Tokamak Pellet and Gas Fueling Simulations

Ravi Samtaney

Computational Plasma Physics Group

Princeton Plasma Physics Laboratory

Princeton University

CEMM Meeting

October 22 2005, Denver CO

Acknowledgement: DOE SciDAC Program

Collaborators

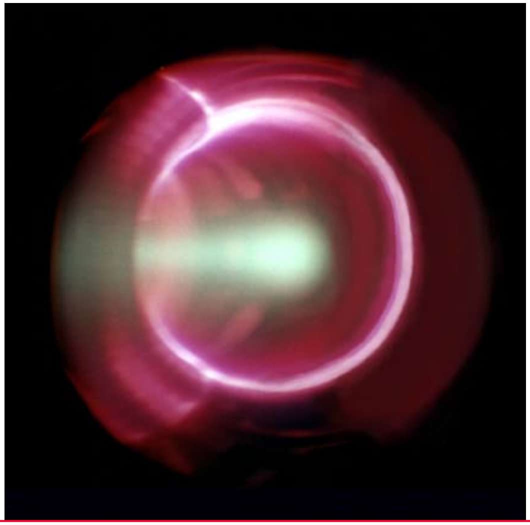
- P. Colella and Applied Numerical Algorithms Group (LBNL)
- S. C. Jardin (PPPL)
- P. Parks (GA)
- Jointly funded CEMM and APDEC SciDAC project. Supported by US DOE Contract No. DE-AC020-76-CH03073
- V. Soukhanouskii (LLNL) - SGI

Outline

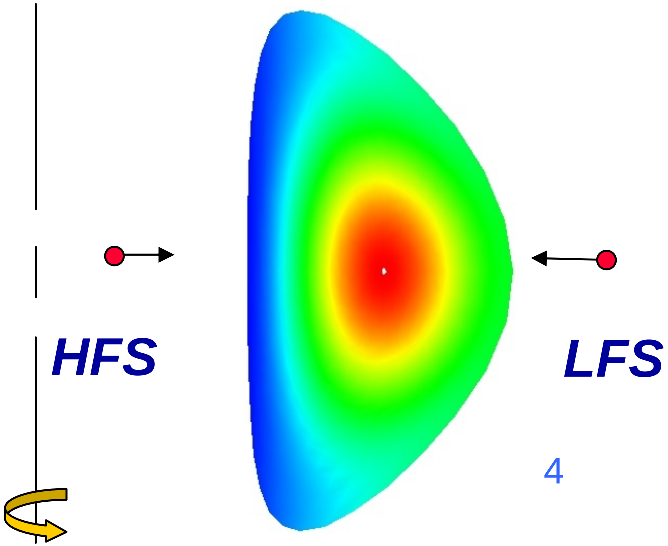
- Introduction and motivation
- Description of physical phenomenon
  - *Spatial and temporal scales*
- Equations and models
- Adaptive mesh refinement (AMR) for shaped plasma in flux-tube coordinates
- Results
  - *HFS vs. LFS Pellet injection*
- Supersonic Gas Injection
  - *Nozzle results*
- Future Directions and Conclusion

Pellet Injection: Objective and Motivation

- 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)*
- Objectives
  - *Develop a comprehensive simulation capability for pellet injection into tokamaks*
  - *Identify the mechanisms for mass distribution during pellet injection in tokamaks*
  - *Quantify the differences between “inside launch” (HFS) and “outside launch” (LFS)*



Pellet injection in TFTR



PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Physical Processes: Description

- Non-local electron transport along field lines rapidly heats the pellet cloud (τ_e).
  - *Frozen pellet encounters hot plasma and ablates rapidly*
  - *Neutral gas surrounding the solid pellet is ionized*
  - *Ionized, but cool plasma, continues to get heated by electrons*
  - *A high β "plasmoid" is created*
- Ionized plasmoid expands
  - *Fast magnetosonic time scale τ_f.*
- Pellet mass moves across flux surfaces τ_a.
  - *So-called "anomalous" transport across flux surfaces is accompanied by reconnection*
- Pellet mass expands along field lines τ_c.
  - *Pellet mass distribution continues along field lines until pressure equilibration*
- Pellet lifetime τ_p

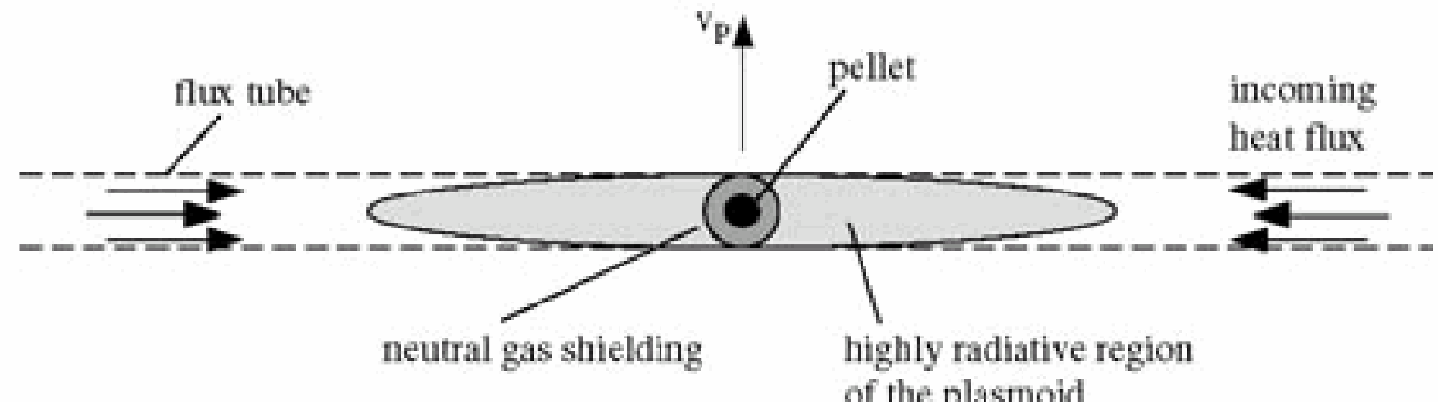


Figure from Müller et al., Nuclear Fusion 42 (2002)

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}

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Related Work - Local vs. Global Simulations

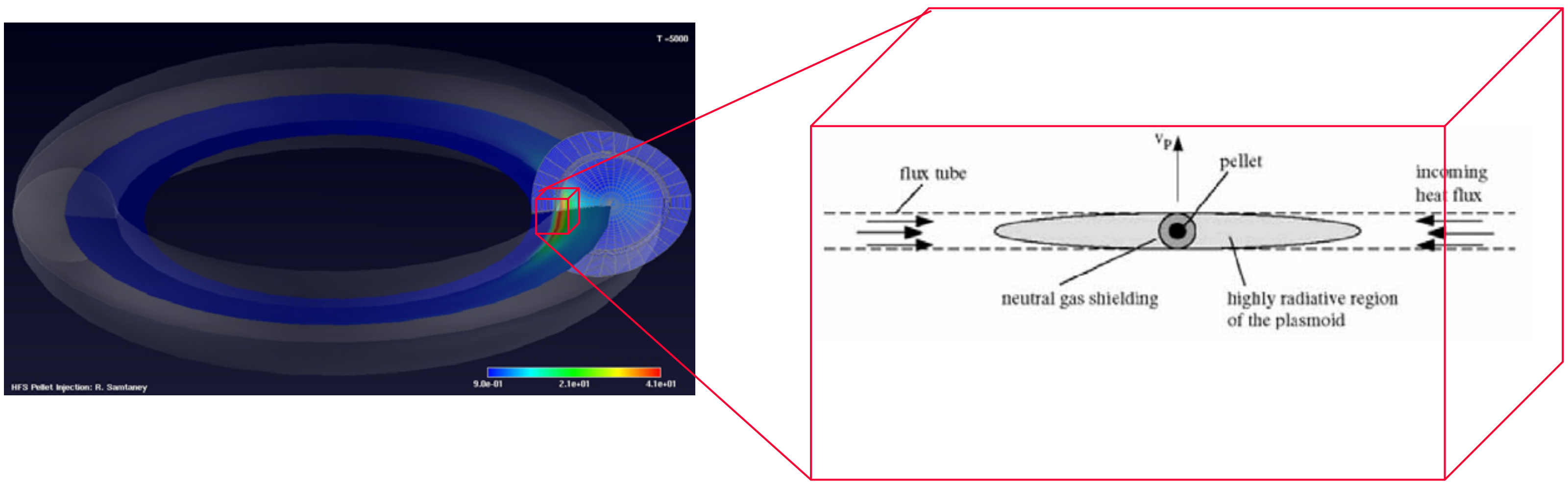
- Earliest ablation model by Parks (Phys. Fluids 1978)
- Detailed multi-phase calculations in 2D of pellet ablation (MacAulay, PhD thesis, Princeton Univ 1993, Nuclear Fusion 1994)
- Detailed 2D Simulations of pellet ablation by Ishizaki, Parks et al. (Phys. Plasmas 2004)
  - *Included atomic processes – ablation, dissociation, ionization, pellet fluidization and distortion, and Semi-analytical model for electron heat flux from background plasma*
- In above studies, the domain of investigation was restricted to only a few cm around the pellet
  - *The magnetic field was **static***

- 3D Simulations by Strauss and Park (Phys. Plasmas, 1998)
  - *Solve an initial value problem. Initial condition consisted of a density "blob" to mimic a fully ablated pellet cloud which, compared with device scales, was relatively large due to resolution restrictions*
  - *No motion of pellet modeled*
- 3D Adaptive Mesh Simulation of pellet injection by Samtaney et al. (Comput. Phys. Comm, 2004)

PPPL PRINCETON PLASMA PHYSICS LABORATORY

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 large range of scales in the problem

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Equations and Models

- Single fluid resistive MHD equations in conservation form

$$\frac{\partial U}{\partial t}+\frac{1}{R}\frac{\partial RF}{\partial R}+\frac{\partial H}{\partial z}+\frac{1}{R}\frac{\partial G}{\partial \phi}=S+\frac{1}{R}\frac{\partial RF_D}{\partial R}+\frac{\partial H_D}{\partial z}+\frac{1}{R}\frac{\partial G_D}{\partial \phi}+S_D+S_{pellet}$$

Hyperbolic terms

Diffusive terms

Density: Ablation
Energy :Electron heat flux

- Additional constraint r¢ **B** =0

- Mass source is given using the ablation model by Parks and Turnbull (Phy. Plasmas 1978) and Kuteev (Nuclear Fusion 1995)

$$\frac{dN}{dt}=-4\pi r_p^2\frac{dr_p}{dt}2n_m=1.12\times10^{16}n_e^{0.333}T_e^{1.64}r_p^{1.33}M_i^{-0.333}$$

  – *Above equation uses cgs units*

- Abalation occurs on the pellet surface $S_n=\dot{N}\delta(x-x_p)$
  – *Regularized as a truncated Gaussian of width 10 r_p*
  – *Pellet shape is spherical for all t*
  – *Pellet trajectory is specified as either HFS or LFS*
  – *Monte Carlo integration to determine average source in each finite volume*

