Adaptive Mesh Refinement MHD for Magnetic Fusion Applications

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Collaborators

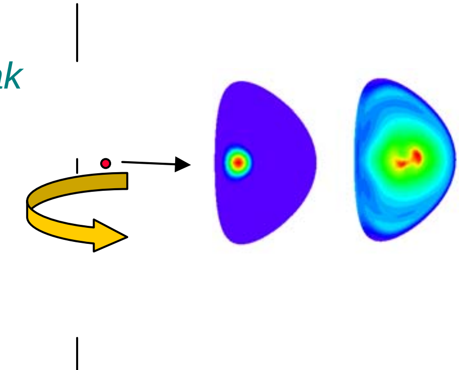
- P. Colella (LBNL, PI APDEC)
- S. C. Jardin (PPPL, PI CEMM)
- ANAG Members (T. J. Ligocki, D. F. Martin and others, LBNL)
- TOPS (D. R. Reynolds and C. S. Woodward, CASC, LLNL)
- P. Parks (GA) and D. Majeski (PPPL)
- V. Wheatley and D. I. Pullin (Caltech)

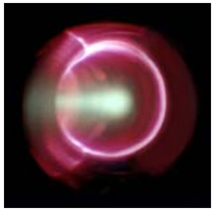
Overview of MHD Applications

Tokamak Refueling (Pellet, Gas)	**Magnetic Reconnection**	**Richtmyer-Meshkov Instability**	**Application**
Ideal MHD **Single fluid Resistive MHD** **Ablation Model** **Electron heating Models** **Anisotropy**	**Single Fluid Resistive MHD** **Two Fluid MHD with Hall Term and Kinetic Alfven Wave**	**Ideal MHD** **MHD Shocks**	**Physics**
3D Cartesian **Tokamak (shaped plasma)**	**2D, 3D Cartesian**	**2D, 3D Cartesian**	**Geometry**
Unsplit Upwind **Implicit for diffusion term** **r¢ B=0 (Projection)** **Newton-Krylov Implicit (Central difference** **r¢ B=0 by construction)**	**Unsplit Upwind** **Implicit for diffusion term** **r¢ B=0 (Projection)** **Newton-Krylov Implicit (Central difference** **r¢ B=0 by construction)**	**Unsplit Upwind** **r¢ B =0 Projection**	**Algorithms Solver**

Pellet Injection: Current Status

- Motivation
  - *Injection of frozen hydrogen pellets is a viable method of fueling a tokamak*
  - *Presently there is no satisfactory predictive model for ITER*
  - *Ratio of pellet size to device size is ~O(10^{-3}) (requires AMR)*
- Pellet-plasma interactions:
  - *Ablation: Considered well-understood*
  - *Mass deposition: Large scale MHD driven but not-so-well understood*
- Objectives
  - *Identify the mechanisms for mass distribution during pellet injection in tokamaks*
  - *Quantify the differences between "inside launch" and "outside launch"*
- Physical model
  - *Single fluid MHD equations describe plasma*
  - *Pellet ablates with an analytic ablation model (Parks 1978, Kuteev 1995)*
  - *Instantaneous heating of ablated mass by electrons*
- Phased approach with varying degrees of complexity
  - *Ideal and Resistive MHD in 3D Cartesian Geometry (Samtaney et al. Sherwood Fusion Theory Conference 2003)*
  - *Ideal MHD in (R,Z,ϕ) coordinates (Samtaney et al. Invited Talk at ICNSP 2003, Computers Physics Communication, 2004; Parks et al. IAEA 2004)*
  - *Ideal MHD in (ξ(R,Z), η(R,Z), ϕ) curvilinear coordinates for shaped plasmas (under development)*
- 3D AMR simulations of pellet injection in (R,Z,ϕ)
  - *Mass redistribution dominantly along magnetic field lines*
  - *"Anomalous" mass redistribution, i.e., outward radial displacement of pellet mass.*
    - *HFS more efficient than LFS*
  - *Pellet injection: Estimated speed up ranged from 16-237*
    - *AMR is a viable approach to* efficiently *resolve the relatively small pellet*





