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Charge breeding at Ganil: improvements, results and comparison with the other facilities

Laurent Maunoury^{1, a)}, Mickael Dubois¹, Pierre Delahaye¹, Arun Annaluru¹, Olivier Bajeat¹, Romain Frigot¹, Stéphane Hormigos¹, Bertrand Jacquot¹, Pascal Jardin¹, Benoit Osmond¹, Ujic Predrag¹, Blaise-Mael Retailleau¹, Alain Savalle¹, Ville Toivanen^{1,2}, Jean-Charles Thomas¹, Julien Angot², P. Sole², T. Lamy², Hannu Koivisto³, Miha Marttinen³ and Olli Tarvainen^{3,4}

¹GANIL, bd Henri Becquerel, BP 55027, F-14076 Caen cedex 05, France

²Univ. Grenoble Alpes, CNRS, Grenoble INP*, LPSC-IN2P3, 38000 Grenoble, France

³Department of Physics, University of Jyväskylä, PO box 35 FI-40014, Jyväskylä, Finland

⁴STFC ISIS Pulsed Spallation Neutron and Muon Facility, Rutherford Appleton Laboratory, Harwell, OX110QX UK

^{a)}Corresponding author: laurent.maunoury@ganil.fr

Abstract. The 1+/n+ method, based on an ECRIS charge breeder 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 charge breeder has been modified based on the experiments performed on the CARIBU Facility at Argonne 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 has 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+ radioactive ion beam. Thus, this year, a ^{38m}K / ³⁸K radioactive ion beam 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 $\sim 2\text{-}4 \times 10^6$ 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 radioactive ion beam 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 delivers regularly radioactive ion beams (RIBs) to the Nuclear Physics community, but they were mainly restricted to radioactive noble gas elements. This limitation was due to the target

39 ion source system (TISS) composed of a hot carbon target connected to an electron cyclotron resonance (ECR) ion
 40 source named NANOGANIII. Physicists expect other exotic nuclei (Mg, Cl, Ni, Cr etc...) to extend their studies such
 41 that they can constrain their nuclear models. In the scope of extending the actual RIBs to those based on condensable
 42 radioactive species, an upgrade of the facility has been undertaken using the well-known $1+ / n+$ method developed
 43 at LPSC Grenoble [1]. The method chosen to achieve the objectives of the upgrade is the development of new TISSs
 44 (Target Ion source Systems) with a high efficiency [2, 3, 4], while preserving main parts of the existing SPIRAL1
 45 facility unchanged: the main building, the TISS handling system and the most parts of the LEBT (Low Energy Beam
 46 Transport) beam lines. Nevertheless, two major modifications have been realized: the transformation of the production
 47 cave to host new TISS's and the installation of a charge breeder after the exit of the cave, downstream from the $1+$
 48 magnetic mass separator, in the middle of the LEBT. Additionally, the building, the safety access system, the nuclear
 49 ventilation system and the fire protection have been upgraded to fulfill the safety authority requirements. In 2019, the
 50 upgraded facility has delivered, for the first time, a condensable type RIB to the physicists: $\sim 2-4 \times 10^6$ pps of
 51 $^{38}\text{Mg}^{8+}$ @ 9 MeV/u while delivering successfully standard RIBs (3 realized) of noble gas element using the previous
 52 NANOGANIII TISS. This paper will focus on the SPIRAL1 Charge breeder (modifications, performances, on-going
 53 R&D) as well as on the ECR type charge breeder projects or operational devices worldwide.

