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Experimental Study on Ion Beam Emittance of ECR Ion Source*

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Abstract With a recently developed electronic-sweep scanner system, we have done series of emittance study on ECR ion source. The electric-sweep scanner system was installed on the beam line of Lanzhou Electron Cyclotron Resonance Ion Source No. 3 experimental platform of Institute of Modern Physics. The influences of magnetic field, microwave, gas mixing and biased disc on the extracted ion beam emittance have been studied in detail. With the experimental results obtained and the empirical results of ion beam emittance and ECR plasma, some conclusions on the relationship between the source tunable parameters and electron cyclotron resonance plasma are made out, which might help understand the working regime of an ECR ion source. The typical results of the experiments and the derived conclusions are presented in this paper.

Key words ECR ion source, emittance, ECR plasma

1 Introduction

The Electron Cyclotron Resonance (ECR) ion sources for multiply charged ions (MCI) have been developed by R. Geller and his colleagues about thirty years ago[1]. Since then ECR ion sources were adopted in some accelerators as their preliminary injectors, which can deliver high charge state, intense and stable ion beams in both continuous and afterglow modes. Although now widely used in many domains, their behavior remains difficult to understand and till now only some semi-empirical and semi-theoretical laws are available. Fig. 1 presents a schematic drawing of an ECRIS: a plasma is created in a chamber where a minimum-B magnetic structure confines the particles; an RF electromagnetic wave is injected into the chamber and interacts resonantly with the electrons of the plasma: the Larmor frequency of the electrons is equal to the frequency of the EM wave so that the electrons are accelerated by the wave electric field towards very high energies, which enables the injected atoms and ions to be stripped up to very high charge states. The created ions are then extracted and accelerated. The minimum-B field is a superposition of an axial mirror field and a radial multiple cusp field (hexapole is usually adopted for ECRIS). The trances on the plasma chamber and on the electrodes surface[2] indicate the plasma loss areas and also reveal the fact that the magnetic field influences ion original emission surface by some way. The magnetic field configuration and the injected microwave together determine the ECR plasma and thus set the intrinsic parameters of the extracted ions, which partly define the extracted ion beam emittance. Some special tricks like the gas mixing and biased-disc techniques help enhance the performance of an ECR ion source by the way of modifying the ECR plasma, which certainly influences the intrinsic parameters of the plasma and the emission conditions of the ions as well. By studying the corre-

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lation between extracted ion beam emittance and the ECRIS tunable parameters (such as magnetic field, microwave power and etc.), we may open a new way to study the working regime of an ECR ion source.

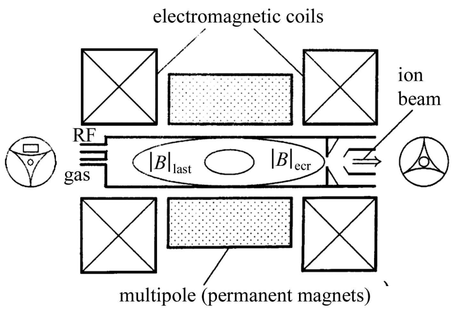

Fig. 1. Sketch of an ECR ion source of multi-charged ions.

2 Experiment setup

To have a global study of the emittance characteristics of an ECRIS, the high performance Lanzhou ECR ion source No. 3 (LECR3) experimental platform[3] was adopted for the experiment setup. The experiment setup schematic plot is given in Fig. 2. Two ESS systems[4] are installed after Faraday cup at both the horizontal and vertical positions to detect the emittance of the analyzed ion beam at the horizontal and vertical directions respectively. Two fluorescent targets are intentionally installed after the Glaser lens and the Faraday cup to present the profiles of the mixed ion beam and the analyzed ion beam respectively. In the following discussion, only the laboratory emittance values are given.

