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Generation of $\boldsymbol{E}\times\boldsymbol{B}$ flow shear by finite orbit width effects from heat sources in tokamaks

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Internal transport barriers (ITBs) have been observed in many magnetic fusion devices [1, 2]. Since the ITB formation leads to the core confinement improvement and the realization of steady state tokamak operation with large bootstrap currents requires the enhanced confinement regime, it has been an intense research field in magnetically confined plasmas.

The ITB formation was initially associated with the formation of a reversed safety factor profile [3]. However, there have been ample experimental observations that ITB can form in the weak or positive q-profile shear when sufficiently strong power is applied to the plasma [4]. This fact suggests that the q-profile shape might not be a sufficient condition for the ITB formation, requiring a physical origin likely related to the applied power itself. Experiments also indicate that threshold power exists for ITB formation and the input power per particle is important [5].

The contemporary paradigm of the transport barrier formation is based on turbulence suppression by strong $\boldsymbol{E}\times\boldsymbol{B}$ flow shear generation [6]. A global gyrokinetic simulation using the GYSELA code [7] has shown that a strong vorticity source generating strong $\boldsymbol{E}\times\boldsymbol{B}$ flow shear is necessary for the ITB formation. However, the mechanism for the strong $\boldsymbol{E}\times\boldsymbol{B}$ flow shear generation is still not clear and remains as one of long-standing unresolved issues in magnetic fusion research.

Regarding these issues, the basic questions that we will address are : 1) What is the physical origin of the strong vorticity source? 2) Is it related to the applied power (more specifically, the input power per particle)? In this work, we try to answer these questions by presenting a possible mechanism for the generation of strong $\boldsymbol{E}\times\boldsymbol{B}$ flow shear relevant to the ITB formation. From gyrokinetic theory and simulation, we show that substantial $\boldsymbol{E}\times\boldsymbol{B}$ flow shear can be generated from neoclassical polarization induced by finite orbit width (FOW) effects associated with radially non-uniform heat sources in tokamak plasmas. Two FOW effects are shown to be responsible for this: 1) the radial drift of particle orbit center due to the variation of the heat source within orbit width and 2) the non-uniformly evolved orbit width by the non-uniform heating.

To calculate analytically the potential driven by a heat source, we solve the axisymmetric part of collisionless gyrokinetic equation considering only slowly varying long-time evolution as Rosenbluth and Hinton [8] did in the calculation of residual flow surviving in collisionless damping processes. Based on the analytic result, we identify the physical origins of the heat source effect responsible for the generation of $\boldsymbol{E}\times\boldsymbol{B}$ flow shear. The particle drift caused by non-uniform heat source and the polarization induced by orbit width change will be discussed. Both FOW effects are proportional to the heating power per particle, which is consistent with experiments indicating that the input power per particle is an important parameter in the ITB formation. To validate the analytic result, we have performed gyrokinetic simulation using the XGC1 code [9] and comparison between them will be presented. Finally, we address the power threshold behavior of ITB. Based on a heuristic model, we drive an ITB transition criterion and estimate threshold power for ITB formation in a typical condition. The estimated value of $\boldsymbol{E}\times\boldsymbol{B}$ shear due to a heat source with a moderate power level is shown to be significant enough to initiate an ITB formation when the profile curvature of heat source is large.

In experiments, the threshold power depends on other conditions besides the heating such as the q-profile, the presence of low order rational surfaces in the vicinity of the ITB, and momentum inputs [2], indicating that there remain other parameters to be considered in the ITB formation. The feasibility study in this work therefore should be extended to consider these parameters. However, at least, it suggests that the heat source effect could be an additional trigger mechanism for the ITB and might play a role in the ITB formation in particular for a monotonic q-profile case.

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