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Reducing turbulent transport in tokamaks by combining intrinsic rotation and the low momentum diffusivity regime

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Driving strong rotation shear is crucial in future tokamak fusion power plants as it reduces turbulent transport [1]. Traditional methods to drive flow shear by Neutral Beam Injection (NBI) are not expected to scale well to large devices [2]. We propose a novel approach in this work: combining intrinsic rotation driven by up-down asymmetric flux surfaces [3] with the Low Momentum Diffusivity (LMD) regime [4].

The physics behind this approach can be understood from the steady-state momentum transport equation (neglecting external sources and the pinch effect):

$$\Pi_i = \Pi_{i,int} - n_i m_i R_0^2 D_{\Pi i} \frac{d\Omega_i}{dr} = 0, \quad (1)$$

where $\Pi_{i,int}$ is the intrinsic momentum flux, n_i is the ion density, m_i is the ion mass, R_0 is the tokamak major radius, Ω_i is the ion toroidal angular frequency, r is the minor radial coordinate, $D_{\Pi i}$ is the ion toroidal angular momentum diffusivity. We typically use Prandtl number $\mathrm{Pr}_i = D_{\Pi i}/D_{Qi}$ to quantify the momentum diffusivity, where D_{Qi} is the heat diffusivity. According to Eq. (1), minimizing the Prandtl number helps drive strong intrinsic flow shear that stabilizes turbulence.

We performed a large number of high-fidelity nonlinear gyrokinetic simulations using circular geometry. We find that LMD is achieved at tight aspect ratio $\epsilon = r/R_0$, low safety factor q, standard magnetic shear $\hat{s} \simeq 1$ and low temperature gradient R_0/L_{Ti} (see Fig. 1). We then tilt the flux surface to be up-down asymmetric (see Fig. 2). We show that the intrinsic momentum flux driven by up-down asymmetry creates strong flow shear in the LMD regime that can significantly reduce energy transport, increasing the critical temperature gradient by up to 25%. In contrast to traditional methods for generating flow shear, this approach requires no external momentum sources and is expected to scale well to large fusion devices. The experimental applicability of this strategy in spherical tokamaks is addressed via simulations by considering actual equilibria from MAST [5] and a preliminary equilibrium from SMART [6].

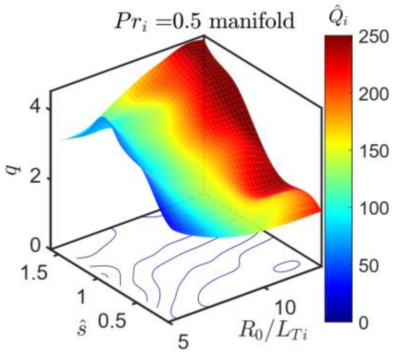

Figure 1: The surface of $Pr_i = 0.5$ for $\epsilon = 0.36$, below which we define as the LMD regime. The color map on the surface represents the ion heat flux $\hat{Q}_i$ in gyroBohm units. The contours in the bottom plane represent lines of constant q values on the surface.

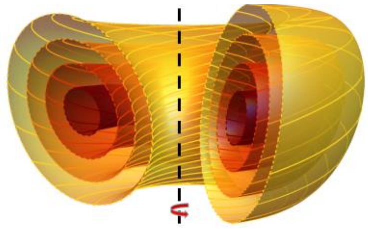

Figure 2: Illustration of up-down asymmetric magnetic flux surfaces.

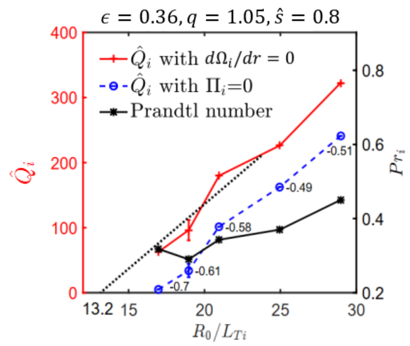

Figure 3: The heat flux $\hat{Q}_i$ for the self-consistent value of flow shear (i.e. ensuring $\Pi_\mathrm{i} = 0$ in Eq. (1)) driven by up-down asymmetric flux surfaces (blue), compared to the same cases without any flow shear (red) for a case inside the LMD regime. The flow shear values (in units of c_s/R_0) required to achieve $\Pi_\mathrm{i} = 0$ are indicated by the numbers neighboring each blue data point. The black dashed line shows a linear extrapolation to estimate the critical gradient for the $d\Omega_i/dr = 0$ cases.

References

[1] A. Peeters et al. 2011, Nuclear Fusion, **51**, 094027.
[2] Y. Liu et al. 2004, Nuclear Fusion, **44**, 232.
[3] J. Ball et al. 2014, PPCF, **56**, 095014.
[4] B. McMillan et al., J. Plasma Phys., **85**, 175850301.
[5] A. Field et al. 2011, Nuclear Fusion, **51**, 063006.
[6] A. Mancini et al. 2021, Fusion Eng. & Design, **171**, 112542.