OPERATION OF AN ECRIS CHARGE STATE BREEDER AT TRIUMF

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Abstract

After initial commissioning of the charge state breeder for radioactive ions at the TRIUMF/ISAC facility further tests on the performance of the system have been done., One of the major problems found was the high background of stable ions from the ECR source. The main source of those is the residual gas and sputtered material from the plasma chamber wall and from the surrounding electrodes. Although, their intensity is small it can be orders of magnitude more than the intensity from the radioactive ions. Therefore, the original stainless steel plasma chamber of the Pantechnik PHOENIX ECR source has been exchanged to aluminium with a pure aluminium coating, all electrodes for injection and extraction of the ions have been replaced with aluminium and the iron joke at the extraction side, which is part of the vacuum system in the PHOENIX source has been coated as well. This combined effect has reduced the amount of background ions substantially. Together with some beam purification in the accelerator chain the background could be reduced to a level acceptable for experiments with radioactive ions. A low transport efficiency of ions with very high charge states can be explained by to charge changing collisions with residual gas

INTRODUCTION

Radioactive ions are produced at the ISAC facility at TRIUMF by bombarding solid targets with protons at 500 MeV and up to a current of 100 µA. The products diffuse out of the hot target into an ion source, are extracted at an energy of several 10 keV and mass separated. With ion sources robust enough to operate in this environment at high temperature and high radiation fields mainly singly charged ions are produced. The ions can be used directly in low energy experiments or they can be injected into a post accelerator for high energy experiments. The post accelerator at ISAC consists of a room temperature radio frequency quadrupole (RFQ) accelerator, a room temperature drift tube linear accelerator (DTL) and a superconducting linear accelerator (SClinac). The acceptance of the RFQ allows the injection of ions up to a mass to charge ratio of 30 amu/e at an energy of 2 keV/amu. It accelerates the ions to 150 keV/amu. The following accelerator sections can accelerate ions with a maximum mass to charge ratio of 7 amu/e. That means for most ions an increase in charge state is necessary. This is usually done by stripping in thin carbon foils after the RFQ. If ions with a mass greater than 30 amu are to be accelerated their charge state has to be increased already before the RFQ and in order to avoid further losses due to the stripping the mass to charge ratio should be below 7 amu/e. A modified charge state breeder PHOENIX electron cyclotron resonance (ECR) ion source from PANTECHNIK has been chosen as it is well adapted to the continuous mode of operation of the rest of the systems. The source has been installed and commissioned in 2010 and first results have been reported [1].

RESULTS

Already in the first experiments two problems have been found. It is the low transmission for very high charge state ions and the background from stable elements.

Charge Exchange

A reason for the low transmission is charge exchange along the beam transport. This process has been investigated earlier with the ECR source being installed at a test facility. Cross sections for the charge exchange in the relevant energy range from 10 -18 q keV have been determined for different ions with charge states up to 24+ [2]. In order to measure the charge state dependence of the transport efficiency $^{40}Ar^{7+}$, $^{56}Fe^{10+}$ and $^{133}Cs^{23+}$ have been selected after the charge breeder. They have been accelerated through RFQ and DTL and the total transmission has been determined. All those ions have a mass to charge ratio close to 5.7 amu/e, so possible mass dependencies in the accelerator are minimized. Table 1 gives the transmission for the different ions together with a theoretical transmission. It assumes charge exchange only in the low energy part with an average pressure of $2\cdot 10^{-7}$ T over 25 m and 70% transmission of the accelerator. Cross sections from [2] have been used. Although, for the lowest charge state the measured value is close to the theoretical expectation for the higher charge states the transmission is less. This indicates that for those charge states charge exchange processes have to be considered as well for higher energies.

Figure 1 shows a beam profile from a $^{133}Cs^{23+}$ beam measured after an electrostatic bender in the low energy section. One can see that in the horizontal bending plane the beam splits in 3 components in this case: the main beam with charge 23+ and two more components with charge 22+ and 21+ respectively. The centre of the beam has been moved off the centre of the beam line for this picture.

