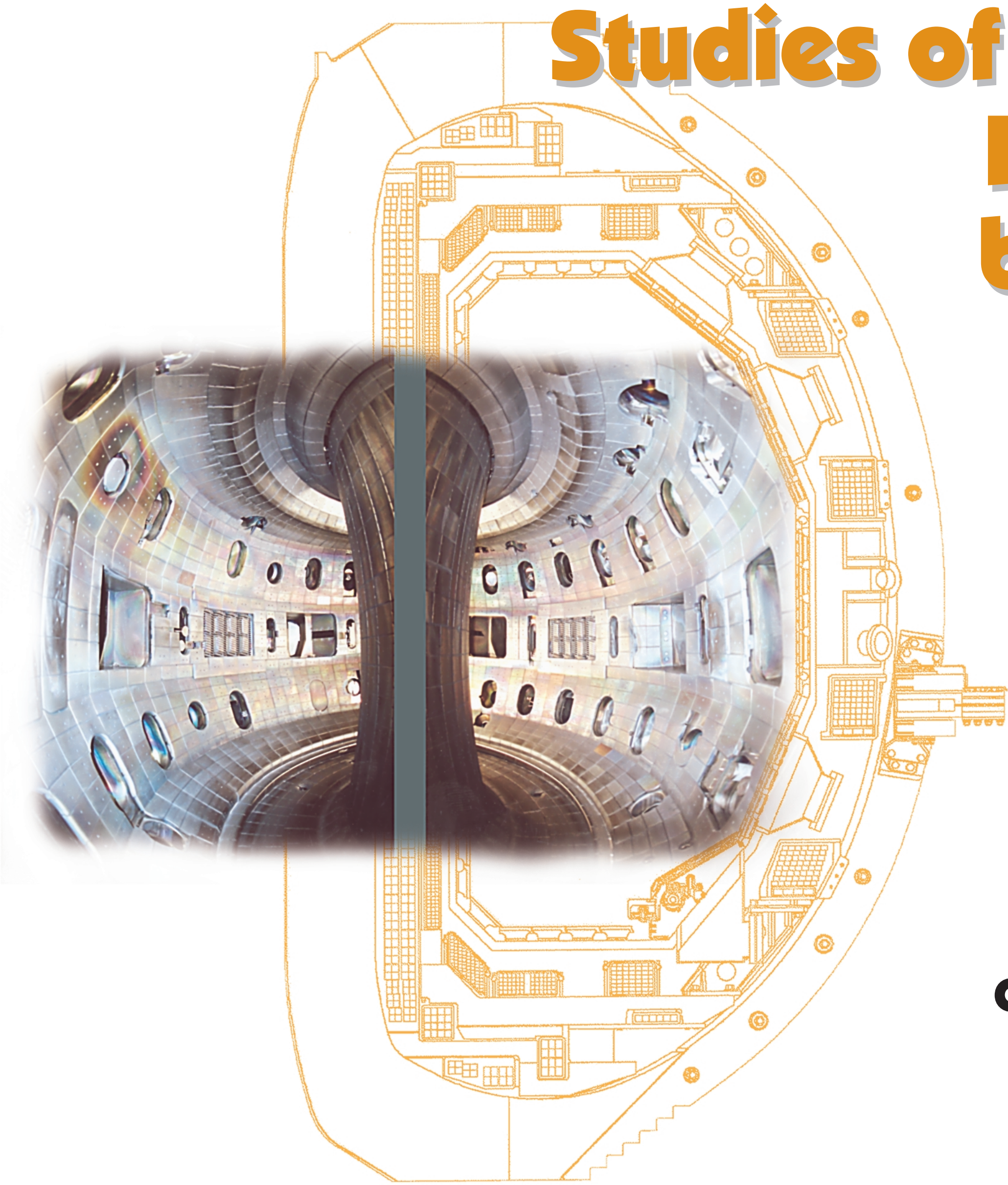
Studies of H–Mode Plasmas Produced Directly by Pellet Injection in DIII–D



by

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in collaboration with

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GENERAL ATOMICS

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OVERVIEW

- H–mode plasmas have been produced by injecting frozen deuterium pellets into L–mode plasmas in DIII–D
  - Pellets injected from the low field, outside edge of the plasma and from the high field, inside plasma edge were both able to produce H–mode plasmas
  - The radial extent of pellet deposition is not important. The production of a steep edge density gradient is important
- The large influx of particles at the plasma edge from the pellet leads to substantial reductions in the edge electron and ion temperatures. The lowered temperatures are still conducive for the formation of the H–mode transport barrier
  - A critical edge temperature is not necessary in these H–mode transitions
- Pellet induced H–modes have LH transitions at plasma parameters far below theoretical predictions
- The power threshold for the H–mode transition is reduced by about 2.4 MW (about 30%) using pellet injection
  - Pellets produced H–mode plasmas at lower input power than reference plasma discharges without pellets, which stayed in L–mode throughout beam heating even in the presence of strong sawteeth

MOTIVATION

- A key issue for the physics of H–mode plasmas is to determine which plasma quantities are critical for the formation of the edge transport barrier
- One approach is to directly perturb the edge plasma conditions and observe the subsequent changes to key edge parameters at the H–mode transition
- One hypothesis for the H–mode transition is that the attainment of a critical edge electron temperature is required for the H–mode transition
  - This can be directly tested using pellet injection
- Injection of frozen deuterium pellets:
  - Dramatically changes the edge electron density and temperature
  - Can trigger H–mode transitions
- Perturbation to the edge plasma condition by pellet injection provides for quantitative comparisons between experimental conditions and theoretical predictions from H–mode transition theories
- Pellet induced H–mode transitions can be accurately preset in time (i.e. the pellet injection time) so that key fluctuation and profile diagnostic systems can be concentrated about that time

EXPERIMENTAL SETUP

- An unbalanced, double-null diverted discharge with the ∇B drift away from the dominant X–point was investigated
  - High H–mode power threshold
  - Clear, steady-state L–mode conditions
  - Pellets were launched from the inside wall, from an upper vertical port and from the outside wall of the vessel

- Operational parameters
  - Plasma current, I_p = 1.6 MA
  - Toroidal magnetic field, B_T = 1.8–2.1 T
  - Target electron density, $\bar{n}_e = 3.0–4.0 \times 10^{19}\ m^{-3}$
  - Auxiliary heating power (NBI) = 4.9–9.2 MW
  - Safety factor: on-axis, $q(0) \approx 1.0$
    edge, q_{95} = 3.3–3.4
  - Elongation, κ = 1.63–1.71
  - Upper triangularity, δ_{upp} = 0.70–0.85
  - Lower triangularity, δ_{low} = 0.28–0.29

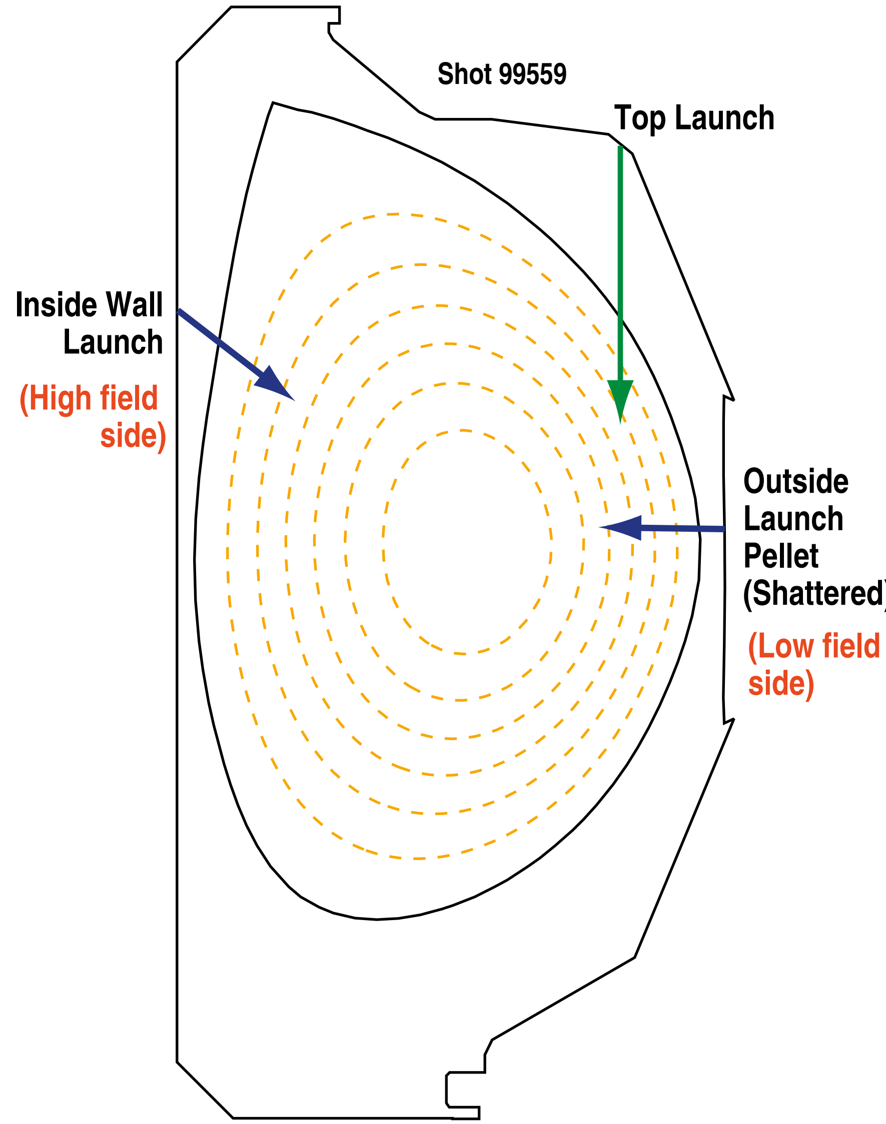
PELLETS WERE LAUNCHED FROM THE LOW FIELD SIDE OR HIGH FIELD SIDE OF DIII–D

- Outside wall launched pellets (low field side) were shattered prior to entry into plasma in order to minimize pellet penetration ⇒ predominantly edge density perturbation

