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Measurement of Supersonic Rotation Accompanied with a Plasma Hole

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Abstract

A supersonic ion flow has been measured with a directional Langmuir probe (DLP) in a plasma hole, which is a monopole vortex with density cavity and is characterized by supersonic ion flow. The measured flow velocity is compared to the $E \times B$ drift velocity. It is revealed that the higher order components of Fourier mode with respect to the probe angle increases in the DLP signal as the flow velocity exceeds the sound velocity. The previously proposed DLP method is extended to apply supersonic flow measurements.

Keywords:

supersonic flow, flow measurement, directional Langmuir probe, E × B drift rotation, ECR plasma

1. Introduction

Plasma flow has been one of interesting topics in laboratory plasmas[1], confined plasmas as well as astrophysical plasmas. Vortical flow, especially, attracts much attention in connection with the formation of nonlinear structure and the fundamental structure in highly developed turbulences. Recently, a monopole vortex with a co-axial density cavity (referred to as "plasma hole") has been observed in an electron cyclotron resonance (ECR) plasma[2]. When the plasma hole occurs, a sharply-peaked electrostatic potential is spontaneously formed, generating a supersonic $E \times B$ rotation of the plasma. Also a steep density gradient is formed near the supersonic rotating region, and this structure seems to be a shock front. Thus an investigation of the interplay between the supersonic rotation and generation of shock-like structure is an important subject to understand the physics of plasma hole.

From the experimental point of view, determination of flow structure depends on the method of measuring flow velocity in plasmas. One of the simplest methods for low-temperature plasmas uses a directional Langmuir probe (DLP) or a Mach probe, for which many theoretical models have been proposed[3,4,5]. Commonly, these theoretical models are valid for subsonic flow cases because they adopt the Bohm criterion for the evaluation of ion saturating current, and may not be extendable to a supersonic flow. On the other hand, our model[6] is based on the property of symmetry of ion current in a flowing plasma, and hence there is a possibility of applying this method to supersonic flow measurements.

In this paper, the effect of supersonic flow on the DLP current is presented, and our previously proposed method is extended to the supersonic region. The experimental setup is described in the next section, the results are shown in section **3**, followed by discussions in section **4**.

2. Experimental setup

The experiments have been performed in the high-density plasma experiment (HYPER-I) device at National Institute for Fusion Science[7]. The HYPER-I device consists of a cylindrical chamber (30 cm in diameter, 200 cm in axial length) and ten magnetic coils, which produce magnetic fields of 1–2 kG on the chamber axis. Plasmas are produced and sustained by electron cyclotron resonance (ECR) heating. A microwave of frequency 2.45 GHz is generated by a klystron amplifier (80 kW CW maximum) and is launched at an open end of the chamber, where the high-field side condition ($\omega_{ce} > \omega$, ω_{ce}: electron cyclotron frequency, ω: wave frequency) is satisfied. The magnetic field configuration is a so-called magnetic beach with the ECR point at 90 cm from the microwave injection window. An electron cyclotron wave is excited in the plasma and fully absorbed before reaching the ECR point[8]. The plasma volume is 30 cm in diameter and 200 cm in axial length. The typical electron density and temperature are about 10^{11} cm^{-3} and 10 eV for the operation pressure 6×10^{-4} Torr (Helium), respectively. The microwave input power in the present experiment is ≤ 8kW.

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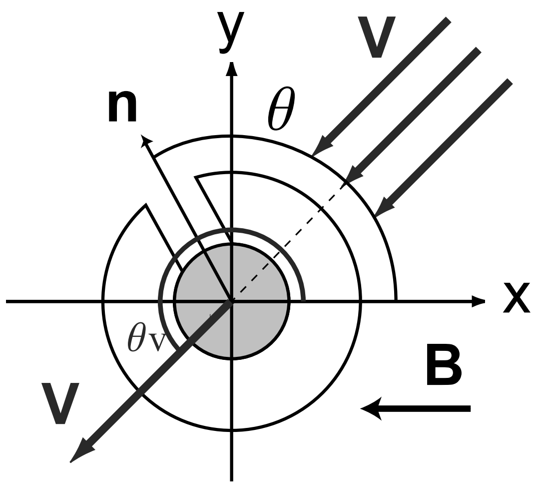

Fig. 1 Cut view of directional Langmuir probe and coordinate system. The *x*-axis is in the direction to the magnetic field, while *y*-axis azimuthal direction. The angle θ is the angle of normal of probe surface, and θ_v the angle of ion flow velocity with respect to the *x*-axis, respectively.

