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A miniaturized 2.45 GHz ECR ion source at Peking University*

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A miniaturized 2.45 GHz permanent magnet electron cyclotron resonance (PMECR) ion source, which has the ability of producing a tens-mA H^+ beam, has been built and tested at Peking University (PKU). Its plasma chamber dimension is Φ30 mm×40 mm and the whole size of the ion source is Φ180 mm×130 mm. This source has a unique structure with the whole source body embedded into the extraction system. It can be operated in both continuous wave (CW) mode and pulse mode. In the CW mode, more than 20 mA hydrogen ion beam at 40 kV can be obtained with the microwave power of 180 W and about 1 mA hydrogen ion beam is produced with a microwave power of 10 W. In the pulse mode, more than 50 mA hydrogen ion beam with a duty factor of 10% can be extracted when the peak microwave power is 1800 W.

Keywords: miniaturized ECR ion source, hydrogen plasma, continuous wave (CW) beam, pulse beam

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1. Introduction

In the past few decades, electron cyclotron resonance (ECR) ion sources have been rapidly developed for various purposes worldwide.[1–5] However, the dimension of 2.45 GHz ECR ion source limits its applications with some compact equipments, such as neutron generator and ion implantation machine.[6,7] Therefore, a miniaturized 2.45 GHz ECR ion source with the ability to produce a tens-mA ion beam is valuable, if its diameter is less than 200 mm and its length is shorter than 150 mm. Lower cost and easier installation are two additional features for this kind of ion source, so as to be suitable for small equipments. Nowadays, the diameters of those ECR ion sources which can deliver the tens-mA ion beam are generally in the range of 250 mm to 700 mm, and their lengths are between 200 mm and 600 mm. For example, the dimension of Spiral 2 light ion source with a penta-electrode extraction system, which has the ability of delivering 8.3 mA D^+ at 40 kV, is Φ448 mm×510 mm.[8] The size of PKU PMECR II ion source with a three-electrode extraction system, which can produce 130 mA H^+ beam at 50 kV, is Φ280 mm×220 mm.[9] Besides, plasma scaling up can be achieved by distributing elementary microwave plasma sources over two or tri-dimensional networks. The source miniaturization is beneficial to resolve the limitation of plasma uniformity for the array of distributing elementary microwave plasma sources.[10]

Many laboratories have carried out studies on source miniaturization for scientific research and industrial application. Two typical ECR ion sources for portable neutron generators have been built in the Lawrence Berkeley National Laboratory (LBNL). In one source, the microwave is coupled to a Φ100 mm×90 mm plasma chamber through a ridge waveguide.[6] In the other source, the microwave power is coupled to a Φ40 mm×50 mm plasma chamber directly via a microwave window.[11] This research provides an exemplification of source miniaturization by the dimension reduction of the plasma chamber. At Saclay, a new type of ion source has been designed to prevent the emittance growth induced in the low energy transfer line (LEBT). It is based on the use of an additional LEBT short length solenoid close to the extraction aperture to create the resonance in the plasma chamber.[12] The length of the extraction system reduces from 300 mm to 50 mm in this way. However, for this structure, special attention should be paid to the spark risk because of the worse vacuum. In general, the dimension of the plasma chamber and the structure of the extraction system are two difficult issues during the miniaturization of a 2.45 GHz ECR ion source.

A study to further decrease the size of a 2.45 GHz ECR ion source has been launched at PKU. Emphasis is put on the plasma chamber and the extraction system. Both physical and structure design are considered carefully to decrease the size of the plasma chamber in this work. An attempt for an integrated design of the source body and extraction system has been made. Technical details will be presented in this paper.

2. Ion source

The principle of physical design of this ion source is to reduce its dimension as much as possible and keep its per-

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formance at the same time. There is a minimum acceptable diameter of the plasma chamber, since too small diameter would lead to the problem of coupling the microwave from the waveguide to the plasma chamber.[13,14] The experiments in our previous work have proved that tens-mA ion beam can be extracted from a Φ30 mm plasma chamber.[9] When the length of the plasma chamber is shorter than 40 mm, it may have a problem to create a stable plasma. So the dimension of the plasma chamber is set as Φ30 mm×40 mm for the miniaturized ion source. In a waveguide, the primary lower-frequency limitation, which is called the cut-off frequency, depends on the physical size. The cut-off frequency is $c/2a$ for a rectangular waveguide and $c/(\sqrt{\varepsilon}\times 3.412R)$ for a circular waveguide, where c is the speed of light in a vacuum, ε is the permittivity of the dielectric, a is the rectangular waveguide width, and R is the radius of the circular waveguide. In order to couple the microwave into a Φ30 mm plasma chamber from a WR-284 waveguide with cut-off frequency 2.079 GHz, a Φ27 mm microwave window with the cut-off frequency of 2.07 GHz has been used. It can realize TE_{10} in the rectangle waveguide and convert to TE_{11} in the circular waveguide.

