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Multipole Vortices in an ECR Plasma

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Abstract

Spontaneous formation of multipole vortices in an ECR plasma is experimentally examined to investigate self-organization and structure formation in a rotating plasma. These vortices are characterized by steep density profiles with the peak densities 4-5 times higher than that of background plasmas. The vortex pattern does not move with time, while the plasma rotates in the direction of electron diamagnetic drift. It is found that there exists axial flow reversal in the rim of vortices.

Keywords:

multipole vortices, self-organization, structure formation, $\boldsymbol{E} \times \boldsymbol{B}$ drift, shear flow, ECR plasma

1. Introduction

Vortex, a localized vorticity distribution, is a common entity of self-organization in rotating fluids, and many works have been done in ordinary fluids and superfluids. Recently, vortex formation and interaction in a non-neutral plasma have been attracting much attention [1,2], and discussed in relation to 2-dimensional Eulerian fluid. On the other hand, a few experimental works have been done in neutral plasmas, in which interplay between a variety of processes such as collective effect, nonlinear effect, viscosity and compressibility etc. is expected to be important. Thus, in the present work it is of primary interest to understand the inherent features of vortex generated in a neutral plasma [3,4].

Here, we concentrate our attention to characterize the multipole vortices observed in an ECR plasma. The experimental results on the spatial structure, density profile, and flow velocity field of the multipole vortices are presented. In Sec. **2**, the experimental setup is described, and the results and discussions are presented in Sec. **3**, where the most simplest structure, a paired-vortices is described in detail. It is found that the two vortices have the same polarity in vorticity, and that the ions flow in the direction of electron diamagnetic drift. It is also found that there exists an axial flow reversal in the rim of vortices.

2. Experimental Setup

The experiments have been performed in the High Density Plasma Experiment (HYPER-I) device at National Institute for Fusion Science [5]. A schematic view of the HYPER-I device is shown in Fig. 1. The

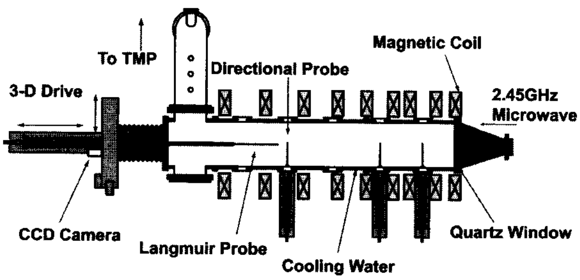

Fig. 1 Schematic of HYPER-I device

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HYPER-I device consists of ten magnetic coils and a cylindrical chamber with the inner diameter of 30cm and axial length of 200 cm. The magnetic field lines are weakly diverging along the chamber axis, and make a so-called magnetic beach configuration. Plasmas are produced and sustained by electron cyclotron resonance (ECR) heating with a 2.45 GHz microwave injected from an open end of the vacuum chamber. Under the typical experimental condition, the ECR point is located at 111 cm from the microwave launching position. The ratio of microwave frequency to electron cyclotron frequency, ω/ω_{ce}, at the injection position is 1.1. The density and electron temperature are typically $n \leq 10^{13}$ cm^{-3} and $T_e \simeq 5$ eV, respectively, with the operation pressure $p_0 \simeq 3 \times 10^{-2}$ Torr (Argon) and 5–10 kW microwave input power.

Ion flow velocity is measured with movable directional Langmuir probes [6] from the radial ports. A three-dimensional (3-D) motor drive is equipped at an open end of the chamber to measure the density profile. A CCD camera is also installed to obtain the end view image of vortices.

3. Results and Discussions

3.1 Multipole Vortices Formation

Figure 2 shows the end view images of the observed structures for different magnetic field intensities. When the operation pressure is higher than 2×10^{-2} Torr, localized structures are spontaneously formed in the plasma. These structures have been found to be rotating plasma columns, and are called as multipole vortices hereafter. The pattern of structures is stationary during the whole period of discharge, and the number of poles (bright regions in the figure) changes with the external magnetic field. When the coil current is I_{coil} = 100 A (Fig. 2(a)), the lowest magnetic field intensity in this experiment, three large vortices are formed in the center of the chamber surrounded by many small vortices. When the coil current is increased (I_{coil} = 103 A), the center vortex disappears, while two vortices in the upper side and the bottom side grow as seen in Fig. 2(b). Although the number of large vortices increases from three to four, the small vortices merge in the peripheral region so that the total number of vortices decreases. For higher magnetic field (Fig. 2(c) and (d)),

