Status of Pellet Injection and ELM Simulations

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Collaborators

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Outline

- Introduction and motivation
- Current Status
  - *AMR code*
  - *JFNK Approach for fully implicit time advance*
- Future directions and conclusion

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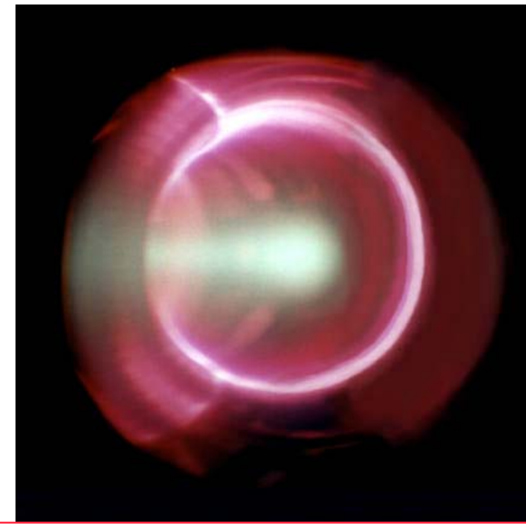
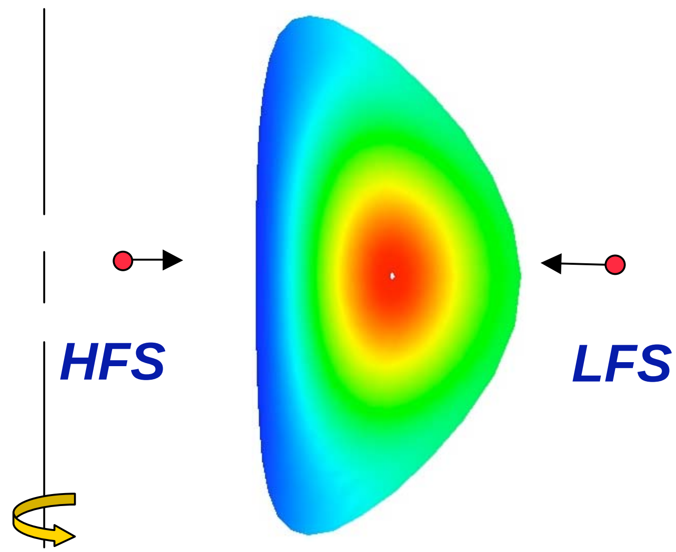
Pellet Injection & Edge Localized Modes

- Motivation
  - *Injection of frozen hydrogen pellets is a viable method of fueling a tokamak*
  - *Presently there is no satisfactory simulation or comprehensive predictive model for pellet injection (esp. for ITER)*
  - *H-mode operation of ITER will be accompanied by edge localized modes (ELMS) (ITER Physics Experts Group,Nucl. Fusion 1999)*
  - *Pellet injection related to ELMS (Gohill et al. PRL, 2001; Lang et al. Nucl. Fusion 2000)*
- Objectives
  - *Develop a comprehensive simulation capability for pellet injection and ELMs in tokamaks (esp. ITER) with modern technologies such as adaptive mesh refinement for spatial resolution and fully implicit Newton-Krylov approach for temporal stiffness*



Pellet injection in TFTR



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Scales and Resolution Requirements

- Time Scales $\tau_e < \tau_f < \tau_a < \tau_c < \tau_p$
- Spatial scales: Pellet radius r_p << Device size L ~O(10^{-3})
- Presence of magnetic reconnection further complicates things
    - *Thickness of resistive layer scales with ~ $\eta^{1/2}$*
    - *Time scale for reconnection is ~ $\eta^{-1/2}$*
- Pellet cloud density ~ O(10^4) times ambient plasma density
- Electron heat flux is non-local
- Large pressure and density gradients in the vicinity of cloud
- Pellet lifetime ~ O(10^{-3}) s →long time integrations

Resolution estimates

Tokamak	Major Radius	N	N_{steps}	Spacetime Points
CDXU (Small)	0.3	2×10^7	2×10^5	4×10^{12}
DIIID (Medium)	1.75	3.3×10^9	7×10^6	2.3×10^{17}
ITER (Large)	6.2	1.5×10^{11}	9×10^7	1.4×10^{19}