- Type: solid deuterium
  Pellet size: 2.7 mm
  Rep rate: up to 10 Hz
  Speed: 100–350 m s^{-1}

Speed for Specific Shots:

Shot	
99559	314, 194 and 160 m s^{-1} (shattered pellets – outside launch)
100162	222 m s^{-1} (inside launch)
100170	235 m s^{-1} (inside launch)



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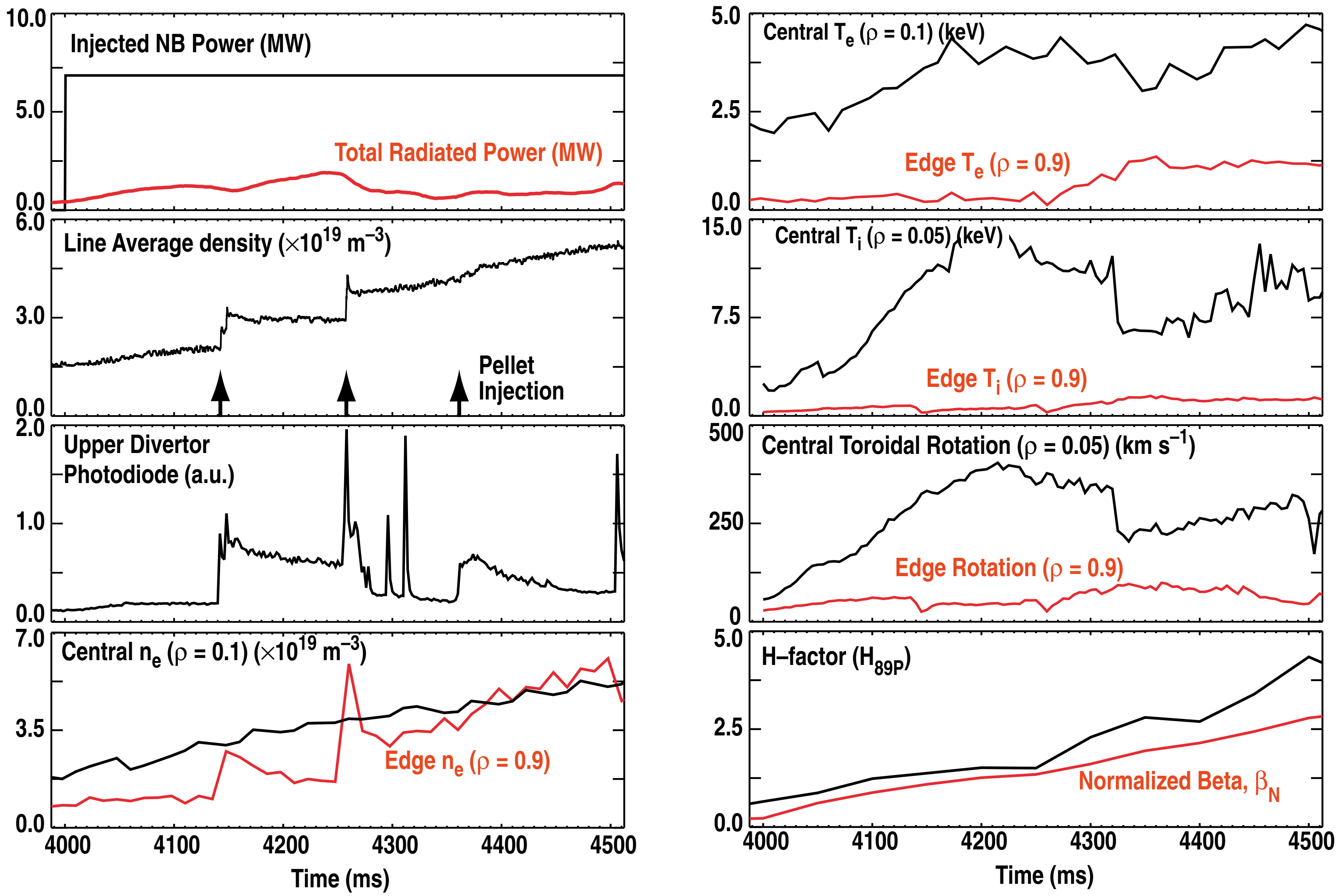
PELLET INDUCED H–MODE (PIH–MODE) TRANSITION PRODUCED BY A LOW FIELD SIDE PELLET



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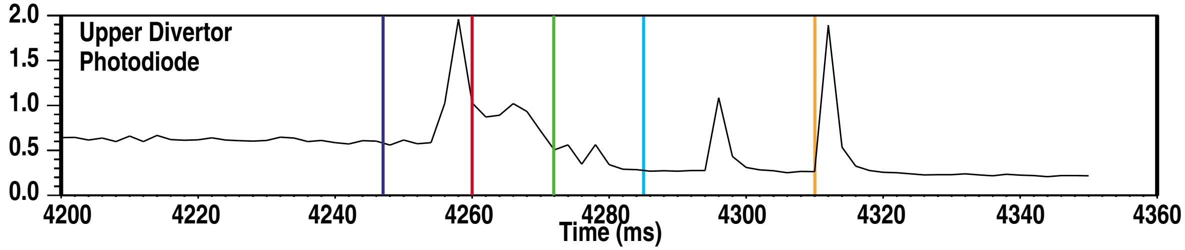
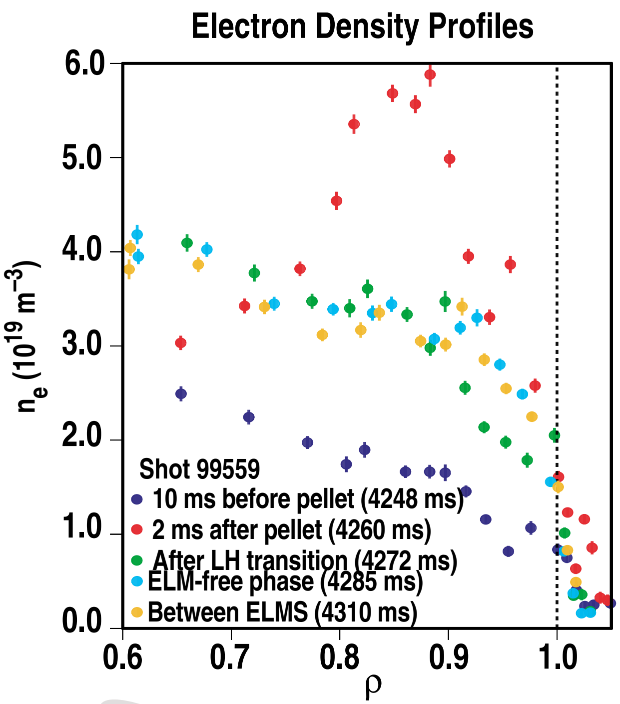
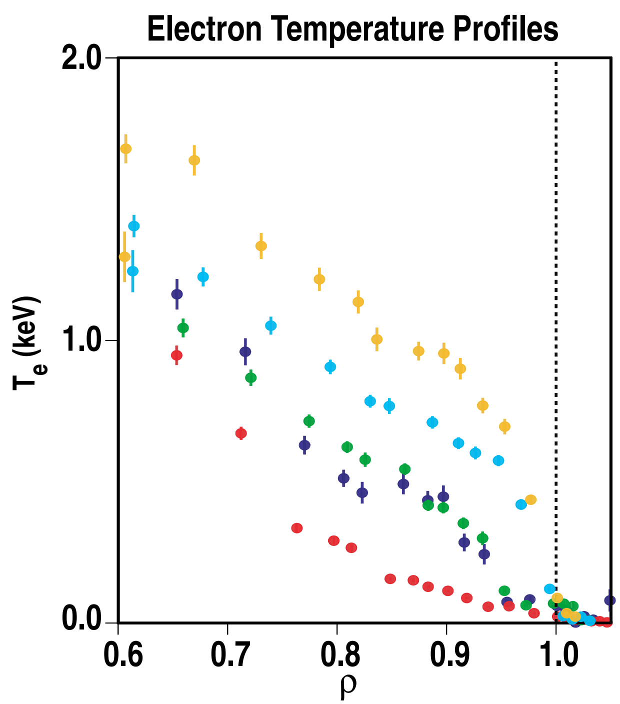
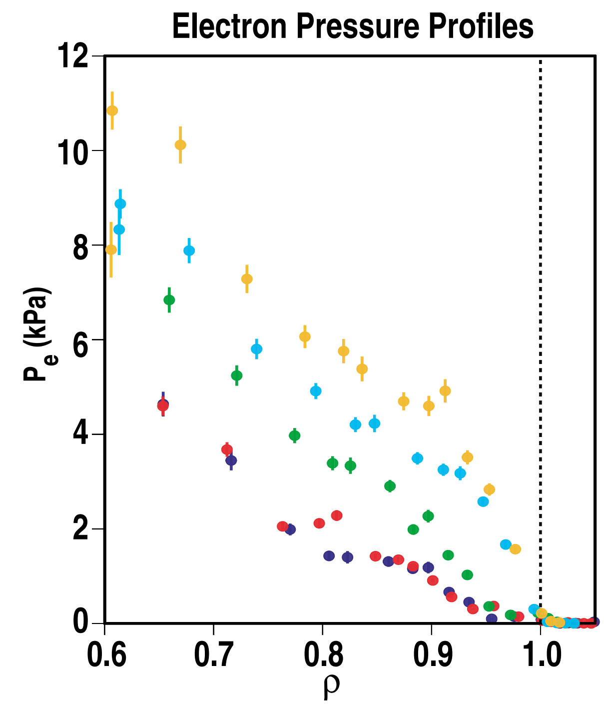
THE EDGE ELECTRON TEMPERATURE IS REDUCED SUBSTANTIALLY AFTER PELLET INJECTION