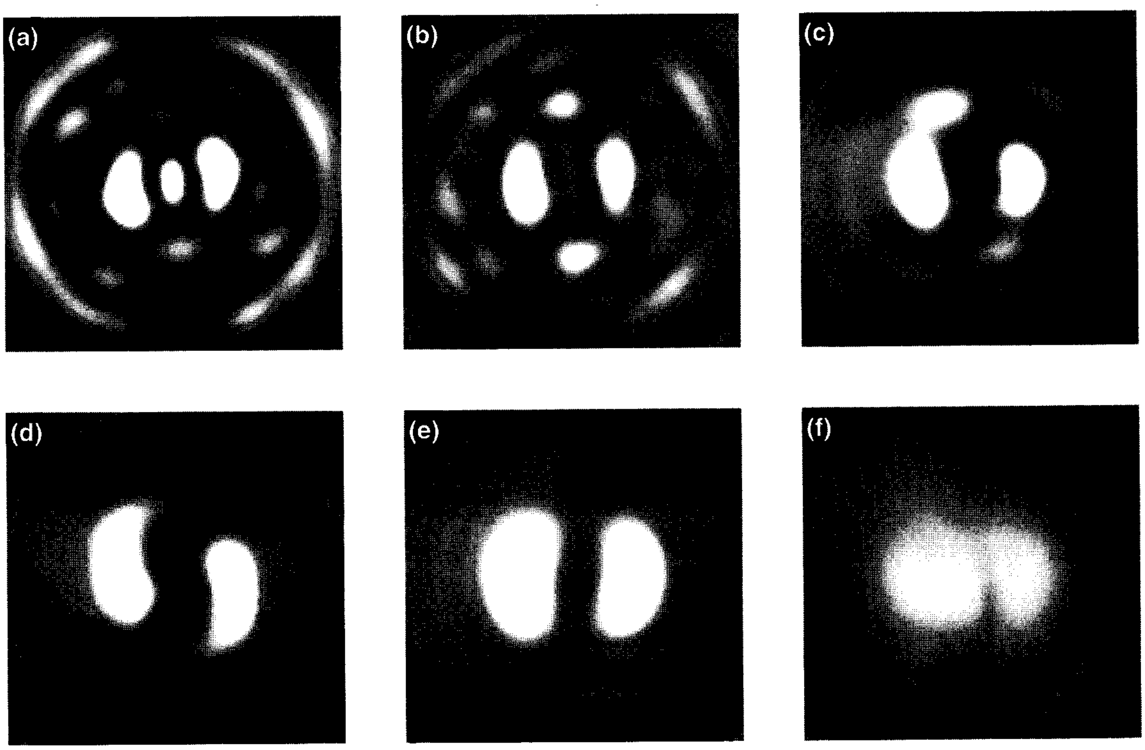

Fig. 2 End-view images of multipole vortices: (a) I_{coil} = 100 A, (b) I_{coil} = 103 A, (c) I_{coil} = 106 A, (d) I_{coil} = 110 A, (e) I_{coil} = 120 A, and (f) I_{coil} = 130 A.

further merging of vortices occurs and small vortices in the peripheral region disappear. The simplest structure observed in the present experiment consists of two large vortices as shown in Fig. 2(e), which is referred to as vortex pair hereafter. The localized structures disappear for the coil current above $I_{\rm coil} \simeq 130$ A (Fig. 2(f)), and uniform plasmas are produced. All these structures presented in Fig. 2(a)–(e) have a common feature, i.e., rotational symmetry with π-radian rotation around the center axis.

A change in the external magnetic field corresponds to a shift of ECR point along the chamber axis. Increasing the magnetic field, the ECR point moves away from the microwave injection window. The experimental observation shows that the number of vortices and the configuration are very sensitive to the location of ECR point. This means that the formation of multipole vortices and generation of global convection are strongly affected by the location of plasma production region. The density profile and ion flow structure have been measured with a Langmuir probe and a directional Langmuir probe, respectively, the results of which are presented in the next subsection.

3.2 Density Profile and Flow Field Structures of Vortex Pair

In this subsection, the characteristic features of the vortex pair are presented. Density contour of the vortex pair measured with a Langmuir probe is shown in Fig. 3. In accordance with the two bright oval regions in the CCD image (Fig. 2(e)), there are two density humps. The full width at half maximum of the density hump is about 10 cm × 5 cm on the cross section perpendicular to the magnetic field. The peak density is 6×10^{12} cm^{-3}, and is 4–5 times higher than that of the background plasma with a flat profile over the whole cross section.

