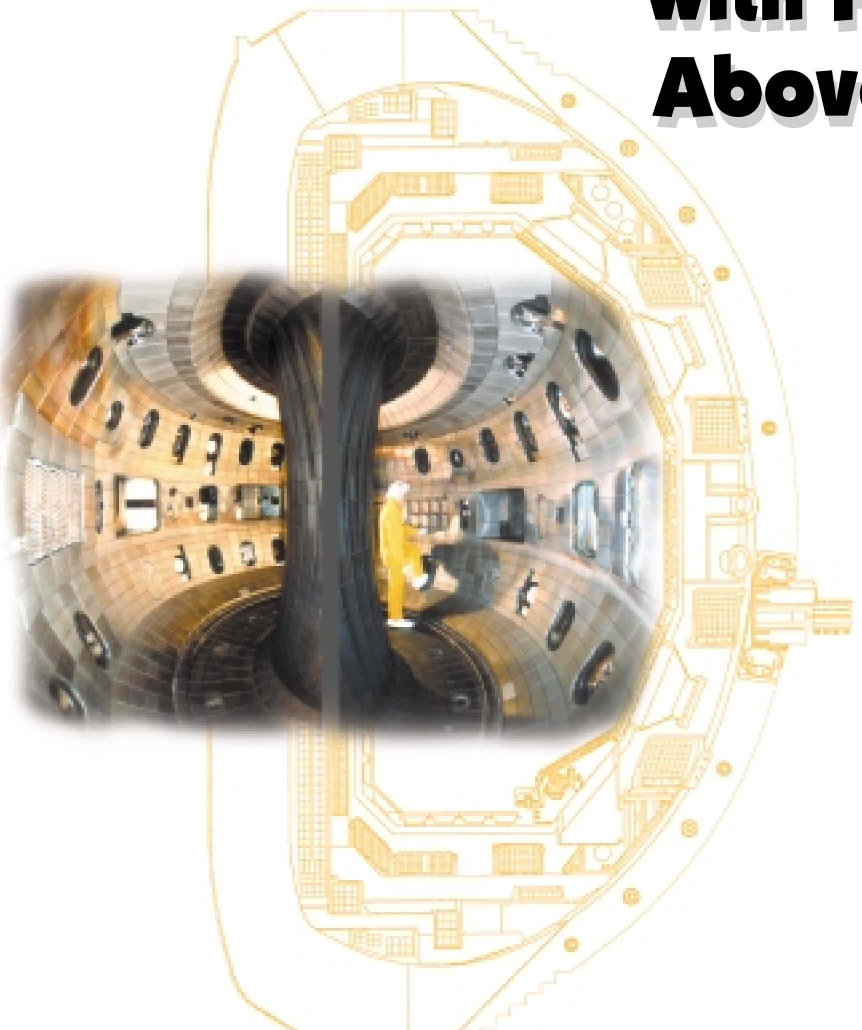
Gas Puff Fueled H-Mode Discharges with High Energy Confinement Above the Greenwald Density on DIII–D



by

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Presented at
the American Physical Society
Division of Plasma Physics Meeting
Quebec City, Canada

October 23–27, 2000

DIII–D
NATIONAL FUSION FACILITY

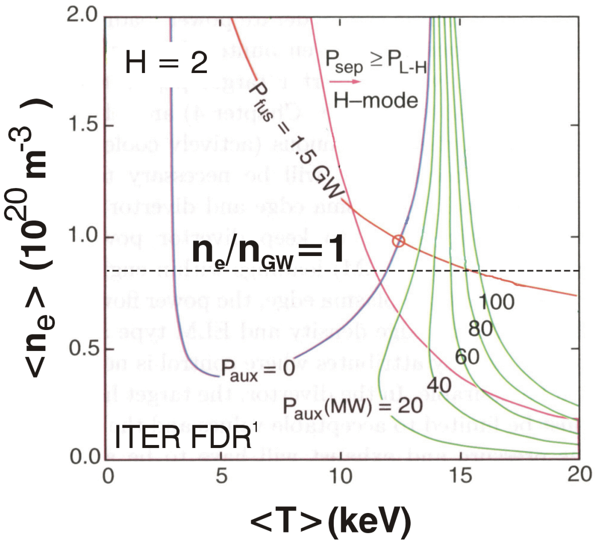
APS2000/wj

Outline, Summary

- n/n_{GW} = 1.4 at $H_{ITER-89P}$=2 with only D_2 puffing
- Continuous rise in n and W terminated by MHD not confinement loss
- High n_e with high H-factor associated with spontaneous peaking of n_e profile
    - anomalous particle pinch
    - stronger peaking at low central T
- Without n_e peaking reduced *H* at high density associated with reduced pedestal pressure with stiff temperature profiles.
    - p^{PED} reduction related to loss of edge second stable access
- Achievable pedestal density improves with decreasing B_T and triangularity at the X-point (n_e^{PED}/n_{GW} up to 0.9)

Benefits of good energy confinement at high n with gas puff fueling in H-mode based tokamak reactors

Ignition Margin, Fusion power, L-H Threshold Margin



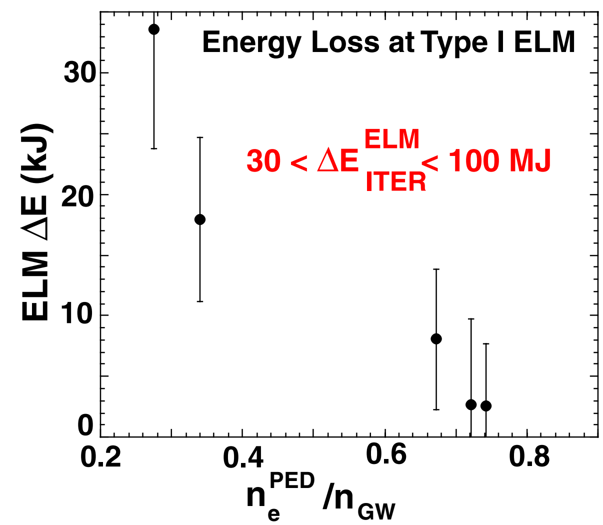
$$\frac{P_{FUS}}{P_{LOSS}} \propto n^{0.4} H^{2.9} (20 - T_{KEV})^2$$

$$P_{FUS} \propto n^2 T^{2.9} (20 - T_{KEV})^2$$

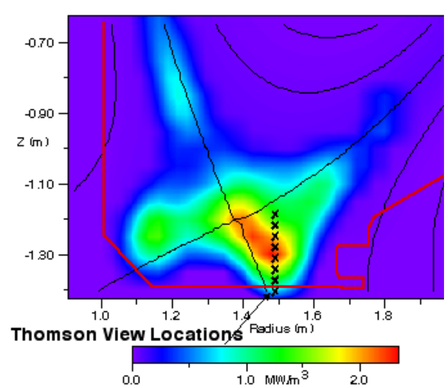
$$\frac{P_{FUS}}{P_{LH}} \propto n^{1.2} T^{2.9} (20 - T_{KEV})^2$$