55 II. Upgraded SPIRAL1

56 The new facility layout is displayed on the fig.1. The Isotopic Separator On Line (ISOL) production method is
 57 combined with the $1+/n+$ method to produce RIBs within an energy range from a few MeV/u up to 20 MeV/u. The
 58 key points for the success of such RIB production method are: being efficient, being fast and being clean; that
 59 philosophy should be applied to all the main devices of the facility: TISS, Charge breeder, LEBT and Post-Accelerator.
 60 The new FEBIAD (Forced Electron Beam Induced Arc Discharge) TISS is represented in green. It is the combination
 61 of the hot carbon target designed for the NANOGANIII TISS [5] connected via a sliding transfer tube to a VADIS
 62 (Versatile Arc Discharge Ion Source) [6] type FEBIAD mono-charged ion source. The hot body of the ion source
 63 allows the beam formation based on a large range of condensable elements, an early test in 2013 [7] demonstrated the
 64 ability of the ion source to deliver beams fulfilling requirements in terms of RIB production for future Physics
 65 programs: $^{21,25,26}\text{Na}$, ^{23}Mg , $^{25,28,29}\text{Al}$, $^{29,30}\text{P}$, $^{31,32,33}\text{Cl}$, ^{37}K etc.... This ion source can be operated in two modes: plasma
 66 mode or surface ionization mode; in surface ionization mode, alkali elements are ionized efficiently thanks to the hot
 67 temperature of the ion source body. In plasma mode, the power supplies of the cathode and anode are switched on to
 68 create and accelerate electrons generating the plasma within the anode body. The figure 2 displays an image of the
 69 Spiral1 Charge Breeder (SP1-CB) in the middle of the LEBT (also indicated in blue in Fig. 1).

70

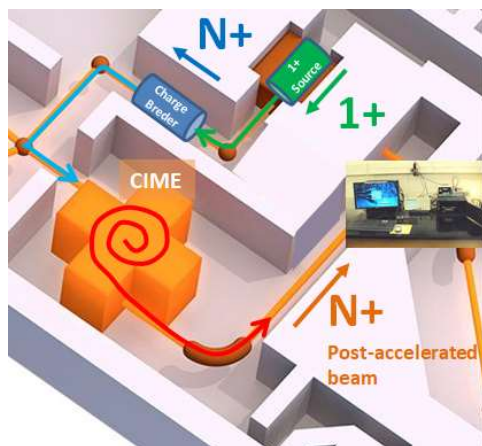


FIGURE 1. Layout of the facility in the $1+/n+$ mode.



FIGURE 2. Photo of the SP1 Charge Breeder installed the middle of the LEBT.

71 During the spring 2019, two runs of RIBs have been taking place. The “shooting through” mode (no plasma present
 72 in the charge breeder) as well as the new “ $1+/n+$ ” mode of operation have been employed [8]. Table 1 sums up the
 73 obtained results. Three experiments have been successfully carried out with the previous NanoganIII TISS ($^{14}\text{O}^{4+}$,
 74 $^{15}\text{O}^{3+}$ and $^{46}\text{Ar}^{9+}$) where the multicharged RIBs were transported through the SP1-CB. The yields on the physicist
 75

76 target are slightly higher after the upgrade of the SPIRAL1 facility compared the ones recorded with the former
77 facility. There are two possible reasons for this observation: firstly, the plasma electrode aperture of the NANOGANIII
78 TISS has been shrunk from 7mm down to 5mm leading to an emittance decrease and secondly, the multicharged RIBs
79 must currently go through the plasma electrode of the SP1-CB which has an aperture diameter of 6.0mm. Henceforth,
80 that defines a good quality source term for transporting the low energy RIBs up to the injection section of the CIME
81 (Cyclotron à Ions de Moyenne Énergie) cyclotron leading to higher transmission efficiency during the post-
82 acceleration. The last row in Table 1 represents the characteristics for the production of the ^{38m}K beam done for the
83 first time with the 1+/n+ method and the upgraded facility. The requested yield on the physicist target was 5.0×10^5 pps
84 and it has been successfully provided at 8.0×10^5 pps; taking into account not only the isomeric form but also the ground
85 state form, the total yield amounts to 4.1×10^6 pps.
86

TABLE 1. Production yields of RIBs achieved in 2019

#in 1+ state / *Isomeric / @(Isomeric + ground state) / &Requested yield

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	$^{14}\text{O}^{4+}@ 7.5\text{Mev/u}$	70,6	$^{16}\text{O}^{5/8+} 95\text{MeV/u}$	≈1300	1.0×10^5	2.7×10^5
	E786S	$^{46}\text{Ar}^{9+}@ 10\text{Mev/u}$	7,8	$^{48}\text{Ca}^{10/19+} 95\text{MeV/u}$	≈600	2.0×10^4	7.0×10^4
	E768S	$^{15}\text{O}^{3+}@ 4,7\text{Mev/u}$	122,2	$^{16}\text{O}^{5/8+} 95\text{MeV/u}$	≈1400	$1,8 \times 10^{7(\#)}$	2.0×10^7
(1+/n+) FEBIAD	E737	$^{38m}\text{K}^{8+}@9\text{Mev/u}$ $5.0 \cdot 10^5 (\&)$	0,9	$^{40}\text{Ca}^{9/20+} 95\text{MeV/u}$	≈800	0	$8.0 \times 10^{5(*)}$ $4.1 \times 10^6 (@)$