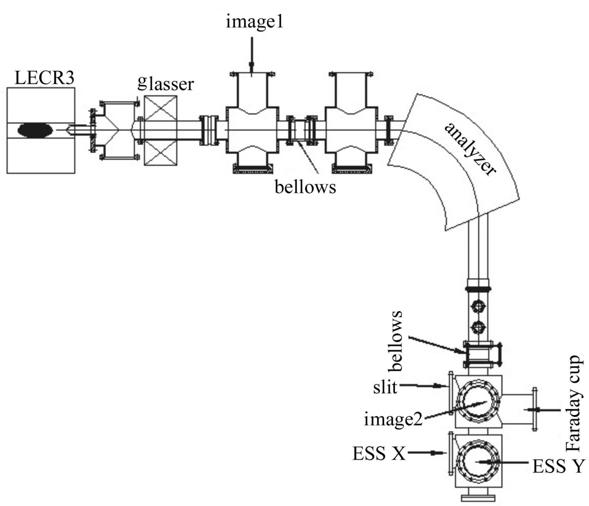

Fig. 2. Experiment setup schematic plot for the emittance study on LECR3 platform.

3 Magnetic field influences

3.1 At different magnetic field modes

In this research, we studied the emittance variation with the change of the RF power under H, M and L magnetic field modes, H, M and L represent high ($B_{\rm inj}=1.58$T, $B_{\rm min}=0.45$T, $B_{\rm ext}=1.17$T), moderate (1.53T, 0.41T, 1.05T) and low (1.45T, 0.36T, 0.93T) magnetic field configuration respectively. The feeding RF frequency is 14.5GHz, and the power varies from 100W to 700W for Ar^{8+} and from 400W to 800W for Ar^{12+}. No other parameters of the source have been modified during the experiments except for the necessary tuning. The results are given in Fig. 3.

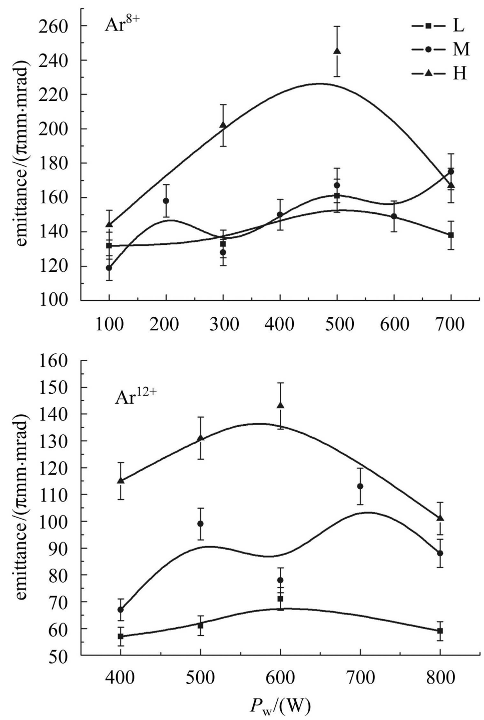

Fig. 3. Influences of different B modes on Ar^{8+} and Ar^{12+} beams.

It is noticed that when the same RF power is fed under different B modes, higher magnetic field configuration induces larger emittance. And under different B-mode, the way that the emittance alters with the increase of RF power is different.

3.2 Influence of extraction magnetic field

In this experiment, two kinds of ions Ar^{8+} and Ar^{14+} were considered. Except for the extraction magnetic field, the other parameters were kept unchanged. The feeding 14.5GHz RF power is 130W for Ar^{8+} and 600W for Ar^{14+} respectively. The experimental data are given in Fig. 4.

We can see that the extraction magnetic field has some influence on the extracted ion beam emittance: the ion beam emittance increases with the increase of the extraction magnetic field B_{ext}. Ion charge state also affects the alteration module of the extracted ion beam emittance with the increment of B_{ext}. From Fig. 4, we can get that Ar^{8+} emittance has 9% increment and Ar^{14+} emittance has 38% increment when B_{ext} is increased from 1.0T to 1.12T.

