Effects of Pellet Injection on Density Profiles - DIII-D Results and Simulations of FIRE

W. A. Houlberg

ORNL

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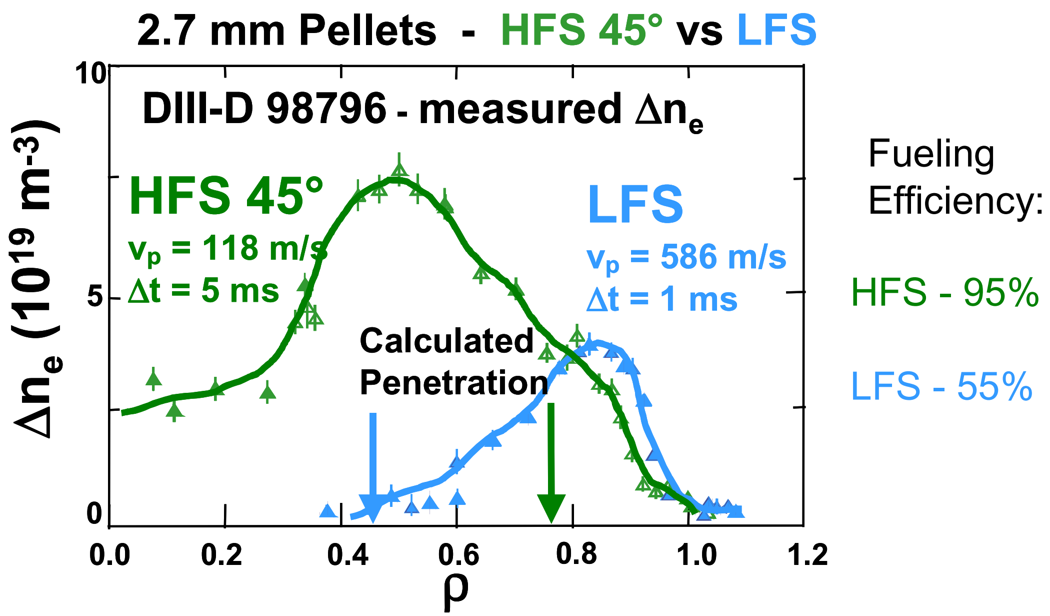
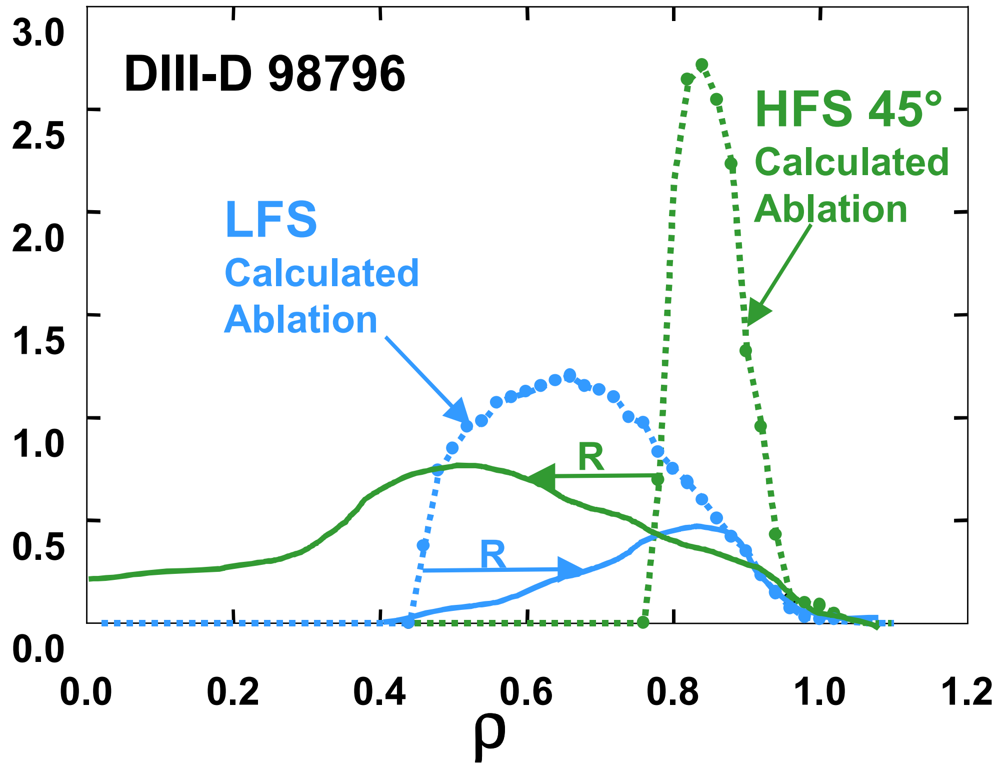
High Field Side (HFS 45°) Pellet Injection on DIII-D Yields Deeper Particle Deposition than LFS Injection



