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Plasma Flow Measurement Using Directional Langmuir Probe

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Abstract

A small directional Langmuir probe has been developed to measure macroscopic flow structure in an electron cyclotron resonance plasma. The unmagnetized condition for ions is met, and the perpendicular flow velocity with respect to the external magnetic field has been measured. The radial potential measurements show that the azimuthal ion flow is due to $\boldsymbol{E} \times \boldsymbol{B}$ drift, and is consistent with the directional probe data. A vector field plot of perpendicular flow exhibits a weak spiral pattern.

Keywords:

Directional Langmuir probe, plasma flow, $\boldsymbol{E} \times \boldsymbol{B}$ drift, plasma rotation, ECR, electron cyclotron wave

1. Introduction

Self-organized and large-scale flow structure in plasmas is of great interest in fundamental plasma physics. So far, much work has been done in measuring parallel flow structures along the magnetic field [1-3] using directional Langmuir probes (DLP), but only a few measurements of perpendicular flow have been made [4]. This is mainly due to the fact that the theory of DLP's applicable to magnetized plasmas is generally much more complicated and is not quantitatively reliable.

However, when the ion Larmor radius ρ_i is larger than the radius of the DLP ρ_p, i.e., the unmagnetized condition for ions is satisfied, we may expect that the theory without magnetic fields is still valid. To realize this condition, a small DLP with a radius ρ_p = 1.5mm was developed, and $\rho_i/\rho_p = 4$ was achieved in an argon plasma, which was produced by electron cyclotron resonance (ECR) heating.

It was experimentally found that the perpendicular drift of ions is due to $\boldsymbol{E} \times \boldsymbol{B}$ drift, which agrees with the result obtained by the potential measurement. We experimentally demonstrated that the directional Langmuir probe under ion-unmagnetized condition can be used to measure perpendicular ion flow velocities with good accuracy.

A vector field plot of plasma flow in the plane perpendicular to the magnetic field has been also obtained, exhibiting a weak spiral pattern.

2. Experiments

The experiments were carried out in the HYPER-I device at the National Institute for Fusion Science. The chamber dimensions were 30cm in diameter and 200cm in axial length. A magnetron oscillator, 2.45GHz and 15kW output, was used to produce ECR plasmas. The rectangular TE_{10} mode from the magnetron was converted to the circular TE_{11} mode, and further converted to a circular polarized (right-hand) TE_{11} mode by a dielectric polarizer. The right-hand polarized microwave was introduced into the chamber along the magnetic field line, through a tapered waveguide and a quartz window.

The magnetic field configuration satisfied the high-field side injection condition at the launching point ($\omega/\omega_{ce} < 1.0$), where ω is the wave frequency and ω_{ce} is the electron cyclotron frequency. An electron cyclotron

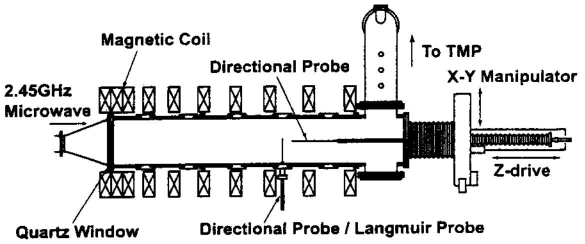

Fig. 1 Schematic of the HYPER-I device.

wave was excited in the plasma, and was fully absorbed before reaching the ECR point. A schematic diagram of the HYPER-I device is shown in Fig.1.

The directional Langmuir probe consists of a titanium wire, 1mm diameter, and a ceramic insulator, 3mm outer-diameter. There is a small hole (1mm diameter) on the side surface of the ceramic insulator; ion saturation current is collected through this hole. When there is a macroscopic ion flow in a plasma, the ion saturation current of a DLP exhibits an anisotropic dependence on the angle between the normal of the collection surface and the flow direction. According to the free fall model [5], the ion saturation current in the presence of ion flow is given by

$$I_s(\theta) = I_{s0} \exp[(\sqrt{T_i/T_e} - V\cos(\theta-\alpha)/C_s)^2], \quad (1)$$

