A Comparison of Fueling with Deuterium Pellet Injection from Different Locations on the DIII-D Tokamak

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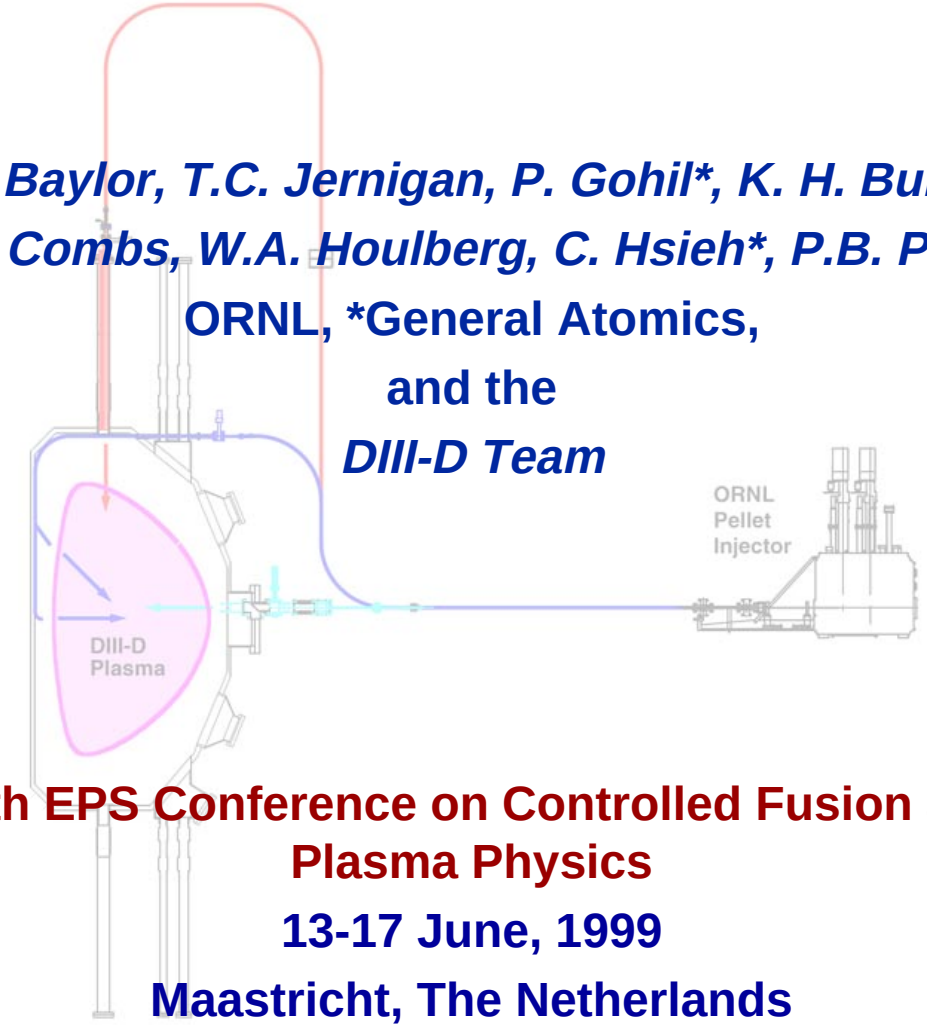

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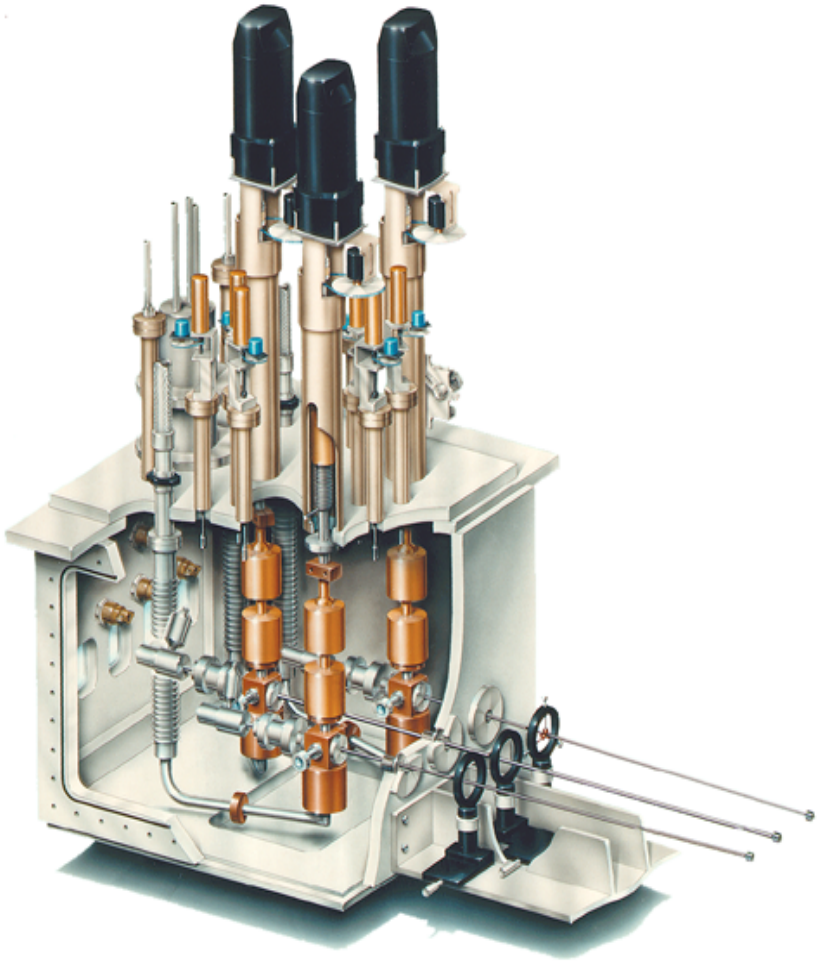
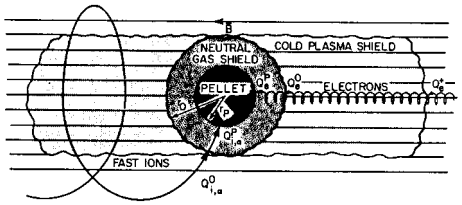
DIII-D Pellet Injection Program

- **Modifications to injector (that was installed on JET 1987-91):**
  - » **All three guns fire 2.7 mm pellets**
  - » **Punch mechanism on one gun to reliably generate slower pellets (<200 m/s)**
  - » **Second gun has oversized barrel that allows slow pellets**
- **2 independent guide tubes on inner wall (HFS) - one on midplane, one at 45 degrees - and one vertical.**
  - » **Can be connected to any of the pellet guns or a gas valve.**
- **Performance tests have been performed on curved guide tubes.**
- **Initial experiments on the vertical injection port were performed in 1998 and on the HFS ports in March-April 1999.**



Pellet Ablation Process is Well Characterized, but Resulting Mass Deposition is Anomalous

Pellet-Plasma Interaction



- **A neutral gas shield forms around the pellet from the heating of the pellet from the streaming plasma electrons.**
- **The neutral gas cloud serves as a heat shield.**
- **A cold plasma sheath forms from the ionized neutrals in the could. The plasma sheath is frozen into the background magnetic field. It too shields the incoming electron heat flux.**
- **A detailed analysis of the model (Milora, Parks) yields an ablation rate that scales as:**

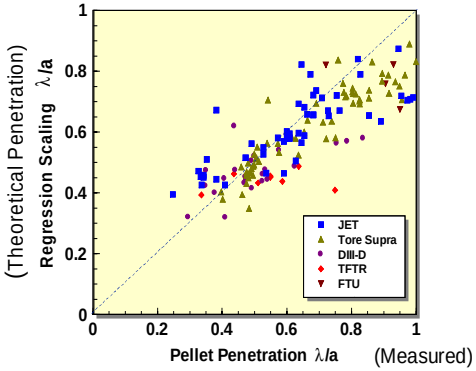
$$\frac{dr_p}{dt} \propto T_e^{1.64}\, n_e^{0.33}\, r_p^{-0.67}$$

- **Penetration depth assuming linear temperature and density profiles then scales like:**

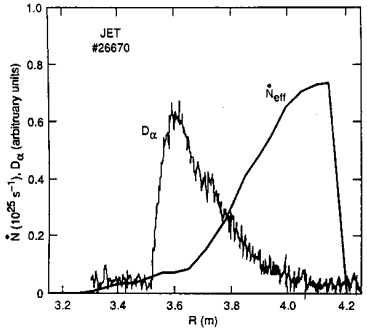
$$\frac{\lambda}{a} \propto T_e^{-5/9}\, n_e^{-1/9}\, r_p^{5/9}\, v_p^{1/3}$$

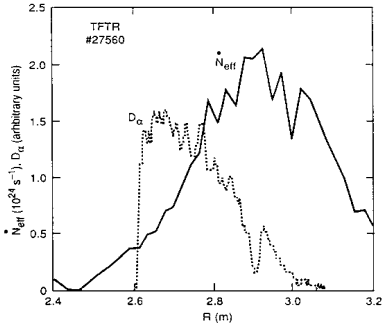
Note the weak dependence on plasma density and pellet velocity.

