Verification and Validation of Particle Simulation of Turbulent Transport in FRC

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Abstract.

This paper reports the verification and validation for particle simulations of microturbulence in the scrape-off layer (SOL) of a field-reversed configuration (FRC), and highlights new physics learned in these FRC simulations including global structures of driftwave instabilities, effects of equilibrium sheared flows and self-generated zonal flows, and effects of kinetic electrons and fully kinetic ions. GTC-X gyrokinetic simulation of the C2-U FRC find that ion temperature gradient (ITG) modes are globally connected and unstable across these regions, while linearly stable inside the separatrix. The unstable global drift waves in the SOL show an axially varying structure that is less intense near the central FRC region and the mirror throat areas, while being more robust in the bad curvature formation exit areas.

GTC-X gyrokinetic simulations with adiabatic electrons find that the E×B flow shear reduces the growth rate and causes a radial tilting of the mode structure on the toroidal plane. Nonlinear simulations find that the E×B flow shear significantly decreases ITG saturation amplitude and ion heat transport in the SOL by reducing both turbulence intensity and eddy size. The turbulence intensity is determined by fluid eddy rotation, which is the dominant saturation mechanism for the SOL ITG instability with a single toroidal mode number. On the other hand, parallel wave-particle decorrelation is the dominant mechanism for the SOL ITG turbulent transport. A random walk model using the guiding center radial excursion as the characteristic length scale and the eddy turnover time as the characteristic time scale fits very well to the scaling of ion heat conductivity with the E×B flow shear. Furthermore, nonlinear simulations find that the ion heat transport decreases with lower collisional damping of the self-generated zonal flows, which have no collisionless damping in the FRC

GTC-X simulations using drift kinetic electrons (DKE) and gyrokinetic ions find that ITG real frequency and growth rate are larger than adiabatic simulation, and mode peak position moves slightly outward. Finally, GTC-X fully kinetic ion (FKI) simulations of the ITG instability in SOL find that both frequency and growth rate are close to gyrokinetic simulations, but radial mode structures are slightly different.

I. Introduction

Following the remarkable progress in magnetohydrodynamic (MHD) stability control in the advanced beam driven field-reversed configuration (FRC) at *TAE Technologies, Inc.*, turbulent transport has become one of the foremost obstacles on the path towards an FRC-based fusion reactor. Significant efforts have been made to kinetic simulation capabilities in FRC magnetic geometry. The Gyrokinetic Toroidal Code (GTC) [1] has been upgraded to simulate driftwave instability in the realistic FRC magnetic geometry using Boozer coordinates [2]. GTC local simulations of the C-2 FRC find that electrostatic driftwaves are locally stable in the core. The stabilization mechanisms include finite Larmor radius effects, magnetic well (negative grad-B), and fast electron short circuit effects [3]. In the scrape-off layer (SOL), collisionless electrostatic drift-waves in the ion-to-electron-scale are destabilized by electron temperature gradients due to the resonance with locally barely trapped electrons. Collisions can suppress this instability, but a collisional drift-wave instability still exists at realistic pressure gradients. Simulation results are in qualitative agreement with C-2 FRC experiments [4]. In particular, the lack of ion-scale instability in the core is not inconsistent with experimental measurements of a fluctuation spectrum showing a depression at ion-scales. The pressure gradient thresholds for the SOL instability from simulations are also consistent with the critical gradient behavior observed in experiments.

Nonetheless, experimental measurements [4] indicate the existence of fluctuations in both FRC core and SOL, with much lower amplitude fluctuations measured in the core. To study the turbulence coupling between core and SOL, we have developed two complementary global particle codes GTC-X and ANC for simulations coupling the core and SOL by using cylindrical coordinates with field aligned mesh. In both codes, ions can be simulated as either gyrokinetic (5D) or fully kinetic (6D) particles, and electrons as gyrokinetic or drift-kinetic particles. This paper reports the verification and validation for both codes, and highlights new physics learned in these FRC simulations including global structures of driftwave instabilities, turbulence spreading from SOL to core, effects of equilibrium sheared flows and self-generated zonal flows, and effects of kinetic electrons and fully kinetic ions.

