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Optimizing charge breeding techniques for ISOL facilities in Europe: Conclusions from the EMILIE project

P. Delahaye, A. Galatà, J. Angot, J. F. Cam, E. Traykov, G. Ban, L. Celona, J. Choinski, P. Gmaj, P. Jardin, H. Koivisto, V. Kolhinen, T. Lamy, L. Maunoury, G. Patti, T. Thuillier, O. Tarvainen, R. Vondrasek, and F. Wenander

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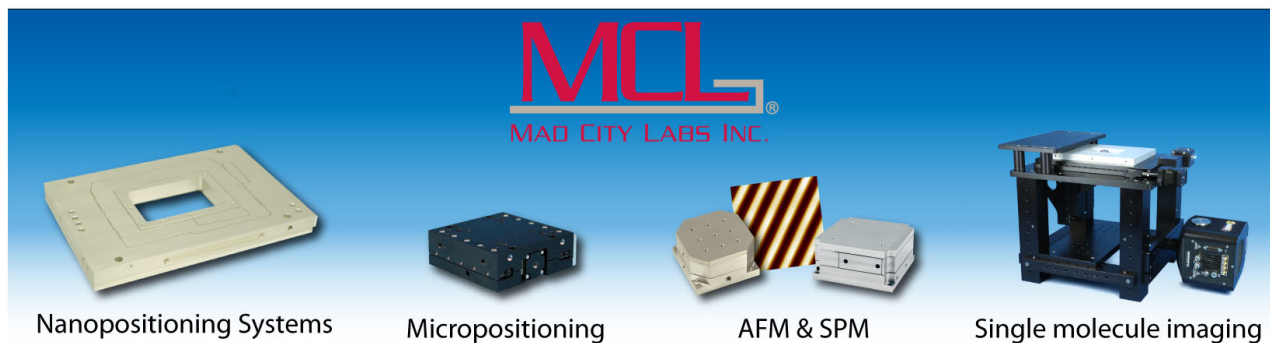
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Optimizing charge breeding techniques for ISOL facilities in Europe: Conclusions from the EMILIE project

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The present paper summarizes the results obtained from the past few years in the framework of the *Enhanced Multi-Ionization of short-Lived Isotopes for Eurisol* (EMILIE) project. The EMILIE project aims at improving the charge breeding techniques with both Electron Cyclotron Resonance Ion Sources (ECRIS) and Electron Beam Ion Sources (EBISs) for European Radioactive Ion Beam (RIB) facilities. Within EMILIE, an original technique for debunching the beam from EBIS charge breeders is being developed, for making an optimal use of the capabilities of CW post-accelerators of the future facilities. Such a debunching technique should eventually resolve duty cycle and time structure issues which presently complicate the data-acquisition of experiments. The results of the first tests of this technique are reported here. In comparison with charge breeding with an EBIS, the ECRIS technique had lower performance in efficiency and attainable charge state for metallic ion beams and also suffered from issues related to beam contamination. In recent years, improvements have been made which significantly reduce the differences between the two techniques, making ECRIS charge breeding more attractive especially for CW machines producing intense beams. Upgraded versions of the Phoenix charge breeder, originally developed by LPSC, will be used at SPES and GANIL/SPIRAL. These two charge breeders have benefited from studies undertaken within EMILIE, which are also briefly summarized here. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4935229>]

I. THE EMILIE PROJECT

A. Scope of EMILIE

Following the seminal work of Tamburella *et al.* for the PIAFE project,¹ the charge breeding technique has been generally adopted by facilities worldwide as an efficient technique to optimize the reacceleration of radioactive ion beams.^{2,3} In Europe, SPES and GANIL/SPIRAL will use an upgraded version of the PHOENIX ECR charge breeder, while ISOLDE has upgrade plans for the Radioactive beam Experiment (REX)-EBIS.

