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Edge and Scrape-off layer turbulence simulations with the accelerated full-f gyrokinetic code GENE-X

B. J. Frei[1], P. Ulbl[1] and F. Jenko[1,2]
[1]Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany
[2] University of Texas at Austin, Austin, Texas 78712, USA
e-mail (speaker): baptiste.frei@ipp.mpg.de

Understanding the turbulent transport in the edge and scrape-off layer (SOL) regions is of primary importance for the future development of magnetic confinement fusion devices. Turbulent transport plays a key role in predicting reactor performance, divertor heat load, and understanding the physics behind the transition from low to high confinement mode.

Due to the challenging plasma conditions in the edge and SOL regions, first-principles gyrokinetic (GK) simulations are required. The turbulence GK code GENE-X has been specifically designed to solve the full-f, electromagnetic, and collisional GK Vlasov-Maxwell system in magnetic geometries with X-points [1]. Although GENE-X simulations provide an accurate description of the relevant physics in these regions, they are computationally intensive, even for medium-sized devices [2]. Therefore, targeting large reactor-relevant devices poses significant numerical and physical challenges.

To address these challenges, we present a novel optimized spectral velocity-space method [3], recently implemented in the GENE-X code. This is the first time that such a numerical scheme is used in a full-f GK code. To verify and validate our approach, we have performed first-of-its-kind spectral turbulence simulations of edge and SOL turbulence, focusing on the TCV-X21 diverted L-mode reference case (see Figure 1) [4]. By comparing our results with experimental measurements [4] and grid-based Eulerian GK simulations using GENE-X [2], we demonstrate that the spectral simulations achieve excellent agreement with validated grid-based simulations on the outboard midplane (OMP) profiles and turbulence characteristics dominated by trapped electron modes. Figure 2 illustrates the OMP electron temperature profiles obtained in the spectral and grid-based GENE-X simulations, as well as the experimental measurements.

Most importantly, the spectral approach outperforms grid-based simulations by achieving a significant speed-up, enabling a large decrease in the velocity-space resolution - by a factor of 50 in this case. This computational acceleration paves the way for new physical investigations using high-fidelity GK simulations of the edge and SOL in large reactor-relevant devices, such as the prediction of the divertor heat load in ITER.

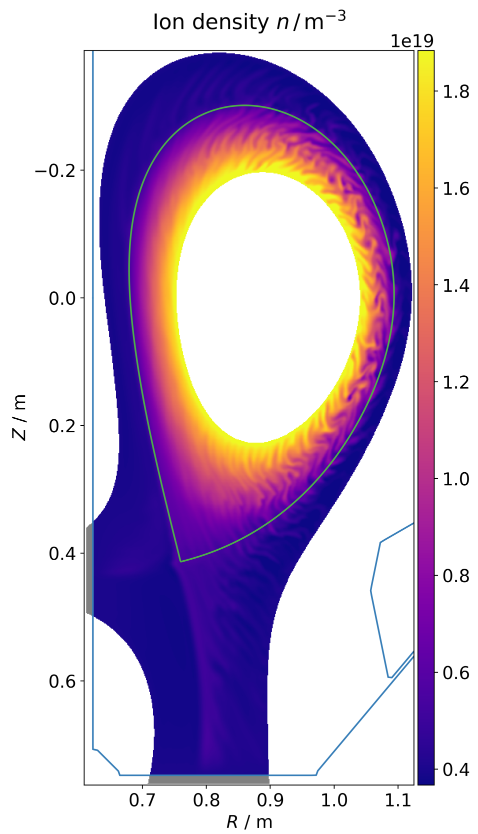

Figure 1. Density snapshot of edge and SOL turbulence in the TCV-X1 diverted L-mode reference case [4] obtained from the spectral simulation.

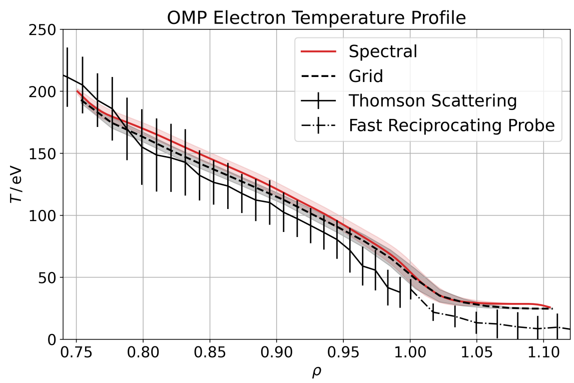

Figure 2. OMP electron temperature profiles from the spectral (red) and grid-based (dashed black) GENE-X simulations, compared with experimental measurements [4].

References

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