HIGH PERFORMANCE H–MODE PLASMAS AT DENSITIES ABOVE THE GREENWALD LIMIT

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*Work supported by U.S. Department of Energy under Contracts DE-AC03-99ER54463 and DE-AC05-96OR22462.

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OUTLINE

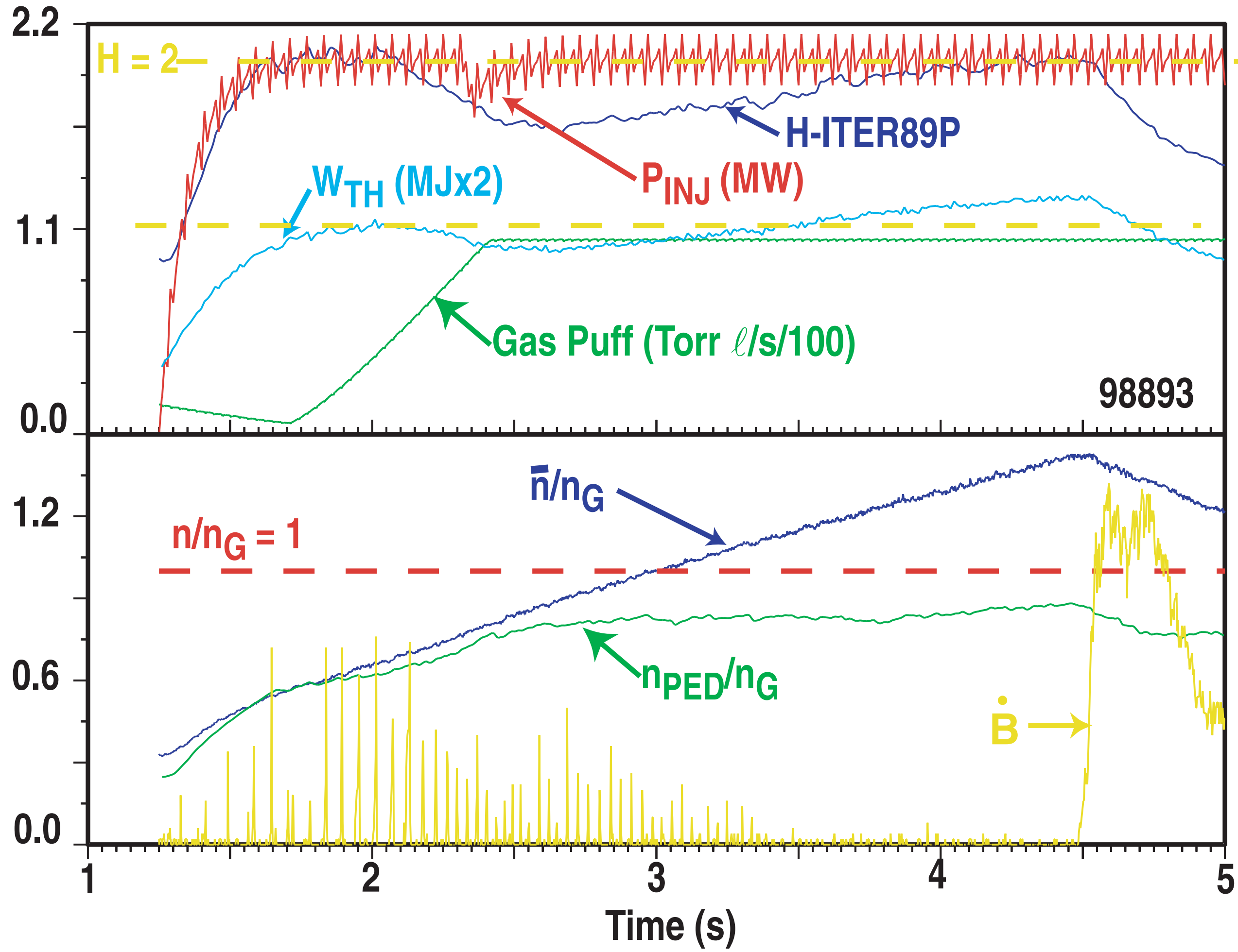
- Introduction
- Summary of observations
- Confinement and stability of high density discharges
  - Core transport is mainly due to ITG (stiff temperature profiles)
  - Stored energy increase with density peaking
  - Classical tearing and NTM drives increase with increasing density
  - Mainly due to steepening of pressure profile at low rational surfaces
  - Tearing mode limits confinement improvement and density increase
- Access to high densities
  - At high power operating window limited by ELMs or NTM
  - At low power operating window limited by H–L transitions
  - Within the window fueling technique and edge transport determine the highest achievable density
  - Model shows fueling more effective in areas of low flux expansion
  - improves with divertor pumping and open geometry
- Conclusions

SUMMARY OF OBSERVATIONS IN GAS-FUELED H–MODE DISCHARGES WITH DENSITIES ABOVE GREENWALD

- Densities up to 1.4 x Greenwald and $H_{ITER89P}$ ~ 1.9 achieved
- Highest densities achieved at low power and q_{95} (P ~ 3 MW, q_{95} ~ 3)
- High densities are easier to achieve with divertor pumping, but the best results have been reproduced target plate pumping
- Best results obtained at low triangularity
- Density profile moderately peaked
- Evolution of stored energy follows evolution of density profile
- Up to the highest density no evidence of radiative instabilities seen
- Tearing mode seen in nearly all high confinement, high density discharges
- Desirable ELM characteristics
- Highly localized coherent mode, m ~ 40, seen with 1 cm of separatrix

GREENWALD LIMIT IS EXCEEDED IN HIGH CONFINEMENT H–MODE

- During density rise, stored energy increases monotonically after an initial dip, eventually exceeding its peak value at low density
- Density rises monotonically during gas fueling, with no evidence of saturation
- High confinement phase is terminated after the onset of 3/2 MHD mode



