

# CONTROL OF PLASMA PROFILES AND TRANSPORT BARRIERS BY PELLET INJECTION IN DIII-D

by

P. GOHIL, L.R. BAYLOR,\* K.H. BURRELL, T.C. JERNIGAN\*

\*Oak Ridge National Laboratory.

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# OVERVIEW

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- **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 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 (by up to 33%) using pellet injection**
  - Pellets produced H-mode plasmas at lower input power than reference plasma discharges without pellets
  - 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

# EXPERIMENTAL SETUP

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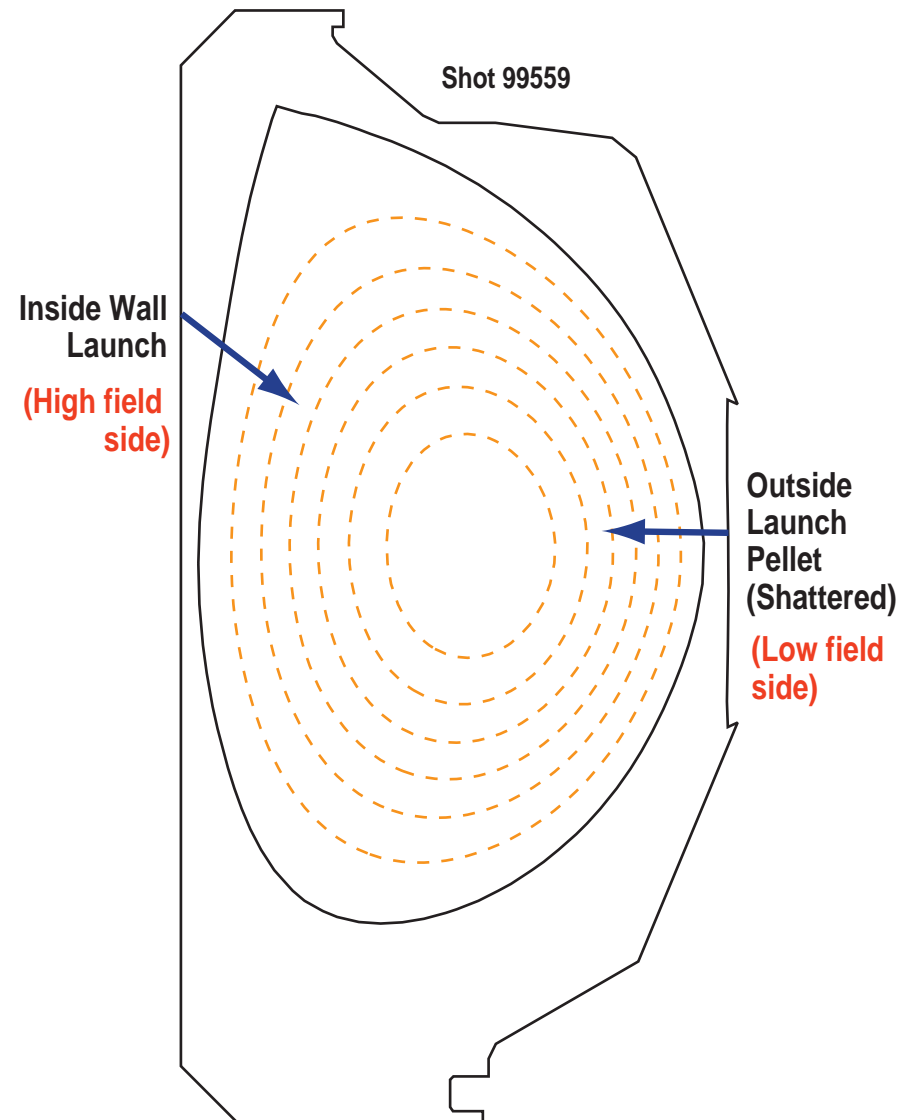
- An unbalanced, double-null diverted discharge with the  $\nabla B$  drift away from the dominant X-point was investigated. This plasma configuration resulted in a high H-mode power threshold such that L-mode conditions were maintained at high input power. Pellets from the high toroidal field side or low toroidal field side were launched into steady L-mode plasmas to determine their ability to produce H-mode plasmas
- Operational parameters
  - Plasma current,  $I_p = 1.6$  MA
  - Toroidal magnetic field,  $B_T = 1.8\text{--}2.1$  T
  - Target electron density,  $\bar{n}_e = 3.0\text{--}4.0 \times 10^{19} \text{ m}^{-3}$
  - Auxiliary heating power (NBI) = 4.9–9.2 MW
  - Safety factor: on-axis,  $q(0) = 0.9\text{--}1.0$   
edge,  $q_{95} = 3.3\text{--}3.4$
- Plasma configuration
  - Unbalanced, double-null diverted discharge, predominantly diverted on upper divertor
  - Elongation,  $\kappa = 1.63\text{--}1.71$
  - Upper triangularity,  $\delta_{\text{upp}} = 0.70\text{--}0.85$
  - Lower triangularity,  $\delta_{\text{low}} = 0.28\text{--}0.29$

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

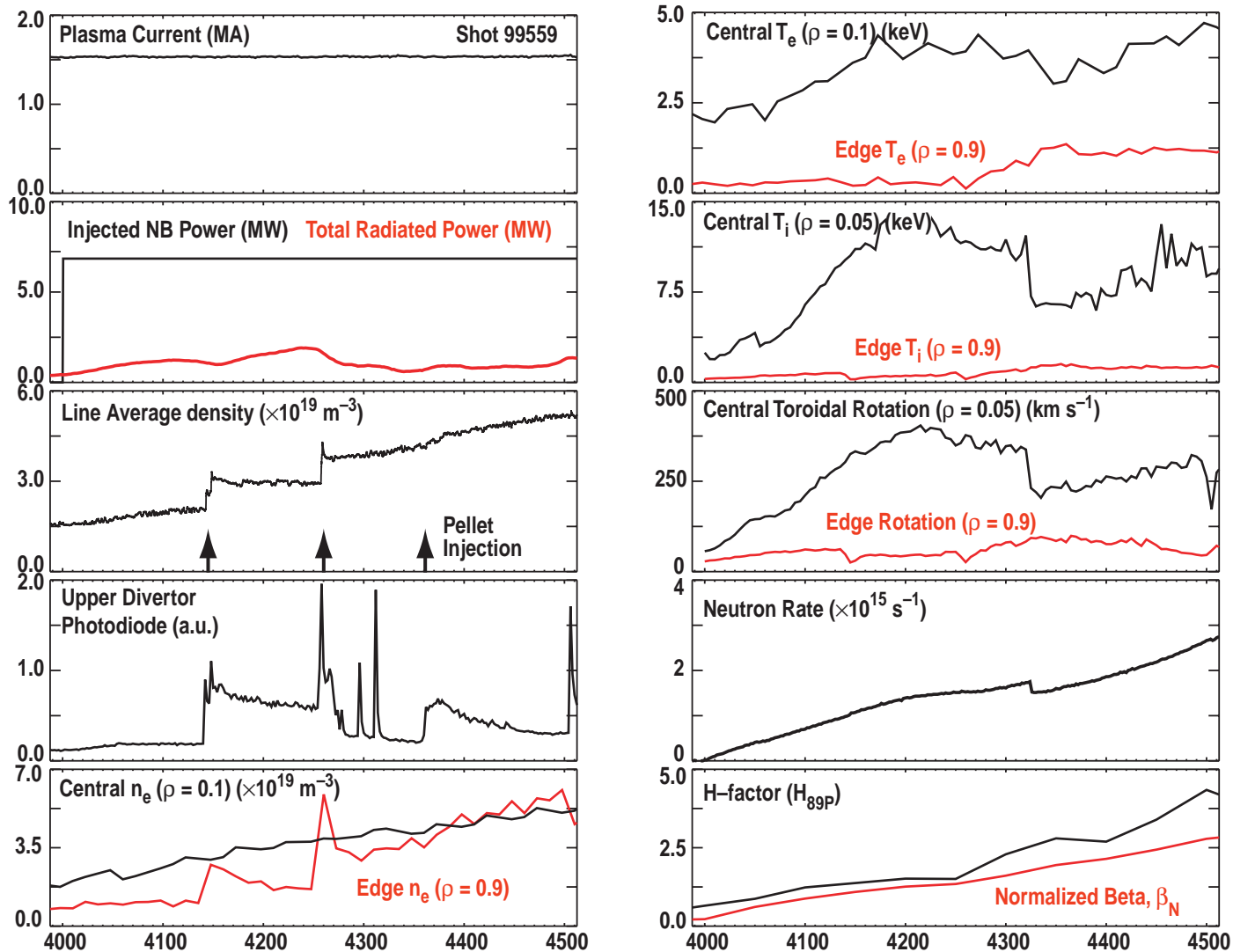
- Outside wall launched pellets (low field side) were shattered prior to entry into plasma in order to minimize pellet penetration  $\Rightarrow$  predominantly edge density perturbation
- Type: solid deuterium  
Pellet size: 2.7 mm  
Equivalent number of particles:  $2 \times 10^{20}$   
Rep rate: up to 10 Hz  
Speed: 100–350 m s<sup>-1</sup>  
Speed for Specific Shots:

## Shot

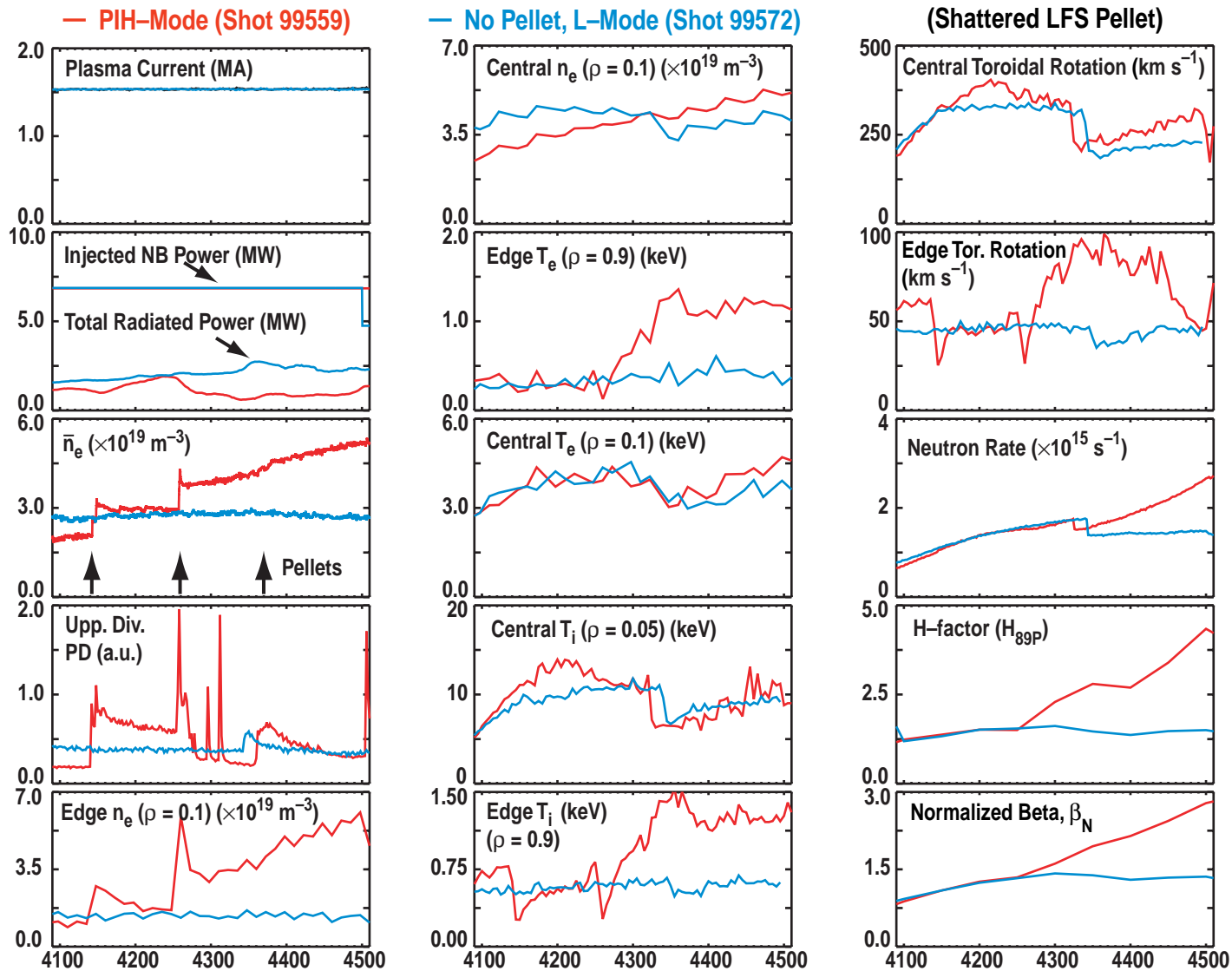
99559	314, 194 and 160 m s <sup>-1</sup> (shattered pellets – outside launch)
100162	222 m s <sup>-1</sup> (inside launch)
100170	235 m s <sup>-1</sup> (inside launch)