- A critical edge temperature is not required for the H–mode transition









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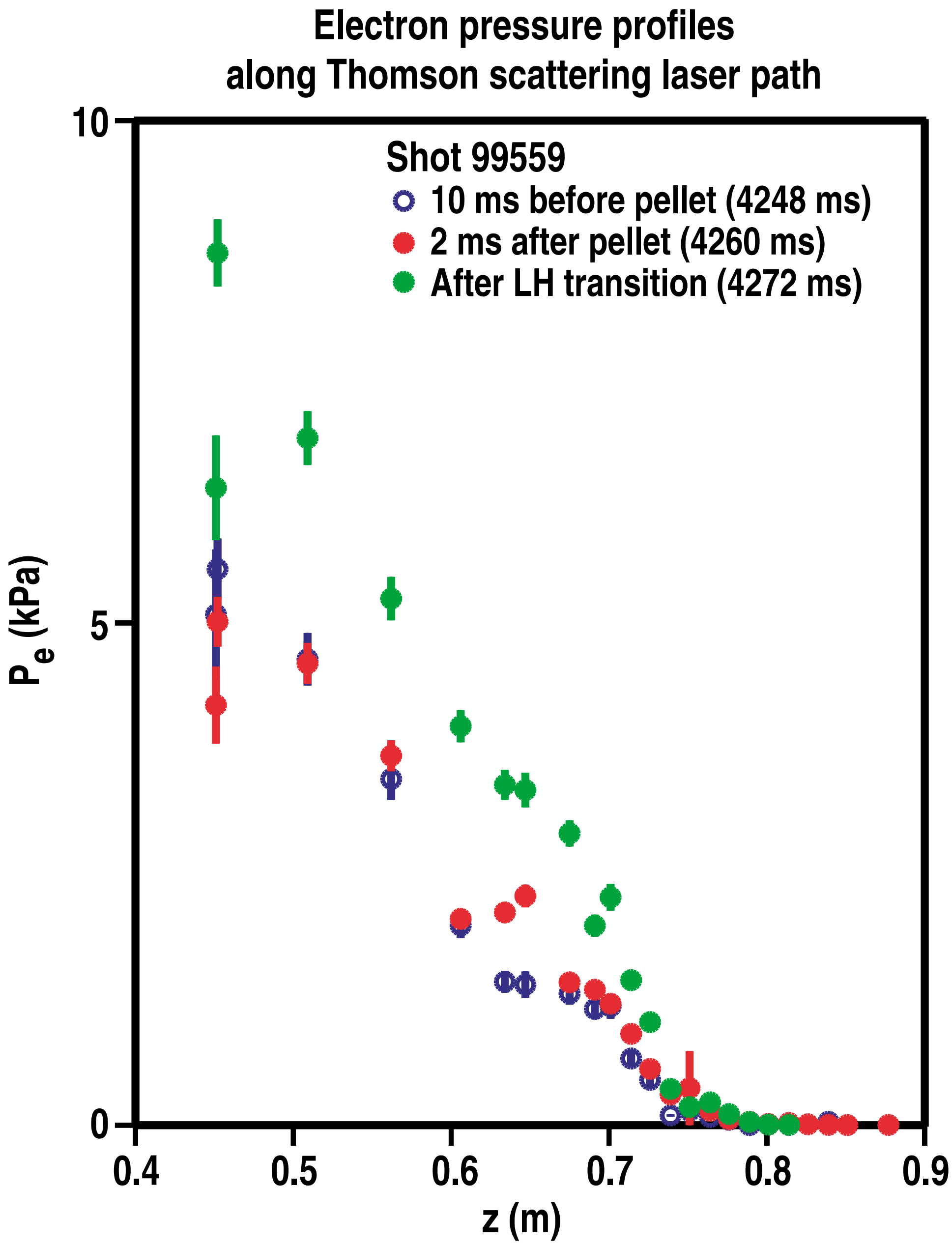
THE INCREASE IN THE EDGE ELECTRON PRESSURE PEDESTAL AND GRADIENT CLEARLY SHOWS THE TRANSITION TO H–MODE



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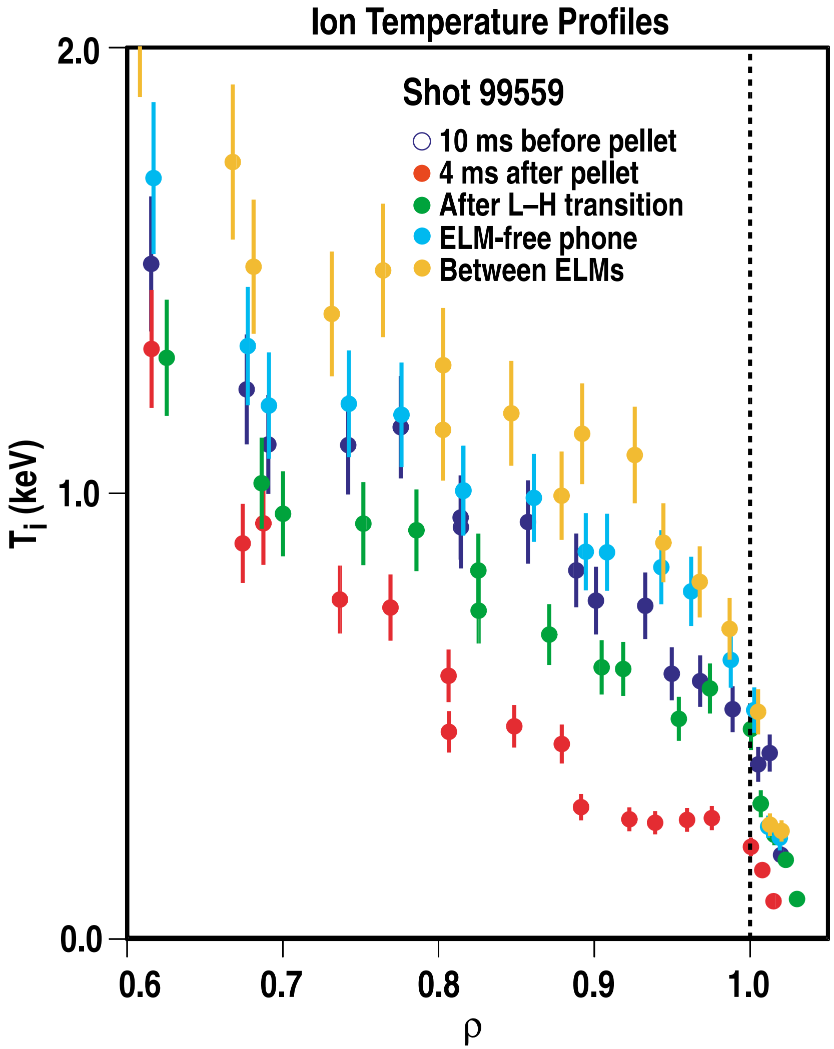
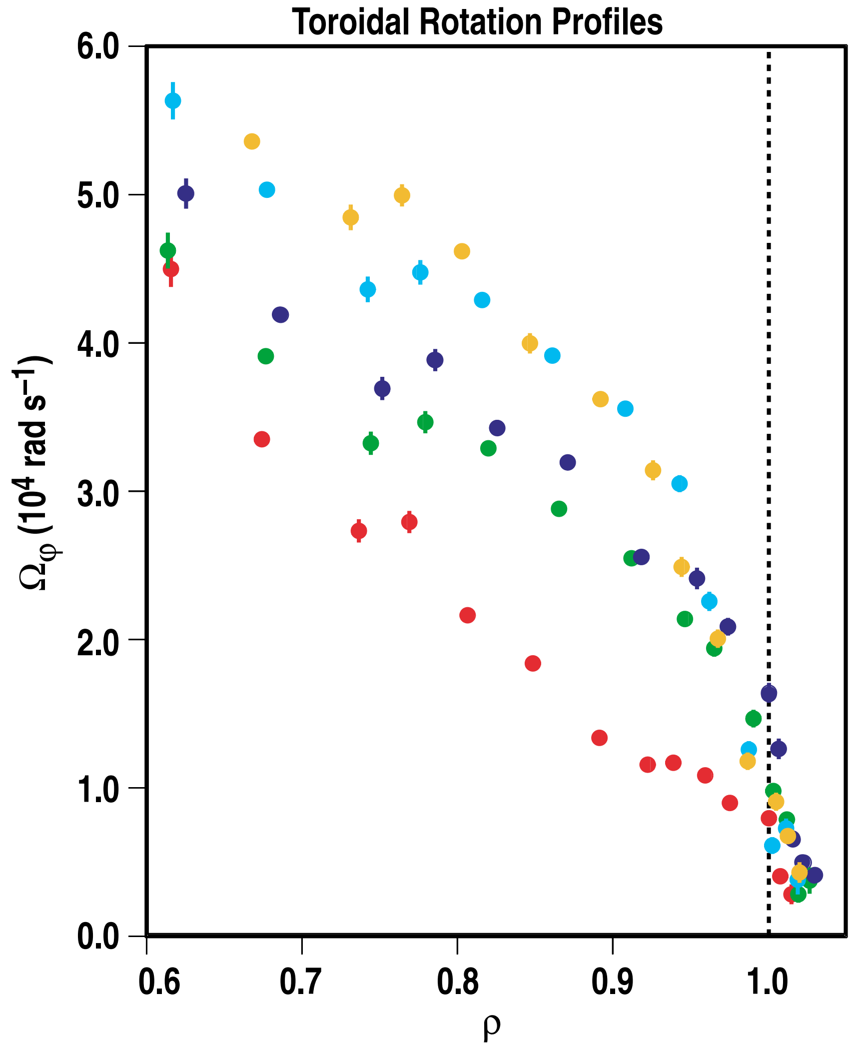
BOTH THE EDGE ION TEMPERATURE AND TOROIDAL ROTATION ARE SIGNIFICANTLY REDUCED AFTER PELLET INJECTION

