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cw	continuous wave
EBIS / T	Electron Beam Ion Source / Tra
ICBT	Innovative Charge Breeding Techniques
ISOL	Isotope Separator On-Line
RFQ	Radio Frequency Quadrupole

EXECUTIVE SUMMARY

With an increased understanding of charge breeding and advanced technological frontiers of Electron Beam Ion Source and Traps (EBIS/T) during the last few years, within the Innovative Charge Breeding Technique (ICBT) task and elsewhere, guidelines for the future generation EBIS/T based breeders can be laid out. The studies have shown that high electron currents and long trapping regions are compatible with high current-density Brillouin-type electron guns, thereby paving the way for faster charge breeding. Tests with high beam intensities indicate that pulsed injection into the EBIS/T is indeed necessary as the attainable neutralization degree for continuous injection is low. Hence, a preparatory cooling stage is still recommended, although instead of using a Penning trap a simpler RFQ cooler-buncher is advised. To avoid space charge limitations in the cooler-buncher, charge breeders with high electron current density are mandatory as the breeding time therefore becomes short and repetition rate high. Very long trapping times, as needed for injection into sub-Hz synchrotrons, is still challenging, particularly for light elements, and future studies are necessary in order to cover the full mass-range of ions. Finally, longer extraction pulses can either be achieved by applying various extraction schemes directly to the EBIS/T, or by adding a debuncher unit, fully continuous (cw) beams could be attainable.

1 INTRODUCTION

Charge breeders for radioactive ions have been operational for almost two decades and the EBIS/T-based type have demonstrated to be efficient, flexible and capable of providing contamination free beams for experiments [1].

The future challenges for EBIS/T breeders lie in higher beam intensities delivered by the ISOL-stage. For instance, at SPIRAL2 the amount of produced neutron-rich ^{132}Sn is expected to be about 10^9 particles per second (pps), and possibly up to 10^{10} pps at a later stage. This is a factor 3 (30) times higher than the most intense beam charge-bred at the REX-ISOLDE low-energy stage, $^{110}Sn^{27+}$, which inherently is faster to charge breed to a specific A/Q than the double-magic ^{132}Sn due to its lower neutron-to-proton ratio. Recently, an interest in using ^{11}C for hadron therapy has emerged [2,3]. This is particularly challenging as apart from demanding very high intensities (>$5 \cdot 10^9$ $^{11}C^{6+}$ per bunch), the ISOL-produced ^{11}C needs to be continuously trapped and stored in between the injection windows into the synchrotron, which operates with a sub-Hz repetition frequency.

The demand for fully stripped heavy ions (or few-electron systems), to be injected into consecutive storage rings, cannot be fulfilled with the present breeding systems [4]. The challenge was raised with the proposal of placing the TSR storage ring after HIE-ISOLDE, where several of the intended experiments and/or beam storage lifetime impose strict conditions on the electron configuration of the charge-bred ions. The TSR@ISOLDE proposal [5] has meanwhile been discarded, but a similar idea involving a storage ring is being pursued [6]. Moreover, higher charge states are also motivated as they allow for higher attainable acceleration energies in the post-accelerating linac/cyclotron [7].

Future facilities also request shorter breeding times, partly to facilitate post acceleration of very short-lived nuclei ($\tau_{1/2}$ a few ms), but also to increase the duty factor of the pulsed extracted beam. In fact, when the beam intensities are increased the wish for cw extraction from the breeder may arise, providing that the post-accelerating structure permits. Note that the time window for charge breeding is long (in most cases in the order of a second) when the ions are to be injected into either storage rings for radioactive beams [8] or synchrotrons for hadron therapy.

How to translate these requests into machine parameters for the charge breeder? The main parameters are the electron current I_e, electron current density j_e and energy E_e, and the trap length L. The individual effects of these on the trapping capacity, ion throughput, breeding time, attainable charge state, ion injection acceptance and vacuum conditions in the breeding region are listed in Table 1. In reality, the first three parameters are not completely decoupled, as for example the perveance limit may necessitate a higher E_e if I_e is to be increased, and j_e and I_e may be linked subject to the electron gun design.

	Trapping capacity	Ion throughput	Breeding time	Attainable charge state	Ion injection acceptance	Vacuum
I_e	$\propto I_e$	$\propto I_e$	Constant	Constant	Increases	Degrades
j_e	Constant	$\propto j_e$	$\propto 1/j_e$	Constant	Decreases	Constant
E_e	$\propto 1/\sqrt{(E_e)}$	$\sim \sigma(E_e)/\sqrt{(E_e)}$	$\propto 1/\sigma(E_e)$	Increases	Decreases	Undefined
L	$\propto L$	$\propto L$	Constant	Constant	Constant	Constant

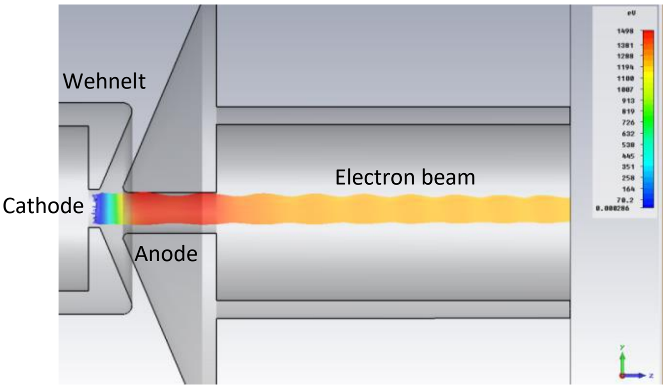
Table 1. Relation between electron-beam key parameters and breeding performance. σ(Ee) denotes the electron impact-ionization cross-section for Q-1, if the particle of interest is extracted as Q.

From Table 1 we can conclude that a larger trap capacity requires a higher electron current and/or a longer trap, without an increase of the electron beam energy. If only the ion throughput is of interest, the electron current density may also be increased as long as the total current is maintained. To reach high charge states the electron beam energy must be sufficiently high to overcome the $(Q\text{-}1)^{th}$ ionization potential, ideally a factor ~3 higher to optimize the electron-impact ionization cross-section while also reducing the effect of radiative electron recombination [9,10]. Charge exchange [11] is mitigated by an excellent vacuum and/or a high electron current density to reduce the time window for the process. As low pressures as $<10^{-11}$ mbar and current densities in excess of 1000 A/cm^2 may be compulsory for very high charge states (see [4,12] for numerical examples). Faster breeding is mainly achieved by boosting j_e, but can also in some cases be achieved by either increasing or lowering the electron beam energy, although the effect is usually less pronounced. In Appendix 1 an analysis of actual beam parameters for a selection of ions is presented. Further examples are to be found in [4].

Within the ICBT task we have focused on the issues of higher beam intensities and faster charge breeding, as well as a higher duty factor of the extracted pulsed beam. The goal has been to validate the feasibility of new concepts for EBIS/T charge breeders. In this report the conclusions are presented and their impact on future EBIS/T charge breeders, and practical guidelines are given. To avoid overloading the document, detailed technical descriptions have been omitted. Furthermore, the quest for very high charge states has not been entirely covered, as ion-ion cooling and high electron beam energies are required, which are only partly available in the present version of the TwinEBIS test bench [13].

