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EBIS/T charge breeding for intense rare isotope beams at MSU

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ABSTRACT: Experiments with reaccelerated beams are an essential component of the science program of existing and future rare isotope beam facilities. NSCL is currently constructing ReA3, a reaccelerator for rare isotopes that have been produced by projectile fragmentation and in-flight fission and that have been thermalized in a gas stopper. The resulting low-energy beam will be brought to an Electron Beam Ion Source/Trap (EBIS/T) in order to obtain highly charged ions at an energy of 12 keV/u. This charge breeder is followed by a compact linear accelerator with a maximum beam energy of 3 MeV/u for ^{238}U and higher energies for lighter isotopes.

Next-generation rare isotope beam facilities like the Facility for Rare Isotope Beams FRIB, but also existing Isotope Separator On-line (ISOL) facilities are expected to provide rare-isotope beam rates in the order of 10^{11} particles per second for reacceleration. At present the most promising

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scheme to efficiently start the reacceleration of these intense beams is the use of a next-generation high-current charge-breeder based on an EBIS/T. MSU has formed a collaboration to develop an EBIT for this purpose. A new high-current EBIS/T breeder will be developed and constructed at MSU, where also first tests on achievable beam rate capability will be performed. The EBIT is planned to be installed at the Isotope Separator and Accelerator facility ISAC at TRIUMF laboratory for on-line tests with rare isotope beams and to provide intense energetic reaccelerated radioactive beams.

The status of the ReA3-EBIS/T in the NSCL reaccelerator project is given with a brief summary of results, followed by a discussion of plans for the future high-intensity EBIS/T charge breeder.

KEYWORDS: Instrumentation for radioactive beams (fragmentation devices; fragment and isotope, separators incl. ISOL; isobar separators; ion and atom traps; weak-beam diagnostics; radioactive-beam ion sources); Ion sources (positive ions, negative ions, electron cyclotron resonance (ECR), electron beam (EBIS))

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1 Introduction

Scientific progress in rare-isotope research requires not only high rare isotope beam intensities but also a wide range of beam energies. Fast beams with energies above 100 MeV/u are readily available at in-flight separation facilities like NSCL/MSU, RIBF/RIKEN or GSI [1]. ISOL beam production at facilities like ISOLDE/CERN, HRIBF/ORNL and ISAC/TRIUMF provides low-energy ($<$ 100 keV, “stopped”) beams [2] and such beams have recently also become available from gas stopping of projectile fragments (NSCL and RIBF) or low-energy reaction and decay products (GSI, ANL, JYFL and other places). Rare isotope beams with energies up to several MeV/u are obtained by reaccelerating the low-energy ISOL beams (REX-ISOLDE, ISAC, HRIBF) or, in the near future, also by reaccelerating stopped beams from projectile fragmentation (NSCL) or decay (ANL). Making reaccelerated beams available with minimum losses and high quality is critical for obtaining a better understanding of element synthesis via the study of key reactions for nuclear astrophysics, for enabling new insight into nuclear structure far from stability or at high excitations via Coulomb excitation and transfer reactions, or for exploring and paving ways to make new heavy elements.

Significant effort is made world-wide in building more powerful rare isotope beam facilities and in upgrading existing facilities with the goal to increase the science opportunities with rare isotope beams. FRIB, the upcoming Facility for Rare Isotope Beams at MSU [3, 4], will be based on a 400 kW 200 MeV/u heavy ion driver, that will provide fast, stopped and reaccelerated beams. Orders of magnitudes higher rare beam intensities are expected from next-generation facilities as compared to present ones: For the ISOL option studied for the FRIB project, beam rates exceeding 10^{12} ions/s have been estimated for a wide range of nuclei, whereas for the proposed upgrade ARIEL at ISAC [5], photo-fission yields of up to 10^{13} particles/s are predicted. In order to fully and safely use these intense beams the technologies for beam manipulation after production have to be pushed to maximum performance, including reacceleration.