- Pellet injection time = 4258 ms
- Integration time = 5 ms





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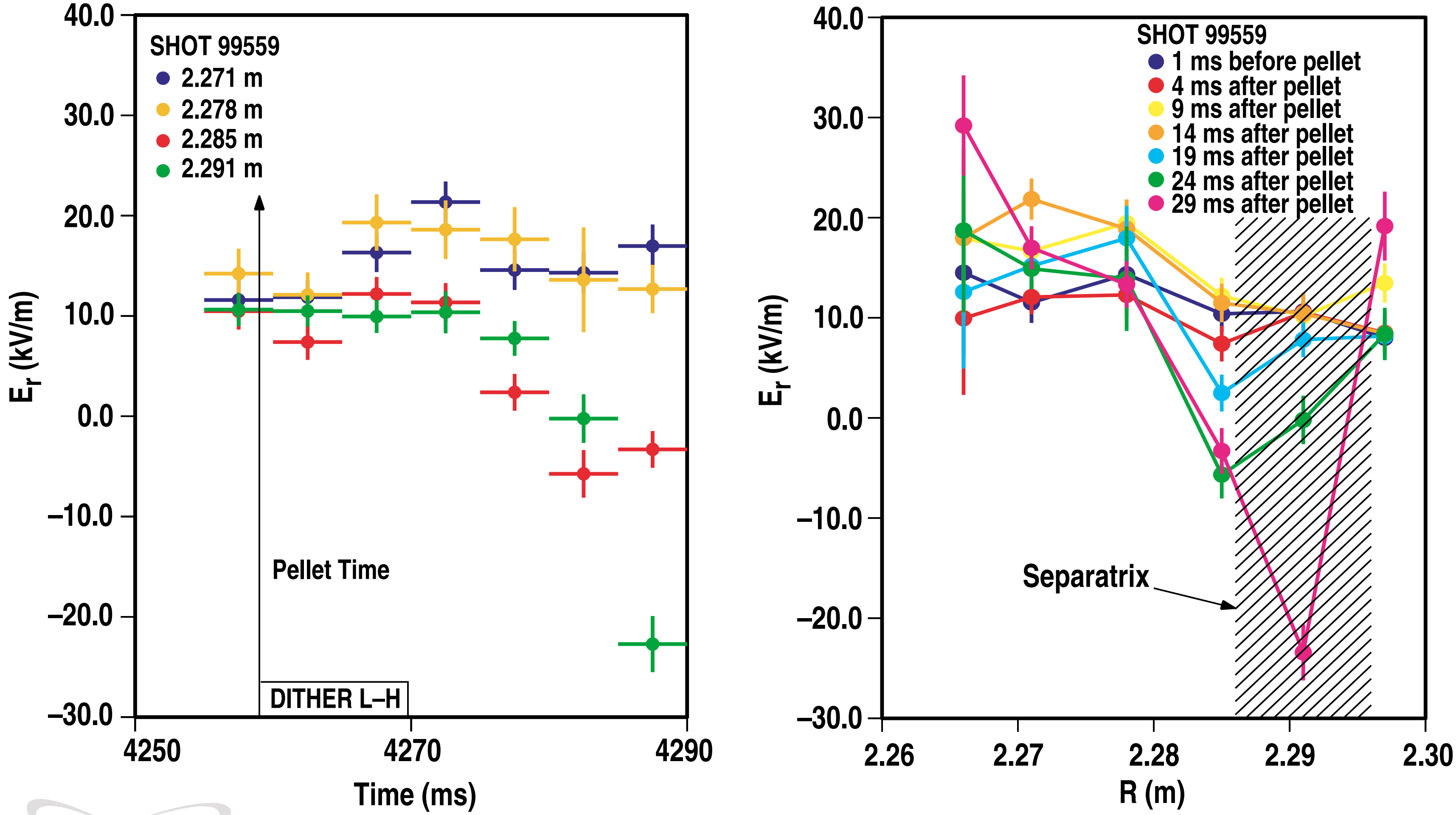
A GRADIENT IN THE EDGE E_r IS ESTABLISHED AFTER PELLET INJECTION AND IS MAINTAINED INTO THE H–MODE

- The E_r measurement is averaged over 5 ms integration time
- Need higher time resolution (1-2 ms) to determine fast changes in E_r



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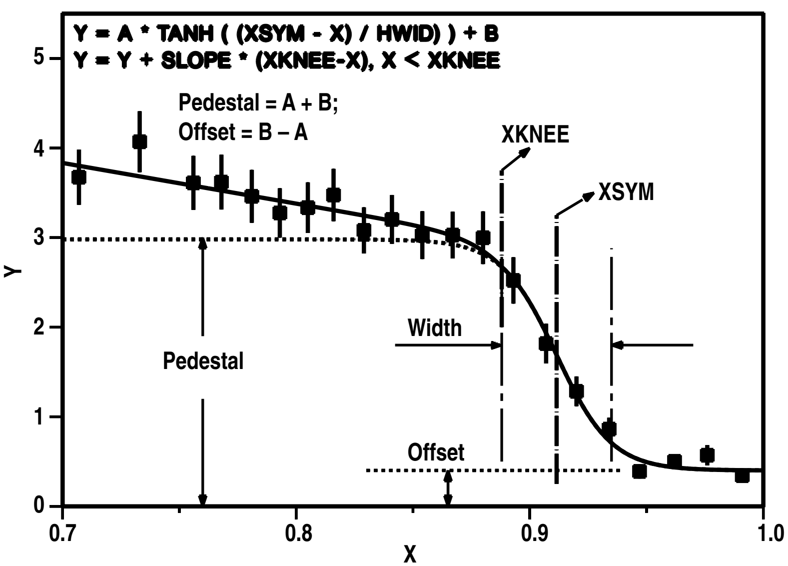
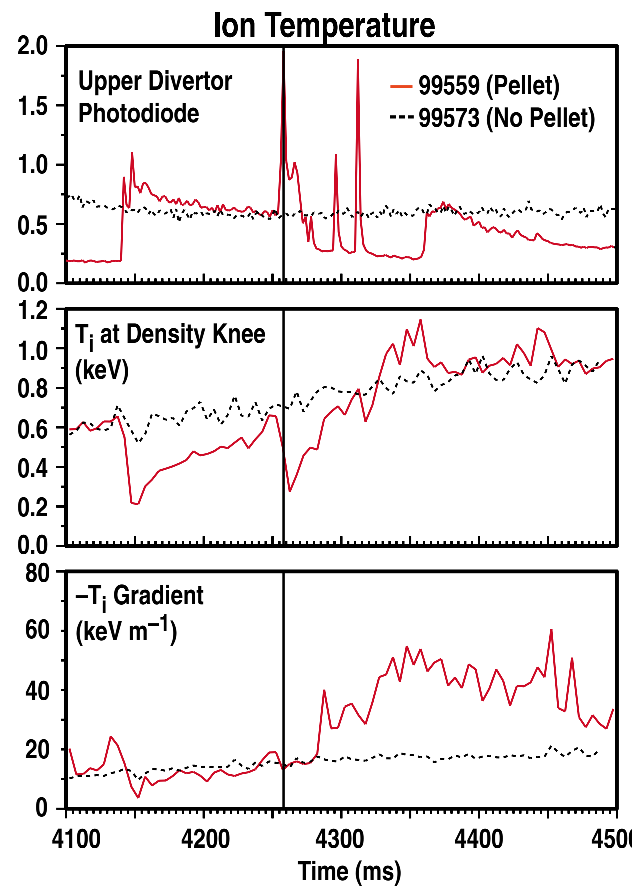
EDGE ION TEMPERATURE PEDESTAL AND GRADIENT INCREASE INTO THE H–MODE

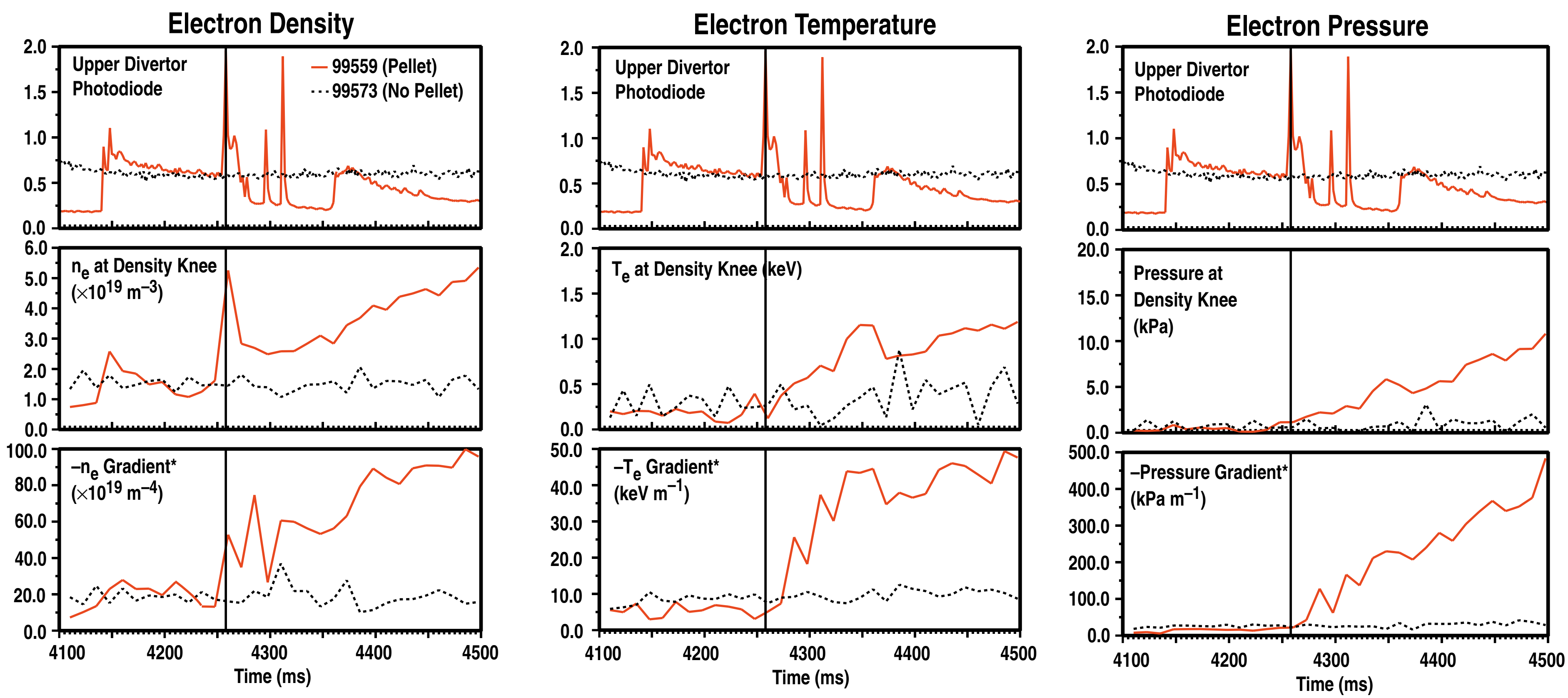
- PIH–mode at P_{NBI} = 6.8 MW (shot 99559)
- Discharge with no pellet stays in L–mode even at higher P_{NBI} = 9.2 MW (shot 99573)
- Tanhfit analysis is used to determine edge local parameters