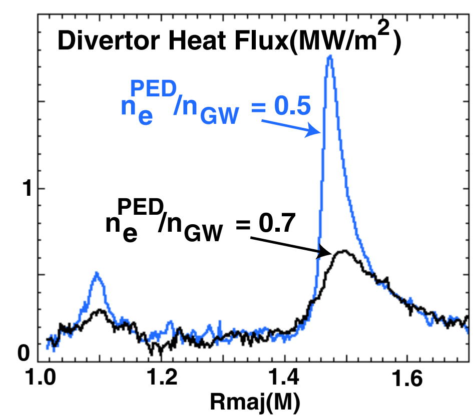
$$n_{GW}(10^{20} m^{-3}) = I_p(MA)/\pi[a(m)]^2$$

Reduced ELM Energy Loss



Reduced Peak Divertor Heat Flux

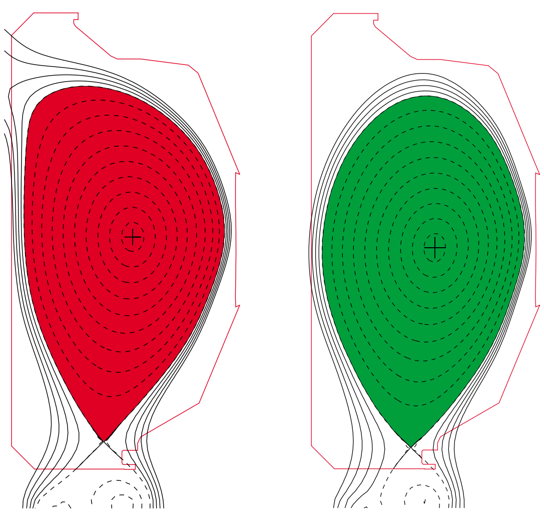


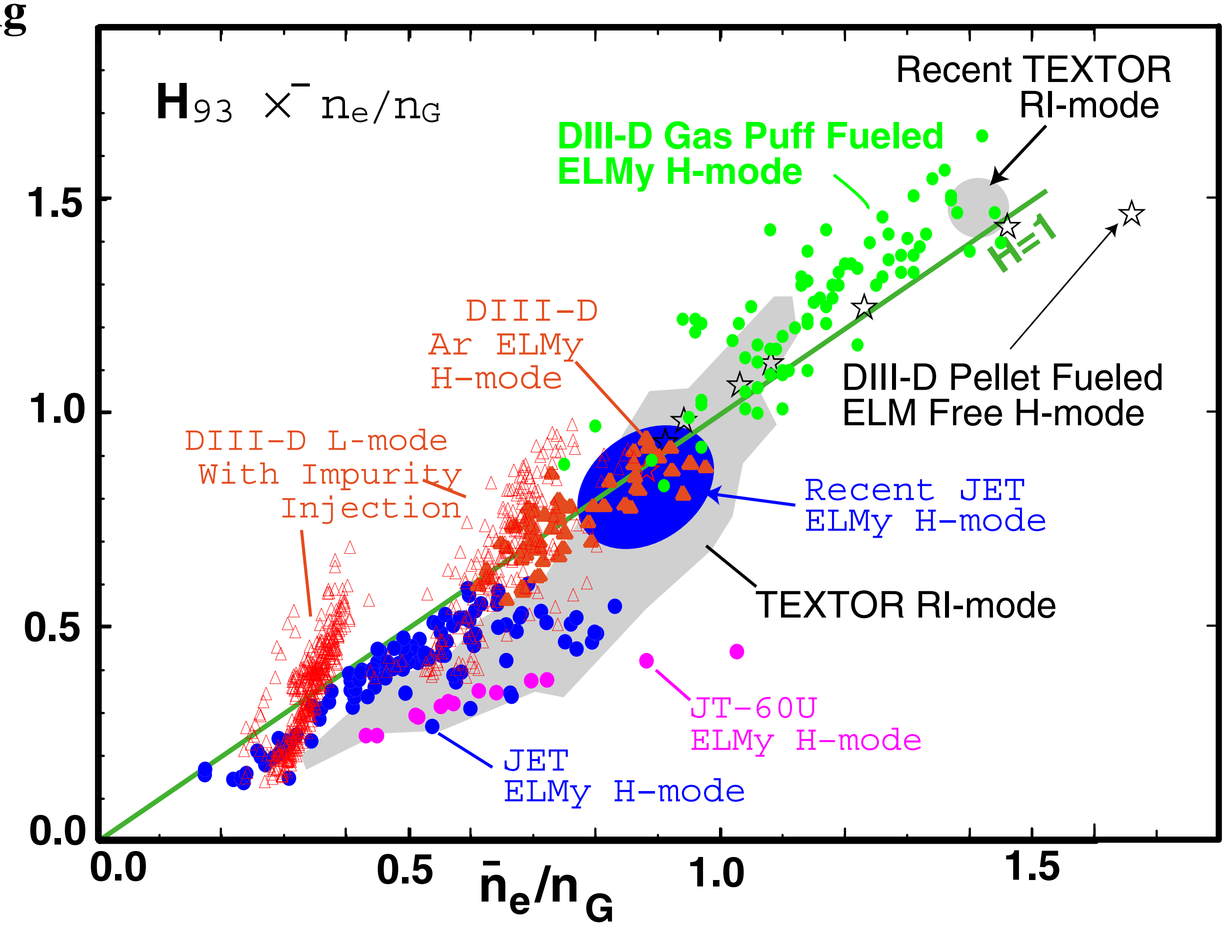


[1]*ITER Physics Basis*, Nucl. Fusion, **39** 2577

Gas puff fueled discharges have performance comparable to pellet fueled and impurity enhanced high density discharges

