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# Observation of Plasma Hole in a Rotating Plasma

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## Abstract

Plasma hole, a cylindrical density cavity, formed in a rotating plasma has been investigated experimentally. The plasma hole is characterized by large aspect ratio (length/radius $\geq$ 30), steep boundary layer between the hole and the ambient plasma (10 ion Larmor radius), and extremely high positive potential (130 V). The flow velocity field associated with plasma hole structure has been measured, and is found to have interesting features: (i) plasma rotates in azimuthal direction at a maximum velocity of order of ion sound speed, (ii) plasma flows radially inward across the magnetic field line, (iii) there present an axial flow reversal between core and peripheral region. It is found that the flow pattern of the plasma hole is very similar to the that of well-developed typhoon with core.

## Keywords:

plasma hole, structure formation, plasma flow, rotating plasma, vortex structure, directional Langmuir probe

## 1. Introduction

Studying self-organized structure formation is of importance to understand macroscopic behavior of plasmas in laboratory and space, and many theoretical and computational studies on this subject have been carried out so far [1,2]. In laboratory, non-neutral plasmas have been used in order to investigate two-dimensional vortical dynamics, relaxation of two-dimensional turbulence into vortex crystals, and so on [3-5]. Recently, various types of vortical structure have been observed in quasi-neutral plasmas [6,7]. Among them, spiral structure and multi-pole vortex were experimentally observed in an electron cyclotron resonance (ECR) plasma, showing that rotating magnetized plasma is a fertile ground for studying self-organized structure formation [8].

In this paper, we present the experimental results on a new type of vortical structure, a plasma hole, observed in a rotating ECR plasma. We also show the three-dimensional velocity field associated with the plasma hole, and compare the flow pattern with that of typhoons.

## 2. Experimental Apparatus

The experiments have been performed in the High Density Plasma Experiment Device I (Hyper-I) at National Institute for Fusion Science (NIFS) [9], which is schematically shown in Fig. 1. The Hyper-I device consists of a cylindrical vacuum chamber (30 cm in diameter and 200 cm in axial length) and 10 magnetic coils arranged to produce a weakly divergent magnetic field configuration. The microwave (2.45 GHz) launched from a high field end of the chamber through a quartz window along the field line excites an electron cyclotron wave (ECW), which produces and sustains the plasma by ECR heating. The ECR point (875 G) locates near the center of the chamber. At another end (low

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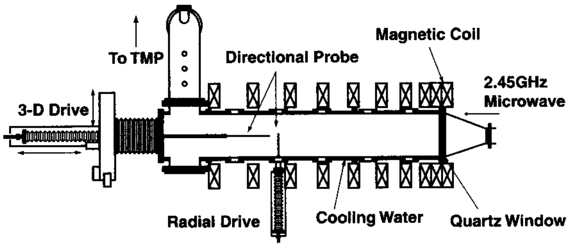


Fig. 1 Schematic of Hyper-I device.

field side), three-dimensional prove drive system is installed to introduce an axial probe. Radially movable probes are introduced from side ports.

The microwave input power and plasma duration time are 4 ~ 15 kW and 1 min., respectively. The typical parameter of the HYPER-I plasma are electron temperature $T_e \sim 30$ eV, maximum density $n_e \sim 1 \times 10^{13}$ $cm^{-3}$ for argon and plasma potential $V_p \sim 30$ V, respectively.

The density and the electron temperature have been measured by a Langmuir probe, and the plasma potential by an emissive probe. The plasma flow has been measured with a directional Langmuir probe (DLP). The velocity $V(\theta)$ flowing at an angle $\theta$ with respect to the reference axis is determined by two ion saturation currents, $I_s(\theta)$ and $I_s(\theta + \pi)$, according to the following relationship [10];

$$\frac{V(\theta)}{C_s} = \frac{1}{K} \cdot \frac{I_s(\theta+\pi) - I_s(\theta)}{I_s(\theta+\pi) + I_s(\theta)}$$

where $\theta$ is the angle between the normal of ion collecting surface of DLP and reference axis, $C_s$ ion sound speed, and $K$ the coefficient of the order of unity, respectively. This relation between flow velocity and DLP currents was experimentally confirmed to be valid for all flow directions with respect to the magnetic field when weakly magnetized condition for ions (ion Lamor radius ≥ probe radius) are satisfied.

