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SPARC EBIT — a charge breeder for the HITRAP project

A. Sokolov,[a,1] F. Herfurth,[a] O. Kester,[b] Th. Stoehlker,[a] A. Thorn,[c] G. Vorobjev[a] and G. Zschornack[c]

[a] *GSI Helmholtzzentrum, Darmstadt, Germany*
[b] *NSCL/MSU, East Lansing, U.S.A.*
[c] *Fachrichtung Physik, TU Dresden, Germany*

E-mail: Al.Sokolov@gsi.de

ABSTRACT: Charge breeding of externally injected, singly-charged ions in an electron beam ion source/trap (EBIS/T) extends the range of elements from which highly-charged ions can be produced with these machines, which is important for numerous atomic and nuclear physics experiments. Existing EBIS/T charge breeders feature electron guns producing intense beams and superconducting magnets generating strong fields to achieve high efficiencies and high ion charge states. We show an alternative possibility to inject, capture, charge-breed and extract ions using a compact room-temperature EBIT based on permanent magnet technology. Singly-charged potassium and rubidium ions injected over the barrier were charge bred and extracted as bare and neon-like ions, respectively. Simulations of injection and capture of singly-charged ions in this EBIT show the challenges and help understanding the results.

KEYWORDS: Ion sources (positive ions, negative ions, electron cyclotron resonance (ECR), electron beam (EBIS)); Accelerator modelling and simulations (multi-particle dynamics; single-particle dynamics)

[1] Corresponding author.

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Contents

1 Introduction

Highly-charged ions (HCI) are essential for numerous physics experiments to understand the atomic structure or to investigate electron dynamics in ion-ion or ion-atom interactions [1]. The length of linear accelerators is inversely proportional to the charge of the accelerated ions, thus, HCI are also a valuable tool to keep costs and complications low. Consequently, many accelerators and many atomic physics labs have a source of highly-charged ions. The species to be ionized is typically fed as a gas into the ionization volume. If that is not possible, feeding with singly-charged ions for charge breeding is used as an alternative. If it is about rare species that come only singly-charged from the production process as for instance at radioactive ion beam facilities based on the ISOL technique [2] the charge state is boosted or bred before re-acceleration or analysis.

The commonly used sources to produce HCI are EBIS/T (electron beam ion source/trap) [3] and ECRIS (electron cyclotron resonance ion source) [4] devices. They are essential parts of many accelerator labs and also radioactive ion beam (RIB) facilities. RIB facilities like REX-ISOLDE [5] and the up-coming rare isotope re-accelerator at the NSCL/MSU [6] use an EBIS for charge breeding. Those devices are optimized for fast and very efficient charge breeding to handle milliseconds lifetime activity and are hence based on high electron currents and superconducting magnets to reach electron current densities of 10^4 A/cm^2 and higher by compression of an Ampere electron beam in a several Tesla strong field.

Recently, a new generation of EBIT devices — the Dresden EBIT type [7], was developed with the idea of low initial and low running costs. These devices are operated at room temperature and work with permanent magnets and hence with much weaker magnetic fields than the superconducting devices mentioned earlier. This type was never used for charge breeding of externally injected ions up to now.

At GSI such a small source is operated as a test ion source for the HITRAP decelerator project [8] to supply experiments with ion species for commissioning. This source is typically operated with gaseous elements but since some experiments require different species for tests, charge breeding in this small, room temperature EBIT became necessary. One example is the use

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of Ca^{14+} ions [9] for laser spectroscopy of the forbidden fine structure transition $2s^2 2p^2 \quad {}^3P_0$ — ${}^3P_1$, which serves as a test for the hyperfine spectroscopy planned for H and Li-like ions, which will be supplied by HITRAP.

2 Experimental setup

The essential parts of the experimental setup are the two ion sources. A surface ion source produces singly-charged ions which are sent towards the electron beam ion trap (EBIT) for charge breeding.

In a surface ion source ions are produced by evaporation of certain elements from a surface with high electron work function. For the described experiments an integrated pellet ionizer based on tungsten was used. Pellets prepared with selected elements or several elements together can be inserted into the ion gun and in our experiment we used potassium and rubidium loaded pellets.