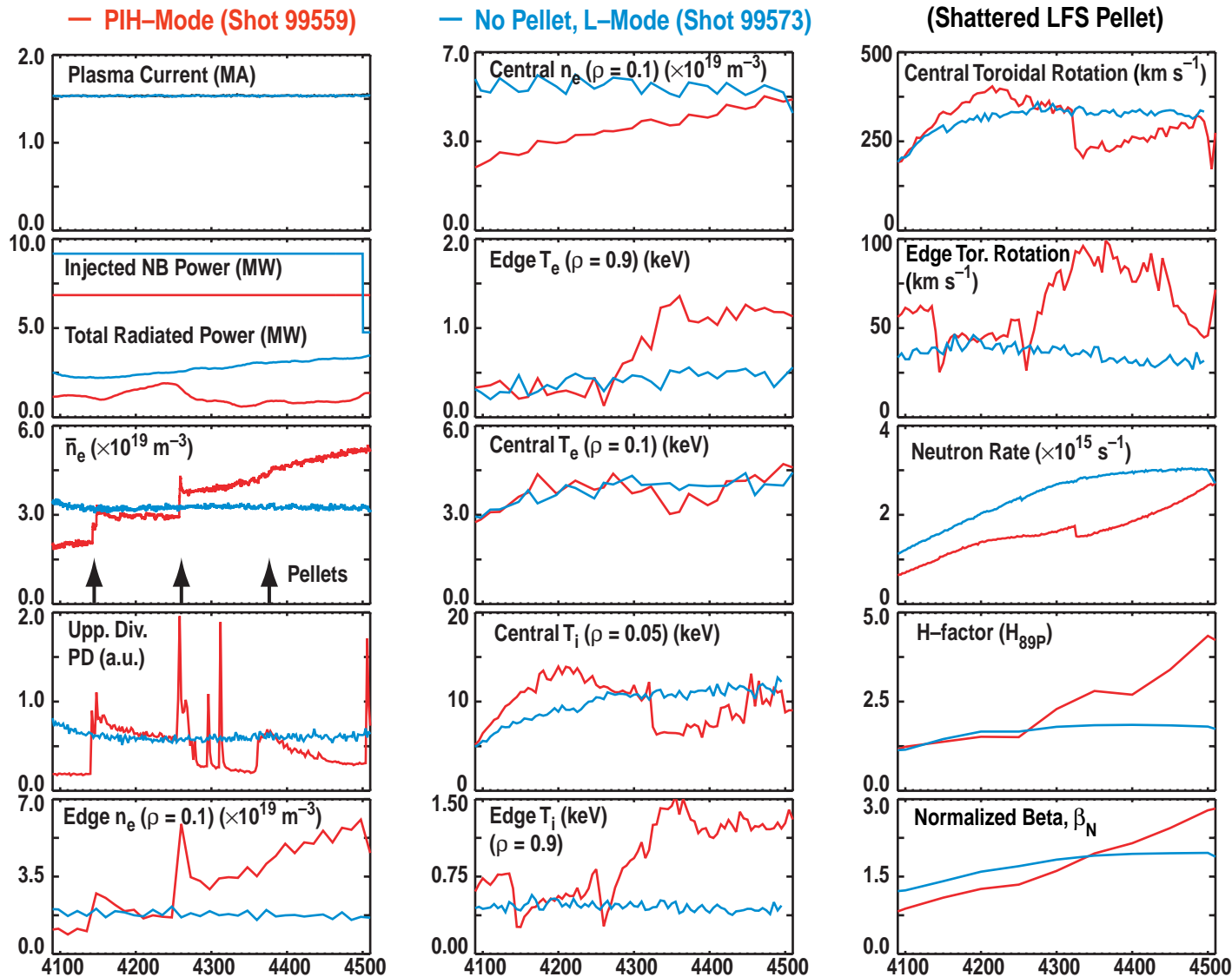
# TEMPORAL EVOLUTION OF PELLET INDUCED H-MODE (PIH-MODE) DISCHARGE (SHATTERED, LOW FIELD SIDE PELLET)



# COMPARISON OF PIH-MODE DISCHARGE WITH NO PELLET L-MODE REFERENCE DISCHARGE ( $P_{\text{NBI}} = 6.8 \text{ MW}$ FOR BOTH DISCHARGES)



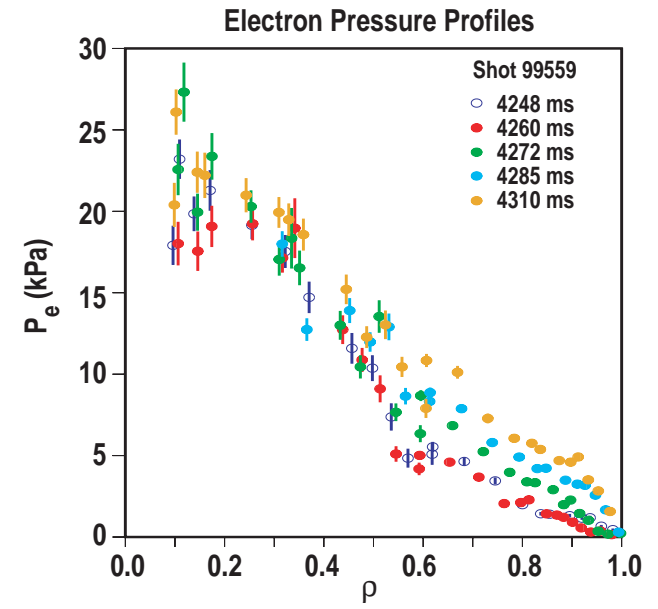
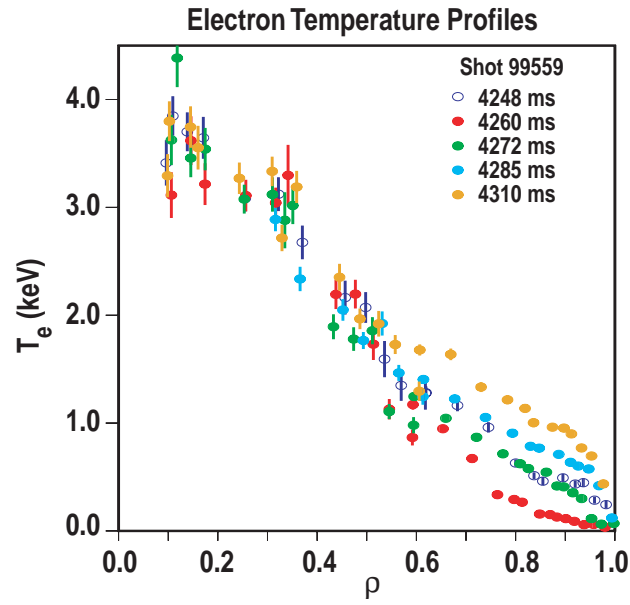
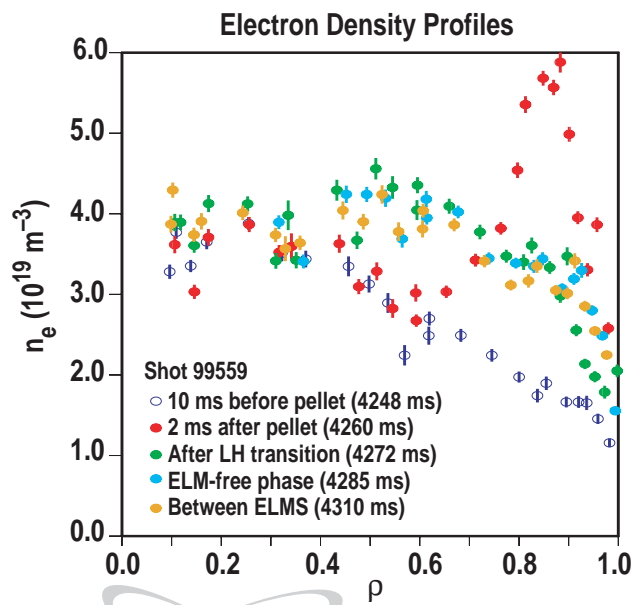
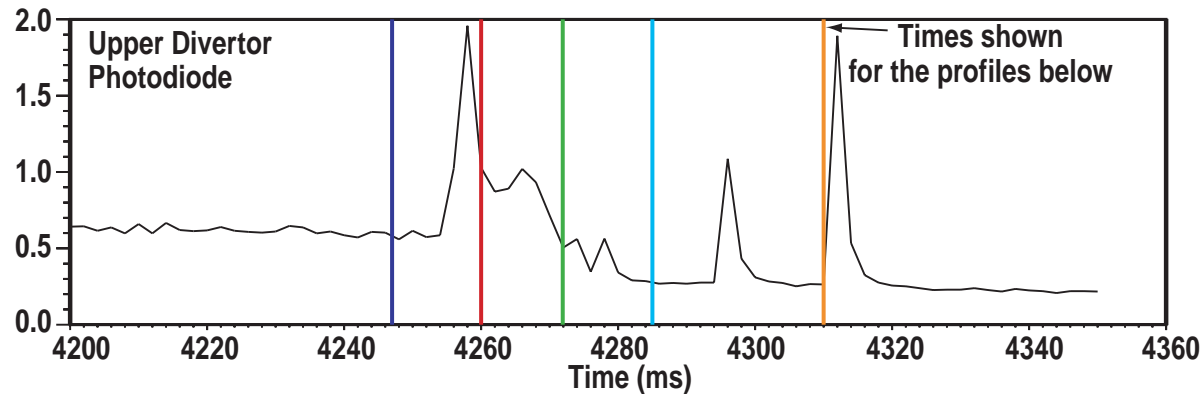
# COMPARISON OF PIH-MODE DISCHARGE ( $P_{\text{NBI}} = 6.8 \text{ MW}$ ) WITH NO PELLETS, L-MODE DISCHARGE ( $P_{\text{NBI}} = 9.2 \text{ MW}$ )



- The power required to access H-mode is reduced by at least 2.4 MW using pellet injection

# EVOLUTION OF ELECTRON KINETIC PROFILES IN THE PELLETT INDUCED H-MODE PLASMA

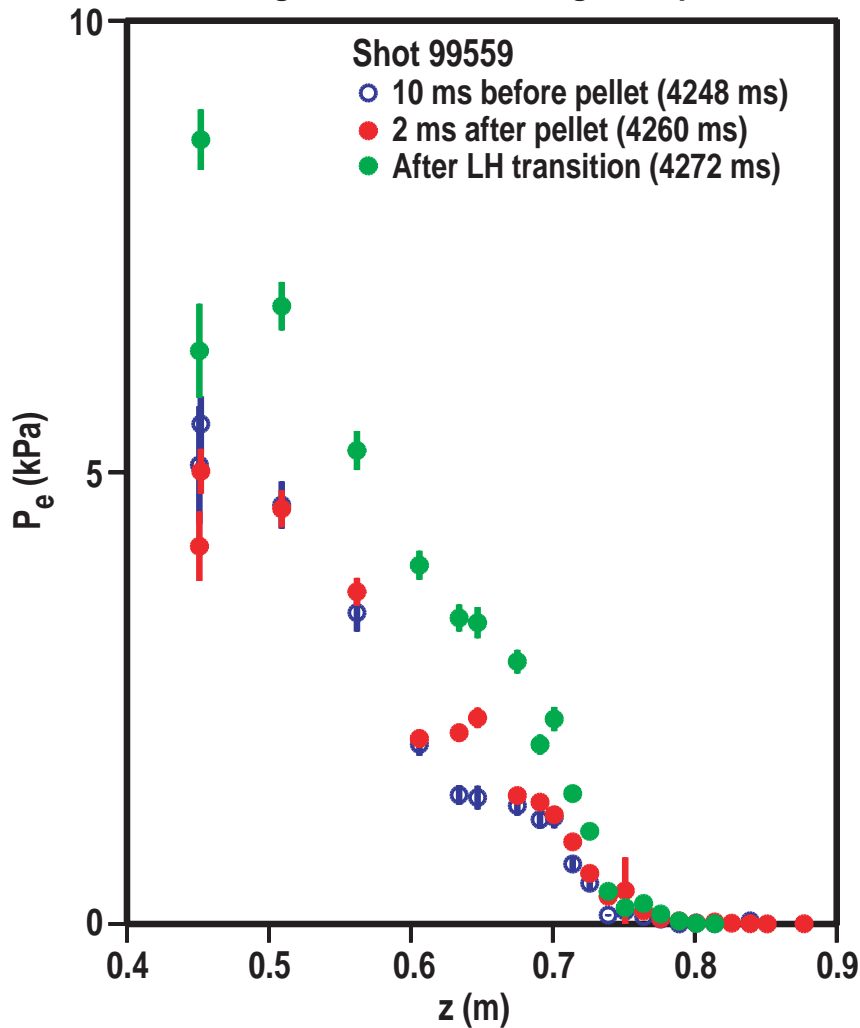
- The edge electron temperature is reduced at the L-H transition — disagrees with H-mode theories requiring edge critical electron temperature



