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Study of the Ion Beam Extraction and Transmission from ECRIS *

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Abstract Experiments concerning the ion beam extraction and transmission have been done in Institute of Modern Physics on the Lanzhou Electron Cyclotron Resonance Ion Source No. 3 experimental platform. We have studied the influences of the plasma electrode extraction aperture, the biased voltage on the screening electrode and the Glaser lens. The emphasis is put on the research how to extract the ions produced in the source more efficiently and how to make the extracted ion beam transmission with less loss. In this paper, the results of the experiments are presented. With the results obtained, systematic analysis has been made and a general physical image has also been brought forward in this paper.

Key words ECR ion source, space charge, ion beam extraction

1 Introduction

Electron Cyclotron Resonance (ECR) ion source is nowadays believed to be the most efficient facility to produce intense multiply charged ion beams. ECR ion source was firstly developed at the end of 1960s in Grenoble France[1]. After these 30 years, there has been great development on this kind of ion source. Special techniques like high-B mode, higher frequency RF feeding, effective secondary electron donors, double-frequency heating and etc have greatly enhanced the plasma density inside the plasma chamber. E.g. for most of the advanced ECR ion sources, the plasma density can be as high as $1 \times 10^{13}\mathrm{cm}^{-3}$[2]. Comparing the high density of the plasma with the extracted ion beam intensity, it is found in the ECR ion source research that there is still much work to be done to increase extraction efficiency of ECR ion source to produce more intense ion beams.

It is obvious that the nowaday ECR ion source can deliver intense ion beam with so many tricks and techniques being adopted. For example, the total drain of mixed ion beam (composed of different charge state ions) extracted from the 18GHz ECRIS in RIKEN was up to 12emA; the Grenoble GTS source could produce a total drain as high as 9emA[3] and a 10emA mixed ion beam was also produced on LECR3[4] (Lanzhou Electron Cyclotron Resonance ion source No. 3) in IMP (Institute of Modern Physics) when optimizing for the production of Ar^{8+}. To extract such an intense mixed ion beams with extraction voltage about 20kV is very hard. The space charge effect in the extraction region and the drifting space is very severe. The strong space charge effect will cause the beam to expand very dramatically in diameter and the ion beam loss will be very abundant in the extraction and transmission space before being analyzed by the analyzer magnet. Therefore, efficient extraction from the ECR plasma and high transport efficiency both are essentially important for the enhancement of the performance of an ECR ion source.

2 Ion beam extraction

The ion beam extraction system of ECR ion source is normally composed of a plasma electrode (PE) and a puller at ground potential. But to improve the performance of the extraction system, triode system (as shown in Fig.8) is often adopted, in which a screening electrode is

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added between the PE and the grounded electrode. Extraction system with more electrodes has also been applied in some laboratories[5, 6].

2.1 Influence of the plasma electrode

PE is the electrode that is set between the plasma and ion beam acceleration region. Its geometric configuration and position will define the plasma boundary and the electric field distribution at the extraction region. To optimize the extraction of different charge state ions, the plasma electrode is usually moved along the symmetric axis of the source. In our research, we intend to find the relationship between the outlet aperture of PE and the extracted ion beam properties.

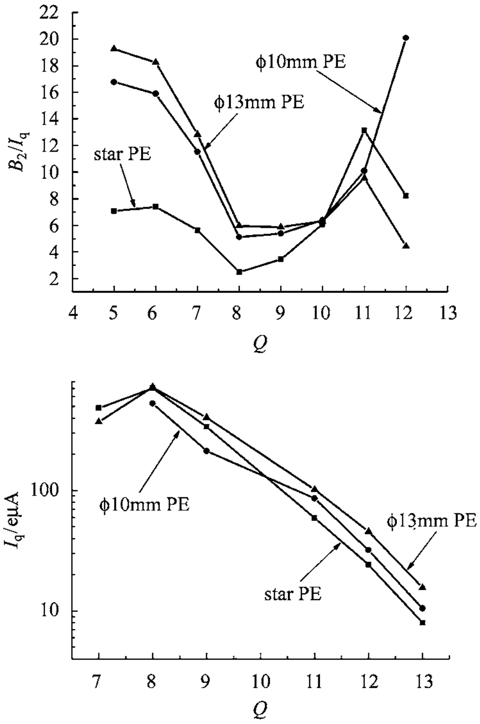

Fig. 1. Dependence of B_2/I_q (above plot) and I_q (below plot) on difference outlet aperture PEs, B_2 is the brightness detected by a fluorescent target and I_q is the ion beam current of Q charge state.