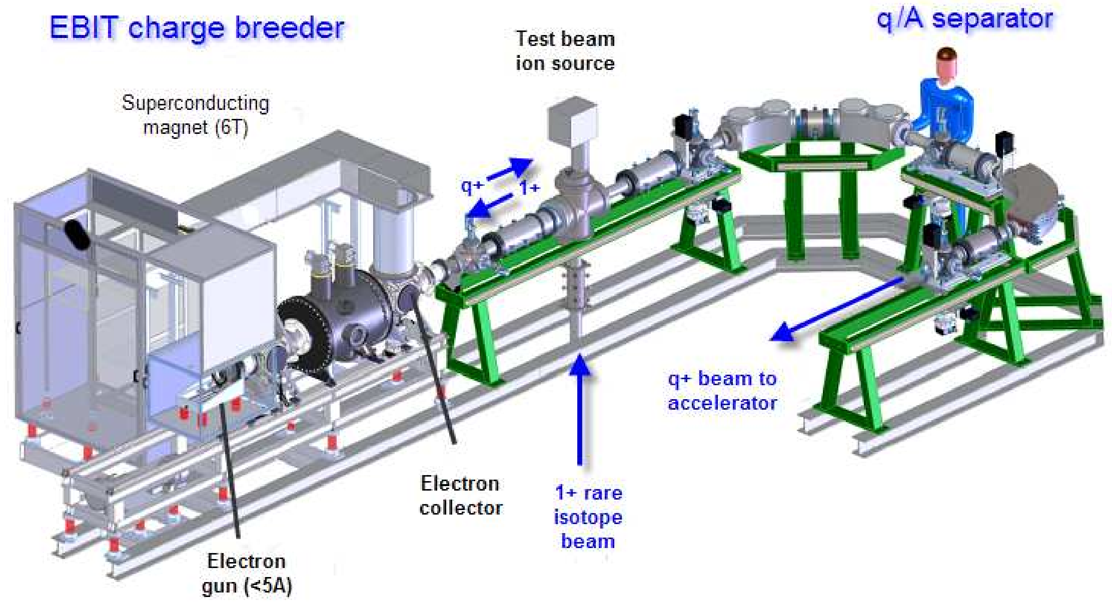

Figure 1. Layout of the ReA3 EBIT and its charge-over-mass (q/A) separator.

2 The ReA3 EBIS/T charge breeder

The NSCL has been the first to thermalize rare isotopes from projectile fragmentation and to use them for an experimental program with high-precision Penning trap mass measurements [6]. Laser-spectroscopy and experiments with reaccelerated beams are currently being added as the next logical steps in making best use of unique beams not available from other production techniques. The main components of the ReA3 reaccelerator are a high-current EBIS/T as charge breeder, a charge-over-mass separator, a room-temperature RFQ linac and a superconducting drift tube linac. Design of the ReA3 reaccelerator is complete and construction is nearing completion: Commissioning work on the EBIS/T charge breeder has already started (see below), while the RFQ and the first two of three superconducting accelerator modules have recently been put in place. ReA3 is expected to provide 3 MeV/u beams towards the end of 2010. For a recent detailed status report on the linac, see [7].

Figure 1 shows the layout of the ReA3 EBIS/T charge breeder and its dedicated charge-over-mass separator. Additional details of the system can be found in a separate contribution to these proceedings [8] and in [9]. The MSU EBIT charge breeder has been designed in collaboration with MPIK in Heidelberg and ISAC/TRIUMF. The TITAN EBIT has been the basis for the design, but a number of changes, described in the text which follows, have been implemented in order to increase the performance of the system and to optimize it for providing highly charged ions for reacceleration.