## 3. Experimental Results

A localized density cavity is spontaneously formed in the center of the plasma column under the operation condition with a pressure of 0.6 mTorr (He) and an input power of 8.5 kW. The CCD image of the plasma hole observed from a chamber end is shown in Fig. 2. It is found that the dark region (refer to as "plasma hole") lies along the magnetic field near the center axis of the cylindrical plasma. The two-dimensional density profile measured at $z$ = 1100 mm is shown in Fig. 3, indicating

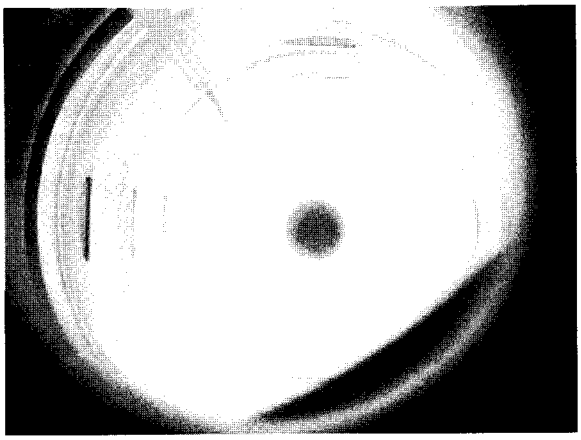

Fig. 2 CCD image of the plasma hole.

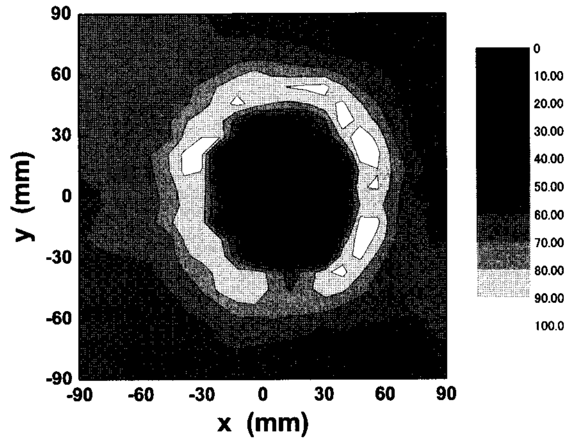


Fig. 3 Density contour on $z$ = 1100 mm plane.

axisymmetric structure ($m$ = 0).

This plasma hole consists of three parts; central core (hole) region, boundary layer, and ambient plasma region. The density in the hole region is about 10 times lower than the maximum density at the boundary layer, and the size is about 6 cm in diameter and is sharply bounded by the thin layer with steep density gradient. The width of the boundary layer is about 2 cm, which corresponds to 10 times the ion Larmor radius. The density profile measured at $z$ = 200 mm (which is not shown in this paper), is similar to that at $z$ = 1100 mm. The aspect ratio of the plasma hole is estimated as $R$(length/radius) ≥ 30.

The plasma potential was measured by a radially movable emissive probe at $z$ = 1100 mm. As seen in Fig. 4, the plasma potential exhibits a dome shape with an extremely high positive value (130 V) at the center,

