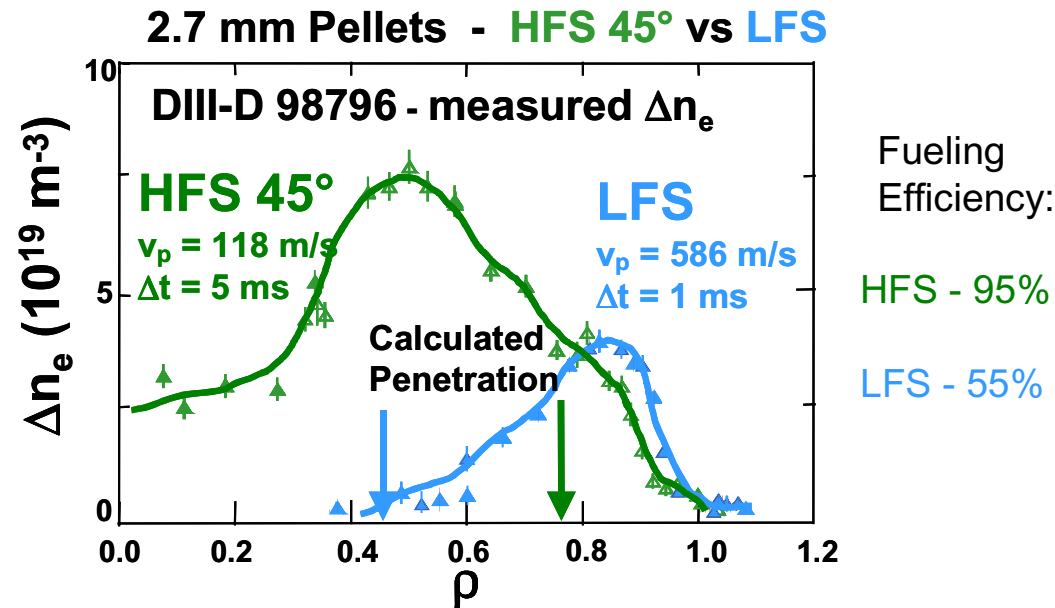


Effects of Pellet Injection on Density Profiles - DIII-D Results and Simulations of FIRE

W. A. Houlberg
ORNL

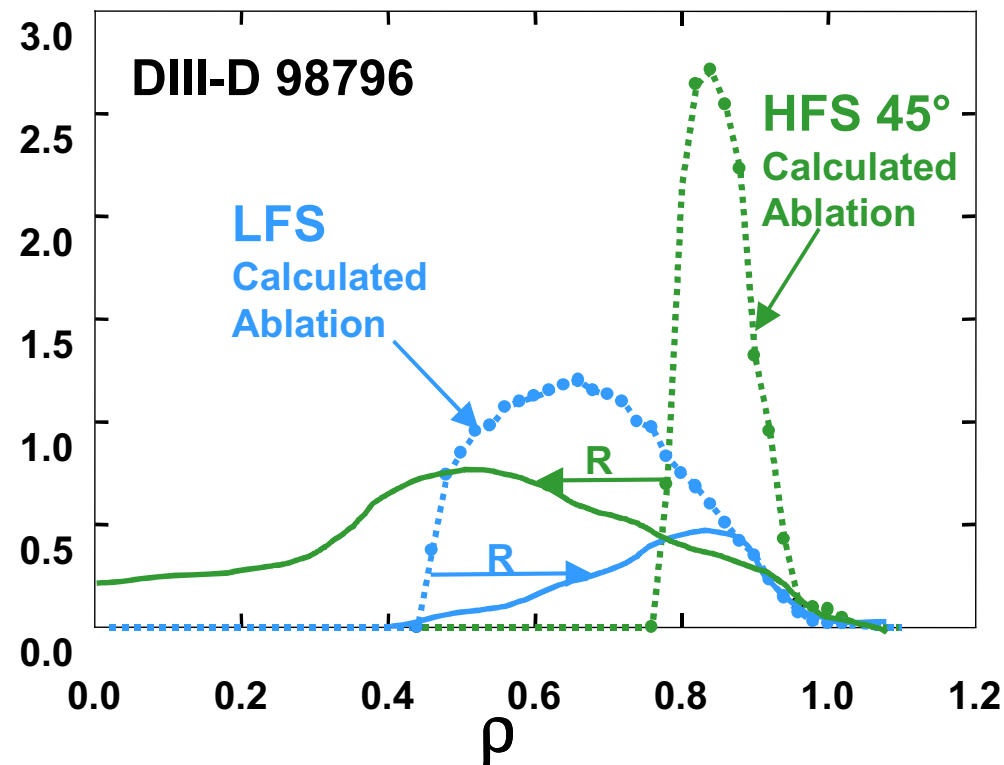
Burning Plasma Science Workshop II
1-3 May 2001
San Diego, California

