Vortex flow evolution in a tokamak magnetic island

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Magnetic islands can be generated in toroidal magnetic fusion machines either intrinsically [1] or externally [2]. Once generated, the magnetic islands typically degrade plasma performance due to profile flattening by parallel collisional transport. However, experiments have showed that the magnetic island can be beneficial for a machine operation: they are closely related with a suppression of edge localized modes which is crucial for a sustainable H-mode operation [3], and furthermore they can lead to an internal transport barrier [4] with a strong ExB flow shear layer [5]. Experiments [6] have showed that the ExB flows in a magnetic island are circulating on the island contours, forming a concentric monopolar vortex.

Fluid and gyrokinetic simulations [7-11] have showed that this ExB vortex flows can be nonlinearly generated from microturbulence, indicating that the vortex flows mediate the magnetic island-microturbulence interaction. This kind of direct flow-turbulence interaction have been extensively studied for the case of zonal flows [12-14].

While there has been significant progress in simulation study of vortex flows in the last decade, analytic studies have been rare [15,16]. A recent analytic study of the vortex flow shearing rate [16] shows a highly anisotropic nature of the vortex flow shearing rate on island contours. However, there has been no analytic work on the time evolution (i.e., damping) of the initially generated vortex flows.

In this work, we have extended gyrokinetic theories of residual zonal flows in tokamaks [17,18] and stellarators [19] to study time evolution on an initial vortex flow in a tokamak magnetic island. We have found that the level of residual vortex flow after fast collisionless damping is higher than the Rosenbluth-Hinton level [17] due to the finite island width. In a longer term, this residual vortex flow is further damped, evolving from a monopolar vortex to a dipolar zonal-vortex flow mixture. This is due to a breaking of helical symmetry of the flow by toroidal precession of the flow-carrying ions [20].

As a result, the streamlines of the flow deviate from the island contours, providing open paths near the X-points for turbulence eddies to move in-and-out of the island separatrix. In other word, the zonal-vortex flow mixture formation effectively reduces the isolated regions in an island. This can make a synergistic effect with turbulence spreading, which has been thought to be a main reason of finite turbulence level inside an island [21] with no linear drive due to flattened profiles.

The mechanism presented in our theory would compete with the parallel collisional relaxation [22] which makes the flow mixture back to the vortex flow. Comparing two corresponding time scales, precession frequency and parallel collisional relaxation rate, we suggest a critical island width $q\rho_{Ti}/\hat{s}$ for a robust monopolar vortex [20]. A magnetic island smaller than the critical island width would have a complex dipolar mixture flow structure.

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