EXTRACTION FROM ECR AND RECOMBINATION OF MULTIPLE-CHARGE STATE HEAVY-ION BEAMS IN LEBT*

P.N. Ostroumov#, A. Barcikowski, S.A. Kondrashev, B. Mustapha, R.H. Scott, and
S.I. Sharamentov, ANL, Argonne, IL 60439, U.S.A.
N.E. Vinogradov, Northern Illinois University, DeKalb, IL 60115, USA

Abstract

A prototype injector capable to produce multiple-charge-state heavy-ion beams has been developed and constructed at ANL. The injector consists of an ECR ion source, a 100 kV platform and a Low Energy Beam Transport (LEBT). The latter comprises two 60-degree bending magnets, electrostatic triplets and beam diagnostics stations. Several charge states of bismuth ions from the ECR have been extracted, accelerated to the energy of 1.8 MeV, separated and then recombined into a high quality beam ready for further acceleration. This technique allows us to double heavy-ion beam intensity in high-power driver linac for future radioactive beam facility. The other application is the post-accelerators of radioactive ions based on charge breeders. The intensity of rare isotope beams can be doubled or even tripled by the extraction and acceleration of multiple charge state beams.

INTRODUCTION

Ion accelerators worldwide use only single-charge state beams from the ion source. ECR Ion Sources (ECRIS) are widely used as injectors of highly charged ions. Current state of the art ECRIS built using superconducting (SC) magnets has recently demonstrated ~6 pμA of uranium ions with charge state 33+ or 34+ [1]. Taking into account the acceleration and stripping efficiencies, the ion source intensity must be doubled to meet the power requirements for the proposed Facility for Rare Isotope Beams (FRIB) [2] and other nuclear physics applications based on high-intensity ion linacs. Obviously, the intensity of single-charge state beams cannot be doubled in the near future and the appropriate solution is to simultaneously extract and accelerate multiple-charge states of the desired heavy-ions. This solution is not appropriate for light ions due to larger charge states separation in the phase space (large q/A separation, where q is the ion charge state and A is the mass number). Fortunately, ion sources produce enough single-charge state intensity for light ions. In addition to future facilities, existing facilities could benefit from the concept of multiple-charge state acceleration as well.

We have designed and built a prototype multiple-charge state injector system to demonstrate the possibility of extracting, analyzing and combining several charge states of a heavy-ion beam from the ion source to the point of injection to an RF accelerator. The injector consists of an ECRIS placed on a High-Voltage (HV) platform and an achromatic LEBT. The system was successfully tested for a two-charge state bismuth beam. This technique can be applied for both the driver and post accelerator in radioactive beam facilities. It is well recognized that the ECRIS and the Electron Beam Ion Source (EBIS) are effective charge breeders for radioactive beams [3]. The intensity of radioactive ions extracted either from an ECRIS or EBIS can be increased by combining several neighboring charge states into the same phase space area for further acceleration. This is especially important for rare isotope beams where doubling or tripling the intensity is critical for certain measurements.

EXPERIMENTAL SET-UP

A 3D model of the injector is shown in Fig. 1. It consists of an ECR ion source, a 100-kV platform and an achromatic LEBT system based on two 60° bending magnets. The stand-alone ECR ion source is built using all permanent magnets, it is described in more detail elsewhere [4]. The HV platform was designed and constructed to accelerate all ion species extracted from the ECR source to higher energy to suppress space charge effects in the LEBT. The focusing is provided by electrostatic Einzel lenses and quadrupole triplets. Rotating wires are used for beam profile measurements. The beam emittance is measured by a specially developed scintillator-based pepper-pot emittance probe described in

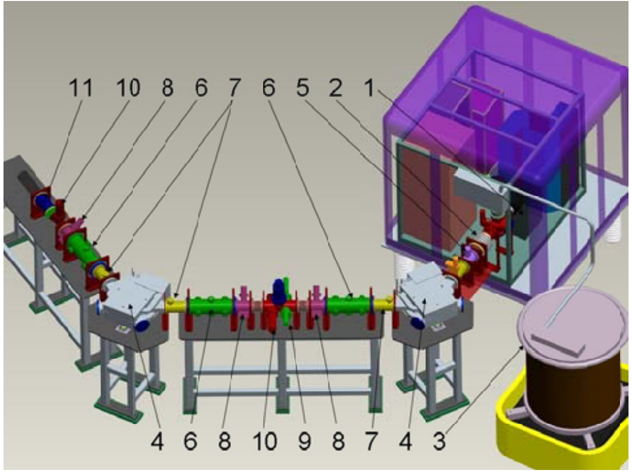

Figure 1: General view of the injector. 1 - ECRIS installed on HV platform, 2 - 75-kV accelerating tube, 3 - isolation transformer, 4 - 60° bending magnet, 5 - Einzel lens, 6 - electrostatic triplet, 7 - electrostatic steering plates, 8 - rotating wire scanner, 9 - horizontal jaw slits, 10 - Faraday cup, 11 - emittance probe.