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



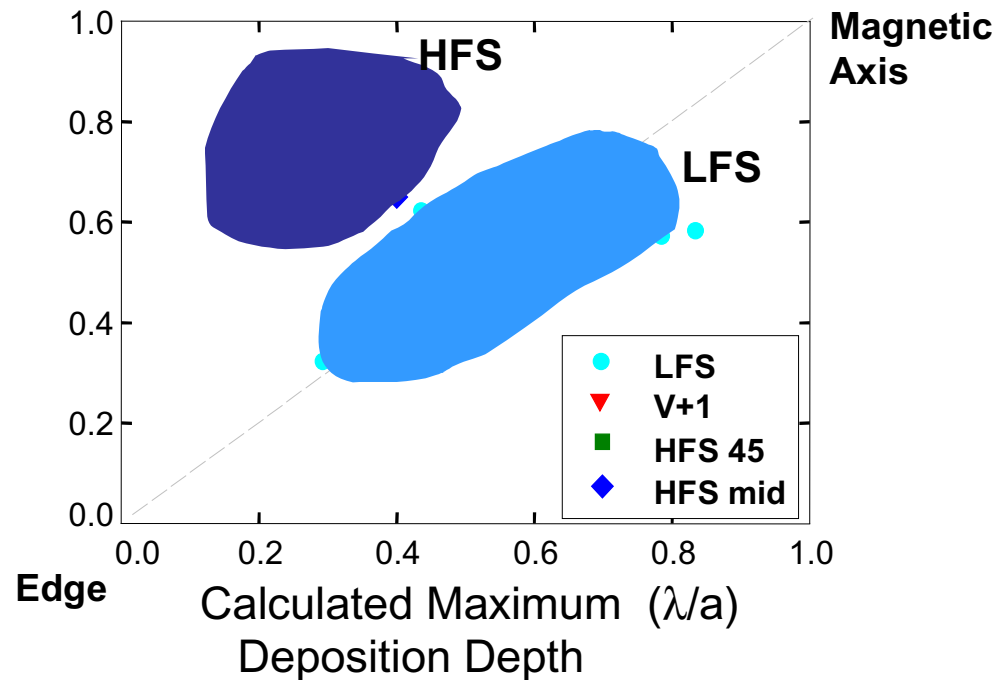
- **Net deposition is much deeper for HFS pellet** in spite of the lower velocity
- Pellets injected into the same discharge and conditions
 - ELMing H-mode, 4.5 MW NBI, $T_e(0) = 3 \text{ keV}$

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, $\varepsilon = a/R$ 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):

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

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^2 , 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, $P_{\text{sep}} > P_{\text{thr}}$:
 - 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