87 # in 1+ state * Isomeric @ Isomeric + ground state & Requested yield
88

89 III. Spiral1 Charge Breeder

90 The SP1-CB is based on the phoenix booster [9] developed at the LPSC laboratory. After working on the ANL
91 (Argonne National Laboratory) ECRCB to learn key parameters of such device [10], modifications have been applied
92 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
93 main modifications done and the outcomes of these experiments. On the SP1-CB, the injection part has been
94 significantly modified by adding a second RF port to inject second RF heating wave within a broad frequency range
95 (8 - 18 GHz); the injection iron plug has been symmetrized; a new gas injection with an outlet close to the ECR plasma
96 has been added; the waveguides orientation has been changed to target the core of the ECR plasma. The majority of
97 the o-Rings have been replaced by metallic gaskets and the plasma chamber is made of aluminum. Two vacuum
98 chambers have been added at each side of the SP1-CB: upstream there is one containing an electrostatic quadrupole
99 triplet to focus and steer the 1+ beam and downstream, a second chamber houses the extraction system with a mobile
100 puller as well as a mobile Einzel lens to extract and form the n+ beam. The validation measurements have been done
101 on the LPSC test bench by means of a thermal ion emission source producing Na, K and Rb mono-charged ions. The
102 first result obtained with Rb^{19+} charge bred ions demonstrated the role of the residual gas pressure: a lower residual
103 gas pressure leads to higher charge breeding efficiency [11]. At GANIL, the residual gas pressure is in the range of
104 10^{-8} mbar each side of the SP1-CB. The second interesting result was the ability of the SP1-CB to produce highly
105 charged ions for the three alkali elements delivered for the tests by the thermo-ionic source (Fig.4). The charge state
106 distributions (CSD) for Na^{q+} and K^{q+} exhibited two maxima: at low charge state (Na^+ and K^+) and high charge state
107 (Na^{7+} and K^{9+}). The peak at low charge state is mostly due to the incoming 1+ ions having weak interaction with the
108 ECR plasma. The typical ΔV curves measured with a charge breeder represents the residual energy of the incoming
109 1+ ions to meet the core of the ECR plasma after passing over the charge breeder plasma potential barrier. For the

110 three cases $\text{Na}^{7+} + \text{H}_2$, $\text{K}^{9+} + \text{He}$ and $\text{Rb}^{19+} + \text{O}_2$, the ΔV value at the maximum charge breeding efficiency are quite similar
 111 [11] around 5-7 V, that observation is astonishing regarding the theory describing a dependency of this value on the
 112 mass of incoming $1+$ ions, the background plasma ions and the temperature of background plasma ions. The last
 113 interesting result was the increase of the charge breeding efficiency of the K^{9+} charge bred ion with the support gas:
 114 lighter the background ion mass the higher is the charge breeding efficiency [11]. These two last results are addressed
 115 in the paper of A. Annaluru [12]. Later, the SP1-CB moved back to GANIL and has been installed in the middle of
 116 the LEBT of the SPIRAL1 facility (Fig.2) in 2016. Additional changes have been done: plasma electrode location;
 117 optimization of the soft iron rings axial location surrounding the hexapole to improve the K^{9+} charge breeding
 118 efficiency (11.6% obtained) [13]; an additional iron tip was added pushing up the magnetic field maximum at injection
 119 from 1.19T up to 1.36T leading to an increase of the charge breeding efficiency of the Na^{8+} from 6% up to 9%.
 120

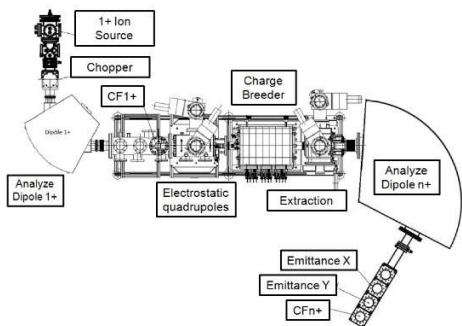


FIGURE 3. Layout of SP1-CB installed at the $1+/n+$ test bench of the LPSC lab..