The EBIT is mounted on a high-voltage platform with variable potential up to 60 kV. An achromatic charge-over-mass separator delivers the highly-charged ions to the linear accelerator. Singly-charged rare isotope ions with 60 keV beam energy from the NSCL gas stopper are supplied

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by a vertical beam line. An electrostatic kicker-bender combination deflects the ions into the direction of the EBIT, where they are continuously captured and charge-bred to the desired charge state. The platform potential is changed prior to extraction to deliver the ions with the correct injection energy (20-60 keV·q) to the linac. Assuming an electron current density approaching 10^4 A/cm^2 charge breeding efficiencies above 50% are expected as well as breeding times of less than 20 ms. With an electron beam current of about 1.5 A available from the present electron gun designs, the NSCL EBIT will be able to hold almost 10^{10} positive charges inside its 8 cm long central trap region, assuming a 10 keV electron beam compensated to 75% (see also table 1 and related discussion). With repetition rates of 10-100 Hz, beam rate capabilities of the order of 10^{10} ion/s and possibly above are expected. The high repetition/dumping rate in combination with the cryogenic temperature in the trap region is expected to keep contamination from charge bred residual gas atoms at an acceptable level.

The main changes compared to the TITAN EBIT breeder are an improved electron gun design and a different magnetic field configuration. Substantial effort was put into numerical simulations of the electron gun to modify the electrode layout and boost the output current. As a result two cathode configurations have been designed and built with an expected electron beam output of 1.5 and 2.5 A, for Ba-dispenser cathodes with 6.35 and 12.7 mm diameter, respectively. Commissioning of the smaller of the two cathode units has successfully started with a temporary 0.2 T magnet setup. The electron current transmitted to the collector has been approaching an Ampere and is expected to improve further when the temporary magnet is replaced by the dedicated 6 T superconducting magnet. The design of the electron collector allows for the absorption of up to 5 A of continuous electron beam current at an energy of 4 keV. According to a thermal stress calculation, the resulting thermal load of 20 kW uses only two thirds of the device's capabilities. The electrical insulation for the electron gun and collector has been dimensioned for an electron energy of up to 30 keV in the trap region.

For optimum acceptance of the injected continuous ion beam in the EBIT, a large-diameter electron beam, not necessarily with highest electron density, is preferable. However for fastest charge state breeding a high electron density, not necessarily within a very large electron beam diameter, is required. In order to find a set of operation parameters for the NSCL EBIT, which satisfy these two conflicting requirements injection simulations have been performed. Two codes have been developed at MSU, which use an analytical space charge expression based on a flat-profile electron beam model and treat the ionization in a near-analytical [10] or Monte-Carlo fashion [11]. The codes use the tested ion trajectory simulation classes from the 'IonCool' package [12]; the applied electron-impact cross-sections have been checked against the CBSIM code [13] for selected atoms and found to be in good agreement. The codes have been used to evaluate different magnetic and electric field configurations and resulted in a hybrid magnet design: The magnet will feature a short 6 T field region for fast and final charge breeding and an extended field region with lower, variable field strength to optimize the acceptance of the system [9]. The short 6 T field region is about 12 cm long in axial direction and can be stretched to 50 cm when the extended field coil is charged for 6 T as well. Due to its cryogenic-temperature bore the EBIT will operate in ultra-high vacuum resulting in very clean highly charged ion beams. The magnet is expected to be ready for commissioning in mid 2010.

