into account not only the isomeric form, but also the ground state form, the total yield amounts to 4.1×10^6 pps.

III. SPIRAL1 CHARGE BREEDER

The SP1-CB is based on the phoenix booster[9] developed at the LPSC laboratory. After working on the ANL (Argonne National Laboratory) ECRCB to learn the key parameters of such a device,[10] modifications have been applied on our Phoenix CB type and tested on the 1+/n+ test bench at LPSC laboratory[11] (Fig. 3) in 2015. Let us remind the main modifications done and the outcomes of these experiments. On the SP1-CB, the injection part has been significantly modified by adding a second RF port to inject second RF heating wave within a broad frequency range (8–18 GHz), the injection iron plug has been symmetrized, a new gas injection with an outlet close to the ECR plasma has been added, and the waveguide orientation has been changed to target the core of the ECR plasma. The majority of the o-rings have been replaced by metallic gaskets, and the plasma chamber is made of aluminum. Two vacuum chambers have been added on each side of the SP1-CB: upstream, there is one containing an electrostatic quadrupole triplet to focus and steer the 1+ beam and downstream, and a second chamber houses the extraction system with a mobile puller as well as a mobile Einzel lens to extract and form the n+ beam. The validation measurements have been done on the LPSC test bench by means of a thermal ion emission source producing Na, K, and Rb mono-charged ions. The first result obtained with Rb^{19+} charge bred ions demonstrated the role of the residual gas pressure: a lower residual gas pressure leads to higher charge breeding efficiency.[11] At GANIL, the residual gas pressure is in the range of 10^{-8} mbar each side of the SP1-CB. The second interesting result was the ability of the SP1-CB to produce highly charged ions for the three alkali elements delivered for the tests by the thermo-ionic source (Fig. 4). The charge state distributions (CSDs) for Na^{q+} and K^{q+} exhibited two maxima: at a low charge state (Na^+ and K^+) and a high charge state (Na^{7+} and K^{9+}). The peak at the low charge state is mostly due to the incoming 1+ ions having weak interaction with the ECR plasma. The typical ΔV curves measured with a charge breeder represent the residual energy of the incoming 1+ ions to meet the core of the ECR plasma after passing over the charge breeder plasma potential barrier. For the three cases $Na^{7+} + H_2$, K^{9+} + He, and $Rb^{19+} + O_2$, the ΔV values at the maximum charge breeding efficiency are quite similar[11] around 5–7 V; this observation is astonishing regarding the theory describing a dependency of this value on the mass of incoming 1+ ions, the background plasma ions, and the temperature of background plasma ions. The last interesting result was the increase in the charge breeding efficiency of the K^{9+} charge bred ions with the support gas: lighter the background ion mass, the higher the charge breeding efficiency.[11] These two last results are addressed in the paper of A. Annaluru.[12] Later, the SP1-CB moved back to GANIL and has been installed in the middle of the LEBT of the SPIRAL1 facility (Fig. 2) in 2016. Additional changes have been done: plasma

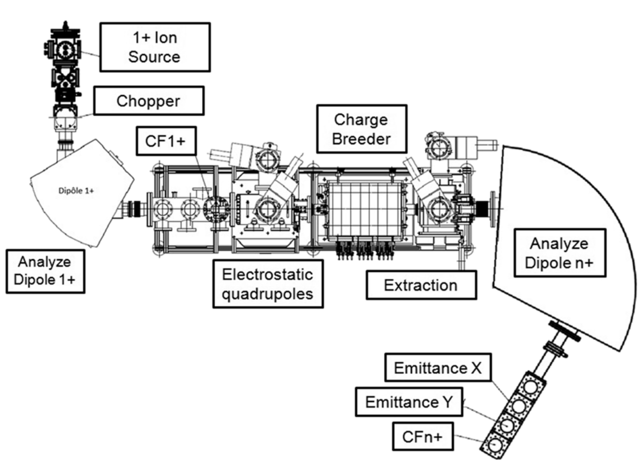

FIG. 3. Layout of SP1-CB installed at the 1+/n+ test bench of the LPSC lab.