To examine the axial structure of the vortices, we have measured the density profile at axially different positions. The results are shown in Fig. 4, in which Fig. 4(a) is for 20 cm from the microwave launching position, and Fig. 4(b) for 110 cm. The density profile in Fig. 4(b) is identical to that measured along the horizontal cord passing through the center of vortices ($y = 0$) in Fig. 3. The density profiles in Fig. 4 have commonly two maxima 4–5 times higher than the background density. The distance between the peaks is about 9 cm for Fig. 4(a), and 10.5 cm for Fig. 4(b), which is attributable to the weak diverging magnetic field. According to these results, it is concluded that the vortex pair is axially extends over 90 cm.

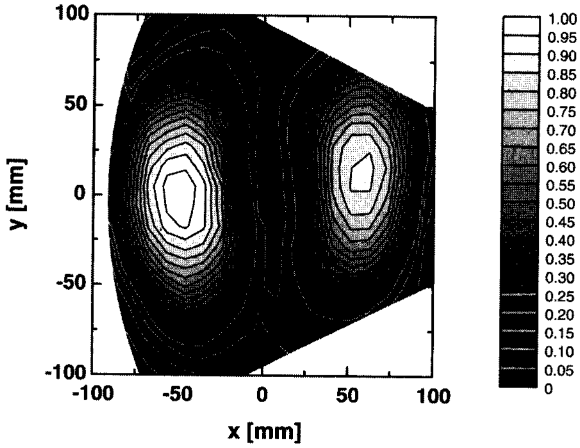

Fig. 3 Density contour of vortex pair. The density is normalized by the maximum density.

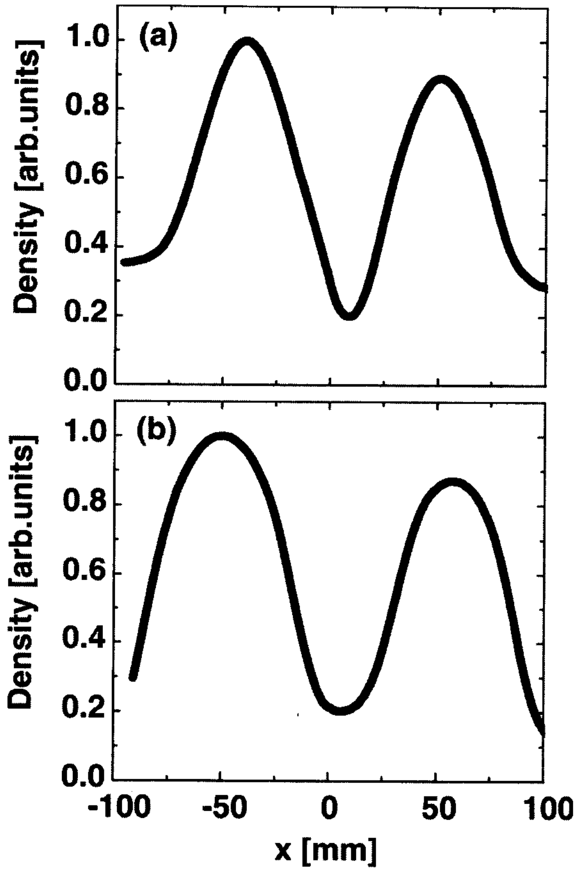

Fig. 4 Density profile at two different axial positions: (a) 20 cm, (b) 110 cm from the microwave injection window. The density profile is normalized by the maximum density.

The azimuthal ion velocity associated with the vortex pair is shown in Fig. 5. The velocity measurements have been done using a directional Langmuir probe [6], along the horizontal cord passing through the center of vortices. The direction of the external magnetic field is perpendicular to this figure, and the direction of magnetic field vector is indicated in the upper right of the figure. The hatched regions in Fig. 5 correspond to the full width at half maximum of the density humps, the dashed lines indicate the positions of the maximum density. The ion velocity is normalized by the ion sound velocity C_S. As seen in Fig. 5, the azimuthal ion flow velocity is proportional to the distance from the center of vortices, exhibiting a rigid-like rotation. The two vortices rotate in the same direction (counterclockwise rotation). The electron flow velocity, which cannot be accurately determined by the directional Langmuir probe, is found to be in the same direction of ion flow.

