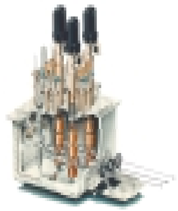
Improved Core Fueling with High Field Side Pellet Injection on the DIII-D Tokamak



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ORNL, *General Atomics, ^MIT, [#]PPPL

from presentation by ***L.R. Baylor*** at the

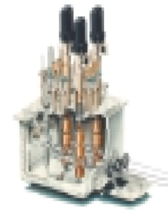
41st APS/DPP Meeting, *Nov.19, 1999, Seattle, WA*

Workshop on Physics Issues for FIRE

1-3 May 2000

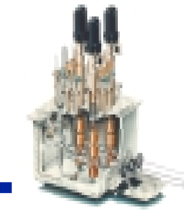
Princeton, NJ

Overview



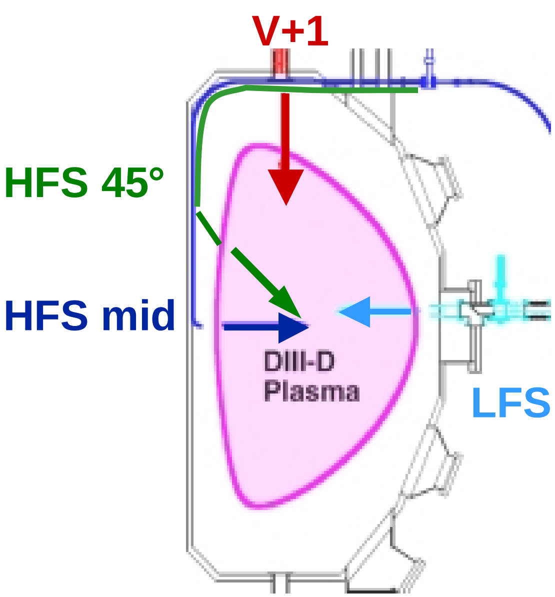
- **Pellet ablatant drifts in the major radius direction on a fast time scale during redistribution process**
- **High field side (HFS) injection lines on DIII-D provide improved core fueling with HFS injected pellets**
  - HFS pellets have efficient fueling with minimized particle loss
- **PEP-mode internal transport barriers (ITB) are formed with HFS pellets followed by central heating**
  - $T_i \sim T_e$ 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.**

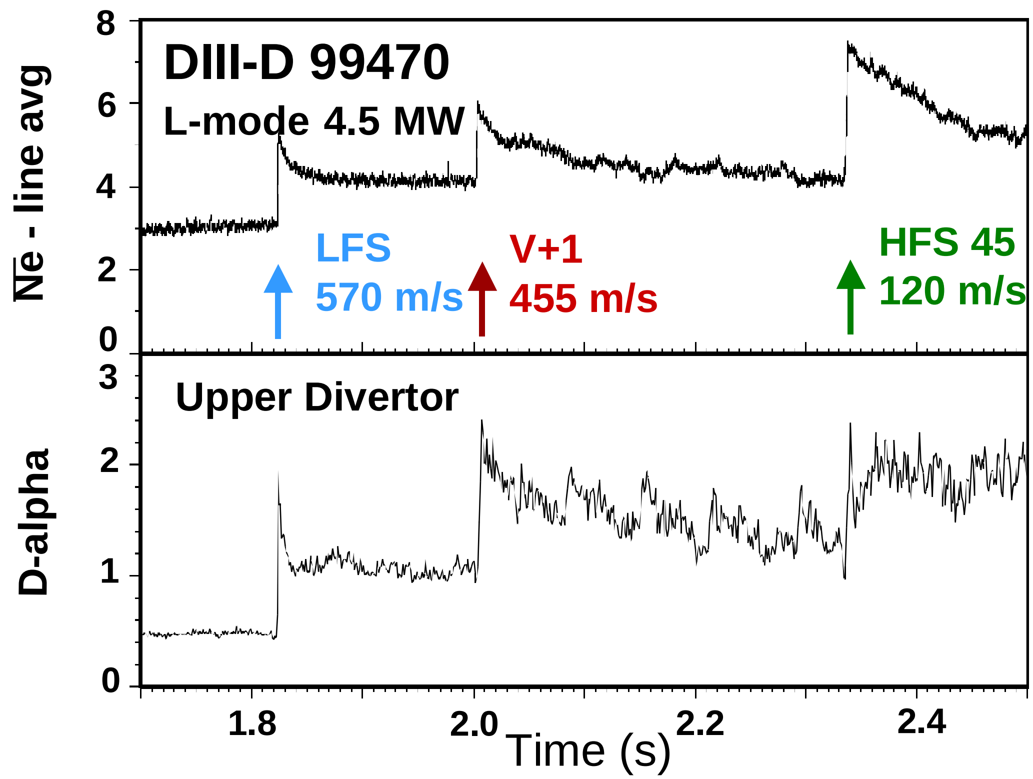
Direct Comparison in L-mode - HFS Pellets Show Less Particle Loss



2.7mm Pellets

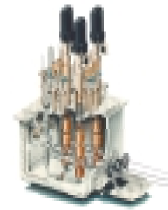
LFS vs V+1 vs HFS 45°



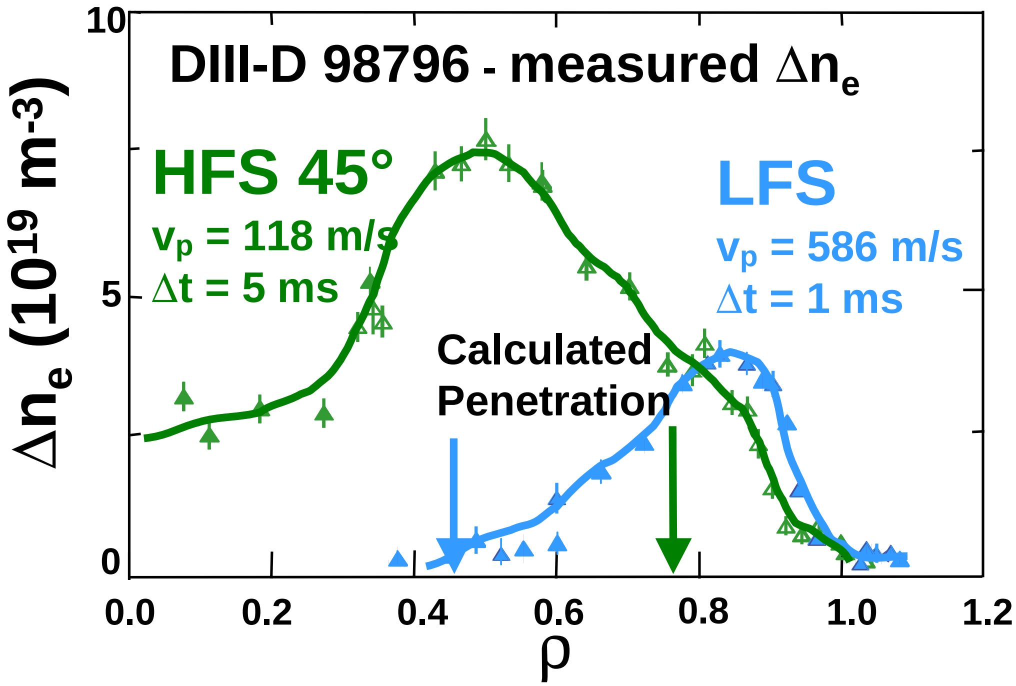


- Pellet comparison from LFS, V+1 and HFS45
- The density perturbation is larger for the HFS pellet
- Divertor D_α shows fewer particles leaving the plasma from the HFS pellet

