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Formation of Dissipative Vortex and Anomalous Viscosity in a Rotating Plasma

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Abstract

A vortex with a deep density-cavity in its center, "plasma hole," has been observed in a rotating magnetized plasma. The flow velocity field and vorticity distribution of the plasma hole are experimentally determined. It is found that the plasma hole is identified as a Burgers vortex and the plasma exhibits anomalous viscosity. This is the first experimental observation of a dissipative vortex in a plasma.

1. Introduction

Plasmas of interest in the research of vortex dynamics are conservative or nearly conservative systems so far, and are close to or equivalent to two-dimensional Eulerian fluids. In real plasmas, however, effects of instability and dissipation might play an important role on the formation of vortices. We have shown that a spiral drift-vortex is generated in a rotating magnetized plasma, and the origin of spiral nature is attributable to the existence of instability. [1,2] On the other hand, the effect of dissipation on vortex formation has not been fully understood. Since macroscopic flow structures excited in a plasma with dissipation (due to viscosity) are subjected to continuous energy damping due to internal friction, vortices survived under the circumstance should be a dissipative structure. Such a vortex, however, has not been experimentally observed in plasmas yet. We present in this paper the experimental results on the formation of dissipative vortex in a plasma , which is identified as a Burgers vortex.

2. Experiments

The experiments have been performed with the High Density Plasma Experiment (Hyper-I) device at National Institute for Fusion Science. Hyper-I is a linear plasma device (30 cm in diameter and 200 cm in length) with ten magnetic coils. The plasmas are produced by electron cyclotron resonance heating, using a microwave of frequency 2.45 GHz and of maximum power 15 kW. The magnetic field configuration is a so-called magnetic beach structure (1.25 kG at z=30 cm, 875 G at z=100 cm). [3] The typical electron temperature and density are 20 eV and 1×10^{12} cm^{-3}, respectively. We have observed a cylindrical density cavity (referred to as plasma hole) in a helium plasma. The perspective image of plasma hole taken by a CCD camera is shown in Fig.1. The central dark region in Fig.1 indicates a deep density hole, the sizes of which are 6cm in diameter and more than 100cm in axial length. The plasma density in the hole region is one tenth of that in the ambient plasma, and the width of transition layer between the hole and ambient plasma is about 1.2 cm, which corresponds to several ion Larmor radii. This steep density gradient is a remarkable characteristic of the plasma hole. The space potential measured with an emissive probe is 110 V at the hole center and 30V in the ambient plasma. There also presents a steep potential gradient in the density transition layer, and the

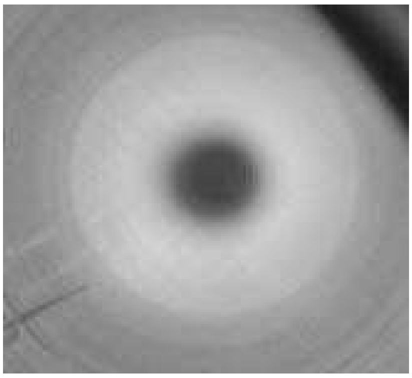

Fig.1 CCD Iimage of Plasma Hole

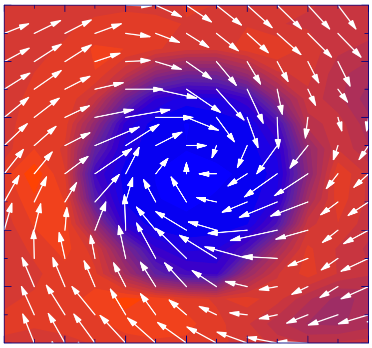

Fig.2 Vector Field Plot of Ion Flow.

electric field in this region is about 40 V/cm, which induces azimuthal rotation of the plasma. Flow vector field associated with the plasma hole has been measured with a directional Langmuir probe (DLP). [4] The vector field plot of ion flow is shown in Fig.2. The flow pattern exhibits a monopole vortical structure with a sink in its center, and the velocity at the hole boundary (r ~ 3 cm) exceeds the ion sound speed. When the direction of magnetic field is inverted, the azimuthal velocity also changes its sign, indicating that the azimuthal rotation is due to $\boldsymbol{E}\times\boldsymbol{B}$ drift. In fact, the maximum azimuthal velocity (3 x 10^6 cm/sec) is well explained by the $\boldsymbol{E}\times\boldsymbol{B}$ drift with the observed electric field (40 V/cm). On the other hand, the radial flow velocity remains unchanged when the polarity of the magnetic field is inverted. This suggests that the driving force of radial flow changes its sign with the magnetic field inversion. The most probable mechanism of occurrence of radial flow is viscous drag force originated from the shear of azimuthal velocity V_θ . This force reverses the direction with the inversion of the magnetic field, and thus the resultant $\boldsymbol{F}\times\boldsymbol{B}$ drift remains unchanged.

