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Observation of Plasma Hole in an ECR Ar Plasma

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Abstract

The first experimental observation of a plasma hole structure in an ECR argon plasma is reported. The plasma hole is a cylindrical density cavity, which is formed spontaneously in the center of the plasma. The steep density gradient between the hole plasma and the ambient plasma is sustained by a thin interfacial layer, the width of which is a few ion Larmor radii. Supersonic rotation is found over the large cross-sectional area of Ar plasma hole. The axial flow can also exceed ion sound speed. Spectral measurements revealed that the neutral density profile exhibits a hole structure as well as that in ion density, the diameter of which is much shorter than the mean free path of neutral particles.

Keywords:
plasma hole, structure formation, macroscopic structure, vortex, supersonic ion flow, rotating plasma, ECR plasma, directional Langmuir probe

1. Introduction

An electric field in a magnetized plasma inevitably drives rotating motion of ions by $E \times B$ drift, giving rise to the formation of macroscopic vortical structures, which has been a topic of interest in plasma physics because of the relation to self-organization and to transport phenomena. Various types of vortical structures have recently been investigated in both nonneutral plasmas [1,2] and quasi-neutral laboratory plasmas [3-5]. One of the structures observed in electron cyclotron resonance (ECR) plasmas appears with sharp density depletion around the central axis, that is, a cylindrical density cavity is spontaneously formed in the plasma. Since a nonluminous cavity region, which seems to be a hole in the plasma, is clearly seen in the perspective image taken by a CCD camera, this structure is referred to as *plasma hole* [4]. So far, the plasma hole has been observed only in an ECR helium plasma (He plasma hole).

In this paper, the first experimental observation of a plasma hole structure in an ECR argon plasma (Ar plasma hole) is reported, especially pertaining to the density profile and the ion flow velocity field. The existence of supersonic ion flow over the large cross-sectional area is a noticeable characteristic of Ar plasma hole in comparison with He plasma hole. A two-dimensional density profile of neutral particles associated with the Ar plasma hole, which has been measured with a spectroscopic method, is shown to examine the formation mechanism of ion density depletion.

2. Experimental setup

The experiments have been performed in the High Density Plasma Experiment (Hyper-I) device at National Institute for Fusion Science (NIFS) [6]. Hyper-I is a linear device, which consists of ten magnetic coils and a cylindrical chamber with the inner diameter of 300 mm and axial length of 2000 mm. The plasma is produced by ECR heating with a microwave of frequency 2.45 GHz. An argon gas has been used at relatively low pressures $p_{Ar} \leq 0.1$ mmTorr. The ion flow velocity field, the density and the electron temperature profiles have been measured with a directional Langmuir probe (DLP) inserted from the radial ports. The details of the DLP and the method of flow-velocity measurement have been given in ref. [6].

A two-dimensional motor drive system with an optical system is equipped at the end of the chamber to carry out spectroscopic measurements. The focal point of the optical system is set to infinity to collect the visible light emitted parallel to the axis of the cylindrical plasma. We have observed the emission lines from the argon ions (488.0 nm) and the neutral argon (425.9 nm). A CCD camera is also installed to take the end view image of the plasma hole.

3. Observation of Ar plasma hole

A CCD image of the Ar plasma hole is shown in Fig. 1, evidently indicating a nonluminous *hole* region. The ion density in the hole is about $10^{10}\,\mathrm{cm}^{-3}$, on the other hand, the density in the bright region (ambient plasma) is nearly one order of magnitude higher than that of the hole region. The

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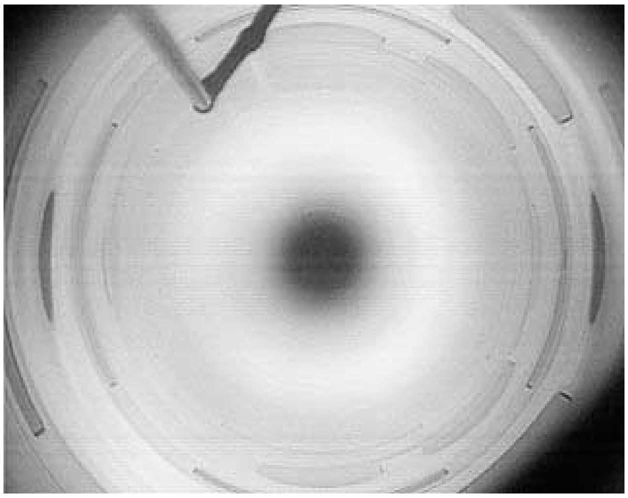

Fig. 1 CCD image of Ar plama hole.

