Available online at www.sciencedirect.com

ScienceDirect

Nuclear Instruments and Methods in Physics Research B xxx (2008) xxx–xxx

NIM B
Beam Interactions with Materials & Atoms

www.elsevier.com/locate/nimb

An electron beam ion trap for the NSCL reaccelerator

S. Schwarz[a,*], G. Bollen[a,b], J.R. Crespo López-Urrutia[c], J. Dilling[d], M. Johnson[a], O. Kester[e], M. Kostin[a], F. Marti[a], C. Wilson[a], P. Zavodszky[a]

[a] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA*
[b] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*
[c] *Max-Planck Institute for Nuclear Physics, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[d] *TRIUMF, 4004 Wesbrook Mall, Vancouver BC, Canada V6T 2A3*
[e] *GSI Darmstadt, Planckstrasse 1, 64291 Darmstadt, Germany*

Abstract

The reacceleration of stopped fast-fragment beams or low-energy ISOL beams to the energy range of 0.3–12 MeV/nucleon allows for experiments such as low-energy Coulomb excitation and transfer reaction studies and for the precise study of astrophysical reactions. The coupling of a reaccelerator to a gas stopper at a fragmentation facility will provide rare isotope beams of nuclides not available at ISOL facilities in this energy regime. The implementation of charge breeding is a key to obtain a compact and cost-efficient reaccelerator and it is foreseen in the development of a reaccelerator at the NSCL at MSU. An Electron Beam Ion Trap (EBIT) will be used for charge-breeding as it has the potential to rapidly and efficiently output highly charged ions in a single charge state. The system will provide highly charged ions at an energy of 12 keV/nucleon to a compact linear accelerator for further acceleration.

PACS: 29.25.Rm; 37.10.Ty; 41.75.Lx

Keywords: Charge breeding; Radioactive ions; Advanced accelerator concepts

---

1. Introduction

With the development of efficient gas stopping techniques [1], low-energy beams are becoming increasingly available at fragmentation facilities [2,3] and these beams are now routinely used for successful high-precision experiments such as Penning-trap mass spectrometry [4,5] and laser spectroscopy [6]. The availability of these unique stopped beams has led to the demand for reaccelerated beams in the energy range of 0.3–12 MeV/nucleon, which will allow for an experimental program ranging from low-energy Coulomb excitation experiments and transfer reaction studies to the study of astrophysical reactions. The connection of a reaccelerator to a gas stopper is of particular importance, since it will provide high quality beams of nuclei not available in this energy regime at any other facility. For this reason reacceleration of stopped fragmentation beams has been made a core component of new and proposed rare-isotope research facilities [7,8].

In order to maximize the scientific reach, the reacceleration scheme must provide: (a) high efficiency for ions of all elements available at the facility (b) beam rate capacity adapted to the maximum secondary beam rates (c) high beam purity to minimize background and to avoid ambiguities in the experimental results (d) variable time structure of the reaccelerated beam from microsecond pulses to continuous beams to meet the experimental requirements.

The reacceleration scheme that was chosen for the NSCL was optimized with respect to these properties. It is based on the acceleration of highly charged n^+ ions (“n^+”-scheme) and offers advantages over schemes based on the acceleration of singly-charged ions.

---

[*] Corresponding author.
E-mail address: schwarz@nscl.msu.edu (S. Schwarz).

0168-583X/$ - see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.nimb.2008.05.056

Please cite this article in press as: S. Schwarz et al., An electron beam ion trap for the NSCL reaccelerator, Nucl. Instr. and Meth. B (2008), doi:10.1016/j.nimb.2008.05.056

2. Options for reacceleration

Reacceleration starting with singly charged ions and subsequent stripping between acceleration stages is a well-established approach to bring stable or rare isotope beams up to energies of a few MeV/nucleon, realized for example at ISAC. However, such systems are complex and costly and have significant losses in efficiency for heavier beams. An example of a 1^+ scheme that was studied at the NSCL as part of the evaluation of different reacceleration options required different RF frequencies together with the operation of a large low-frequency RFQ on a high-voltage platform, complicated inter-digital drift tubes and a large number of $\lambda/4$ cryostats. The system requires three charge-state strippers, each of which introduces efficiency losses. Calculated transmission efficiencies for such a system range from about 50% for light elements ($Z < 10$) (single charge states) to 10–15% for the sum of 4–5 charge states in the case of heavier elements ($Z > 50$).