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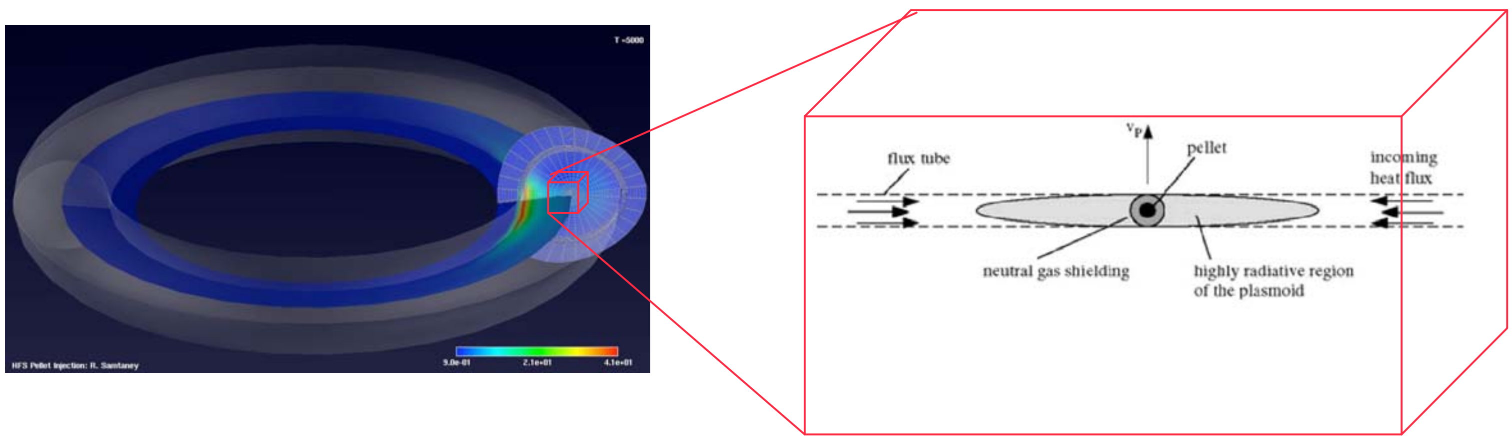
Pellet Injection: Current Work

- Combine global MHD simulations in a tokamak geometry with detailed local physics including ablation, ionization and electron heating in the neighborhood of the pellet



- AMR techniques to mitigate the complexity of the multiple spatial scales in the problem
- Newton-Krylov approach for wide range of temporal scales.

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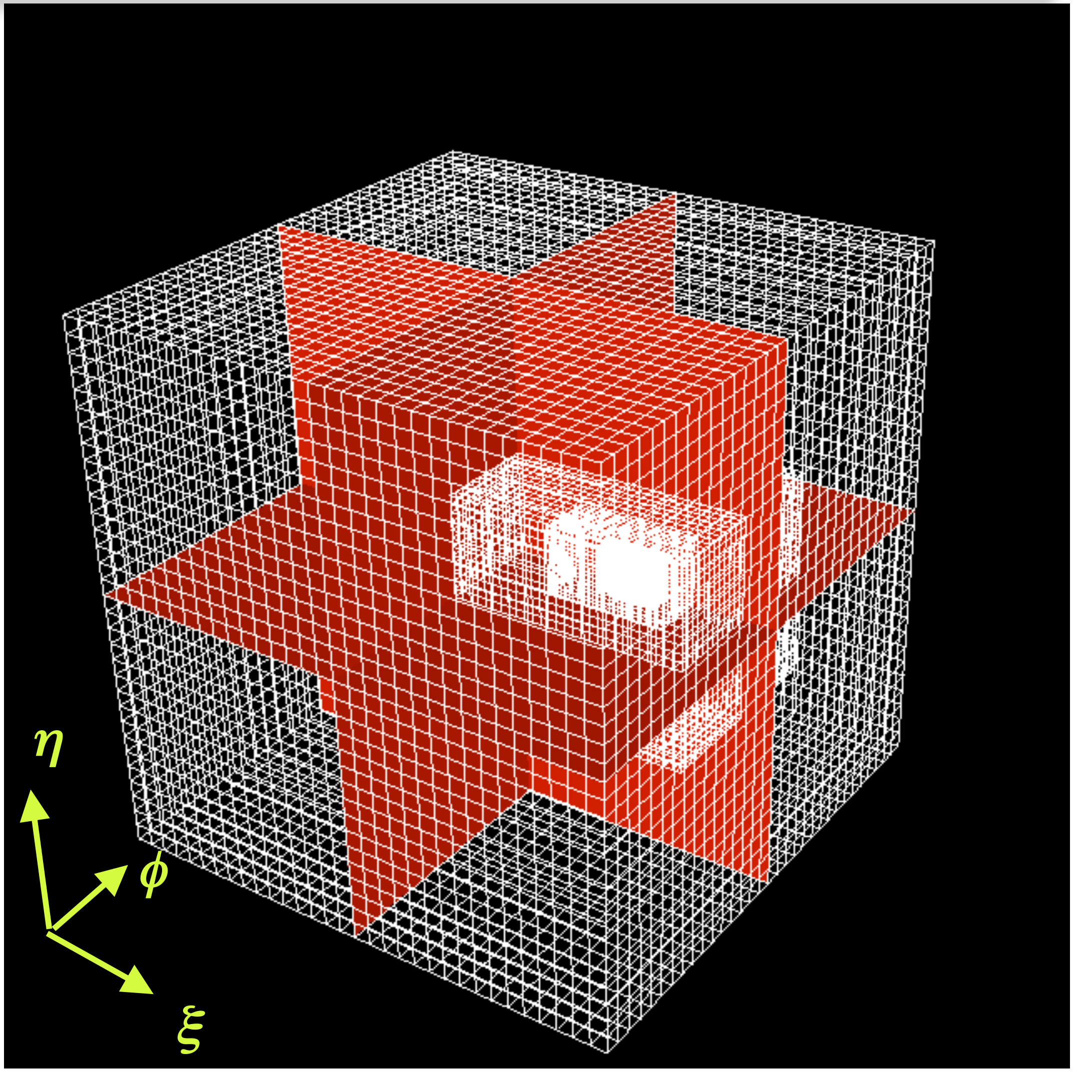
Numerical Methods

