Comparison of Pellet Injection Measurements with a Pellet Cloud Drift Model on the DIII-D Tokamak

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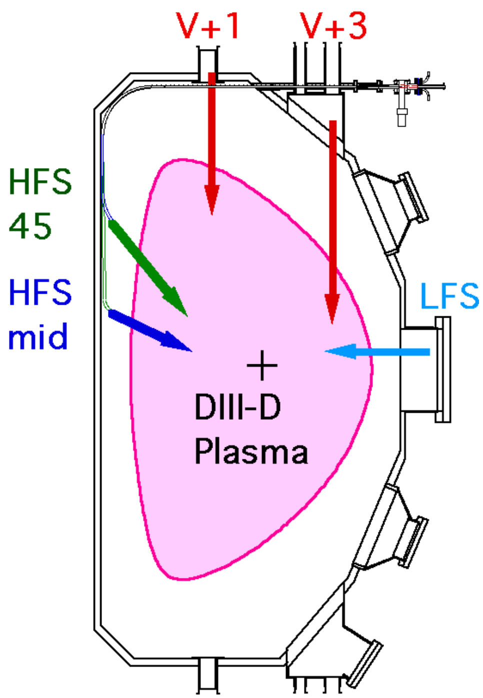
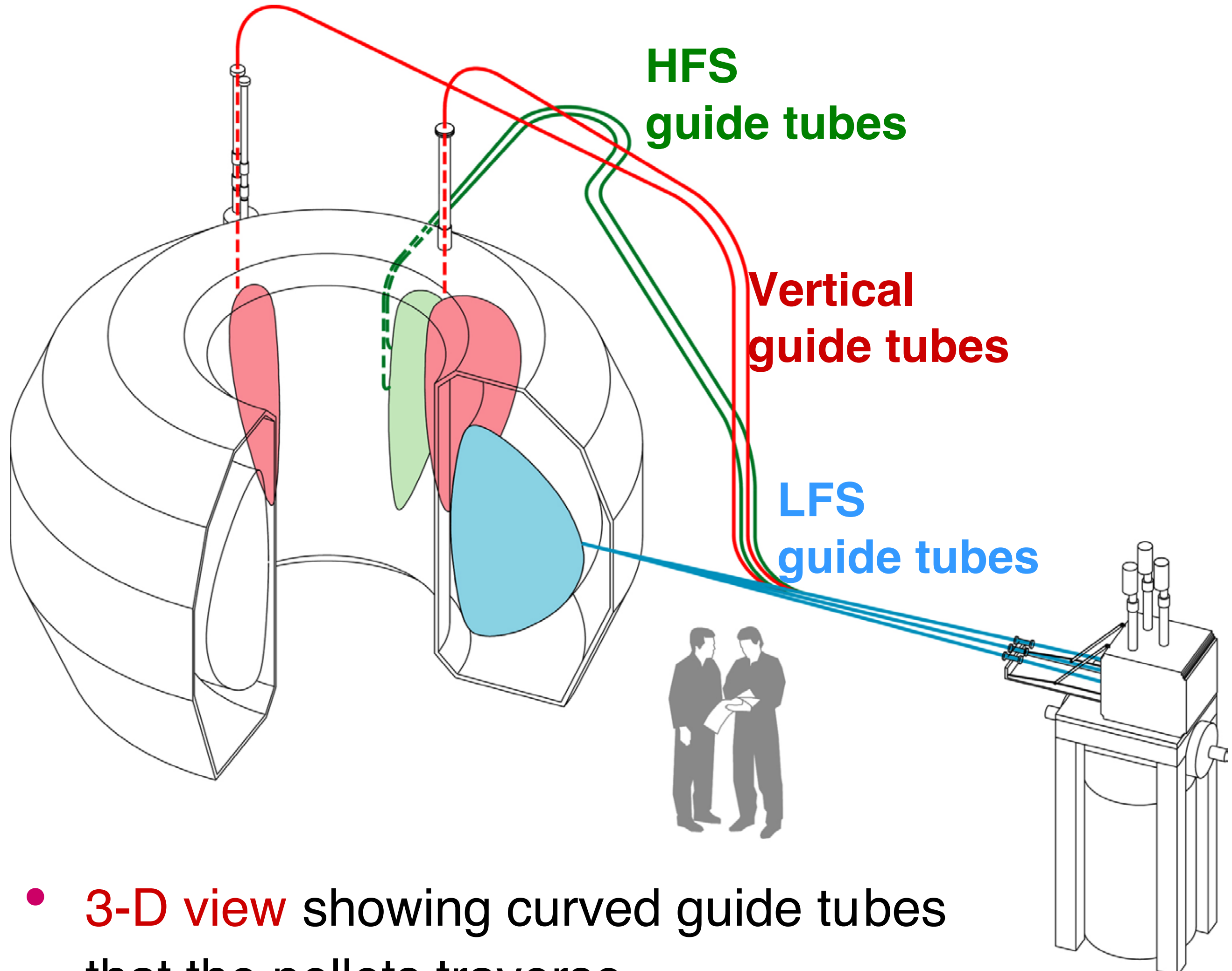
Abstract

Deuterium pellet injection has been used on the DIII-D tokamak from different injection locations to study pellet-fueling efficiency. When the injection point is inside the magnetic axis of the plasma, the fueling efficiency is significantly higher (approaching 100% in some circumstances) than when the injection point is outside of the magnetic axis. Drifting of the pellet cloud from regions of high to low magnetic field has been hypothesized to explain the experimental results. A pellet cloud drift model by Parks, et al., *Phys Plasmas 7, 1968 (2000)*, has been extended and implemented in a code to compare with the experimentally measured pellet deposition profiles. Measurements of the Hα spectra emitted from the pellet cloud have been made and are used to compare with assumed cloud parameters in the drift model. Comparisons of the resulting fuel deposition profile from different injection locations and the model calculations are presented.

DIII-D Pellet Injection Locations - 2001



- Elevation view of pellet trajectory in the plasma



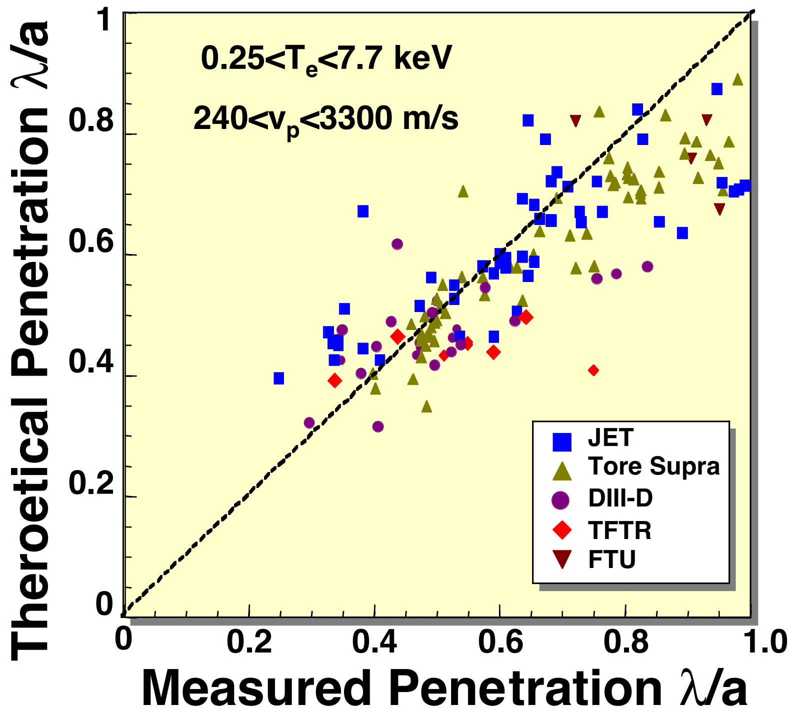
- 3-D view showing curved guide tubes that the pellets traverse