In these experimental conditions, a plasma hole is generated spontaneously[2]. The flow velocity field of ions accompanied with the plasma hole consists of azimuthal rotation, axial flow and radial inward flow. The azimuthal rotation is driven by the $\boldsymbol{E} \times \boldsymbol{B}$ drift induced by the sharply-peaked electrostatic potential, where the radial electric field reaches the maximum value of 2 kV/m. The corresponding $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity is comparable to the ion sound velocity, $C_s \simeq 2 \times 10^6$ cm/s. We have measured the ion flow velocity at two radial positions: (a) r = 30 mm, supersonic region, and (b) r = 70 mm, subsonic region.

The ion flow velocity was measured with a directional Langmuir probe (DLP), which collects a directed ion current through a small opening (1 mm diam) made on the side wall of the ceramic insulator (3 mm diam). The coordinate system is shown in Fig. 1. The ion flow velocity at a certain angle θ with respect to the reference axis, $v(\theta)$, is obtained by measuring two ion saturation currents, $I_s(\theta)$ and $I_s(\theta + \pi)$, and by using the following relation:[6]

$$\frac{v(\theta)}{C_s} = \frac{1}{\alpha} \frac{I_s(\theta+\pi) - I_s(\theta)}{[I_s(\theta+\pi) + I_s(\theta)]/2}, \tag{1}$$

where θ is the angle between the normal of electrode of DLP and the reference axis, C_s the ion sound speed. The factor α is of the order of unity and is determined by comparing the same $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity obtained from the potential measurement. In this experiment, an $E \times B$ drift velocity of a subsonic flow region is used to determine the value of α, giving $\alpha = 2.3$.

3. Experimental Results

The ion saturation current as a function of the angle of probe normal, $I(\theta)$, was measured at two radial positions. In the subsonic flow region (r = 70 mm), we observed two dips in the DLP current at the angle 90° and 270°, i.e., the directions perpendicular to the magnetic field. The ion Larmor radius is comparable to the probe radius, $(\rho_i/r_p) \sim 1$, for the helium plasma, thus the ion is weakly magnetized. The two dips are attributable to the effect of magnetic field. On the other hand, the ion saturation current in supersonic region (r = 30 mm) has no dips at the directions perpendicular to the magnetic field, which is shown in Fig. 2. There are one peak at $\theta \simeq 30°$ and one dip at $\theta \simeq 290°$. These two angles seem to have no symmetry and the profile is rather distorted from the average.

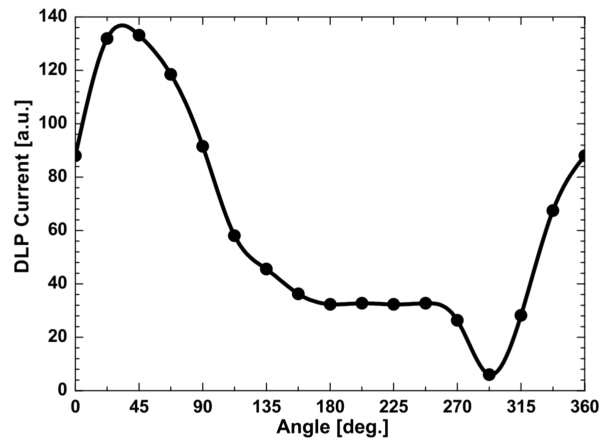

Fig. 2 Ion saturation current of DLP as a function of probe angle in a supersonic flow.

Although the ion saturation current $I(\theta)$ includes the effect of the magnetic field, it can be completely eliminated with the use of eq. (1)[2]. The Fourier component of $\Delta I/\langle I \rangle$ ($\Delta I = I(\theta + \pi) - I(\theta)$ and $\langle I \rangle = [I(\theta + \pi) + I(\theta)]/2$) for both the subsonic and supersonic cases are shown in Figs. 3 and 4, respectively. In these figures, the averaged components (m = 0) are not shown. In the subsonic flow case, the amplitude of fundamental mode $2a_1$ (see eq. (3)) and the flow velocity are connected with the relation $|v/C_s| = 2a_1/\alpha$. The amplitude of the fundamental mode is 0.56 (Fig. 3), thus the ion flow velocity is determined to be $0.24C_s$. The higher modes in Fig.

