Theoretical analysis of a new extraction system for a DUHOCAMIS operating in a high magnetic field*

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Abstract A new extraction system is designed for a penning ion source DUHOCAMIS (dual hollow cathode ion source for metal ion beams) being installed at the Institute of Heavy Ion Physics, Peking University. We have analyzed theoretically the central particle trajectories in the extraction region for ions having different q/m ratios and then compared our results with the simulation results of CST (Computer Simulation Technology) software. The validity of the system is verified and some analytical formulas are obtained which will be used for the optimization of the extraction system as well as the experimental setup.

Key words ion source, ion extraction system, particle motion equation

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1 Introduction

The extraction system is very important to the plasma ion source due to its determination to both the plasma emission surface and the initial particle trajectories. Many theoretical analyses [1–4] and much calculation work [5–9] have been done to design the extraction system. Using PBGUNS code and CST software, we have designed a new extraction system including a triode extractor, an electrostatic deflector and a magnetic shield for a DUHOCAMIS operating in high magnetic field.

However, whether this system can extract ions with different q/m ratios effectively and what their optimal deflection voltages are still remain uncertain, which are key parameters to design and optimize the system. By theoretical analysis for the central ion trajectories in the extraction region, i.e., dividing the extraction region into several sub-regions according to the field distribution and solving the corresponding particle motion equations, both problems are solved and the validity of the new extraction system is proved.

2 The new extraction system of DUHOCAMIS

A Penning ion source generally works in a low intensity (0.1–1 T) homogeneous magnetic field by using a radial extraction method [10]. The magnetic field often serves as a mass analyzer because of the low magnitude [10–14].

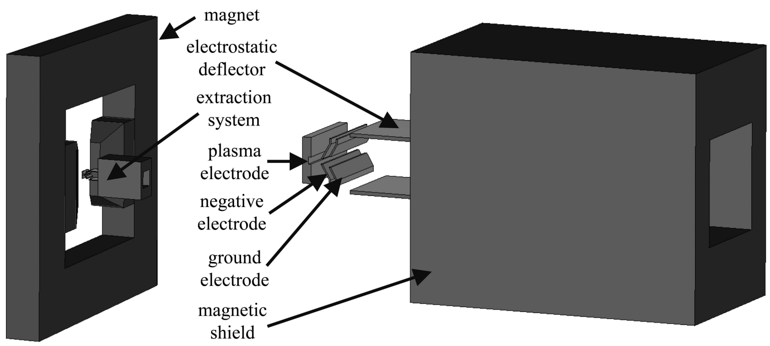

Fig. 1. Configuration of magnet and extraction system.

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However, the magnetic field of a DUHOCAMIS under development at the Institute of Heavy Ion Physics, Peking University, has two features [14]: high magnetic field intensity (~0.5 T) and high magnetic mirror ratio (~2). The high field intensity makes the above method useless for the large deviation of the extracted ions from the axis, thus we designed a new extraction system with a triode extraction system followed by an electrostatic deflector and a magnetic shielding body (in Fig. 1, magnet coins are omitted). Parameters of the arrangement and key values of each component are shown in Table 1.

Table 1. Magnet and extraction system parameters.

parameters	value
magnetic field/T	~0.5
magnetic mirror ratio	~2
voltage of plasma electrode/kV	⩽50
voltage of negative electrode/kV	−2
slit of plasma electrode/mm×mm	2×45
slit of negative electrode/mm×mm	3×50
slit of ground electrode/mm×mm	6×50
negative/ground electrode angle/(°)	60
acceleration distance/mm	6 (3–10)
deceleration distance/mm	3
location of the deflector/cm	3–9
deflection voltage/kV	<10
distance between deflection plates/cm	3
location of the shield/cm	8–25
aperture of the shield/cm×cm	6×6
thickness of the shield/cm	4, 2

The simulation results show that by adjusting the deflection voltage to an appropriate value, the deviation of a certain ion beam can be reduced after being extracted from the system, but the deviation degrees of ions with deferent q/m ratios extracted are still uncertain, which are the key parameters for designing and optimizing the extraction system by determining the distance between two deflection plates and thus the deflection voltages. By theoretical analysis of the central particle trajectories in the extraction region, we found the key parameters that influence the particle movements and deviation values of different ions when extracted from the system and their corresponding deflection voltages.