The implementation of charge-state boosting as the first step in a reaccelerator is recognized as the best way to obtain a very compact and cost-efficient reacceleration scheme. A compact linac composed of a room-temperature RFQ and SRF structures is used and all resonators are operated at the same frequency. If a high efficiency can be obtained for breeding ions into a single charge state, then the performance of the n^+ reacceleration scheme will surpass that of the 1^+ scheme. Reacceleration with charge breeding was first demonstrated at REX-ISOLDE [9] at CERN, where an Electron Beam Ion Source, REX-EBIS [10], is used as a charge breeder.

2.1. ECR-based charge breeding

There are two different approaches for boosting the charge state of an atomic ion. The most common approach relies on passing the ions through Electron Cyclotron Resonance Ion Sources (ECRIS). There is a lot of experience with ECRIS systems due to their use as sources of high intensity, moderately charged ions for stable beam accelerators. They are also considered as charge breeders (for a recent review see [11]). A number of studies have been made of the charge-state boosting performance of ECRIS systems for 1+ ions at, for example, LPSC [12], TRIUMF [13], ISOLDE [14] and KEK [15]. The PHOENIX source [12] is one example of a dedicated charge breeder system. Performance tests with stable beams [12] showed a breeding efficiency of about 4% for $Sn^{1+} \rightarrow Sn^{22+}$. Typical breeding times for such charge states are >100 ms. An undesired feature of ECR sources are the large currents (>mA) of stable ions that come along with the beam of interest. To date no reaccelerator has been reported to operate with an ECR as a charge breeder.

2.2. EBIS/T-based charge breeding

Alternative systems for boosting the charge states of atomic ions are the Electron Beam Ion Traps (EBIT) [16] and the Electron Beam Ion Sources (EBIS) [17]. The ions are radially trapped in these devices by the space charge of an intense electron beam and are ionized to very high charge states by electron impact. The ions are confined longitudinally in an additional electrostatic potential usually generated with a set of cylindrical electrodes. The main differences between an EBIS and an EBIT are the length of the trapping region and the electron current density. The EBIT systems typically use a much shorter trapping region and a much higher electron beam density than the EBIS devices. A common feature of the devices is their operation at ultra-high vacuum, which results in a very small background current. A very small source diameter also leads to a low emittance of the extracted highly charged ion beam. EBIT devices are in wide use for spectroscopic studies of trapped, highly-charged stable ions and they have been shown to be very efficient sources of highly-charged stable ions. The charge-breeder REX-EBIS at ISOLDE/CERN, operating with an electron current density of 200–250 mA, allowed for the breeding of Na^{1+} to Na^{8+} (peak charge) within 18 ms and breeding times of 150 ms have been found for Cs^{1+} to Cs^{32+}. Average charge breeding efficiencies of 10% and in isolated cases >20%, have been observed [10]. A dedicated EBIS for charge breeding studies, MAXEBIS [18], has been brought into operation recently at GSI in Darmstadt. A group at Brookhaven National Lab has successfully developed a high performance EBIS, the RHIC Test EBIS [19], for stable beams. An electron beam of 10 A at 20 keV in this new device provides an electron density larger than 400 A/cm^2, which provides a charge capacity that exceeds 3×10^{11}. The maximum beam rate that could be obtained with a 100 Hz repetition rate in such a device would be in the range of 10^{12} ions/s.

