MF2-I1 AAPPS-DPP2020

4th Asia-Pacific Conference on Plasma Physics, 26-31Oct, 2020, Remote e-conference

Effects of the non-perturbative mode structure on energetic particle transport

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Energetic particles (EPs) are known to change the properties of shear Alfvén waves in tokamaks, and for this reason non-perturbative models have to be used to describe EPs' linear and non-linear evolution. It has been reported that EPs can modify the Alfvén eigenmode structures with respect to the mode radial location and width[1], and can cause significant mode structure symmetry breaking[2]. Meanwhile, the mode frequency, as the eigen value of the linear system, or as a solution of the nonlinear dynamic system, can also change due to the EP effects. In turn, the non-perturbative mode structures are expected to bring the impacts on the linear growth rates, mode saturation levels and the EP transport.[3,4,5]

In this work, EP transport is studied with the consideration of the mode structures symmetry breaking properties due to a finite radial wave vector k_s. A theory motivated radial mode structure of the form $A(s) = \exp[-\sigma(s-s_0)^2]$ with complex parameters σ and s_0 is used to describe not only the width ($\propto 1/\sqrt{Re\{\sigma\}}$) and the mean location ($Re\{s_0\}$) of the bell-shaped radial structure, but also the radial wave phase variations (Im{σ}, Im$\{s_0\}$), where s is the normalized radial coordinate. The values of (σ, s_0) are fitted from the results given by the gyrokinetic eigenvalue code LIGKA[6] and modified to mimic different experimental[7] and simulation[8] observations. The impact on EP transport is investigated using the drift-kinetic code HAGIS[9].

The effects of the mode structure symmetry breaking on the mode saturation level and the EP transport are analyzed based on ASDEX-Upgrade parameters.[10] In the presence of mode structure symmetry breaking which is relevant to the simulation and experimental observations, the growth rate as well as the particle and energy transport level can vary by ~10%. The velocity-space averaged parallel velocity of EPs in the inner region s = 0.2 ~ 0.5 can change its sign for different mode structures as shown in the right frame of Fig. 1, demonstrating the importance of the mode structure symmetry breaking on EP toroidal velocity reversal. This large effect (~100%) on the mean parallel flow could have implications for EP current drive and the transport in the burning plasmas. This demonstrates the feature of toroidal momentum transport in the presence of EPs, as an extension to the momentum transport studies for bulk plasmas.

The results are compared with more self-consistent hybrid and gyrokinetic simulations to understand the role of the EP non-perturbative effects and identify the applicability of the LIGKA-HAGIS scheme for the EP transport modelling. Experimental observations and the consequences of non-perturbative mode structures on the EP confinement in burning plasmas are discussed.

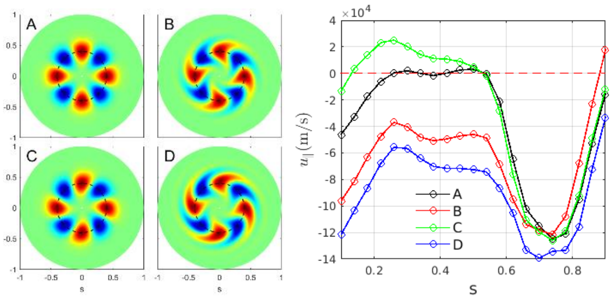

Fig. 1. Left: 2D mode structure. Right: The radial profile of the EP parallel velocity, $u_\parallel = \left(\int \delta f \cdot v_\parallel \, dv^3\right) / \left(\int f \, dv^3\right)$, at saturation.

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