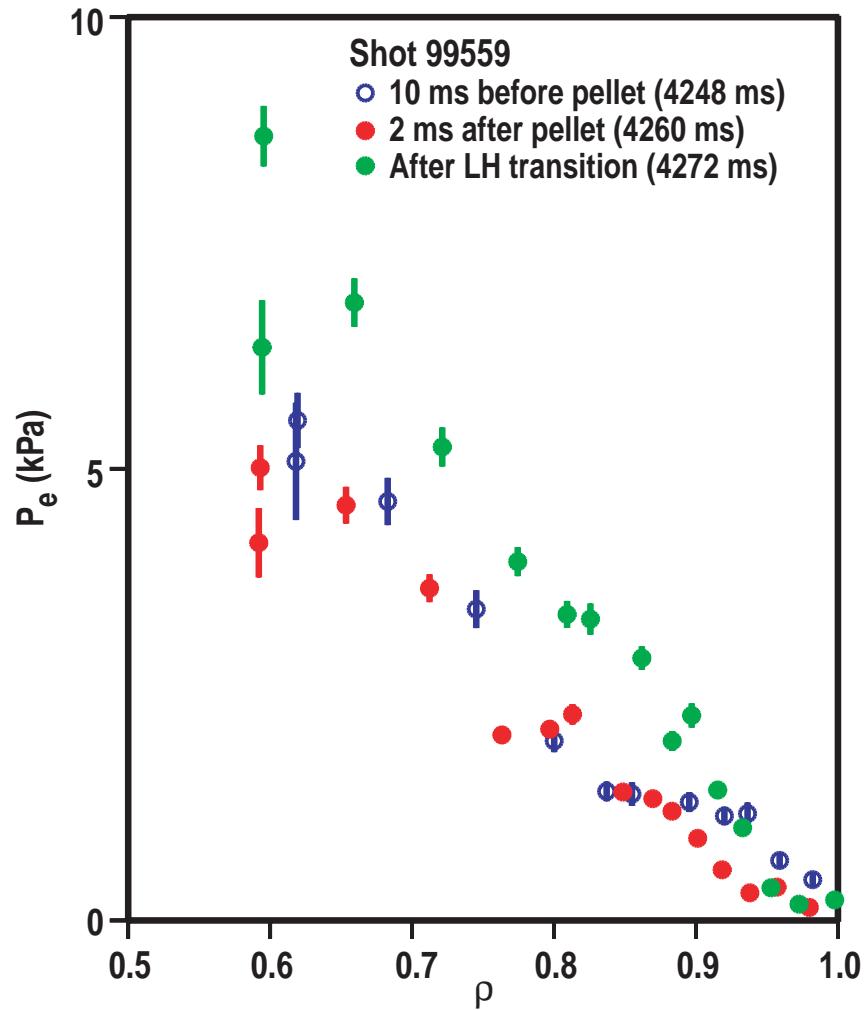


# THE INCREASE IN THE EDGE ELECTRON PRESSURE PEDESTAL AND GRADIENT CLEARLY SHOWS THE TRANSITION TO H-MODE

Electron pressure profiles along Thomson scattering laser path



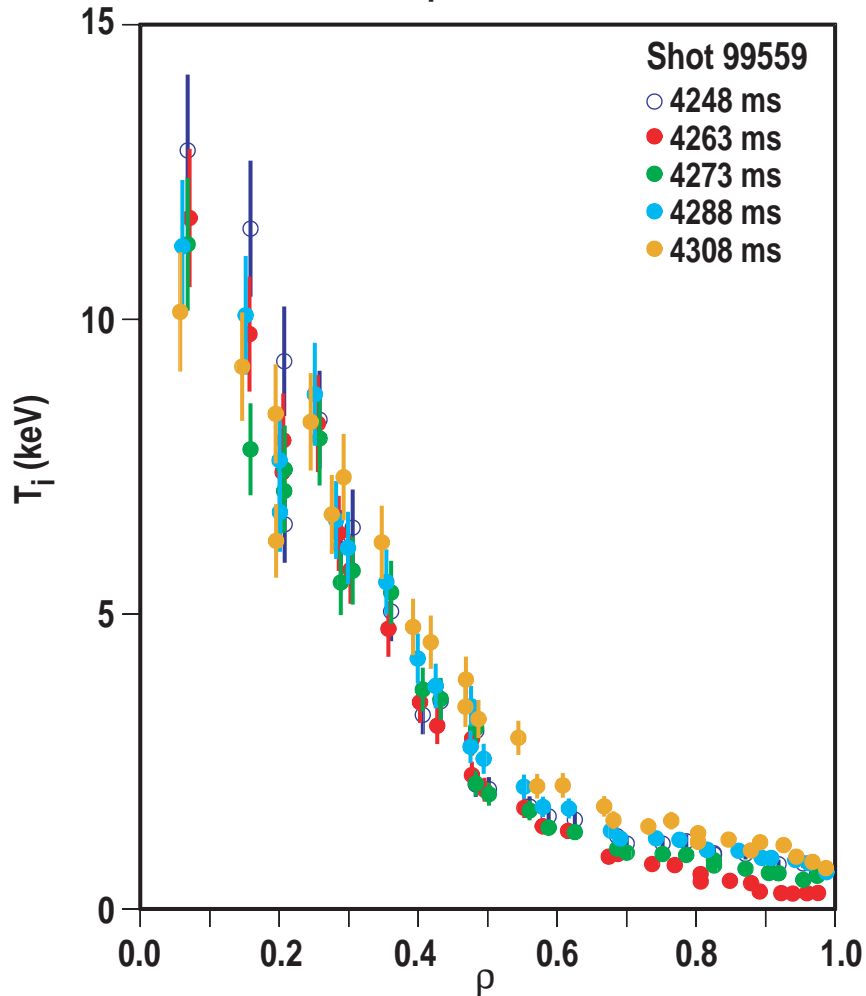
Electron pressure profiles in normalized toroidal flux coordinates