We calculate the z-component of vorticity at each point by performing the line integration defined by the following equation:

$$\omega = (rot\,\boldsymbol{v})\cdot e_z = \sum \boldsymbol{v}\cdot \; \boldsymbol{d}l/\Delta S \,, \tag{1}$$

where the integration path is taken along the minimum square passing through the neighbouring four velocity vectors, and ΔS the area bounded by the integration path. Figure 3 shows the vorticity distribution as a function of radius, where the error bars correspond to the dispersion of the data, and the closed circles indicate the average values. It should noted that the vorticity is localized in the central hole region, and negligible in the ambient plasma, showing a Gaussian profile represented by the solid curve.

3. Discussions

In order to understand the mechanism of vorticity concentration observed in the experiment, we consider vorticity dynamics for ion fluid. Taking a curl of the momentum equation for ion fluid in a uniform magnetic field, we obtain the following vorticity equation:

$$\frac{\partial \boldsymbol{\omega}}{\partial t} + \boldsymbol{v}\cdot\nabla\boldsymbol{\omega} = \boldsymbol{\omega}\cdot\nabla\boldsymbol{v} - \boldsymbol{\omega}\nabla\cdot\boldsymbol{v} + \nu\Delta\boldsymbol{\omega}\,, \tag{2}$$

where ν is the kinetic viscosity. This equation is identical to that of normal fluids except a constant vector, which comes from the ion cyclotron frequency vector $(\boldsymbol{\omega} \to \boldsymbol{\omega} + \boldsymbol{\Omega}_{ci})$. Thus, we can discuss vorticity dynamics of ion fluid with the same physical picture as ordinary fluids.

When there presents an inward convection $(V_r = -\alpha r,\ \alpha > 0)$, vorticity localization may occur through the balance between diffusive process due to viscosity and concentration due to convection, generating a stationary structure. This is known as Burgers vortex. [5, 6] The vorticity profile of Burgers vortex is given by a Gaussian distribution, which is characterized by the total circulation Γ at the initial time and the scale length of the vortex l,

$$\omega(r) = \frac{\Gamma}{\pi l^2} \exp[-\frac{r^2}{l^2}], \qquad (3)$$

where the quantity l is determined by the square root of the ratio of viscosity to magnitude of inward convection,

$$l = \sqrt{\frac{2\nu}{\alpha}}, \qquad (4)$$

The solid curve in Fig.3 indicates the best fit Gaussian profile, for which the parameters are taken to be $\Gamma = 7.7 \times 10^7\ \mathrm{cm}^2/\mathrm{sec}$ and $l = 3.0\ \mathrm{cm}$. Then, the azimuthal velocity is uniquely determined by integrating eq.(3) and is given by

$$\upsilon_\theta(r) = \frac{\Gamma}{2\pi r}\left(1 - \exp\left[-\frac{r^2}{l^2}\right]\right), \qquad (5)$$

which behaves as $V_\theta \propto r$ (rigid rotation) for $r << l$ and $V_\theta \propto 1/r$ (vorticity free rotation) for $r >> l$. Figure 4 shows the azimuthal velocity V_θ as a function of radius. The experimental results are also plotted in the figure by closed circles, showing a good agreement with the theoretical values.