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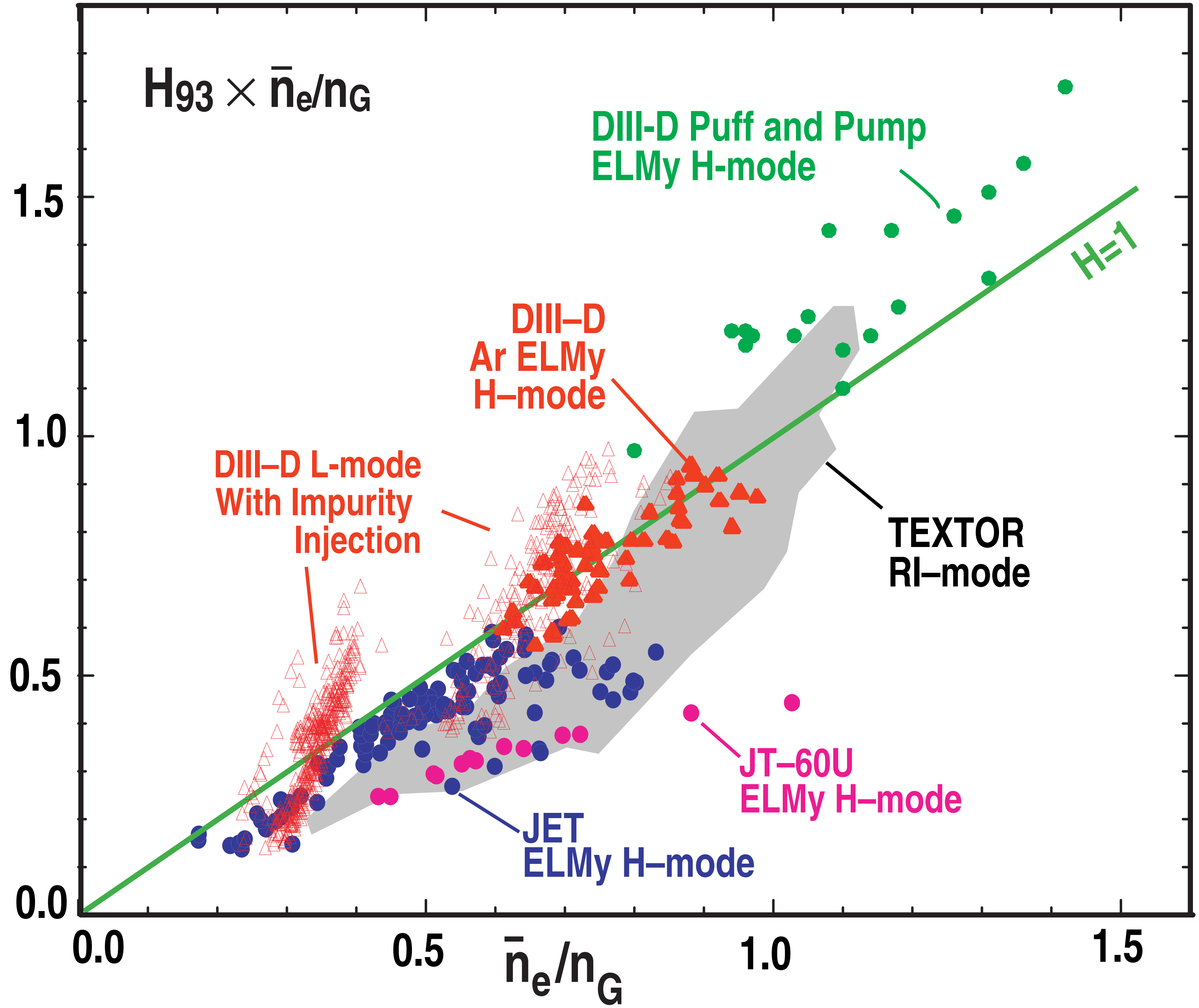

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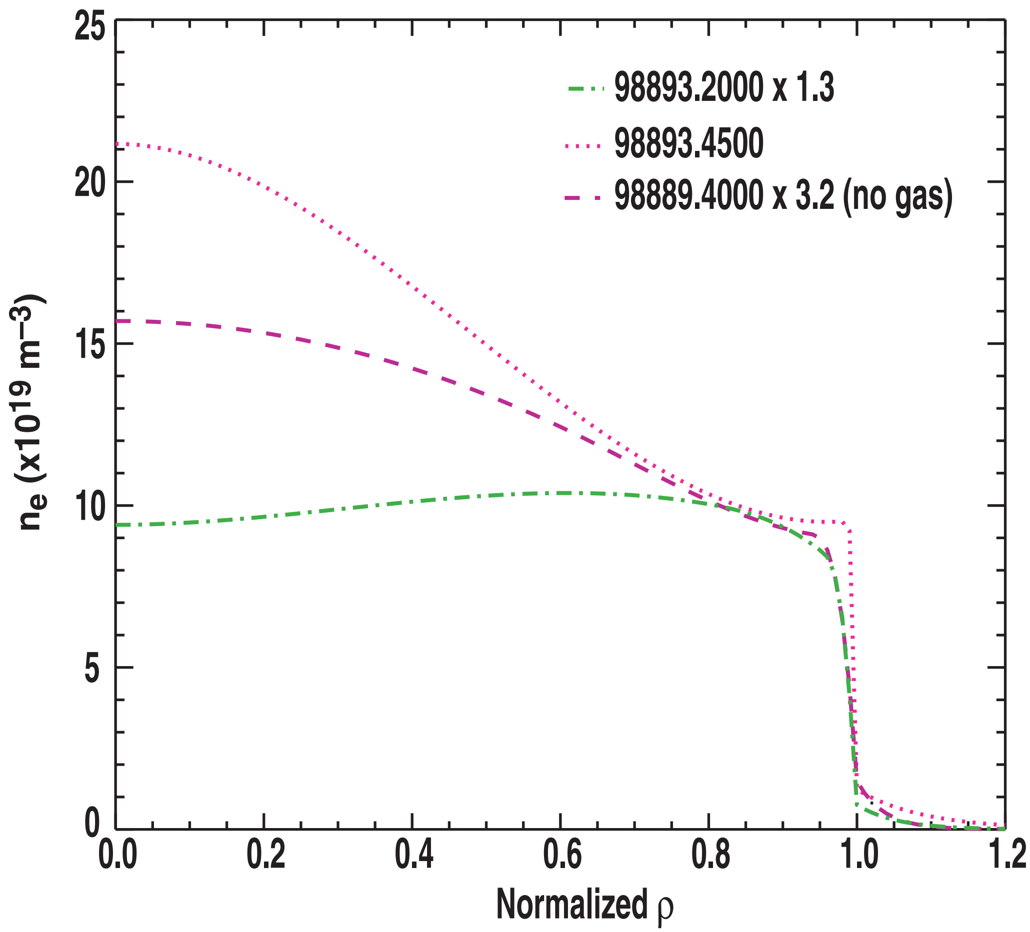
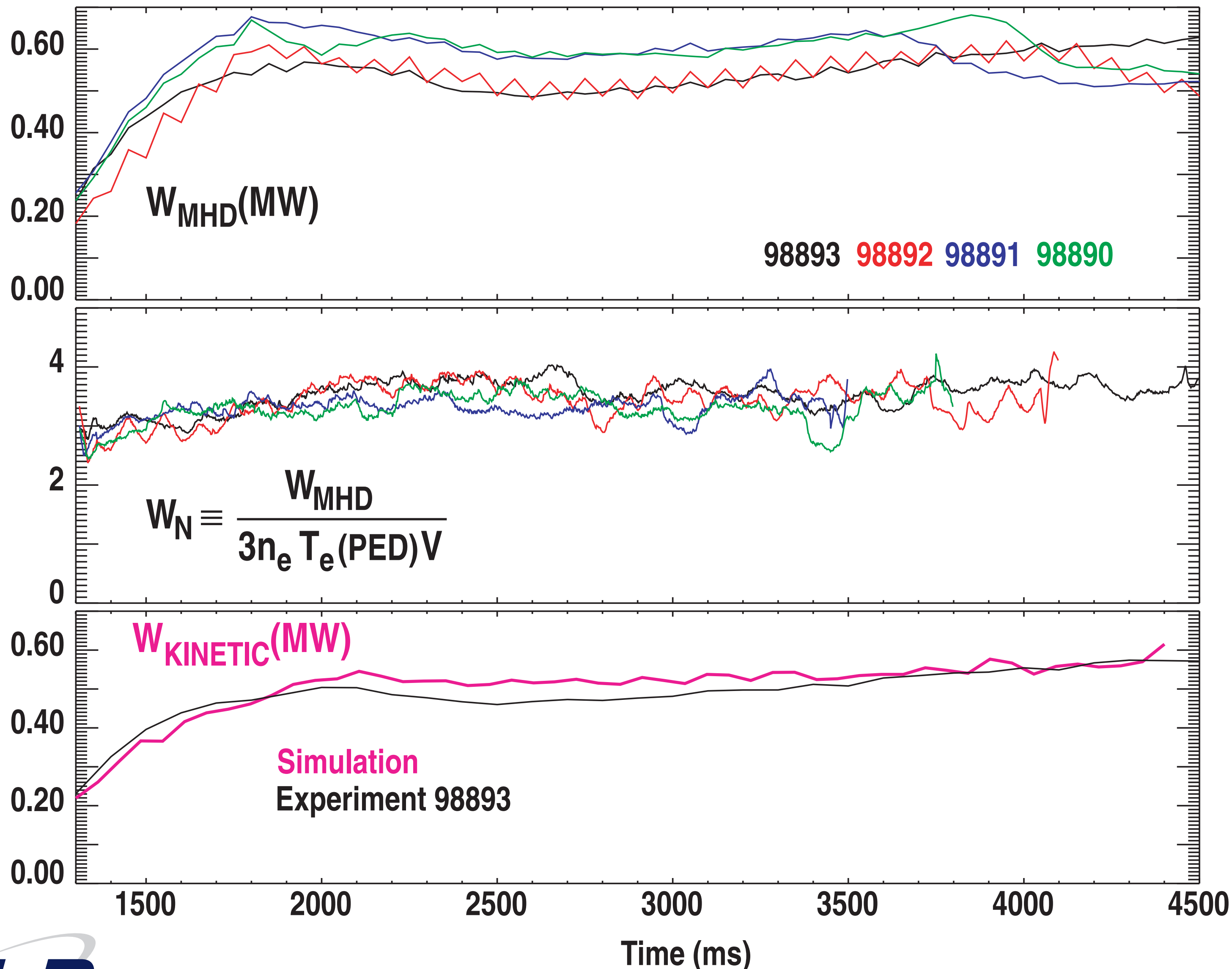
DENSITY PROFILE EVOLUTION IS A KEY FACTOR IN CONFINEMENT AND TEARING MODE BEHAVIOR