Marrs and Slaughter evaluated the potential gains associated with using a high-intensity EBIT (5 A, 10^5 A/cm^2 for 30 keV electrons) as a charge-booster for RIA [20]. They found that such a device would have charge-breeding properties for rare isotopes superior to any other device at present. For example, neon-like Sn^{40+} could be produced in about 3 ms. Very narrow charge-state distributions can be obtained by tuning the electron beam energy. For

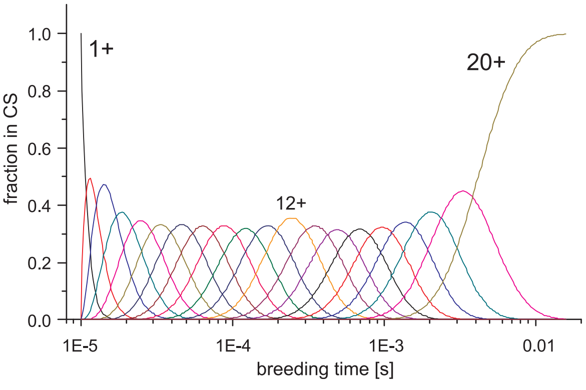

Fig. 1. Charge state evolution for Ti^{+}-ions in an EBIT with a current density of 10^4 A/cm^2 and an electron energy of 5 keV.

Please cite this article in press as: S. Schwarz et al., An electron beam ion trap for the NSCL reaccelerator, Nucl. Instr. and Meth. B (2008), doi:10.1016/j.nimb.2008.05.056

closed-shell configurations it was experimentally found that a breeding efficiency of up to 90% can be achieved [21]. Closed-shell breeding is illustrated in Fig. 1. The figure shows the calculated charge state evolution for Ti^+-ions in an EBIT with an assumed current density of 10^4 A/cm^2 and an electron energy of 5 keV. For the given electron energy the breeding process stops at the He-like charge state after a breeding time of only ≈10 ms.

Very recently an EBIT charge breeder has been built by the Max Planck Institute for Nuclear Physics in Heidelberg for a collaboration with TRIUMF. This charge breeder [22,23] will be used for TITAN [24], an ion trap project intended to measure highly charged-ions of rare isotopes produced at ISAC. The device has successfully passed the first offline tests and is now being commissioned at TRIUMF. The expected performance of the TITAN charge breeder is close to that required for an efficient reacceleration scheme at the NSCL. The EBIT charge breeder planned for the NSCL, to be discussed in more detail in the following, will be similar to the TITAN EBIT in many aspects.

3. The NSCL reaccelerator concept

Fig. 2 illustrates the NSCL n^+ reacceleration concept. The beam from the gas stopper will be sent into an EBIT charge breeder, located on a high voltage (HV) platform. The platform voltage can be raised to a potential of a few tens of keV during breeding and before extraction to match the velocity of the newly created, highly charged ions to the requirements of the following RFQ-accelerator. The n^+ ions will pass through an achromatic Q/A separator to select a charge state and to suppress unwanted background ions before entering the accelerator. The accelerator is designed to accept beams from the EBIT with a charge to mass ratio of approximately 1/4. The beam, extracted from the EBIT with an energy of 48 keV × Q, will be transferred into an RFQ for bunching and acceleration to 0.6 MeV/nucleon. The beam will then be further accelerated in a superconducting linac to an energy of 3 MeV/nucleon, with the option to further boost the output energy to 12 MeV/u. Details of the design can be found in [25]. For highest efficiency both in continuous and pulsed beam operation, an optional second EBIT would allow a pair of EBITs to operate in a "push–pull" mode.

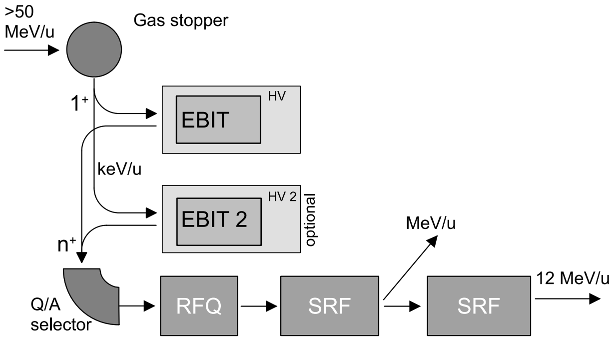

Fig. 2. Concept of EBIT-based reacceleration at the NSCL.

4. The EBIT charge breeder

The charge breeder for the NSCL will be based on a modified design of the TITAN EBIT. Modifications are considered to optimize the performance of the system with respect to the reacceleration of rare isotope beams. The performance of the EBIT is given by the acceptance of the incoming singly charged ion beam, the breeding efficiency into a particular state in a given breeding time and the extraction efficiency.

