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NEW PROGRESS OF THE MINIATURIZED MICROWAVE ION SOURCE AT PEKING UNIVERSITY*

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Abstract

The generation of plasma in a microwave ion source involves confining electrons using a static magnetic field and energizing them with an electromagnetic field that transmitted into the plasma chamber. However, according to electromagnetics theory, there is always a cut-off size in circular wave guides for a given frequency. For a 2.45 GHz microwave, this dimension is 72 mm, which should theoretically prevent transmission of the microwave into the discharge chamber and no plasma can be generated. Since 2006 Peking University(PKU) has successfully developed a series of permanent magnet 2.45 GHz microwave ion sources (PKU PMECRs) with a discharge chamber less than 50 mm, capable of delivering tens of mA beams for accelerators. To explain this anomalous phenomenon, a hybrid discharge heating (HDH) mode that combines surface wave plasma (SWP) and electron cyclotron heating (ECH) has been proposed. This HDH mode not only successfully explains PKU PMECRs, but also predicts that the optimized inner diameter of the plasma chamber is 24 mm, which is confirmed by experiments involving different liners in the miniaturized microwave ion source.

INTRODUCTION

Microwave ion sources (MISs) operating at 2.45 GHz have found widespread use in scientific research, industry, agriculture, and medical science due to their high intensity, low emittance, high stability, simple structure, low cost, and long lifetime[1]. For example, tens even hundred milliampere H^+, D^+, etc. ion beams have been obtained by 2.45GHz ECR sources, such as CEA/Saclay, PKU [2][3]. Their rms emittance is about 0.2 π·mm·mrad. Through long term operation test, CEA/Saclay has made a record with 103 hours CW beam operation with no spark or plasma fault occurred in 2001. In 2016, PKU group improved this non-spark record up to 300 hours. Up to now, no new long term CW beam operation result can be found in the world.

Recently, there has been growing interest in high current miniaturized microwave ion sources (MMISs) for use in compact equipment such as neutron generators, ion thrusters, and ion implanters [4-6].Despite impressive performance exhibited by MMISs generating overdense plasma ($n>10\ n_{cutoff}$) over the past few decades [7,8], theoretical studies on the breakdown mechanism of MMISs remain perplexing. Conventional microwave transmission theory suggests that the chamber diameter of a 2.45 GHz MIS should be larger than the cutoff size of a 2.45 GHz microwave [9], implying that microwaves cannot penetrate into the plasma chamber of MMISs with a diameter smaller than 72 mm.

In our previous work, a novel HDH mode is put for-ward to understand the complex mechanism of the MMISs [10]. The HDH mode believes that the initial stage of plasma establishment is based on SWPs and the plasma maintenance is based on ECH. In this paper, we will present the HDH mode in details. Meanwhile, the optimized inner diameter of the plasma chamber will be investigated systematically.

THE MINIATURIZED MICROWAVE ION SOURCE

The MMIS of PKU is composed of microwave window, plasma chamber, permanent magnet rings, and extraction system. A schematic diagram of the source body of the MMIS is presented in Figure 1. The 2.45 GHz microwave of TEM mode produced by microwave generator is transmitted through coaxial line, then transformed to TE10 mode in the coaxial-waveguide transition by a N-type conector and transformed to TE11 mode in circular microwave window and finally injected into the plasma chamber. The microwave window is composed of 3 alumina layers with the diameter of 27 mm. A piece of BN is placed behind the microwave window, which faces
plasma to protect the alumina from the backbombarded electrons. The dimension of plasma chamber is Φ30 mm×40 mm. The mirror magnetic field is produced by a set of permenant magnets surrounded plasma chamber. The diameter of the chamber can be changed by inserting liners with different inner diameters. In addition, three NdFeB permanent magnet rings are installed around the plasma chamber to provide a magnetic field for the plasma confinement. The magnetic field distribution is presented in Figure 2, it can be found that the axial magnetic field is a magnetic-mirror field with B_{max} > 875 Gs. A 50 kV three-electrode extraction system consisting of a plasma electrode, suppressor electrode and ground electrode is used for beam extraction.