- Initially, the edge density increases relative to the core, resulting in a flat or slightly hollow density profile
  - During this phase the global confinement decreases
- As the density wave moves inward, the profile becomes peaked
  - During this stage, stored energy increases monotonically, and eventually exceeds its initial value
  - Pressure profile becomes steeper in the plasma interior



- The confinement behavior is strongly suggestive of stiff transport
- Some pedestal pressure loss occurs at high density

STORED ENERGY BEHAVIOR EXPLAINED BY STIFF TRANSPORT MODEL
GFL23 CODE SIMULATION AGREES WITH EXPERIMENT



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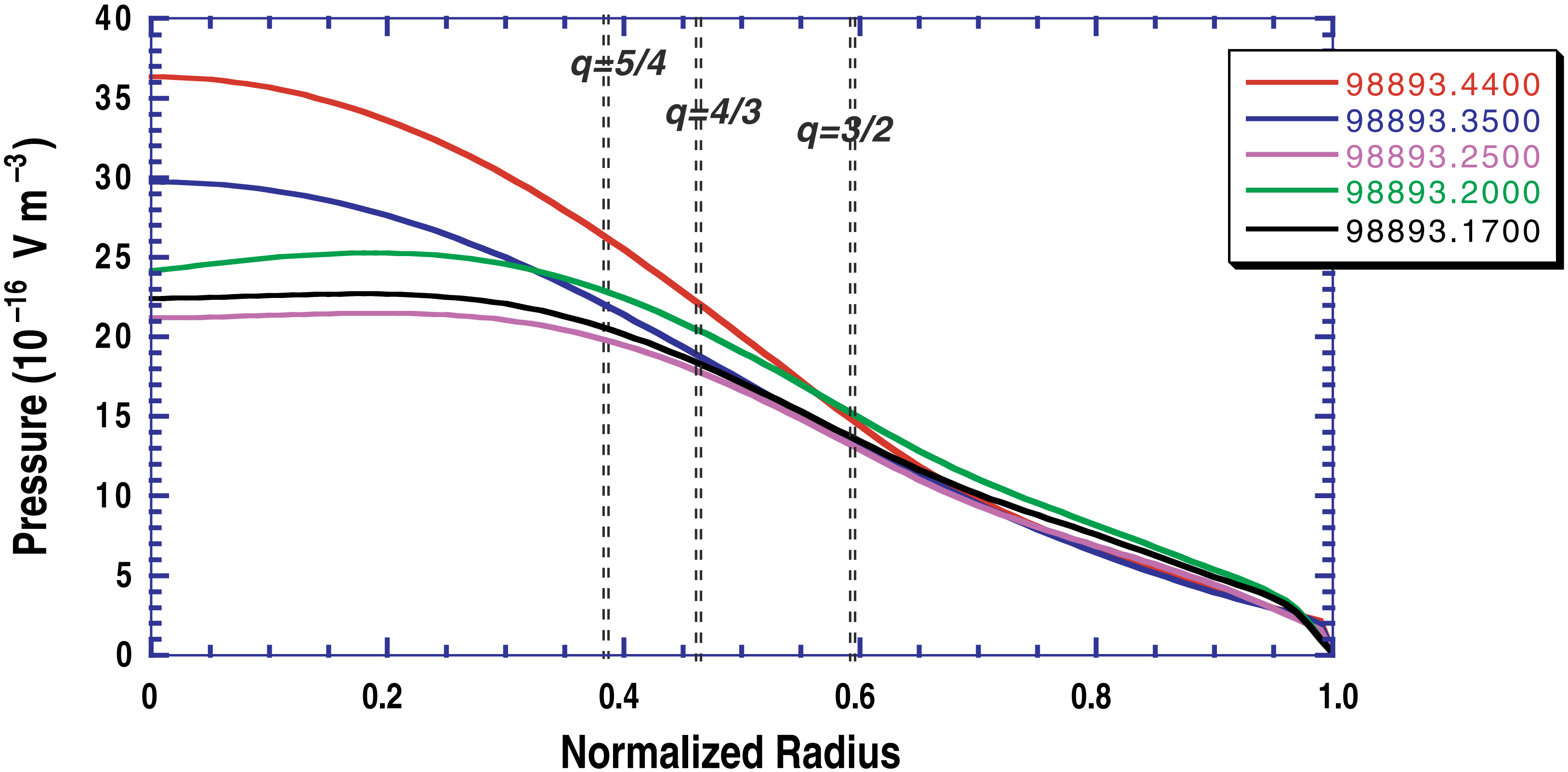
PRESSURE GRADIENT INCREASES WITH TIME "DESTABILZES NTM"



