Influence of Electrostatic and Magnetic Fluctuations on ECH Supra-Thermal Electron Transport and Toroidal Torque in Tokamak Plasma

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In magnetically confined fusion plasmas, the suppression of the turbulent transport which degrades heat and particle confinement is a critical issue. Plasma flow shear is widely recognized to play an important role in the suppression of turbulent transport [1]. Thus, efficient methods to drive and control shear flows are needed.

Spontaneous toroidal flow generation during electron cyclotron heating (ECH) has been reported in various devices such as JT-60U and LHD [2,3], which suggests that ECH may be able to drive and control toroidal flows. In order to clarify the mechanisms of ECH-driven toroidal flow, both experimental and theoretical studies have been conducted, focusing on the behavior of supra-thermal electrons (SEs) generated by ECH. In our previous work, it is found that a three-dimensional magnetic field can enhance SE transport, generating a large toroidal driving force (toroidal torque) on the bulk plasma and our numerical results are in reasonable agreement with experimental observations [3]. Although SE transport induced by non-axisymmetric magnetic fields explains ECH-related toroidal flow generation well in heliotron/stellarator plasmas, numerous spontaneous toroidal flows have also been observed in tokamak devices. In completely axisymmetric tokamak plasmas, SEs do not generate net toroidal torque, except through the finite orbit width effect, which is negligible for electrons [4]. However, some degree of non-axisymmetry is inevitably present in real tokamaks due to effects such as toroidal field ripple, resonant magnetic perturbations (RMPs), and electromagnetic fluctuations induced by micro-instabilities.

From the perspective of turbulent transport, recent gyrokinetic-based investigations have indicated that kinetic electron dynamics may play an essential role in the spontaneous formation of internal transport barriers and turbulent transport in electron-heated plasmas [5,6]. These findings have highlighted the importance of the turbulent transport of SEs and its effects in addition to the turbulent transport of thermal particles which have been extensively studied.

In this study, we investigate the transport of ECH–driven SEs and the resulting toroidal torque in the presence of electrostatic and magnetic fluctuations induced by ion-scale micro-instabilities. We perform drift-kinetic based simulations, using an orbit-following type of Monte Carlo code GNET [7], focusing on the behavior of ECH-generated SEs. As a model for the fluctuations, we assume ion-scale micro-instabilities such as drift waves.

Figure 1 compares the radial profiles of the toroidal torques in the case without fluctuation (left), with electrostatic fluctuations, $e\langle|\phi|\rangle/T_e = 10^{-2}$, (mid.) and with magnetic fluctuations, $e\langle|\tilde{A}_\parallel|\rangle/m_e v_{th} = 10^{-5}$, (right). The red lines in Fig. 1 denote the J×B torque, the Lorentz force acting on the bulk plasma which arises from the radial diffusion of SEs, the blue ones denote the collisional torque referring to the toroidal momentum transfer from SEs to bulk plasma via Coulomb collisions, and the green ones are the sum of the J×B and collisional torques. The left panel confirms that the J×B and collisional torques cancel each other out, resulting in no net toroidal torque in an axisymmetric tokamak plasma, as pointed out in previous works [3, 4]. The middle panel demonstrates that in the presence of fluctuations, the J×B torque dominates the toroidal momentum balance and generates a finite net toroidal torque. The radial torque profile near the heating point qualitatively reproduces the experimentally observed toroidal flow generation in JT-60U [2]. The right panel also shows magnetic fluctuations can enhance the J×B torque. The direction of the electrostatic fluctuation induced torque is found to be reversed compared to that in the case with magnetic fluctuations and that observed in stellarator devices [3].

In the presentation, we will show more detailed results on parameter dependencies and discuss the differences in the radial profiles of torque for electrostatic and magnetic fluctuations, as shown in Fig. 1, and the transport model for SEs that explains these differences and parameter dependencies.

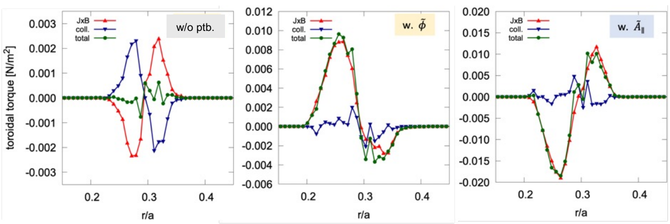

Figure 1: Radial profile of the ECH-related toroidal torques. (left): without fluctuations. (mid.): with electrostatic fluctuations. (right): with magnetic fluctuations.

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