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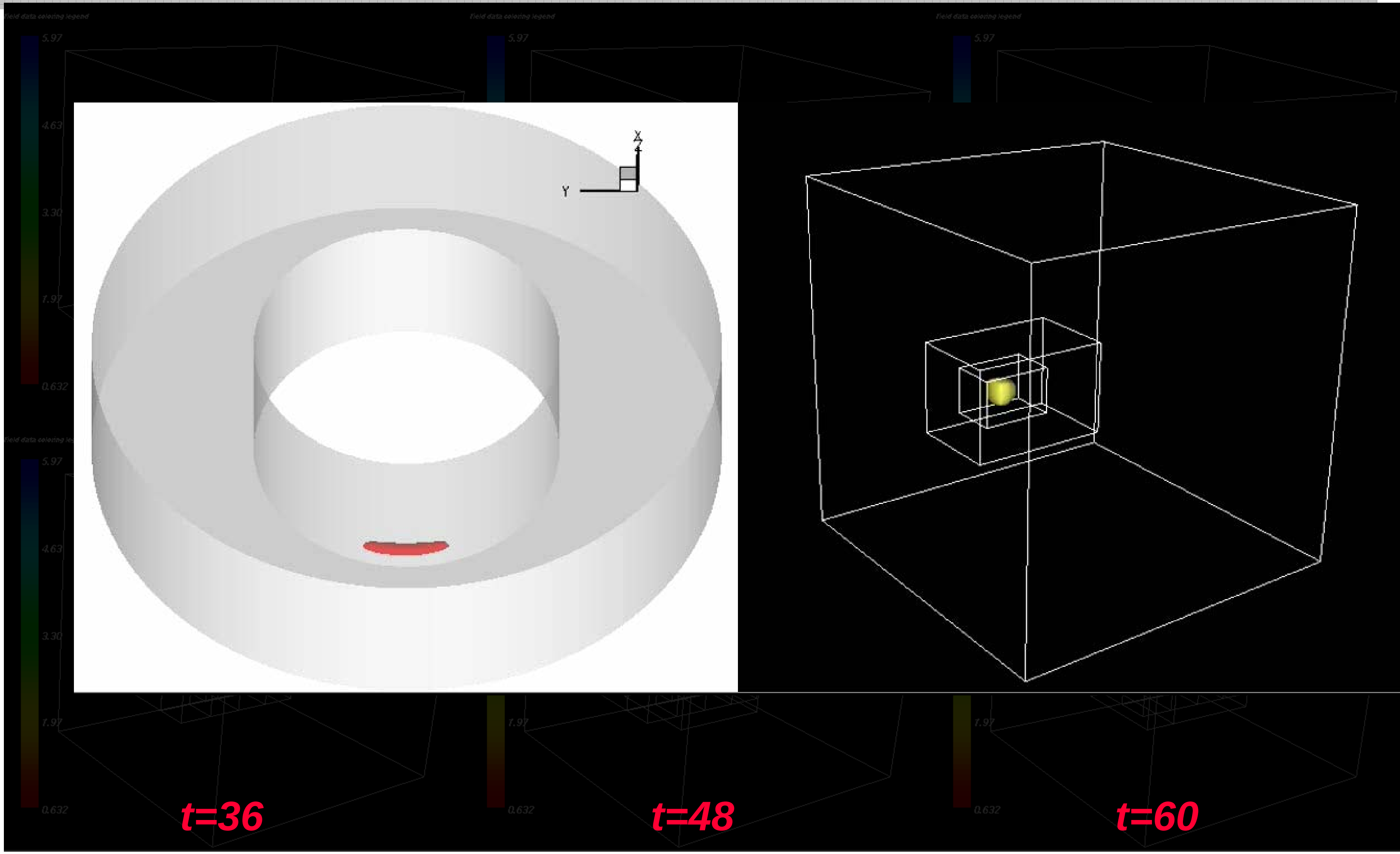
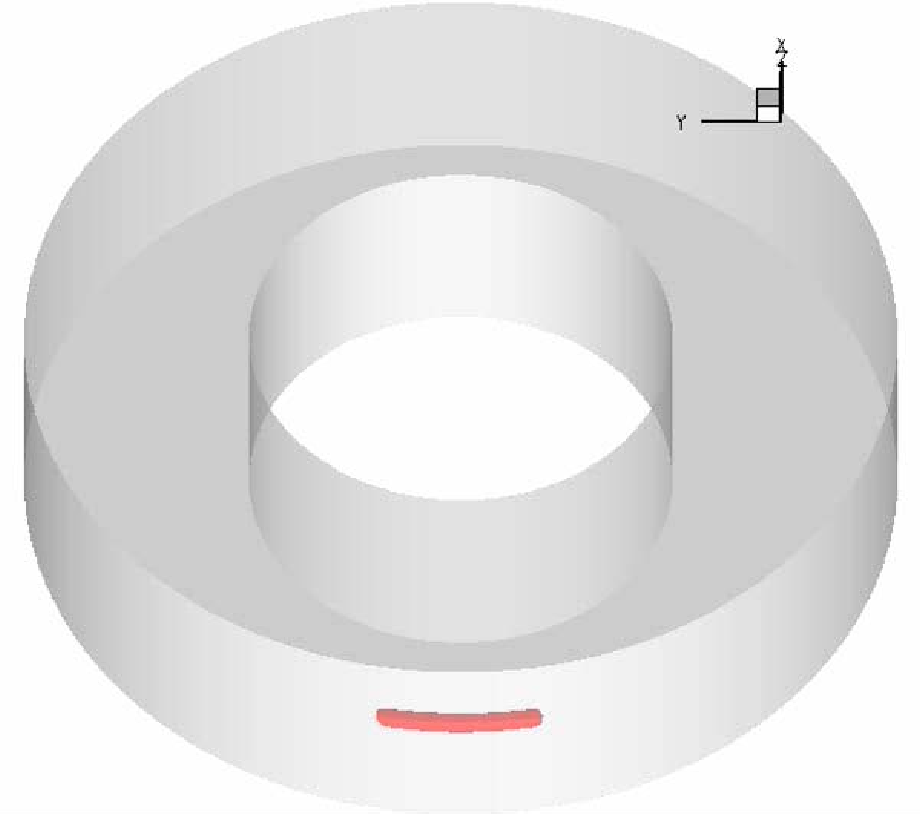
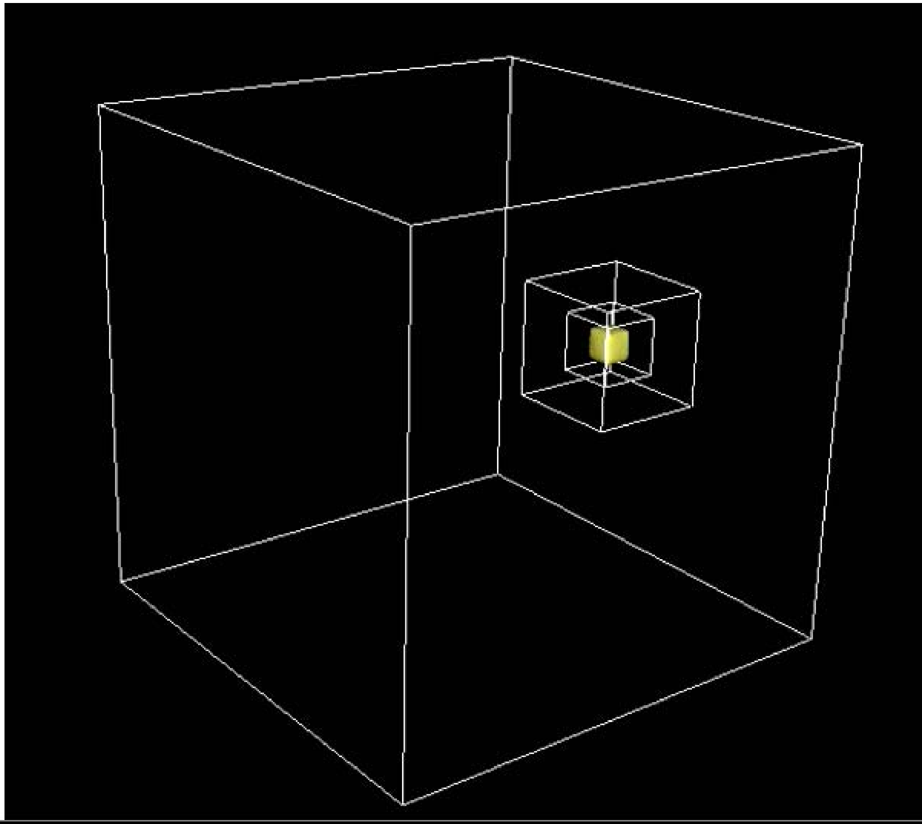
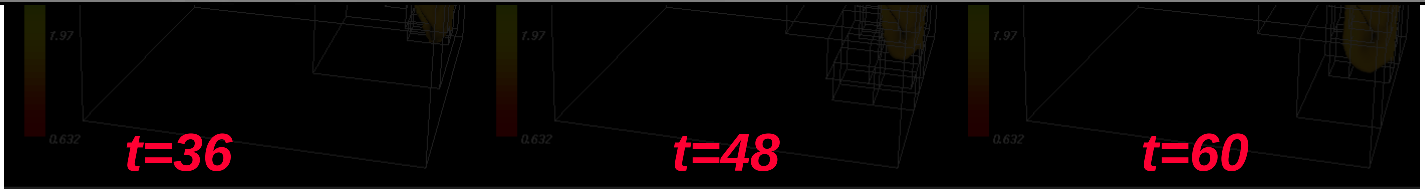
Pellet Injection: HFS Launch