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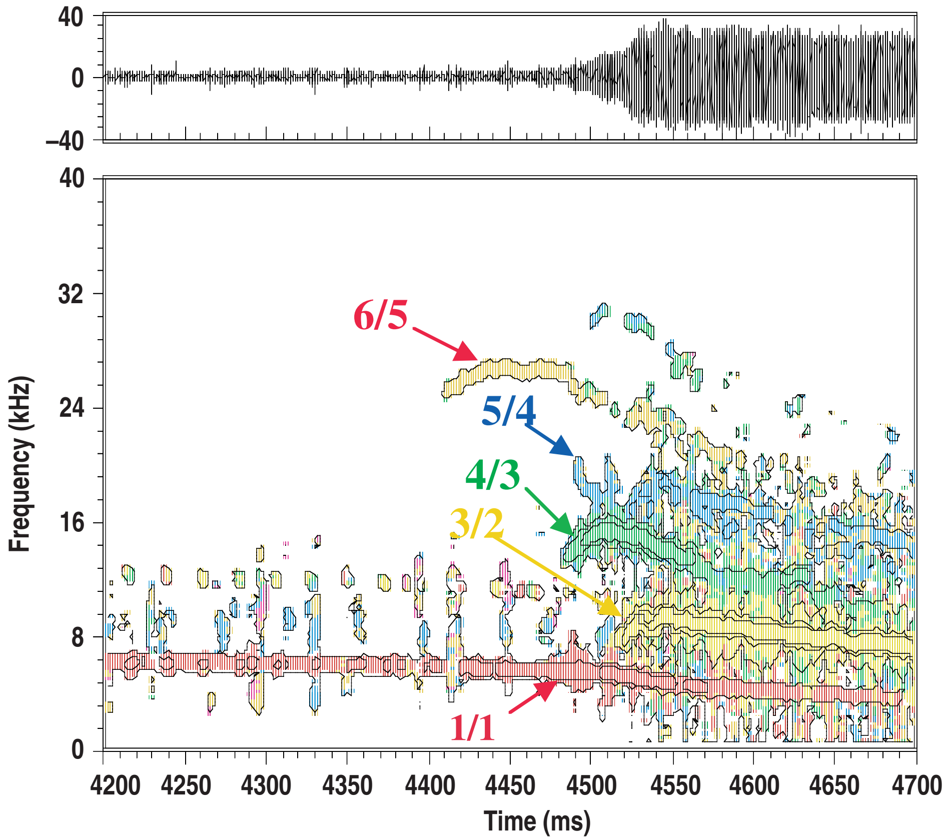
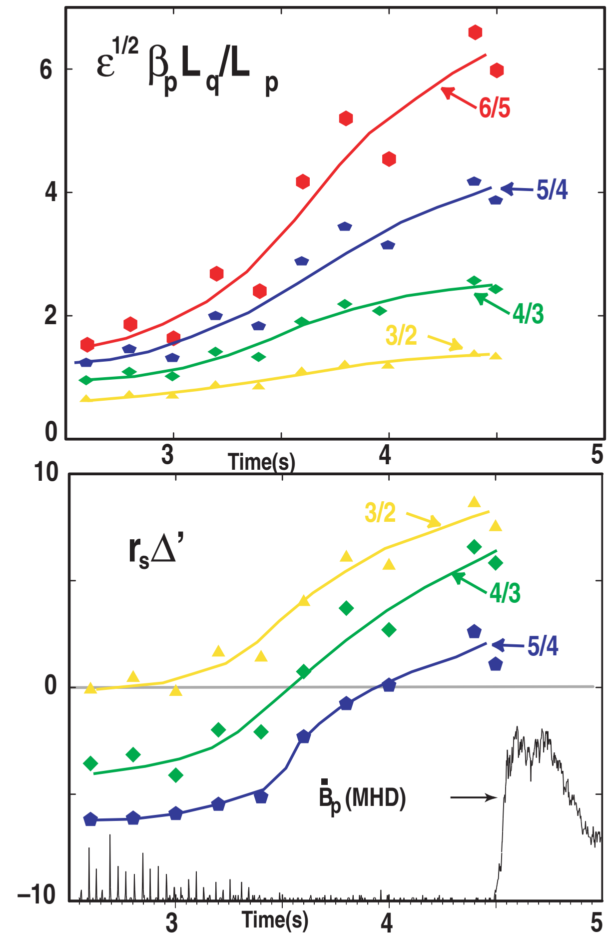
PRESSURE PROFILE PEAKING DESTABILIZES MHD MODES

- Termination of high n_e, high τ_E discharges is correlated with onset of MHD modes; m/n = 3/2, 4/3, 5/4, 6/5,...., at $1.4 < \beta_N < 2.0$
- Both classical and neoclassical tearing mode drives increase with time





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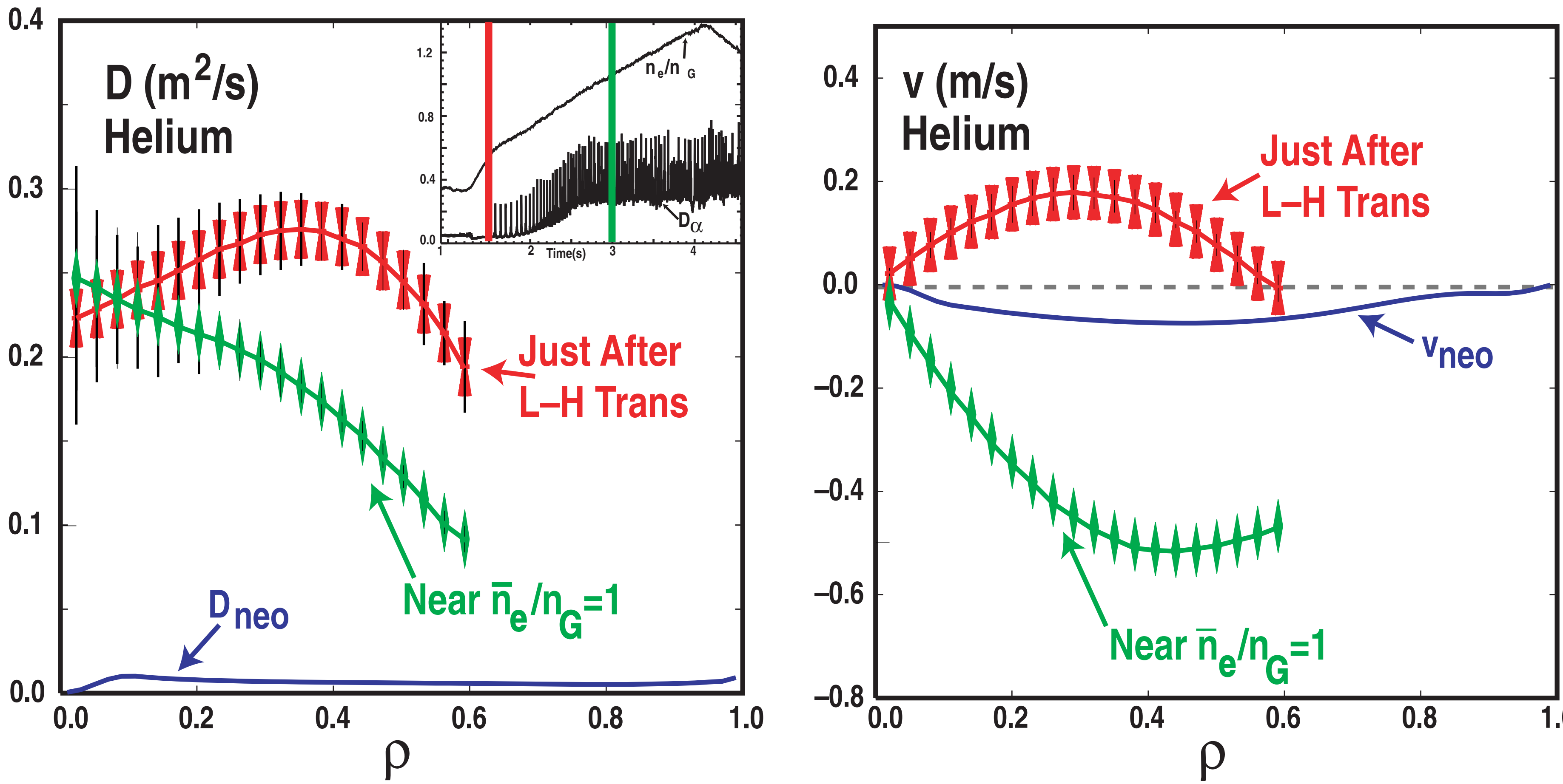
AT HIGH DENSITY PARTICLE DIFFUSIVITY DECREASES AND A LARGE PARTICLE PINCH DEVELOPS

- D and v measurements from He puff
- Helium pinch is much larger than neoclassical (Ware) value

