The microwave absorption of ceramic-cup microwave ion source*

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Abstract An experiment system of ceramic-cup microwave ion source has been built here. Its microwave absorption efficiency as a function of the magnetic field and the pressure is presented. When the microwave incident power is 300~500W the microwave absorption efficiencies are more than 90% if the system is optimized and the magnetic field at the microwave window is 0.095T.

Keywords Intense neutron tube, Microwave ion source, Absorption efficiency

CLC numbers O571.53, TL929, TN62

1 INTRODUCTION

The purpose of studying ceramic-cup microwave ion source is to develop intense neutron tube of which neutron yield is 5×10^{12}n/s. Ion source is one of the main components of the neutron tube and the microwave ion source is a new kind being developed in recent years. Compared with the Penning ion source, the duoplasmatron ion source and the high frequency ion source, the microwave ion source has the main advantages of higher atomic ion ratio, lower stable performance pressure, no electrode required in the discharge area.[1]

The common ECR (Electron Cyclotron Resonance) ion sources employ 2.45 GHz microwave coupled with a microwave window to terminate the longitudinally magnetized plasma. The microwave ion source is used for plasma etching and ion implantation,[2~4] as well as for plasma propulsion and fusion applications. These studies have demonstrated that the microwave ion source can heat the plasma at the ECR resonance, polarize waves and produce high-density plasma efficiently.

Microwave absorption efficiency is a major parameter of the microwave ion source. It is very important for improving operational stability of the ion source, increasing atomic ions ratio and utilizing energy efficiently. The microwave absorption efficiency as a function of magnetic field distribution and pressure was studied and some satisfied results obtained.

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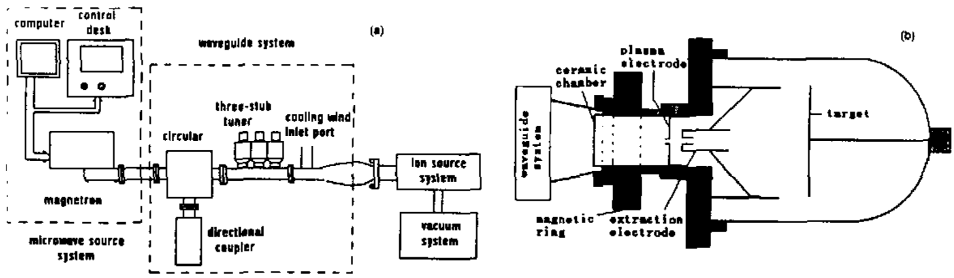

Fig.1 The scheme of the experimental setup of the microwave ion source
(a) The block graph of experiment facilities, (b) Ion source and vacuum system

2 EXPERIMENTAL FACILITIES

The scheme of the experimental setup of the microwave ion source is shown in Fig.1a.It consists of a microwave source, a microwave guide system, an ion source system and a vacuum system (shown in Fig.1b). The microwave power is generated by a CW power (MPG-2010C provided by High-energy Institute of Electronic Science- technology University) at a frequency f=2.45 GHz and introduced into the plasma chamber via a vacuum window which worked also as a matching element in the microwave circuitry. The forward microwave power can be continuously varied from 300 to 1000 W and controlled by a computer. The microwave guide system includes a circulator, a directional coupler and a three-stub tuner. The incident P_i and the reflected power P_r are measured and monitored by the directional coupler. The three-stub tuner is installed adjacent to the plasma chamber to match the plasma impedance with that of the microwave source circuit. To protect the magnetron from reflected power, the circulator with a dummy load is installed to the magnetron waveguide output. Plasma resonance chamber made of 95%Al_2O_3 ceramic material is explored, of which the outer diameter is 50 mm, the inner diameter 40 mm, the length 100 mm, and the bottom thickness about 10mm. The ceramic-cup plasma resonance chamber is employed in order to meet the special requirement of the intense neutron tube. Intense neutron tube needs high-beam currents, dissipating a few to tens of kilowatt power in the target. Cooling systems based on water or Freon as the coolant are used, so it is better to put the target to be at zero potential. However, high voltage isolation is still a problem for ion source with 200~250 kV high potential. The Al_2O_3 ceramic material can transport microwave without impedance and isolate to high voltage excellently. In addition, it can increase microwave absorption efficiency because its dielectric coefficient is high and it can work at high temperature, so it is the moderate material for our study. The magnetic ring is placed along axis of plasma chamber. Moving the magnetic ring causes changes in the distribution of the magnetic field. The detail of the magnetic ring design will be described in next section. The vacuum house is made of glass through which we can observe the phenomenon of ion extraction. Extraction peak voltage is adjustable in the range of 0~30 kV. There is a 20 kΩ resistance between the extraction electrode and the target, which is used to restrain the secondary electron. The vacuum system can provide a low pressure up to 10^{-3} Pa.