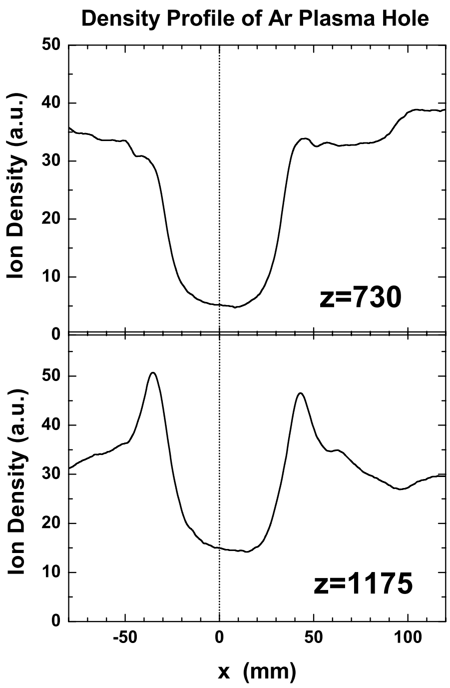

Fig. 2 Density profiles of Ar plasma hole ($z = 730$ mm and $z = 1175$ mm).

hole structure has been spontaneously formed in the center of the plasma under the operation condition with the pressure $p_{Ar} \sim 8 \times 10^{-5}$ Torr and an input power of 3 kW. Figure 2 shows the ion density profiles measured at two different axial positions, $z = 730$ mm and $z = 1175$ mm, where z denotes the distance from the microwave injection window. It can be clearly seen that the ion density distribution has a good axial symmetry and builds up a steep transition layer to the ambient plasma. This shock-like density gradient is sustained by the thin interfacial layer between the hole plasma and the ambient plasma, the width of which is about 20 mm, i.e., a few ion Larmor radii. It should be noted that the size of the plasma hole is almost constant (60 mm) at two different axial positions, indicating two-dimensional nature of the plasma hole structure. At $z = 1175$ mm, the ion density reaches its maximum at the transition layer ($x \sim 40$ mm), which is

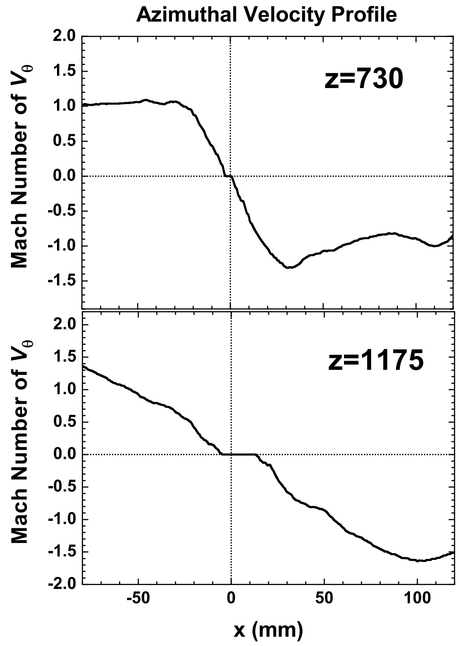

Fig. 3 Azimuthal velocity profiles of Ar plasma hole ($z = 730$ mm and $z = 1175$ mm).

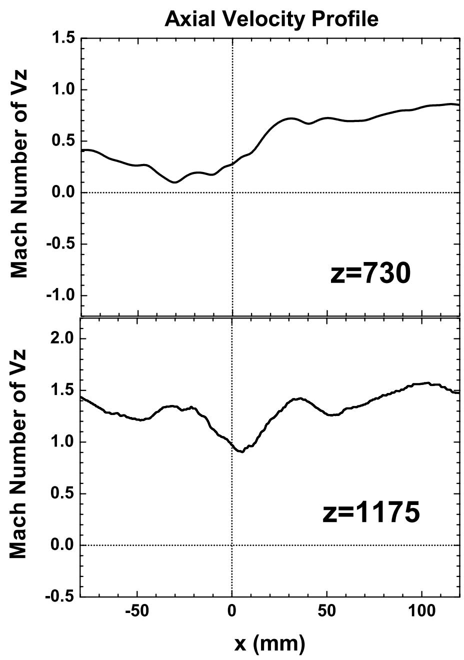

Fig. 4 Axial velocity profiles of Ar plasma hole ($z = 730$ mm and $z = 1175$ mm).

similar to that of He plasma hole.

4. Flow structure of Ar plasma hole

The profiles of azimuthal and axial ion-flow velocity measured at two different axial positions are shown in Fig. 3 and 4, respectively. As seen in Fig. 3, the plasma rotates azimuthally in the clockwise direction (direction of ion diamagnetic drift) when viewing from the end of the chamber. It is also confirmed from the plasma potential measurement that the rotation is driven by the $\boldsymbol{E} \times \boldsymbol{B}$ drift. The hole plasma (core region) shows nearly rigid rotation at

z = 730 mm, however, it weakly rotates at z = 1175 mm. It should be noted that the ambient plasma rotates at a supersonic speed in both positions. The supersonic ion flow is also found in the axial direction at z = 1175 mm, as shown in Fig. 4, where the flow direction is from the microwave injection point to the chamber end. Although the existence of supersonic ion flow over the large cross-sectional area is a noticeable and important characteristic of the Ar plasma hole in comparison with the He plasma hole, quantitative treatment for the supersonic flow field requires more reliable interpretation of the DLP data or other diagnostic methods such as laser induced fluorescence (LIF) spectroscopy [7].

