Improving Scalability for Edge Plasma Transport with Neutral Gas Species

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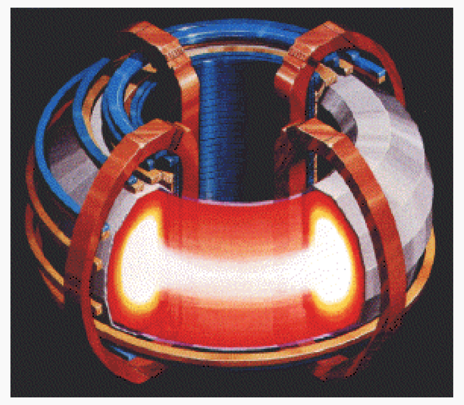
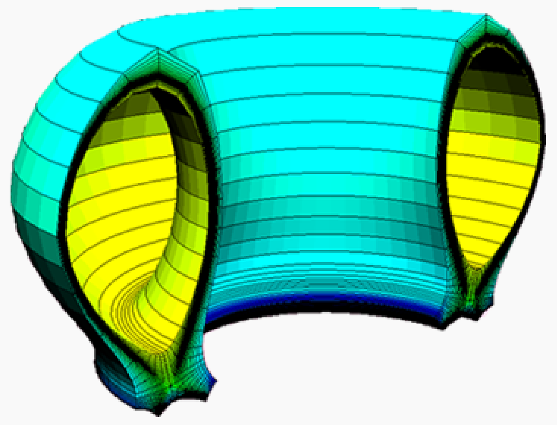
Introduction

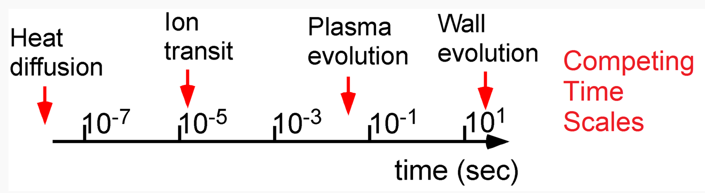
- We study simulations of the edge region of a Tokamak magnetic confinement fusion reactor using UEDGE.
  - UEDGE is a 2D parallel edge plasma application developed by T. Rognlien et al. (LLNL)

- UEDGE is one of the edge plasma transport components in FACETS
  - FACETS: Framework Application for Core-Edge Transport Simulations based at Tech-X Corporation
  - PI: John Cary, `https://www.facetsproject.org`
  - FACETS goal: Strong coupling between core, edge and wall Tokamak regions during simulation

Governing Physics

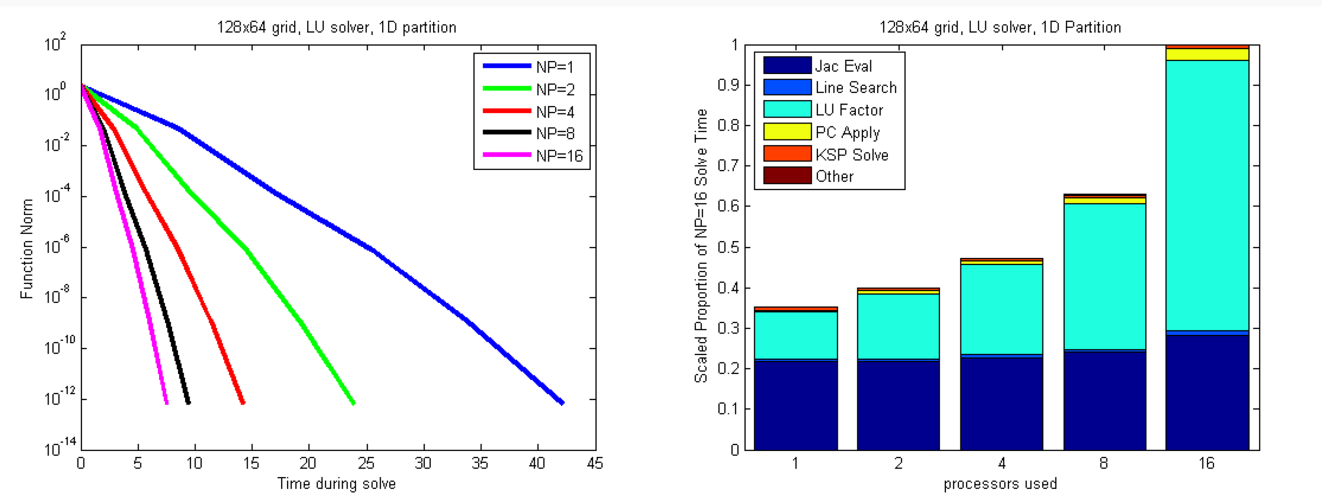
- UEDGE uses a fluid transport model conserving particles, momentum and energy.
- Challenges in edge region simulations
  - Strong nonlinearities
  - Competing demands of plasma and neutral gases
  - Large range of spatial and temporal scales