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Electron Heat Flux Model

- Semi-analytical Model by Parks et al. (Phys. Plasmas 2000)
  - *Assumes Maxwellian electrons and neglects pitch angle scattering*

$$-\nabla \cdot q_e = \frac{q_\infty n}{\tau_\infty}\left[g(u_+) + g(u_-)\right]$$

Where $g(u) = u^{\frac{1}{2}} K_1(u^{\frac{1}{2}})/4$, $u_\pm = \frac{\tau_\pm}{\tau_\infty}$ *and* $\tau_\pm = \pm\int_{\mp\infty}^{\boldsymbol{x}} n(s)ds$

- Solve for opacities as a "steady-state" solution to an advection-reaction equation $\frac{d\tau}{ds} = n(\boldsymbol{x})$ $\hat{b}\cdot\nabla\tau = n(\boldsymbol{x})$
  - *Upwind method*
    - *Advection velocity is **b***

$$\frac{d\tau}{d\zeta} + \hat{\boldsymbol{b}}\cdot\nabla\tau = n(\boldsymbol{x})$$

- Ansatz for energy conservation
  - *Sink term on flux surface outside cloud*

$$-\nabla \cdot q_e = \frac{1}{V_\psi - V_{cloud,\psi}}\int_{cloud,\psi} \nabla . q_e$$

Curvilinear coordinates for shaped plasma

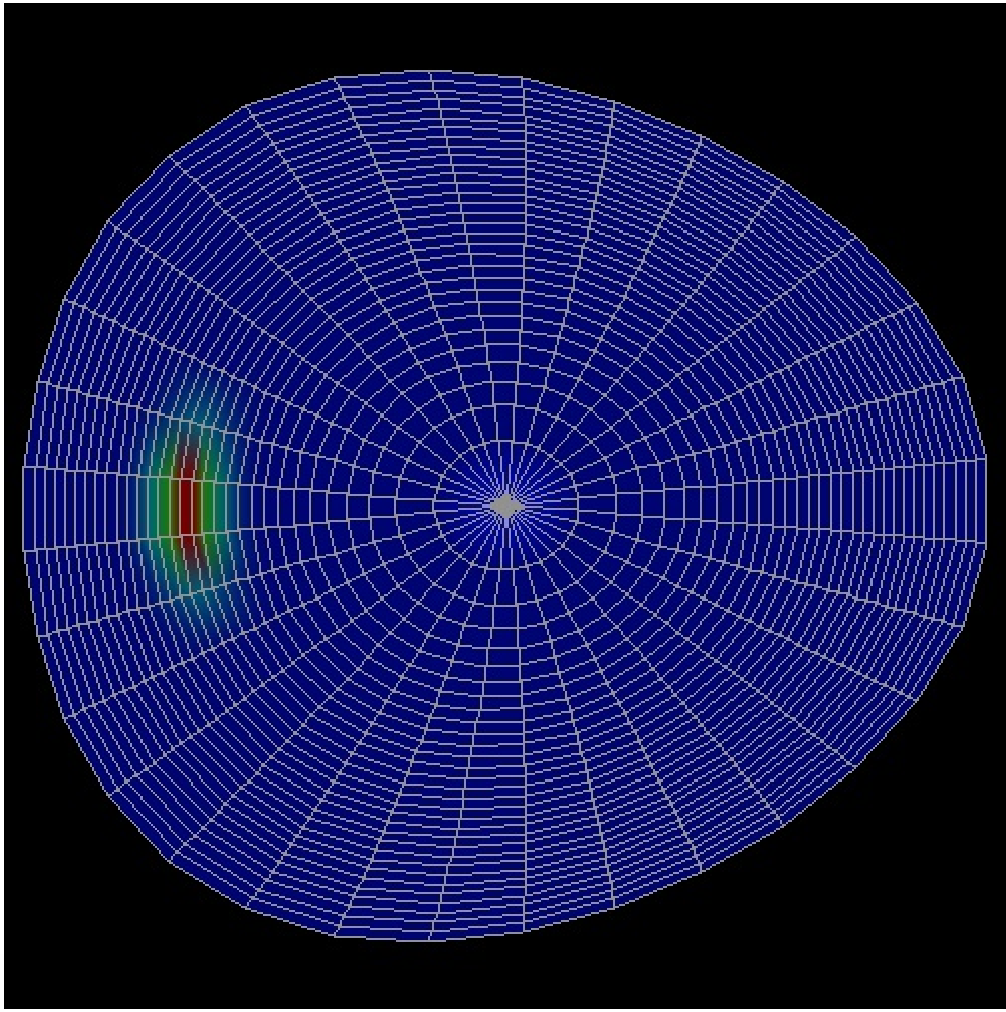
- Adopt a flux-tube coordinate system (flux surfaces ψ are determined from a separate equilibrium calculation)
  - *R´ R (ξ, η), and Z´ Z (ξ, η)*
  - ξ ´ ξ *(R,Z), and* η ´ η*(R,Z)*
  - Flux surfaces: $\psi = \psi_0 \xi$
  - ϕ *coordinate is retained as before*
- Equations in transformed coordinates

$$\frac{\partial UJ}{\partial t} + \frac{1}{R}\frac{\partial R\tilde{F}}{\partial \xi} + \frac{1}{R}\frac{\partial R\tilde{H}}{\partial \eta} + \frac{1}{R}\frac{\partial \tilde{G}}{\partial \phi} = \tilde{S}$$

$$\tilde{F} = J(\xi_R F + \xi_z H) = z_\eta F - R_\eta H,$$

$$\tilde{H} = J(\eta_R F + \eta_z H) = -z_\xi F + R_\xi H,$$

$$\tilde{G} = JG, \ \tilde{S} = JS.$$



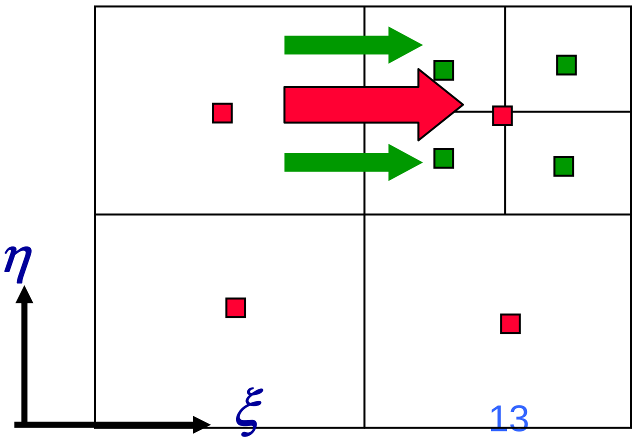
PRINCETON PLASMA PHYSICS LABORATORY

Numerical method

- Finite volume approach
- Explicit second order or third order TVD Runge-Kutta time stepping
- The hyperbolic fluxes are evaluated using upwinding methods
  - *seven-wave Riemann solver*
  - *Harten-Lee-vanLeer (HLL) Method (SIAM Review 1983)*
- Diffusive fluxes computed using standard second order central differences
- The solenoidal condition on B is imposed using the *Central Difference* version of <u>Constrained Transport</u> (Toth JCP 161, 2000)
  - ***r ¢ B*** *≠ 0 on coarse mesh cells adjacent to coarse-fine interfaces*
- **<u>Initial Conditions:</u>** Express B=1/R(φ **£ r** ψ + g(ψ) φ) ≠ fnc(φ). Initial state is an MHD equilibrium obtained from a Grad-Shafranov solver.
- **<u>Boundary Conditions</u>**: Perfectly conducting for $\xi=\xi_o$, zero flux (due to zero area) at $\xi=\xi_i$, and periodic in η and φ

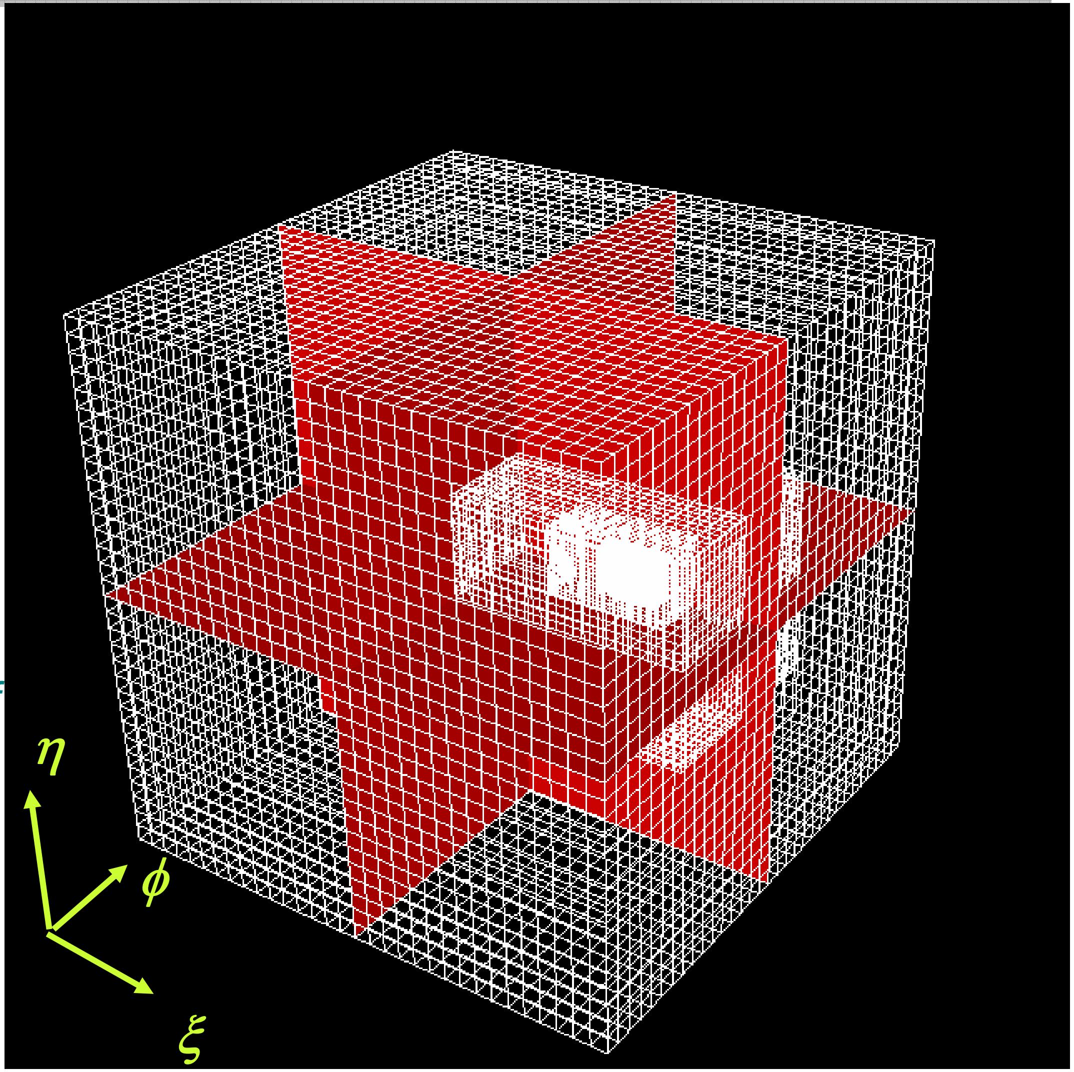
Adaptive Mesh Refinement with Chombo

- ***Chombo*** is a collection of C++ libraries for implementing block-structured adaptive mesh refinement (AMR) finite difference calculations (http://www.seesar.lbl.gov/ANAG/chombo)
  - *(Chombo is an AMR developer's toolkit)*
- Adaptivity in both space and time
- Mesh generation: necessary to ensure volume preservation and areas of faces upon refinement
- Flux-refluxing step at end of time step ensures conservation