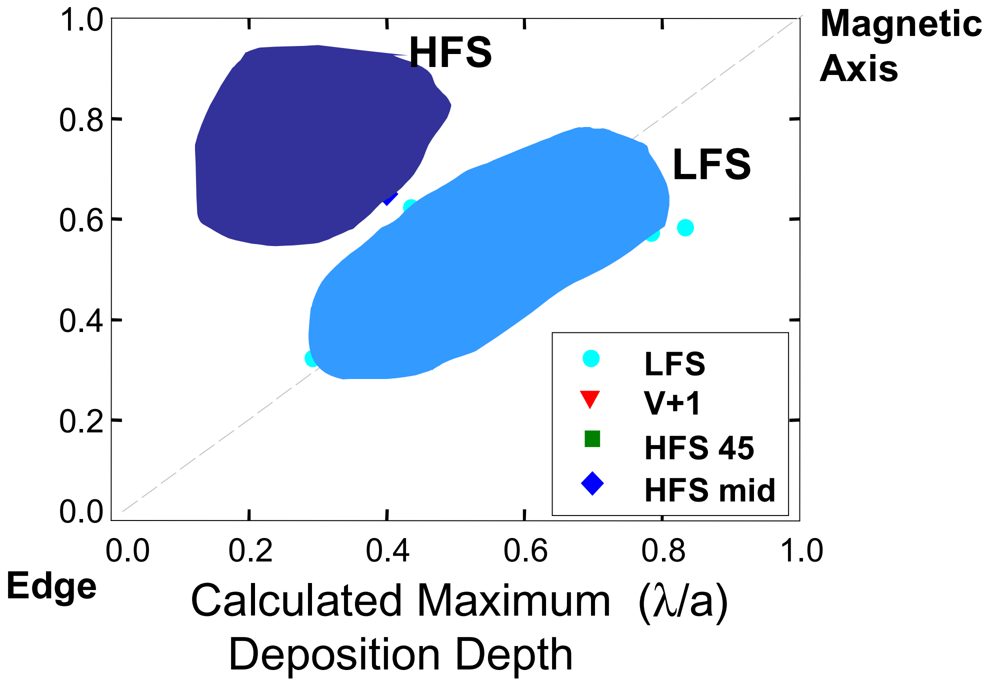
- **Net deposition is much deeper for HFS pellet in spite of the lower velocity**
- **Pellets injected into the same discharge and conditions**
  - **ELMing H-mode, 4.5 MW NBI, $T_e(0)$ = 3 keV**

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



- The net **deposition profile is consistent with a major radius drift** from the calculated ablation profile

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**

Locally Applied Global Confinement Model

- **Neoclassical plus anomalous transport**
- **Fixed anomalous conductivity and diffusivity profiles:**
  - **Normalized to yield global L-mode confinement (ITER-97L):**

    $$\tau_E^{97L}(s) = 0.023\, I^{0.96}\, B_t^{0.03}\, P^{-0.73}\, n_{19}^{0.40}\, M^{0.2}\, R^{1.83}\, \varepsilon^{-0.06}\, \kappa^{0.64}$$

    where I is the plasma current in MA, B_t is the toroidal field in T, P is the heating power in MW, n_{19} is the electron density in 10^{19} m^{-3}, M is average ion mass in AMU, R is the major radius in m, ε = a/R is the inverse aspect ratio, and κ is the plasma elongation