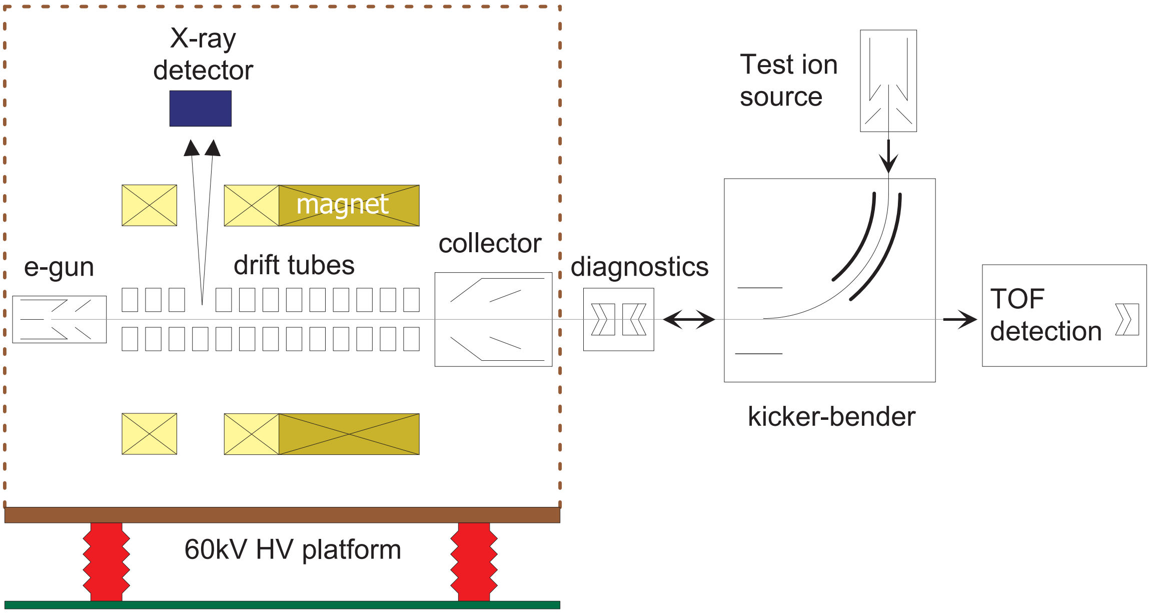

Figure 2. Sketch of the planned high-intensity EBIS/T charge breeder and its diagnostic beam line.

3 A next-generation intense-RIB charge breeder

MSU has formed a collaboration to develop a charge breeder for the reacceleration of rare isotope beams with beam rates up to and exceeding 10^{11} ions/s. Intention to fund this project has been announced by the US Department of Energy. Incorporating the experience gained with the ReA3-EBIS/T, a new high-current EBIS/T breeder will be developed and constructed at MSU. The prototype will be commissioned and tested for beam rate capability (i.e. total ion throughput in particles per unit time) with stable beams at NSCL. At a mature stage the charge breeder will be moved to ISAC, the high-power ISOL facility at TRIUMF for a demonstration of the complete system with charge breeding and acceleration of intense rare isotope beams with the ISAC RFQ/LINAC.

The general layout of the proposed high-intensity EBIT charge breeder is shown in figure 2. The main components are a superconducting magnet system mounted on a support structure together with the vacuum enclosures for the electron gun and the collector. Connected to the collector chamber is an electrostatic beam line which will be used to provide singly charged ions from a test ion source to the EBIT and to transport highly charged ions from the EBIT to beam diagnostic systems. A kicker-bender combination allows one to switch between the two modes of beam transport within microseconds.

The support structure for the electron gun, magnet system and collector will be designed as a high-voltage platform. Final operation will require switching between two high-voltage levels: The platform will be biased at 60 kV while injecting singly charged ions into the EBIT and switched to a different voltage while extracting highly-charged ions to meet the velocity conditions set by the ISAC linear accelerator.

The superconducting magnet system will be scaled to 9 Tesla for higher electron current density and fastest charge-breeding. The electron gun and collector will be designed to allow for operation with electron beam currents up to 10 A. They can be biased to provide up to 30 keV electron energy. For the initial tests at MSU a short diagnostic beam line will be set up, equipped with a test ion source, a beam inflector and the necessary ion optics for beam transport. Beam diagnostics will include current and beam profile measurements of the injected and extracted beams. A fast ion detector will allow for a charge-over-mass analysis of the extracted ions via time-of-flight mass measurement. In the following we will discuss various aspects of the most critical components of the system in more detail.

