B-I17 AAPPS-DPP2019

AAPPS-DPP2019, 4-8,11.2019, Hefei, China / APPC-14, 17-22, 11, 2019, Kuching, Malaysia

Verification and Validation of Integrated Simulation of Energetic Particles in Toroidal Plasmas

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I would report progress on integrated simulations to improve physics understanding of energetic particles (EP) confinement and EP interactions with burning thermal plasmas. The goal of SciDAC Center for Integrated Simulation of Energetic Particles in Burning Plasmas (ISEP) is to develop a predictive capability of EP physics in fusion plasmas through exascale simulation and to deliver an EP module incorporating both first-principles simulations and high fidelity reduced transport models to the future whole device modeling (WDM) project.

As the first step in developing the predictive capability, verification and validation of linear simulations of Alfven eigenmodes in the current ramp phase of DIII-D L-mode discharge #159243 have been carried out by eight gyrokinetic, gyrokinetic-MHD hybrid, and eigenvalue codes from US, EU, and Japan [1]. The simulated most unstable reversed shear Alfven eigenmode (RSAE) frequencies agree with experimental measurements if the minimum safety factor q_{min} is adjusted within experimental errors. A toroidal Alfven eigenmode (TAE) is found to be unstable in the outer edge, consistent with the experimental observations. Electron temperature fluctuations and radial phase shifts from simulations using synthetic diagnostics show no significant differences with the experimental data for the strong RSAE, but significant differences for the weak TAE. Furthermore, gyrokinetic toroidal code (GTC) simulations find that the most unstable ion temperature gradient (ITG)-like mode has an amplitude peaking in the core, but large fluctuations nonlinearly spread to the whole radial domain. These results indicate that RSAE and TAE in this DIII-D experiment could interact nonlinear with each other and with the microturbulence. Finally, GTC simulations of TAE have also been validated in JET [2], HL-2A [3], and KSTAR [4] tokamaks.

Nonlinear simulations of the RSAE and TAE in DIII-D discharges show that the dominant saturation mechanism is the shearing of zonal flow (n=m=0 mode), although nonlinear AE coupling between different toroidal modes also reduces saturation amplitude of the most unstable mode . The effects of zonal current is much smaller than the zonal flow. Zonal fields (zonal flow and zonal current) are nonlinearly forced driven by the RSAE/TAE three-wave couplings with a growth rate twice the linear TAE growth rate. Localized current sheets with $k_{||}=0$ but finite n are nonlinearly generated with a growth rate about 3 times of AE growth rate. This current sheets is driven by a nonlinear ponderomotive force and can lead to nonlinearly-driven tearing instabilities. The linear TAE mode structures are broken up by the zonal flow nonlinear ExB convection [5]. The nonlinear coupling between unstable AEs with microturbulence will also be presented.

The ISEP goal's to perform long time, global kinetic simulations of EP physics in burning plasmas requires effective utilization of the full power of the next generation supercomputers. The real physics production runs show a GPU speed up of 20 times over CPU and scale up to the whole Summit computer, which is currently the world's fastest supercomputer.

[1] Verification and validation of integrated simulation of energetic particles in fusion plasmas, S. Taimourzadeh et al, *Nuclear Fusion* **59**, in press (2019).
[2] Gyrokinetic simulations of Toroidal Alfven Eigenmodes excited by energetic ions and external antennas on the Joint European Torus, V. Aslanyan et al, *Nuclear Fusion* **59**, 026008 (2019).
[3] Simulation of toroidicity-induced Alfven eigenmode excited by energetic ions in HL-2A tokamak plasmas, Hongda He et al, *Nuclear Fusion***58**, 126023 (2018).
[4] Multiple toroidal Alfven eigenmodes with a single toroidal mode number in KSTAR plasmas, H. Rizvi, C. M. Ryu, and Z. Lin, *Nuclear Fusion* **56**, 112016 (2016).
[5] Verification and Validation of Integrated Simulation of Energetic Particles in Toroidal Plasmas, Z. Lin et al, in Proceedings of the 26th International Conference on Plasma Physics and Controlled Nuclear Fusion Research (Ahmedabad, 2018). Paper IAEA-CN-258/TH/P2-17.