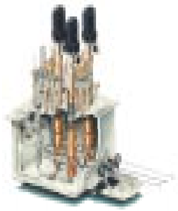
Improved Core Fueling with High Field Side Pellet Injection on the DIII-D Tokamak



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

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Abstract for an Invited Paper
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Improved Core Fueling with Pellets Injected from the High Field Side of the DIII-D Tokamak[1]

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Deuterium pellets have been injected into DIII-D plasmas from the high field side (HFS) leading to the formation of peaked density profiles with a peaking factor $(n_e(0)/ < n_e >)$ in excess of 2.5. The peaked density profile plasmas formed with the high field side pellets develop internal transport barriers when centrally heated. The transport barriers are formed in conditions where $T_e \sim T_i$ and q(0) is above 1. Deeper core fueling is possible with HFS injected pellets than with the same size pellets injected from the low field side (LFS), despite a factor of four lower velocity. The peaked density profiles, characteristic of the internal transport barrier, persist for several energy confinement times and survive through L-mode to H-mode transitions.

P ellets are injected from the inner wall, outer midplane, and a vertical port with the three guns on the DIII-D pellet injector using curved guide tubes. Density profiles after injection show pellet mass deposited inside the penetration radius for the HFS injected pellets, suggesting that a drift of the pellet ablatant occurs in the major radius direction. Pellets injected from the LFS show shallower mass deposition than the HFS or vertical pellets despite much higher pellet speeds. This apparent fast outward drift of the deposited pellet mass is hypothesized to occur from ∇B and curvature induced effects. The pellets injected from the different locations are also used as probes to investigate transport barrier physics and modify plasma edge conditions. Transitions from L to H-mode have been triggered by pellets from both the HFS and LFS, effectively lowering the H-mode threshold power by 2 MW. Pellets injected into H-mode plasmas are found to trigger edge localized modes (ELMs). The ELMs triggered by pellets injected from the inner wall and vertical port are of similar to Type 1 ELMs, while the ELMs triggered from the outer midplane pellets are of significantly longer duration.

[1]Research sponsored by the U. S. Department of Energy, under contracts DE-AC05-96OR22464, DE-AC03-89ER51114, and DE-AC02-76CH03073.

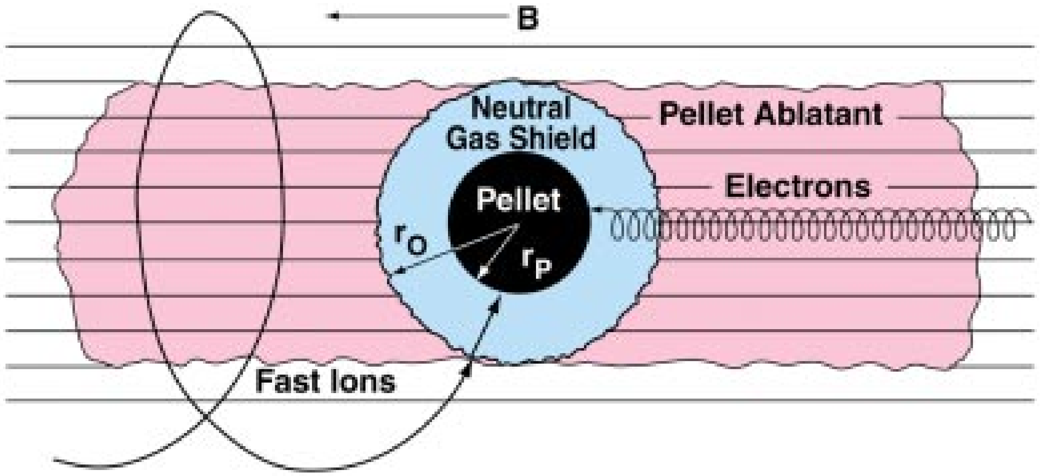
[2]In collaboration with T.C. Jernigan, S.K. Combs, W.A. Houlberg, Oak Ridge National Laboratory, P. Gohil, K.H. Burrell, C.M. Greenfield, General Atomics, G.L. Schmidt, Princeton Plasma Physics Laboratory

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.**

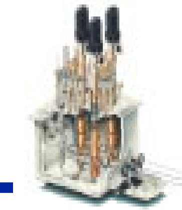
Pellet Mass Deposition is Different from Ablation Process

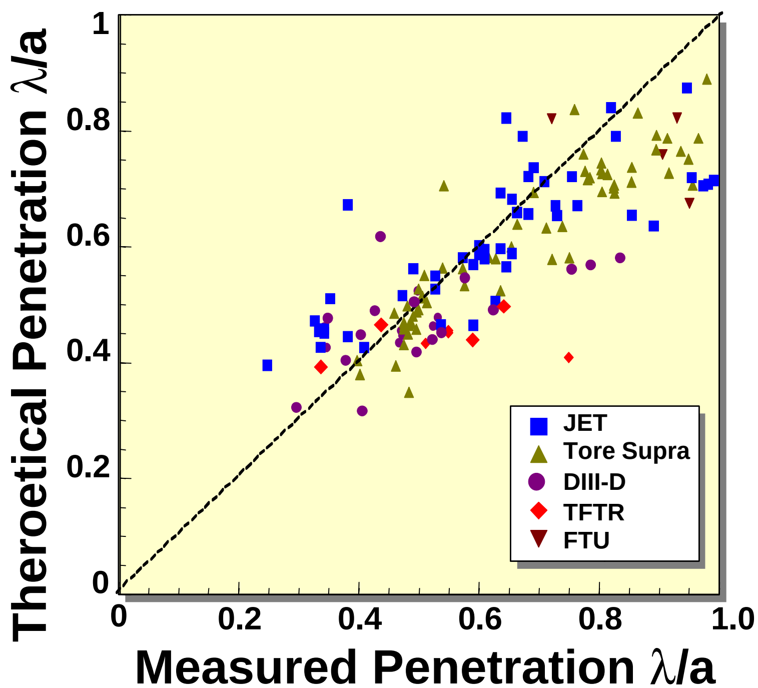
- **Pellet ablation well understood with neutral gas shielding (NGS) model** (Parks, Milora, Pegourie, Kuteev)
  - Assumes pellet particles remain where ionized

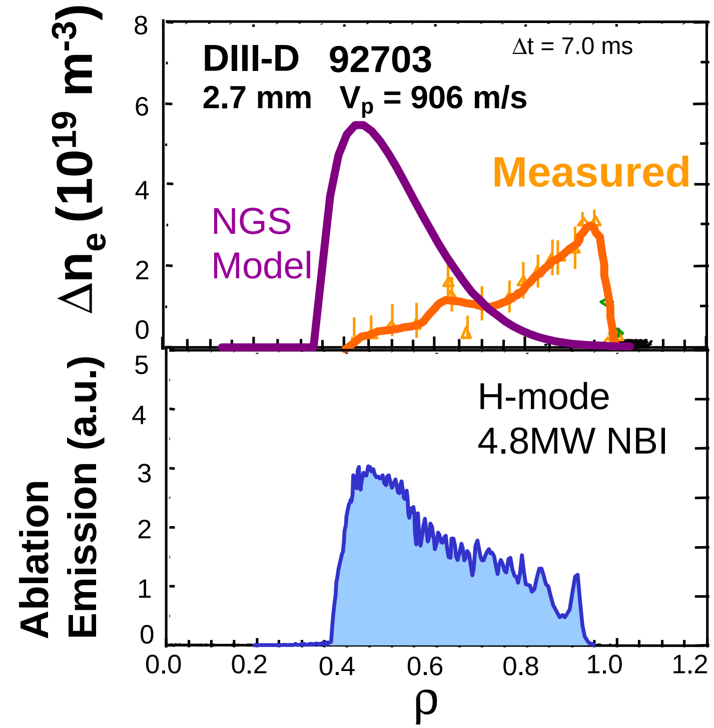


- **Pellet Deposition describes where the pellet mass is distributed in the plasma.**
  - Measured density profile before and after pellet ablation.
  - Data suggests it is vastly different from simple ablation model