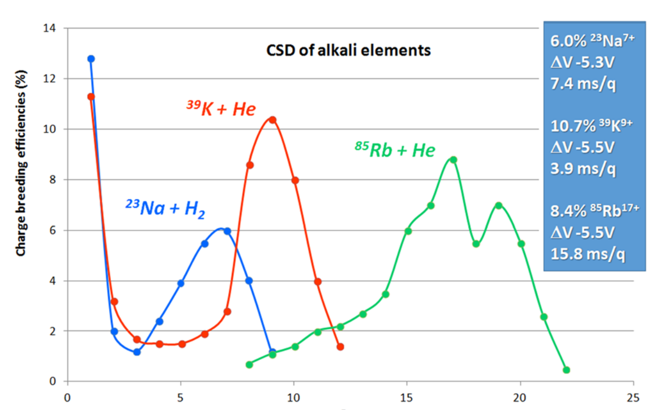

FIG. 4. Charge state distribution of the Na^{q+}, K^{q+}, and Rb^{q+} measured during the validation period at the LPSC lab.

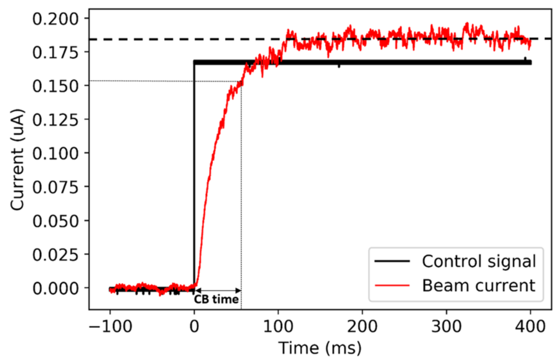

FIG. 5. N+ beam current response to a chopped incoming 1+ ion beam.

electrode location; optimization of the soft iron ring axial location surrounding the hexapole to improve the K^{9+} charge breeding efficiency (11.6% obtained);[13] and an additional iron tip added pushing up the magnetic field maximum at injection from 1.19 T up to 1.36 T, leading to an increase in the charge breeding efficiency of the Na^{8+} from 6% up to 9%.

In collaboration with the University of Jyväskylä ion source group, a campaign of charge breeding time measurement at the SPIRAL1 facility has been realized with the SP1-CB regarding the potassium charge bred ions. The objective was to study and find a set of SP1-CB parameters, which minimizes the charge breeding time while maximizing the charge breeding efficiency; this set matches the best RIB production environments to maximize the yields on the physicist's target regarding the SP1-CB device.[14] Figure 5 displays a typical measurement used to deduce the charge breeding

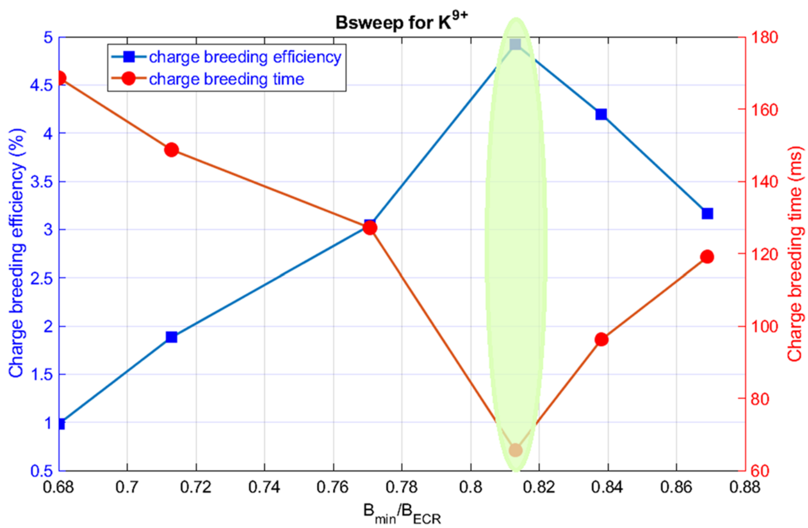

FIG. 6. Evolution of the charge breeding efficiency and charge breeding time vs B_{min}/B_{ECR}.