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

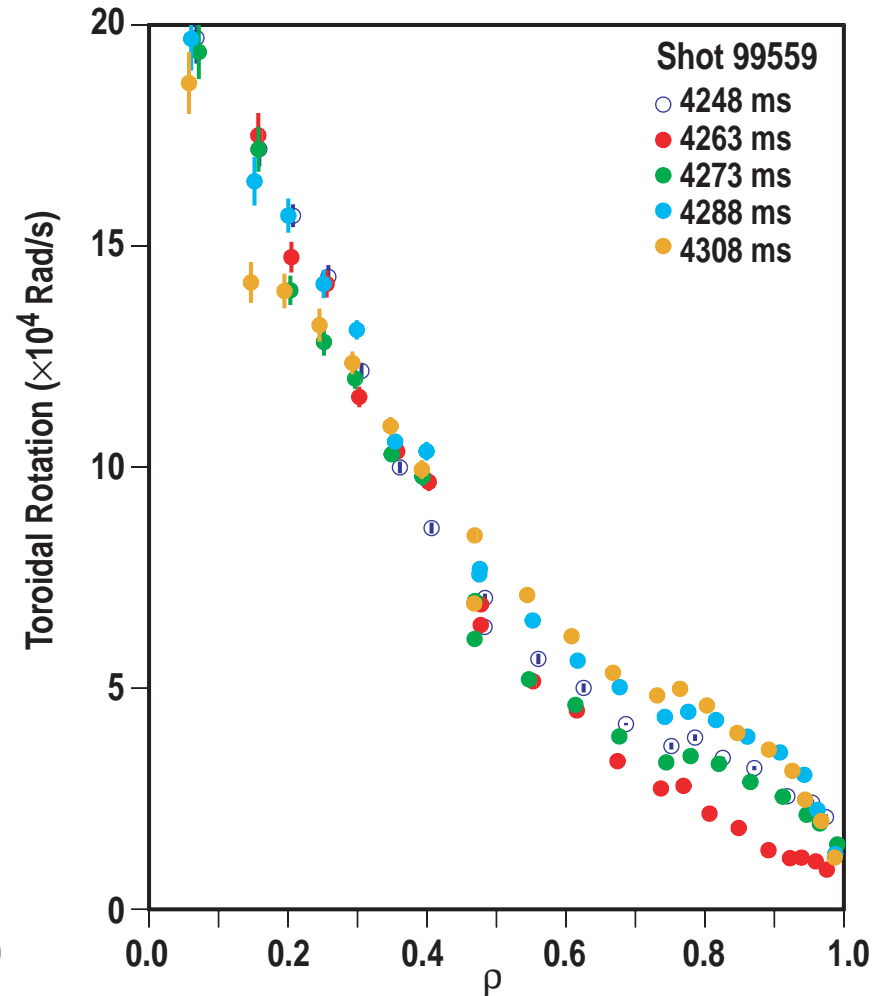
● Pellet injection time = 4258 ms

Ion Temperature Profiles

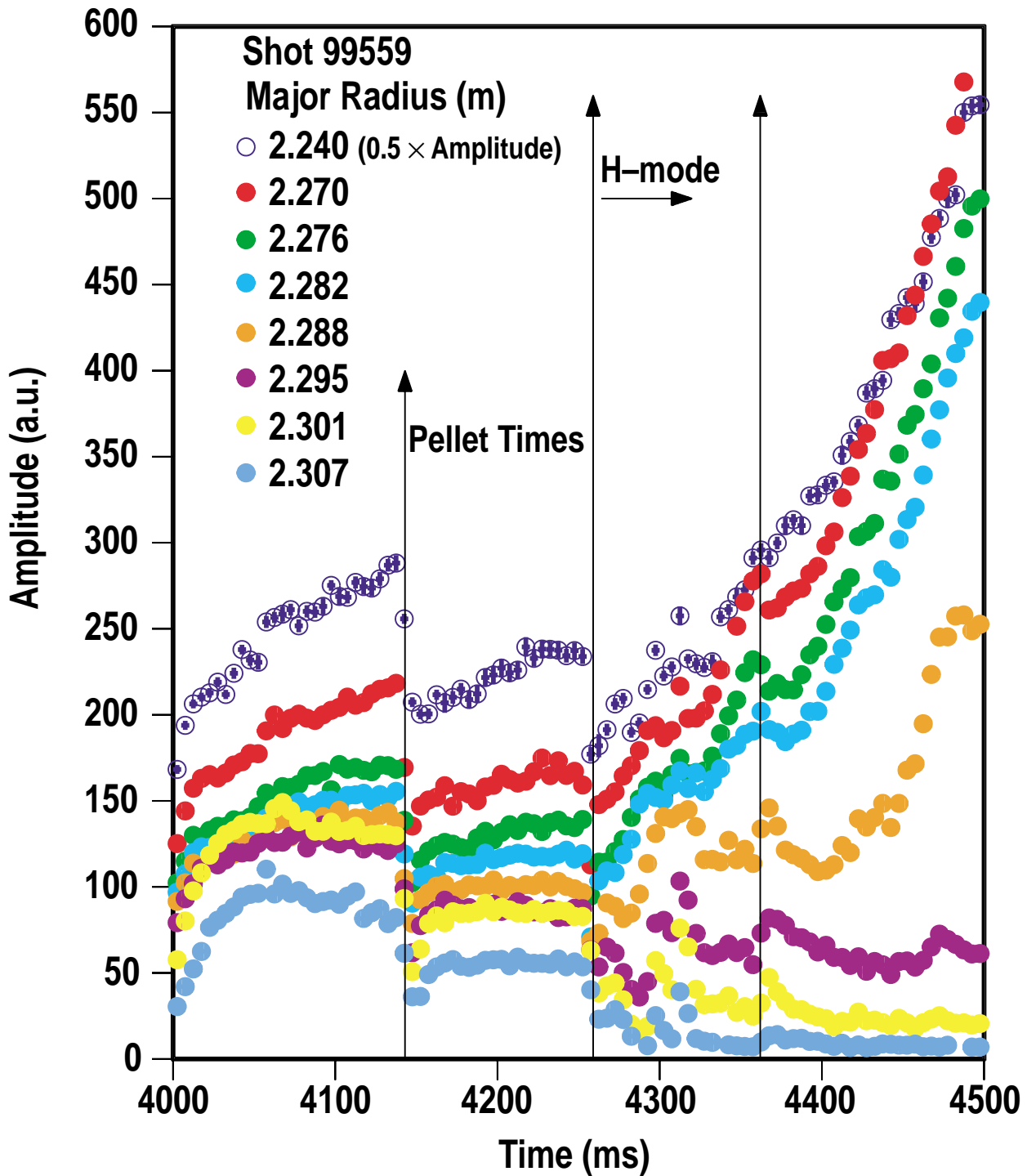


● Integration time = 5 ms

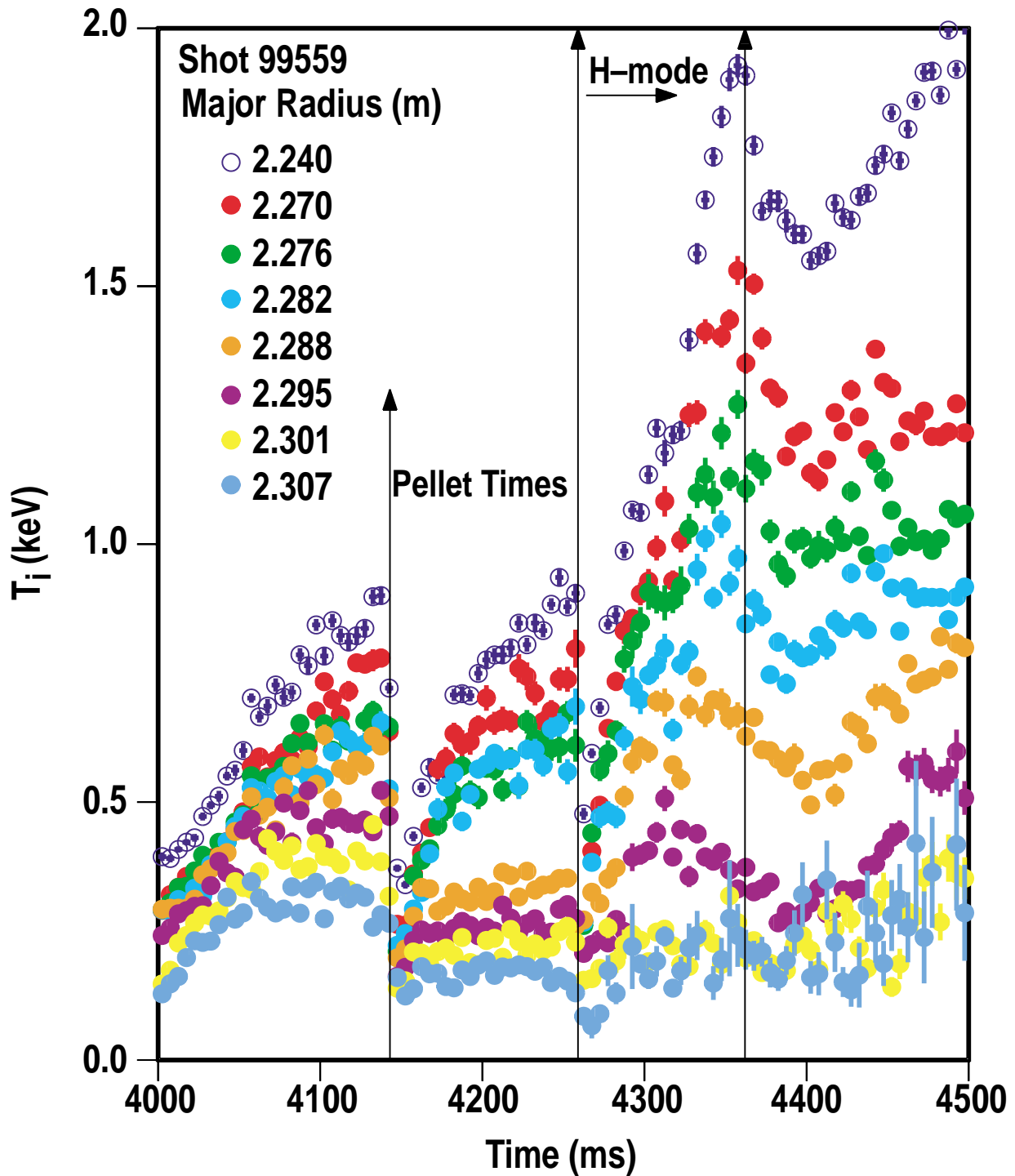
Toroidal Rotation Profiles



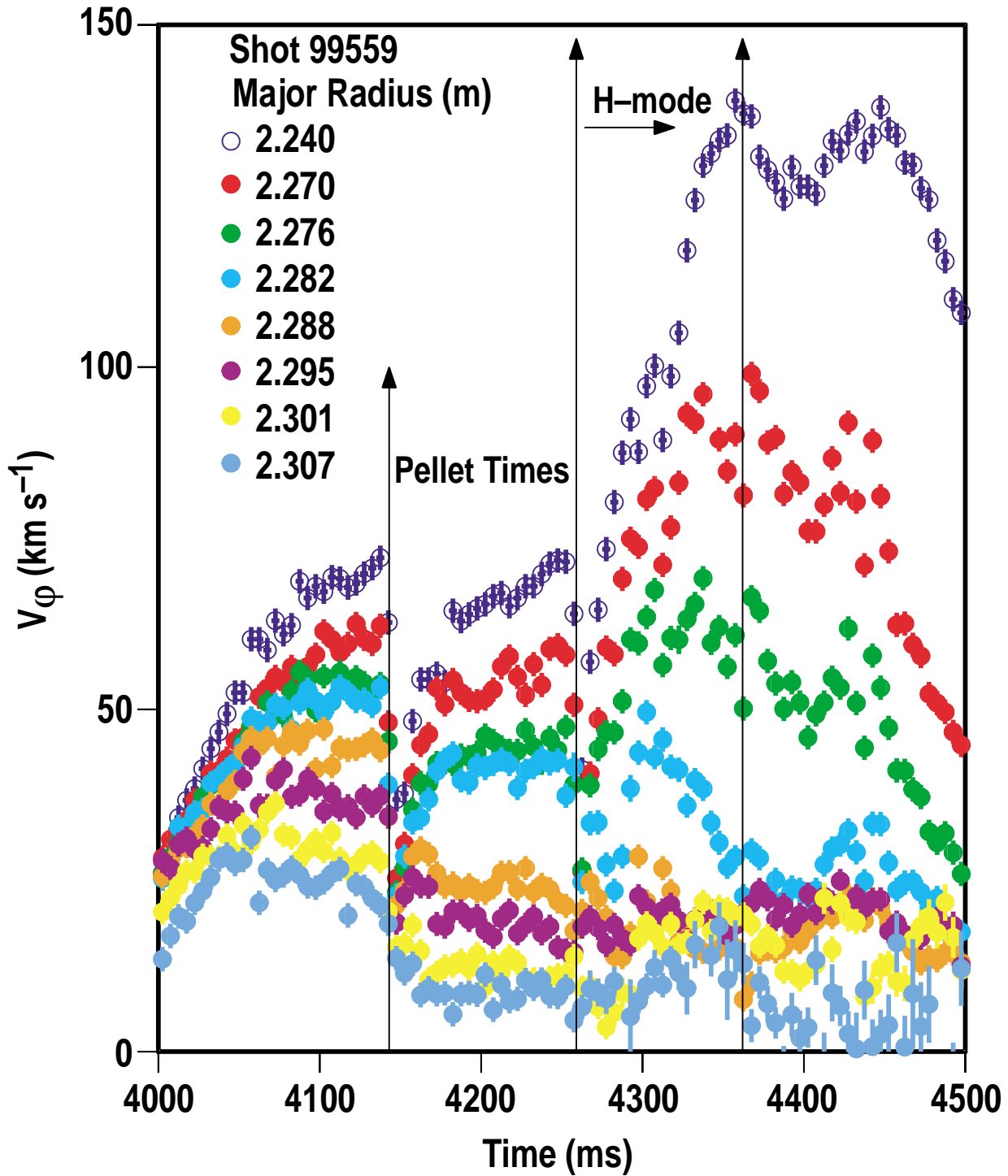
# EVOLUTION OF THE SIGNAL AMPLITUDES OF THE CER CHORDS SHOW THE REGIONS OF IMPROVED CONFINEMENT AT THE PLASMA EDGE



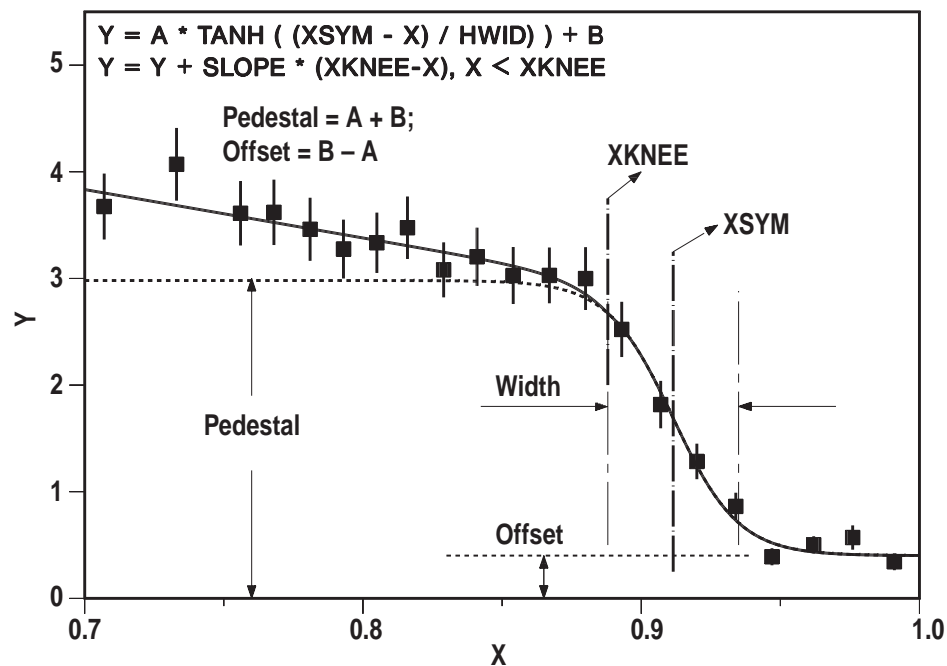
# EVOLUTION OF EDGE ION TEMPERATURE ALSO SHOWS THE POSITION AND TIME OF IMPROVED CONFINEMENT AT THE PLASMA EDGE



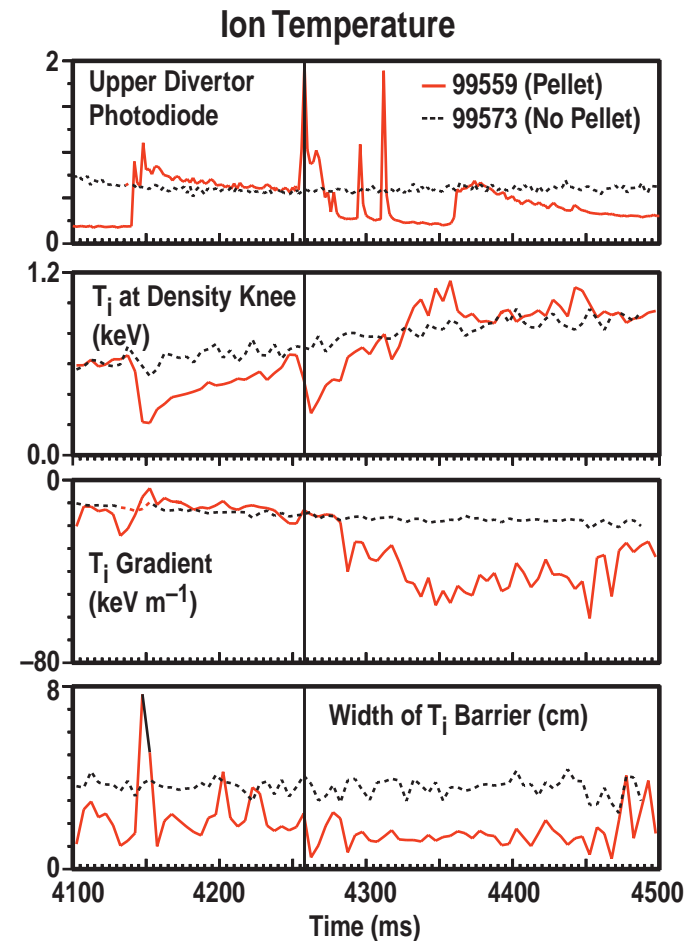
# EVOLUTION OF TOROIDAL ROTATION



# TANHFIT ANALYSIS IS USED TO DETERMINE EDGE LOCAL PARAMETERS

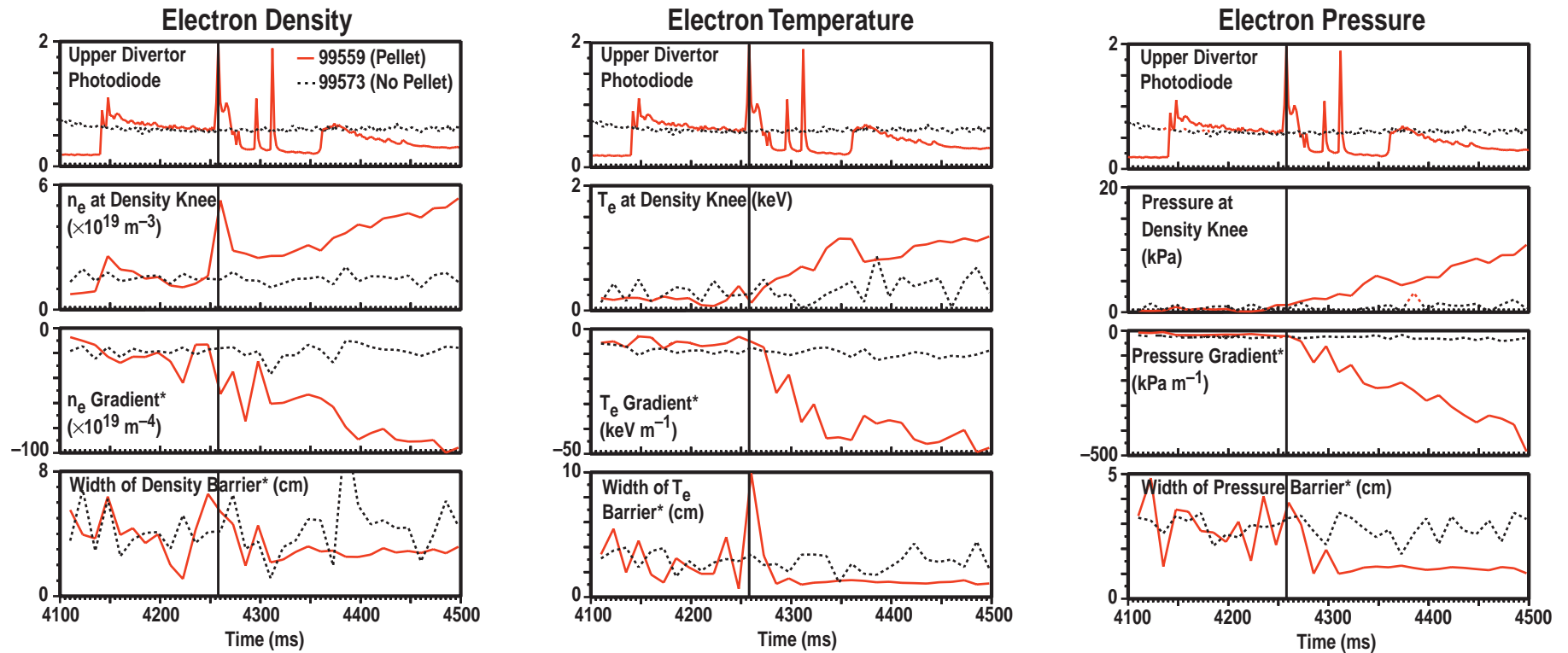


● Note: gradients are shown on a negative scale



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

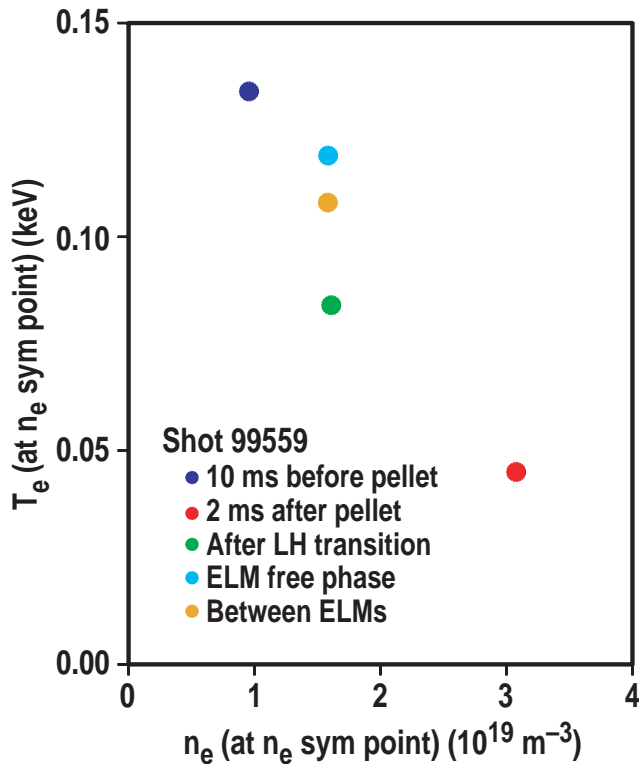
- PIH-mode at  $P_{\text{NBI}} = 6.8$  MW (shot 99559)
- Discharge with no pellet stays in L-mode even at higher  $P_{\text{NBI}} = 9.2$  MW (shot 99573)