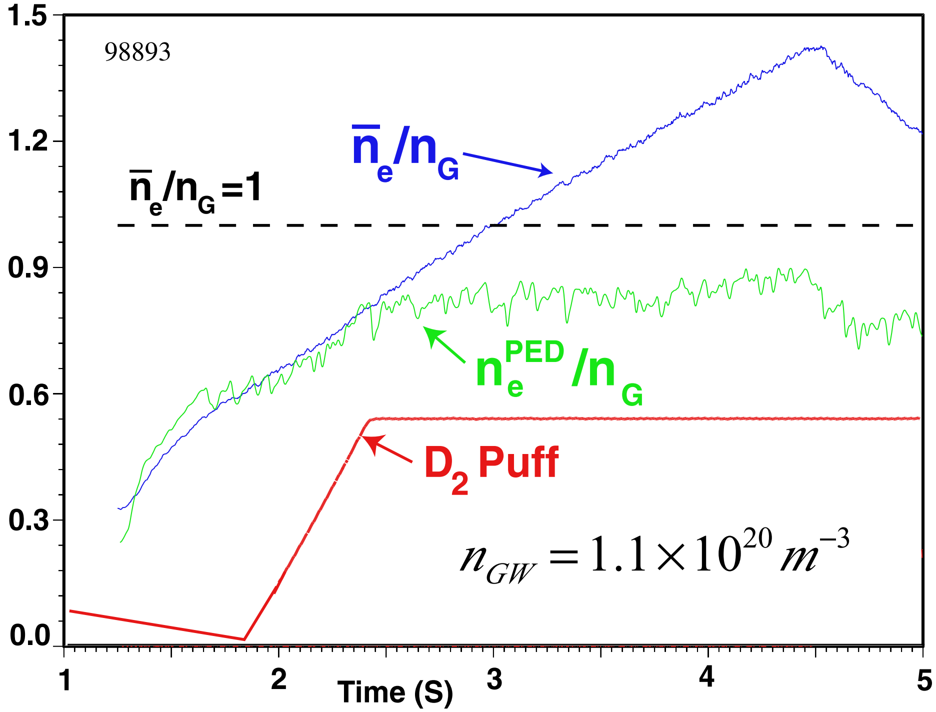
- Single null with ∇B toward the x-point; triangularity $0 < \delta < 0.5$
- Reactor relevant $2.5 < q_{95} < 6.0$, most at $q_{95} = 3.2$, $I_P = 1.2$ MA
- $1 < \beta_N < 2$, ($\beta_N = 2$ at $\bar{n}_e / n_{GW} = 1.3$)
- Most with divertor pumping

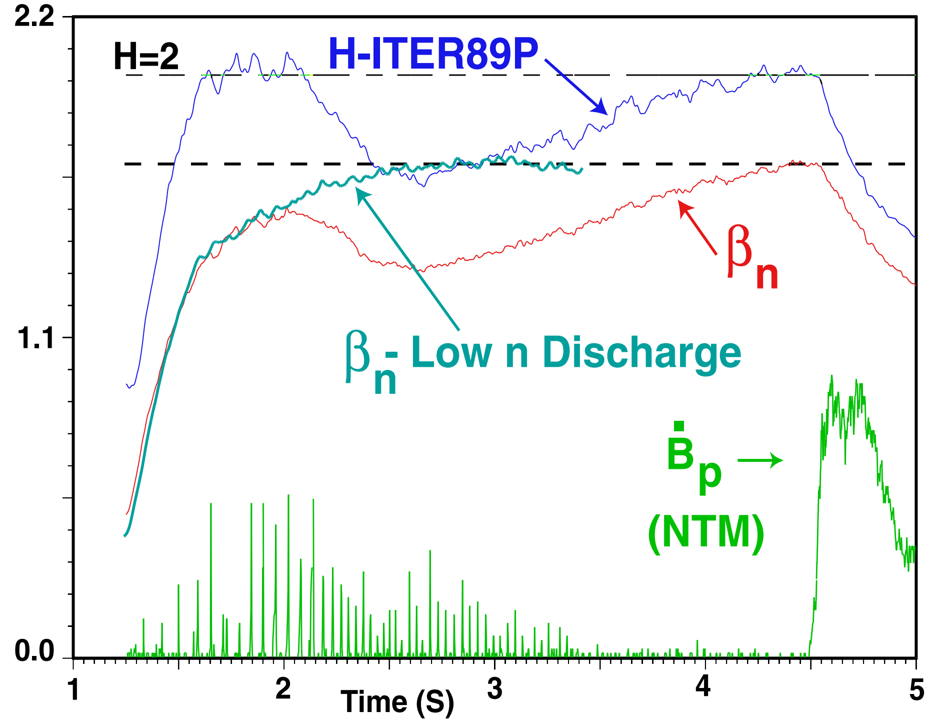




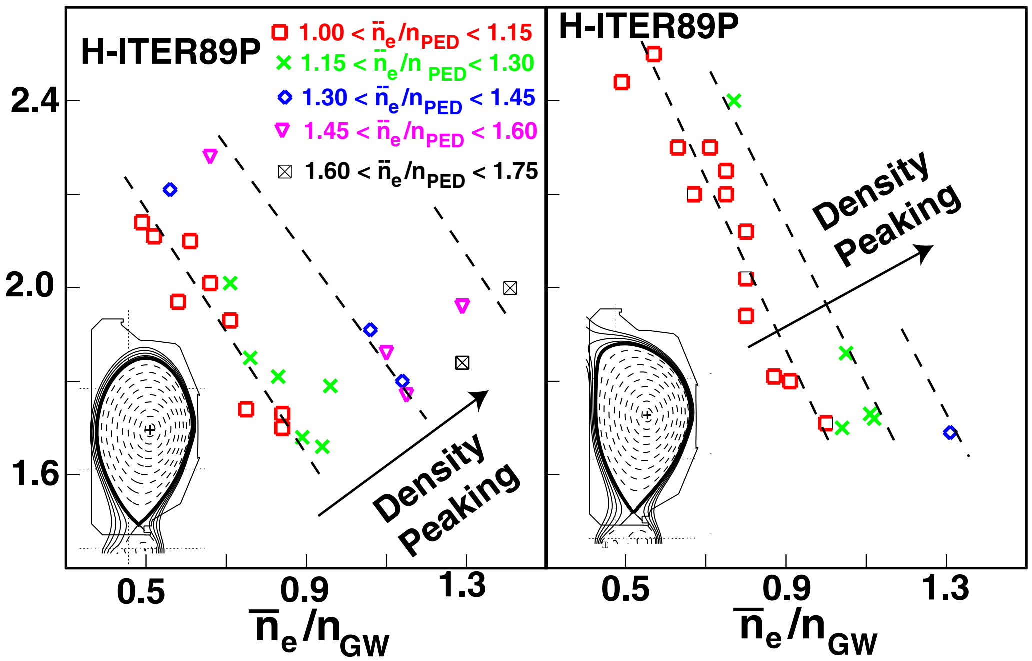
Highest density discharges show continuous increase in n and W