3 DESIGN OF MAGNETIC RING

The microwave ion source is also called the microwave-driven ion source. The absorbed microwave is used for electron acceleration and this results in excitation and ionization of particles, and formation of plasma. When microwave energy accelerates the free electron, ECR mechanism is utilized. Microwave frequency is equal to the frequency of the electron under ECR condition (ω_{ce}).

$$\omega_{ce} = Be/m = \omega_{rf}$$

where B is the magnitude of the local magnetic field, e and m are electron charge and mass, respectively. $B = B_{ce}$=0.0875 T for 2.45 GHz microwaves. ω_{ce} and ω_{rf} are the electron cyclotron frequency and the microwave radiation frequency, respectively.

According to Popov[5], microwaves are linearly polarized waves. They can be decomposed into the right-hand polarized (RHP) waves and the left-hand polarized (LHP) waves. It is well known that only the RHP waves can be dissipated in the ECR heating and the LHP waves cannot be absorbed in ECR. The high level of microwave power absorption (>95%) was reported in the overdense plasma. These experiment results could be achieved only if there is a mechanism that stops microwave propagation downstream and provides a very high level of microwave power absorption of both RHP and LHP waves. An interpretation of the efficient absorption of linearly polarized wave entering the overdense ECR-type plasma is based on the experimentally observed transformation of RHP and LHP waves into short wavelength plasma waves which strongly attenuate in Landau damping. It occurs at sites where the plasma density is close to N_{cr} (N_{cr} is the maximum plasma density through which the microwave cannot propagate in the absence of the magnetic field) and the angle between the magnetic field strength (B) and the wave propagation direction is small.[5] When pressure is lower than 1 Pa, $B > B_{ce}$ and $B < B_{ce}$ Landau damping could be a major mechanism of microwave plasma maintenance. On the other hand, according to Stevens' theoretical analysis[6] and the experimental results on optimizing and coupling microwave of ECR plasma source, when the microwave window reaches matching condition of 1/4 wavelength, it acts as a 1/4 wavelength transformer. With the growing of plasma density, the magnetic field at the microwave window would be greater than that in ECR condition.