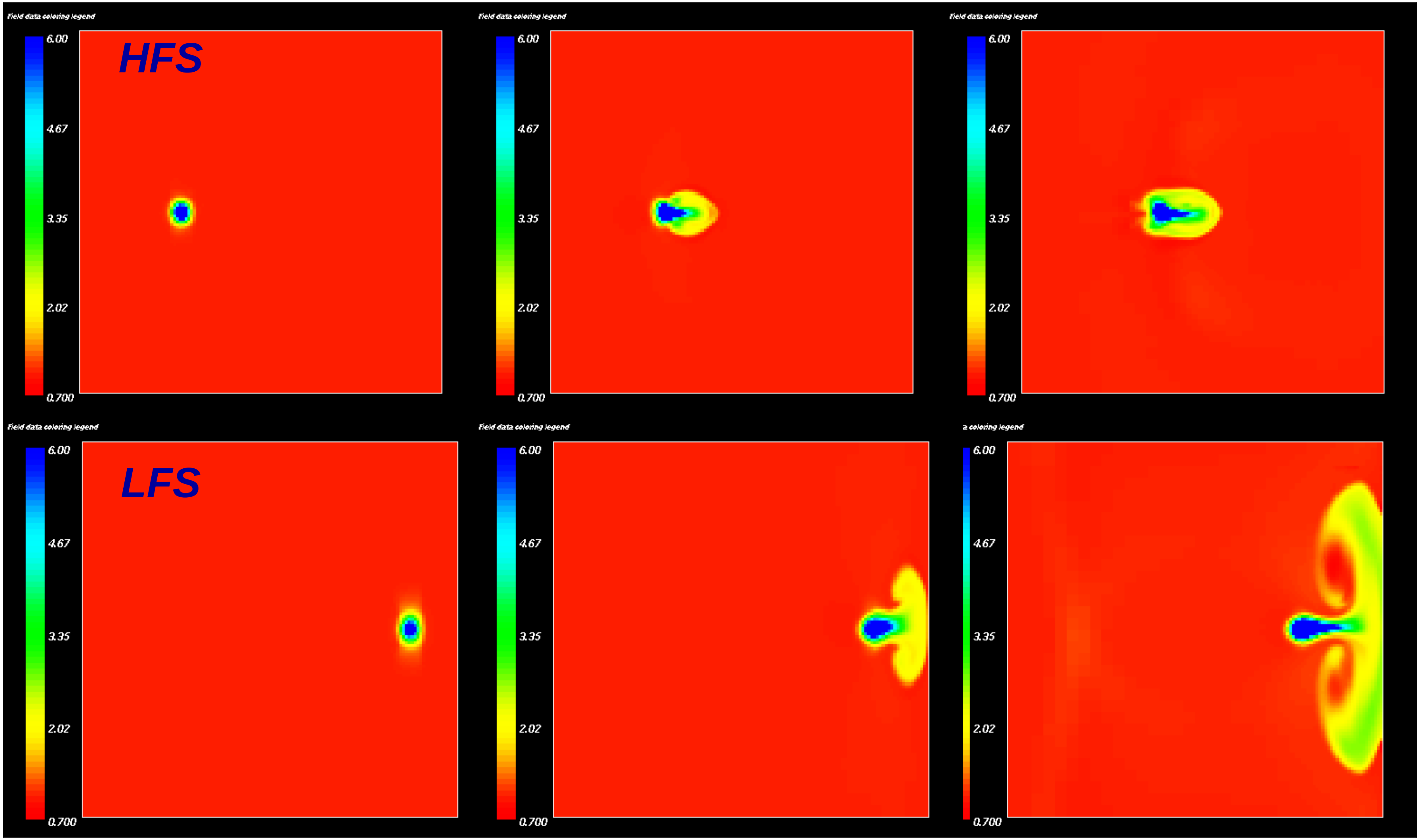
Pellet Injection: LFS Launch







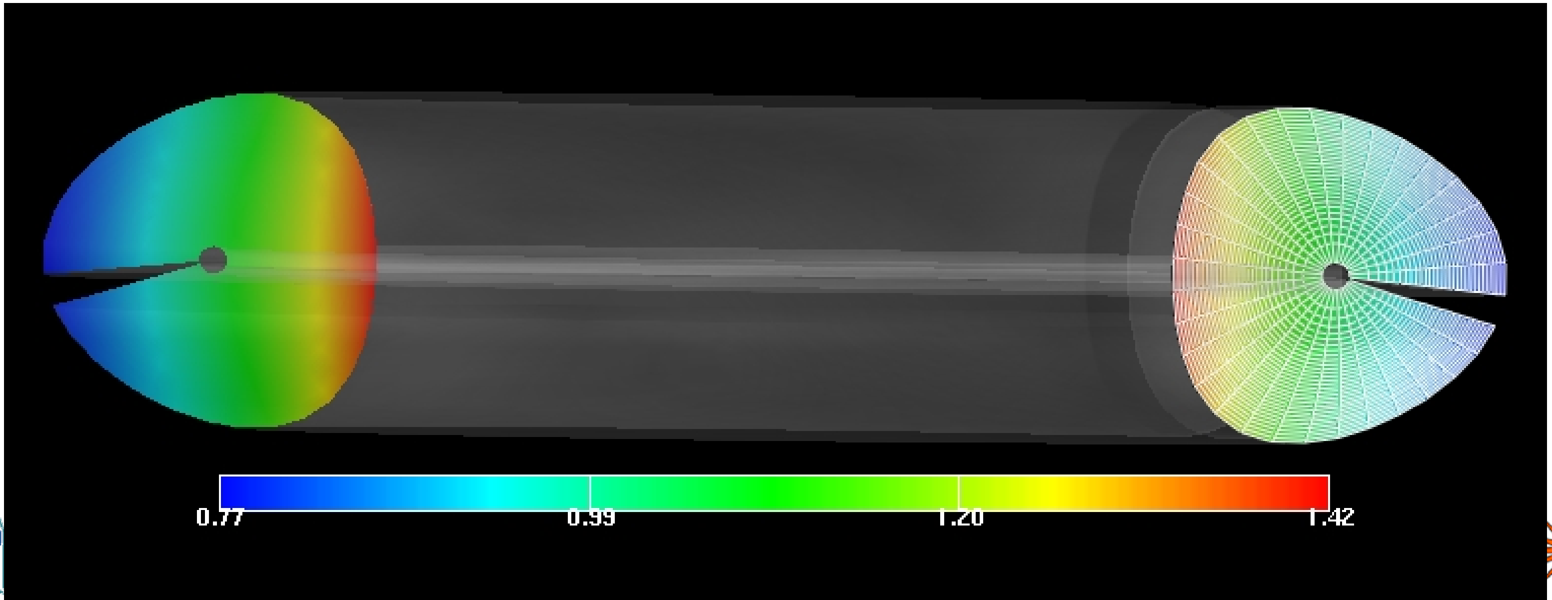
Pellet Injection: HFS vs. LFS



"Anomalous" transport across flux surfaces

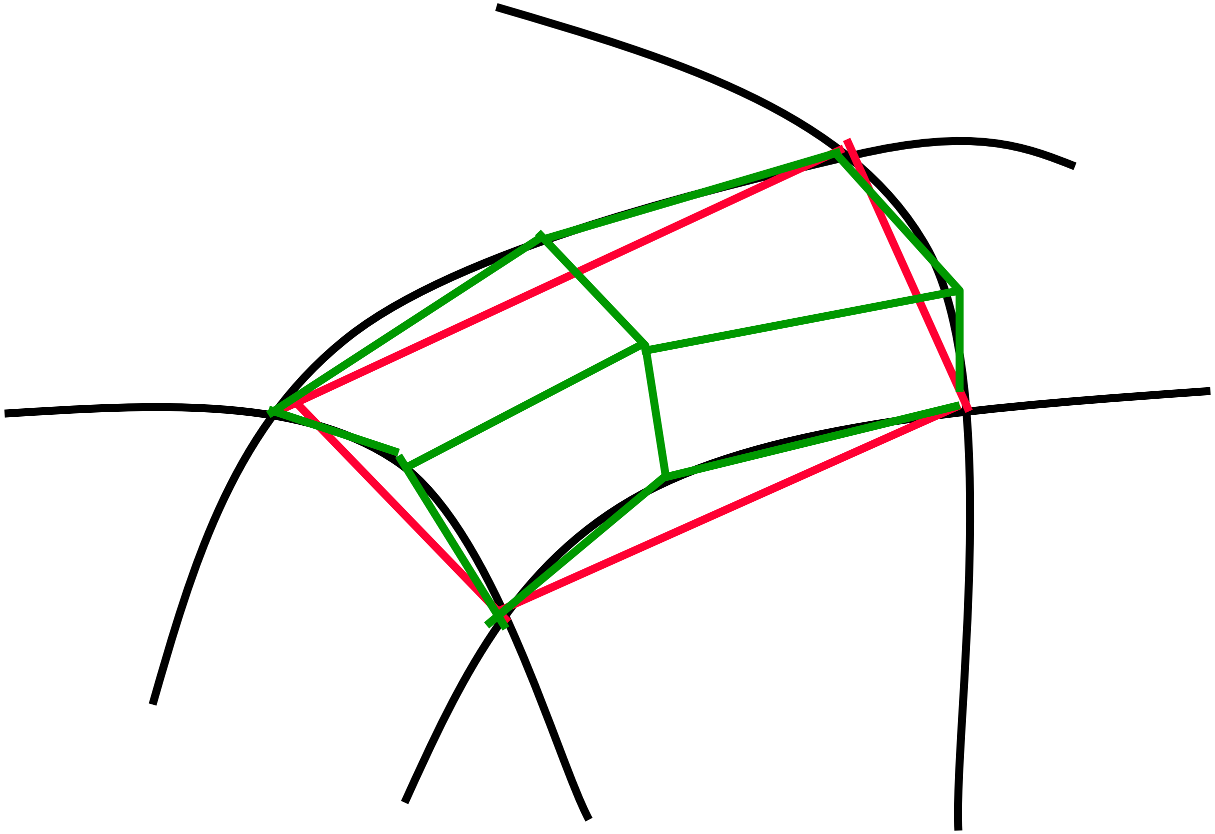
Pellet Injection – Future Plan

- Complete development of resistive MHD in ($\xi(R,Z)$, $\eta(R,Z)$, ϕ) curvilinear coordinates
  - *Semi-implicit treatment of diffusion terms requires solving elliptic PDEs in curvilinear coordinates*
  - *Preservation of equilibrium input from a separate Grad-Shafranov solver*
    - *Subtract the toroidal equilibrium component of B for increased robustness;*
    - *subtract out the truncation errors*
- Model improvements
  - *Incorporate model for electron heating involves integration along field lines (desirable but exact implementation with AMR is difficult) (Collaboration with Parks, General Atomics)*
  - *Heat conduction anisotropy*