EDGE LOCAL PARAMETERS DETERMINED FROM TANHFIT ANALYSIS CLEARLY SHOW THE TRANSITION TO H–MODE WITH PELLET INJECTION

- A critical ∇n_e of between 3-5×10^{20} m^{-4} is required for the H–mode transition (≡6-10 ×10^{20} m^{-4} at midplane)



*Spatial measurements are along the laser path in the z-direction, not at the midplane

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THE EXPERIMENTAL RESULTS WERE COMPARED WITH THREE MODELS OF THE H–MODE

- Rogers et al. (Proc. 17th IAEA Fusion Energy Conf., Yokohama, Japan, 1998, paper IAEA-CN-69/THP2/01). Based on 3–D simulations of the Braginskii equations

$$\alpha_{MHD} \approx \frac{2\mu_0 \, q_{95} \, \kappa^{1/2} \, a \, r_{xpt}^2 \, (2000 \, P/L_P)}{R_0 \, | \, B_T \, | \, d\psi/dR} \qquad \alpha_{DIAM} = \left(\frac{\rho_s \, c_s}{L_{pi,e}}\right)\left(\frac{t_0}{L_0}\right)$$

Transport is suppressed for $\alpha_{MHD} \gtrsim 0.5$ and $\alpha_{DIAM} \gtrsim 0.5$ (for DIII–D)

- Pogutse et al. (Proc. 24th EPS Conf., 1997, paper P3-1041). Based on stabilization of Alfvén waves parameterized in terms of normalized beta, β_N, and the normalized collision frequency, ν_n

$$\beta_N = \left(\frac{m_i}{m_e}\right)^{1/2} \frac{4\pi \, n_0 \, T_{0e}}{B_0^2} \, \frac{1}{k_{\parallel} \, \chi_{0p}} \quad ; \qquad \nu_n = \left(\frac{m_i}{m_e}\right)^{1/4} \frac{\chi_{0p}^{1/2}}{\lambda_e \, k_{\parallel}^{1/2}}$$

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THE EXPERIMENTAL RESULTS WERE COMPARED WITH THREE MODELS OF THE H–MODE (Continued)

χ_{0p} characterizes the pressure gradient scale length,

$k_{\parallel}$ is the parallel wavenumber,

λ_e is the mean free path

Transport is suppressed when $\beta_N > \beta_{CRIT} = 1 + \nu_n^{2/3}$

- Wilson et al. (Proc. 17th IAEA Fusion Energy Conf., Yokohama, Japan, 1998, paper IAEA-F1-CN-69/TH3/2). Based on stabilization of peeling modes at collisionality $\gtrsim$ 1 parameterized in terms of α_{MHD} and ν^*

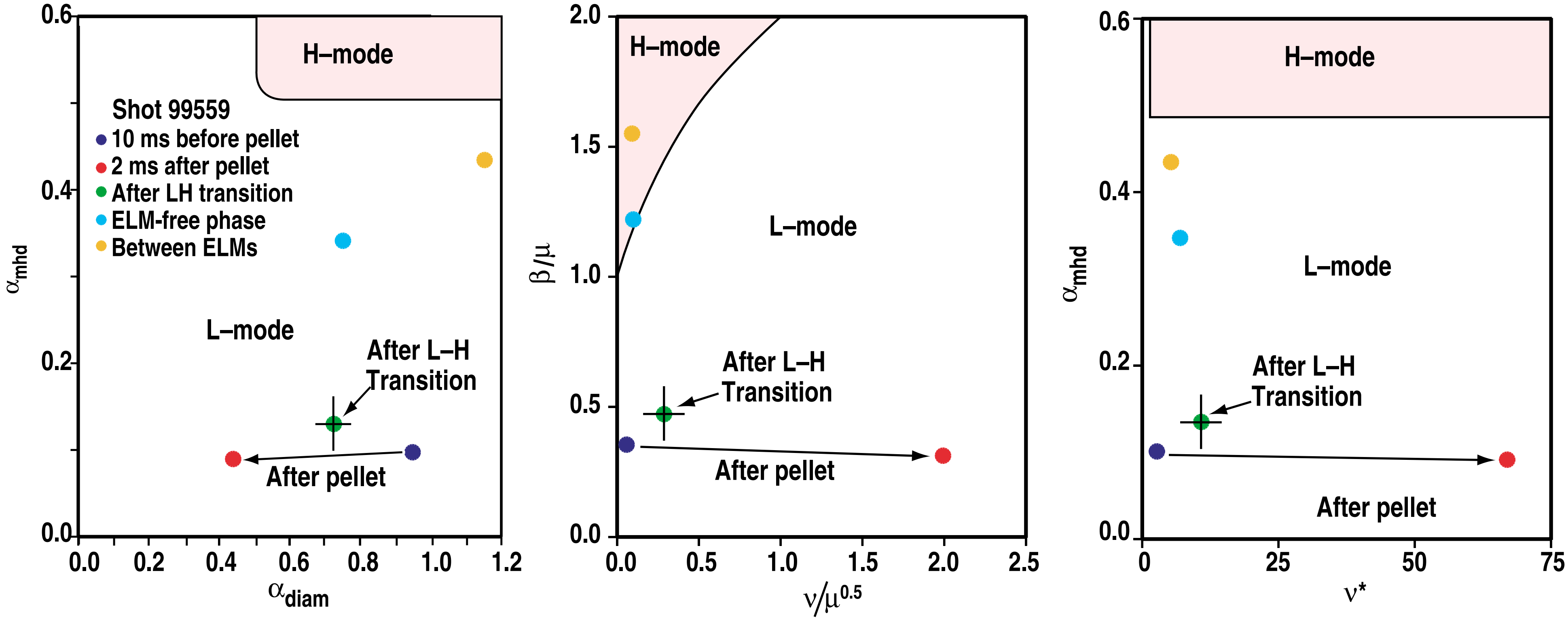
Transport is reduced when $\alpha_{MHD} \gtrsim 0.5$ and $\nu^* \gtrsim 1$

PELLET INDUCED H–MODES HAVE L-H TRANSITIONS AT PLASMA PARAMETERS FAR BELOW THEORETICAL PREDICTIONS

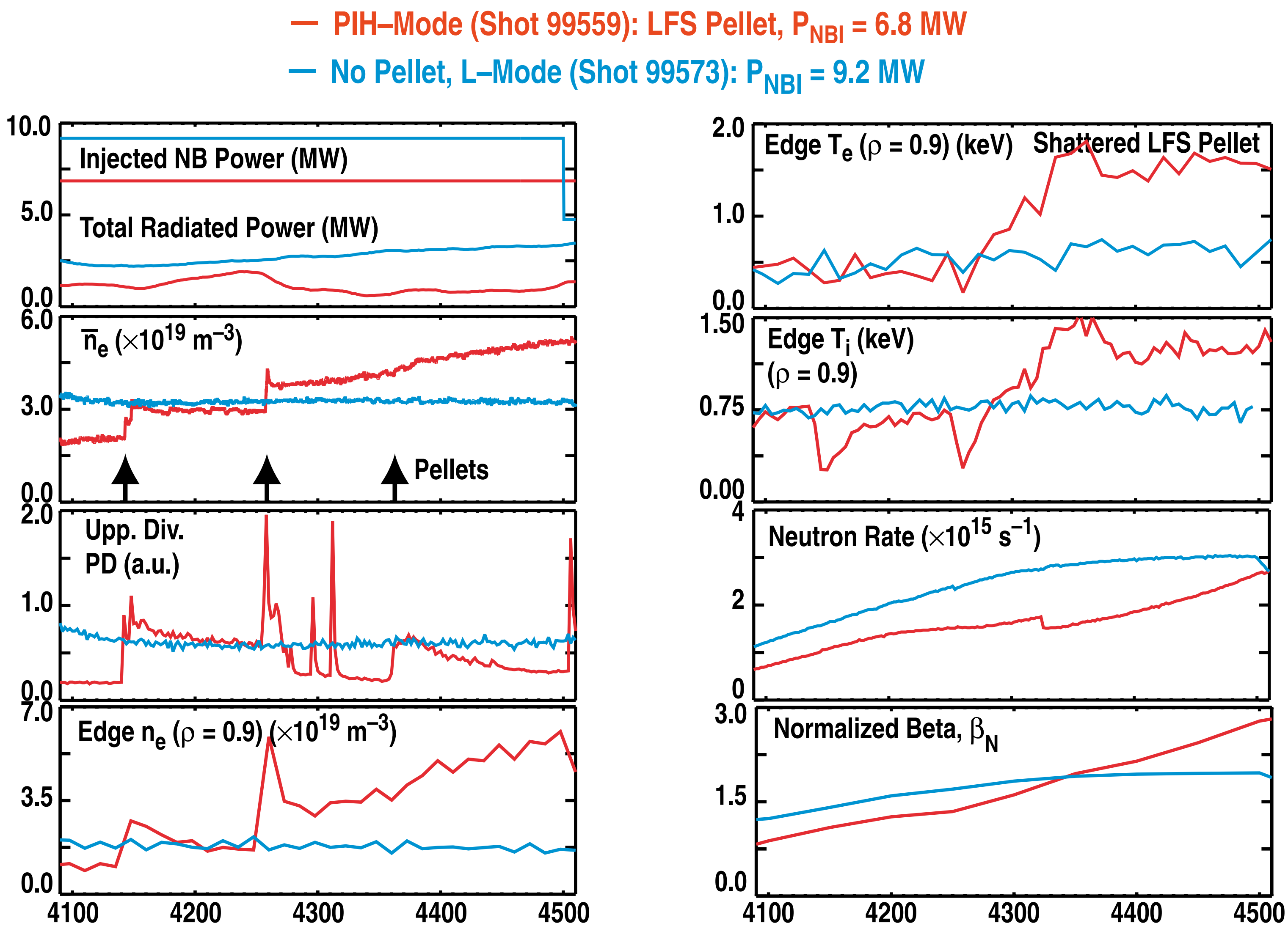
Rogers et al. Proc. 17th IAEA Fusion Energy Conf. Yokohama, Japan 1998, paper IAEA-CN-69/THP2/01