Penetration and Deposition



- **A comparison of the measured penetration depth with the calculated depth agrees well over a range of data from many devices. (**Nucl. Fusion 37, 445 (1997) **)**

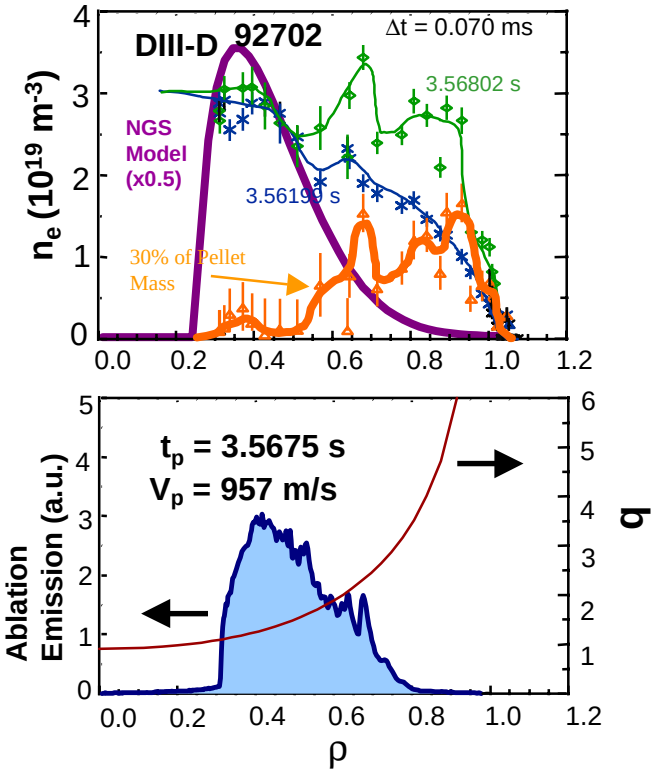




- **A comparison of the ablation light emission (which qualitatively matches the theoretical ablation rate) with the effective ablation rate from the deposition showed a strong outward shift for these low field side injected pellets. (**Nucl. Fusion 32, 2177 (1992) **)**

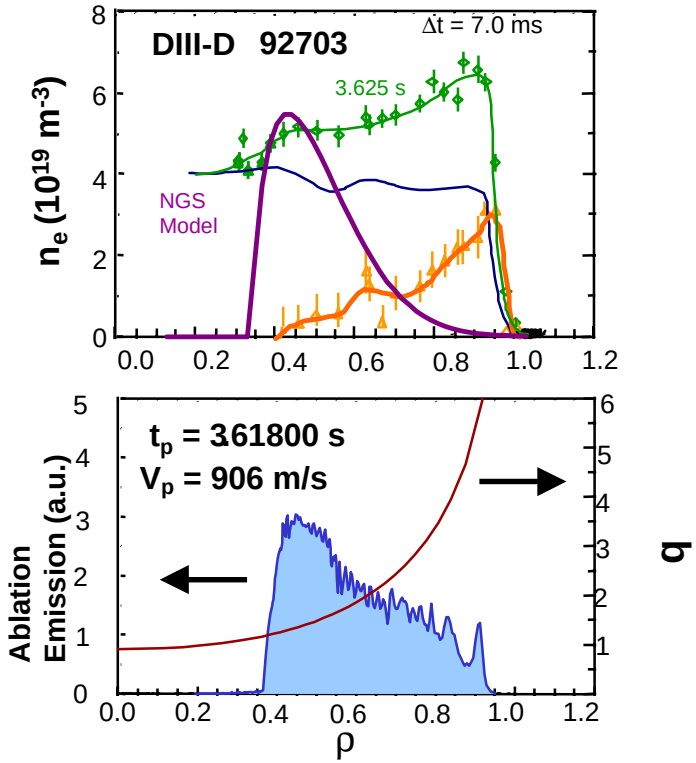
Pellet Deposition Profile from LFS Injection is Anomalous on DIII-D

L-mode



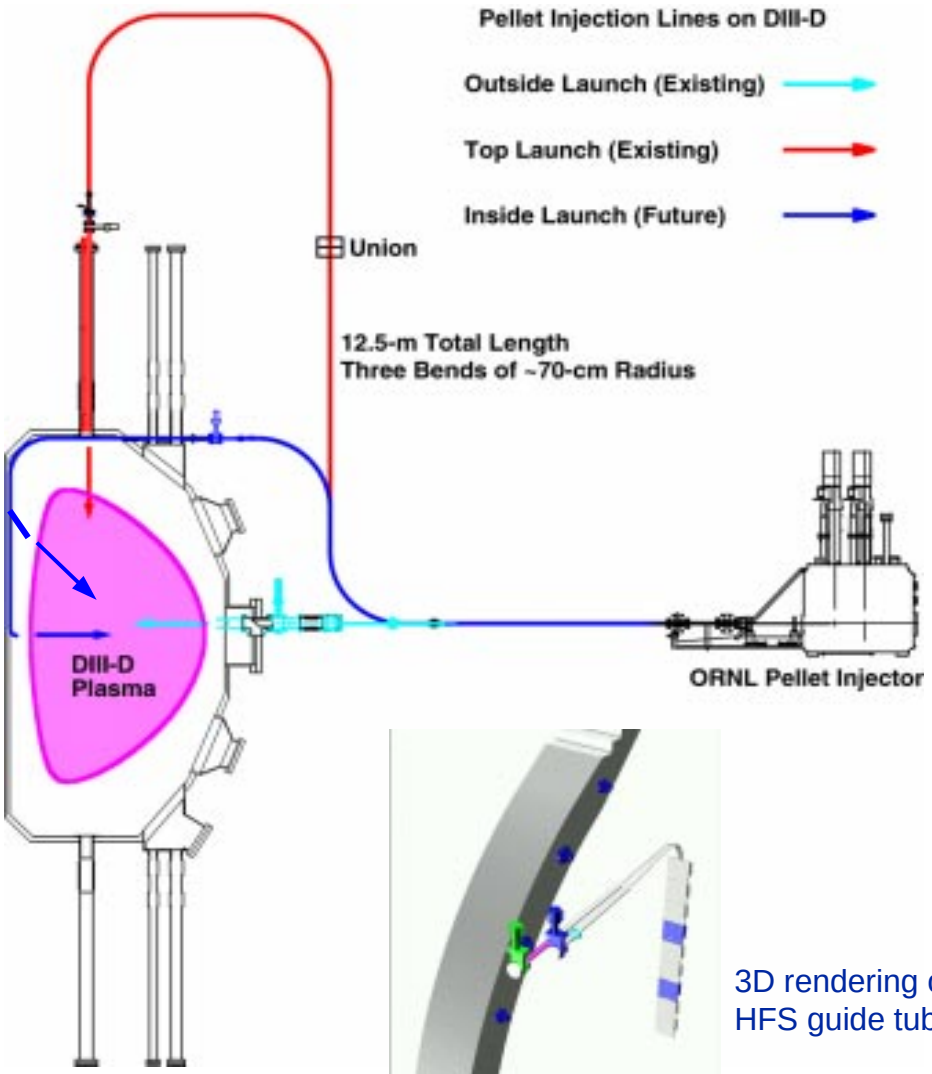
- The deposition of a 2.7 mm pellet (9x10^{20} atoms) in an L-mode plasma (4.8 MW NBI) determined from Thomson scattering density measurement 0.070 ms after ablation of the pellet.

H-mode



- The deposition of a 2.7 mm pellet (9x10^{20} atoms) in an ELM-free H-mode plasma (4.8MW NBI) from Thomson scattering density measurement 7.0 ms after ablation of the pellet.

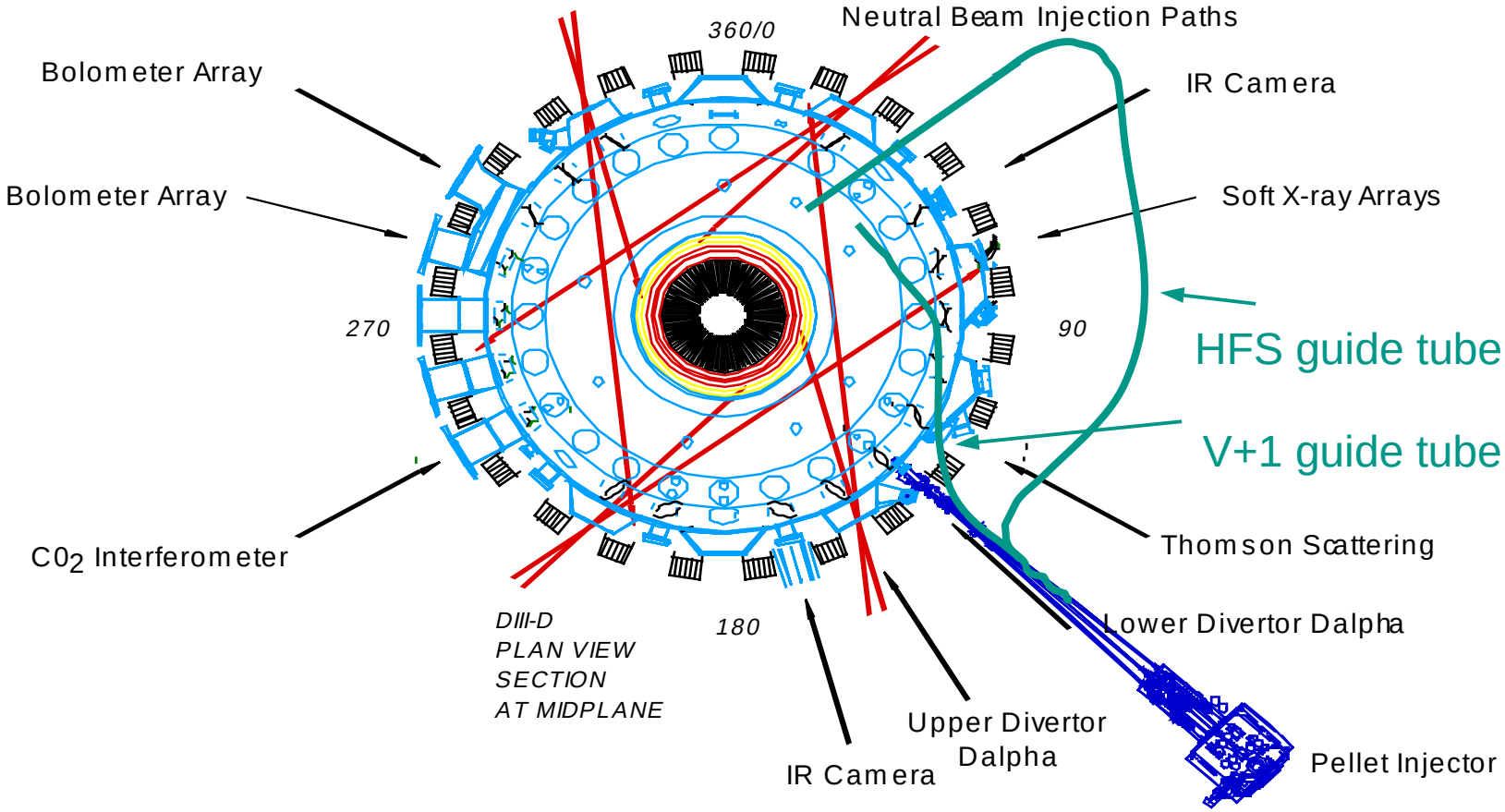
Layout for Pellet Injection Locations



3D rendering of internal HFS guide tubes.

