Scalable preconditioners for coupled plasma/neutral boundary transport simulations*

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Predicting the behavior of the boundary region that encompasses the plasma periphery and material-wall interactions is crucial for the design and operation of magnetic fusion energy devices for many reasons, including that plasma exhaust flux is near material heat-flux limits and contamination of the hot core from sputtered impurities must be kept below well-established levels. Simulating the transport of plasma and neutral species in the tokamak boundary involves numerous unknowns and physical mechanisms having a wide range of space and time scales. Consequently, such simulations are computationally intensive and optimizing their parallel efficiency, especially for whole-device simulations, is a high priority.

The large range of time scales necessitates an implicit time discretization for long-time simulations, and Jacobian-free Newton-Krylov methods have proven robust and efficient to solve the resulting nonlinear systems. A key aspect of overall performance is preconditioning, which transforms the linearized operator into an equivalent form whose inverse action approximates that of the Jacobian, but at smaller cost. The choice of preconditioning algorithm is key for low computational cost and scalable parallelism. This work presents advances in parallel preconditioners that exploit the different characteristics of plasma and neutral transport. Preconditioners such as Additive Schwarz and ILUT are numerically effective for these problems only with such a significant level of domain overlap or fill that they act globally, thereby limiting scalability. Analysis indicates that it is primarily the neutral species that requires global coupling in the preconditioner.

To overcome this bottleneck to parallel efficiency, we have developed a new component-wise preconditioner, termed FieldSplit, that applies separate preconditioning algorithms to the plasma and neutral components while maintaining the overall matrix-free Newton-Krylov approach. Because the plasma variables outnumber the neutral variables, especially when many charge states of impurities are included, the more demanding neutral preconditioner becomes a minor cost in the overall computation, greatly improving the parallel scaling. Numerical results are presented for the UEDGE 2D boundary transport code, demonstrating that the FieldSplit preconditioner is much cheaper to form and apply than traditional preconditioners (e.g, Additive Schwarz, ILU, or even LU) in the parallel setting. We describe the newly developed `PCFieldSplit` capability in the PETSc library, which enables construction of this preconditioner at runtime with no changes to the application code. Numerical scaling results were obtained on the Fusion computer in the Laboratory Computing Research Center at Argonne National Laboratory.

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