Improved Core Fueling with High Field Side Pellet Injection on the DIII-D Tokamak

presented by ***L.R. Baylor***

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for

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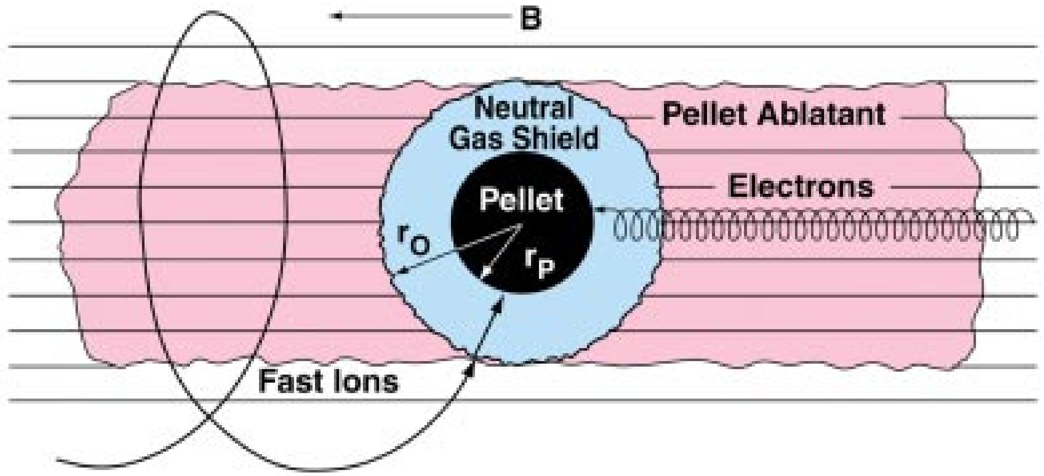
Overview

- **Pellet ablatant drifts in the major radius direction on a fast time scale during redistribution process**
- **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
- **PEP-mode internal transport barriers (ITB) are formed with HFS pellets followed by central heating**
  - $T_i \approx T_e$ and strong negative central shear
  - Reduced transport is seen in both the ion and electron channels
- **HFS pellets trigger L to H-mode transitions with a reduced power threshold.**
  - Plasma parameters in PIH-mode transitions below theoretical predictions
- **HFS injected pellets during H-mode trigger ELMs with reduced magnitude and duration compared with LFS injected pellets.**

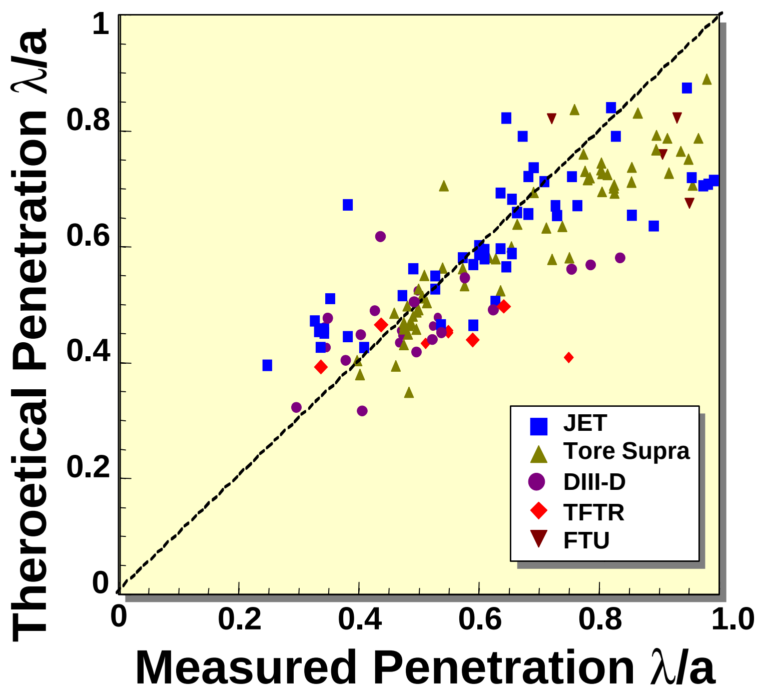
Pellet Mass Deposition is Different from Ablation Process

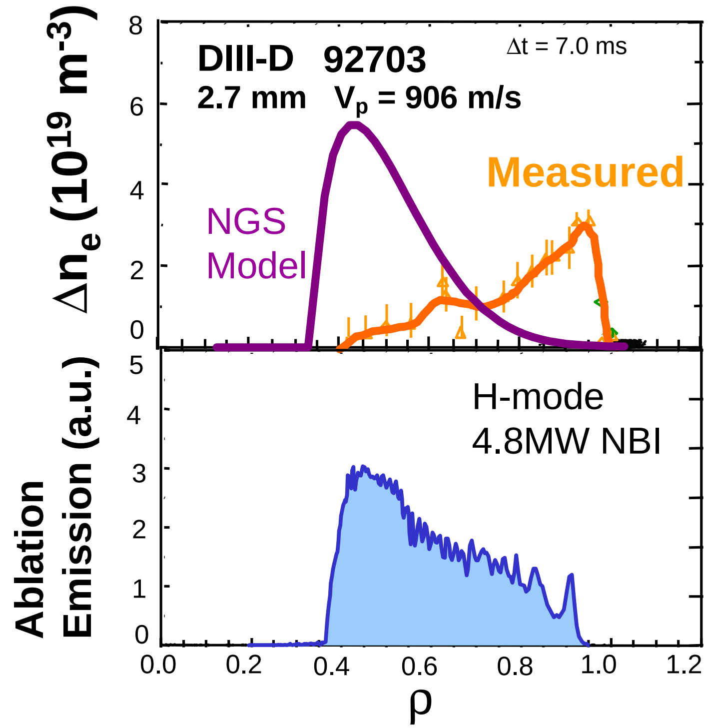
- **Pellet ablation well understood with neutral gas shielding (NGS) model** (Parks, Milora, Pegourie, Kuteev)
  - Assumes pellet particles remain where ionized



- **Pellet Deposition describes where the pellet mass is distributed in the plasma.**
  - Measured density profile before and after pellet ablation.
  - Data suggests it is vastly different from simple ablation model

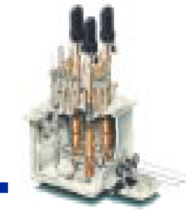
Pellet Penetration is Well Characterized, but Deposition Profile from LFS Injection is Anomalous

