32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-4.105 (2005)

Study of poloidal flow driven by ion Bernstein waves in helical confinement device

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Introduction

Turbulence suppression is one of the key issues in nuclear fusion research. One of the methods used to suppress the turbulence is the formation of flow shear. It is theoretically predicted that a poloidal flow is driven by power absorption of ion Bernstein waves (IBW) or fast waves through ion cyclotron damping[1]. Confinement improvement during ion Bernstein wave heating was observed in various confinement devices[2].

In conventional analysis of plasma flow in tokamaks, only the poloidal viscosity affects the flow because of tokamaks' axisymmetry. In this research, we estimate the plasma flow driven by ion Bernstein waves in non-axisymmetric configurations, (especially in the Heliotron J device), in which both the poloidal and toroidal viscosities must be taken into consideration. Momentum input is estimated by use of a ray tracing method, and plasma flows and the radial electric field are calculated in the plateau regime.

Wave trajectory and power absorption

The momentum input is calculated by use of a ray tracing method. Since only the IBW is considered, the dispersion relation for electrostatic waves is used.

In this research, a plasma in the Heliotron J device[3] is studied. Heliotron J configuration is composed of straight sections and corner sections. In the corner sections, the magnetic configuration is similar to that in tokamaks. The magnetic configuration is chosen to be a so-called "standard magnetic configuration". The magnetic field strength on the axis and the wave frequency are 1.3T and 16.8MHz, respectively. The second harmonic ion cyclotron resonance layer is located at $\rho = 0.65$, where ρ is the normalized minor radius. The ion Bernstein waves are expected to be damped at this layer. It is assumed that, in a deuterium plasma, a ray with $k_{\parallel} = 3.0\text{m}^{-1}$ starts at the point of $\rho = 0.89$ on the equatorial plane in the corner section. The departure point locates between the second and third harmonic ion cyclotron layers. The density and temperature profiles are assumed as $n_e = n_{e0}(1-\rho^8)$ and $T_e = T_i = T_{e0}(1-\rho^2)$. The central electron density and temperature $n_{e0} = 1.0 \times 10^{19}\mathrm{m}^{-3}$ and $T_{e0} = T_{i0} = 200\mathrm{eV}$ are assumed. With these parameters, the ray trajectory is computed, and the result is shown in Fig. 1. The ray travels into the central region with oscillation along the magnetic line of force. In the vicinity of the second harmonic ion cyclotron resonance layer, almost all the wave power is absorbed by ions. In toroidal helical devices, it has been shown in previous works that an up-shift of the refractive index parallel to the magnetic field, $n_{\parallel}$, occurs, leading to electron Landau damping[4]. In the particular case of Heliotron J, however, since the magnetic configuration at the ray starting point resembles that of a tokamak, no $n_{\parallel}$ up-shift occurs, and the ray reaches the cyclotron resonance layer.

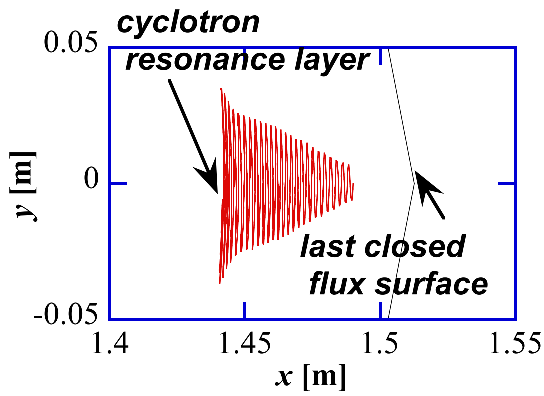

Figure 1: Trajectory of IBW ray. The ray starts at (x, y, z)=(1.49m, 0.0m, 0.0m) and the power is absorbed near the 2nd ion cyclotron resonance layer.

