EMISSION SPECTROSCOPY DIAGNOSTIC OF PLASMA INSIDE 2.45 GHZ ECR ION SOURCE AT PKU*

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Abstract

The 2.45 GHz permanent magnet electron cyclotron resonance ion source (PMECR) at Peking University (PKU) can produce high current hydrogen molecular ions H_2^+ and H_3^+ under different conditions, but the physics processes and plasma characteristics within the discharge chamber are not very clear until now. Langmuir probe, laser detachment, absorption spectroscopy and optical emission spectroscopy are common approaches for diagnosing the plasma. Among those methods, optical emission spectroscopy is a simple *in situ* one without disturbing the plasma. To better understand the plasma producing processes, a new ion source with transparent quartz discharge chamber was designed at PKU so that plasma diagnostic can be performed through directly detecting the light generated within ECR zone by fibre optics. A collisional radiative (CR) model is used to calculate plasma parameters like electron density n_e and electron temperature T_e for non-equilibrium plasma in ECR ion source.

INTRODUCTION

High current hydrogen molecular ion source for the generation of both H_2^+ and H_3^+ ions is developing at PKU as they can be potentially applied in high current linac, cyclotron or medical synchrotron[1][2]. The 2.45 GHz ECR ion source at PKU, which can produce more than 100 mA proton, was chosen as the device for obtaining molecular ions. Studies on the inner dimension of source chamber, opreation pressure, microwave power and also pulsed duration indicated some promising results that pure 40 mA H_2^+ and 20 mA H_3^+ ions could be generated with both species fractions approximating 50% by only tuning the operation parameters[3][4]. Besides, a 2.45 GHz microwave driven negative ion source developed at PKU got some promising results that more than 15 mA H^- ions was extracted in pulsed mode recently[5]. These experimental results make us want to know more about the plasma behaviours which are very important in the generation and destruction of H_2^+, H_3^+ and H^- inside the source. Obviously, the pressure inside discharge chamber will influence electron temperature which determines the cross-sections of many interaction processes, and RF-power will also contribute a lot to electron density. It will be better to figure out the relation of these parameters with plasma characteristics, so diagnosis was introduced for getting more information about crucial plasma parameters in ECR ion source such as electron density, electron temperature etc.

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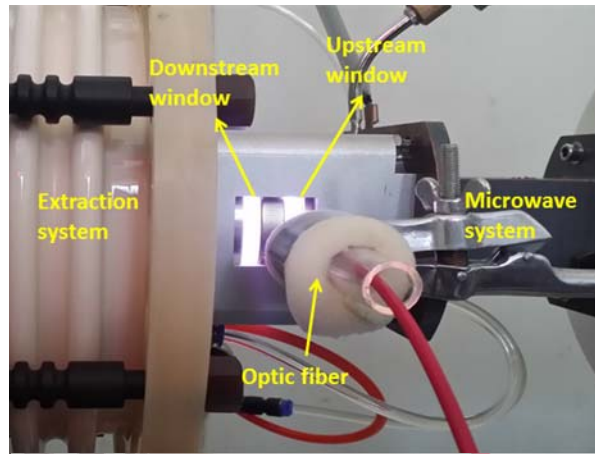

Figure 1: Photo of the ion source with transparent window.

Langmuir probe is a commonly used method to diagnose plasma inside ECR plasma. R. Gobin *et al.*, at CEA/Saclay utilized Langmuir probe to measure electron temperature for the development of H^- ion source, and the measured T_e was 6.7 eV before the microwave-break grid and 3.5~5.3 eV behind the grid[6]. But as they indicated, the Langmuir probe was sometimes hard to interpret under strong RF power and magnetic field environment, and it could only indicate some trends inside ECR plasma[7]. Recently, laser detachment method and absorption spectroscopy method have been developed, but the facilities are complicated and hard to realize with ECR ion source. By comparison, optical emission spectroscopy method is a simple and non-invasive approach to diagnose the plasma by analysing the light emitting from ECR cavity with optic fiber, high revolution spectrometer and auxiliary noble gas[8]. For this reason, a new ion source with transparent quartz chamber was designed and constructed so that the light from plasma could be seen from outside without disturbing the vacuum. The diagnostic method and preliminary results will be presented in this paper.