4.1. Breeding efficiency

The time required for the charge breeding of ions inside an electron beam is set by the product of breeding time τ and electron current density j. This product, also known as ionization factor, is determined by the cross sections for successive electron impact ionization. As a consequence, a short breeding time implies large current density. As an example, Fig. 3 shows the required time to breed ions into either bare, He-like or Ne-like atomic states as a function of nuclear charge Z. An electron current density of 10^4 A/cm^2 has been assumed and the electron energy was set to twice the atomic binding energy of the last electron to be removed. Cross sections are based on Lotz's empirical formula [26]. The figure illustrates that an electron current density of 10^4 A/cm^2 is needed for the breeding of ions up to $Z < 35$ into Ne-like or higher charge states within 10 ms. A breeding time of this order will be needed in order not to lose rare isotopes in the breeding process to radioactive decay. With an appropriate compression of the electron beam, this current density can for example be

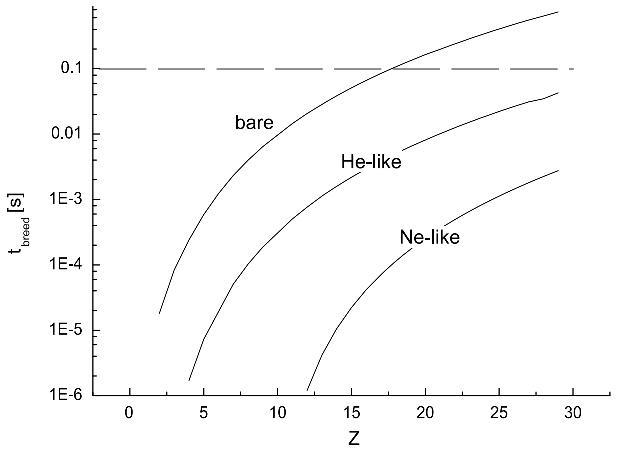

Fig. 3. Breeding times to obtain bare, He-like or Ne-like atomic states from singly-charged ions as a function of nuclear charge Z. The calculation assumed an electron current density of 10^4 A/cm^2. The electron energy was set to twice the atomic binding energy of the last electron to be removed.

Please cite this article in press as: S. Schwarz et al., An electron beam ion trap for the NSCL reaccelerator, Nucl. Instr. and Meth. B (2008), doi:10.1016/j.nimb.2008.05.056

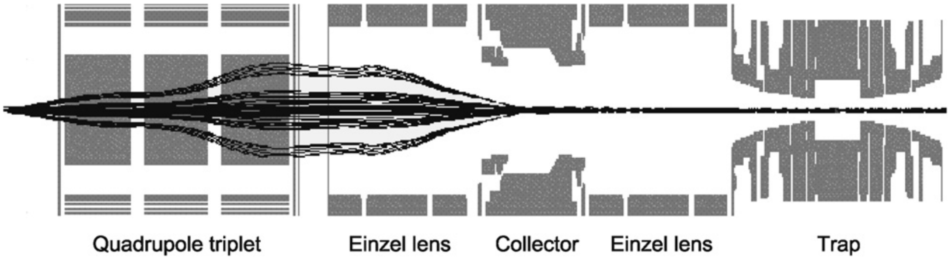

Fig. 4. Trajectories of injected ions.

obtained with an EBIT providing a magnetic field strength of 3 T and electron currents exceeding 0.5 A. The TITAN-EBIT, designed for its magnetic field strength of up to 6 T and electron currents of up to 5 A should be able to provide even larger current densities.

4.2. Acceptance

The highest acceptance for a continuously injected beam is obtained, if a long trap region is combined with a large electron beam radius and high electron current density. In order to explore the required operating parameters to obtain large acceptance for the future NSCL EBIT, injection simulations have been performed based on the TITAN-EBIT configuration. As injection mode the overbarrier [27] injection mode has been investigated. The calculation has been carried out in three steps: First the radial coordinates of ions injected into the EBIT are calculated. The calculations use the magnetic field as dictated by the design of the EBIT's superconducting magnet and the electrodes' electric field as obtained with the Laplace-solver package Simion. To account for the space charge generated by the electrons, a flat-profile electron beam was used with a radius as given by the Herrmann-formula [28]. Fig. 4 shows sample trajectories of ions injected into the EBIT through a series of lenses and the electron collector.