In this investigation, we have tested three PE with outlet apertures of ϕ10mm, ϕ13mm and a star shape one (the three angles of this electrode are consistent with the position of the sputtering marks on PE[7, 8]). When equipped with different PE, the extracted ion beam intensity, brightness and the emittance are detected after being analyzed. Fig. 1 gives the influences of different outlet aperture PE on the extracted ion beams. During these experiments, the feeding RF power is fixed to 800W, the position of the extraction system is also fixed. And the other parameters are adjusted to optimize the production of different charge state ion beams. Easy to see from Fig. 1 that the larger the outlet aperture, the larger the extracted ion beam intensity. But we can notice that the star shape PE can only enhance the beam intensity of medium charge state ion beams but for higher charge state ion beams, larger round outlet aperture PE seems to be more effective. While for the ion beam brightness, the smaller outlet aperture PE provides better results. It might be because the larger outlet aperture provokes the increase of the aberration of the extracted ion beam. For the medium charge state ion beam extraction, with the ϕ13mm and star shape PE we achieved the production of 1emA Ar^{8+} for the first time in IMP. Fig. 2 presents the photographs of ϕ13mm and star shape PEs respectively.

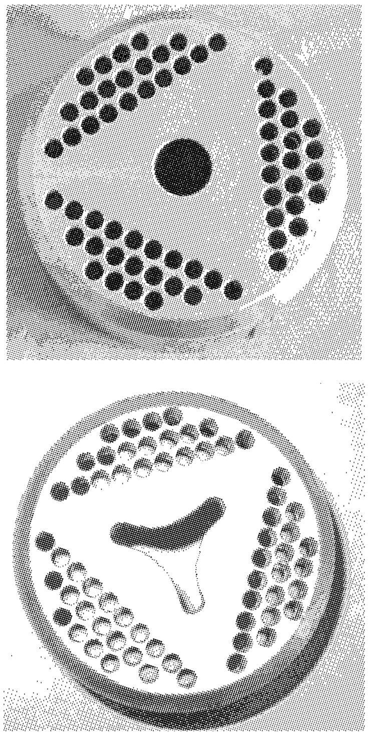

Fig. 2. Photographs of ϕ13mm round outlet aperture PE (above plot) and the star shape outlet aperture PE (below plot).

With the latest developed ESS emittance scanner system[9], we measured the emittances of different charge state ion beams for both ϕ10mm and ϕ13mm outlet aperture PEs. The results are clearly shown in Fig. 3. Fig. 3 indicates that larger aperture PE results in the increment of emittance for certain charge state ion beam. Two main reasons may account for this phenomenon: 1) larger outlet aperture of the PE causes the increase of the extracted ion beam emittance; 2) with larger outlet aperture, more intense ion beam is extracted, and it induces stronger space charge effect, which leads to the increase of extracted ion beam emittance. Accordingly, there will be a matter to determine the right outlet aperture for ion beam extraction. Larger aperture PEs are adopted when intense ion beam is more important, e.g. when ECRIS is used for some atomic physics research experiments who need intense high charge state ion beam. While for the cyclotron accelerator injection, smaller aperture PEs are preferred sometimes.

