Spontaneous Formation of a Plasma Hole in a Rotating Magnetized Plasma: A Giant Burgers Vortex in a Compressible Fluid

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(Received 17 July 2001; published 26 July 2002)

Spontaneous formation of a cylindrical density cavity, or ''plasma hole,'' has been observed in a rotating magnetized plasma. Density of the plasma hole is one-tenth of that of ambient plasma and is bounded by a steep transition layer of the order of several ion Larmor radii. The flow velocity field associated with the plasma hole is experimentally determined, exhibiting a monopole vortical structure. It is found that the vorticity distribution is localized near the center of the hole and is identified as a Burgers vortex. This is the first experimental observation of a Burgers vortex in a plasma.

DOI: 10.1103/PhysRevLett.89.075001 PACS numbers: 52.30.–q, 52.35.We

Vortex is a nonlinear excitation in multidimensional continuous media, and the dynamics of vortices has been a topic of interest in plasma physics. A localized electric field caused by potential perturbation in a magnetized plasma inevitably drives a vortical motion by $E \times B$ drift, and the excited vortices may generate a large scale structure or a turbulent state depending on the condition imposed on the systems. Transport phenomena are affected by the structure of velocity field, and so by the presence of vortices. The role of the electrostatic wave has been considered to be important on the vortex formation, and drift wave vortices have been intensively studied [1–3]. Recently, the dynamics of point vortices has been experimentally examined using non-neutral plasmas, and interesting results have been observed [4,5].

So far, plasmas of interest in the research of vortex dynamics are conservative or nearly conservative systems, which are close to or equivalent to two-dimensional Eulerian fluids. In real plasmas, however, two effects, instability and dissipation, will play an important role on the formation of vortices [6–8]. Instability is, of course, the necessary condition for self-generation of structures. Besides, the instability may change the spatial pattern itself. The present authors showed that a spiral vortex is generated in a rotating magnetized plasma, and the origin of the spiral nature is attributable to the existence of instability [9,10].

On the other hand, the effect of dissipation on the property of vortex is not fully understood. Since macroscopic flow structures excited in a plasma with finite viscosity are subjected to continuous energy damping due to internal friction, vortices surviving in this circumstance should be a dissipative structure. However, such vortices have not been experimentally observed in plasmas yet. We report in this Letter the experimental results on a self-organized vortex as a dissipative structure.

The experiments have been performed with the High Density Plasma Experiment (Hyper-I) device at the National Institute for Fusion Science. Hyper-I is a cylindrical 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 [11]. The magnetic field configuration is a so-called magnetic beach structure (1.25 kG at $z = 30$ cm, 875 G at $z = 100$ cm). The electron temperature and density were $\simeq 20$ eV and $\leq 1 \times 10^{12}$ cm^{-3}, respectively, and the duration time of discharge was ≤ 60 s. A helium gas was used with the operation pressures (6–8) $\times 10^{-4}$ Torr.

A cylindrical density cavity (referred to as plasma hole) was spontaneously formed in the plasma [12], for which the radial density profile and the perspective image taken by a CCD camera are shown in Fig. 1. Once the hole structure has arisen, it remains unchanged for an increase of the microwave input power. The central dark region of the inset picture of Fig. 1 indicates the density hole, the

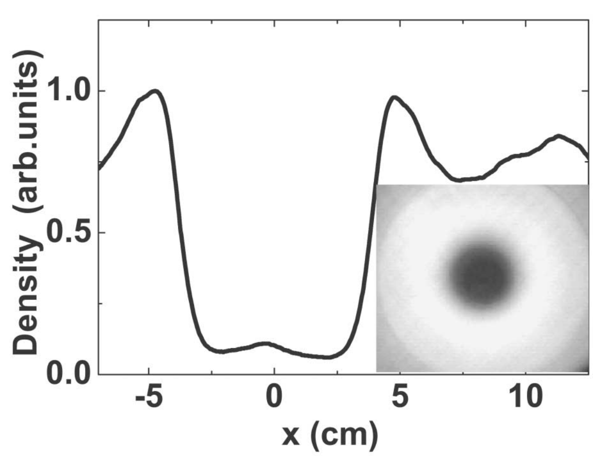

FIG. 1. Radial density profile of the plasma hole ($z = 110$ cm) and the perspective image taken by a CCD camera located at the end of the chamber.

sizes of which are 6 cm in diameter and more than 100 cm in axial length. The density of hole plasma is one-tenth of that in the ambient plasma, and the width of the 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 electron temperature exhibits a nearly uniform profile and is 20 eV in the ambient region and 25 eV in the hole region. The space potentials measured with an emissive probe are +130 V at the hole center and +25–+45 V in the ambient plasma. There also exists a steep potential gradient in the density transition layer, and the electric field in this region is 40 V/cm, which results in azimuthal rotation of the plasma.