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



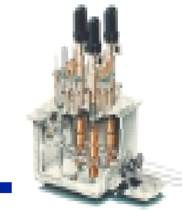
Fueling Efficiency:

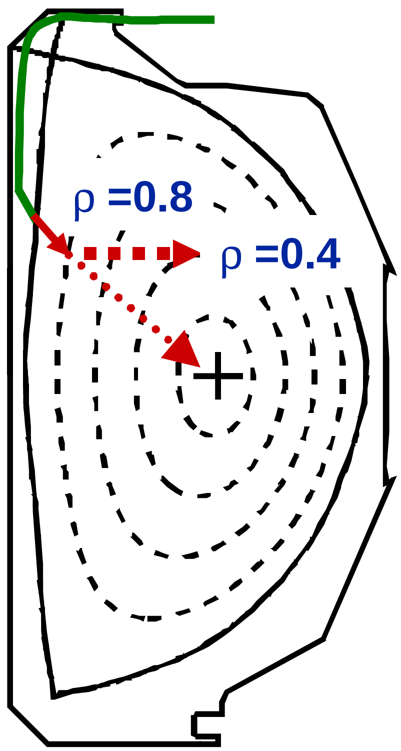
HFS - 95%

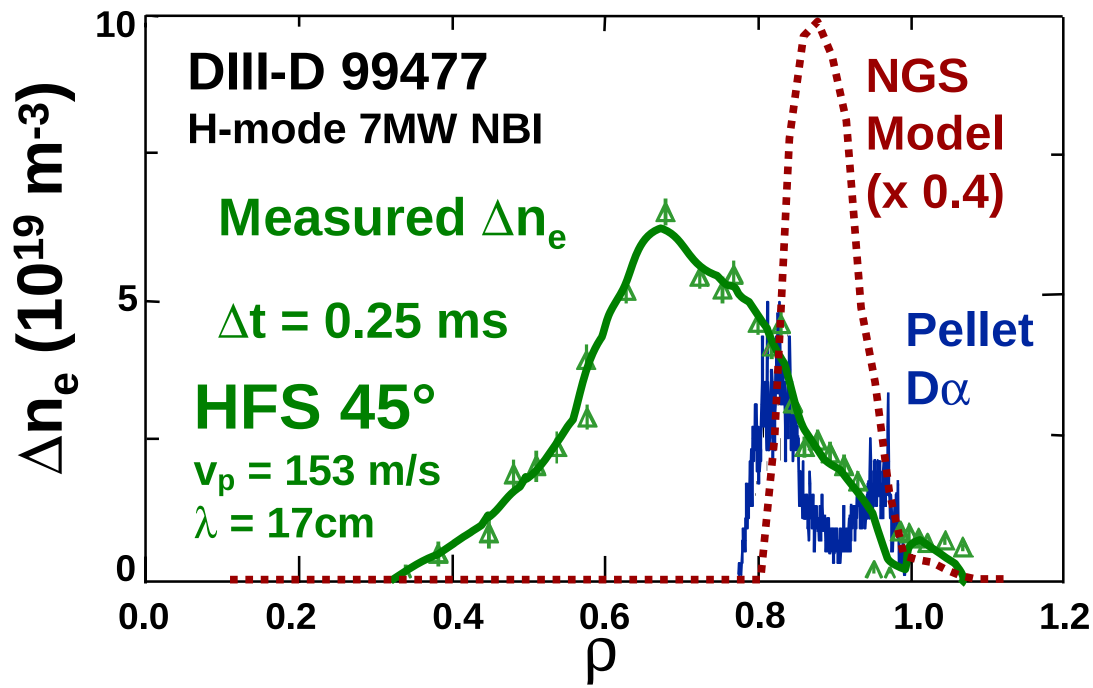
LFS - 55%

- 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

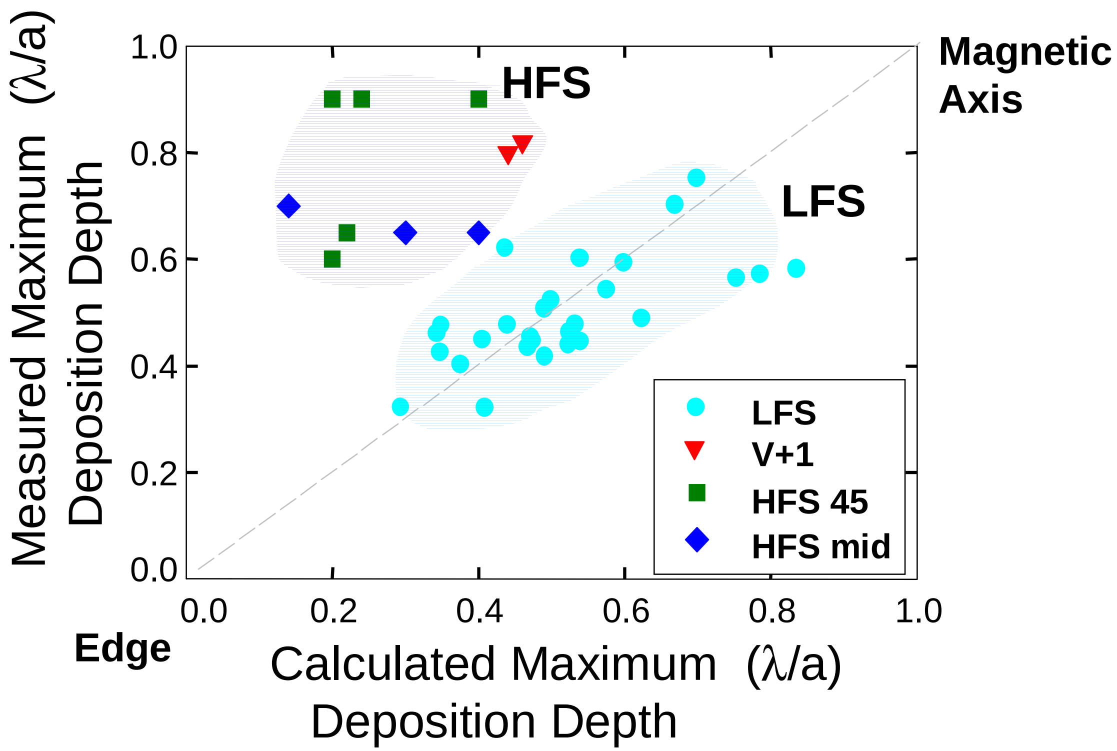






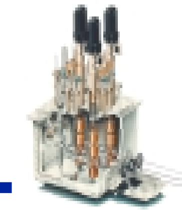
- The deposition shows deeper fueling than predicted
- Pellet Dα emission agrees with ablation model (PELLET code)
- A radial drift of 20 cm is inferred from the data - for comparison with detailed drift model by **Parks (UI1.05)**