- Simulations use $\Delta t \in [10^{-4}, 10^{-3}]$ s, appropriate for coupling to time-dependant core models.
- Numerous coupled variables in the basic simulation
  - Hydrogen ion H^+ temperature, density, parallel velocity
  - Electron e temperature and Neutral Hydrogen H density
- Impurity charge states add many more variables

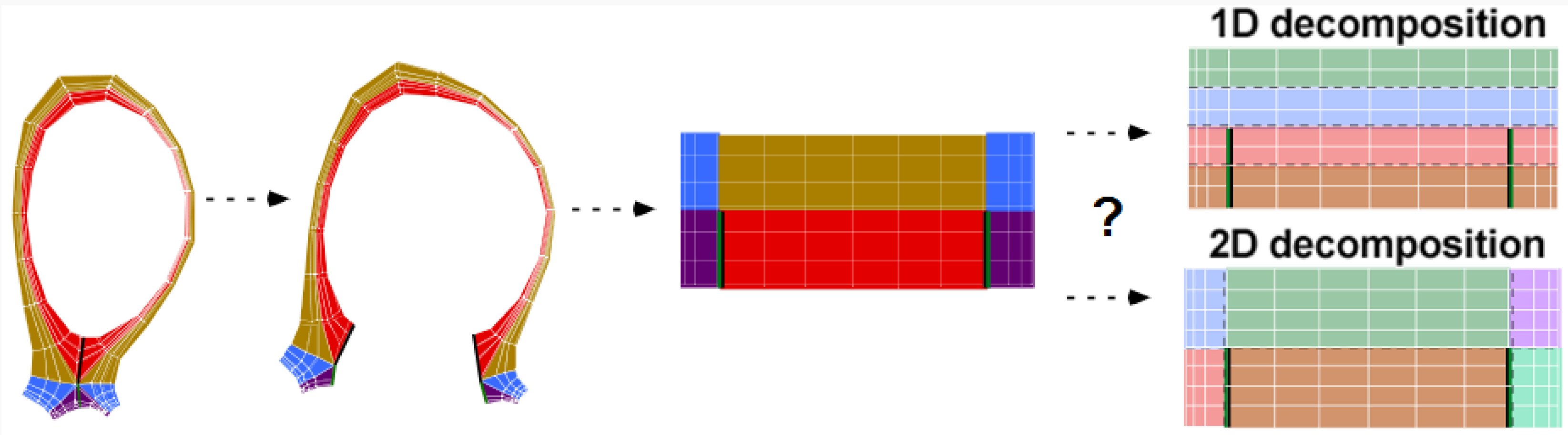
Algorithms

- Implicit time discretization with nonlinear solves via preconditioned Jacobian-free Newton-Krylov
  - The choice of preconditioner is vital to achieving scalability
- PETSc is used to conduct the simulation in parallel
- Early experiments showed limited scalability
  - The direct solver becomes overwhelmed by the cost of LU factorization and associated communication.