The flow velocity field associated with the plasma hole has been measured with a directional Langmuir probe [13]. The vector field plot of the ion flow velocity measured at an axial position 110 cm from the microwave launching point is shown in Fig. 2. The flow pattern exhibits a monopole vortical structure with a sink at the center, and the velocity at $r \sim 3.0$ cm exceeds the ion sound speed (the scale is indicated at the top left corner of the figure). When the direction of the magnetic field is reversed, the azimuthal velocity V_θ also changes its sign, indicating that the azimuthal rotation is due to the $E \times B$ drift. In fact, the maximum azimuthal velocity $V_\theta(\sim C_s = 3 \times 10^6$ cm/s) is well explained by the $E \times B$ drift with the observed electric field (40 V/cm). On the other hand, the radial velocity remains unchanged when the polarity of the magnetic field is changed. This suggests that the driving force changes its sign with the magnetic field inversion. The most probable cause of radial motion is the azimuthal friction force originated from $V_\theta(r)$. This force changes

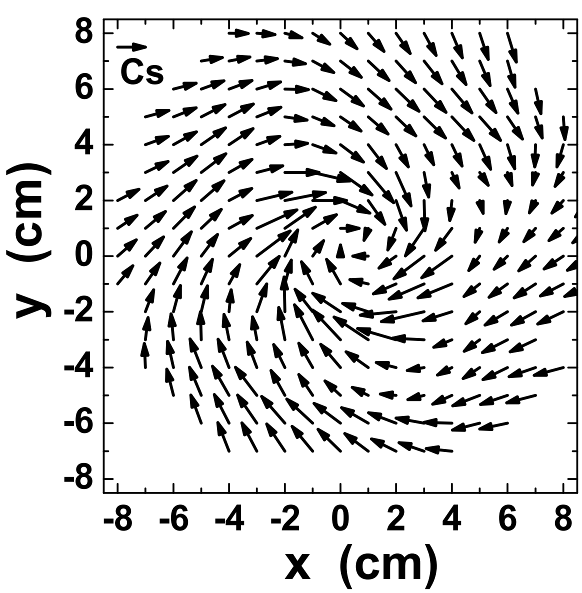

FIG. 2. Two-dimensional velocity field measured at $z =$ 110 cm. The magnitude of arrow corresponding to the ion sound speed is shown at the top left of the figure.

the sign with the inversion of the magnetic field because V_θ changes its sign, and thus the resultant $F \times B$ drift remains unchanged. Recently, radial flow induced by viscosity has also been observed in other experiments [14].

In our plasma, the space potential is set up to adjust the axial electron loss, and is usually positive. The existence of extremely high potential means that the electrons in the hole region are much more likely to escape than in the ambient region. According to the experimental observation on the line intensity ratio for ions and neutrals, the neutral density profile exhibits a cavity structure similar to the plasma hole; in other words, neutral "burn-out" occurs in the hole region. The electron-neutral collision frequency substantially decreases in this region, and the electrons are ready to run away from the plasma. Therefore, a very high positive potential is produced to reduce the electron loss.

It is worth pointing out that the characteristic scale length of neutral burn-out is smaller than the mean free path of neutrals. The effective path of inflow neutrals should be more elongated than that of free streaming. It is considered that the neutral fluids azimuthally rotate because of collisions with the $E \times B$ rotating ions. Thus, the faster the ion rotates, the further the lack of neutrals proceed in the column center. This process provides the positive feedback mechanism for generating a plasma hole.

In the hole region, radial inflow should be exhausted to conserve the particle balance. Since the recombination rate ($\sim 10^{12}$ cm^{-3} s^{-1}) is negligibly small compared with ionization rate ($\sim 10^{16}$ cm^{-3} s^{-1}), the volume recombination process cannot explain the particle balance in the hole region. There should be an axial flow to exhaust the influx, and actually we have experimentally confirmed the existence of axial flow streaming at a velocity $\sim 0.5 C_s$, which is localized in the hole region. The flow field structure is three dimensional, and is similar to that of a typhoon.

