Charge breeding of stable and radioactive ion beams with EBIS/T devices

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Abstract. Radioactive ion beams (RIBs) are an important tool for experiments at the foremost frontier of nuclear physics. The quasi-continuous radioactive beams from target ion sources of RIB-facilities have to be accelerated to energies at and beyond the Coulomb barrier. An efficient acceleration requires a suitable A/q of the ions determined by the accelerator design, which can be reached via the stripping method or by using a charge state breeder like the REX-ISOLDE system. In order to get comparable efficiencies for a charge state breeder with the stripping scheme, the breeding efficiency in one charge state has to be optimized by narrowing the charge state distribution. In addition good beam quality and thus small emittances are required to achieve best transmission in the following accelerator, which is mandatory for high intensity RIBs. For EBIS/T devices the maximum intensity of the radioactive ion beam is a critical issue, and high current EBIS/T devices will be necessary to deal with intensities of second generation RIB facilities.

INTRODUCTION

Nuclear physics experiments with exotic nuclides are at the foremost frontier of nuclear physics [1]. Thus acceleration of the radioactive ions to energies below and at the Coulomb barrier is required. Precise measurements need brilliant beams with small energy spreads, in order to use the very low intensities of short living isotopes with highest efficiencies. A new tool to prepare isotopes for injection into a post accelerator of for low energy experiments is the charge breeding method [2]. The capability to increase the charge state of an isotope, using a high charge state ion sources allows the adjustment of the charge state to the accelerator requirements and the reduction of the post accelerator size. In addition, the highly charged ions can be beneficial for low energy Penning trap assisted spectroscopy for instance, as shown by the TITAN project at TRIUMF [3]. Planned facilities like MAFF, SPES, SPIRAL II and EURISOL have identified the need of a breeding system due to budget and space restrictions.

The ions sources which are used for charge state breeding are the electron beam ion source (EBIS) and the electron cyclotron resonance ion source (ECRIS). Both types of charge state breeder have been examined within the framework of an EU-RTD project “charge breeding” [4]. Two breeding systems have been set up at ISOLDE / CERN: The REXEBIS charge state breeder and the PHOENIX ECRIS test bench. The principal scheme of a charge state breeder is shown in Fig. 1. The charge breeder...
system is part of the beam preparation of the singly charged isotopes for injection into an experimental set-up or post accelerator.

![Diagram of a charge state breeding system](image)

**FIGURE 1.** Schematics of a charge state breeding system. In case of an EBIS/T based system the injection and extraction has to be done via the collector side.

The isotopes are injected via a buffer gas emittance cooler into the EBIS/T device, in order to match the emittance of the generated beam of the isotopes to the small acceptance of the breeder and to bunch the beam for pulsed injection. Three devices are well suited for this beam preparation process, the Penning trap, which is used in case of REX-ISOLDE [5], an RFQ-ion guide [6] and the rf-funnel [7]. The phase space cooling process is performed by frictional forces while the ions interact with the buffer gas atoms. The ions have to be confined in an electromagnetic or an rf-field, which guides the ions through the device and avoids any losses. A new concept, which will be able to cool intense ion beams up to the \( \mu \)A region, is the rf-funnel, where thin ring electrodes with varying inner diameter surround the buffer gas volume. Those stacks of iris-shaped electrodes create a more box shaped potential distribution, which allows the confinement of ions in a large volume with reasonable electrode voltages [8].

A charge breeder requires an additional mass or A/q-analyzer in order to separate the highly charged isotopes from rest gas contaminants, which are produced in the high charge state ions sources as well [9]. In the EBIS/T case an achromatic separator might be required due to the energy spread of the ion beams extracted from an EBIS/T. The maximum energy spread corresponds to the potential depression of the electron beam times the charge state of the ion species. The relative energy spread depends on the acceleration voltage and the final beam energy of the LEBT section. In case of REXEBIS the space charge potential of the electron beam is 51 V assuming typical operation conditions of 200 mA electron beam current and 3.5 keV electron
beam energy. The potential depression towards the wall is about 185 V for a beam radius of 0.25 mm and a tube radius of 5 mm. A typical EBIS platform voltage is 20 kV and therefore the energy spread can become ±0.5%, which would restrict the resolution of the charge state selector afterwards.