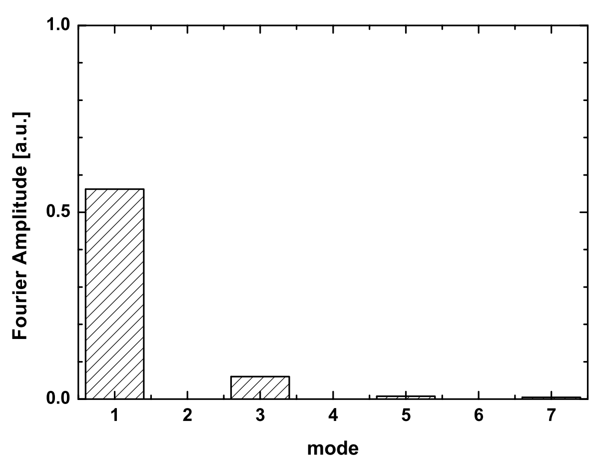

Fig. 3 Fourier amplitude of $[I(\theta) - I(\theta + \pi)]/\langle I \rangle$ in a subsonic flow.

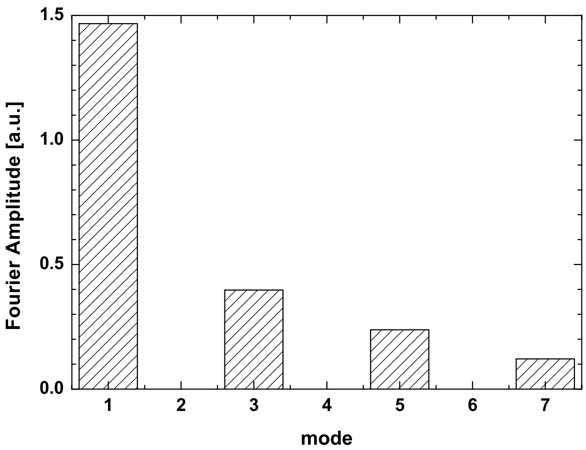

Fig. 4 Fourier amplitude of $[I(\theta) - I(\theta+\pi)]/\langle I\rangle$ in a supersonic flow.

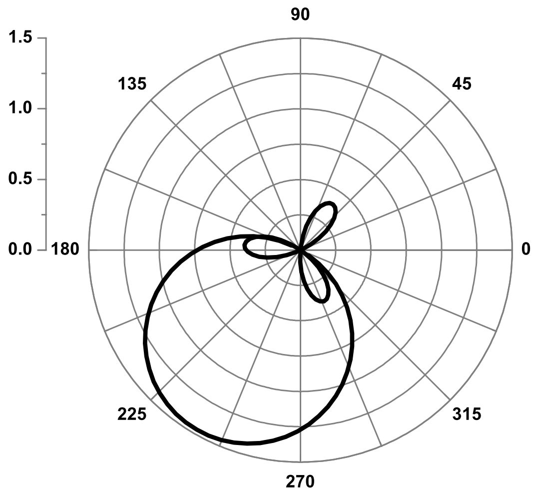

Fig. 5 Polar plot of Fourier components m = 1, 3 in a supersonic flow.

3 are negligible compared to the fundamental mode, showing the validity of DLP method. In the supersonic flow measurement, however, the amplitude of higher odd modes, m = 3, 5,···, are not negligible (see Fig. 4).

The polar plot of the Fourier modes m = 1, 3 of the supersonic case are plotted in Fig.5, where the magnetic field lies in the x-axis (180°), and the y-axis (90°) corresponds to the azimuthal direction. The ion flow has both the rotational component (v_y<0) and axial component along B (v_x<0). Considering the radial electric field is outward, we can conclude that the rotational flow is due to $E \times B$ drift. Actually, the rotational component of fundamental mode in the subsonic case is 0.39, which corresponds to $|v_y/C_s| = 0.17$, while the $E \times B$ drift velocity at the same position is 2.8×10^5 cm/s ($\simeq 0.18C_s$). In the supersonic flow measurement (Fig. 5), however, the rotational component of the fundamental mode is 1.27 corresponding to $|v_y/C_s| = 0.55$. On the other hand, the $E \times B$ drift velocity at the same position is 1.4×10^6 cm/s ($\simeq 0.9C_s$). The disagreement in the supersonic flow case is attributable to the distortion of flow field around the probe, which is mainly expressed by the contribution from m = 3 mode.