The EMILIE project⁴ gathers 8 European laboratories to tackle the present issues of both ECRIS and EBIS charge breeding techniques for future facilities, in particular the following:

- the low duty cycle of the EBIS beam, by the development of an EBIS beam debuncher;

- the beam purity limitations of ECR charge breeders, by using appropriate materials and treatments to the surfaces exposed to vacuum, properly dimensioning the pumping system and optimizing the resolution of the following spectrometer;
- the relatively low capture of light and metallic ions in ECR charge breeders, by optimizing the 1+ ion beam optics.

B. EMILIE’s experiments

During the EMILIE project, a number of experimental results have been obtained. These concern, for example, the study of the 1+ beam capture under different conditions using the Phoenix ECR charge breeder at LPSC,^{5–7} the capture of light ions using the Argonne National Laboratory (ANL) ECR charge breeder,^{8,9} and the charge breeding of carbon beams at LPSC.¹⁰ A prototype of hot 1+ ECR ion source was also developed by LPSC.⁶ The SPIRAL 1 charge breeder makes use of an early version of Phoenix tested at ISOLDE¹¹ which has been upgraded to make use of UHV and pure aluminum Al components, an optimized gas injection system,

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an electrostatic quadrupole triplet, and movable grounded tube at injection to allow more possibilities to tune the 1+ beam optics.⁹ The device is now under test at LPSC.¹² The ECR charge breeder for SPES, recently tested at LPSC, has shown very good performances for Rb and Cs ions,¹³ with a very low emittance of the charge bred beams and an excellent stability. The EBIS beam debuncher is being commissioned at LPC Caen and has produced the first preliminary results which are reported for the first time in this paper.

II. EBIS BEAM DEBUNCHER

A. A Paul trap as debuncher

In the past years, REX-EBIS has been routinely delivering beams with high charge states and good purity for experiments with post-accelerated beams at ISOLDE. Despite the very attractive performances of the EBIS charge breeder for radioactive ion beams, the time structure of the extracted beam can become a show stopper for many experiments looking at large events dynamics, such as in-beam experiments: with typical pulse duration below 1 ms for repetition rate of ~ 10 Hz, problems of dead-time, pile-up or fake coincidences dramatically increase already with typical intensities as low as 10^5 - 10^6 pps, as observed with the MINIBALL gamma array. In order to overcome this limitation, the EMILIE collaboration has developed a prototype of Paul trap as debuncher for the highly charged ion beam delivered by an EBIS-type charge breeder. Such Paul trap would allow delivering a continuous beam to the experiments over a 100% duty cycle and presents in this respect an advantage over the slow extraction modes currently used—and possible debunching schemes to be developed—in EBIS charge breeders, which cannot extract beams while charge breeding. As indicative objectives, the prototype should eventually demonstrate the following performances:

- a maximum of $\pm 20\%$ current fluctuation for the debunched beam, for cycles up to 200 ms;
- an overall efficiency above 50% ($\sim 80\%$) for the whole process, including injection and debunching, for cycles up to 200 ms;
- in the long run, a pressure in the trap down to 5×10^{-12} mbar or below to avoid sizeable recombination losses during the debunching process.

The prototype of EBIS beam debuncher is based on a segmented Paul trap with a characteristic internal radius $r_0 = 1.5$ cm and a length of about 50 cm (Fig. 1). It comprises 23 segments which have been coupled for simplicity by groups of 2 to 3 to 8 arbitrary waveform generators (Lecroy arbstudio generators) and amplifiers. It is therefore a slightly downscaled version of the one presented in Ref. 4. The trap geometry is inspired from the ISOLDE ion COOLer (ISCOOL):¹⁴ 2 couple of rods, on which a RF voltage is applied, permit to confine the ions radially, while the longitudinal ion motion is controlled by blades inserted in the symmetry planes of the quadrupole. In contrast to ISCOOL, the structure of the Paul trap is open, permitting an efficient pumping of the trapping volume, to avoid charge recombination of the highly charged ions with the residual gas. Fig. 2 presents a photograph of the prototype built by LPC Caen.

