Pellet Injection on DIII-D from Multiple Directions (With Applications to NSTX)

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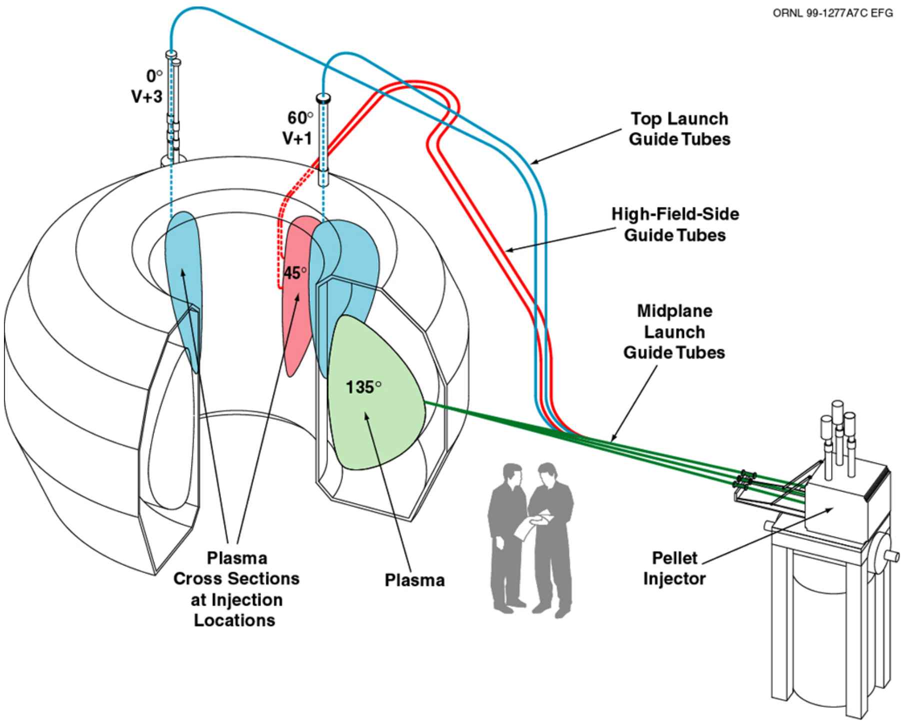
Deuterium pellets have been injected into DIII-D from the inside wall, the outside, and the top. When the injection point is inside the magnetic axis of the plasma, the fueling efficiency has proven to be significantly higher (approaching 100% in some circumstances) than when the injection point is outside of the magnetic axis. This is attributed to the outward radial motion of the ablated plasma cloud, P.T.Lang, et. al,Phys.Rev.Lett.79,1478 (1997). A plasma deposition model by Parks, P.B. Parks Phys Plasmas 5, (2000), has been incorporated in the pellet code to compare with the experimental deposition. An additional slow injector (v_{pellet} <= 200 m/s) has been installed. This will allow comparison with inside launch injection near the mid-plane vs injection from higher on the inside wall. Studies have also been conducted to explore pellet induced transport barriers, both internal (PEP-mode) and edge (H-mode).

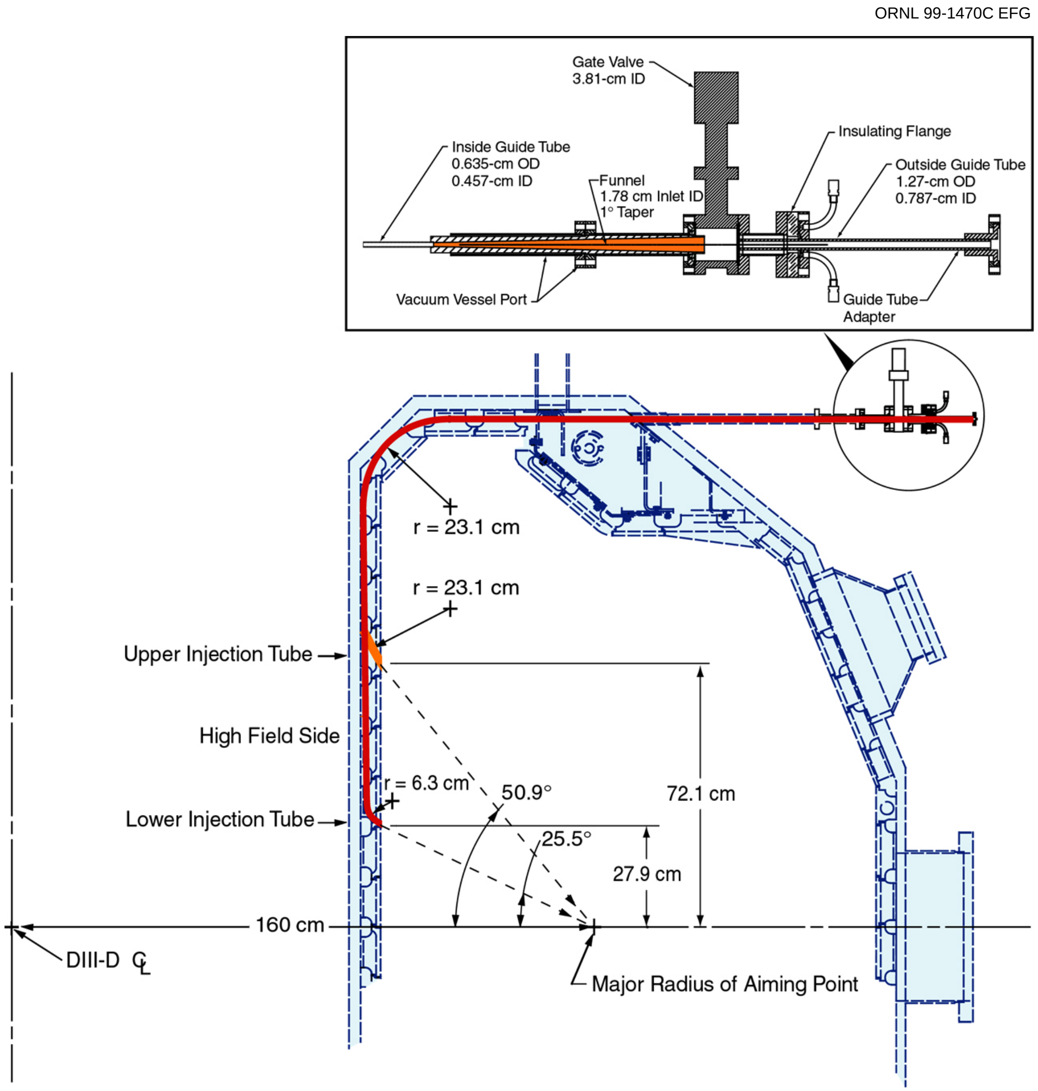
DIII-D Pellet Injection System – Transport Guide Tubes

- Straight guide tubes (≈4 m)
  - Three independent standard low-field-side (LFS) injection tubes: 135º port
- Curved guide tubes (≈12.5 m)
  - Two independent vertical injection tubes: 0º (V+3) and 60º (V+1) ports
  - Two independent HFS injection tubes on inner wall: 45º upper and lower ports
  - Special tube with tight bend radius for LFS injection experiments with fractured pellets
- Performance tests were done at ORNL on mockups of DIII-D "roller-coaster" tube runs
  - Special ORNL components were developed for attaching multiple tube sections and size transitions
  - Pellet speeds are limited to ≈200 m/s for survival in HFS tube runs and ≈400 m/s for vertical installations
  - Combs, SOFE Proceedings, 1999

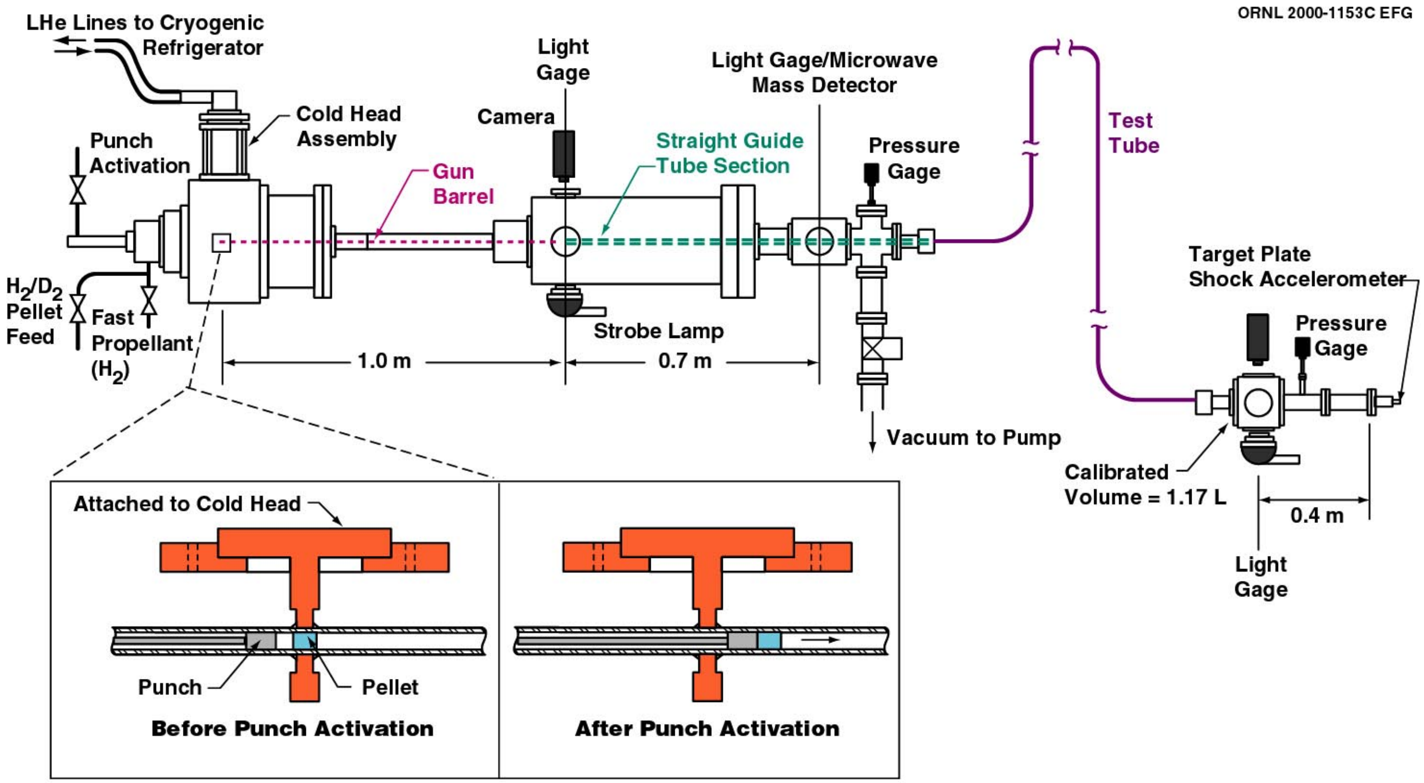


Any guide tube can be connected to any pellet gun (or a gas valve)

