Property of Microturbulence in Small-aspect-ratio Tokamak and its Implication to Conventional Aspect Ratio Tokamak

S. Ku, J. Lang, C.S. Chang, S. Kaye, A. Diallo, W. Guttenfelder, Y. Ren, V. Soukhanovskii
Princeton Plasma Physics Laboratory
sku@pppl.gov

In NSTX, it has been a long-standing observation that the ion thermal transport rate is closer to neoclassical rate, especially in H-mode plasmas, than that in conventional tokamaks [1,2]. Higher $E_r \times B$ shearing rate or decreased amount of bad curvature [3,4] in a tight aspect-ratio tokamak has often been quoted as possible explanation. As a result of the less anomalous nature of the ion transport, the electron channel dominates plasma thermal transport in most of the regimes. This is true even when the ion temperature gradient is well above the ITG (ion temperature gradient) instability criticality. Since the thermo-nuclear fusion cross-section is sensitive to ion temperature, it is critical to have a more complete understanding of the ion thermal transport phenomenon, together with the electron transport phenomenon.

A recent computational study using the full-f gyrokinetic code XGC1 reveals a new, strong turbulence-reduction effect in a tight aspect-ratio plasma. The new effect is from the fact that most of the particles are trapped in a tight aspect-ratio plasma and that most of the radial banana orbit excursion occurs at the high magnetic field side, hence enhancing the ∇B/curvature-drift driven charge-separation activities at the good curvature side and reducing it at the bad curvature side. This phenomenon is from the special property of a tight aspect-ratio plasma: magnetic field lines have high (low) B_θ/B ratio at low-B (high-B) side, making the banana orbits to spend most of their time at the high-B side. This new effect is related to the latter mechanism discussed above [3,4]: It goes one step further by adding a detailed kinetic neoclassical driver to the simple picture of the "decreased amount of bad curvature." Combined kinetic simulation of neoclassical and turbulence dynamics is needed for the study of this new effect. This presentation will comprehensively review all three effects and discuss its implication to the conventional aspect ratio plasmas including ITER. Effect on the electron turbulence and transport will also be presented. Experimental validation results will be a strong part of the presentation.

XGC1 is a full-f -- sometimes called a full delta-f or a total-f -- extreme scale HPC PIC code that simulates the neoclassical and turbulence physics together in a realistic diverted magnetic field geometry. XGC1 includes gyrokinetic ions, drift-kinetic electrons, Monte Carlo neutrals, and heat, torque, and particle sources. It uses fully nonlinear Fokker-Planck collision operation in Landau form. XGC1 can run either in the delta-f mode without the neoclassical driver, similarly to other conventional delta-f codes, or in full-f mode with the neoclassical driver. The electrostatic turbulence and neoclassical capabilities of XGC1 have been verified against other delta-f codes, other full-f codes, and analytic solutions; and this capability will be used for the present study. XGC1 in the full-f mode can self-consistently study the background $E_r \times B$ shearing effect, the simple good/bad curvature effect as previously known [3,4], and the new neoclassical turbulence effect in combination with the good-bad curvature effect. This type of comprehensive particle-in-cell simulation has been made possible by using majority of the world's #2 capability of Cray XK7 Titan at ORNL.

Figure 1 shows the electrostatic potential (or density) fluctuations from nonlinear delta-f ITG turbulence (without the neoclassical ∇B/curvature driver) from XGC1 in the edge region of a NSTX H-mode plasma (shot #139047), where plasma is unstable to the ITG modes according to the conventional criterion [5]. Other delta-f codes in local analysis have also shown unstable ITG modes at a similar radius. We have then performed the same plasma simulation in XGC1 in full-f mode, keeping the neoclassical and turbulence drivers together self-consistently. The main difference in these two simulations is the absence or existence of the neoclassical ∇B/curvature driver. The simple effect from "decreased amount of bad curvature" is included in both cases. To our surprise, the ITG turbulence is significantly mitigated in the full-f case. Figure 2 shows the ratio in the $|\delta n|^2$ level between full-f and delta-f simulations. Factor of 5 reduction in $|\delta n|$ can be seen. XGC1 has NOT observed this kind of difference in conventional aspect ratio tokamaks.