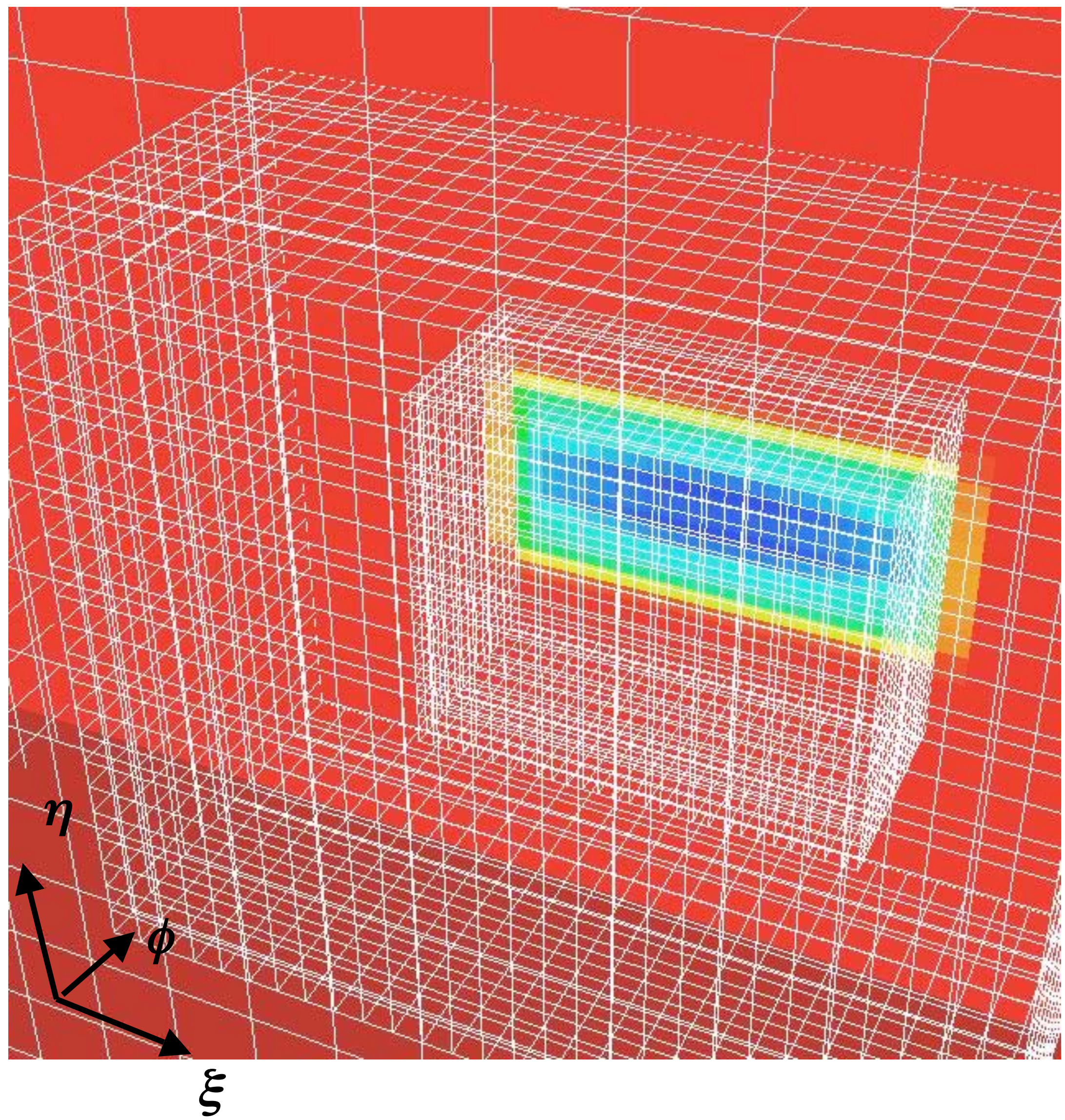
- Finite volume approach
- Adaptive mesh refinement method
  - *explicit second order time stepping*
  - *spatial stiffness*
  - *Chombo package (developed at LBNL)*
- Jacobian-Free Newton Krylov (JFNK) Method
  - *temporal stiffness*
  - *Sundials package (developed at LLNL)*
- The hyperbolic fluxes are evaluated using upwinding methods
  - *seven-wave Riemann solver*
  - *Harten-Lee-vanLeer (HLL) method*
- Diffusive fluxes computed using standard second order central differences

Pellet Injection: AMR

- Meshes clustered around pellet
- Computational space mesh structure shown on right
- Mesh stats
  - *32^3 – base mesh with 5 levels, and refinement factor 2*
  - *Effective resolution: 1024^3*
  - *Total number of finite volume cells:113408*
  - *Finest mesh covers 0.015 % of the total volume*
  - *Time adaptivity:*
    $1\ (\Delta t)_{base} = 32\ (\Delta t)_{finest}$