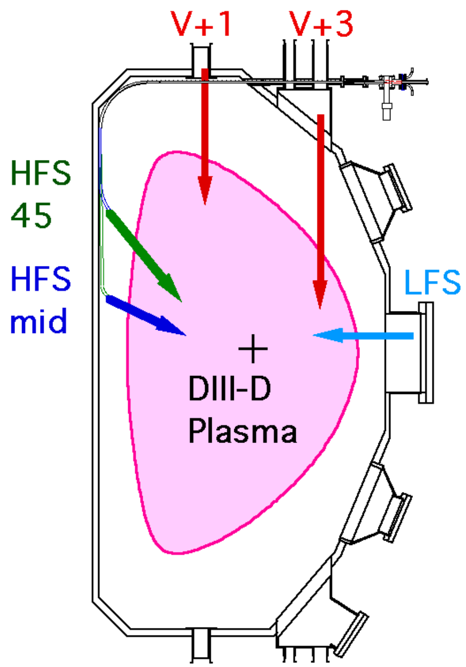
HFS Pellet Internal Injection Tubes on DIII-D

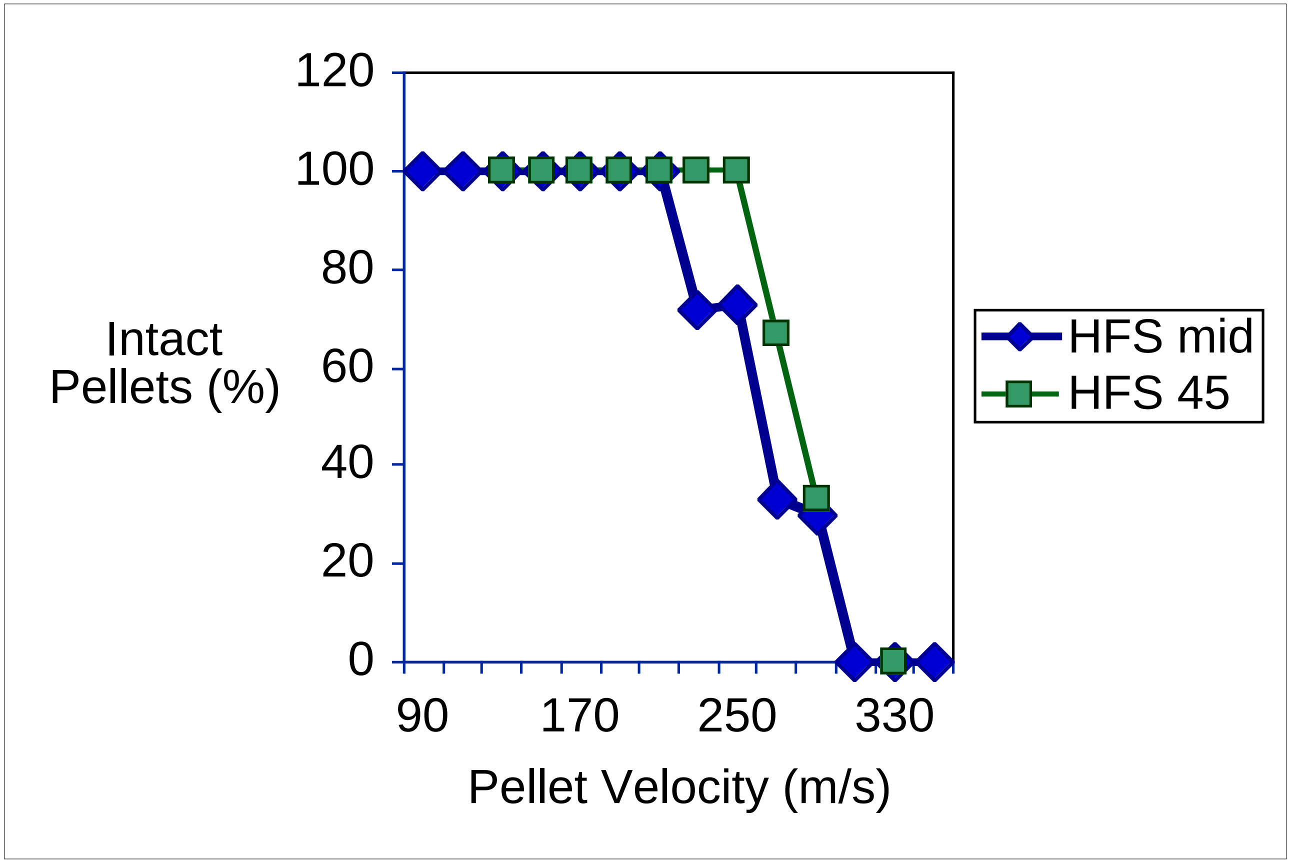


ORNL Pipe-Gun Facility Was Modified and Used for Testing Curved Guide Tubes and Mock-Ups of Inside Launch Pellet Injection on DIII-D, JET, and LHD



Results from ORNL Mockup of DIII-D HFS Guide Tube Geometry Give Maximum Speed Allowed for Intact Pellets (2.7-mm D_2 Pellets)



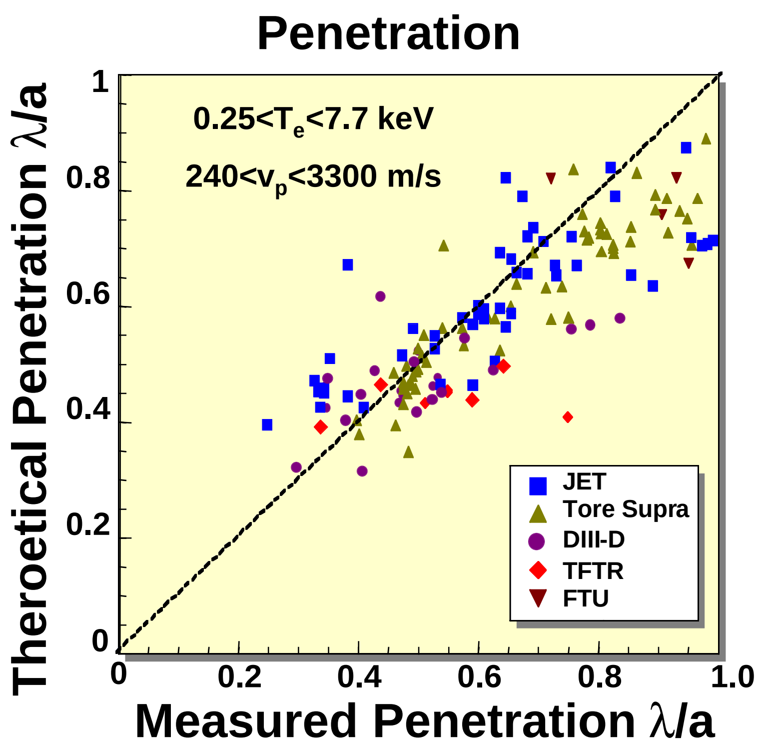


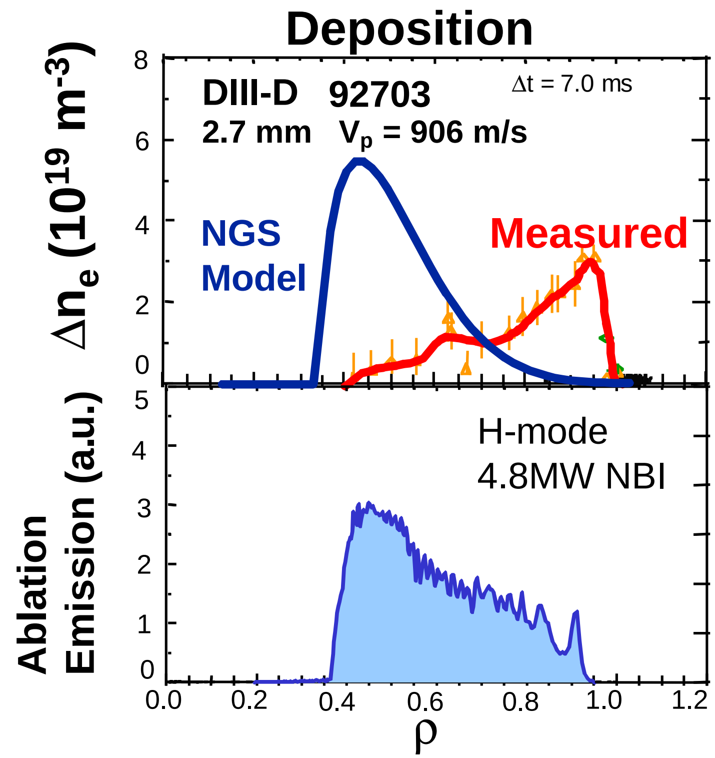
$Vmax_{HFS\_45}$ = 250 m/s **$Vmax_{HFS\_mid}$ = 210 m/s**

