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Axisymmetric steady-state flows in tokamak plasmas under the visco-resistive setting

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Plasma rotation has been recognized as a key ingredient in the confinement properties of heat and particles in tokamak plasmas. Large speeds could, for example, be beneficial in mitigating some deleterious MHD instabilities, such as resistive wall modes and neoclassical tearing modes. Moreover, intrinsic plasma rotation has been reported in various devices and experimental conditions.

In modern tokamaks, magnetic field lines are reconstructed in real times using the Grad-Shafranov equation. This amounts to consider that tokamak plasma axisymmetric equilibria are necessarily static. Consequently, intrinsic plasma rotation in this approach is viewed as being only due to turbulence (coming from 3D effects).

Montgomery and coworkers were the first to question/relax the zero-flow hypothesis and to consider the steady-state Navier-Stokes equation keeping the diffusive viscous term and the nonlinear *(**v**.**grad**)**v*** term [1]. Adding Maxwell equations while accounting for the external drives due to the toroidal electric field, necessary to produce the toroidal current, and the toroidal magnetic field, one is left with a closed system of partial differential equations. This problem was reconsidered [2] using the open-source PDE solver FreeFem++ [3] to compute the ensuing axisymmetric steady-state flows in tokamak plasmas under the visco resistive MHD setting.

It was shown [4] that the toroidal velocity field is naturally antisymmetric unless either the domain or the boundary conditions violate the up-down symmetry. For up-down symmetric boundary conditions and plasma domain, the computed velocities turn out to be very small with zero net flow [2,4] in agreement with existing results [1].

Imposing external $n=0$ magnetic perturbations was shown [4] to offer a way to break the natural up-down symmetry of the system and produce a net toroidal flow. Using realistic parameters, numerical results [4] indicate that $n=0$ perturbations of the magnetic configuration may be used to increase $n=0$ steady-state speeds and promote tokamak plasma confinement while preserving axisymmetry.

Lately, imposing an up-down inhomogeneous heating was also shown to break up-down symmetry and increase axisymmetric steady-state velocities [5]. Yet, there exists interestingly some self-consistent limitation of this effect: a very large temperature gradient becomes less efficient as the self-consistent temperature convection decreases the effective symmetry breaking in the system. Therefore, in the current state of investigation, we do not consider this scenario as the most promising.

Purely geometrical symmetry-breaking effects, such as shaping of the plasma cross-section domain [6], appear contrarily as an efficient way to make tokamak plasma rotate up to the desired fractions of Alfvén velocity necessary to stabilize resistive-wall modes [7].

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