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

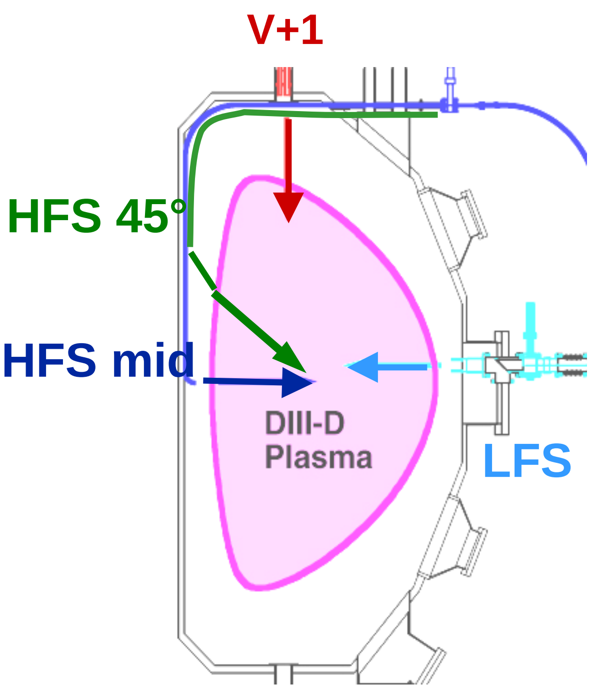




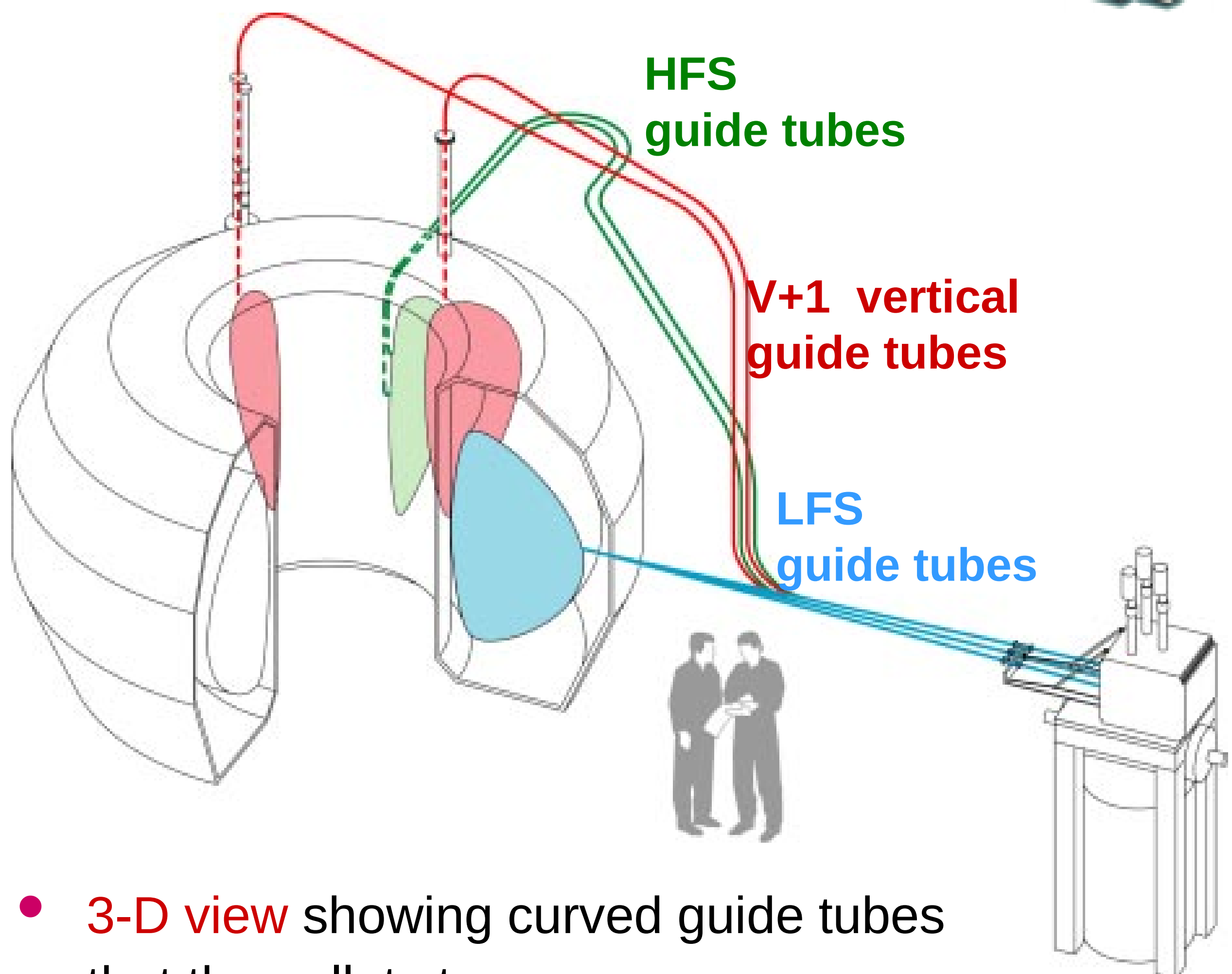


- Maximum Penetration depth agrees well with theory over a range of data from many devices. (Baylor, et al., *Nucl. Fusion* 37, 445 (1997))
- Mass deposition implies fast radial transport during the ablation process.
- ASDEX Upgrade first experiment to try HFS injection to test this hypothesis. (Lang,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