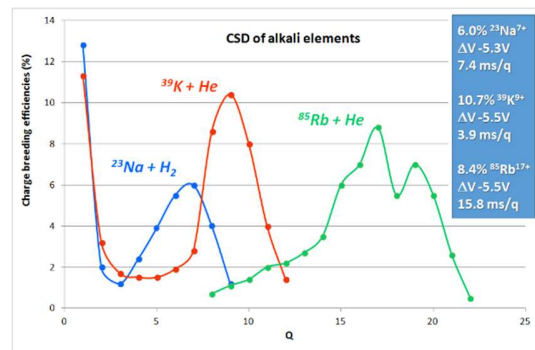


FIGURE 4. Charge state distribution of the Na^{q+} , K^{q+} and Rb^{q+} measured during the validation period at the LPSC lab.

121
 122 In collaboration with the University of Jyväskylä ion source group, a campaign of charge breeding time
 123 measurement at the SPIRAL1 facility has been realized with the SP1-CB regarding the potassium charge bred ions.
 124 The objective was to study and find a set of SP1-CB parameters which minimizes the charge breeding time while
 125 maximizing the charge breeding efficiency; that set matches the best RIB production environments to maximize the
 126 yields on the physicist's target regarding the SP1-CB device [14]. Figure 5 displays a typical measurement used to
 127 deduce the charge breeding time. In black, the control signal is applied to the power supply of the chopper upstream
 128 from the SP1 CB such that the incoming $1+$ beam is pulsed. In red, the beam current signal measured on the faraday
 129 cup downstream from the SP1-CB after the $n+$ mass analyzis magnet. The charge breeding time is calculated from the
 130 rising edge of the signal by taking the time difference between the control signal and 90% of the saturation current of
 131 the charge bred ion. The K^{9+} charge bred ion has been selected for this study. The SP1-CB is tuned such to maximize
 132 the charge breeding efficiency. The experiment consists of sweeping the charge breeder parameters ($B_{\text{min}}/B_{\text{ECR}}$; RF
 133 power; ΔV and $1+$ incoming current) while keeping the other ones constant. Figures 6, 7, 8 and 9 present the evolution
 134 of the charge breeding times as well as charge breeding efficiencies versus the sweep parameters. Figure 6 deals with
 135 the $B_{\text{min}}/B_{\text{ECR}}$ parameter; it is clear that there is a minimum in the charge breeding time curve corresponding to a
 136 maximum of the charge breeding efficiency matching the specific number $B_{\text{min}}/B_{\text{ECR}}=0.8$. This 0.8 value is well known
 137 to be at the edge of the plasma stability / instability region and to lead to the production of highly charged ions [15].
 138 Regarding Fig.7, there is a drop of the charge breeding time curve down to $\text{RF}_{\text{power}} = 270\text{W}$ followed by a plateau
 139 while the charge breeding efficiency curve depicts a maximum at this RF_{power} value. Regarding the incoming $1+$ current
 140 parameter (Fig.8), both curves (charge breeding time and charge breeding efficiency) show a steady and smooth
 141 evolution (increase and decrease respectively) which runs away from the goal describes above. Lastly, Fig.9
 142 demonstrates that the energy window to charge bred K^{9+} is rather large ($\pm 3\text{V}$ of ΔV corresponding to a decrease of
 143 30% in charge breeding efficiency). The charge breeding time decreases continuously with increasing ΔV . These
 144 results provided a set of operating parameters for the SP1-CB which satisfies the objectives set above (e.g. Table2).
 145 These experimental outcomes can assist in the operation of the charge breeder but to go beyond, more experiments
 146 must be planned and performed in parallel with the development of plasma modeling to acquire the connection
 147 between these two observables: charge breeding time and charge breeding efficiency. Elsewhere in these proceedings
 148 [16], the connection between the ion source parameters and cumulative confinement time of different charge states of

149 K is discussed. But still, an open question remains: what is (are) the physical process(es) which bond those two
 150 observables together?
 151

TABLE 2. Set of SP1-CB parameter which maximize 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

