ANALYZING AND MATCHING STUDY OF MIXED HIGH INTENSITY HIGHLY CHARGED ION BEAMS*

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Abstract

Electron cyclotron resonance (ECR) ion sources are widely used in heavy ion accelerators for their advantages in producing high quality intense beams of highly charged ions. However, it exists challenges in the design of the Q/A selection systems for mixed high intensity ion beams to reach sufficient Q/A resolution while controlling the beam emittance growth. Moreover, as the emittance of beam from ECR ion sources is coupled, the matching of phase space to post accelerator, for a wide range of ion beam species with different intensities, should be carefully studied. In this paper, the simulation and experimental results of the Q/A selection system at the LECR4 platform are shown. The formation of hollow cross section heavy ion beam at the end of the Q/A selector is revealed. A reasonable interpretation has been proposed, a modified design of the Q/A selection system has been committed for HIRFL-SSC linac injector. The features of the new design including beam simulations and experiment results are also presented.

INTRODUCTION

The advances in electron cyclotron resonance (ECR) ion sources that are being achieved by producing high current beams of highly charged ions have made the design of the associated charge to mass ratio Q/A selection system more challenging. In the future, the total ion beam current extracted from an ECR ion source could reach several 10 mA. Serious space charge effect will reduce the resolution of the Q/A selector by increasing the beam size in the slit position and degrading the beam quality. Moreover, the coupled asymmetric beam extracted from the sextupole magnet field used to confine ECR plasma makes the analyzing more complicated. When the beam transmits through a Q/A selector line, the effects of aberrations and coupling in magnetic elements will be obvious, which will also deteriorate the beam quality and reduce the resolution of the system.

The Q/A selection system of LECR4 is designed taking account of all kinds of ion beams produced by the ion source, i.e. from proton to uranium ion beam. However, commissioning results [1] show that the beam quality of high intensity heavy ion beams is rather poor. Studies [2] have been carried out to investigate the possible causes. This study is focusing on the space charge effect on the Q/A selection system. Recent simulations and experimental results at the LECR4 platform are reported and discussed in this paper. The research on LECR4 has provided basis for the design of a new Q/A selection system for LECR4. The features of the new design including beam experiments are also presented in this paper.

EXPERIMENTS AND SIMULATIONS AT LECR4

Experimental Setup

LECR4[3] is an ECR ion source to provide ion beams from Carbon to Uranium for HIRFL-SSC linac injector[4,5]. It uses unique liquid evaporation cooling method at room temperature coils to reach maximum 2.5 T magnetic field.

Fig. 1 shows the original layout of the Q/A selection system of LECR4. It mainly consists of a solenoid lens, a double focusing 90° analyzing magnet, two slits mounted for both the horizontal and the vertical directions, and beam diagnostic devices in a diagnostic chamber, including a faraday cup, a fluorescent target, and an Allison type emittance measurement device. The solenoid lens is directly attached to the extraction flange of the source body to provide an initial focusing and control the size of the beam into the analyzing magnet. Furthermore, the solenoid takes on the responsibility of the tuning flexibility of the system to deal with all kinds of ion species produced by the ion source.

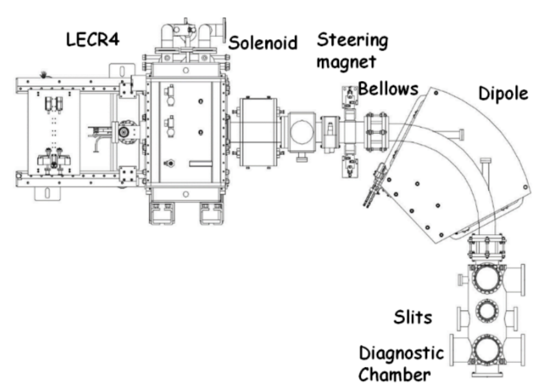

Figure 1: Layout of the multi-component A/Q selection system for LECR4.