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

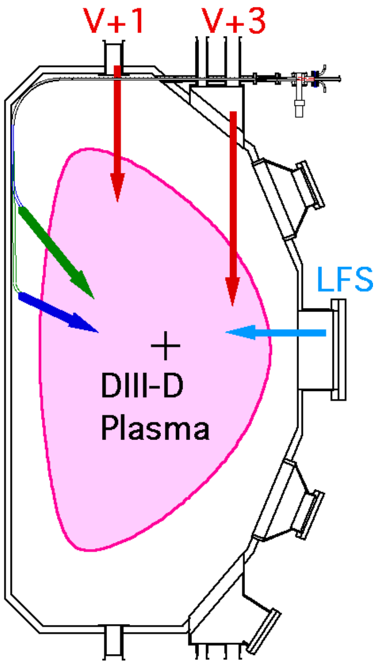
Pellet Penetration is Well Characterized, but Deposition Profile from LFS Injection is Anomalous

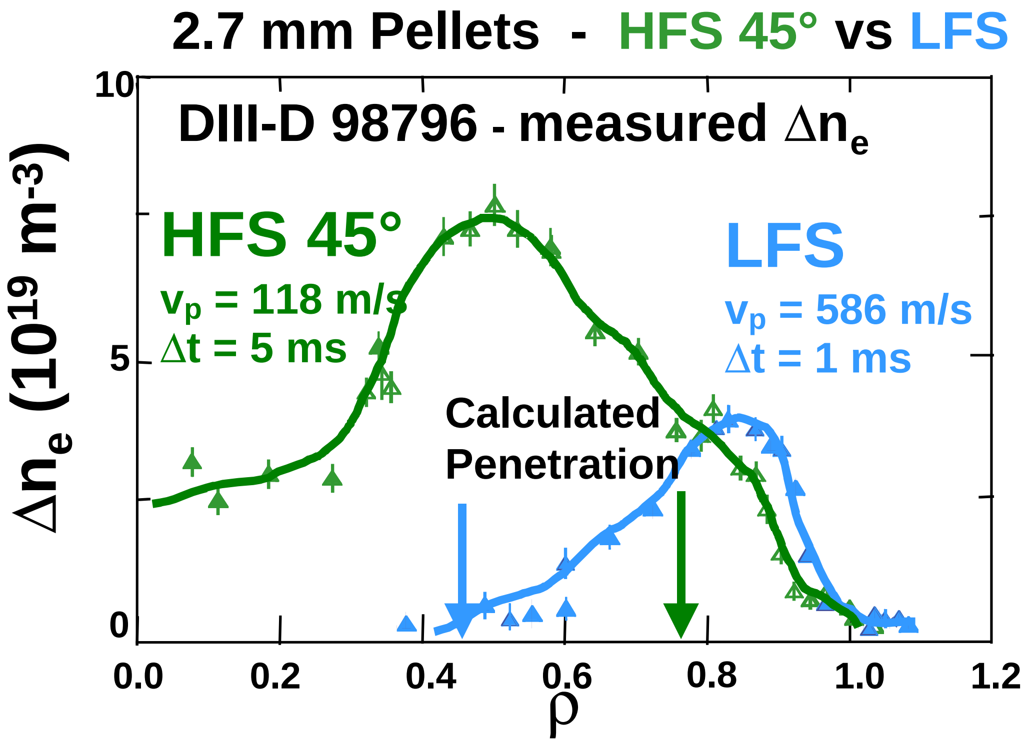




- Maximum Penetration depth agrees well with theory over a range of data from many devices, $\lambda/a \sim T_e^{-5/9} v_p^{1/3}$ (Baylor, et al., *Nucl. Fusion* 37, 445 (1997))
- Mass deposition implies fast radial transport during the ablation process
  – ASDEX Upgrade first experiment to try HFS injection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

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





Fueling Efficiency:

HFS - 95%

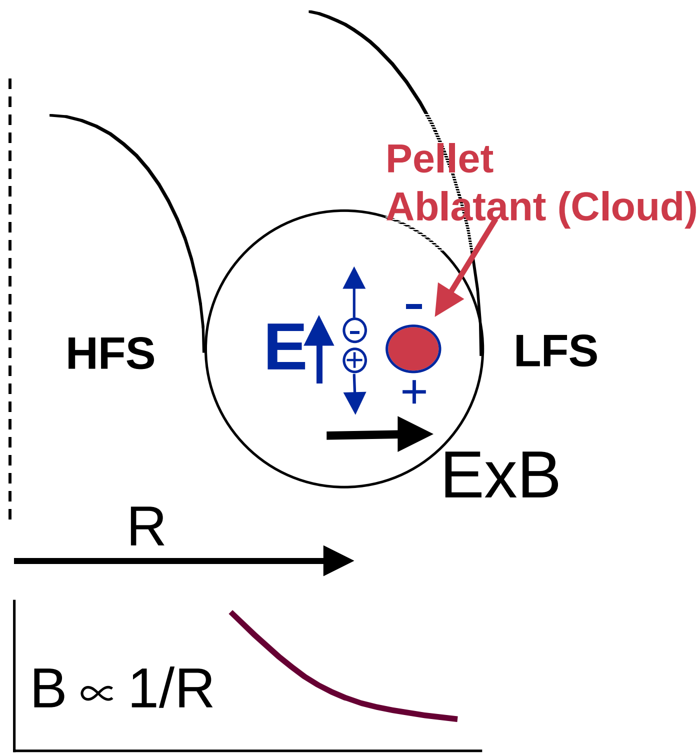
LFS - 55%

- 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)

Theoretical Model for Pellet Radial Drift

ExB Polarization Drift Model of Pellet Mass Deposition

(Rozhansky, Parks)

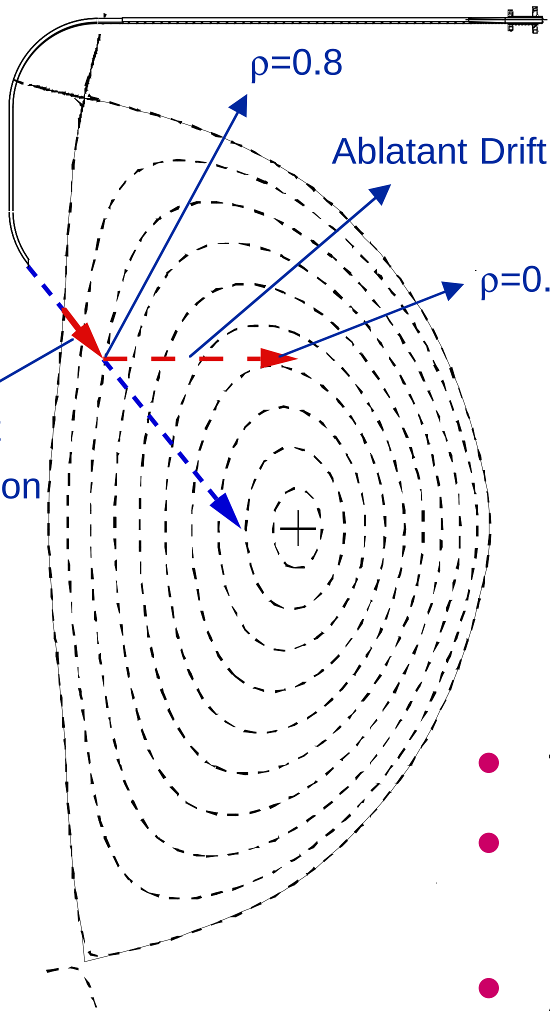


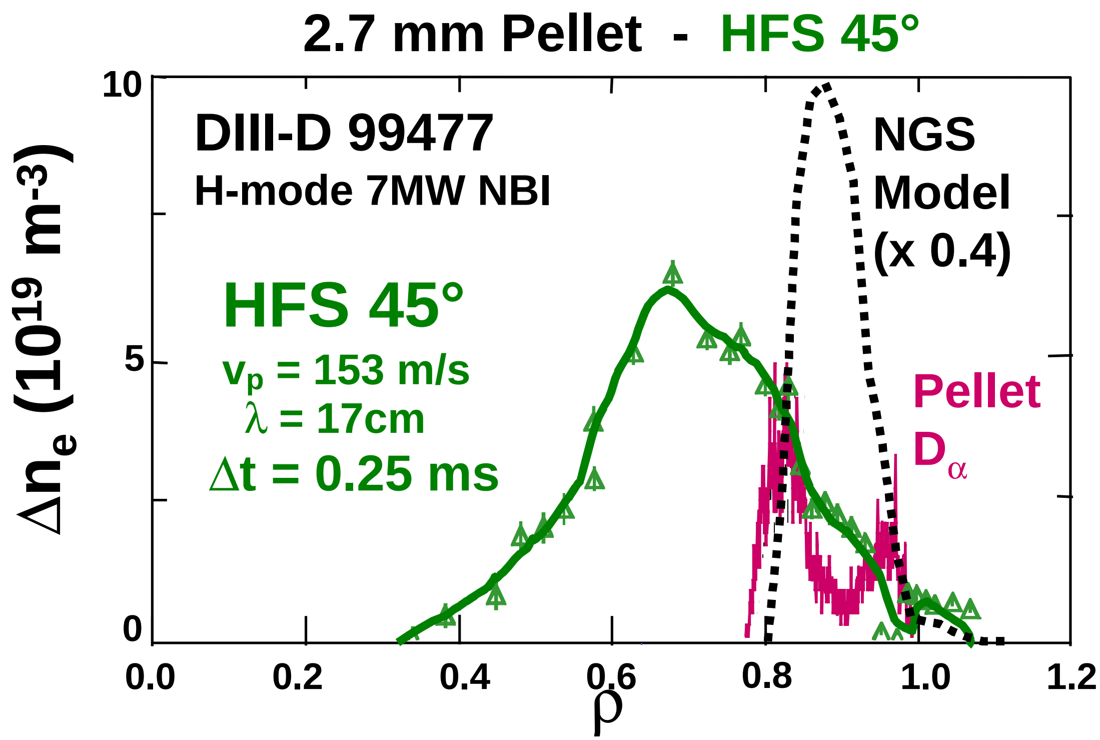
- Polarization of the ablatant occurs from ∇B and curvature drift in the non-uniform tokamak field:

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

- 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).)

