Particle-in-cell (PIC) simulation has been proven to be a powerful tool for studying nonlinear physics in both fusion and space plasmas. In particular, advances in the massively parallel gyrokinetic particle simulation during the last two decades have led to fundamental understanding for turbulence and transport in fusion plasmas, e.g., the paradigm of turbulence self-regulation by zonal flows and the physics underlying the transport scaling. Nevertheless, many key issues in turbulent transport regarding coherent structures, electron transport, transport barriers, and energetic particles remain to be resolved. A critical hindrance to the progress in these areas is that none of the existing turbulence simulation codes in the world fusion program can address these physics issues adequately and efficiently due to the difficulties associated with the complicated toroidal geometry and the disparate spatial-temporal scales.

This paper describes recent progress in the development and applications of a global gyrokinetic toroidal code (GTC). Realistic geometry is handled using a symmetry magnetic coordinate with straight magnetic field lines. A global field-aligned mesh is implemented to efficiently represent the quasi-2D toroidal eigenmodes. Particle motion is governed by the guiding center Lagrangian equations. Elliptic Poisson equation is solved on an unstructured mesh using a scalable finite element method. Global effects are rigorously treated with experimental profiles and MHD equilibria. The small electron mass presents numerical difficulty for simultaneously treating the dynamics of ions and electrons in simulations of electromagnetic microturbulence and Alfvénic instabilities in high pressure plasmas. A fully kinetic electron model, split-weight scheme, has been developed to reduce the numerical noise of electrons by separating the adiabatic and non-adiabatic electron responses. A related fluid-kinetic hybrid electron model, based on an expansion of the electron response using the electron-ion mass ratio as a small parameter, has been implemented in GTC.

The nonlinear physics of the turbulence in toroidal geometry driven by the temperature gradients of the ions (ITG) and electrons (ETG), respectively, has been investigated. The local transport coefficient in the ITG turbulence exhibits a gradual transition, from Bohm scaling for device sizes corresponding to present-day tokamak experiments, to gyro-Bohm scaling for larger fusion reactors. The key to reconciling the deviation from gyro-Bohm transport scaling with microscopic fluctuations has been identified as the turbulence spreading from the linearly active (unstable) zone to the linearly inactive (stable) zone in the presence of radial variation of the pressure gradient. The transport level in the ETG turbulence from global simulations is well below the value reported by flux-tube simulations. The transport scaling is gyro-Bohm although the radial length of ETG streamers scales with the machine size. ETG modes saturate via nonlinear toroidal mode couplings, which transfer energy successively from unstable modes to stable low-n modes (n is the toroidal mode number) and high-n damped modes. The turbulence is dominated by these nonlinear excited low-n streamers, which have smaller characteristic frequency and are more prone to the shearing effects of the zonal flows. Finally, GTC simulations of the turbulence driven by the trapped electron mode (TEM) will be discussed.