Neutral Density Profile Determines the Vorticity of Ion Flow in a Charge Exchange-dominated Plasma

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A net momentum exchange during the charge exchange process produces an effective force acting on ions, which may dominate the ambipolar electric field to drive the ions into the anti- $\boldsymbol{E} \times \boldsymbol{B}$ vortical motion. In this circumstance, the logarithm of the neutral density profile determines the vorticity distribution of the ion flow field.

Keywords: vorticity, neutral density, stream function, charge exchange process, tripolar vortex

Recently, vortex formation has been attracting much attention in regard to structure formation [1,2], transport phenomena, and turbulent flow in plasmas, and accordingly there is an increasing demand for a way to measure the vorticity experimentally.

The perpendicular flow velocity of a plasma with an external magnetic field is usually given by the $\boldsymbol{E} \times \boldsymbol{B}$ drift and the diamagnetic drift. The vorticity is then determined by $\nabla_\perp^2 \phi$ and $\nabla_\perp^2 \log n$ (ϕ the potential, n the density of plasma). In particular in pure electron plasmas [3], the perpendicular velocity is determined only by the $\boldsymbol{E} \times \boldsymbol{B}$ drift, and hence the vorticity distribution turns out to be identical to the electron density distribution with the aid of the Poisson equation. This is a great advantage from an experimental point of view, because the vorticity distribution can be obtained without measuring the flow velocity field. In ordinary plasmas, however, the vorticity should be determined by measuring both the potential and density profiles or by directly measuring the flow velocity vectors in order to utilize $\nabla \times \boldsymbol{v}$. In this paper, we report an experimental example in which the vorticity distribution of the ion flow field can be obtained from the neutral density profile.

As shown in Fig. 1(a), we have observed that a tripolar vortex occurs in an argon plasma, and more interestingly the ion flow direction is opposite to that of the $\boldsymbol{E} \times \boldsymbol{B}$ drift. Figure 1(b) depicts the observed azimuthal velocity profile (solid circles) and the $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity profile (open circles) along the horizontal chord (y = 0). This result indicates the existence of a force acting on the ions other than the radial electric force. To explain the mechanism of anti- $\boldsymbol{E} \times \boldsymbol{B}$ vortical motion, we consider the equation of motion for ions under charge-exchange dominant conditions [4]. A net momentum transfer during the charge exchange process may produce an effective force acting on the ions. The perpendicular flow velocity for ions is then given by

$$v_\perp = \frac{1}{\omega_{\rm ci}^2 + \nu_{\rm in}^2}\Big[\frac{e}{M}(\omega_{\rm ci}\boldsymbol{e}_z \times \nabla_\perp \phi - \nu_{\rm in}\nabla_\perp \phi) + v_{\rm Ti}^2(\omega_{\rm ci}\boldsymbol{e}_z \times \nabla_\perp \log n_{\rm i} - \nu_{\rm in}\nabla_\perp \log n_{\rm i}) + (\omega_{\rm ci}\nu_{\rm in}D_{\rm eff}\boldsymbol{e}_z \times \nabla_\perp \log n_{\rm n} - \nu_{\rm in}^2 D_{\rm eff}\nabla_\perp \log n_{\rm n})\Big], \tag{1}$$

where $\nu_{\rm in}$ is the charge exchange collision frequency, and $D_{\rm eff}$ is the effective diffusion coefficient. The term $\omega_{\rm ci}\nu_{\rm in}D_{\rm eff}\boldsymbol{e}_z \times \nabla_\perp \log n_{\rm n}$ represents the $\boldsymbol{F} \times \boldsymbol{B}$ drift motion due to the effective force, which is defined as the momentum input rate during the charge exchange

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process per unit volume, *i.e.*, $v_{\rm in} M\ n_{\rm i} D_{\rm eff} \nabla_\perp \log n_{\rm n}$. Taking the *curl* of the above equation, we have the z-component of vorticity:

$$\omega_z = \frac{\omega_{\rm ci}}{\omega_{\rm ci}^2 + \nu_{\rm in}^2} [\nabla_\perp^2 (\frac{e}{M}\phi + \upsilon_{\rm Ti}^2 \log n_{\rm i} + \nu_{\rm in} D_{\rm eff} \log n_{\rm n})], \tag{2}$$