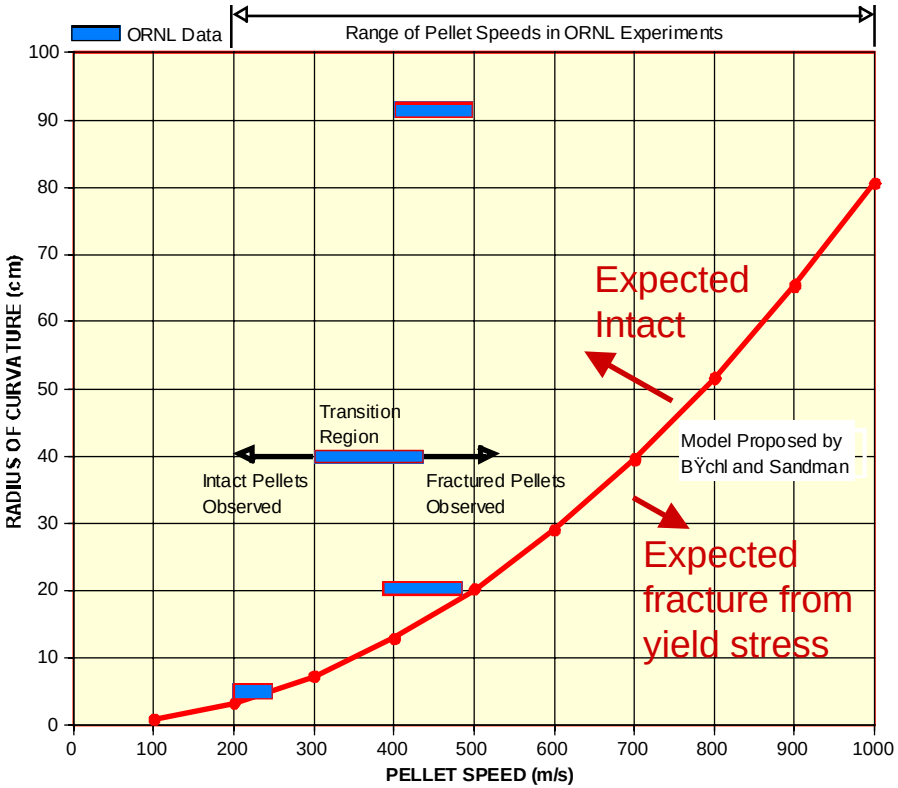
- Curved guide tubes are being used to connect the existing ORNL pellet injector to vertical ports and upper horizontal ports for HFS injection.
- Initial experiments with HFS injection have been performed in 1999. (EPS P1.048)

DIII-D Pellet Launch Diagnostic and Locations - Vertical and HFS Launch ~90° Toroidally from Injector



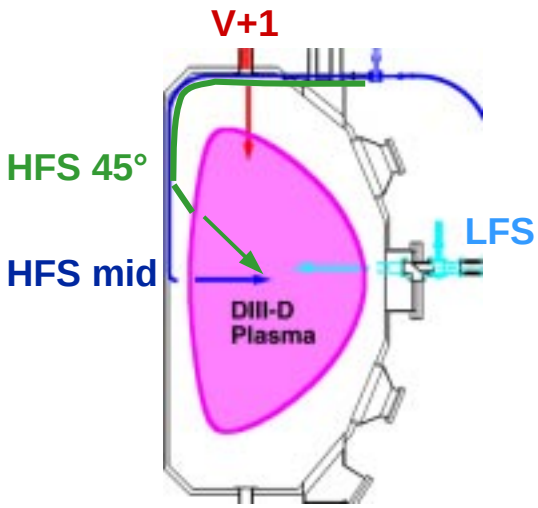
Pellet Integrity Through Curved Guide Tubes

- **ORNL curved guide tube tests:**
  - » **For sharp bends (<15 cm), pellet integrity appears to follow the stress limit curve**
  - » **For weaker bends the integrity of pellets is worse than expected from the stress limit and it is difficult to maintain intact pellets above 400-500 m/s**
  - » **Indications are that the high velocity limit is due to multiple collisions with tube walls**

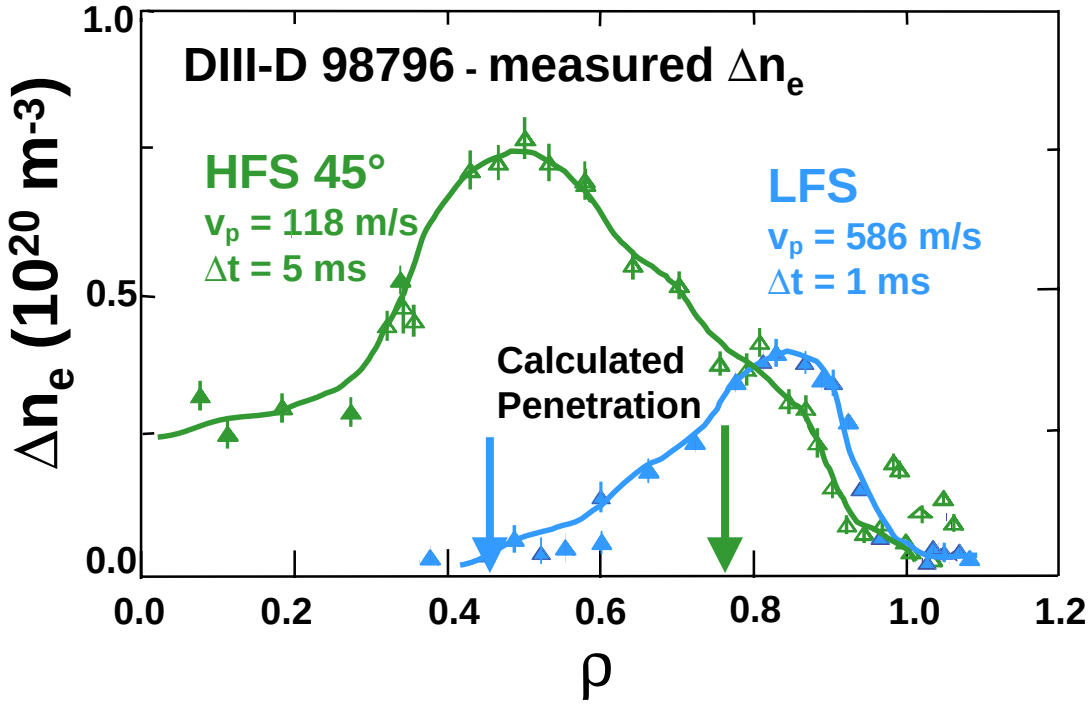


High Field Side (HFS 45°) Pellet Injection on DIII-D Yields Deeper Particle Deposition than LFS Injection

2.7 mm Pellets - HFS 45° vs LFS



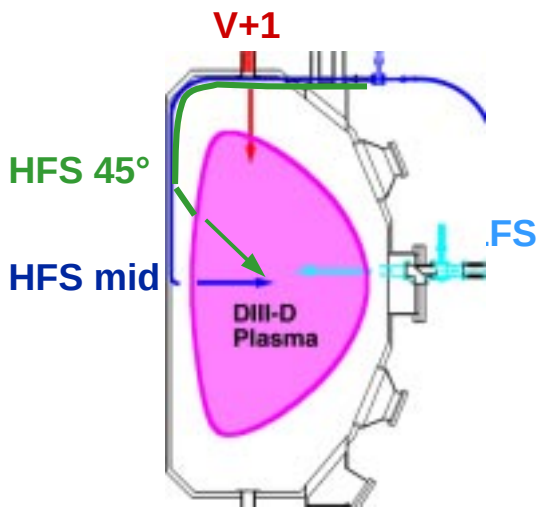
Four positions of pellet injection guide tubes installed on DIII-D

