6th Asia-Pacific Conference on Plasma Physics, 9-14 Oct, 2022, Remote e-conference

Recent progress on numerical development toward core-edge modeling of stellarators

Toseo Moritaka[1], Michael Cole[2], Robert Hager[2], Seung-Hoe Ku[2], C-S. Chang[2], Seiji Ishiguro[1]
[1] Department of Helical Plasma Research, National Institute for Fusion Science
[2] Princeton Plasma Physics Laboratory, Princeton University
moritaka.toseo@nifs.ac.jp:

Gyrokinetic simulation of stellarator edge plasma is an unexplored territory due to the geometric/magnetic complexity and the algorithmic/numerical difficulties associated with it. In addition, the core and edge need to be simulated together to get reliable physics results, including the heat-flux to the divertor plates. X-point Gyrokinetic Code (XGC) is a global code developed for whole-volume modeling of tokamaks[1][2]. XGC utilizes the particle-in-cell method with unstructured meshes to include the edge region outside the last closed flux surface (LCFS)[3]. The edge plasmas have non-Maxwellian distributions under the significant influence of binary collision and other ionization / charge exchange processes. These features are considered through the novel numerical schemes using velocity space meshes[1][4][5][6]. XGC has been employed for studying the kinetic dynamics of edge plasmas and core-edge coupling phenomena[7][8].

We will present recent progress on numerical schemes and code developments toward whole-volume modeling of stellarators[9]. The numerical schemes relevant to the local interactions, such as binary collision and ionization, would be commonly applicable for tokamaks and stellarators. On the other hand, the numerical schemes relevant to the spatial geometries, such as unstructured mesh generation, particle-mesh interpolation and finite-element field solver on the unstructured mesh, should be improved for stellarator geometries. We have implemented three-dimensional spline interpolation and a mesh generation scheme based on flux coordinates in non-axisymmetric equilibrium data. The extended version of XGC has successfully demonstrated ion temperature gradient mode and neoclassical transport in the core regions of Large Helical Device and other stellarators[9][10][11][12].

However, applying the gyrokinetic model to stellarator edge regions is still challenging because of complicated magnetic field structures. Magnetic field lines in the edge region direct away from the torus direction and are entangled with each other to form a stochastic structure. Therefore, an unstructured mesh along the flux function on each toroidal cross section is unsuitable for solving the gyrokinetic Poisson equation with flux-average and perpendicular gradient operators. We develop a new mesh generation scheme and iterative solver to address this issue[13]. A numerical optimization technique is employed to construct curved surfaces locally perpendicular to the equilibrium magnetic field. Numerical field line tracing defines mesh vertices. The resulting mesh adaptively refines the stochastic and the divertor regions with long magnetic field lines. The curved surfaces are useful to determine the perpendicular gradient operator. Higher order spline interpolation is utilized in the particle-mesh interpolation. The developed schemes are applied for the edge region of LHD with HINT or extended VMEC equilibria. We calculate gyro-center motion from LCFS to the helical divertors. Global electric fields are obtained from the typical gyro-center density profile in the edge region. We will discuss the correlation among plasma conditions at LCFS and the divertors under the particle drift motions based on the particle and field calculations.

Large-scale computations are also required for future whole-volume modeling of stellarators including core and edge turbulent phenomena. We will show the current status of code optimization and measured performances on the cutting-edge computer systems.

References

[1] S. Ku, C-S. Chang, R. Hager, *et al.*, Phys. Plasmas **25**, 056107 (2018).
[2] E. D'Azevedo, S. Abbott, T. Koskela, *et al.*, Chapter 24. The Fusion Code XGC: Enabling Kinetic Study of Multiscale Edge Turbulent Transport in ITER. In Exascale Scientific Applications: Scalability and Performance Portability; CRC Press: Boca Raton, FL, USA, 2017.
[3] F. Zhang, R. Hager, S. Ku, *et al.*, Eng. Comput. **32**, 285–293 (2016).
[4] S. Ku, R. Hager, C-S. Chang, *et al.*, J. Comput. Phys. **315**, 467–475 (2016).
[5] E-S. Yoon, and C-S. Chang, Phys. Plasmas **21**, 032503 (2014).
[6] R. Hager, E-S. Yoon, S. Ku, *et al.*, J. Comput. Phys. **315**, 644–660 (2016).
[7] S. Ku, C-S. Chang, P. Diamond, Nucl. Fusion **49**, 115021 (2009).
[8] C-S. Chang, S. Ku, A. Loarte, *et al.*, Nucl. Fusion **57**, 116023 (2017).
[9] T. Moritaka, R. Hager, M. Cole, *et al.*, Plasma **2**, 179 (2019).
[10] M. Cole, R. Hager, T. Moritaka, *et al.*, Phys. Plasmas **26**, 082501 (2019).
[11] M. Cole, T. Moritaka, R. Hager, *et al.*, Phys. Plasmas **27**, 044501 (2020).
[12] T. Moritaka, H. Sugama, M. Cole, *et al.*, Nucl. Fusion, submitted.
[13] T. Moritaka, M. Cole, R. Hager, *et al.*, Plasma and Fusion Res. **16**, 2403054 (2021).