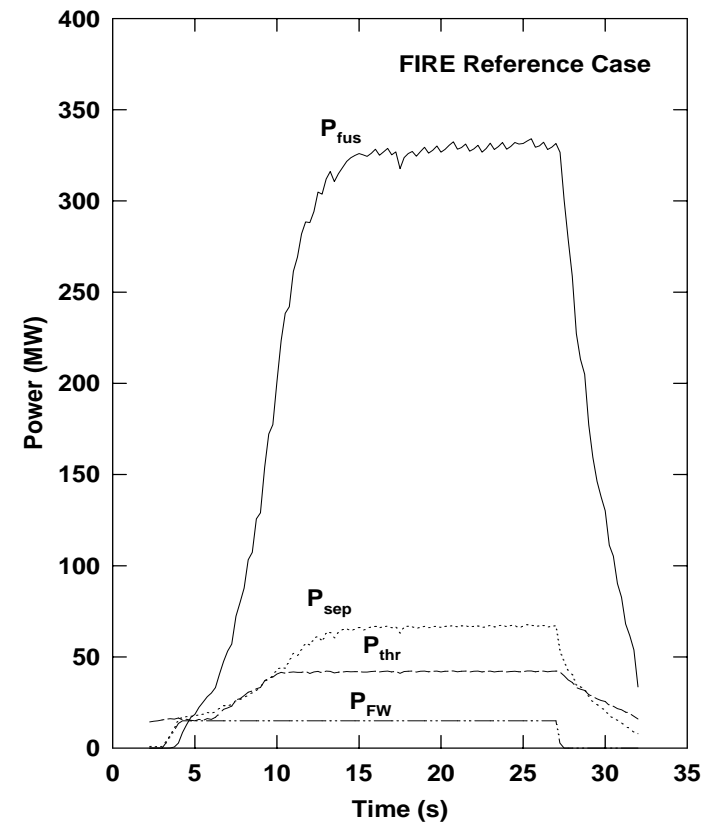
High field copper machine for burning plasma studies:

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

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

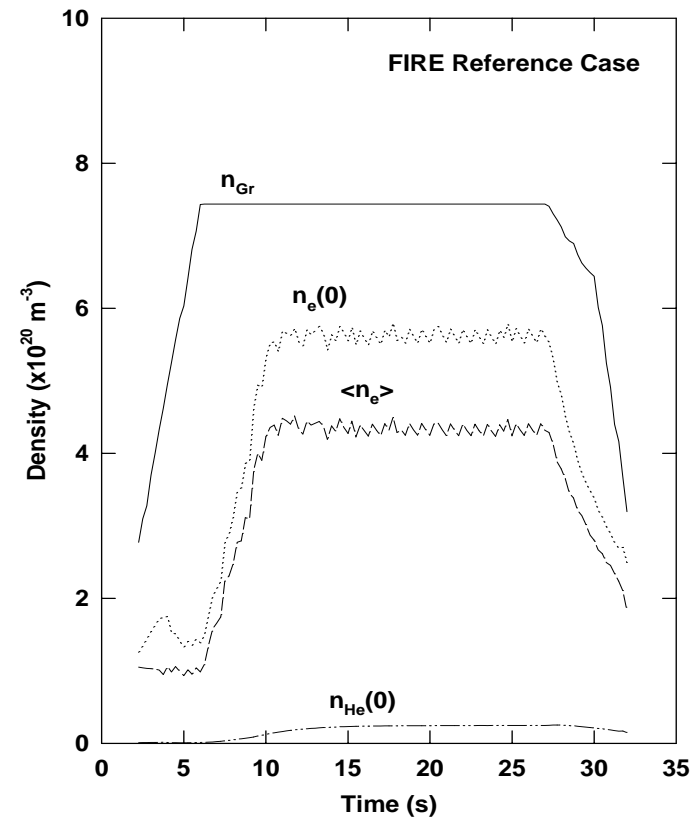
L-H Transition During Rampup FIRE H-Mode Case