where I_{s0} is the ion saturation current without plasma flow, and C_s is the ion sound velocity. The quantities θ and α are the angle of the normal of the ion collection surface and the direction of the flow velocity vector with respect to the horizontal axis, respectively. The quantity $\ln[I(\theta)/I(\theta+\pi)]$ is therefore proportional to $\cos(\theta-\alpha)$;

$$\frac{V}{C_s}\cos(\theta-\alpha) = -K \ln\left[\frac{I_s(\theta)}{I_s(\theta+\pi)}\right], \quad (2)$$

where $K = \sqrt{T_e/T_i}/4$ for the free fall model. In the kinetic model [2], eq.(2) remains unchanged except for the coefficient K, which is of order unity. The $\cos\theta$-dependence of $\ln[I(\theta)/I(\theta+\pi)]$ can be used to experimentally confirm whether or not the DLP works properly. Figure 2 shows $\ln[I(\theta)/I(\theta+\pi)]$ as a function of probe angle θ, which was obtained with a DLP introduced from a radial port. As seen in this figure, $\ln[I(\theta)/I(\theta+\pi)]$ agrees well with a cosine curve with $\alpha = 239°$, indicating that the DLP works properly. The azimuthal velocity is almost straight downward (270°), and the deviation of α from 270° indicates that there is a parallel flow along the magnetic field. In this case, the magnetic field intensity is 800G, the electron density $\simeq 5 \times 10^{11}$cm^{-3}, and the electron temperature is 8eV.

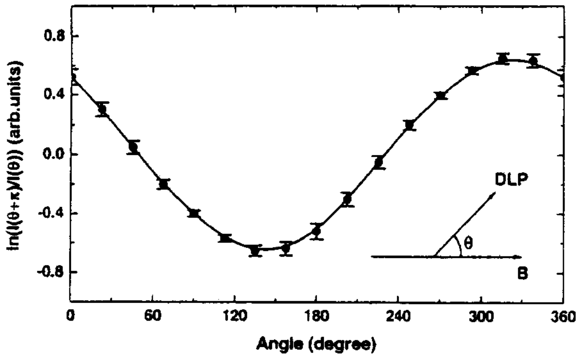

Fig. 2 Directional Langmuir Data as a function of angle θ.

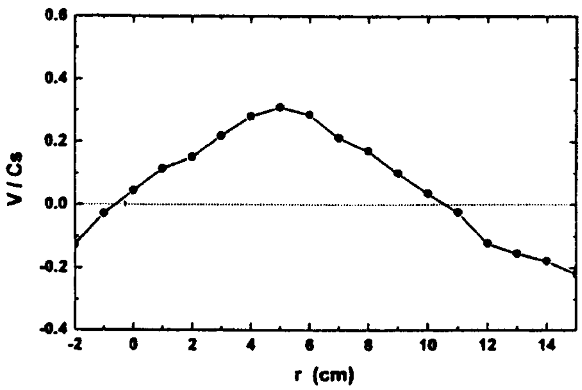

Fig. 3 Radial profile of azimuthal flow velocity.

The radial profile of azimuthal velocity is shown in Fig. 3. As seen in the figure, the plasma rotates like a rigid rotor in the core region ($r \leq 5$cm) ,while in the peripheral region, there is a strong shear and the flow direction is reversed near the wall ($r > 14$cm). The strong shear region is of great interest from the viewpoint of instability, and the experimental results will be reported elsewhere.

The flow direction of electrons was the same as ions, indicating that the azimuthal plasma flow was caused by $\boldsymbol{E} \times \boldsymbol{B}$ drift. Then, by measuring the radial potential profile, we are able to confirm the accuracy of the DLP by comparing the $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity with that obtained by the DLP. Since the derivative of the potential $\partial\phi/\partial r$ is very sensitive to the small noise due to experimental errors, we shall, instead of these velocities, compare the potential itself, which is determined from the DLP data, by the following equation:

$$\phi_{\mathrm{DLP}}(r) = \frac{c \cdot C_s}{B} \int^r K \ln \left[\frac{I_s(3\pi/2)}{I_s(\pi/2)} \right] (r') \, \mathrm{d}r'. \quad (3)$$