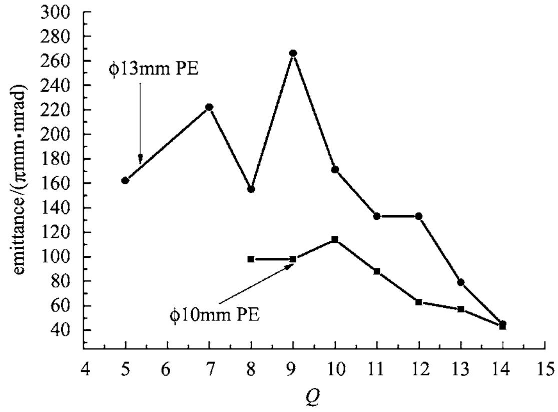

Fig.3. Influence of the PE outlet aperture on the ion beam emittance.

2.2 Influence of screening electrode (SE)

For many high performance ECR ion source, triode extraction system (or accel-decel system as shown in Fig. 8) is usually adopted. A negative HV can be applied on this electrode to suppress the secondary electrons in the drifting space and prevent them from entering the acceleration region. In this way, the secondary electrons in the drifting space could be possibly used to compensate the space charge. In our experiment, all of the parameters of LECR3 source were kept constant, and by altering the HV on the SE (the extraction HV is 20kV) we studied the properties of the investigated ion beam. Fig.4 gives the results obtained. We can see from Fig.4 that with the increase of the negative HV on the SE, the obtained ion beam current enhances at the same time, but very high negative HV will result in a decrease of the ion beam current, which is supposed to be the reason of the alteration of the ion beam transmission optical system. The non-monotonic phenomenon of the experimental results reveals that some instabilities of the extracted ion beam might be caused by the increasing of the biased HV on SE and also indicates that the biased HV affects the transmission optics and the emission boundary of the plasma. While for total drain of the ion source, it decreases with the increase of the applied negative HV, and when the HV is very high (~ – 2kV), the total drain approaches a constant value.

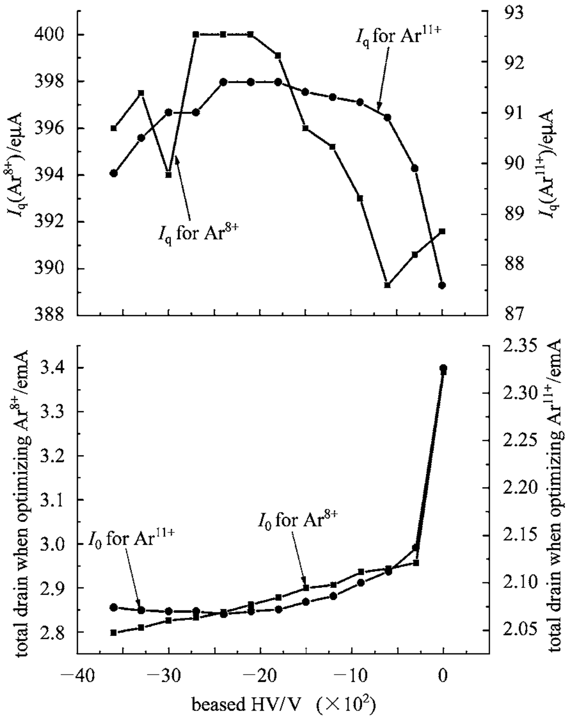

Fig.4. Influences of the SE applied HV on I_q and the total drain of the ion source I_0.

Reconsidering the results given in Fig.4, we might notice the ion beam current and total drain current of the source response very significantly to the change of the negative HV when the applied HV is within the margin of 0 — – 600V. The following experiment has been done concerning the alteration of the extracted ion beam current and the total drain when applied HV is within – 600V—600V. The obtained results are given in Fig.5. Easy to deduce from the plot that the HV applied on SE is able to adjust the ion emission surface (plasma boundary). Proper adjustment is favorable for the extraction of ion beam. Even when applied HV on SE is positive, the extracted ion beam current is possible to be increased. The total drain current variation versus the biased voltage which is presented by the experiment is helpful to understand the ion beam extraction and transmission mechanism which is discussed in the following sections.