DIII-D Pellet Injection Locations - 1999

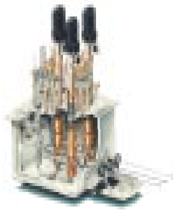


- Elevation view of pellet trajectory in the plasma

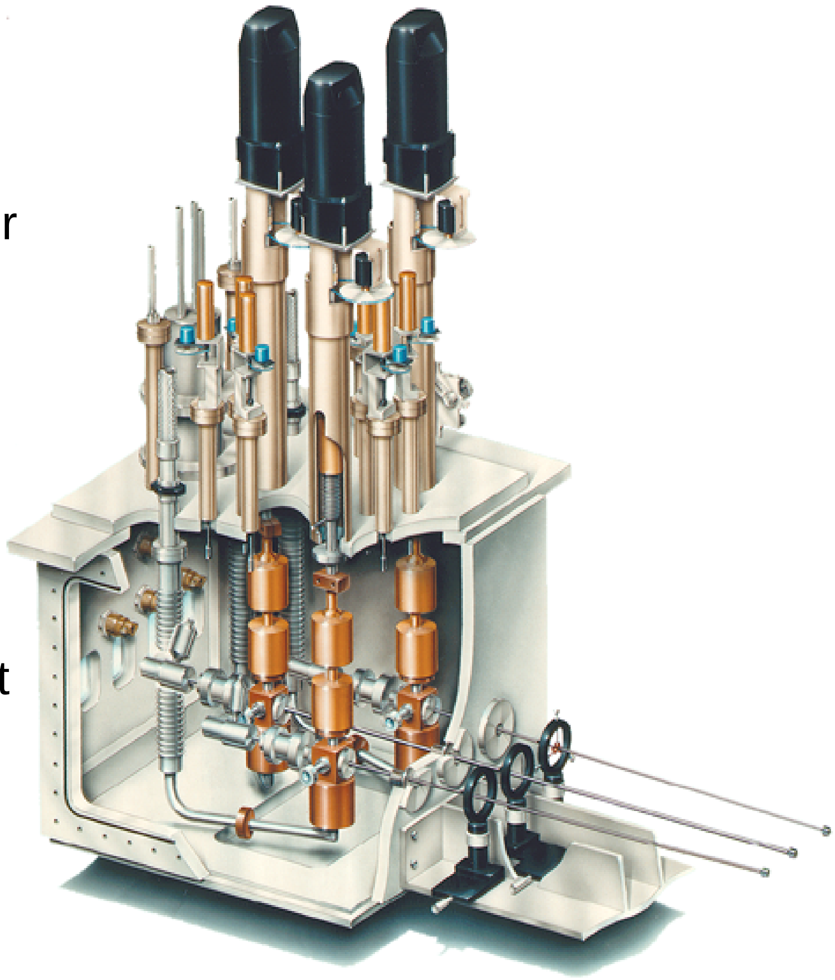


- 3-D view showing curved guide tubes that the pellets traverse

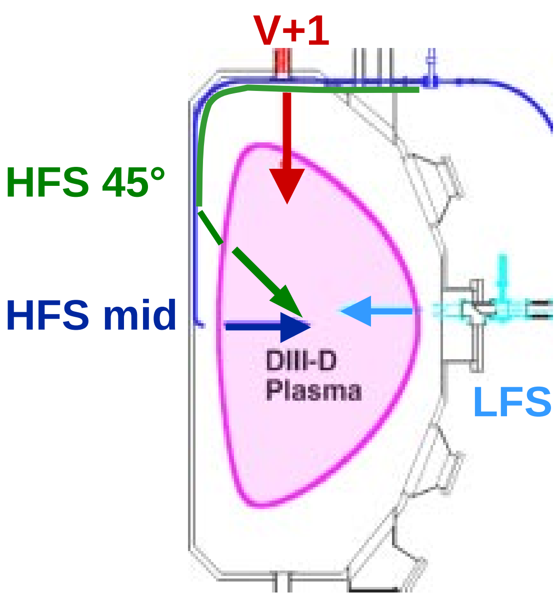
Pellet Injection Program on DIII-D

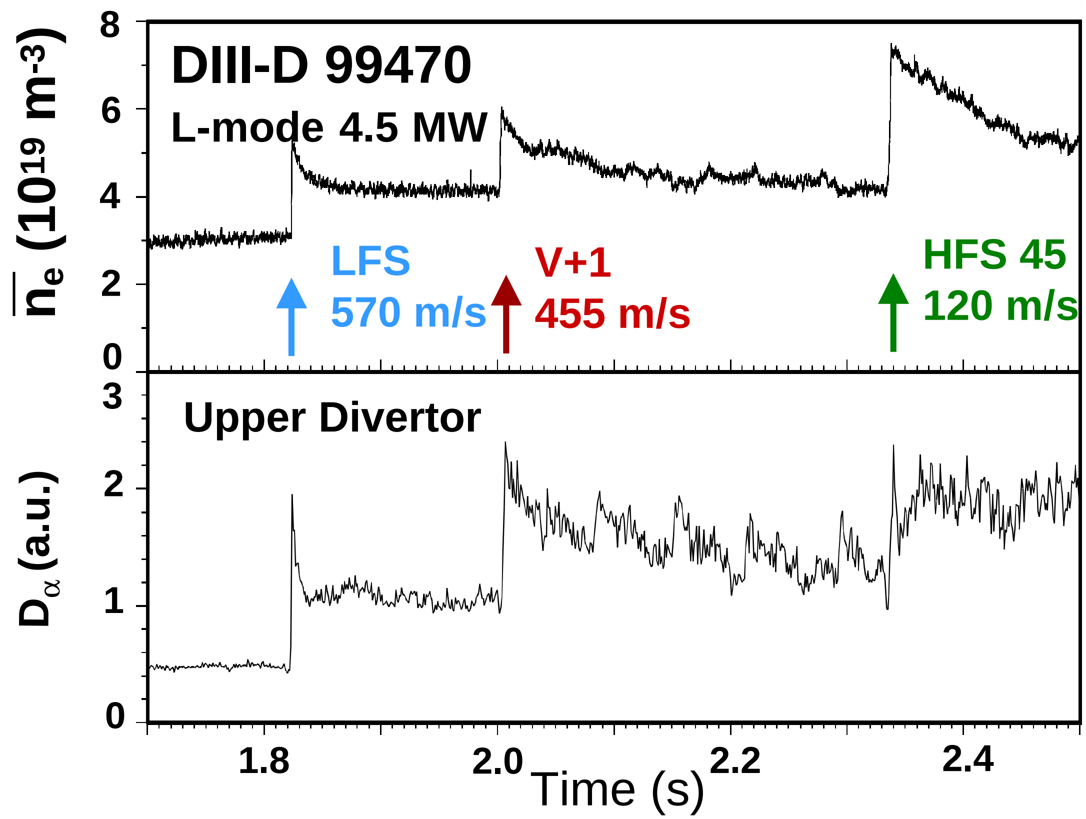


- Modifications to injector (that was installed on JET 1987-91):
  - All three guns fire 2.7 mm pellets
  - Punch mechanism to generate slower pellets (< 300 m/s)
  - Enabling Technology
- 2 independent guide tubes on inner wall (HFS) - midplane, 45° and vertical V+1
  - Can be connected to any of the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



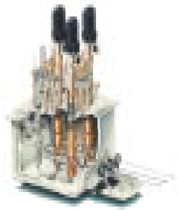
Direct Comparison in L-mode - HFS Pellets Show Less Particle Loss



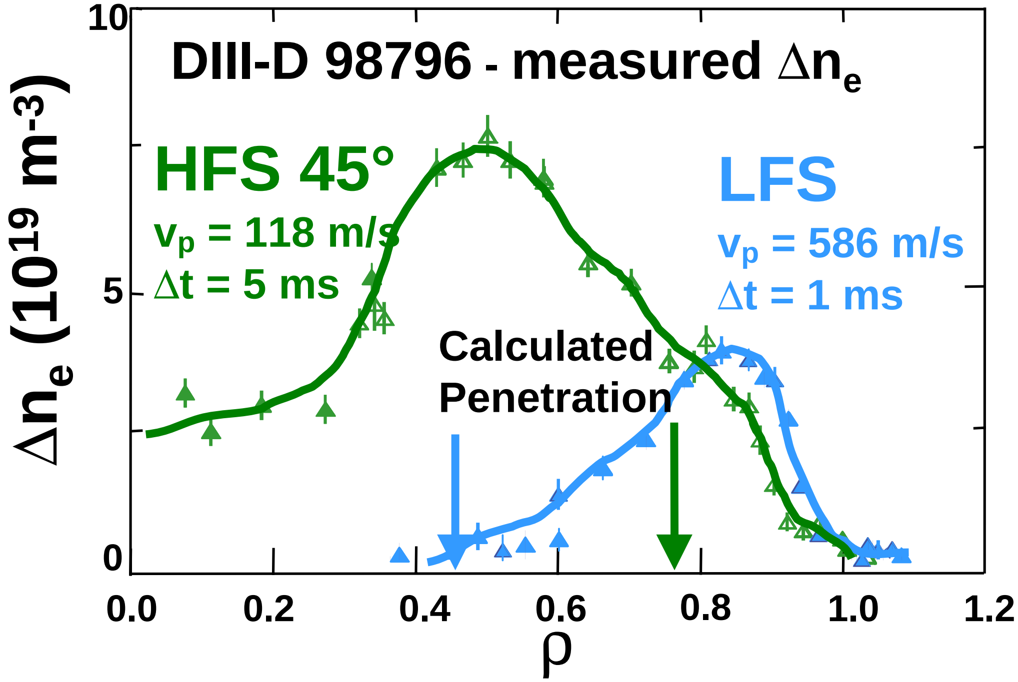


- Pellet comparison from LFS, V+1 and HFS45
- The density perturbation is larger for the HFS pellet
- Divertor D_α shows fewer particles leaving the plasma from the HFS pellet

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



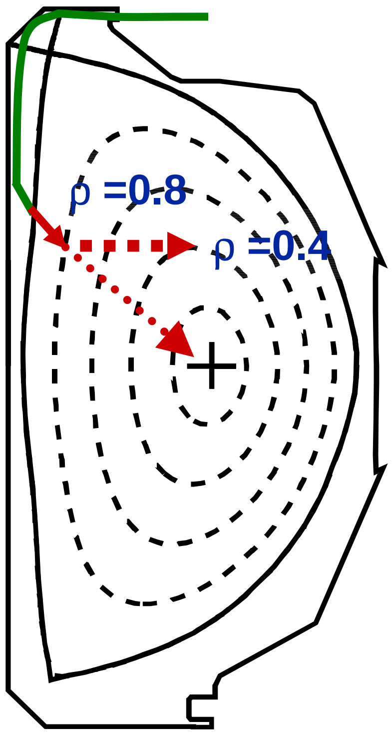
Fueling Efficiency:

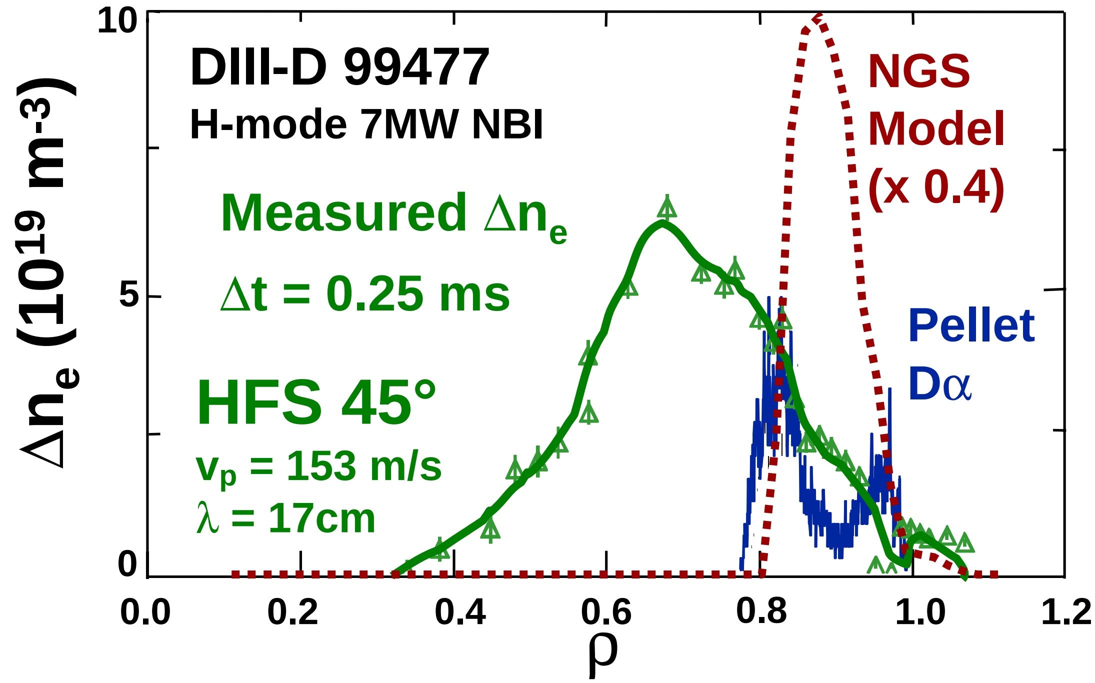
HFS - 95%

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)

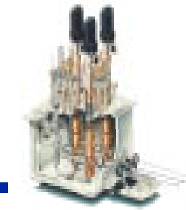
DIII-D HFS 45° Pellet Injection Deposition Suggests Major Radius Drift of Ablatant