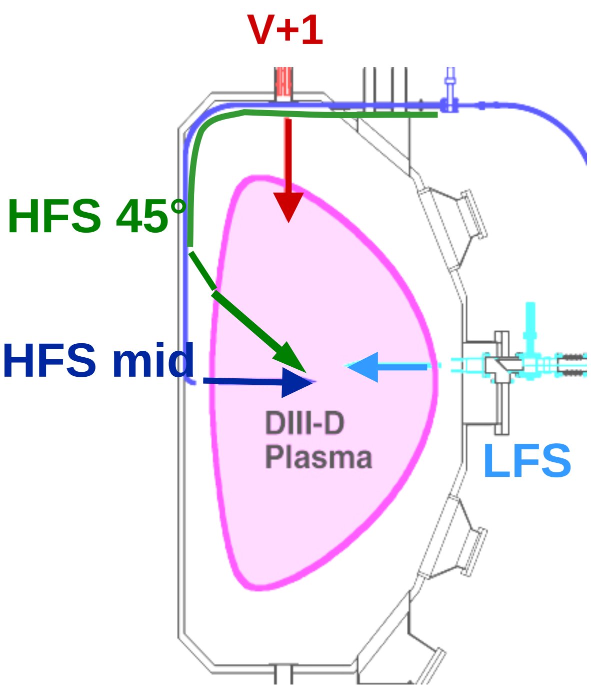


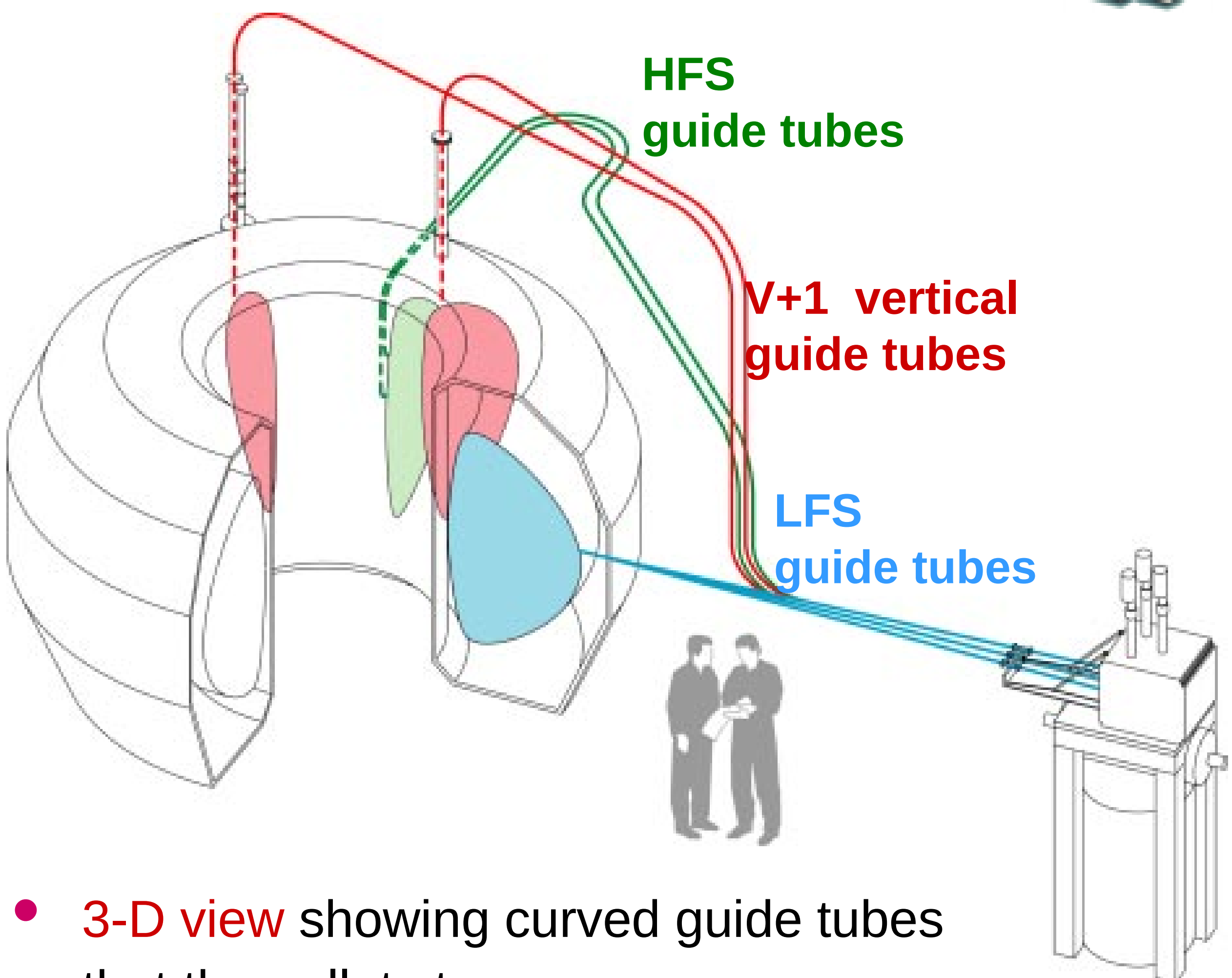


- Maximum Penetration depth agrees well with theory over a range of data from many devices. (Baylor, et al., *Nucl. Fusion* 37, 445 (1997))
- Mass deposition implies fast radial transport during the ablation process.
- ASDEX Upgrade first experiment to try HFS injection to test this hypothesis. (Lang,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

DIII-D Pellet Injection Locations - 1999



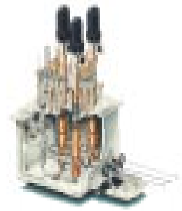




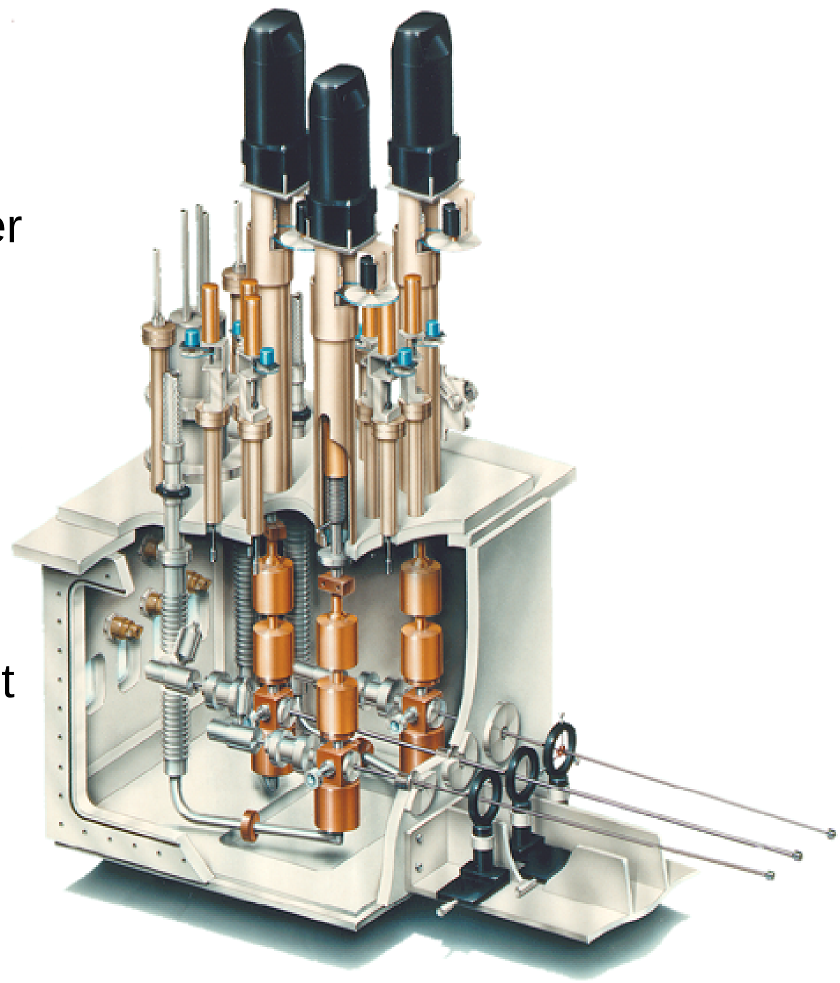
- Elevation view of pellet trajectory in the plasma

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

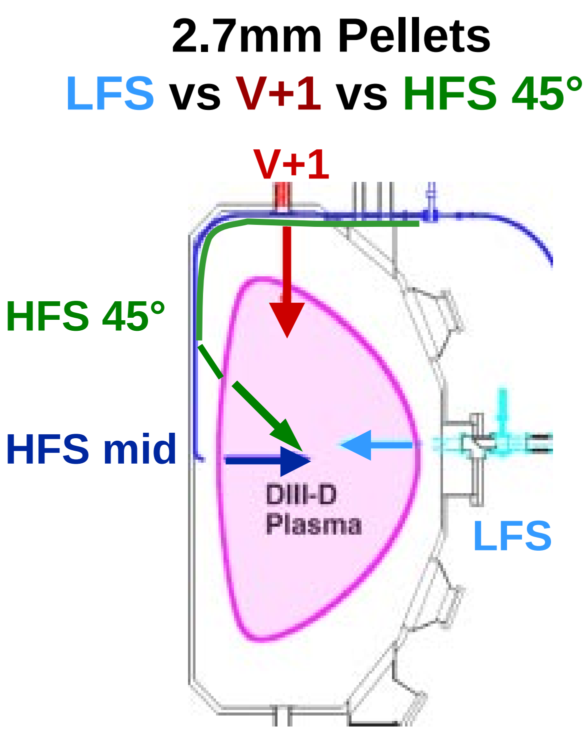
Pellet Injection Program on DIII-D

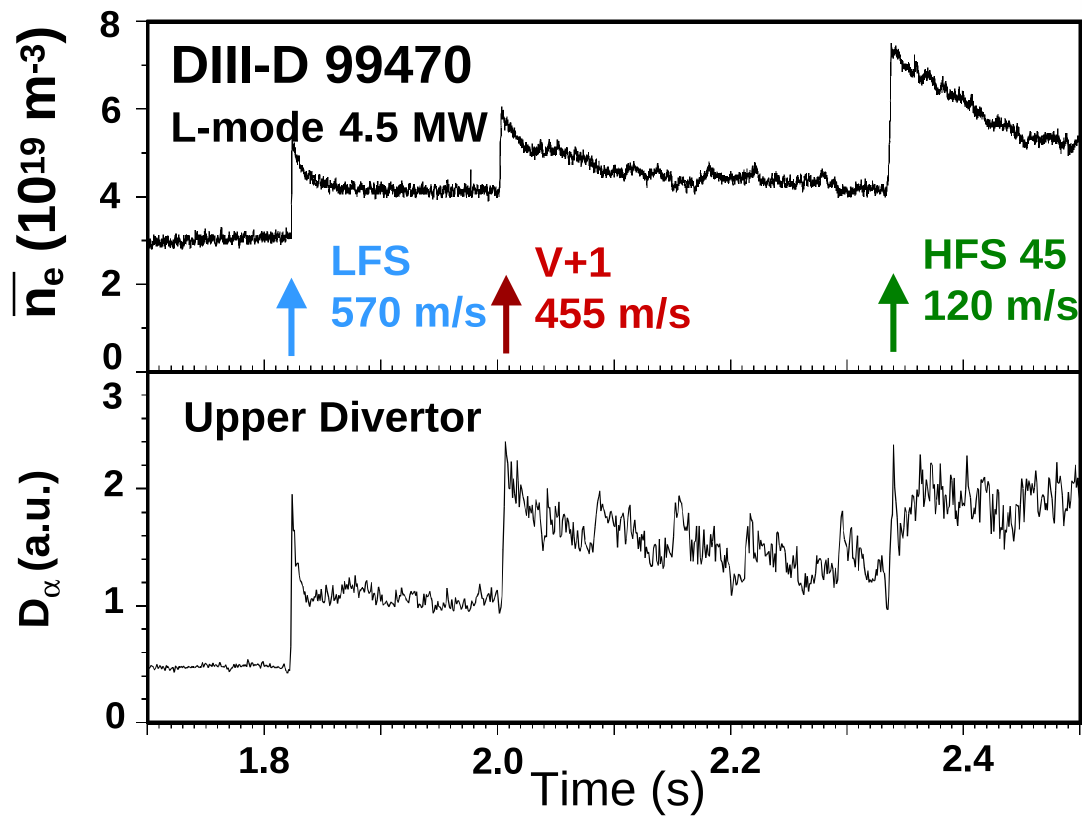


- Modifications to injector (that was installed on JET 1987-91):
  - All three guns fire 2.7 mm pellets
  - Punch mechanism to generate slower pellets (< 300 m/s)
  - Enabling Technology
- 2 independent guide tubes on inner wall (HFS) - midplane, 45° and vertical V+1
  - Can be connected to any of the pellet guns or a gas valve
- Curved guide tube limits speed to 250 m/s for intact pellets (Combs, SOFE Proceedings, 1999)



