Contribution ID: **824** Type: **Regular Poster**

Mechanism of toroidal flow generation by electron cyclotron heating in HSX and LHD plasmas

Thursday 13 May 2021 12:10 (20 minutes)

We clarify the toroidal flow generation mechanism by electron cyclotron heating (ECH) in stellarator/heliotrons comparing the HSX and LHD experiment results. Radial diffusion of energetic electrons by ECH produces a canceling return current, which then generates a $j_r \times B$ torque that can play an important role in the toroidal rotation in the ECH plasmas. We investigate the energetic electron distribution by ECH by applying GNET code, which can solve the 5D drift kinetic equation for the energetic electrons. We evaluate the $j_r \times B$ torque and the collisional torque due to the friction of the toroidal drift motion of the energetic electrons. As a result, we obtained a significant torque due to the ECH and found that the torque becomes larger in the Mirror configuration than that in the quasi-helically symmetric (QHS) configuration in HSX. Solving the momentum balance equations and Maxwell's equation with the $j_r \times B$ torque, we evaluate the toroidal flow velocity and compare simulations with HSX experiments. The obtained flows have good agreement with ones in HSX experiments. Moreover the simulated toroidal flows driven by ECH are consistent with that of the LHD experiment retults.

Introduction

Recently, spontaneous toroidal flows have been observed in electron cyclotron heating (ECH) plasmas in many tokamak and helical devices such as JT-60U, LHD and HSX. To clarify the underlying mechanism, many experimental[A] and theoretical studies have been undertaken. The effects of the magnetic configuration on plasma flow are intensively investigated in HSX, where two typical magnetic configurations are considered. One is the Quasi-Helically Symmetric (QHS) configuration, which has a quasi-helical symmetry in $|B|$ and is dominated by the $(m, n) = (1, 4)$ mode. The other is the Mirror configuration, where a set of auxiliary coils adds toroidal mirror terms, the $(0, 4)$ and $(0, 8)$ modes, to the magnetic field spectrum to break the helical symmetry. The parallel neoclassical viscosity of the QHS configuration is smaller than that of the Mirror configuration, so we expected that the toroidal flow velocity in the QHS configuration would be more significant than that of the Mirror configuration. However a smaller toroidal flow was observed in the QHS configuration. The mechanism of the toroidal flow generation has not been understood well yet.

Simulation model

ECH can drive the radial electron current j_e due to the radial motion of suprathermal electrons [B]. The net current in the steady state should be canceled to maintain the quasi-neutrality, so the return current, $j_r(= -j_e)$, flows by the bulk ions by ambipolar condition. Therefore, the bulk plasma feels the $j_r \times B$ torque due to the return current. On the other hand, the suprathermal electrons drift toroidally due to the precession motion. During the slowing down of the suprathermal electrons, they transfer their momenta to the bulk plasma due to collisions[C].

In this study, we investigate the behaviors of energetic electrons by ECH, which can generate the radial current and thus make the $j_r \times B$ torque in the HSX and LHD plasmas. Also, we evaluate the collisional torques, by collisions between energetic electrons and bulk plasma. We apply the GNET code, which can solve a linearized drift kinetic equation for energetic electrons by ECH in 5-D phase space[B]

$\frac{\partial \delta f}{\partial t} + (\mathbf{v}_d + \mathbf{v}_\parallel) \cdot \frac{\partial \delta f}{\partial \mathbf{r}} + \dot{v} \cdot \frac{\partial \delta f}{\partial \mathbf{v}} - C(\delta f) - L(\delta f) = S^{\rm ql}(f_{\rm Max})$,

where C, L, and $S^{\rm ql}$ are the collision operator, the orbit loss, and the ECH heating source, respectively. We solve the momentum balance equation to evaluate the toroidal flow velocity, and we introduce the $j_r \times B$ torque effect with using Maxwell's equation[D]. we evaluate the toroidal flows driven by ECH and compare them with experimental ones.

HSX plasma

In the perfectly symmetric configuration, the forces in the symmetry direction cancel each other. As seen in Fig. 1, the $j_r \times B$ torque and the collisional torque cancel each other, and the component parallel to the helical symmetry direction is very small in the perfectly helically symmetric configuration[E]. However non-symmetric magnetic modes enhance the radial current j_e. Thus, even in the QHS configuration the $j_r \times B$ torque is dominant and there is a net force in the symmetry direction due to other small non-symmetric modes. The force in Mirror configuration is more than twice as large as that in QHS configuration with the same input power. The collisional torque is so small as being negligible in QHS and Mirror configurations. Solving the momentum balance equations with $j_r \times B$ torque, the obtained flow velocity is shown in Fig.2. Here the absorption power calculated by ray-tracing code is 24kW in QHS configuration and 16kW in Mirror configuration. The integrated torque in Mirror configuration is about 4 times larger than QHS configuration even though the less heating power. The obtained flow in QHS configuration has a narrow peak, but the total toroidal flow in Mirror configuration is larger than that in QHS configuration.

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LHD plasma
We evaluate the toroidal torques by ECH and the toroidal flow in the balanced NBI heating plasma of LHD, where the torque by the NBI heating is relatively small. Figure 3 (left) shows the toroidal torque by ECH and balanced NBI heating. Here NBI torque is evaluated with FIT3D code, which is a module for NBI heating in TASK3D, the integrated transport code for helical plasmas. We evaluate the toroidal flows driven by ECH torque, solving the 1D radial diffusion equation, and compare them with the experimental observations. As shown in Fig.3 (right), the obtained flows have good agreements with the experimental ones. The toroidal flow velocity is around zero with the balanced-NBI torque, while the flow velocity can reach 20km/s with the additional ECH torque.

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Session Classification: P5 Posters 5

Track Classification: Magnetic Fusion Theory and Modelling