In an EBIT a high-density electron beam collides with atoms and ions which leads to subsequent ionization by electron impact. To allow for multiple collisions and hence multiple ionization the ions are stored in a volume where the electron beam is sent through. Our EBIT has a trap region that is effectively 1.5 cm long and formed by three concentric drift tubes situated in a 0.25 T magnetic field created by two ring-shaped permanent magnets in a Helmholtz configuration. An IrCr cathode was operated to produce an electron current of 25 mA, which results in an electron current density of around 100 A/cm^2, when the electron beam is magnetically compressed to 0.1 mm radius. The electron beam was accelerated to 7.4 keV and ions with an energy of 5 keV per charge were then extracted.

A scheme showing the two sources as they are arranged in the experiment is shown in figure 1. The surface ion source is installed directly facing the EBIT for direct injection minimizing distortions of the cylindrically shaped beam that would be caused by bending the beam. A cylindrical ion beam provides best overlap between ion and electron beams inside the EBIT. In between the two sources a quadrupole deflector is placed, which can be pulsed to high voltage to deflect the extracted ion pulse from the EBIT towards the analyzing dipole magnet — the multi-passage spectrometer.

An experimental cycle started with the injection phase followed by the charge breeding within the EBIT. Finally, the charge bred HCI were extracted, bent by 90^o with the quadrupole and analyzed by charge-to-mass ration in a dipole magnet.

The ion beam intensities were measured with Faraday cups connected to a triggerable electrometer. In addition, a silicon pin-diode X-ray detector with beryllium window was mounted just outside of the EBIT monitoring the charge breeding process inside the EBIT via X-rays[1] emitted through a beryllium window.

3 Simulations

In order to determine the optimal parameters for injection of externally produced singly- charged ions into the EBIT, simulations using SIMION 7.0 [10] were carried out. The EBIT was simulated with electrode geometry and magnetic field from [11,12]. The relatively weak magnetic field of

[1] Typically we monitored not clearly resolved K_α and K_β lines with maxima around 3.3 keV and 3.6 keV.

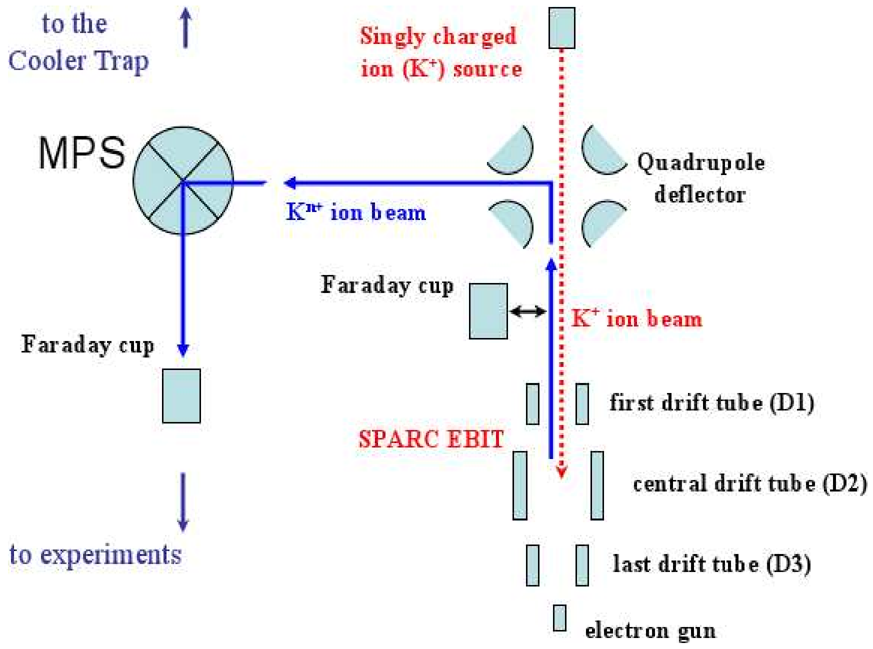

Figure 1. Schematic HITRAP test ion source setup at GSI. The main elements of the setup are: the SPARC EBIT with its electrodes and electron gun, the surface ion source for production of singly-charged alkaloids, the quadrupole deflector for fast switching between single ion beam injection into the EBIT and extraction of charge bred ion beams towards experiments or for analysis, and the multi-passage spectrometer (MPS) for magnetic analysis of the charge state distribution.