LECR4 Beam Emittance

In the original beam line design, nonlinear forces, such as space charge effect and aberrations in magnets [6], were not fully taken into account, resulting in bad transmissions for high current ion beams. Recent simulation results show that the second-order aberration

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in the analyzing magnet appears to be a prior cause leading to the obvious beam phase space aberration and emittance blow-up. However, the focusing solenoid lens at the ion source exit could take effect to adjust the beam angle and size in the analyzing dipole, so as to mitigate the degradation of the beam brightness. Fig. 2 shows the measured beam profile of $^{209}Bi^{27+}$, $^{209}Bi^{28+}$, $^{209}Bi^{29+}$ and the measured beam emittance of $^{209}Bi^{28+}$ at the diagnostic chamber. As is shown, the beam profile seems hollow in the x-y space, but the measured beam emittance has good performance at the exit of A/Q selection system, in the case of drain current of 2.4 mA. Fig. 3 shows the measured beam profile and beam emittance of $^{209}Bi^{28+}$, $^{209}Bi^{29+}$ at the diagnostic chamber with drain current of 5.8 mA. As is shown, the adjacent heavy ions $^{209}Bi^{28+}$, $^{209}Bi^{29+}$ cannot be separated at the slits as the beam profile becomes too large due to the space charge effect of low energy high intensity heavy ions beam. Fig.3(b) shows the corresponding beam emittance measured in the diagnostic chamber.

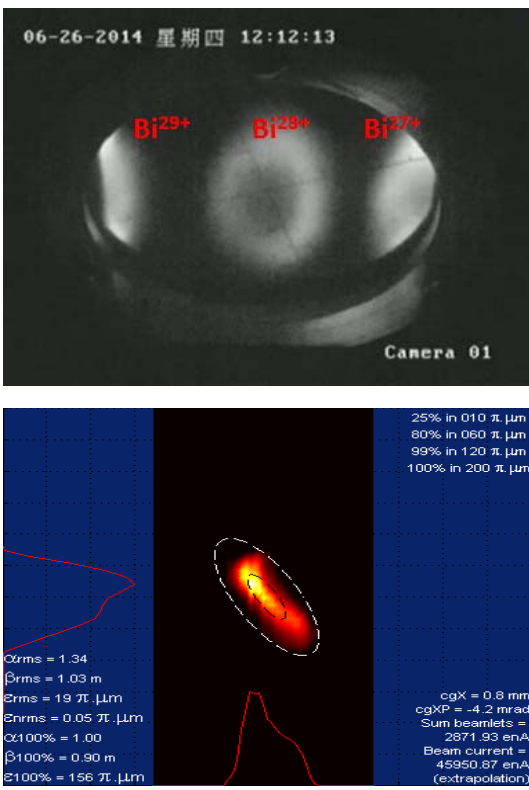

Figure 2: Measured $^{209}Bi^{27+}$, $^{209}Bi^{28+}$, $^{209}Bi^{29+}$ beam profile (a) and beam emittance (b) of $^{209}Bi^{28+}$ at the exit of A/Q selection system. Extraction voltage for the ion source is of 23 kV, microwave frequency is of 18 GHz and drain current is of 2.4 mA.

Space Charge Effect of Mixed Heavy Ions Beam on the Momentum Resolution of the Q/a Selection System

For each Q/A selector, the goal is to achieve high momentum resolution and at the same transmission as well as low beam emittance. To obtain a relatively high resolution ion separation, usually the beam optics of the Q/A analysis system is based on that a beam waist should be formed at the location of the slits. However, there are several factors deciding the position of the beam waist. The factors include the initial beam conditions at the ion source exit, the focusing strength of the solenoid, the structure parameters of the analyzing magnet, space charge effect, and so on. To have better understanding of the space charge effect on the location of the beam waist formation and the momentum resolution of the beam selection system, simulations of multi-charge mixed heavy ion beams are carried out with both high and low current ^{209}Bi beams. For LECR4, single solenoid design is not enough to make the beam waist at the slits location in the case of variable beam currents and initial beam conditions.