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

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



THE POWER REQUIRED TO ACCESS H–MODE IS REDUCED BY AT LEAST 2.4 MW INJECTED POWER USING PELLET INJECTION



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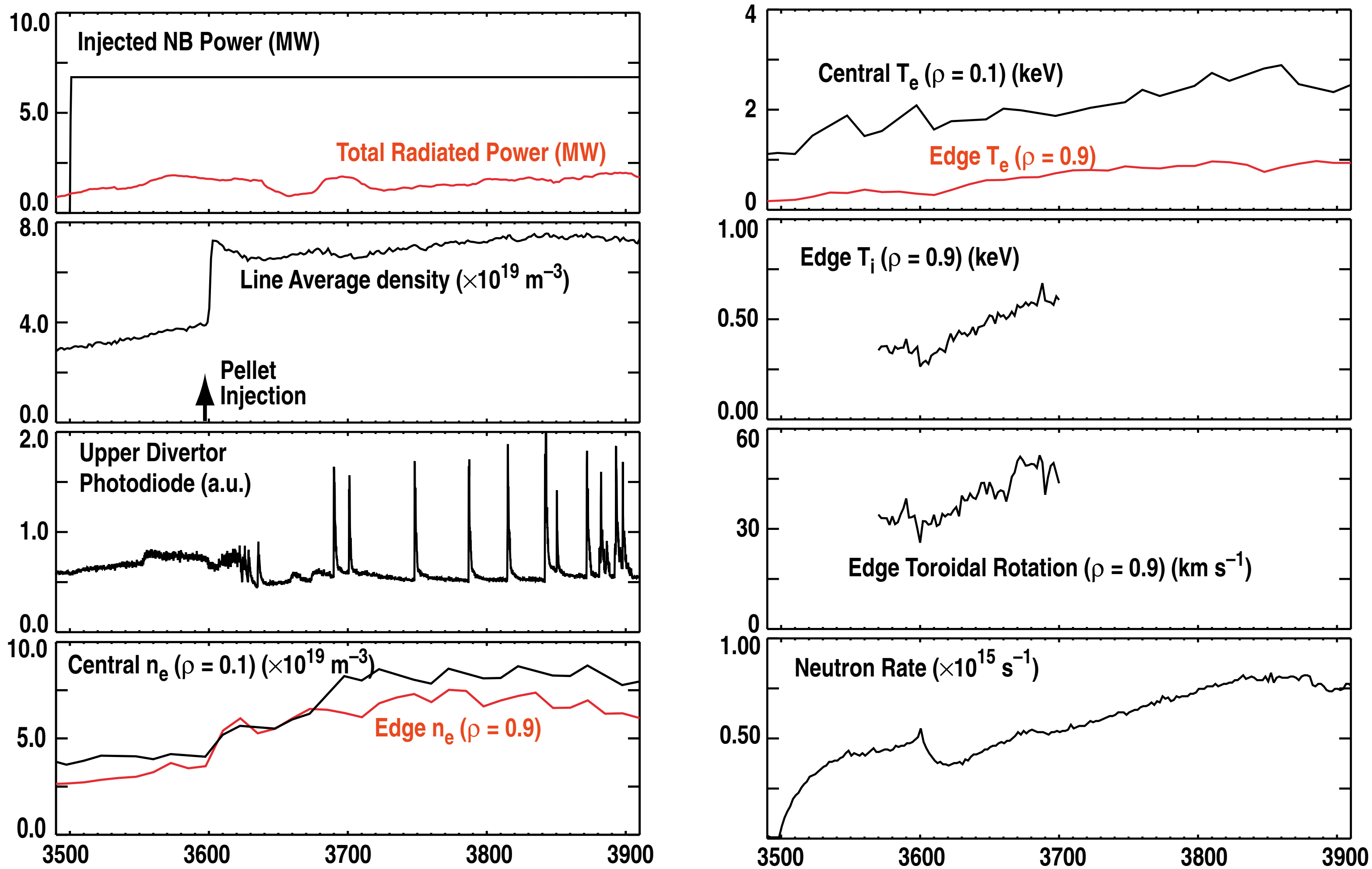
PIH–MODE TRANSITION PRODUCED BY HIGH FIELD SIDE LAUNCHED PELLET (P_{NBI} = 6.7 MW)



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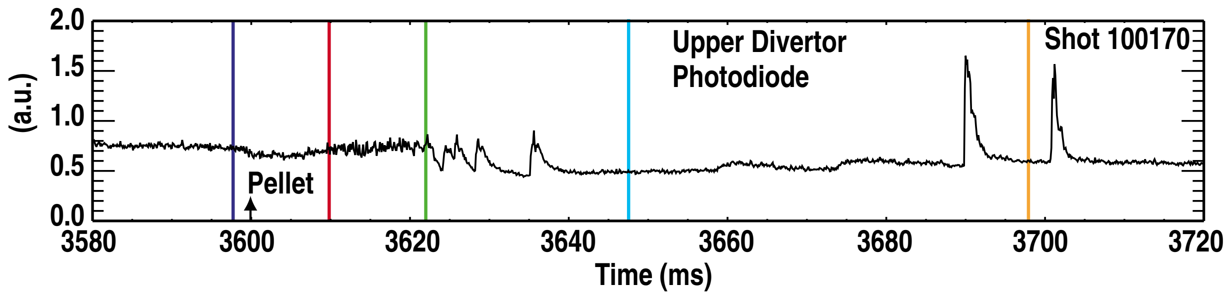
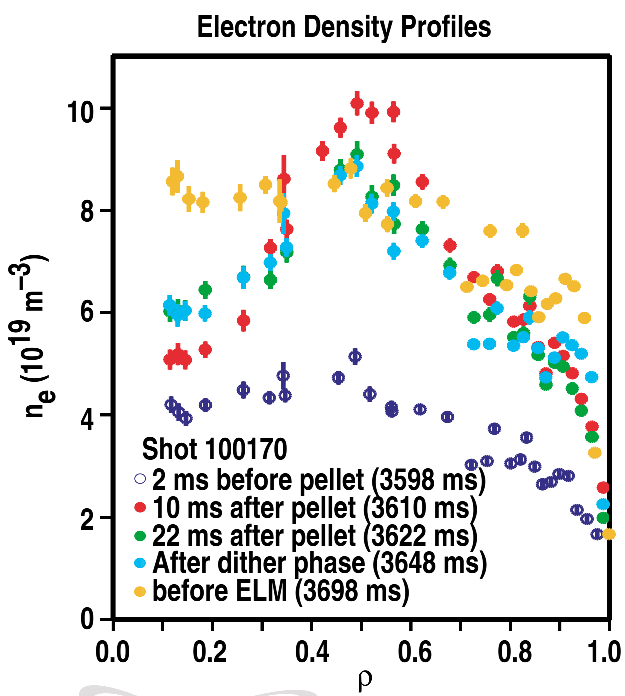
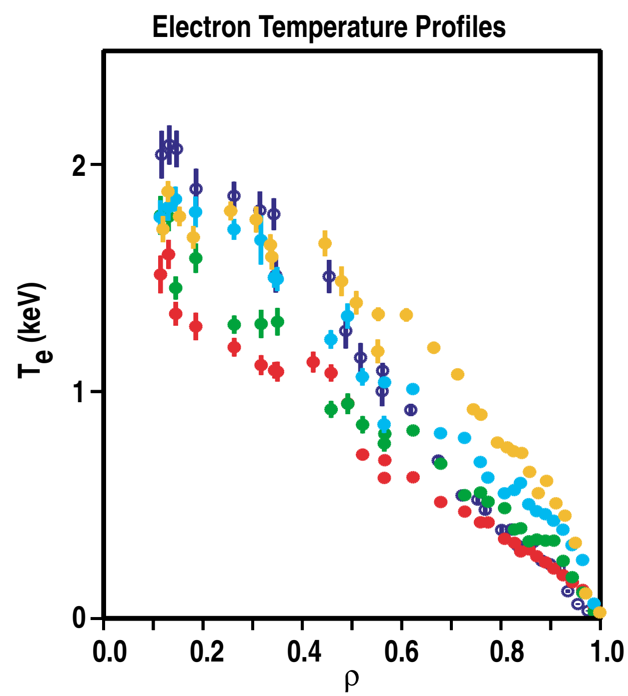
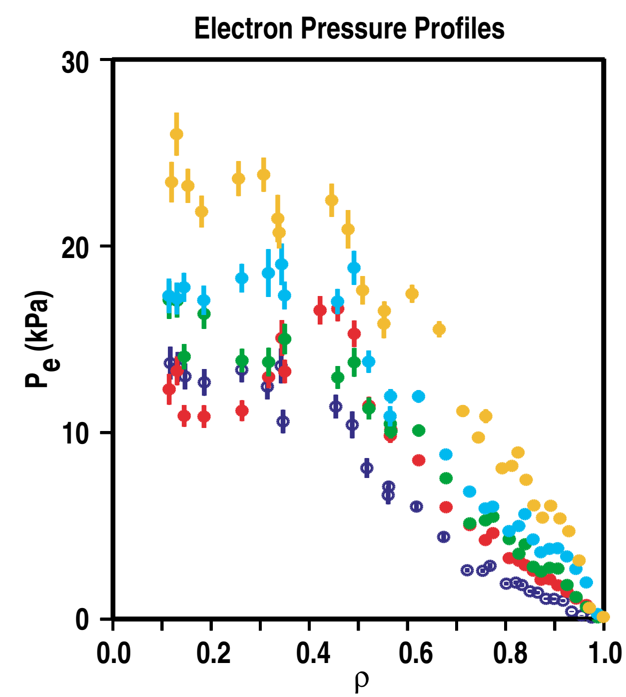
THE HFS PELLET PENETRATES MUCH FURTHER INTO THE PLASMA INTERIOR, BUT STILL PRODUCES A SIGNIFICANT DENSITY GRADIENT AT THE PLASMA EDGE