RESULTS FROM THE REXEBIS CHARGE STATE BREEDER

The feasibility of an EBIS/T charge state breeder has been proven with the REX-ISOLDE Penning trap – EBIS concept. A pulsed accelerator like the REX-ISOLDE LINAC needs short injection pulses, where the EBIS is intrinsically well suited. The strong points of the EBIS are the high beam purity, short breeding times, high charge states and good beam emittance. The weak points in comparison to the ECRIS are the need for beam matching at injection, which requires buffer gas emittance cooling and makes the set-up complicated, and the restricted ion capacity. The EBIS is capable of handling low intensity beams, <1 nA.

The ISOLDE beam of 35 π mm mrad (60 keV) can not be injected into the EBIS with high efficiency without any beam preparation, because of the small transverse acceptance of the electron beam confining the injected ions. Thus a large Penning trap, the REXTRAP [10] accumulates, bunches and phase space cools the continuous ISOL-beam. The singly charged ions coming from ISOLDE with 60 keV energy are retarded by the Penning trap platform potential of nearly 60 kV and injected continuously into the trap, where they are accumulated and cooled. After 10-20 ms determined by the required charge breeding time inside the EBIS, 10 μs long bunches with a measured emittance of 10 π·mm·mrad for 80% of the beam at 30 keV beam energy are extracted from the trap re-accelerated by 60 kV and transferred to the EBIS via a beam transfer line consisting of two kicker bender assemblies and two electrostatic quadrupole triplet lenses. After charge breeding to a charge-to-mass ratio > 0.22 the ions are injected into the RFQ accelerator via an achromatic mass separator.

All elements except for He can be handled by the trap with efficiencies (extracted cooled ions / injected ions) up to 50%. Space charge effects start occurring for more than 10⁸ ions/pulse, with an efficiency decrease and emittance increase as a result [11]. That means, presently the Penning trap-EBIS concept has a limited ion throughput of ~10⁸ ions/s.

Because of the pulsed beam injection into the EBIS, its platform-potential can be ramped between injection and extraction and thereby the potential of the ISOL production part is decoupled from the injection energy into the LINAC. The REXEBIS charge state breeder can handle ion life-times down to some 10 ms. Within the running period of the RTD-project charge breeding, a variety of nuclides has been charge bred [12]. Radioactive ions from ⁶Li²⁺ to ¹⁵⁶Eu²⁺ have been delivered to experiments at MINIBALL and the second beam line behind the LINAC. In addition ¹³⁰Ba²⁺ and ¹⁵³Sm²⁺ have been produced using breeding times of 18 ms and 38 ms, respectively. Cs ions have been injected into the REXTRAP from the trap ion source, Ba and Sm ions from the ISOLDE separator. The Samarium ions (A/q = 5.46) have been accelerated in the RFQ for ion implantation into Silicon Carbide as radiotracers.
The EBIS system can easily handle and separate radioactive beam intensities in the pA (and even sub-pA) region from the residual gas. A spectrum of charge bred radioactive ions is shown in Fig.2. The peaks of the radioactive ions are resolved from the rest gas contamination, mainly $^{20}$Ne which is the buffer gas of REXTRAP. The mass resolution of the A/q-separator following the EBIS is $(A/q)/\Delta(A/q) \sim 100$, which is sufficient to select a charge state in an A/q-range with low rest gas contamination. The purity of the extracted beam is of high importance for most experiments. The EBIS is a ultra high vacuum device operating in the low $10^{-11}$ mbar region, and the noise level beside any A/q-peak is not measurable, that means smaller than 100 fA.

![Figure 2](image_url)  
**FIGURE 2.** Charge state distribution of $^{25}$Na charge bred within 19 ms in REXEBIS.