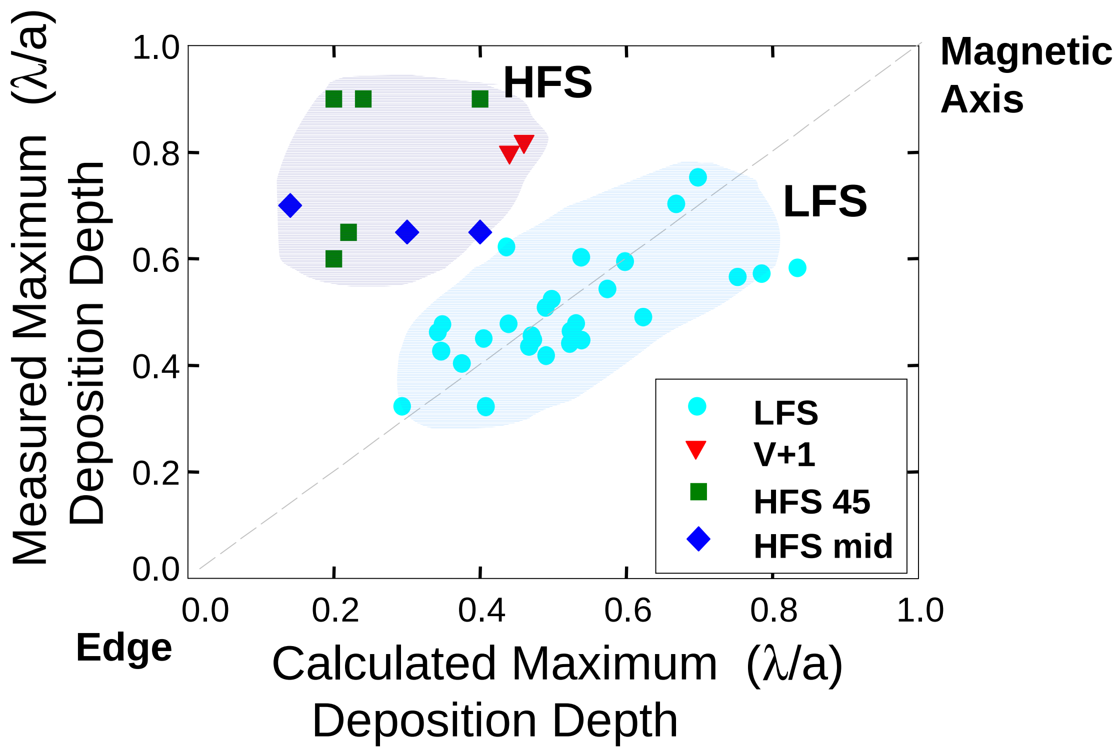




- The deposition shows deeper fueling than predicted
- Pellet Dα emission agrees with ablation model (PELLET code)
- A radial drift of 20 cm is inferred from the data - for comparison with detailed drift model by **Parks (UI1.05)**

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

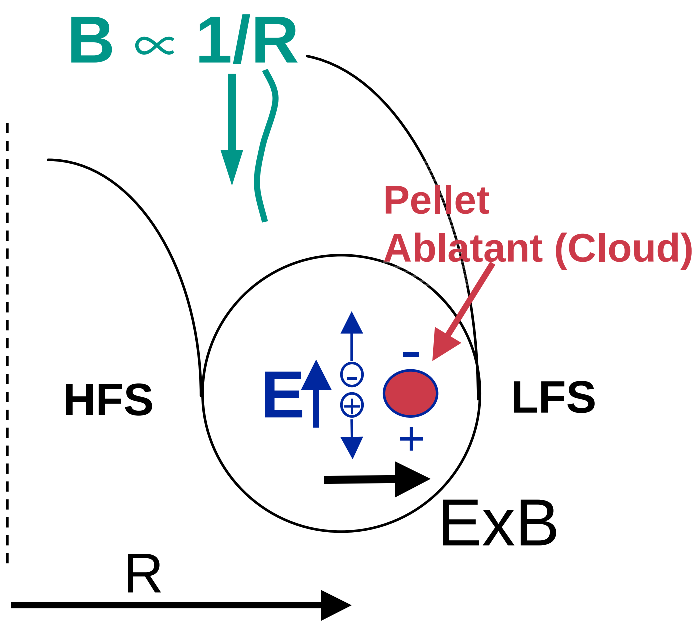




- HFS and Vertical injection show deeper than expected deposition of pellet mass from simple ablation model
- LFS pellet maximum deposition depth agrees with simple model

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:

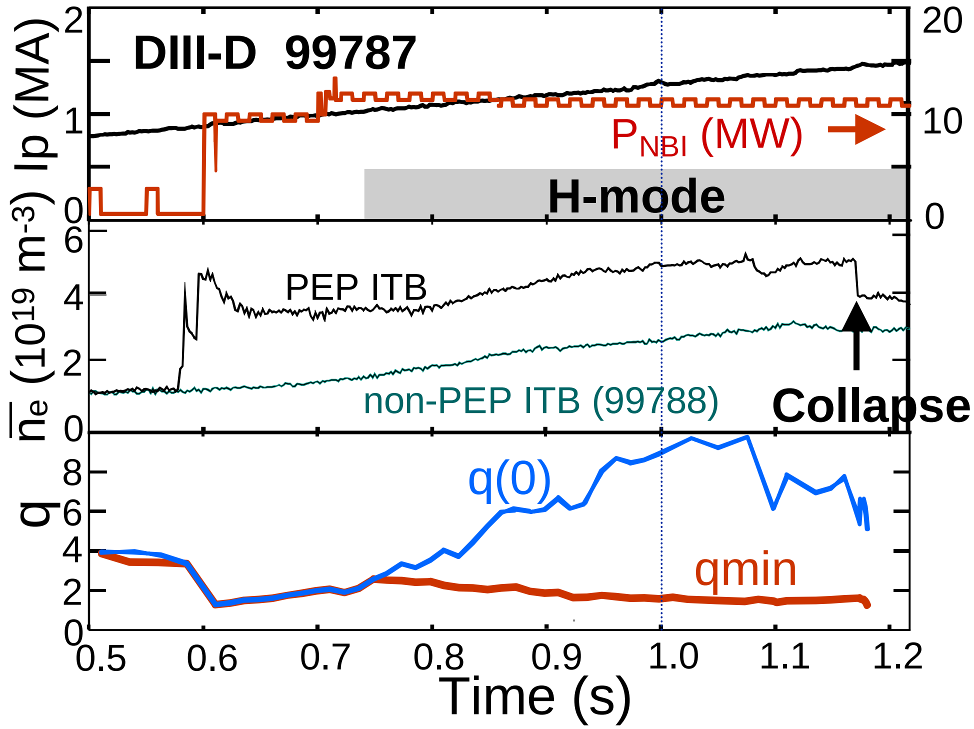
$$\vec{\mathbf{v}}_{\nabla B} = \frac{W_\perp + 2W_\parallel}{eB^3}\vec{\mathbf{B}}\times\overrightarrow{\nabla \mathbf{B}}$$

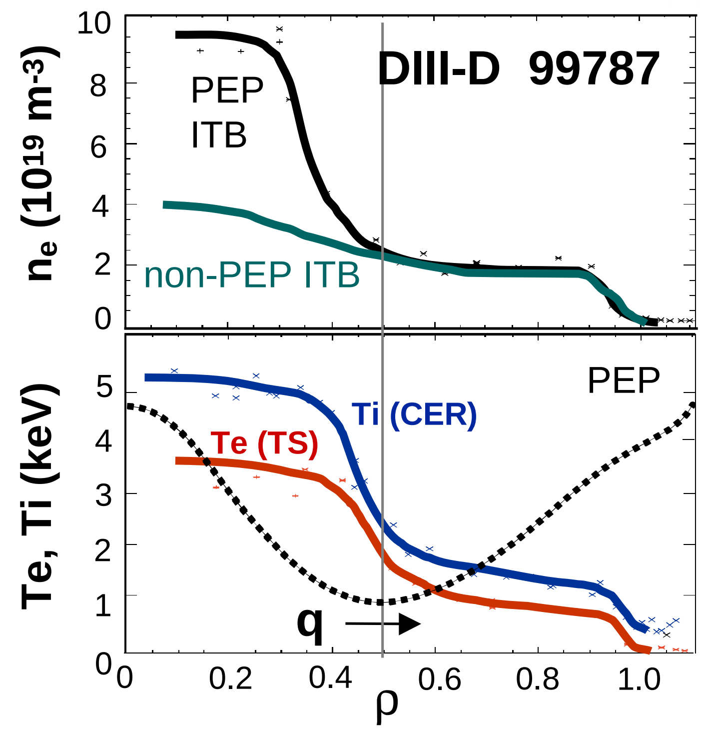
- The resulting E yields an ExB drift in the major radius direction
- The velocity of ablatant ≈ $c_s(2L/R)^{0.5}$. For DIII-D this is ≈ 2 km/s, i.e. faster than the pellet (deKloe, Mueller, Phys.Rev.Lett. (1999))
- ΔR stronger at higher plasma β
- Detailed model by P.B. Parks (UI1.05)

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

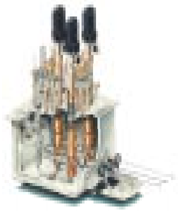
HFS Pellets During Current Rise Lead to Internal Transport Barrier - PEP mode