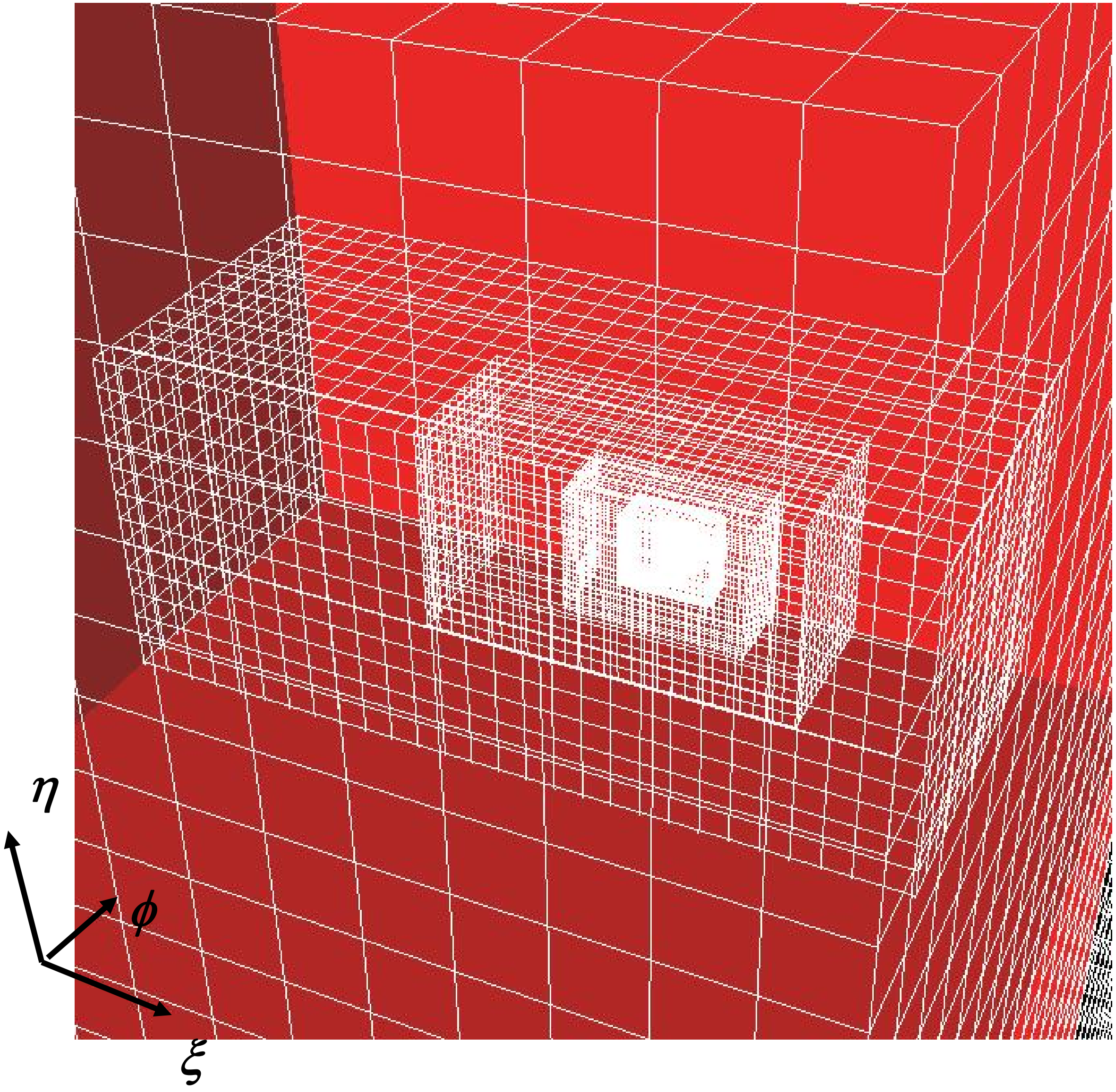


Pellet Injection: AMR

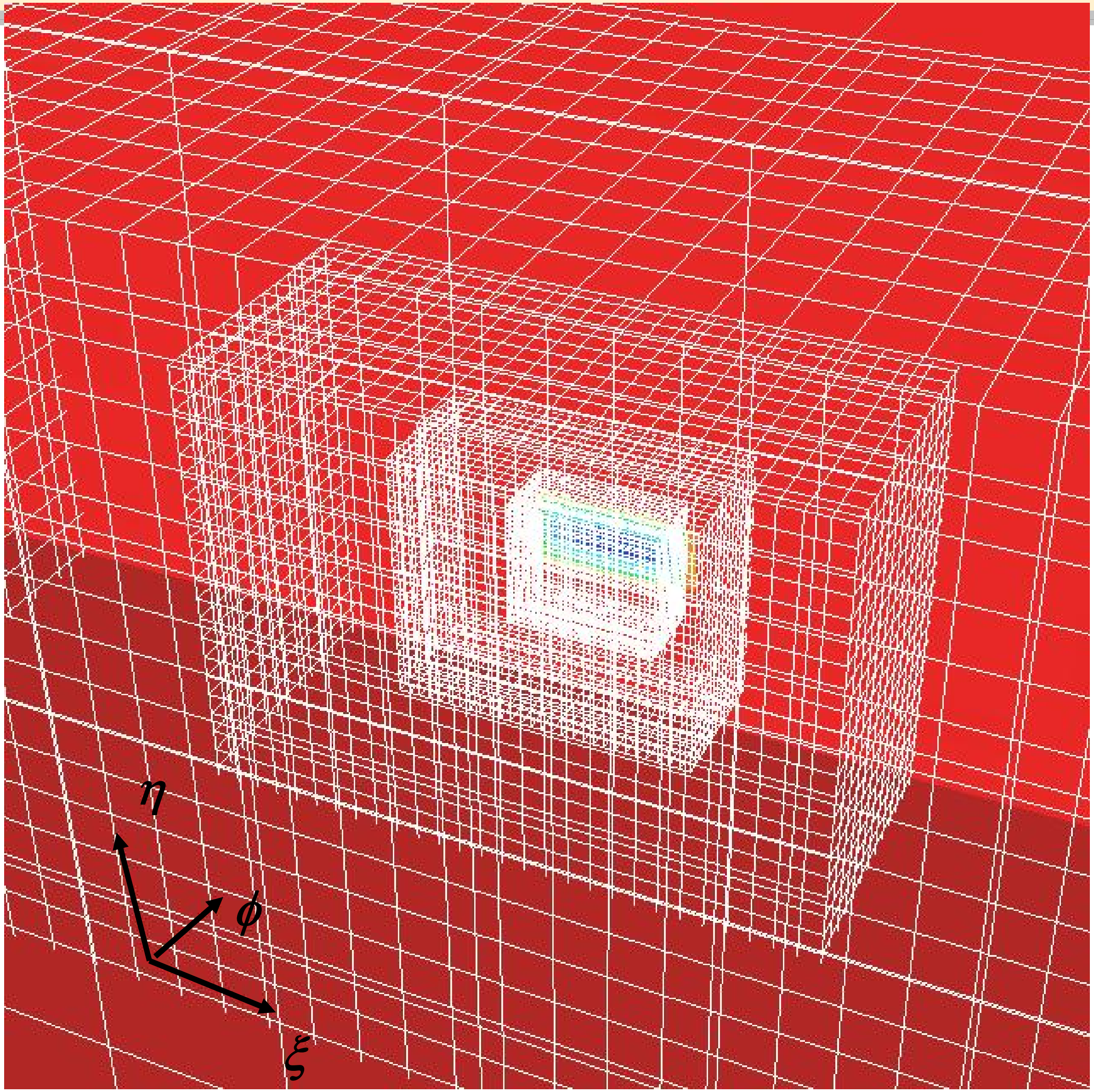
- Meshes clustered around pellet
- Computational space mesh structure shown on right
- Mesh stats
  - *32^3 – base mesh with 5 levels, and refinement factor 2*
  - *Effective resolution: 1024^3*
  - *Total number of finite volume cells:113408*
  - *Finest mesh covers 0.015 % of the total volume*
  -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



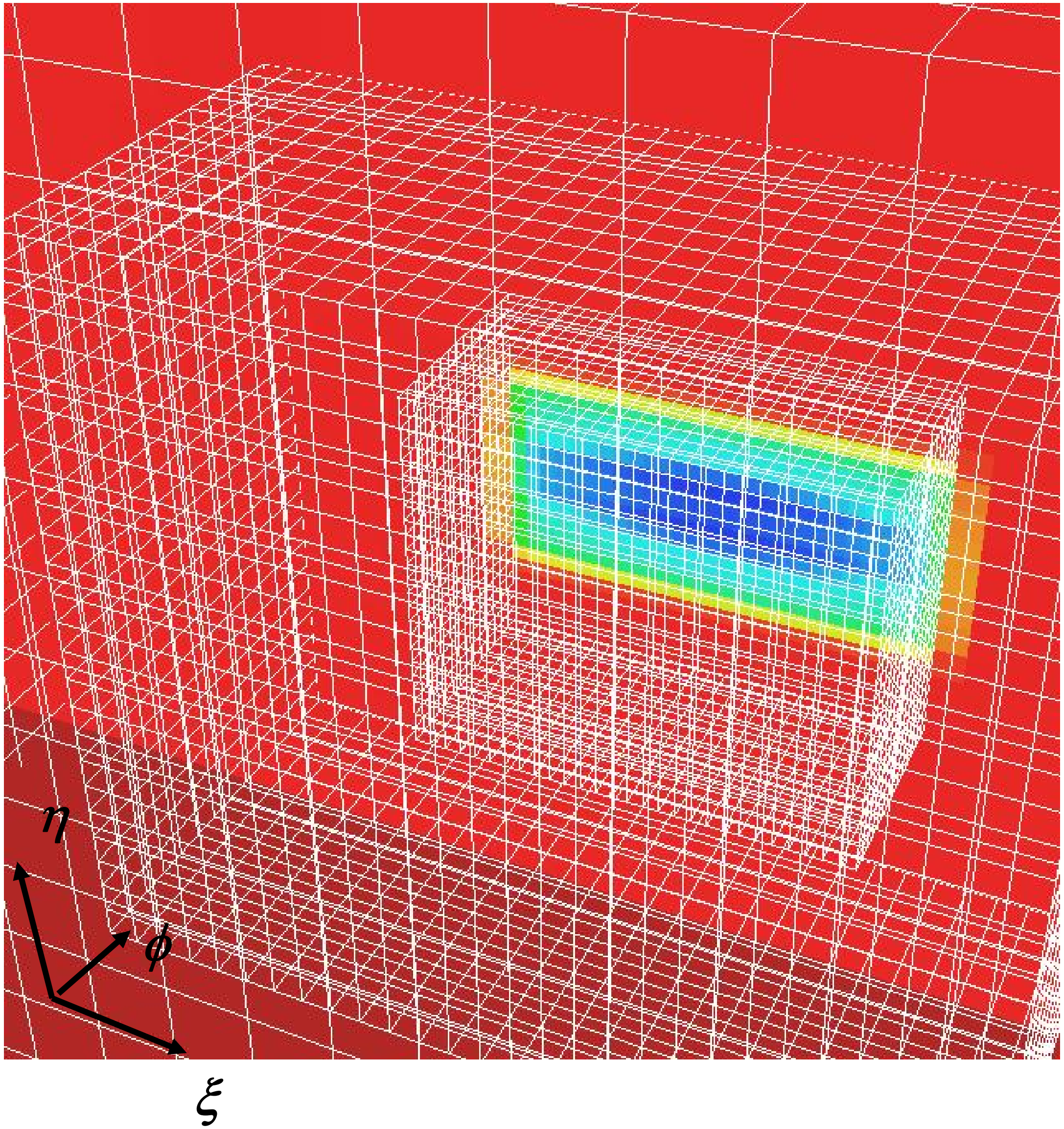
Pellet Injection: Zoom into Pellet Region