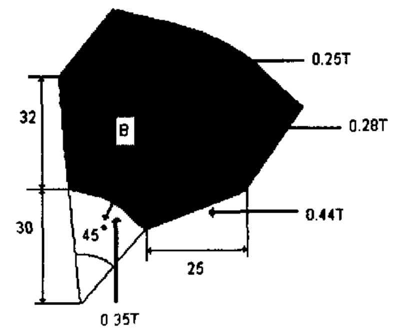

Fig.2 the structure and magnetic field strength of single NdFeB magnetic block

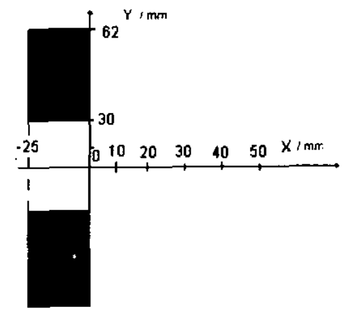

Fig.3 the structure of the $\phi 124 \times \phi 60 \times 25$ mm magnetic ring

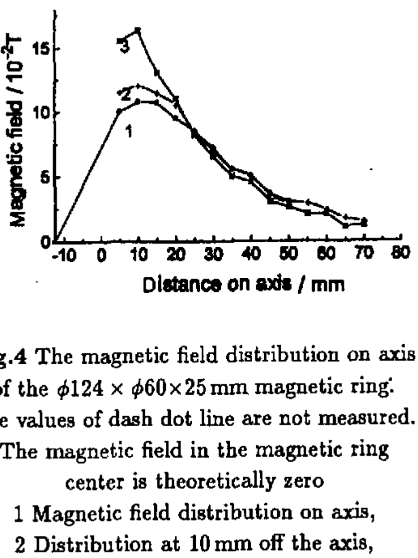

Fig.4 The magnetic field distribution on axis of the $\phi 124 \times \phi 60 \times 25$ mm magnetic ring. The values of dash dot line are not measured. The magnetic field in the magnetic ring center is theoretically zero
1 Magnetic field distribution on axis,
2 Distribution at 10 mm off the axis,
3 Distribution at 20mm off the axis

Based on above mechanism and Taylor's study[7~9] on magnetic field mode of dc proton source in Chalk River Laboratory, Canada, we have designed a kind of magnetic field mode.[10] We employ eight NdFeB magnetic blocks with 25 mm in thickness to adhesive as a $\phi 124 \times \phi 60 \times 25$ mm magnetic ring. The shape of NdFeB magnetic block and its magnetic field strength is shown in Fig.2.

The magnetic ring made by eight NdFeB magnetic blocks is shown in Fig.3.Its magnetic field distribution along axis is shown in Fig.4. From Fig.4, it can be seen that the magnetic field distribution is rather uniform and the region (0.085 ~0.095 T) is about 5 mm.

4 EXPERIMENT RESULT

Microwave incident power is 300~500 W in the experiments and the gas pressure is $2\times10^{-3} \sim 10^{-1}$ Pa. The best impedance matching between microwave electric circuit and ion source is got by tuning three-stub tuner, and the microwave absorption efficiency as a distribution on axis of function of magnetic field and the pressure is studied.

4.1 The relations between microwave absorption and magnetic field distribution

The magnetic field distribution is varied by changing the position of the magnetic ring along the axis of the plasma chamber, which is shown in Fig.5. By varying the distance (S) between microwave window and magnetic ring surface, the magnetic field distribution in the plasma chamber is varied. This variation affects greatly microwave absorption. The position of the plasma resonance chamber is fixed in experiment and the magnetic field distribution is varied by changing S, so the microwave absorption is changed. The relation between microwave absorption efficiency and S is shown in Fig.6. The microwave absorption efficiency as a function of the magnetic field distribution is shown in Fig.7.

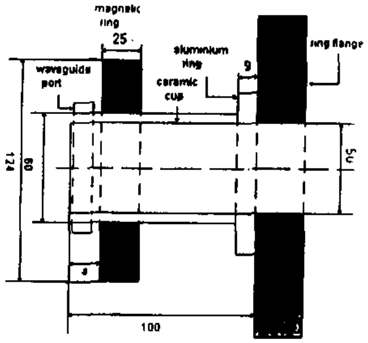

Fig.5 Magnetic ring position on plasma resonance chamber

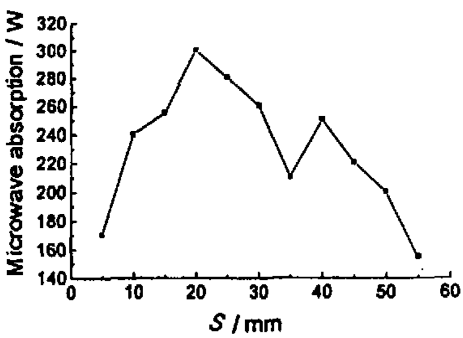

Fig.6 The microwave absorption against S

From Fig.6 and Fig.7, it can be known that when the magnetic field at microwave window is 0.095 T(S=20 mm), the microwave absorption is optimal. The absorption efficiency is 100% when the incident microwave power is 300 W.

