High-order Implicit-Explicit Time Integration for the Kinetic Simulation of Magnetized Plasmas

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Kinetic models for the plasma dynamics in the edge region of a tokamak (magnetic confinement fusion device) are characterized by a wide range of time scales that span several orders of magnitude. These may include ion and electron transport time scales, acoustic waves, collisional processes, Alfven waves, and the plasma frequency. This makes efficient numerical time integration challenging, where the scales of interest are slower than the fastest scales in the model. We describe the implementation and performance of high-order implicit-explicit (IMEX) methods in COGENT, a finite-volume, open-source code for gyrokinetic and fluid simulations of magnetized plasmas in complex geometries [1]. The governing equations include an arbitrary number of kinetic or fluid models of charged species and may include fluid models for neutral species. The kinetic partial differential equations (PDEs) are discretized on high-dimensional "phase-space" (physical and velocity space) grids, while the fluid PDEs are discretized on physical space grids; thus, the algorithm evolves solutions with multiple dimensionalities. The tokamak-edge geometry is represented with mapped, multiblock grids, and spatial derivatives are discretized with a fourth-order finite-volume method in the mapped coordinates [2]. We implement high-order multi-stage additive Runge-Kutta (ARK) methods [3] that require the partitioning of the right-hand-side (RHS) of the semi-discrete ordinary differential equation (ODE) into "stiff" and "nonstiff" components; the stiff component is integrated implicitly in time, while the nonstiff component is integrated explicitly. We present a modified ARK method that allows a nonlinear function on the left-hand-side, i.e., it solves an ODE of the form $d[M(u)]/dt = R(u)$. The resulting nonlinear system is solved using the Jacobian-free Newton Krylov (JFNK) approach [4]. The performance of the IMEX time integration depends on effectively preconditioning the linear solve; we describe an operator-split multiphysics preconditioner where tailored preconditioners for each implicit physics term are wrapped in an operator-split algorithm to precondition the complete stiff RHS. We investigate the computational performance and convergence of the ARK methods for simulations representative of tokamak-edge plasma dynamics.

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[1] COGENT, https://github.com/LLNL/COGENT

[2] Dorr, M., Colella, P., Dorf., M., Ghosh, D., Hittinger, J., Schwartz, P. O., High-order Discretization of a Gyrokinetic Vlasov Model in Edge Plasma Geometry, Journal of Computational Physics, 373, 2018, 605-630.

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[4] Knoll, D. A., Keyes, D. E., Jacobian-free Newton–Krylov methods: a survey of approaches and applications, Journal of Computational Physics, 193, 2004, 357-397.

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