Wade



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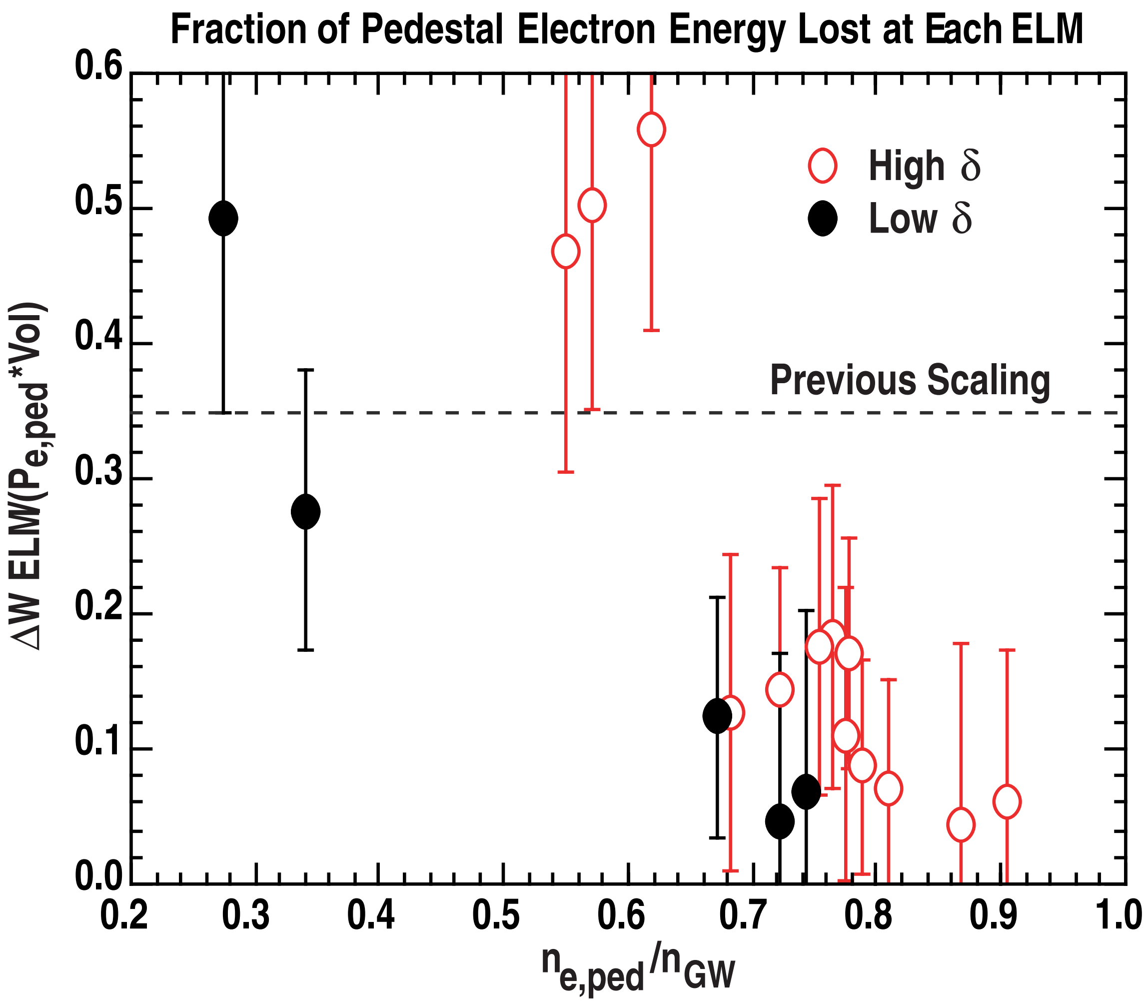
ELM ENERGY DECREASES AT HIGHER DENSITY

- ELM size decreases by factor >5 as density increases; only at highest density does edge pressure begin to decrease
- At high triangularity normalized ELM energy decreases at higher density than low triangularity
- ELM energy is normalized to pedestal pressure, ($P_{e,ped}$ x Plasma vol.)