Alternative Injection Locations for Optimized Fueling

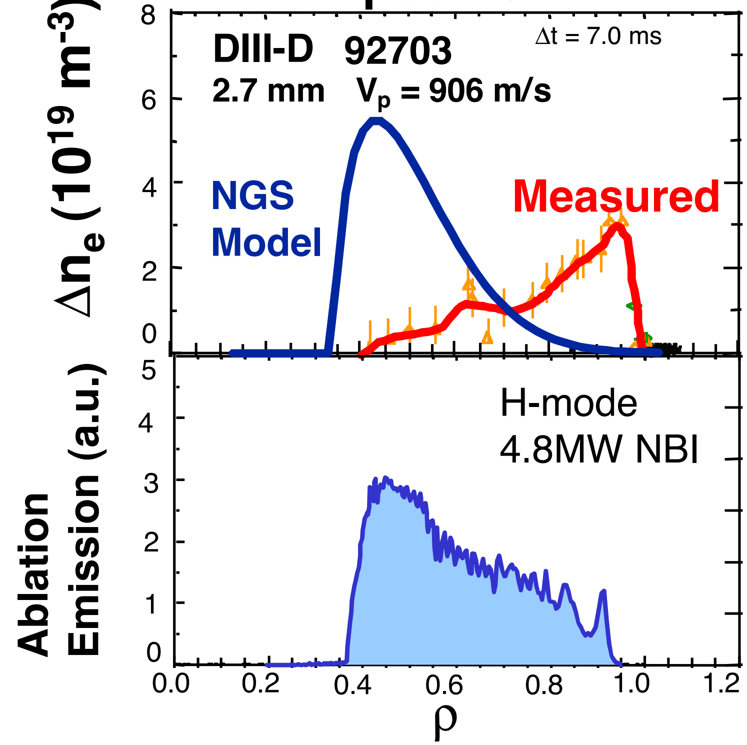
- **Pellet penetration is well characterized, but deposition profile from LFS injection is anomalous**
  - ELMs triggered by LFS pellets are substantial and long lasting
- **Alternative injection locations have been installed to investigate pellet fueling deposition from top ports and inner wall ports**
- **High field side (HFS) injection lines on DIII-D provide improved core fueling with HFS injected pellets**
  - HFS pellets have efficient fueling with minimized particle loss
  - ELMs triggered by HFS pellets are similar to background ELMs
- **Vertical injection inside magnetic axis provides improved fueling compared to LFS miplane or vertical LFS trajectory**
  - Vertical mounted injector may be optimal for reactor fueling

Pellet Penetration is Well Characterized, but Deposition Profile from LFS Injection is Anomalous

Penetration



Deposition



- Maximum Penetration depth agrees well with theory over a range of data from many devices, $\lambda/a \sim T_e^{-5/9} v_p^{1/3}$ (Baylor, et al., *Nucl. Fusion* 37, 445 (1997))
- Mass deposition implies fast radial transport during the ablation process
- ASDEX Upgrade first experiment to try HFS injection to test this hypothesis (Lang, et al., *Phys. Rev. Lett.* 79, 1478 (1997.))

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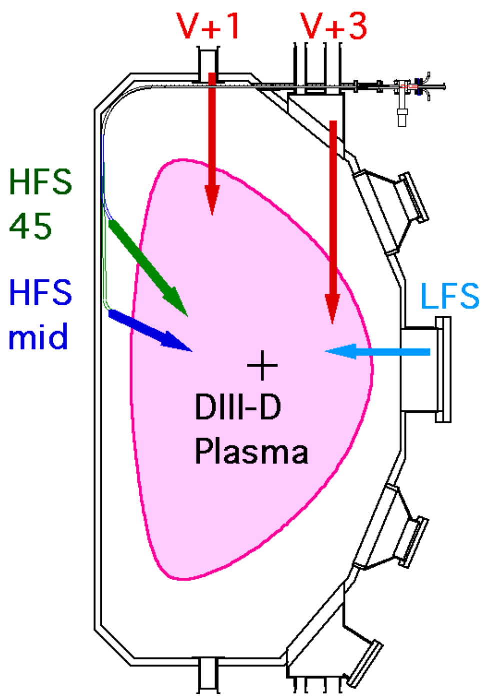
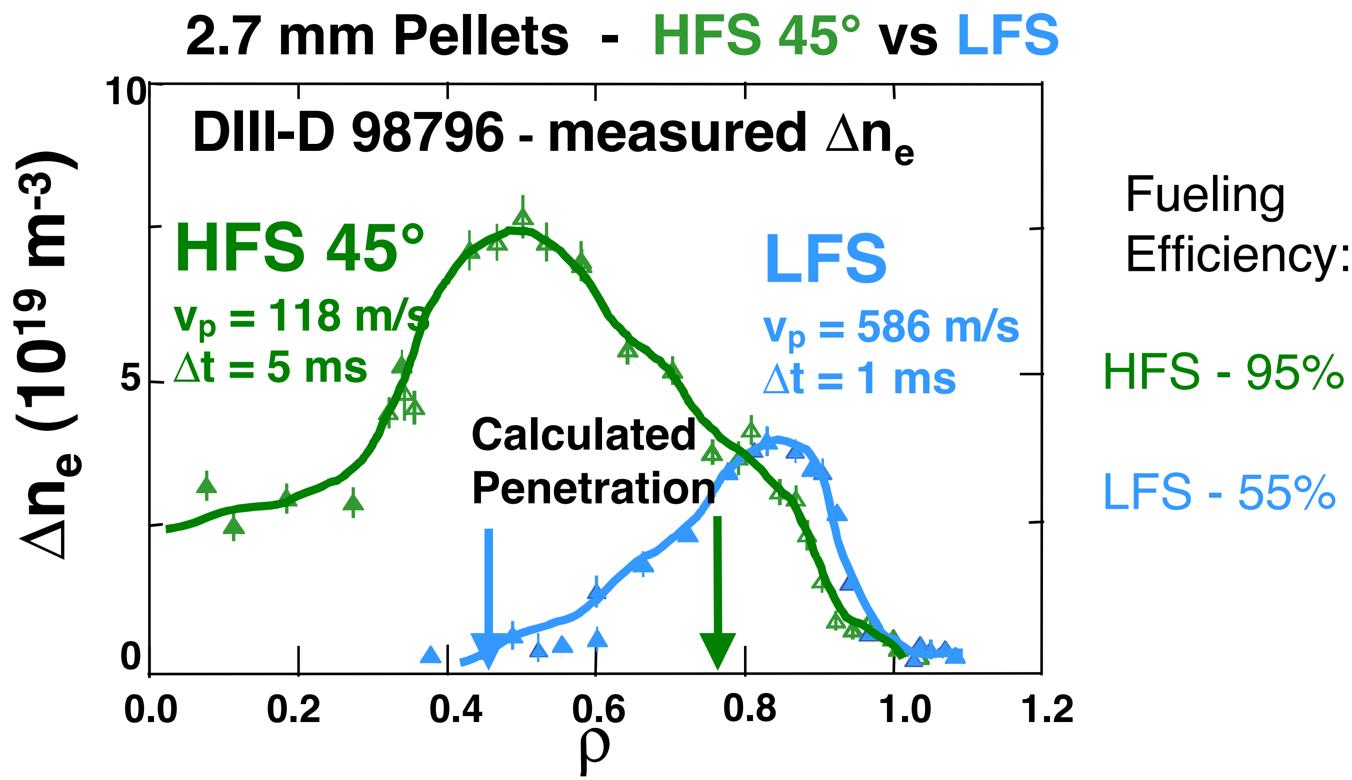
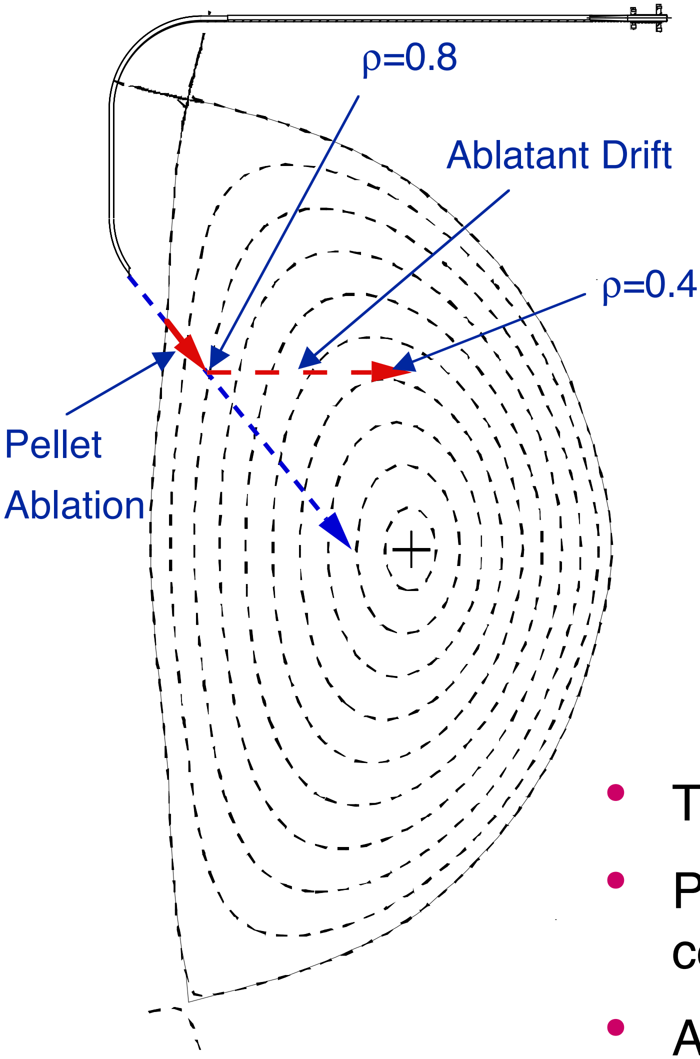
High Field Side (HFS 45°) Pellet Injection on DIII-D Yields Deeper Particle Deposition than LFS Injection

