The Evolution of Discharge Mode Transition in Helicon Plasma through ICCD Images

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The evolution of discharge mode transition in helicon plasma with Boswell type antenna was explored by integrated capacitively coupled detector (ICCD) through images. The discharge mode transition through ICCD images was then affirmed by Langmuir electrostatic probe, and the optical emission spectroscopy (OES) measurement in Ar plasma based on the jumped plasma density in the mode transition. We then believe that ICCD as a novel diagnostic technology can be used to diagnose the helicon plasma.

1. Introduction

Helicon plasma works in three operational mode, which is initiated from the capacitively coupled E-mode discharge to the inductively coupled H-mode discharge, and then finally to whistle wave W-mode discharge along with the increase of the RF power or external magnetic field [1-10]. The mode transition is assumed primarily causing from collisions [5], collisionless Landau damping [6], and the evanescent Trivelpiece-Gould (TG) wave on the resonance cone [7-8], as well as "resonance cone boundary" [11]. There are various methods to diagnose the plasma parameters and the mode transition, including the magnetic probe [4], Langmuir probe [3], and the relative intensity of Ar spectrum by optical emission spectroscopy (OES) [4, 12]. The normal camera was also used to study the helicon plasma [13]. The camera with a 488 nm bandpass filter was once used to photo the plasma when the magnetic field and power were varied by Blackwell et al [13]. But the low resolution images only provided the discharge in a glow mode, no mode transition was found due to the long exposure period.

In this paper, we used the time-integrated capacitively coupled detector (ICCD, Princeton Instruments MAX2) to diagnose the helical plasma mode transition based on the high resolution of 2 ns exposure time. In particular, we expected to find the mode transition from the images. We investigated in detailed the influence of endplates, the tube length, and the process parameters on helicon plasma mode transition by ICCD from the first frame. As a confirmation, the Langmuir single probe and optical emission spectroscopy (OES, Avantes Avaspec 2048Avantes) in Ar plasma were also used to diagnose the mode transition.

2. Results and Discussion

Fig. 1 is ICCD photos which were taken in the cross-section of glass tube. They illustrated discharge variations by images. The photos of each frame corresponded to time- integrated light emitted from the plasma at diffident conditions.

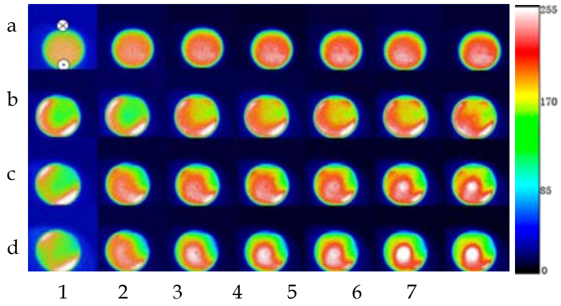

Fig. 1 Discharge images taken by ICCD for mode transition resolution. Columns (a), (b), (c) and (d) corresponded to the plasmas in the cross section with magnetic field varying from (a) 0 G; (b) 200G; (c) 300G; to (d) 400G. For each array from left to the right corresponded to the applied powers from 200W, 300W, 400W, 600W, 900W, 1000W to 1700W (notated as a1, a2, a3, a4, a5, a6 and a7). The inset ⊗ and ⊙ in the image denoted the location of antenna legs in and out, respectively. All pictures were taken at exposure time of 2 ns, gain of 255, accumulation of 200, scale intensity of 5%/95% preudo-color when the plasma was generated in 23 sccm Ar and 0.3 Pa working pressure .

In Fig. 1 the columns of (a), (b), (c) and (d) corresponds to the discharges taken in 0 G, 200 G, 300 G and 400 G magnetic fields, respectively. And the array from left to the right are the applied powers varied from 200 W to 1700 W. From Fig. 1 (a1) to Fig. 1 (a7), i.e. no magnetic field was applied, we found that the glow becomes much uniform, the intensity gradually increases along with the increase of RF power. The plasma density n_e increased from 10^8 cm^{-3} to $10^{10} cm^{-3}$ and the plasma potential V_p varied from 50 V to 70 V indicate that it is typically capacitively coupled plasma (CCP), in which Ohmic heating is dominant mechanism and the coupling efficiency is relatively lower.

