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Progress in the Development of the SEL Macroscopic Modeling Code

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SEL is a recently-developed, massively-parallel, time-dependent, nonlinear macroscopic fluid modeling code. Spatial discretization uses high-order Spectral ELements on a logically rectangular grid. Spectral elements exhibit the same exponential convergence of spatial truncation error as global spectral methods while also allowing domain decomposition for parallization and grid adaptation to localized structure and complex geometry. Time discretization uses a full, nonlinearly-implicit time step, allowing efficient treatment of problems with strong flow and 2-fluid effects. Nonlinear system solution uses Newton-Krylov methods based on the PETSc and MPI libraries. All physical equations are expressed in conservative, flux-source form, allowing details of discretization to be separated from specification of these equations and facilitating the formulation of new physics problems. 1D and 2D versions of the code are fully operational. The 1D code uses a version of Adaptive Mesh Refinement (AMR), automatically concentrating the grid in regions of sharp gradients, optimizing the use of the available grid while minimizing its size.

Two major improvements have been made to the code over the past year. The first concerns efficient parallel operation. Static condensation has been implemented for effective preconditioning of the Krylov subspace methods. Higher-order finite elements are eliminated in terms of the lower-order terms by means of small, local, direct solves which parallelize perfectly, reducing the size and condition number of the matrix requiring global iterative solution. The number of dependent variables is reduced by a factor of order $np/2$, with np the degree of the Jacobi polynomial basis functions used, reflecting the volume-to-surface ratio of each grid cell. Iterative solution of the condensed global matrix is further accelerated by exploiting advanced methods available in the PETSc library. An additive Schwarz incomplete LU factorization with generous overlap and moderate fill-in is found to be a very effective preconditioner for the GMRES Krylov-subspace method. These improvfed methods also avoid limits previously encountered on convergence for large time steps. The speed of the code has improved since last year by a factor of order 200.

The second improvement, still under the development, concerns 2D and 3D adaptive gridding. An essential feature of magnetic plasma confinement is a very high degree of anistropy. Magnetic fields are very effective at restraining the motion of plasmas across magnetic fields, but almost totally ineffective at restraining it along the field. As a result, both wave propagation speeds and diffusive transport coefficients can differ by many orders of magnitude along and across the field. If a small amount of the large parallel flows is allowed to numerically corrupt the much smaller transverse flows, the results can be meaningless. Conventional AMR methods in 2D and 3D, using a grid oblique to the magnetic field, fail to resolve this anisotropy. The most effective approach is the use of magnetic flux coordinate grids. Such grids have been used effectively, for example in the NIMROD code, based on a static, axisymmetric initial equilibrium field. If the simulation is followed for a sufficiently long time, the dominant field can develop helical distortion, requiring new methods of automatically aligning the grid with the evolving, non-axisymmetric field. Since non-axisymmetric fields do not in general possess nice, nested flux surfaces, an exact point-wise flux coordinate system is not achievable. We are developing a variational approach to grid alignment, designed to give a best-fit solution while effectively dealing with regions of multiple small islands and stochasticity. Approximate flux surfaces constitute the null space of a large, sparse, real, symmetric, semi-definite matrix. Efficient numerical methods for deteremining this null space are being developed, based on the PARPACK library. Visualization techniques are used to verify that the resulting coordinate system is reasonable. Once this is done, the solution can be periodically interpolated to the newly aligned grid, using high-order spectral elements to minimize interpolation error. Adaptation can then be achieved by packing the grid in one dimension, normal to the approximate flux surfaces, using methods developed in the 1D version of the code.

Operation of the code will be illustrated with examples of 2D incompressible magnetic reconnection in the presence of strong flow shear, driven by combined tearing and Kelvin-Helmholtz instabilities.