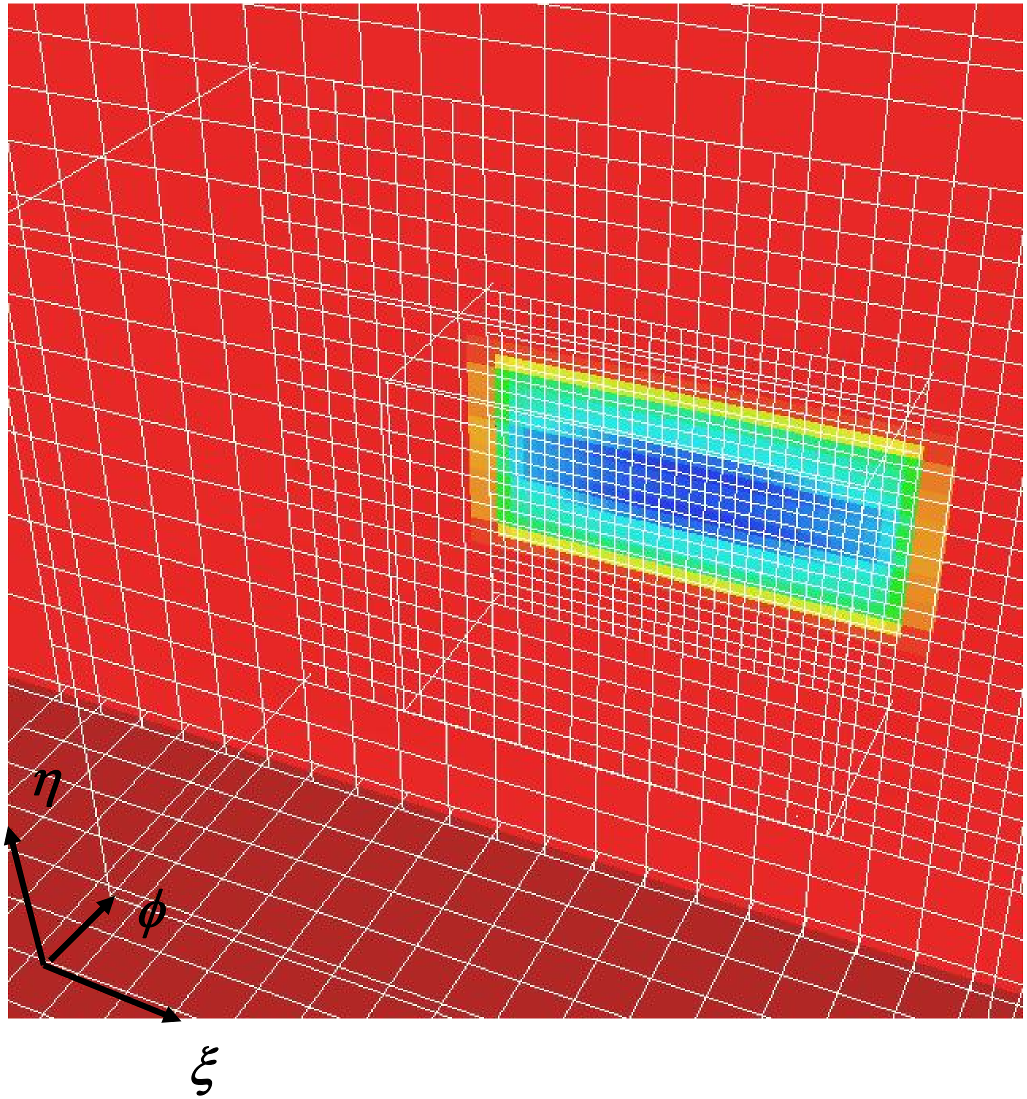
Pellet Injection: Further Zooming In



Pellet Injection: Pellet in Finest Mesh

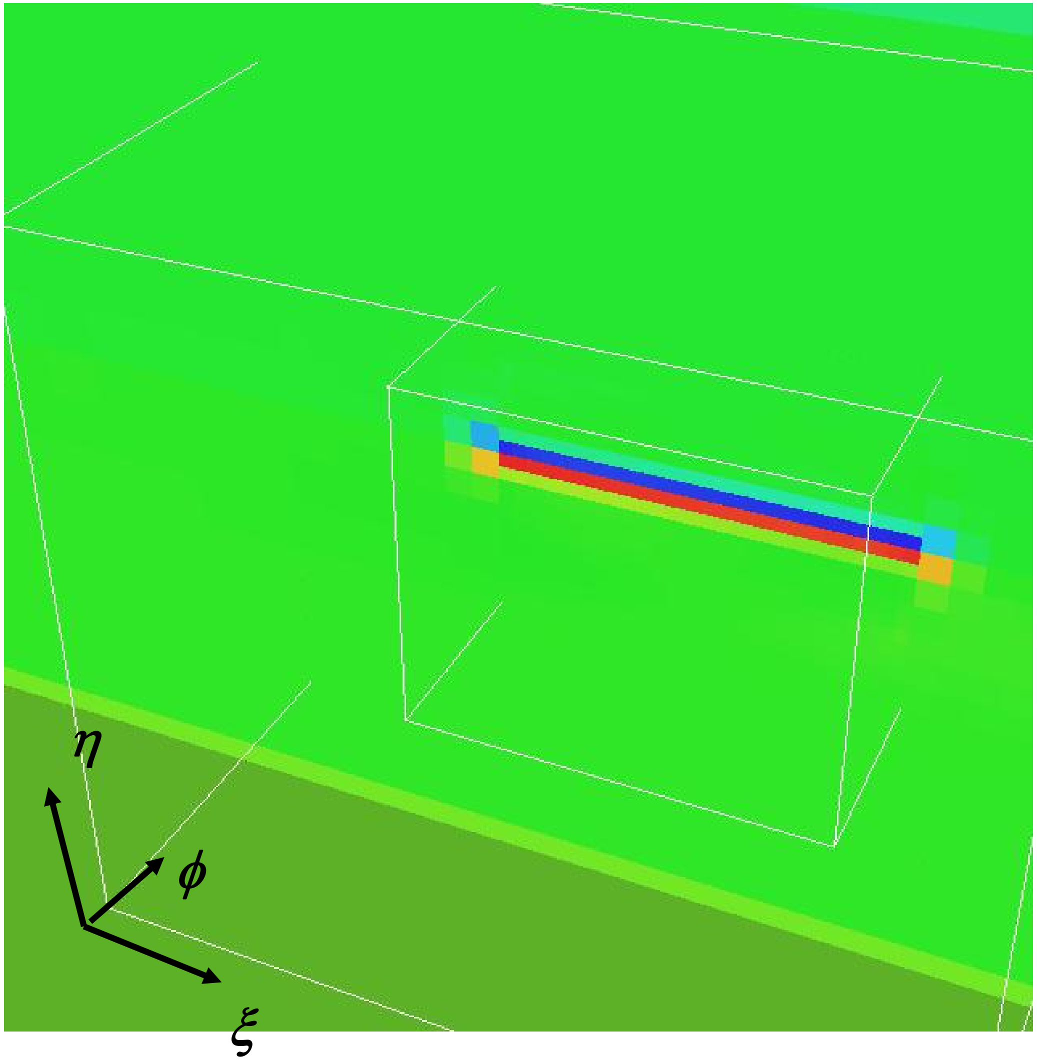


Pellet Injection: Pellet Cloud Density



Pellet Injection: Zoom in on B-field

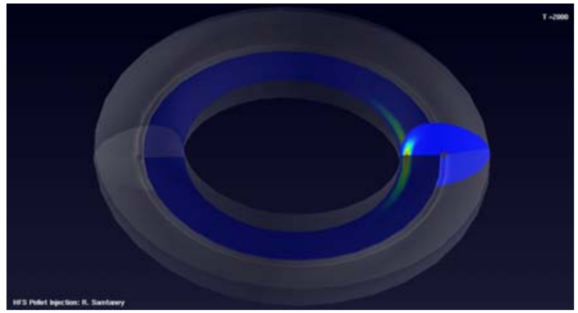
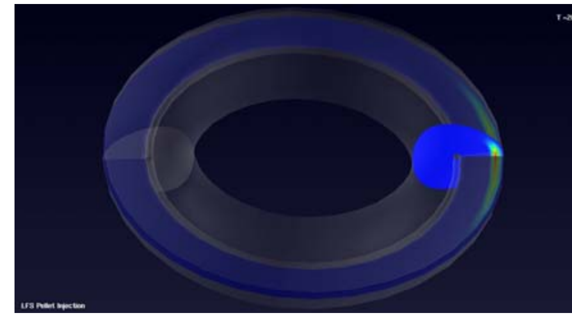
- Radial component of **B is initially zero near pellet**
- Classical anti-parallel morphology indicative of reconnection
- B -field of field close to the pellet is distorted



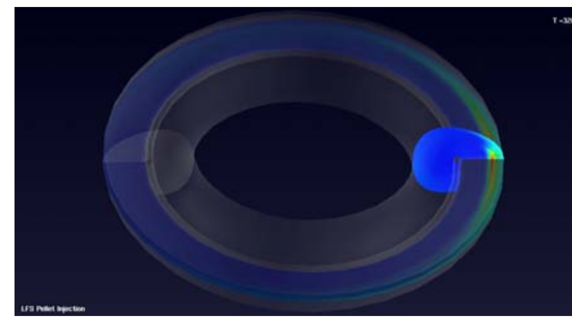
PPPL PRINCETON PLASMA PHYSICS LABORATORY

Results - HFS vs. LFS

B_T = 0.375T
n_0=1.5£ $10^{19}/m^3$
T_{e1}=1.3Kev
β=0.05
R_0=1m, a=0.3 m
Pellet: r_p=1mm,
v_p=1000m/s