2 HIGH ELECTRON CURRENT DENSITY BEAMS

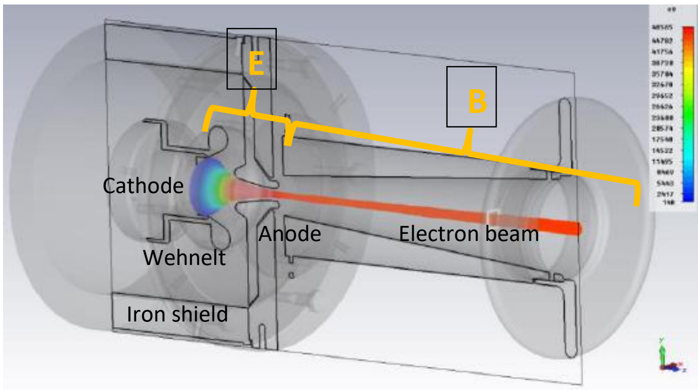
The first operational charge breeder for radioactive ions, the REXEBIS [14], uses a semi-immersed electron gun. The cathode is located in a magnetic field of approximately 0.2 T and the emitted electrons are adiabatically compressed to a higher electron current density by the magnetic field and reach an operational current density of 100-125 A/cm^2 in the trapping/breeding region where the magnetic field is 2 T. This type of electron gun is relatively easy to design and operate, long trapping regions are viable, and very high currents have been demonstrated [15,16]. Therefore, the CARIBU and RAON charge breeders are also based on the same concept. The major drawback of the immersed electron gun type is the limited current density, where around 700 A/cm^2 is the state-of-the-art. This is partly dictated by a limited cathode electron emission, but also by the beam optics that constrains the attainable ratio between magnetic field strengths at the electron gun and the trapping region. Fig. 1 illustrates the immersed electron beam propagation in the gun region.



$0.05<B_{cath}<0.3$ T
$j_e<700$ A/cm^2
$I_e<20$ A

Figure 1. Simulated electron beam from an immersed electron gun type. The compression of the current density je scales linearly with the B-field. The color scale indicates the electron beam energy.

Two other charge breeders, TITAN EBIT [15] and ReA EBIS [18], instead make use of Brillouin electron guns where in principle a significantly higher electron current density can be attained. The electron beam is first compressed electrostatically in the gun region, which is shielded from the external magnetic field, and once it leaves the anode, by the magnetic field (see Fig. 2). Current densities in excess of 5000 A/cm^2 have been achieved, although until recently exclusively with short (<10 cm) trapping regions and for low currents (<200 mA) [19]. Under such circumstances these devices are not suitable for charge breeding of radioactive ions where a longer trap and higher current are needed in order to obtain good ion trapping efficiency. Besides, this type of electron gun is more difficult to design as the electron beam optics is sensitive to misalignments and electron beam losses may easily occur if the matching conditions are not fulfilled [19]. The design values for the currents of the above mentioned breeders have not been reached, in fact, the initial electron gun for ReA EBIS had to be exchanged for a modified version [22]. In addition, there are doubts if the demonstrated high current density is compatible with high current beams. The question has therefore been if future charge breeders can and should be based on the Brillouin-type electron flow; if reliable gun designs for high current and low electron beam losses in combination with long trapping regions are attainable.



E- and B-field compression regions
>5000 A/cm^2 in the trapping region
Typical currents of some 100 mA

Figure 2. Simulated electron beam from an electron gun of Brillouin-type. Note that in this particular case the magnetic field was not applied and therefore the beam expands from the space charge in the B-field region.

2.1 MEDeGUN

The MEDeGUN electron gun [23] was designed to bridge the gap between high-intensity low-repetition rate EBISes and low-intensity high-repetition EBITs. The electron gun is of Brillouin-type with a Pierce geometry of 1.0 A/V$^{1.5}$. The design parameters are 1 A at 10 kV, with a possibility to reduce the beam voltage to 7.5 kV inside the trapping region. In a 2 T field the electron current density was simulated to be 3.1 kA/cm^2, provided no plasma instabilities occur, while 7.5 kA/cm^2 is expected if the beam is injected into a trapping region with 5 T. The electron gun has been installed at the TwinEBIS test bench [13] at CERN, which features a 0.7 m long trapping region immersed in a 2 T field. Thereby, the combined setup has the parameters needed to answer the above question about feasibility of high-current Brillouin guns.

The electron gun was commissioned during two runs: one occurring in 2017 and a second one at the beginning of 2019. In between the two, some modifications to the electron gun and the TwinEBIS drift-tube structure were carried out. During the first commissioning run, the design goals for the electron current and energy (1 A at 10 keV) were already reached [24]. The electron loss current, which is an indicator of the beam quality, was less than 1 mA under these operating conditions. However, when the beam energy in the trapping region was lowered, the loss current rapidly increased and the minimum acceleration voltage into the trapping region was found to be around 8.5 kV. The high losses at the lower beam energy levels indicate either non-ideal beam matching conditions in the electron gun region [19], transverse misalignment of the electron gun with respect to the main solenoid field, or excessive electron reflection from the collector region [21]. The first reason automatically implies a non-optimal electron current density in the trapping region, but also the transverse misalignment may signify a lower electron current density than expected. In addition, the poor results at low energy suggested that this electron beam could not have been injected into a stronger magnetic field, something that is necessary for a very rapid charge breeding.

After some minor modifications of the electron gun and the drift-tube structure the tests were resumed and the efforts were focused on operating the electron beam with a lower beam energy inside the trapping region of the EBIS. During these tests we could reduce the electron beam energy (effective value including the self-induced retardation from the space-charge potential) down to approximately 3 keV for a current of 1 A with maintained low anode losses, indicating that the electron beam is sufficiently well-behaved to be injected into at least a 5 T field solenoid. The limit for the lower energy is due to the Bursian limit, i.e. the beam being reflected by its own space-charge at a low velocity. Furthermore, we demonstrated that a 1.5 A beam can be transmitted at 8 kV acceleration voltage (corresponds to an effective energy of around 5.2 keV). The high current at a moderate acceleration voltage results in a large trapping capacity of the EBIS, almost $1.8 \cdot 10^{11}$ charges; to be compared to $1.2 \cdot 10^{12}$ charges for the 1.9 m long RHIC EBIS operating with a 10 A electron, although with a lower electron current density of ~600 A/cm^2 and to $2.4 \cdot 10^{10}$ charges at REXEBIS for normal operational parameters. Thereby, the handling of higher radioactive beam intensities, an objective of ICBT, is partially addressed. This will be discussed in more details in the next section. At the time of writing this report, the electron current density has not been measured and the low loss current is no guarantee for a correct current density compression. With the newly commissioned time-of-flight system connected to the TwinEBIS setup, current density measurements were initiated this autumn, although an electrical power-cut caused severe damage to the electron gun and the system therefore had to be opened and rebuilt; a process that will stretch until after the termination of ENSAR2.

