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Prospects for advanced electron cyclotron resonance and electron beam ion source charge breeding methods for EURISOLa)

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Prospects for advanced electron cyclotron resonance and electron beam ion source charge breeding methods for EURISOL^{a)}

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As the most ambitious concept of isotope separation on line (ISOL) facility, EURISOL aims at producing unprecedented intensities of post-accelerated radioactive isotopes. Charge breeding, which transforms the charge state of radioactive beams from 1+ to an n+ charge state prior to post-acceleration, is a key technology which has to overcome the following challenges: high charge states for high energies, efficiency, rapidity and purity. On the roadmap to EURISOL, a dedicated R&D is being undertaken to push forward the frontiers of the present state-of-the-art techniques which use either electron cyclotron resonance or electron beam ion sources. We describe here the guidelines of this R&D. © 2012 American Institute of Physics. [doi:10.1063/1.3665960]

I. CHARGE BREEDING FOR ISOL FACILITIES

Since the pioneering work of Tamburella *et al.* for the PIAFE project,¹ the charge breeding technique in electron cyclotron resonance source (ECRIS) and electron beam ion source (EBIS) has nicely evolved. It is in particular due to the development of the PHOENIX electron cyclotron resonance (ECR) charge breeder at LPSC, and to the development of REX-EBIS at ISOLDE by the REX-ISOLDE collaboration. The relative success obtained with both charge breeders can be attested by the number of facilities which are starting using or developing one or the other technique.²⁻⁵ On the roadmap to EURISOL, SPES, and SPIRAL 2 plan to use a PHOENIX ECR charge breeder, while ISOLDE has upgrade plans for REX-EBIS. However, for both techniques, a number of known issues remain.⁵

- While ECR charge breeders have very high intensity capabilities, EBIS are intrinsically limited by space charge capacity (up to 10^{10} charges/bunch).
- EBIS provide high charge states and correspondingly low mass-over-charge ratios down to $A/q \sim 3$. In contrast, ECR charge breeders are limited so far to an operational range of $4 < A/q < 8$ depending on the atomic number and neutron excess of the considered nuclide, thus limiting the accessible energy.

- The EBIS natural mode is pulsed which eventually complicate data acquisition and triggers event pileup for intensities as low as 10^6 pps for in-beam experiments.
- Charge breeding efficiencies in one charge state range from 15% to 1%. However for ECR charge breeders, the injection of light masses has always showed poor/modest results (subpercent efficiencies for a single charge state for masses below 20). Moreover efficiencies for metallic ions are about two times lower than for rare gases.
- ECR charge breeders exhibit a large stable beam background on the whole exploitable range of A/q after a classical dipole separator. The background is typically a few nA between the A/q peaks of the support gas.

Even though the relative complementarity of the two charge breeders could be exploited at EURISOL, i.e., EBIS for low to moderate intensity beams of exotic isotopes and ECRIS for higher intensities,⁵ there is a wide range of situations for which the improvement of both charge breeder performances would be highly beneficial.

II. A DEBUNCHER FOR EBIS-BASED CHARGE BREEDER

During the past decade, the REX-EBIS at REX-ISOLDE has proven to be a reliable charge breeder, particularly suited for radioactive beams with intensities ranging from a few 100 to 10^9 pps and low duty cycle post-accelerators. With an electron beam intensity of up to 400 mA only, it is a rather mod-

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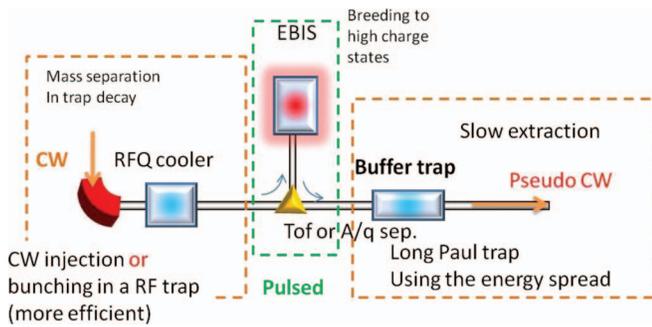


FIG. 1. (Color online) EBIS and debuncher concept for continuous wave (CW) beams.

est device compared to the TITAN (Ref. 6) or NSCL electron beam ion traps (EBITs).⁷ For the future ISOL facilities and eventually EURISOL, the major limitation of such kind of charge breeder will be its pulsed operation, in front of the well-known space charge capacity issue.

The ^{132}Sn beam is a typical example, because of its popularity for physics (it is doubly magic) and as secondary beam to be used for two-step reactions. It will be produced in copious amounts at SPIRAL 2: latest predictions give about 10^{10} pps as 1+ beam. The typical performances for REX-EBIS like are a charge breeding time of 180 ms, a maximal capacity of 3×10^{10} charges (assuming it reaches 50% of the theoretical one) and an average charge state of 33+. In these conditions the maximum current which could be accepted by a REX-EBIS like charge breeder would be of the order of 5×10^9 pps, just below by a factor of 2. Comparing to the expected performances of the baseline Phoenix ECR charge breeder, a REX-EBIS-like charge breeder would therefore provide the possibility to obtain high purity and higher energies at no efficiency cost for a wide range of isotopes (about 80% of the SPIRAL 2 beams) and at the cost of some efficiency for the most intense beams. The gain in energy is significant: with a peak charge state of 21+ for the ECR charge breeding of ^{132}Sn as observed at ISOLDE, the maximum energy after the Cyclotron d'Ions de Moyenne Energie would be only 6.8 AMeV only, while it would be 15 AMeV using a REX-EBIS like charge breeder providing the 33+ charge state.

