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Potential Structure and Quasi-neutrality Breaking of Plasma Hole

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1. Introduction

Electric field in magnetized plasmas drives a rotating motion by $E \times B$ drift, giving rise to macroscopic structures. Recently spontaneous formation of a cylindrical density-cavity structure, which is referred to as *plasma hole*, has been observed in a laboratory ECR plasma. [1, 2] From the viewpoint of flow structure, the plasma hole is a monopole vortex with a sink and is identified as a dissipative vortex (Burgers vortex). Since the azimuthal rotation is driven by $E \times B$ drift, the fact that the maximum rotation velocity exceeds the ion sound speed implies the existence of strong electric field, and the problem of interest is how such a strong electric field is self-generated in the plasma. In this paper, we present the results of potential profile measurement of the plasma hole. On the basis of Poisson's equation, we also present an estimation of the degree of quasi-neutrality breaking occurred in the plasma hole.

2. Experimental

The experiments have been performed with the High Density Plasma Experiment (HYPER-I) device at National Institute for Fusion Science. [3] HYPER-I is a cylindrical plasma device (30 cm in diameter and 200 cm in length) with ten magnetic coils. The plasma is produced by electron cyclotron resonance heating in a *magnetic beach*, where the microwave power is 5 kW and the frequency is 2.45 GHz. A helium gas has been used with the operation pressure of 0.6 mmTorr. Typical plasma parameters are as follows: the electron temperature is 20 eV, the plasma density 10^{10}cm^{-3} (hole plasma) – 10^{11}cm^{-3} (ambient plasma).

Floating emissive probe method [4] has been adopted to measure the plasma potential profile. The emissive probe has been constructed as follows: the emissive filament is made of a small loop of tuntalum wire (0.2 mm in diameter) welded to tungsten rods (0.8 mm in diameter), which are mounted in a two-hole ceramic insulator. The measurement circuit is grounded through a high impedance load resister. As the electron emission from the heated filament becomes sufficiently high, the probe potential comes to indicate the plasma potential directly, which has been experimentally confirmed by the *I-V* characteristics of the emissive probe.

3. Results and Discussions

The radial density profile measured with a Langmuir probe is shown in Fig. 1 (a). A deep density hole exists at the center of the cylindrical plasma, and this is why we call this structure *plasma hole*. The density in the hole plasma is indeed one tenth of that in the ambient plasma. A typical potential profile of the plasma hole, together with the potential profile without the plasma hole, is shown in Fig. 1 (b), in which two distinctive features can clearly be seen: (i) The potential has a *bell-shaped* structure and sharply increases toward the center, the maximum value exceeding more than 100 V, which is five times higher than the electron temperature. The drastic increase in plasma potential begins from the density transition layer (x ~ 30-50 mm), in which the density profile has the steepest gradient. (ii) There is a spatial oscillation in potential profile around x ~ 50 mm, indicating the alternation of the electric field direction. We have also measured the two-dimensional potential profile to confirm the axisymmetric profile. On the other hand, the potential profile of a plasma without any characteristic structure exhibits no spatial irregularity, and the maximum value is, as is expected, approximately equal to the electron temperature.

Since the plasma hole has the intense electric field (40 V/cm) compared to that without plasma hole (~1 V/cm), the breakdown of charge neutrality may takes place in the hole plasma. The quasi-neutrality breaking can be evaluated from the Poisson's equation $-\nabla^2\phi = 4\pi e\,\delta n$, where $\delta n = n_{\mathrm{i}} - n_{\mathrm{e}}$. Assuming the magnitude of the potential $|\phi| \simeq T_{\mathrm{e}}/e$, and the characteristic scale-length is equal to plasma radius L, we have the normalized density difference as $\delta n/n \sim (\lambda_D/L)^2$, where λ_D is the Debye length. A typical value of $\delta n/n$ for a plasma without plasma hole is estimated to be of the order of 10^{-6} under our experimental conditions ($T_{\mathrm{e}} \sim 20\,\mathrm{eV}$, $L = 15$ cm and $n \sim 10^{11}\,\mathrm{cm}^{-3}$). It should be noted that $\delta n/n$ represents the degree of quasi-neutrality breaking, or non-neutrality, of the plasma. By taking the second derivative of measured potential profile, the value of $\delta n/n$ can be calculated directly. As shown in Fig. 2, $\delta n/n$ of the plasma without plasma hole is of the order of 10^{-6}, which coincides with the expected value from the Poisson's equation. The degree of quasi-neutrality breaking of the plasma hole is, however, considerably greater than the expected value for a plasma without plasma hole. The quantity $\delta n/n$ attains its maximum value (8×10^{-4}) within the hole plasma region (ion-rich); it is about 10^3 times higher than that of quasi-neutral plasma. In addition, the electron-rich layer can be seen in the interface layer (x ~ 35-50 mm) between the hole and the ambient plasma.