- 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



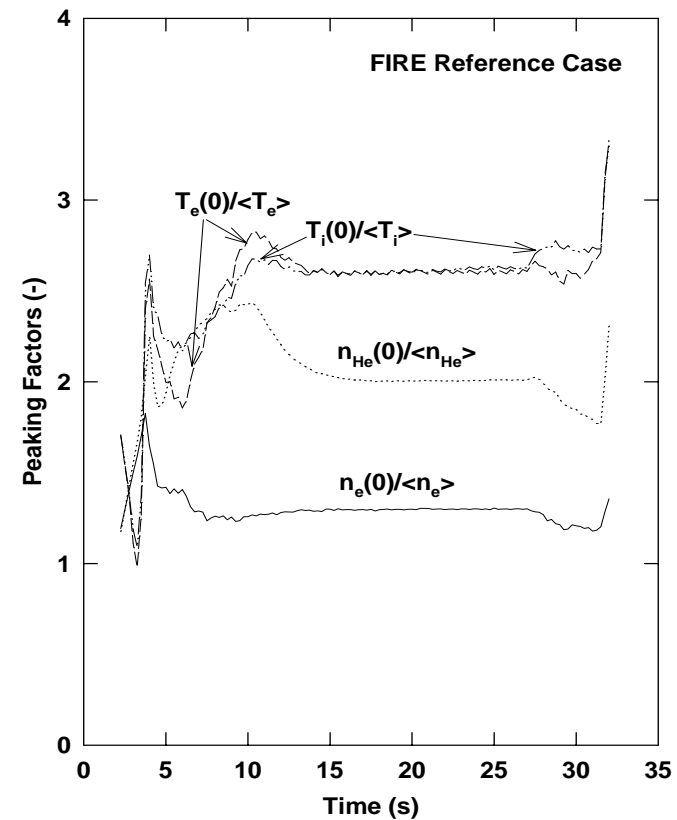
Low Startup Density Facilitates L-H Transition FIRE H-Mode Case

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



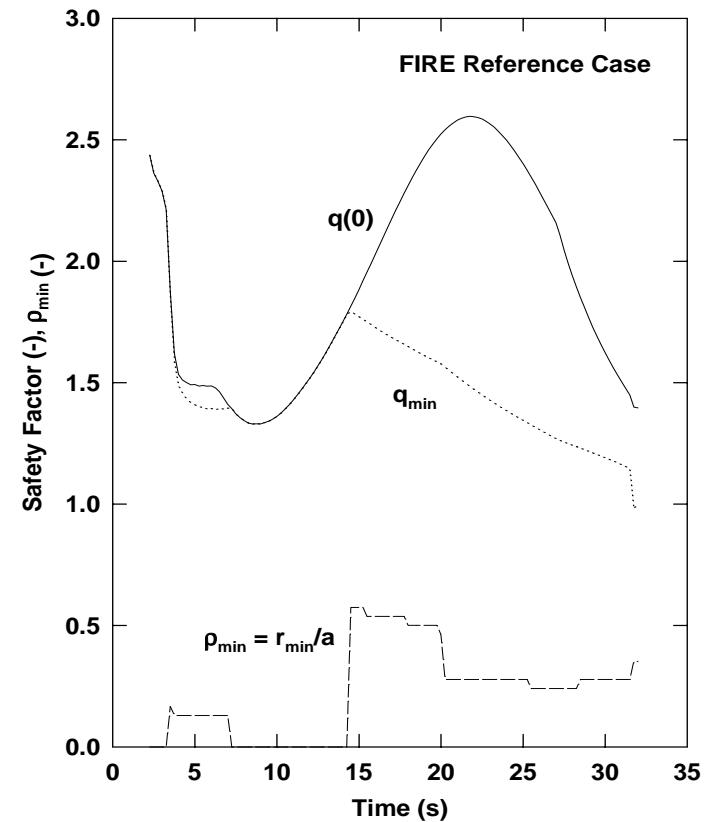
Density Profile Peaking is ~1.2 FIRE H-Mode Case