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#ostroumov@anl.gov

[5]. Our injector differs from any other ECR source on a HV platform currently used in various applications worldwide. Specifically, we extract all ion species available form the ECR source and separate them after acceleration by the platform potential. For the purpose of these experiments, we use a bismuth ion beam which is relatively simple to produce using an oven heated to 550°C. The ECR is equipped with two RF amplifiers set to 12.8 GHz and 13.8 GHz with total RF power up to 1.5 kW. Oxygen is used as a support gas to produce higher charge states of ^{209}Bi ions. The injector system allows us to accelerate all ion species up to $q\times100$ keV total kinetic energy.

The bismuth ion beam is first extracted by applying a 15 kV potential to the source and then accelerated by a 75 kV platform potential. Fig. 2 shows the beam currents for the different charge states extracted from the source. Depending on the operational parameters, a total current of 4 mA is extracted from the ECR. In the scope of our experiment, we are interested to work with ^{209}Bi^{20+} and ^{209}Bi^{21+} to reduce charge spread. Our long-term operation experience has showed that the most stable operation of the ECR and the lowest beam emittances can be achieved for beam intensities of ~1.0 pμA for the charge states 20+ and 21+ of bismuth.

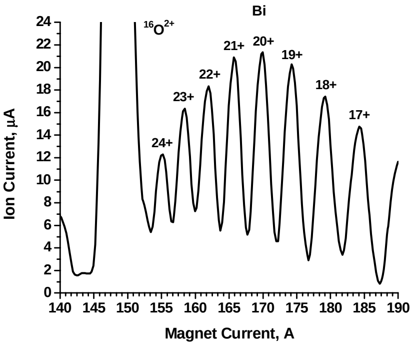

Figure 2: Bismuth beam intensities for different charge states.

INJECTOR DESIGN AND SIMULATION

The ECR ion source generates multi-component ion beams with total intensity up to 4 mA. The main purpose of the LEBT is to select particular ion specie and match it into the following RF accelerator. The selection of the required ion specie is usually performed by adjustable horizontal jaw slits located in the high-dispersion area of the LEBT downstream of the first bending magnet. Several charge states of ion beam downstream of the selection slits can be re-combined into a beam with the same transverse phase space if the LEBT is an achromatic system.

The standard beam optics computer code COSY [6] was used to design and optimize the original layout of the LEBT by taking into account terms through third order. However, COSY does not include space charge effects. Therefore, numerical studies of beam dynamics in the LEBT have been performed using the multi-particle code TRACK [7]. TRACK can simulate a multiple-component ion beam through pre-calculated 3D fields taking into account space-charge effects. The magnetic field of the ECR extraction region and electrostatic fields in the initial part of the beam line that consists of a puller electrode, Einzel lens and grounded electrodes were calculated using the EM-Studio software. 3D representation of magnetic field including fringe fields was implemented using genuine configuration of the 60° bending magnet. Similarly, the electric fields of the triplets were implemented into TRACK. TRACK simulations have shown that the bending magnet must provide strong vertical focusing in order to compensate for space charge forces. The LEBT system shown in Fig. 1 is achromatic providing ~25 mm separation on the slits for neighboring charge states of bismuth beam tuned for 20+ as the central charge state.

The exact phase space distribution of ion beams extracted from the ECR is very complicated (see [8-9], for example) and can not be reproduced with any available computer code. For the initial design of the LEBT we have used simplified, axial-symmetric multi-component ion beams with the parameters best fitted to the measurements performed downstream of a 90° magnet [10]. For the tuning and operation of the actual LEBT system, we have developed and applied specific optimization algorithms within the code TRACK. These algorithms use the measured data such as the horizontal (H) and vertical (V) beam profiles from the wire scanners and H-profiles from the slits to adapt the computer model to the actual beam line. The first optimization step is to determine the beam emittance and Twiss parameters at the source that reproduce the measured beam profiles after the first bending magnet. The second step is to optimize the setting of nine quadrupoles to provide (a) no angular dispersion on the slits and (b) 100% beam transmission downstream of the slits.

EXPERIMENTAL RESULTS

The measured beam profiles of a two-charge state bismuth beam (20+, 21+) on the wire scanner behind the first magnet have been used to fit the initial beam emittance and Twiss parameters at the source to use for further tuning and operation of the LEBT. For realistic beam dynamics simulations we track 17 beams simultaneously (O and Bi as in Fig. 2). The quadrupole settings were then optimized using TRACK to re-combine the ^{209}Bi^{20+} and ^{209}Bi^{21+} beams with $q_0=20.5+$ as the central charge state. Setting the values obtained by TRACK we noticed a very good agreement between the simulation and the actual measurements.

After we obtained initial beam parameters upstream of the first magnet, the LEBT was re-tuned to provide zero angular momentum dispersion at the separation slits placed at the mid-point of the LEBT. Figure 3 shows the linear and angular dispersions along the LEBT. We notice a good separation of the charge states, which is important to cleanly select a single- or a multiple-charge state beam.