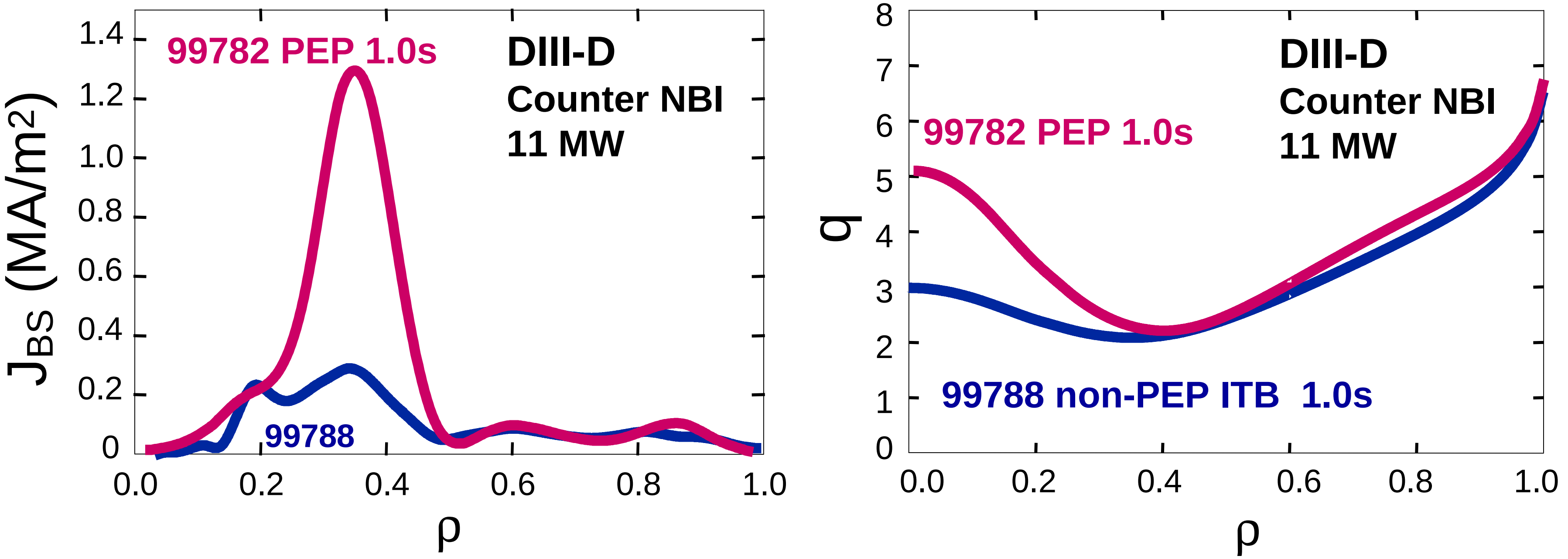




- HFS 2.7mm pellets injected during current rise produce highly peaked density profiles that develop PEP ITB with $T_i \approx T_e$
- PEP survives transition to H-mode and can persist for > 1s
- Core collapse occurs as qmin reaches 3/2
- Steepest n_e, T_e, T_i gradients occur inside ρ_{qmin}

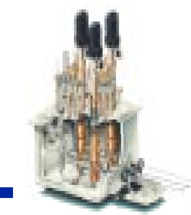
Strong Off-Axis Bootstrap Current Drives Negative Central Shear in PEP ITB

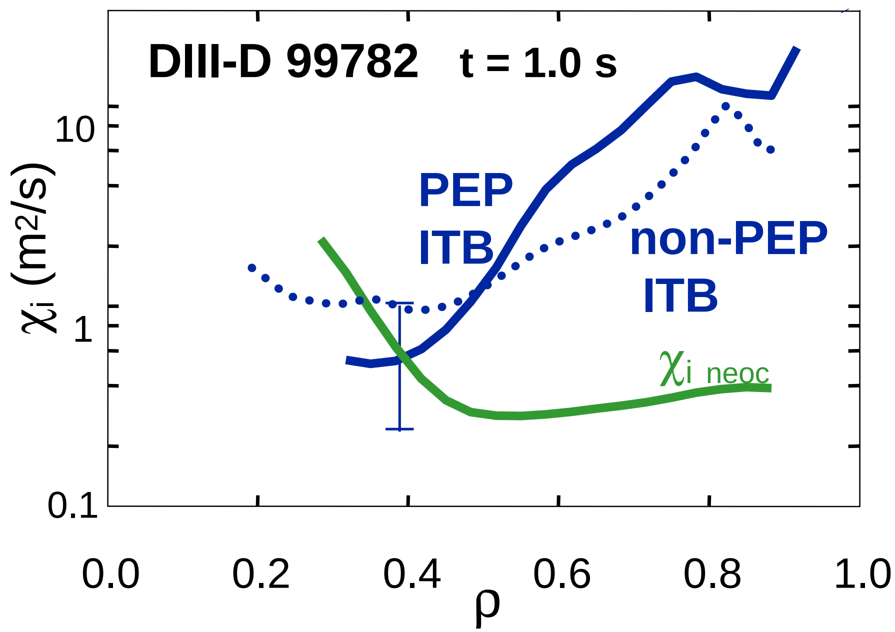


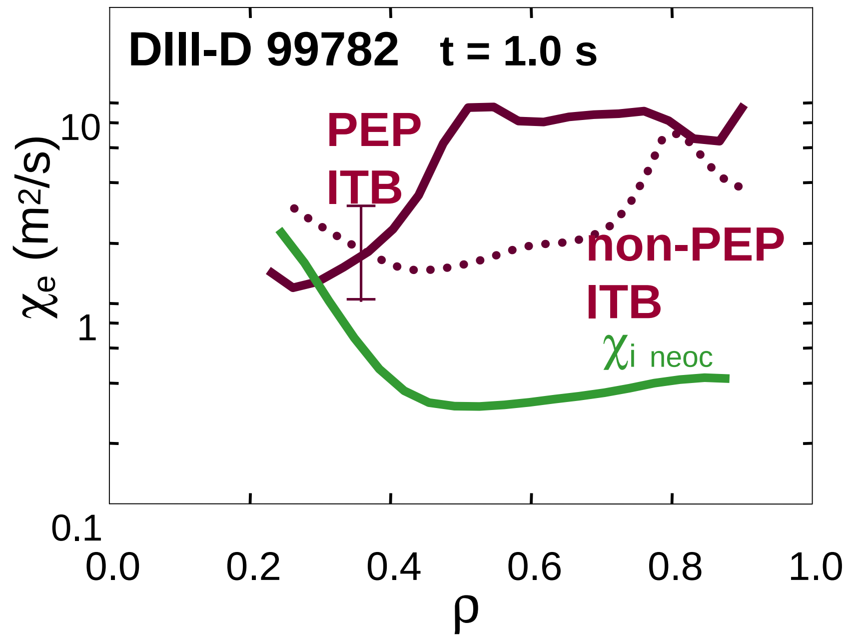


- Bootstrap current from NCLASS shows strong off-axis contribution in the PEP-mode
- Safety factor (q) profile determined with MSE data has stronger negative central shear in PEP than non-PEP ITB comparison