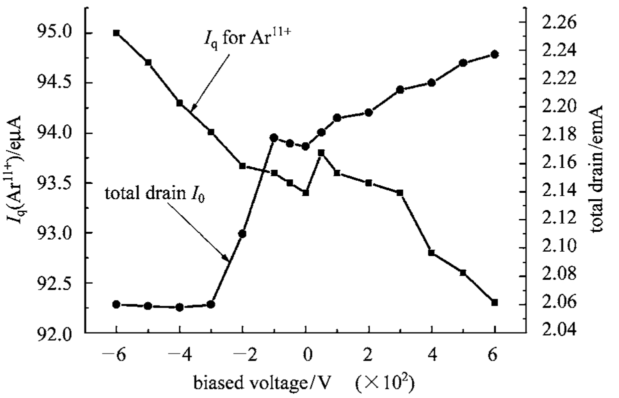

Fig.5. The dependence of I_0 and I_q on SE applied HV when optimizing for Ar^{11+} production.

3 The drifting space

The extracted ion beam from an ECR ion source is a mixed ion beam composed of different charge state ion beams. For some advanced ECR ion source, the extracted ion beam is very intense, e.g. 8emA, and the charge states of the component ions are usually very high, and nevertheless the extraction HV is normally very low (e.g. 15—20kV). These reasons make the space charge effect in the drifting space is very severe, and the influence on the transmission of the ion beam is very large. With a latest developed PC code PBGUNS[10], we can simulate the influence of space charge effect on the extracted ion beam, and the simulation result is illustrated in Fig.6. We can deduce from the plot that with the enhancement of the space charge compensation percentage in the drifting space, ion beam emittance can be greatly reduced and the luminance of the incident ion beam is increased at the same time. To get good quality ion beam, the space charge in the drifting space should be compensated or decreased.

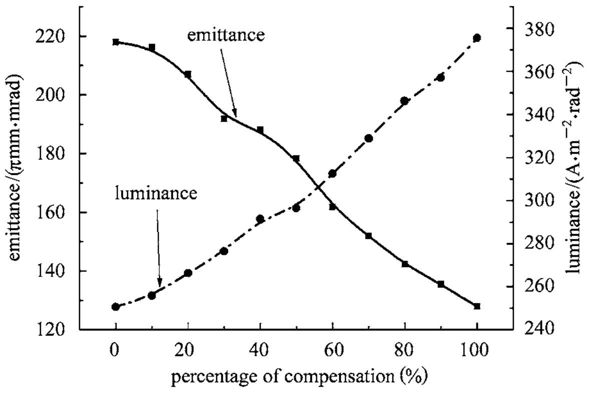

Fig.6. Influences of space charge effect on the ion beam quality.

Glaser lens is a magnetic lens to adjust the ion beam transmission optical system. It is installed normally close to the ion source and it provides the ion beam a weak transverse focus force and helps to form a waist at the object point of the analyzer magnet (for the LECR3 platform). To get a good understanding of the influence of Glaser lens on the ion beam transmission, we studied the analyzed ion beam brightness and the intensity alteration with the change of the Glaser lens. Fig.7 gives the typical results obtained from the experiments. Two kinds of ion beams have been studied: Ar^{8+} and Ar^{13+}. We can see from the plot that the maximum beam current for certain ion is obtained with the optimized magnetic field (proportional to the exciting current) of the Glaser lens. The higher the ion beam charge state, the larger exciting current is needed for the optimization. We also notice that the best brightness can not be obtained at the same time when the beam current is the largest. That indicates a good quality ion beam can be achieved without obtaining the maximum ion

