§2. Radial Force Balance in Plasma Hole and Anomalous ExB Drift Solution

Yoshimura, S.,
Yamaguchi, H., Tomida, A., Miyake, F. (Nagoya Univ.),
Kono, M. (Chuo Univ.),
Tanaka, M.Y. (Kyushu Univ.)

Spontaneous formation of a vortex structure with density hole around the central axis, *plasma hole*, has been observed in an ECR plasma produced in the HYPER-I device. The flow pattern of the plasma hole exhibits a monopole vortex with a sink at the center, and the rigid rotation observed in central region is a characteristic of the flow. So far we have considered that the flow pattern is explained by the ExB drift, however, we should note that the introduction of an effect of the centrifugal force is required when adopting the cylindrical coordinates.

Ion fluid equation in cylindrical coordinates is written as

$$\frac{\partial \boldsymbol{\upsilon}}{\partial t} + (\boldsymbol{\upsilon}\cdot\nabla)\boldsymbol{\upsilon} = -\frac{\nabla P_i}{m_i n_i} + \frac{e}{m_i}\left(-\nabla\phi + \frac{1}{c}\boldsymbol{\upsilon}\times\boldsymbol{B}\right) + \nu_{eff}\nabla^2\boldsymbol{\upsilon},$$

where m_i is the ion mass, e the elementary electric charge, $P_i = n_i T_i$ the ion pressure, ϕ the electric potential, ν_{eff} the effective viscosity coefficient. We normalize the velocity to ion sound speed and introduce the non-dimensional potential as follows:

$$\boldsymbol{\upsilon}/C_s \to \boldsymbol{\upsilon},\ \ e\phi/T_e \to \phi.$$

The force balance in the radial direction is given as

$$\frac{\partial}{\partial r}\left(\frac{\upsilon_r}{2}\right)^2 - \frac{\upsilon_\theta^2}{r} = -\frac{T_i}{T_e}\frac{\partial}{\partial r}\ln n_i - \frac{\partial\phi}{\partial r} + \frac{\Omega_i}{C_s}\upsilon_\theta, \quad (1)$$

where Ω_{ci} is the ion cyclotron frequency. Here we use the steady state condition and assume the uniform temperature profile. Weak viscous force in the radial direction is neglected. From eq. (1) it can be seen that the radial force balance is determined by five forces: dynamic pressure gradient, centrifugal force, pressure gradient, electric force and Lorentz force. Defining the total potential by adding the dynamic pressure, electric potential and pressure, we can derive the following quadratic equation that determines the azimuthal flow velocity.

$$\left(\frac{C_S}{\Omega_i}\frac{\upsilon_\theta}{r}\right)^2 + \frac{C_s}{\Omega_i}\frac{\upsilon_\theta}{r} - \frac{C_s^2}{\Omega_i^2}\frac{1}{r}\frac{\partial\Phi}{\partial r} = 0 \quad (2)$$

$$\Phi = \phi + \frac{T_i}{T_e}\ln n_i + \frac{\upsilon_r^2}{2}.$$

Eq. (2) can be solved easily, and we have two solutions for the azimuthal flow velocity.

$$\frac{C_s}{\Omega}\frac{\upsilon_\theta}{r} = \frac{1}{2}\left[-1 \pm \sqrt{1 + 4\frac{C_s^2}{\Omega^2}\frac{1}{r}\frac{\partial\Phi}{\partial r}}\right] \quad (3)$$

In order to understand the physical meaning of this solution, we expand the second term on the right hand side by assuming the small potential gradient. The solution with the plus sign in front of the square root is rewritten as

$$\upsilon_\theta \approx \frac{C_s}{\Omega_i}\frac{\partial\phi}{\partial r}. \quad (4)$$

This corresponds to an ordinary ExB drift. On the other hand, the solution with the minus sign is given by

$$\upsilon_\theta \approx -\frac{\Omega_i}{C_s}r - \frac{C_s}{\Omega_i}\frac{\partial\phi}{\partial r}. \quad (5)$$

The principal term is the first term on the right hand side since we have assumed small potential gradient. This solution, which exhibits a rigid rotation even in the absence of an electric field, is referred to as the anomalous ExB solution. It represents the balance between centrifugal force and Lorentz force, whereas the ExB solution represents the balance between electric force and Lorentz force.

Figure 1 demonstrates the azimuthal flow velocity profile constructed from the connection of anomalous and ordinary ExB drift, where we use the total potential determined experimentally. Characteristic rigid rotation (-sqrt) is found in the central region, which suggests that the centrifugal force dominates the radial electric force. Meanwhile the ordinary ExB drift (+sqrt) is found in the outer region. In order to compare this result to the flow profile measured with directional Langmuir probe, a reliable calibration is required, which is our future work.

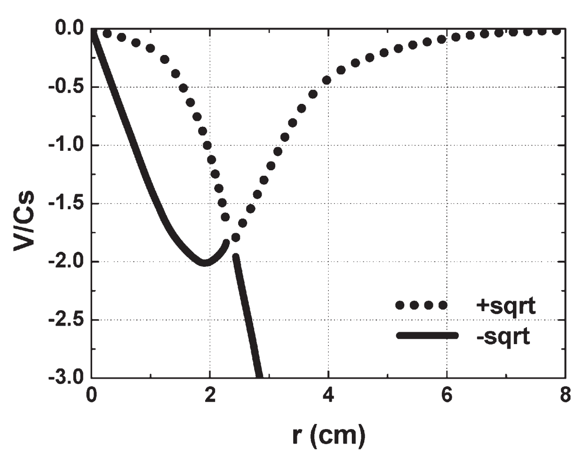

Fig. 1 Azimuthal flow velocity profile of plasma hole. (Calculation)