152
 153

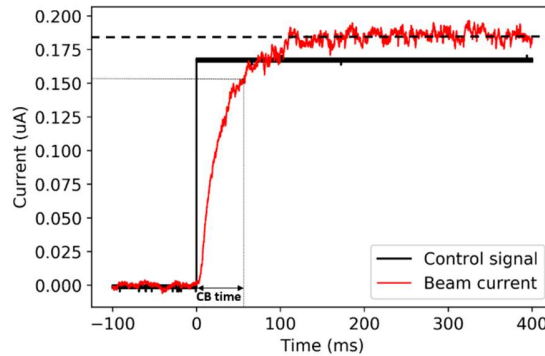


FIGURE 5. N+ beam current response to a chopped incoming 1+ ion beam

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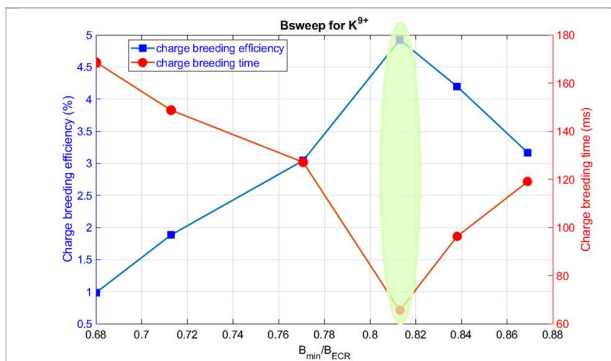


FIGURE 6. Evolution of the charge breeding efficiency and charge breeding time versus B_{\min}/B_{ECR}

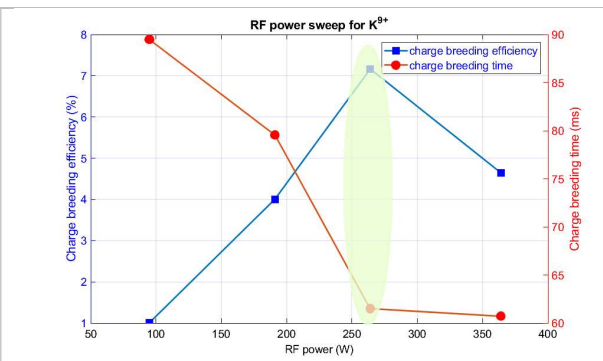


FIGURE 7. Evolution of the charge breeding efficiency and charge breeding time versus RF power

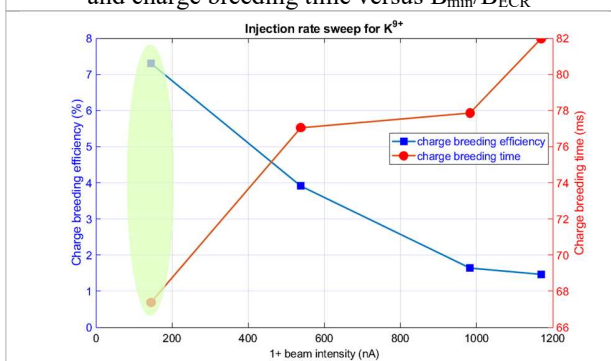


FIGURE 8. Evolution of the charge breeding efficiency and charge breeding time versus 1+ beam intensity

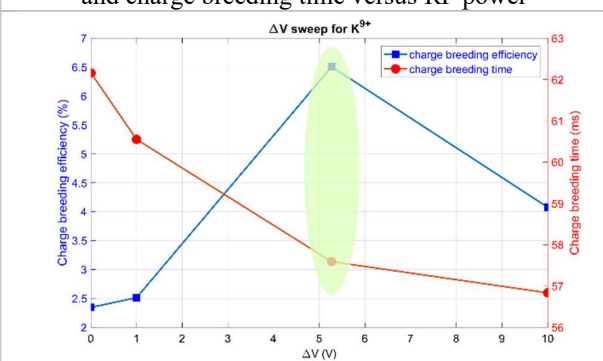


FIGURE 9. Evolution of the charge breeding efficiency and charge breeding time versus ΔV