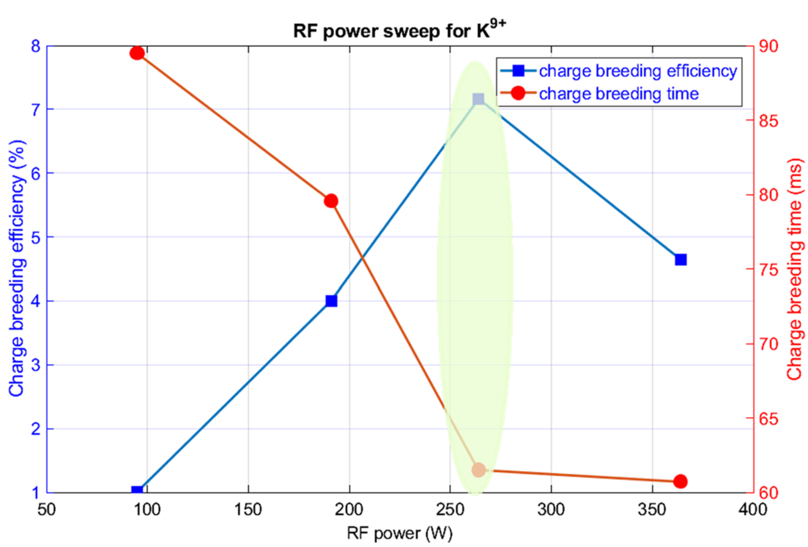

FIG. 7. Evolution of the charge breeding efficiency and charge breeding time vs RF power.

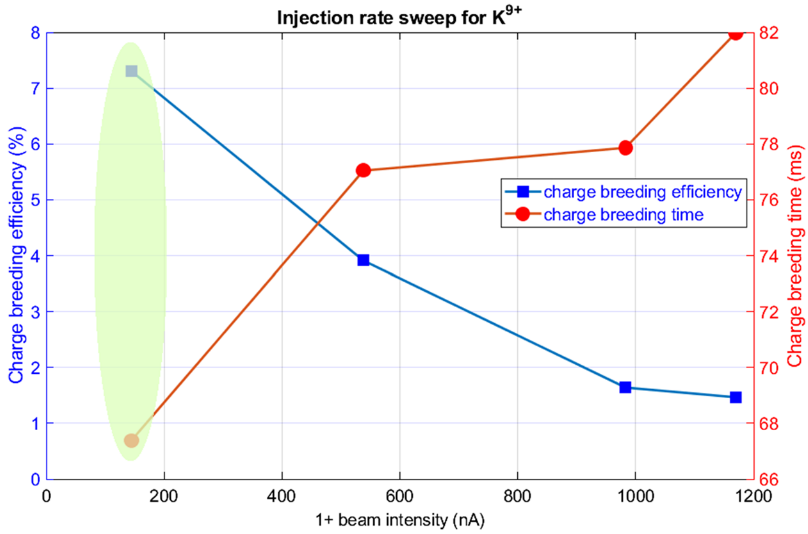

FIG. 8. Evolution of the charge breeding efficiency and charge breeding time vs 1+ beam intensity.

time. In black, the control signal is applied to the power supply of the chopper upstream from the SP1 CB such that the incoming 1+ beam is pulsed. In red, the beam current signal measured on the Faraday cup downstream from the SP1-CB after the n+ mass analysis magnet. The charge breeding time is calculated from the rising edge of the signal by taking the time difference between the control signal and 90% of the saturation current of the charge bred ion. The K^{9+} charge bred ion has been selected for this study. The SP1-CB is tuned such to maximize the charge breeding efficiency. The experiment consists of sweeping the charge breeder parameters (B_{min}/B_{ECR}; RF power; ΔV and 1+ incoming current), while keeping the other ones constant. Figures 6–9 present the evolution of the charge breeding times as well as charge breeding efficiencies vs the sweep parameters. Figure 6 deals with the B_{min}/B_{ECR} parameter; it is clear that there is a minimum in the charge breeding time curve, corresponding to a maximum of the charge breeding efficiency matching the specific number $B_{min}/B_{ECR} = 0.8$. This value is well known to be at the edge of the plasma stability/instability region and to lead to the production of highly charged ions.[15] Regarding Fig. 7, there is a drop in the charge breeding time curve down to $RF_{power} = 270$ W followed by a plateau, while the charge breeding efficiency curve depicts a maximum at this RF_{power} value. Regarding the incoming 1+ current parameter (Fig. 8), both curves (charge breeding time and charge breeding efficiency) show a steady and smooth evolution (increase and decrease, respectively), which deviates away from the goal described above. Finally, Fig. 9 demonstrates that the energy window to charge bred K^{9+} is rather large (±3 V of ΔV corresponding to a decrease of 30% in charge breeding efficiency). The charge breeding time decreases continuously with increasing ΔV. These results provided a set of operating parameters for the SP1-CB, which satisfies the objectives set above (e.g., Table II). These experimental outcomes can assist in the operation