When the magnetic field direction is inverted, no remarkable change has been observed in the vortical pattern except for a change in the azimuthal position (tilting of the horizontal cord with respect to chamber axis). Figure 6 shows the azimuthal ion velocity for the inverted magnetic field case. The asymmetric profile in the azimuthal ion velocity is attributable to the tilting of vortex pattern. It is easily found that the rotation of ion flow changes its direction in this case. This result implies that the ion rotation is due to $\boldsymbol{F} \times \boldsymbol{B}$ drift with a force $\boldsymbol{F}$ acting in the radial and inward direction. The potential profile measurement revealed that the electric field in the vortex is radially outward ($\leq$ 1 V/cm) and that the rotation direction is opposite to that of $\boldsymbol{E} \times \boldsymbol{B}$ drift. It is worth nothing that $\boldsymbol{E} \times \boldsymbol{B}$ rotation velocity with a electric field $E \sim 1$ V/cm is 1×10^5 cm/s $\simeq 0.3$ C_S. The experimental result shows that there exists an inward force, which dominates an electric field of the order of 1 V/cm. The origin of inward force is not fully understood yet, and the experiments are now in progress.

The axial ion flow profile is shown in Fig. 7, which is independent of the direction of the magnetic field. In the core region of each vortex (hatched region), the direction of axial flow is the same as that of μ grad-B force, where μ is the magnetic moment. On the other hand, in the peripheral regions, the flow direction is opposite to that of the core regions, exhibiting the existence of strong shear in axial velocity at the edge region. The vortex pair is considered to be confined within this shear layer.

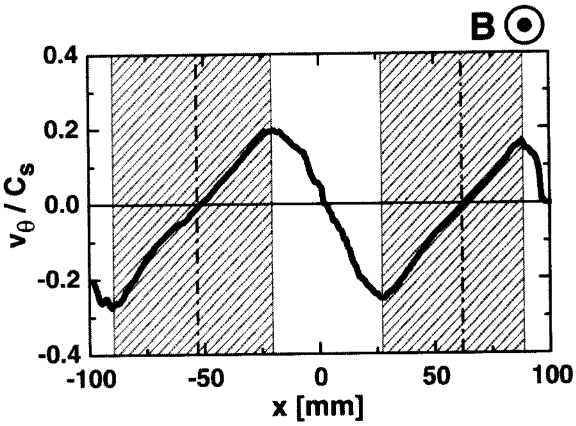

Fig. 5 Azimuthal velocity profile

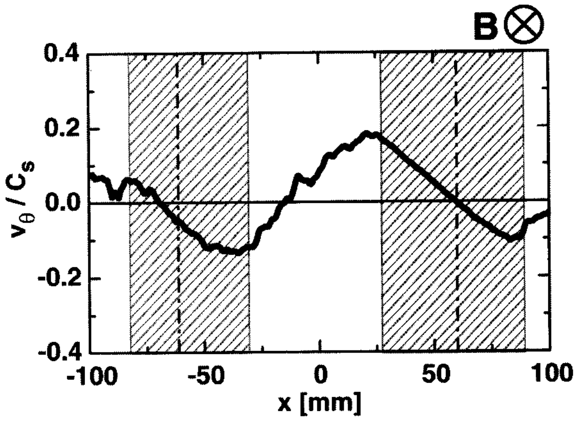

Fig. 6 Azimuthal velocity profile with reversed magnetic field.

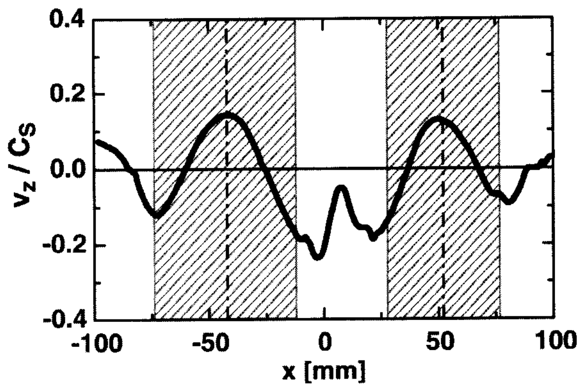

Fig. 7 Axial velocity profile

4. Summary

We have observed spontaneous formation of multipole vortices in an ECR plasma. The vortex pattern is stationary during the whole period of discharge. The number of poles decreases with increasing the external magnetic field, and the vortex pair remain as the simplest structure. It is found that two vortices have the same polarity in vorticity and the direction of ion rotation is opposite to that of $\boldsymbol{E} \times \boldsymbol{B}$ drift. The existence of strong shear layer in the axial velocity seems to be important for the confinement and arrangement of vortices.

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