2.2 Electron beam results outside ICBT

During the ENSAR2 period another EBIS has undergone commissioning, the CANREB charge breeder [25] that will serve at the ARIEL radioactive beam facility. The design and construction were carried out at Heidelberg MPI-K by J. Crespo Lopez-Urrutia's team. The concept differs from the MEDeGUN and TwinEBIS in many aspects, for instance the trapping region is at cryogenic temperature, the trap length is shorter (variable between 74-260 mm), and both the electron gun and collector designs are different from the CERN versions. Nevertheless, some very impressive results have been obtained. During the commissioning phase an electron beam of 884 mA was transported into a 6 T Helmholtz coil set at a beam acceleration voltage of 5000 V. A current density in excess of 5000 A/cm^2 was also claimed, however, this current density is an extrapolation to a 1 A beam from a measurement carried out at 64 mA with a correspondingly lower density.

2.3 Outlook high current density beams

The achieved results from the MEDeGUN commissioning within the ICBT task are indeed important steps forward for improved charge breeding performances, and the commissioning of CANREB corroborates the potential of charge breeders exploiting Brillouin electron guns. Still, at this stage the final proof of a high current density existing also for high currents is lacking. An answer is expected during 2020.

If the upcoming verifications of the effective electron current density would show that a high density is indeed not attainable for Brillouin beams operated at a higher current of approximately 1 A, then an alternative track has to be found. The EBIS group at CERN has therefore in parallel to the Brillouin gun tests been investigating the possibilities of using a so-called non-adiabatic element in an immersed electron gun in order to control and improve the electron beam optics. The attainable electron density will not be as high as for an optimal Brillouin gun and will only scale with the magnetic field as for a traditional immersed electron gun, but it is predicted that higher B-field ratios between the cathode and the trapping-region can be attained [26]. In addition, this electron gun could then be equipped with a new dispenser cathode type, capable of providing emission densities up to 50 A/cm^2 [27]. Electron current densities inside the trapping region of 1000 A/cm^2, or above, could then be obtained also for high electron currents (>1 A). First tests of are foreseen at REXEBIS during spring 2020.

3 HIGH INTENSITY ION BEAMS

An EBIS/T is inherently a pulsed machine, where the ions to be charge bred are first prepared in a cooler-buncher (either in the form of a Penning trap or an RFQ cooler) and consequently injected into the breeder as a short bunch. After charge breeding the ions are extracted in a pulse, with varying length as discussed below. The ion throughput is therefore ions/s = capacity · repetition rate, where the capacity is the number of ions per bunch, while the repetition rate is normally the inverse of the breeding time, although the post accelerator or the cooler-buncher may impose extra time constraints. For instance, a room-temperature post-accelerating linac has a limited duty factor and repetition rate (for REX-ISOLDE it is 10% and 50 Hz), which is not the case for a superconducting cw machine. The capacity is either limited by the cooler-buncher or the EBIS/T.

Future radioactive beam facilities are expected to deliver significantly higher beam intensities than the ones presently in operation, even as high as 10^{12} particles/s for the most abundant isotopes [28]. The increased intensities can be addressed by a larger breeder capacity and/or a faster charge breeding. The considered cancer treatment facilities may only request $2{\cdot}10^9$ ^{11}C per second, although due to the low repetition rate the number of ions per bunch is high, around $6{\cdot}10^9$ [29]. This demand can only be addressed by a large breeder capacity. Furthermore, the sub-Hz repetition rate is challenging not only from a space charge point-of-view, but also due to the long collection and holding time in the charge breeder stage of the 1+ ions that are semi-continuously produced in the ISOL-stage at a moderate rate.

3.1 LIMITATIONS IN COOLER-BUNCHER

The ultimate space-charge capacity of a Penning trap is given by the Brillouin limit as [30]:

$$N^+ = B^2{\cdot}\varepsilon_0{\cdot}V_{cloud} / (2{\cdot}m_{ion}), \qquad (1)$$

where N^+ denotes the number of elementary charges, B the magnetic field, V_{cloud} the ion cloud volume inside the Penning trap and m_{ion} the ion mass. For an RFQ cooler-buncher the capacity can be expressed as [31]:

$$N^+ = \pi{\cdot}\varepsilon_0{\cdot}L{\cdot}V_0 / (4{\cdot}e{\cdot}Q), \qquad (2)$$

with L, V_0 and Q denoting trap length, rod voltage and ion charge state, respectively. To arrive to this compact form a Mathieu q_r parameter of approximately 0.5 was assumed. The buffer-gas cooling time inside a Penning trap is approximately 10-30 ms, while significantly shorter - in the order or 1 ms - for an RFQ cooler-buncher. The trapping capacities should be compared with that of an EBIS/T, which in most cases is larger and can be approximated with:

$$N^- = I_e{\cdot}L / (e{\cdot}v_e) \qquad (3)$$

where N^- denotes number of elementary charges in the electron beam, L the trap length, and I_e and v_e the electron beam current and velocity, respectively.

If the Penning trap is the space-charge limiting element in the charge breeder stage, one should observe a clear dependence of the ion throughput on the ion mass. Partly because heavier ions require a longer breeding time translating into a lower repetition rate, but also due to the $1/m_{ion}$ relation in the Brillouin limit. The throughput was measured at REX-ISOLDE for different ion masses and the result is shown in Fig. 3. As predicted the ion throughput decreases rapidly with the ion mass.

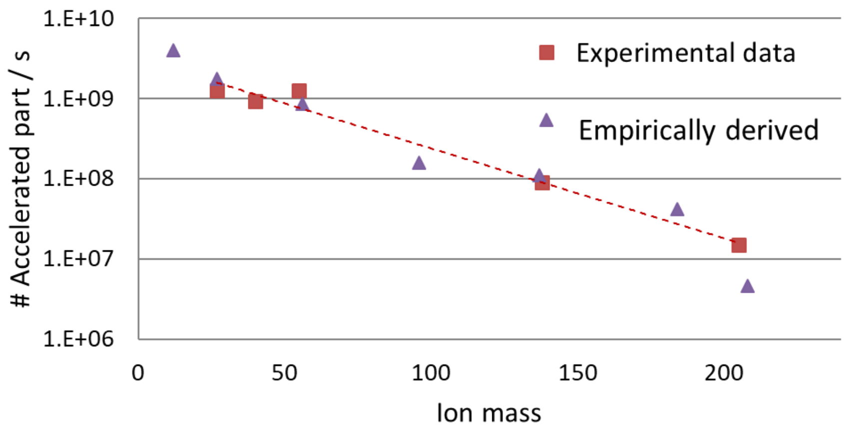


Figure 3. Measured ion throughput through the REX-ISOLDE charge breeder stage consisting of REXTRAP (a large Penning trap) followed by REXEBIS. The machine was operated in normal mode, i.e. cooling-bunching in the trap with consecutive pulsed injection into the EBIS and charge breeding to a typical A/Q (varying between 3.6 and 4.5 for the different ions). The empirically derived data points have been calculated assuming the Penning trap has reached the Brillouin limit (this is an uncertain assumption) and a total transmission through the Penning trap and EBIS of 5%. The breeding time was calculated with CBSIM [32] for an electron current density of 100 A/cm^2. The unknown effective trapping volume inside the Penning trap was derived by fitting the measured and calculated number of accelerated ions for one mass data point.