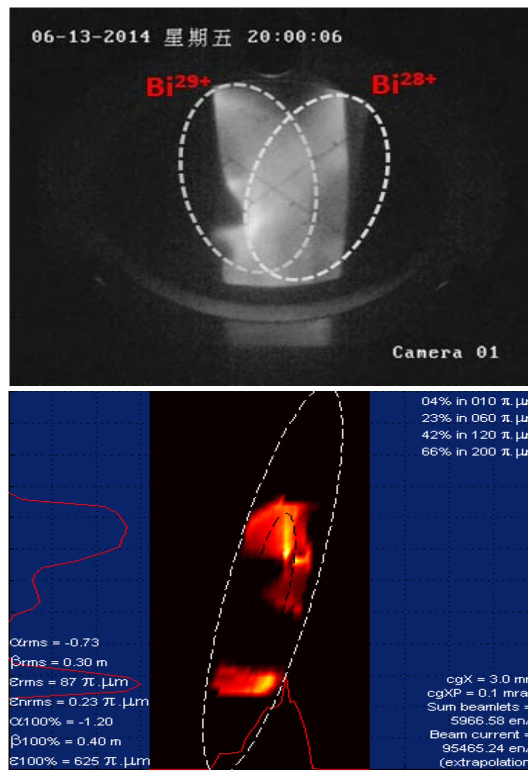

Figure 3: Measured $^{209}Bi^{28+}$, $^{209}Bi^{29+}$ beam profile (a) and beam emittance (b) of $^{209}Bi^{28+}$ at the exit of A/Q selection system. Extraction voltage for the ion source is of 23 kV, microwave frequency is of 18 GHz and drain current is of 5.8 mA.

In the tuning of the ECR injection beam line of single solenoid design, it is repeatedly noted that the analysed beam had a pronounced tendency to be hollow. One explanation of the beam hollow is "short focusing" [7,8] by the magnetic solenoid of beam components with charge/mass ratios higher than the desired beam. Higher Q/A beam components are brought to sharp foci before reaching the analysis magnet. These foci inside the column of desired beam lead to a high space-charge condition driving the lower Q/A beam radially outwards.

In order to expeditiously test the hollow formation hypothesis and make a first attempt to eliminate it, a PIC code has been developed based on Beampath[9] for

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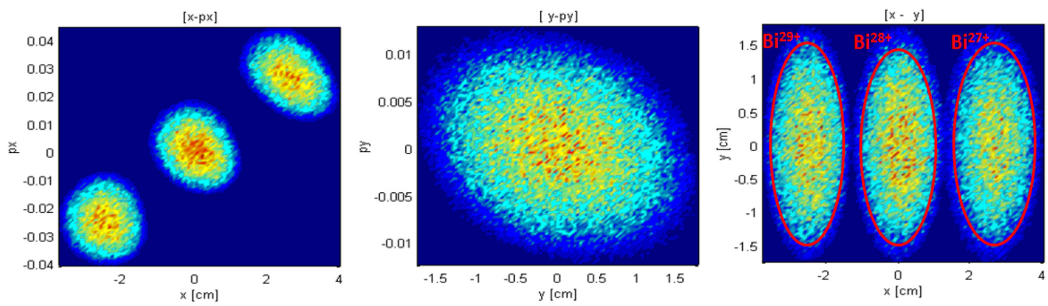
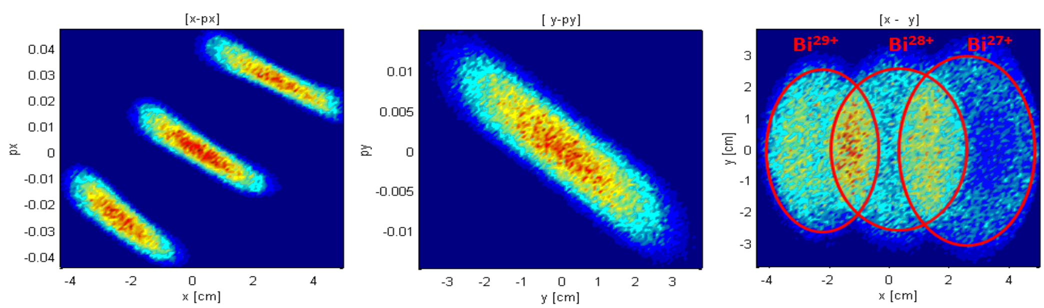
simulation of high intensity mixed heavy ions beam transport. The simulation particles include beams of 26 different ion types, Bismuth ions with the charge state of 19+ to 37+ and Oxygen ions with the charge state of 1+ to 7+, which is given by the measured beam charge state distribution from LECR4. The extraction voltage of the ion source is set to 23 kV and the space charge neutralization factor is supposed to be nearly 0.82, for a good agreement with the experimental results.