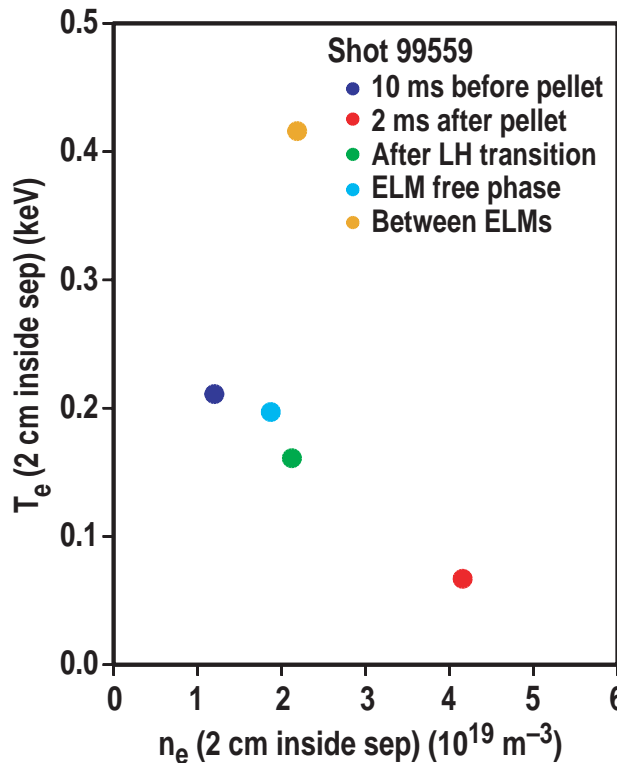
\*Spatial measurements are along the laser path in the z-direction, not at the midplane

# VARIATION OF THE EDGE ELECTRON TEMPERATURE AND ELECTRON DENSITY AT DIFFERENT LOCATIONS ALONG THE DENSITY GRADIENT

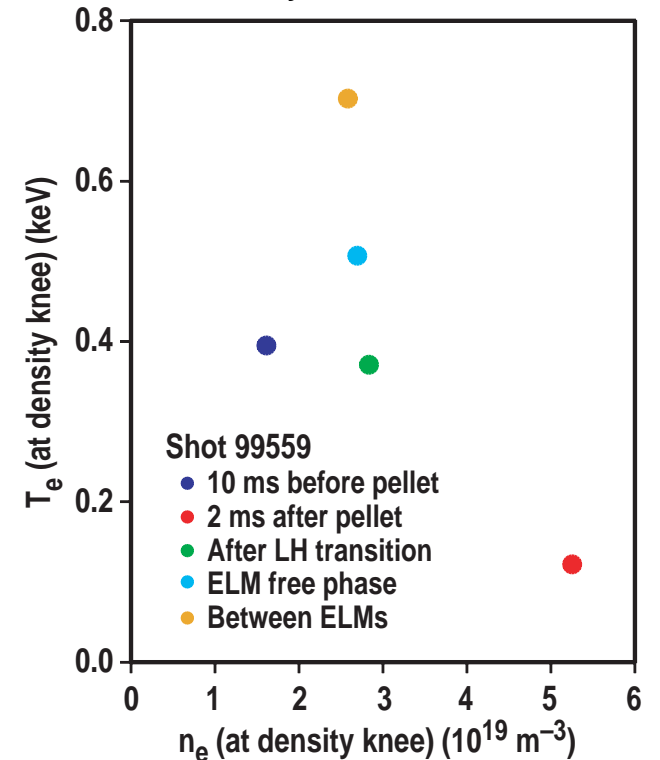
The edge electron temperature at the density symmetry point in H-mode is still below the L-mode value



$T_e$  and  $n_e$   
2 cm inside the separatrix



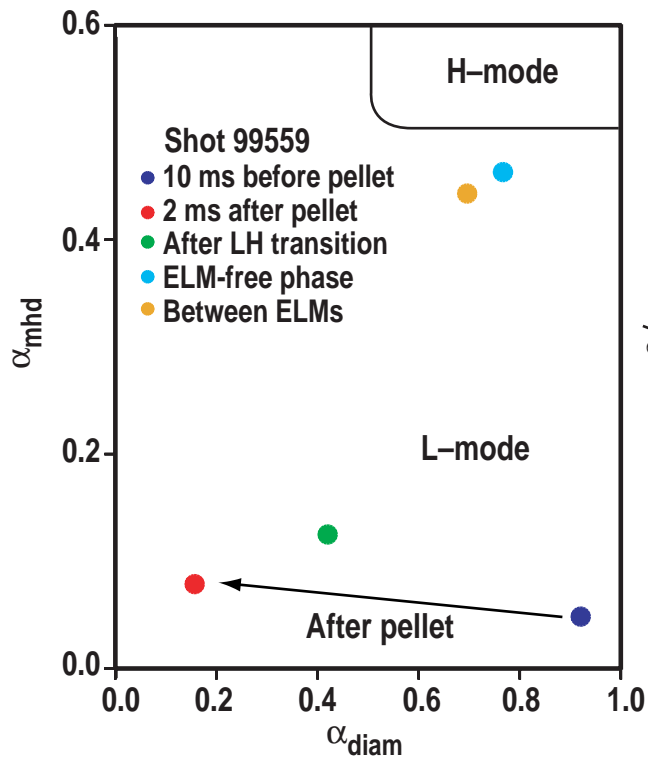
The edge electron temperature increases significantly at nearly the same edge electron density into the H-mode



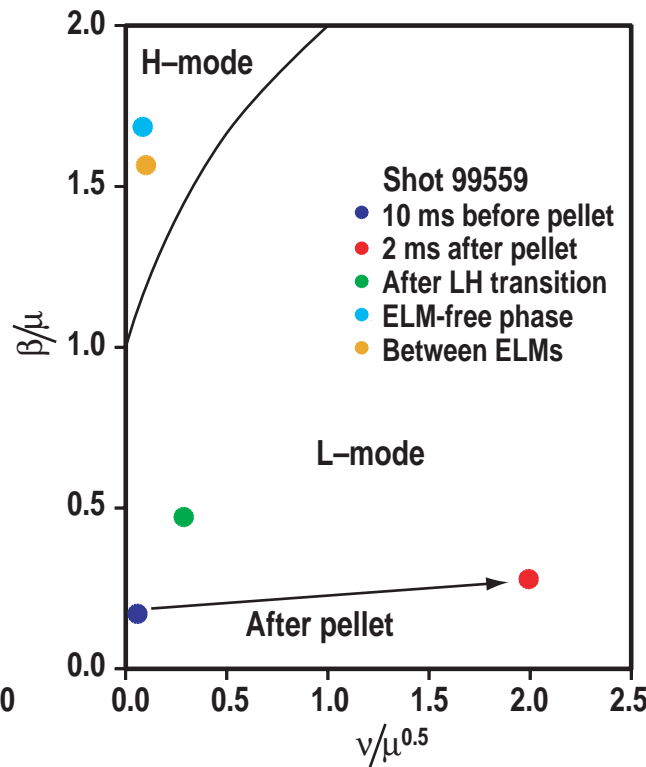


# PELLET INDUCED H-MODES HAVE LH TRANSITIONS AT PLASMA PARAMETERS FAR BELOW THEORETICAL PREDICTIONS

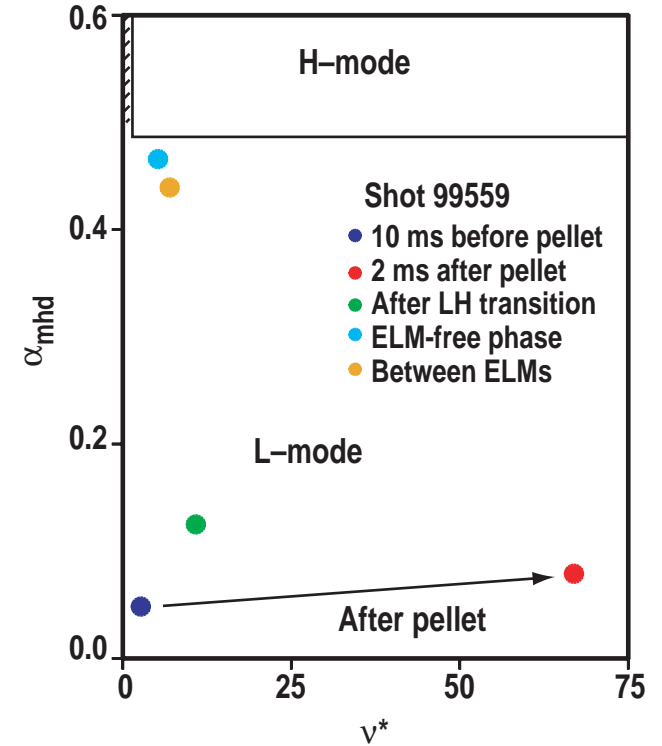
Rogers et al. Proc. 17th IAEA Fusion Energy Conf. Yokohama, Japan 1998, paper IAEA-CN-69/THP2/01



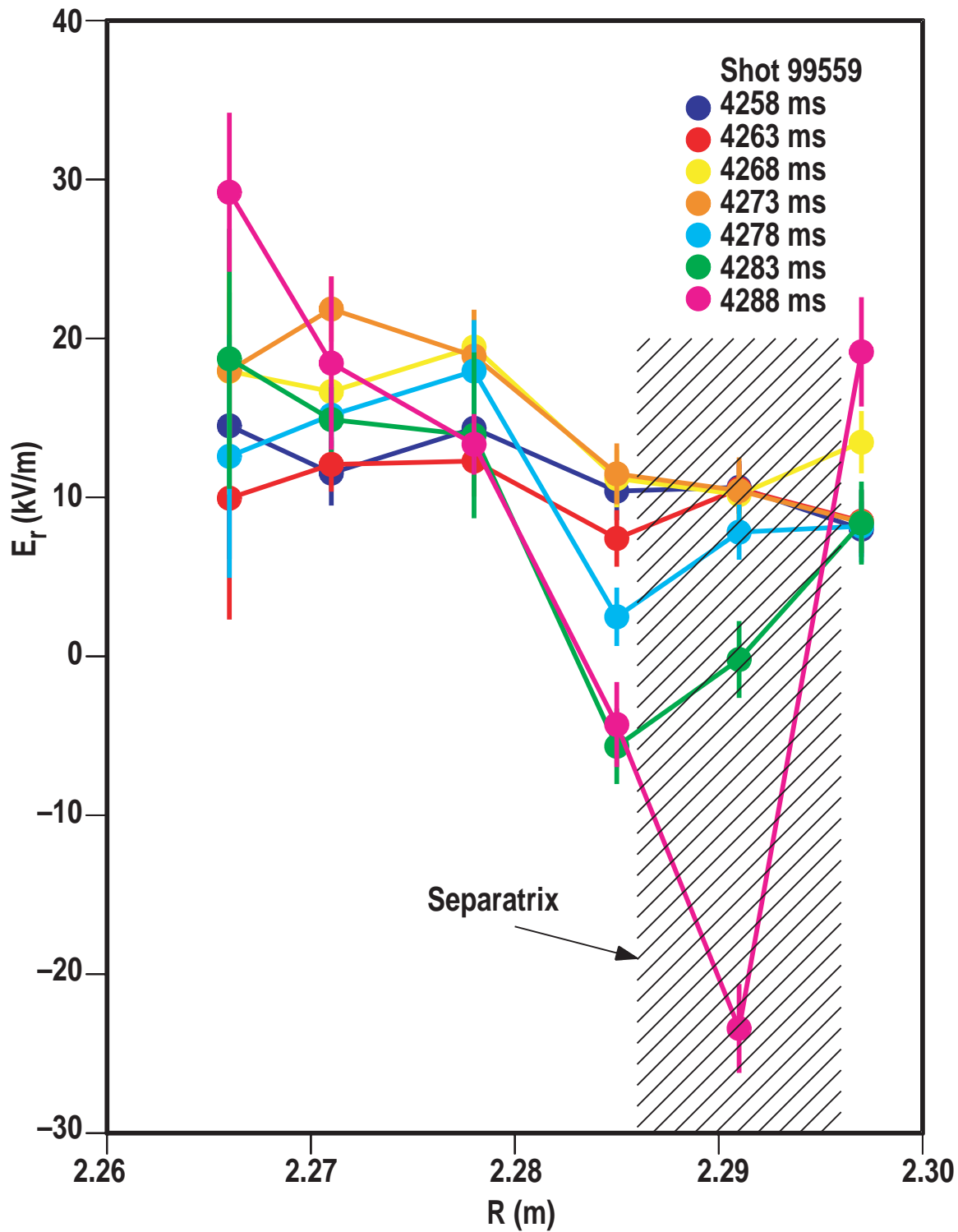
Pogutse et al. Proc. 24th EPS Conf. 1997 (P3-1041)