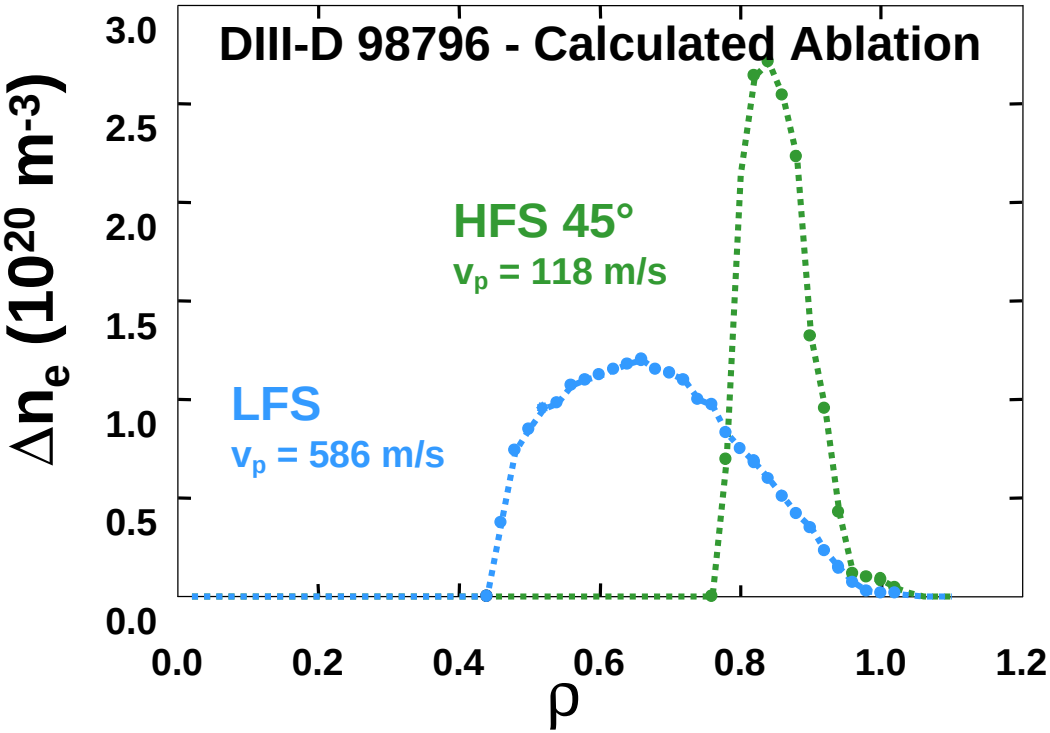


- Net deposition is much deeper for the lower velocity HFS 45° pellets.
- The pellets were injected into the same discharge under the same conditions (ELMing H-mode, 4.5 MW NBI, $T_e(0)$ = 3 keV).
- Net deposition profile - Thomson Scattering 1-5 ms after injection.

PELLET Ablation Code Predicts LFS Pellet Injection is Deeper than HFS 45° Injection

2.7 mm Pellets - HFS 45° vs LFS

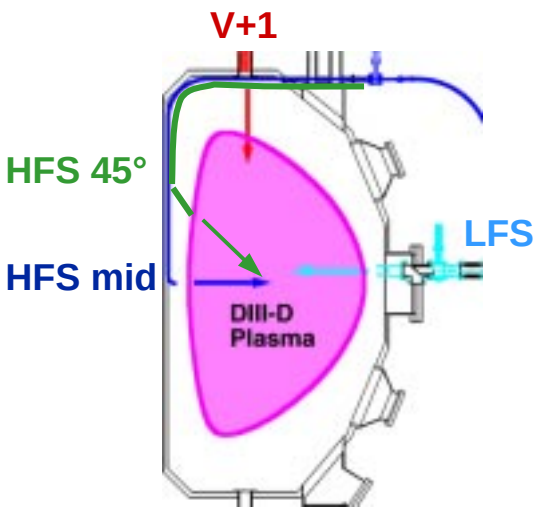


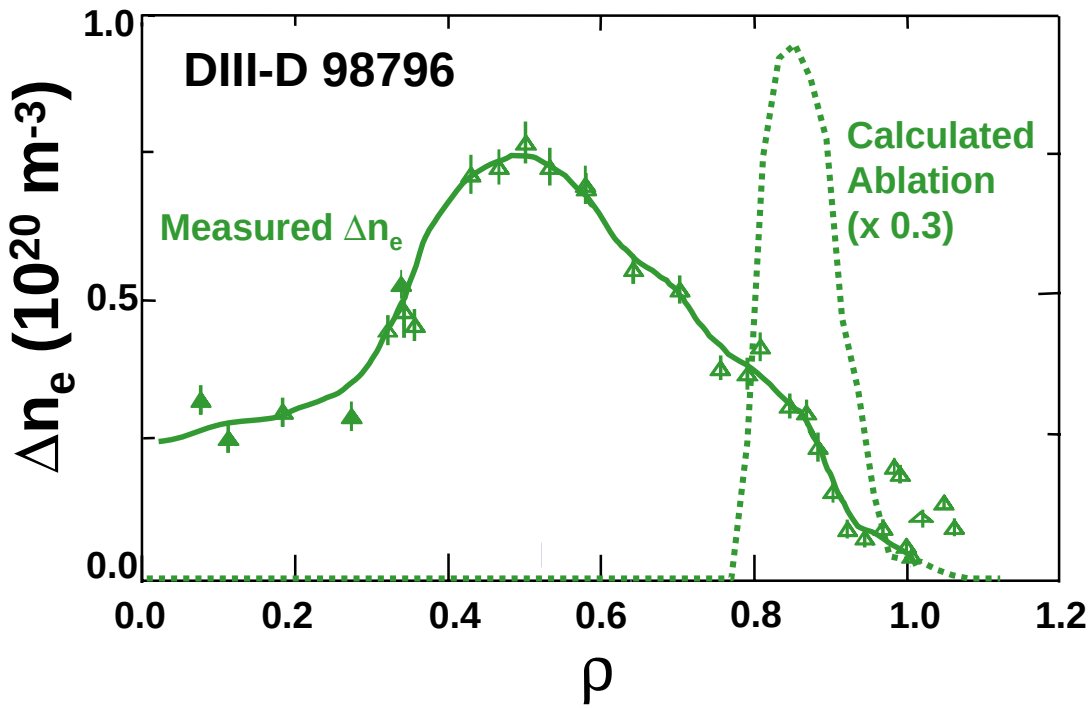


- The calculated HFS 45° penetration is much shallower than the calculated LFS penetration.
- Ablation profile - calculated by the PELLET code (NGPS ablation model, no radial drift), using measured v_p and plasma profiles.

DIII-D HFS 45° Pellet Injection Yields Much Deeper Particle Deposition than Expected

2.7 mm Pellet - HFS 45°

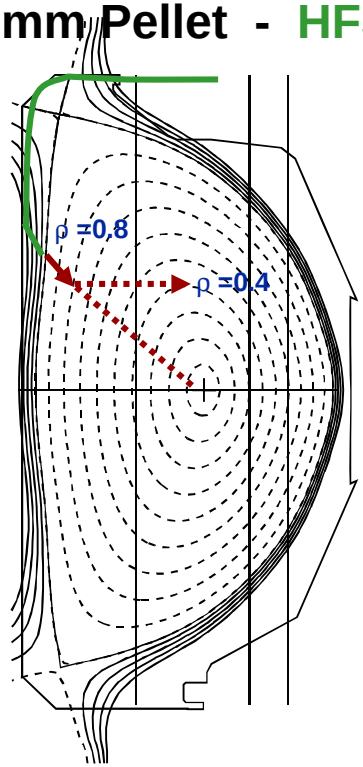


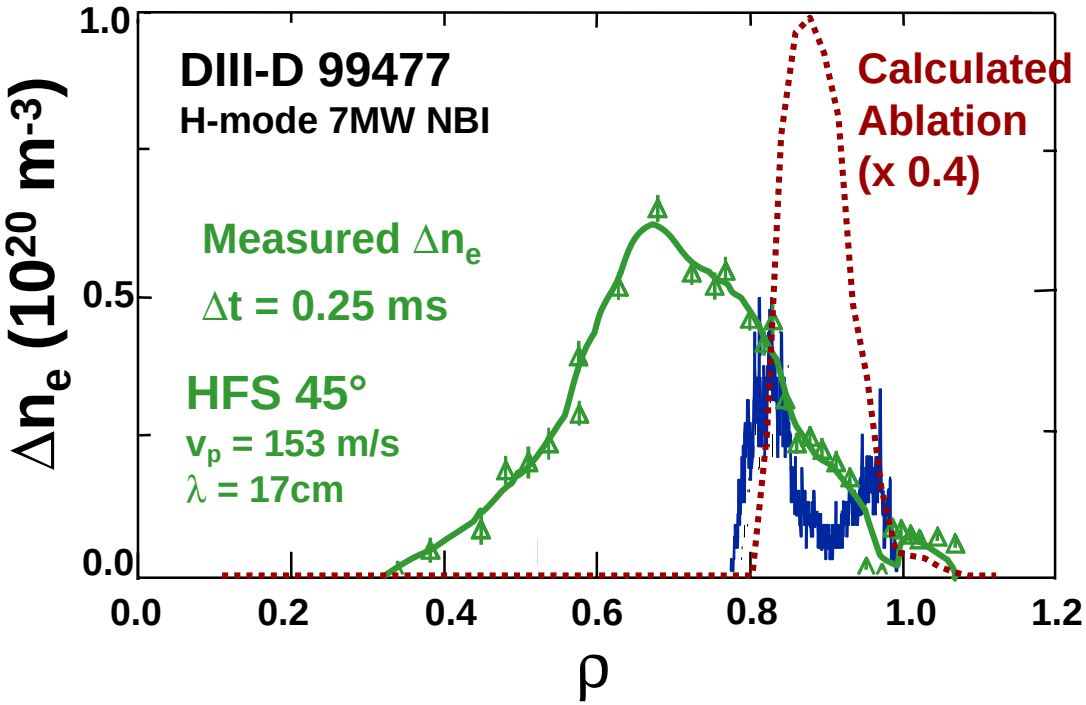


- The net deposition indicates fueling to the axis, while the ablation model indicates only partial penetration.
- Net deposition profile - measured by TS 5 ms after injection.
- Ablation profile - calculated by PELLET.