4. Conclusion

The characteristic potential profile of the plasma hole has been measured with an emissive probe. The potential has a bell-shaped structure and its maximum value is five times higher than the electron temperature. The quantity $\delta n/n$ of the plasma hole has been calculated from the Poisson's equation and the potential data; it is about three orders of magnitude higher than that of the ambient plasma. It is found that the quasi-neutrality breaking occurs in the plasma hole, producing the very high potential ($\phi \sim 5T_{\mathrm{e}}$) and the resultant supersonic ion flow in azimuthal motion. It is also found that the double layer structure does exist in the transition layer between the hole and ambient plasma. The elucidation of the mechanisms of occurrence and sustainment of this quasi-neutrality breaking is left for future study.

References

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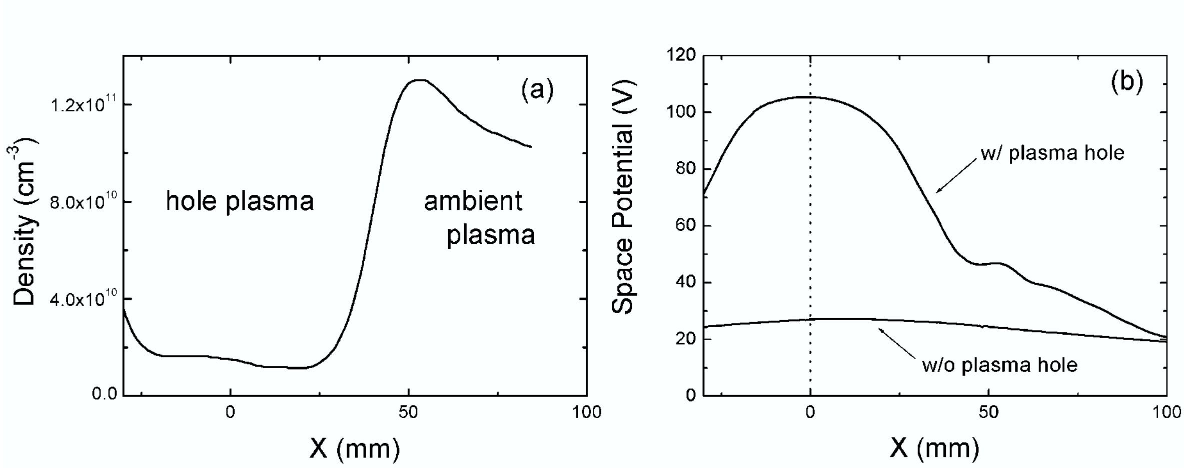

Figure 1 *(a) Density profile of the plasma hole. (b) Potential profile of the plasma hole. Potential profile without plasma hole is also plotted.*

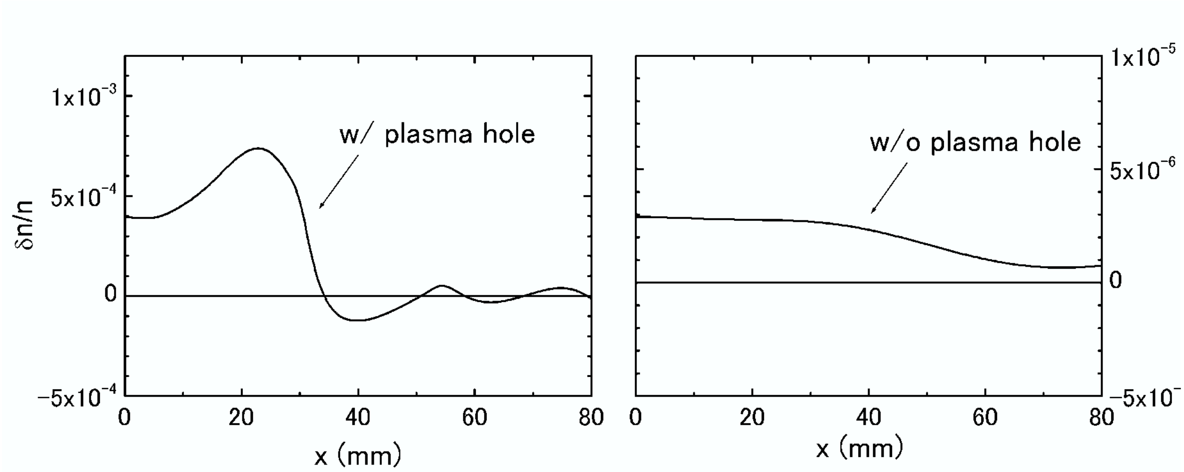

Figure 2 *$\delta n / n$ profile of the plasma hole and of ordinary plasma without plasma hole.*