4.2 The relations between microwave absorption efficiency and pressure

Based on section 4.1, the magnetic ring is kept in the optimized position (S=20 mm), where the magnetic field at the microwave window is 0.095 T. Then by varying the pressure the relation between microwave absorption efficiency and pressure is obtained, which is shown in Fig.8.

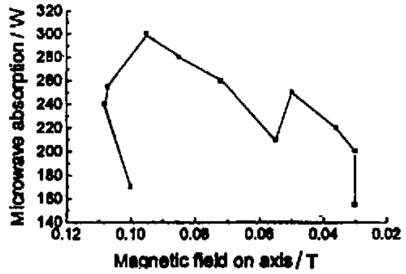

Fig.7 The relation between microwave absorption efficiency and the axial magnetic field

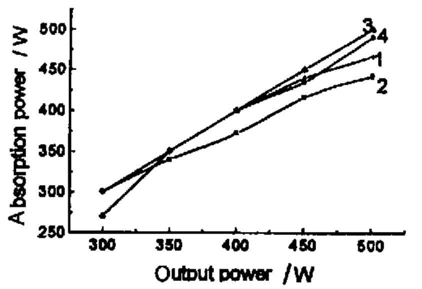

Fig.8 the relations between microwave absorption efficiency and pressure
1- 2×10^{-3} Pa, 2- 3×10^{-2} Pa, 3- 4×10^{-1} Pa, 4- 1.5Pa

From Fig.8, it can be seen that the microwave absorption efficiency is hardly affected by the pressure. It decreases slowly with the increasing of the incident microwave power.

5 DISCUSSION

Microwave absorption efficiency is related to the following parameters: impedance matching between microwaves electric circuit and plasma source, magnetic field strength and its distribution, and pressure.

Theoretically, the impedance of a plasma-filled ion source depends on electron temperature, electron density, as well as magnetic field and its distribution. In addition, electron density and electron temperature change in a highly complicated way, depending on the absorbed microwave power, gas pressure, and magnetic field. In practice, when the geometric structure of the ion source, pressure, and magnetic field are determined, the plasma parameters are fixed, depending on absorbed microwave power. The best station of impedance matching between the microwave circuit and the ion source can be obtained by tuning three-stub tuner.

The key to the microwave absorption is the magnetic field at the microwave window. When the magnetic field strength at the microwave window is greater than 0.0875 T of ECR, the microwave power absorption was located mainly in two sites: (1) near the microwave window (2~3 cm) where the microwave electric field seems to have a maximum amplitude and plasma density has a steep gradient with a magnitude of N_e close to N_{cr} (Landau damping), and (2) at sites along the plasma chamber where the magnetic field has a value of 0.0875 T(ECR heating). Since only the RHP wave can be absorbed in ECR, it is necessary to provide a 0.095 T magnetic field at the microwave window. The condition is obtained by adjusting the magnetic field distribution. From Fig.6 and Fig.7, it can be seen that when the magnetic ring is moved a small distance, the magnetic field distribution in the chamber changes and the microwave absorption efficiency varies a lot. When the magnetic field at the microwave window is 0.095 T, the microwave absorption is in optimum station. It is up to 100% when the incident microwave power is 300 W. This result is also in agreement with Stevens' conclusion.[6]

From Fig.8, it can be known that the microwave absorption efficiency varies very little with the pressure. It shows that the microwave absorption is still good at low pressure, which is important for the intense neutron generator, because the chance of collision between ions and neutral molecules is smaller at low pressure than that at high pressure. This avoids discharge and is useful in solving the high voltage isolation problem.

Based on these results, the experiments of the ion extraction, ion beam optics and the atomic ions ratio will be done in the future.

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