    S.M. Kaye and the ITER Confinement Database Working Group, *Nucl. Fusion* **37**, 1303 (1997)
  - **Profile:** $\chi_i(\rho) = \chi_e(\rho) = \chi(0)[1+4\rho^2]$, $D(\rho) = \chi(\rho)/2$
  - **Ion Temperature Gradient (ITG) transport would show a richer profile variation due to dependence on temperature and density gradients**
- **D, T and He recycle:**
  - **90% of outgoing flux recycled inside separatrix**

L-H Transition Model

- **L-H transition power threshold (IPB98-4):**

$$P_{thr}(MW) = 0.082\, n_{20}^{0.69}\, B_t^{0.91}\, S^{0.96}\, M^{-1}$$

  where n_{20} is the electron density in 10^{20} m^{-3}, B_t is the toroidal field in T, S is the surface area at the separatrix in m^{-3}, and M is average ion mass in AMU

  ITER Physics Basis, *Nucl. Fusion* **39**, 2175 (1999)

- **Suppress edge transport when power across separatrix exceeds the threshold, $P_{sep} > P_{thr}$:**
  - **By a factor of 5 for $0.95 < \rho < 1.0$**
  - **ELM effects are lumped into the suppression factor**
  - **Generally this gives an H-factor ~ 2**

Alpha, Auxiliary Heating and Fueling Models

- **Inside pellet launch:**
  - **Assume uniform Δn profile**
  - **Similar to DIII-D observations**

  L.R. Baylor, et al., (Proc. 18th Int. Conf., Sorrento, 2000) IAEA, Vienna
- **Fast wave ICRF:**
  - **Empirical match to strong and weak absorption limits**

  W.A. Houlberg, S.E. Attenberger, *Fusion Technol.*, **26**, 566 (1994)
  - **Ehst-Karney current drive**

  D.A. Ehst, C.F.F. Karney, *Nucl. Fusion,* **31** 1933 (1991)

  Fusion alphas:
  - **Multi-group time-dependent classical thermalization**

  S.E. Attenberger, W.A. Houlberg, *Nucl. Technol./Fusion*, **4**, 129 (1983)

Fusion Ignition Research Experiment Parameters

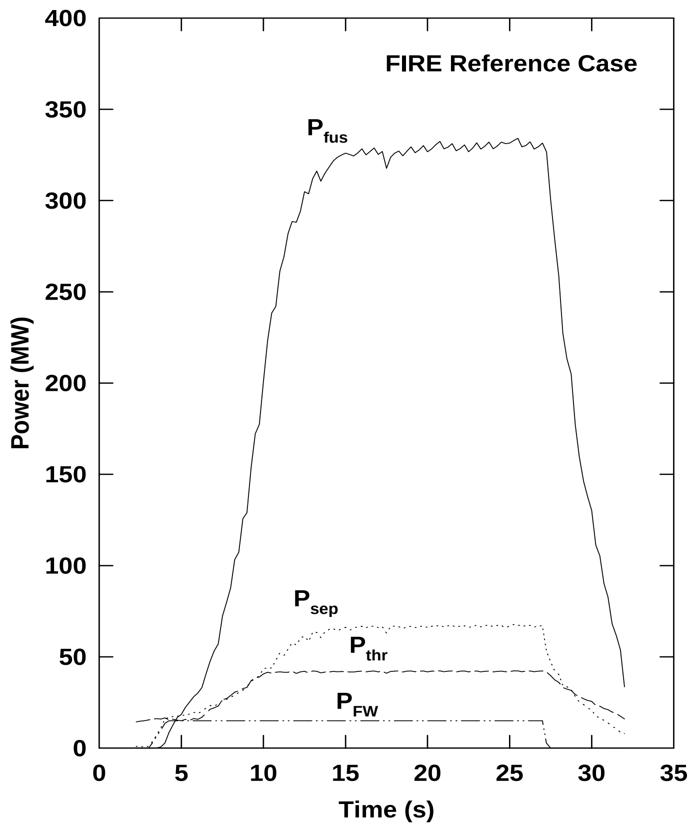
High field copper machine for burning plasma studies:

Major radius	$R_0 = 2$ m
Minor radius	$a_0 = 0.525$ m
Toroidal field	$B_t = 10$ T
Toroidal current	$I = 6.44$ MA
Elongation	$\kappa = 1.8$
Triangularity	$\delta = 0.4$

D.M. Meade, et al., (Proc. 18th Int. Conf., Sorrento, 2000) IAEA, Vienna

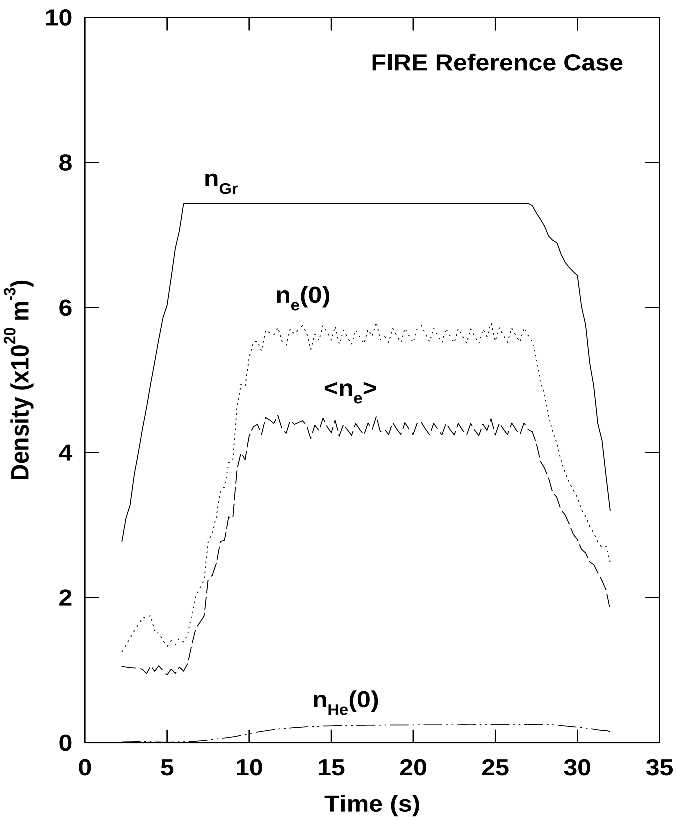
L-H Transition During Rampup
FIRE H-Mode Case

- **The fast wave power is ramped up during the current rise phase and held constant at 15 MW from 4-27 s for a high-Q fusion burn**
- **The $P_{sep} > P_{thr}$ at ~4 s and stays at or above the threshold until the ramp-down phase**
- **Small oscillations in the fusion power are responses to the fuel pellets**
- **The fast wave power and/or density can be reduced for lower fusion power studies**



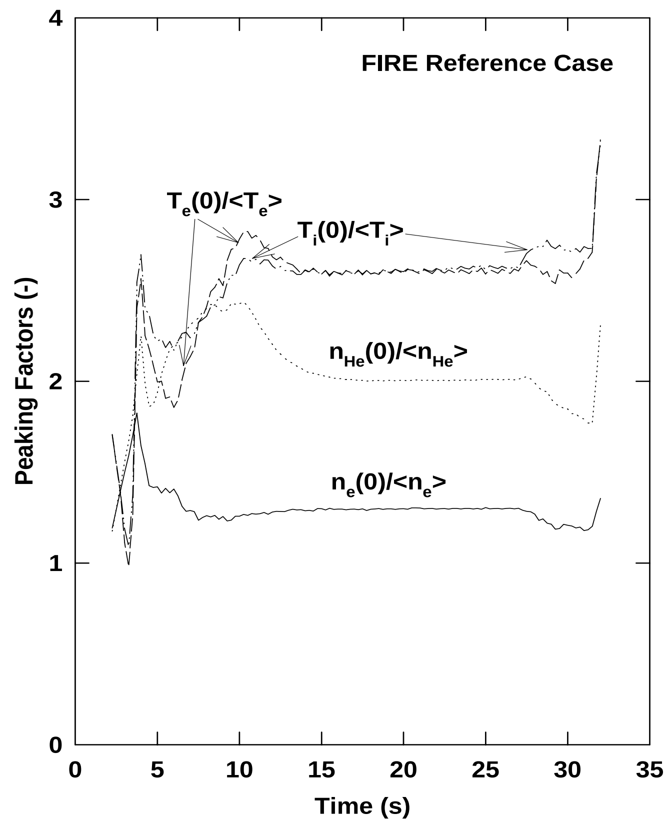
Low Startup Density Facilitates L-H Transition FIRE H-Mode Case