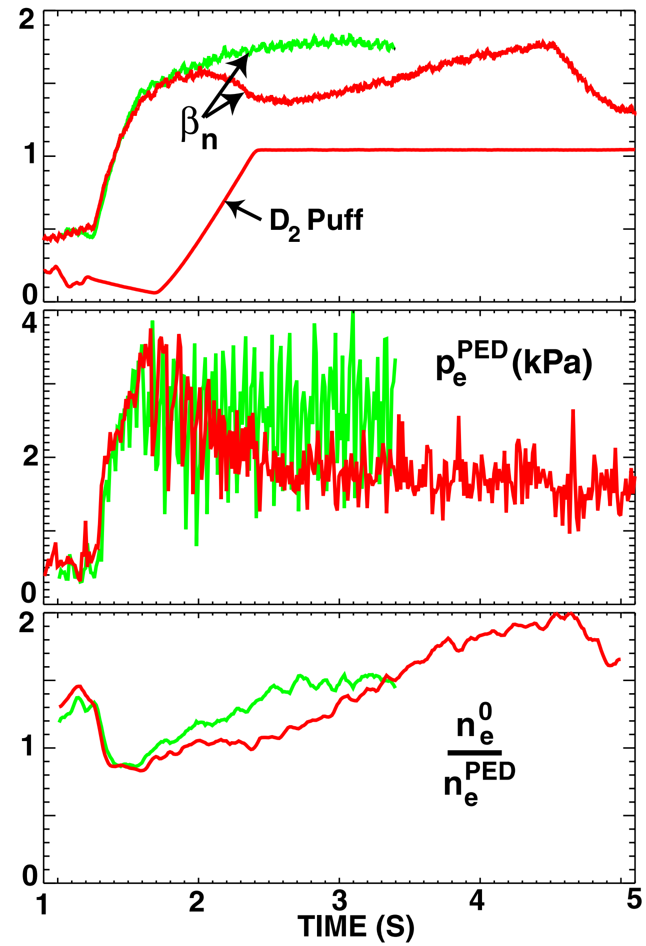
- Plasma stored energy, W, increases with density after an initial decrease following the start of gas injection
- n and W increase limited by MHD not confinement reduction
- Stored energy is comparable to low density discharge at the same heating power.



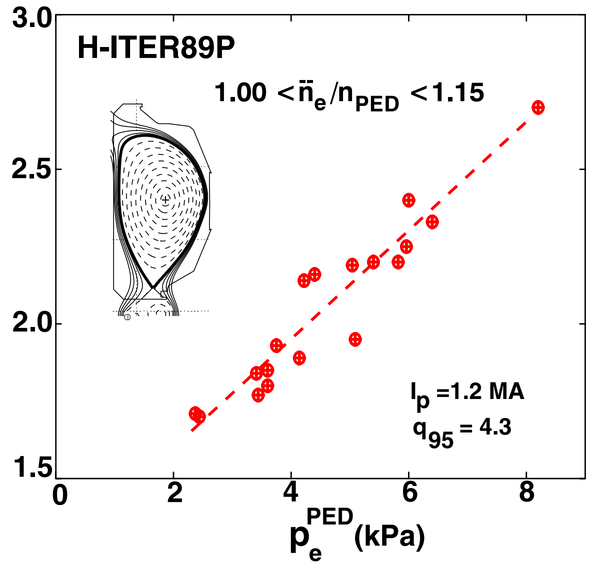


Peaking of the density profile compensates for loss of H-mode pedestal energy at high density



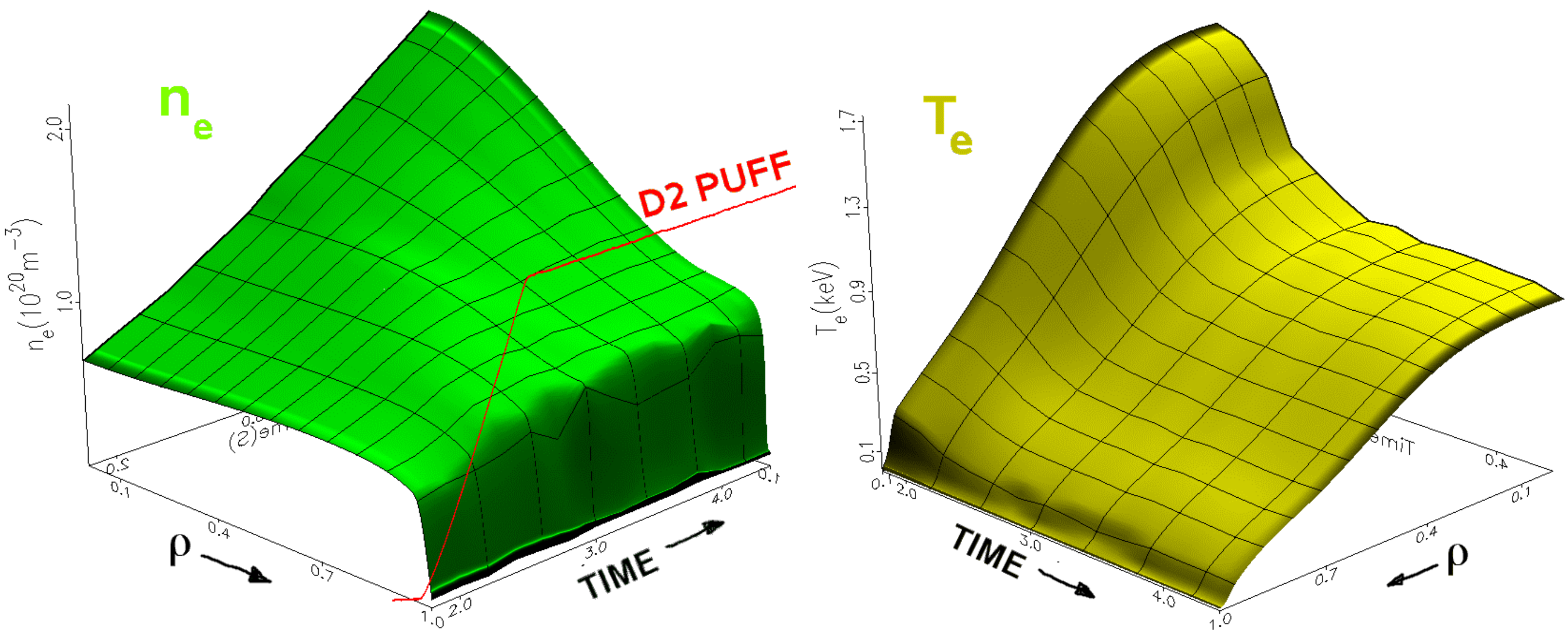


- Reduction in H correlated with reduction in pedestal pressure
- Stored energy is recovered with density profile peaking