155

156 **IV. SPIRAL1 Outlooks**

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

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

169
170 The next R&D in the coming years will be done in three directions: 1+ beam optics; fundamental studies and
171 technical improvements. To optimize the 1+ ion transport from the production cave to the injection of the SP1-CB, a
172 simulation program (SIMION 3D associated with TraceWin) as well as an experimental one will start end of 2019.
173 These programs will permit get a full control over the 1+ beam optics and to find out the best 1+ beam characteristics
174 accomplishing a high charge breeding efficiency for all produced elements over the complete range of LEBT energy.
175 Regarding the work of A. Annaluru [14] for determining plasma parameters achieving the best charge breeding
176 efficiencies for three cases (Na+He, K+He, K+O₂), this study must be extended to other cases (Rb+He, Rb+O₂, Na,
177 K, Rb+H₂) to get a large set of plasma parameters needed for determining the optimized ECR plasma features applied
178 to an ECR charge breeder. At the same time, in collaboration with the ion source group of the University of Jyväskylä,
179 charge breeding time measurements ought to be pursued to determine the absolute confinement time values as well as
180 the evolution of this observable with the charge breeder parameters and its coupling with the charge breeder efficiency.
181 That findings will lead to new ideas in the aim of defining the ultimate features of a high performance charge breeder
182 device. Two techniques will be applied to the SP1-CB to enhance the performances and the reliability of this machine:

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

191 **V. ECR type Charge Breeder overview and related R&D**

192 The charge breeders based on ECRIS are nowadays still quite popular, as it will be shown in the following in a
193 few examples. The SPES project (Selective Production of Exotic Species) at LNL (Legnaro, Italy), aims to produce
194 RIBs by the interaction of a high energy and intense proton beam on a uranium carbide target in the framework of an
195 ISOL facility. An upgraded Phoenix Booster will be used to boost the mono-charged RIB to an multicharged one
196 available for a post-acceleration with the ALPI superconducting LINAC at LNL. The charge breeder is already on-
197 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+
198 beam will be transported up to the SPES-CB and similarly a n+ beam extracted from the SPES-CB will be transported
199 till the end of the n+ beam line (April 2020). By September 2020, the complete 1+/n+ process will be experienced
200 using stable beams.

201 At the ISAC (Isotope Separator and Accelerator) facility, part of the TRIUMF lab (Vancouver, Canada), the charge
202 breeder technique [19] has been implemented since 2008. The mono-charged RIBs are produced by bombardment of
203 a solid target with protons of up to 500MeV and 100μA using a robust ion source surviving the high dose rate
204 environment. Isotopes from more than 15 elements have been charge bred providing post-accelerated RIBs spanning
205 the mass range from ²¹Na up to ¹⁶⁰Er; typical charge breeding efficiencies have been measured within 1-5% range.
206 The main issues so far have been a high background contamination and a too long charge breeding time process (≈20
207 ms*q). A new R&D program started addressing the background reduction using the two-frequency heating technique

208 (stabilization of the ECR plasma). In parallel, emittance measurement campaigns combined with intense extraction
209 modeling simulations are under progress to optimize the beam properties of the n+ charge bred ions.

210 At Texas A&M University, a new injection scheme, associated to a specific radioactive ion production technique,
211 has been developed to inject the mono-charged RIBs into the CB-ECRIS: an energetic beam of light ions bombards a
212 thin target, the radioactive products are transported by a flow of helium gas and their charge state are narrowed down
213 to the 1+ charge state. Hence, an RF SextuPole Ion-Guide (SPIG) of 2.5m has been designed [20] and tested to
214 transport and inject the mono-charged RIB into the CB-ECRIS. Using first, a stable Cs¹⁺ ion beam, and second, a
215 ²²⁸Th radioactive source delivering radioactive products of ²²⁰Rn⁺ and ²¹⁶Po⁺ guided by the He gas, a global charge
216 breeding efficiency of ≈50% has been achieved. Successfully, RIBs of ¹¹⁴In¹⁹⁺ and ¹¹²In²¹⁺ have been accelerated by
217 the K500 Cyclotron.

218 At the CARIBU (CALifornium Rare Isotope Breeder Upgrade) facility, part of the ANL lab (Chicago, USA),
219 different methods and techniques [21] have been employed to address the contamination reduction: CO₂ snow
220 cleaning, parts of ECRCB being made of ultra-high purity aluminum (99.9995%) and vacuum coated with ultra-high
221 purity aluminum. Even if the successes of these practices have been established, the last method presents some
222 unwanted contaminant: Mo, Ta, W. Therefore, a new coating procedure is under progress (Atomic Layer Deposition)
223 to get rid of those impurities.

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

230 In conclusion, regarding all these developments and R&D, it is clear that the ECR type charge breeder has a real
231 future by enhancing its global performances: lower contamination, higher charge breeding efficiency and better
232 control over the charge breeding time in order to play an important role in the existing and the future radioactive ion
233 beam production facilities.
234

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240

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