3 Theoretical analysis

Because of the magnetic shield, the effects of magnetic field on ion movements after the deflector are neglected. The space between the plasma electrode and the deflector is divided into three sub-regions according to the distribution characteristics of the fields: acceleration region S_1, magnetic deflection region S_2 and electric deflection region S_3, which are shown in Fig. 2. S_1, S_2 and S_3 represent the length of different regions. (The small amount of shift of regions S_2 and S_3 because of the interaction between deflector and acceleration electrodes are taken into account in the following theoretical analysis. In this setup, S_1=0.75 cm, S_2=1.75 cm and S_3=6.00 cm). O_1, O_2 and O_3 are the origins of the three coordinates for theoretical analysis. The plasma emission surface is at O_1, at a distance of 0.50 mm from the origin of the system O. B_1, B_2, B_3 and E_1, E_2, E_3 are the corresponding magnetic and electric field distribution for each region. B_0 is the magnetic field intensity at the center of the magnet. F_E and F_B represent the electric and magnetic force, respectively. U is the plasma electrode voltage and V is the electric potential of the deflector. Δx_1, Δx_2 and Δx_3 are the radial deviation values from the z-axis when ions are extracted from the system.

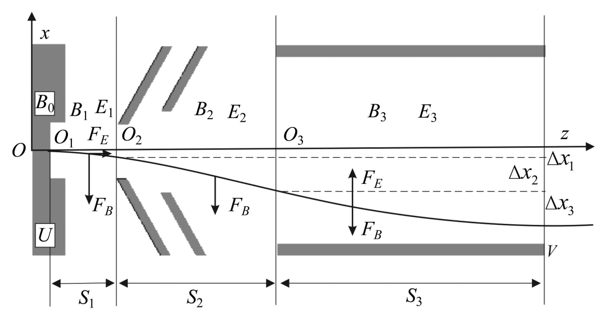

Fig. 2. Three regions along the trajectory.

Figure 3 shows the measured and calculated magnetic field distributions when the magnet works at 76 kilo-ampere-turns. From this we can see that the measured and simulation results fit well with each other, and the shield has screened out most of the fringe magnetic field. Thus we can use the simulation field distribution in the following theoretical analysis.

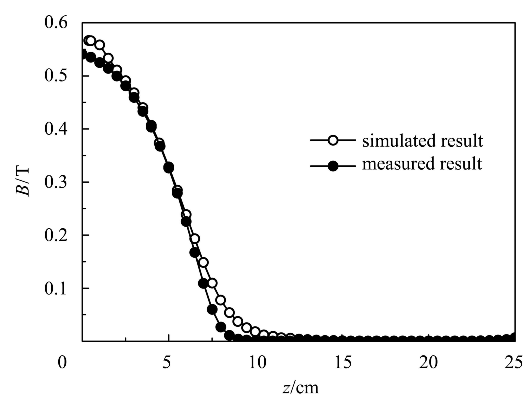

Fig. 3. The measured and calculated magnetic field distributions.

To solve the particle motion equations for the three sub-regions, some assumptions are needed to simplify the distribution of the electric and magnetic fields.

The simplified assumptions of the acceleration region: 1) The magnetic field strength is constant throughout the acceleration region and using B_1= 0.5592 T at the midpoint of this region from the simulation result; 2) The electric field is homogeneous within the whole region: E_1=U/S_1.

