METHODS TO OBTAIN HIGH INTENSITY PROTON ION BEAMS WITH LOW EMITTANCE FROM ECR ION SOURCE AT PEKING UNIVERSITY*

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Abstract

With the development of accelerator technology, to obtain an ion beam with high intensity and low emittance is becoming one of the main goals of research for ion sources. At Peking University (PKU) we have developed several 2.45 GHz Permanent Magnet Electron Cyclotron Resonance (PMECR) ion sources for different projects. More attentions were paid on beam intensity increasing and beam emittance reduction. The essential methods to improve beam intensity are increasing the plasma density inside the discharge chamber and improving extraction efficiency of the wanted ions. To suppress the emmitance increasing of an extracted beam, the shape of the electrodes as well as the voltage of suppression electrode and the perveance of extraction system have been carefully selected. With these efforts, a 120 mA total proton beam with a duty factor of 10% has been extracted from the PMECR ion source at 50 kV, and the measured normalized rms emittance is less than 0.2 π mm.mrad. The beam current density at the extraction aperture is as high as 424 mA/cm^2.

INTRODUCTION

The production of high current beams with low emittance is a key point for ion source to satisfy the requirements of different accelerators in the coming years, either related to the industrial applications and to the research projects. Some of the accelerator projects are designed to use H^+/D^+ ion beam with currents in the range of several tens or even hundreds of milliampere, such as IPHI [1], TRASCO [2], FAIR [3], CPHS [4], IFMIF [5] and PKUNIFTY [6] projects. The parameters of these projects are shown in Table 1.

The 2.45 GHz electron cyclotron resonance (ECR) ion source is a good choice to produce these high current beams with low emittance because it has outstanding advantages of high reliability, high availability, compact structure, good reproducibility, high duty factor, and the ability to operate in Continuous Wave (CW) mode or pulsed mode. To obtain an intense beam with low emittance from the ECR ion source, necessary methods should be adopted to increase the extracted beam intensity with the improvements in plasma density and extraction efficiency, and to reduce the beam emittance at the same time. At PKU we have developed several 2.45 GHz ECR ion sources with these requirements for different projects [7-9]. During the research process, we made great efforts to improve plasma density and extraction efficiency. The extraction geometry improvements as well as the higher voltage of the suppression electrode and the optimized perveance of the extraction system have also been tested to reduce beam emittance of the ion source. Details will be described in the following sections.

Table 1: High Current Accelerator Requirements

	p/D$^+$	mA	ms	Hz	Duty factor	π mm.mrad
IPHI	p	100	CW	CW	100%	0.25
TRASCO	p	30	CW	CW	100%	0.2
FAIR	p	100	1	4	0.4%	0.28
CPHS	p	50	0.5	50	2.5%	0.2
IFMIF	D$^+$	125	CW	CW	100%	0.25
PKUNIFTY	D$^+$	50	1	100	10%	0.2

BEAM INTENSITY IMPROVEMENTS

Increasing Plasma Density

Microwave Coupling Methods: Coupling improvements between microwave and plasma are a key factor to design more powerful ECR and microwave ion sources. Experimental results confirm that an optimization of the microwave coupling can significantly increase the plasma density of the ECR ion sources [10]. For the microwave driven ion source, ridged waveguide [11], coaxial cable [12] and dielectric microwave window (with thickness equivalent to λ/4 or 3λ/4) [7, 13] are three types normally used for microwave coupling. The ridged waveguide has significant advantages in long lifetime and high coupling efficiency, and the coaxial cable and dielectric window can have simple structure for the compact ion source. At PKU, the results of compared experiments showed that the function of dielectric microwave window with special design is equivalent to a ridged waveguide for microwave coupling [9]. Finally, the dielectric microwave window is adopted for the 2.45 GHz PMECR ion source because of the system complexity of the ridged waveguide and the high power loss of the coaxial cable in transmission, although its lifetime is limited with backstream electron bombardment.