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

2.7 mm Pellet - HFS 45°

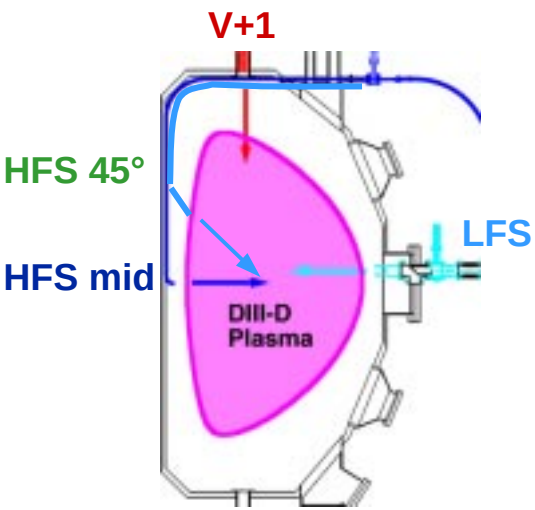


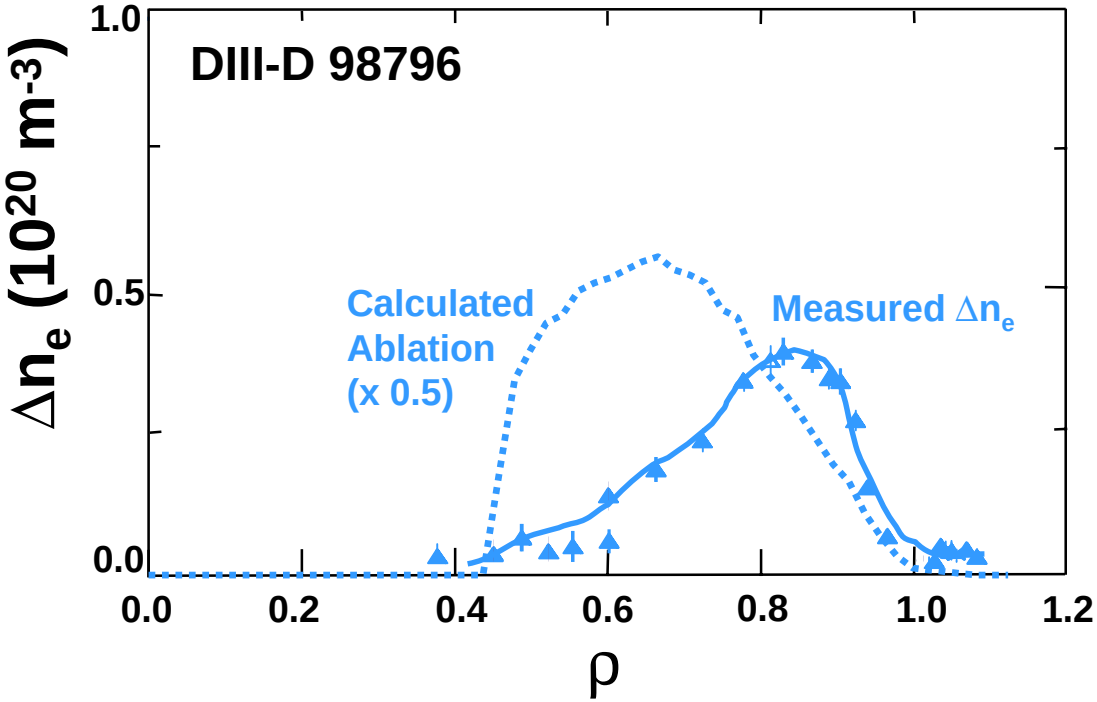


- The net deposition indicates deeper fueling than pellet light emission which agrees with ablation model penetration depth.
- Net deposition profile - measured by TS 0.25 ms after injection.
- Ablation profile - calculated by PELLET using measured profiles.

LFS Injection Yields Expected Penetration, but Exhibits and Outward Shift in Deposition and Mass Loss

2.7 mm Pellet - LFS

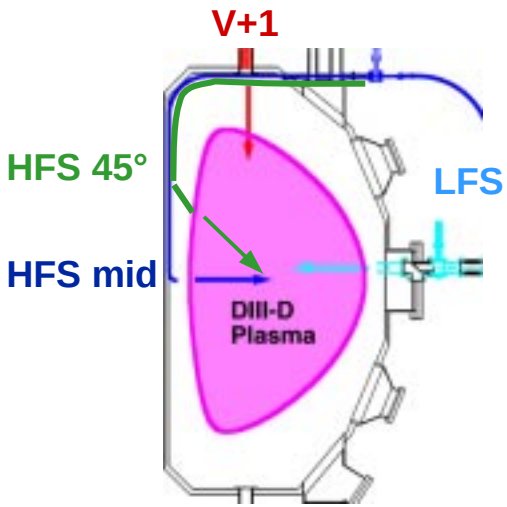


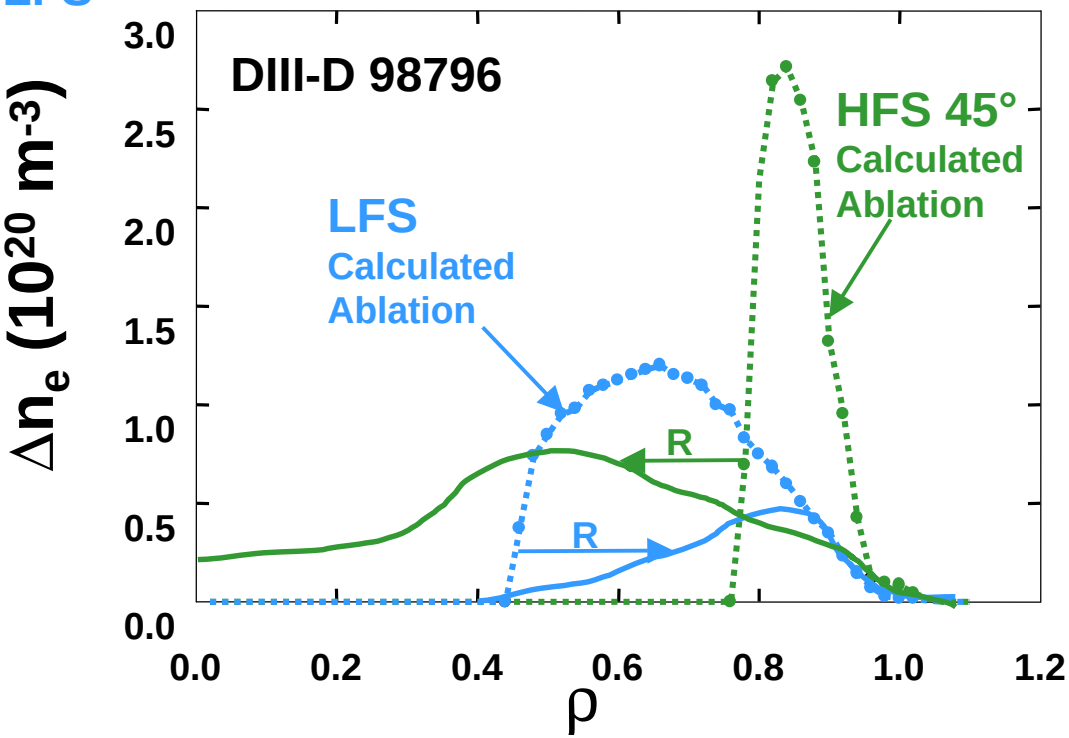


- The net deposition is shifted outward in minor radius and the integral is less than the injected mass.
- Net deposition profile - measured by TS 1 ms after injection.
- Ablation profile - calculated by PELLET.

The Difference Between Ablation and Net Deposition Profiles Indicates Major Radius Drift of Ablatant

2.7mm Pellets - HFS 45° vs LFS

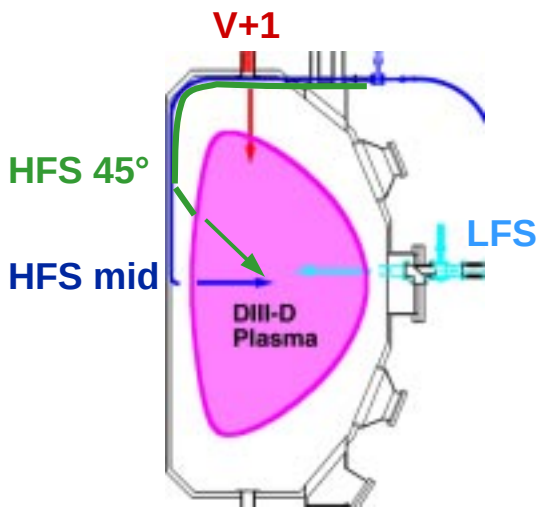


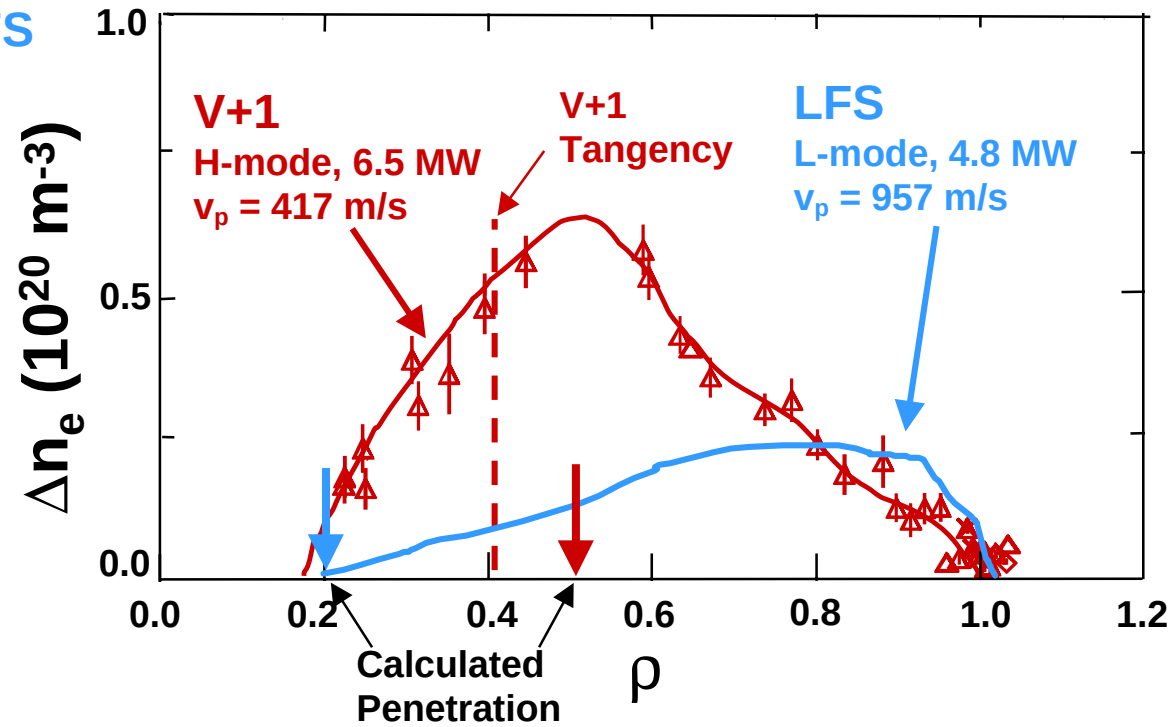


- The net deposition profile is consistent with a major radius drift from the calculated ablation profile.
- New D_α radiation monitors will help distinguish whether the ablation model needs to be amended or post-ablation drift added