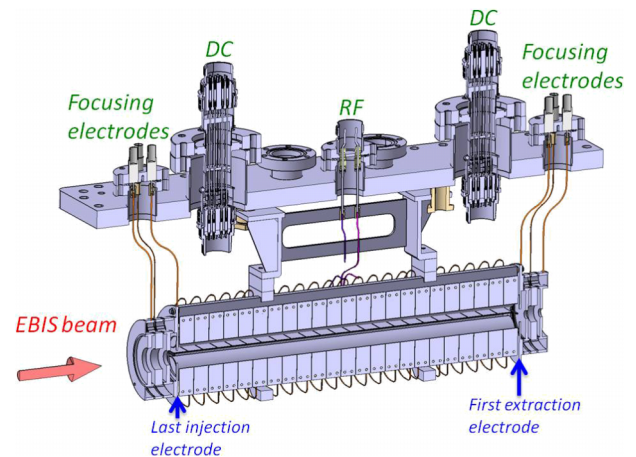


FIG. 1. EMILIE debuncher. The RF drives the radial ion motion, while the DC segments permit to manipulate the longitudinal phase space of the EBIS bunch. The trap length is 50 cm. The red arrow shows the direction of the EBIS beam.

B. Preliminary tests at LPC Caen

The EBIS beam debuncher is presently being tested with stable and singly charged alkali ions continuously delivered from a Kimball physics ion source¹⁵ at LPC Caen. The trap is installed on the SHIRaC¹⁶ test bench, which is equipped by standard turbo-molecular pumps: at the present stage, a pressure down to 10^{-7} mbar is achieved, not suited for tests with highly charged ions. Such tests will have to be done at a later stage, using getter pumps and highly charged ions at GANIL and/or ISOLDE. At the SHIRaC test bench, 5 keV beams of Cs^+ and Na^+ have been injected into the debuncher with typical intensities of 50 nA. The high voltage of the debuncher platform was optimized for transmission and trapping to a value of 4980 V, resulting in an energy for the ions travelling through the trap of the order of 20 eV. Extracted ions are either observed with a Faraday cup or a double stage Micro-Channel Plate (MCP) system F1094 from Hamamatsu¹⁷ biased with a voltage of 1400 V. The MCP system was found linear in the dynamic range used for the experiments. Injecting and extracting the beam continuously, transmissions of more than 90% were obtained with the following RF peak-to-peak amplitudes and frequencies: 2000 V and 1.6 MHz for $^{23}\text{Na}^+$ ions and 2300 V and 2.2 MHz for $^{133}\text{Cs}^+$ ions. Using these voltages, trapping half-lives of the order of 100 ms could be



FIG. 2. EMILIE debuncher built at LPC Caen.

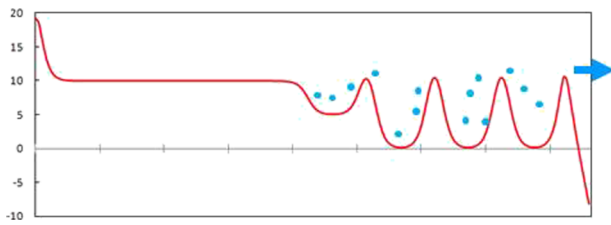


FIG. 3. Principle of the debuncher: ions are slowly extracted from the trap by lifting the voltages of the group of segments one after the other.

observed for Na^+ ions and longer than a few s for Cs ions. The reason of the higher trapping losses for Na remains to be investigated. A fast voltage switch on the last injection electrode of the debuncher (Fig. 1) permits to define injection and trapping cycles: with a voltage lower than 5 kV enter the trap, while for higher voltages (5100 V) ions outside the trap are repelled while ions inside the trap are trapped. During the whole cycle, the first extraction electrode (Fig. 1) is set at 5150 V to contain the injected ions. Once injected, the ions are slowly extracted by ramping up successively the segments of the trap, as shown on Fig. 3. The energy of the extracted ions is, in principle, defined by the voltage of the first extraction electrode.