In order to have good impedance matching and long lifetime, a double-layer dielectric microwave window is developed for our PMECR ion source at PKU [13]. The microwave window should be installed at the location of high magnet field more than 875 Gs within the ion source

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to ensure the injection of microwave power. The window consists of three alumina blocks with dielectric constant 9 and it works as vacuum seal as well. In the meantime, 2 mm BN (Boron Nitride) disk toward the plasma is used to protect alumina blocks and to increase the plasma density with a high secondary electron emission coefficient. A cut away view of the ion source with the microwave window is shown in Fig. 1. The size of the alumina block is 30 mm in thickness (equivalent to about $3\lambda/4$), which is advantageous for the plasma to absorb microwave power. With this special designed microwave window, a 96.3 mA / 50 keV H^+ beam was obtained when 0.95 kW microwave power was fed into the discharge chamber in CW mode [14]. The experimental results show that coupling efficiency ($\eta=FP/(FP+RP)$, FP is forward power and RP is reflected power) between the microwave line and plasma is as high as 97.2% ~ 98.8% with the help of three-stub tuner.

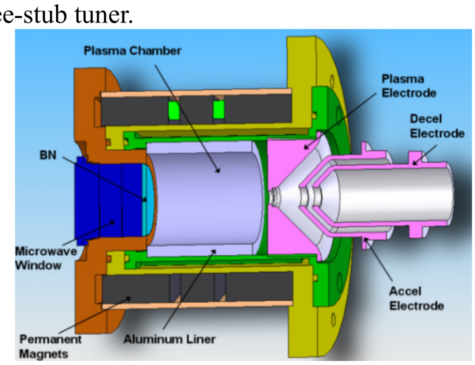

Figure 1: A cut away view of the ion source.

Material and Inner Size of Discharge Chamber: Increasing ECR plasma electron density is another way to improve the plasma density and beam intensity, and it also has positive effects on the plasma stability and reduces the necessary input microwave power at a given beam output [15]. With theoretical analysis, different materials of the discharge chamber or inserted liner with different secondary electron emission can influence the plasma electron density. Experiments with liners of the same size but different materials including Cu, Al, stainless steel and alumina, confirm that the ion source with an aluminum liner can produce the highest beam current [16]. That because Al is easy to be oxidized and a thin alumina film with high secondary electron emission coefficient is formed on the surface of aluminum liner, but the secondary electron emission of the pure alumina liner is weakened due to the contaminated surface. Furthermore, the aluminum material has the advantage of easy fabrication and good thermal conductivity. So it becomes our preferred chosen for the PMECR ion source to increase the plasma density. The structure of aluminum liner is shown in Fig. 1.

The experiment results showed another advantage of the liner with different inner diameters of 64 mm, 45 mm, 40 mm, 35 mm and 30 mm. The diameter of plasma chamber becomes smaller with a liner, which is helpful to a further increase of the plasma density and the atomic ion fraction [8]. Fig. 2 shows the beam current and beam intensity both increase with the reduction of discharge chamber diameters. Therefore, in order to obtain high plasma density, a suitable aluminum liner should be used in the discharge chamber.

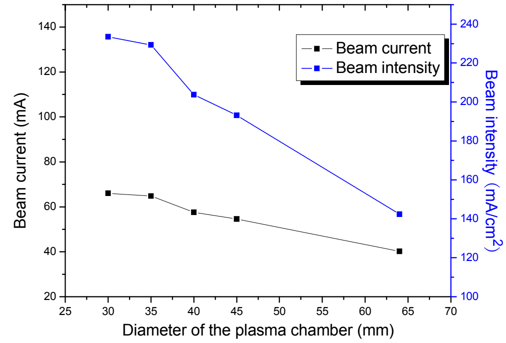

Figure 2: The dependence of beam current and beam intensity on the plasma chamber diameter.

Stable Plasma Sheath

Based on the plasma dynamics theory, a double-layer sheath will be formed at the geometry pinch location. And a voltage jumping appears at that location to keep the plasma at stable state. The particle density at geometry pinch region is increased a lot because of the geometry changes. The principle is plotted in Fig. 3 (left). If the plasma is not stable, the double-layer sheath will oscillate and the jumping voltage will change. As a result the extracted beam will be unstable accompanying with low extraction beam current. The pre-acceleration structure is a good method to solve this problem and it will be carefully studied on our test bench in the near future. The pre-acceleration structure consists of an insulator flake placed on plasma electrode and a thin electrode attached to the flake. A schematic plot of it is shown in Fig. 3 (right). When a pre-accelerator voltage of several hundreds volt was applied between the thin electrode and the plasma chamber, the stable double sheath was obtained, resulting in higher extraction beam current and a decreased beam divergence [17].