3.1 Magnet system

The magnetic field required for focusing and transport of the electron beam will be provided by a 9 T superconducting magnet system. The configuration presently foreseen will be similar to the hybrid one for the ReA3 EBIT (see above), with its two independent adjacent field regions that allow for the optimization of both acceptance and breeding performance. The trapping region will be located in a split-coil system to provide optical access to the trap region. The optimum field configuration will be based on detailed simulations that will have to be benchmarked with experimental data, obtained with MSU's ReA3 breeder and with other EBIS/T systems available in the collaboration. Radial ports in the cryogenic shield and the outer vacuum chamber make it possible to observe X-rays from the trapping region and to inject gas into the system for diagnostics purposes and for ion-ion cooling [14, 15]

3.2 The electron beam system

A key to achieving fast and efficient charge breeding is an intense electron beam with a high electron beam current density. For the proposed system electron currents up to 10 A are foreseen. The beam current density inside the EBIT is mostly determined by the field strength in the trap region and the residual field at the cathode of the electron gun. Assuming proper compression of the electron beam from the (almost field-free) cathode into a 9-Tesla magnet, current densities of up to 10^5 A/cm^2 can be expected. While this target value is about an order of magnitude higher than reported current densities [16], it had already been projected for the application of a high intensity EBIT as a charge booster in 1999 [17]. A careful design of the electrode structure guiding the electron beam from the gun to the collector will be required to avoid complications such as beam instabilities due to the sizeable space charge generated by the electron beam. As an example, a 10 A electron beam with an energy of less than 25 keV will produce a space-charge potential of more than 1 kV inside the beam. Depending on the details of the cathode and inner radius of the electrode structure, the total space-charge potential for that electron beam will reach several kV.

Different options will be considered for the electron gun. One is an upgrade of the electron gun design of the ReA3 EBIT, which currently uses Ba-dispenser cathodes of up to 12.7 mm diameter in a near Pierce-type geometry. Simulations predict electron currents of up to 2.5 A at 10.5 kV extraction voltage, i.e. the difference between anode and cathode voltage. In order to reach an electron current of 10 Ampere, higher anode voltages and a larger cathode diameter would be needed and the latter would require a higher beam compression ratio to maintain or increase the electron current density. First tests of the ReA3 EBIT electron gun with the 6 T superconducting magnet will start soon and provide important information on how well this gun design works with respect to the magnetic field suppression at the cathode surface. Another option for the gun design is a system similar to that of the RHIC EBIS [18]. This design uses IrCe cathodes with emission current densities up to 50 A/cm^2. While this gun design already exceeds 20 A current it requires a larger distance between the gun and the main magnet's field region, increasing the size of the system and making it more complex. A significant redesign of the semi-immersed gun would likely be required to reach the required beam compression. For the proposed breeder detailed simulations of the different electron gun concepts will be performed to identify the source concept that provides the necessary beam current and current density.

The electron collector also needs to be carefully designed because of the potentially high power densities involved in stopping the multi-ampere electron beam. The deposited power by the electron beam can be minimized by its deceleration before it hits the collector, but this option is limited by the perveance limit for a space charge dominated beam. For a 10 A beam a deceleration to 8-10 keV is realistic, resulting in a total power deposition of up to 100 kW. An alternative scheme to obtain the required electron densities might be the so-called 'reflex' mode of operation [19], which uses an oscillating electron beam from a low-current cathode. This scheme is attractive as it might avoid the need for high-current cathodes, high-power collectors and their consequences, but it will have to be evaluated carefully for reliability of operation before possible implementation. It remains to be evaluated whether the dissipated power from a reflex-mode ion beam can cause a significant heat load to the cryogenic trap structure.

3.3 The trapping electrode structure

For the proposed new breeder, a cryogenic trap system in thermal contact with the 4.5 K superconducting coil with a length of up to one meter is expected. To reduce possible memory effects caused by the accumulation of contaminants from the cryogenic trap structure, the breeder could be warmed up during maintenance/shutdown times. The electrodes close to where the ions will accumulate are equipped with slits for X-ray diagnostics, making the system an EBIS/EBIT hybrid. The geometry of the electrodes is critical since it influences the potential depression due to the space charge of the electron beam. The anticipated electron currents can produce space charge potentials in the kV range. The inner diameter of the electrodes will have to be chosen carefully to avoid undesired variations of the space charge potential along the axis of the EBIT. These unwanted ion traps can reduce the ion capacity of the electron beam and inhibit a complete extraction of charge bred ions.

