New understanding of microturbulence property in small-aspect-ratio tokamak and its implication to conventional aspect ratio tokamak

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In NSTX plasmas, it has been a long standing puzzle that the ion thermal transport rate is found to be closer to neoclassical rate, especially in H-mode plasmas, than that in conventional tokamaks [1]. As a result, the electron channel dominates plasma thermal transport in most of the regimes. This is true even at radii where the ion temperature gradient is above the well-known ITG instability criticality, hence where the conventional delta-f simulations show strong ITG (ion temperature gradient) turbulence. This could imply existence of unknown toroidicty or geometry factors in the well-studied ITG-driven turbulence. 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. Because of its low aspect ratio, NSTX is an excellent test bed for studying the toroidicity-related geometry effect on the plasma turbulence and transport.

One common feature of all the gyrokinetic codes that studied NSTX turbulence physics is that they have neglected the neoclassical driving force resulting from the Grad-B drift of the particles across the radial plasma gradient. Neoclassical effect arises from the toroicity effect. This neglect is from the simplified perturbative delta-f approach of those codes, which assume that there exists a good scale separation between the neoclassical physics and the turbulence physics to the level that the neoclassical Grad-B driver can be neglected. Many delta-f codes may contain the Grad-B drift in the particle motions, but not the self-consistent neoclassical Grad-B driver across the background plasma gradient. Since the neoclassical toroicity effect is stronger at lower aspect ratio, it is more desirable to perform this study in NSTX. As a matter of fact, the key concept of the toroidal confinement is to improve the deleterious kinetic effects from Grad-B drift.

Unlike in a conventional delta-f code, a full-f code -- sometimes called a full delta-f code or a total-f code -- contains the neoclassical Grad-B driver across the background plasma gradient self-consistently with the neoclassical particle motions. XGC1 is such a code; currently solving for neoclassical and electrostatic microturbulence physics self-consistently with each other, and incoudes gyrokinetic ions, drift-kinetic electrons, Monte Carlo neutrals, and heat, torque, and particle sources in diverted geometry. It uses fully nonlinear Fokker-Planck collision operation in Landau form. XGC1 can run either in the delta-f mode without the neoclassical driver, as was done in other delta-f codes, or in full-f mode with the neoclassical driver. The code has been cross-verified against other delta-f codes, other full-f codes, and analytic solutions.

Figure I shows the electrostatic potential or density fluctuations from nonlinear delta-f ITG turbulence 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 local criterion. Other delta-f codes in local analysis have also shown linearly unstable ITG modes at a similar radius. However, the corresponding enhancement of the ion thermal flux above the neoclassical value has not been observed in the experiment. We have then performed the same plasma simulation in XGC1 in full-f mode, keeping the neoclassical driver. To our surprise, the ITG turbulence is mitigated in this case. XGC1 has NOT observed this kind of difference in conventional aspect ratio tokamaks.

From a careful examination, it has been found that there are two new toroidicity mechanisms in play for the mitigation or suppression of the ITG turbulence in NSTX: 1) a greater poloidal variation of background electric potential in NSTX than in a conventional tokamak, and 2) the stabilizing Grad-B driver effect at high magnetic field side. The first mechanism is understood from the greater poloidal neoclassical variation of the electrostatic potential by the larger in-out asymmetry of B in NSTX (poloidal mode number m=1), which has been well-validated in NSTX experiment [1]. We also see other low-m number (m>1) variations of the n=0 background electrostatic potential from the nonlinear mode coupling effect. This give rise to a finite-m, sheared ExB convective stabilization from the background mean field, in addition to the well-known m=0 $E_r \times B$ shearing effect. The second mechanism is understood from the fact that the trapped particles spend more time at the stabilizing side (high field side) in NSTX, hence most of the radial Grad-B motion occurs there. The net minetic interchange effect from Grad-B could then be to the stabilizing direction. Similar effect on the pure turbulent radial ExB driver, without the additional Grad-B driver, has already been discussed in the literature [2], and is naturally included in the delta-f and full-f simulations. The long wave turbulence comes back in the form of nonlinear energy cascade when we include the kinetic electrons in the simulation (so that we include TEMs, resistive and other drift wave turbulence), which enhance the electron transport with weaker effect on the ion thermal transport.

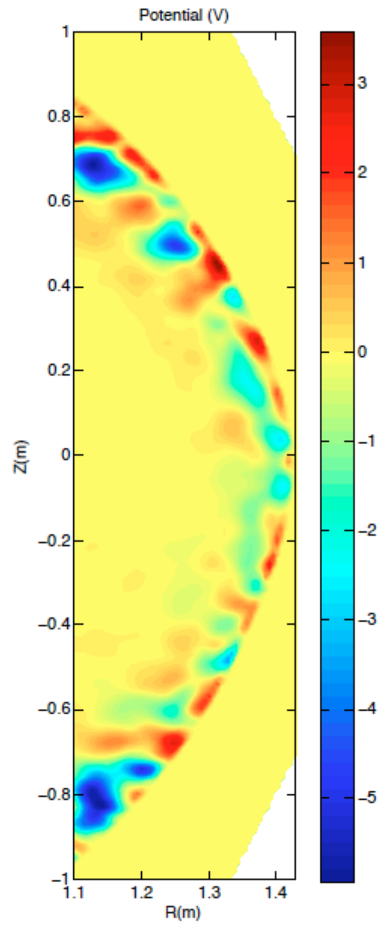

Figure 1: Electrostatic potential fluctuation in the delta-f mode XGC1 from ITG turbulence across NSTX H-mode edge pedestal

Both mechanisms are not expected to be unique to the low aspect ratio tokamaks. Impurities and ICRH tail ions can enhance the neoclassical poloidal potential variation in a conventional aspect ratio tokamak [3] and contribute to the first mechanism. In most cases, the impurities and ICRH tail ions produce higher potential at low magnetic field side [3], causing the ions to spend more time at high field side to contribute also to the second mechanism. Detailed analysis, analytic understanding, and experimental validation will be presented.

[1] S. Kaye et al, Nucl. Fusion 53 (2013) 063005
[2] G. Rewoldt et al., Phys. Plasma 3 (1996) 1667
[3] C.S. Chang et al., Nucl. Fusion 23, 935 (1983)