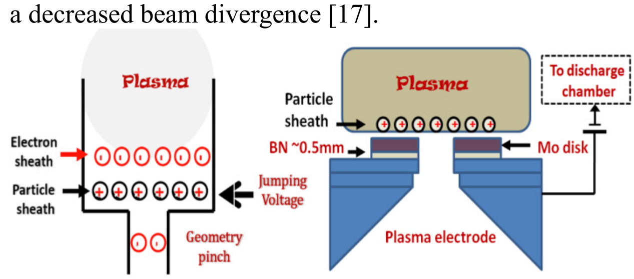

Figure 3: The double layer sheaths caused by geometry pinch (left) and the schematic plot for the pre-accelerator structure (right).

EMITTANCE REDUCTION

Shape of Electrodes

The electric-field distribution around extraction region is determined by the shape of the electrodes which can also influence the ion emissive surface. In order to reduce the beam divergence and obtain low emittance a new tri-electrode extraction system with electrodes of 90° cone apex angle has been developed replacing the original plane extracting electrodes. PBGUNS simulation and comparative experiments between the different extraction systems were carried out on our test bench [18]. The simulation results are shown in Fig. 4. Experiments as the same as simulation results indicated the electrodes with new shape greatly improved the beam distribution and emittance.

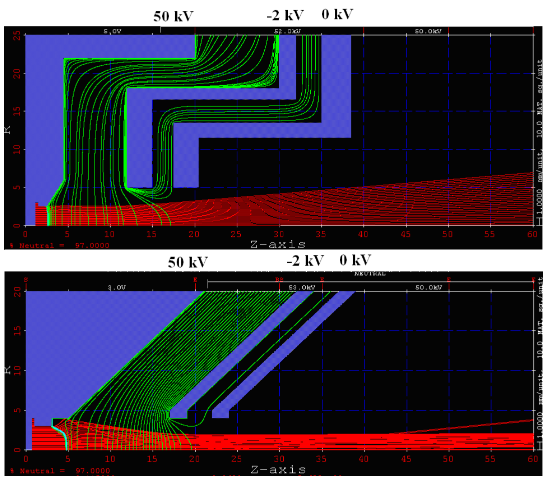

Figure 4: Simulation results of different electrodes.

Voltage of Suppression Electrode

Experimental results show that the beam divergence is sensitive to the voltage of the suppression electrode [18]. The maximum beam half angle varied from more than 65 mrad to 35 mrad as the suppression voltage was changed from -2.3 kV to -2.8 kV, but maintained the level around 35 mrad when the suppression voltage varied from -2.9 kV to -3.8 kV. The reason of these results is that a high voltage applied on the suppression electrode can adjust the ion emission surface and minimize the space charge effect in the drifting region. So, a suitable suppression voltage is the effective method to reduce the beam emittance.

Perveance of the Extraction System

The perveance is defined as the ratio of the beam current I to the three-halves power of extractor voltage V. This parameter depends mainly on the extraction ratio (r/d) of the aperture radius r to the electrode spacing d (between plasma electrode and extraction electrode). A high perveance, which means a high ratio of (r/d), is usually required in order to extract the greatest number of ions from the source for a given extraction voltage [19]. However, the high perveance will cause an increase of the beam divergence [20]. At the same time, the increase of extraction aperture will result in big gas flow, and the reduction of electrode spacing will exacerbate the high voltage spark, especially for the electrodes with 90° cone apex angle. Therefore, the perveance should be optimized to avoid the divergence effect and emittance growth.

CONCLUSION

The beam intensity and emittance are related to many parameters of the ECR ion source. To obtain an intense beam with low emittance should consider all of the factors that influence the beam quality, including of the microwave coupling efficiency, the discharge chamber liner, the extraction efficiency, the electrode geometry, the suppression voltage and the perveance of extraction system. Through the improvements and optimizations of these above parameters, we have extracted 120 mA proton beams from a single 6 mm diameter aperture with high beam density of 424 mA/cm^2 and low rms emittance of less than 0.2 π mm.mrad.

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