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



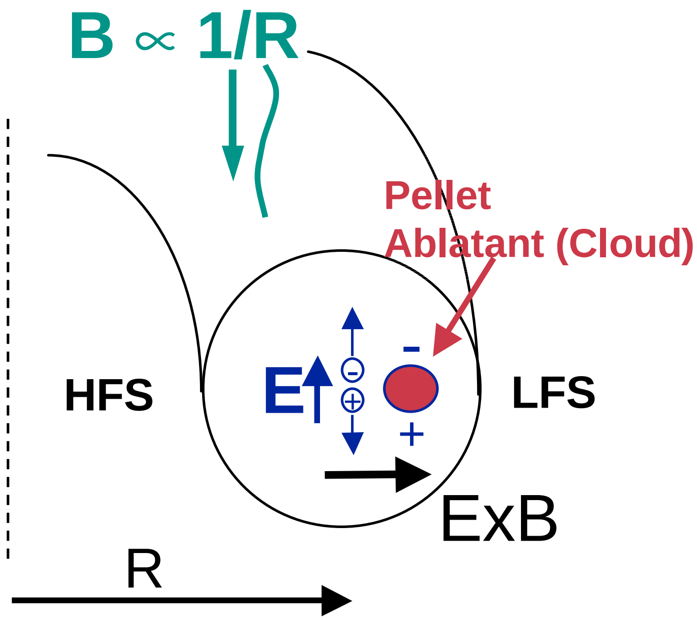
- HFS and Vertical injection show deeper than expected deposition of pellet mass from simple ablation model
- LFS pellet maximum deposition depth agrees with simple model

Theoretical Model for Pellet Radial Drift



ExB Polarization Drift Model of Pellet Mass Deposition

(Rozhansky, Parks)

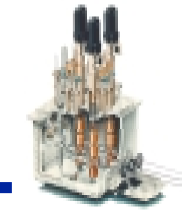


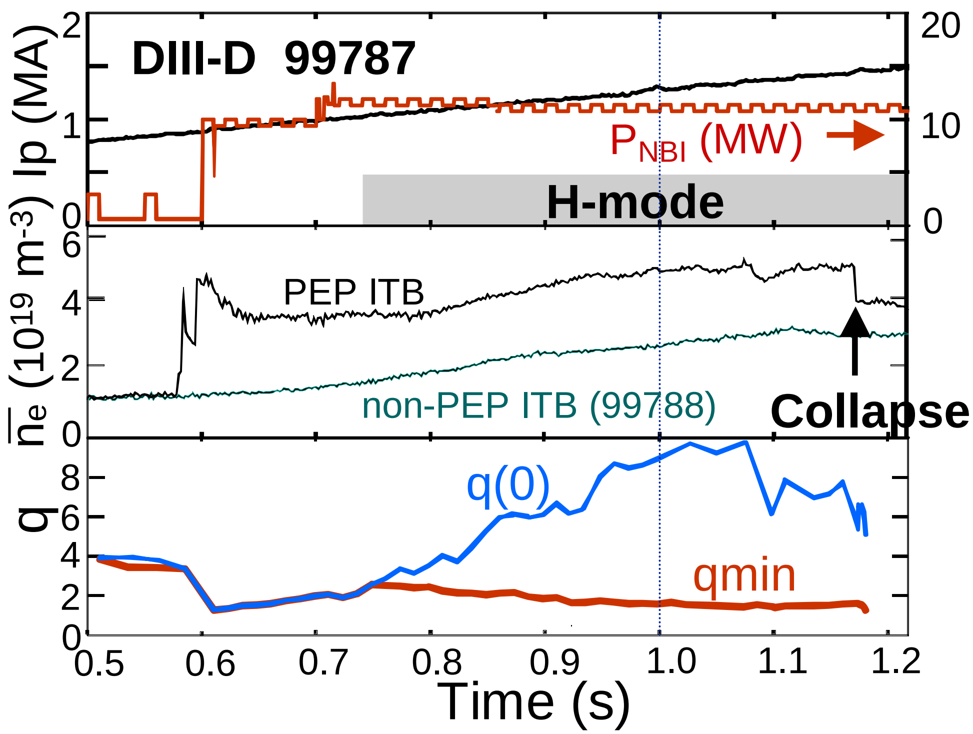
- Polarization of the ablatant occurs from ∇B and curvature drift in the non-uniform tokamak field:

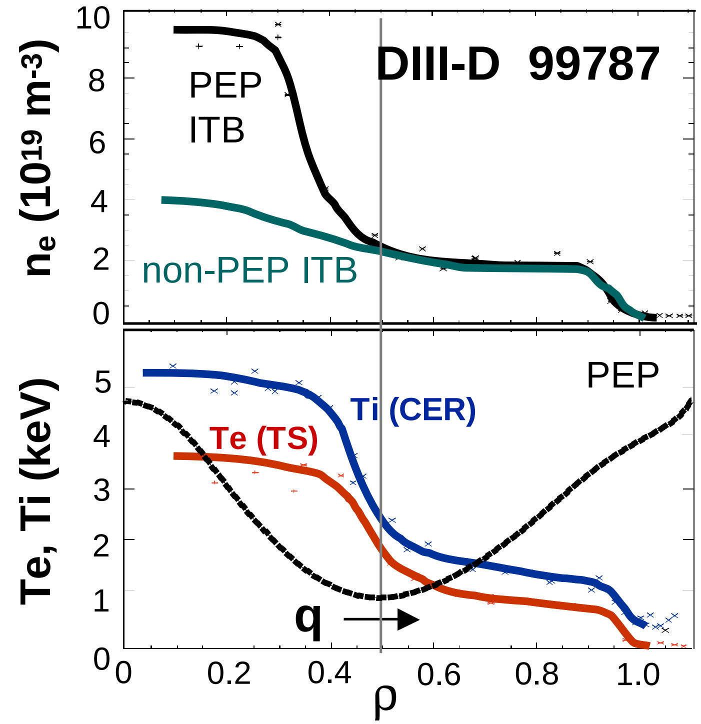
$$\vec{\mathbf{v}}_{\nabla B} = \frac{W_{\perp} + 2W_{\parallel}}{eB^3} \vec{\mathbf{B}} \times \overrightarrow{\nabla \mathbf{B}}$$

- 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)