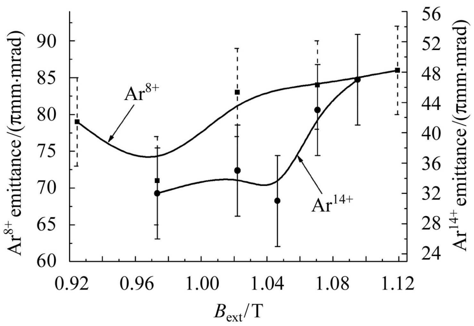

Fig. 4. Influence of extraction magnetic field on the extracted ion beam emittance.

4 Microwave influences

4.1 RF power

The experiment results are also illustrated in Fig. 3. Easy to see, under the same B-mode, the beam emittance varies with the feeding RF power: the higher the RF power, the larger the ion beam emittance. This is consistence with G. Melin and A. G. Drentje's theory[5] on the calculation of ion temperature T_{i}. But when RF power is larger than a certain value, the variation tendency alters which indicates another working regime of the plasma.

4.2 RF frequency

Under the condition of 500W RF power feeding, ($B_{\mathrm{inj}}=1.6$T, $B_{\mathrm{min}}=0.44$T, $B_{\mathrm{ext}}=1.1$T) for 14.5GHz running and (1.6T, 0.47T, 1.21T) for 18GHz running, we measured the influence of RF frequency on the ion beam emittance, as is shown in Fig. 5. The other parameters are kept unchanged except for the Glaser lens and magnetic analyzer.

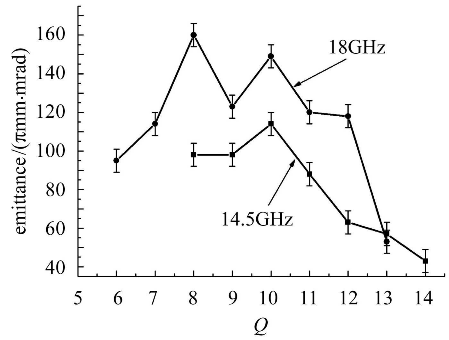

Fig. 5. Emittances of different charge state ion beams when different frequency microwave is used to heat an ECRIS.

Easy to see, higher frequency RF power feeding induces larger emittance for the same charge state ion beam. This might be the reason of the increase of ion temperature T_{i} with the increase of RF frequency when the same RF power is fed, which can be deduced from G. Melin's formula to estimate T_{i}[5, 6]. From Fig. 5 we can also conclude that the ion beam emittance decreases with the increase of charge state. This result is well consistent with D. Wutte's[7] and P. Sortais'[8] results.

5 Gas mixing and biased-disc[9] influences

In this experiment, four kinds of ion beams have been taken into account, and they are Ar^{6+}, Ar^{8+}, Ar^{11+} and Ar^{13+}. During the experiment, the feeding 14.5GHz RF power was kept as P_{w} = 600W, and the magnetic field B_{inj} = 1.5T, B_{min} = 0.43T, B_{ext} = 1.16T was also kept unchanged. To have a systematic investigation of the influences of these two aspects, this experiment is divided into four groups: (1) no mixing gas + no voltage on biased-disc, (2) mixing gas + no voltage on biased-disc, (3) no mixing gas + biased-disc, (4) mixing gas + biased-disc. The mixing gas is $^{16}O_2$ and the voltage on the biased-disc is −26V if the voltage is applied. The results are shown in Fig. 6.

Fig. 6 indicates that mixing gas can effectively reduce the emittances of higher charge state ion beams.

When a negative voltage is applied on the biased-disc, the emittance of the investigated ion beam is also decreased. When the mixing gas and biased-disc effects work together, the reduction of the considered ion beam emittance is not the superposition outcome of these two effects. It is also obvious that in any condition the ion beam emittance becomes smaller with the increase of the ion charge state, and the difference between the four groups is smaller when the ion charge state is very high.