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

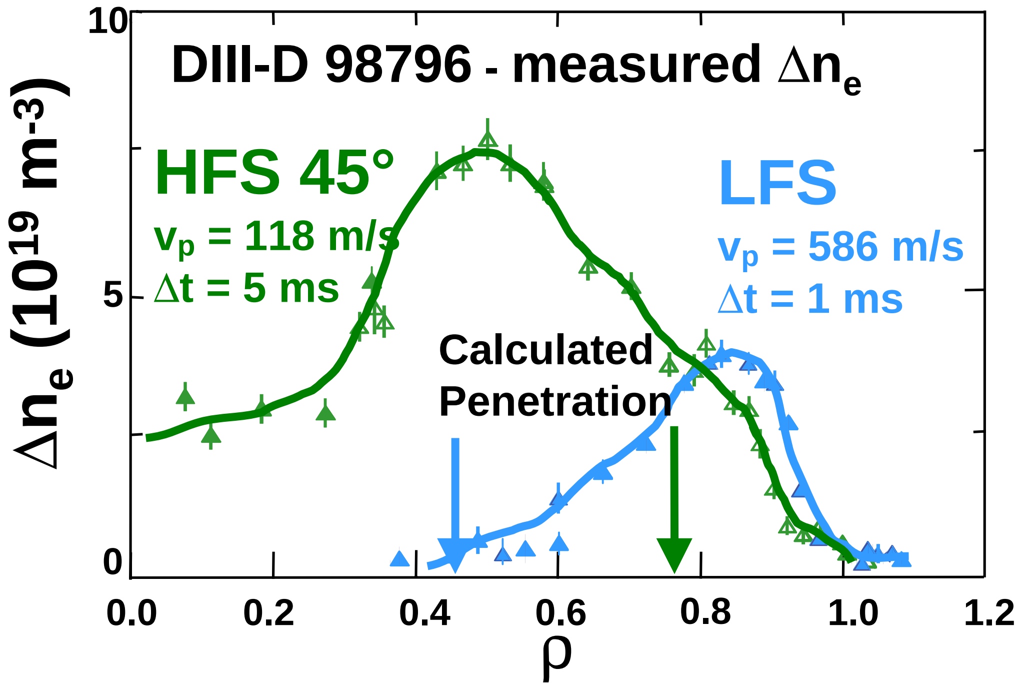




- Pellet comparison from LFS, V+1 and HFS45
- The density perturbation is larger for the HFS pellet
- Divertor D_α shows fewer particles leaving the plasma from the HFS pellet

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



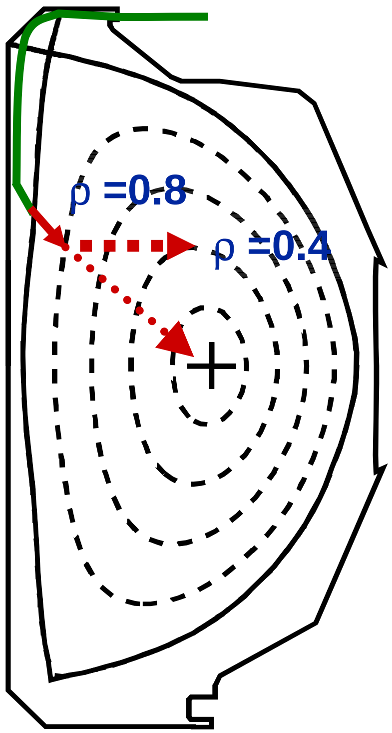
Fueling Efficiency:

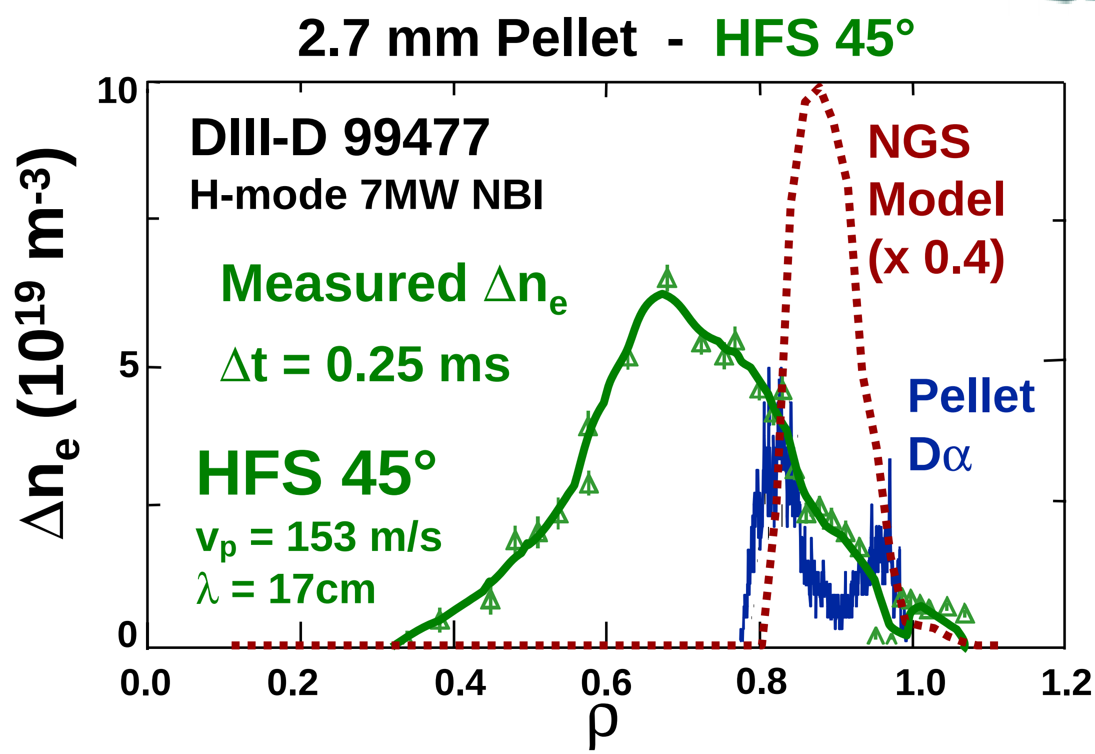
HFS - 95%

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)

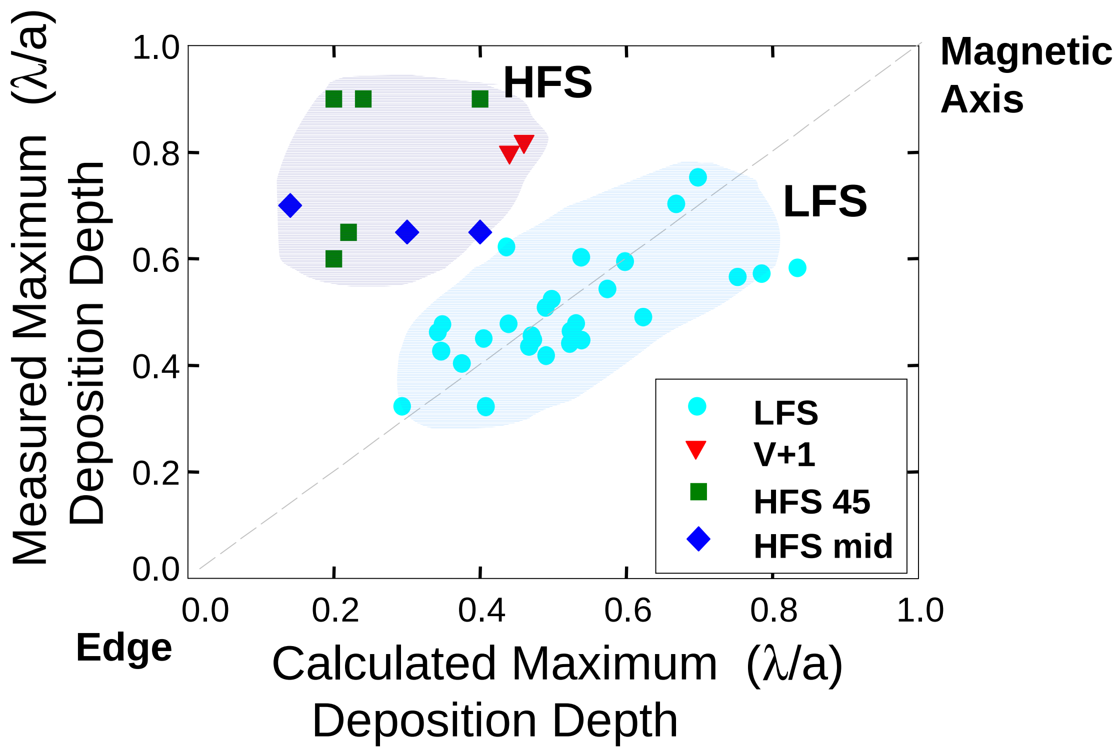
DIII-D HFS 45° Pellet Injection Deposition Suggests Major Radius Drift of Ablatant