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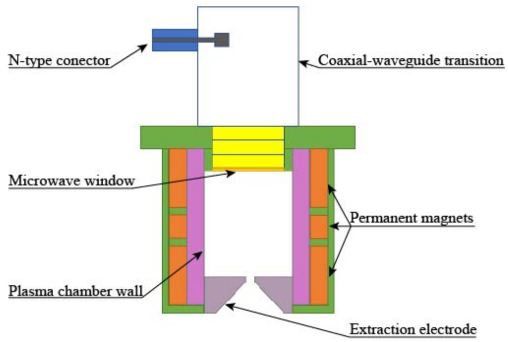

Figure 1: Schematic diagram of the source body of the miniaturized microwave ion source at PKU.

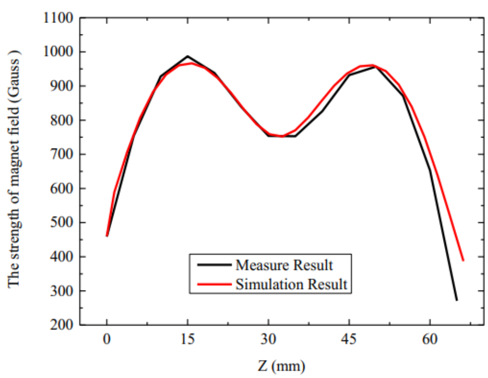

Figure 2: The axial magnetic field distribution of the MMIS.

SIMULATION OF HDH MODEL

The HDH mode believes that the initial stage of plasma establishment is based on SWPs and the plasma maintenance is based on electron cyclotron resonance. In this work, the numerical simulation of the hybrid discharge mode is made using the Ø30 mm MMIS at PKU based on COMSOL Multiphysics, plotted in Figure 3. The temporal behaviour of the plasma density and hot electron temperature up to the steady state condition are calculated and presented. In our simulation, the gas pressure of hydrogen in the plasma chamber is 10 Pa, and the microwave power supplied on the microwave window is 100 W.

As presented in Figure 4, the electron density increases dramatically with the elapse of time, while the electron temperature gradually increases with the elapse of time and reaches the highest value of 36 eV at 2.5×10^{-7} s, then gradually decreases and finally reaches a certain stable value [10].

Furthermore, at the stage of stable plasma, the plasma properties are analysed in pure ECH or SWPs. As shown in Figures 5 and 6, the electron density increases as the inner diameter increases from 20 mm to 30 mm in the mode of pure ECH. What stands out is that in the mode of SWP without the confinement of magnetic field, however, the electron density can reach the maximum when the inner diameter is 24 mm and then decreases as the inner diameter decreases or increases. The simulation of stable plasma in MMIS points out the possibility of further miniaturization of MMIS.

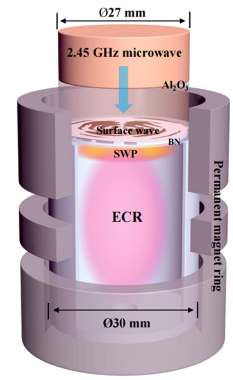

Figure 3: Schematic diagram of the HDH mode for MMIS.

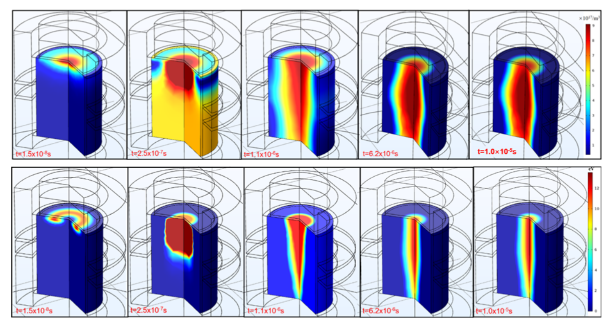

Figure 4: Profiles of the electron density (up) and electron temperature (down) at different time steps [8].