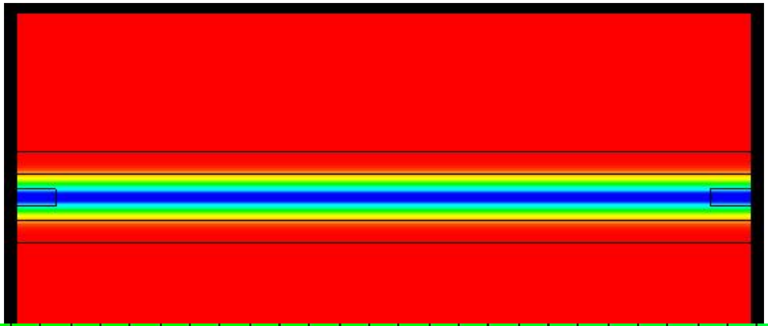
AMR For Mapped Grids – Issues

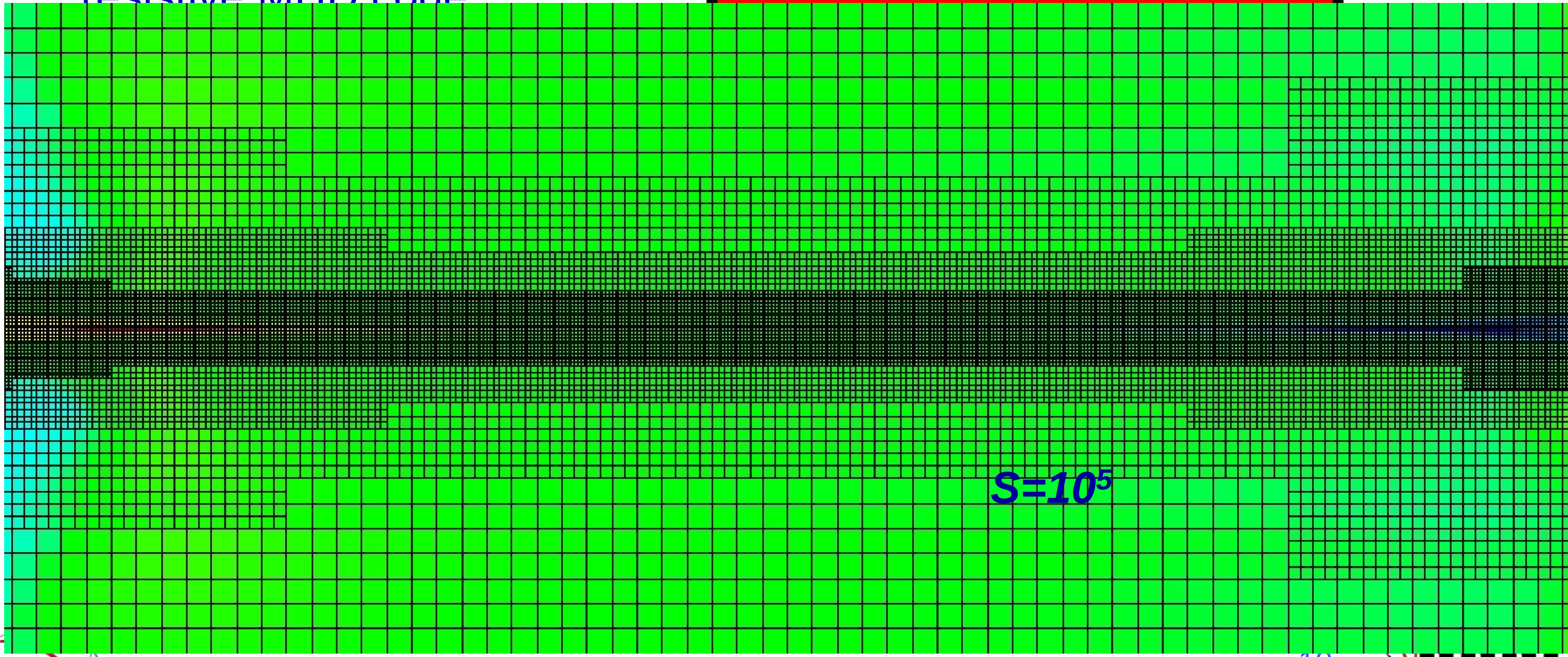
- Upon refinement, the volumes of the cells are not conserved. With care, conservation can be achieved.
- Interpolation routines at coarse-fine boundary need modification to account for non-uniform cells.



Magnetic Reconnection - Current Status

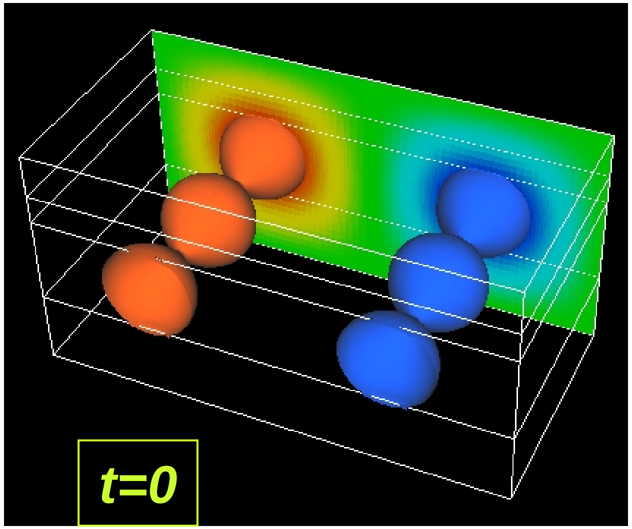
- MR is an important canonical problem in plasma physics
- Semi-implicit single-fluid resistive MHD code