3.2 CONTINUOUS INJECTION INTO EBIS/T

To circumvent the space-charge limitation the common notion has been to bypass the cooler-buncher and perform continuous (also called accu-mode [33]) injection into the EBIS/T. The attainable beam throughput, if solely assessed by the electron beam space-charge capacity and breeding time, could then be increased significantly as shown in Fig. 4. Nonetheless, a satisfactory breeding efficiency has to be demonstrated in order for this alternative process to be useful.

Prior low-intensity tests at REX-ISOLDE have demonstrated breeding efficiencies as high as 5% (single charge state) for continuous injection [34,35], although still a factor 3 lower than for optimal bunched injection. The theoretical basis for a lower expected efficiency for continuous injection compared to standard pulsed injection has been examined in several articles and reports, see for example [14, 36]. However, what has mainly been considered in the discussions is the reduced transverse acceptance and limited 1+ ion trapping probability linked to continuous injection, which will affect the injection efficiency. The negative influence of high beam intensities and long trapping times on the efficiency have not been methodically addressed until these studies. Earlier tests within the EURONS integrated activity showed that for continuously injected K+ beams the efficiency remained unaffected when the injected current increased from 50 to 500 pA, although this was for a short breeding time of 9.5 ms [36]. When the breeding time was increased to 49.5 ms, and therefore the neutralization degree increased, a slightly lower efficiency was noted. The neutralization levels of the electron beam at the end of the breeding cycle for the 500 pA case, including an estimated contribution from residual gas ions, were still very low, 0.3% and 1% for the 9.5 ms and 49.5 ms breeding times, respectively.

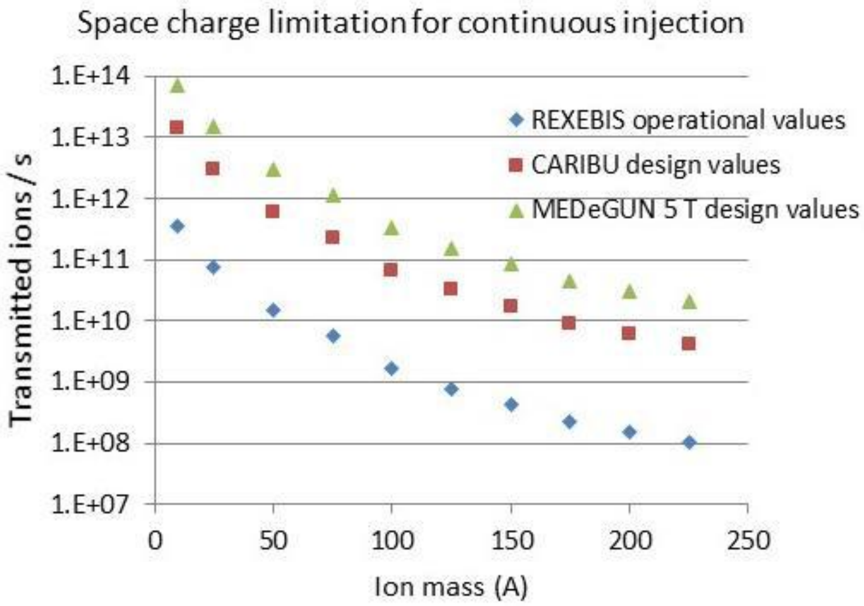


Figure 4. Number of extracted charge bred ions per second as function of ion mass. The values are upper estimations based on space-charge capacity and breeding times of three breeders, and assumes that a sufficient amount of 1+ ions are injected to account for possible injection and breeding losses. The REXEBIS is assumed to operate with 0.2 A and 100 A/cm^2, CARIBU [37] with 2 A and 500 A/cm^2 and MEDeGUN with 1 A in a 5 T solenoid rendering ~5000 A/cm^2.

Within the ICBT task the continuous beam studies were revived, but now with higher beam currents being injected into REXEBIS in combination with longer holding times. The aim was to evaluate the idea of using a Penning trap - EBIS combination as a preparatory stage for subsequent post acceleration of ^{11}C. The results were not as encouraging as expected and the full account is given in [38]. Fig. 5 quantifies the decrease in efficiency coming from the limited space charge capacity of the EBIS. The period time was fixed within each of the two measurement series, while the continuously injected current was varied. For 100 ms period time, the current starts saturating already at a few 10^7 C^{6+} ions extracted from the EBIS. This exemplary case corresponds to only 1% neutralization of the electron beam. It seems that in the continuous injection mode, we cannot fill the EBIS properly. In addition, the 1^+ to 6^+ breeding efficiency, in the order of 1%, is extremely poor. The mediocre performance can be explained by a combination of lower injection capture efficiency and high loss rates. When injecting continuously, the injection barrier is constantly at an intermediate height and CO^+ ions enter the EBIS approximately 125 eV over the barrier. Hence, the ions have a high initial residual kinetic energy in the trapping region (approximately 240 eV). After ion thermalization, that is redistributing the ion energy according to a Maxwell-Boltzmann distribution and expecting to occur within some ms, an equilibrium between the injected current and axial losses over the injection barrier is established. Electron-ion heating effects may further increase the ion energy, but only becomes significant when the breeding time is long [39], especially for the 400 ms case in Fig. 5. Thus, for the continuous injection mode the losses upon injection and via over-the barrier escape are significant and limit the filling of the EBIS drastically. Operation at RHIC EBIS has shown that a higher neutralization using continuous injection can be achieved when orders of magnitudes higher currents than used at the REX-ISOLDE tests are injected, hence, at the cost of efficiency [40].

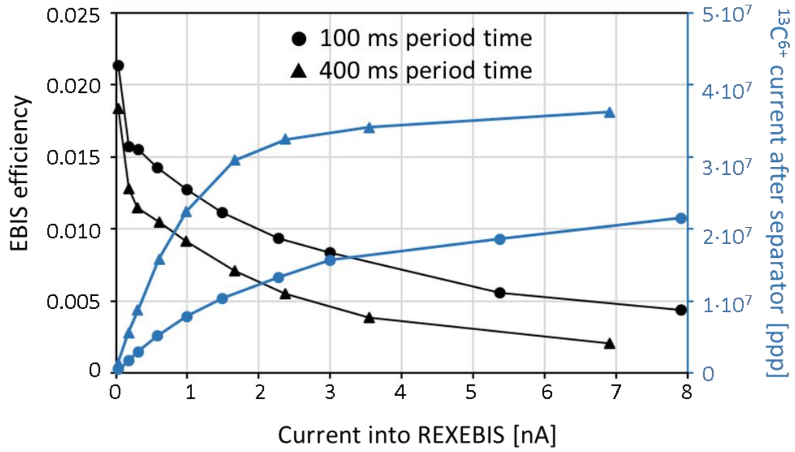


Figure 5. EBIS efficiencies into charge state 13C6+ for an increasing input intensity of CO+ injected continuously during a 100 ms and 400 ms period time [38].