The efficiency of the complete breeding system is the ratio between the number of ions injected into the RFQ and the number of ions injected into the Penning trap. The trap efficiency does not exceed 50%. For high intensities (>10$^5$ ions/s) the efficiency drops down to 4%, dependent on the species and the intensity. The transmission from trap to EBIS is about 85%. The mass separator transmission is about 90%. The maximum ratio of ions in one charge state for light ions, if no charge state at shell closure is selected, is about 30%. This should allow 22% efficiency in one charge state. The extracted charge-bred ions have a charge state distribution, with approximately 25% of the ions in the main charge state. The best efficiency result obtained for the REXEBIS is ~10% for potassium breeding. The average efficiency over the whole range Li to Cs is between 5 and 10% [13], and for higher intensities the efficiency can drop to as low as 2%. In order to examine the charge state distribution and the number of ions in the different charge state, an analysis of $^{23}$Na spectrum has
been performed in order to determine the ratio of the different charge states. Therefore higher beam intensity of 100 pA has been injected which led to clear signals in the charge state distributions. The spectra have shown that a maximum abundance of 30% can be reached for light ions. Hence there must be losses in the injection process, in order to explain the measured overall efficiency. Thus the main losses occur in the injection and extraction cycle, which is a matter of improvement for the future operation.

The extracted beam can either be cw or bunched. In the REXEBIS a $t_{\text{FWHM}}$ of $\sim20$-$30 \, \mu s$ with an estimated energy spread of a few ten eV times $q$ is achieved, but faster (down to $<10 \, \mu s$) and slower (ms) extraction is in principle feasible, resulting in higher and lower energy spread, respectively. The acceptance of an EBIS is limited to approximately $10 \, \pi \cdot \text{mm} \cdot \text{mrad}$ (95%) at 60 keV beam energy [14]. The geometrical emittance of the REXEBIS has been measured as $\sim10 \, \pi \cdot \text{mm} \cdot \text{mrad}$ (95%) for highly charged ions at 20 kV extraction voltage. The value of the emittance is dependent on the ion neutralization of the electron beam and on the ion species. For longer confinement times, i.e. increased compensation level with low charged ions like He$^+$, the emittance amounts to 35-70 $\, \pi \cdot \text{mm} \cdot \text{mrad}$. Figure 3 shows emittance measurements of the EBIS beam behind the A/q-separator for different degrees of compensation and for different ion species. For emittance measurements of the LINAC beam, a beam intensity of several nA has been required. Therefore He-gas has been injected into the EBIS.

![FIGURE 3.](image)

**FIGURE 3.** Right: Typical EBIS emittances of $10 \, \pi \, \text{mm} \, \text{mrad}$ for highly charged ions from REXEBIS. Left: The electron beam has been neutralized with He-ions, in order to provide intense beams of several nA for beam emittance measurements with the REX-ISOLDE LINAC.
ADVANCED CHARGE BREEDING

The first charge state breeder using an EBIS/T device has shown the feasibility of the method. However, further improvements are required to become competitive with the stripper scheme for post acceleration for instance [15]. The objective of further developments of an EBIS/T charge state breeder is the optimization of the breeding efficiency, the beam quality and of the beam preparation before injection into an accelerator or a Penning trap via a separator. There are several techniques, which will be beneficial for the breeding efficiency and the beam quality. The breeding of highly charged ions used for Penning trap assisted spectroscopy requires high efficiency and good beam quality as well. Some critical issues of an EBIS/T based charge state breeder are the following:

1) To narrow the charge state distribution by manipulation methods to obtain the highest efficiency in a single charge state. 2) To optimize the transverse and longitudinal emittance of the extracted beams, using cooling techniques in the beam preparation and in the ion source itself. 3) To optimize the injection efficiency by using the ions of a partially compensated electron beam to increase the stopping ratio of externally injected ions. 4) Improving the breeding times and beam intensity with advanced EBIS/T devices.