3.4 Expected performance

The proposed high-intensity charge breeder will combine the high current density of an EBIT with the large storage capacity of an EBIS. The charge capacity is calculated as $f\,I_e L/\sqrt{E_e}\cdot\sqrt{m_e/2/e}$ with the trap length L, the electron energy E_e, the electron current I_e, the compensation degree f and the mass m_e and charge e of the electron. If the energy E_e is given in eV and the other quantities in SI-units, $f\,I_e L/\sqrt{E_e}\cdot 1.305\cdot 10^{13}$ will give the charge capacity in multiples of electron charges [20]. With current densities of 10^4 - 10^5 A/cm^2 breeding times of less than 10 ms and a storage capacity of up to a few 10^{11} charges can be expected. A beam rate capability of up to 10^{13} ions per second appears to be theoretically possible.

A maximum $A/q = 5$ is sufficient for the reacceleration of highly-charged ions in a linac. This means that the charge states to be reached are quite moderate, for example $q = 56^+$ for uranium

Table 1. Expected breeding performance with beam energies adjusted to closed atomic shell energy gaps for different neutron-rich isotopes of elements from Ne to U. The electron-beam current is assumed to be 10 A, the maximum current density to be $5{\cdot}10^4$ A/cm^2.

Isotope	Charge state	A/q	Electron beam energy [keV]	Breeding time, 60% in single charge state [ms]	Ion capacity (75% neutralization)
^{29}Ne	10	2.9	6	0.6	$1.0{\cdot}10^{11}$
^{48}Ar	18	2.67	12	5.7	$4.0{\cdot}10^{10}$
^{92}Kr	34	2.7	11	8.2	$2.2{\cdot}10^{10}$
^{136}Xe	44	3.09	7	6.5	$2.1{\cdot}10^{10}$
^{212}Pb	54	3.93	5	7.2	$2.0{\cdot}10^{10}$
^{241}U	64	3.76	7	12.8	$1.5{\cdot}10^{10}$

which would then be krypton-like. Electron beam energies up to $E_e = 30$ keV are typically sufficient, suitable to reach fully stripped ions up to $Z = 45$ (Rhodium) and He-like ions up to $Z = 88$ (Radium) if needed. For the proposed breeder the limiting factor to reach the desired charge states $A/q = 5$ is not the maximum electron beam energy for 30 keV but the available breeding time. This time may be limited either by the half life of the isotopes or by the cycle period needed to maximize the beam rate capability. The time required to reach a certain charge state depends on the electron-impact ionization cross-sections and the electron beam current density. The cross sections are energy dependent and reach a maximum value at about 2.7 times the ionization energy from one charge state to the next. The beam rate capability is determined by the storage capacity of the electron beam for positive charges and the rate at which the accumulation, breeding, and extraction cycle can be repeated. The ion storage capacity is determined by the trap length, the electron beam current and the electron beam energy.

Table 1 gives examples of calculated breeding times and ion capacities for different isotopes. The quoted breeding time is the time calculated with CBSIM [13] for the specified charge-state to reach 60% of the charge-state distribution. As the (re)accelerator will be able to accept one charge state for a given species, breeding into a single charge state is essential to maximize efficiency. The ion capacity is the total number of ions in the given charge state that the EBIT can hold. It is calculated from the charge-capacity formula given above assuming that this charge state compensates 75% of the electron charge in a 1 m long trap. Reported compensation degrees range from 25% to 68% [21, 22] and depend on the ion temperature relative to the trap depth. In order to reach the projected 75 % compensation for the future EBIT careful ion transfer and effective cooling techniques will be mandatory. A current density of $5{\cdot}10^4$ A/cm^2 is assumed but it is likely that higher current densities are achievable in the proposed device. The table shows that breeding times of the order of 10 ms or less are required to reach single noble-gas like charge states with A/q ≤ 5. Due to the short breeding times, repetition rates of 100 Hz appear feasible. Operating experience from REXEBIS shows that switching the potentials for the trap electrodes and the HV-cage can indeed be performed at repetition rates exceeding 50 Hz [23]. With a repetition rate of 100 Hz beam rate capabilities of 10^{12} ions/s for medium heavy ions and even higher for lower-Z ions appear realistic.