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

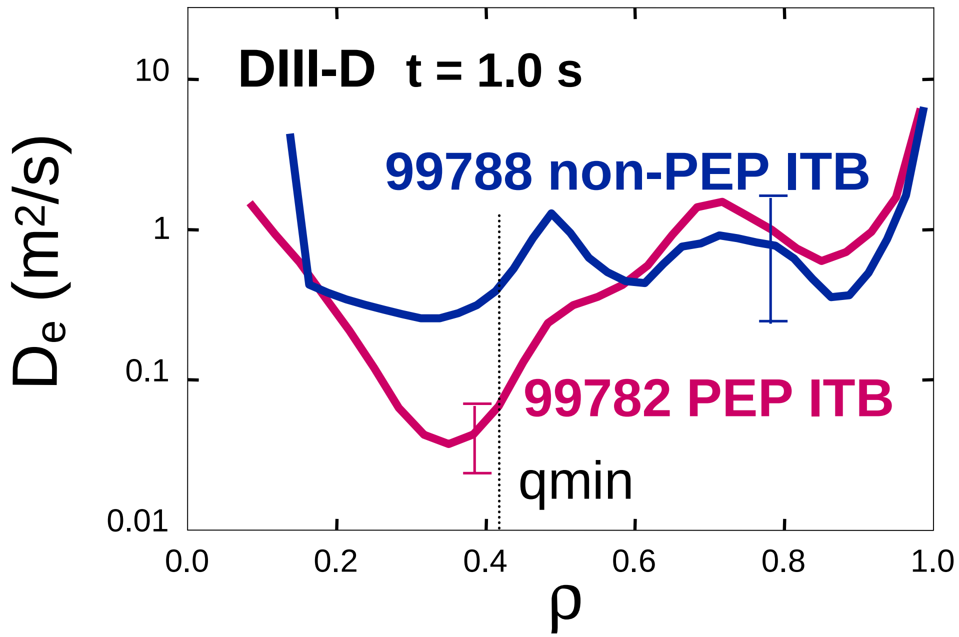






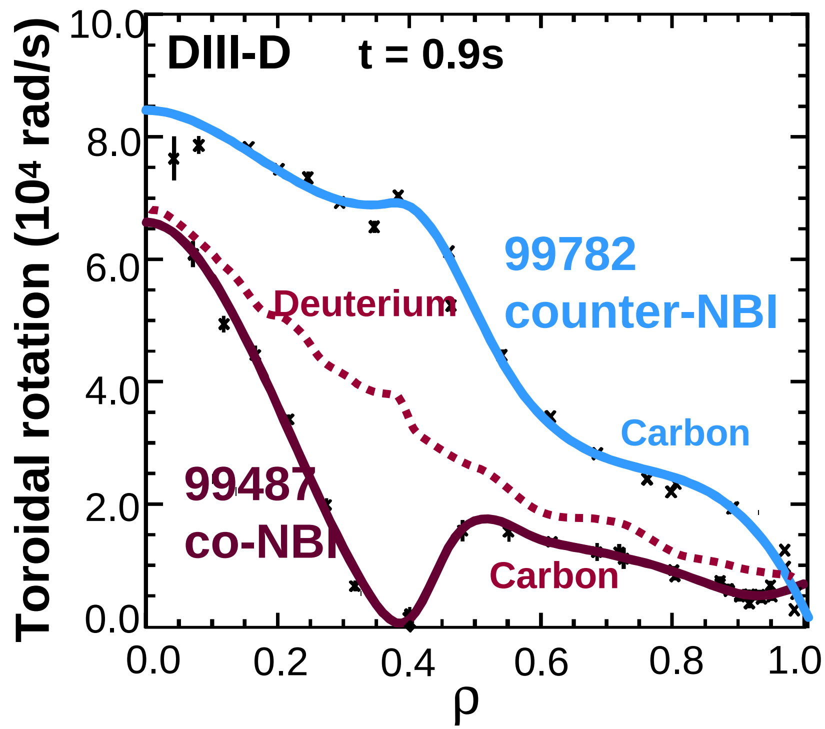
- TRANSP calculation of thermal diffusivities shows ITB in core region out to ρ = 0.4 as expected from the strong gradients in the kinetic profiles.
- ITB in PEP case is comparable to non-PEP ITB, both approach neoclassical levels.
- ω_{EXB} becomes large enough to suppress ITG turbulence as in the non-PEP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

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



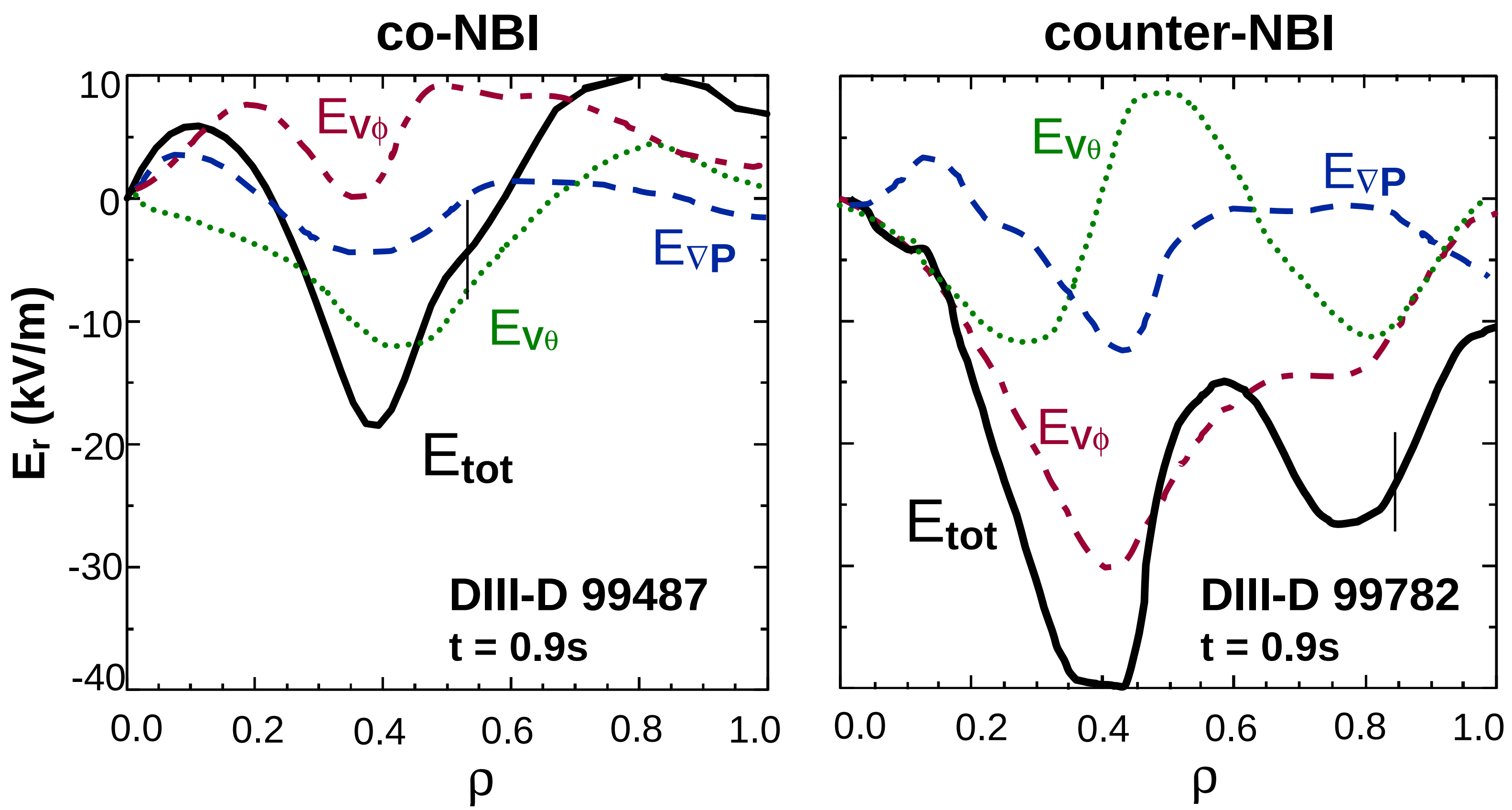
- TRANSP calculation of electron particle diffusivity shows reduced core particle transport in PEP just inside the barrier region (ρ=0.4)
- Both PEP and non-PEP ITBs show strong increase toward axis as profiles become flat

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



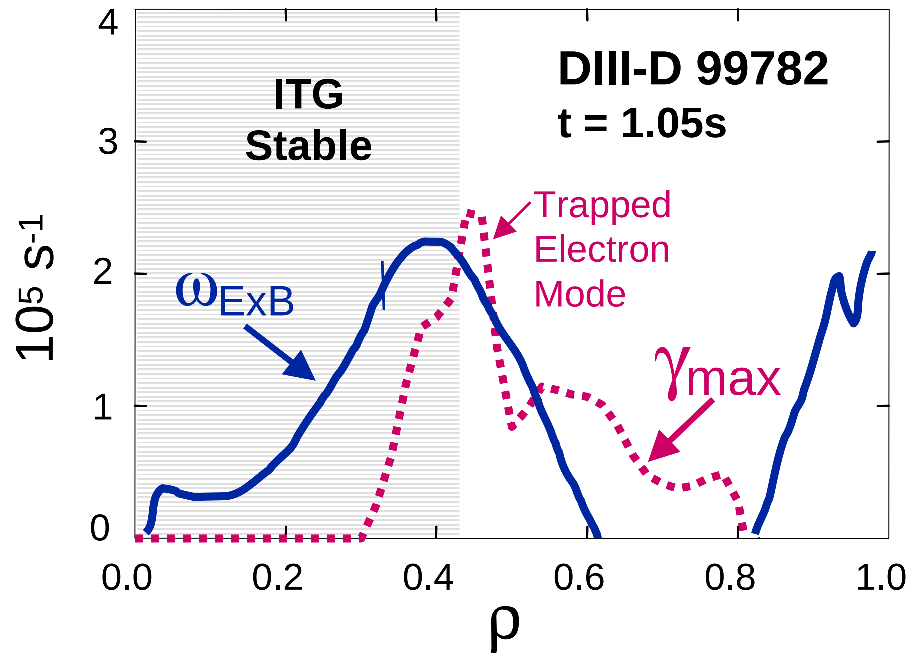
- Toroidal carbon rotation in PEP-mode shows a “notch” with co-NBI similar to that seen on TFTR supershots due to neoclassical parallel momentum exchange. (D. Ernst, et al. Phys. Plasmas 1998.)
- NCLASS calculated deuterium rotation profile is monotonic.