- The deposition shows deeper fueling than predicted
- Pellet Dα emission agrees with ablation model (PELLET code)
- A radial drift of 20 cm is inferred from the data - for comparison with detailed drift model by **Parks (UI1.05)**

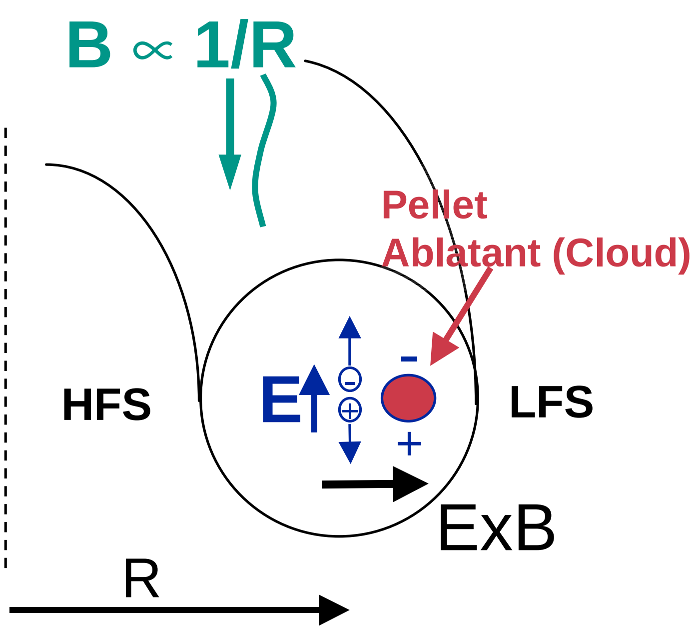
HFS Pellet Injection on DIII-D Yields Deeper Particle Deposition than Predicted by Ablation Model



- HFS and Vertical injection show deeper than expected deposition of pellet mass from simple ablation model
- LFS pellet maximum deposition depth agrees with simple model

Theoretical Model for Pellet Radial Drift

ExB Polarization Drift Model of Pellet Mass Deposition
(Rozhansky, Parks)

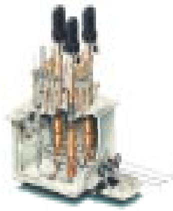


- Polarization of the ablatant occurs from ∇B and curvature drift in the non-uniform tokamak field:

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

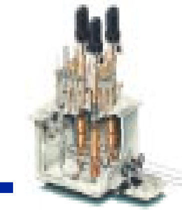
- The resulting E yields an ExB drift in the major radius direction
- The velocity of ablatant ≈ $c_s(2L/R)^{0.5}$. For DIII-D this is ≈ 2 km/s, i.e. faster than the pellet (deKloe, Mueller, Phys.Rev.Lett. (1999))
- ΔR stronger at higher plasma β
- Detailed model by P.B. Parks (UI1.05)

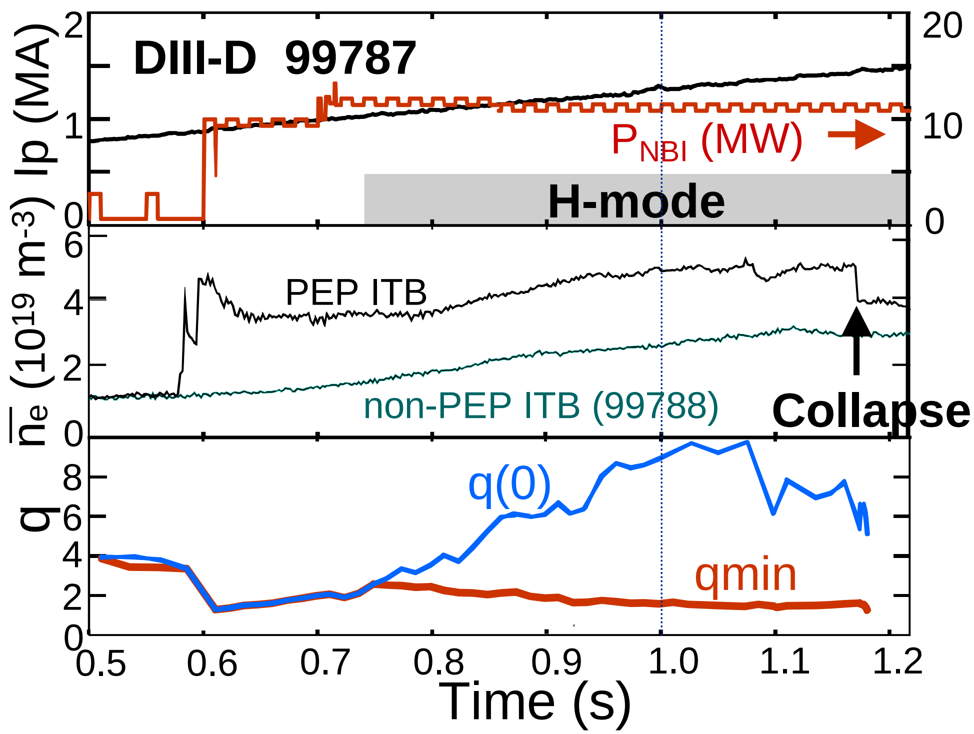
Application of High Field Side Injected Pellets

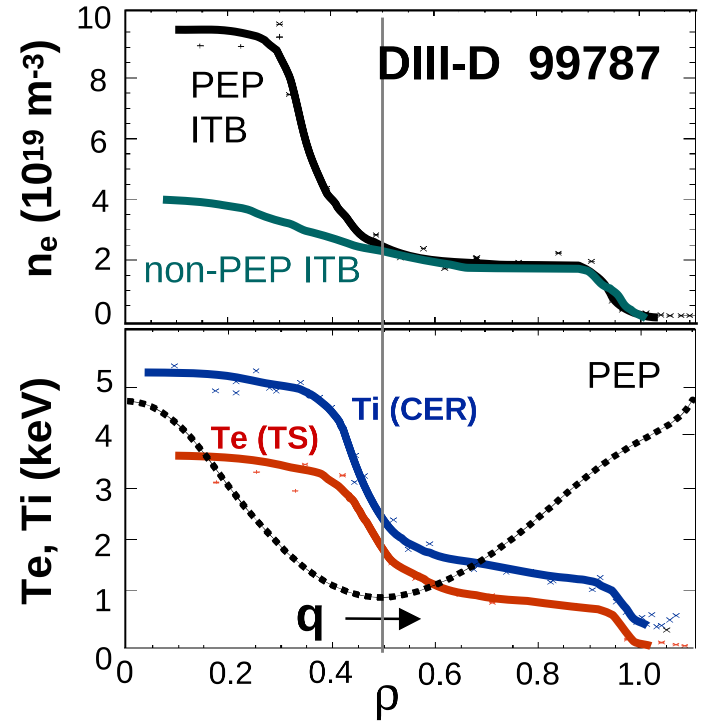


- **PEP-mode** - overview and transport summary
- **PIH-mode** - pellet induced H-mode overview
  - Pellets enable test of transition theory
- **Pellet induced ELMs** - edge localized modes
  - HFS/LFS pellet comparison