Momentum input

The momentum input is calculated by taking an analogy with quantum mechanics, where momentum of a photon is $\hbar\vec{k}$ with $\hbar$, the Planck constant. Momentum input $\Delta\vec{p}$ may be written as

$$\Delta\vec{p} \propto \Delta\left(I\vec{k}\right)$$

where $I = P/P_0$, that is the ratio of the wave power to the initial wave power.

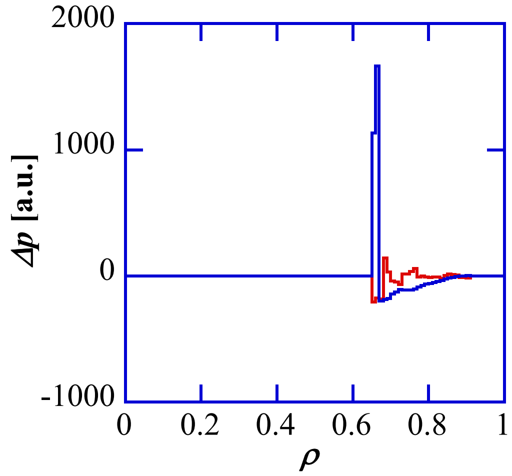

Figure 2: Radial profile of momentum input. Blue and red lines show the profiles of $\Delta p_{\perp}$ and $\Delta p_{\parallel}$, respectively.

Figure 2 shows the radial profile of the momentum input. The blue line shows the input $\Delta p_{\perp}$, which is perpendicular to both the magnetic field and $\nabla\Psi$, where Ψ is the toroidal magnetic flux. A strong momentum input due to the ion cyclotron damping is obtained near $\rho = 0.65$. This strong input is due to the large perpendicular refractive index of IBW. Before the cyclotron damping occurs, a weak input is obtained in the opposite direction. The red line shows the momentum input parallel to the magnetic field, $\Delta p_{\parallel}$. The parallel momentum input is smaller than $\Delta p_{\perp}$ and varies its sign with the minor radius because of the oscillation of the trajectory. These results show that the momentum input is driven by the cyclotron damping of waves.

Driven poloidal flow

In order to estimate plasma flow, plasma viscosity must be taken into consideration. The viscosity varies depending on collisionality. For relevance to the plasma parameters of Heliotron J, the viscosity of the plateau regime is employed. The parallel and toroidal viscosities in this regime are

$$\begin{cases} \left\langle \vec{B}\cdot\nabla\cdot\overleftrightarrow{\pi} \right\rangle &= 3\left(\mu^P \vec{V}\cdot\nabla\theta + \mu^t \vec{V}\cdot\nabla\zeta\right) \\ \left\langle \vec{B}_t\cdot\nabla\cdot\overleftrightarrow{\pi} \right\rangle &= 3\left(\mu_t{}^P \vec{V}\cdot\nabla\theta + \mu_t{}^t \vec{V}\cdot\nabla\zeta\right) \end{cases} \tag{1}$$

where $\vec{B}$, $\vec{B}_t$, $\overleftrightarrow{\pi}$, and $\vec{V}$ are the magnetic field, the toroidal magnetic field, the viscosity tensor, and flow velocity, respectively, the coefficients μ^P, μ^t, $\mu_t{}^P$, and $\mu_t{}^t$ are as defined in Ref. [5], and the heat flux is assumed to be zero. Here, the Hamada coordinates (V, θ, ζ) are used, where V, θ, and ζ are the volume enclosed by the toroidal flux surface, the poloidal and toroidal angles, respectively. The angle bracket denotes the averaging along the flux surface.