A straightforward and effective method to narrow the charge state distribution is the breeding using the accurate adjustment of the electron beam energy. One can adjust the electron beam energy below the ionization energy at atomic shell closures in order to collect most of ions in the charge state at shell closure. This possibility of narrowing the charge state distribution has been proposed for an EBIS for the LHC project [16] and is applicable for heavy isotopes like fission fragments for instance. As the radiative recombination rate increases approximately as \((q+Z)^2\), where \(q\) is the charge state and \(Z\) the nuclear charge, the maximum number of ions in one charge state at shell closure is limited, but still enhanced [17]. One can adjust the electron beam energy to energies which enhance the dielectronic resonance (DR) cross section for the dedicated ion species. In that way that the recombination rate counteracts the ionisation rate and stops the ionization at a certain charge state. A problem are the rather low energies, which restrict the number of positive charges which can be confined within the electron beam due to the perveance limit.

Since the mass of a heavy ion and the ionizing electron are very different it is possible to excite resonantly the cyclotron and magnetron frequencies of ions without affecting the electrons too much. Due to space charge effects the frequencies are shifted, but for harmonic potentials the shifts are constant. This allows to selectively excite certain \(A/q\)-values and to shift them out off the beam and to reduce the overlap with the ionizing electrons. In this way the charge breeding can be stopped at a specific charge state leading to a narrowing of the charge distribution around a specific charge state. To force the radioactive ions back to the axis for extraction, quadrupole excitation together with ion-ion cooling has to be explored. If the \(A/q\)-resolution \((10^{-4})\) is good this charge distribution narrowing can be performed for a specific isobar, allowing for a purification of the required ion species.
The ion-ion cooling between light and heavy ions may be used to improve the centering of the wanted species either on the beam axis in case of an EBIS or on the magnetic axis of an ECRIS. As the beam emittance in the magnetic field increases according to eq.(1) with ion radial position \( r_{\text{ion}} \), it is mandatory to get the charge bred ions close to the axis shortly before extraction. The principle of ion cooling in EBIS and ECRIS has been summarized in ref. [18]. The application of ion-ion cooling anyhow will improve the beam emittance and is the essential tool to provide brilliant beams for further experiments.

\[
E_{r,r'} = 2r_{\text{ion}} \sqrt{\frac{\Delta U_{\text{dep}}}{U_{\text{acc}}} + \frac{r_{\text{ion}}^2 B^2 q}{2mU_{\text{acc}}}}
\]

with \( U_{\text{acc}} \) = electron beam energy, \( \Delta U_{\text{dep}} \) = potential depression of the electron beam space charge

The ion-ion cooling can be manipulated by introducing a cooling gas, that partially neutralizes the electron beam and by a non-complete confinement caused by a lowered collector barrier for instance. In ref. [19] it has been shown that in a partially neutralized beam the ions are more concentrated to the axis and the overlap between the ions and the electron beam is larger than in case of a clean electron beam. Newly created ions have significantly smaller energies and thus the energy input due to collisions is smaller. In addition hot ions can take out energy much faster over the reduced collector barrier than in transverse direction, thus enhancing the evaporative cooling mechanism of highly charged ions [20]. Beside the benefit for the beam transverse phase space a partially compensated electron beam might improve the injection efficiency in an EBIS as well [21]. The mean ion-ion collision time is orders of magnitude smaller than the round trip time of injected ions within the electron beam and therefore the ion collisions assist the trapping of the injected ion species. Figure 4 shows the principle of the proposed injection and cooling scheme.

For EBIS/T devices the improvement of the breeding time and of the ion capacity is required to envisage the breeding of heavy ions and intensities up to \( 10^{12} \) ions/s. Those improvements require electron beam currents of several amps and current densities of about 1000 A/cm\(^2\). At Brookhaven a successful development of a highly performing EBIS, the RHIC Test EBIS [22], has been carried out. A 10 A pulsed electron beam at 20 keV has an electron density larger than 400 A/cm\(^2\). In each pulse, injected \( \text{Au}^+ \) ions are transformed to \( 1.5 \cdot 10^9 \text{ Au}^{33+} \) within 40 ms (with 8 A and 0.7 m long trap) and the charge capacity of the trap exceeds \( 3 \cdot 10^{11} \) charges. The injection efficiency has not been measured, but the acceptance should be large because of the large electron beam diameter. The high electron current density enables a short breeding time, which means higher efficiency for short-lived species, and a larger ion turnover. In addition the repetition rate can be increased. With 100 Hz rep rate the maximum intensity, which could be bred would be in the range of \( 10^{12} \) ion/s.
FIGURE 4. Schematics of the injection into a partially compensated electron beam and use of a Coulomb-target for increasing the injection efficiency and ion-ion cooling for improving the beam emittance.