This quantity is essentially identical to the space potential ϕ when the DLP data are quantitatively correct. Figure 4 shows the radial profiles of these potentials, where the space potential obtained by a Langmuir probe is shown by closed circles, and the solid line indicates ϕ_{DLP}. The integration constant is chosen so that a best-fit curve to the experimental data is obtained, and $K = 0.67$ is assumed. As seen in the figure, there is good agreement between the space potential and the calculated one (eq.(3)), and we can conclude that the directional Langmuir probe can determine the perpendicular flow velocity with fairly good accuracy.

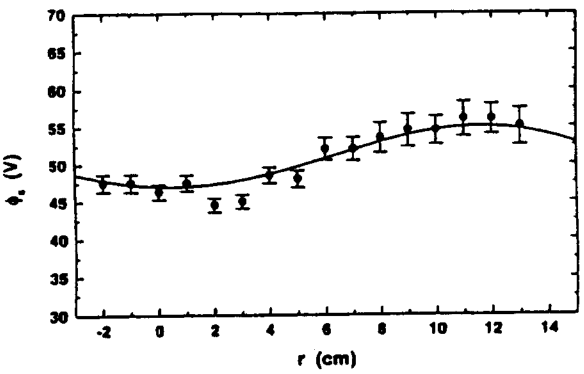

Fig. 4 Radial potential profile.

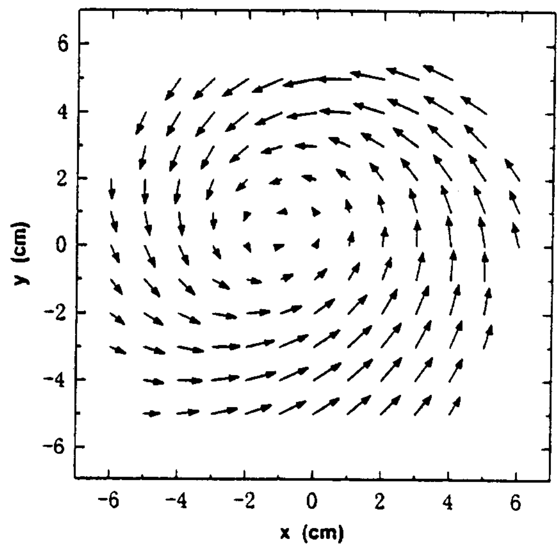

Fig. 5 Vector field plot of perpendicular flow structure.

A vector field plot of perpendicular flow structure is constructed to visualize the flow pattern in the plane perpendicular to the magnetic field. A 2-dimensional positioning system and an axially introduced DLP were used to measure the perpendicular ion flow. The x- and y-components of the flow velocity were determined by the following quantities:

$$\frac{V\cos(\alpha)}{C_s} = K \ln \left[\frac{I_s(\pi)}{I_s(0)} \right],$$

$$\frac{V\sin(\alpha)}{C_s} = K \ln \left[\frac{I_s(3\pi/2)}{I_s(\pi/2)} \right], \quad (4)$$

where $I_s(m\pi/2)$ $(m = 0, 1, 2, 3)$ stands for ion saturation current at angles $\theta = m\pi/2$ $(m = 0, 1, 2, 3)$. Combining the above quantities to make a velocity vector , we can construct a vector field plot of perpendicular flow, the result of which is shown in Fig.5. As seen in the figure, the azimuthal rotation due to $\boldsymbol{E} \times \boldsymbol{B}$ drift is the dominant flow, however, there is a weak radialy converging flow, and the resultant pattern exhibits a weak spiral. To sustain this flow pattern, there should be a parallel flow in the core region near the center axis. Parallel flow measurements are now in progress.

3. Conclusions

We have developed a small directional Langmuir probe to meet the ion-unmagnetized condition. The perpendicular ion flow has been measured using the DLP. When the unmagnetized condition for ions is satisfied, the DLP can be used to determine the flow velocity. Experiments with DLP's under ion-magnetized condition is of importance for measurements in confinement systems, which is left for future work.

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