the EBIT compresses the electron beam two- to threefold down to 0.1 mm in radius measured for a similar source with an ”X-ray imaging” method [12]. The magnetic field does not influence the trajectories of the externally produced incoming ion beam noticeably. Thus, only the space charge of the dense electron flux creates the trapping potential for ions in radial direction. The electron beam potential can be described by the analytical formula [13,14]:

$$V_{SCP}(r) = \begin{cases} 2V_0 \ln \frac{R}{r}, & r > r_{\mathrm{e-beam}} \\ V_0 \left(2\ln \frac{R}{r_{\mathrm{e-beam}}} + \left(1 - \frac{r^2}{r^2_{\mathrm{e-beam}}} \right) \right), & r \leqslant r_{\mathrm{e-beam}}. \end{cases} \tag{3.1}$$

Here V_0 = 4.3 V is determined by the total electron charge per unit length, $r_{\mathrm{e-beam}}$ is the electron beam radius, and R the central drift tube radius. For our EBIT $r_{\mathrm{e-beam}}$ equals 0.1 mm and the drift tube radius is 2.5 mm resulting in a potential difference for singly-charged ions of around 32 V between central drift tube potential and the bottom of the potential well in radial direction. The space charge potential calculated using formula (3.1) was superimposed on the electric potential created by the voltages applied to the drift tubes.

In figure 2 the schematic potential distribution along the beam axis is displayed. Singly-charged ions are injected with a kinetic energy determined by the difference ΔU_B between the surface ion source potential U_K^+ and the potential at the place of injection U_{D1}. To simplify the simulation[2] it was assumed, that the K^+ ions get further ionized as soon as they cross the electron

[2] We also disregarded the screening of the electron space charge potential by potassium and residual gas ions as well as collisions of injected ions with electrons or already trapped ions.

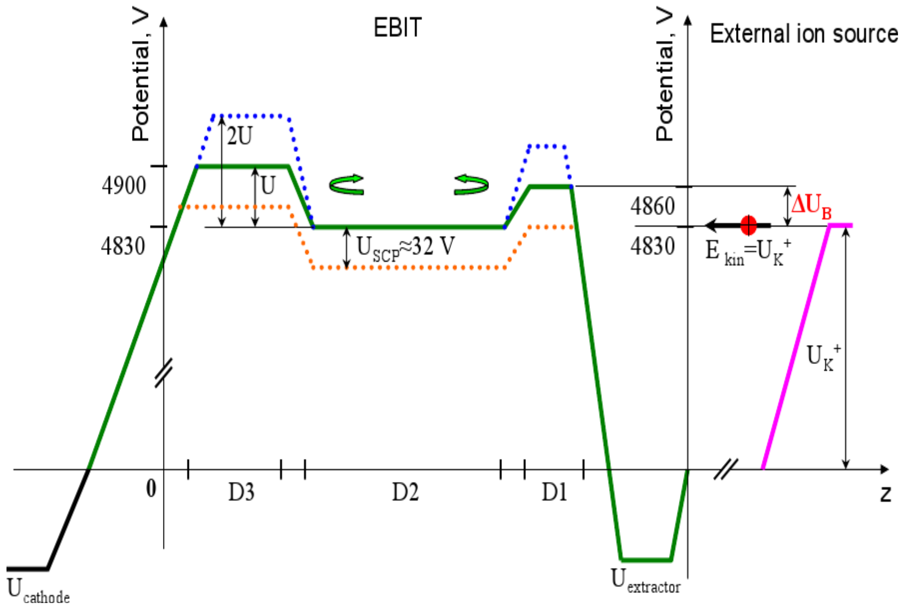

Figure 2. Schematic potential distribution along the optical axis. The green line represents the potential without electron beam and the dashed orange line with the electron beam space charge potential which has the depth U_{SCP}. The barrier potentials seen by ions in the 2+ state with respect to the central drift tube potential are indicated by the blue dashed line. ΔU_B is the difference between the first drift tube potential (U_{D1}) and the surface ion source potential (U_K^+).