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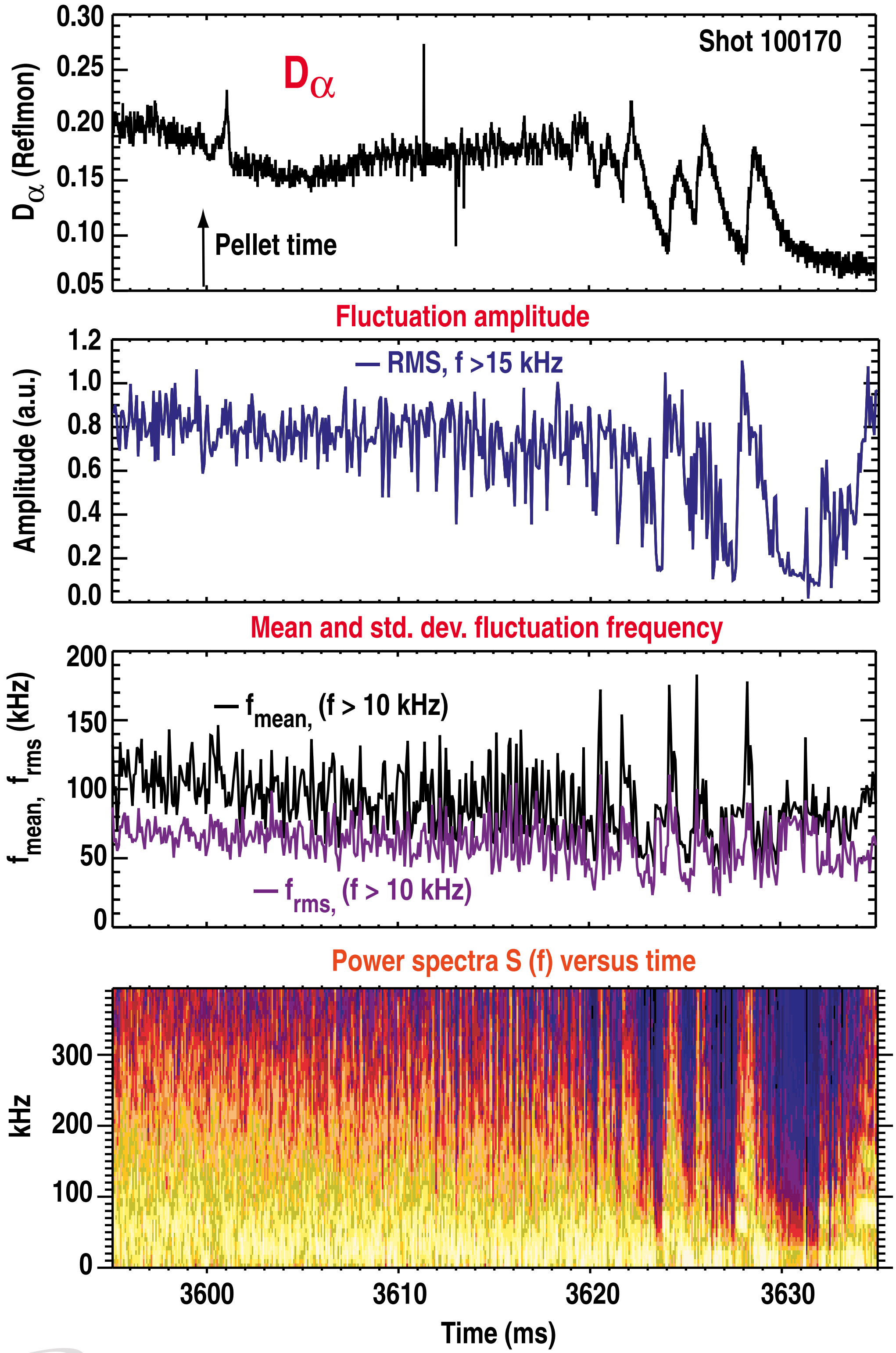
FAST DITHERING OR BURSTING OF FLUCTUATION APPEAR ~10 ms AFTER PELLET INJECTION

- Fast dithering develops into ELM free H–mode



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UCLA Electrical Engineering

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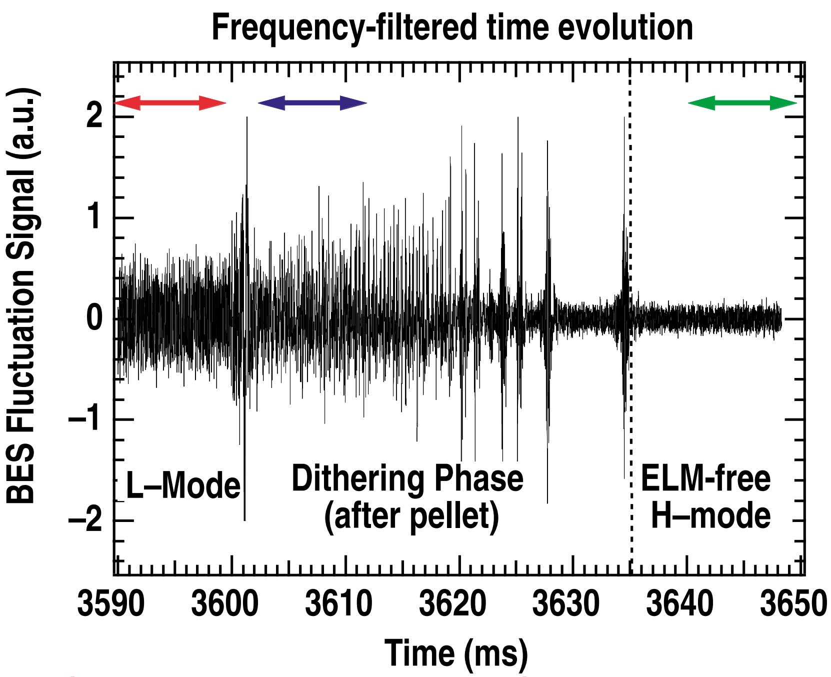
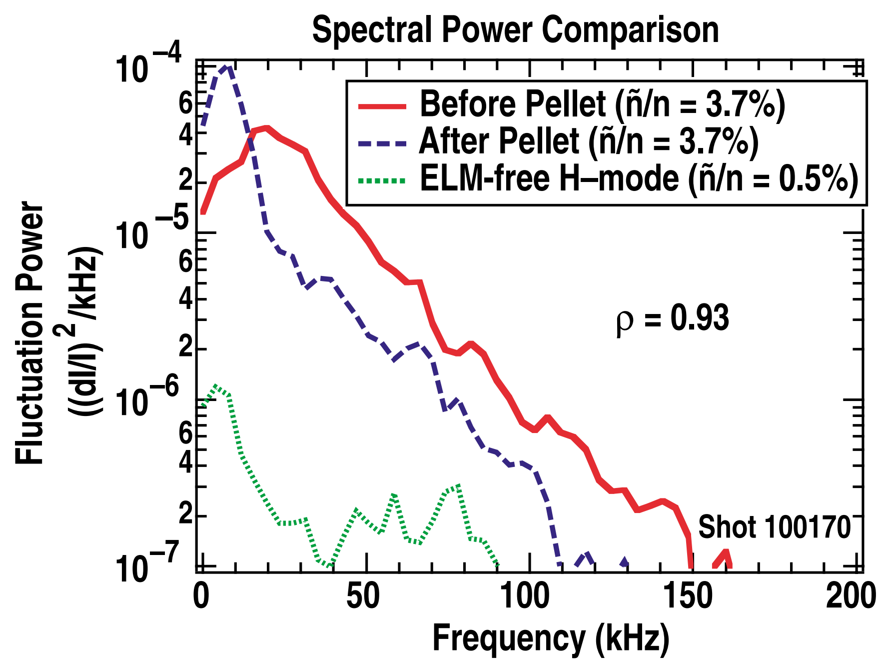
EDGE TURBULENCE DURING PELLET-INDUCED H–MODE TRANSITION