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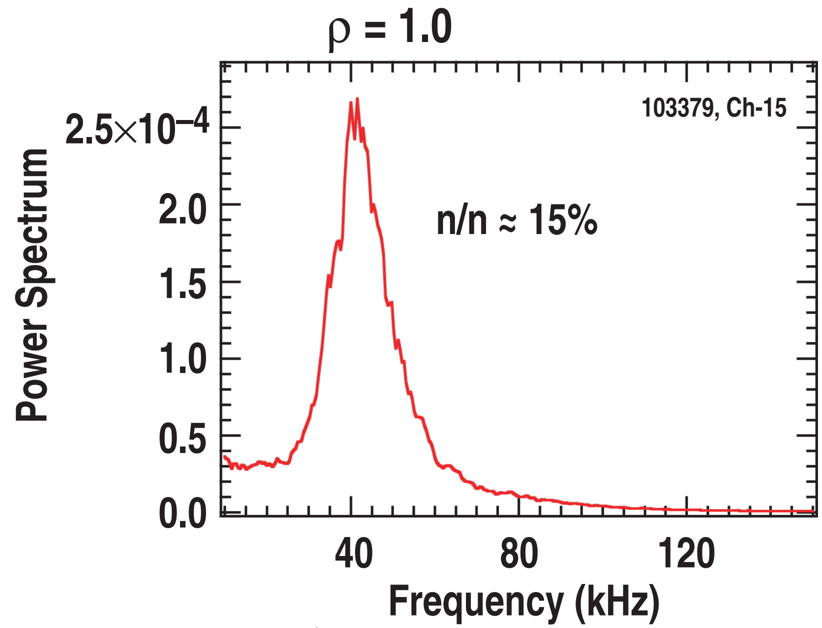
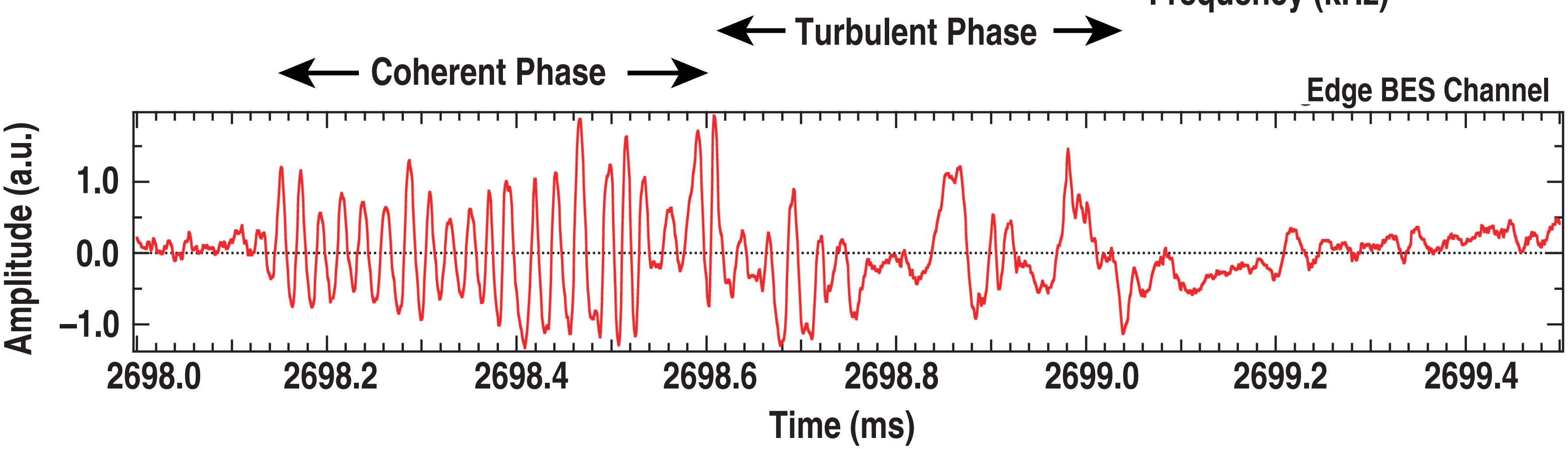
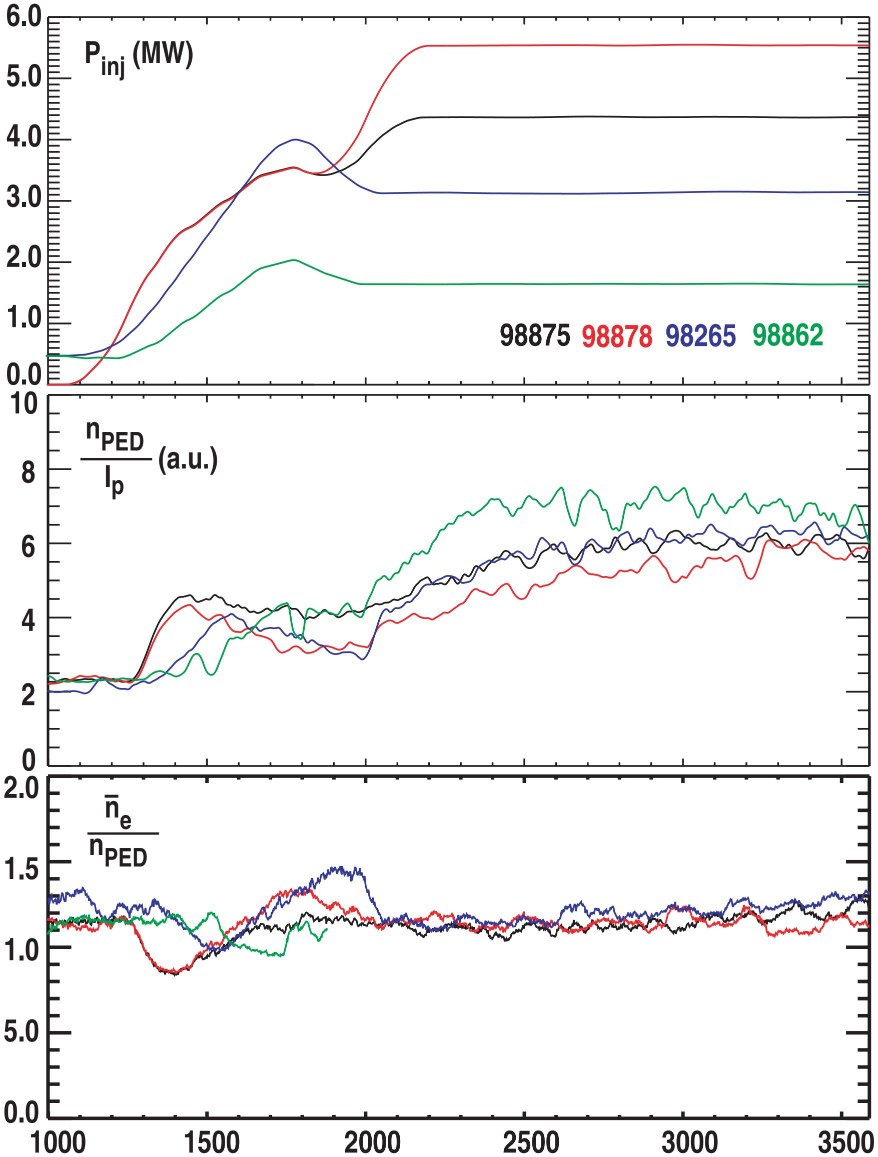
REPEATING PHASES OF HIGH FREQUENCY COHERENT OSCILLATIONS ARE FOLLOWED BY "TURBULENT" BREAKUPS

- Modes localized to narrow region near separatrix (< 1 cm from sep.)
- Traveling in electron diagmagnetic drift direction, v≈5 km/s
- λ≈12 cm., (m≈40 if wavelength constant poloidally)