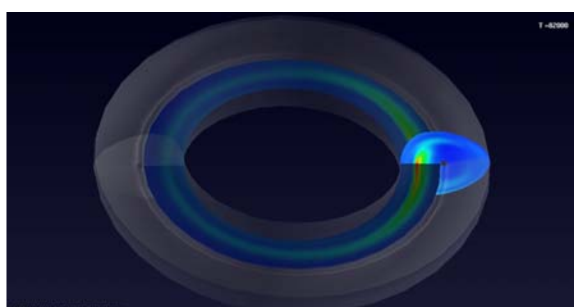
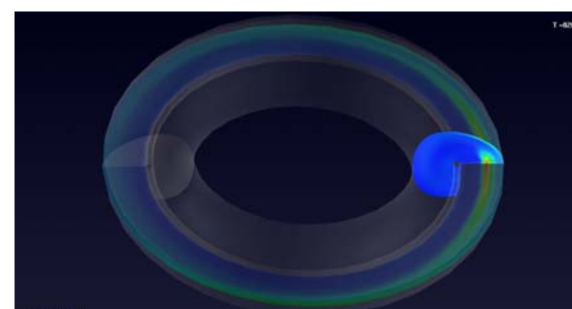



t=7


QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

ρ

t=100

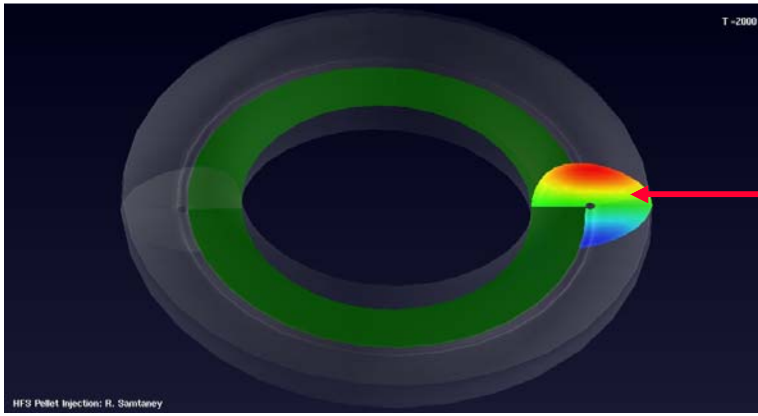



t=256

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Results - B-field Distortion

