Global Particle-in-Cell Simulation of Fusion Plasmas

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Abstract

This paper describes progress in the US DOE SciDAC Center for Integrated Simulation of Energetic Particles in Burning Plasmas (ISEP) to improve physics understanding of energetic particle (EP) confinement and EP interactions with burning thermal plasmas. Since ignition relies on self-heating by energetic fusion products (α-particles), EP confinement is a critical issue for the international burning plasma ITER experiment -- the crucial next step in the quest for clean and abundant energy. Predictive EP capability will require exascale, integrated first-principles simulation of nonlinear interactions of multiple kinetic-magnetohydrodynamic (MHD) processes. We further develop and apply the multi-physics gyrokinetic code GTC to perform long time, global kinetic simulations of EP physics in burning plasmas, by utilizing the full power of the GPU-based Summit supercomputer.

As a particle-in-cell code, GTC tracks individual charged particles in a Lagrangian frame in a continuous phase-space, whereas the moments (number density, charge density and current density etc) of particle distribution of different species (thermal ion, thermal electron, fast ion, fast electron, etc.) are simultaneously computed on a stationary Eulerian field mesh. The electromagnetic fields are then solved on the field mesh using proper combinations of Poisson equation, Ampere's law, Faraday's law and force-balance equations with finite difference and finite element methods. This field mesh is also used to interpolate the local electromagnetic fields at the particle positions in phase-space.

GTC uses MPI domain decomposition, particle decomposition, and OpenMP shared memory partitioning to scale up to millions of CPU cores to take advantage of the memory hierarchy. Thanks to closed collaborations with computational scientists through ASCR CAAR and SciDAC projects, GTC has been ported to GPU-based supercomputers including Titan and Summit. The computationally expensive particle and field subroutines are fully ported and optimized on GPU using OpenACC and CUDA. Using realistic fusion simulation parameters, GTC shows near-ideal weak scaling performance up to the full capacity of Titan computer with GPU. GTC has recently demonstrated good scalability on more than 20% of Summit and achieved an unprecedented speed of pushing one trillion particles for 1 time step in 2 seconds wall-clock time using 928 nodes on Summit. GTC is one of the two fusion codes selected by the DOE Center for Accelerated Application Readiness (CAAR) and has received a DOE INCITE (2019-2021) award with 2% of Summit time.