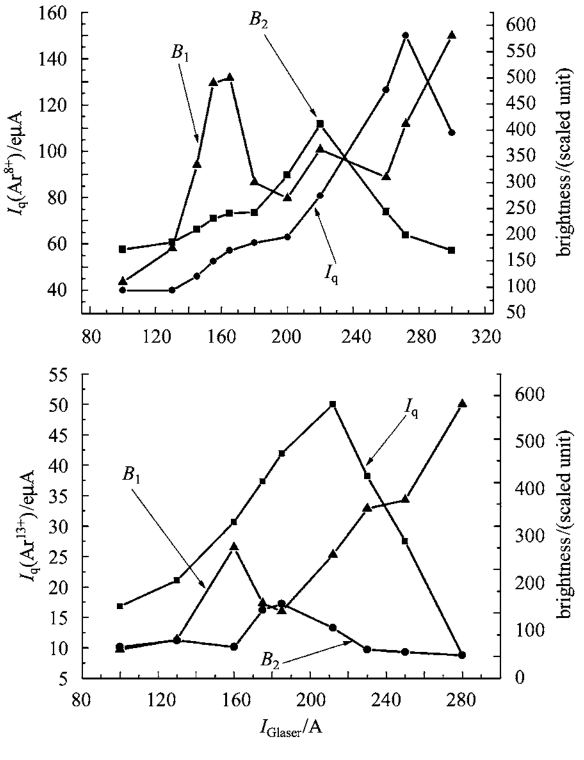

Fig.7. I_q, B_1 and B_2 dependences on the Glaser lens exciting current. Above plot is obtained when investigating Ar^{8+} ion beam and below plot is for Ar^{13+} ion beam. B_1 is the brightness of the mixed ion beam detected after Glaser lens.

beam current. By tuning the exciting current, good ion beam quality is achievable at the Faraday cup.

Another conclusion can also be made with the results given in Fig.7. When we try to optimize the transmission of certain charge state ion beam, the other charge state ion beams are not well optimized for the transport: they are weakly focused (lower charge state ions beams) or over focused (higher charge state ion beams) by the Glaser lens, which makes the other charge state ion beams be lost quickly in the drifting space only after a short transmission length. This physical process is also well verified by the latest ion beam transmission simulation code MCIBS[11] developed in IMP. This process indicates the Glaser lens has the ability of ion beam preselection. The unwanted ion beams is abandoned after the Glaser lens and the wanted ion beam is optimized for the transmission. Thus, the space charge in the drifting space (between the Glaser lens and the analyzer magnet) is not as severe as expected.

4 Analysis of ion beam transmission after being extracted

According to the experimental results and the corresponding discussion presented above, we can make out a conceptional physical image of the ion beam transmission after being extracted from an ECR ion source.

4.1 Total drain current of an ECR ion source

The total drain curent of an ECR ion source is normally denoted by the following equation:

$$I_0 = I_t + I_e + I_g, \tag{1}$$

where I_t is the total current extracted from the source, I_e is the current of external secondary electrons that enter into the source plasma, and I_g is the leak current of the source to the ground. Normally I_g is the leak current through the cooling water of the source (depends of the cooling water resistance and the extraction HV), and for LECR3 it is usually 0.1emA. I_t is principally limited by two conditions: the space charge limited current or the emission capability of the ion source[12]. For the space charge limited I_t, it follows the Child-Langmuir equation:

$$I_t = \frac{4\varepsilon_0}{9}\sqrt{\frac{2Qe}{M}}\frac{U^{3/2}}{d^2}\cdot S, \tag{2}$$

where Q is the ion charge state, M is the mass of the ion, U is the applied extraction HV on the source, d is the distance between the PE and SE (or the grounded electrode for diode extraction system) and S is the area of the PE outlet aperture. As for the case of emission capability limited, we can have the following equation:

$$I_t = n_i e\sqrt{kT_i/M}, \tag{3}$$

where n_i is the ion density at the extraction region, k is the Boltzmann constant, and T_i is the ion temperature (n_i and T_i depend on the ion source working condition). Generally, the working module of extracted ion beam follows one of the effects that dominates. For high performance ECR ion sources, when optimizing the production of high charge state ion beams, the effect denoted by equation (3) dominates.