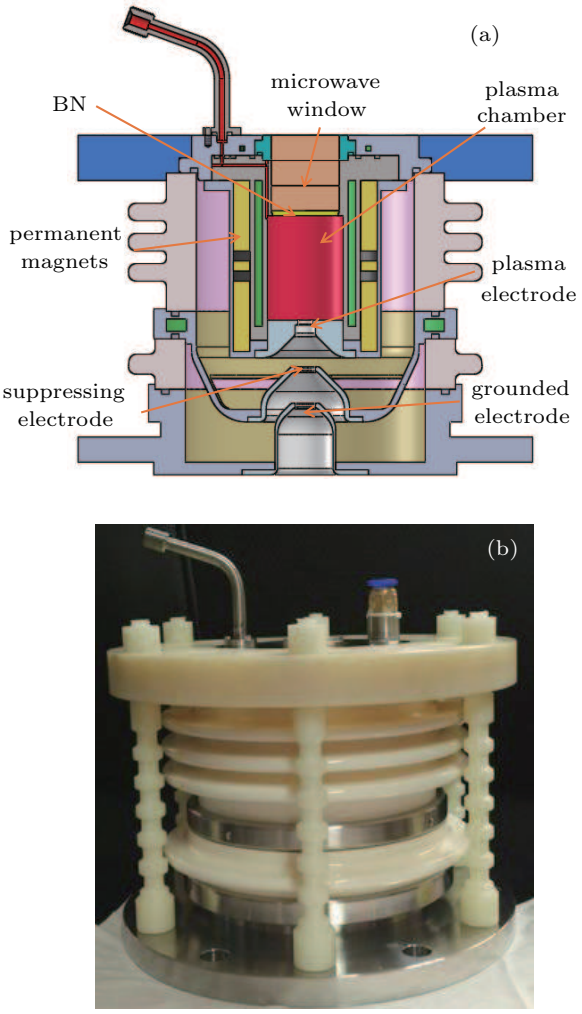


Fig. 1. (color online) A cut away view (a) and a photo (b) of the miniaturized ion source.

The structure design of the miniaturized 2.45 GHz ECR ion source should consider several factors, such as reliable insulation, good mechanical performance, heat-conducting property, enough cooling, etc. We have used a half-embedded structure for the ion source in PKUNIFTY.[15] Based on that experience, a complete-embedded structure is developed for the miniaturized 2.45 GHz ECR ion source. In this structure, the source body is embedded in the extraction system, which is shown in Fig. 1. The isolation distance of the extraction voltage is fully utilized in this structure, so the length of the whole source including the extraction system is only 130 mm. In the radial direction, the plasma chamber, permanent magnet ring, ceramic insulator, and mounting flange should be arranged, and the cooling channel and necessary isolation gap should be arranged, too. After optimization, the diameter of the whole source is Φ180 mm.

To avoid the permanent magnet demagnetization caused by heat, a water-cooling channel that passes around the plasma chamber is used. The water-cooling pipe also passes around the microwave window to reduce the heat loading effect. Thermal analysis results with ANSYS Workbench are plotted in Fig. 2. The water-cooling is enough for the miniaturized ion source. Another water pipe has been added in the pedestal of the suppressing electrode. It can improve the withstand voltage of the extraction system by minimizing the contamination on the acceleration columns and reduce the spark risk caused by the reflection electron heating.

The microwave window consists of three pieces of alumina ceramics about Φ27 mm× 10 mm each and a piece of boron nitride (BN) or silicon nitride (SiN) about Φ27 mm×2 mm which is used to protect the ceramics from the bombarding of electrons. The microwave window not only can couple the microwave from the waveguide to the plasma chamber, but also can work as vacuum sealing. The three-electrode extraction system consists of plasma electrode, suppressing electrode, and grounded electrode. They are made of stainless steel. The aperture diameters of the plasma electrode, suppressing electrode, and grounded electrode are 6 mm, 8 mm, and 8 mm, respectively. The magnetic field distribution along the source axis is saddle-shaped as usual.[16]

The structure of the miniaturized ion source is much more compact than our standard ion source. Figure 3 shows a comparison of the source body between the miniaturized ECR ion source (Φ100 mm×88.5 mm) and the standard ECR ion source (Φ150 mm×117 mm). They have the same components including microwave window, plasma chamber, permanent magnetic rings, plasma electrode, and the cooling structure.