DIII-D Vertical Pellet Injection DIII-D Yields Particle Deposition Inside the Tangency Radius of the V+1 Port

2.7mm Pellets - V+1 vs LFS

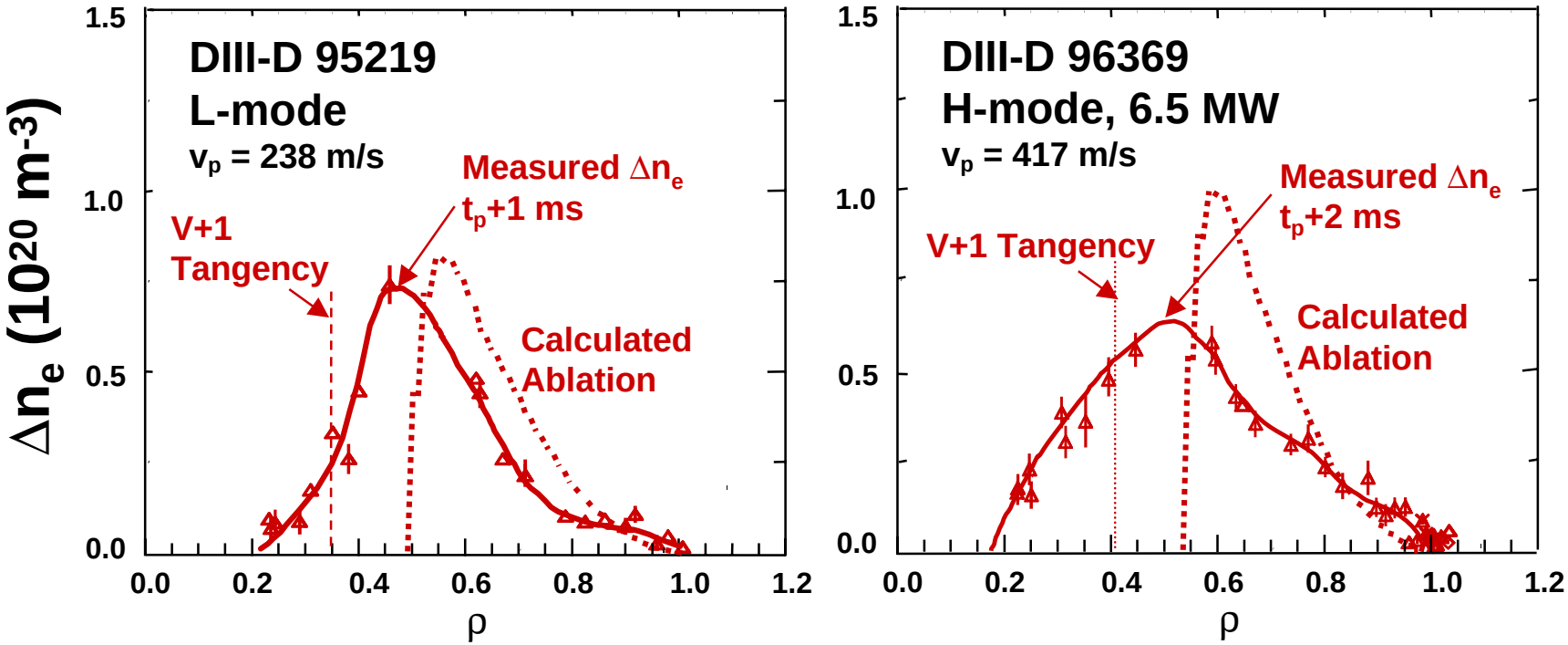




- The calculated penetration (PELLET code) is short of the midplane for the vertical injection, but mass appears inside that radius.
- The measured mass penetration for V+1 injection is comparable to the LFS case, but V+1 case has lower pellet velocity and higher NBI power.

DIII-D Vertical Pellet Injection in both L- and H-mode Yield Deeper than Expected Particle Deposition

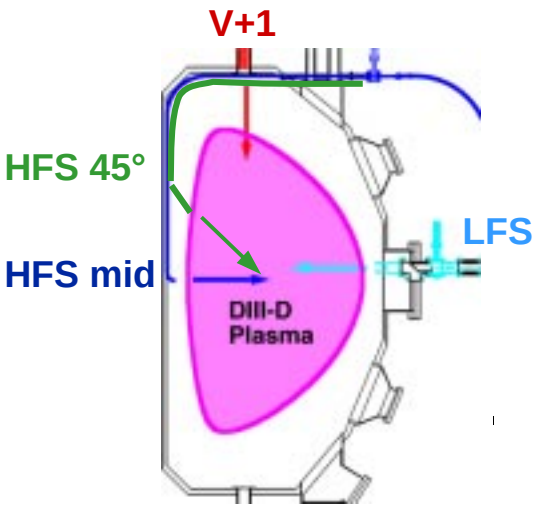
2.7mm Pellets - V+1

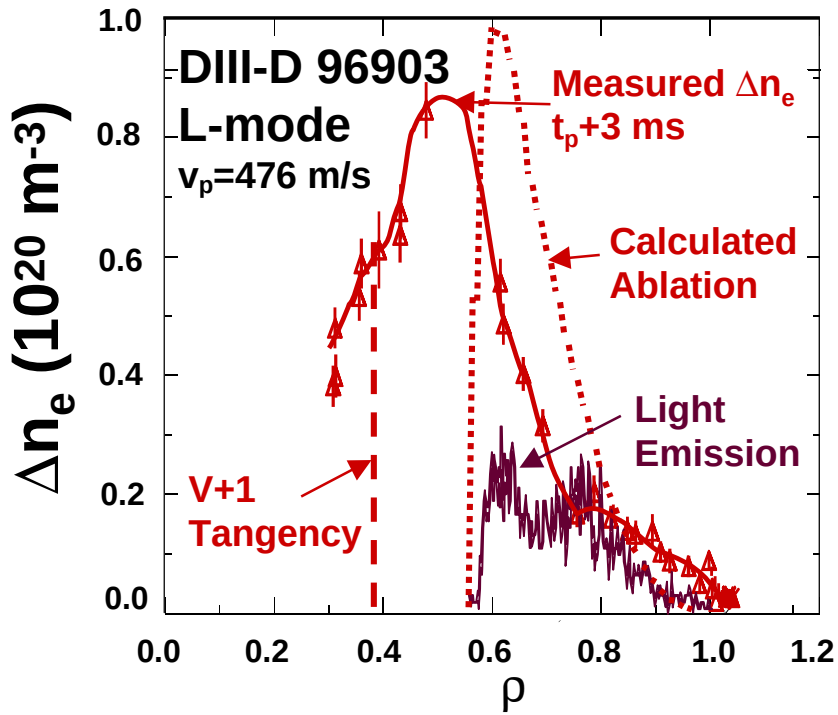


- Deposition is seen inside both the port radius and expected penetration penetration in both L-mode and H-mode.
- Ablation profile - calculated by PELLET.

Pellet Light Emission Indicates that Post-Ablation Drift of the Pellet Mass is the Cause of Deeper Deposition