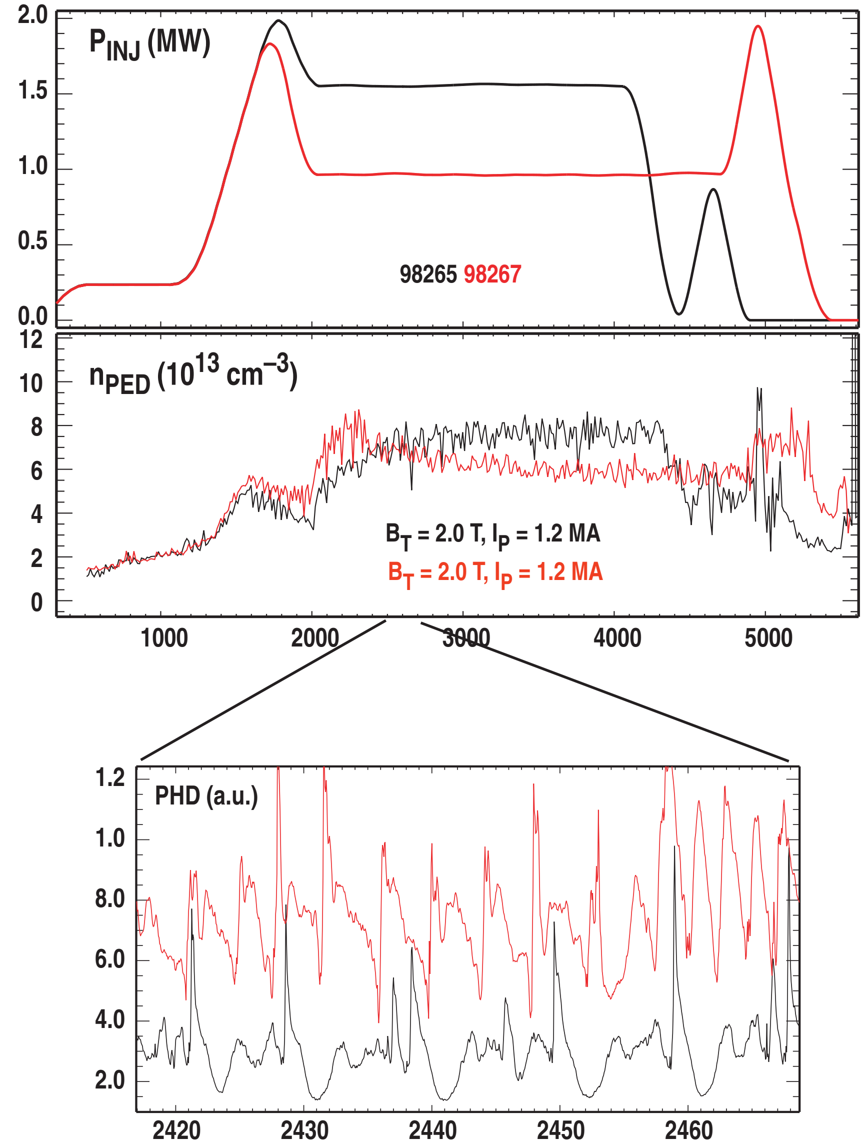




NORMALIZED PEDESTAL DENSITY DECREASES WITH INCREASING POWER



NEAR H–MODE POWER THRESHOLD DENSITY PEDESTAL DECREASES



- ELM frequency and duration increase at low power

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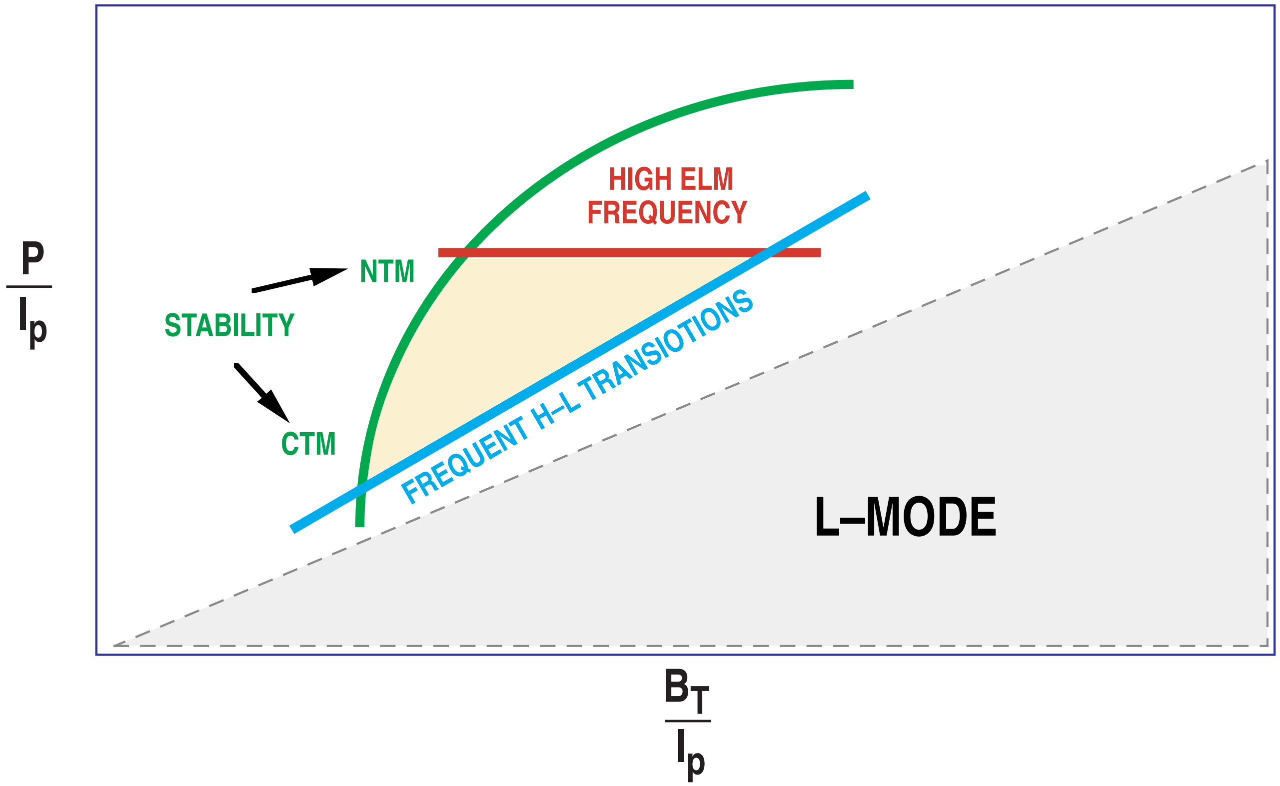
HIGH–DENSITY OPERATING WINDOW IS RESTICTED BY PARTICLE LOSS DUE TO TEARING MODE, H-L TRANSITIONS, AND ELMS



- Within the window density is determined by transport and fuelling
  - Desnity can be increased by increasing fueling efficiency
  - Beyond the window boundaries non-transport particle losses reduce maximum achiveable density
- Operating window shrinks in configurations with large H–mode power threshold

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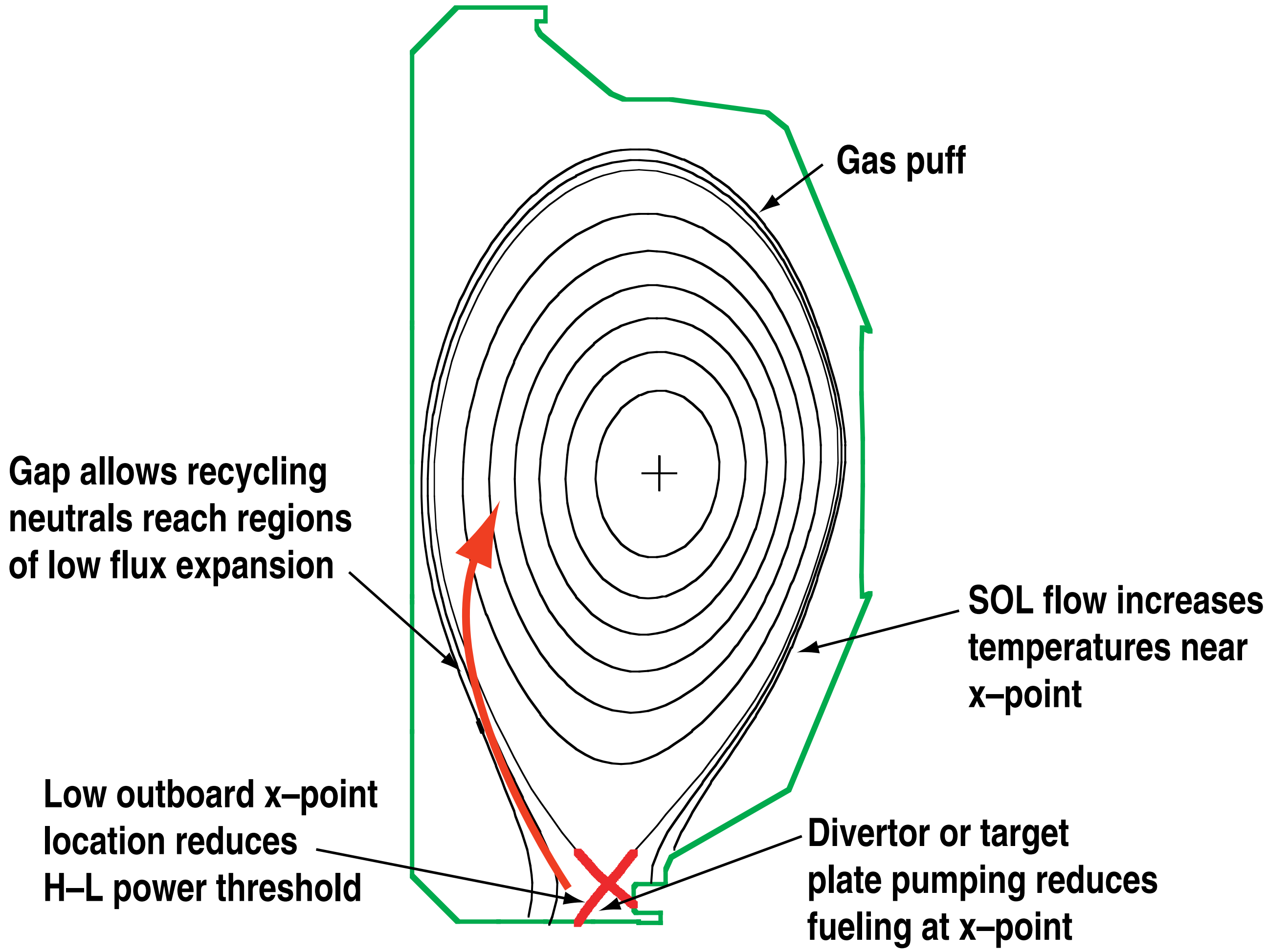
HIGHEST NORMALIZED DENSITIES WERE OBTAINED IN LOW q SINGLE NULL DIVERTOR