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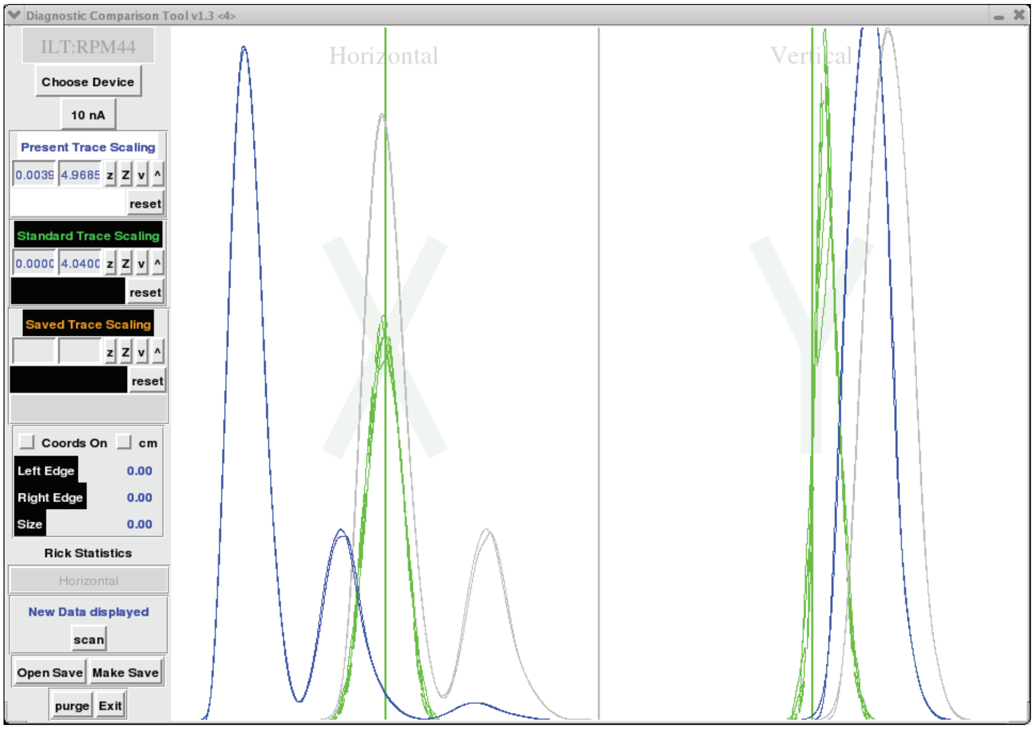

Figure 1: Cs^{23+} beam profile (blue) at the focal plane of first bender in front of the RFQ. The center of the beam has been moved in horizontal (x) direction to show more beam components.

Table 1: Measured and Theoretical Transmission from the Charge State Breeder to the End of the DTL

ion	measured transmission	theoretical transmission
$^{40}Ar^{7+}$	54.6%	56.2%
$^{56}Fe^{10+}$	37.2%	53.5%
$^{133}Cs^{23+}$	27.3%	43.3%

Background

Soon after the first test experiments with radioactive ions it became obvious that the background of stable ions with a mass to charge ratio close to the one of the charge bred radioactive ions is too high for most of the proposed experiments. At ISAC the typical yield of radioactive ions not too far off the region of stable isotopes is up to about 10^8/s and rapidly goes down when leaving this valley of nuclear stability. Thus, with charge state breeding efficiencies of several percent the number of highly charged radioactive ions will be 10^6/s or less. The total current extracted from the ECR source is typically at some 100 μA. It consists mainly of ions from the support gas, in our case helium, and from the residual gas: hydrogen, oxygen, nitrogen, carbon and some noble gases. The charge state of the radioactive ion has to be chosen in such a way, that the mass to charge ratio does not coincide with a charge state of one of those ions. Also the less abundant isotopes of these elements have to be considered. In some cases this may result in a lower efficiency if a non optimum charge state has to be chosen.

Other sources of background are sputtered ions from the material of the plasma chamber and the surrounding electrodes. Their intensity is usually much less, but can still reach several 10-100 pA, which in most cases is much higher than the current of the charge bred radioactive ions. Non-gaseous elements which could be clearly identified either by their mass to charge ratio or after acceleration by their energy are Si, Fe, Ni, Cr, Mo, Sn. All of those have several stable isotopes in their natural abundance and can form several charge states, which lead to mass to charge ratio in the interesting range below 7 amu/e.

In order to minimize the influence of the background, both the gas composition and the wall material should be as pure as possible. This will reduce the number of background ions and possibly open up some "clean" areas in the mass to charge ratio range. A background reduction by several orders of magnitude by grinding and carefully cleaning the surface of an aluminium plasma chamber has been reported by N. Imai et al. [3].

The residual gas pressure in the source is normally kept below $5 \cdot 10^{-8}$ T measured on both sides of the source. It is achieved by pumping with a combination of cryogenic and turbo pumps. As all vacuum seals are done by using Viton o-rings it is not possible to bake the system for a further reduction of the baseline pressure. The support gas is pure helium.

