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On-line charge breeding using ECRIS and EBIS

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ABSTRACT

The efficient and rapid production of a high-quality, pure beam of highly charged ions is at the heart of any radioactive ion beam facility. Whether an electron cyclotron resonance (ECR) ion source or an electron beam ion source (EBIS) is used to produce these highly charged ions, their operating characteristics will set the boundaries on the range of experiments which can be performed. In addition, time structure and duty cycle have to be considered when defining the operating parameters of the accelerator system as a whole. At Argonne National Laboratory (ANL), an ECR charge breeder was developed as part of the Californium Rare Ion Breeder Upgrade (CARIBU) program. The charge breeding efficiency and high charge state production of the source is at the forefront of ECR charge breeders, but its overall performance as part of the accelerator system is limited by pervasive background and relatively long breeding times. As such, an EBIS charge breeder has been developed and is running in an off-line configuration. It has already demonstrated good breeding efficiencies, shorter residence times, and reduced background and is scheduled to replace the ECR charge breeder in late 2015. The resultant change in duty cycle and time structure necessitates changes to the overall operation of the facility. The experiences with these breeders, as well as from several other facilities which already utilize an ECR or EBIS for charge breeding, help to define the operational characteristics of each technology – their strengths, their weaknesses, and the possible paths to improvement.

1. Introduction

As more charge breeders come on line, the variety of design and the operational experience gained are helping to better define solutions to the problems encountered with the charge breeding technique. New breeders are being commissioned for SPES [1], SPIRAL [2], and VECC [3] with others in the planning and design stages [4]. Faced with many of the same operational challenges – predominantly beam purity for ECR breeders and for EBIS breeders the efficient injection of a large number of particles accompanied by a slow extraction – these new breeders incorporate into their design and construction many of the lessons learned from existing charge breeders, and as such, the performance gap between the two devices is narrowing.

2. ECR charge breeding

ECR sources have been utilized as charge breeders for many years, first to ionize radioactive species which were introduced into the source via a carrier gas [5] and later to ionize radioactive species introduced directly into the plasma as 1+ ions [6]. A room temperature ECR ion source has solenoid coils providing an axial confining field and a permanent magnet hexapole providing radial confinement. The plasma is excited by RF typically in the 10–14 GHz range. For charge breeding, the 1+ ions are introduced into the plasma from the injection side of the source, thermalized in the plasma, undergo stepwise ionization via collisions with energetic electrons, and are then extracted for subsequent acceleration [7]. It is a CW device which can accept several eμA of injected beam, has a good efficiency, and can produce the high-quality, highly-charged ion beam necessary for injection into an accelerator system [8].

Fig. 1 shows the charge breeding performance for the Phoenix ECR sources tested at ISOLDE [9] and LPSC [10], the TRIAC source [11], the TRIUMF source [12], the ANL source [13,14], and the recently commissioned SPES charge breeder (built by LPSC for the LNL group) [15]. The radioactive beam species are denoted with a halo around them.

3. EBIS charge breeding

The EBIS fulfills the same role as the ECR, the production of highly charged ions, but its confining fields are produced via trap electrodes, a superconducting solenoid, and the electron beam

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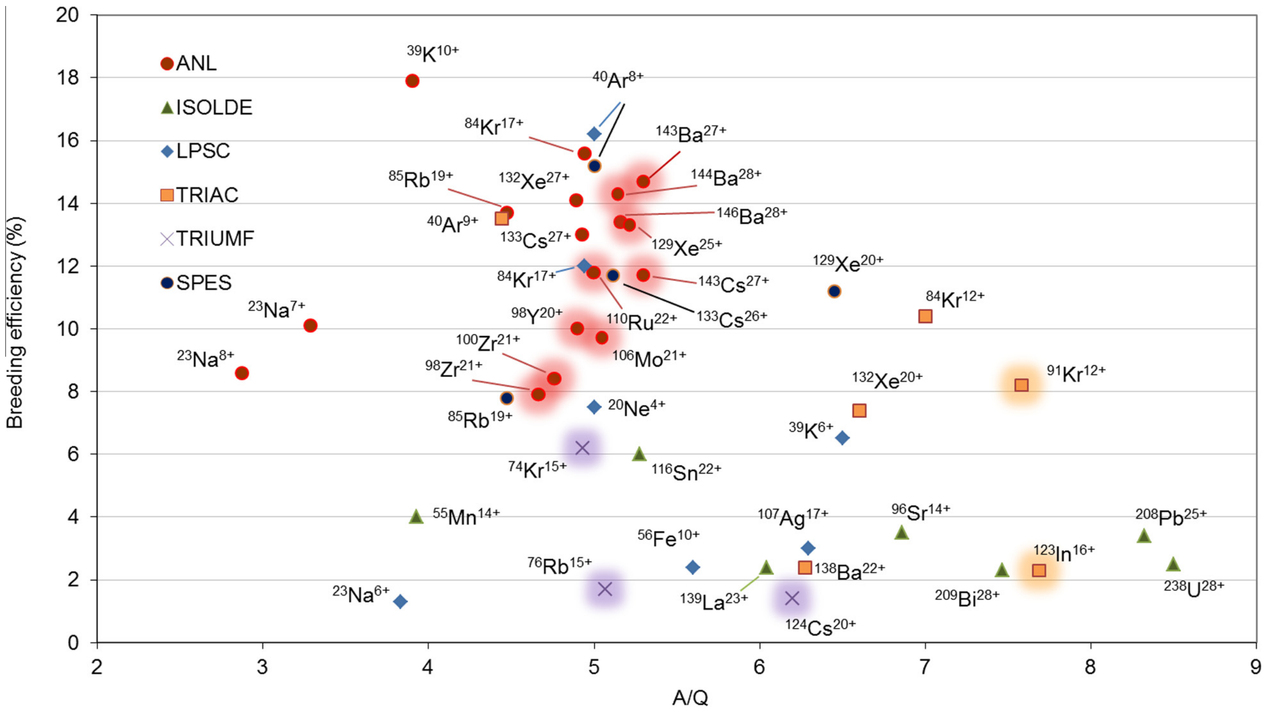