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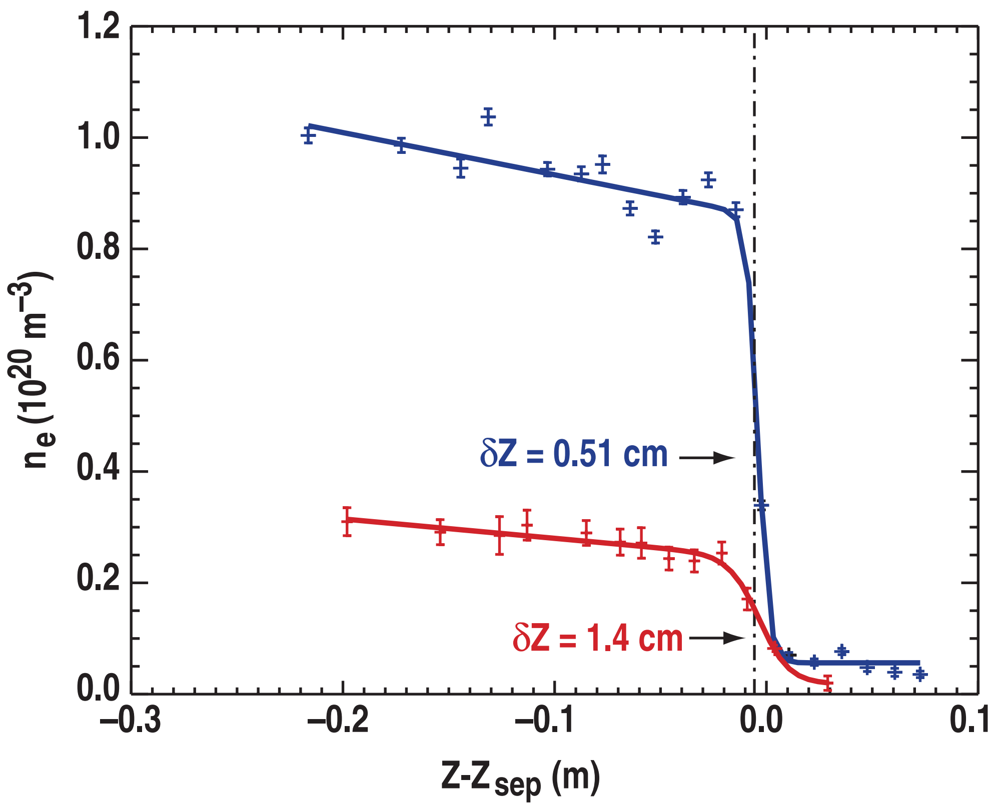
IN A QUIESCENT BOUNDARY PLASMA PEDESTAL DENSITY IS TIGHTLY COUPLED TO THE SEPARATRIX DENSITY

- In H–mode plasmas, density pedestal is the main component of the line average density

- With gas fueling alone, Engelhardt-Wagner model shows that the density pedestal height is tightly coupled to the separatrix density
  - $n^2_{PED} \propto n_{SEP}$
  - The scaling of the density pedestal width predicted by the Engelhardt model agrees with DIII–D data

- Since divertor detachment sets and upper bound on the acceptable level of the separatrix density, it also limits the pedestal density

DENSITY PEDESTAL WIDTH SCALES INVERSELY WITH DENSITY PEDESTAL HEIGHT AS PREDICTED BY MODEL



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PEDESTAL DENSITY INCREASES IF GAS FUELING SOURCE IS CONCENTRATED IN AREAS OF LOW FLUX EXPANSION

- Extension of Engelhardt-Wagner model to poloidally asymmetric configurations shows

  $$n_{PED}^2 \propto n_{SEP} \bullet f(\theta_0)$$

  - where $f(\theta_0)$ is the magnetic flux expansion at the location of the neutral source

- Divertor recycling neutral source is concentrated near X–point, where flux expansion is maximum
  - Open geometry allows neutrals escape to regions of low flux expansion
    - ★ Increases n_{PED} relative to n_{SEP}
  - Divertor pumping with gas puffing away from the divertor shifts the fueling source away from the X–point
    - ★ Can significantly increase n_{PED}^2 / n_{SEP}

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CONCLUSIONS

- Greenwald limit can be exceeded in gas fueled H–mode
- Fueling limit can prevent access to desired densities
  - Fueling is more effective in regions of low flux expansion
    - ★ Increases achievable pedestal density
    - ★ Divertor pumping shifts fuel source away from the high flux expansion region near X–point
  - Fueling demand increases at high power due to ELM-induced particle loss and at low power transitions to short lived L–mode states
    - ★ Favors configurations with low H–mode power threshold and low amplitude infrequent ELMs
- Confinement degradation seen in many devices at high density is not a manifestation of density limit
- Stiff transport model explains confinement behavior in DIII–D high density DIII–D H–mode discharges
  - Density peaking increases confinement

EXTENSION OF ENGELHARDT-WAGNER MODEL

$D_\perp d^2 n_e/d\xi^2 \;=\; \int n_n\, n_e\, \sigma\, V_e\, d\theta$ (1)

$V_H\, dx/d\xi\, \partial n_n/\partial\xi \;=\; -n_n\, n_e\, \sigma\, V_e,$ where ξ is the flux coordinate (2)

Integrating Eq. (2), assuming constant edge temperatures, yields;

$n_n \;=\; n_n(\theta,0)\, g(\xi)^{f(\theta)},$ where $f(\theta) \equiv dx/d\xi,$

Assuming $n_n(\theta,0) \;=\; \delta(\theta-\theta_0)$, obtain the equation describing the edge density

$d^2 n_e/d\xi^2 \;=\; f(\theta_0)\,(\sigma V_e/2V_H)\, dn_e^2 \big/ d\xi$

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EXTENSION OF ENGELHARDT-WAGNER MODEL . . .

Except for the $f(\theta_0)$ factor, this is the same result as given by Wagner with the solution:

$$n_e = n_{PED} \tanh [C - (\sigma V_e / 2V_H) f(\theta_0) n_{PED} \xi]$$

where $C \equiv 0.5 \sinh^{-1}(U)$, $U \equiv \left[\left(\sqrt{D}\,\tau_{//}\right)\sigma \frac{V_e}{V_H}\right] f(\theta_0) n_{PED}$, and $\tau_{//}$ is particle confinement time in SOL

For $U \leq 1$ $\quad n_{PED}/n_{SEP} \propto 2/U \quad$ » $\quad n_{PED}^2 \propto n_{SEP}/f(\theta_0)$

[1]W. Engelhardt, W. Fenenberg, J. Nucl. Mater. 76–77 (1978) 518.
A more transparent description of the Engelhardt model can be found in, “The Plasma Boundary of Magnetic Fusion Devices,” by Peter Stangeby, Inst. of Phys. Publishing, Bristol (2000) 175.

[2]Wagner and Lackner, Physics of Plasma Wall Interactions in Controlled Fusion, Nato Series B: Physics Vol. 131, Plenum Press, New York, p. 968.

FUELING REQUIRED TO ACHIEVE A DESIRED DENSITY HAS A MINIMUM AT A HEATING POWER OF ROUGHLY TWICE THE H–L BACK TRANSITION POWER THRESHOLD

- AT high power ELMs tearing mode can expel particles faster than transport

$$\Gamma_{ELM} \propto n_e(PED)\,\nu_{ELM} \propto \left[\frac{n_e(PED)}{I_P}\right]\frac{P}{I_P^{1/2}} \quad .$$

- At low power, near H–L threshold, ELM frequency and duration increase
  - Particle loss during ELMs can exceed the available fueling rate

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