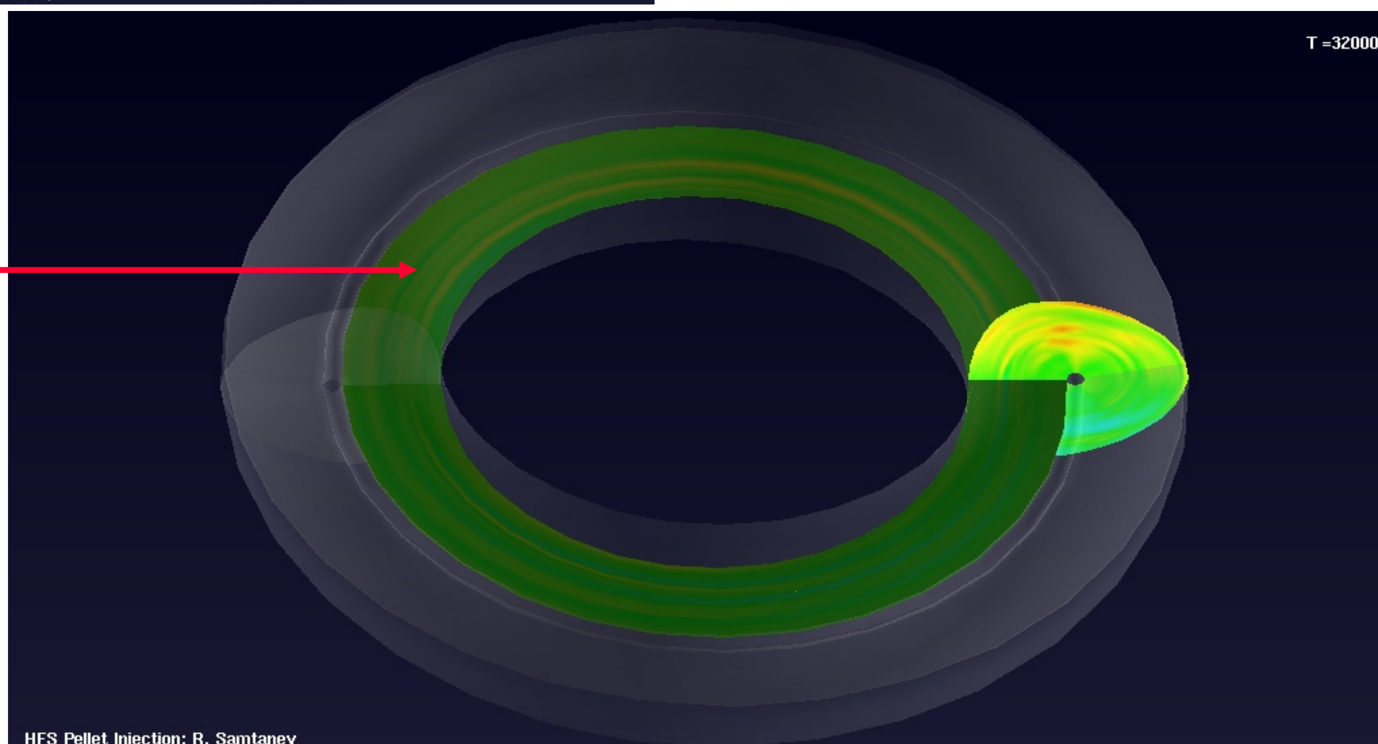
B_R



Initial Equilibrium

t=6.2

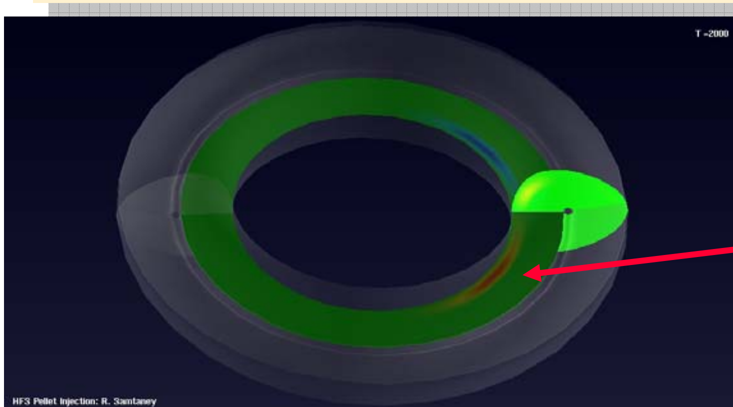
Striations



t=98

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

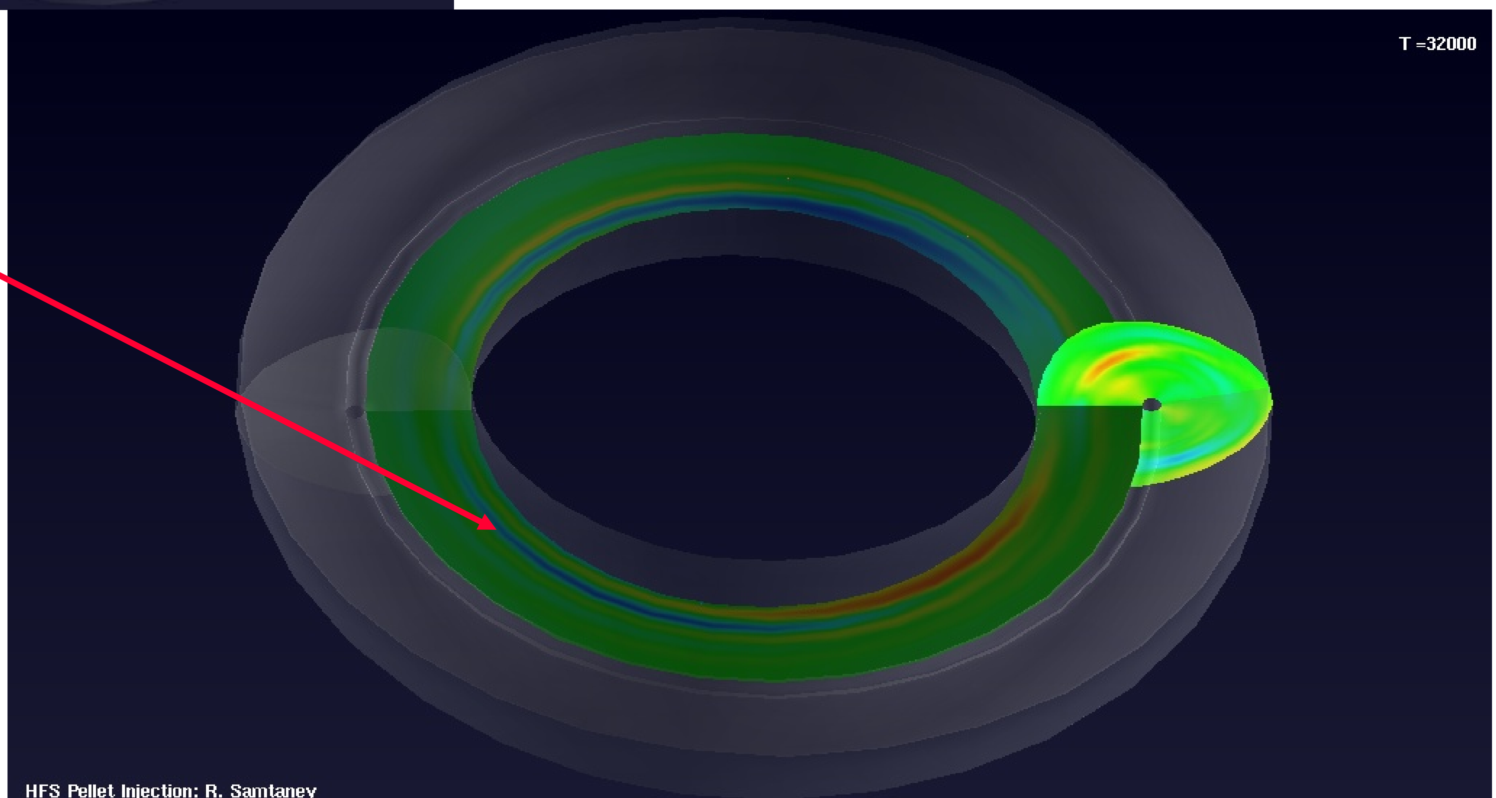
Results - Velocity u_ϕ



Early expansion along field lines

t=6.2

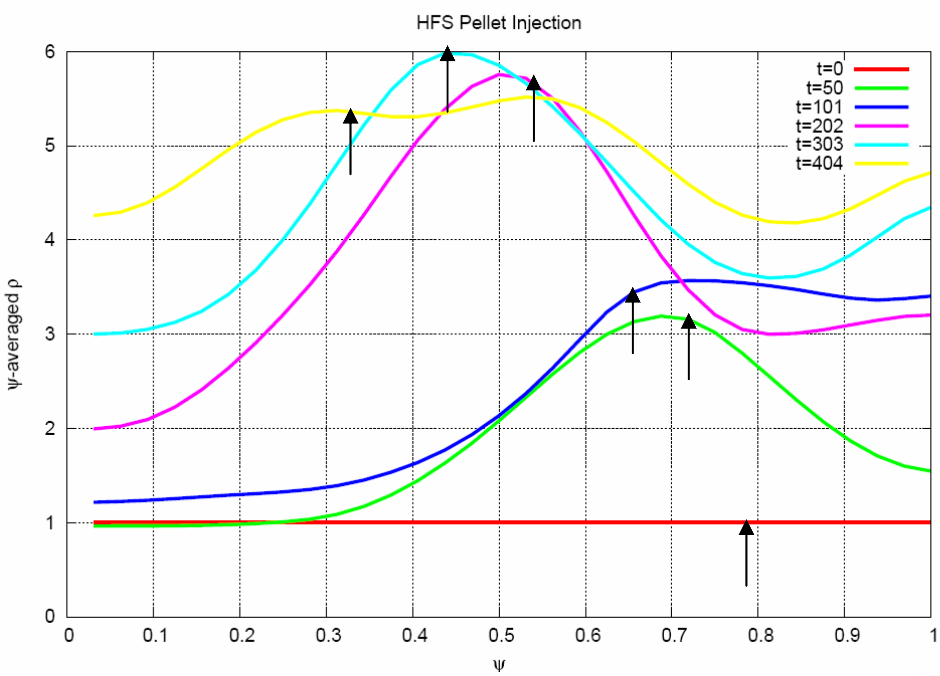
Striations

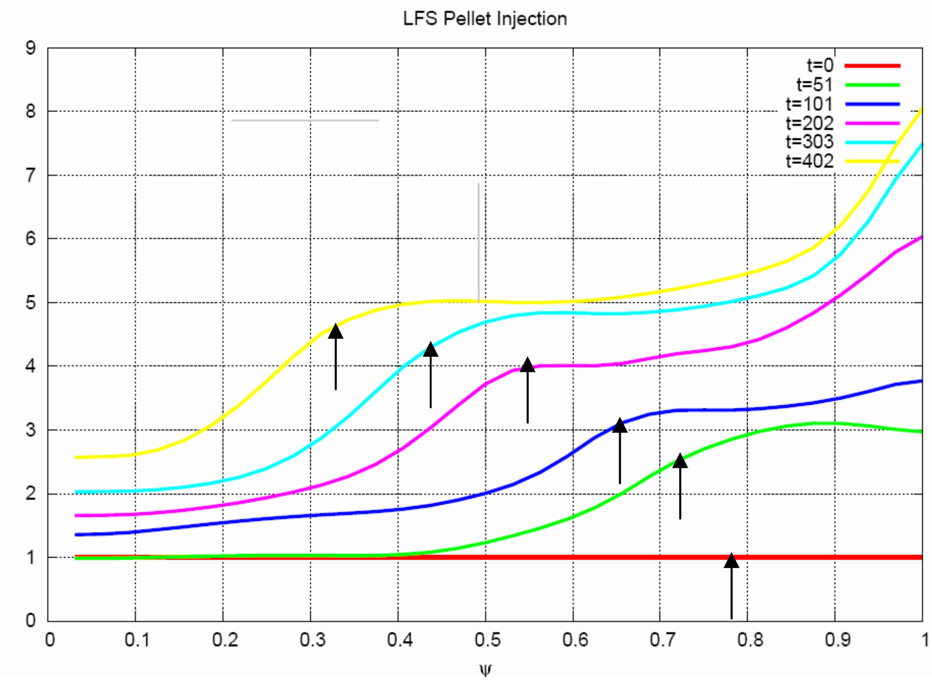


t=98

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

HFS vs. LFS - Average Density Profiles



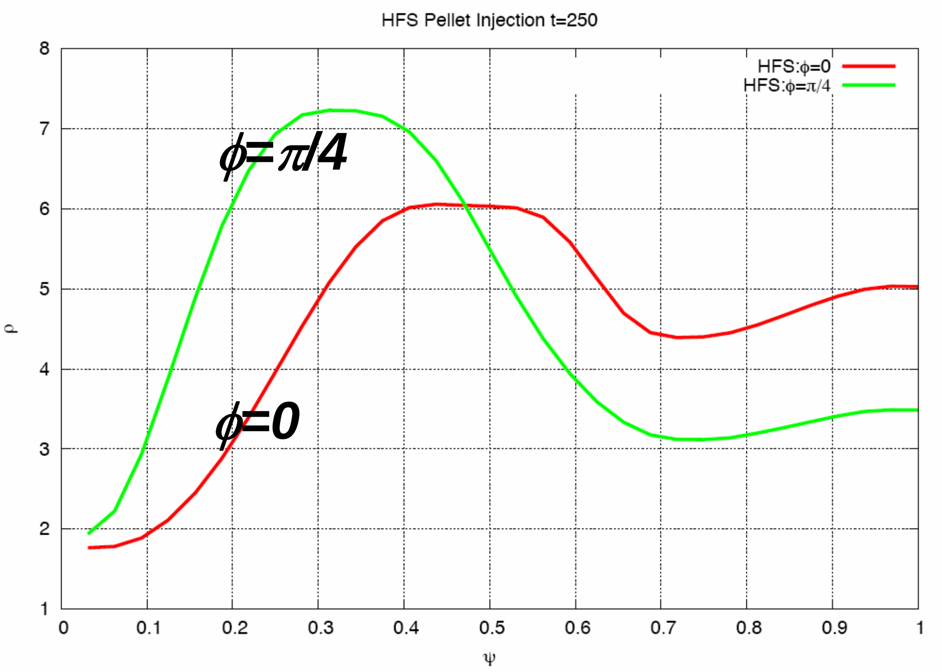


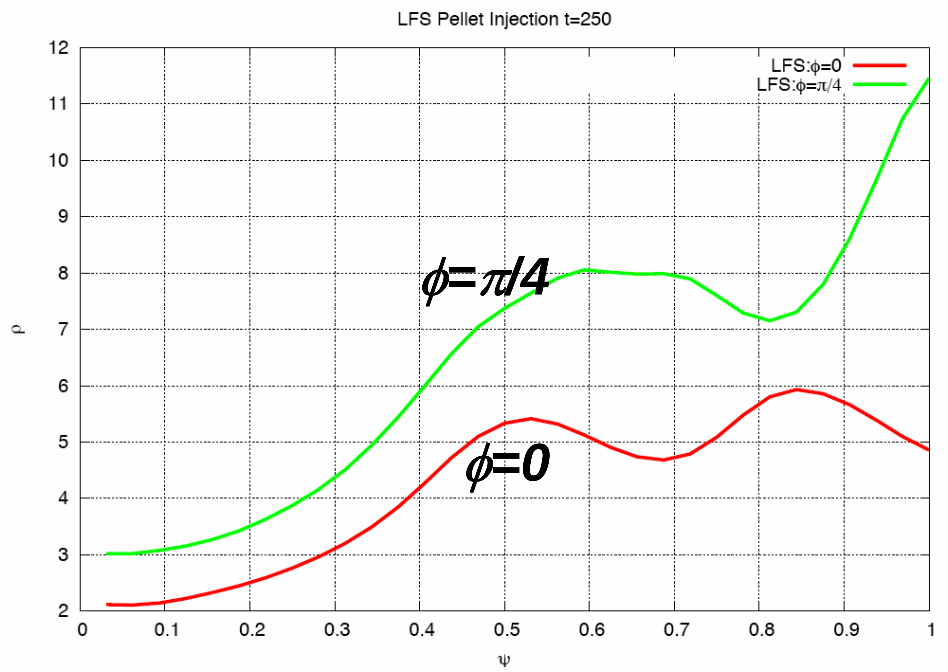
HFS Pellet injection shows better core fueling than LFS