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

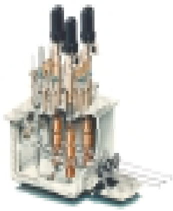


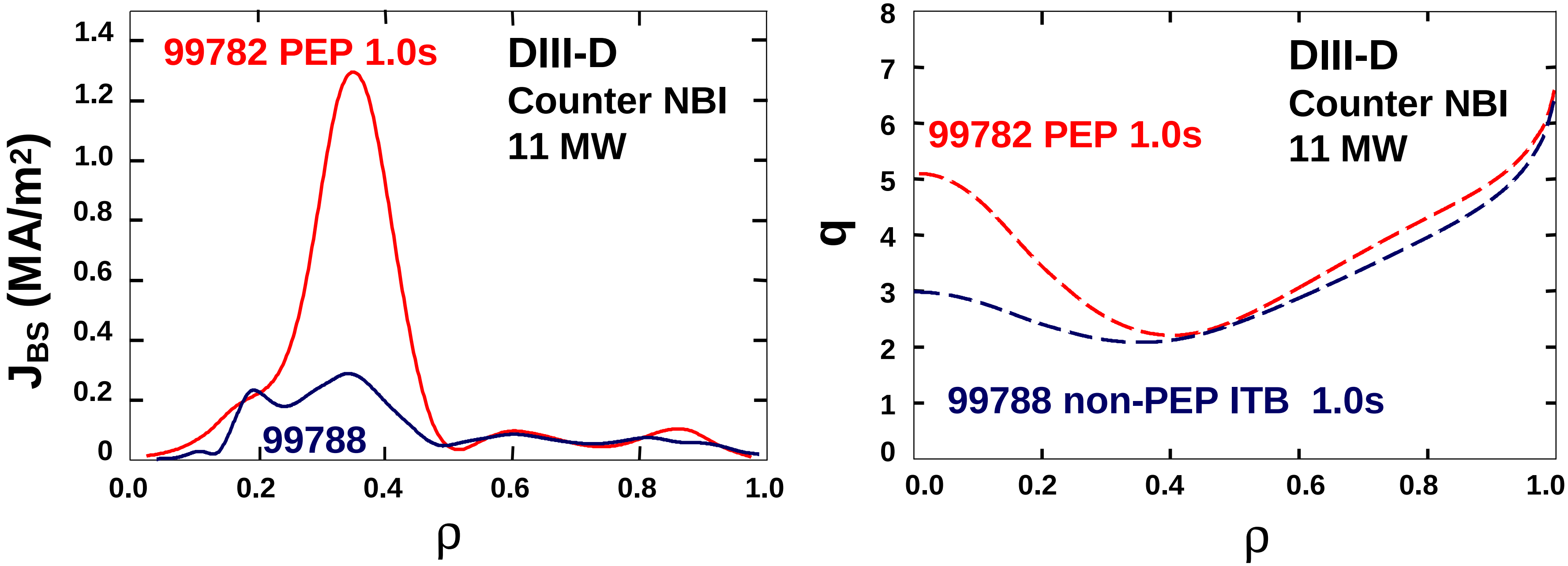




- HFS 2.7mm pellets injected during current rise produce highly peaked density profiles that develop PEP ITB with $T_i \approx T_e$
- PEP survives transition to H-mode and can persist for > 1s
- Core collapse occurs as qmin reaches 3/2
- Steepest n_e, T_e, T_i gradients occur inside ρ_{qmin}

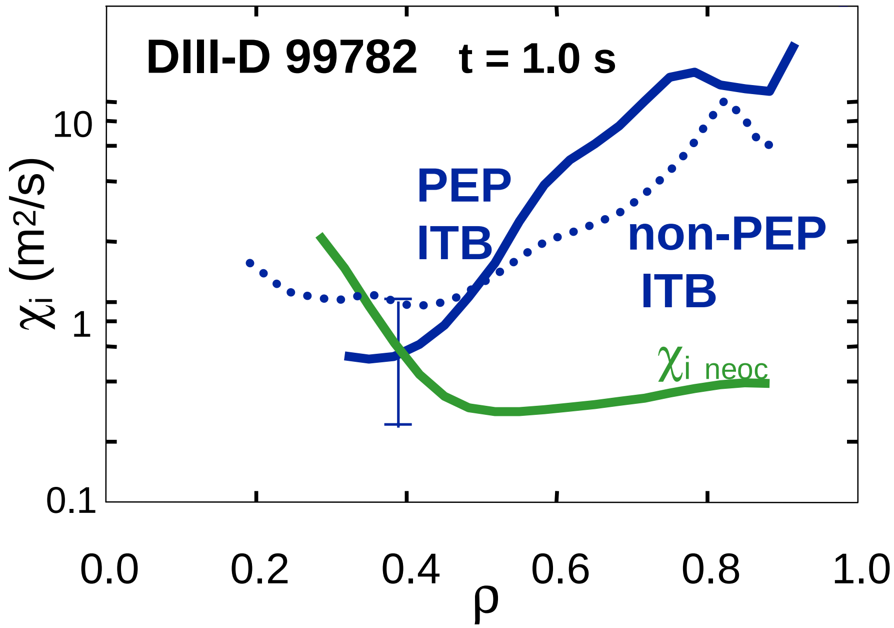
Strong Off-Axis Bootstrap Current Drives Negative Central Shear in PEP ITB

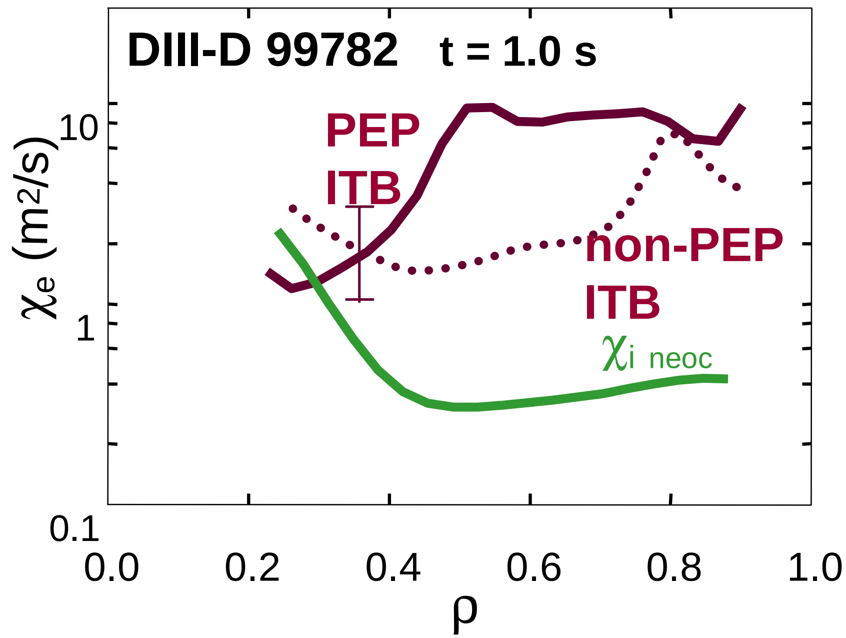




- Bootstrap current from NCLASS shows strong off-axis contribution in the PEP-mode
- Safety factor (q) profile determined with MSE data has stronger negative central shear in PEP than non-PEP ITB comparison

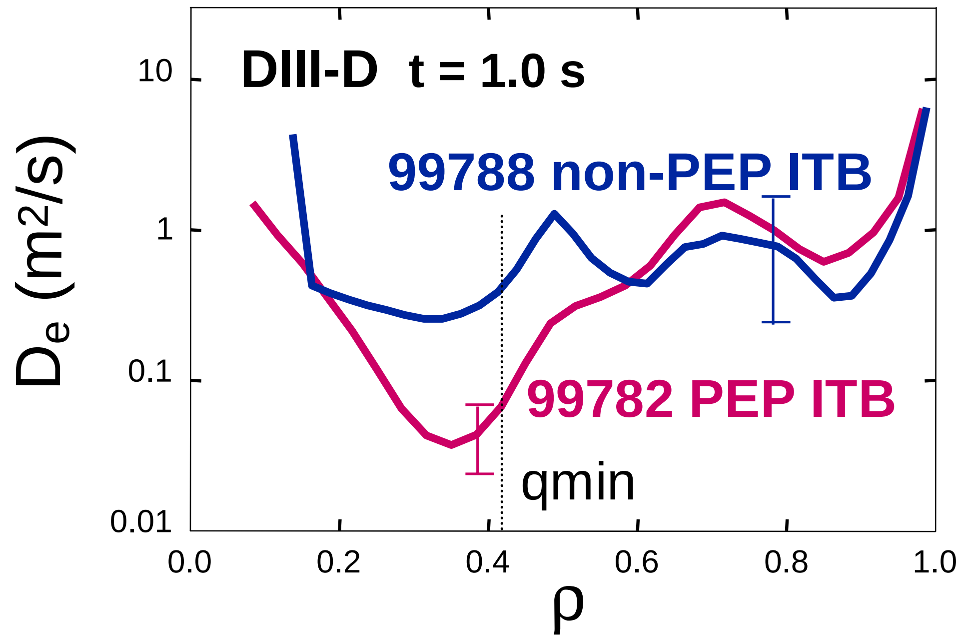
PEP-mode has thermal diffusivity in the core approaching neoclassical levels