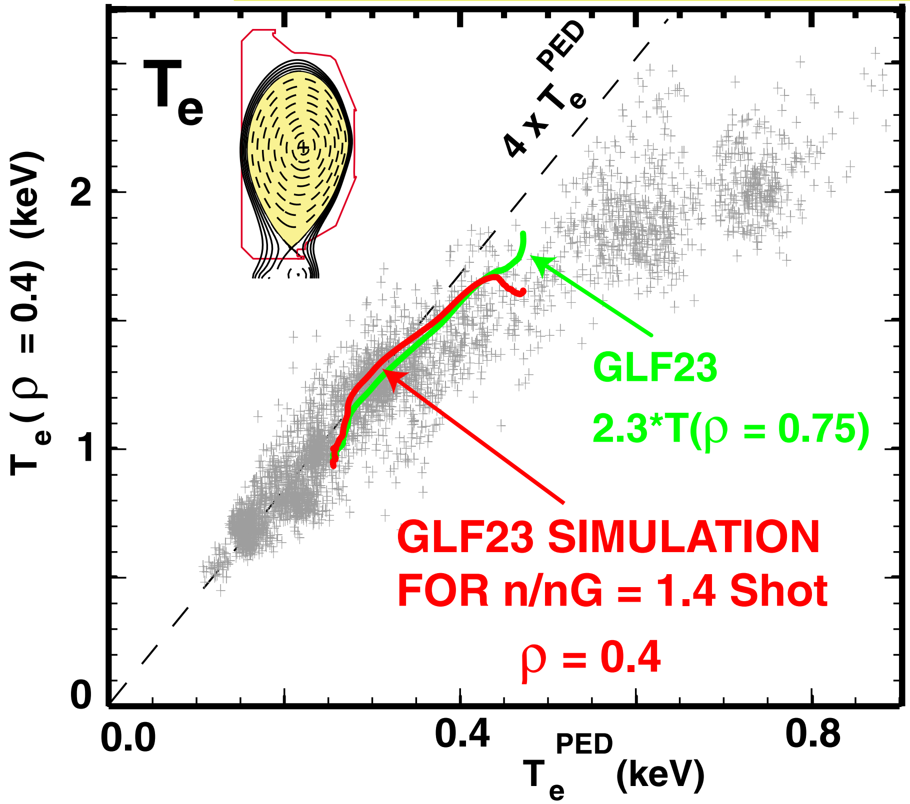
Profile evolution in high density discharge

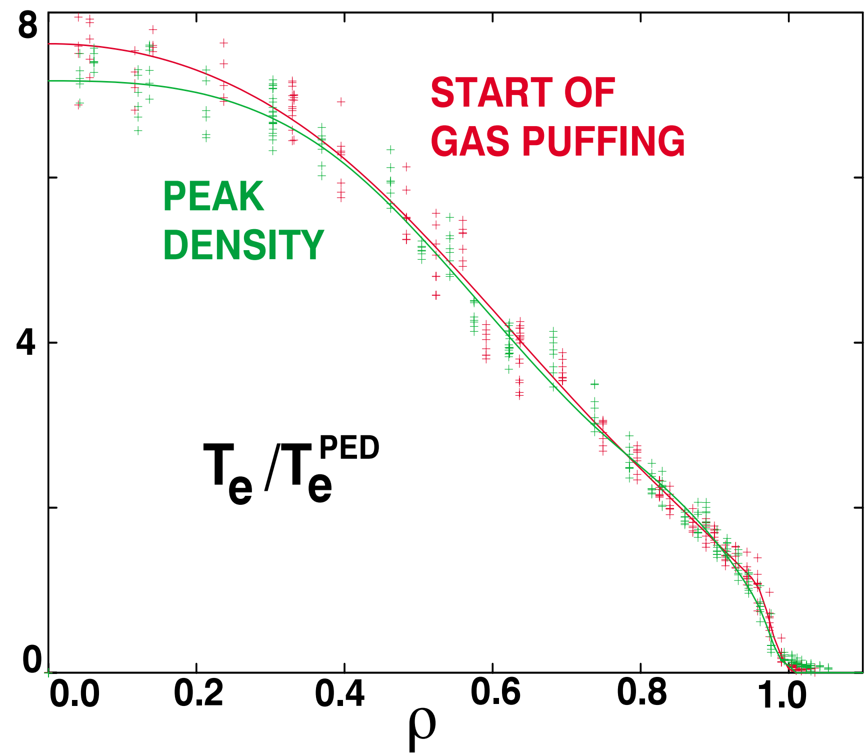
- H-mode pedestal density and temperature profile reach steady state while density profile peaks continuously after beginning of D_2 puffing



Reduction in W at high n can result from reduced p^{PED} with stiff temperature profiles

$$T(\rho) = T^{PED} f(\rho) \Rightarrow W_{Total} \propto p^{PED} g(n^0 / n^{PED})$$