Pellet Injection: Pellet in Finest Mesh



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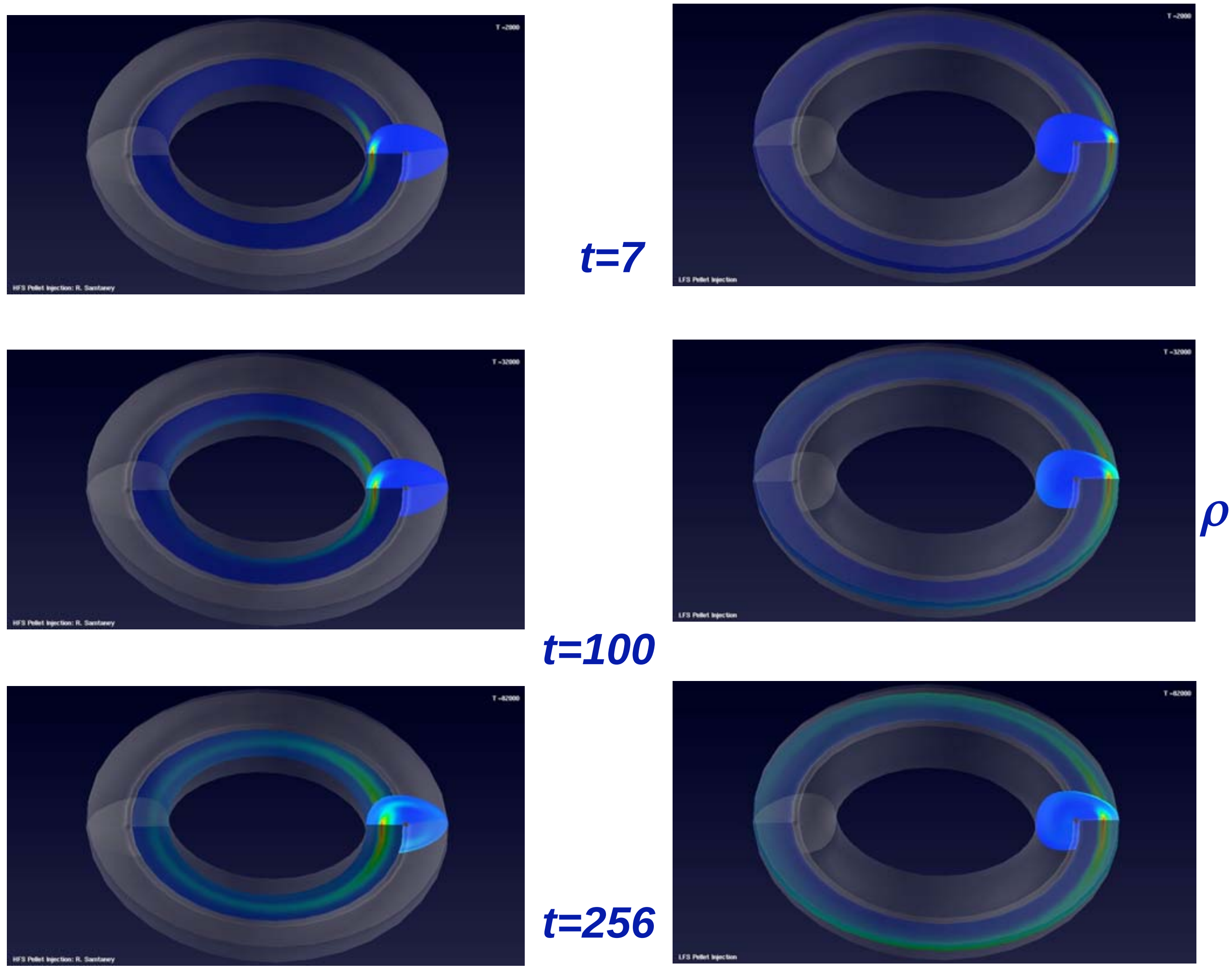
Results - HFS vs. LFS

B_T = 0.375T
n_0=1.5× 10^{19}/m^3
$T_{e\infty}$=1.3Kev
β=0.05
R_0=1m, a=0.3 m
Pellet: r_p=1mm,
v_p=1000m/s