The components of I_e are a bit more complicated. The following content will give the discussion concerning the source of the current:

4.1.1 The electrons coming from the drifting space

In the transmission space the mixed ion beam collides with the residual gas and makes part of it ionized, and a large amount of free electrons are produced simultaneously. Additionally, lots of secondary electrons are also produced when the lost ion beam bombards the vacuum tube. Under the influence of Coulomb force induced by the positive ion beam, the secondary electrons move to the center of the transmission tube. The center-collected electrons will diffuse along the symmetric axis in two directions: upstream and downstream (as is illustrated in Fig. 8). For the electrons move upstream, if their motion is not suppressed, they will go into the acceleration region where they are accelerated by the electric field there. Most of the accelerated electrons can enter the ion source plasma with an energy of eU. The incoming of the external electrons will apparently increase the load of the ion source. The incoming electron beam has very high longitudinal energy (usually 10 —30keV), and also because of this characteristics they can not be confined by the mirror field. The high energy electrons will impinge the injection flange of the source or biased disk and result in the outgasing problem. And what is more, the electrons entering the acceleration space will be most likely to cause penning discharge at the extraction region, which is not wanted for ECR source running. A triode extraction system can help solve this problem. The biased HV on the screen electrode can suppress the diffusion of the electrons to the acceleration region. According to experimental results discussed in section 2.2, the current of this kind of electrons (without suppression) should be at the order of 0.3emA (usually depends on the working condition of the source and the applied biased HV on SE).

4.1.2 Electrons from the acceleration region

After being extracted from the ion source, some of the badly focused ion beam will bombards the outer surface of the puller, and large amount of secondary electrons are then produced. These secondary electrons will be accelerated to PE by the extraction electric field. Then the electrons are under the influence of the resultant force of magnetic force and Lorentz force:

$$\boldsymbol{F} = -e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}), \tag{4}$$

which makes the electrons do helix motion. Normally the electrons can not enter into the source plasma and they are most likely to impinge on the inner surface of PE, which makes the load of the ion source increase (the quantity of this current depends on extracted ion beam, the geometry design of the extraction system and so on). Some of the electrons can follow the magnetic lines of flux and finally bombard other equipments of the ion source (such as the ceramic insulator). Since the vacuum condition at the extraction region is usually not very good and there also exists the high magnetic field, too much electrons at the extraction region can possibly cause frequent penning discharge there which influences the operation of an ECR ion source.

4.1.3 Cold secondary electrons from the injection side

For most ECR ion sources, to enhance the source performance some extra electron donors are applied to increase the cold secondary electron injection efficiency. Biased-disc is one of the often adopted donors[13]. Applied negative voltage on the metallic disc makes the positive ion bombard the disc continuously, which induces the emission of lots of secondary electrons. The negative voltage will also repulse the cold secondary electrons to enter the source plasma. The loss of the ions on the biased-disc and the entering of the cold electrons into the plasma both result in the increase of the load of the source. The corresponding current of this part is usually at the order of 0.1emA, and it also depends on the plasma condition and the applied negative voltage on the biased-disc.

4.2 Space charge effect

Space charge effect influence on the transmission ion beam is different at different region along the extraction and drifting line. According to the effect strength and property, the extraction and drifting space can be divided into 4 regions a, b, c and d as is illustrated in Fig.8. The region a is the ion emission region. The ion density in this region is very high, and the resultant space charge effect is extremely strong. However, there exist lots of warm background electrons that might make some compensation to the space charge. Nevertheless, the space charge compensation rate in this region is still very low. The region b is the ion beam acceleration region. Space charge effect in this region is significantly strong since the ion beam density in this region is high and no electrons can be reserved in this region for space charge compensation. The space charge in region b is uncompensated. As for region c, by applying negative high voltage on SE, the movement of the diffusion electrons to the acceleration region is effectively suppressed. But the suppression electric field can not screen the extraction field in the whole region. Some electrons are still driven into the acceleration region by the extraction field. However the left electrons can provide a good compensation to the space charge in c region. In the region d, the secondary electrons produced there diffuse in two directions. The electrons diffusing upstream are mostly suppressed by the negative HV applied on SE and could be used for space charge compensation there. While for the electrons diffusing downstream, they are not suppressed and therefore move along the beam axis to the analyzer magnet till lost there. In conclusion, the space charge in d region is well compensated, but not totally compensated. Two possible solutions can be applied to increase the compensation ratio in this region: 1) injecting electronegative gas (like SF_6, CF_4, etc.) into this region to increase the negative charge density there[14]; 2) an einzel lens is supposed to be installed at the entrance of the analyzer magnet (as is illustrated in Fig.9). Thus the electrons' diffusion to the analyzer magnet is suppressed. This einzel lens together with SE forms a good electron constraint in d region, which is meant to be favorable to space charge compensation.