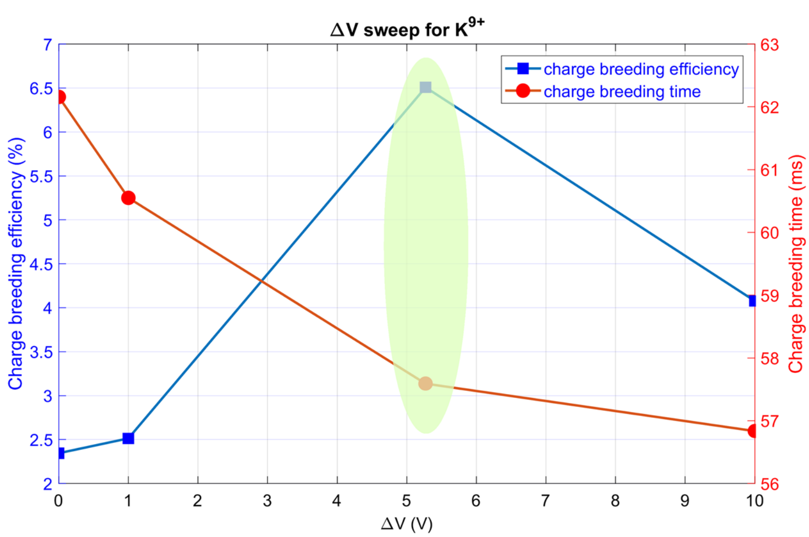

FIG. 9. Evolution of the charge breeding efficiency and charge breeding time vs ΔV.

TABLE II. Set of the SP1-CB parameter, which maximizes the charge breeding efficiency, while minimizing the charge breeding time.

B_{min}/B_{ECR}	RF_{power} (W)	1+ incoming current (nA)	ΔV (V)
0.8	270	180	5.3

of the charge breeder, but to go beyond, more experiments must be planned and performed in parallel with the development of plasma modeling to acquire the connection between these two observables: charge breeding time and charge breeding efficiency. Elsewhere in these proceedings,[16] the connection between the ion source parameters and cumulative confinement time of different charge states of K is discussed. However, an open question remains: what is (are) the physical process(es), which bonds these two observables together?

IV. SPIRAL1 OUTLOOKS

Even as the upgraded SPIRAL1 facility has successfully started delivering RIBs to physicists in 2019, there are many improvements that are still required to reach a fully operational machine and to deliver the new RIBs requested by nuclear physicists. During the first operation of the 1+/n+ system, we faced several issues, which must be addressed.

- RIB tuning and optimization longer than expected, which reduces the available beam time to physicists.
- Some issues remain, concerning the control of the optics of 1+ beams up to the SP1-CB limiting the efficiency of 1+ beam injection. The 1+ beam optimization seems to vary strongly from TISS to TISS, and the 1+ beam extraction conditions are not yet fully understood. Furthermore, we lack diagnostics for radioactive ion beams upstream the charge breeder.
- Charge breeding efficiencies are lower for RIBs than for stable beams by a factor of 2–3.
- Contamination must be addressed because it is a limitation for experiments as well as for SP1-CB tuning.

The next R&D in the coming years will be done in three directions: 1+ beam optics, fundamental studies, and technical improvements. To optimize the 1+ ion transport from the production cave to the injection of the SP1-CB, a simulation program (SIMION 3D associated with TraceWin) as well as an experimental one will start at the end of 2019. These programs will permit to get a full control over the 1+ beam optics and to find out the best 1+ beam characteristics, accomplishing a high charge breeding efficiency for all produced elements over the complete range of LEBT energy. Regarding the work of Annaluru[14] for determining plasma parameters achieving the best charge breeding efficiencies for three cases (Na + He, K + He, K + O_2), this study must be extended to other cases (Rb + He, Rb + O_2, Na, K, Rb + H_2) to get a large set of plasma parameters needed for determining the optimized ECR plasma features applied to an ECR charge breeder. At the same time, in collaboration with the ion source group of the University of Jyväskylâ, charge breeding time measurements ought to be pursued to determine the absolute confinement time values as well as the evolution of this observable with the charge breeder parameters and its coupling with the charge breeder efficiency. These findings will lead to new ideas in the aim of defining the ultimate features of a high performance charge breeder device. Two techniques will be applied to the SP1-CB to enhance the performances and the reliability of this machine.

- Double frequency heating: the purpose is to be able to get a highly stable plasma and extracted beam and specially to get a better control of the charge state distribution by matching the optimized charge state to the final energy of the post-accelerated beam.
- Liners: by profiting from a research collaboration agreement between SPES and LPSC, this technique will be tested to address the contamination reduction into the charge breeder. The idea is to test several liners made of different materials and measure the contamination with many charge breeder configurations (magnetic fields, RF power, and background plasma).