The initial beam parameters are calculated indirectly through the forward-tracking & back-evolution method, according to the measured beam emittance at the slits position. Fig. 4 shows The x-x',y-y' and x-y phase space of $^{209}Bi^{27+}$, $^{209}Bi^{28+}$, $^{209}Bi^{29+}$ at the exit of A/Q selection system without space charge. According to the results, the beam hollow didn't appear in the case of no space charge and the heavy ions with the adjacent charge states can be separated clearly at the slits position. While for high current beam, when strong space charge dominates the beam transmission, only one solenoid in a certain range is not enough to control the beam waist position, and the beam waist moving downstream (far away from the ion source). Corresponding beam simulations have also demonstrated a similar phenomenon, as shown in Fig. 5. It has a good consistency with the experimental results as in Fig. 3.



(a) (b) (c)

Figure 4: The x-x' (a),y-y' (b) and x-y (c) phase space of $^{209}Bi^{27+}$,$^{209}Bi^{28+}$,$^{209}Bi^{29+}$ at the exit of A/Q selection system without space charge effect.



(a) (b) (c)

Figure 5: The x-x' (a),y-y' (b) and x-y (c) phase space of $^{209}Bi^{27+}$,$^{209}Bi^{28+}$,$^{209}Bi^{29+}$ at the exit of A/Q selection system with the total beam current of 5.8 mA and space charge neutralization factor of 0.82.

A MODIFIED DESIGN OF Q/A SELECTION SYSTEM

Based on the research of LECR4 Q/A selector, an updating selection system for LECR4 has been designed to handle the higher beam intensities. Fig.6 shows the schematic design of the new Q/A selection system. As the actual beam envelope and beam waist cannot be controlled with a single solenoid lens, an additional solenoid is introduced before the dipole magnet. Considering the spatial arrangement in the beam line, the solenoid is placed at the entrance of the steering magnet. Double solenoids provide more flexibility for the Q/A selection system to match for a variety of ion species. Moreover, the two solenoids with opposite polarity have the capability to counteract the beam coupling in the transverse phase space from the ECR ion source. In this scheme, the first solenoid is used to control the beam diameter in the beam channel and the second plays a supplementary role to adjust the position of the beam waist at the slits, especially for those high-current heavy-ion beams. For the modified Q/A selector, the focusing strength of the first solenoid is reduced which results in larger beam profiles and lower space charge forces, it helps to eliminate the hollow formation. The utilization of the two solenoids could tactfully solve the conflict between the beam transmission and the resolution of the system.

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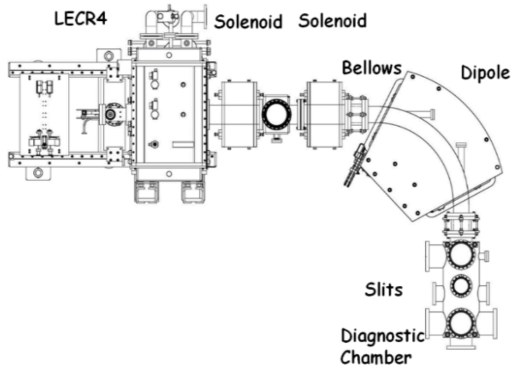

Figure 6: Layout of the updating ion selection system for LECR4.

In order to verify the momentum resolution and beam transmission of the new Q/A selection system, simulations are performed with $^{209}Bi^{28+}$ beam. The revised PIC code is employed to carry out the multi-species ion tracking. Realistic 3D magnetic fields of the solenoid lens and analyzing magnet along the beam line are imported in the simulation. Adopting the realistic fields in the simulation will help to verify the beam line design. The total beam current extracted from the ion source is of 5.5 mA, with an assumed space charge compensation degree of 82%. We assumed all ion species have the same initial conditions as in the simulations for Fig.4 and 5. Fig. 7 shows the simulated particle distribution on the focal plane for different charge states, which indicates a good separation for ions with different mass-to-charge ratios and the beam hollow disappears as the field strength of the first solenoid is reduced.