- The **low startup plasma density facilitates the L-H transition**
- **Density ramp keeps $P_{sep} > P_{thr}$**
- **The density oscillations are due to pellet perturbations**
- **Operation is well below the Greenwald density limit**



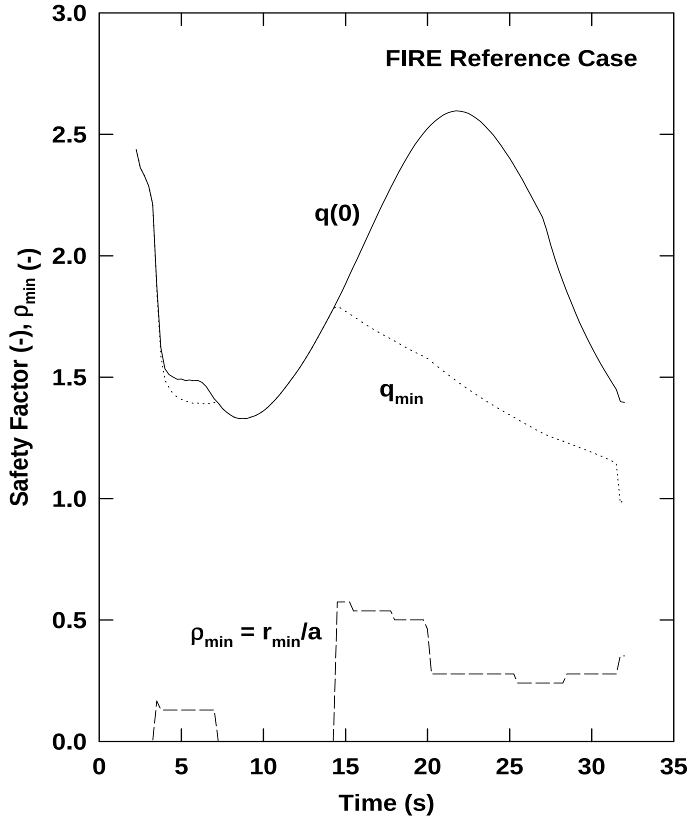
Density Profile Peaking is ~1.2
FIRE H-Mode Case

- The **plasma profile peaking factors show a wide variation** during the different phases
- The density profile:
  - Peaks strongly during the startup phase when direct penetration of the pellets is deep
  - Is moderately peaked (~1.2) during the burn
- The temperature profiles:
  - Peak early in response to the fast wave heating
  - Broaden during the density rise
  - Peak in response to the central alpha heating



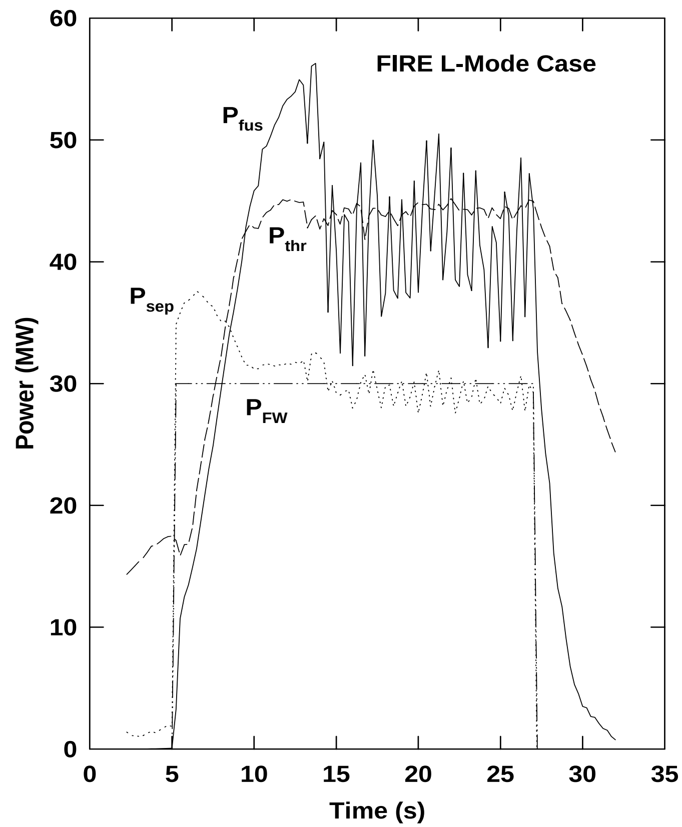
Persistent Reversed Magnetic Shear FIRE H-Mode Case