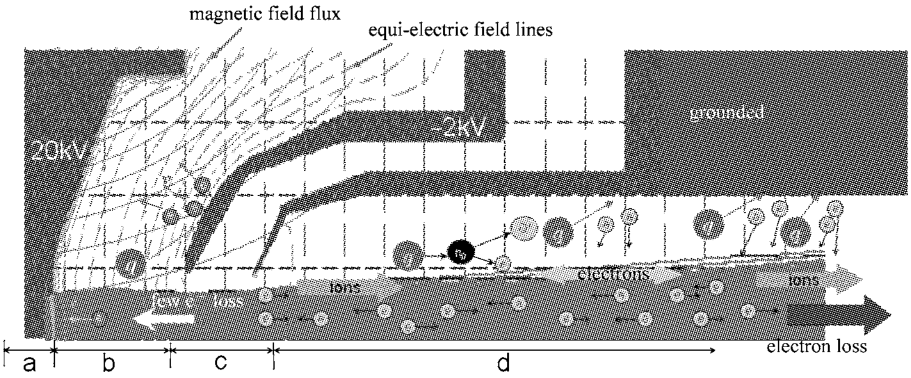

Fig.8. Schematic plot of ion beam extraction and transmission of ECR ion source.

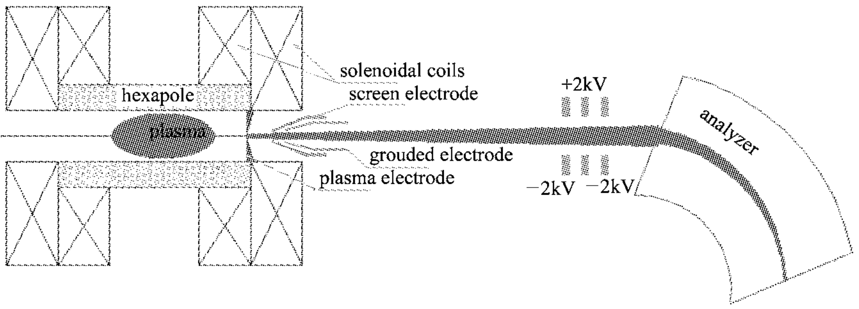

Fig.9. An ion beam extraction and transmission system design for ECR ion source for better mixed ion beam transmission.

5 Conclusion

Ion beam extraction and the mixed beam transmission systems are very important for an ECR ion source. Well-designed systems can help enhance the performance of the source. Larger plasma electrode outlet aperture helps increase the extracted ion beam intensity, but the ion beam quality might become worse and the analyzed ion beam emittance increases. The screening electrode is very helpful to ion beam extraction. By tuning the applied negative HV on SE, good adjustment of the plasma emission meniscus configuration is possible for efficient extraction. Additionally, the applied negative HV can prevent the secondary electrons from entering into the acceleration space and help increase the space charge compensation in the drifting region. According to this paper, good space charge compensation is possible in the mixed beam transmission space by taking some effective measures like electronegative gas feeding and installation of an einzel lens at the entrance of the analyzer magnet.

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ECR 离子源束流引出与传输的研究*

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摘要　针对 ECR 离子源的束流引出及传输研究,在中国科学院近代物理研究所的 LECR3 离子源实验平台上开展了大量的实验.实验中研究了等离子体电极引出孔径、反射电极(抑制电极)偏压以及 Glaser 透镜等因素对束流引出与传输的影响.研究的重点是试图通过系列实验与分析来研究如何能更有效地引出强流离子束流并减小其在传输空间的损失.给出了实验的主要结果,结合这些数据对 ECR 离子源的束流引出与传输进行了较全面的分析,并综合这些实验结果与分析结果得出了该物理过程的一般物理图像.

关键词　ECR 离子源　空间电荷　束流引出

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