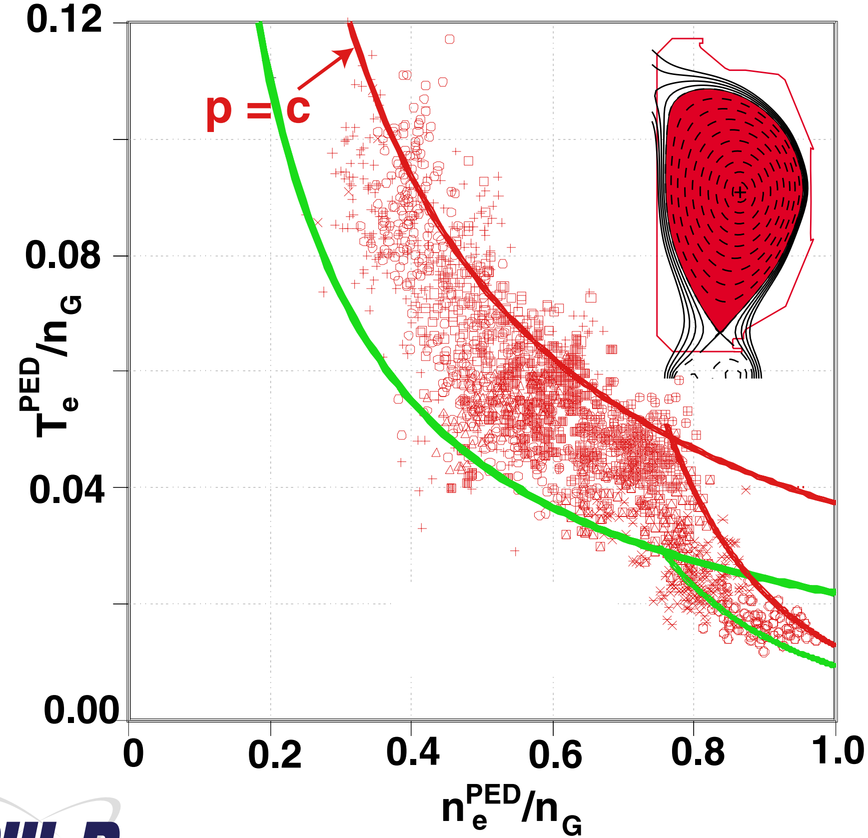


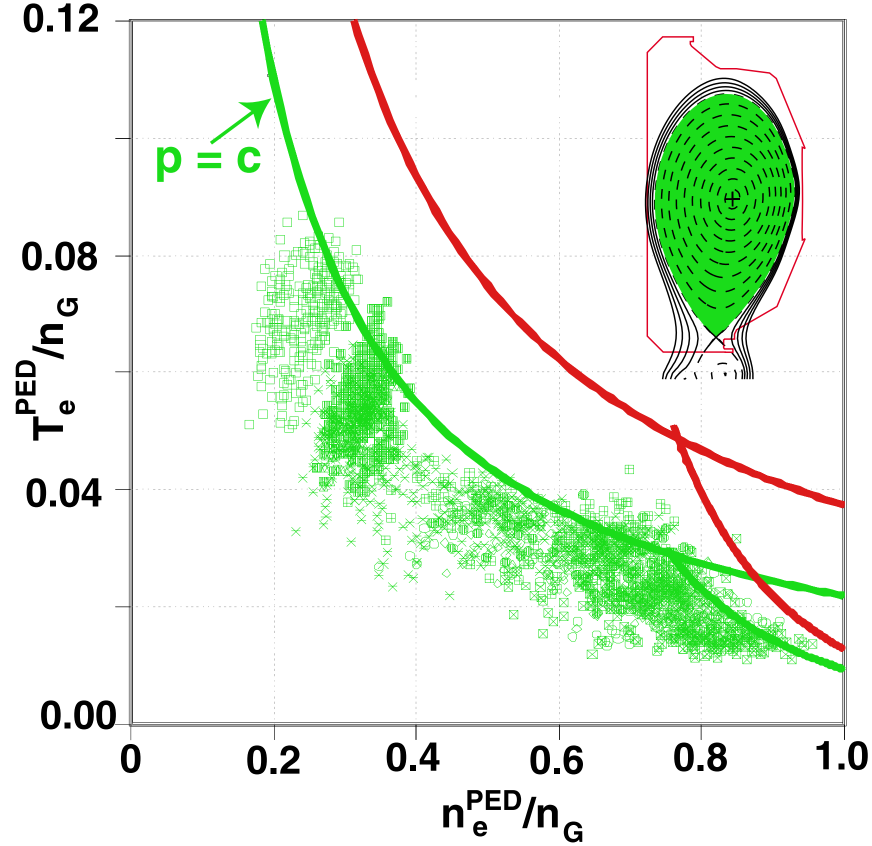


- GKS indicates ITG is fastest growing mode
- GLF23 transport simulation give stiff T profile in agreement with experiment, no ITB

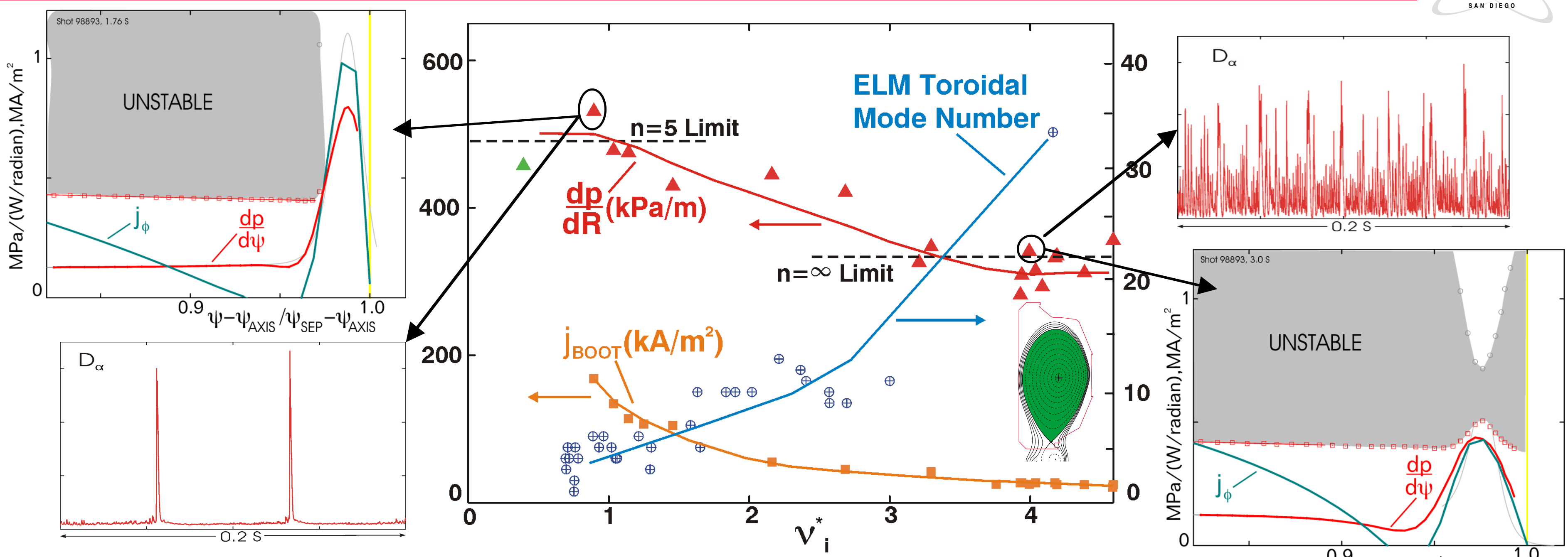
Reduction in H-mode pedestal pressure at high density