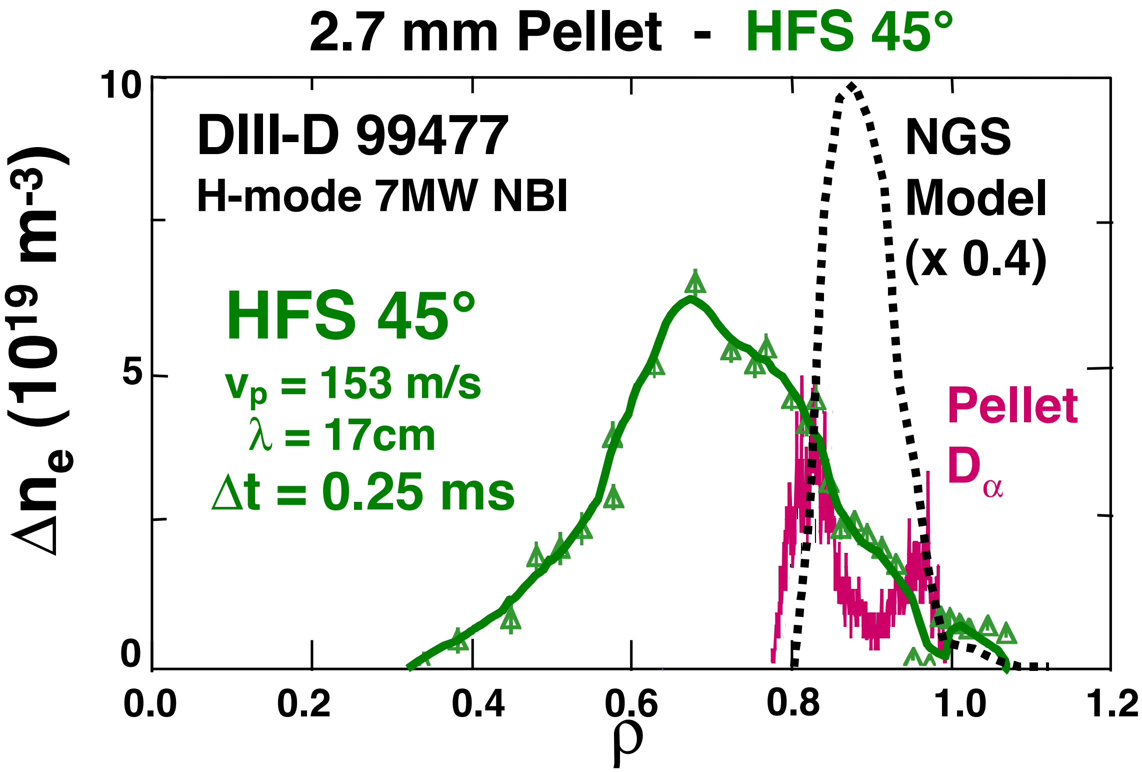




- Net deposition is much deeper for HFS pellet in spite of the lower velocity
- Pellets injected into the same discharge and conditions (ELMing H-mode, 4.5 MW NBI, $T_e(0)$ = 3 keV)

HFS 45° Pellet Injection Deposition Suggests Major Radius Drift of Ablatant





- The deposition shows deeper fueling than predicted
- Pellet D_α emission agrees with ablation model (PELLET code)
- A radial drift of 20 cm is inferred from the data - for comparison with detailed drift model. (Parks, P.B., *Phys Plasmas* 2000)

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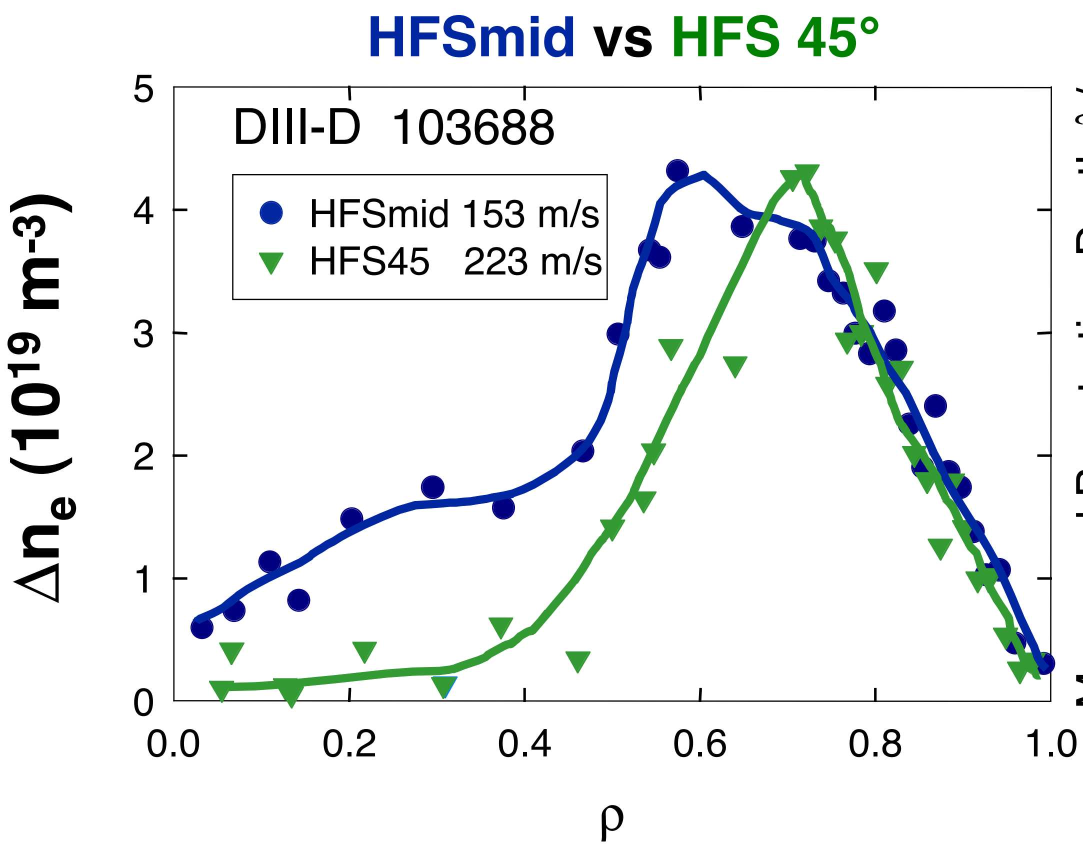
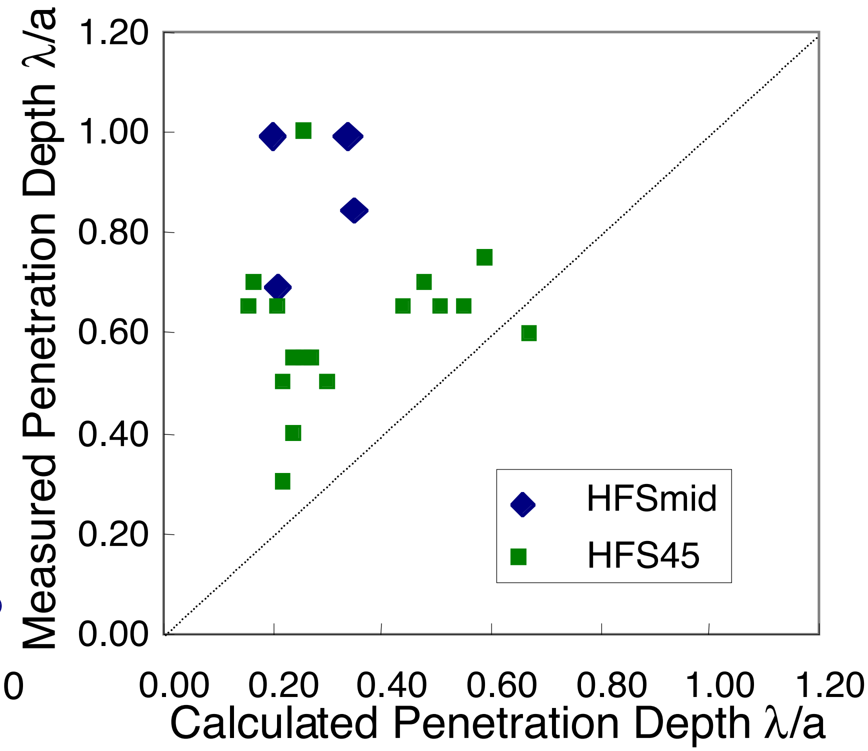
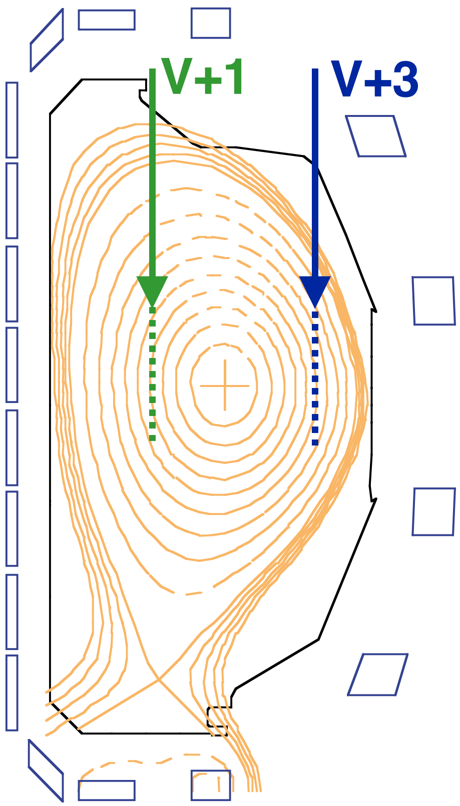
HFS Comparison
HFSmid Yields Deeper Deposition than HFS45