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

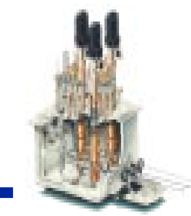


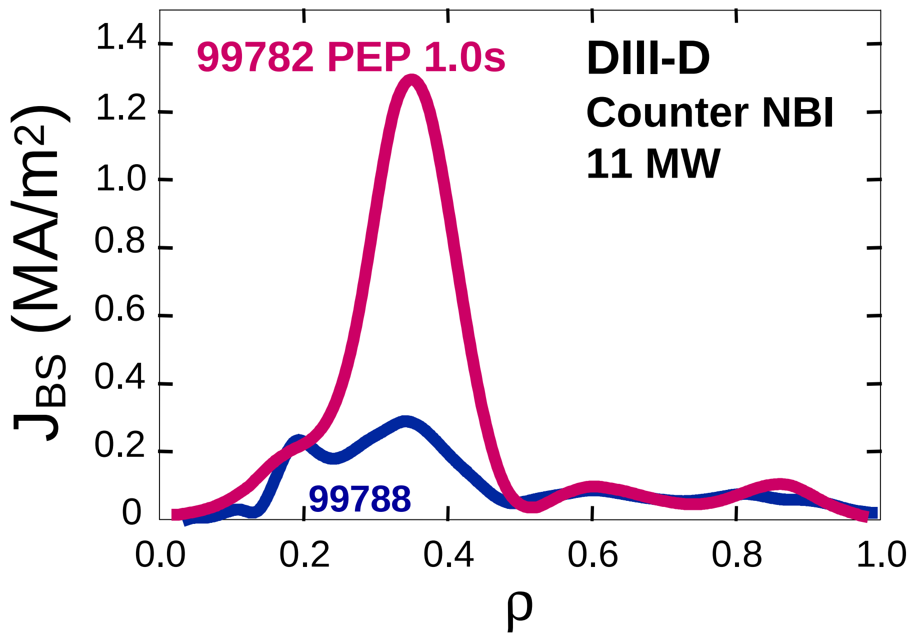


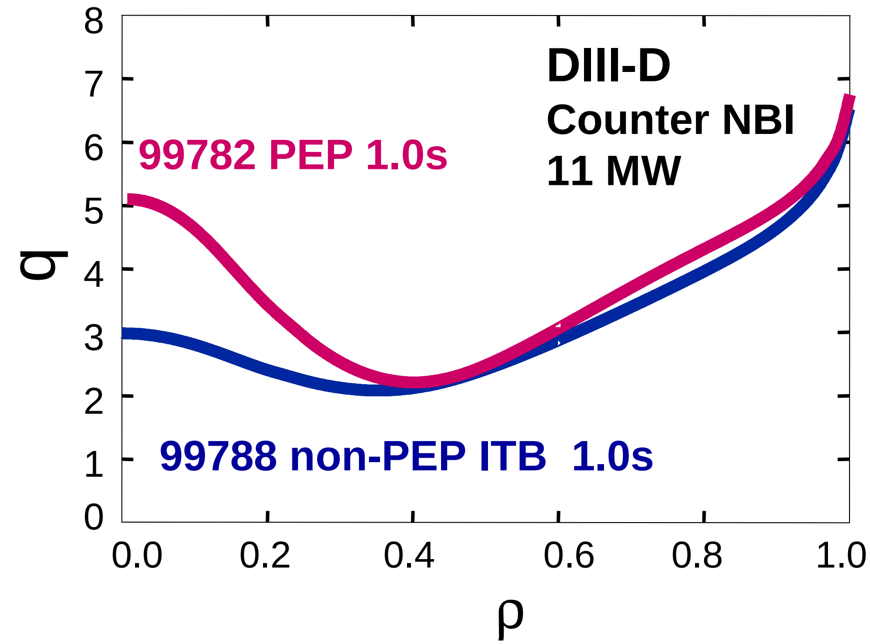


- $\color{red}{\text{HFS 2.7mm pellets injected during current rise}}$ produce highly peaked density profiles that develop PEP ITB with $T_i \approx T_e$
- PEP survives transition to H-mode and can persist for > 1s
- Core collapse occurs as qmin reaches 3/2
- Steepest n_e, T_e, T_i gradients occur inside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

Strong Off-Axis Bootstrap Current Drives Negative Central Shear in PEP ITB

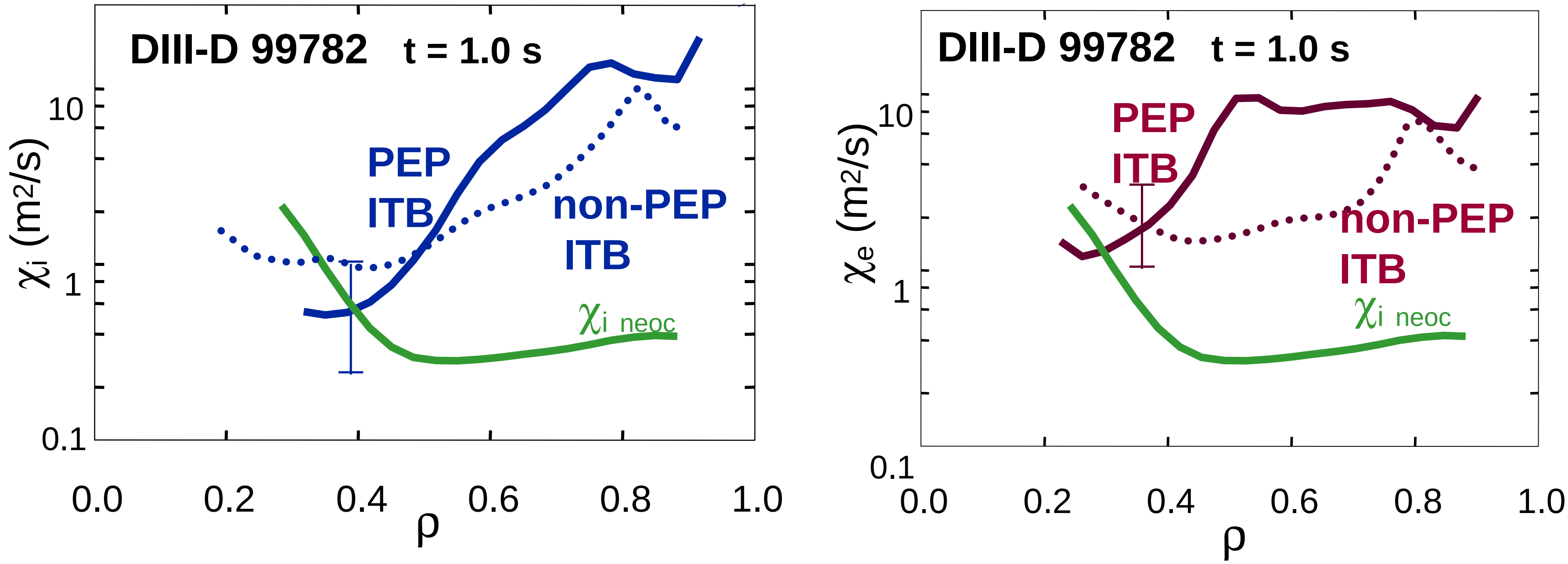






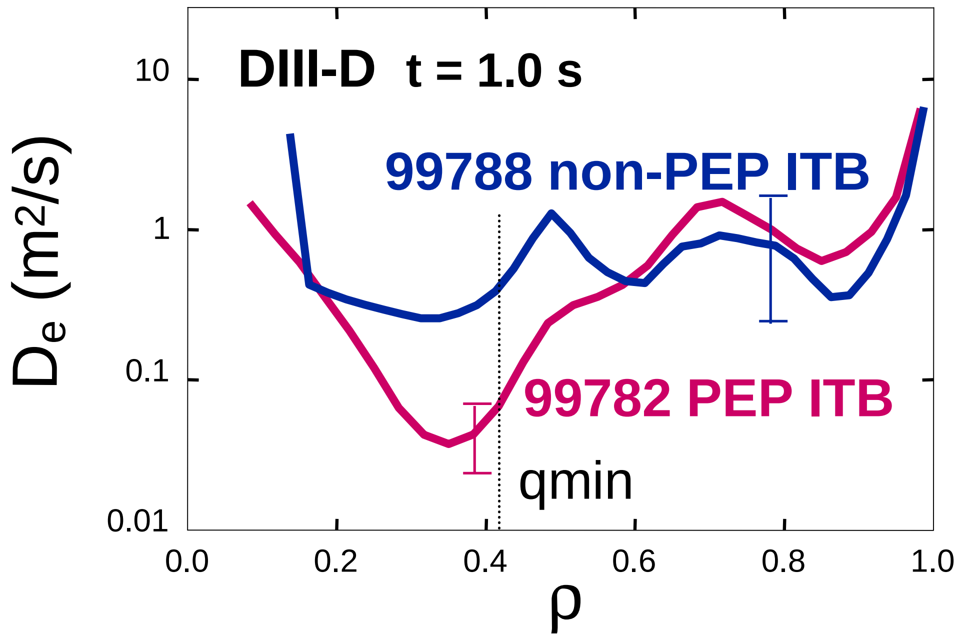
- Bootstrap current from NCLASS shows strong off-axis contribution in the PEP-mode
- Safety factor (q) profile determined with MSE data has stronger negative central shear in PEP than non-PEP ITB comparison

PEP-mode has thermal diffusivity in the core approaching neoclassical levels



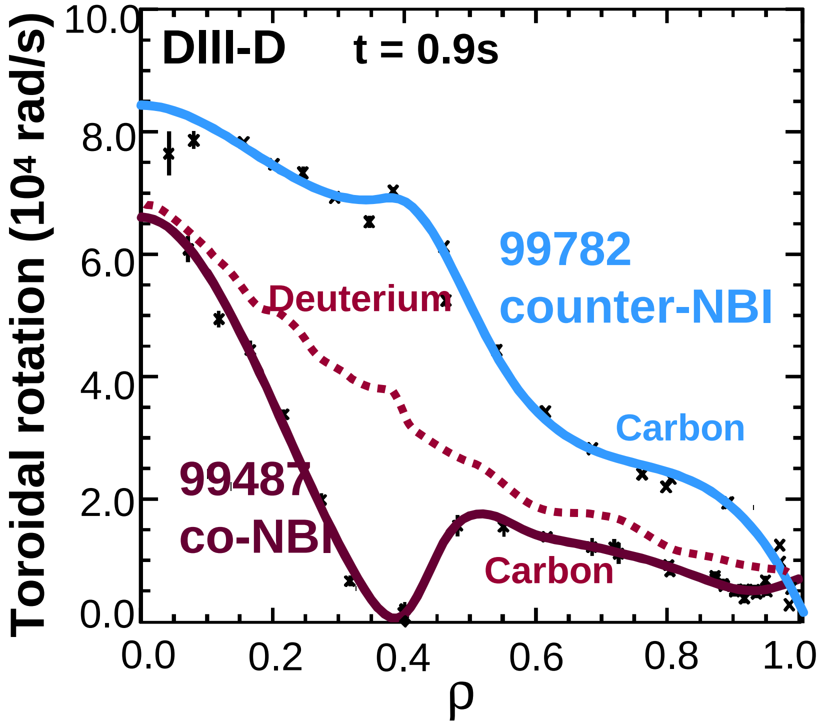
- TRANSP calculation of thermal diffusivities shows ITB in core region out to $\rho = 0.4$ as expected from the strong gradients in the kinetic profiles.
- ITB in PEP case is comparable to non-PEP ITB, both approach neoclassical levels.
- ω_{EXB} becomes large enough to suppress ITG turbulence as in the non-PEP ITB plasmas. (C.M. Greenfield, BI2.01)