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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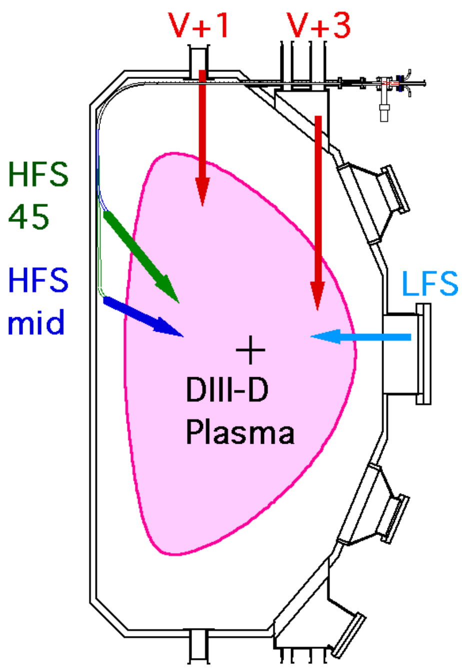
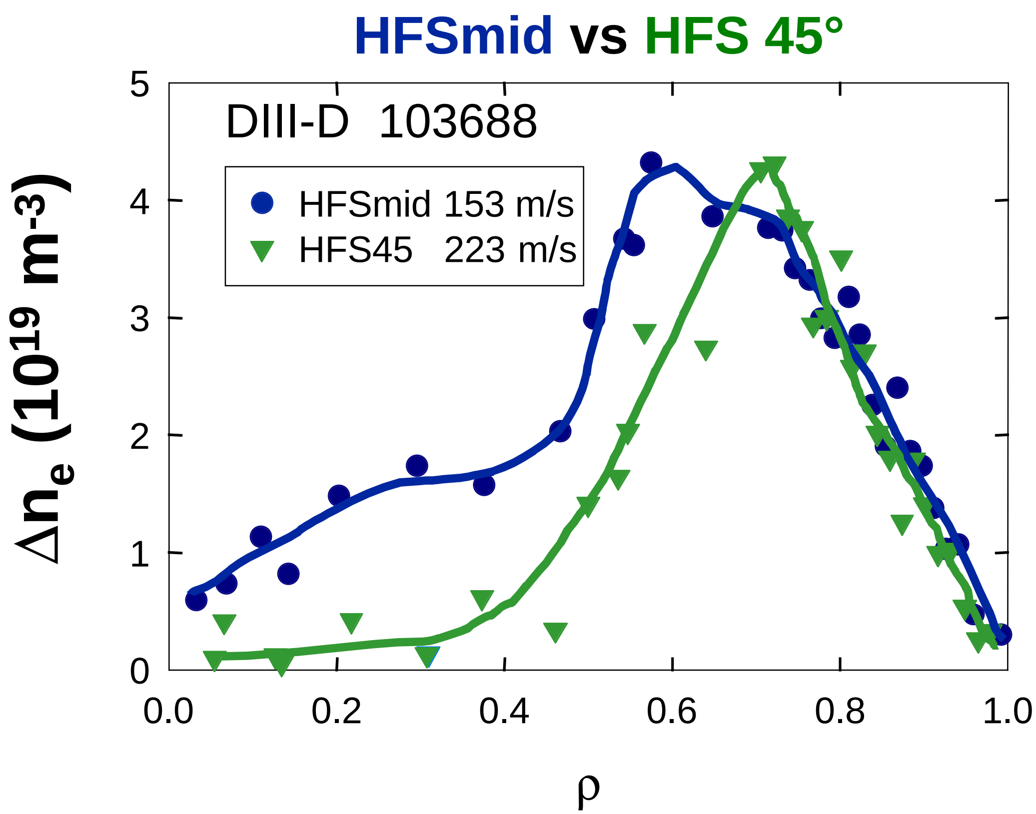
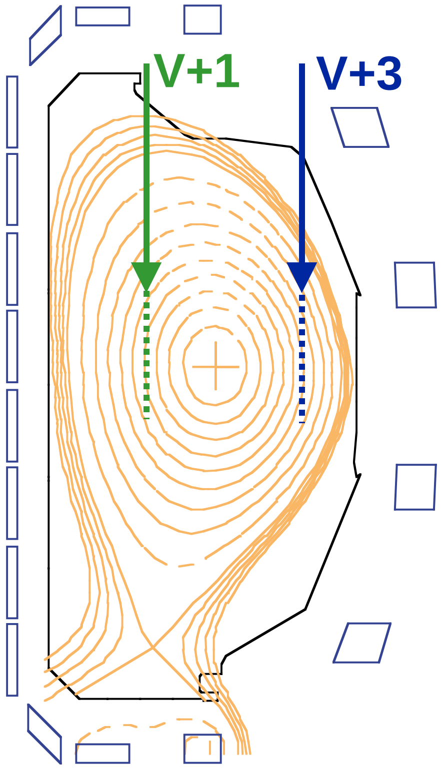
Preliminary HFS Comparison
HFSmid Yields Deeper Deposition than HFS45

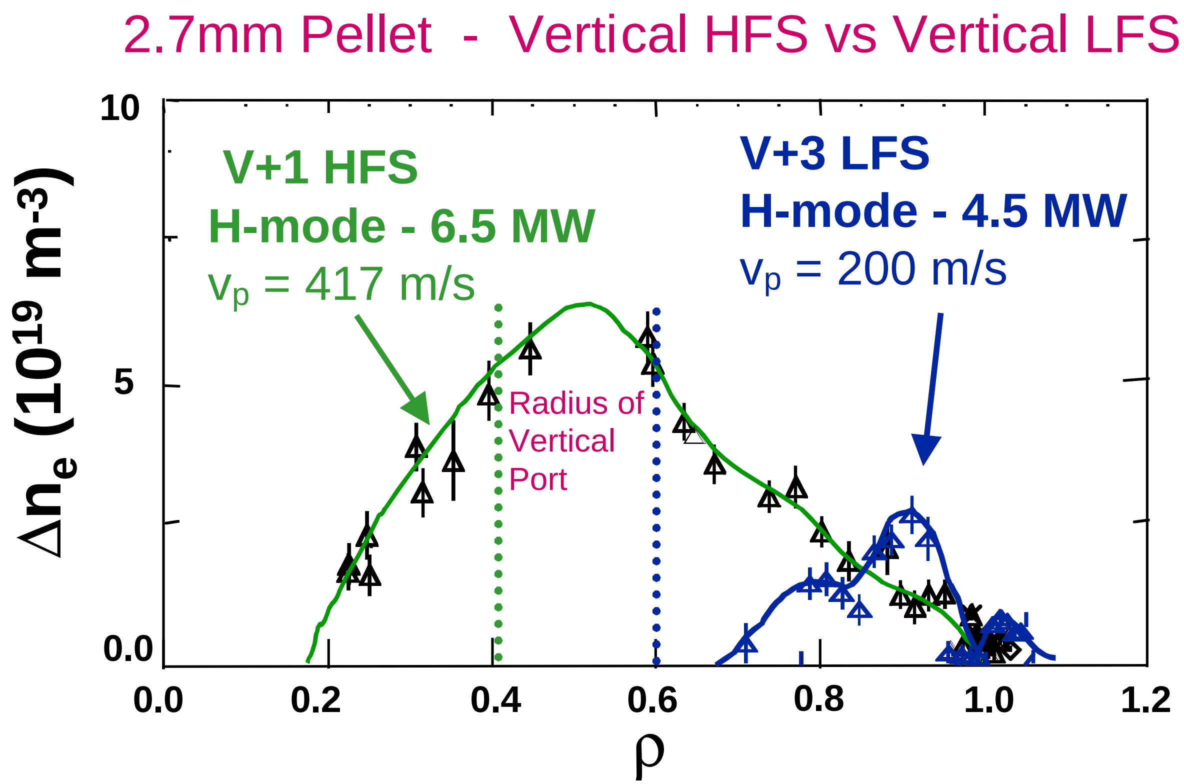




- A direct comparison of same size 2.7mm pellets in the same shot shows shows slightly deeper fueling from HFSmid than from HFS45 trajectory

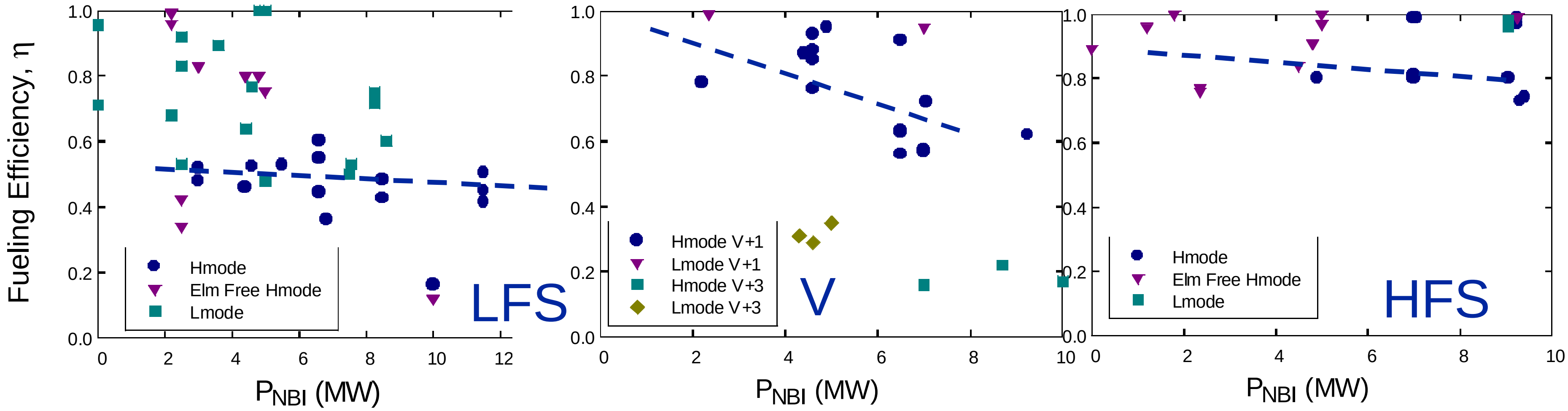
Both Vertical HFS and LFS Pellet Injection are Consistent with an Outward Major Radius Drift of Pellet Mass





- 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.