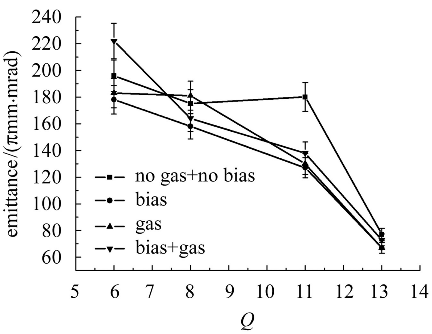

Fig. 6. Gas mixing and biased-disc influence on extracted ion beam emittance from an ECRIS.

6 Analysis and discussion

Many aspects are related to the emittance of an ECR ion source, which makes the corresponding study very sophisticated. It was demonstrated that the emittance of the source depends upon the plasma parameters: the electron density n_e and temperature T_e; the plasma potential ϕ; the ion temperature T_i, the magnetic field at the extraction B and the design of the extraction system can strongly affect the plasma boundary and thus influence the emittance[10]. Moreover it has been observed and proved theoretically that the emittance is a function of the charge state, as is shown in Fig. 5. Till now many experimental and theoretical studies have been done on ECRIS emittance, but it is too hard to have a comprehensive physical image. Someone considers the influence of the ion temperature of an ECR plasma, and assumes that there is no longitudinal component of the extraction electric field and also neglects the influence of the edge effect of the hexapole to the plasma density spatial distribution[11], a useful estimation of the emittance is given as (since the extraction hole is very small compared to the inner radius of hexapole, influence of hexapole magnetic field can be neglected.):

$$\varepsilon = r\sqrt{\frac{T_i}{2QeU}} + r^2 B\sqrt{\frac{Qe}{8MU}}\ , \qquad (1)$$

where Q is the charge state, U is the extraction HV, r is the outlet aperture of the plasma electrode, M is the mass of the ion.

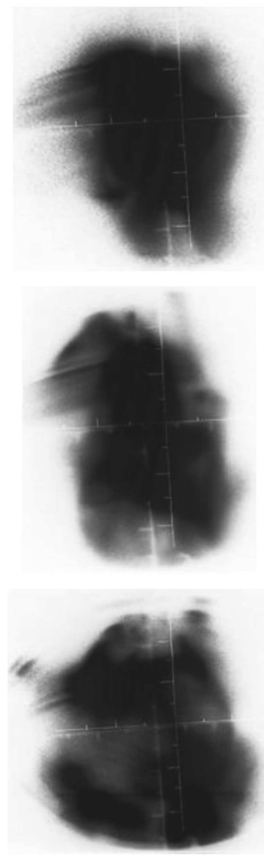

Fig. 7. Ion beam profiles of Ar^{6+} at different RF power: 50W (top plot), 200W (middle plot) and 500W (bottom plot).

Supposing that when the extraction magnetic field is varying, while the other parameters keep constant, we may have $\varepsilon = \varepsilon_0 + k(Q)^{1/2} \cdot B$, which indicates that the emittance is proportional to B. Here, $k(Q)^{1/2}$ is the slope coefficient. We can conclude the higher the ion charge state, the faster the emittance increases with the increase of B (as illustrated in Fig. 4). From Eq. (1) we can see the influence of the ion temperature to the ion emittance. According to G. Melin and A. G. Drentje's theoretical calculation results of ion temperature T_i, it is remarked that the more RF power fed into the plasma, the higher the ion temperature. So, it is reasonable that the ion beam emittance gets some augmentation when more RF power is fed (as shown in Fig. 3). ECRIS plasma is a complicated self-consistent system. When RF power is larger than a certain value, the emittance variation tendency alters, which indicates another regime of the plasma. Similarly, for different B-mode, the working regime of an ECR ion source is different, and therefore the emittance variation mode alters in some way. Additionally, it was also observed on the fluorescent target that RF power influences the extracted ion beam profile a lot. At different RF power the profile is different (as is shown in Fig. 7), which indicates different quality ion beams have been delivered to the experimental terminal.