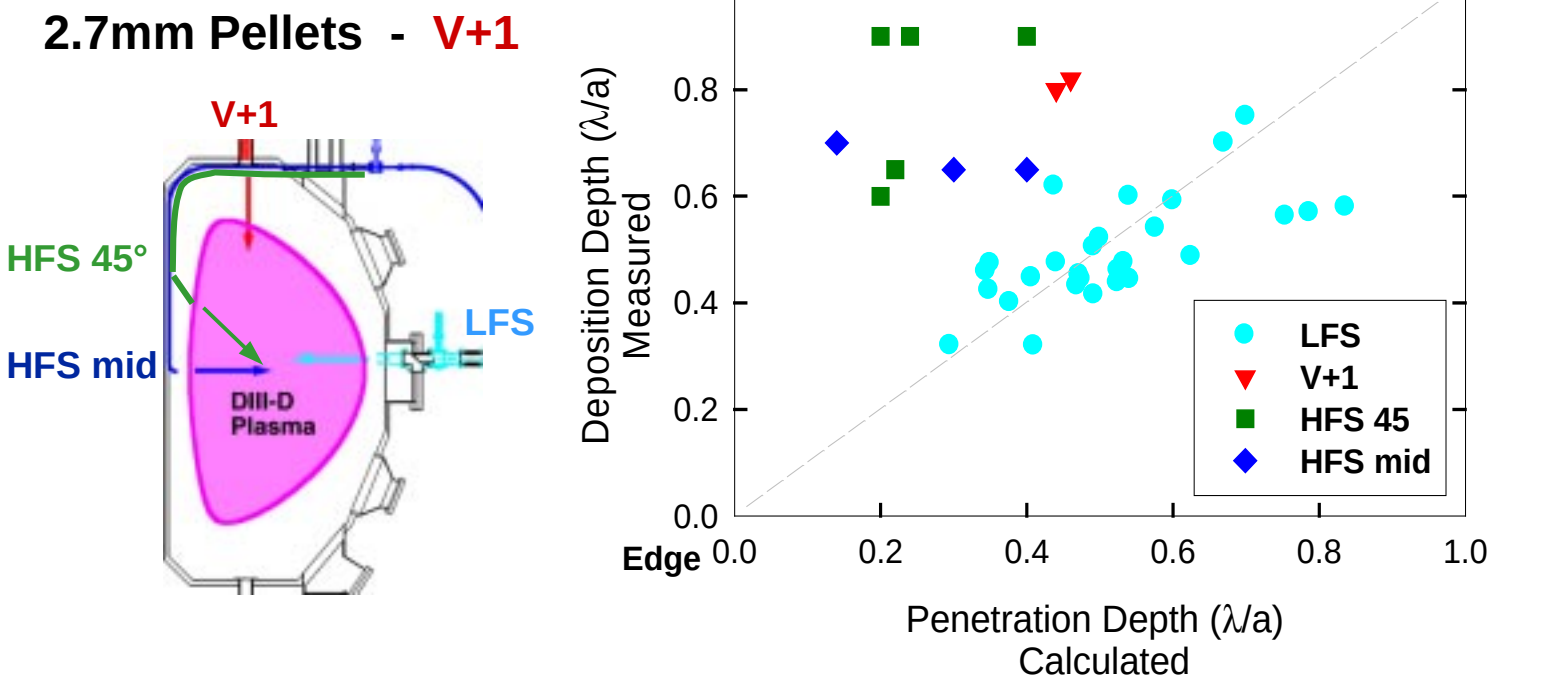
2.7mm Pellets - V+1





- The calculated pellet lifetime and duration of the deposition profile agree, but both are short of the measured net deposition.
- This indicates that post-ablation drift of the pellet mass is important.

HFS Pellet Injection on DIII-D
Yields Deeper Particle Deposition than Predicted

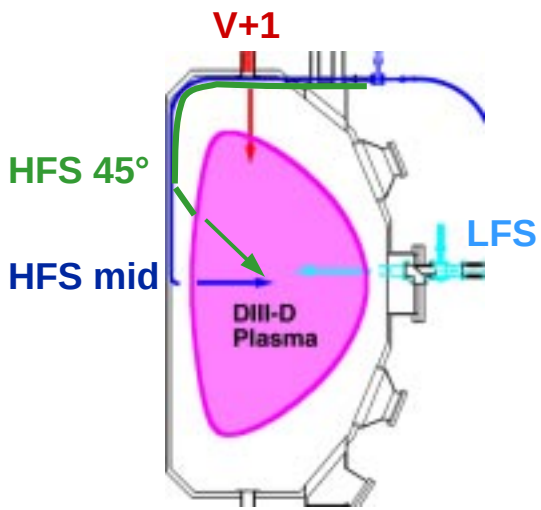


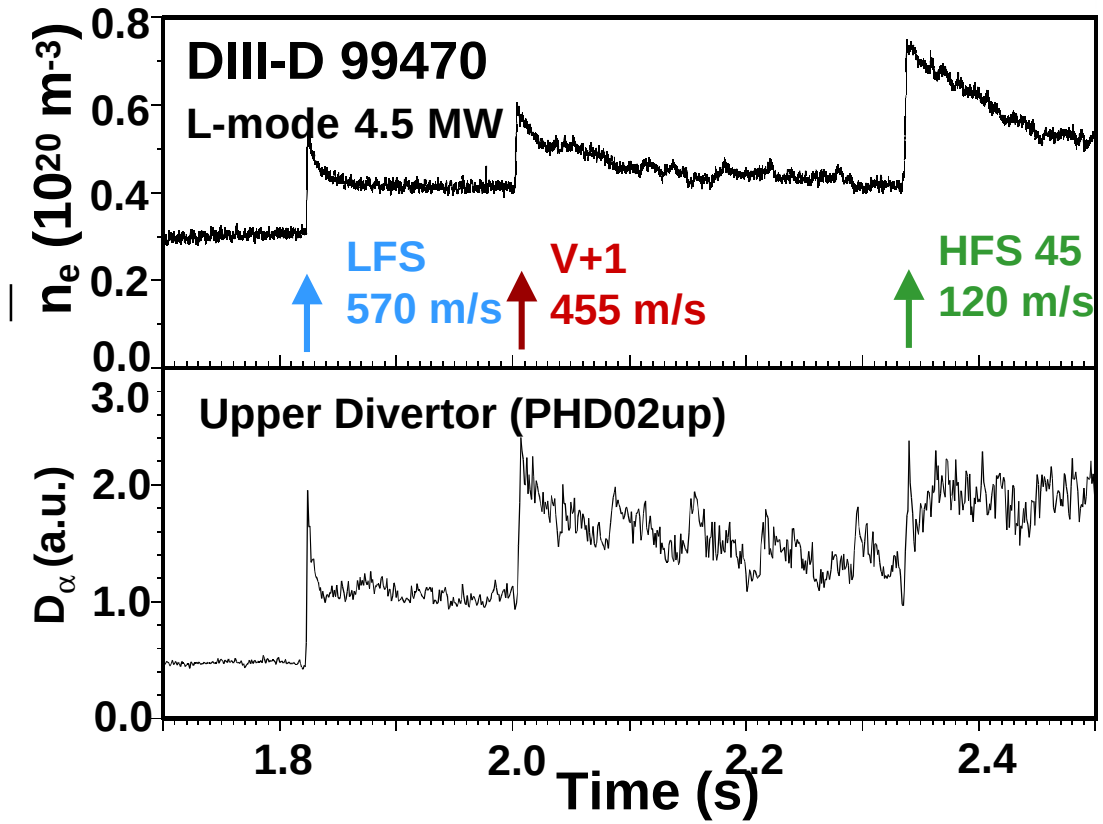
- The net deposition depth measured by Thomson scattering after pellet injection on DIII-D is compared with the calculated pellet penetration depth. The inner wall and vertical injection locations all show deeper than expected depth of the density perturbation.

Direct Comparison in L-mode - HFS Pellets Show Less Particle Loss

2.7mm Pellets

LFS vs V+1 vs HFS 45°



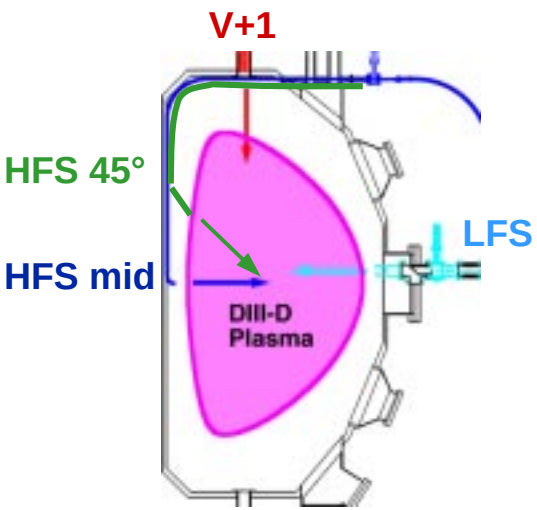


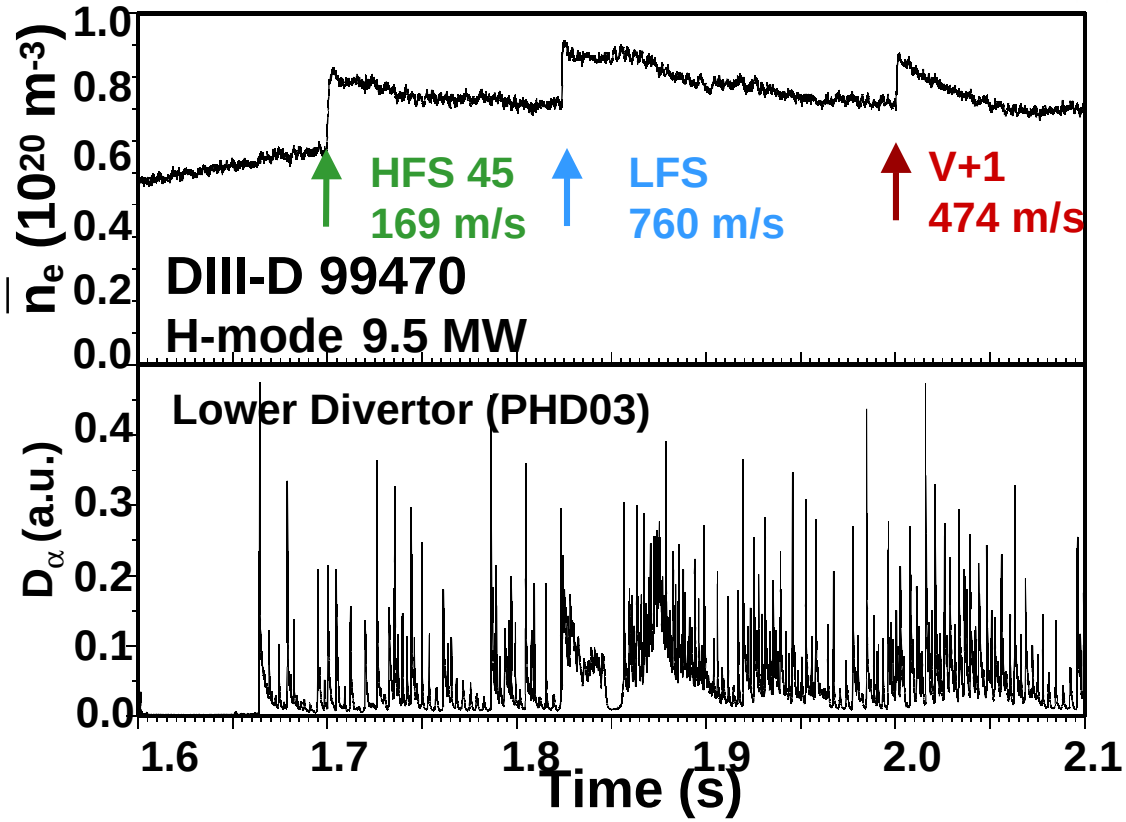
- 2.7mm pellets were injected into the same 4.5 MW USN L-mode plasma from the LFS, V+1 and HFS45 ports.
- The density perturbation is much larger for the HFS pellet and D_α in the divertor shows fewer particles leaving the plasma from the HFS pellet.