The simplified assumptions of magnetic deflection region are as follows. 1) As the potential difference between the negative electrode and ground electrode is relatively smaller compared with the acceleration voltage (2 kV≪50 kV), the influence of the electric field on the ion movement can be neglected in this region, thus the motion of particles in the z-direction is quasi-drift movement with velocity: $v_0=\sqrt{2qU/m}$. 2) The first order approximation of the magnetic field distribution is selected and can be expressed as a linear function: $B_2=B_{02}-k_2z$, where B_{02}=0.5454 T, and k_2=4.5010 T/m from fitting the simulation results.

The simplified assumptions of the electric deflection region are as follows. 1) As the work done by the deflection electric field on the particles is far smaller than the particles' energy themselves, $(W_E/W)_{\max}=V/2U\ll 1$, motion of the particles in z-direction can be considered approximately as uniform linear motion with velocity v_0. 2) Equivalent electric field is used in this region. The simulation result shows that the equivalent length is 7.5 mm, and because of the interaction between the acceleration electrodes and the deflector, the center of the field moved to 7.03 cm along the z-axis. 3) The magnetic field distribution is expressed as a linear function, $B_3=B_{03}-k_3z$, where B_{03}=0.4516 T and k_3=6.0213 T/m from fitting the simulation results.

After the abovementioned simplified assumptions, we have solved particle motion equations for the three sub-regions. The motion equations and their solutions of ion with charge state q and mass m can be expressed as follows.

Acceleration region:

$$-m\frac{\mathrm{d}^2x}{\mathrm{d}t^2}=qv_zB_1, \tag{1}$$

$$x=-\frac{1}{3}B_1\sqrt{\frac{2qS_1}{mU}}z^{\frac{3}{2}}. \tag{2}$$

Magnetic deflection region:

$$-m\frac{\mathrm{d}^2x}{\mathrm{d}t^2}=qv_0(B_{02}-k_2z), \tag{3}$$

$$x=-\sqrt{\frac{q}{2mU}}\left(-\frac{1}{6}k_2z^3+\frac{1}{2}B_{02}z^2+B_1S_1z\right)-\frac{1}{3}B_1S_1^2\sqrt{\frac{2q}{mU}}. \tag{4}$$

Electric deflection region:

$$-m\frac{\mathrm{d}^2x}{\mathrm{d}t^2}=q\left[v_0(B_{03}-k_3z)-\frac{V}{d}\right], \tag{5}$$

$$x=-\sqrt{\frac{q}{2mU}}\left[-\frac{1}{6}k_3z^3+\frac{1}{2}\left(B_{03}-\frac{V}{d}\sqrt{\frac{m}{2qU}}\right)z^2+\left(-\frac{1}{2}k_2S_2^2+B_{02}S_2+B_1S_1\right)z\right]-\sqrt{\frac{q}{2mU}}\times\left(-\frac{1}{6}k_2S_2^3+\frac{1}{2}B_{02}S_2^2+B_1S_1S_2\right)-\frac{1}{3}B_1S_1^2\sqrt{\frac{2q}{mU}}. \tag{6}$$

At the same time, it demands that particles are parallel to the z-axis when extracted from the system, which results in another equation:

$$\frac{V}{d}\sqrt{\frac{m}{2qU}}=\frac{B_1S_1+B_{02}S_2+B_{03}S_3-(1/2)k_3S_3^2}{S_3}. \tag{7}$$

Taking into account the coordinate translation and connecting the ion trajectories of different regions, the above theoretical results are compared with the simulation results by using CST software for ions Al^{2+} and Ta^{2+} trajectories in the extraction region, as shown in Fig. 4. When we set the acceleration voltage to 50 kV, the theoretical results of the deflection voltage obtained from Eq. (7) are 10555 V and 4088 V, which are nearly consistent with the simulation results 9225 V and 3875 V for the minimal deviations of beams extracted from the system. The deflection voltage and the deviations from the z-axis between theoretical and simulation results both fit well with each other. These deviations may come from 1) the linear approximation of the electric and the magnetic fields in three sub-regions; 2) paraxial approximation of the magnetic field along the particle trajectories; or 3) the axial velocities of particles are considered as a constant after the acceleration region, etc.