EXPERIMENTAL SETUP

The ion source is a permanent magnet ECR ion source named PMECR IV (Patent Number: ZL 201110026605.4). For diagnosing the plasma, the discharge chamber is made of quartz which has a high transmissivity for 400 ~800 nm light [9]. The magnetic field is provided by three NdFeB rings which are separated by non-magnetic metal gaskets. Based on above designs, the light from plasma can be detected through gaps between magnetic rings as shown in Fig.1. There are two positions where diagnosis can be carried out. One is located at ECR zone

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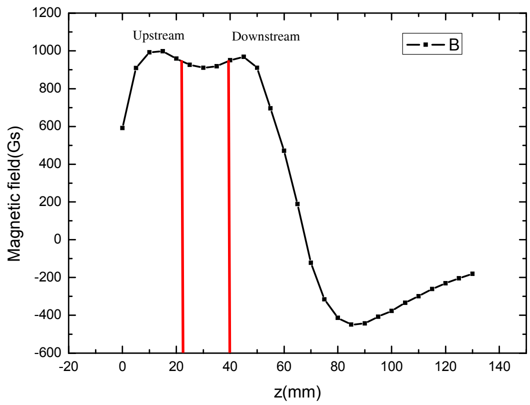

Figure 2: Magnetic field and relative positions of upstream and downstream view points.

and another is downstream closing to extraction hole, and they are located at 18.5 mm (upstream point) and 35.5 mm (downstream point) away from injection point separately as shown in Fig. 2. The ion source can generate nearly 90 mA ion beam with pure hydrogen.

The diagnostic system is composed of fiber, spectrometer (AvaSpec USL3648) and computer etc. It can collect light from 410 nm to 920 nm with a revolution of 0.09 nm~0.18 nm. The light intensity was calibrated by tungsten lamp. As hydrogen needs to mix with noble gases He and Ar at the same time, a three channels gas control system with calibrated flow meters was used to mix gases with specified fractions. The fibre detector was mounted on the test bench vertically to central axis of the source as show in Fig.1.

DIAGNOSTIC METHOD

As the plasma in 2.45 GHz ion source is low-pressure, low-temperature non-equilibrium one, collisional radiative (CR) model which considers both collisional and radiative processes can be used [10]. The method is described in [11], [12] in detail. In hydrogen plasma, the exited state of atomic hydrogen can be generated from atom, molecule and also ions(H^+,H_2^+,H_3^+ etc.), so its density

$$n_H(p) = n_H n_e R_H(p) + n_{H_2} n_e R_{H_2}(p) + n_i n_e R_i(p) \, , \quad (1)$$

where R_H, R_{H_2} and R_i are population coefficients of atom, molecule and ions calculated by CR model. Obviously, the processes for the generation of emission line from hydrogen plasmas are too complicated for calculating T_e and n_e as all involved reactions need to be considered.

For measuring T_e and n_e in H_2 plasma, helium with E_{thr}≈23 eV and argon with E_{thr}≈13 eV were introduced into hydrogen plasma as auxiliary diagnostic gases. 10% He and 10% Ar are mixed with H_2 in our experiment and the diagnosis is based on the assumption that specified lines of noble gases are generated from direct excitation of ground state atoms, and Electron energy distribution function (EEDF) is Maxwellian. So, the intensity of emission can be simply written as

$$I_{pk} = n(p)A_{pk} = n_0 n_e R_0(p)\cdot A_{pk} = n_0 n_e X_{pk}^{eff}(T_e, n_e, \ldots) \quad , (2)$$

where n_0 is the density of certain noble atom, p and k are the exited states of the atom. A_{pk} is the spontaneous emission coefficient for the transition, and

$$X_{pk}^{eff}(T_e, n_e, \cdots) = R_0(p)\cdot A_{pk} \quad (3)$$

is effective emission rate coefficient from state p to state k which is available from Atomic Data and Analysis Structure (ADAS) database [13]. The line ratio method can cancel the dependence directly on electron density, solid angle and integral time etc.:

$$\frac{I_{pk}^1 = n_1 X_{pk}^{eff}(T_e, n_e, \ldots)}{I_{mn}^2 = n_2 X_{mn}^{eff}(T_e, n_e, \ldots)} , \quad (4)$$

m, n are different exited states from p , k of same atom or different atom. As line intensity I, particle density n can be measured with calibrated spectrometer and flow meters, the only unknown quantities are T_e *and* n_e. For electron density, the line ratio of He 587.56 nm and He 706.52 nm is recommended as the line ratio which is very sensitive on n_e and less sensitive on T_e with T_e ranging from 1~10 eV [14]. And likewise, the line ratio of He line at 728 nm to the Ar line at 750 nm is suitable for T_e diagnosis which is particularly sensitive on electron temperature. Here, all the results are only line-of-sight averaged parameters.

PRELIMINARY RESULTS

In our experiment, 0.1 sccm Ar and 0.1 sccm He were mixed with 1.0 sccm H_2. Microwave generated by magnetron was coupled into discharge chamber to ignite plasma. The light with pure hydrogen was purple, and it became a little blue with Ar and He (Fig.3). Obviously, the plasma would become weak with mixed gases.