During the very first tests described here, a cycle of 12.5 ms was applied: Na^+ ions were injected during 500 μs (injection voltage set down to 0 V), subsequently trapped for 1.5 ms and eventually released over the next 10 ms by ramping one after the other the voltages of the groups of segments. The maximum voltages of the ramps ranged from 25 V to 75 V. Fig. 4 shows the signal observed on the MCP superimposed to the electrode voltages (in arbitrary units for more visibility). An overshoot of ions is observed at the time the voltage of the injection electrode is suddenly switched to a higher value. This signal is interpreted as ions gaining enough energy to pass over the extraction electrode voltage during the brief moment of the injection voltage switch. The debunched beam is shown in detail in Fig. 5. The structure created by the successive ramps is clearly visible. At this preliminary stage, a rough estimate gives an efficiency of about 30% for the overall trapping and debunching process. 50% was found with Cs^+ following a

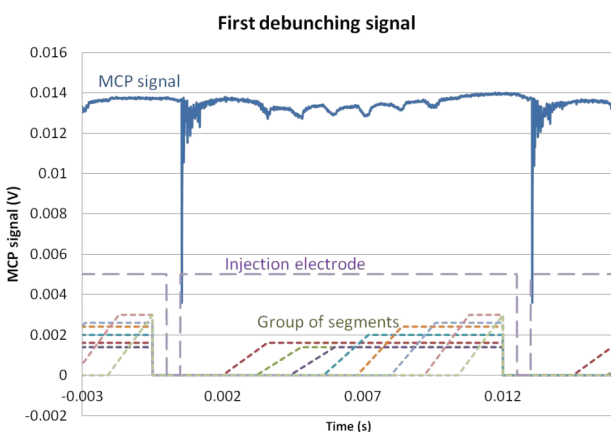


FIG. 4. Debunching sequence. The dashed lines are the voltages applied to the successive group of segments of the trap and the injection electrode (in a.u.). The MCP signal as observed on the oscilloscope is shown in plain line. It is negative, with a base level of about 14 mV.

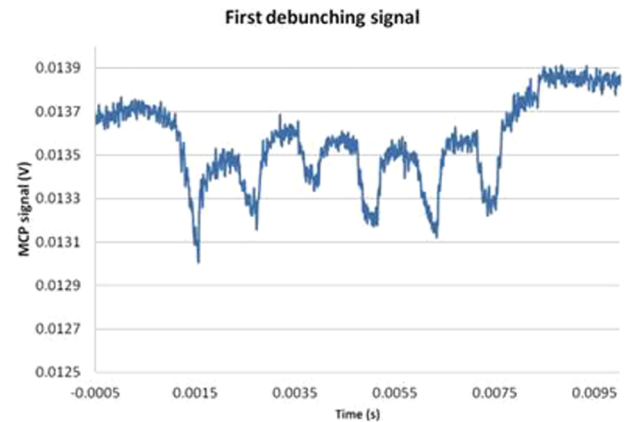


FIG. 5. Zoom on the debunched ion cloud signal (negative signal on top of a baseline of 13.9 mV).

similar procedure, although in this case the debunched signal was slightly shorter and more irregular. The debunched ion cloud of Fig. 5 is already much longer than the slow extraction pulse from REX-EBIS shown in Fig. 3 of Ref. 18. A tiny RF voltage (100 kHz, <10 V amplitude) was superimposed to the high voltage of the platform to mimic the effect of the EBIS beam energy dispersion. For such a tiny voltage, the debunched signal remains very similar.

Obviously, the different voltages and timings still need some optimizations to achieve the performances described in Section II A. In Fig. 5, each peak corresponds to an individual voltage ramp of a group of segments. The use of non-linear voltage ramps will be investigated in order to achieve less than $\pm 20\%$ fluctuations on the debunched beam current. The RF, injection, and debuncher platform voltages have been found to be critical parameters for the capture and trapping efficiencies. These voltages still require fine tuning. Beyond these optimizations which still have to be done, the next important steps for the study of the debuncher are as follows:

- the use of a deflector to better define a pulsed beam at injection, with a typical length of 50 μs as in the normal operation of REX-EBIS;¹⁸
- the use of Li^+ ions, whose A/q ratio will be closer to the multi-charged ions from EBIS, and for which the RF voltage system is *a priori* better optimized;
- the use of a suitable acquisition system in order to detect single ions on the MCP and to study the debunching over longer times;
- the tests with multi-charged ions at GANIL, using one of the different ECRISs available there.