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

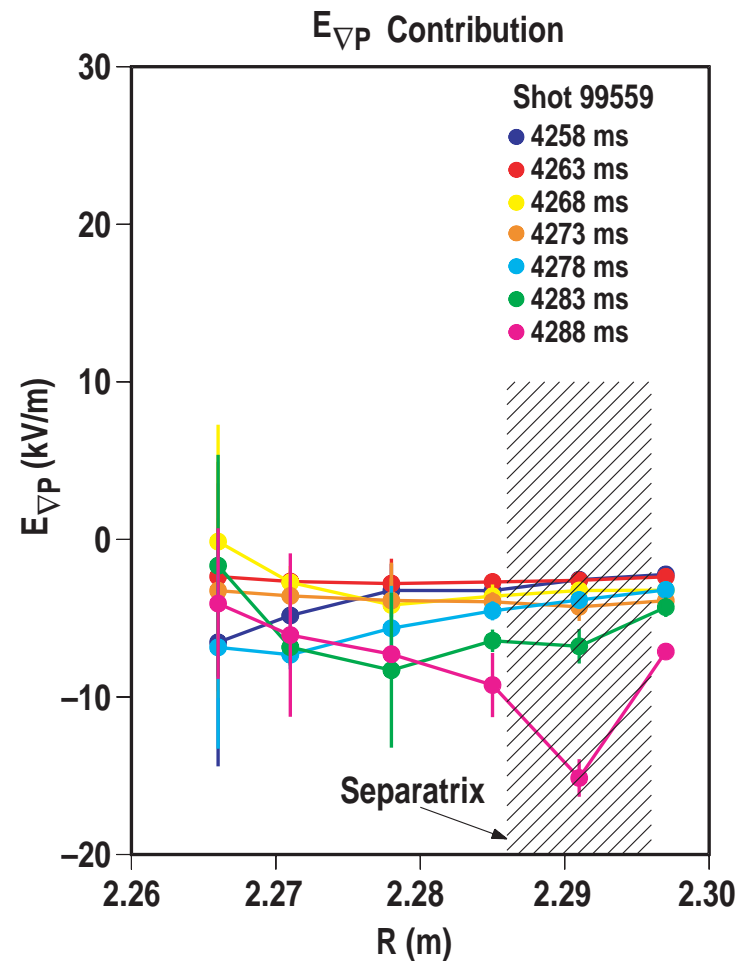
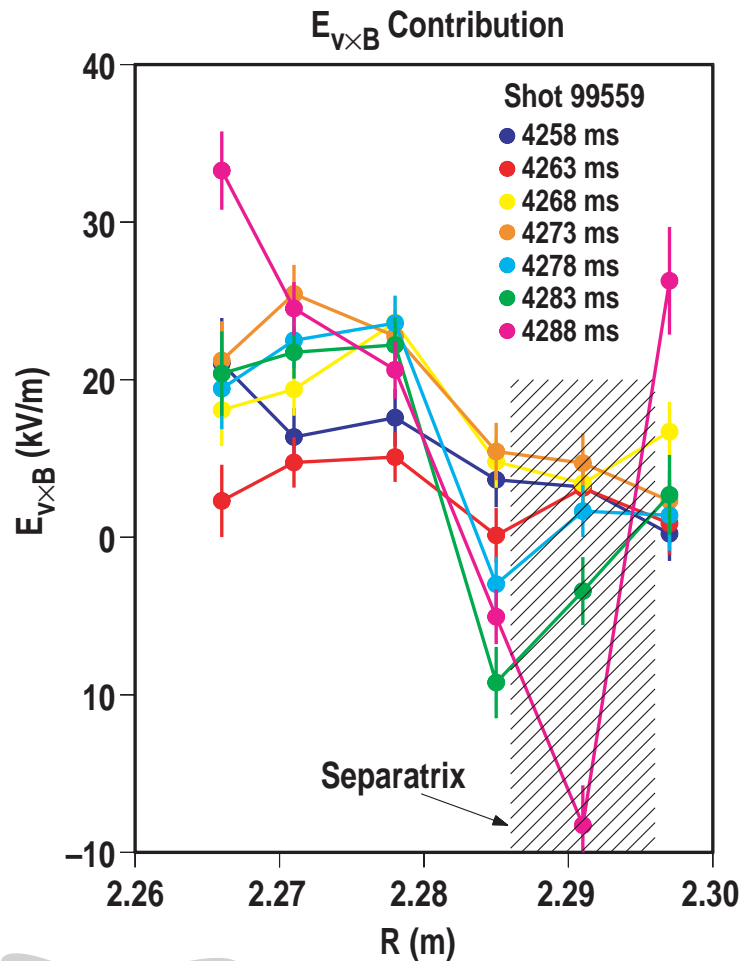


# THE SHEAR IN THE EDGE $E_r$ PROFILE GRADUALLY INCREASES AFTER PELLET INJECTION

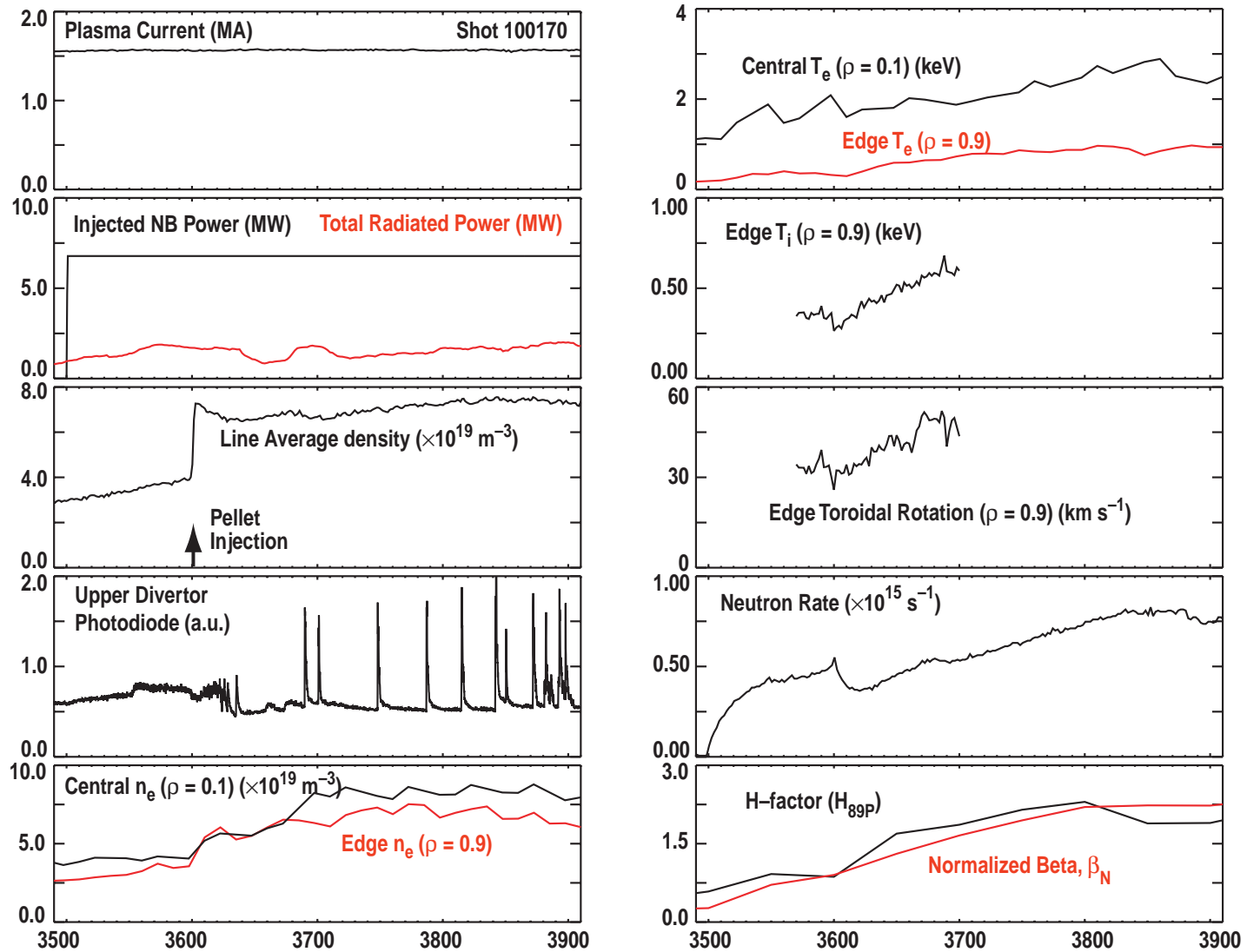


# CHANGES IN THE TOROIDAL AND POLOIDAL ROTATION OF THE CARBON IMPURITY ION HAVE THE GREATEST EFFECT ON $E_r$

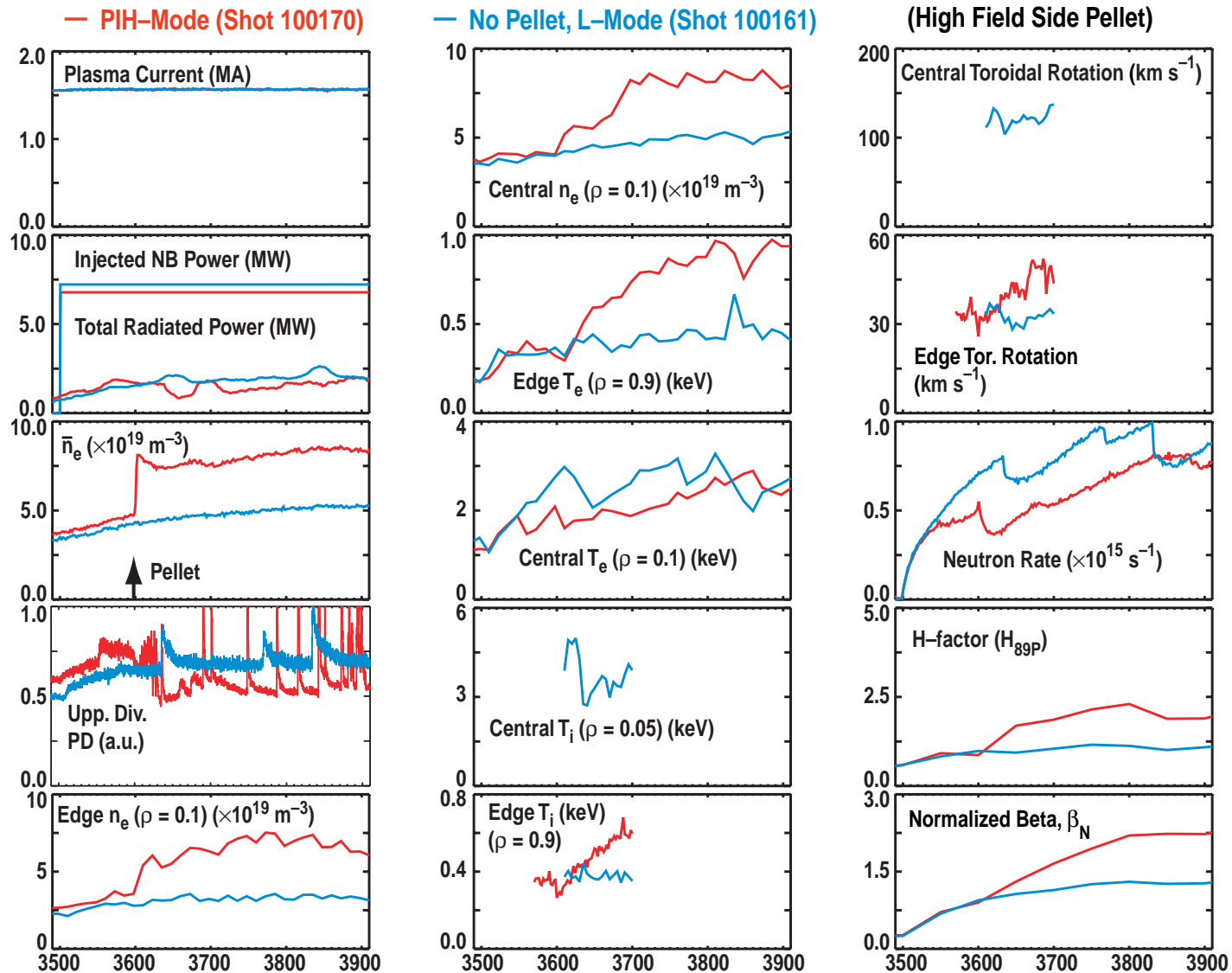
- $E_r = \frac{\nabla P_i}{Zen_i} - \underline{v} \times \underline{B} = E_{\nabla P} + E_{v \times B}$
- Integration time of measurement = 5 ms