To verify that a larger fraction of the EBIS/T space charge can at least be occupied for normal pulsed injection, a test with injection of Ar+ was carried out. Fig. 6 shows the Ar^{11+} beam (black), measured after the REX separator for an increasing number of injected particles into REXEBIS. In order to avoid confounding space charge effects inside the Penning trap, the pulsing was artificially arranged with electrostatic kickers (see [38] for details). The optimal breeding time varied between 40 and 45 ms with the intensity. At approximately $7.5{\cdot}10^8$ injected charges, space charge effects in the EBIS start becoming visible and cause a saturation of the total extracted current. The measured neutralization at this point was 25%, and 30% could be attained for this configuration with an even higher current being injected. Thus, indeed a reasonably high electron beam neutralization can be attained, not only for gas injection, which was already known, but also for pulsed injection. The main explanation is the lower energy of the 1+ ions when entering the trapping region, although the heavier mass may also influence the results positively.

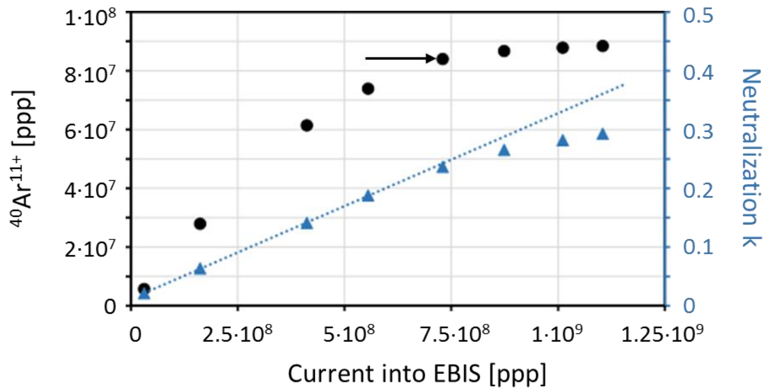


Figure 6. $^{40}Ar^{11+}$ intensity after the REX separator in particles per pulse (ppp) (black) and neutralization k of the EBIS (blue), for an increasing $^{40}Ar^{+}$ input intensity. Above $7.5{\cdot}10^8$ particles injected into the EBIS, saturation effects start to become visible, as indicated by the black arrow. The total $^{40}Ar^{11+}$ output saturates at $9{\cdot}10^7$ ions per pulse. A neutralization of 30% could be obtained. Figure taken from [38].

3.3 CONCLUSIONS ON INJECTION MODE OPTIONS

It has already been shown that a cooler-buncher is required in order to achieve the optimal breeding efficiency of an EBIS/T for lower and moderate beam intensities. In fact, the retrofitting of an RFQ cooler-buncher to the ReA EBIS, which was initially foreseen to operate with continuous injection from a gas cell into a high-current, high-density EBIS, further supports this argument. Thereby all EBIS/T charge breeders for radioactive ions feature a cooler-buncher, either in the form of a Penning trap (as at REX-ISOLDE) or an RFQ cooler-buncher (as at TITAN TRIUMF, ReA at NSCL/MSU, CARIBU ANL and soon at RAON Korea).

The carbon tests described above show that the concept of bypassing the cooler-buncher for high intensity beams may not work due to poor injection efficiency combined with a high initial ion energy leading to excessive losses, at least not for light ions like carbon. However, the concept needs a follow-up and should be tested for:

- heavier ions as they may benefit from ion-ion cooling with lighter elements present in the trapping region.
- heavier ions as initial capture (i.e. 1+ to 2+ conversion) is more likely due to the lower velocity and higher ionization cross section.
- not fully stripped ions (but for example A/Q~4) as the electron-ion heating will also be lower.

Different scenarios could be simulated using novel charge breeding simulation codes. In any case, high-intensity beams (not to be injected into a storage ring or synchrotron) should not be tackled by a Penning trap but an RFQ cooler-buncher, which has a rapid cooling time of ~1 ms, followed by an EBIS/T with a very high electron current density. In Fig. 4 the theoretical throughput using MEDeGUN, operated with a 5 T solenoid, is shown.

The final case to address is long trapping times combined with high intensities, for example hadron therapy using ^{11}C. In this situation alternative trapping methods have to be considered, such as cryogenic trapping and subsequent release of neutral ^{11}CO into the EBIS (see [38] for details). For elements to be injected into a storage ring for radioactive beams, preparation of the 1+ ions in an RFQ cooler-buncher might still be considered. According to equation 2, the holding capacity of a 0.5 m long RFQ, operated with a 1 kV rod voltage, could be as high as $2 \cdot 10^{10}$ ions (charge state 1+). Nevertheless, a systematic investigation covering elements over the full mass-range and from the different chemical groups is mandatory, as reactions with residual gases in the cooler-buncher may drastically reduce the holding time. Furthermore, tests have shown that the extracted beam emittance is increasing significantly with the beam current when operated in continuous mode [41].

4 SLOW ION EXTRACTION

An EBIS/T is inherently a pulsed machine, expelling the charge-bred ions in a short bunch of some tens to a few hundreds of microseconds, whereas the breeding time varies between a few ms and a second. The high instantaneous beam-intensity when the bunches arrive to the experimental setups may be problematic, which was observed at ISOLDE with the MINIBALL array already for time-averaged intensities as low as a few 10^5 pps [42,43]. Longer pulses, or even cw if the post accelerator design permits, may be preferred.

4.1 SLOW ION EXTRACTION DIRECTLY FROM THE EBIS/T

The conventional method to extend the ion pulse being injected into the post accelerator is by means of slow extraction [44] from the EBIS/T. This technique has been elaborated during the ENSAR2 period also by other EBIS/T groups. For instance, varied extraction lengths were tested and used routinely at REX-ISOLDE [45]. The applied voltage functions for the extraction barrier are calculated based on measurements of the axial energy distributions of the radioactive ions species of interest [46]. Fig. 7 shows how the pulse length can be extended. Significantly longer extraction times have been used at NSCL/MSU for the ReA EBIS, where a sequence of 0.9 s breeding and 0.9 s extraction was applied, with the ions being spread over more than 300 ms with a Gaussian-like distribution [47].

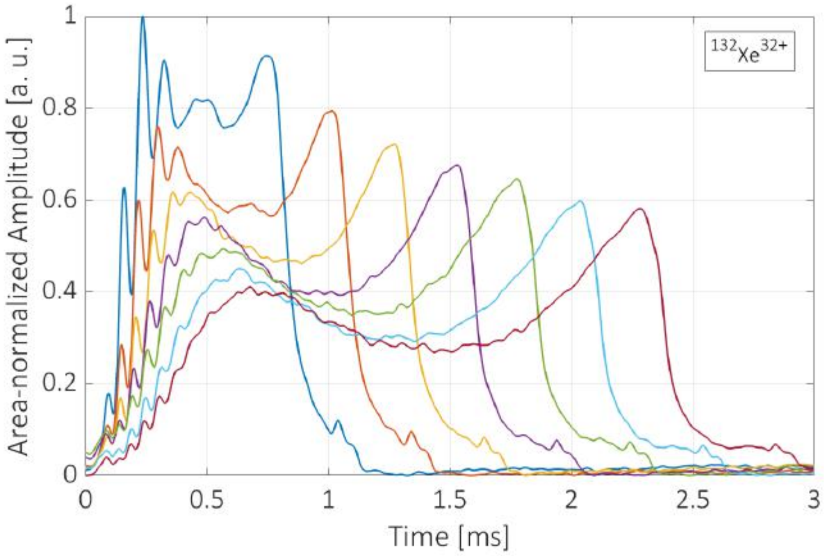


Figure 7. Time structures lengthening, acquired with an MCP, when extending the extraction voltage step-function from 1.0 ms to 2.5 ms (0.25 ms steps). The $^{132}Xe^{32+}$ beam was extracted from REXEBIS and the normal non-manipulated pulse length is <200 us. Figure taken from [45].