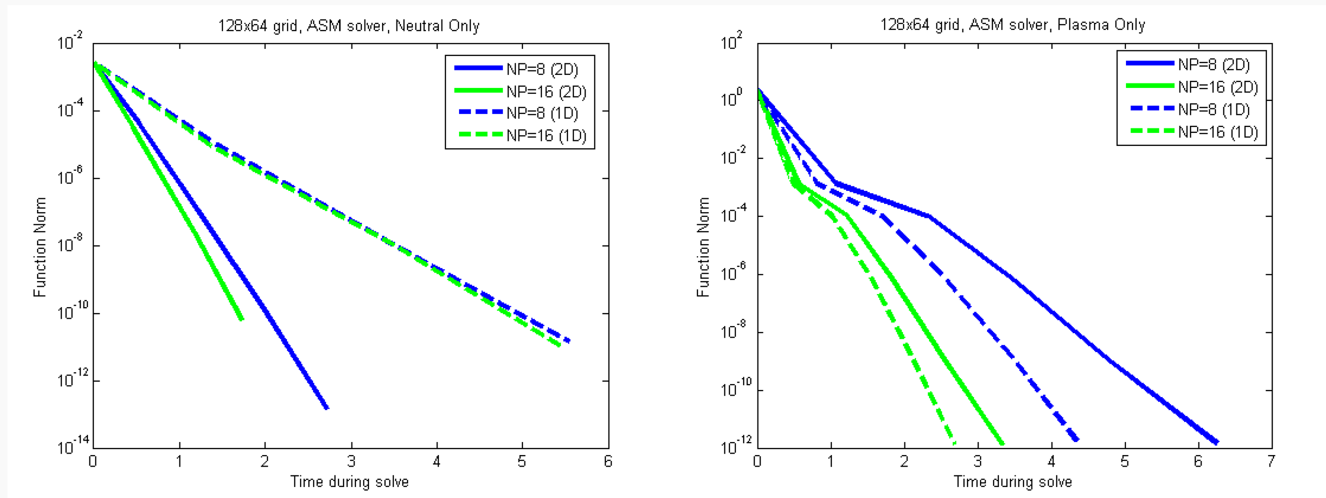


Partitioning and Mixed Preconditioners

- To improve the scalability of the solver we must examine the partitioning



- The physics at work have contrary demands on scalability
  - Neutral gas terms prefer a 2D partition
  - Plasma transport terms prefer a 1D partition



(a) Neutral terms only (b) Plasma terms only

Results: FieldSplit Preconditioning

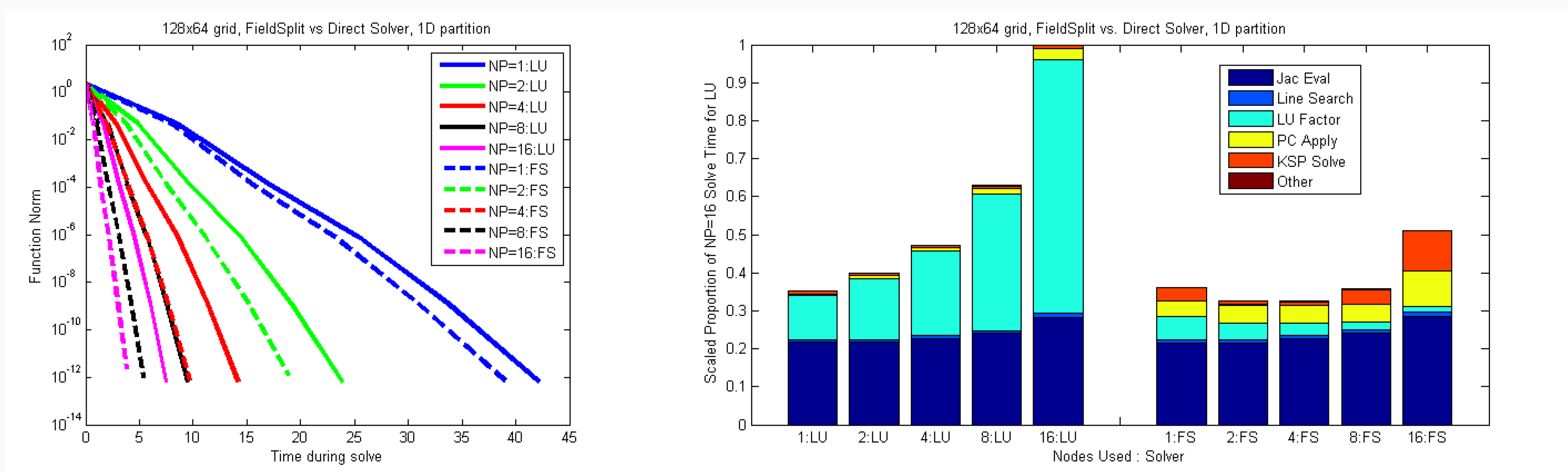
- To leverage our knowledge of competing partition demands we can:
  - Work on a 1D partition, preferred by plasma variables
  - Use the ASM to solve the plasma terms, with a direct solve on each domain
  - Solve the neutral terms with an isotropic-appropriate solver, multigrid (AMG)

$$\begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix} \to \text{Reorder to blocks} \to \begin{pmatrix} A_1 & A_2 \\ A_3 & A_4 \end{pmatrix}$$

$A1$ Plasma Terms Only
$A2$ Neutral to Plasma Coupling
$A3$ Plasma to Neutral Coupling
$A4$ Neutral Terms Only

- FieldSplit preconditioning is available in PETSc
- The simplest version of FieldSplit is Additive, where each component has a separate solve and all coupling terms are neglected