Fig. 1. Charge breeding performance for the Phoenix ECR sources tested at ISOLDE and LPSC, the TRIAC source, the TRIUMF source, the ANL source, and the recently commissioned SPES charge breeder (built by LPSC for the LNL group). The radioactive beam species are denoted with a halo around them.

itself. Ionization is still stepwise, but in contrast to the broad electron energy distribution produced in an ECR stretching from a few eV to an MeV [16], the EBIS electron beam is monoenergetic allowing greater control over the peak charge state produced and the time it takes for its production. For charge breeding, the 1+ ions enter the trap region, an electrostatic barrier is then raised. Provided there is good overlap with the electron beam, the ions undergo stepwise ionization and after some time the trap is opened releasing the highly-charged ions [17]. An EBIS is an inherently pulsed device and requires preparation of the 1+ beam in a RFQ cooler/buncher before charge breeding in order to attain the highest efficiency [18].

Up until recently, the only data for EBIS charge breeding has been from the REX-EBIS group [19] shown in Fig. 2. Over the last decade, their EBIS has demonstrated efficiencies as high as 23%, and this includes the efficiency of the REXTRAP which prepares the ions for injection into the EBIS. Two new data points have been added to this graph – a potassium beam produced by the MSU ReA EBIT in 2013 [20] and a cesium beam recently produced by the EBIS at Argonne [21].

4. ANL charge breeding program

In support of CARIBU – a program to provide radioactive species for the ATLAS experimental program [22] – ANL has developed an ECR breeder as well as an EBIS breeder. The ECR breeder has been delivering charge bred radioactive ion beams to the ATLAS experimental program for the last several years. While its charge breeding efficiency and high charge state production have been at the forefront of ECR charge breeding, its overall performance as a part of the accelerator system has been hindered by the pervasive background present in ECR ion sources.

As such, the EBIS breeder has recently been commissioned and is scheduled to replace the ECR in late 2015. The primary motivation for replacing the ECR with an EBIS is the level of beam contamination present in an ECR – typically on the order of several pA. Additional benefits of an EBIS include an improved charge breeding efficiency and faster breeding time [23,24]. However, the fact that an EBIS is a pulsed device as opposed to the CW nature of the ECR necessitates changes in accelerator operation and the manner in which beam will be delivered to target.

4.1. ANL ECR charge breeder

The ANL ECR breeder [25] (Fig. 3) is a room temperature source, and the plasma is excited with two RF frequencies – a 10.44 GHz klystron and an 11–13 GHz traveling wave tube amplifier (TWTA). It has an open hexapole structure providing good pumping to the plasma chamber region resulting in a base plasma chamber pressure of 2×10^{-8} Torr. The open structure also allows the RF and support gas to be introduced into the plasma chamber between the hexapole bars. This scheme eliminates the need for cut-outs in the field shaping iron to accept the RF waveguides and results in a highly symmetric axial magnetic field where the ions enter the plasma. This differs from other ECR breeders presently in existence which are closed hexapole devices with the RF injected along the long axis of the source. The 1+ ions are introduced into the plasma through a grounded high-purity aluminum tube mounted on a linear motion stage. The stage has a 30 mm range of travel, and thus the deceleration point of the 1+ ions can be adjusted on-line without disturbing the source conditions. The source is designed to operate at a 50 kV potential although it typically operates at 36 kV.

To set up the charge breeder and develop charge breeding techniques, stable 1+ beams are produced by a surface ionization source or an RF discharge source with injected intensities ranging from 2 to 500 enA. The 1+ diagnostics station includes a fully shielded Faraday cup for measuring the stable 1+ beam (FC1) and an aluminum foil shrouded silicon surface barrier detector (SBD1) for measuring radioactive beams via beta decay. The *n*+ diagnostics station includes a Faraday cup (FC2) for the stable beams and a silicon barrier detector (identical to SBD1) for the