Intrinsic toroidal rotation in tokamaks from global total-f gyrokinetic simulations

Hongxuan Zhu, T. Stoltzfus-Dueck, R. Hager, S. Ku, and C. S. Chang
Princeton Plasma Physics Laboratory
e-mail (speaker): hzhu@pppl.gov

Tokamak plasmas can rotate toroidally without external momentum input. Understanding the physics behind such intrinsic toroidal rotation is important for the safe operation of future reactors. Core rotation is dominantly determined by the turbulent momentum flux, and much theoretical and computational research effort has been based on the delta-f gyrokinetic formulation in simplified local flux-tube geometry. However, a symmetry in coordinate transformation then prevented net turbulent momentum flux to the lowest order in ρ_i/a, where ρ_i is the ion gyroradius and a is the tokamak minor radius. This led to a long debate over symmetry-breaking mechanisms, as well as the accuracy of the gyrokinetic equation. Edge rotation is affected by complicated factors such as realistic geometry across the last-closed flux surface, flows in the scrape-off layer, interactions with neutrals, and ion orbit loss. With the advance in computing power, global gyrokinetic simulations with realistic geometry and more physical ingredients are expected to provide new understanding for this topic.

Here, we use the global total-f particle-in-cell gyrokinetic code XGC1 and its axisymmetric version XGCa to study toroidal rotation driven by turbulent and neoclassical processes. We simulate a DIII-D H-mode plasma with gyrokinetic ions and drift-kinetic electrons. Core and edge rotation are studied together through the whole-volume plasma simulation. In a gyrokinetic plasma, the toroidal-angular-momentum density is driven by the divergence of the radial momentum flux of ion gyrocenters, including the parallel-momentum flux from the grad-B and curvature drift (denoted $\Pi_\parallel^D$), the parallel-momentum flux from the $E\times B$ drift (denoted $\Pi_\parallel^E$), and the $E\times B$-momentum flux from the $E\times B$ drift (denoted $\Pi_{E\times B}$). Most theoretical research on core rotation has focused on $\Pi_\parallel^E$ while assuming $\Pi_{E\times B}$ is smaller by a factor $k_r\rho_i B_\theta/B$ and $\Pi_\parallel^D$ is at a small neoclassical level. However, our simulation results showed that in the core, $\Pi_\parallel^D$ is not at neoclassical level in the presence of turbulence, and it tends to balance $\Pi_\parallel^E$ due to interactions between turbulence and zonal flows (Figure 1). Due to this balance, $\Pi_{E\times B}$ could make significant contribution to toroidal rotation. These results are consistent with other global gyrokinetic codes such as GYSELA and GT5D. We also compare with a theoretical explanation of nonzero $\Pi_\parallel^D$ in Ref. [1].

In the edge, turbulence is suppressed in the deep E_r well, which is formed due to the H-mode density pedestal. Therefore, edge toroidal rotation is mainly driven by $\Pi_\parallel^D$. However, the edge $\Pi_\parallel^D$ is different from its value in a neoclassical plasma, which is due to nonlocal interactions between finite ion orbit width and turbulence at the pedestal top (Figure 2) [2,3]. We developed an orbit-flux formulation to identify different physical processes that contribute to $\Pi_\parallel^D$, including collisions, turbulence, heating, and neutral ionization [4,5]. In particular, through this formulation we identify the contribution from collisional and turbulent ion orbit loss in edge toroidal rotation [6,7].

References
[1] Garbet *et al.*, New J. Phys. **19**, 015011 (2017).
[2] Müller *et al.*, Phys. Rev. Lett. **106**, 115001 (2011).
[3] Seo *et al.*, Phys. Plasmas **21**, 092501 (2014).
[4] Stoltzfus-Dueck, Nucl. Fusion **60**, 016031 (2020).
[5] Stoltzfus-Dueck and Zhu, Plasma Phys. Control. Fusion **63**, 115001 (2021).
[6] Zhu *et al.*, Nucl. Fusion, **62**, 066012 (2022).
[7] Zhu *et al.*, Nucl. Fusion, **63**, 066009 (2023).

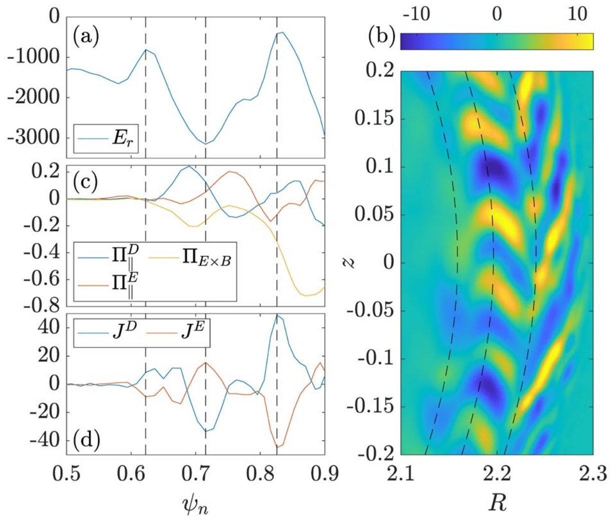

Figure 1 In the core, turbulent mode structures are distorted according to the local zonal-flow velocity indicated by E_r. The corresponding gyrocenter radial currents J (A) and momentum fluxes Π (N·m) also correlate with the zonal-flow velocity.

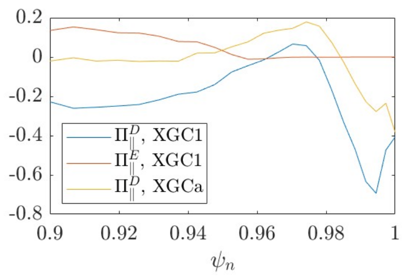

Figure 2 In the edge, turbulence is suppressed in the deep E_r well so $\Pi_\parallel^E \approx 0$. However, due to nonlocal interactions with turbulence, $\Pi_\parallel^D$ in a turbulent plasma from XGC1 is different from a neoclassical plasma from XGCa.