III. EXPERIMENTS WITH THE PHOENIX CHARGE BREEDER

The studies undertaken with the Phoenix ECRIS in the framework of EMILIE have already been summarized to a large extent in Refs. 6 and 7. The most recent results with the Phoenix charge breeder for SPES¹³ and SPIRAL 1¹² are presented at this conference. We recall here only the significant progresses or studies to outline the contribution of the EMILIE project in the latest development of this technique.

A. Multi-ionization in ECRIS charge breeders

The first studies undertaken within EMILIE aimed at gaining understanding of the capture and charge breeding processes in ECRIS charge breeders. The comparison of the performances of the Phoenix charge breeder with the JYFL ECRIS⁵ showed similar performances for both ECRIS for rare gases, with an enhancement of the high charge states using the double frequency heating technique. At that early stage, the beneficial effect of the gas mixing observed with the JYFL ECRIS for efficiencies and charge states was not clear in the Phoenix charge breeder. In contrast with higher charge states, 1+ and 2+ beams extracted from the charge breeder are not captured in the ECR plasma but represent the beam propagating through the plasma, the 2+ charge state being mostly in-flight ionized. Uncaptured fractions of the 1+ and 2+ beams of Rb, and Cs metallic elements propagating through the charge breeder were used as insightful probes of the plasma of the Phoenix charge breeder.⁷ The probability for a 1+ ion to travel through the plasma without being captured permitted to derive orders of magnitude for the ion-ion collision frequencies and plasma densities. The results revealed that ion-ion collisions dominate the ion dynamics for high charge states, while low charge state ions are magnetized (for typical charge states $q \leq 3$). The electron density estimated is typically one order of magnitude below the critical density for a 14.5 GHz microwave frequency.

B. Improvement of performances

In contrast with rare gases, metallic elements are not recycled from the plasma chamber walls. For this reason, the global charge breeding efficiencies measured for the metallic elements have always been below those measured for the rare gases. This difference is amplified for light elements, for which the capture is hindered by a high velocity spread of the 1+ beam.¹⁹ In order to achieve optimal performances for the metallic beams, the 1+ beam optics has to be carefully optimized, as the charge breeding process is conditioned by a direct capture of the 1+ beam.

A significant step forward was done with the CARIBU ECRIS charge breeder^{20,21} to reduce the efficiency disparity between rare gases and metallic elements. Compared to Phoenix, the CARIBU charge breeder has an open hexapole which permits to inject the RF radially, through the hexapole structure, and an efficient pumping to the plasma chamber. Using such configuration permits to preserve the symmetry of the magnetic field at injection. Such feature is believed to be an important ingredient for the 1+ beam injection.⁸ The grounded tube transporting the 1+ ions to the plasma chamber held at high voltage is tunable in position. The CARIBU charge breeder is also using double frequency heating and benefits from the cooled beams from the CARIBU gas cell and ion cooler.

The latest versions of the Phoenix charge breeder^{6,9,13} incorporate a number of modifications which resulted in a similar improvement: the iron cone at injection which was originally truncated for the passage of the RF port was redesigned in order to restore the magnetic field symmetry