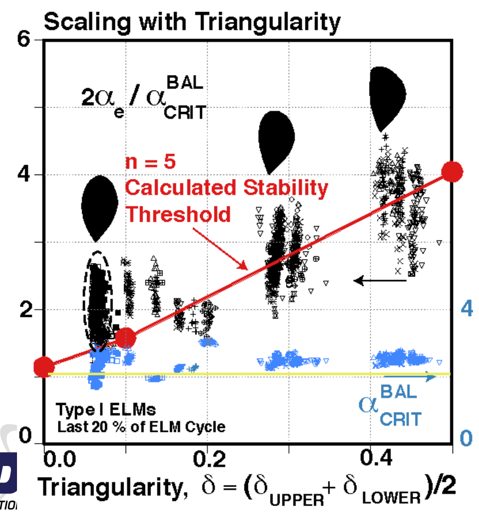
- Pressure reduction begins in the range $0.6 < n_e^{PED}/n_{GW} < 0.8$.
- At higher triangularity reduction begins at similar n_e^{PED}/n_{GW}
- Stronger reduction at higher triangularity





Loss of edge second stable access may account for the reduction in edge pressure gradient at high density

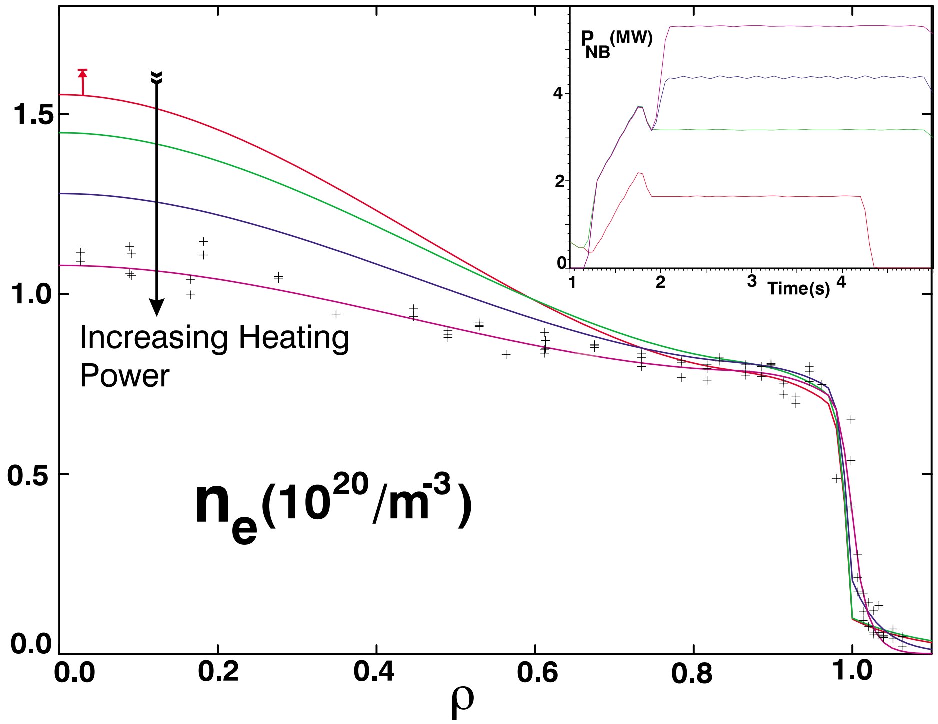


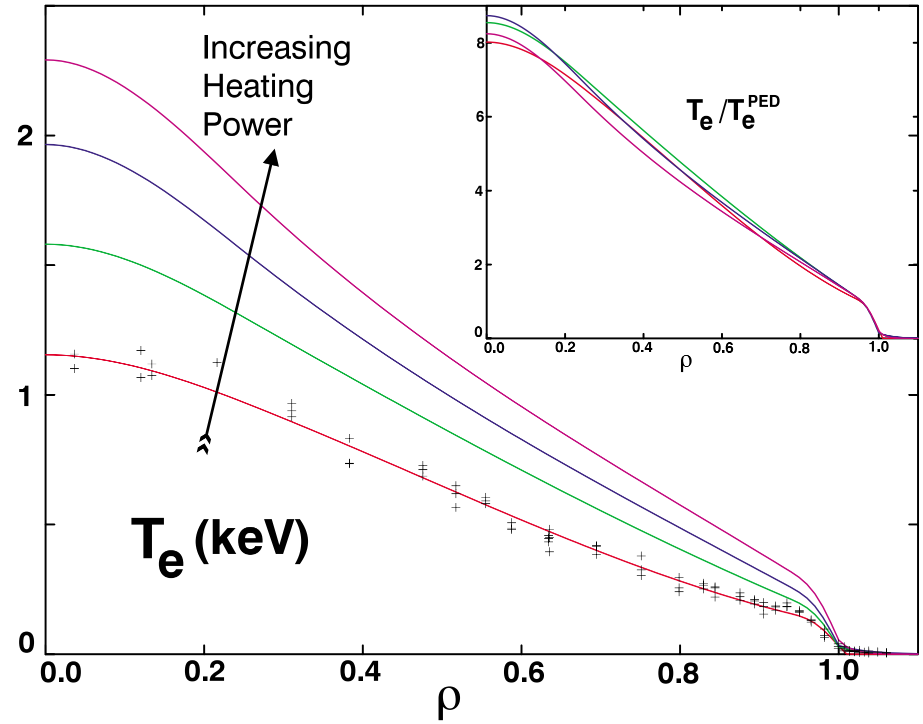


- With increasing edge density or $\nu^* \propto n/T^2$.
  - Calculated j_{BOOT} decreases ⇒ edge magnetic shear increases, $S \approx S_0 - 2\left\langle j_{TOR}^{EDGE} \right\rangle / \bar{j}_{TOR}$, ⇒ SS access lost
  - ELM modes increase in n.
  - Pressure gradient is reduced from calculated limit for n=5 edge localized ideal kink/ballooning (GATO) to ideal nigh n ballooning mode limit (BALOO).