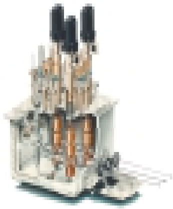
- TRANSP calculation of thermal diffusivities shows ITB in core region out to $\rho = 0.4$ as expected from the strong gradients in the kinetic profiles.
- ITB in PEP case is comparable to non-PEP ITB, both approach neoclassical levels.
- ω_{EXB} becomes large enough to suppress ITG turbulence as in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

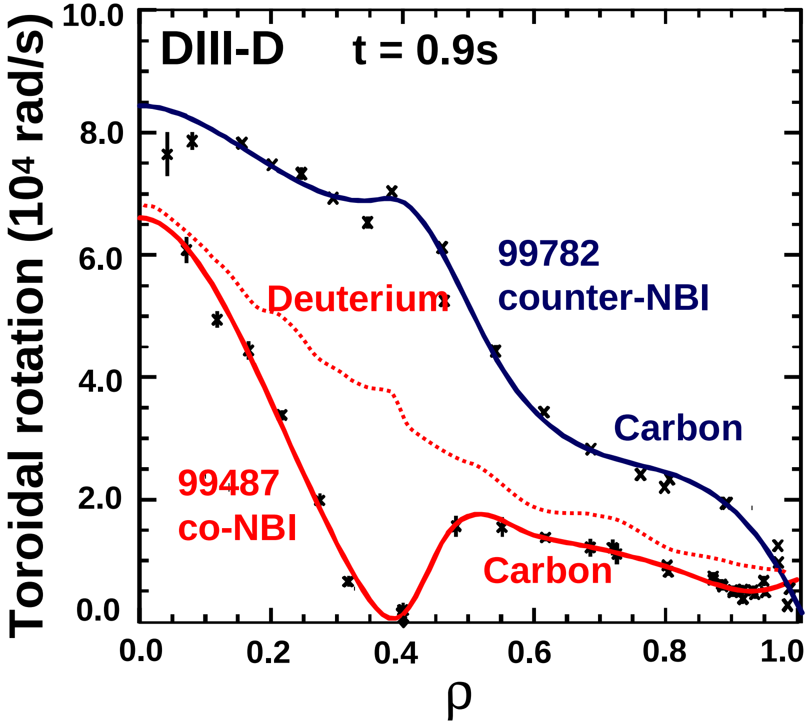
PEP-mode has lower electron particle diffusivity in core from non-PEP ITB comparison



- 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

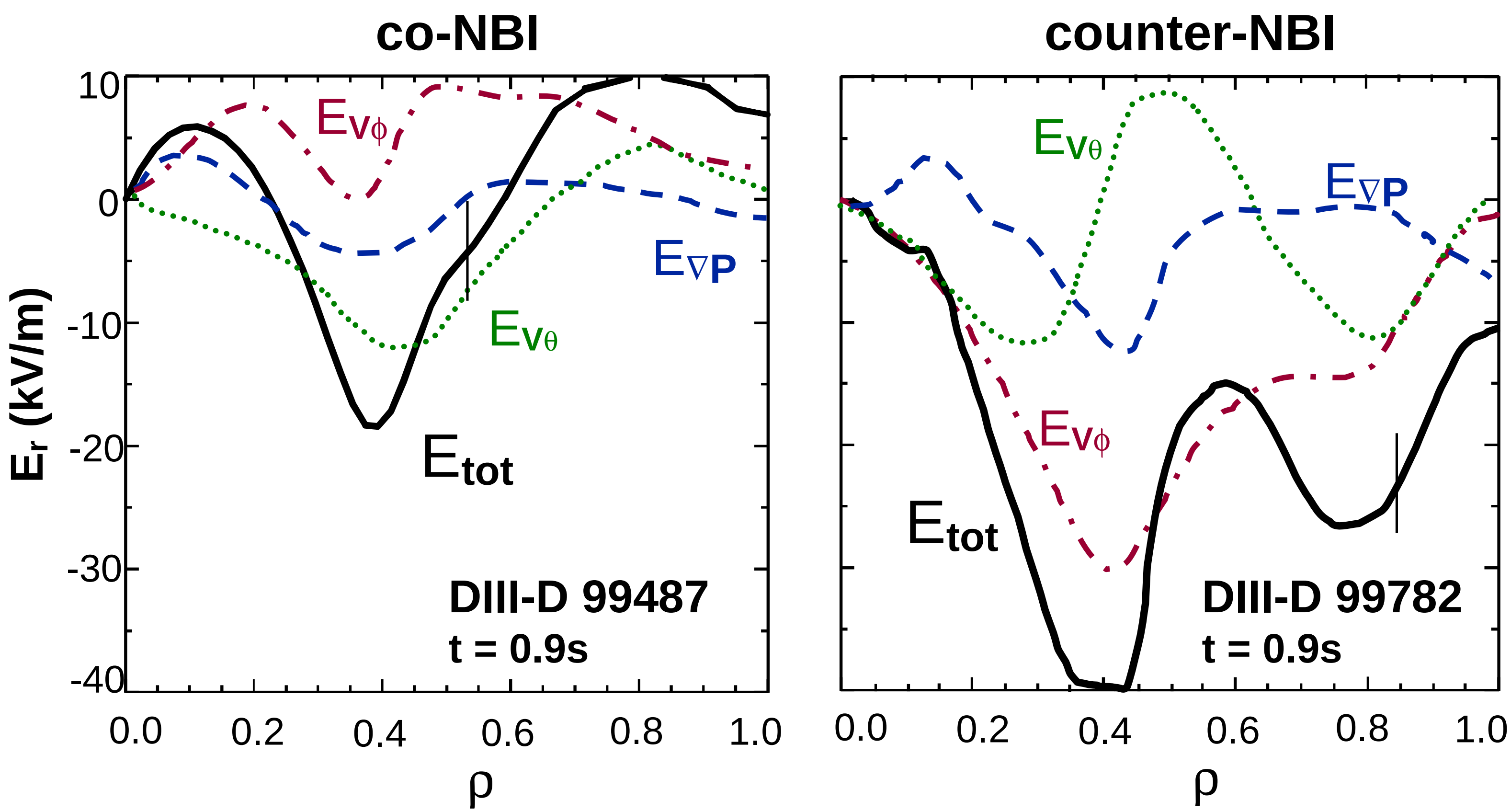
Toroidal Rotation Profile Shows Strong Difference between co-NBI and counter-NBI PEP-mode





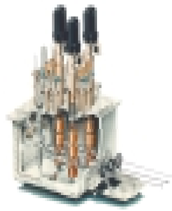
- Toroidal carbon rotation in PEP-mode shows a “notch” with co-NBI similar to that seen on TFTR supershots due to neoclassical parallel momentum exchange. (D. Ernst, et al. Phys. Plasmas 1998.)
- NCLASS calculated deuterium rotation profile is monotonic.