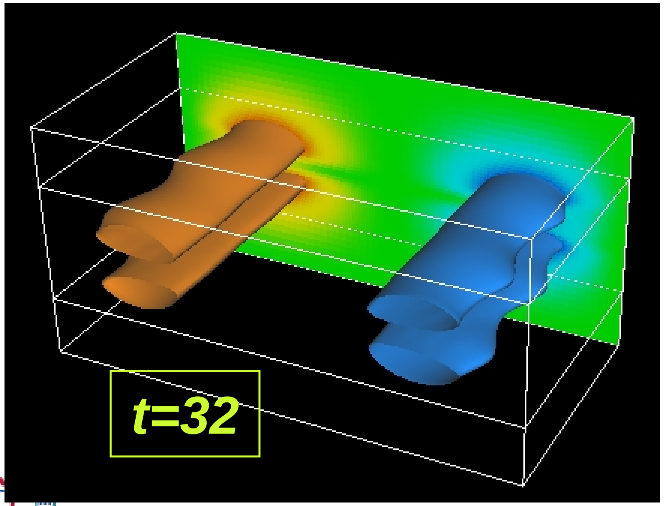


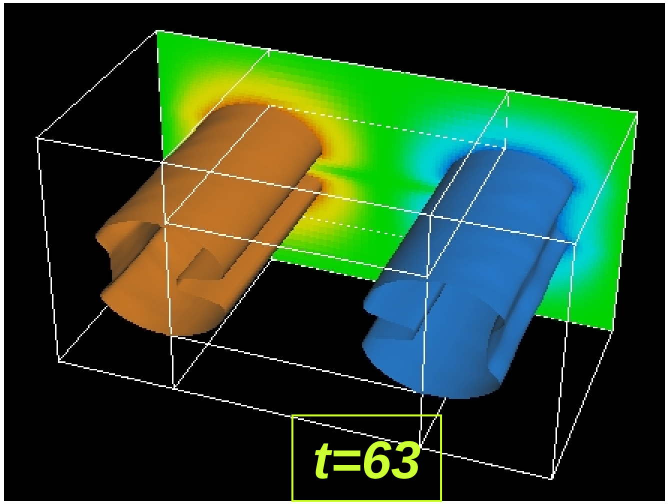


Magnetic Reconnection - Current Status

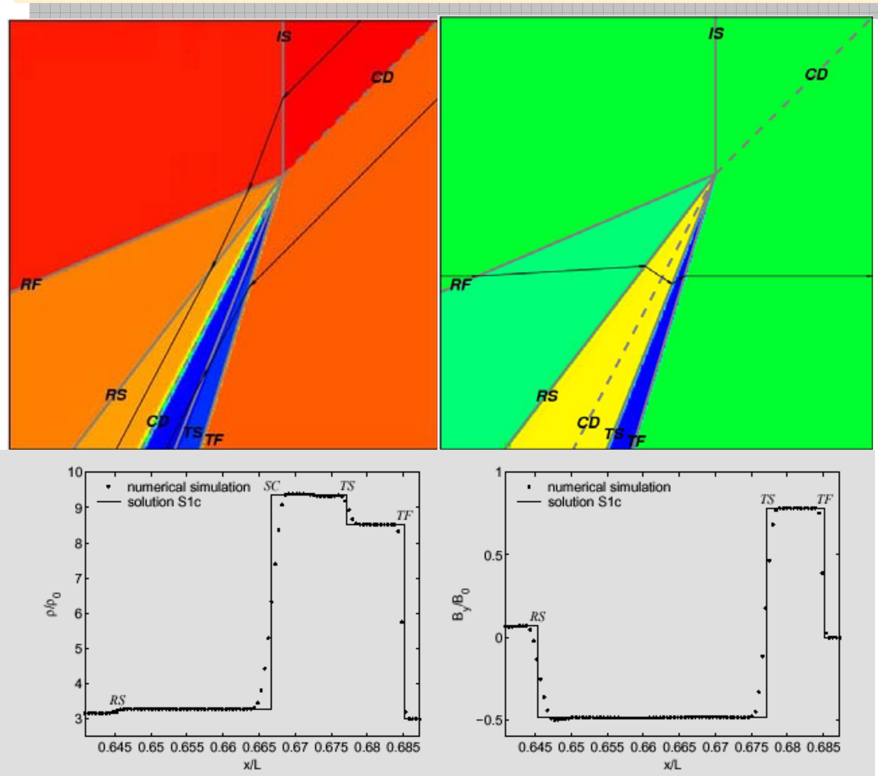
- 3D Reconnection
  - *Perturb the 2D GEM configuration*
  - *Periodic in Z*
  - *B_z=1*
  - *S=200*
  - *Essentially 2D*

