Edge Localized Modes

- Fast (∼ 100μs) eruption from the edge of tokamak plasmas
- If uncontrolled in ITER, these would release ∼ 20 MJ
- World-wide effort to understand and control these events

The BOUT++ Simulation Code

- Based on BOUT written by X. Xu, et. al. from LLNL [1]
- New 3D simulation code developed at York with LLNL and ANL
- Simulates plasma fluid equations in curvilinear coordinate systems
- Runs on workstations, clusters, large-scale machines, e.g., Cray XE6

ELM Equations

\[ \frac{d\omega}{dt} = B_0^2 \cdot \nabla \left( \frac{J_0}{B_0} \right) + 2B_0 \times \kappa_0 \cdot \nabla p \]

References


Software Design Issues

- Time integration and Newton-Krylov nonlinear solvers using SUNDIALS (LLNL) or PETSc (ANL)
- Coordinate system and differential operators
- Parallel communications using MPI

Jacobi-free Newton-Krylov Method

At each timestep, we solve the nonlinear system

\[ F(x) = 0, \]

where \( F : \mathbb{R}^n \rightarrow \mathbb{R}^n \) by a Newton-Krylov method

\[ x_{k+1} = x_k - [F'(x_k)]^{-1} F(x_k), \quad k = 0, 1, \ldots \]

where \( x_0 \) is an initial approximation to the solution and \( F'(x_k) \), the Jacobian, is nonsingular at each iteration. In practice, the Newton iteration is implemented by the following two steps:

1. (Approximately) solve \( F'(x_k) \Delta x_k = -F(x_k) \)
2. Update \( x_{k+1} = x_k + \alpha \Delta x_k \)

where \( 0 < \alpha \leq 1 \) is a scalar. Jacobian-vector products in Krylov methods are computed matrix-free via

\[ F'(u)a \approx \frac{F(u+h\cdot a)-F(u)}{h} \]

Facets

- Framework Application for Core-Edge Transport Simulations
- FACETS goal: Modeling of a fusion device from the core to the wall
- Work in progress: Incorporating BOUT++ as a FACETS component

Performance Analysis

Figure 1: Strong scaling using CrayPAT on Hopper (NERSC) using 128 pb (nx=128, ny=128, nz=64) [2]

MPI Collectives

Figure 2(a) shows the ratio of MPI collection at high concurrency (65,536 processors) for test case 1. Figure 2(b) indicates that the ratio of MPI collectives at high concurrency (65,536 processors) for test case 1 is 0.35.

Ongoing and Future Work

- Research on robust and scalable preconditioners
  - Algebraic approaches that use sparse approximate Jacobian information
  - Leverage physics knowledge, including field splittings for fast Alfvén waves, fast magnetoionic waves, and thermal conductivity along the field lines
- Experiments with communication-reducing Krylov methods
- Exploration of IMEX techniques for flexible timesteping
- Incorporation into FACETS and exploration of multiphysics coupling issues
- Research on additional modeling capabilities