HFS Pellet Injection on DIII-D Yields Higher Fueling Efficiency than LFS Pellets



LFS Fueling Efficiency in H-mode ~ 50%

V+1 Fueling Efficiency in H-mode ~ 60-90 %

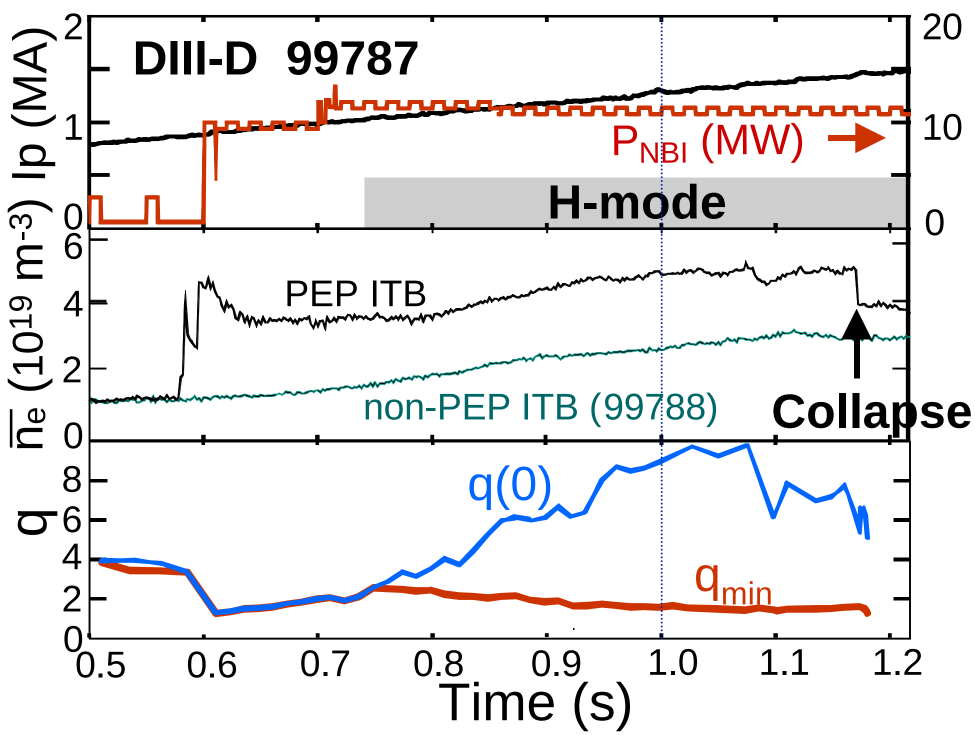
HFS Fueling Efficiency in H-mode ~ 90%

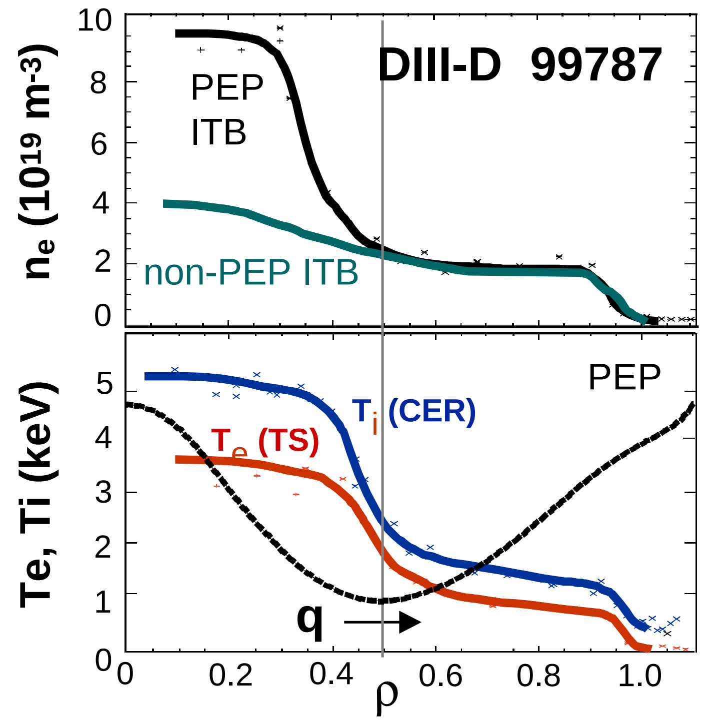
- HFS injection exhibits almost ideal fueling efficiency.
- Vertical injection provides higher fueling efficiency than LFS injection.
- LFS pellet fueling efficiency affected by major radius drift and by pellet ELM interaction.

Application of Pellets for Transport Barrier Formation: Internal Barriers

- **PEP-mode** - overview and transport summary
  - HFS pellets produce peaked density profile with $T_i \approx T_e$
  - Internal transport barriers can be produced both with strong Negative Central Shear (NCS) and weak internal shear (WS) depending upon pellet timing and beam timing and direction relative to the plasma current
  - Pellets provide a tool to produce core transport barriers with parameters unobtainable by other methods thus providing a wider range to test physics of barrier formation and sustainment
  - Baylor, et al, IAEA 2000

HFS Pellets During Current Rise Lead to Internal Transport Barrier - PEP mode





- HFS 2.7mm pellets injected during current rise produce highly peaked density profiles that develop PEP ITB with $T_i \approx T_e$
- PEP survives transition to H-mode and can persist for > 1s
- Core collapse occurs as q_{min} reaches 3/2
- Steepest n_e, T_e, T_i gradients occur inside ρ_{qmin}

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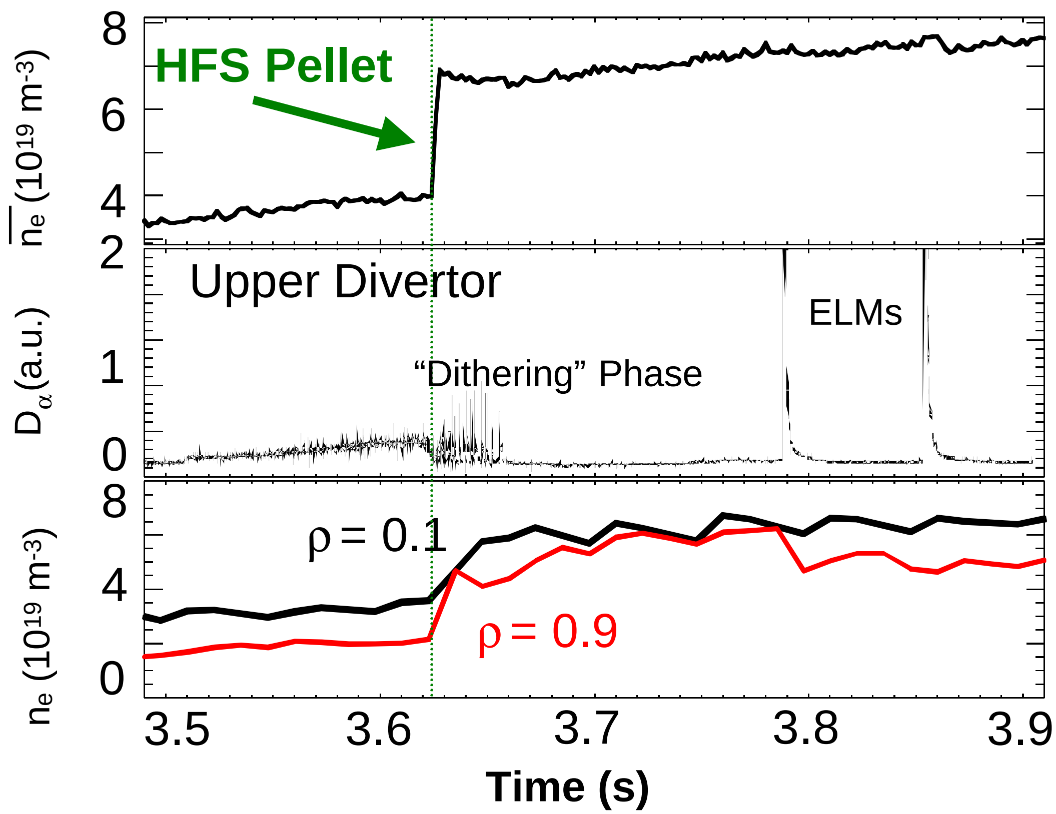
Application of Pellets for Transport Barrier Formation: Edge Barriers