Global mode structures of ITG instabilities in FRC-- We used GTC-X to simulate the global properties of drift waves in the C2-U FRC, in which the core and SOL plasmas are connected with formation sections and divertors. The ion temperature gradient (ITG) modes are globally connected and unstable across these regions, while linearly stable inside the separatrix [5]. The unstable global drift waves in the SOL show an axially varying structure that is less intense near the central FRC region and the mirror throat areas, while being more robust in the bad curvature formation exit areas (Fig. 1).

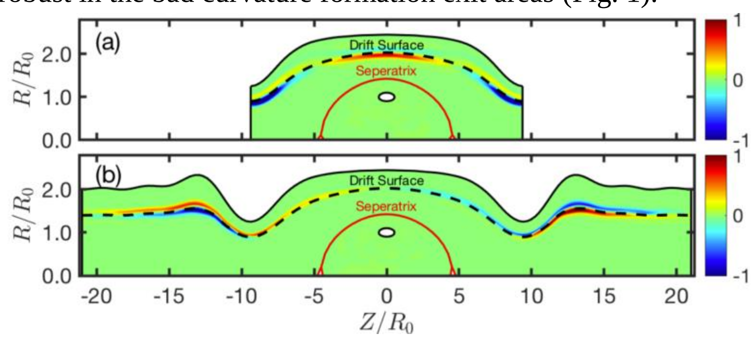

Fig.1. *Comparison of 2D poloidal mode structures of electrostatic potentials from GTC-X simulations of ITG instability using different parallel domains [5]. The dashed lines show the flux surfaces with the maximum mode amplitude. The blue solid line is the separatrix.*

Turbulence spreading from SOL to core in FRC-- With the updated cross-separatrix capabilities, ANC global nonlinear turbulence simulations find that linear ITG instabilities grow in the SOL, generating fluctuations which spread from SOL to core [6,7]. After saturation of the linear instabilities, a balance of the inward spread and local damping in the core is achieved. The steady state toroidal wavenumber spectrum shows lower amplitude core fluctuations and larger SOL fluctuations with amplitude decreasing towards shorter wavelengths, which are consistent with experimental measurements (Fig. 2).

Effects of sheared flows-- Radial electron fields due to electrode biasing have been implemented in GTC-X and first verified in simulation of the ITG with a rigid toroidal rotation, which shows a Doppler shift in real frequency but little change in growth rate. Linear simulations with sheared flows find that the ITG is significantly suppressed with this equilibrium ExB shearing rate is comparable to the growth rate in the absence of the sheared flows (Fig. 3). Both negative and positive shear can stabilize ITG by tilting the mode structure on the radial-toroidal plane. Consistently, turbulent transport is greatly reduced by the sheared flows in nonlinear simulations [8]. Self-generated zonal flows have also been found to significantly reduce the ITG saturation amplitude and transport level [9]. Logical sheath boundary condition and presheath potential have been calculated in a simple geometry and will be implemented in GTC-X FRC geometry.

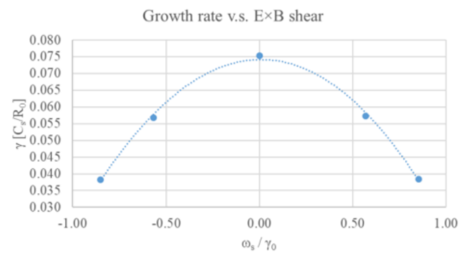

Fig. 3. *ITG growth rate γ as a function of ExB shearing rate ω_s, where γ_0 is the growth rate when ω_s=0.*

Effects of kinetic electrons and fully kinetic ions-- GTC-X simulations using drift kinetic electrons (DKE) and gyrokinetic ions find that ITG real frequency and growth rate are larger than adiabatic simulation, and mode peak position moves slightly outward. A considerable component of the electrostatic potential with poloidal harmonic m=0 (e.g., parallel wavevector $k_{\|}$=0) appears in the DKE simulation, which implies that the DKE model is necessary in FRC simulation. Finally, GTC-X fully kinetic ion (FKI) simulations of the ITG instability in SOL find that both frequency and growth rate are close to gyrokinetic simulations, but radial mode structures are slightly different. We will utilize the new FKI capability to study effects of energetic particles and high frequency (e.g., lower hybrid) instabilities in FRC turbulence and transport.

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