# EVOLUTION OF PELLET INDUCED H-MODE DISCHARGE WITH HIGH FIELD SIDE PELLET ( $P_{\text{NBI}} = 6.7 \text{ MW}$ )

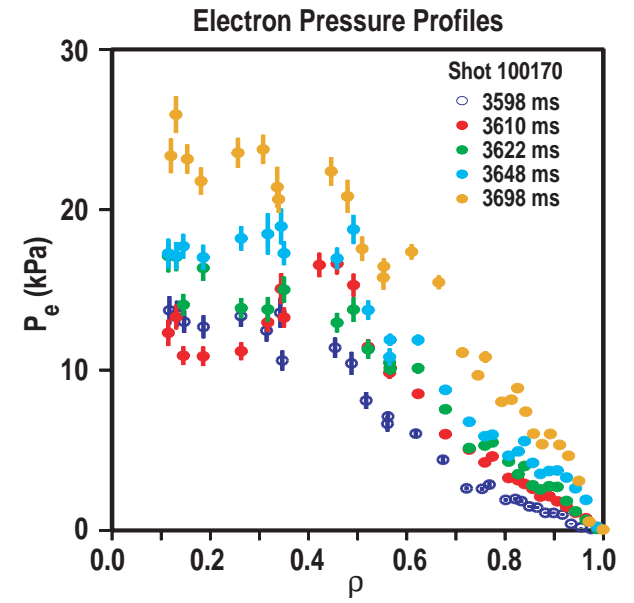
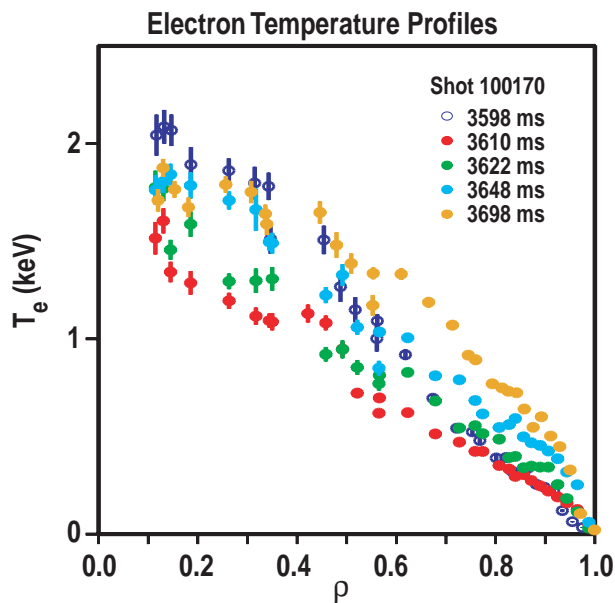
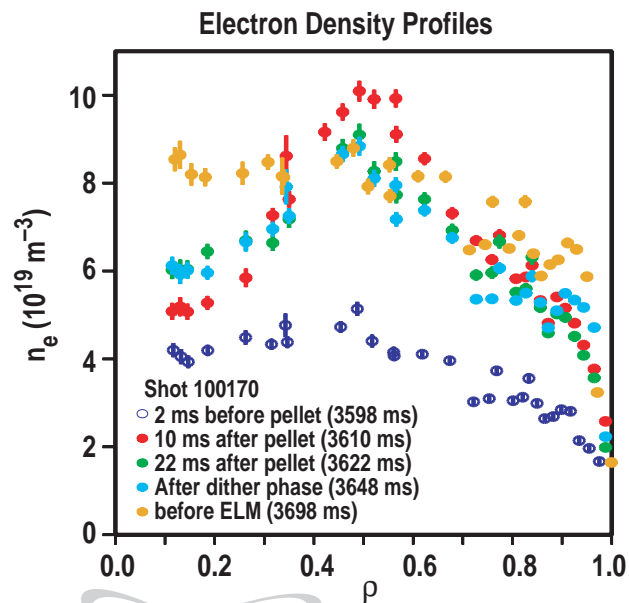
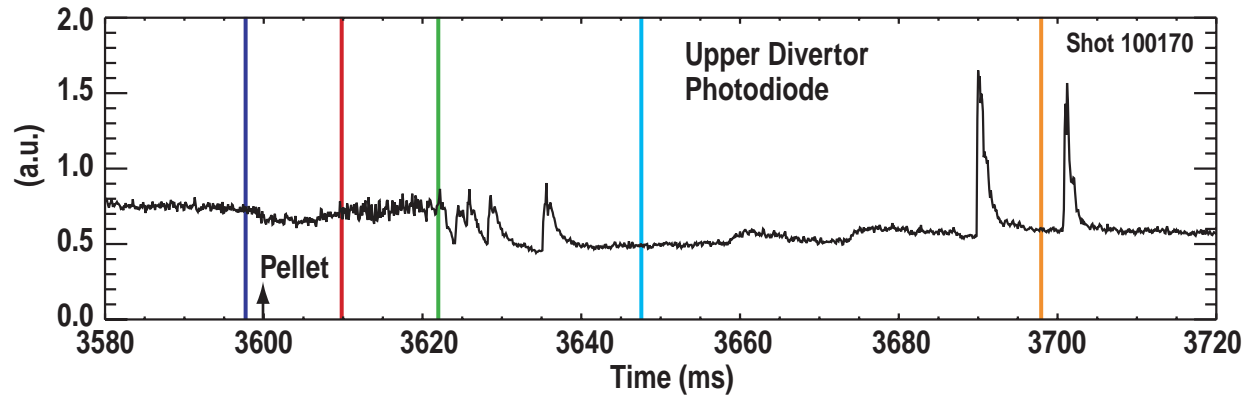


# COMPARISON OF PIH-MODE DISCHARGE ( $P_{\text{NBI}} = 6.7 \text{ MW}$ ) WITH NO PELLETT, L-MODE DISCHARGE ( $P_{\text{NBI}} = 7.2 \text{ MW}$ )



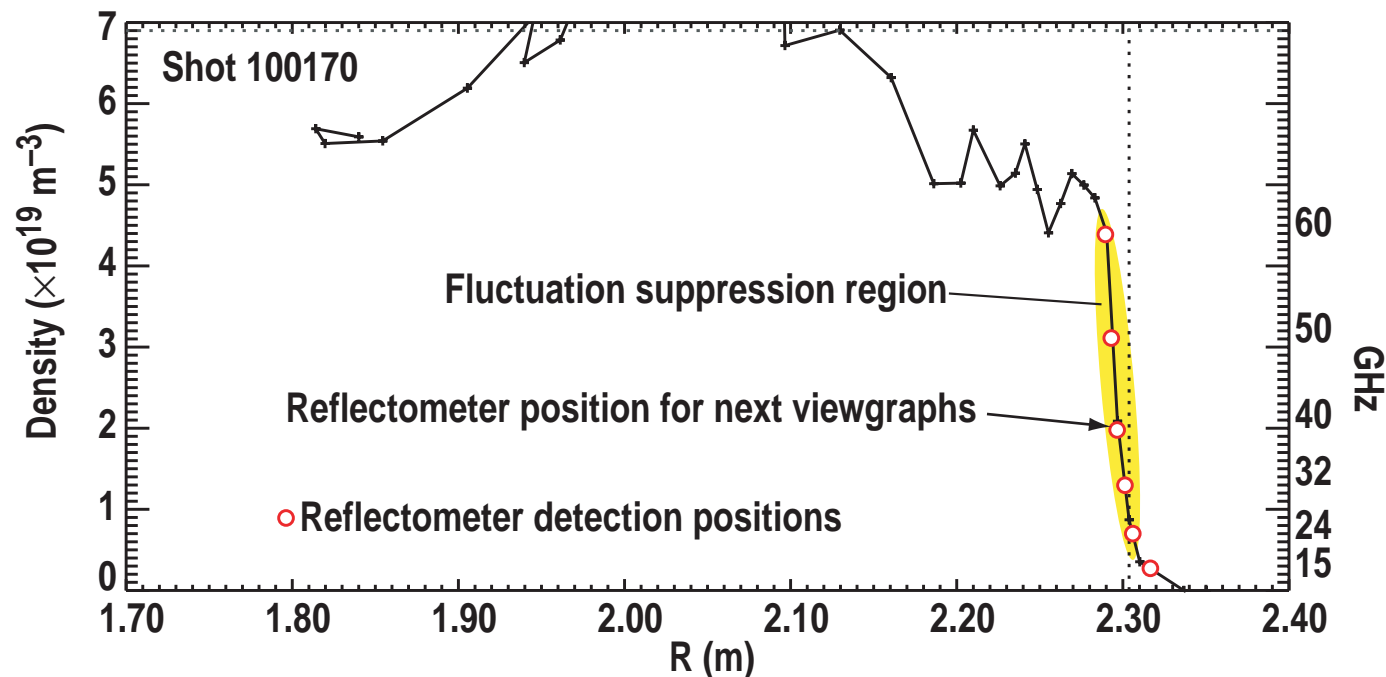
# DEVELOPMENT OF ELECTRON PROFILES IN PIH-MODE PLASMA PRODUCED BY HIGH FIELD SIDE PELLETT

- The HFS pellet penetrates much further into the plasma interior, but still produces significant density perturbation at the plasma edge



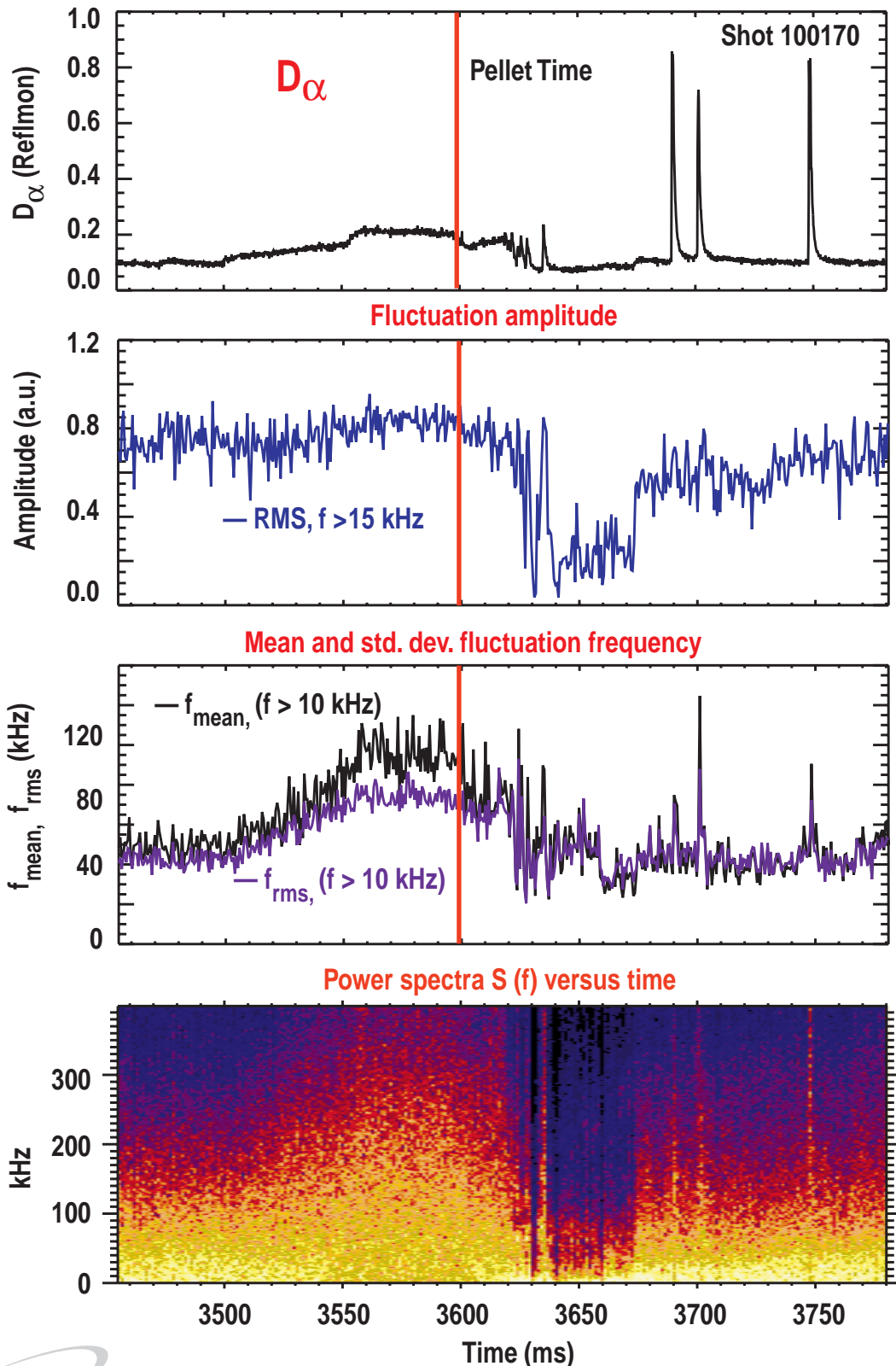
# FLUCTUATION SUPPRESSION IS OBSERVED SHORTLY AFTER PELLET INJECTION

- Fast dithering or bursting of fluctuation levels appear ~10 ms after pellet injection (see following viewgraphs)
- Fast dithering develops into ELM free H-mode (see following viewgraphs)
- Behavior of fluctuation suppression very similar to that observed in spontaneous H-mode (see following viewgraphs)



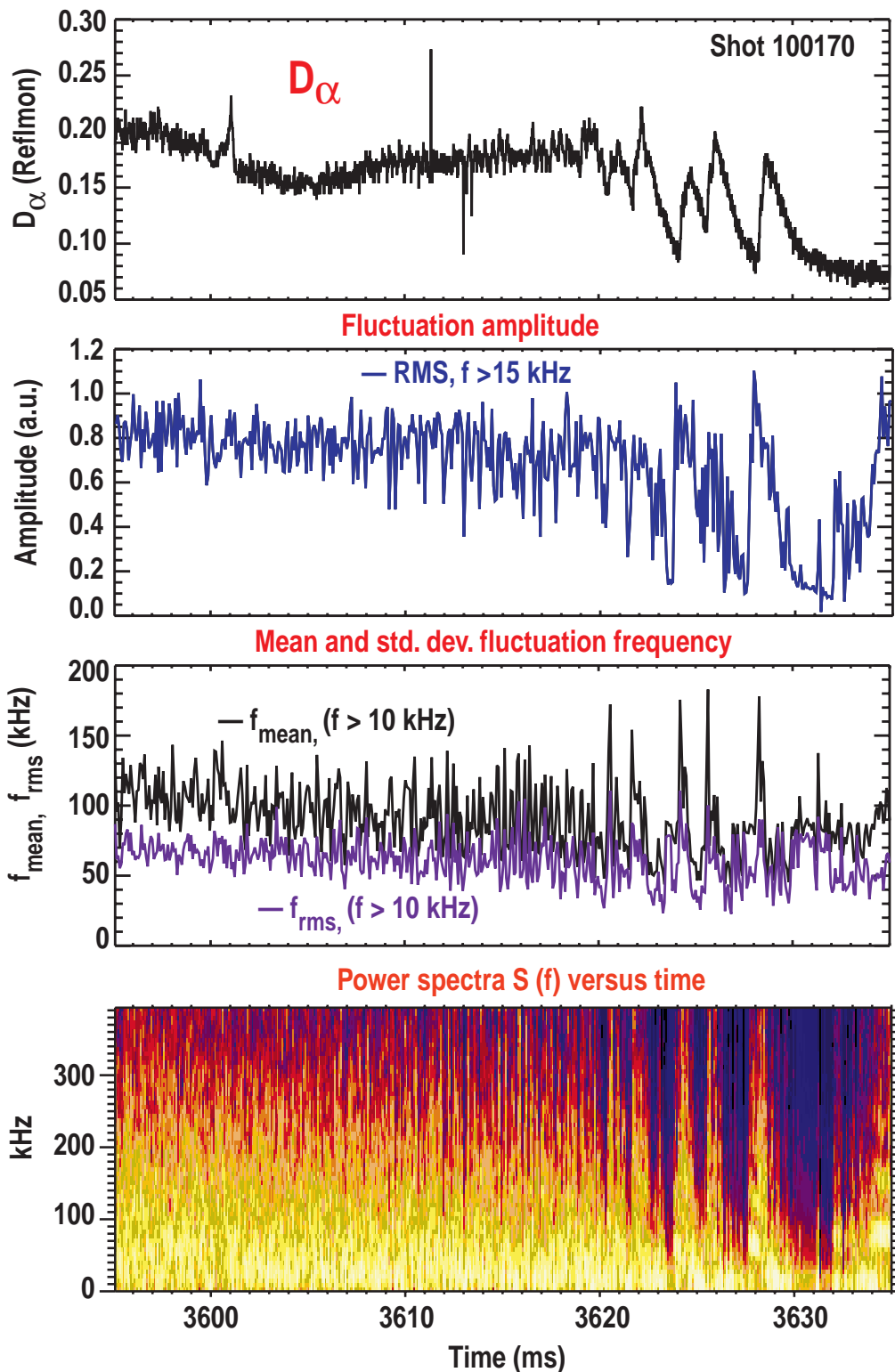
# FAST DITHERING DEVELOPS INTO ELM FREE H-MODE