Although relatively easy to implement, this method has a few drawbacks. First, the extracted beam may never become fully continuous. In the ReA EBIS example above, a duty factor of approximately 17% was achieved. Second, as the ions are held inside the EBIS/T for an overall longer time, now including both the charge breeding and slow extraction phases, the holding time inside the Penning trap (or RFQ cooler-buncher) has to increase, with possibly increased losses in this device if the intensities are high. The longer storage time in the EBIS/T may also lead to ion losses from the electron beam as the ions will gain more energy from electron-ion collision [48], although with properly adjusted outer barrier, this effect should be mitigatable. Finally, as the slow extraction mode extends the total hold-up time T_{holdup} in the preparation stage, it may be detrimental for short-lived ions. The average total hold-up time for a radioactive ion released continuously from the ISOL-stage is:

$$<T_{holdup}> = T_{bunch}/2 + T_{breed} + T_{extraction}/2 \qquad (4)$$

where T_{bunch} denotes the bunching time in the cooler-buncher, T_{breed} the charge breeding time and $T_{extraction}$ the extraction time. As the cooler-buncher precedes the charge breeder, $T_{bunch} = T_{breed} + T_{extraction}$, thus:

$$<T_{holdup}> = 1.5 \text{ x } T_{breed} + T_{extraction} \qquad (5)$$

For rapid ion extraction where $T_{extraction} << T_{breed}$, the average holdup time $<T_{holdup}> = 1.5 \text{ x } T_{breed}$, while if a 50% extraction duty factor is requested, $<T_{holdup}> = 2.5 \text{ x } T_{breed}$.

4.2 Ion debuncher

An alternative to employing slow extraction directly from the EBIS/T is to introduce an ion debuncher after the charge breeder, as has been further investigated within the ICBT task, and will be reviewed below. With such a device a fully continuous extraction beam can be obtained, as the slow ion extraction process is performed externally in parallel with the charge breeding process. The average ion hold-up time, that now comprises a cooler-buncher, breeder and finally an ion debuncher, will in this case be:

$$<T_{holdup}> = 2 \text{ x } T_{breed} \qquad (6)$$

and the previously mentioned additional space-charge effect in the cooler-buncher is also avoided.

A prototype of this device was developed within the EMILIE project [49]. The debuncher is designed as a linear Paul trap, with a few modifications. In contrast to normally operating RFQ cooler-bunchers, where the entrance barrier is constantly allowing for ions to enter, the entrance barrier of the EMILIE debuncher is pulsed. The potential of the gate is low during the injection period and thereafter raised to a higher potential during the trapping and ion release phase. The physical length of the debuncher is defined implicitly by the ion capacity of EBIS and its ion extraction time. The extraction with the EMILIE debuncher is performed by increasing the potential of the DC segments inside the debuncher, while the exit DC gate electrode has a constant potential. For the full technical design the reader is referred to [50,51].

A summary of the results obtained within the ICBT study are presented here, while details are to be found in [51]. For the functionality tests, beam bunches as would be expected out of an EBIS were emulated by switching on/off the entrance barrier of the debuncher. The beam was injected into the debuncher during a period of 10 - 20 μs with an optimal energy of 30 eV inside the trapping region. The injection efficiency was estimated to vary between 18% and 30%, due to not fully adapted beam optics at the SHIRaC test bench. Injection efficiencies exceeding 85% were simulated for optimized conditions. Trapping lifetimes without losses well beyond 1 s could be measured for Li^+ ions. The slow ion extraction was successfully demonstrated for 10, 100 and 800 ms trapping times, with a variation in the extracted beam intensity being less than 30%. The 800 ms case is presented in Fig. 8. Finally, it was also demonstrated that it is possible to perform simultaneous beam extraction and beam injection with this debuncher prototype. This was possible due to the flexible potential arrangement of the DC segment groups inside the debuncher, and the creation of an auxiliary buffer trap at the end of the debuncher, that is used to provide ions while another ion batch is injected from the EBIS.

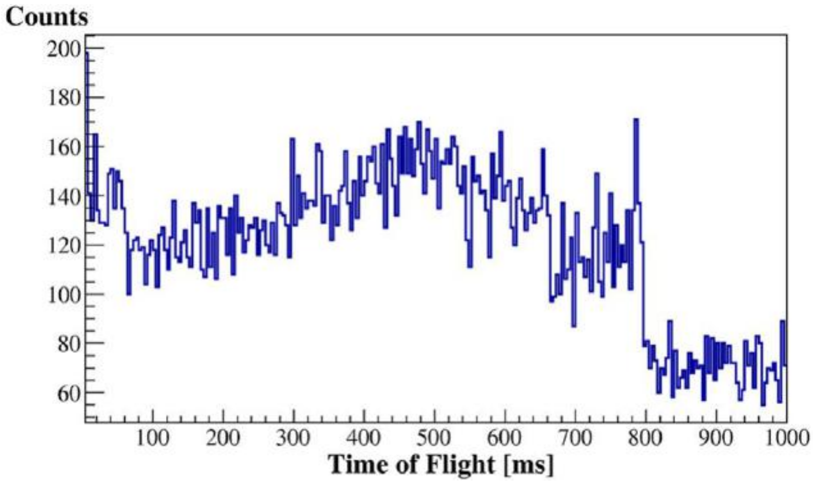


Figure 8. Beam pulse of Li^+ ions extracted from the debuncher operated with 800 ms period time. Figure taken from [51].

4.3 OUTLOOK FOR ION DEBUNCHER

In order to transform the ion debuncher prototype into an operational machine three more matters need to be proven. First of all, the ion injection optics have to be improved and adapted to injection from an EBIS, and the actual injection efficiency has to be tested for fully realistic EBIS/T beams, where the pulse length and energy spread will vary depending on the ion type and breeding conditions. Secondly, and most importantly, the vacuum compatibility of the debuncher has to be addressed since losses due to collisions and charge exchange with the residual gas must be avoided. The total path of the trapped ions inside the debuncher is very long – of order of kilometers. During the test, a pressure of 10^{-7} mbar was obtained, which did not cause significant losses for single ionized Li ions injected with a low energy into the trap (~30 eV) and stored for up to 1 s. However, for multiply charged ions a vacuum in the order of 10^{-11} mbar or below, as in the EBIS/T itself, would be required to prevent charge exchange, and the use of better materials, ionic pumps or cryopumps would have to be considered. Eventually, the space charge limitations should be experimentally measured. Based on the design parameters (see equation 2) and comparisons with existing RF devices [52,53], bunching capacities in the order of 10^9, or even 10^{10} ions, could expected.