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



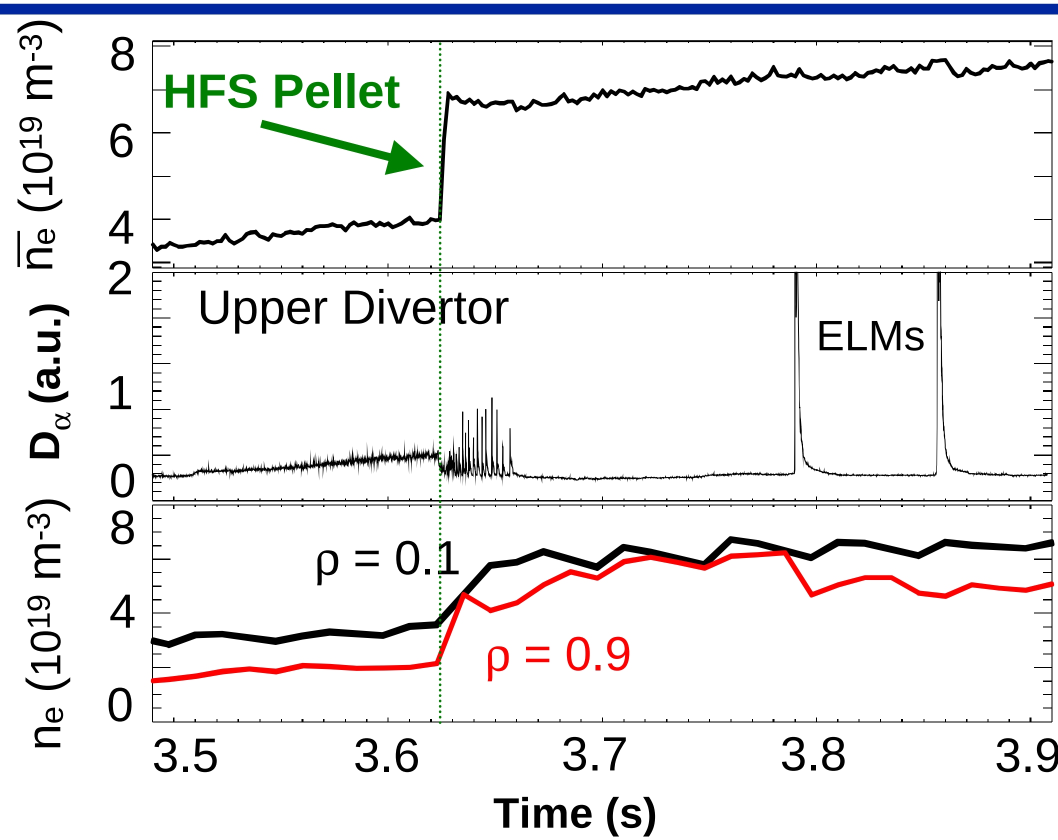
Gyrokinetic Stability Calculation

- 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

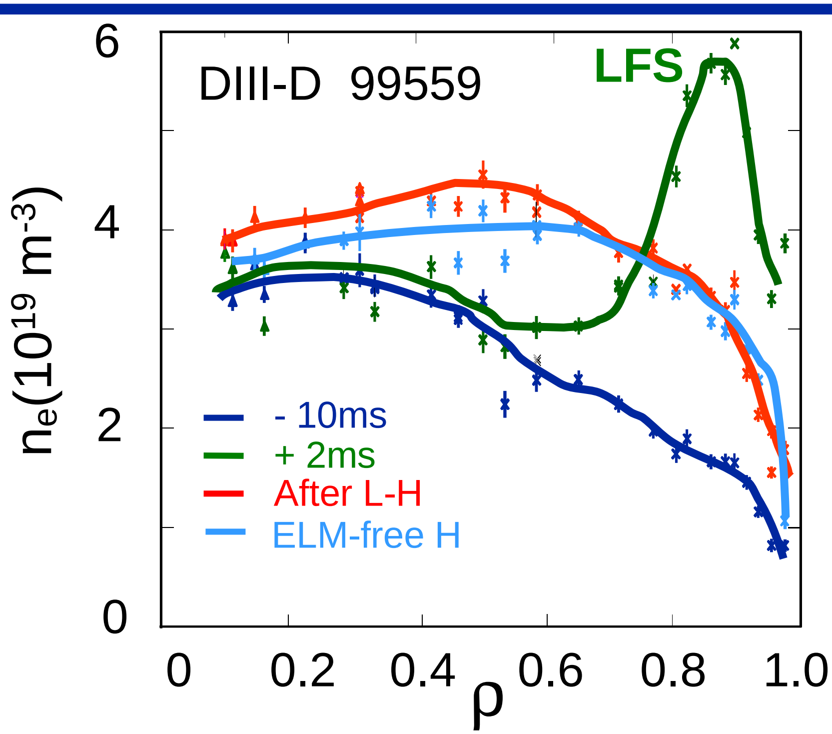
HFS Pellets have induced H-mode Transitions

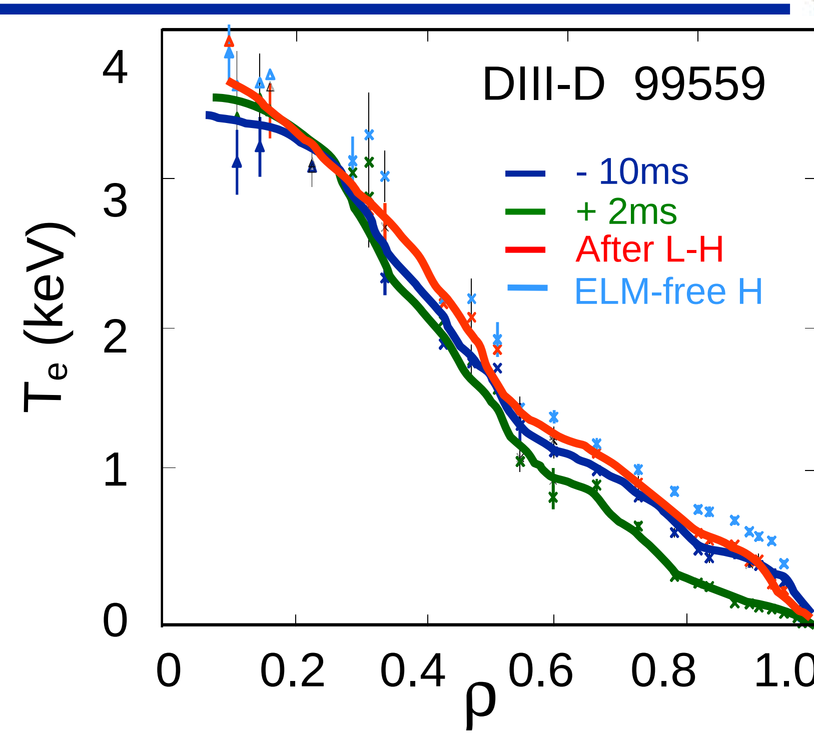


L-mode Target
4.8MW NBI
Upper Single Null

- 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)

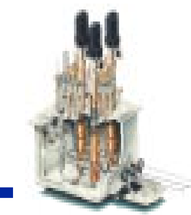
Pellet Induced H-mode Transition Occurs at Lower Edge Temperature





- 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

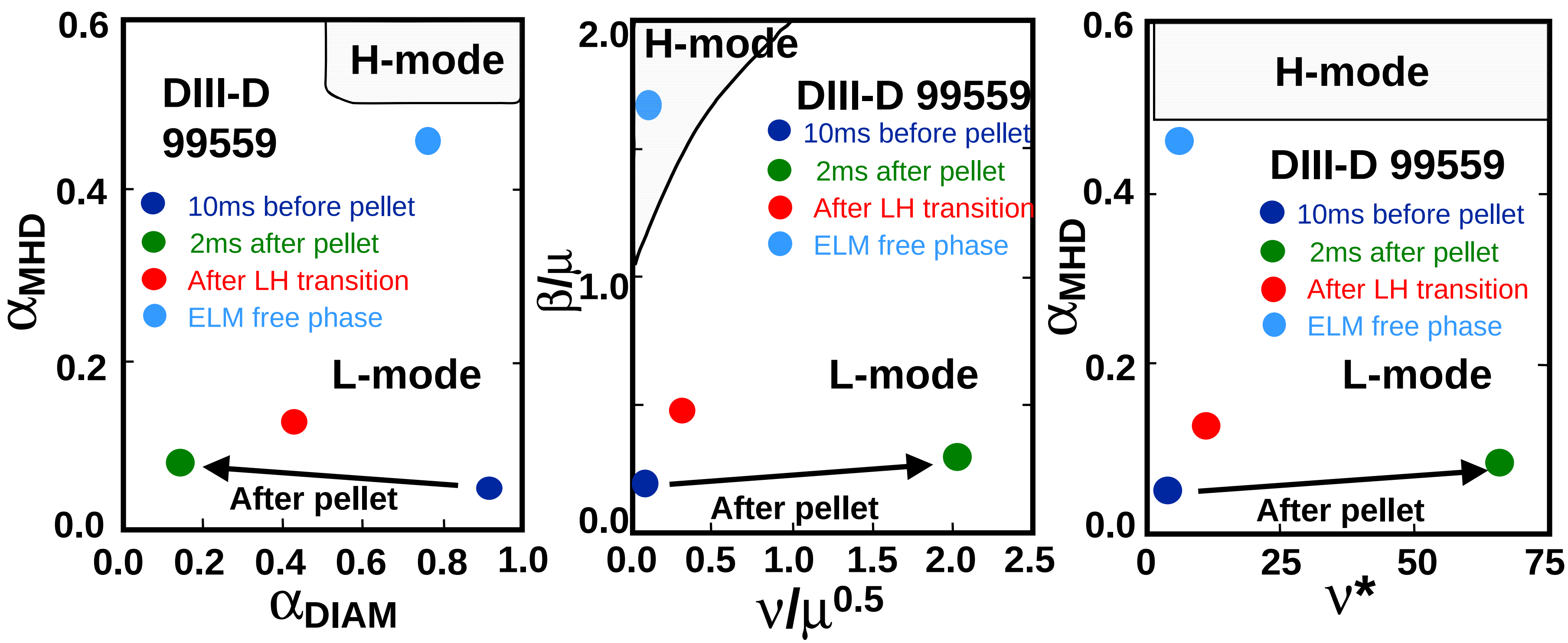
Pellet Induced H-modes have Transitions at Plasma Parameters far Below Theoretical Predictions