With average RF power 200 W (10% duty factor), we investigated the relation between T_e and the operation pressure measured in the vacuum vessel after extraction system. It is shown in Fig.4 that the electron temperature increases obviously from 2 eV to 14 eV with pressure decreasing from 3×10^{-3} Pa to 6×10^{-4} Pa at both upstream and downstream points. The energy transfer between electron and other particles will decrease with lower pressure which means fewer particles and lower collision frequency, so the energetic electrons will loss less energy

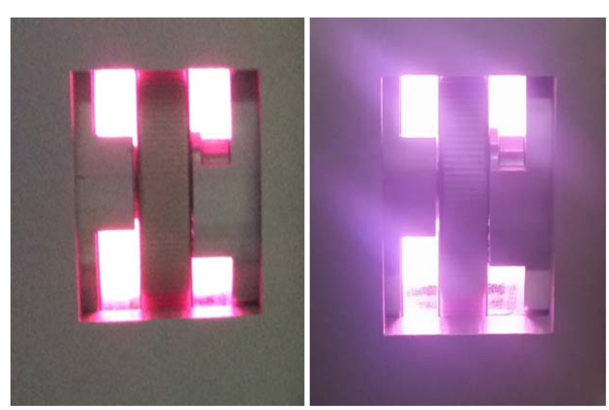

Figure 3: Discharge with pure H_2 (left) and mixed gases (right).

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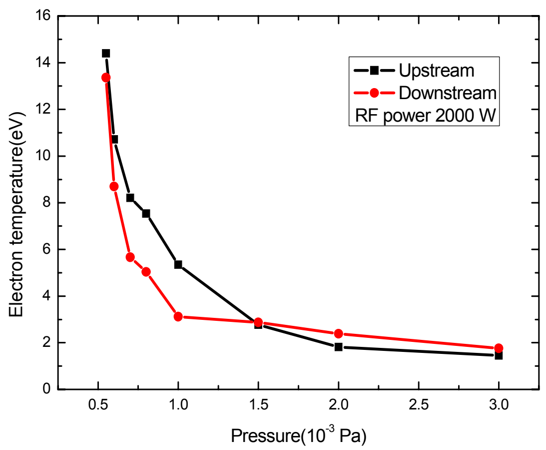

Figure 4: Average electron temperature vs operation pressure at upstream and downstream diagnosis point.

and the electron average temperature will increase. This phenomenon may explain the experimental result in [3] that H_2^+ fraction increases with pressure decreasing as the generation of H_2^+ needs higher temperature. In the other hand, the generation of H_3^+, which is easy to be destructed by energetic electrons, needs lower temperature which is available with high pressure. Fig.4 also shows that the electron temperature measured upstream is higher than the downstream point with lower pressure. But with higher pressure, the T_e measured at downstream and upstream points was close due to more frequent energy transfer in this condition. The T_e was slightly enhanced with more RF power measured upstream (Fig.5). The electron density in the cavity ranged from 5.5×10^{11} cm^{-3} to 9.0×10^{11} cm^{-3} with 100 W average RF power (10% duty factor). The error of spectroscopic method is estimated to be 25% ranging with electron density [10].

CONCLUSION

Plasma characteristics are important in the generation of H_2^+, H_3^+ and also H^-. The physical processes are more complicated than proton generation. Emission

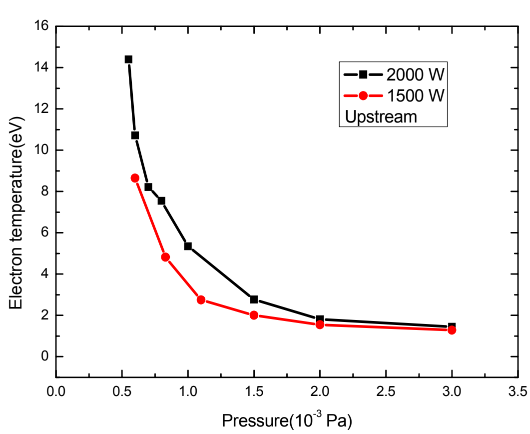

Figure 5: Average electron temperature vs operation pressure with different rf power at upstream diagnosis point.

spectroscopy diagnostic was chosen as a no invasive method to figure out the T_e and n_e in the ECR ion source with a new designed ion source. Preliminary experiment indicated that electron temperature increased with pressure decreasing, and it could be as high as 14 eV which was advantageous for the yield of H_2^+. Electron density diagnosis was also performed, and the measured value was the magnitude of 10^{11} cm^{-3}. There are some factors influencing the accuracy of diagnosis such as opacity of light in the plasma, non-Maxwellian electron energy distribution in ECR plasma, dissociation degrees of mixed gases, instrumental error etc. Detailed analysis of the influence of these factors will be performed in the future to improve the accuracy of the diagnosis.

ACKNOWLEDGMENTS

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