- PIH-mode - pellet induced H-mode overview
  - Pellets have reduced H-mode power threshold by up to 33%
  - Pellets enable test of transition theory
  - Steep edge density gradient is necessary for H-mode transition
  - However, injection location and extent of deposition not critical to the transition
  - Gohil, et al, to be published in Phys Rev Lett

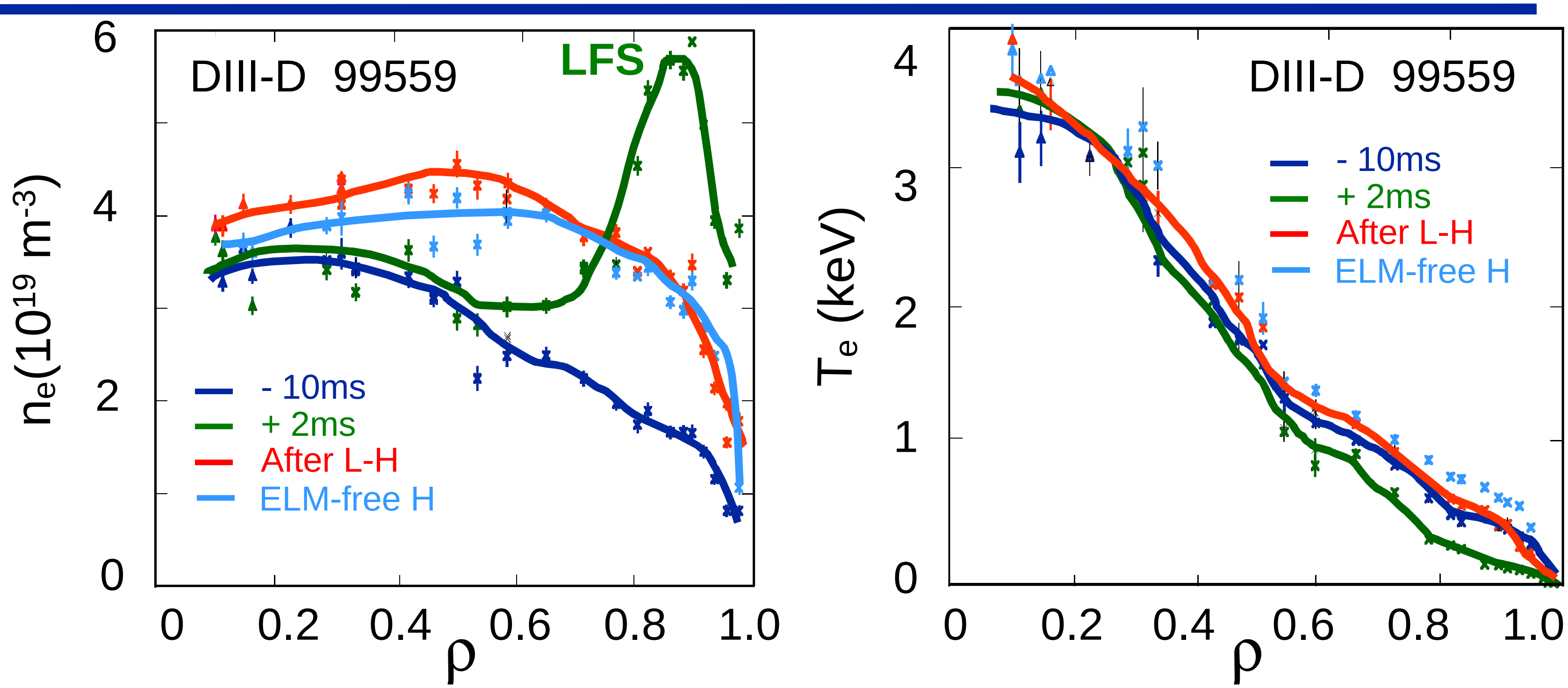
HFS Pellets have induced H-mode Transitions



L-mode Target
4.8MW NBI
Upper Single Null

- HFS pellet induces H-mode transition that is maintained
- H-mode power threshold reduced by 2.4MW (up to 33%) using pellet injection (Gohil,P. submitted for publication)

Pellet Induced H-mode Transition Occurs at Lower Edge Temperature



- A critical edge temperature is not indicated in these H–mode transitions
  - Edge T_e and T_i are reduced following pellet injection
- Pellet induced H–modes have L-H transitions at plasma parameters far below theoretical predictions

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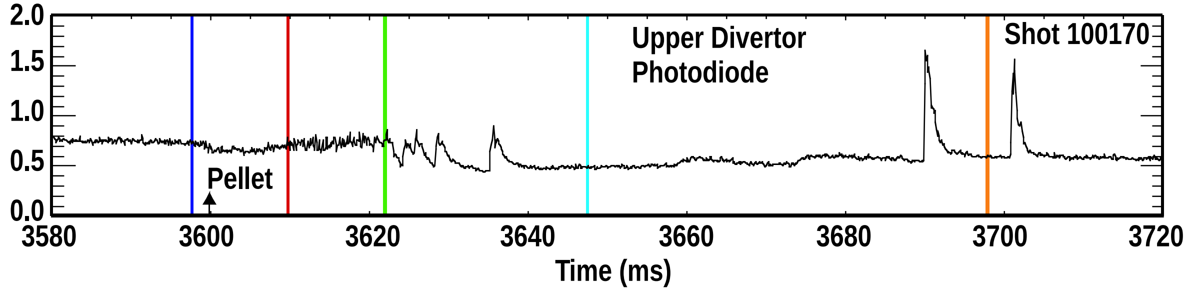
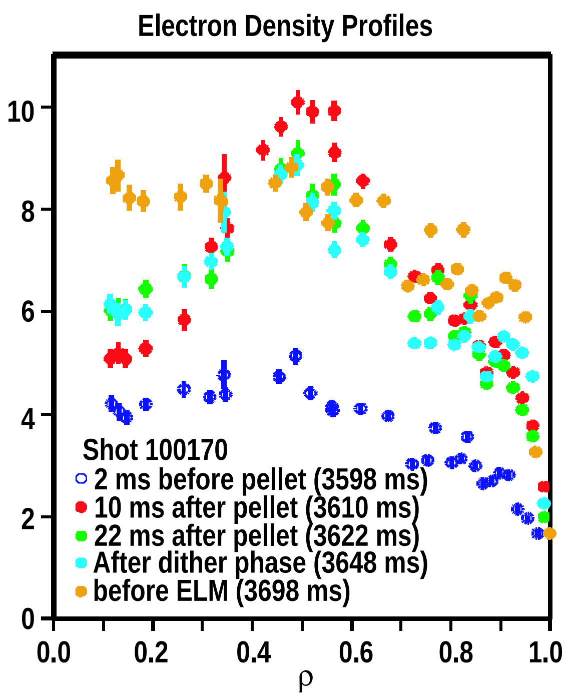
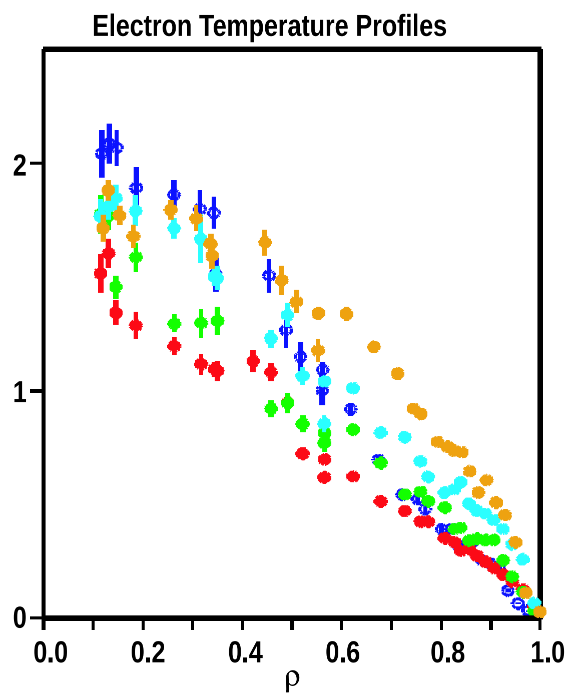
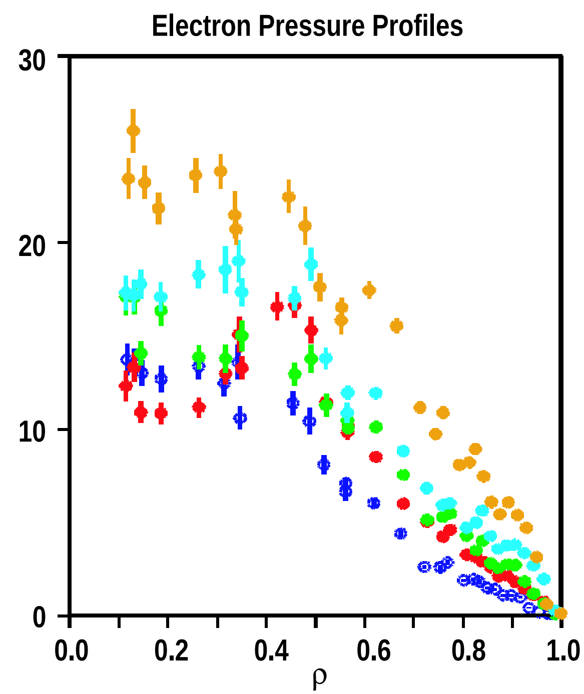
The HFS Pellet Penetrates Much Further, But Still Produces A Significant Density Gradient At The Plasma Edge