PEP-mode has lower electron particle diffusivity in core from non-PEP ITB comparison



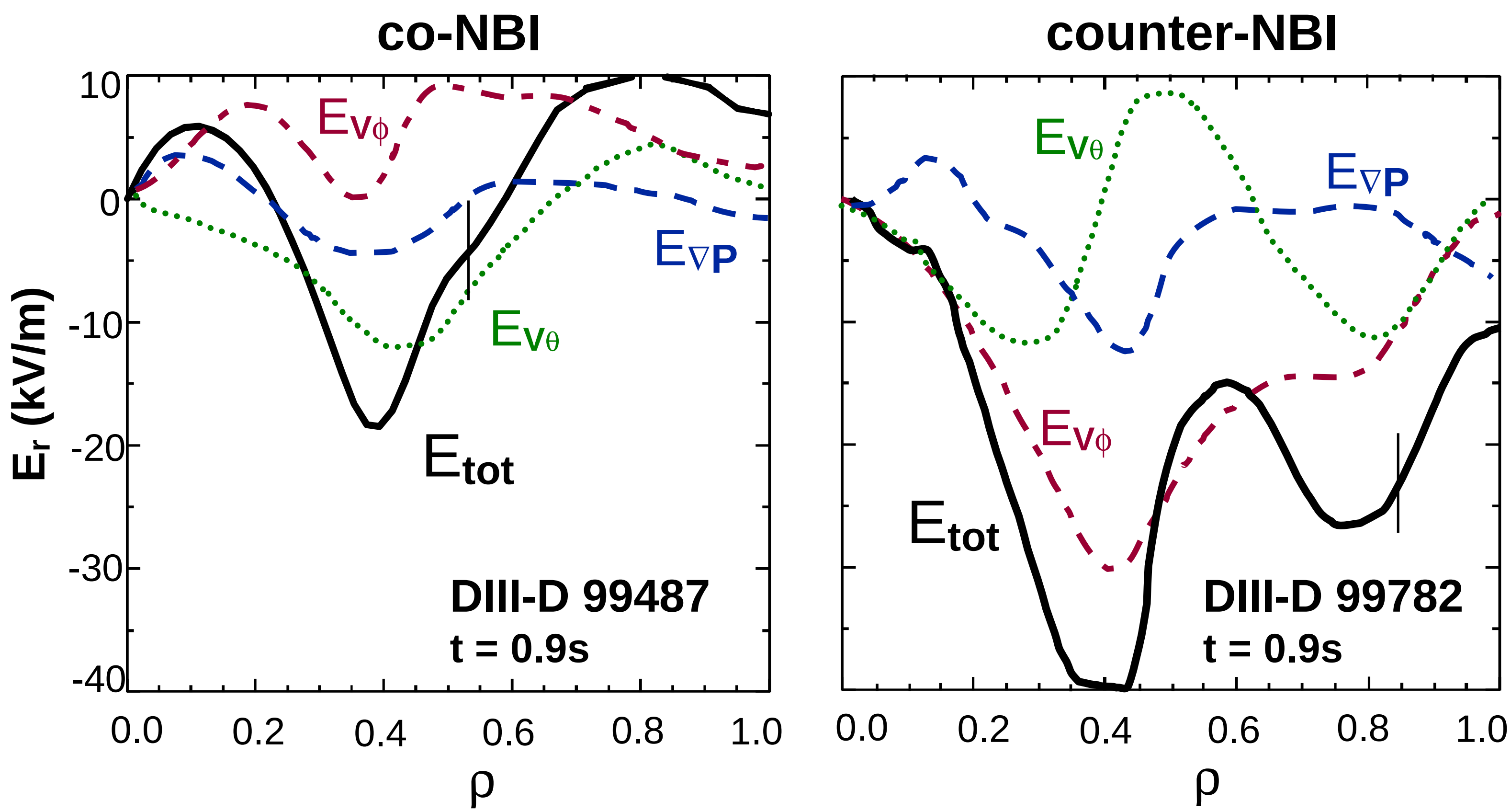
- TRANSP calculation of electron particle diffusivity shows reduced core particle transport in PEP just inside the barrier region (ρ=0.4)
- Both PEP and non-PEP ITBs show strong increase toward axis as profiles become flat

Toroidal Rotation Profile Shows Strong Difference between co-NBI and counter-NBI PEP-mode



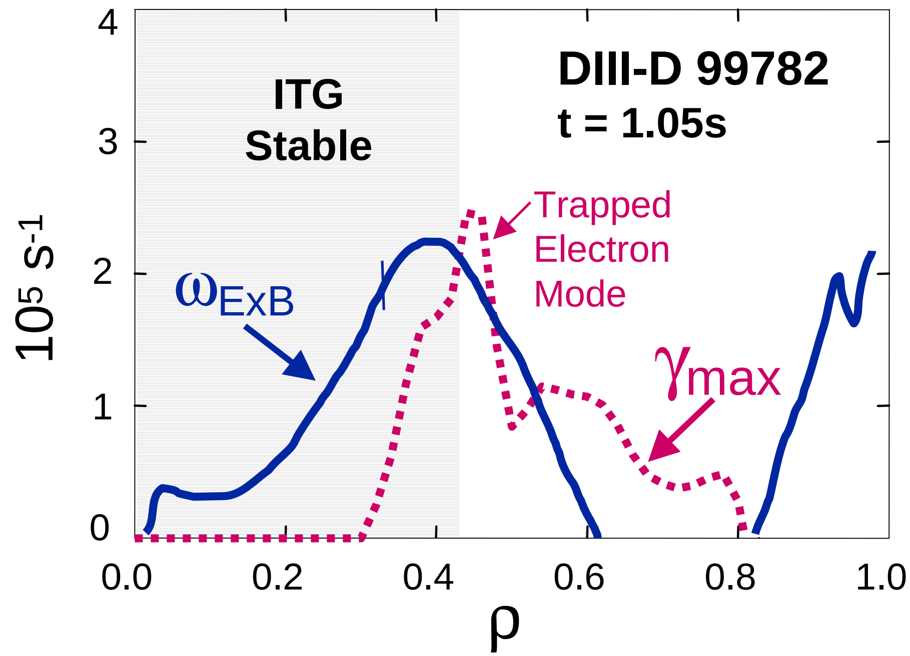
- Toroidal carbon rotation in PEP-mode shows a “notch” with co-NBI similar to that seen on TFTR supershots due to neoclassical parallel momentum exchange. (D. Ernst, et al. Phys. Plasmas 1998.)
- NCLASS calculated deuterium rotation profile is monotonic.

Radial Electric Field has a Well at PEP ITB Location that is Deeper for Counter-NBI



- Radial force balance calculation of Er has well at ITB and notch location.
- Toroidal rotation is dominant term: $E_r = (Zen)^{-1} \nabla P + v_\phi B_\theta - v_\theta B_\phi$

ITG Modes are Stabilized in PEP-mode ITB Core Region



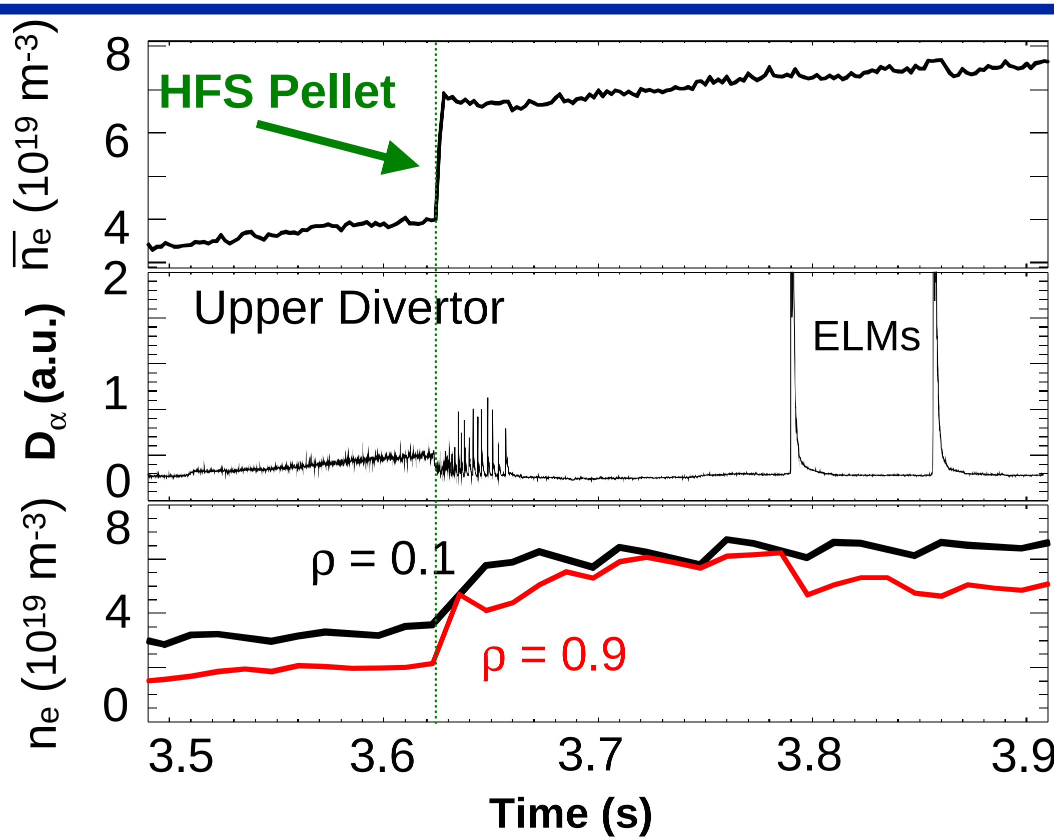
Gyrokinetic Stability Calculation

- The ExB shearing rate exceeds the ITG growth rate inside the ITB

$$\omega_{ExB} = \frac{(RB_\theta)^2}{B} \frac{\partial}{\partial \psi}\left(\frac{E_r}{RB_\theta}\right)$$