The injected RF frequency affects the plasma of an ECR ion source a lot, such as n_{e}, n_{i}, ϕ, T_{e}, T_{i} and etc. Thus, the influence to the emittance of the extracted ion beam is obvious. It is empirically believed that higher RF frequency might induce larger emittance, which is experimentally demonstrated in Fig. 5. G. Melin et al theoretically think that T_{i} is associated with the other parameters of an ECRIS plasma by the following correlation:

$$T_{\mathrm{i}}^{7/2}=k_{\mathrm{ei}}k_{\mathrm{c}}a^2\left(\frac{n_{\mathrm{e}}^2Q_{\mathrm{eff}}}{\sqrt{T_{\mathrm{e}}}}\right)\times \left(\frac{\sum\limits_{\mathrm{i}}\sqrt{A_{\mathrm{i}}}\sum\limits_{Q}I_{\mathrm{i}}^{Q}Q^3\cdot\sum\limits_{\mathrm{i}}\frac{1}{A_{\mathrm{i}}}\sum\limits_{Q}I_{\mathrm{i}}^{q}Q^3}{\sum\limits_{\mathrm{i}}\sum\limits_{Q}I_{\mathrm{i}}^{Q}Q^3\cdot\sum\limits_{\mathrm{i}}\sum\limits_{Q}\frac{I_{\mathrm{i}}^{Q}}{Q^3}}\right), \qquad (2)$$

here, Q_{eff} is the average charge state. If the same ion species is considered, the other parameters can be neglected in the analysis expect for $n_{\mathrm{e}}^2Q_{\mathrm{eff}}/\sqrt{T_{\mathrm{e}}}$ item. Assuming under the same RF power feeding condition, since the plasma density n_{e} has got its maximum at lower RF power injection and the maximum n_{e} value is related to the RF frequency ω by the equation: $n_{\mathrm{e}}\propto\omega^{2}$[12], and the coefficient Q_{eff} is empirically proved to be proportional to ω provided that high enough magnetic field is available[13], then under the same condition, higher RF frequency induces larger T_{i}, and according to Eq. (1), the increment of extracted ion beam emittance is obvious.

When mixing gas is added to the ECRIS plasma, the ions of auxiliary gas has the ion cooling effect on the main gas ions (especially on the higher charge state ions) resulting from the mass effect in ion-ion collisions[6], thus the ion temperature of higher charge state is lowered. In addition, the plasma potential ϕ is also decreased by the mixing gas effect. Then accordingly, emittance of higher charge state becomes smaller. The biased-disc is believed to apply an external disturbance to the plasma. When negative voltage is applied on the biased-disc, the plasma potential is possibly reduced, and therefore the transverse velocity of the extracted ions is decreased, which results in lower ion beam emittance.

Although much experimental work has been dine on the correlation of ECRIS plasma and the extracted ion beam emittance, it is still a preliminary test. Many questions are still open. More precise and systematic experiments are expected.

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ECR离子源束流发射度的实验研究*

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摘要 利用最新自行研制的电扫描发射度探测系统,在ECR离子源上进行了一系列关于ECR离子源引出束流发射度的研究.这套电扫描发射度探测系统安装在中国科学院近代物理研究所(兰州)的LECR3试验平台的束运线上.试验中,通过测量相关参数,研究了磁场、微波、掺气效应及负偏压效应等对引出束流发射度的影响.利用实验所得的结果与关于ECR等离子体和离子源束流发射度的半经验理论,分析推导了离子源各可调参数与ECR等离子体的直接关系,这为分析探索ECR离子源的工作机制提供了一定的参考依据.

关键词 ECR离子源 发射度 ECR等离子体

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