The phase of the higher mode (m = 3) has a characteristic feature in the supersonic flow case. It is nearly 180° different from that of fundamental mode. This result sharply contrasts with that of the subsonic flow case, where the phase difference between these modes is not clear and the amplitude of m = 3 mode is negligibly small. The appearance of m = 3, 5,··· modes may be related to the existence of supersonic flow, and therefore be utilized to evaluate the flow velocity in the supersonic region, which is discussed in the next section.

4. Discussions

Here we consider the effect of supersonic flow on a DLP current. For a plasma with a finite ion flow velocity $\boldsymbol{v}$ and a magnetic field $\boldsymbol{B}$, the ion saturation current of DLP is modified from I_0, and is written as

$$I(\theta) = I_0[1 + F_v(\boldsymbol{v} \cdot \boldsymbol{n})]\,[1 + F_B((\boldsymbol{B} \cdot \boldsymbol{n})^2)], \qquad (2)$$

where I_0 is the ion saturation current without the flow and the magnetic field, F_v and F_B are the correction term due to the effects of ion flow and magnetic field, respectively. In subsonic cases, the correction term F_v is expressed as $F_v(\boldsymbol{v} \cdot \boldsymbol{n}) = -a_1 \cos(\theta - \theta_v)$, while the term F_B is expressed as $F_B((\boldsymbol{B} \cdot \boldsymbol{n})^2) = b \cos 2\theta$, where a and b are positive and θ-independent factors of the order of $a_1 \sim v/C_s$, $b \sim (\rho_i/r_p)^2$, respectively. We have assumed so far that the ion flow is too small to be disturbed by the existence of probe.

However, the probe immersed in a supersonic flow may change the flow field around the probe, because compressibility becomes important. In this situation, the factor F_v may have the higher order correction terms, which are in general θ-dependent. Considering the symmetry of the flow past a cylinder (probe), the effective correction term F_v may be written as

$$F(\boldsymbol{v} \cdot \boldsymbol{n}) = -\left[a_1 + a_2 \cos(\theta - \theta_v) + a_3 \cos 2(\theta - \theta_v) + \cdots\right]\cos(\theta - \theta_v). \qquad (3)$$

Here we include the correction term $a_2 \cos(\theta - \theta_v) + a_3 \cos 2(\theta - \theta_v)$ for simplicity. With the help of the even property of $b \cos 2\theta$, we can eliminate the effect of magnetic field by making of the quantity $\Delta I/\langle I\rangle$

$$\Delta I/\langle I\rangle = C_1\cos(\theta - \theta_v) + C_3 \cos 3(\theta - \theta_v) + C_5 \cos 5(\theta - \theta_v), \qquad (4)$$

where $\Delta I = I(\theta + \pi) - I(\theta)$ and $\langle I\rangle = [I(\theta + \pi) + I(\theta)]/2$, and the Fourier amplitudes are $C_1 = 2a_1(1 + \frac{3}{4}a_2 + \frac{5}{8}a_2^2) + a_3(1 + a_2)$, $C_3 = \frac{1}{2}a_1a_2(1 + \frac{5}{4}a_2) + a_3(1 + \frac{3}{4}a_2)$ and $C_5 = \frac{1}{8}a_1a_2^2 + \frac{1}{4}a_2a_3$, respectively. The expansion is taken to the order of 5θ. The eq. (4) is reduced to eq. (1) when $|a_1/a_2| \ll 1$ and $|a_3/a_1| \ll 1$. Thus the factors a_2 and a_3 represent the disturbance around the probe caused by the compressibility of the flowing plasma. Solving these equations with the experimental result (C_1 = 1.47, C_3 = −0.40), we have a_1 = 1.1, where the value C_5, which is too small to be distinguished from the experimental error, is determined by a_1 and a_2 in the first iteration. Then the flow velocity is given by $v/C_s = 2a_1/\alpha$ = 1.0. The rotational component of flow velocity is $|v_y/C_s|$ = 0.86, while the $E \times B$ drift velocity is $v_{E \times B}/C_s \simeq 0.9$, showing a good agreement.

A DLP measurement has been carried out for both a supersonic and a subsonic flow, and the results are compared to the $E \times B$ drift velocities obtained by the potential measurements. The higher modes (m = 3, 5, ···) in Fourier amplitude of the quantity $\Delta I/\langle I \rangle$ appears as the flow velocity approaches to the ion sound velocity because of compressibility in the supersonic flow. A simple model including the higher modes due to flow field distortion is formulated to evaluate the supersonic flow velocity, extending applicability of the previously proposed DLP method. There is a good agreement between the predicted value and experimental one.

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