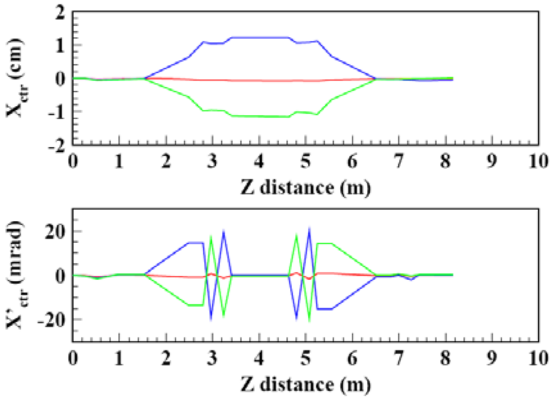

Figure 3: Linear and angular dispersions along the LEBT.

At the end of the LEBT, the beam emittance was measured for the following three different operation modes: 1) only $^{209}Bi^{20+}$ is selected by the slits; 2) only $^{209}Bi^{21+}$ is selected; 3) both $^{209}Bi^{20+}$ and $^{209}Bi^{21+}$ are selected. The beam parameters are given in Table 1. The focusing triplet upstream of the emittance probe is tuned to provide ~ 30 mm beam diameter on the emittance probe. Only several percent adjustment of quadrupole setting with respect to the pre-calculated values is required in order to combine the dual-charge state bismuth beam. 100 % beam transmission from FC-1 to FC-2 has been achieved with typical beam currents of: $I_{20+} = (20.9 \pm 0.2)\,\mu A$, $I_{21+} = (21.3 \pm 0.2)\,\mu A$

$$I_{20+,21+} = (42.1 \pm 0.4)\,\mu A$$

Figure 4 shows the H- and V-beam profiles on the wire scanner downstream of the second magnet while the pepper-pot images of single- and dual-charge state bismuth beam are shown in Figure 5. As can be seen from these figures, two charge states of bismuth beam are perfectly combined into the same phase space area. The emittances and Twiss parameters of the beam derived from the pepper-pot data for the three operation modes of the LEBT are listed in Table 1. As seen from this table, perfect recombination is achieved in the vertical plane while the horizontal Twiss parameters are slightly different. Further improvement of the phase space parameters of the dual-charge state beam can be achieved by providing better matching into the first magnet using an electrostatic doublet which will be installed upstream of the first bending magnet.

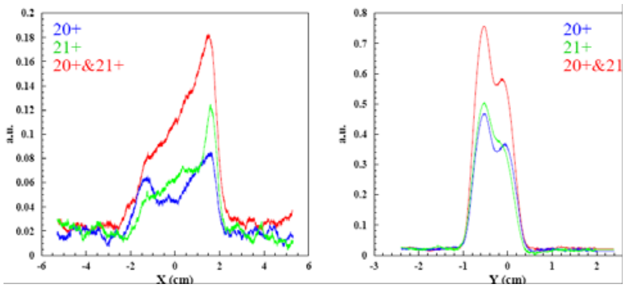

Figure 4: Measured bismuth beam profiles on the wire scanner downstream of the second bending magnet.

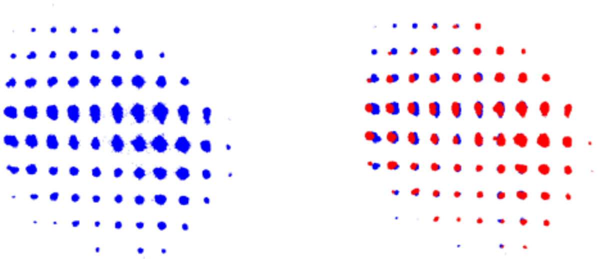

Figure 5: Pepper-pot image of the combined bismuth beam with charge states 20+ and 21+ (on the left) and superimposed images of $^{209}Bi^{20+}$ (blue) and $^{209}Bi^{21+}$ (red) beams transported individually (on the right).

Table 1: RMS normalized emittances and Twiss parameters of individual charge states (20+, 21+) and combined bismuth beams at the end of the LEBT.

Parameter	$^{209}\mathbf{Bi}^{20+}$	$^{209}\mathbf{Bi}^{21+}$	$^{209}\mathbf{Bi}^{20+}+^{209}\mathbf{Bi}^{21+}$
ε_X (π µm)	0.092	0.081	0.087
α_X	0.816	-0.125	0.259
β_X (mm/mrad)	2.93	3.17	2.68
ε_Y (π µm)	0.055	0.059	0.057
α_Y	-2.92	-3.33	-3.32
β_Y (mm/mrad)	0.779	0.902	0.895

CONCLUSION AND OUTLOOK

Several charge states of bismuth ions from an ECR ion source have been extracted, accelerated to an energy of 1.8 MeV, separated and then recombined into a high quality beam ready for further acceleration. This technique allows us to double the intensity of heavy-ion beams in high-intensity linacs for future radioactive beam facilities and other nuclear physics applications. Another important application of the concept of multiple charge state extraction and acceleration is in post-accelerators of radioactive ions based on charge breeders.

Currently we are modifying LEBT to improve transmission and recombination of three charge states of the bismuth beam. Also, the possibility to incorporate sextupoles into the LEBT is being investigated.

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