- 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**



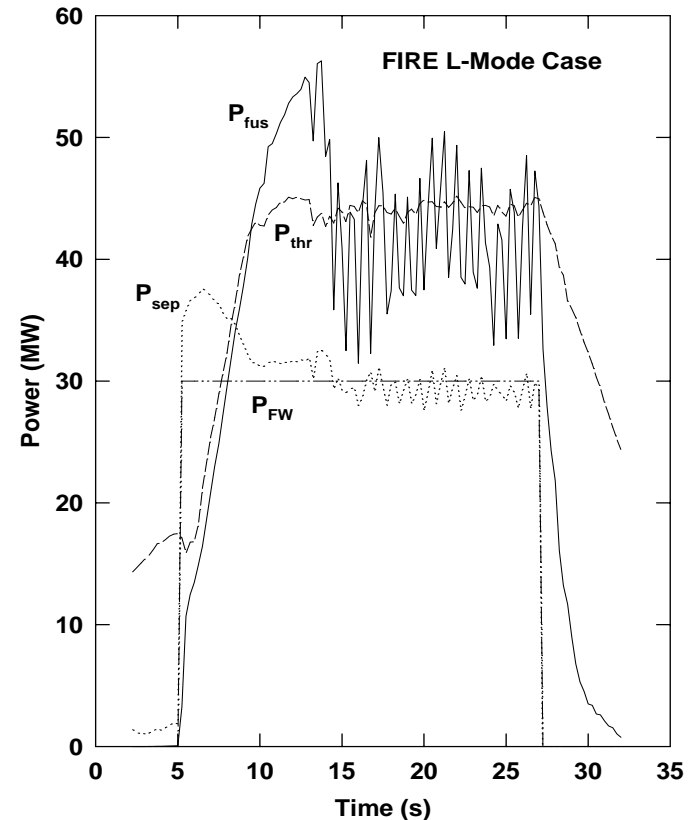
Persistent Reversed Magnetic Shear FIRE H-Mode Case

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



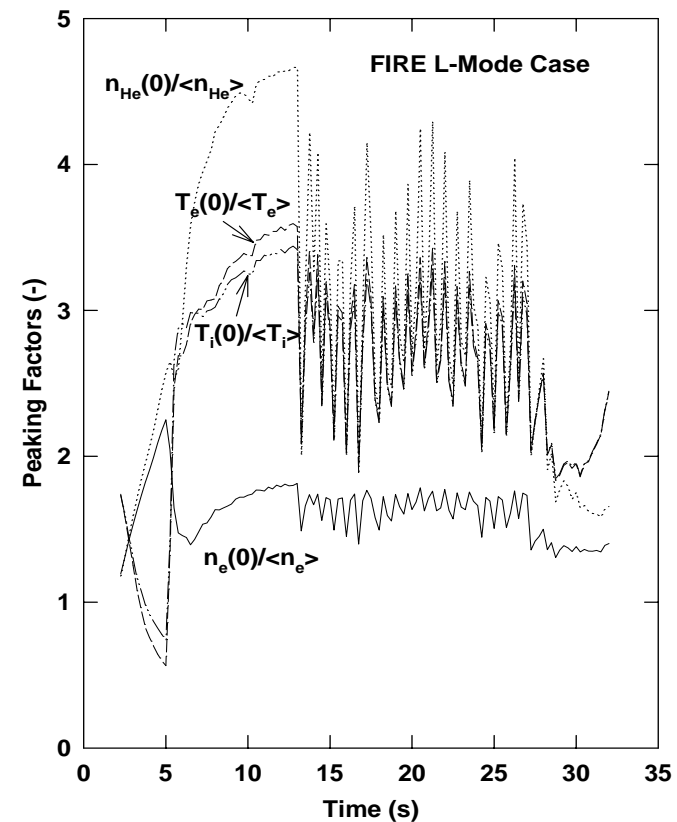
Strong Fusion Sawtooth Oscillations FIRE L-Mode Case

- 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 penetration**, 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