Equation (7) indicates that when the beams are extracted with a minimal deviation from the z-axis after the extraction system under a certain magnetic field distribution, the acceleration voltage U, deflection voltage V and charge-mass ratio q/m of the ions interact with each other. Thus we obtain the optimal theoretical deflection voltages (<10 kV) for different ions with different acceleration voltages when extracted from the system (Fig. 5).

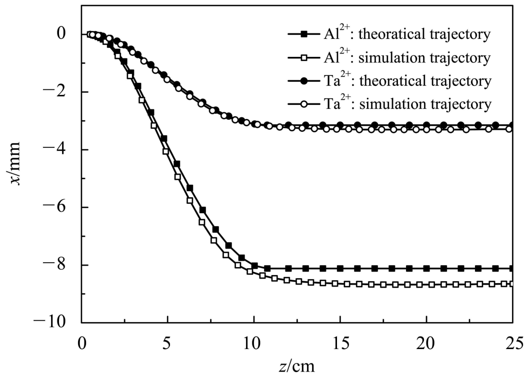

Fig. 4. Comparison between theoretical and simulative trajectory.

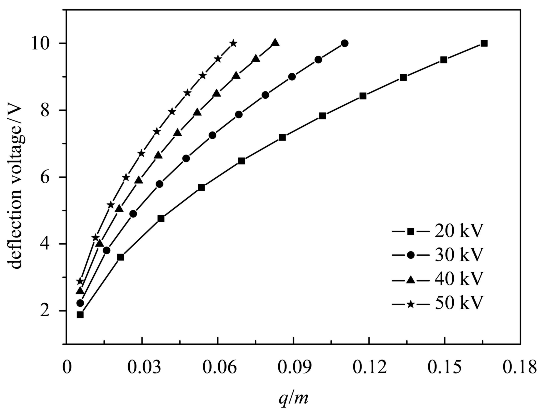

Fig. 5. Optimal deflection voltages of different ions under different acceleration voltages.

From Eq. (6), the deviations from the z-axis of ions with different charge-mass ratios under different acceleration voltages can be obtained, and the results are depicted in Fig. 6. From this we can conclude that many kinds of metal ion beams can be extracted from the new extraction system effectively as these deviations are smaller than half the distance between the two deflection plates, i.e., 7.5 mm. Eqs. (6) and (7) can be used to optimize the design of the extraction system, Figs. 4 and 5 will be used to direct the experimental setup.

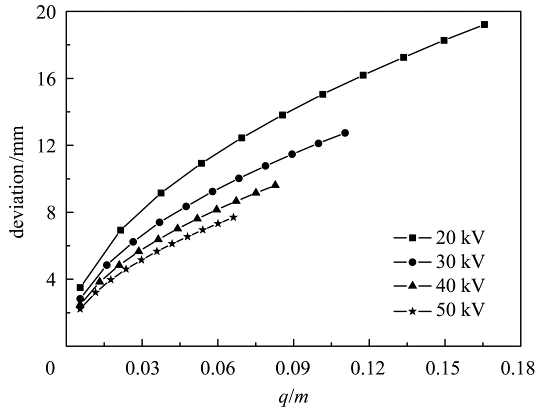

Fig. 6. Deviations of different ions under different acceleration voltages.

4 Conclusions

In this paper, following the theoretical analysis of particle motions in the extraction region, we verified the validity of the extraction system and obtained the optimal deflection voltages for different extracted ion beams. The results based on our theoretical work will hopefully support the new experimental setup which is under development. However the little deviations of both the deflection voltages and the ion trajectories between theoretical and simulation results caused by approximations, as mentioned above, should be considered during the experiments.

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