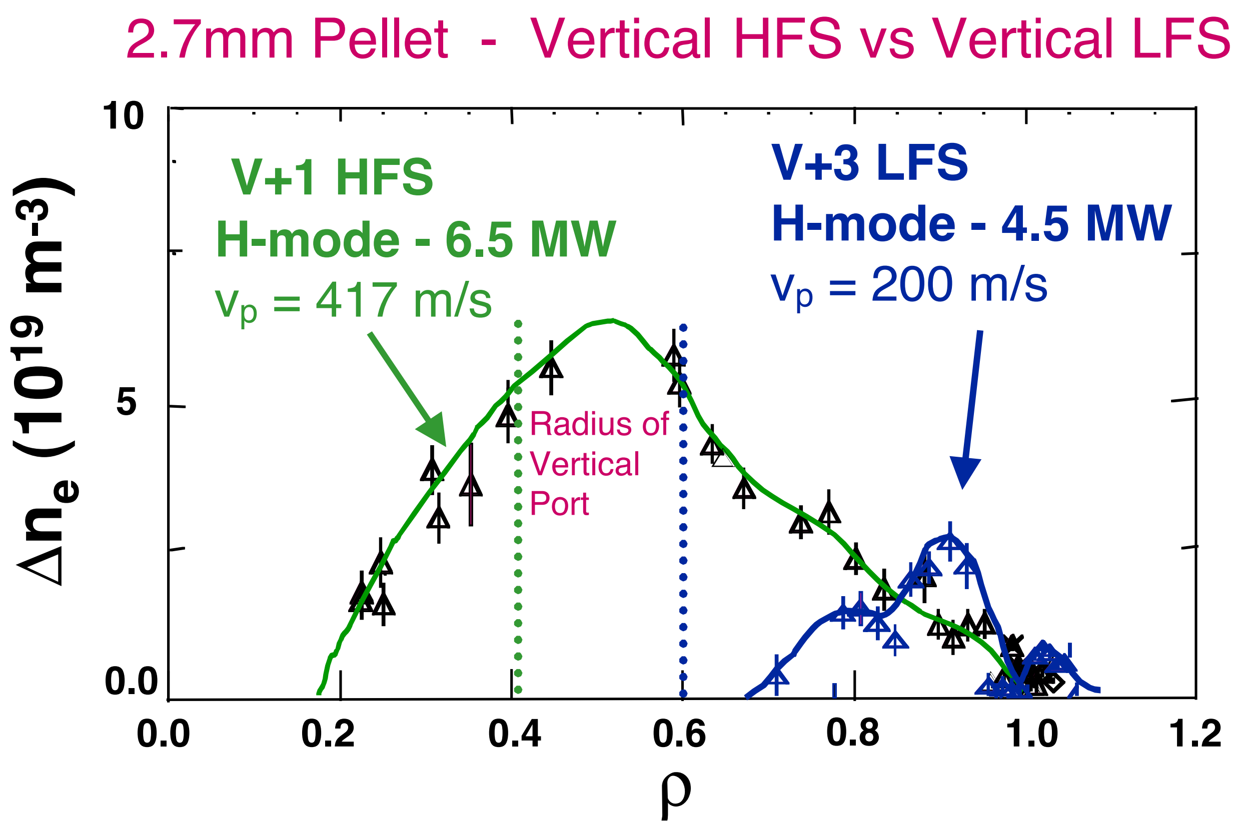




- A direct comparison of same size 2.7mm pellets in the same shot shows shows slightly deeper fueling from HFSmid than from HFS45 trajectory. Database results also show this trend.

Both Vertical HFS and LFS Pellet Injection are Consistent with an Outward Major Radius Drift of Pellet Mass



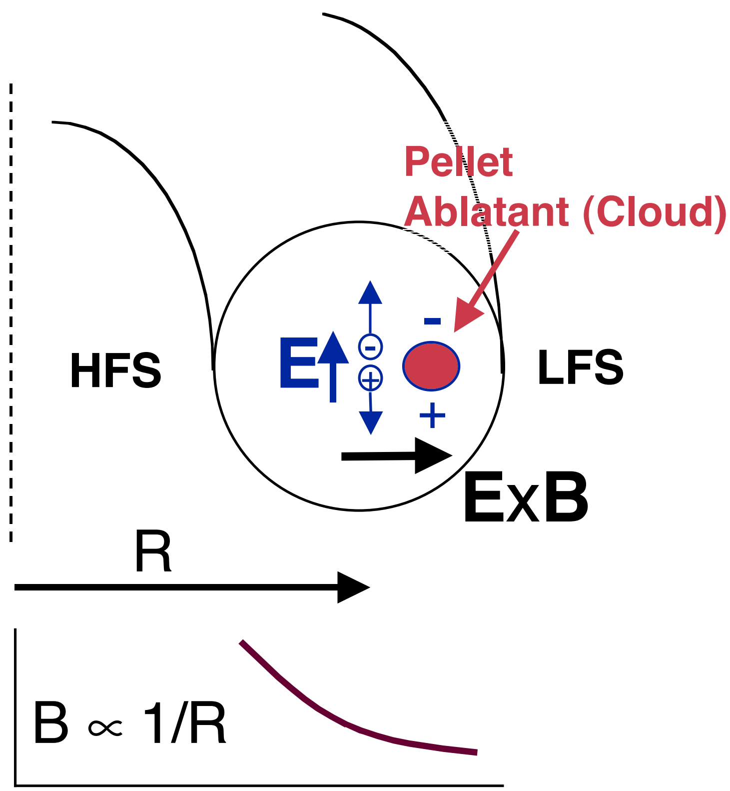


- The net deposition profile measured by Thomson scattering 2-4 ms after pellet injection on DIII-D. V+1 HFS indicates drift toward magnetic axis while V+3 LFS suggests drift away from axis.

Theoretical Model for Pellet Radial Drift

ExB Polarization Drift Model of Pellet Mass Deposition

(Rozhansky, Parks)



- Polarization of the ablatant occurs from ∇**B** and curvature drift in the non-uniform tokamak field:

$$\vec{\mathbf{v}}_{\nabla B} = \frac{W_\perp + 2W_\parallel}{eB^3}\vec{\mathbf{B}} \times \overrightarrow{\nabla \mathbf{B}}$$

- The resulting **E** yields an **ExB** drift in the major radius direction
- The velocity of ablatant ≈ $c_s(2L/R)^{0.5}$. For DIII-D this is ≈ 2 km/s, i.e. faster than the pellet (deKloe, Mueller, *Phys.Rev.Lett.* (1999))
- ΔR stronger at higher plasma β
- Detailed model by Parks, P.B. (*Phys. Plasmas* 1968, (2000).)