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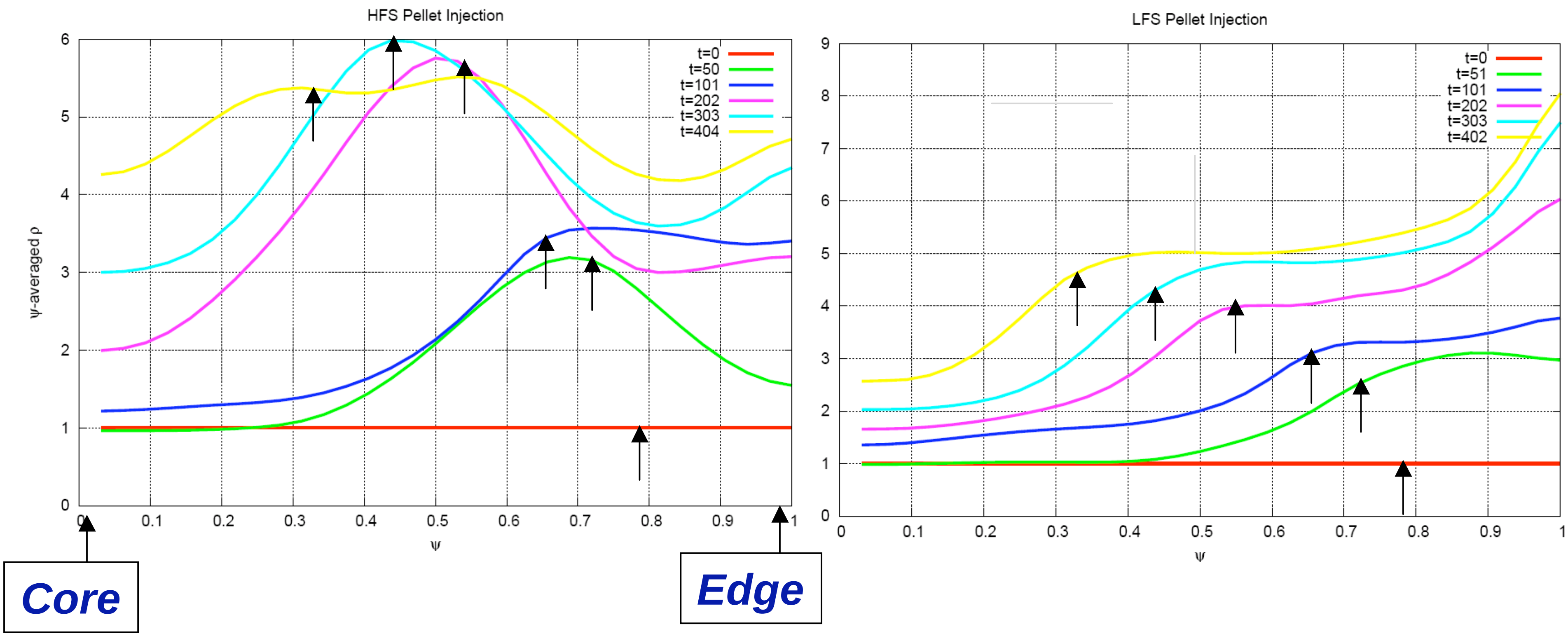
HFS vs. LFS - Average Density Profiles



HFS Pellet injection shows better core fueling than LFS

Arrows indicate average pellet location

JFNK Fully Implicit Approach for Resistive MHD

- Time step set using explicit CFL condition of fastest wave: $\Delta t_{\mathrm{cfl}} \leq \frac{\Delta x}{||v + c_f||_1}$
- Pellet Injection: pellet radius r_p = 0.3 mm, injection velocity v_p = 450 m/s, fast magneto-acoustic speed $c_f \approx 10^6$ m/s:
  - *To resolve pellet need $O(10^7)$ time steps*
- Longer time steps (implicit methods) are a practical necessity
- Fixed time step, two-level θ-scheme using a Jacobian-Free Newton-Krylov nonlinear solver [KINSOL]:

$$f(U^n) = U^n - U^{n-1} - \Delta t\,[\theta\, g(U^n) + (1-\theta)\, g(U^{n-1})], \quad g(U) = \nabla\cdot(F^p(U) - F^h(U))$$

  - $\theta = 1 \Rightarrow$ *Backward Euler* $[O(\Delta t)]$; $\theta = 0.5 \Rightarrow$ *Cranck-Nicholson* $[O(\Delta t^2)]$

- Adaptive time step, adaptive order, BDF method for an up to 5th order accurate implicit scheme [CVODE]:

$$f(U^n) = U^n - \sum_{i=1:q} \alpha_{n,i}\, U^{n-i} - \Delta t_n\, \beta_{n,1}\, g(U^{n-1}) - \Delta t_n\, \beta_0\, g(U^n)$$

Time step size and order adaptively chosen based on heuristics balancing accuracy, nonlinear & linear convergence, stability

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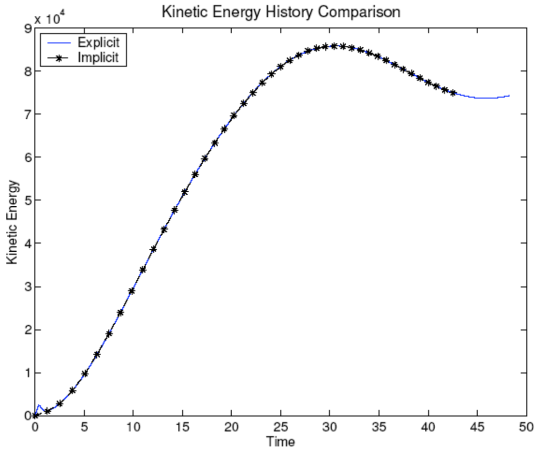
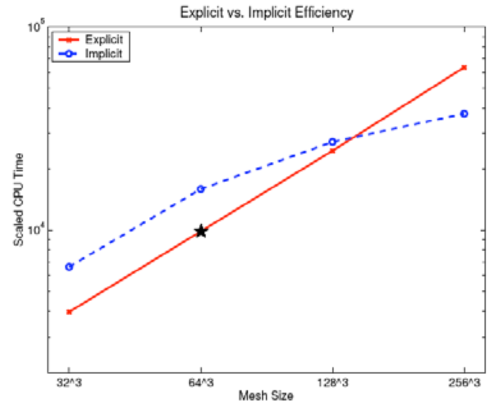
Pellet Injection - Implicit Simulations