beam, i.e. the charge of the injected K^+ ions was changed to 2+ as soon as the ion trajectory entered the volume occupied by the electron beam. As the potential barrier for doubly charged ions doubles they become trapped as indicated in figure 2. The simulation was repeated varying ion injection energies to optimize injection. The K^+ beam rms emittance was deduced from IGUN [15] simulations of the surface ion source to be 20 π mm·mrad.

To estimate the fraction of the beam captured inside the EBIT, 500 ions were started one by one in front of the extraction electrode of the source. The initial conditions were: 1) a round beam with a radius of 2 mm and an emittance of 20 π mm·mrad 2) a uniform distribution of ions in the 4D phase space (XX'YY') 3) a monochromatic beam with a kinetic energy determined by the surface ion source potential. In figure 3 one can see ions in 2D phase space (YY') started in front of the EBIT at two different potentials: 10 eV above the barrier electrode potential and 10 eV below. Red dots mark the ions that crossed the electron beam and hence changed their charge state to 2+ and got captured. The black dots are those ions which were lost; note that still a lot of them are in between the captured ions. The capture is dependent on the radial position and radial velocity component of the ion, thus adjacent dots in YY' space can be separate in XX' phase space. For an incoming ion from a potential 10 eV higher than the first drift tube potential (i.e. ΔU_B = 10 eV) we obtained a capture probability of around 6 %. One can see from the picture that the number of captured (accepted) ions in the EBIT is lower when the surface ion source potential is set below the first drift tube potential, i.e. for ΔU_B = -10 eV the capture probability is only 2 %. For even lower injection energies, like ΔU_B = -20 eV the capture probability is still lower (0.2 %), as it is for higher energies ΔU_B = 20 eV.

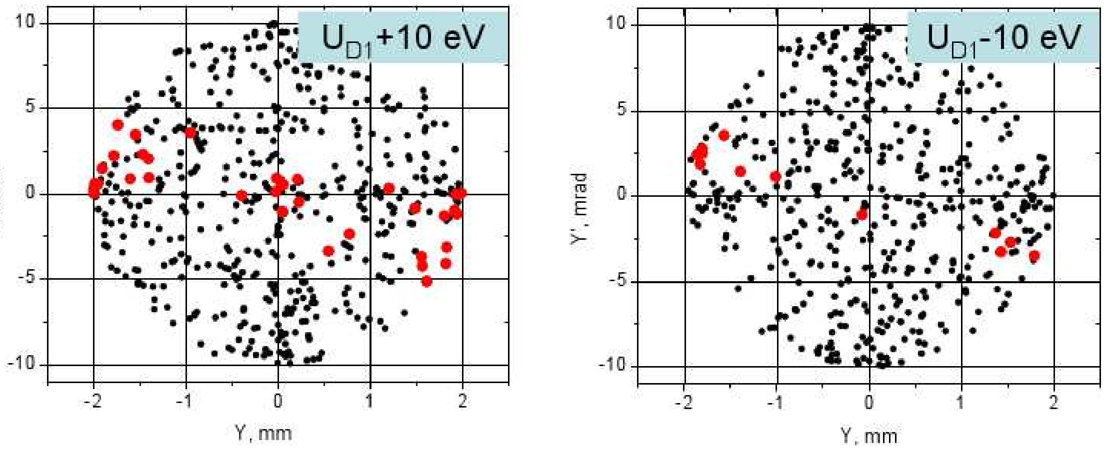

Figure 3. Ion distribution in transversal phase space from a 20 π mm·mrad ion beam. Ions that were captured in the EBIT, are marked as red dots. The left and right figure assumes ion energies 10 eV above and below the potential of the first drift tube respectively.