When the magnetic field was 300 G in Fig.1 (c 1-7), the increase of rf power leads to the discharge mode transition. At the applied power of 200 W (Fig.1 (c1), the bright glow appears on the tube boundary and forms the symmetric coronet on the right side of the antenna legs rather than under the antenna. Further the increase of rf power the bright glow locating on the top left gradually disappears, leaves the one on opposite side as Fig.1 (c2) shows. When the powers were increased now from 600 W, 700 W to 800W the bright glow in right side gradually moves to the center and forms a bright circle in Fig.1 (c3), (c4) and (c5)), respectively. When the power was over 900 W a blue column, i.e. "big blue", appears in the tube center as Fig.1 (c6) and (c7) show. We believe that the two jumps in the light density and the variation of the glow location occurring at 200 W~400 W and 800 W~9000 W by ICCD, corresponds to the discharge mode transition in Fig.1 (c2) and Fig. 4(c6). We predict that ICCD images can be used to distinctly reveal the mode transition from E- to H, and H to W-mode.

Comparison of Fig. 1 (b), (c) and (d), the role of magnetic field on discharge mode transition is also revealed. In Fig. 1(b 3) when magnetic field was 200 G and P_{rf} was 600 W, there is one bright glow. When the magnetic field was above 300 G, the bright glow move to the center from the both sides of antenna legs as Fig.1 (d1), (d2), and (d3) display. It seems that at a higher magnetic field the mode can transfer from E- to W-mode even the applied power is relatively low. It may be first evident by images even it was predicted by J P Rayner in Ar plasma [14].

Fig.1 (d3) to (d7) indicate that the W-mode cannot be sustained at a high RF power when magnetic field is lower than 200 G. The glow area gradually moves to the boundary rather than to the central of tube, which is the typical H discharge mode.

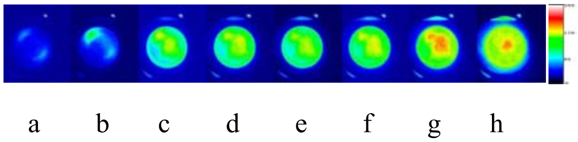

Fig. 2 Discharge images taken by ICCD with a 480 nm filter. From left to the right are the applied powers varied from 200W, 300W, 400W, 600W, 800.900W, 1000W to 1700W (noted as a, b, c, d, e, f, g and h) when the working pressure was 0.3Pa, and 300G magnetic field strength

Furthermore, we investigated the variation of Ar II (480.6 nm) line in the helicon plasma through ICCD. The Ar II (480.6 nm) line was obtained by a bandpass optical filter with a central wavelength of 480 nm and 10 nm of half-bandwidth placed in front of camera. As known the Ar II (480.6 nm) line is emitted from ionization of Ar atom by high energy. It has a short lifetime (approximately to 7 ns). We adopted the applied power as done in Fig.1 (c). In Fig. 2 one can see that the variation of light intensity is similar to that appeared in Fig. 1 for full wave length condition: when the applied power is above 900W (W-mode), Ar Ⅱ line unveils distinctly even it is very weak. The center peak of radial profile in Fig. 2(h) is identical to B Clarenbach results, which hints the fast electron play a critical role on the Ar II generation in W-mode helical plasma. The 480.6 nm Ar II line ($4p^4P^0_{5/2}$) has a much higher excitation energy, 19.2 eV and 35 eV for excitation from the ground state of the argon ions (two-step process) and atoms (single-step process), respectively. It needs a high energy species to excite and ionize Ar atom to then generate it, which is distinctly evident of W-mode plasma generation in this helical discharge.

3. Conclusions

In this paper we firstly distinguished the three discharge mode transitions in helical plasma by ICCD. We noticed that the images were well agreement with the data by Langmuir probe and the OES. Based on the high resolution ArII (480.6 nm) line image we resulted the appearance of fast electrons in the W-mode helical plasma, the pre-accelerated electrons coming from the boundary near the antenna play the critical role on the generation of fast electron. Besides, it was directly evidence the influence of endplate on the mode transition images. Due to ICCD is a no disruption method, we believe it will be very evaluable in the plasma diagnostic.

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