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

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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

Fueling Efficiency:
- HFS - 95%
- LFS - 55%
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 \( \kappa \) is the plasma elongation

S.M. Kaye and the ITER Confinement Database Working Group, Nucl. Fusion 37, 1303 (1997)
- Profile: \( \chi_t(\rho) = \chi_e(\rho) = \chi(0)[1+4\rho^2] \), \( D(\rho) = \chi(\rho)/2 \)
- 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 \( 10^{20} \text{ m}^{-3} \), \( B_t \) is the toroidal field in T, \( S \) is the surface area at the separatrix in \( \text{m}^{-3} \), and \( M \) is average ion mass in AMU.
  

- 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 $\Delta n$ profile
  – Similar to DIII-D observations

• Fast wave ICRF:
  – Empirical match to strong and weak absorption limits
  – Ehst-Karney current drive

Fusion alphas:
  – Multi-group time-dependent classical thermalization
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 \( \delta = 0.4 \)

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 $P_{\text{sep}} > P_{\text{thr}}$ 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
The current ramp generates moderate reversed magnetic shear.

The bootstrap current drives a strong shear reversal over the inner half of the plasma radius.
The confinement is assumed to stay in L-Mode for the entire simulation.

During the burn, $P_{\text{sep}} < P_{\text{thr}}$

The lower operating temperature yields lower bootstrap current and faster current penetration, which leads to sawtooth activity beginning at $\sim 12.5$ s.

The amplitude of power fluctuations from sawtooth activity is much stronger than that from pellets.
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