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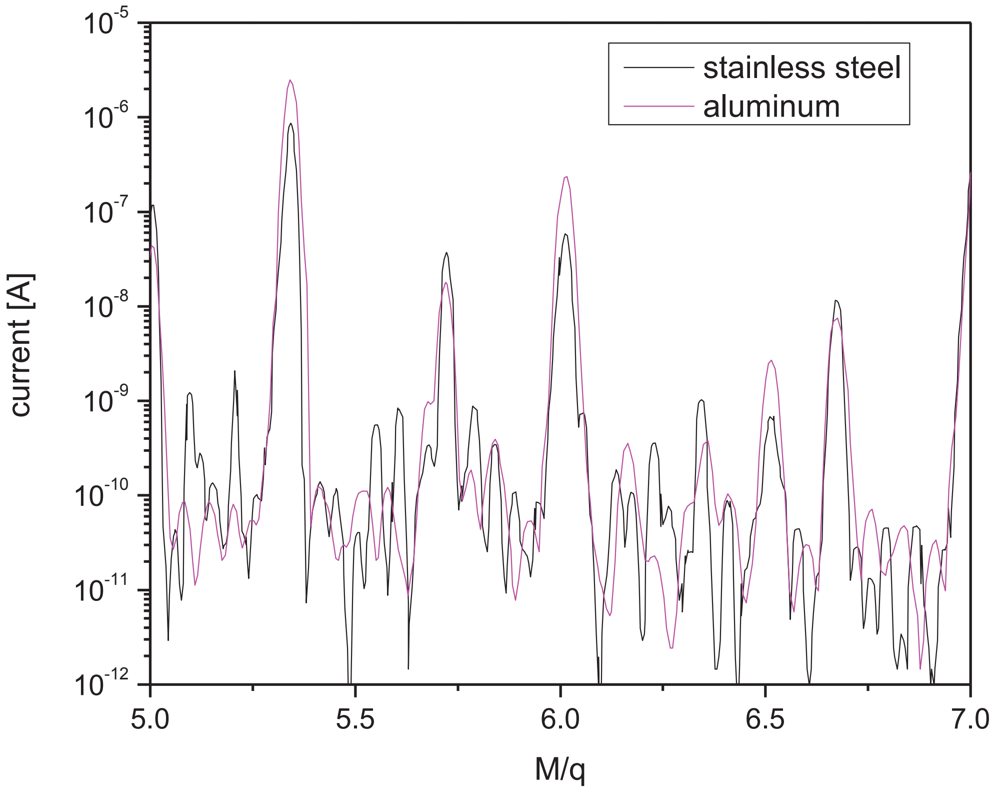

Figure 2: Ion current as function of M/q ratio for a stainless steel and aluminium plasma chamber.

The original PHOENIX source has been equipped with a plasma chamber made of stainless steel. The source has been modified by us to allow an easier adaptation of the ion energy in order to meet the velocity acceptance of the RFQ for different mass to charge ratios. On the injection side we have added a two step deceleration system also with stainless steel electrodes and on the extraction side a two step acceleration system made from copper and stainless steel components. On the extraction side the iron from the magnetic field coils is exposed to the vacuum as well.

To reduce the background from sputtered material the plasma chamber has been exchanged to one made of aluminium. This reduced the background by some small amount but the main components were still present. Therefore, in a second attempt the plasma chamber has been coated with pure aluminium, all electrodes at the injection and extraction side have been exchanged to aluminium and the magnet iron has been coated as well. The result can be seen in Figure 1. It shows a mass spectrum from the source with the stainless steel chamber and with the coated aluminium chamber. Although, the intensity of ions from the gaseous elements is about the same, the intensity of the other components has been reduced by about 2 orders of magnitude.

In the summer of 2012 this set up has been used the first time for a test with radioactive ions in 2 different runs with the acceleration of $^{76}Rb^{15+}$ and $^{94}Rb^{15+}$. Due to insufficient time for conditioning the efficiency in both cases was only about 1% resulting in some 10^5 highly charged ions per second. Background ions which could be identified from their total energy after the acceleration were in case of mass 76 $^{61}Ni^{12+}$ and the direct isobars $^{76}Se^{15=}$ or $^{76}Ge^{15+}$. For mass 94 the direct isobars Zr and Mo could be seen together with some $^{69}Ga^{11+}$ and $^{119}Sn^{19+}$. In both cases the total intensity of the background was several pA.

SUMMARY AND OUTLOOK

Two problems for the charge state breeding for the post acceleration of radioactive ions have been identified. The beam transport of the highly charged ions can be compromised by charge exchange in collisions with residual gas ions in the beam lines. Especially for very high charge states above 15+ not only the low energy part of the installation has to be taken into account, but also the high energy section.

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The second challenge is the background from an ECR charge state breeder, which originates from residual gas ions and sputtered material from the plasma chamber and its surrounding. It could be demonstrated that this background can be reduced by carefully choosing the materials, which may come into contact with the plasma or beam. Improvements of the vacuum and the purity of the support gas can reduce gaseous components in the extracted beam. The design of the PHOENIX charge state breeder allows only small improvements as it utilizes o-ring vacuum seals and does not allow baking at high temperature. Future sources for charge state breeding should be designed to comply with ultra high vacuum standards.

At ISAC additional cleaning techniques along the accelerator chain will be used for further purification of the beam. Although, it will be difficult to eliminate direct isobars the mass resolution of the accelerator chain can be increased by introducing additional slits and carefully reducing the acceptance in energy and mass by choosing relative phases in the RF fields of the different accelerator components. A mass resolving power of up to 1000 has been demonstrated. In some cases additional stripping at high energy may be used for beam purification. This will reduce the final beam intensity but the improvement in the ratio of desired ion to background ions may be essential for the experiment. Results on measurements dealing with the in flight purification of the beam and the tools developed for this will be published elsewhere [4].

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