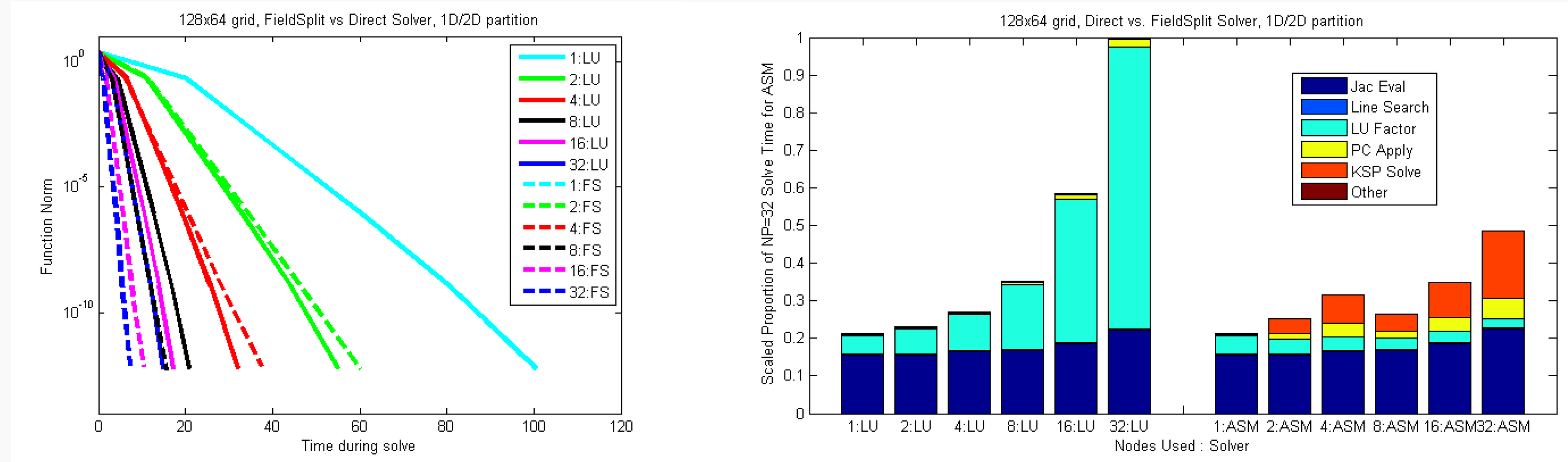
$$\begin{pmatrix} A_1 & A_2 \\ A_3 & A_4 \end{pmatrix} \to \text{Preconditioned by} \to \underbrace{\begin{pmatrix} A_1^{-1} & 0 \\ 0 & A_4^{-1} \end{pmatrix}}_{Additive}$$



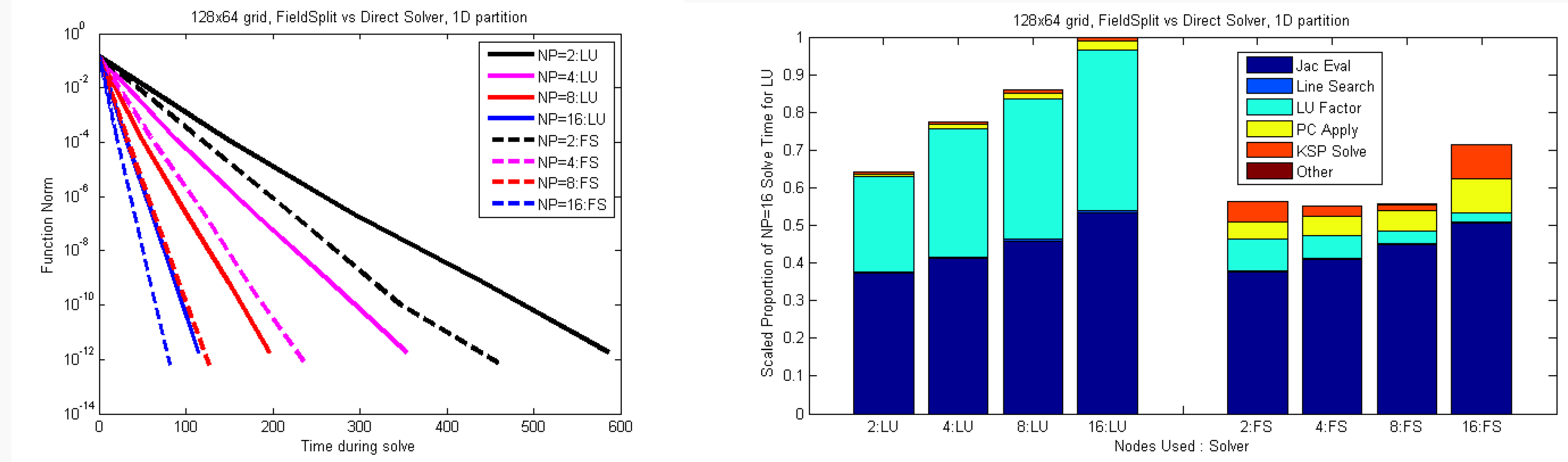
- By handling the troublesome terms (neutral gases) separately we can use a more scalable solver on the easier terms (plasma).
  - 1D partitioning allows for the majority of variables (plasma) to be on their natural domain.