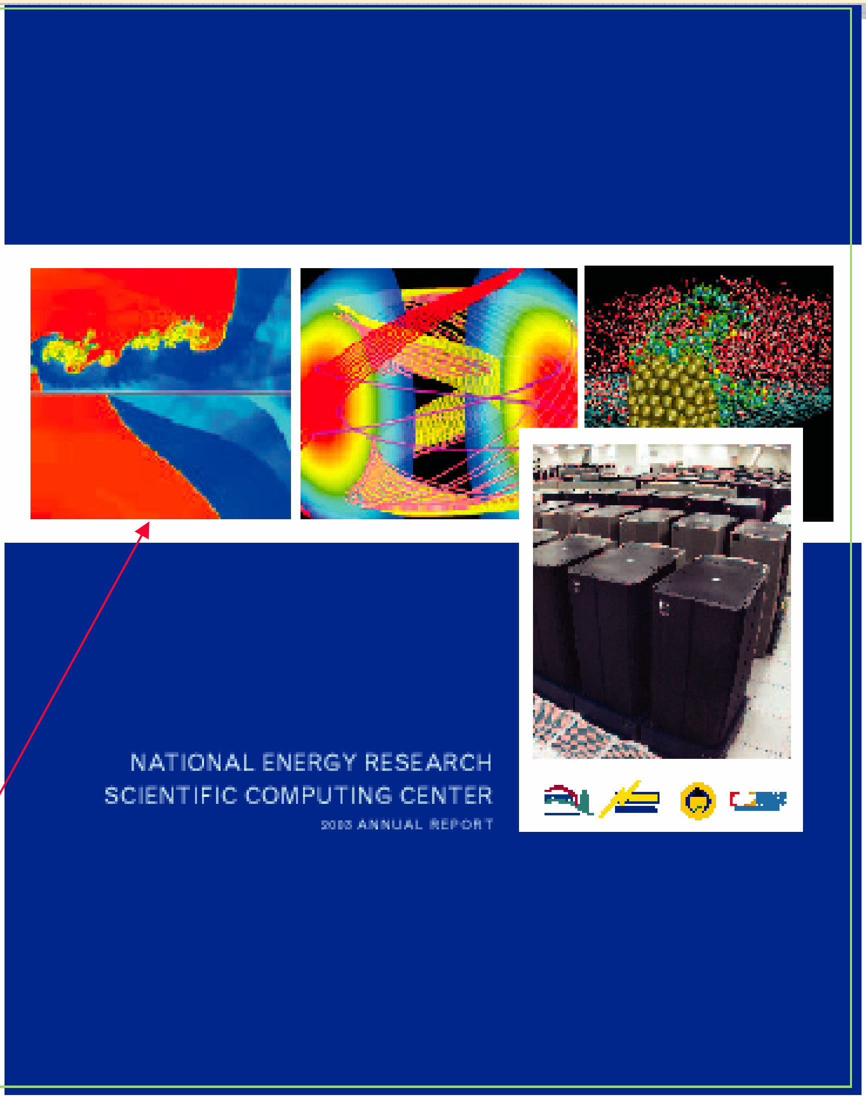






Richtmyer-Meshkov Instability - Status

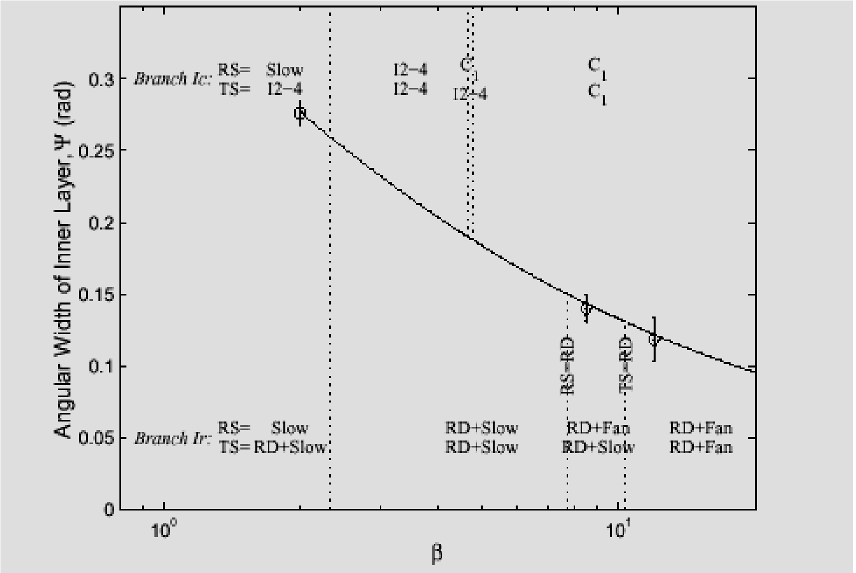




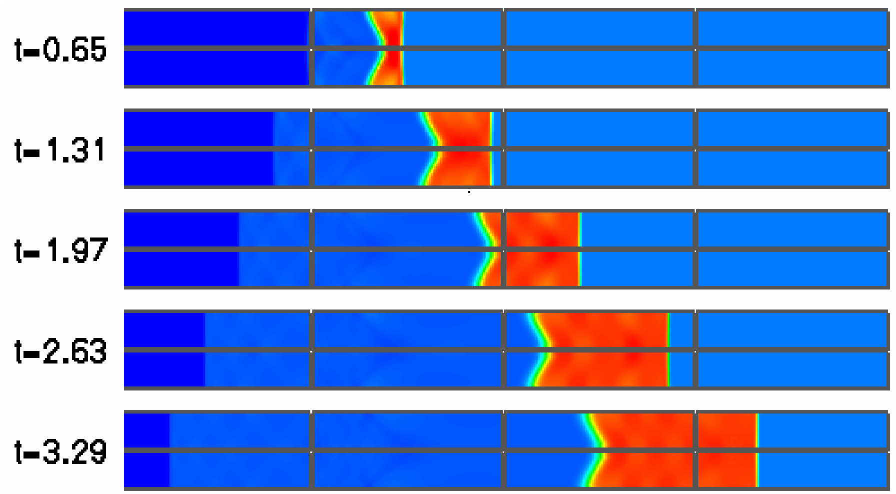
- Close agreement between analysis and simulations.
- RMI stabilization by a magnetic field (Samtaney, Phys. Fluids 2003)
  - *Ideal MHD simulations*
- Cover of NERSC Annual Report

Richtmyer-Meshkov Instability - Status

- Transitions in Solution Type with Increasing β
- Singular approach to the hydrodynamic limit with Increasing β
  - $\beta \to \infty$: *solutions $\to$ hydrodynamic triple-point, except shocked hydrodynamic contact replaced by an inner layer, with angular width $\propto \beta^{-1/2}$ (Wheatley, Pullin and Samtaney, Journal of Fluid Mechanics – to appear 2004)*



- 3D RM Simulations demonstrate suppression of instability for canonical flow in 3D (Pullin, Wheatley & Samtaney, Intl. Workshop on Phys. Of Comp. Turbulence, Cambridge 2004)



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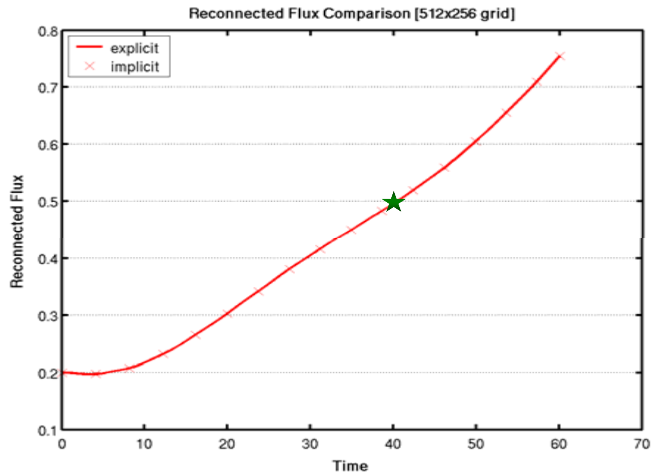
Implicit Method – Motivation and Status