Radial Displacement Model for Drift of Pellet Mass

- A quantitative model by Parks describes the drift phenomenon. The ablated mass was assumed to be a series of cloudlets. A scaling law for the penetration depth assuming a spatially uniform plasma.

$$\Delta R = \frac{0.46 r_p^{1/3}}{M_0 \kappa_c B} \frac{T_{e\infty}^{11/6}}{(\ln \Lambda_{en})^{2/3}} \left(\frac{W}{n_{e\infty}} \right)^{1/6} \langle \Psi \rangle$$

where $\langle \tilde{\Psi} \rangle$ is a toroidal drive integral. For definition of the other parameters see Parks, P.B. (*Phys. Plasmas* 1968, (2000).)

- An enhancement to the model to include cloudlet drift in a spatially inhomogeneous plasma has recently been made. In this model the plasma pressure profile is assumed to be given by:

$$p(t) = \frac{\beta_\infty(0)}{\beta_0} \left[\frac{1-(r(t)/a)^\alpha}{1-(r(0)/a)^\alpha} \right]^\delta$$

Enhancements to Radial Displacement Model for Drift of Pellet Mass

- The problem entails coupling the equation of motion for the drift velocity and radial penetration distance with the 1-D time dependent parallel expansion model. The non-dimensional drift equation becomes:

$$h(\xi)\frac{du}{dt} = -\frac{u}{I} + g\Psi[t, p(t)]$$

where u is the radial velocity, ξ is the radial position, g is a dimensionless acceleration parameter and I is the dimensionless cloud inertia.

- The non-dimensional acceleration function then becomes:

$$\Psi[t, p(t)] = \int_0^1 \frac{\eta(x,0)}{\eta(x,t)}\left[p(x,t) - p_\infty(t)\right]dx$$

where x is the normalized Lagrangian distance (z/L_c) from the midplane of the cloudlet.

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Radial Displacement Model for Drift of Pellet Mass – Additional Effects to Consider

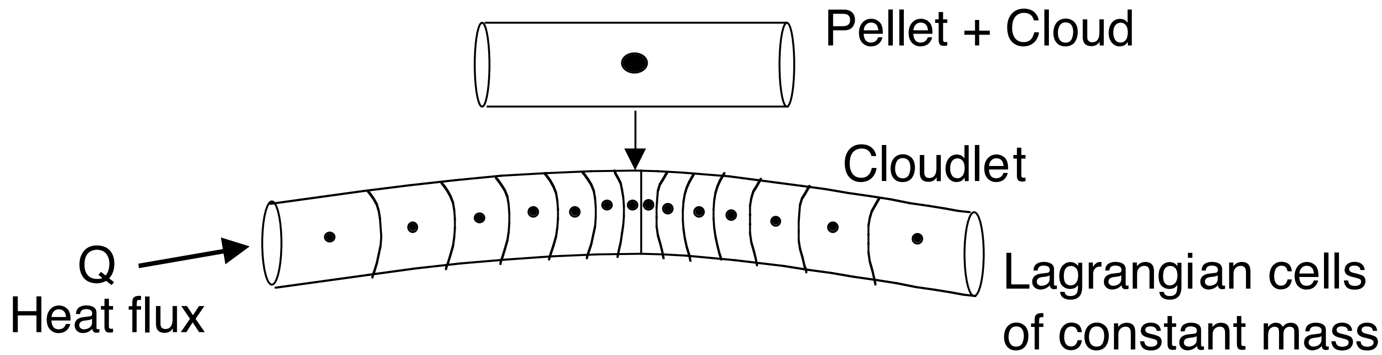
- The model does not include any dissipative effects such as diffusion of the cloud radially as it expands along the field lines. The cloud diameter is assumed constant as it moves.

- Because of the lack of a dissipative effect, the model would predict that pellets injected from the LFS are completely expelled from the plasma. We know this is not the case as shown in slides above, where up to 50% of the pellet mass from LFS pellets is retained in the plasma.

- The model assumes that the plasma is unperturbed in front of the pellet – thus it does not include the possibility that the cloudlet moves in front of the pellet to pre-cool the plasma. This effect would enhance the pellet penetration and reduce the radial drift drive mechanism.

1-D Lagrangian Code – Pellet Relaxation Lagrangian (PRL)

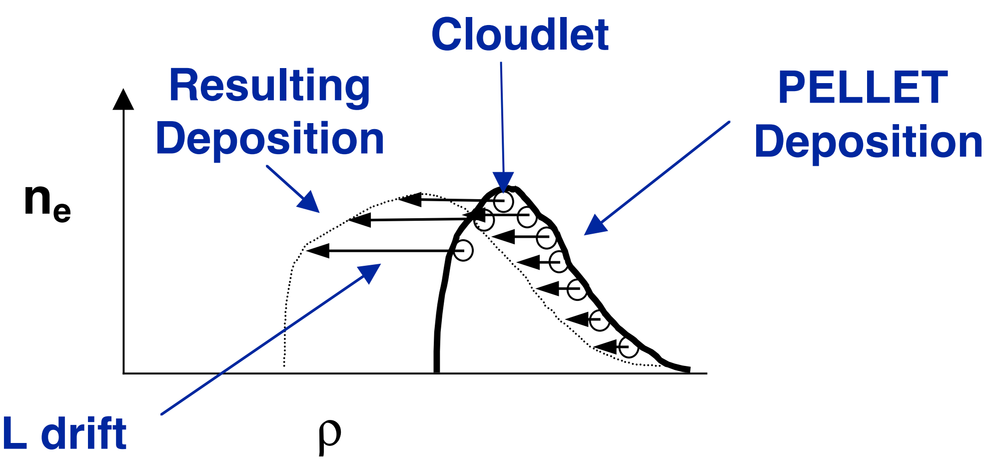
- The parallel temporal expansion dynamics for a discrete cloudlet is described by a 1-D Lagrangian fluid model.
- Lagrangian coordinates do not determine a given point in space, but a given fluid mass [Zel'dovich]. The Eulerian coordinate x does not enter the equations explicitly.



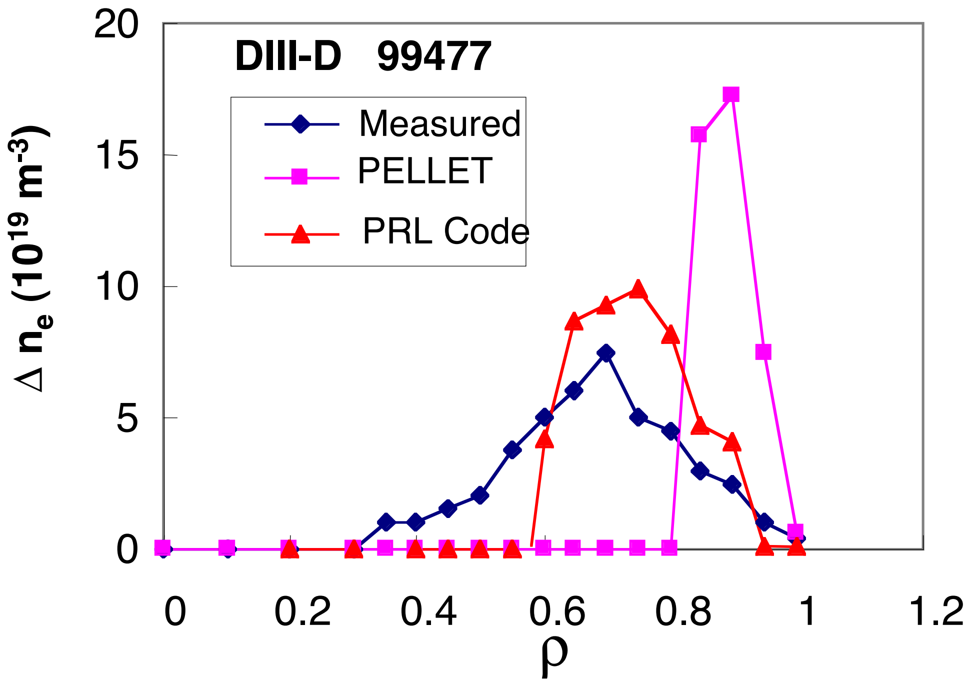
- The gas dynamic flow variables are expressed in terms of Lagrangian coordinates that express the changes in density, pressure, and velocity of each fluid element with time.

Modeling with Pellet Relaxation Lagrangian (PRL)

- The pellet ablation is modeled with the PELLET code to get the particle source rate from the pellet.
- The PRL code uses the pellet size at each point along the ablation track to calculate the penetration of a cloudlet originating at that point.
- The experimental plasma profiles are fed into PRL to calculate the cloudlet relaxation.
- The ablation deposition is then shifted for each cloudlet to give a resulting plasma density profile, which can be compared with experiment.