Results: Scalability for More Complex Problems

- Initially the neutral H velocity was computed with a simpler algebraic model. Below are results with its inclusion in the nonlinear solve.
  - A 2D partitioning is preferred for this problem, which is first available at NP=8.

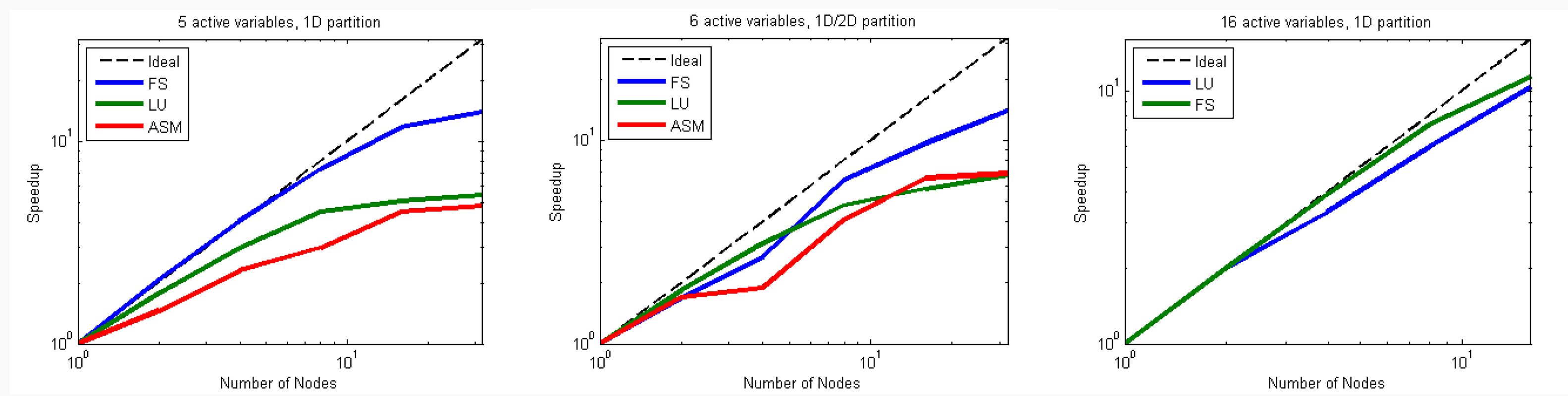


- We also enjoy improved scalability in the presence of a Neon impurity and the 11 new variables added as a result.



Conclusions and Future Work

- FieldSplit overcomes a major limitation to parallel scalability for a combined neutral/plasma edge model.



- Will we lose scalability as $\Delta t \to 1$ as needed in steady-state problems?
- As the number of partitions in the domain increases communication becomes a greater proportion of each processor's work.
  - To minimize this communication cost, present in FieldSplit, we want to try redundant preconditioning on small blocks.
  - How can the overlap between domains in ASM be increased to improve speed?
  - Will lagging the Jacobian evaluations hurt scalability?
- The goal of the FACETS project is Core-Edge-Wall coupling
  - How can this physics preconditioning be applied in such a multiphysics setting?
  - What more complicated FieldSplits are possible?
- Coupling terms can be retained via the Schur complement ($S \approx (A_1 - A_2 A_4^{-1} A_3)$), although at greater cost than Additive FieldSplit

$$\underbrace{\begin{pmatrix} I & 0 \\ -A_4^{-1}A_3 & I \end{pmatrix} \begin{pmatrix} S^{-1} & 0 \\ 0 & A_4^{-1} \end{pmatrix} \begin{pmatrix} I & -A_2 A_4^{-1} \\ 0 & I \end{pmatrix}}_{Schur}$$

  - While not needed so far, will this coupling be useful in multiphysics preconditioning?

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