5. Discussion

The plasma hole is characterized by the cylindrical density cavity, the size of which is about 60 mm in diameter. The mean free path of neutral argon under our experimental condition is more than 400 mm, which is much longer than the diameter of the plasma hole. In order to examine whether a hole structure of which the scale is shorter than the neutral mean free path can be formed, the two-dimensional spectroscopic measurement has been carried out. The intensities of emitted spectral lines from neutrals and ions are, respectively, given by $I_{ArI} \propto n_i n_n$ and $I_{ArII} \propto n_i^2$, where the quasi-neutrality condition and the constant electron temperature are assumed. Figure 5 shows the electron temperature profile of the Ar plasma hole at z = 730 mm. Although the electron temperature slightly decreases with radial distance from 12 eV to 9 eV, neglecting the effect of T_e variation on the collision cross section is justified. Hence the neutral density profile is obtained by the following relation:

$$n_n(r) \propto \frac{I_{ArI}(r)}{\sqrt{I_{ArII}(r)}}. \tag{1}$$

Thanks to the two-dimensional nature of the plasma hole, the optical measurement, which is a line-integrated quantity along the axial direction, provides the radial distribution.

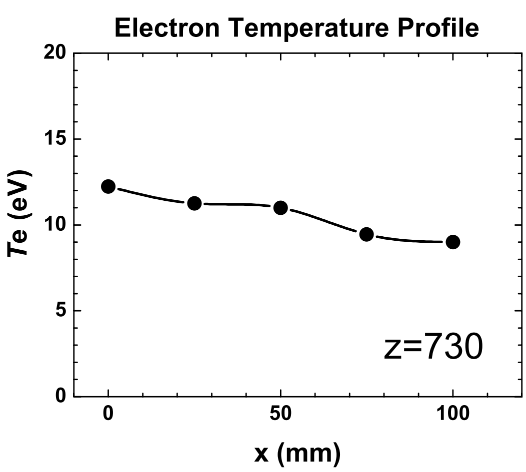

Fig. 5 Electron temperature profile of Ar plasma hole (z = 730 mm).

The two-dimensional neutral density profile of the Ar plasma hole is shown in Fig. 6. The remarkable point is that the neutrals do form a hole structure, the size of which is approximately the same size of the ion density depletion and is much shorter than their mean free path. Here, we consider the plasma production profile in connection with the density structure of Ar plasma hole. The number of particles ionized in unit time and unit volume is given by

$$\langle \sigma v \rangle_i n_e n_n \propto I_{ArI}, \tag{2}$$

where the quantity $\langle \sigma v \rangle_i$, product of the ionization cross section and electron thermal velocity averaged over velocity distribution function, is a constant under constant electron temperature. Hence, the profile of $I_{ArI}(r)$ is proportional to the profile of ionization rate per unit volume. Figure 7 shows the line intensity profile of ArI, indicating that the distribution of the number of ionization events in unit time and volume is also concave one. Thus we can conclude that one of the causes of ion density depletion is the localization of plasma production due to formation of *neutral particle hole*. As a possible explanation for neutral hole formation, it is suggested that rotating motion of the neutrals induced by collisions with the rotating ions makes the apparent radial mean free path short, since the radial projection of arc length corresponding to the ionization length is much shorter than that in a free streaming case.

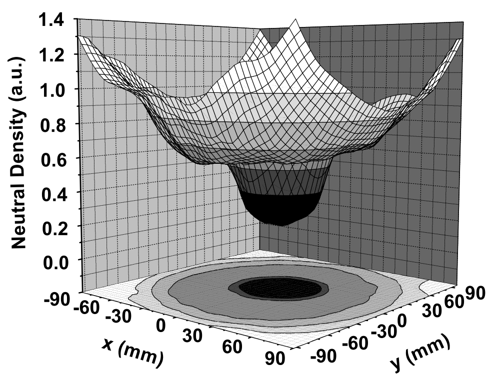

Fig. 6 Two-dimensional neutral density profile of Ar plasma hole.

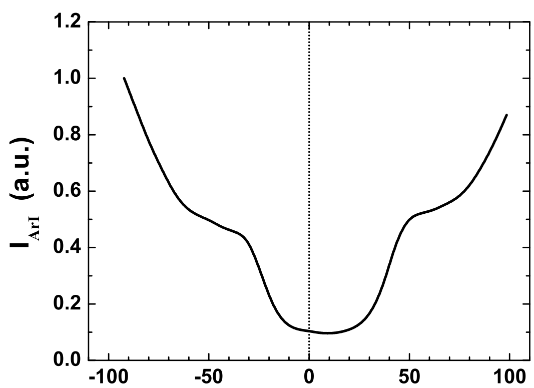

Fig. 7 Line intensity profile (ArI: 425.9 nm) of Ar plasma hole.

6. Conclusion

A plasma hole structure in an ECR argon plasma was first observed and examined experimentally. The Ar plasma hole is characterized by ion density depletion with the steep transition layer and the existence of azimuthal and/or axial supersonic ion flow. The two-dimensional neutral density profile was measured spectroscopically, revealing that the neutrals also form a hole structure as well.

Acknowledgements

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