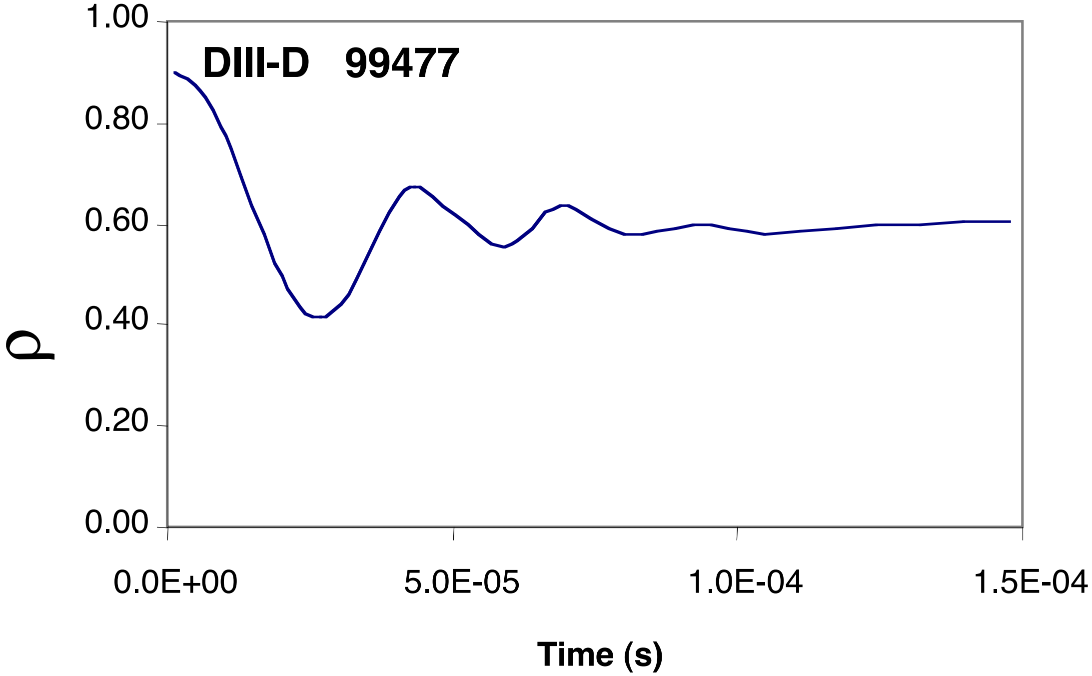


PRL Code Coupled with Ablation Model Predicts Reasonable Deposition Profile



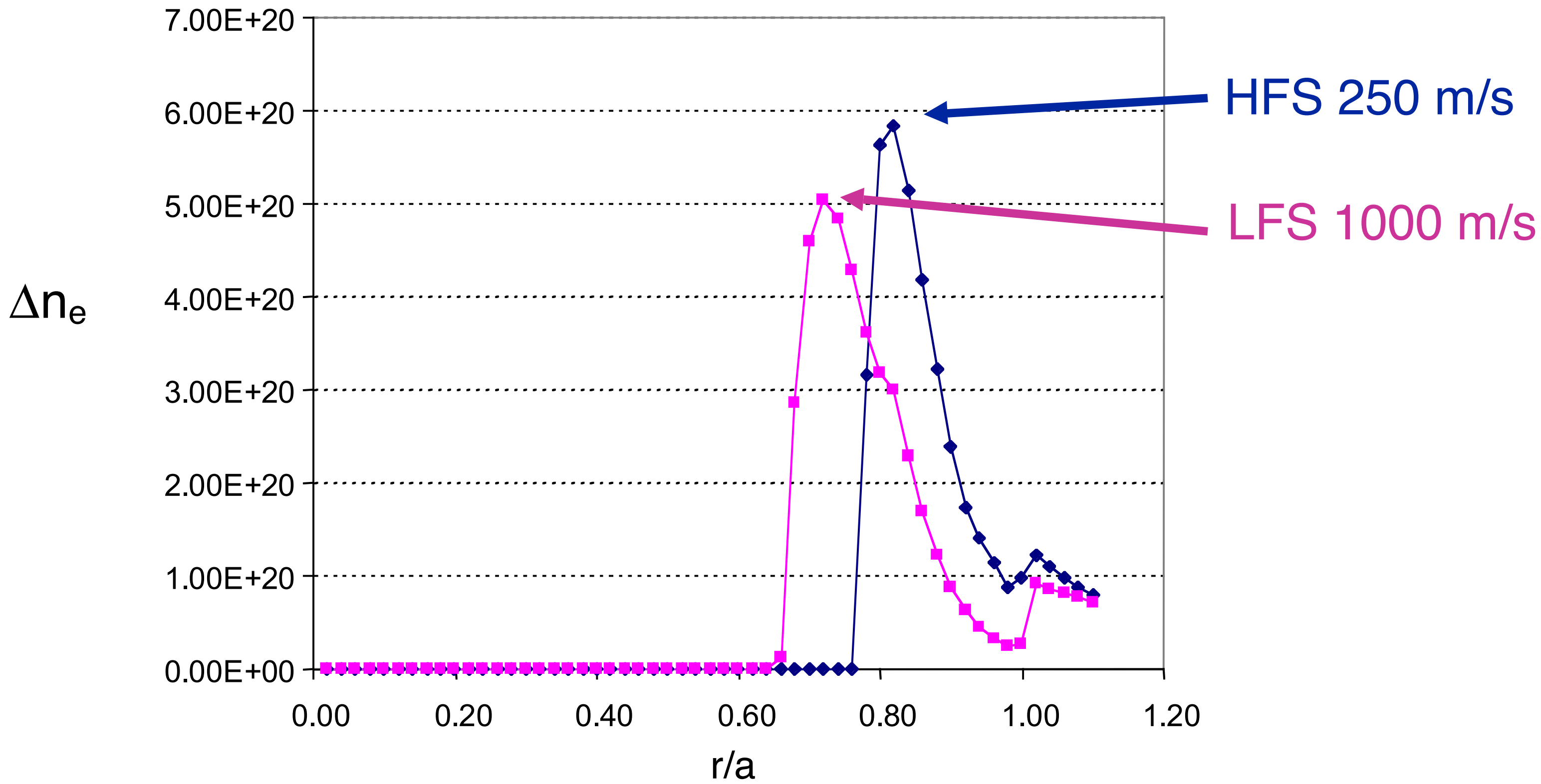
- Comparison of the resulting mass deposition from a 2.7mm pellet from the experimental density profile change (measurement), pellet ablation code (PELLET), and **E**x**B** drift model (PRL code) coupled with the ablation code output.

PRL Code Time Scale of **ExB** Drift



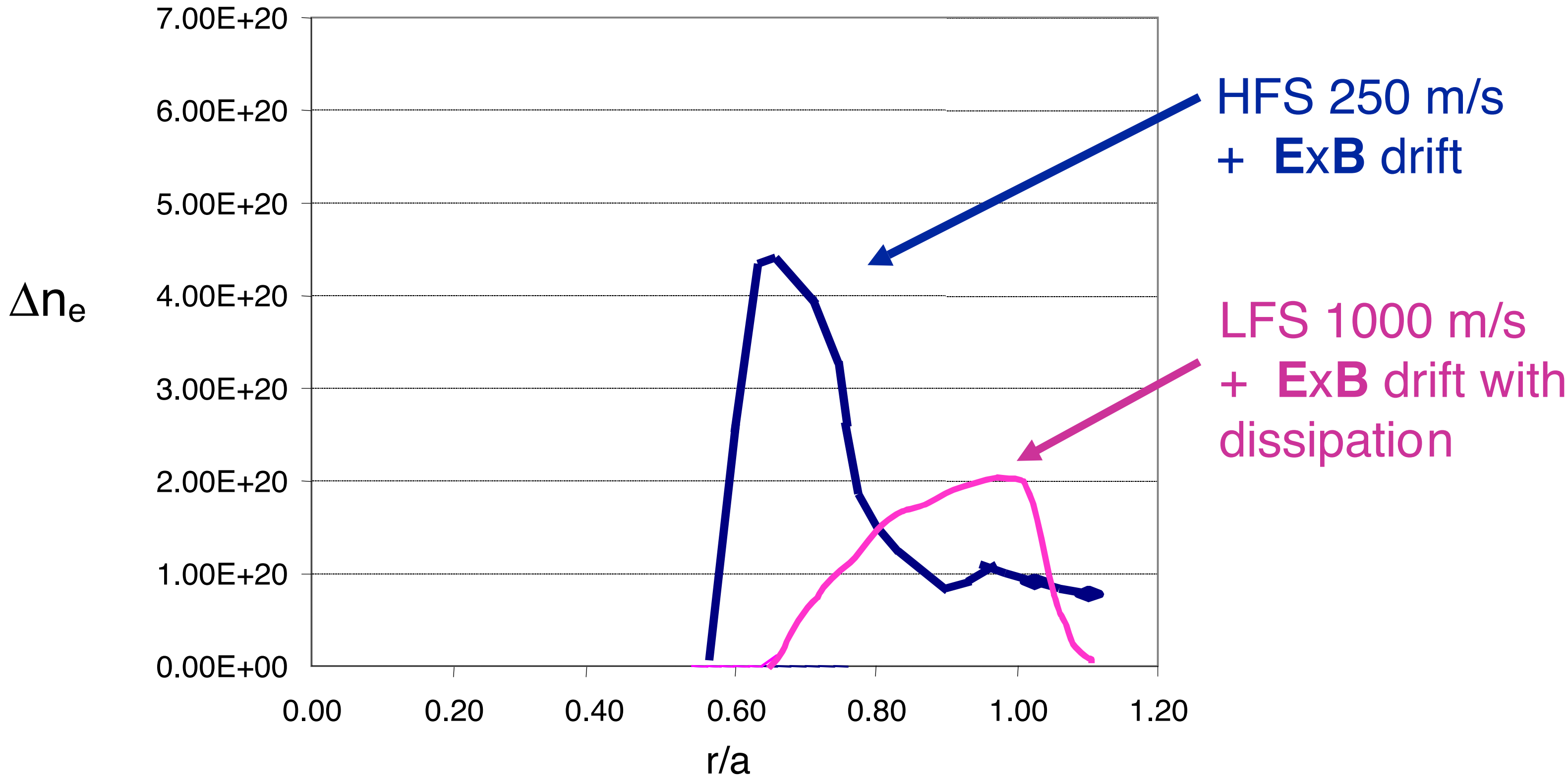
- The position of the pellet cloudlet that starts at $\rho = 0.9$ is plotted as a function of time. The time scale for the cloudlet to reach its final position is on the order of 50 μsec. This is consistent with experimental observations that the drift occurs in less than 250 μsec.
- The cloudlet speed reaches 10^4 m/s, much faster than the pellet, thus pre-cooling the plasma in front of the pellet.