5 GENERAL CONCLUSIONS AND OUTLOOK

The general guideline for future EBIS/T-based charge breeders is to employ a Brillouin-type electron gun capable of producing very high current densities in the trapping region and therefore a rapid charge breeding. Recent tests show that the technology is mature and novel cathode types may improve the performance even further. An RFQ cooler-buncher preceding the breeder is a necessity in order to achieve a satisfactory breeding efficiency, and to accommodate high ion beam throughput a fast charge breeding is mandatory. To reduce the instantaneous particle impact of post-accelerated ions onto the experimental setups, one can either rely on direct slow extraction from the EBIS/T charge breeding region, or implement an ion debuncher after the EBIS/T, although further development is still required for this option.

Suggestions for future actions were already mentioned in the three core sections above and will therefore not be repeated. However, one major design aspect needs to be attended - the question of having the drift-tube structure at cryogenic temperature or at room temperature. In the latter case, the superconducting solenoid is thermally shielded from the vacuum tube surrounding the drift-tube structure and the ultrahigh vacuum is obtained by either turbo, ion or sublimation pumps in combination with non-evaporable getters and thermal bake-out. For the cryogenic case, which mainly relies on cryogenic pumping, the drift-tube structure and beams can either have a common vacuum with the superconducting coil and the thermal shields, or be separated from them. One can also imagine a case with both vacuum, and thermal, separation between the solenoid region and the drift-tube structure, where the temperature of the latter can vary between room temperature (or higher) to cryogenic temperatures using a separate cryo-cooler. In any case, there are various questions that have to be considered for the different systems:

- *Vacuum* – In order to reach extremely high vacuum, a cold bore approach has to be used, as room temperature devices are limited to low 10^{-11} mbar. The pumping speed is usually very high in cryogenic systems, however, if a bake-out of the drift-tube structure is required, a thermal separation between the solenoid and beam regions is compulsory. Furthermore, common vacuum systems may also suffer from He cold leaks from the solenoid region, producing bursts of He gas that can affect the electron beam and the extracted ion beam, as reported by NSCL/MSU. Electron beam losses and electrical discharges may also cause more severe pressure increase than in room temperature systems.

  When comparing the contamination of stable beams, stemming from the vacuum conditions inside the breeders, the REXEBIS exhibits a similar or even slightly lower contamination level than the ReA EBIS [34,60], if the peaks of neon gas diffusing from the Penning trap are disregarded.

  Finally, with cryogenic drift-tube structure a more confined gas injection region, to be used for ion-ion cooling or gas injection of ^{11}CO [61] for example, can be attained.

- *Thermal load from electron beam* – Apart from deteriorating the vacuum, electron beam losses may also add to the thermal load, which can become critical in a cryogenic system for larger electron beam currents. Even losses smaller than one per mille can results in a heat load of several Watts for a 10 keV beam. RF heating of the drift-tube structure [62] might also add to the thermal load unless precautions are taken.

- *Memory effects* - During the design of the first generation EBIS charge breeders, a drift-tube structure at room temperature was used as an argument to avoid so-called memory effects (observed at the TITAN EBIT [63]). Long-lived radioactive ions, or stable high-intensity beams used for setup of the machine, could be frozen onto the surfaces and be desorbed during a subsequent beam time if the surfaces would be hit by ions or part of the electron beam. That could then introduce unwanted contaminations to the beam. The actual risk of this has not been systematically assessed until now. Condensable elements could in principle also create memory effects in a room temperature system, but this has not been observed at REX-ISOLDE.

  Related to this are radioactive contamination issues that may occur in a common vacuum system. Long-lived radioactive ions, lost during the breeding cycle, can end up in the solenoid part of the magnet if a common vacuum system is used. This radioactive contamination may significantly complicate the repair and maintenance interventions.

- *Complexity* – As already pointed out above, the vacuum generation in a cryogenic system is in principle straightforward. A room temperature system, on the other hand, has to feature vacuum bake-out, which implies a cooling mantle between the vacuum tube housing the drift-tube structure and the magnet bore in order to protect the latter from too high temperatures during bake-out. Such a tube will increase the bore radius of the magnet, thus increasing the stored energy in the magnet, and making the construction more expensive. If the room temperature system has to be vented to atmosphere, a bake-out cycle has to follow and that takes almost a week, including the cabling of the bake-out elements. For a cryogenic device with a common vacuum, the complete system has first to be the warmed up before opening, and thereafter the cooling down phase has to follow. If active heating elements are present in the system, one may in best case be able to perform a full cycle within one week.

A cryogenic cold bore design increases the risk of misalignments due to thermal contraction and overall more complex suspension mechanics dealing with thermal decoupling of the cold components. On the other hand, the technique is mature and functional designs are readily available.

The alternative of a cold inner bore with a separated vacuum system is more complicated than the common vacuum solution. The greatest flexibility designates a system with separated vacuum that is also thermally isolated, which can therefore operate at various temperatures. The design is however significantly more complicated, and a separate cooling system (e.g. cryo-cooler) for the drift-tube structure is required.

Out of the six operational, or scheduled to soon become operational, EBIS/T charge breeders for radioactive beams, three of them have the drift-tubes at cryogenic temperature (TITAN EBIT, ReA EBIS and CANREB), all with a common vacuum design. The other three (REXEBIS, CARIBU and RAON) use room temperature bores. The latter approach is believed to be more conservative, although the exceptional vacuum conditions that can potentially be achieved in a cryogenic device are attractive.

6 References

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7 Appendix 1

In this appendix the required electron beam parameters for a selection of beams, listed in Table 2, are identified. A few of them, $^{78}Ni^{22+}$, $^{74}Kr^{25+}$, $^{132}Sn^{44+}$ and $^{228}Ra^{57+}$ with an A/Q-ratio varying between 3 and 4, are aimed for traditional post acceleration. The elements $^{78}Ni^{28+}$, $^{96}Ru^{44+}$ and $^{176}Lu^{68+}$ have an electron configuration specific for storage ring experiments.

Element	Z	A/Q	$E_{ionisation}$ (Q-1) (eV)	E_e (eV)	j_e (A/cm²)	f(Q)	I_e (A)
$^{78}Ni^{22+}$	28	3.5	1800	5940	900	0.44	0.3
$^{78}Ni^{28+}$	28	fully stripped	10400	34320	15500	0.45	0.9
	same as above but with 1 s breeding time				1550		9.0
$^{74}Kr^{25+}$	36	3.0	1220	4030	200	0.35	0.4
$^{96}Ru^{44+}$	44	fully stripped	26300	86790	140000	0.45	2.3
	same as above but with 1 s breeding time				14000		23
$^{132}Sn^{44+}$	50	3	6770	22340	5300	0.29	1.8
$^{176}Lu^{68+}$	71	Li-like	17100	56430	60000	0.32	4.0
	same as above but with 1 s breeding time				6000		40
$^{228}Ra^{57+}$	88	4	3740	12340	1400	0.20	2.5

Table 2. Charge breeding parameters for a selection of elements and charge states. $E_{ionisation}$(Q-1) denotes the ionization potential of charge state Q-1, E_e the optimal electron energy for ionization of charge state Q-1 and f(Q) signifies the fraction of beam in charge state Q. The electron current density j_e and beam electron current I_e values are derived for a charge breeding time of 0.1 s (unless otherwise specified) and a capacity requirement of 10^8 particles per pulse at charge state Q with 0.1 neutralization of the electron beam. Parameters marked in orange are specifically challenging and parameters in red are considered realistically impossible within a foreseeable future.