- Edge shearing rate is strong due to H-mode edge barrier

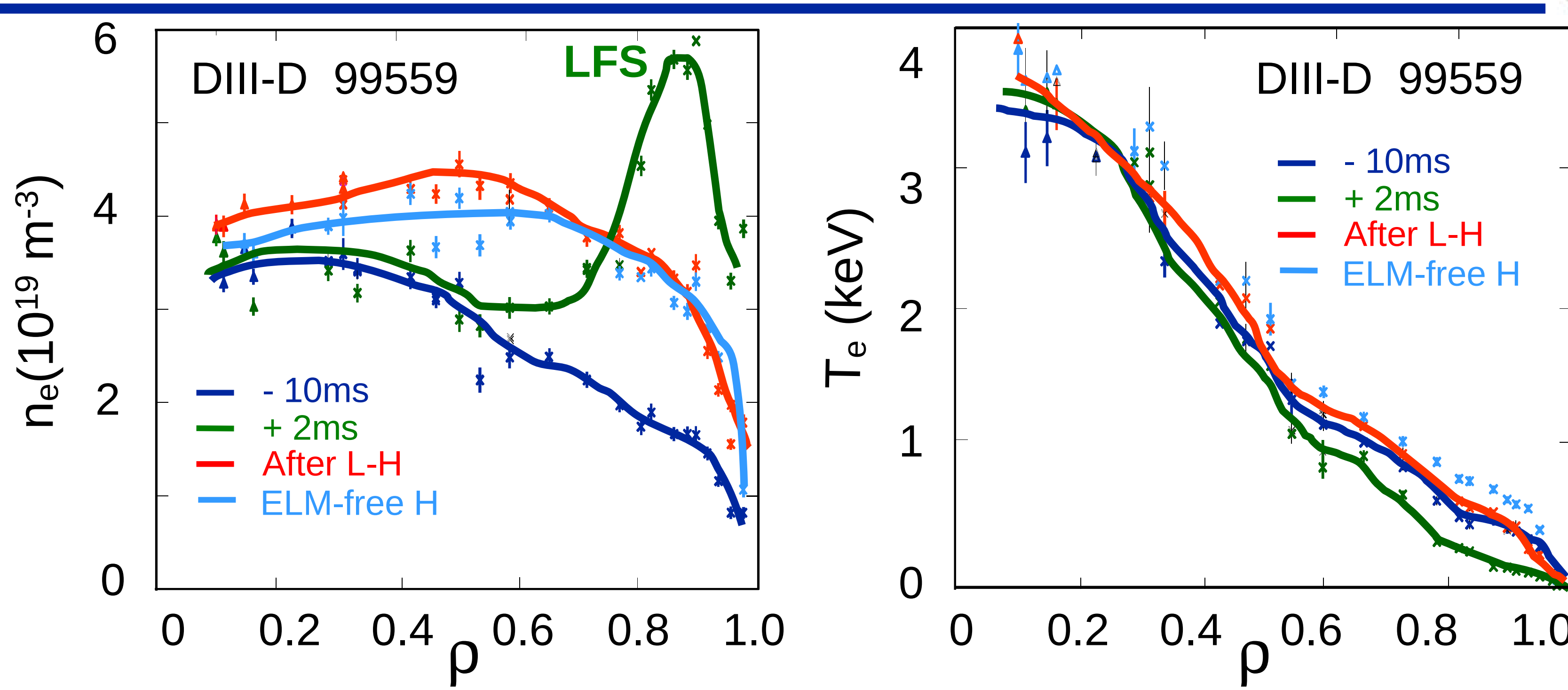
HFS Pellets have induced H-mode Transitions



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 (P. Gohil CP1.62 - Mon. PM)

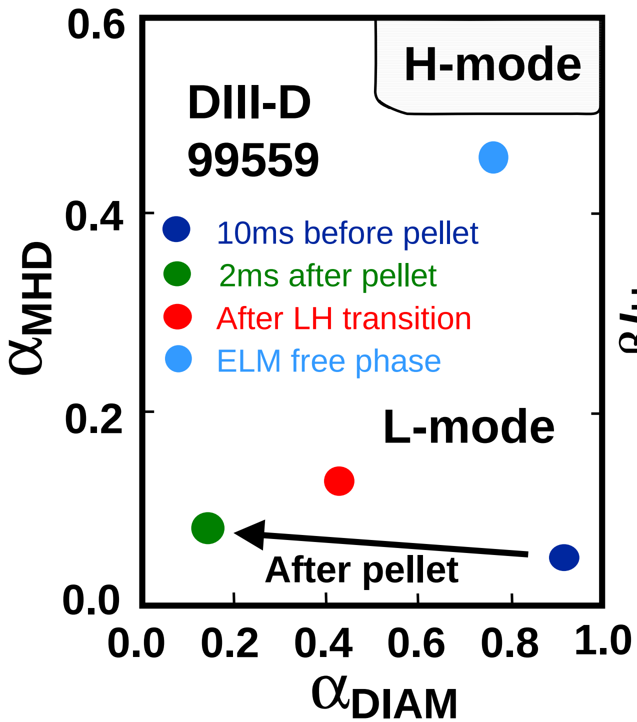
Pellet Induced H-mode Transition Occurs at Lower Edge Temperature



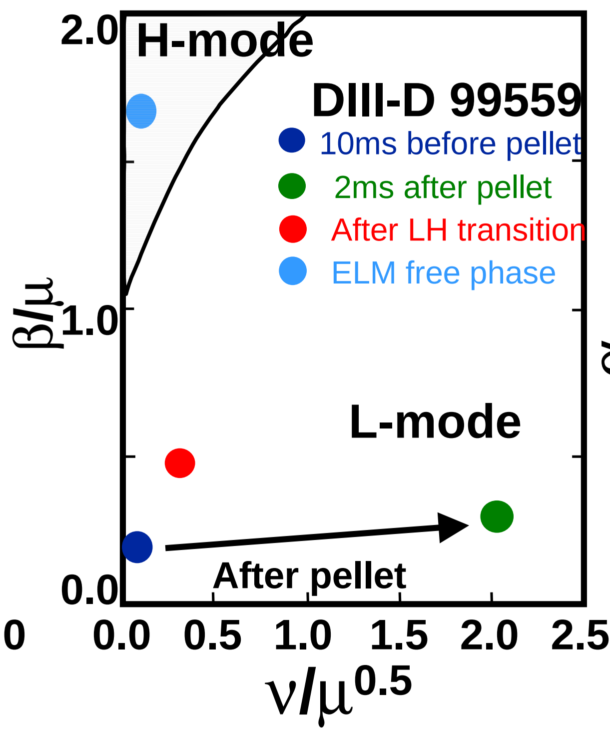
- A critical edge temperature is not indicated in these H–mode transitions
  - Edge T_e and T_i are reduced following pellet injection
- Pellet induced H–modes have L-H transitions at plasma parameters far below theoretical predictions

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

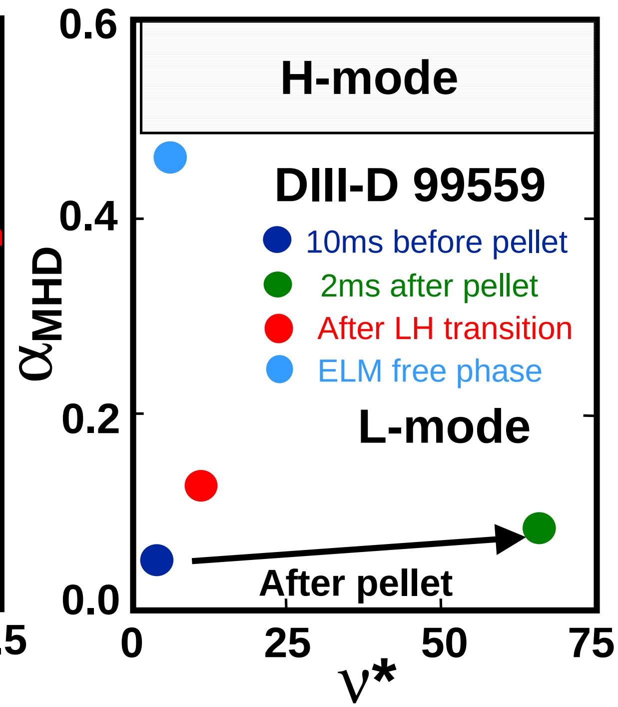
Rogers et al. Proc. 17th IAEA Fusion Energy Conf. Yokohama, Japan 1998, IAEA-CN-69/THP2/01



Pogutse et al. Proc. 24th EPS Conf. 1997 (P3-1041)