FIRE - Pellet Deposition Using NGS Model



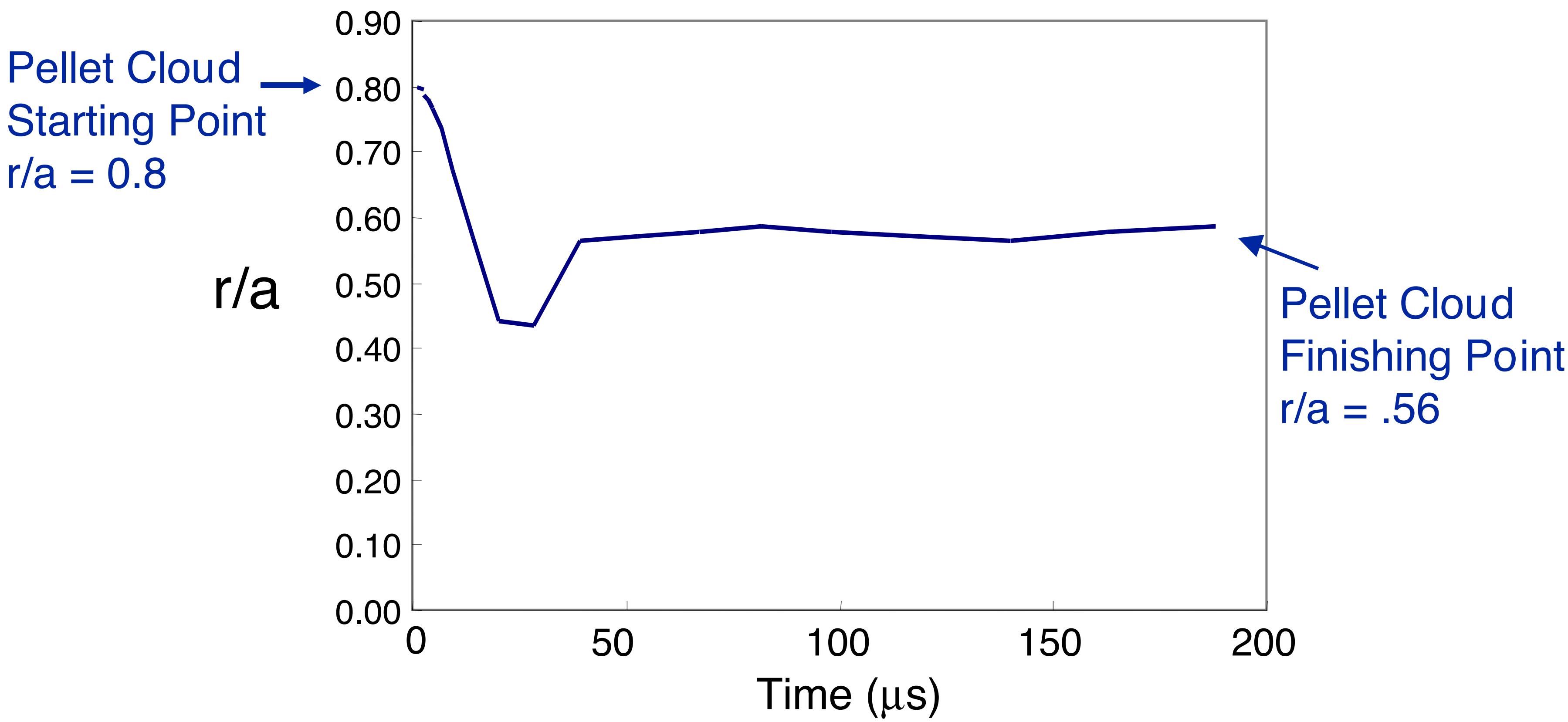
The deposition from a 4mm pellet injected from the outside midplane (LFS) and inner wall (HFS). The calculation uses the PELLET code with the NGS model into a FIRE 11 keV H-mode plasma.

FIRE - Pellet Deposition with Parks **ExB** Drift Model



The resulting deposition from a 4mm pellet injected from the outside midplane (LFS) and inner wall (HFS) including **E**x**B** drift effects to NGS pellet ablation. The calculation uses the Pellet Relaxation Lagrangian code to model the cloudlet displacement from **E**x**B** drift. Dissipation is ad hoc scaled from DIII-D results.

FIRE - Pellet Cloudlet HFS Motion
Parks **ExB** Drift Model



The cloudlet motion in the plasma as a function of normalized time. This cloudlet is born at the peak of the ablation rate and moves inward an additional 50% from its starting location.

Strauss MHD Model for Drift of Pellet Mass

- An MHD simulation of the perturbation [Strauss] from pellet injection has led to a scaling law for the pellet displacement.

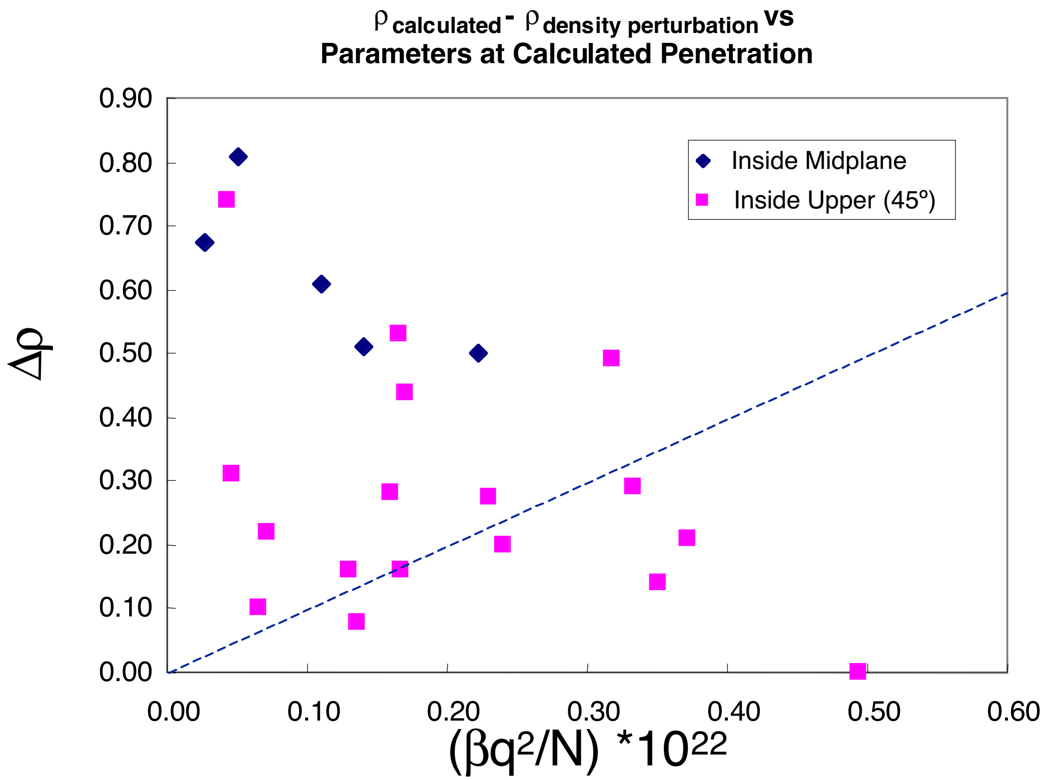
  The displacement δx can be written for the case where the pellet perturbation is large compared to background density ($\delta n/n >> 1$) as:

$$\delta x \approx \beta q^2 R \frac{\delta n}{n}$$

- Scaling of the measured displacement determined from the difference in an ablation code (PELLET) [Houlberg] penetration from the Thomson scattering density perturbation ($\Delta t < 2$ms) with this formula is possible.