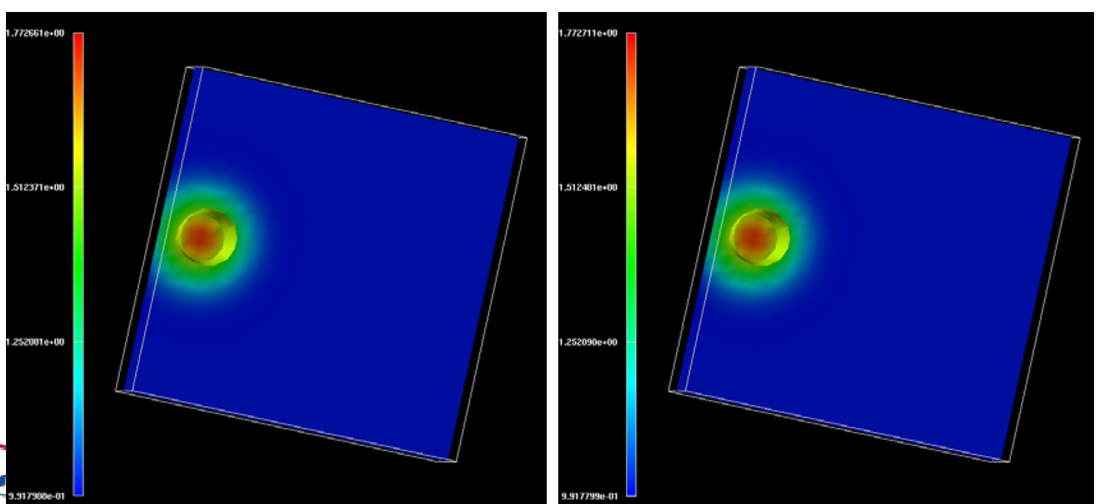
- Estimates of resolved resistive MHD simulations of pellet injection in CDXU
  - *$O(10^6$-$10^7)$ time steps (explicit method)*
  - *With AMR need $O(10^5)$ time steps on coarsest mesh*
  - *Resolution/time step requirements more stringent for larger devices*
  - *Implicit treatment can reduce the number of time steps*
- Long term goal: Develop an AMR MHD solver using Chombo coupled with SUNDIALS for implicit time stepping (APDEC, TOPS, CEMM)
- Developed an implicit conservative, solenoidal B, single fluid resistive MHD code in collaboration with TOPS (D. R. Reynolds, C. S. Woodward, CASC, LLNL)
  - *Nonlinear solver based on inexact Newton iteration*
  - *Krylov iterative method (GMRES) as the linear solver*
  - *Spatial accuracy can be set to $O(h^2)$ or $O(h^4)$*
  - *Test cases: linear wave propagation, GEM reconnection and pellet injection*

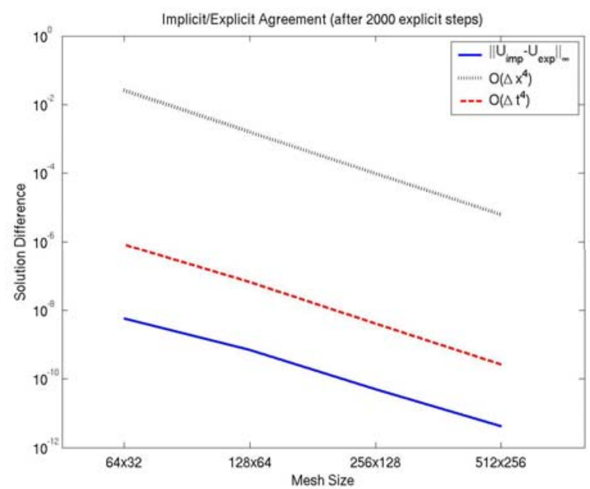
Implicit Method – Current Status

- GEM Reconnection Challenge in 2D
  - *Implicit 3-4 times faster ($O(dt^2)$) and 35 % faster ($O(dt^4)$) than explicit*
- Pellet injection in 3D Cartesian geometry
  - *Surrogate for the real pellet injection problem in 3D tokamak geometry*
  - *Same time stepping constraints due to large toroidal field*
- **<u>No preconditioning</u>** for linear solves



Implicit and explicit methods agree on reconnected flux "Star" agree with published results (Brin et al. J. Geophysical Research 2001)





Implicit Method – Future Plan

- Develop "physics-based" preconditioners (Chacon & Knoll 2003)
  - *Expect that implicit solvers will speed up if preconditioners are chosen wisely*
- Curvilinear coordinates for shaped plasmas
- Develop strategies for coupling with Chombo to achieve AMR

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Summary and Future Plan

- Magnetic reconnection in 3D and high S in 2D
- Pellet injection in (R,Z,ϕ) agrees qualitatively on the differences between HFS and LFS pellet launches
- RM instability suppression demonstrated in 3D, and developed analytical theory in 2D
- Progress on implicit NK

- Tokamak geometry for shaped plasmas for refueling simulations
- Anisotropic transport
- Include electron heating model
- Supersonic gas injection
- Implicit treatment – preconditioners, AMR

Linear Wave Propagation Tests

- Domain [0:2]x[0:2]
- Wavenumber vector: $k_x = n\,\pi$, $k_y = m\,k_x$
  - *(n,m)=(1,1), (1,2), (1,3)*
- Angle between wave direction and $\mathbf{B}_0$ varied from 0 to $\pi/2$
- Amplitude of waves $\varepsilon = 10^{-5}$
- Equilibrium state: $\{\rho_0, 0, 0, 0, B_{x,0}, B_{y,0}, p_0\}$
  - $\rho_0 = 1$, $p_0 = 0.1$
  - $|B_0| = 1$
- t_{end}¼ 2
- Computed with nonlinear code (nonlinearities ~ $O(\varepsilon^2)$)