- The current ramp generates moderate reversed magnetic shear
- The bootstrap current drives a strong shear reversal over the inner half of the plasma radius



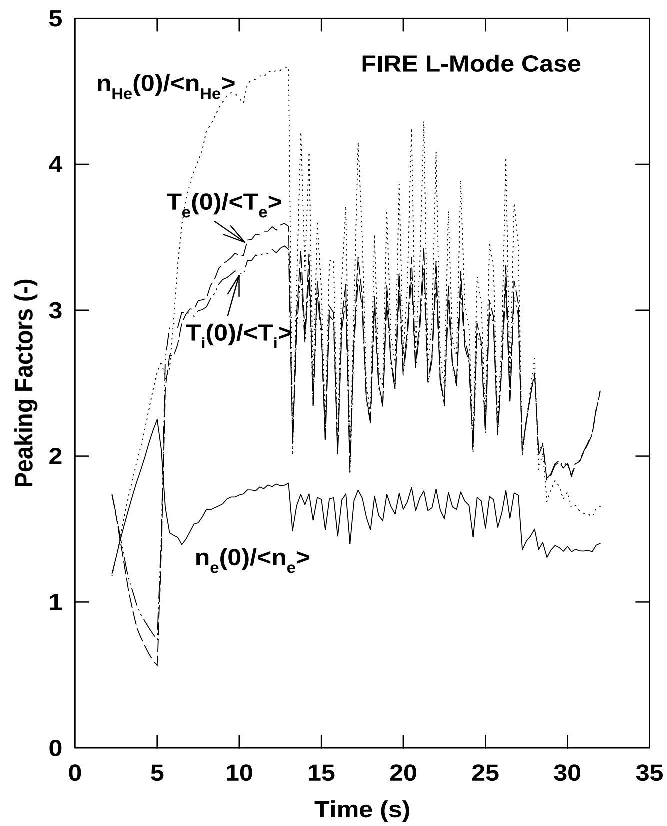
Strong Fusion Sawtooth Oscillations
FIRE L-Mode Case

- **The confinement is assumed to stay in L-Mode for the entire simulation**
- **During the burn $P_{sep} < P_{thr}$**
- **The lower operating temperature yields lower bootstrap current and faster current penetation, which leads to sawtooth activity beginning at ~12.5 s**
- **The amplitude of power fluctuations from sawtooth activity is much stronger than that from pellets**



Stronger Density Peaking
FIRE L-Mode Case

- L-mode operation leads to stronger density peaking (~1.7) even in the presence of sawtooth activity because of the lower particle confinement and increased rep rate for pellet fueling
- Density peaking in L-mode improves the fusion rate over flat densities from gas fueling
- Axial temperature fluctuations are very large from sawtooth activity



Summary

- Flexibility in the B_t, I, n, and P_{aux} and fueling rates during rampup can be used to:
  - Reduce the L-H transition threshold
  - Access a range of reversed magnetic shear conditions
- Inside launch pellet injection:
  - Yields moderate peaking in H-mode plasmas (~1.2) because of the good particle confinement and weak refueling requirements
  - Yields stronger peaking in L-mode plasmas (>1.5) to give an extra margin for performance
  - Should generate much smaller oscillations than sawtooth activity
  - May enhance ITBs (not included in these studies)
- Reversed magnetic shear conditions:
  - Can be initiated by tailoring startup
  - Are enhanced by bootstrap current in high confinement plasmas