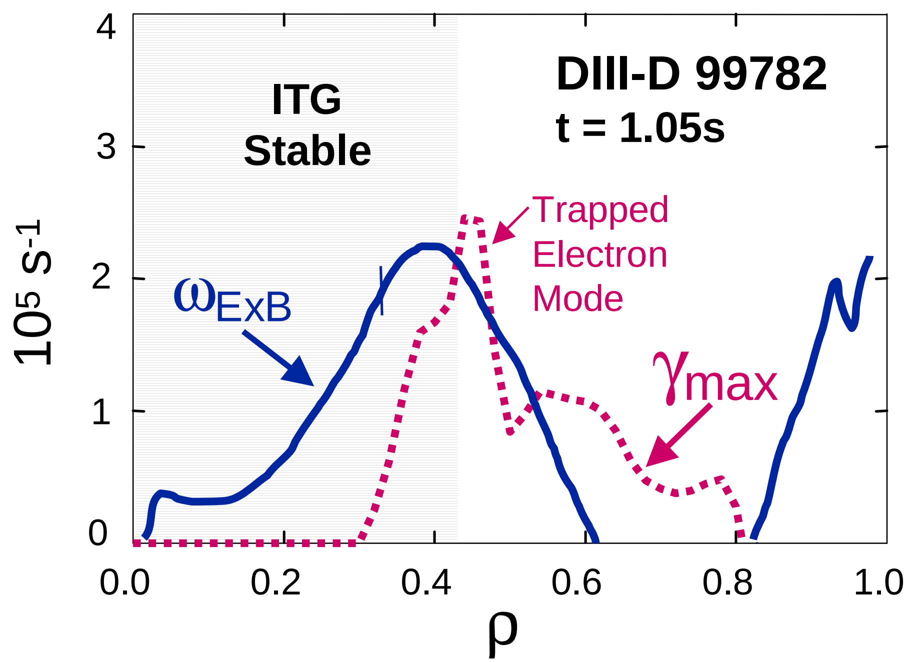
Radial Electric Field has a Well at PEP ITB Location that is Deeper for Counter-NBI



- 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





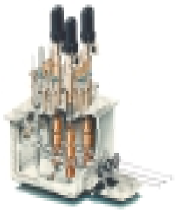
Gyrokinetic Stability Calculation

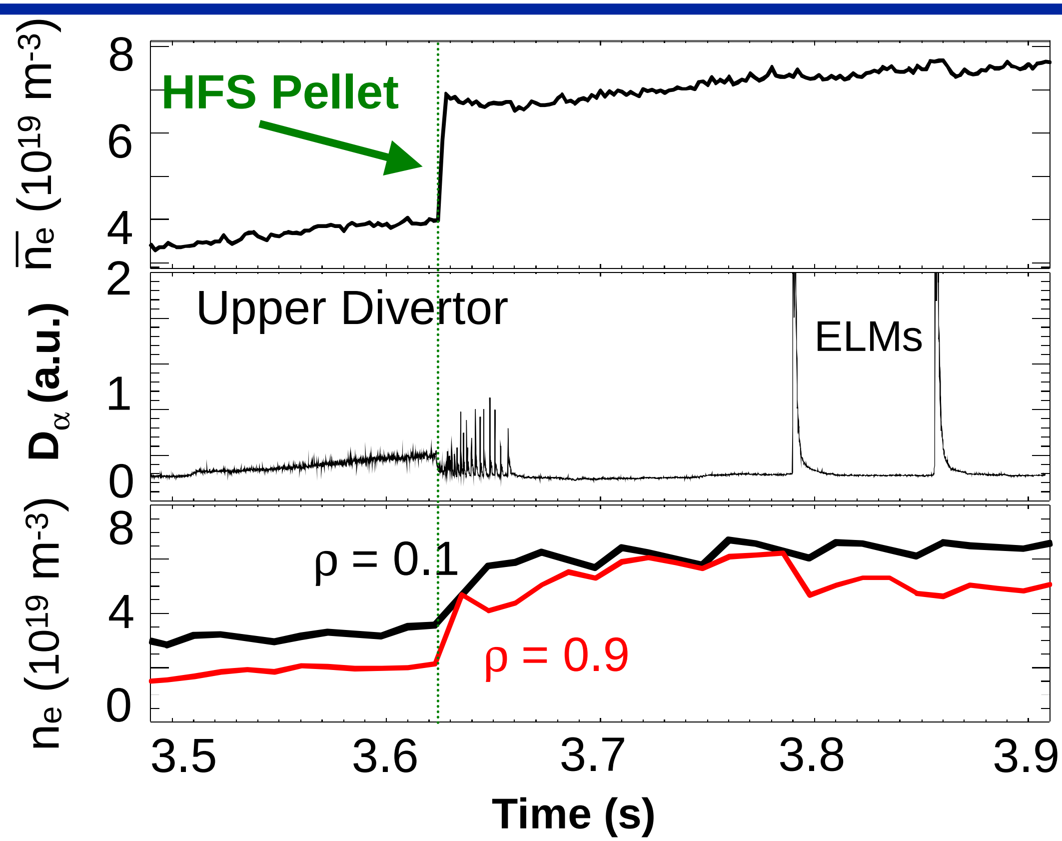
- The ExB shearing rate exceeds the ITG growth rate inside the ITB