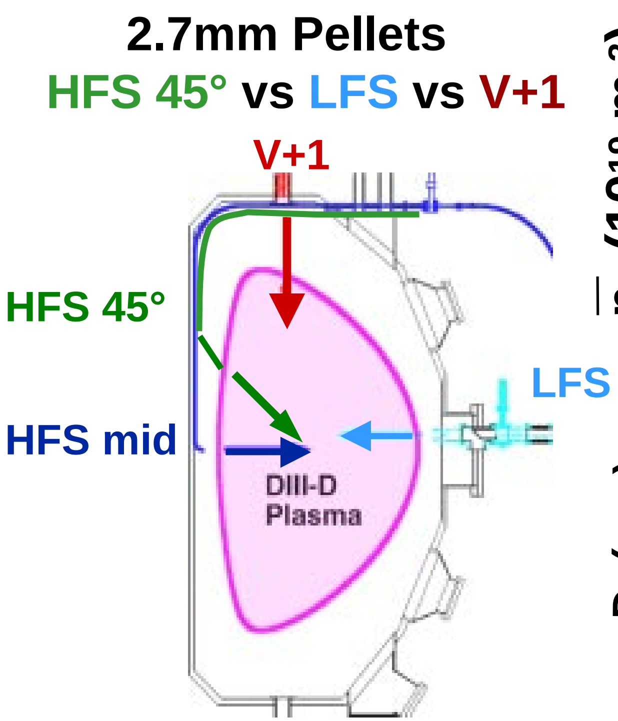


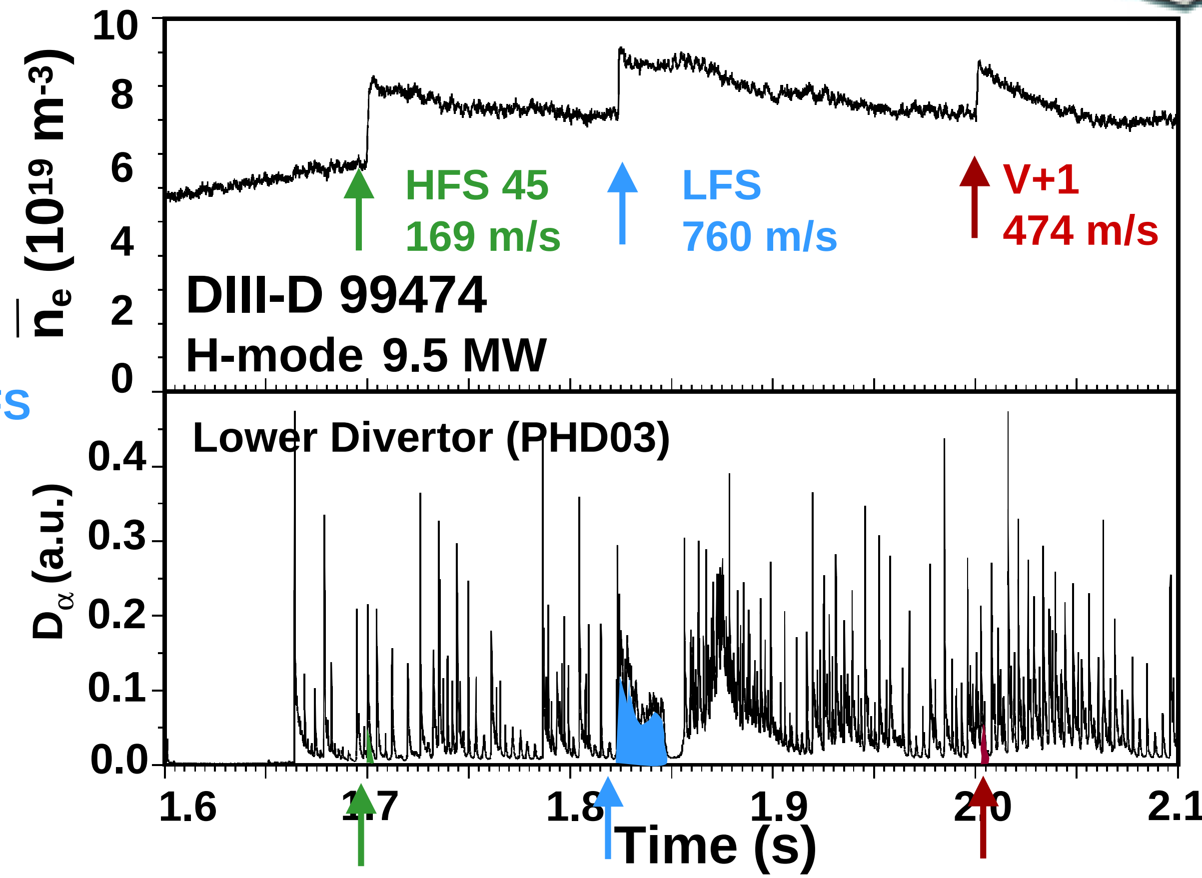
Wilson et al. Proc. 17th IAEA Fusion Energy Conf. Yokohama, Japan 1998, IAEA-F1-CN-69/TH3/2



- For more details see poster by P. Gohil et al (CP1.62 - Mon. PM)

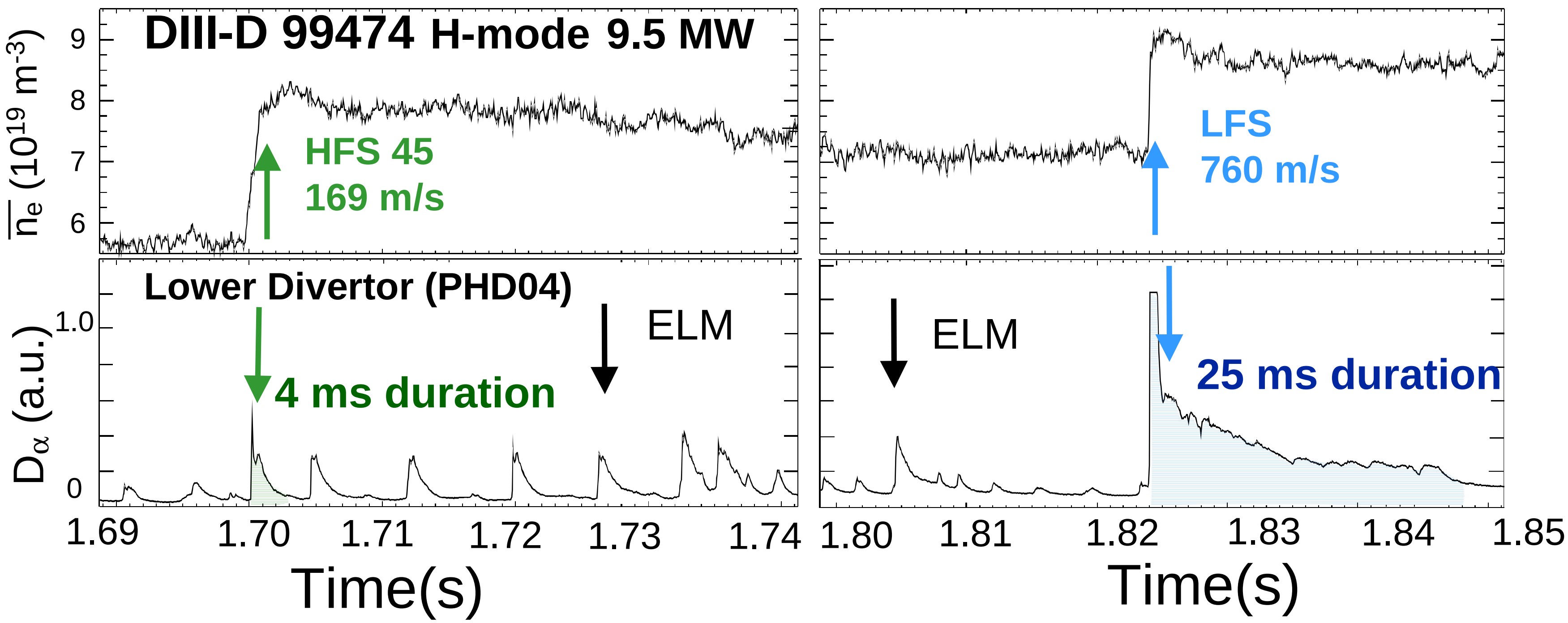
Direct Comparison in H-mode -
HFS Pellets Trigger Smaller ELMs





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

HFS Pellets produce different ELM characteristics than LFS pellets.



- HFS pellet induced ELMs are small like background ELMs
- LFS pellets induce large ELMs much longer lasting than background ELMs. ExB drift loss of particles may be responsible.
- P´ modification at edge may be different for HFS and LFS pellets (J.R. Ferron, UI1.01)

Summary of Observations

- **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 proposed as explanation
- **HFS injection ports installed on DIII-D take advantage of the radial drift and lead to improved core fueling with HFS injected pellets**
- **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)
  - Triggers for L to H-mode transitions for reduced power threshold
  - HFS pellets trigger ELMs with reduced magnitude and duration

Summary of Observations - continued

- **First PEP-mode experiments with Er determined**
  - Strong off-axis JBS and negative central shear
  - The PEP-mode ITB shows reduced transport in ions and electrons
  - ExB shear plays a critical role in ITG stabilization and density peaking affects the ETG stability
- **HFS pellets can trigger L to H-mode transitions with a reduced power threshold**
  - Transition occurs without critical edge temperature
  - Plasma parameters below theoretical predictions for transition
- **HFS injected pellets during H-mode trigger ELMs with reduced magnitude and duration compared to LFS injected pellets**
- **HFS pellet injection is unique enabling technology that has led to several areas of new physics understanding on DIII-D**