- Behavior of fluctuation suppression very similar to that observed in spontaneous H-mode



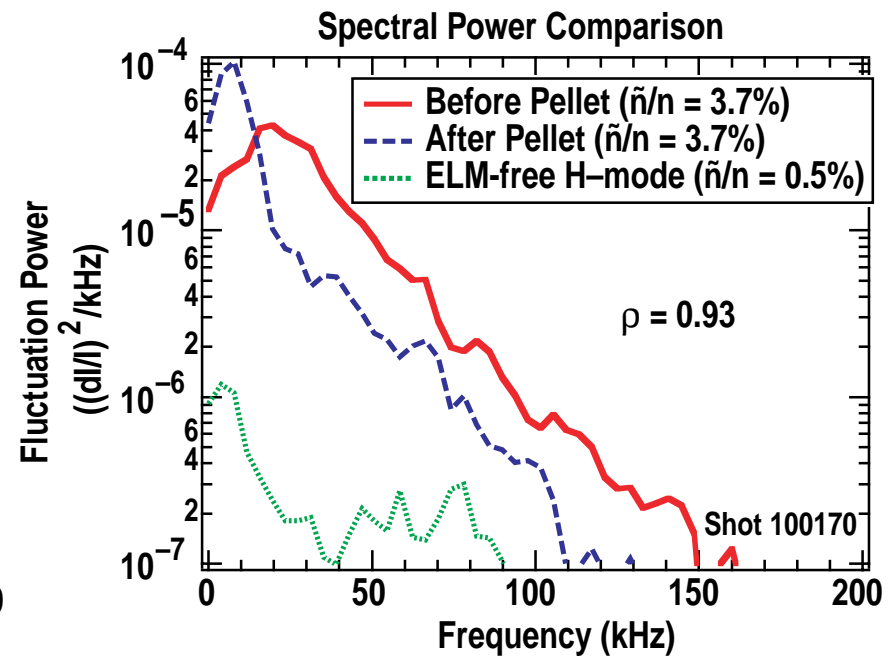
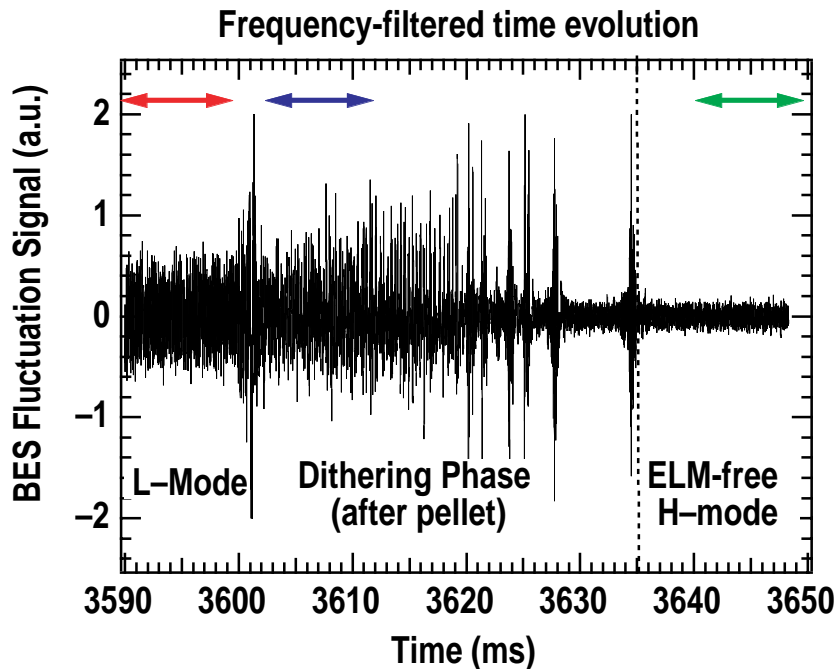


# FAST DITHERING OR BURSTING OF FLUCTUATION APPEAR ~10 ms AFTER PELLET INJECTION



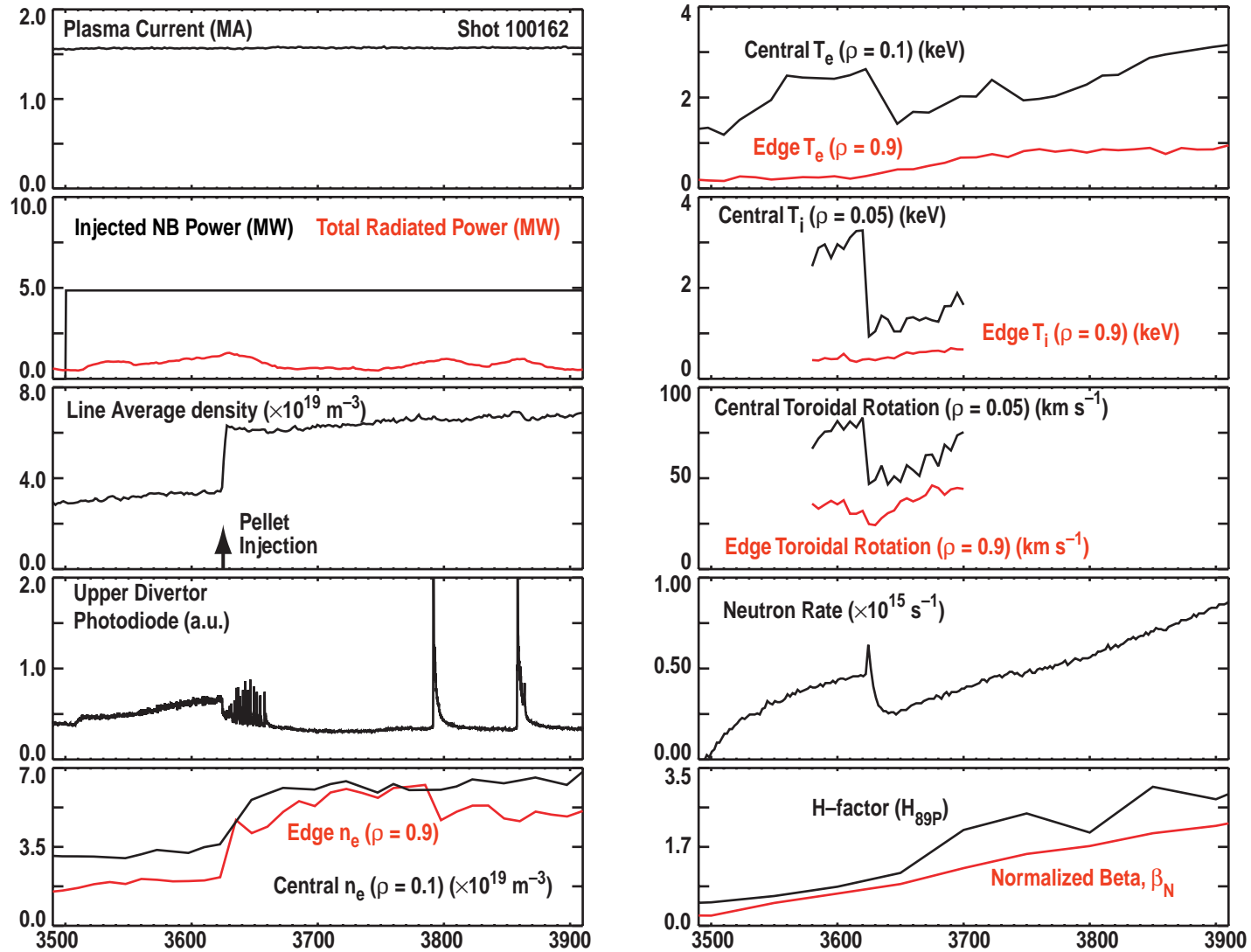
# EDGE TURBULENCE DURING PELLETT-INDUCED H-MODE TRANSITION

- Beam Emission Spectroscopy measurements show different stages of transition behavior ( $0 < k < 3 \text{ cm}^{-1}$ ,  $2 \leq f \leq 200 \text{ kHz}$ ,  $\rho = 0.93$ )
- 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)

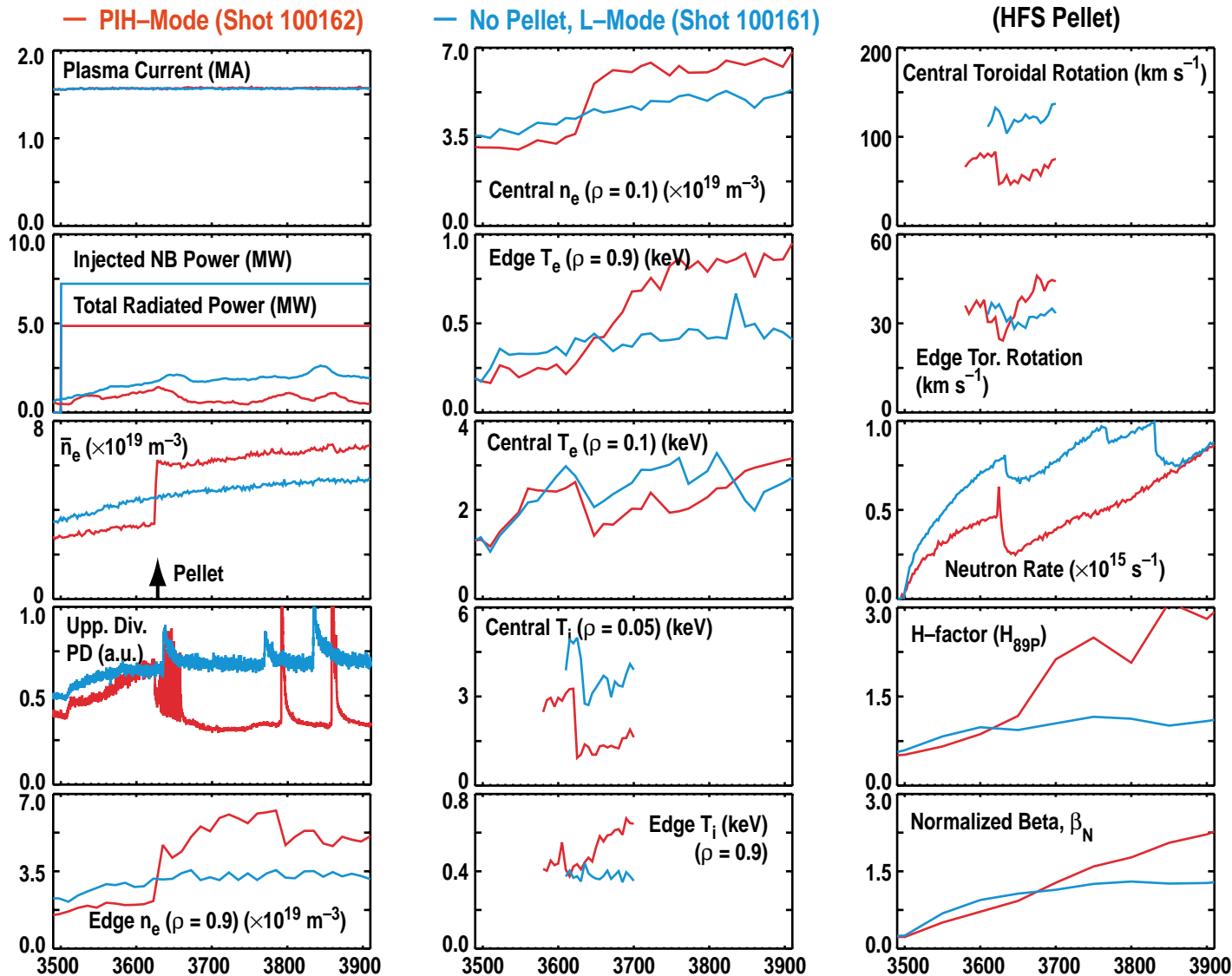


- 1) Pre-pellet L-mode phase (moderate fluctuations)
- 2) Post-pellet, L-mode  $\rightarrow$  dithering phase (lower frequency fluctuations, dithers)
- 3) H-mode (very low fluctuation level)

# PIH-MODE DISCHARGE WITH HIGH FIELD SIDE PELLETT AT REDUCED NBI POWER ( $P_{\text{NBI}} = 4.9 \text{ MW}$ )



# COMPARISON OF PIH-MODE DISCHARGE ( $P_{\text{NBI}} = 4.9 \text{ MW}$ ) WITH NO PELLETS, L-MODE ( $P_{\text{NBI}} = 7.2 \text{ MW}$ ) USING HIGH FIELD SIDE PELLETS



- The power required to access H-mode is reduced by 2.3 MW using high field side pellet injection

# SUMMARY

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- **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 edge electron and ion temperatures are substantially reduced by the large influx of particles from the pellet**
  - The lowered temperatures still lead to an H-mode transition
  - 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)

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- 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 (by up to 33%) 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