In summary, our simulations yield highest capture efficiency for ions that are injected slightly above the first drift tube potential. But, the assumption that the ions change their charge state as soon as they cross the electron beam is too simple. In reality the ionization cross section is finite and hence the ionization probability increases with the time the ion spend in overlap with the electron beam. In case of the SPARC EBIT the overlap is especially important due to a short trap length and the resulting short drift time (several μs) inside the ion source.

The ion-electron beam overlap increases as the ions are injected with an energy just above the potential barrier. A high potential barrier inhibits the injection of more divergent ions as seen in figure 3 on the right hand side because the more divergent ions cannot pass the potential well and are reflected instead of injected. As a result, the optimal injection energy will be a balance between injection efficiency and beam overlap, higher energy yields better injection efficiency, but smaller beam overlap and vice versa. As the ionization cross section is in contrast to the simulations in reality below unity, the ion-electron beam overlap is more important than found in the simulations and hence the optimal ion injection energy is expected to be lower than in the simulations.

4 Experimental results and discussion

To demonstrate that charge breeding is possible and to characterize the ion beam and EBIT settings for optimal charge breeding two types of experiments have been carried out. The X-rays emitted from the ionization volume during charge breeding are characteristic and have been monitored for injection and process optimization. For further characterization the charge bred ions were extracted and analyzed charge-state separated using a dipole magnet.

To find the best injection settings the signal on the X-ray detector was monitored while changing the most important parameters. The voltage of the last drift tube was set 90 V above the surface ion source potential, to force the singly-charged ions to drift twice through the ionization volume of the EBIT. The surface ion source potential was set 5 V higher than the drift tube potential at the entrance side of the EBIT. To avoid retuning of the ion beam transport from the K^+ source to the EBIT

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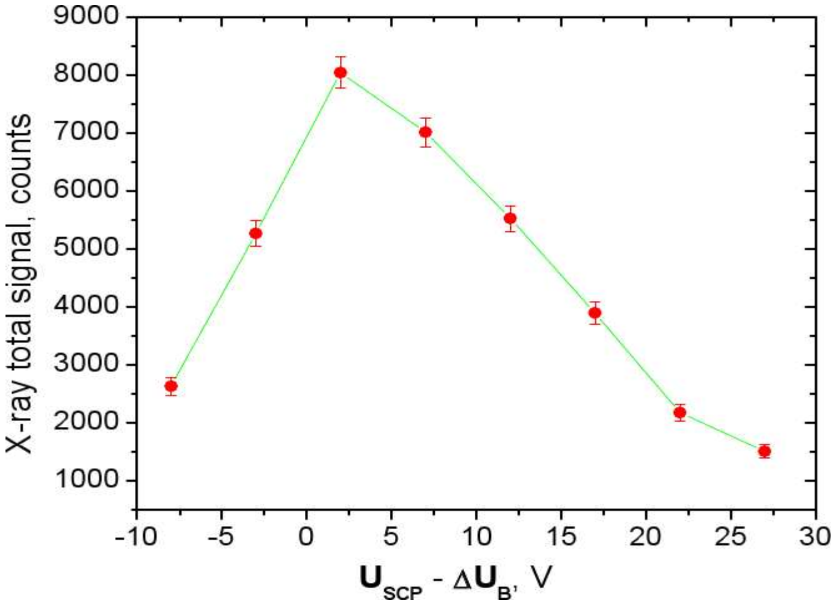

Figure 4. X-ray signal versus $U_{SCP} - \Delta U_B$ (compare to figure 2). The solid line is to guide the eye.

and to avoid beam losses that could be misinterpreted as charge breeding efficiency related losses, the ion source potential was kept unchanged at 5 V above the central drift tube potential. Then the potential of the first drift tube was systematically changed to vary the ion energy at injection monitoring the X-ray signal. This variation has nearly the same influence on the ion capture as the change of the ion energy in the simulations; the only difference is that the trap depth in longitudinal direction changes accordingly, which has only little influence on the overall capture-process.