FUTURE CHARGE BREEDING EXPERIMENTS

Within the next years several EBIS/T charge breeder will come online mainly for research in atomic and nuclear physics. The planned breeder of the TITAN facility at TRIUMF and of the NUSTAR project at GSI [23] will charge breed radioactive ions for low energy experiments. The exotic isotopes will be delivered by the ISAC facility for TITAN and by the SUPER FRS of the future GSI fragmentation facility. In case of the GSI project, the energetic fragments will be stopped in a buffer gas cell and subsequently transferred to the different low energy experimental places. In both projects nuclear binding energies via mass measurements and determination of Q-values will be performed in high precision Penning trap experiments.

A third project is foreseen with the Frankfurt Cryogenic EBIS (MAXEBIS) within a collaboration between IAP Frankfurt and the department of physics of the LMU München. The Frankfurt MAXEBIS has been redesigned for high electron current up to 3 A and a new collector has been installed which can sustain 15 kW beam power. The new collector shielding has been examined for magnetic fields of the SC-coils of about 5 T. The magnetic field distribution on axis is in good agreement with the magnetic field calculations including the saturation of the iron shielding at 3 T. In addition the inner structure of the MAXEBIS has been redesigned, in order to allow higher retardation voltages for beam injection, suppression of Penning discharges and a better pumping of residual gases, by using the cryogenic surface of the cold inner bore of the MAXEBIS cryostat. A small Ba\(^+\)-ion source has been designed, which will provide beams for the injection of the ions into the MAXEBIS. The source uses surface ionization on a heated tungsten matrix to provide singly charged ions. A Ba-
source-body from HeatWave Labs Inc. of 6 mm diameter, providing 10 mA/cm² current density is used. First injection experiments will be carried out this year concentrating on the injection efficiency with and without a Coulomb-target and on emittance cooling of highly charged ions. Thereafter the MAXEBIS will be installed at the Maier-Leibnitz-Laboratorium München together with the MAFFTRAP [24] for precision mass measurements and Penning trap assisted spectroscopy. The resolving power for mass measurements is proportional to the charge state of the trapped ion (see eq.(2))

\[
R = \frac{\delta m}{m} \approx \frac{T_{rf} q B \sqrt{N}}{m}
\]

with \(T_{rf} = \) rf-excitation duration, \(N = \) number of detected ions

Thus with an excitation time of 10-100 ms, \(N=10000\) ions, \(B = 6\) T and \(q \sim 40\) a resolution \(R = 10^8 \times 10^9\) is within reach. Several interesting physics cases can be addressed, for example the determination of the life time and mass of long lived fission isomers (\(T_{1/2} > 1\) ms) [25] and separation of those isomers from ground state nuclei. The highest charge states could give access to bound state ß-decay, where the electron is created in a previously unoccupied atomic orbital rather than in the continuum [26]. Thus a decaying isotope can still be trapped, because the charge state remains the same, but the mass of the nucleus changes, which can be measured to high precision. In addition QED test with highly charged ions will be possible for a breeder-trap combination, if the precision of the resolution reaches sub keV level.

**CONCLUSIONS**

Charge breeding of stable and exotic isotopes offers unique possibilities for nuclear and atomic physic experiments, at low and high energies. The feasibility of EBIS/T devices for charge breeding and the possibility of future improvements have been pointed out. These improvements are expected from the Coulomb-target, the ion-ion-cooling process and high performance EBIS/T devices. Beside the optimization of the breeding process brilliant beams of highly charged ions for low energy experiments will result from those advanced charge breeding projects.

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