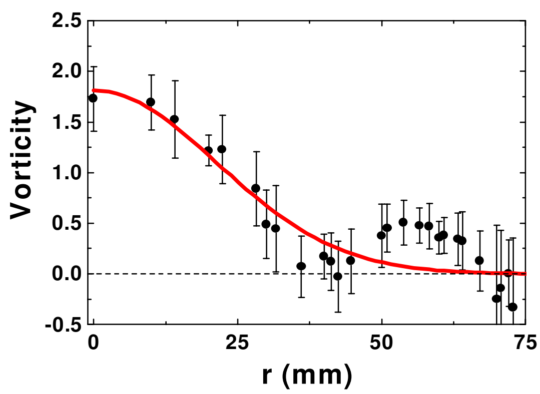

Fig.3 Vorticity Profile

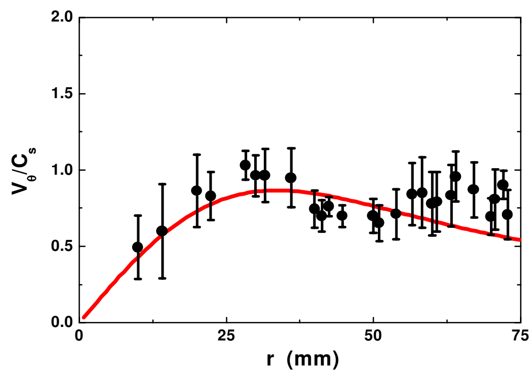

Fig.4 Azimuthal Velocity Profile

Presence of inward convection is of essential importance on the formation of Burgers vortex, and is assumed so far. The radial velocity component as a function of radius is depicted in Fig.5, showing that there exists in fact an inward flow proportional to the radius. According to these results, the localization of vorticity observed in the present experiment is identified as a Burgers vortex. [7] Finite viscosity of fluids induces irreversible thermalization of fluid motions due to internal friction. We have experimentally determined the radial profile of dissipation rate by using the rate-of-strain tensor $e_{\alpha\beta}$. It is found that $e_{r\theta}$ term dominates the rest of all, and 61 % of the total dissipation is produced by this term. It is emphasized that this term corresponds to the dissipation of azimuthal rotaion by internal friction. It is found that the dissipation layer is located in the periphery of the plasma hole, and the energy of vortical motion transported by viscous diffusion is finally consumed

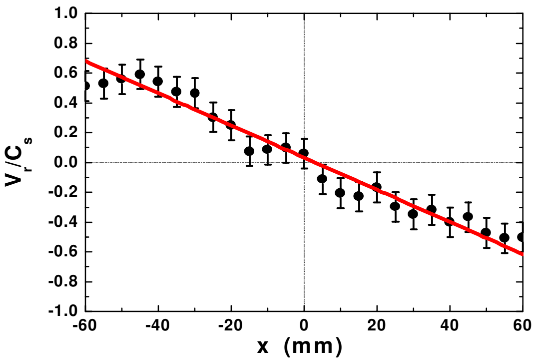

Fig.5 Radial Velocity Profile

into heat in this layer. It should be pointed out that the energy dissipation undertakes stationary nature of the plasma hole, which is organized in a plasma with continuous input of energy. The plasma hole is a dissipative structure in a rotating magnetized plasma.

The viscosity coefficient ν_{eff} can be estimated from the scale of vortex l and the coefficient α of inward flow using the relation eq.(4). Substituting $\alpha = 4.4\times10^5\ \mathrm{sec}^{-1}$ from the experimental data and $l = 3.0\ \mathrm{cm}$ into the above relation, we have $\nu_{eff} = 2\times10^6\ \mathrm{cm}^2/\mathrm{sec}$, which is four orders of magnitude higher than the classical value $\nu_c = 1\times10^2\ \mathrm{cm}^2/\mathrm{sec}$ [8], and still one order of magnitude higher than the anomalous viscosities observed in magnetically confined plasmas.

One of possible cause of viscosity anomaly might be attributable to the breaking of quasi-neutrality in the hole plasma. Using the Poisson equation and potential data, the normalized density difference $\delta n/n$ $(\delta n = n_i - n_e)$ is of the order of $(\lambda_D/R)^2$ (λ_D: Debye length, R: plasma radius), and is 10^{-3} in the hole region in contrast to that in the ambient plasma 10^{-6}. Therefore the Debye shielding is insufficient in the hole region, and the potential leaks to outside far beyond the scale of Debye length. This long range interaction might make it possible to transport momentum in azimuthal direction faster to the radial direction. Another possibility of the origin of viscosity anomaly might be attributable to turbulence induced by instability of electrostatic waves such as drift wave turbulence or lower hybrid turbulence etc., since there exists strong inhomogeneity in density profile. Unfortunately, we have not experimentally identified the origin of viscosity anomaly yet, and the detailed analysis remains for future study.

4. Conclusions

We have observed the plasma hole in a rotating magnetized plasma, and identified it as a Burgers vortex in a compressible fluid. The remarkable characteristic of the Burgers vortex in a plasma is a deep density hole with a shock-like transition layer at the boundary. The vorticity distribution well agrees with a Gaussian profile. The effective viscosity far exceeds the classical value. Although the viscosity anomaly is not fully understood yet, the implication of the present result is that plasma is much more "*sticky*" than expected. Therefore Burgers vortex as a dissipative structure will play a crucial role in structure formation in plasmas.

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