where we assumed the weak functional dependence of $1/(\omega_{\rm ci}^2 + \nu_{\rm in}^2)$ on $\boldsymbol{r}$. Here the ratio of the first term to the third in the right is estimated to be $\leq 10^{-1}$ and the second term to the third $\leq 10^{-2}$ using our experimental conditions ($p \leq 3 \times 10^{-2}$ Torr, $n_{\rm i} \leq 10^{13}$ cm^{-3}, $T_{\rm e} \approx 3$ eV, $T_{\rm e}/T_{\rm n} \sim 20$, $B \sim 1$ kG, $D_{\rm eff} \sim 5D_{\rm collisional}$). Thus the effective force due to neutral particles may overcome the electric field and pressure. The vorticity is then determined only by the neutral density profile to give

$$\omega_z \propto \nabla_\perp^2 \log n_{\rm n}. \tag{3}$$

In this case, the quantity $\log[n_{\rm n}(\boldsymbol{r})]$ becomes the stream function of the ion flow field.

We have measured the flow velocity components and the neutral density profile, and compared the z-component of $\nabla \times \upsilon$ with $\nabla_\perp^2 \log n_{\rm n}(\boldsymbol{r})$ for the plasma, in which the anti- $\boldsymbol{E} \times \boldsymbol{B}$ tripolar vortex is formed [5]. Figure 2(a) shows the z-component of vorticity distribution determined based on the flow velocity field [6]. In the figure, the positive vorticity is localized in the central region, while the negative ones are located in both sides of the center vortex, forming a tripolar structure having three aligned vortices with alternate signs of polarity of rotation. We emphasize that the rotation directions of these vortices are completely opposite to that of the $\boldsymbol{E} \times \boldsymbol{B}$ drift determined based on potential measurement.

Figure 2(b) shows the contour map of $\nabla_\perp^2 \log n_{\rm n}(\boldsymbol{r})$. The neutral density profile $n_{\rm n}(\boldsymbol{r})$ was determined by the ratio of the ArI (425.9 nm) intensity to the square root of ArII (488.0 nm) intensity. Although the line emission intensity of the present experiment is an integrated quantity whose line of sight is parallel to the plasma axis, this method is justified as far as the plasma is uniform along the axis, which has been experimentally confirmed. The second-order derivative of neutral density profile $\nabla_\perp^2 \log n_{\rm n}(\boldsymbol{r})$ was obtained by using the Fast Fourier Transform, in which the short wavelength modes (noises) were removed. The contour map shown in Fig. 2(b) also exhibits a tripolar structure fairly similar to that shown in Fig. 2(a), which means that the effective force due to neutrals $\nu_{\rm in} D_{\rm eff} \nabla_\perp^2 \log n_{\rm n}$ in fact dominates the radial electric field.

The importance of our experimental results lies in the fact that the effective force generated by the neutral density profile may overcome the ambipolar electric field in a charge exchange-dominated plasma. In such a circumstance, the logarithm of the neutral density profile acts as the stream function, which makes it possible to obtain the vorticity distribution without laborious measurements of the flow velocity field.

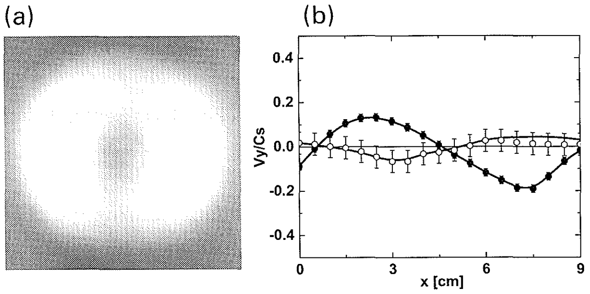

Fig. 1 (a): End view image of a tripolar vortex in an argon plasma; (b): Azimuthal flow velocity profile. The $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity is plotted by the open circles, showing opposite rotation.

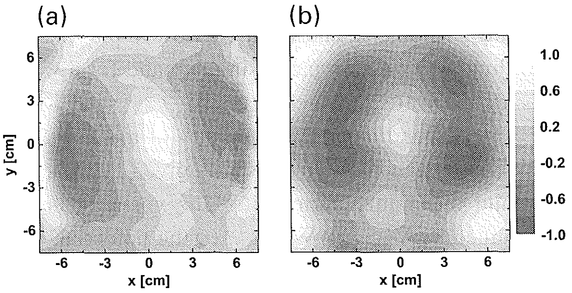

Fig. 2 (a): Vorticity distribution obtained by $\nabla \times \upsilon$; (b): Contour map of $\nabla_\perp^2 \log n_{\rm n}$.

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