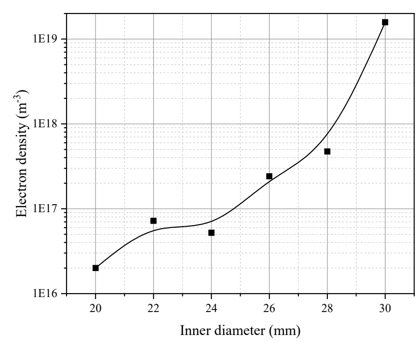

Figure 5: Dependence of electron density on inner diameter with pure ECH mode.

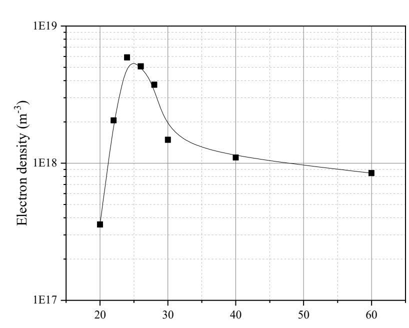

Figure 6: Dependence of electron density on inner diameter with pure SWPs which means no confinement by magnetic field.

EXPERIMENT RESULTS

According to the simulation results, 4 stainless steel liners with different inner diameters are inserted into the plasma chamber of the MMIS. The dependence of high voltage load on pressure, with different liners, is shown in Figure 7. As the pressure increases, the changed point of pressure describes the high voltage load starts to have a rapid growth and the maximum point is the pressure related to the maximum of high voltage load. With the different liners, the high voltage loads have the same changing trend. The dependence of maximum point and change point on the inner diameter is shown in Figure 8.

Among the four liners, the MMIS with the inner diameter of 24 mm can produce the highest high voltage load above 40 mA which is the higher than ones with other liners. This experiment result confirms the stable plasma of simulation, which means in stage of the plasma maintenance, SWPs is important to produce overdense plasma in MMIS.

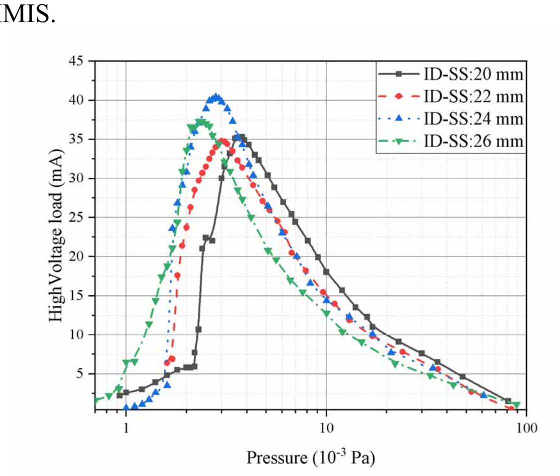

Figure 7: Dependence of hydrogen beam current on pressure with different chamber diameters.

DISCUSSION AND OUTLOOK

In this work, the HDH mechanism is proposed and studied based on the MMIS at PKU. The spatial and temporal evolution and stable discharge of the electron temperature and electron density have been investigated. The changing trends of electron density with increasing inner diameters in pure ECH mode and pure SWP mode are compared. Preliminary experiments indicate that the MMIS has even better performance than the traditional PMECR at PKU and the optimized diameter of plasma chamber is 24 mm. All of these results have illustrated the rationality of the HDH mode. This work, we believe, is helpful to the comprehension and miniaturization of MISs.

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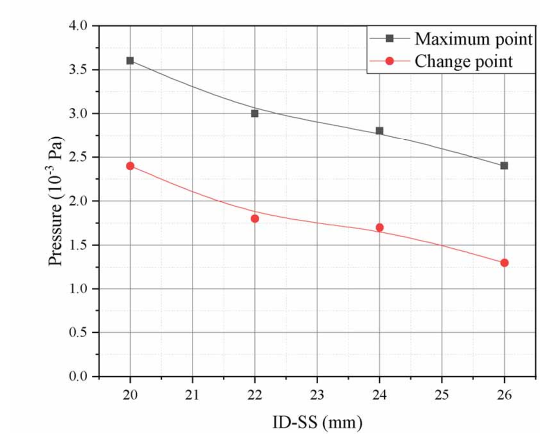

Figure 8: Dependence of maximum point and change point on the inner diameter of liners.

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