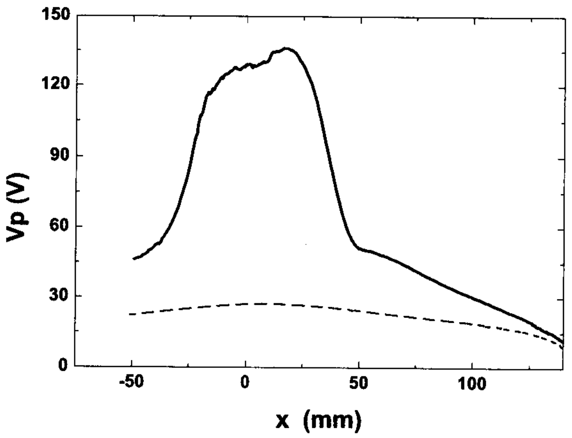


Fig. 4 Plasma potential profile at $z = 1100$ mm. Solid line indicates the plasma potential in the presence of hole structure under operating condition $6 \times 10^{-4}$ Torr (He) and 8.5 kW microwave input, dashed line the potential of the uniform plasma under operating condition $2 \times 10^{-3}$ Torr (He) and 9.6 kW microwave input.

while that of ambient plasma is about 40 V. The maximum potential gradient is about 40 V/cm at the boundary layer. The dashed line in Fig. 4 shows the typical potential profile of an uniform plasma without the hole structure.

The velocity profiles of plasma flow measured by DLP at $z$ = 1100 mm are shown in Fig. 5. As seen in Fig. 5(a), the plasma rotates azimuthally in the direction of $E \times B$ drift and the maximum flow velocity is of the order of ion sound speed at the boundary layer where the electric field also reaches the maximum. Figure 5(b) shows that the plasma flows radially inward with subsonic velocity. It is interesting to note that the parallel flow along the magnetic field shows a flow reversal as seen in Fig. 5(c); in the ambient region the plasma flows from the ECR region located at $z \sim 800$ mm to the chamber end, while in the hole region the flow direction is from the chamber end to the ECR region. The axial flow also has the maximum value at the boundary region.

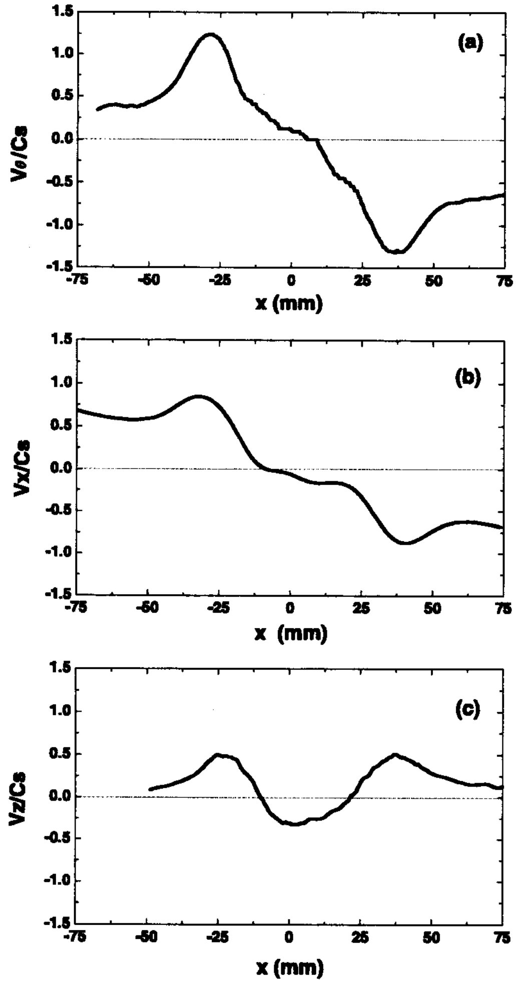


Fig. 5 Velocity profiles of plasma flow measure by DLP at $z = 1100$ mm with the coefficient $K = 0.5$. (a): the azimuthal flow velocity, (b): the radial flow velocity, and (c): the axial flow velocity.

## 4. Discussion

The azimuthal flow profile shows that the plasma hole is considered to be a monopole vortical structure. The vorticity determined by velocity field at $z$ = 1100 mm is concentrated upon inner region of the hole and is much small in other regions, which is shown in Fig. 6. According to this vorticity distribution, it is found that the plasma hole has Rankine-type vortex structure.