Electron beam energy

Let us first consider the electron beam energy. The energy must exceed the ionization energy of bound electrons to be removed, for reaching the requested charge state. To maximize the cross section for electron impact ionization and to reduce the effect of radiative recombination it is advantageous to utilize an electron beam with an energy approximately 3 times higher than the ionization potential. The ionization potentials, as well as the optimal electron beam energy, are listed in columns 4 and 5 of Table 2. The Ru and Lu cases do need special attention as the electron beam acceleration voltages required are relatively high (> 50 kV).

Electron current density

As the next step we define the electron current density required to reach the desired charge state within the available charge breeding time (imposed by the repetition rate of the post accelerator). For simplicity, although not fully correct for Ni^{28+}, Ru^{44+} and Lu^{68+}, we are neglecting the charge exchange process with the residual gases. In the EBIS the ionization and radiative recombination processes depend on the so-called ionization factor ($j_e\tau_{breed}$) – the product of the electron beam current density and the charge breeding time. For a given charge state and electron energy, this allows us to trade breeding time for current density or vice versa. To establish the ionization factor (not including relativistic effects) we have used the atomic simulation program developed by H. Pahl [54].

In the cases of bare Ni and Ru, the charge state distributions will reach a stationary equilibrium defined by the ratio of ionization and recombination cross-sections at the given electron energy. With a beam energy of 34 and 87 keV in the two cases, the predicted fractions are 0.9 and 0.55, respectively. In the calculation, however, we have based our electron current density estimation on the cases when the fully stripped charge state is equally abundant as the H-like state, as this is attained with a more modest electron beam current density. Nevertheless, if a charge breeding time of 0.1 s is imposed, we arrive at staggering electron current densities for the fully stripped Ru, as well as for Li-like Lu. The limiting current density for the immersed flow electron beam optics using the most advanced present technologies is about 800 A/cm², that is two orders of magnitude lower. The advanced and ambitious EBIS/T projects using Brillouin-type optics with double beam compression still under development are aiming for 10^4 A/cm². Thus, within a foreseeable future these charge breeding requirements cannot be fulfilled, neither can fully stripped Ni within a 0.1 s breeding time be achieved. However, as these beams are to be injected into a storage ring, in many cases operating with a sub-Hz repetition, j_e can be relaxed. If a breeding time of 1 s is acceptable, the current densities will be reduced by a factor 10, although it will have effects on the required current if the ion throughput requirement should be respected (see below).

The Kr^{25+} case is trivial and well below present technological limits for reliable immersed flow EBISes, even achievable with the present version of REXEBIS. The remaining cases would require a Brillouin-type electron gun, and the $^{132}Sn^{44}$ may still be challenging to reach, although on paper doable with CANREB and MEDeGUN (5 T) if a lower electron current is acceptable.

Beam intensities

The limitation on the beam intensity comes from the fact that the total positive ion charge will partly neutralize the confining space-charge field of the electron beam, making the radial confinement of the ions weak and reducing the overlap of the electron and ion beam. This in turn leads to longer breeding times or even ion losses in radial direction. For heavier highly stripped ions the heating of the confined ions by collisions with electrons becomes an issue and requires a deliberate introduction of light ion species in amounts exceeding the heavy ions in order to remove excessive energy by means of evaporative cooling [55]. Therefore, the maximum neutralization of the electron beam by heavy ions is rarely designed in excess of 0.1, as part of the total neutralization will be due to cooling and also residual gas ions. Furthermore, it should be noted that only 15-45% (mainly depending on the proton number) of the particles are in the desired charge state Q, while the others occupy lower or higher charges. This adds a factor 2-6 in lost effective space charge capacity.

For an assumed intensity of 10^9 pps and a desired repetition rate of 10 Hz, the number of particles per pulse is 10^8. The most challenging case is lutetium, partly because of the high charge state (68+), but also because of the high electron beam energy required. Neglecting relativistic effects, we find that a sufficient space charge of the electron beam will be provided by a 4 A electron beam for a 1 m long trap. Although such high current, and higher, is routinely attained at RHIC EBIS [15,16], it is not operated with a 100% duty factor and with a high compression 56 keV beam energy. Among other technical challenges, the deposited power in the collector will be very difficult to handle [56]. For the same reason Ru^{44+} ions are also very technically demanding. On the other hand, for the Ra^{57+} case the difficulty lies, not in the deposited power, but in the combination of a low beam energy and a high current, leading to a high perveance of the beam. The remaining cases are from a current point-of-view doable with present technology (although not necessarily in combination with the listed current densities).

Coming back to the three isotopes foreseen for injection into a ring and the above discussed option of charge breeding for 1 s. As given by the ionization factor, the electron current density would then be a factor 10 lower and at least Ni^{28+} will be within reach. However, the lower repetition rate would require a factor 10 higher electron beam currents, which is out of technical reach. A low repetition rate in combination with a reduced ion throughput is therefore the only way forward.

Summary

With these few beam examples, different challenging breeding aspects have been highlighted. Individually they may all be addressable - except for the high electron current density - but the combination of requirements makes the design difficult for several of the cases. Particularly if other breeding parameters, such as transverse ion acceptance and breeding efficiency are to be fulfilled in addition. It would lead too far to include these aspects here, as well as the stability criteria for high current density beams which is discussed in [57], therefore the reader is referred to [58,59]. Another relevant aspect, that is the. Nevertheless, in order to arrive to feasible technical specifications for the demanding cases, trade-offs in terms of repetition rate (charge breeding time), charge state and/or ion throughput are required. Table 3 gives examples of how this can be addressed, with only the fully stripped Ru and Li-like Lu still be technically demanding.

Element	Z	A/Q	Repetition rate (Hz)	pps	E_e (eV)	j_e (A/cm^2)	f(Q)	I_e (A)
$^{78}Ni^{22+}$	28	3.5	10	10^9	5940	900	0.44	0.3
$^{78}Ni^{28+}$	28	fully stripped	1	10^8	34320	1550	0.45	0.9
$^{74}Kr^{25+}$	36	3.0	10	10^9	4030	200	0.35	0.4
$^{96}Ru^{44+}$	44	fully stripped	0.5	10^7	86790	7000	0.45	0.5
$^{132}Sn^{44+}$	50	3	5	10^8	22340	2650	0.29	0.4
$^{176}Lu^{68+}$	71	Li-like	0.5	10^7	56430	3000	0.32	0.8
$^{228}Ra^{57+}$	88	4	1	$5\cdot10^8$	12340	1400	0.20	1.25

Table 3. Same elements as in Table 2, but now with relaxed parameters for the most challenging cases. The repetition rate has been adjusted as well as the ion throughput, denoted as particles per second (pps).