The new Q/A selection system has been constructed and the beam commissioning is done. Fig.8 shows the measured beam profile of $^{209}Bi^{28+}$ and the measured beam emittance of $^{209}Bi^{28+}$ at the beam diagnostic chamber. As is shown, double solenoids have enough capability to form a beam waist at the position of the slits to ensure adequate ion separation. The measured beam profile is similar to the simulation results in Fig.7. The phase space distributions of the particles in the x-x' and y-y' seem to be in a better condition compared to that with the single solenoid design, but obvious high order aberrations are shown on the x-y plane, which indicates that the effect of high-order aberrations and nonlinear space charge of mixed heavy ions beam cannot be ignored and need to be further investigated deeply.

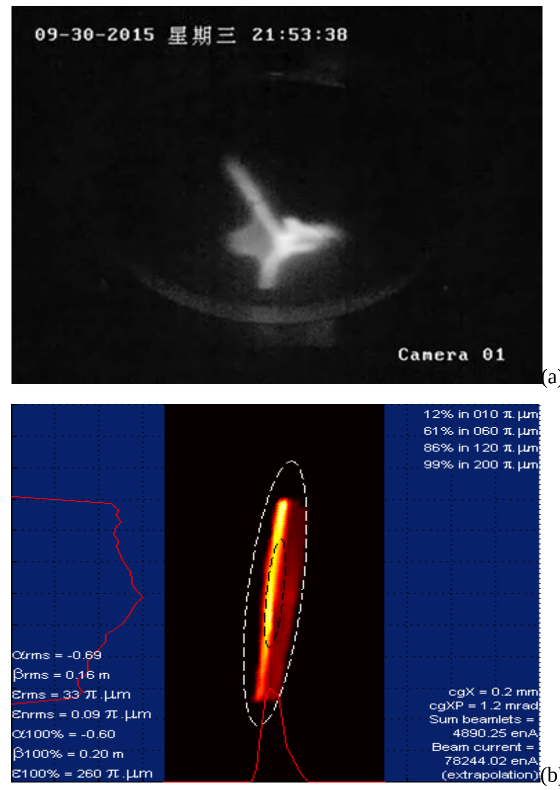

Figure 8: Measured $^{209}Bi^{28+}$ beam profile (a) and beam emittance (b) of $^{209}Bi^{28+}$ at the exit of A/Q selector system. Extraction voltage for the ion source is of 23 kV, microwave frequency is of 18 GHz and drain current is of 5.5 mA.

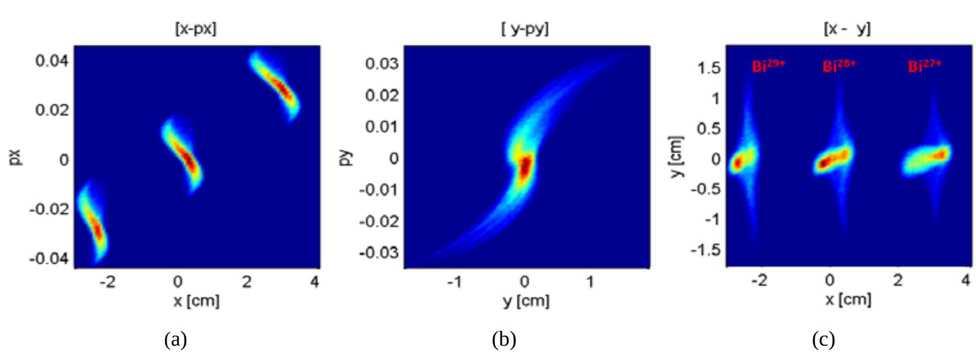

Figure 7: The x-x' (a), y-y' (b) and x-y (c) phase space of $^{209}Bi^{27+}$, $^{209}Bi^{28+}$, $^{209}Bi^{29+}$ at the exit of A/Q selector system with the total beam current of 5.5emA and space charge compensation degree of 82%.

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SUMMARY AND OUTLOOK

Simulations and experiments have been carried out to investigate the original Q/A selection system at LECR4. The results show that, for high-intensity ion beams, the momentum resolution of the system is deteriorated due to the space charge effect and the beam hollow appears under strong solenoid field, driven by space charge defocused field of the multi-species ions. The updated Q/A selection system with additional solenoid has been designed and tested. Test results show that the matching problem for various species of ion beams is well solved; the modified selector has sufficient Q/A resolution and works well.

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