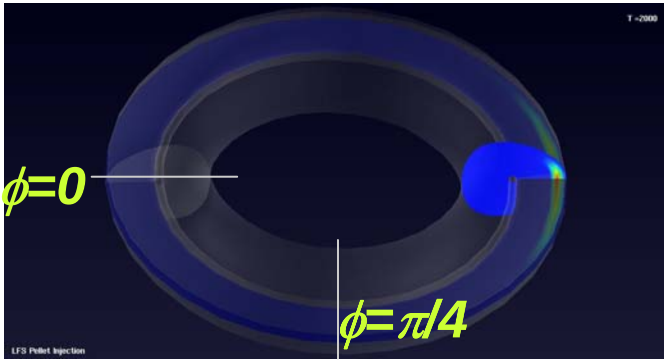
Arrows indicate average pellet location

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

HFS vs. LFS: Instantaneous Density Profiles



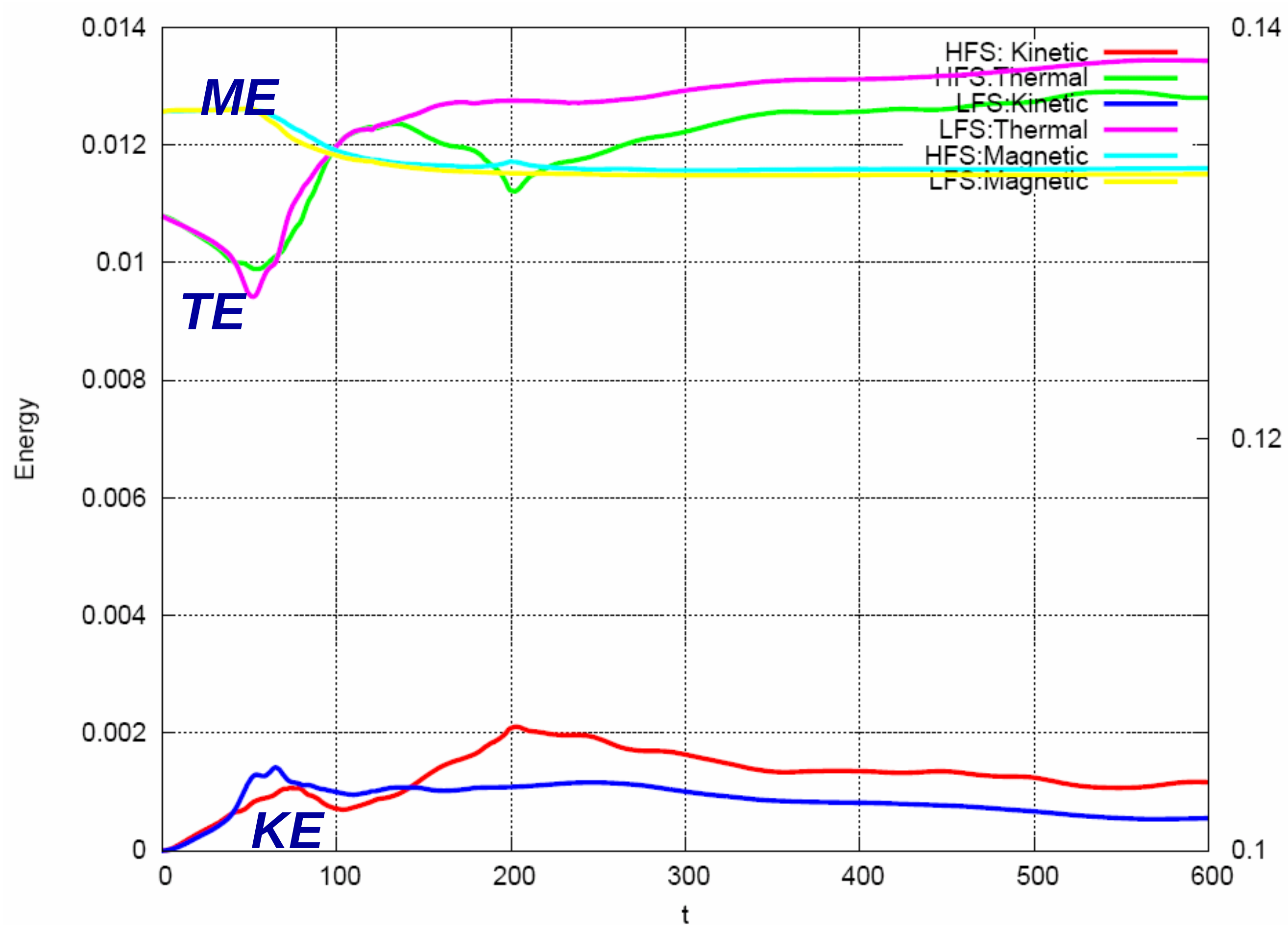




Radially outward shift in both cases indicates higher fueling efficiency for HFS

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Results – Energy budget



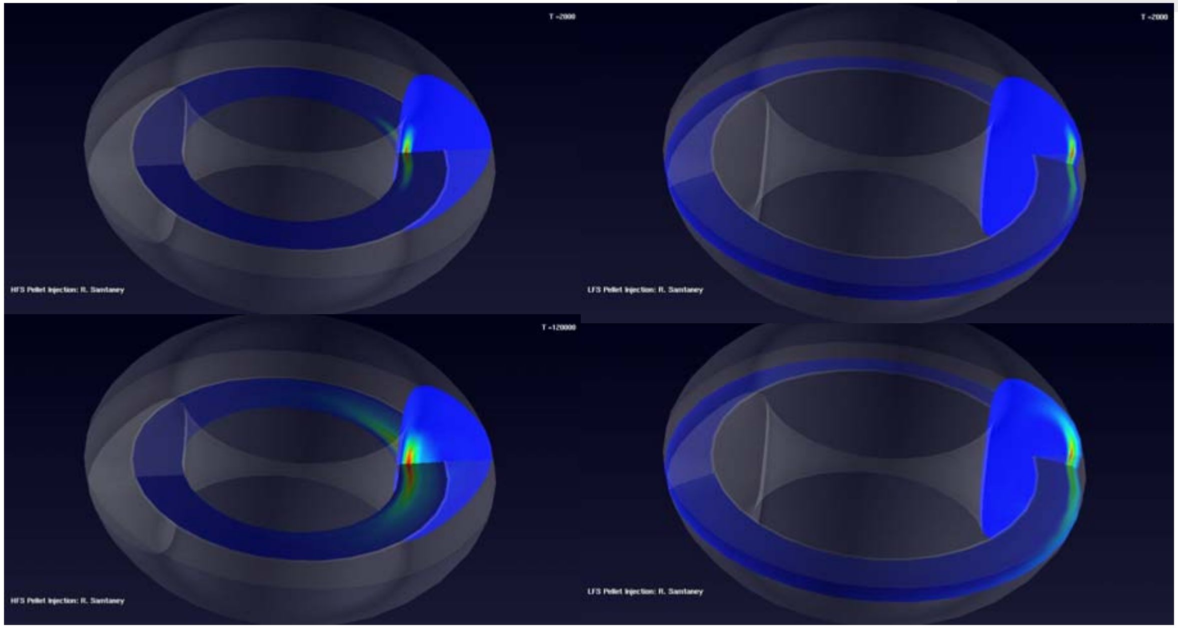
For 0<t<120: Rapid redistribution of thermal energy by electrons

Kinetic energy increases at expense of thermal energy

Thermal energy increases due to reconnection

Results ("DIII-D"): HFS vs. LFS

- B_T= 1T
- T_{e1}=4-6Kev
- n_o=1.5 £ $10^{19}/m^3$
- β=0.036
- R_0=1.7m a=0.55m
- Pellet: radius r_p=1mm, velocity v_p=1000m/s



Larger core fueling for HFS than LFS

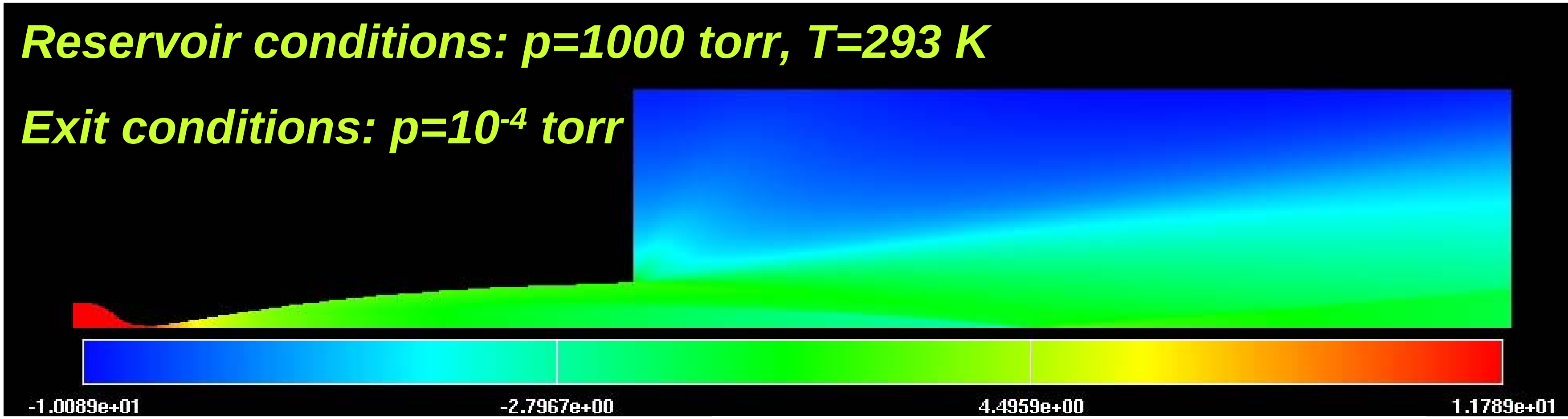
HFS ***LFS***

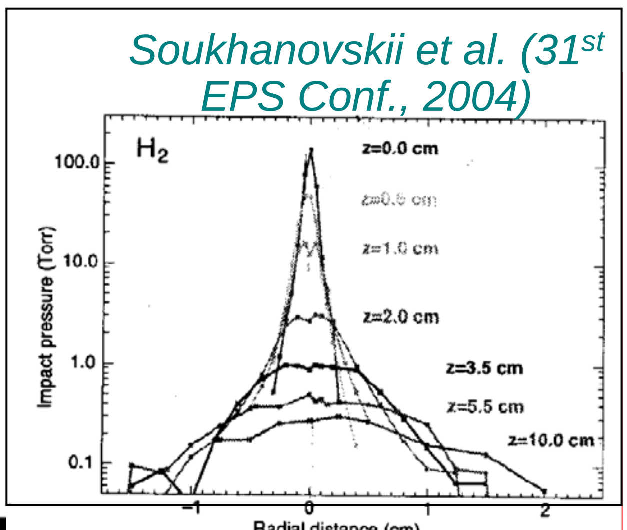
Supersonic Gas Injection

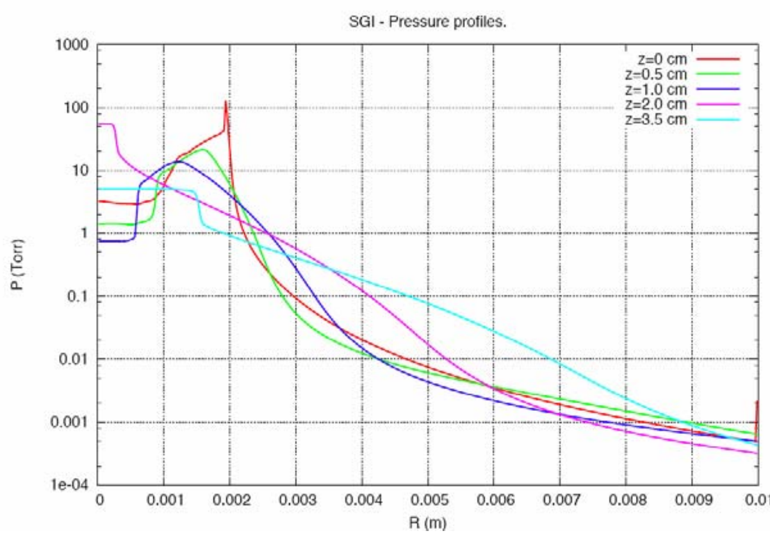
- New method for refueling
- SGI Experiments on NSTX
  - *Scaled down nozzle designed for hypersonic flows (M=8)*
- Computational modeling with “Nozzle” code
  - *Equations in conservative form*
  - *Finite volume approach*
  - *Explicit time stepping approach*
  - *Second order accurate in space and time*
  - *Efficient parallel and scalable implementation*
  - *Includes ionization model (Saha eqn. for equilibrium ionization)*
  - *Handle arbitrary moving or static geometries in 2D and axisymmetry*
    - *Also extensible to 3D static boundaries*
    - *Level-set approach to handle arbitrary geometry*

Nozzle code: Results

- Nozzle (Specified inflow. Outflow BC is characteristic)