In figure 4 one can see the measured dependence of the X-ray intensity on $U_{SCP} - \Delta U_B$ (see also figure 2). The appearance of the X-ray signal is a clear evidence for trapping and charge breeding in the EBIT. The increase of the X-ray signal for a larger potential difference (ΔU_B) is explained with an increasing trap depth and better overlap between electron and external ion beams. The steep decrease below $U_{SCP} - \Delta U_B = 2$ V is due to the reflection of the K+ beam at the first drift tube. The calculated depth of the potential well (32 V) formed by the electron beam means that there should be only a very small background signal[3] from Bremstrahllung, when $U_{SCP} - \Delta U_B \leqslant 0$ V. The anyhow detected X-rays can be explained with small differences (few Volts) between the nominal power supply voltages and the actual ones or an overestimated electron beam radius which would yield a deepened electron space charge potential well.

After the optimal first drift tube potential has been established, the same measurements were done varying the central drift tube potential relatively to the K+ ion source potential. The highest signal was observed when both potentials matched each other.

In summary we found that the ions should be injected slightly above the bottom of the potential well created by the electrons. That means if compared to the simulations that the ionization probability is the dominating factor for the total charge breeding efficiency.

With the best settings for injection after a certain time the trap was emptied lowering the first

[3] Around 1.500 counts were measured without injected ion beam for a time interval as used for the other measurements.

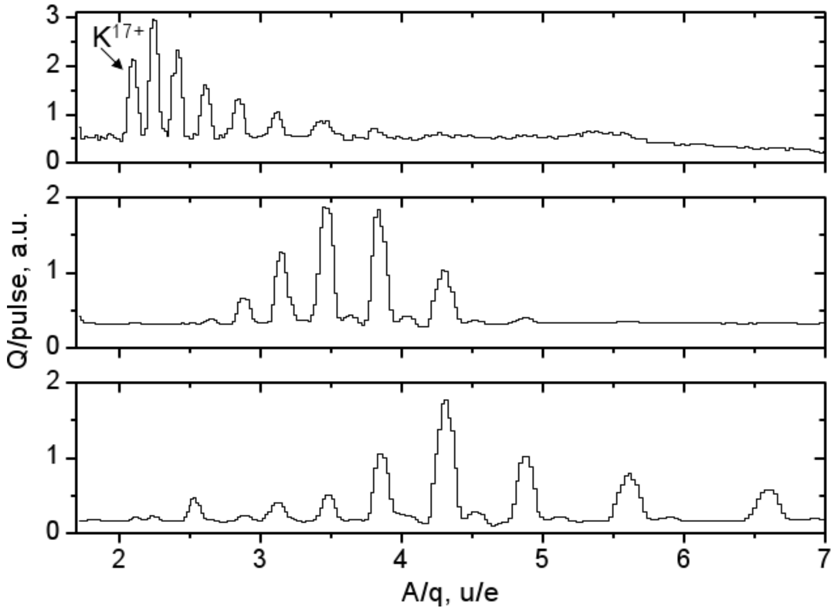

Figure 5. Magnetic scans of extracted K^{n+} ions after 1000 ms, 100 ms and 50 ms (from top to the bottom) of confinement for continuous over-barrier injection.

drift tube potential and the extracted ion pulse was analysed. In figure 5 magnetic scans of the extracted ion pulse for externally injected and charge bred K^+ ions are displayed.

Note that the trap capacity is almost fully exploited with the best settings found in the optimization and only K-ions remain in the trap after 100 ms of ionization time as they effectively push light residual gas ions out of the trap. One second after the injection, He-like potassium ions were observed in the extracted ion pulse. The total charge breeding efficiency was calculated as the ratio of all potassium ions with charge 2+ to 17+ extracted from the trap to the number of ions produced by the singly charged ion source during the injection time. The number of charge bred ions was obtained analyzing the extracted ion pulse and the number of injected K^+ ions was measured directly on a movable Faraday Cup behind the K^+ ion source. The total charge breeding efficiency was $6*10^{-4}$ %, not consistent with the simulations. However, the simulation was done for single ions, so that space charge effects that reduce the efficiency were not included. The injection of many ions will screen the electron potential and reduce or even destroy completely the capture efficiency beyond a certain moment when the trap capacity is exhausted.