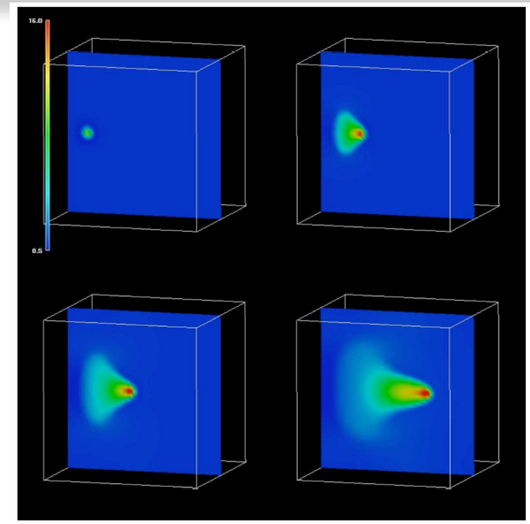
- Choose a model problem with a similar separation of time scales
  (Reyolds et al. JCP 2006)

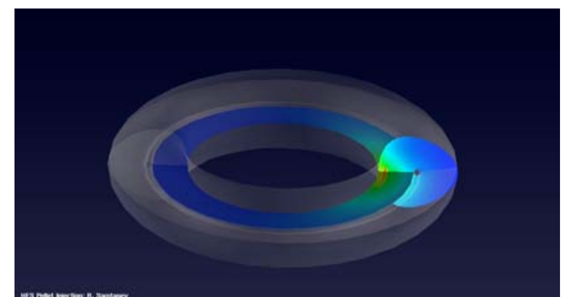


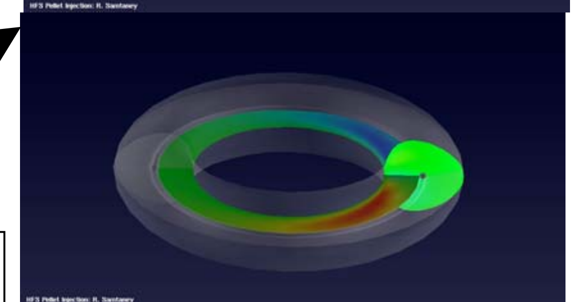
Good agreement between explicit and implicit methods



Implicit (no preconditioners) overtakes explicit method as problem size gets larger.







Implicit simulations in a toroidal geometry. $\Delta t = 100 \Delta t_{explicit}$

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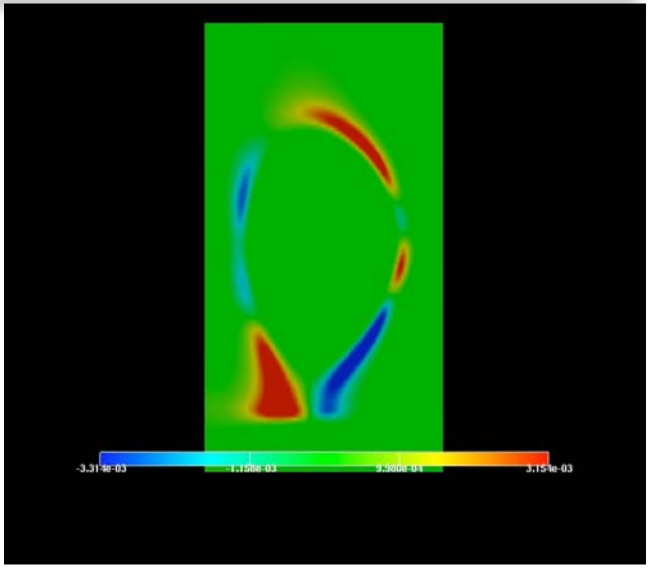
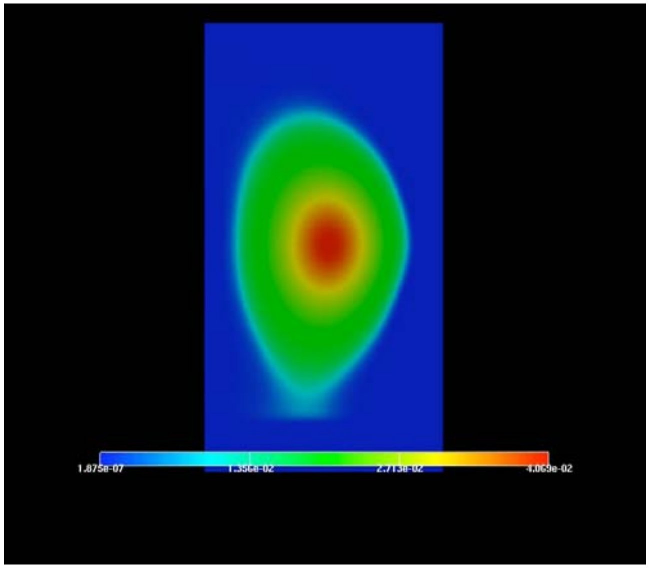
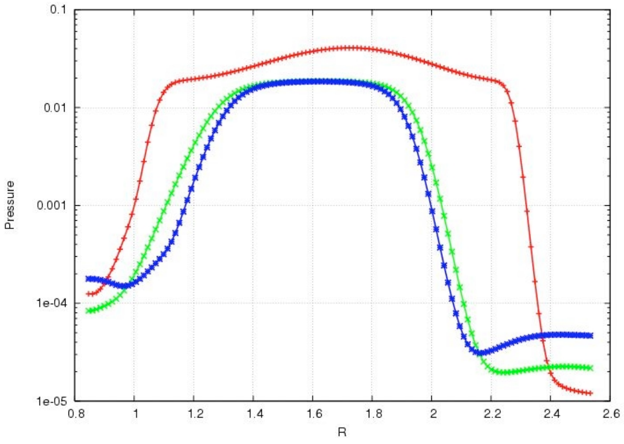
Current Status: ELM Simulations