3.5 Challenges and R&D work

A variety of studies will have to be performed in order to meet the performance goals outlined above. Simulations of electron-beam formation and compression will be essential in the beginning of the project to be able to reliably provide the targeted 10^4 - 10^5 A/cm^2 electron current density and safely collect the produced electron beam. Magnet design will be the second large simulation aspect early into the project. The magnet field distribution not only affects the formation and compression of the electron beam but also the ion acceptance. The simulation codes used so far to calculate the acceptance of the ReA3 EBIT made simplifications as to the electron-beam shape. More realistic electron-beam profiles, consideration of space-charge compensation, the inclusion of ion-cooling and heating mechanisms are planned to improve the predictive power of the codes. Data from the ReA3 EBIS/T and other charge breeders will be essential input to benchmark the simulations.

During the commissioning phase the electron gun and collector will be tested first, yielding vital information on the performance of the electron gun (e.g. its perveance) and the heat distribution at the collector. Studying and optimizing the capture and charge breeding of stable ions will be the central part of the commissioning work at NSCL. X-ray spectroscopy and the analysis of time-of-flight spectra will be the main diagnostic tools allowing for: the determination of charge-state distributions and the total efficiency of the system (injection, breeding into specific charge-states and ejection), information on electron beam and ion cloud parameters (e.g. emittance, energy spread). As an example, we envisage to determine the current density by measuring the electron beam diameter in the trap region through the observation of X-rays emitted from trapped highly charged ions with a CCD camera [24]. Techniques such as the breeding near atomic shells and the deliberate recombination at dielectronic resonances by tuning the electron beam energy [25] will be employed to narrow charge state distributions. As indicated above, the expected space charge potential of a 10 A electron beam is on the order of several kV. The impact of the resulting energy spread of the electron beam on the applicability of dielectric resonances to manipulate the charge state balance will have to be evaluated. The use of electronic-shell closures to favor certain charge states (e.g. He-like) still appears feasible, as the difference in ionization potential between adjacent charge states is separated by more than a few keV in heavy ions. In addition, the electron-impact ionization cross section of highly charged ions as a function of the beam energy decays slowly past its maximum and the full-width of the distribution is rather large. Cooling methods (e.g. introducing cooling gases) to counter ion-heating processes in the charge breeder, to enhance ion acceptance and emittance and to maximize the charge capacity of the device will be examined.

Once the performance of the breeder has been demonstrated at MSU with intense stable beams, the system will be shipped to TRIUMF, installed at a prepared position and re-commissioned for a full system test with rare isotopes.

Acknowledgments

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References

[1] For an overview of the in-flight production method and related facilities, see e.g.
D.J. Morrissey and B.M. Sherrill, *In-Flight Separation of Projectile Fragments*, *Lect. Notes Phys.* **651** (2004) 113.

[2] For an overview of the ISOL method and facilities, see e.g.
P. Van Duppen, *Isotope Separation On Line and Post Acceleration*, *Lect. Notes Phys.* **700** (2006) 37.

[3] Facility for Rare Isotope Beams, http://www.frib.msu.edu/.

[4] G. Bollen, *FRIB — Facility for Rare Isotope Beams*, *AIP Conf. Proc.* **1224** (2010) 432.

[5] S. Koscielniak et al, *ARIEL and the TRIUMF e-linac initiative, a 1/2-MW electron linac for rare isotope beam production*, in Proceedings of *LINAC08, XXIV Linear Accelerator Conference*, Victoria, British Columbia, Canada, September 29 – October 3 2008.

