Enhancing Boundary Plasma Simulations: Key Advances from the ABOUND SciDAC Project

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The ABOUND SciDAC project has significantly advanced the BOUT++ framework, enhancing our understanding and control of Edge Localized Modes (ELMs) and other critical plasma phenomena. Key improvements include more efficient and robust plasma simulations, new insights into ELM dynamics through focused simulations on zonal flows and fields, and enabling simulations with the HYPRE 3D solver for low-n toroidal mode numbers for the first time. BOUT++ simulations have also unveiled the connection between upstream turbulence properties and downstream divertor heat flux width for DIII-D QH-mode experiments. Molecular collisional-radiative simulations reveal that plasma detachment at the divertor target exhibits hysteresis bifurcation and significantly higher recombination temperatures due to molecular processes. We are developing code-coupling of BOUT++ with GEM and SOLPS-ITER for integrated simulations, exploring gyrokinetic pedestal micro-turbulence in small/grassy ELM regimes with the GEM gyrokinetic code, and examining divertor-plasma detachment under negative triangularity using the SOLP-ITER code. Computational speed has dramatically increased with GPU acceleration. Advanced algorithms have enhanced the temporal resolution of simulations using SUNDIALS with modern multi-rate (MRI) methods, while integration with the ADIOS2 framework has optimized data management. Enhanced visualization techniques have enabled clearer interpretations of complex datasets and physics mode structures. These efforts have significantly improved the predictive capabilities and efficiency of BOUT++ and other ABOUND codes, contributing to the fusion community's understanding of critical behaviors and potentially influencing future tokamak design and operations for optimizing plasma confinement and exhaust solutions.

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