- Developed a JFNK implicit code to simulate ELMs in (R,ϕ, Z) coordinates
  - *Vacuum modeled as a high resistive cold plasma*
  - *Preconditioners*
    - *Local wave speed decomposition with directional splitting for hyperbolic terms*
    - *Multigrid for diffusion terms*
- Explicit time stepping AMR MHD code
  - *Needs implicit treatment of diffusion terms*
- Upwind method useful to treat large gradients at plasma “edge”



- No real results yet :-(

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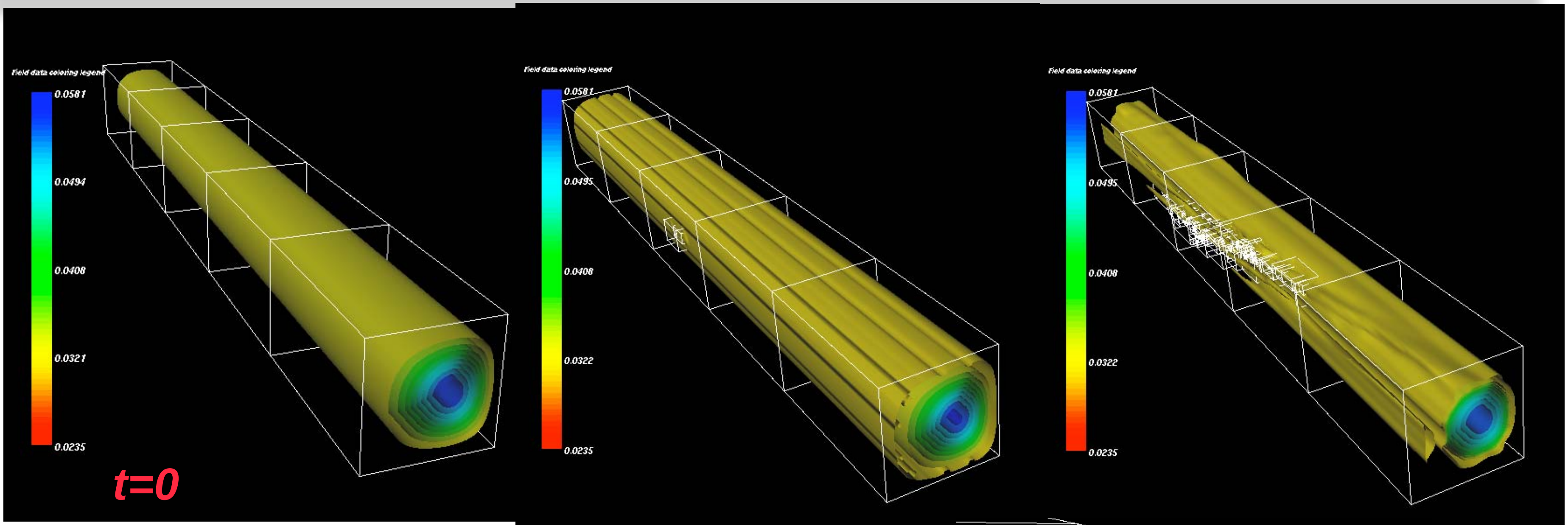
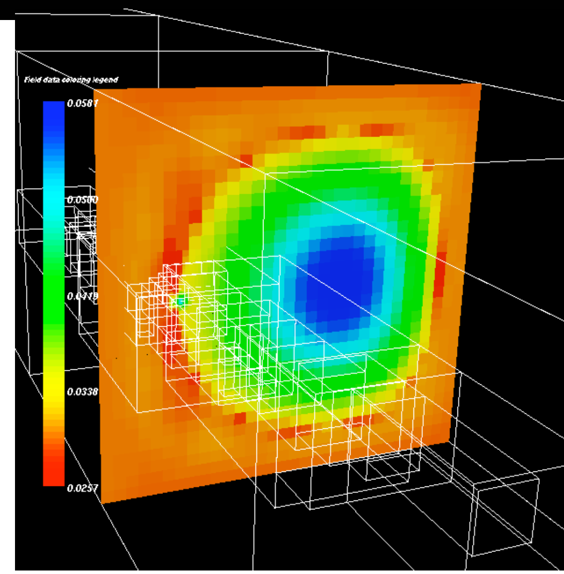
Pellet Injection and ELMs



- Experimentally it is known that pellet injection can induce ELMs in H-mode
- In preliminary simulations, we observe perturbation of outer flux surfaces caused by pellet injection