[6] R. Ringle et al, *Precision mass measurements with LEBIT at MSU*, *Int. J. Mass Spec.* **251** (2006) 300.

[7] O. Kester et al., *The MSU/NSCL re-accelerator ReA3*, in Proceedings of SRF2009, 14th International Conference on RF Superconductivity, Berlin Germany, September 20–25 2009.

[8] A. Lapierre et al., *The MSU EBIT at NSCL*, 2010 *JINST* **5** c07001.

[9] S. Schwarz et al, *The NSCL electron beam ion trap for the reacceleration of rare isotopes coming to life: First extraction tests with a high-current electron gun*, *Rev. Sci. Instrum.* **81** (2010) 02A503.

[10] S. Schwarz et al., *A high-current electron beam ion trap as a charge breeder for the reacceleration of rare isotopes at the NSCL*, *Rev. Sci. Instrum.* **79** (2008) 02A706.

[11] E. Gavartin, *Acceptance calculations for a charge breeder based on an electron beam ion trap*, MSc. Thesis, Michigan State University (2008).

[12] S. Schwarz, *IonCool — A versatile code to characterize gas-filled ion bunchers and coolers (not only) for nuclear physics applications*, *Nucl. Instr. Methods Phys. Res.* **A 566** (2006) 233.

[13] R. Becker, O. Kester and Th. Stoehlker, *Simulation of charge breeding for trapped ions*, *J. Phys. Conf. Ser.* **58** (2007) 443.

[14] M.A. Levine, R.E. Marrs, J.R. Henderson, D.A. Knapp and M.B. Schneider, *The Electron Beam Ion Trap: a New Instrument for Atomic Physics Measurements*, *Phys. Scripta* **T 22** (1988) 157.

[15] P. Beiersdorfer et al., *Observation of Lifetime-Limited X-Ray Linewidths in Cold Highly Charged Ions*, *Phys. Rev. Lett.* **77** (1996) 5353.

[16] A.J. González Martínez et al., *State-Selective Quantum Interference Observed in the Recombination of Highly Charged Hg*$^{75+\dots78+}$ *Mercury Ions in an Electron Beam Ion Trap*, *Phys. Rev. Lett.* **94** (2005) 203201.

[17] R.E. Marrs and D.R. Slaughter, *A High Intensity Electron Beam Ion Trap for Charge State Boosting of Radioactive Ion Beams*, *AIP Conf. Proc.* **475** (1999) 322.

[18] J. Alessi et al., *EBIS Preinjector Construction Status*, in Proceedings of *LINAC08, XXIV Linear Accelerator Conference*, Victoria, British Columbia, Canada, September 29 – October 3 2008.

[19] E.D. Donets, *Electron beam ion sources in the reflex mode of operation*, *Rev. Sci. Instrum.* **71** (2000) 810.

[20] F. Wenander, *An EBIS as heavy ion source for the LHC pre-injector*, *AIP Conf. Proc.* **572** (2000) 48.

[21] O. Kester et al, *The MAXEBIS at GSI as a test ion source for charge breeding and for HITRAP*, *Rev. Sci. Instrum.* **79** (2008) 02A705.

[22] F. Wenander et al, *REXEBIS, Design and Initial Commissioning Results*, *AIP Conf. Proc.* **572** (2001) 59.

[23] F. Wenander et al, *The REX-ISOLDE charge breeder as an operational machine*, *Rev. Sci. Instrum.* **77** (2006) 03B104.

[24] S.B. Utter et al, *Position and size of the electron beam in the high-energy electron beam ion trap*, *Nucl. Instr. Methods Phys. Res.* **A 428** (1999) 276.

[25] J. Crespo López-Urrutia et al., *Optimization of the charge state distribution of the ion beam extracted from an EBIT by dielectronic recombination*, *Rev. Sci. Instrum.* **75** (2004) 1560.

2010 JINST 5 C10002