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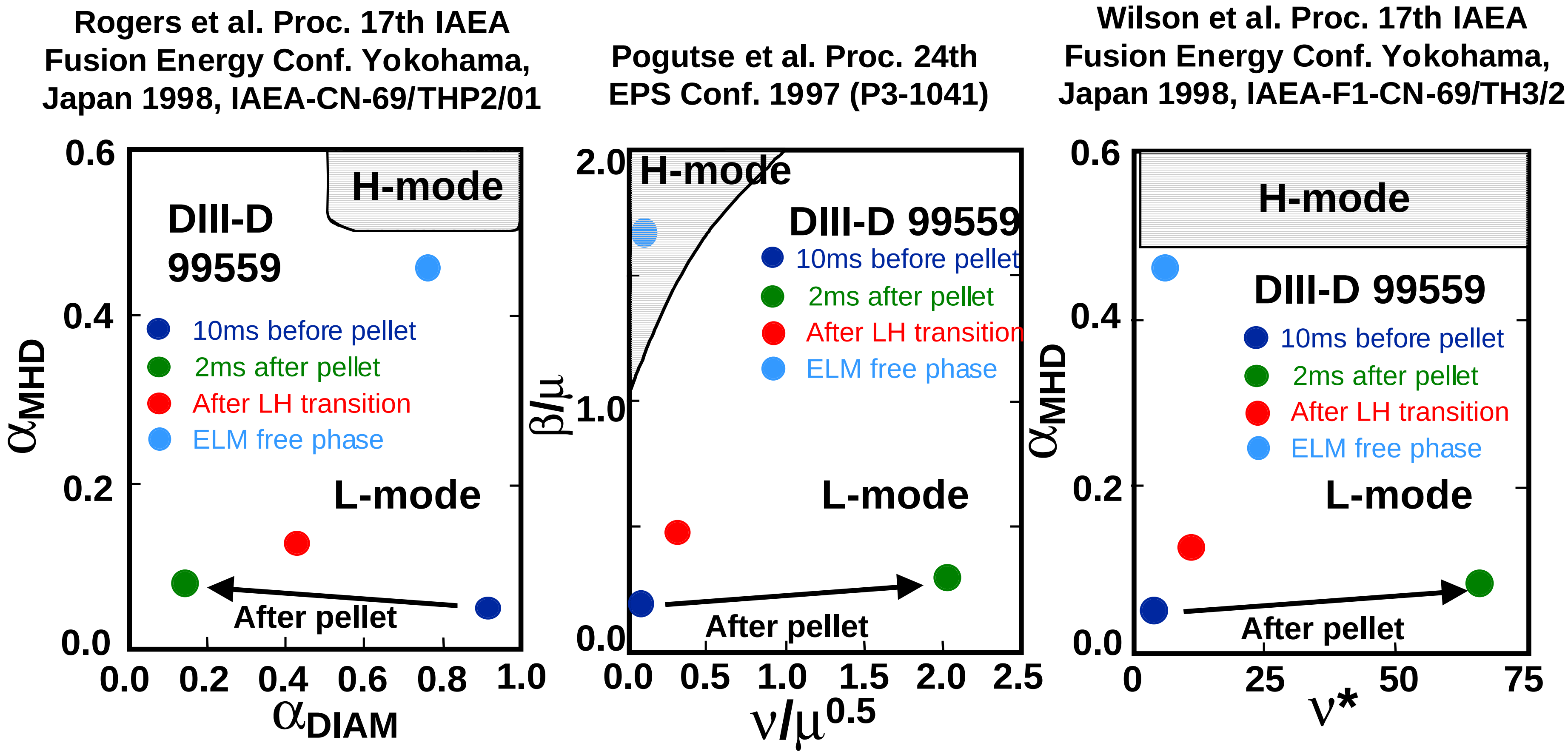
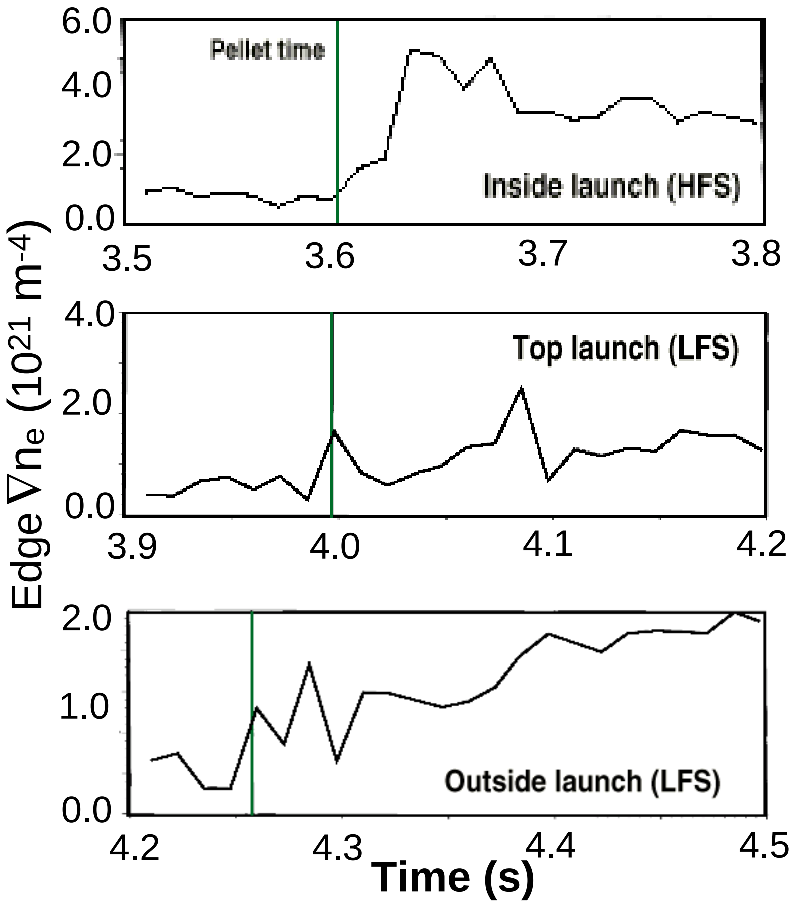
Pellet Induced H-modes have Transitions at Plasma Parameters far Below Theoretical Predictions



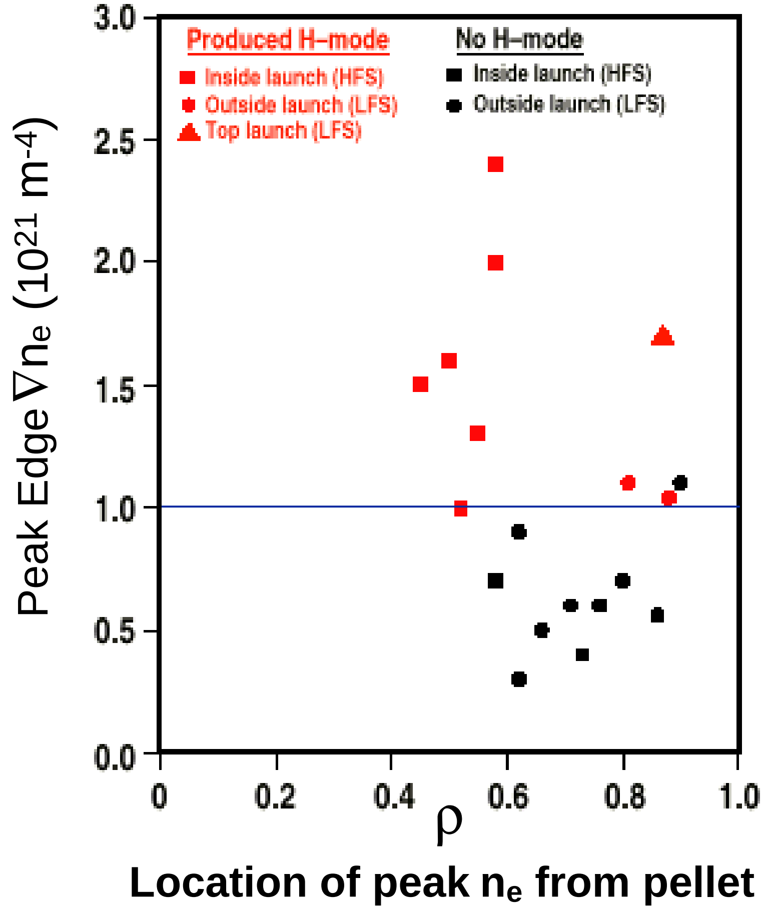
- Comparison of experimental edge local parameters with predictions from theories of H-mode transitions.

A Steep Edge Density Gradient is Necessary for the H-mode Transition

Value of Edge ne is critical



No correlation with deposition extent



- Extent of the pellet deposition is not important for H-mode transition but a threshold gradient of $1X10^{21}$ m^{-4} appears critical

Conclusions

- HFS injection ports installed on DIII-D and 2 guns modified for slower pellet speeds (v_{pellet} < 200 m/s) to take advantage of the radial drift and lead 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
  - ExB polarization drift model is appears qualitatively correct, but there is insufficient data for a quantitative evaluation

- The new HFS pellet injection tool has been applied successfully for:
  - PEP-mode ITB formation with $T_i \approx T_e$, (unlike other ITB regimes) and first measurement of E_r in PEP-mode
  - Triggers for L to H-mode transitions for reduced power threshold

- HFS pellet injection is unique enabling technology that has led to several areas of new physics understanding on DIII-D