This information is then used to evaluate the fraction of time the ions spend inside the electron beam when they orbit inside the EBIT. In a third step the actual time the ions spend in the trap is used together with breeding cross-sections [26] and the results from the preceding two simulation steps to obtain the probability of ions ending up in the 2^+-state as a function of beam emittance. The calculations have been performed for a combination of electron currents (0.5, 1.5 and 5 A), different compressions of the electron beam as it enters the EBIT from the electron gun and different trap lengths. To vary the compression of the electron beam different combinations of magnetic field strength at the cathode $B_c = (0, 800\text{ G})$ and in the center of the EBIT $B = (1\text{ T}, 6\text{ T})$ have been explored. The results of these simulations are documented in detail in [29].

In summary, a moderate compression of the electron beam resulting from a residual magnetic field of several hundred Gauss at the electron gun, an electron current of $\approx$2 A and trap lengths of >0.3 m appears to be a reasonable parameter set to obtain good acceptance. However, the electron current density obtained in this case will be insufficient to continue the charge-breeding of ions on a millisecond timescale. The two most attractive options to combine high acceptance and fast subsequent breeding are: (a) Use two trap regions with different magnetic field strength, e.g. a 4-coil magnet system with a low-field trap optimized for high acceptance and a high-field trap (6–9 T) for fastest breeding to high charge states. (b) Use one trap, but change the compression of the electron beam with time: For accumulation one could apply a lower compression of the electron beam than for the breeding process. The compression can for example be adjusted by changing the magnetic field at the cathode with a compensation coil. These options are currently being investigated.

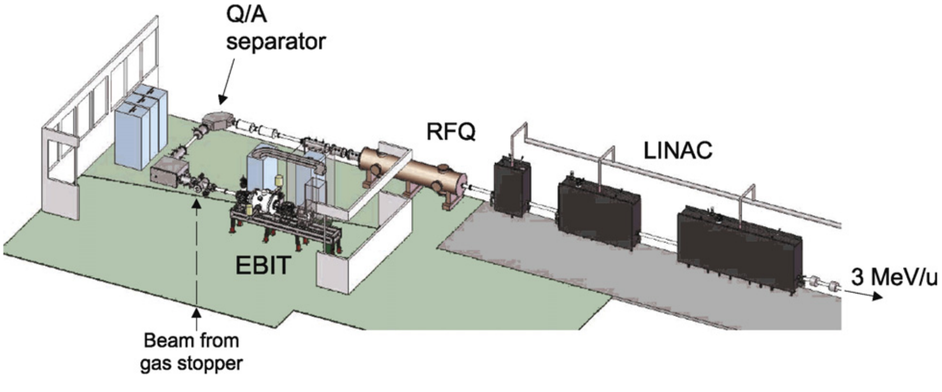

Fig. 5. Preliminary design of reaccelerator at the NSCL.

Please cite this article in press as: S. Schwarz et al., An electron beam ion trap for the NSCL reaccelerator, Nucl. Instr. and Meth. B (2008), doi:10.1016/j.nimb.2008.05.056

5. Summary

A high-current EBIT is being designed as a charge breeder for the reacceleration of stopped fragmentation beams at the NSCL. Simulation work is ongoing to ensure that the EBIT efficiently and rapidly produces highly-charged ions. Fig. 5 shows a preliminary design of the reaccelerator, located on the second floor in the experimental area at the NSCL. The EBIT will be located in an enclosed area that will provide both a clean environment and HV protection. Low-energy beams from the gas stopper will enter the EBIT beamline at a switchyard near the electron collector. The charge-bred ions are injected into the 'C'-shaped mass-over-charge selector, before they are accelerated by the RFQ and subsequent LINAC-section to an energy of initially up to 3 MeV/u and later to 12 MeV/u.