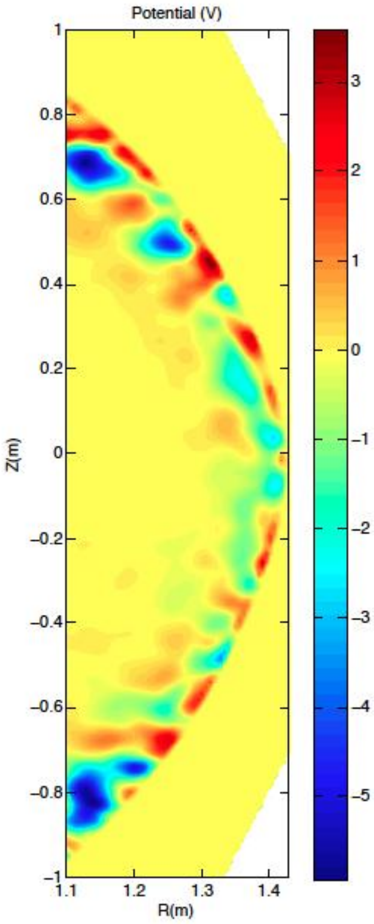

FIG 1: Electrostatic potential fluctuation in the delta-f mode XGC1 from ITG turbulence in a NSTX H-mode plasma (#139047)

There is another physical effect that can give rise to similar turbulence reduction in a conventional aspect ratio tokamak plasma. If the electrostatic potential can be higher at the low-B side, the banana particles spend longer time at the high-B side and contribute to the turbulence stabilization through the same physics. There are multiple practical mechanisms that can induce higher electrostatic potential at the low-B side of a tokamak plasma [6]. The first one is the neutral beam driven plasma rotation, as evidenced in NSTX by the higher electron density at low-B side [7]. Impurity particles could easily strengthen this mechanism at a lower toroidal rotation speed through enhanced centrifugal force. The second one is the creation of ICRH heated minority tail ions at low-B side. Creation of ECH heated tail-electron population at low-B side could give opposite effect. When an in-out potential asymmetry is created, the nonlinear mode coupling mechanisms could create low-m number equilibrium ExB shearing to weaken turbulence. All these physics needs to be considered, together with the well-known mean $E_r \times B$ shearing phyiscs, in the interpretation of microturbulence and transport physics in the present-day tokamaks and in the prediction for ITER.

Even when ITG turbulence is mitigated or suppressed, the long wave turbulence comes back in the form of nonlinear energy cascade when the kinetic electron turbulence is included in the simulation, which enhances the electron transport with relatively weaker effect on the ion thermal transport. Reduction of the electron turbulence level from the physical mechanism discussed here will also be included in the presentation.

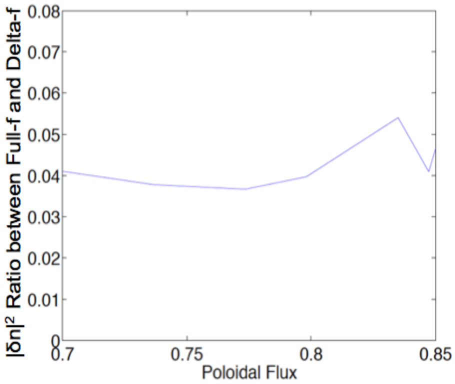

FIG 2: Radial profile of $|\delta n|^2$ from full-f XGC1 normalized to delta-f XGC simulation.

[1] S. Kaye et al., Nucl. Fusion 53 (2013) 063005
[2] W.X. Wang et al., Phys. Plasmas 13 (2006) 092505
[3] G. Rewoldt et al., Phys. Plasma 3 (1996) 1667
[4] M.A. Beer et al., Phys. Plasmas 4 (1997) 1792
[5] A. Diallo et al., Nucl. Fusion 53 (2013) 093026
[6] C.S. Chang et al., Nucl. Fusion 23 (1983) 935
[7] J.E. Menard et al., Nucl. Fusion 45 (2005) 539