- Beam Emission Spectroscopy measurements show different stages of transition behavior ($0 < k < 3\ cm^{-1}$, $2 \le f \le 200$ kHz, $\rho = 0.93$)
- Power spectra condenses to low frequency after pellet injection
  - Integrated power remains nearly the same
- H–mode phase shows markedly reduced fluctuation level (2 orders of magnitude reduction in power)





1) Pre-pellet L–mode phase (moderate fluctuations)

2) Post-pellet, L–mode → dithering phase (lower frequency fluctuations, dithers)

3) H–mode (very low fluctuation level)

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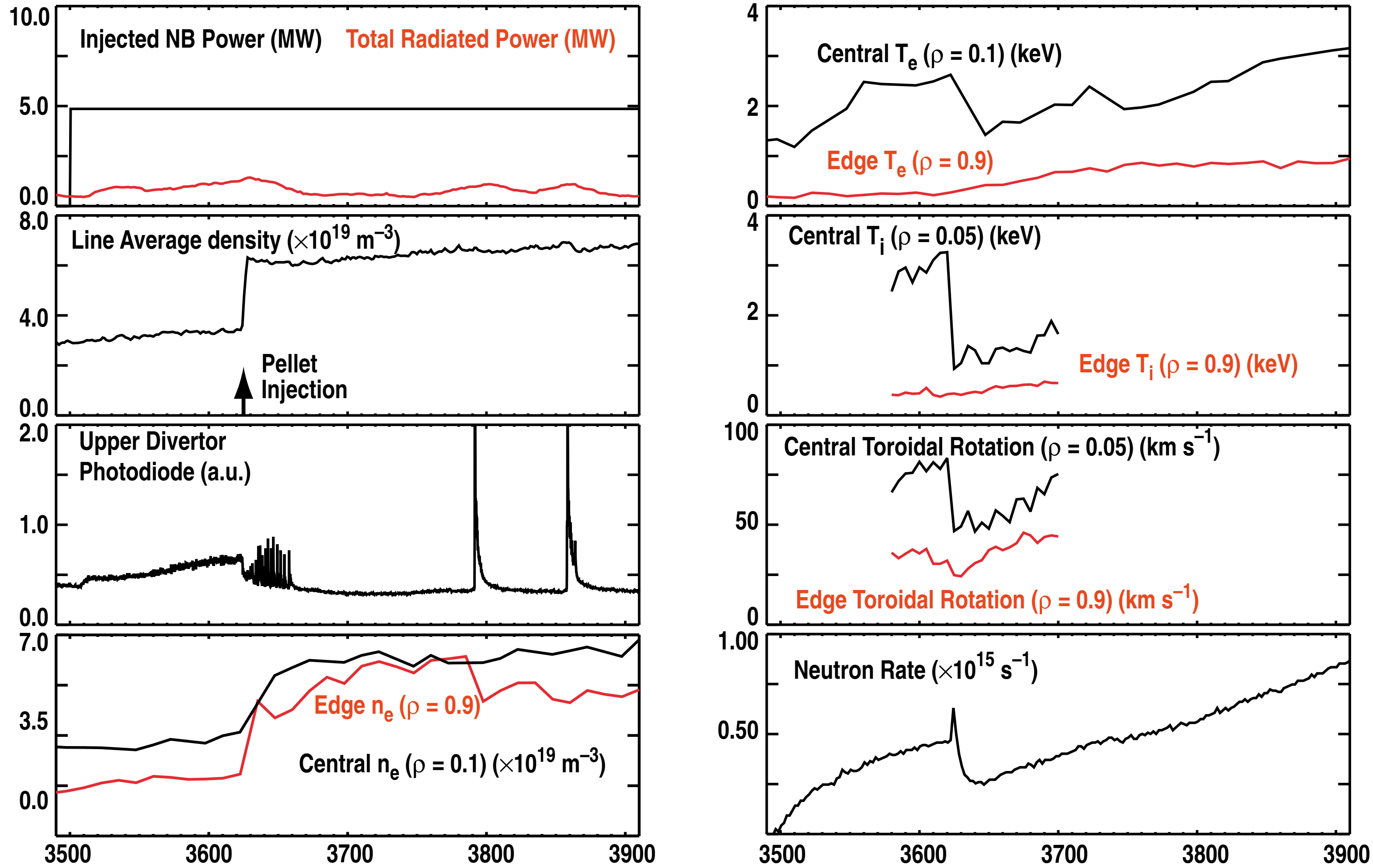
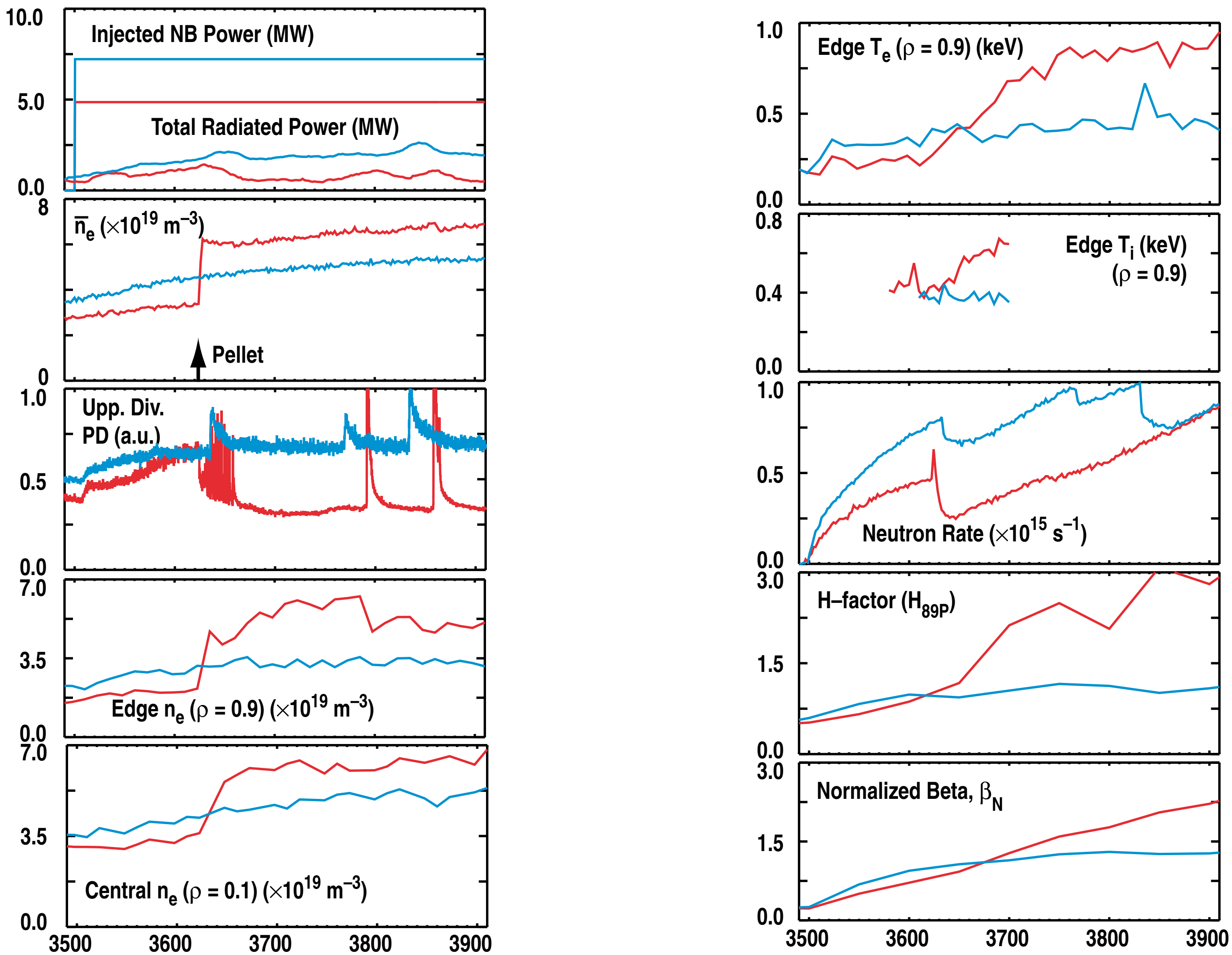
PIH–MODE TRANSITION PRODUCED BY A HIGH FIELD SIDE PELLET AT REDUCED NBI POWER (P_{NBI} = 4.9 MW)



THE POWER REQUIRED TO ACCESS H–MODE IS REDUCED BY 2.3 MW INJECTED POWER USING HIGH FIELD SIDE PELLET INJECTION

— PIH–Mode (Shot 100162): HFS pellet, P_{NBI} = 4.9 MW

— No Pellet, L–Mode (Shot 100161): P_{NBI} = 7.2 MW



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SUMMARY

- **H–mode plasmas have been directly produced by injecting frozen deuterium pellets into L–mode plasmas**
  - Pellets injected from the low toroidal field side and high field side were both able to produce H–mode transitions
  - The production of a steep edge density gradient is important, and not the radial extent of pellet deposition
- **The edge electron and ion temperatures are substantially reduced by the large influx of particles from the pellet**
  - The H–mode transition still occurs at the lowered temperatures
  - A critical edge temperature is not necessary in these H–mode transitions
- **Pellet induced H–modes have LH transitions at plasma parameters far below theoretical predictions**
- **Just after pellet injection, the edge fluctuations exhibit fast dithering or bursting behavior before steady H–mode conditions are achieved**
  - Similarly, fluctuation bursting is observed in transitions to VH–mode plasma and plasmas with internal transport barriers

SUMMARY (Continued)

- The shear in the edge E_r increases gradually during the period of fluctuation bursts
  - E_r measurement is averaged over bursts so cannot determine fast changes in E_r
  - Future experiments will have increased time resolution
- The power threshold is reduced by about 2.4 MW injected power (about 30%) using pellet injection
  - Pellets produced H–mode plasmas at lower input power than reference plasma discharges without pellet
  - Reference plasma discharges without pellets stayed in L–mode throughout the applied neutral beam heating even in the presence of strong sawteeth and higher NBI power