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

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

HFS Pellets have induced H-mode Transitions

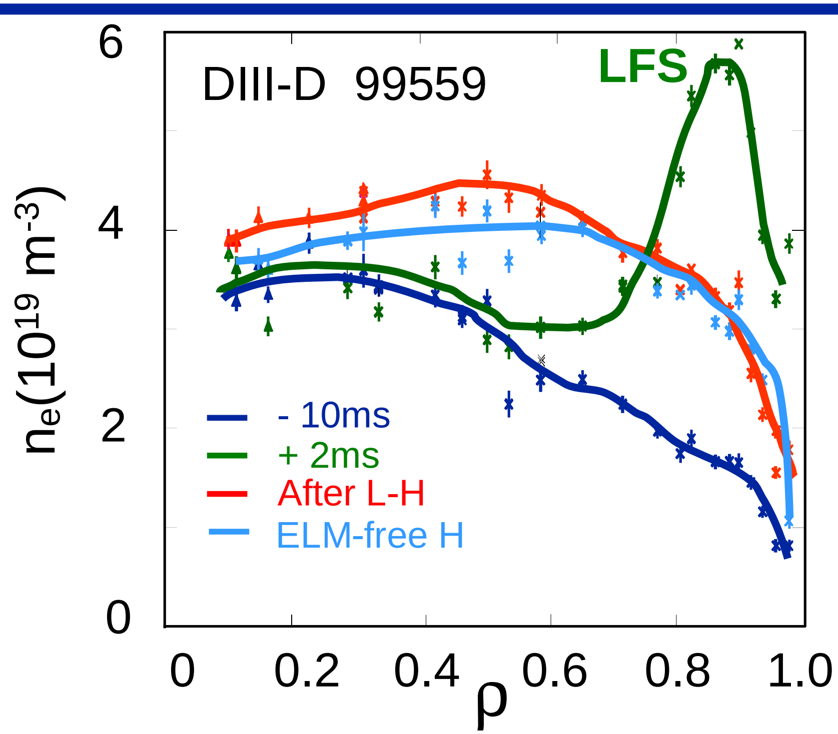


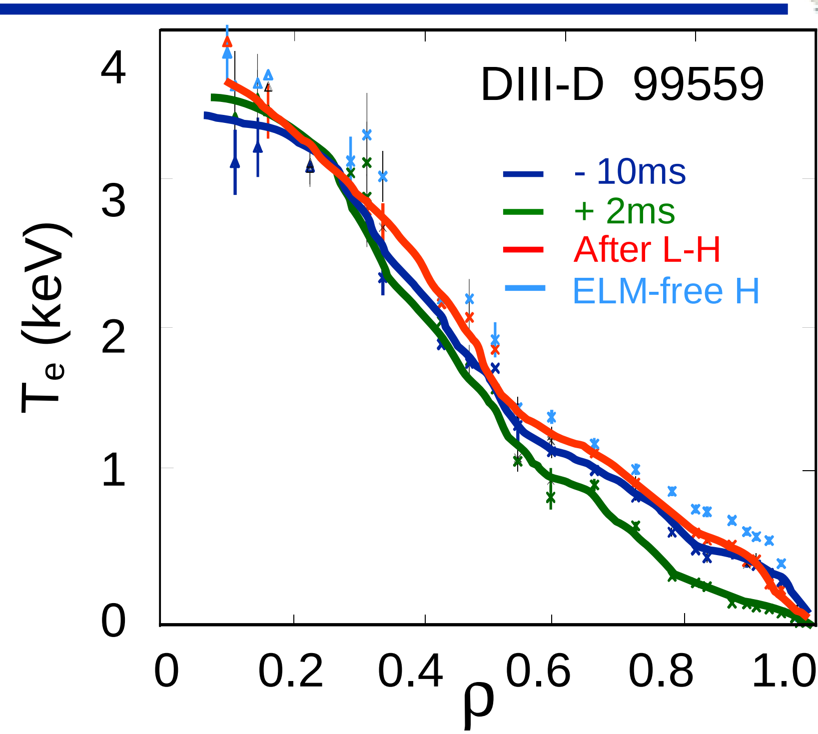


L-mode Target
4.8MW NBI
Upper Single Null

- 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)

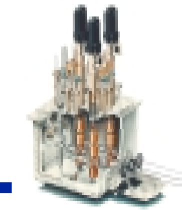
Pellet Induced H-mode Transition Occurs at Lower Edge Temperature



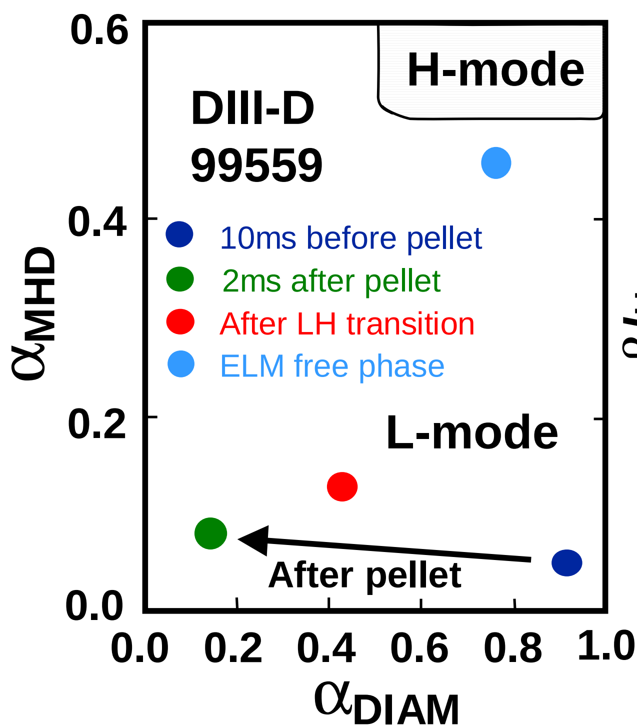


- A critical edge temperature is not indicated in these H–mode transitions
  - Edge T_e and T_i are reduced following pellet injection
- Pellet induced H–modes have L-H transitions at plasma parameters far below theoretical predictions

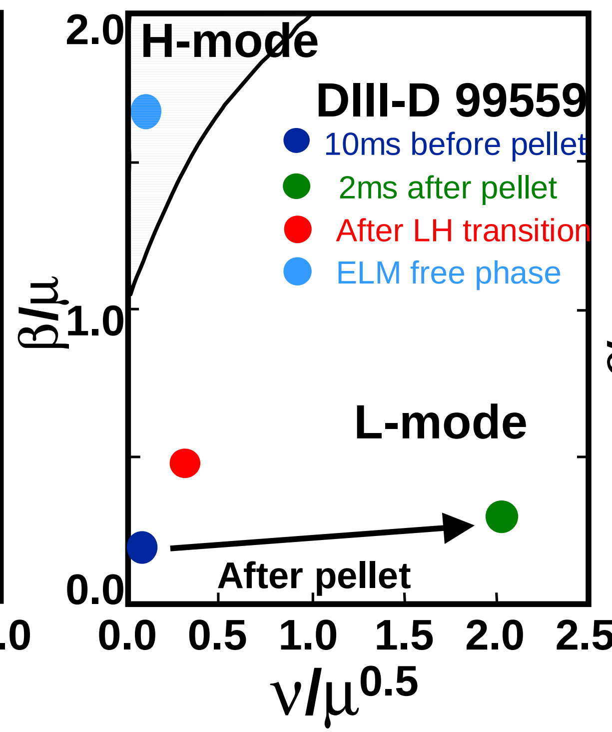
Pellet Induced H-modes have Transitions at Plasma Parameters far Below Theoretical Predictions



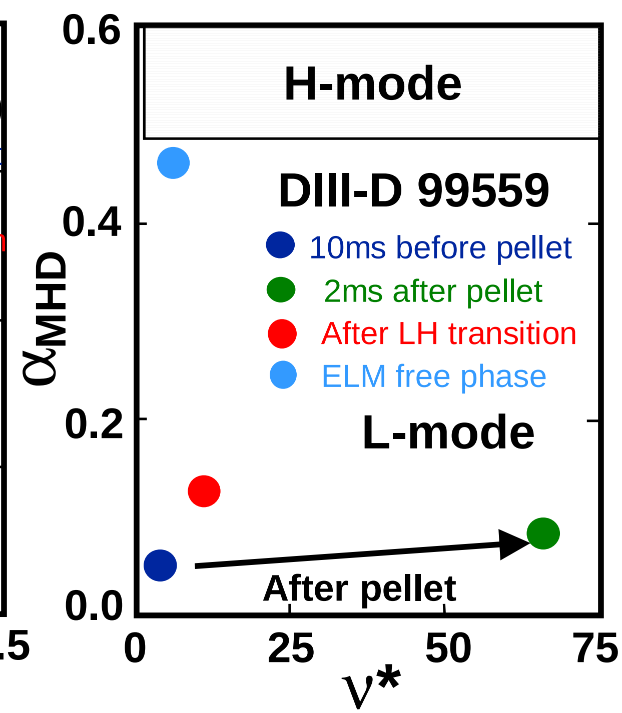
Rogers et al. Proc. 17th IAEA Fusion Energy Conf. Yokohama, Japan 1998, IAEA-CN-69/THP2/01



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

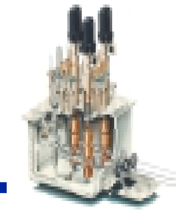


Wilson et al. Proc. 17th IAEA Fusion Energy Conf. Yokohama, Japan 1998, IAEA-F1-CN-69/TH3/2



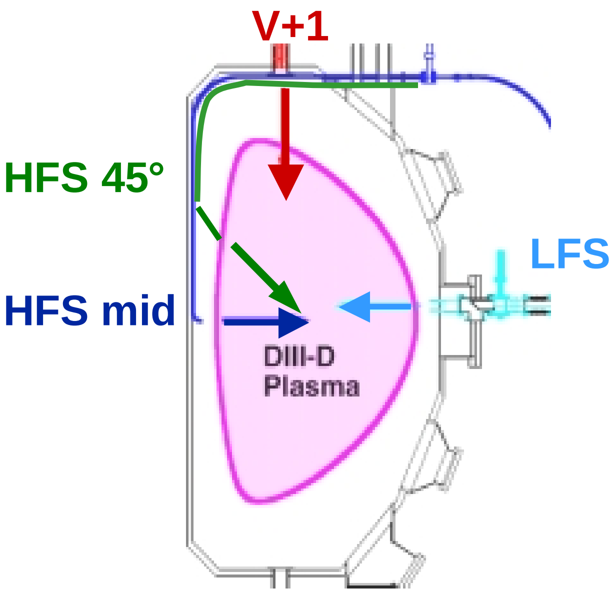
- For more details see poster by P. Gohil et al (CP1.62 - Mon. PM)