at injection. The axial magnetic field gradient was finely tuned by means of two movable iron rings mounted around the hexapole, to yield best efficiencies with Na⁺ ions.⁶ The grounded tube of the LPSC charge breeder was replaced by a conductance²² which has been found beneficial for the HF coupling and the efficiency for Ar ions. The SPIRAL charge breeder⁹ incorporates a movable grounded tube similar to the CARIBU charge breeder. Particular efforts were done to optimize the vacuum level, as a low residual gas pressure was found to be beneficial for the overall charge breeding efficiency in the CARIBU²³ and in the LPSC charge breeder.⁶ As a byproduct, with a low residual pressure in the charge breeder down to a few 10^{-8} mbar, the use of the gas mixing technique has been found useful for optimizing the charge breeding of the light ions of interest for the upgraded SPIRAL facility.¹² The SPIRAL 1 charge breeder should alternatively make use of He or O₂ support gas for optimizing the charge breeding efficiencies, charge states, and charge breeding times. In general, the new generation ECR charge breeders, which include the SPES and SPIRAL 1 charge breeders, are catching up with the performances of the EBIS ones for metallic ions as can be attested in Fig. 6. A difference persists for light ions though, for which the direct capture remains difficult to optimize. A slight improvement of the efficiencies as well as the attainable charge states is expected with the SPIRAL 1 and SPES charge breeders when using double frequency heating, which remains to be tested. The charge breeding times quoted in Fig. 6 can significantly vary according to the plasma conditions, RF power, magnetic confinement, support gas flux and nature in the ECRIS charge breeder. In comparison, REX-EBIS is a more predictable machine. The total ion manipulation at REX-ISOLDE consists of accumulation in REXTRAP and charge breeding in REX-EBIS.²⁴ For comparable charge states, the total preparation time is similar to the shortest charge breeding times reported here.

Finally, the concern of beam purity is also being addressed for the new Phoenix charge breeders. The SPIRAL charge breeder makes use of an aluminum plasma chamber, aluminum

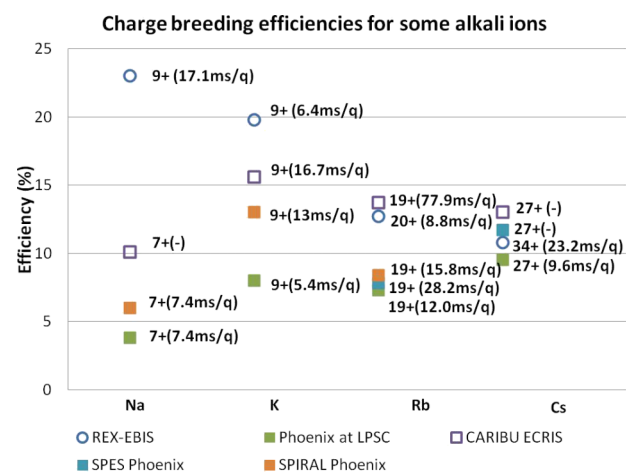


FIG. 6. Charge breeding efficiencies obtained at REX-ISOLDE as compiled, for example, in Ref. 24 compared to the most recent CARIBU ECRIS efficiencies²⁰ and latest measurements with the LPSC,^{6,25} SPIRAL,¹² and SPES¹³ Phoenix charge breeders. The average charge breeding time per charge state is given in brackets. In the case of REX-EBIS, this time contains the additional accumulation time in the REXTRAP ion cooler.

plasma electrode, and UHV components to reduce the number and quantity of stable contaminants. In the SPES charge breeder, special treatments were applied to the extraction iron plug and the stainless steel plasma chamber. SPES will make use of a Medium Resolution Mass Separator (MRMS) downstream the charge breeder, placed on a 160 kV high voltage platform, which should achieve a resolving power of 1/1000 at 10% of the peak for the extracted charge bred beams.²⁶ In the case of GANIL/SPIRAL 1, the CIME cyclotron is an efficient separator,²⁷ as suppression factors of the order of 10^6 were readily achieved for relative difference in masses of 5×10^{-4} .

IV. OUTLOOK

In the course of the EMILIE project, the experimental results presented here have permitted to (i) perform the first tests of the EBIS beam debuncher, (ii) gain understanding in the physical processes specific to ECRIS charge breeders, and (iii) improve the performances of the Phoenix charge breeder for the future SPES and GANIL/SPIRAL facilities. In the future, more experimental data will come from the on-line SPES and SPIRAL charge breeders, which should certainly help in developing further the ECRIS charge breeding technique. The tests of the EBIS beam debuncher will be pursued at LPC Caen and GANIL during the next years in the framework of the EURISOL JRA of ENSAR 2.

ACKNOWLEDGMENTS

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