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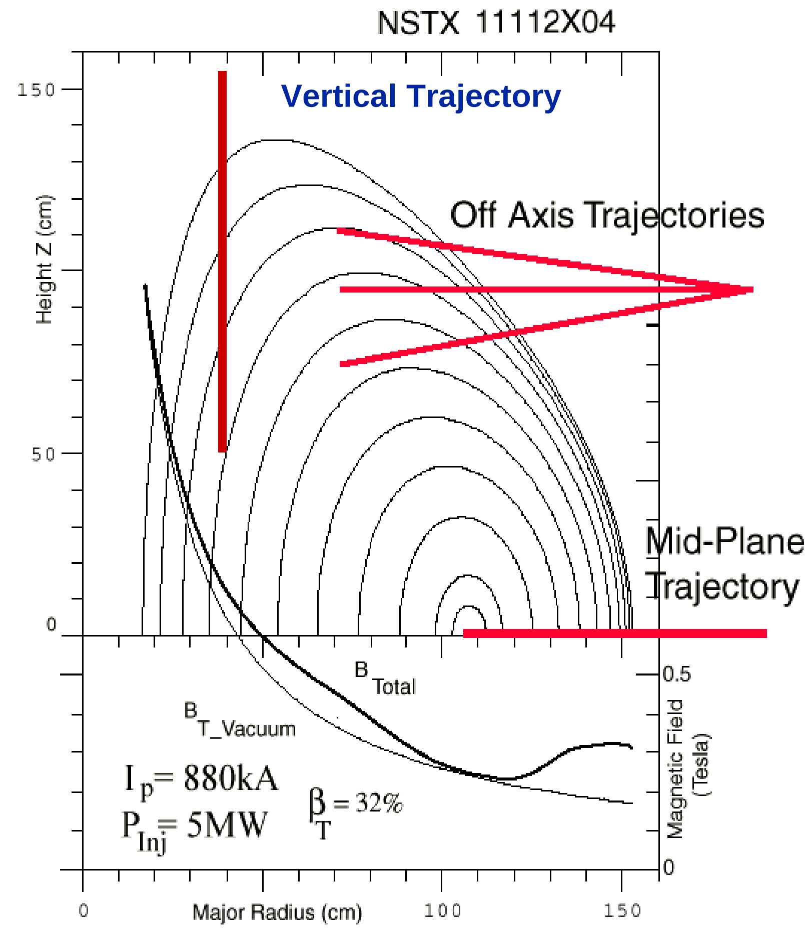
NSTX Application - Pellet Fueling System Will Extend NSTX Plasma Parameters and Capabilities

- Pellet injection will extend NSTX operating regime
  - START achieved $n_e(0)$ of $5x10^{20}$ m^{-3}, n_{GW} of 1.6 with vertical pellet injection
- Pellets will provide a potential advanced confinement regime trigger
  - Pellet induced H-mode (DIII-D), PEP-mode
- Pellet fueling system will provide a tool for core particle transport studies

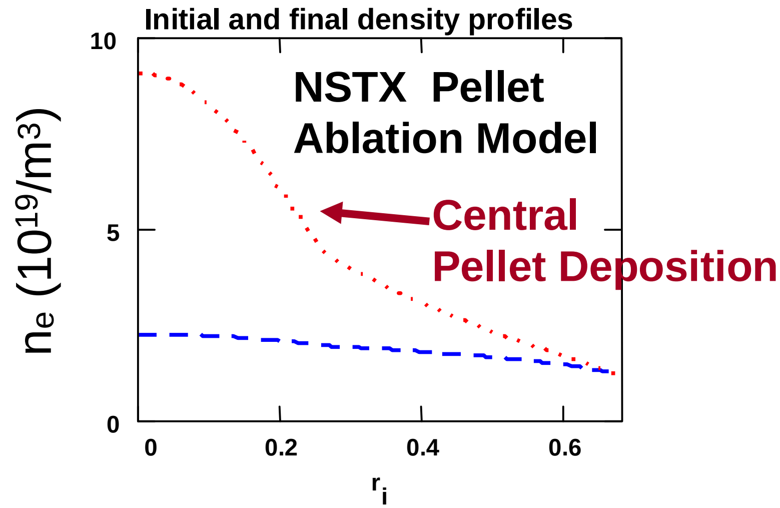
NSTX Application - Proposed Injection Geometry

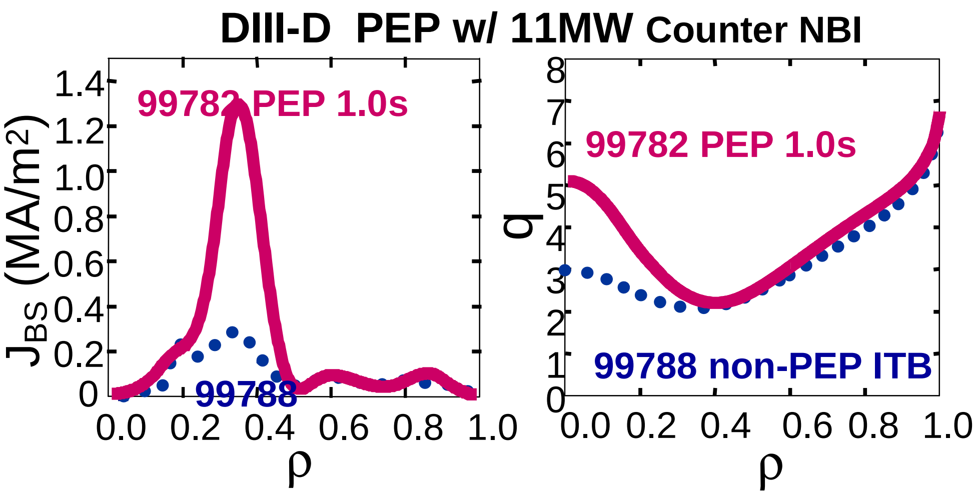
- Several injection trajectories can be used to investigate different NSTX physics objectives:
  - Outside midplane - ITB formation, density limit, transport, ∇B drift
  - Off axis - ITB formation with off axis shear in rotation
  - Vertical - HFS fueling, transport
- For NSTX, ∇B is inward on LFS in high beta cases, which may yield inward drift of pellet ablatant instead of outward drift seen in tokamaks.



Central penetration gives steep density gradients for advanced performance

- Example when pellet “expires” on axis :
  - 1.8mm, 1 km/s, $T_e(0)$ = 1.5keV
  - Shafranov shift reduces distance to axis
  - model uses self limiting ablation (finite heat reservoir of flux surfaces)
- Expected to produce strong off axis peaking of the bootstrap current and shear reversal as observed on DIII-D.





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PPPL

NSTX Application - Radial Electric Field Modification by Pellet Injection

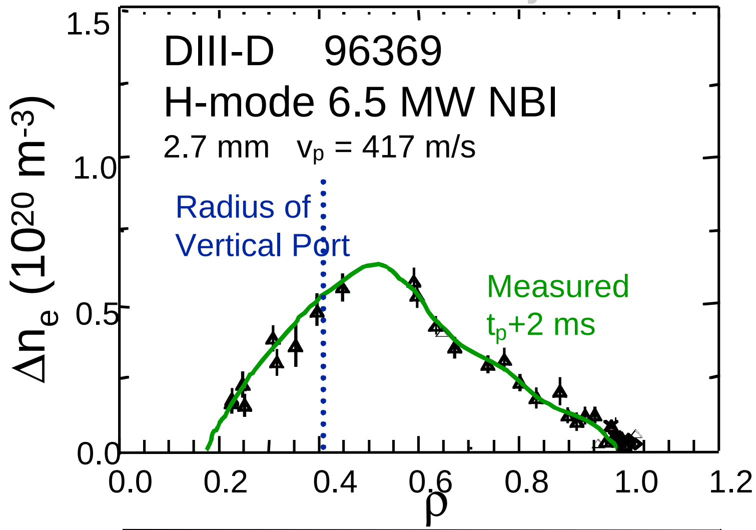
- The radial electric field can be modified by a pellet primarily due to the reduction in v_φ where there is strong mass deposition from the pellet. E_r from the radial force balance:

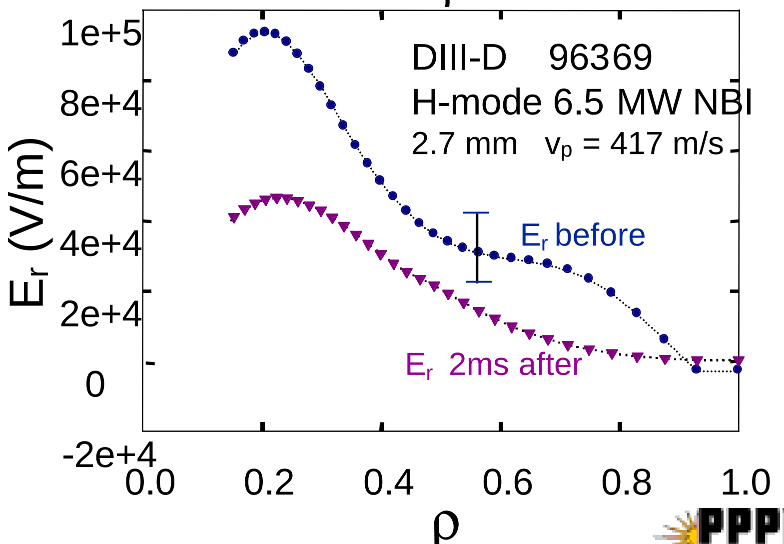
$$E_r = \nabla P/Zen + v_\varphi B_\theta - v_\theta B_\varphi$$

- Example from DIII-D shows strong change in Er induced by deep deposition of vertical HFS injected pellet.

- Partial penetration can lead to strong gradient in Er for barrier formation.

Vertical HFS Injection





NSTX Application - Highlights of Pellet Injector Features and Capabilities for Plasma Experiments

- **Flexible low-cost pipe-gun injector system proposed for installation on NSTX**
  - Number of pellets / size: 4 pellets / ~1.8 mm
  - Pellet speed: 200-1500 m/s
  - steerable injection line for central or off-axis density perturbation
- **Pellet injection tool applications:**
  - Extending operating regime to high density ($n >> n_{GW}$)
  - Particle confinement and transport studies
  - Peaked density profiles for PEP-mode ITB formation with $T_i \sim T_e$, (unlike other ITB regimes)
  - Off-axis density/rotation perturbation for ITB formation
  - Triggers for L to H-mode transitions for reduced power threshold