Direct Comparison in H-mode - HFS Pellets Trigger Smaller ELMs

2.7mm Pellets

HFS 45° vs LFS vs V+1

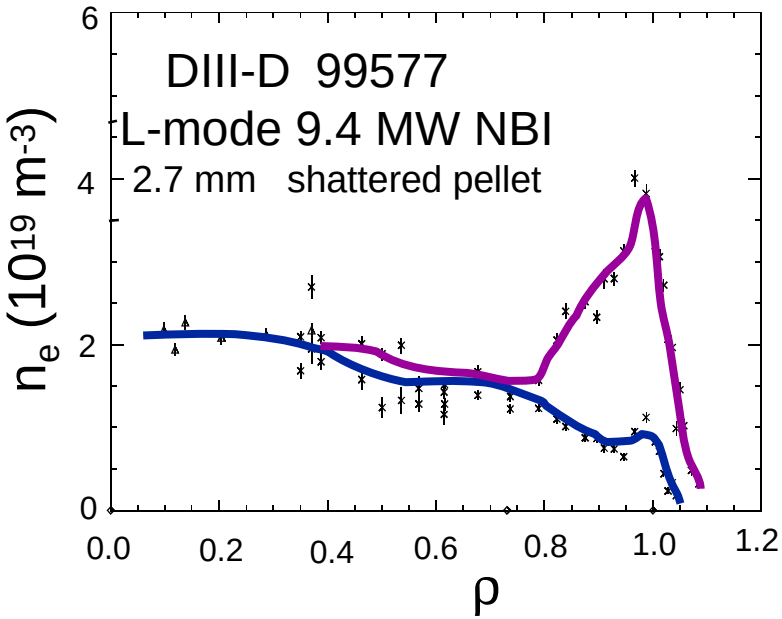




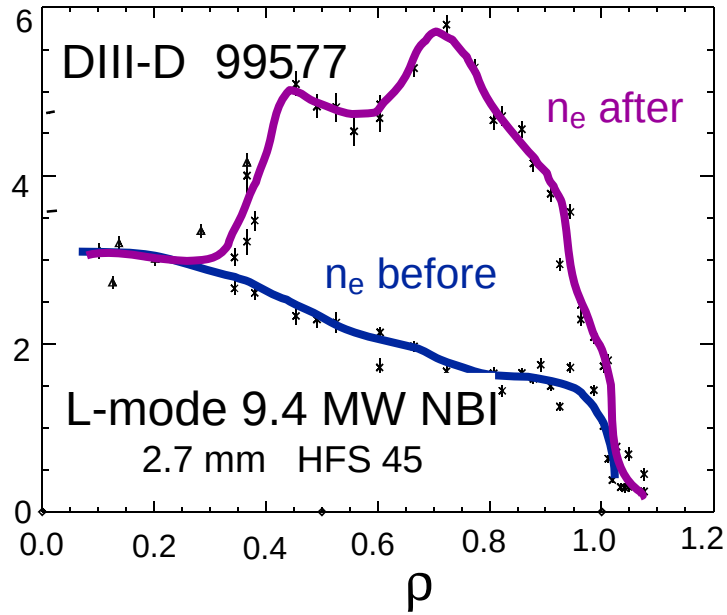
- 2.7mm pellets were injected into the same 9.5 MW DN H-mode plasma from the HFS45, LFS, and V+1 ports.
- ELMs are triggered by the pellets, but are much smaller for the HFS pellets.

New Pellet Injection Tools on DIII-D for Density Profile Modification

LFS Shattered Pellet Injection

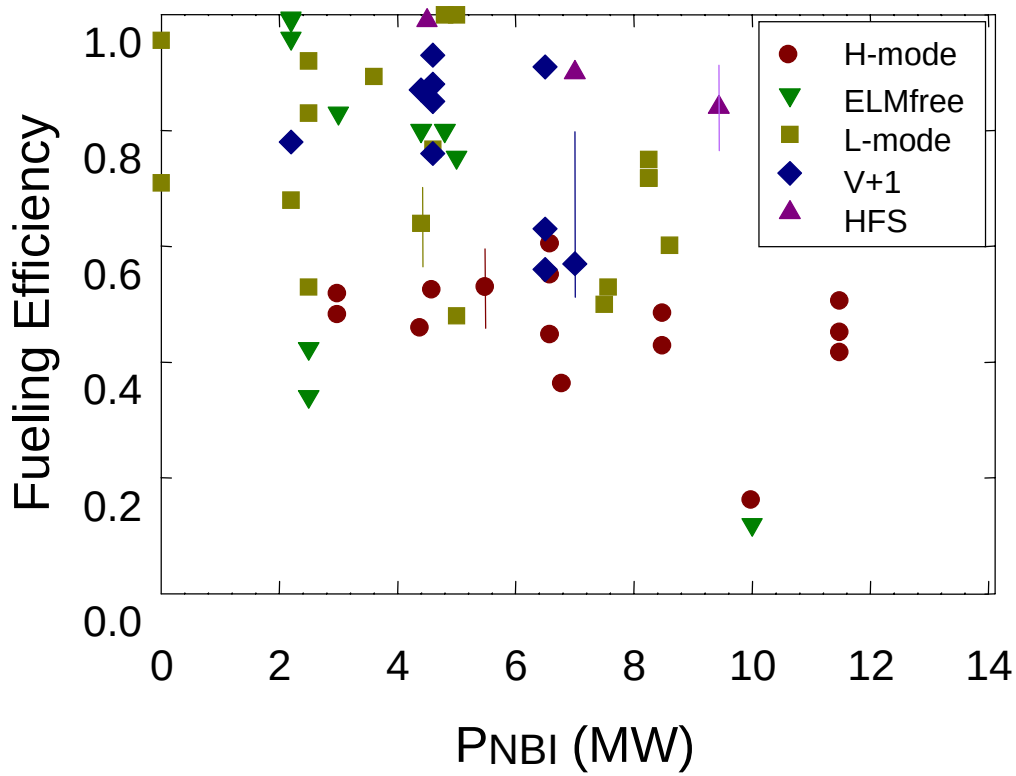


HFS 45 Inner Wall Injection



- The density profile modifications measured from Thomson scattering 5ms after injection for a shattered pellet injected from the outside midplane (LFS) and from a whole pellet injected from the inner wall (HFS45) location.
- Both were successfully used to trigger L - to H-mode transitions.

HFS Pellet Injection on DIII-D Yields Higher Fueling Efficiency



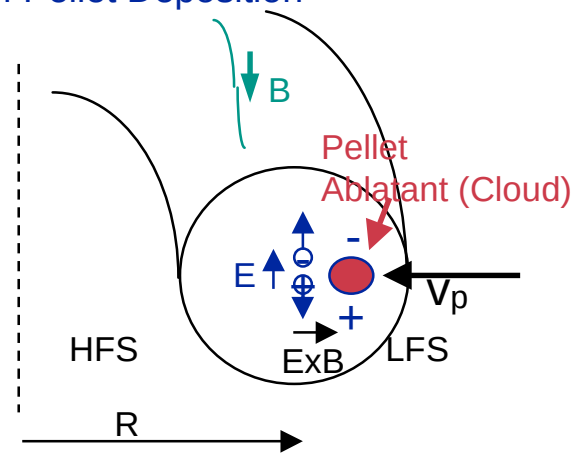
- Fueling efficiency has been determined for a wide range of conditions.
- For LFS injection the efficiency drops sharply with increased power.
- HFS pellets show high fueling efficiency in all conditions examined.

Theoretical Model for Anomalous Deposition

Models Proposed to Explain Apparent Drift in Pellet Deposition

- ExB polarization induced drift: (Rozhansky, Parks)
  - > Polarization of the ablatant occurs due to grad B and curvature drift in the non-uniform tokamak field. ($v_{\nabla B} = W_{\perp}/e\ B x \nabla B/B^3$)
  - > The corresponding ExB drift of the ionized ablatant is in the direction of the major radius.
- MHD effect: (Strauss, Phys. Plasmas (1998) 2676.)
  - > Perturbed non-equilibrium relaxes with major radius displacement.
  - > Does not predict R displacement from vertical injection.
- High beta plasmoid: (Lang, Lengyel)
  - > High-β blob accelerated in major radius direction due to toroidal curvature.

ExB Polarization Drift Model of Pellet Deposition



- Polarization of the ablatant occurs due to grad B and curvature drift in the non-uniform tokamak field. ($v_{\nabla B} = W_{\perp}/e\ B x \nabla B/B^3$)
- The corresponding ExB drift of the ionized ablatant is in the direction of the major radius.
- The polarized ablatant spreads along the magnetic field line at the sound speed c_s.
- The characteristic velocity of ablatant in the direction of the major radius is $\approx c_s\ (2l/R)^{0.5}$. This is on the order of 2 km/s, i.e. faster than the pellet. A detailed model of the radial drift is under development by **Parks (P3.071).**

Summary

- A redistribution of pellet mass appears to occur on a fast (<100 μs) time scale in the plasma major radius direction.
- Pellets injected vertically inside the magnetic axis show mass deposited inside the tangency radius of the vertical injection line.
- Both HFS and vertical injection look promising for fueling while minimizing the mass loss and ELM magnitude.
- DIII-D experiments utilizing HFS pellets for PEP mode internal transport barrier studies and to trigger L to H-mode transitions are examples of successful uses of this new pellet injection tool.