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

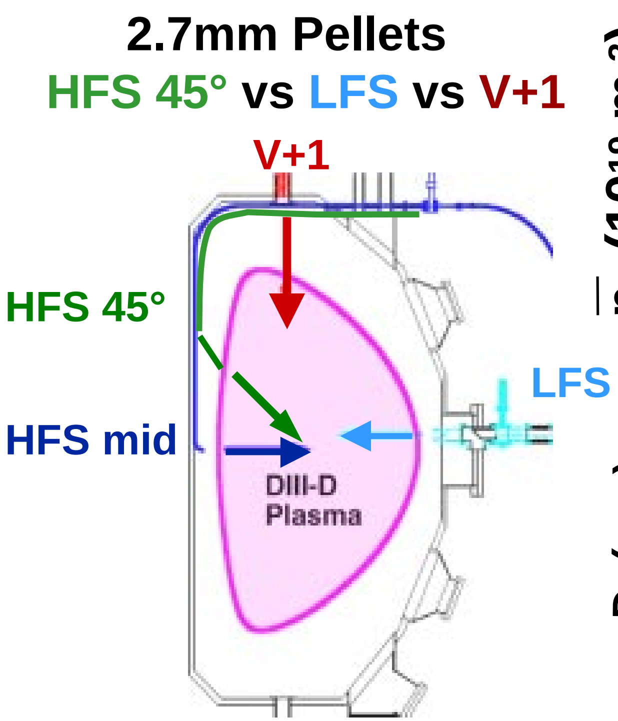
Pogutse et al. Proc. 24th EPS Conf. 1997 (P3-1041)

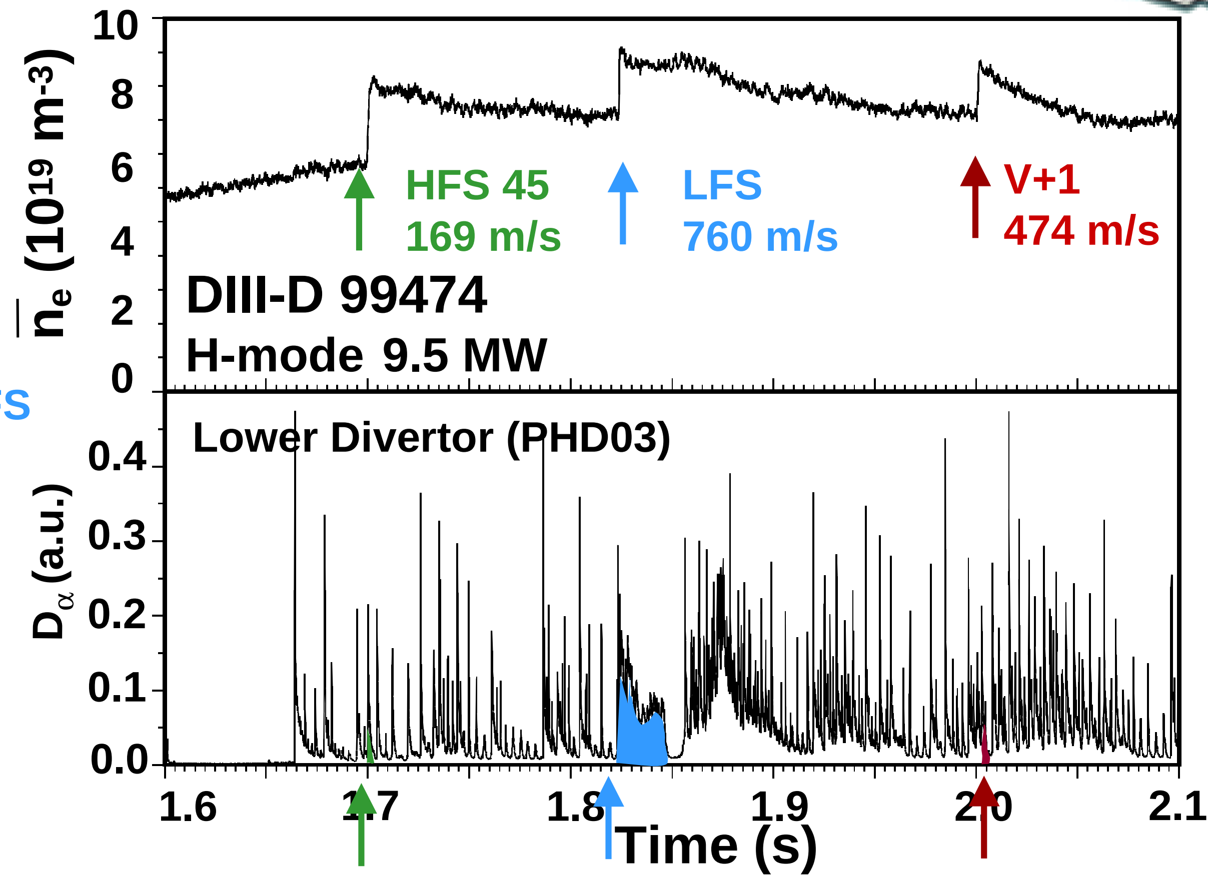
Wilson et al. Proc. 17th IAEA Fusion Energy Conf. Yokohama, Japan 1998, IAEA-F1-CN-69/TH3/2



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

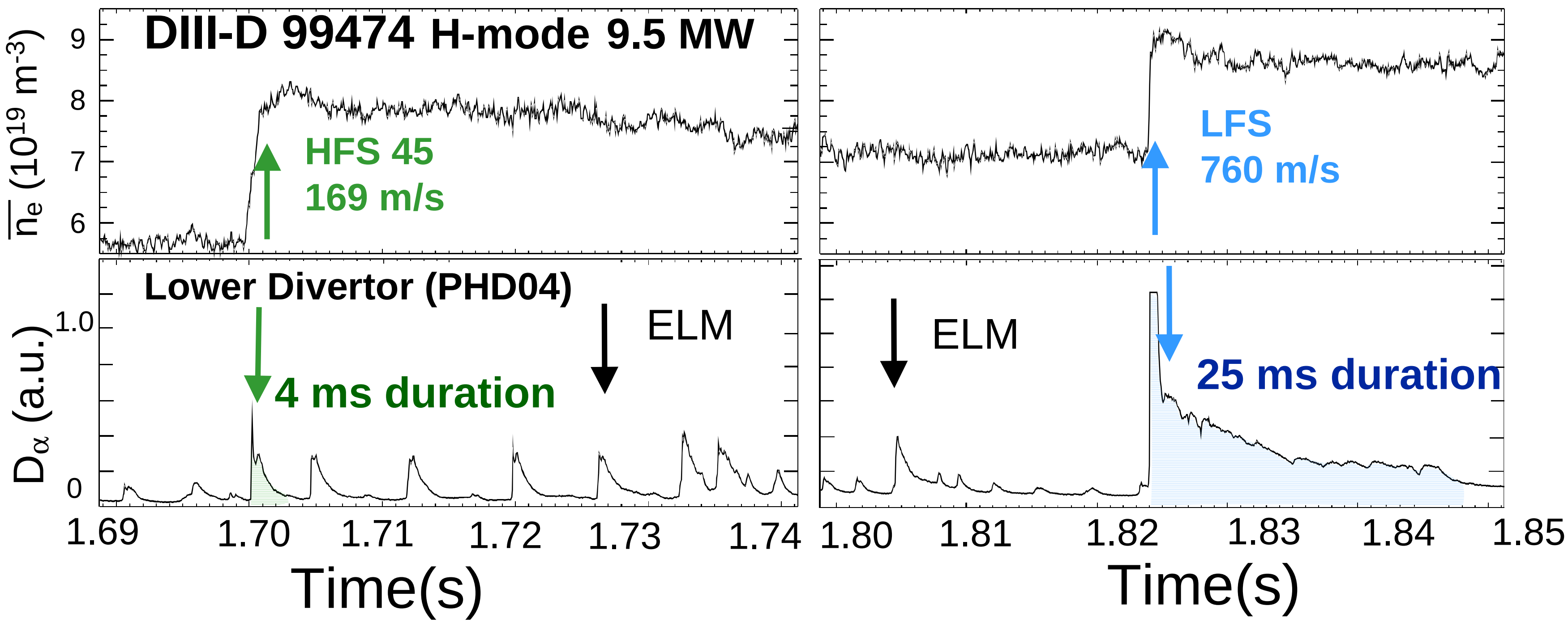
Direct Comparison in H-mode -
HFS Pellets Trigger Smaller ELMs





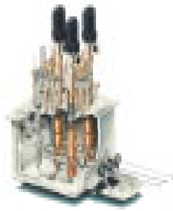
- 2.7mm pellets injected into the same 9.5 MW NBI DN H-mode plasma from HFS45, LFS, and V+1
- ELMs are triggered by the pellets, but are much smaller for the HFS pellets

HFS Pellets produce different ELM characteristics than LFS pellets.



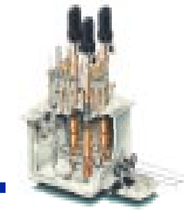
- HFS pellet induced ELMs are small like background ELMs
- LFS pellets induce large ELMs much longer lasting than background ELMs. ExB drift loss of particles may be responsible.
- P´ modification at edge may be different for HFS and LFS pellets (J.R. Ferron, UI1.01)

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**