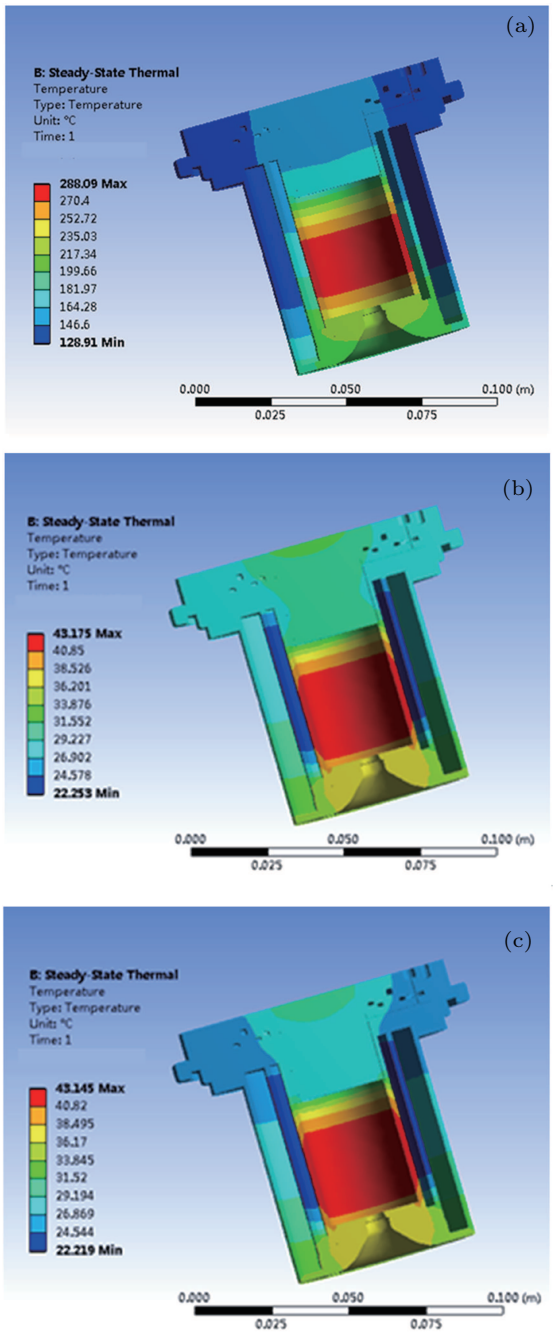


Fig. 2. (color online) Heat loading within the source body: (a) without water cooling, (b) only one water cooling around the plasma chamber, (c) both plasma chamber and microwave window with water cooling.

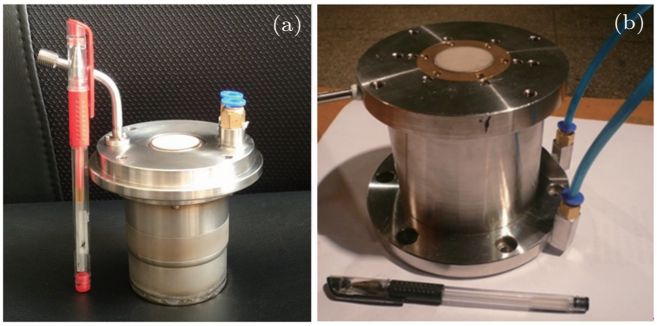


Fig. 3. (color online) The comparison of the source body between (a) the miniaturized ECR ion source and (b) the standard ECR ion source.

3. Experiment results

3.1. Pulse beam

The experiments have been carried out on the PKU ion source test bench described in Ref. [9]. The 2.45 GHz magnetron-based generator (GMP 30 K) provided by Sairem company has been used and the waveguide output is WR-340 (BJ26). The microwave transfers through the rectangular waveguide and couples to the plasma chamber via a Φ27 mm microwave window. The total beam current and proton ratio have been measured with the factor of microwave power and the gas pressure. In the pulse mode, the total beam current of hydrogen can reach 52 mA at 40 kV when the peak microwave power is 1800 W with a duty factor of 10% and the pressure in the vacuum chamber is 1.2×10^{-3} Pa, which indicates a better microwave coupling in our source. The proton fraction measured with the analysis magnet can reach 88% as shown in Fig. 4.

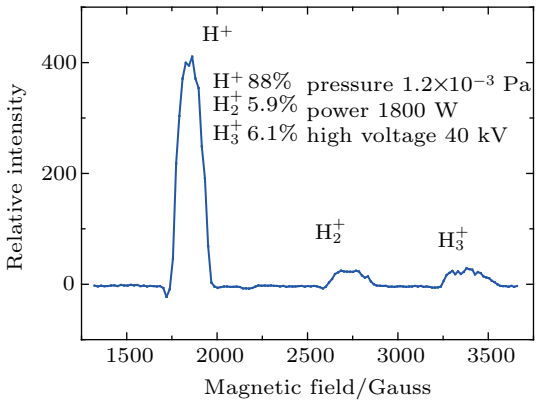


Fig. 4. (color online) The biggest proton fraction in pulse mode.