Despite the very attractive performances of the EBIS charge breeder, the time structure of the extracted beam would

be 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, pileup or fake coincidences would dramatically increase already for intensities as low as 10^6 pps.

In order to overcome this limitation, the EMILIE (“enhanced multi-ionization for short-lived isotopes produced at EURISOL”) collaboration is studying a prototype of Paul trap which could be used as debuncher for the highly charged ion beam delivered by an EBIS-type charge breeder. This device would be a cost-effective solution compared to the one previously proposed at NSCL (Ref. 5) and in the framework of the EURISOL design study,³ consisting of two EBIS(T) in push-pull configuration. The EBIS-debuncher configuration is schematically shown in Fig. 1.

The prototype will be a long segmented Paul trap whose features will be optimized for the efficient capture, trapping and debunching of the highly charged ion pulses. In order to avoid recombination, ultra-vacuum technology will be applied. The typical pulses characteristics from REX-EBIS are a pulse duration of $30 \mu\text{s}$; maximum energy spread of 50q eV.⁸ As a consequence, typical parameters for the trap can be defined: 1 m long trap with 2 cm internal radius, an RF of 2 MHz and 500 V amplitude, and a set of dc voltages up to 100 V applied to the segments. The depth of the pseudopotential trapping well would be of the order of 60q eV, and the maximum capacity of the order of 5×10^9 ions per bunch. For a period of 180 ms, this translates into 2.5×10^{10} pps which is slightly above the EBIS limit. A typical dc program performing the debunching is shown in Fig. 2.

III. OPTIMIZATION OF ECR CHARGE BREEDER PERFORMANCES

As previously pointed out, the ECR-based charge breeding technique was accurately characterized during the past decade. This technique has a large acceptance in terms of intensity and emittance, robustness and reliability, however, it presents some drawbacks. First of all the charge state distribution extracted from an ECR-based charge breeder is wider (like in classical ECRIS) and is peaked at lower charge states than the one extracted from the EBIS (like in classical ECRIS). Second, the absence of wall recycling in the case of

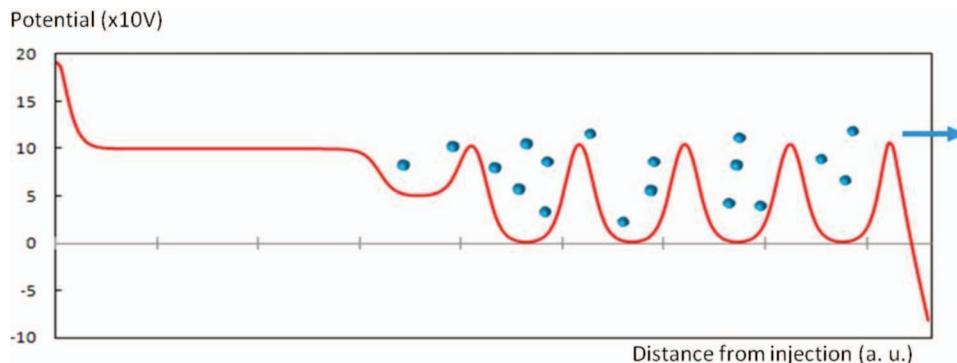


FIG. 2. (Color online) One of the many dc programs that can be envisaged for flattening the pulses from the EBIS. In this case the EBIS pulse is distributed in many different potential wells which are slowly extracted.

condensable elements, leads to a total capture of the $1+$ beam of about 30% and therefore limits the breeding efficiency for a single charge state. Third, the spectra acquired at the output of the ECR-based charge breeder revealed the presence of a stable background (in the order of nA) between the peaks of the support gas. Fourth, the charge breeding of light ions revealed to be difficult. The aim of the present proposal (WP3) is to apply numerical studies and experimental techniques in order to overcome the difficulties listed above.

The performance of an ECR-based charge breeder could be improved without a strong impact in terms of costs by accurately studying the plasma-microwave coupling into the plasma chamber cavity. In fact, depending on the coupling, a given microwave power level can lead to very different performances in terms of extracted currents and charge state distribution. The proper coupling with the PHOENIX plasma chamber will be studied in order to improve the plasma characteristics and to minimize the losses on the plasma chamber. This will reduce the outgassing from the wall, leading to a lower stable background in the spectra and a much more stable plasma.

The lower efficiency observed for condensable elements with respect to gaseous ones is a consequence of the fact that the “single capture” process is not so efficient. The capture of the $1+$ beam and its influence on the ECR plasma (as observed during some experiments performed at LPSC within a LPSC/INFN-LNL collaboration), will be numerically studied. It has been recently shown by the ion source group at INFN-LNS that different injected microwave frequencies can lead to different ECR plasma shapes, the impact of such phenomenon on the $1+$ beam capture will be investigated.

The experimental activity will consist, on one side, in a check of the outcome of the numerical simulations and, on

the other, in applying all technological aspects that revealed (during the past years) to have an influence on charge breeding performances. A new plasma chamber will be designed and built and different UHV material will be tested in order to lower as much as possible the stable background. Then, a high efficiency and reliable low charge states ion source ($1+$ to $3+$) will be built: it will facilitate the study of the capture process and will possibly permit to improve the breeding efficiency for light ions (as shown in the past by LPSC). The magnetic gradients of the Phoenix booster will be optimized in order to obtain an optimum electron energy spectrum increasing the stability of the plasma. To conclude, special attention will be paid to the reproducibility of all the results: the so called “blind tuning” in the case of condensable elements will be extensively tested.

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