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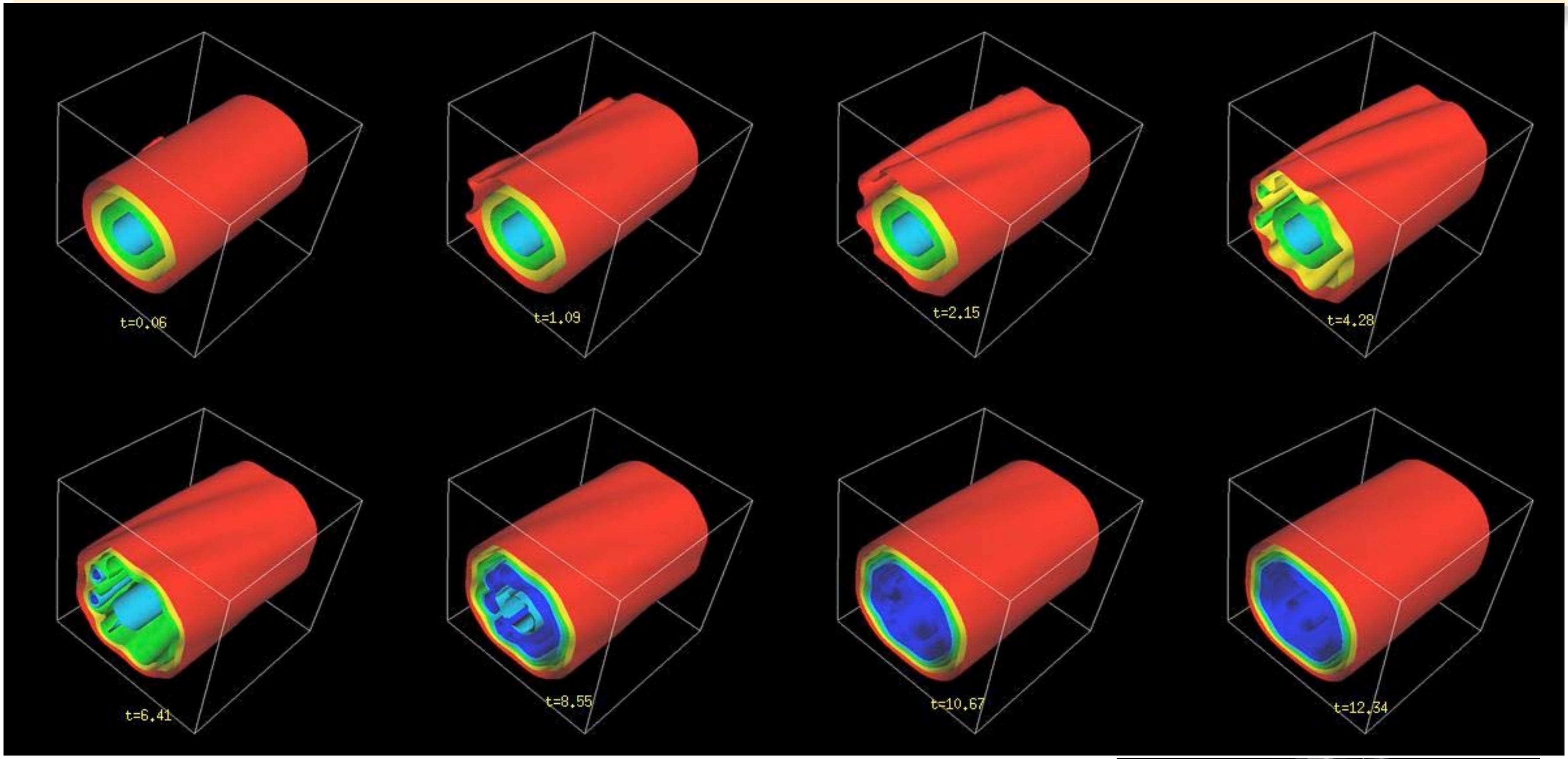
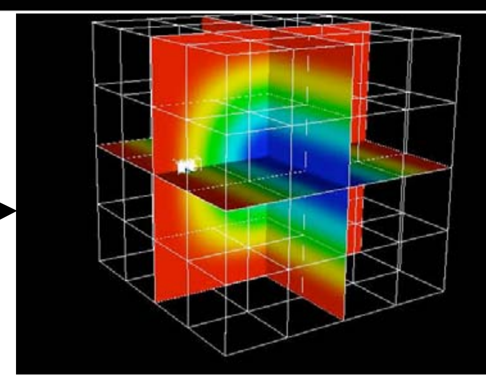
Pellet Injection - Flux Surface Perturbations



AMR Mesh structure
Effective resolution 1024^3



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Summary and Future Plan

- Pellet injection simulations with an AMR MHD code utilizing flux tube geometry
  - *AMR is necessary to resolve detailed local physics*
- Preliminary simulations using a fully implicit Newton Krylov approach presented
- Future plan
  - *Refinement of the models ("atomic physics"- ionization, dissociation) for pellet injection; include anisotropic heat conduction*
  - *Implement pre-conditioning techniques in fully implicit JFNK code*
  - *ELM simulations and pellet induced ELMs*
    - *Couple with TSC for initial conditions (Jardin)*
    - *Semi-implicit AMR simulations and fully implicit JFNK simulations*
  - *<u>Proposed work under SciDAC-2</u>: Combine adaptive and fully implicit methods to manage the wide range of spatial and temporal scales*

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