A Massive Space-Time Parallel Particle-In-Fourier Framework for Kinetic Plasma Simulations

Kinetic plasma simulations play a critical role in applications of societal relevance such as nuclear fusion and building the next-generation of compact particle accelerators. They are also widely used in studying astrophysical phenomena and industrial plasma processes. Particle-In-Fourier (PIF) schemes are attractive for long-time integration of kinetic plasma simulations as they conserve charge, momentum and energy, exhibit a variational structure, do not suffer from aliasing and have excellent stability properties. However, they are typically more expensive than the commonly used Particle-In-Cell (PIC) schemes due to the requirement of non-uniform discrete Fourier transforms (DFT) or fast Fourier transforms (FFT). In this talk, we present a Parareal-based parallel-in-time integration method for PIF schemes by employing a PIF scheme of coarser tolerance for nonuniform FFTs or the standard PIC scheme as coarse propagators towards the goal of performing long-time integration simulations. We show an error analysis of the algorithm as well as numerical validation of the results with Landau damping, two-stream instability, and Penning trap test cases in 3D-3V. Finally, we also present massively parallel full-system scaling studies from space-time parallel implementation of the PIF schemes in the open-source, performance-portable library "Independent Parallel Particle Layer" (IPPL) on JUWELS and JEDI supercomputers with A100 and GH200 GPUs. The space-time parallelization provides up to 4-6 times speedup compared to spatial parallelization alone and achieves a push rate of more than 1 billion particles per second for the benchmark plasma mini-apps considered.