Database Comparison with Strauss MHD Model

- A database of inner wall launched pellets has been formed to look at the scaling of the Strauss MHD simulation.



- Initial results do not suggest very good agreement with this scaling. More data is needed with stronger variations in q in order to better examine this model.

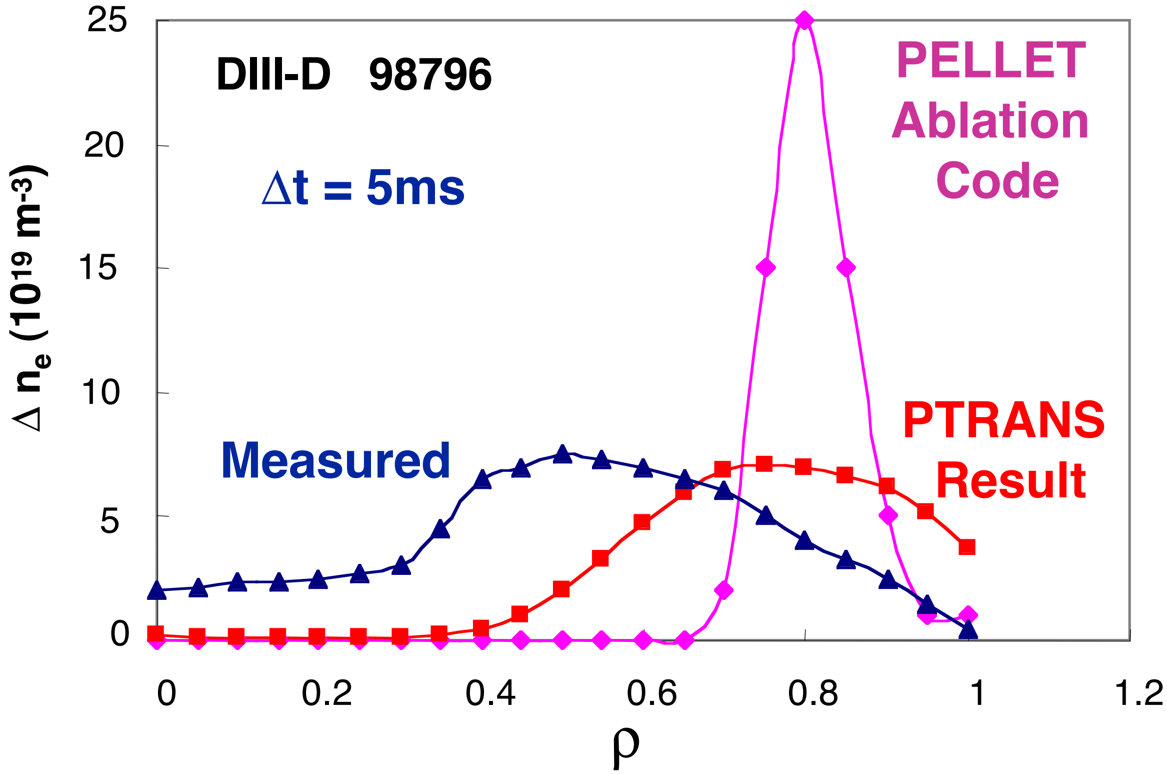
Conclusions

- HFS pellet injection on DIII-D has demonstrated a strong radial drift of the pellet mass that leads to improved core fueling with HFS injection.
- The pellet mass drifts in the plasma major radius direction on a fast (<100 μs) time scale during the redistribution process.
  - An **E**x**B** polarization drift model is formulated to explain the radial displacement and enhanced for plasma profile effects
  - A pellet relaxation Lagrangian code has been developed to model the relaxation phenomenon from the **E**x**B** drift
  - Comparison of the modeled drift with measured deposition yields reasonable agreement – drift speed much faster than pellet speed
- The major radius drift from the polarization drift model scales with plasma β and looks favorable for burning plasma experiments.
- The mass penetration depth from the DIII-D inner wall pellet database does not scale as expected from the Strauss MHD model of pellet mass displacement.

References

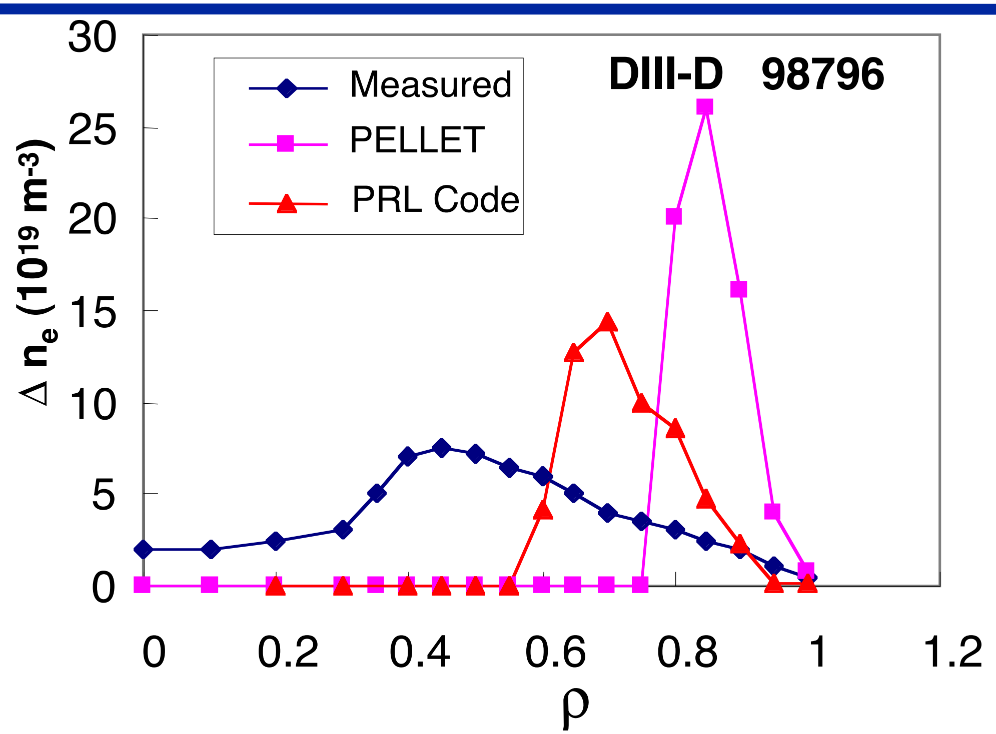
- **Baylor, L.R., et al.,** Phys. Plasmas, **4** (2000) 1878.
- **Lang, P.T., et al.,** Phys. Rev. Lett. 79, (1997) 1478.
- **Baylor, et al.,** *Nucl. Fusion* 37, (1997) 445.
- **Parks, P.B., Sessions, W.D., Baylor, L.R.,** Phys. Plasmas, **8** (2000) 1968.
- **Houlberg, W.A., et al.,** Nucl. Fusion 28 (1988) 595.
- **Zel'dovich, Y., Raizer, Y.,** "Physics of Shock Waves and High-Temperature Hydrodynamic Phenonena", Academic Press, New York, 1966.
- **Strauss, H.R., Park, W.,** Phys. Plasmas, **5** (1998) 2676.

Strong Diffusion is not Sufficient to Explain the Deposition Profile



- PTRANS modeling of the electron density profile evolution shows that the apparent inward drift is not likely explained by a 1 m^2/s diffusion coefficient.

PRL Code Coupled with Ablation Model Predicts Deposition Profile



- Another Comparison of the resulting mass deposition from a 2.7mm pellet from the experimental density profile change (measurement), pellet ablation code (PELLET), and **E**x**B** drift model (PRL code) coupled with the ablation code output.