From the fluid equation in steady state and Eq. (1), flux-averaged poloidal and toroidal flow velocities are given as

$$\begin{cases} V^\theta &= \dfrac{\mu_t{}^t \left\langle \vec{B}\cdot\vec{F}_{ext}\right\rangle - \mu^t \left\langle \vec{B}_t\cdot\vec{F}_{ext}\right\rangle}{3\left(\mu^P \mu_t{}^t - \mu_t{}^P \mu^t\right)} \\ V^\zeta &= \dfrac{\mu_t{}^P \left\langle \vec{B}\cdot\vec{F}_{ext}\right\rangle - \mu^P \left\langle \vec{B}_t\cdot\vec{F}_{ext}\right\rangle}{3\left(\mu^P \mu_t{}^t - \mu_t{}^P \mu^t\right)} \end{cases}$$

where $V^\theta = \vec{V}\cdot\nabla\theta$, $V^\zeta = \vec{V}\cdot\nabla\zeta$, and $\vec{F}_{ext}$ are the poloidal and toroidal contravariant components of flow velocity, and the external force, respectively.

Regarding the external force $\vec{F}_{s,ext}$ as momentum input per unit volume and time, flow velocity is evaluated. Figure 3 shows poloidal and toroidal flow velocities in the case of 200kW of injected power. It seems that poloidal and toroidal flows are driven strongly at the cyclotron resonance layer, where the both velocities reaches 2×10^5m/s. In the conditions employed, the estimated poloidal and toroidal flow velocities are about the same. From the flow velocity, the radial electric field and the electric potential are estimated by multiplying the fluid equation by $\nabla\Psi$ and integrating the electric field, respectively. The estimated electric field is stronger than 2.0×10^5V/m at its maximum. However, since the region where a strong electric field is formed is narrow, the difference of the electric potential

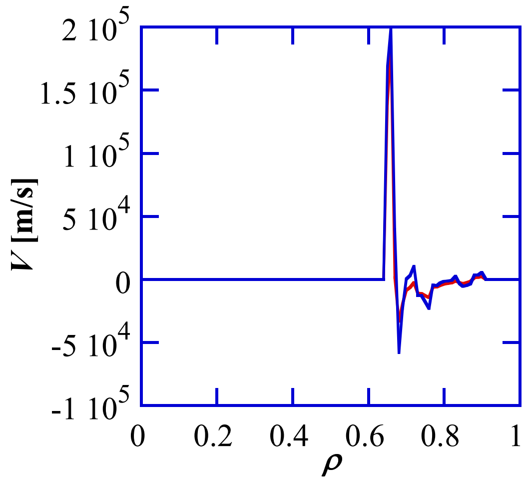

Figure 3: Profile of the flow velocity. The poloidal and toroidal flow velocities are shown in the red and blue lines.

between the plasma center and the periphery is not so large, i.e., about 400V. In JFT-2M tokamak, a transport barrier was formed when the gradient of the radial electric field exceeded 1.2×10^6V/m^2[6]. From these theoretical and experimental observations, it is thought likely that local absorption of IBW through ion cyclotron damping causes a strong radial electric field and a transport barrier.

Summary

Trajectories and power deposition of IBW are calculated by use of a ray tracing calculation. In case of the Heliotron J device, the ray travels toward the central region with an oscillatory motion along the magnetic field and the power is damped locally through ion cyclotron damping. Taking an analogy to quantum mechanics, the momentum input is estimated and the local input is found in the vicinity of the cyclotron resonance layer. While in conventional studies for axisymmetric tokamaks only poloidal viscosity is taken into consideration, we estimate the flow velocity in a non-axisymmetric configuration with the poloidal and the toroidal viscosity in the plateau regime. It is found that, in case of 200kW of input power, the flow velocity reaches 2×10^5m/s. The estimated electric field is stronger than that in the JFT-2M tokamak, where a transport barrier was formed.

These results encourage us to carry out experiments of ion Bernstein wave heating in non-axisymmetric configuration devices. Supposing that phenomena mentioned above are observed, it will be possible in practical experiments to place a transport barrier at a desired location by shifting the ion cyclotron resonance layer.

Acknowledgement

The authors would like to acknowledge F. Sano, T. Mizuuchi, K. Kondo, S. Kobayashi, S. Yamamoto, students and technical staff of Heliotron J for fruitful discussions.

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