The next step was to inject potassium ions in a pulsed over-barrier mode. For that the beam injection was stopped after 20 ms, which is enough to fill the trap. This method increases the efficiency and narrows the charge state distribution [14]. After the injection was stopped the number of stored ions did not change significantly and the captured ions were further ionized to charge states as high as 19+. Pulsed over barrier injection improved the efficiency to 0.02 %, already closer to simulations, and increased the abundance of the highest charge state. A more detailed description of the experiment on charge breeding of K^+ ions can be found in [16].

After successful K^+ charge breeding we injected several other singly-charged ion species into the trap. A multi alkali-earth element pellet was installed into the ion gun to create a beam of

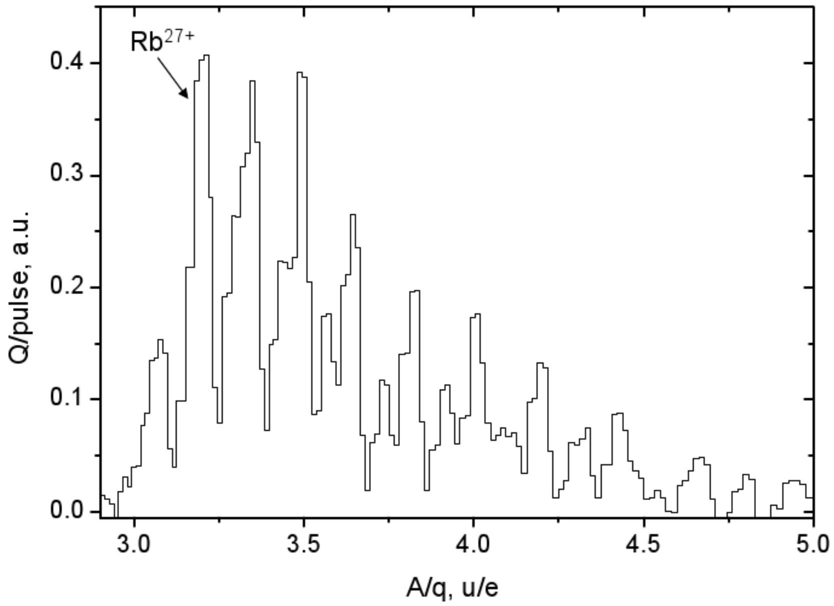

Figure 6. Spectrum of charge bred Rb ions extracted after 500 ms of confinement.

approximately 45 % Rb^+, 35 % Na^+ and 20 % K^+ ions. As it was discussed in [14] the EBIT acceptance does not depend on the mass of the injected ion species for electrostatic trapping, which was also shown in our simulations.

From that mixed beam we expected to get Rb^{n+} ions from the EBIT, as the Rb-ions are the heaviest species in the trap in comparison to residual gas, Na- and K- ions, since all lighter ions will be expelled from the trapping volume due to ion-ion collisions. A magnetic scan of the extracted ion pulse can be seen in figure 6 that shows the expected composition. Charge breeding of Rb^+ ions for 500 ms led to a maximum charge state of 27+. The double feature in the spectrum is due to the two naturally abundant rubidium isotopes.

5 Conclusion and outlook

We demonstrated charge breeding in a new generation of EBIT devices - small room temperature ion sources based on permanent magnets. Singly-charged ions were injected, captured, charge bred and extracted. Our experiments in combination with simulations showed that the charge breeding efficiency is very sensitive to the overlap of ion and electron beams and requires a careful matching of the incoming ion beam energy to the potentials in the EBIT including the electron space charge potential. The overall charge breeding efficiency in a pulsed over-barrier injection scheme was determined to 0.02 % for K^+ and Rb^+ injection. While the qualitative features of ion beam injection and charge breeding have been simulated correctly the overall efficiency is still one order of magnitude higher than measured. This is attributed to neglected ionisation cross sections, space charge effects and a remaining mismatch for injection of the singly-charged ion beam into the EBIT.

From the practical point of view our successful charge breeding increases the variety of elements in high charge states which will be available for experiments and tests of the HITRAP Cooler Trap as well as for HITRAP experiments.

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