3.2. CW beam

In continues wave (CW) experiments, a 2.45 GHz solid state microwave generator (GMS200W) offered by the Sairem company, in which the microwave output is a coaxial cable N-type female plug, has been used instead of a magnetron-based generator and a circulator used in the pulse experiment. This generator is more compact than the magnetron-based generator and has a very good frequency spectrum even at low power.[17] A coaxial-to-waveguide transducer with an N-type male plug and a WR-340 (BJ26) microwave output can transfer the microwave efficiently. The maximal current of the CW hydrogen ion beam is 21.7 mA, as shown in Fig. 5. The maximal current is obtained for the microwave power of 180 W at 40 kV when the pressure in the vacuum chamber is 1.8×10^{-3} Pa. This source is a suitable candidate for some ion implantation machines because about 1 mA ion beam can be obtained with lower microwave power. It has proved that the ion beam current of hydrogen reaches 1.1 mA with a microwave power of 10 W, and a 1.0 mA He^+ ion beam is pro-

duced with a microwave power of 15 W. Furthermore, we carried out some experiments to research the relationship between the component of the current and the gas pressure to understand the physical process in the miniaturized ion source.

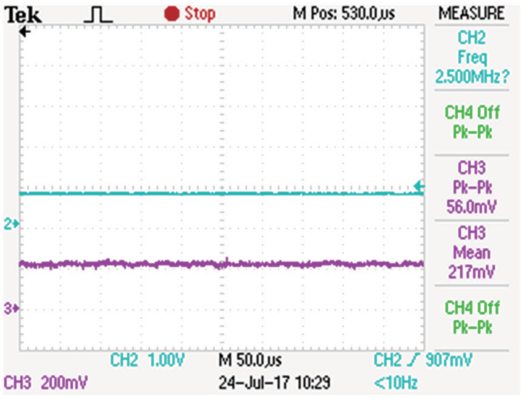


Fig. 5. (color online) The waveform of CW beam (180 W). Blue: microwave signal, pink: total current.

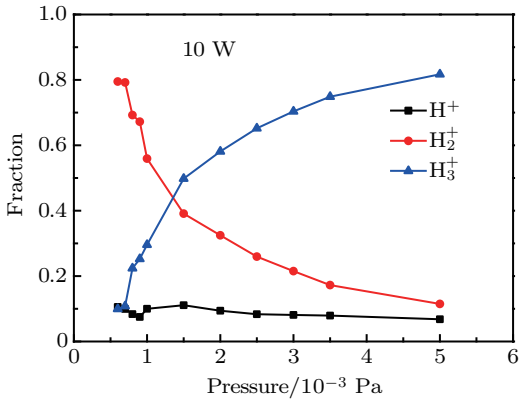


Fig. 6. (color online) The fraction of H^+, H_2^+, H_3^+ as a function of gas pressure.

H_2^+ and H_3^+ ions inevitably exist in the extraction beam of a proton ion source as their production is the essential process in hydrogen plasma, and their yields sufficiently depend on the operation parameters. Figure 6 shows the fraction of the H^+, H_2^+, H_3^+ as a function of the gas pressure when the total current is 1.1 mA with the microwave power of 10 W. It is obvious that the fraction of H^+ is only 10% in the whole range of gas pressure. Cluster ions (H_2^+ and H_3^+) are the majority in the ion beam. The gas pressure plays an important role in the fraction of H_2^+ and H_3^+. The fraction of H_2^+ decreases as the gas pressure increases, the fraction of H_3^+ has an opposite trend totally. The highest fraction of H_2^+ ions reaches 79.5% with lower gas pressure 6×10^{-4} Pa and the highest fraction of H_3^+ ions reaches 81.7% with higher gas pressure 5×10^{-3} Pa. The experimental results and the theoretical analysis both show that lower gas pressure is beneficial for a pure H_2^+ beam and higher gas pressure is beneficial for a pure H_3^+ beam.

4. Conclusion and perspectives

A miniaturized ECR ion source with integrated design of source body and extraction system, whose total size is Φ180 mm×130 mm, has been built and tested at PKU. It has proved that the microwave can couple to a Φ30 mm×40 mm plasma chamber through a Φ27 mm microwave window efficiently. A 52 mA hydrogen ion beam in pulse mode with duty factor of 10% and a 20 mA CW beam have been obtained by changing the operation parameters. Furthermore, it can produce the H_2^+ with the fraction 79.5% and the H_3^+ with the fraction 81.7% by changing the gas pressure. It is beneficial to understand the physical process in the 2.45 GHz ECR ion sources. More research on the plasma behavior of this ion source based on these results will be performed in the future.

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