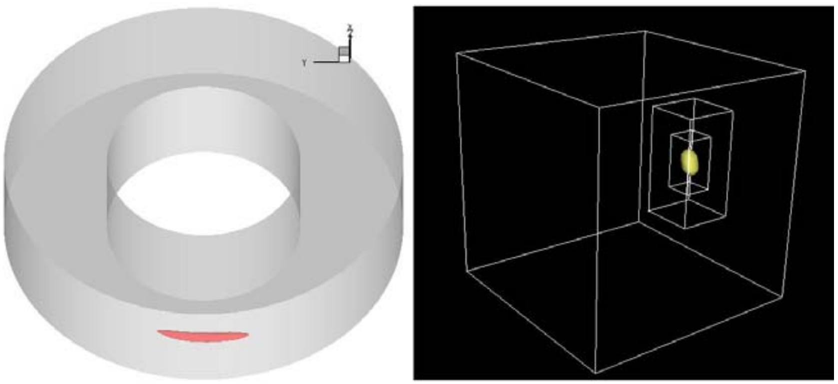




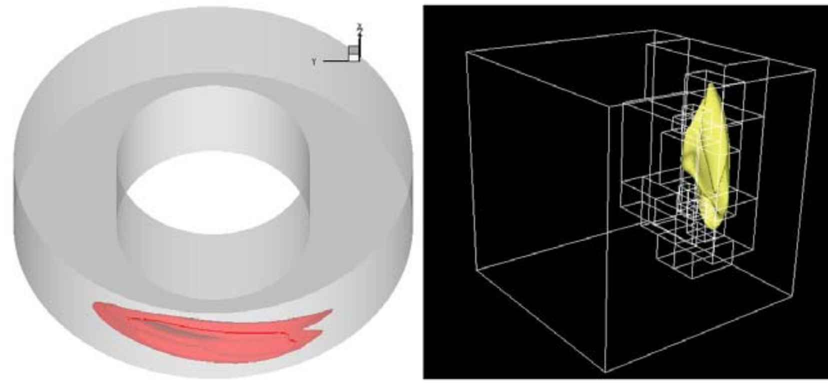


Boundary layer effects may be important in experiments

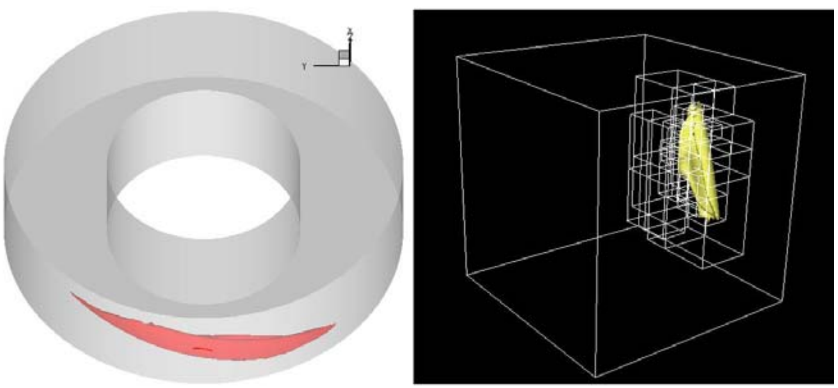
Pellet Injection: LFS Launch



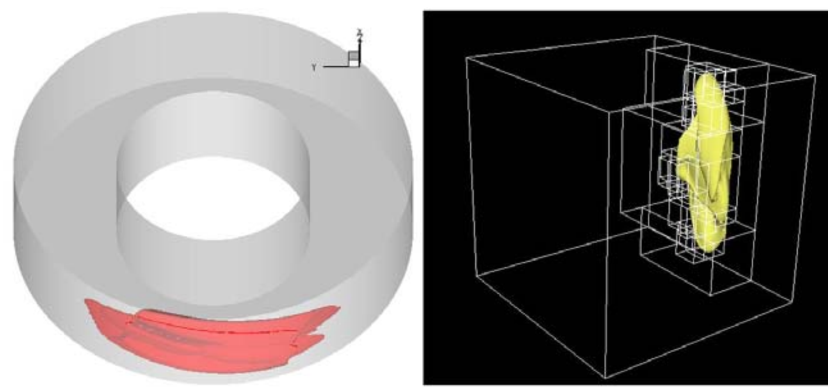
t=2



t=40



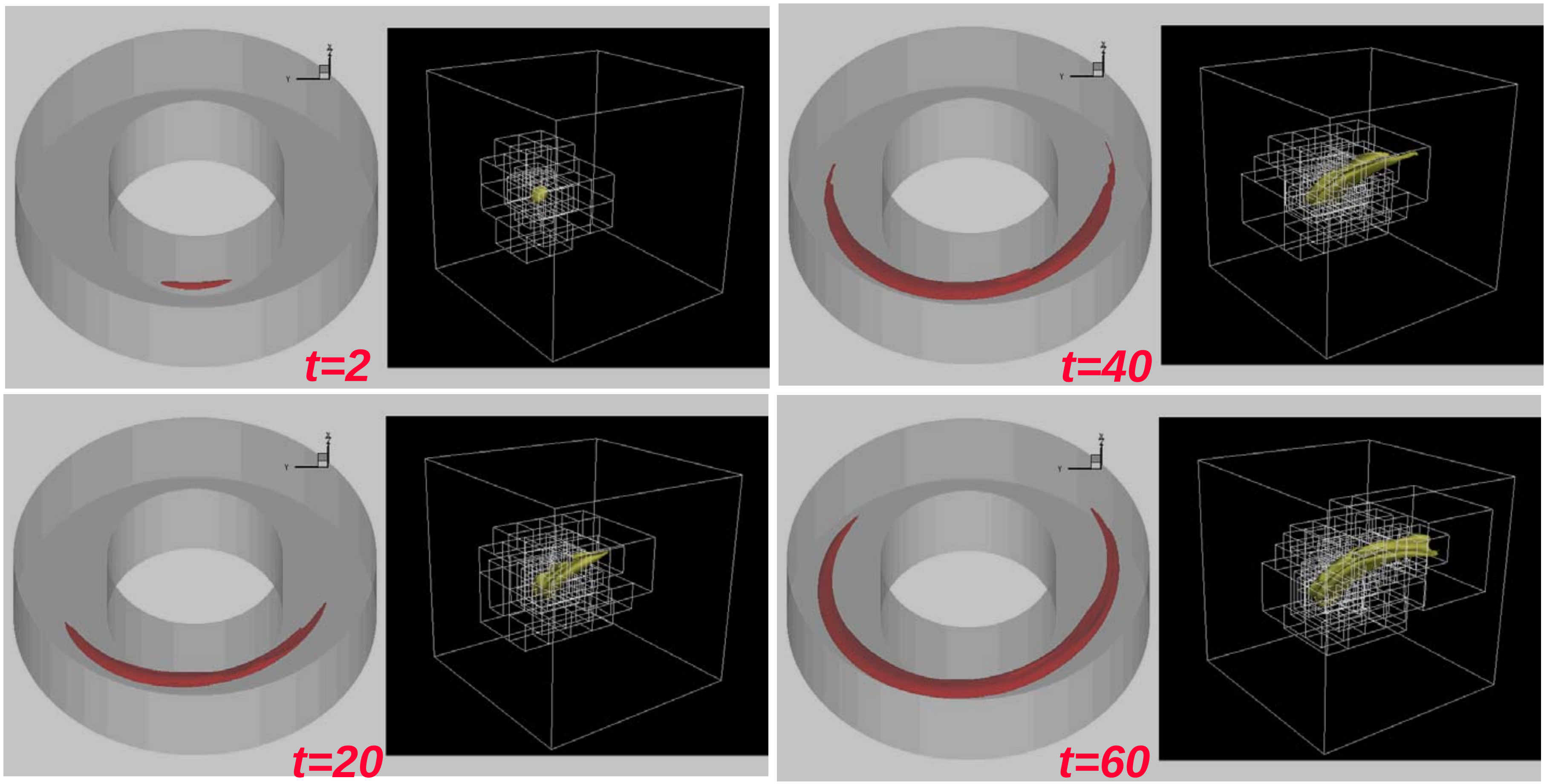
t=20



t=60

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

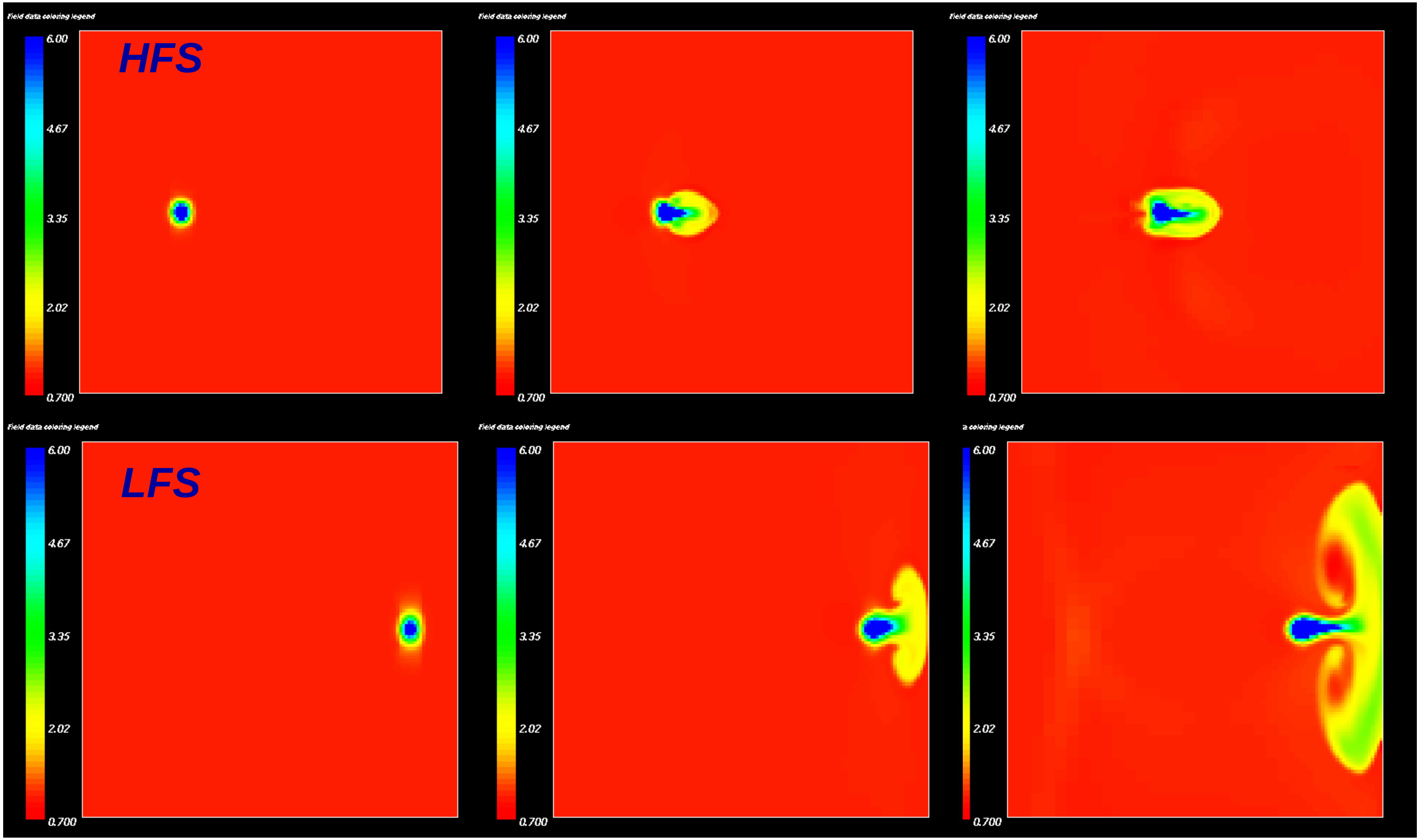
Pellet Injection: HFS Launch



PPPL
PRINCETON PLASMA
PHYSICS LABORATORY

Note: Left (right) side of frame shows physical (computational) space.

Pellet Injection: HFS vs. LFS



Anomalous transport across flux surfaces

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Conclusion and Future Directions

- Pellet injection simulations performed with an AMR code with flux tube geometry
  - *Numerical method is upwind, conservative and preserves the solenoidal property of the magnetic field*
  - *Physics of non-local electron heat flux included in the simulations*
  - *HFS vs. LFS pellet launches*
    - *HFS core fueling is more effective*
    - *Outward radial shift due to **r** B and E x B*
    - *Simulation results are consistent with previous studies, and qualitatively consistent with experimental observations*
- Compared supersonic gas injection into NSTX
  - *Boundary layer profiles may be important and will be included in the Nozzle code*
- Future work
  - *Higher resolution AMR runs for DIII-D*
  - *Validation against DIII-D experiments*
  - *Predictions for ITER*
    - *Vertical launches (HFS is hard to achieve for ITER)*
  - *Continue validation of gas injection*
  - *Effect of ionization and EM forces on gas injection*

PPPL PRINCETON PLASMA PHYSICS LABORATORY