V. ECR TYPE CHARGE BREEDER OVERVIEW AND RELATED R&D

The charge breeders based on ECRIS are nowadays still quite popular, as it will be shown in the following with a few examples. The SPES project (Selective Production of Exotic Species) at LNL (Legnaro, Italy) aims to produce RIBs by the interaction of a high energy and intense proton beam on a uranium carbide target in the framework of an ISOL facility. An upgraded Phoenix Booster will be used to boost the mono-charged RIB to a multicharged one available for a post-acceleration with the ALPI superconducting LINAC at LNL. The charge breeder is already on-site, and it has been tested on the 1+/n+ test bench of the LPSC lab.[17,18] During the coming months, a stable 1+ beam will be transported up to the SPES-CB, and similarly an n+ beam extracted from the SPES-CB will be transported until the end of the n+ beam line (April 2020). By September 2020, the complete 1+/n+ process will be experimented using stable beams.

At the ISAC (Isotope Separator and Accelerator) facility, part of the TRIUMF lab (Vancouver, Canada), the charge breeder technique[19] has been implemented since 2008. The mono-charged RIBs are produced by bombardment of a solid target with protons of up to 500 MeV and 100 μA using a robust ion source surviving the high dose rate environment. Isotopes from more than 15 elements have been charge bred providing post-accelerated RIBs, spanning the mass range from ^{21}Na up to ^{160}Er; typical charge breeding efficiencies have been measured within the 1%–5% range. The main issues so far have been a high background contamination and a too long charge breeding time process (≈20 ms $*$ q). A new R&D program started addressing the background reduction using the two-frequency heating technique (stabilization of the ECR plasma). In parallel, emittance measurement campaigns combined with intense extraction modeling simulations are under progress to optimize the beam properties of the n+ charge bred ions.

At Texas A&M University, a new injection scheme, associated with a specific radioactive ion production technique, has been developed to inject the mono-charged RIBs into the CB-ECRIS: an energetic beam of light ions bombards with a thin target, the radioactive products are transported by a flow of helium gas, and their charge state is narrowed down to the 1+ charge state. Hence, an RF SextuPole Ion-Guide (SPIG) of 2.5 m has been designed[20] and tested to transport and inject the mono-charged RIB into the CB-ECRIS. Using first a stable Cs^{1+} ion beam and second a ^{228}Th radioactive source delivering radioactive products of $^{220}Rn^{+}$ and $^{216}Po^{+}$ guided by the He gas, a global charge breeding efficiency of ≈50% has been achieved. Successfully, RIBs of $^{114}In^{19+}$ and $^{112}In^{21+}$ have been accelerated by the K500 Cyclotron.

At the CARIBU (CAlifornium Rare Isotope Breeder Upgrade) facility, part of the ANL lab (Chicago, USA), different methods and techniques[21] have been employed to address the contamination reduction: CO_2 snow cleaning, parts of ECRCB being made of ultra-high purity aluminum (99.9995%), and vacuum coated with ultra-high purity aluminum. Even if the successes of these practices have been established, the last method presents some unwanted contaminants: Mo, Ta, W. Therefore, a new coating procedure is under progress (Atomic Layer Deposition) to get rid of these impurities.

The LPSC lab, with its high expertise in ECR ion sources and being the cradle of charge breeders, has an R&D program[22] to go beyond the conventional charge breeder performances by modifying the magnetic configuration as well as the plasma volume. The pursued goal is to increase the charge breeding efficiency, to improve the effectiveness of the 1+ capture process and to reduce the pollutants. For that purpose, two milestones are defined: end of 2019, reshuffling the coils and yokes to especially reduce the size (thickness) of the middle coils regarding the previous version; and end of 2020, modification of the hexapole to enlarge the plasma volume.

In conclusion, regarding all these developments and R&D, it is clear that the ECR type charge breeder has a real future by enhancing its global performances—lower contamination, higher charge breeding efficiency, and better control over the charge breeding time—in order to play an important role in the existing and the future radioactive ion beam production facilities.

ACKNOWLEDGMENTS

The authors would like to thank warmly the worldwide colleagues who participated in discussions as well as in experiments toward the success of the upgraded facility and who gave materials to write this paper: Thomas Thuillier from LPSC; Alessio Galatà from SPES, INFN; Don May from Texas A&M; Friedhelm Ames and Joseph Adegun from ISAC, TRIUMF; and R. Vondrasek from CARIBU, ANL.

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