Proto FSP Center for Plasma Edge Simulation (CPES)

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I. Introduction

Successful fusion performance of ITER is dependent in large measure on the achievability of a high plasma pedestal just inside and across the last closed flux surface. A high pedestal is usually destroyed by edge localized mode (ELM) instabilities, which delivers the pedestal energy to the material wall and erodes it at rates unacceptable to ITER operation and maintenance. Thus, a high pedestal must be achieved without deleterious ELM effects, a very difficult but necessary combination for the success of ITER. At the present time, neither pedestal height, nor the ELM behavior can be reliably predicted for ITER due to lack of physics understanding. It is accordingly of vital importance to develop a predictive capability with high physics fidelity for the pedestal equilibrium and associated transport dynamics, and for the ELM crash and resulting heat load on the material wall.

II. Advanced Computing

Unlike in the plasma core, the magnetic field has both closed (pedestal) and open regions (scrape-off) with magnetic separatrix surface between them. This makes it difficult to use the convenient field-line following coordinates and regular mesh. Nonlinear interaction of the turbulence dynamics with the strong neoclassical physics associated with the steep pedestal and open magnetic field lines, is important. This requires a self-consistent integrated simulation of the neoclassical and turbulence physics. Neutral particles play a critical role in the pedestal buildup. Thus, neutral recycling at the arbitrary shaped wall and atomic collision processes need to be simulated together with the plasma. Plasma in the steep pedestal and open field line is non-Maxwellian and strongly kinetic. In order to properly deal with these geometric and physics complexity of the edge plasma, large scale first-principles simulations on high performance computer systems need to be carried out. Two new, related particle codes are under development for edge kinetics: XGC0 and XGC1. XGC0 is a time dependent equilibrium code, which is already in production mode. XGC1 is a 3D turbulence code, whose electrostatic turbulence capability is under verification. XGC0 and XGC1 are being coupled to linear and nonlinear ELM codes (ELITE, M3D/NIMROD) for a long time multiscale simulation of pedestal growth, ELM crash, scrape-off transport and divertor heat load. The coupled simulations are facilitated by workflows within SDM Kepler framework. This framework is keeping track of the provenance during the coupling, producing visualizations from the XGC, Elite and M3D/NIMROD codes, and analyzing data during their execution. Furthermore, during the execution of these coupled codes, the simulation metadata is being kept into a database, and the bulk data is automatically backed up to HPSS. A web-based dashboard has been created to provide secure access to monitor current runs along with older runs.

Typical XGC1 developmental runs need thousands of Cray XT, Jaguar processors at ORNL and typical production runs require over ten thousand processors. HPC is an essential tool for this project. There are also existing cutting-edge core turbulence codes participating in CPES, which are being utilized for probing turbulence transport candidates under edge-like plasma conditions to lead the direction in XGC1 development.

III. New Scientific Discoveries

New scientific discoveries utilizing leadership class computing resources have been made as a result of strong partnerships with computer science and applied mathematics teams within the CPES project. (i) For the first time, XGC1 solved for 2D kinetic equilibrium across the magnetic separatrix (from pedestal top to scrape-off) under a steep pedestal profile. The electric potential in the scrape-off region is positive, while it is negative in the pedestal region, as observed experimentally. A strongly sheared global ExB convective flow pattern has been found in the entire edge region, which can be linked to the turbulence suppression in the H-mode. Spontaneous rotation sources are identified in the pedestal and scrape-off regions, which can propagate inward and become important to the stabilization of resistive wall mode (one of the most dangerous instabilities in ITER). (ii) For the first time, XGC0 explained that the 3D resonance magnetic field perturbations (RMPs) drop the pedestal density, but not the temperature, as observed in the experiments. RMP is one of few candidates to suppress the ELM crash in ITER. A significant density drop needs to be avoided in order for the RMP technique to be a useful tool in ITER. Findings from XGC0 can shed light on this important issue. (iii) For the first time, a kinetic pedestal buildup process is coupled to the MHD ELM crash on a computer science KEPLER framework. This is a significant first step to predict the ELM cycle, pedestal height, and the divertor heat load. (iv) A new coarse graining technique has been developed to solve the growing weight issue in the delta-f particle simulation. (v) Other discoveries include the identification that the trapped electron mode can be strongly unstable in the edge pedestal, a theory that the edge rotation source can propagate inward by off-diagonal turbulence momentum pinch, and the invention of two new nonlinear collision techniques which can dissipate noise growth and speed up the particle motion simulation under Coulomb collisions.