References

[1] G. Bollen, et al., these proceedings, doi:10.1016/j.nimb.2008.05.058.
[2] L. Weissman et al., Nucl. Instr. and Meth. A 540 (2005) 245.
[3] M. Wada et al., Nucl. Instr. and Meth. B 204 (2003) 570.
[4] G. Bollen et al., Phys. Rev. Lett. 96 (2006) 152501.
[5] P. Schury et al., Phys. Rev. C 75 (2006) 055801.
[6] T. Nakamura et al., Phys. Rev. A 74 (2006) 052503.
[7] URL: <http://www.nscl.msu.edu/future/isf>.
[8] B.M. Sherrill, Nucl. Instr. and Meth. B 204 (2003) 765.
[9] O. Kester et al., Nucl. Instr. and Meth. B 204 (2003) 20.
[10] F. Wenander, P. Delahaye, R. Scrivens, R. Savreux, The REX-ISOLDE Collaboration, Rev. Sci. Instr. 77 (2006) 03B104.
[11] T. Lamy, R. Geller, P. Sortais, T. Thuillier, Rev. Sci. Instr. 77 (2006) 03B101.
[12] T. Lamy et al., Rev. Sci. Instr. 73 (2002) 717.
[13] F. Ames, R. Baartman, P. Bricault, K. Jayamanna, M. McDonald, M. Olivo, P. Schmor, D.H.L. Yuan, T. Lamy, Rev. Sci. Instr. 77 (2006) 03B103.
[14] P. Delahaye, C.J. Barton, K. Connell, T. Fritioff, O. Kester, T. Lamy, M. Lindroos, P. Sortais, G. Tranströmer, F. Wenander, Rev. Sci. Instr. 77 (2006) 03B105.
[15] S.C. Jeong et al., Rev. Sci. Instr. 75 (2004) 1631.
[16] M.A. Levine et al., Nucl. Instr. and Meth. B 43 (1989) 431.
[17] E.D. Donets, Nucl. Instr. and Meth. B 9 (1985) 522.
[18] O. Kester, H. Zimmermann, R. Becker, M. Kleinod, Rev. Sci. Instr. 77 (2006) 03B102.
[19] A. Pikin, J.G. Alessi, E.N. Beebe, A. Kponou, K. Prelec, Rev. Sci. Instr. 77 (2006) 03A910.
[20] R.E. Marrs, D.R. Slaughter, AIP Conf. Proc. 475 (1999) 322.
[21] R.E. Marrs, M.A. Levine, D.A. Knapp, J.R. Henderson, Phys. Rev. Lett. 60 (1988) 1715.
[22] G. Sikler, J.R. Crespo López-Urrutia, J. Dilling, S. Epp, C. Osborne, J. Ullrich, Eur. Phys. J. A 25 s01 (2005) 63.
[23] M. Froese, C. Champagne, J.R. Crespo López-Urrutia, S. Epp, G. Gwinner, A. Lapierre, J. Pfister, G. Sikler, J. Ullrich, J. Dilling, Hyperfine Interact. 173 (2006) 85.
[24] P. Delheij, L. Blomeley, M. Froese, G. Gwinner, V. Ryjkov, M. Smith, J. Dilling, Hyperfine Interact. 173 (2006) 123.
[25] X. Wu, M. Doleans, Q. Zhao, G. Gorelov, T.L. Grimm, F. Marti, R.C. York, D. Lawton, G. Bollen, in: Proceedings of Particle Accelerator Conference 2007, Joint Acc. Conf. Website.
[26] W. Lotz, Zeitschrift für Physik 206 (1967) 205.
[27] R. Becker, M. Kleinod, E. Donets, A. Pikin, in: Proceedings of 3rd European Particle Accelerator Conference, Edition Frontières, Gif-sur-Yvette, 1992, p. 981ff.
[28] G. Herrmann, J. Appl. Phys. 29 (1958) 127.
[29] S. Schwarz, G. Bollen, M. Kostin, F. Marti, P. Zavodszky, Rev. Sci. Instr 79 (2008) 02A706.

Please cite this article in press as: S. Schwarz et al., An electron beam ion trap for the NSCL reaccelerator, Nucl. Instr. and Meth. B (2008), doi:10.1016/j.nimb.2008.05.056