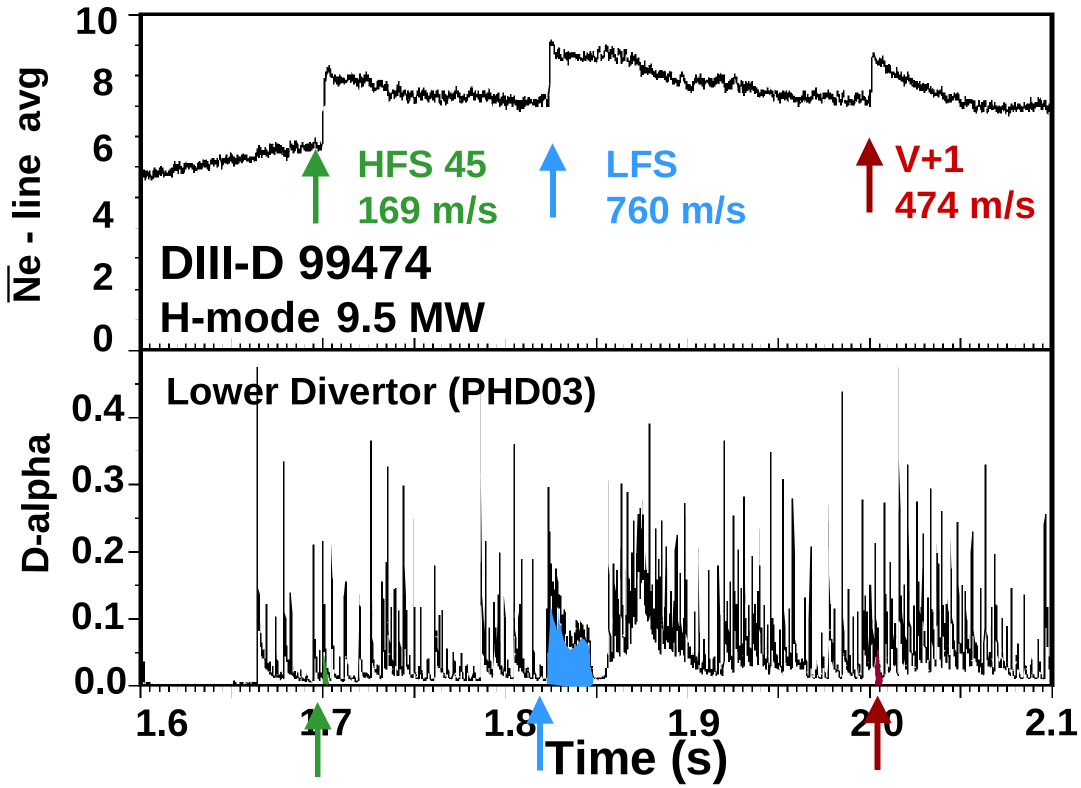
Direct Comparison in H-mode -
HFS Pellets Trigger Smaller ELMs



2.7mm Pellets

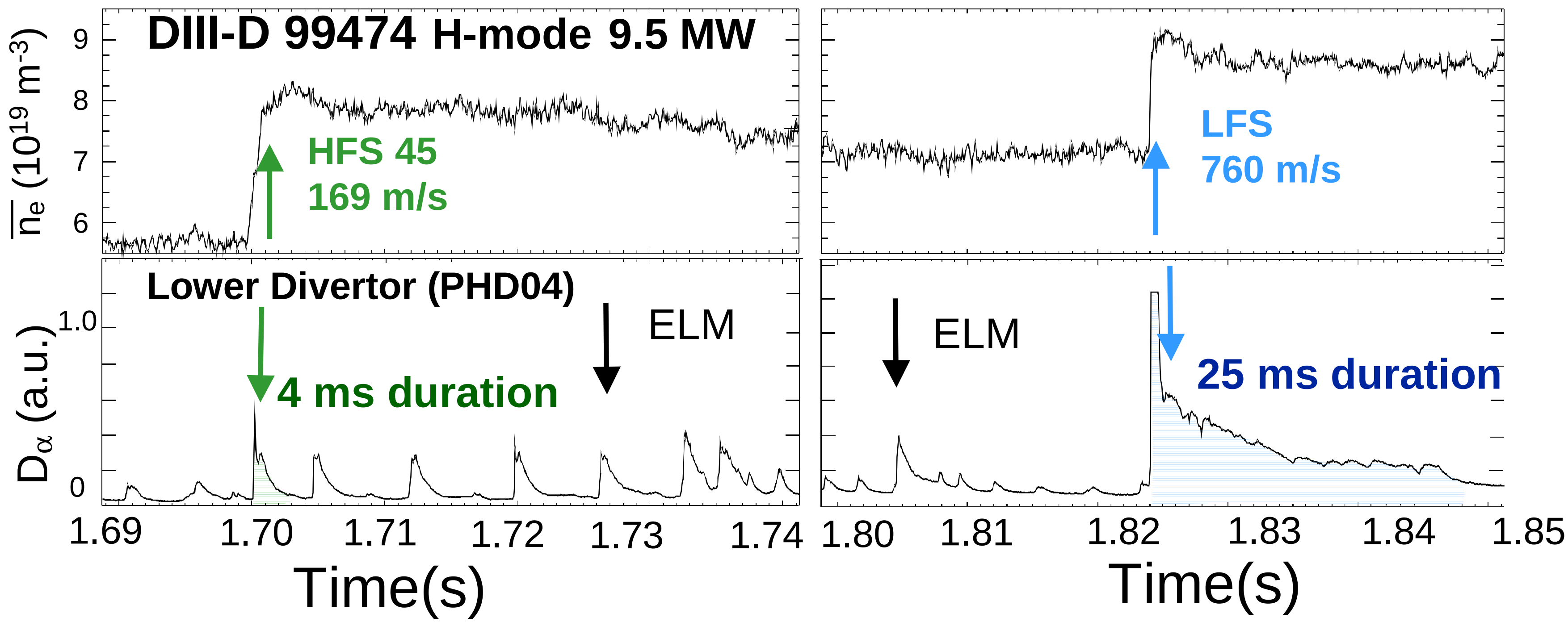
HFS 45° vs LFS vs V+1





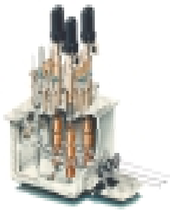
- 2.7mm pellets injected into the same 9.5 MW NBI DN H-mode plasma from HFS45, LFS, and V+1
- ELMs are triggered by the pellets, but are much smaller for the HFS pellets

HFS Pellets produce different ELM characteristics than LFS pellets.



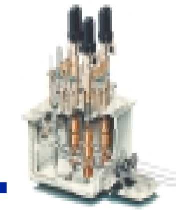
- HFS pellet induced ELMs are small like background ELMs
- LFS pellets induce large ELMs much longer lasting than background ELMs. ExB drift loss of particles may be responsible.
- P´ modification at edge may be different for HFS and LFS pellets (J.R. Ferron, UI1.01)

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 $T_i \sim T_e$, (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**