We calculate the z component of vorticity at each point by performing the line integration defined by the following equation: $\omega_z = (\nabla \times \boldsymbol{V})_z \sim \oint \boldsymbol{V} \cdot d\boldsymbol{l}/\Delta S$, where the integration path is taken along the minimum square passing through the neighboring four velocity vectors, and ΔS is 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 data, and the closed circles indicate the average values. It is 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.

In order to understand the mechanism of vorticity concentration, we consider here vorticity dynamics for ion fluid. Taking a curl of the momentum equation for ion fluid in a uniform magnetic field, we obtain the vorticity equation, which is equivalent to that of normal fluids [15]. Thus, we can discuss the vorticity dynamics in the same sense as in normal fluids.

When an inward convection is presented ($V_r = -\alpha r$, $\alpha > 0$), vorticity concentration occurs to be balanced with the diffusive process due to viscosity, generating a

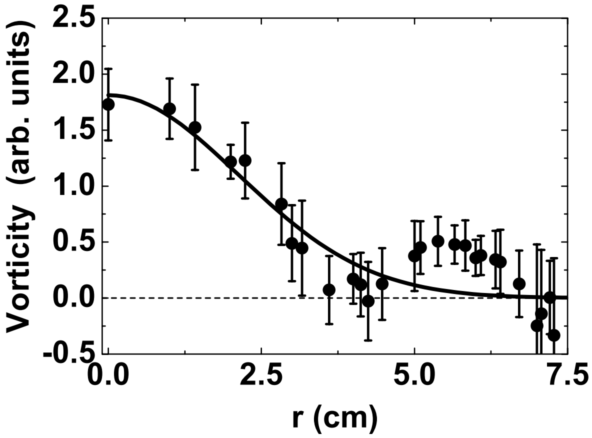

FIG. 3. Vorticity as a function of radius. The solid curve indicates the vorticity distribution given by Eq. (1), where $\Gamma = 7.7 \times 10^7\ \mathrm{cm}^2/\mathrm{s}$ and $l = 3.0$ cm.

stationary structure, which is known as Burgers vortex [16,17].

By using the variable transformation [18,19], the vorticity equation (z component) is transformed into the diffusion equation, and then the solution 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,

$$\omega_z^{(B)} = \frac{\Gamma}{\pi l^2} \exp\left(-\frac{r^2}{l^2}\right), \tag{1}$$

where the quantity l is determined by the ratio of viscous diffusion to convective concentration of vortices, and is given by the relation $l = (2\nu/\alpha)^{1/2}$. The solid curve in Fig. 3 indicates the best-fit Gaussian profile, for which the parameters are taken to be $\Gamma = 7.7 \times 10^7\ \mathrm{cm}^2/\mathrm{s}$ and $l = 3.0$ cm. The azimuthal velocity is uniquely determined by integrating Eq. (1) and is given by

$$V_\theta^{(B)} = \frac{\Gamma}{2\pi r}\left[1 - \exp\left(-\frac{r^2}{l^2}\right)\right], \tag{2}$$

which behaves as $V_\theta \propto r$ (rigid rotation) for $r/l \ll 1$ and $V_\theta \propto 1/r$ (vorticity free rotation) for $r/l \gg 1$. Figure 4(a) 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.

The 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. 4(b), showing that there exists, in fact, an inward convection expressed by $V_r = -\alpha r$ in the plasma. According to these results, the localization of vorticity observed in the present experiment is identified as a Burgers vortex.

Finite viscosity causes irreversible thermalization of vortical motion due to friction of the fluid. We have experimentally determined the radial profile of the dissipation rate by the following equation [15]:

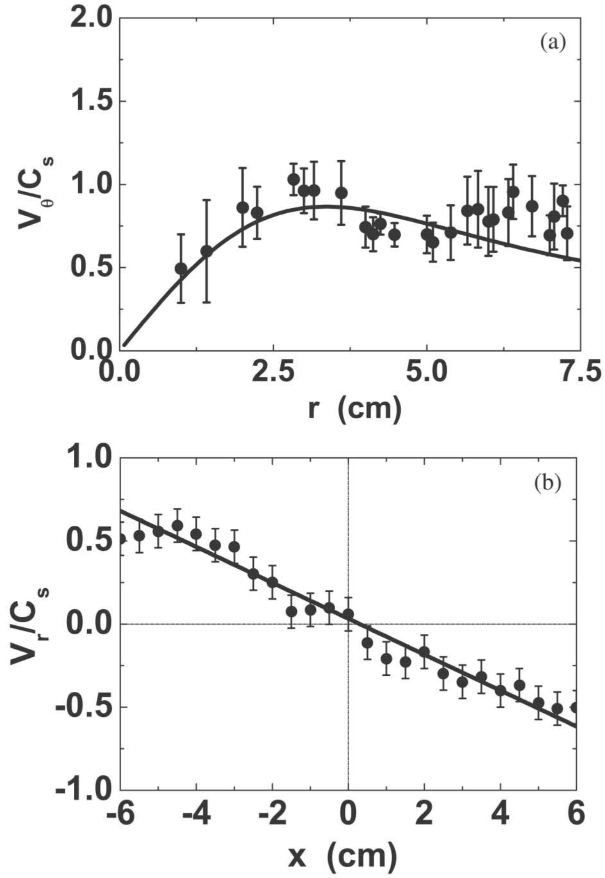

FIG. 4. (a) Azimuthal flow velocity as a function of radius. The solid curve indicates Eq. (2). (b) Radial flow velocity as a function of radius.

$$\sigma'_{ik}\frac{\partial V_i}{\partial x_k} = \eta[2(e_{rr}^2 + e_{\theta\theta}^2 + e_{zz}^2) + e_{\theta z}^2 + e_{zr}^2 + e_{r\theta}^2] - \frac{2}{3}\eta(e_{rr} + e_{\theta\theta} + e_{zz})^2 \tag{3}$$

where σ'_{ik} is the viscous stress tensor, $\eta(= mn\nu)$ the dynamic viscosity, and $e_{\alpha\beta}$ the (α, β) component of the rate-of-strain tensor in the cylindrical coordinates, respectively. The derivatives in this equation are obtained by differentiating the best-fit curve for the experimental data. It is found that the term $e_{r\theta}^2 \sim [r\partial(V_\theta/r)/\partial r]^2$ dominates all of the rest and is 61% of the total dissipation rate. It is emphasized that this term corresponds to the dissipation of vortical motion by internal friction. As seen in Fig. 5, 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 as heat in this layer. It is pointed out that the energy dissipation undertakes the 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 kinematic viscosity can be estimated from the scale of vortex l and the coefficient α of inward flow using the

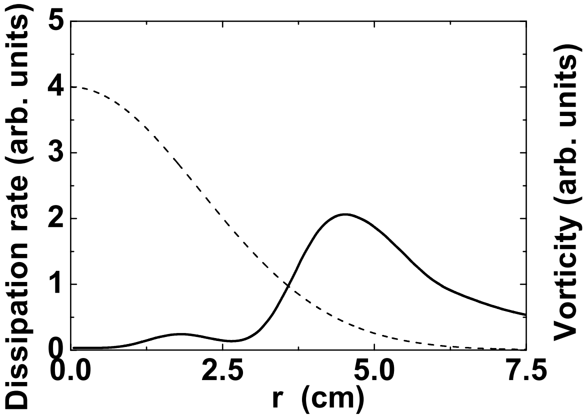

FIG. 5. Dissipation rate as a function of radius. The dashed curve indicates the vorticity distribution.

relation $l = (2\nu/\alpha)^{1/2}$. Substituting $\alpha = 4.4 \times 10^5\ s^{-1}$ from the experimental data and $l = 3.0$ cm into the above relation, we have $\nu_{eff} = 2.0 \times 10^6\ cm^2/s$, which is 4 orders of magnitude higher than the classical value $\nu_c = 1 \times 10^2\ cm^2/s$ [20], and still 1 order of magnitude higher than the viscosities observed in magnetically confined plasmas $\nu = (0.5\text{–}10) \times 10^4\ cm^2/s$ [21]. The anomaly of viscosity may be attributable to the breaking of quasineutrality 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 estimated to be 10^{-3} in contrast to that in the ambient plasma 10^{-6}, which is of order of $(\lambda_D/R)^2$ (λ_D: Debye length, R: plasma radius). Therefore the Debye shielding is insufficient in the hole region, and the potential leaks to the outside far beyond the scale of Debye length. When there is a potential perturbation in some part of the hole plasma, it involves the neighboring plasma in collective motion with this long-range force. Consequently, the plasma in the hole region behaves like a rigid body. The other possibility of viscosity anomaly may be attributable to turbulence induced by instability of electrostatic waves such as drift wave turbulence or lower hybrid turbulence, etc. Unfortunately, we have not experimentally identified the origin of viscosity anomaly. The detailed analysis remains for future study.

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 shocklike transition layer at the boundary. The vorticity distribution agrees well with a Gaussian profile. This means that the mechanism of vortex formation, the balance between convective concentration and viscous diffusion of vorticity, still acts as the basic process. 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 on structure formation in plasmas.

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