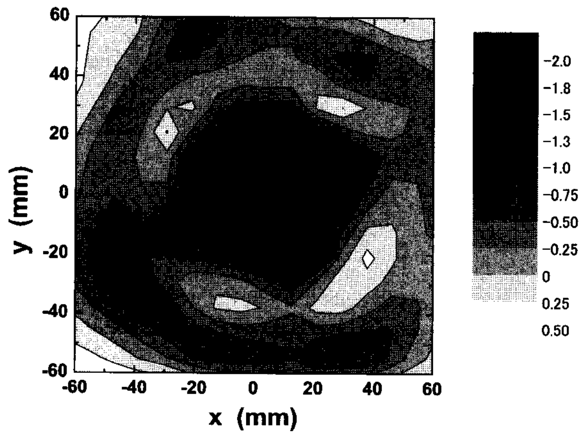


Fig. 6 Vorticity contour on $z = 1100$ mm plane.

When the magnetic field was inversed, the hole structure reappeared in the plasma without any change in size, however, the azimuthal flow was in the opposite direction. This indicates that the azimuthal flow is due to the $E \times B$ drift. The radial and axial flows do not change their directions even if the magnetic field is reversed. This is the same property of vortices formed in Coriolis fields. This implies that there present a large convective-cell motion in $r - z$ plane.

Plasma hole and typhoon, which is a typical vortex-structure in neutral fluids in nature, have some common properties; (i) the azimuthal flow forms a single-vortex structure, (ii) the radial flow is in inward direction, (iii) a flow reversal is present in axial direction, and (iv) the core structure (eye of typhoon) is formed at the center. In order to compare the two flow structures in more detail, the azimuthal velocity of the plasma hole is plotted as a function of the radius $r$ in Fig. 7, and the following relation is found;

$$V_\theta \propto r^\alpha$$

$$\alpha = \begin{cases} 1 & (0 \le r \le r_0) \\ -0.5 \sim -1 & (r \ge r_0) \end{cases}$$

where $r_0$ (~ 30 mm) is the position at which the azimuthal velocity reaches maximum. In many typhoon cases, it is well known that $\alpha \sim 1$ in the core region and $\alpha \sim -0.5$ in the outer region. Thus the plasma hole and typhoons have very similar flow pattern in spite of the differences of dynamics of fluid motion, such as, the basic equations, the radial force balance and so on. This implies that a common scenario is underlying in generating plasma hole structure, and is very interesting and important from the viewpoint of vortex-structure formations and self-organization in plasmas.

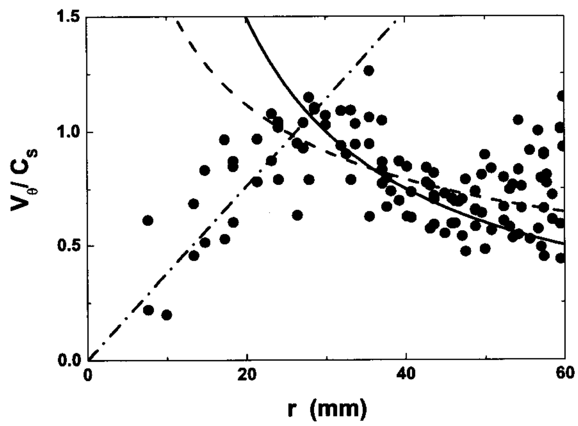


Fig. 7 Azimuthal velocity as a function of the distance from the center of rotation. Dashed line indicates the relation $V_\theta \propto r^\alpha$ with $\alpha = 1$, solid curve with $\alpha = -1$, broken curve with $\alpha = -0.5$, respectively.

## 5. Conclusion

Plasma hole structure was observed in a rotating plasma and experimentally examined. The plasma hole is characterized by large aspect ratio, steep boundary layer and extremely high positive potential. Moreover, flow velocity associated with the plasma hole is measured using DLP. The plasma rotates azimuthally in the direction $E \times B$ drift at the maximum velocity of order of ion sound speed, and flows radially inward. A flow reversal is present in axial direction. This flow pattern is very similar to that of typhoons, suggesting that the presence of common scenario in forming vortical structure.

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