Density peaking is stronger under conditions that reduce central T or improve central confinement

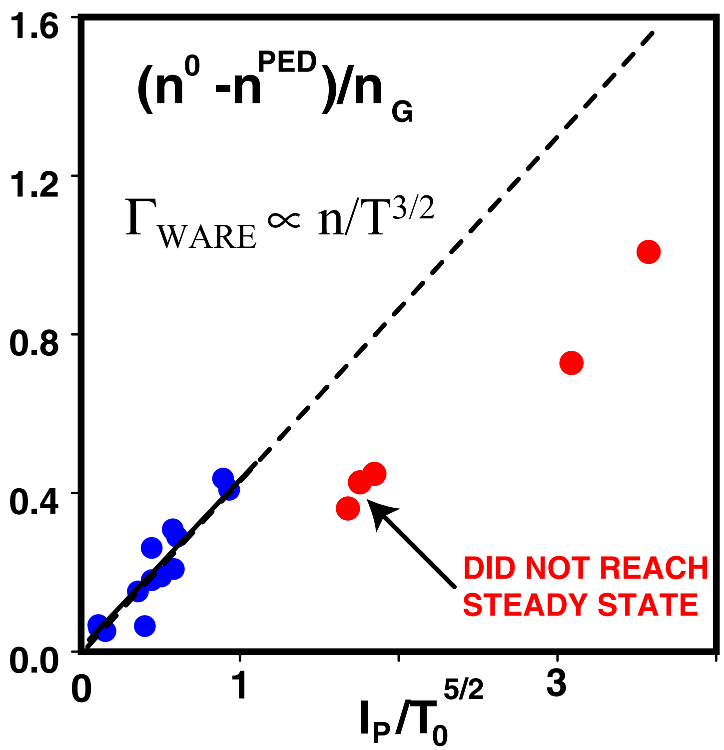
- **Low heating power** ⇒ T_0 reduced and τ increased
- **Higher Gas Puff** ⇒ T_0 reduced through profile stiffness.
- **Low B_T** ⇒ T less peaked at lower q
- **High Ip** ⇒ T less peaked at lower q, τ increases with Ip.

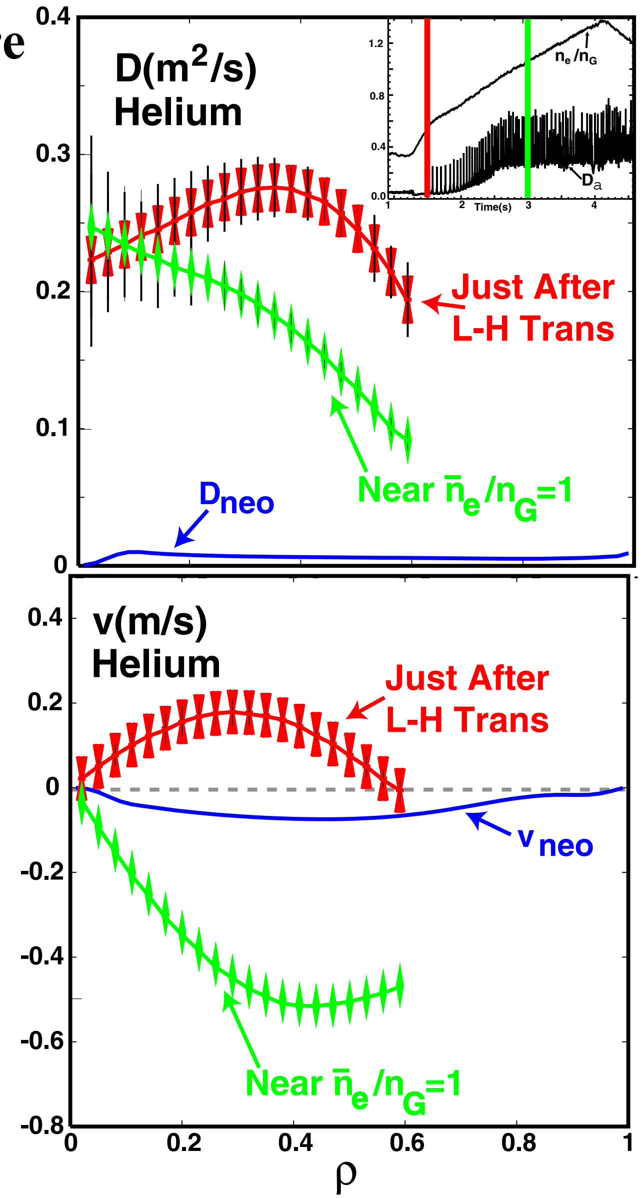




High density discharges develop large particle pinch and have decreasing particle diffusivity

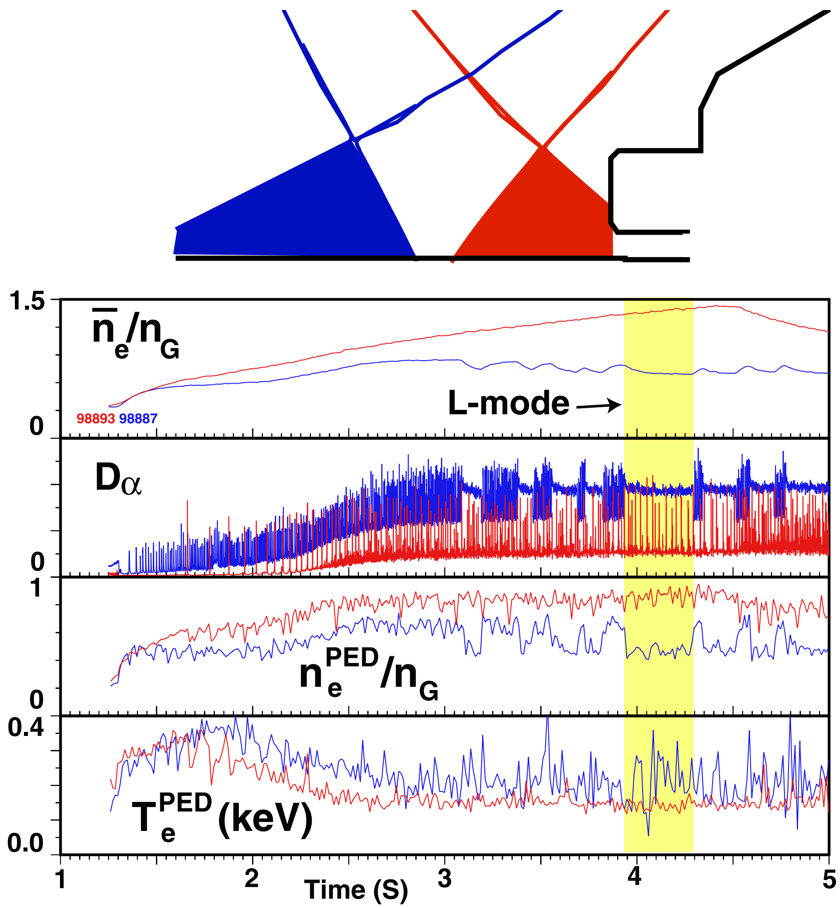
- Inverse scaling with central temperature suggests neoclassical pinch
- Pinch speed measured from He density profile evolution (CER) much larger than neoclassical.

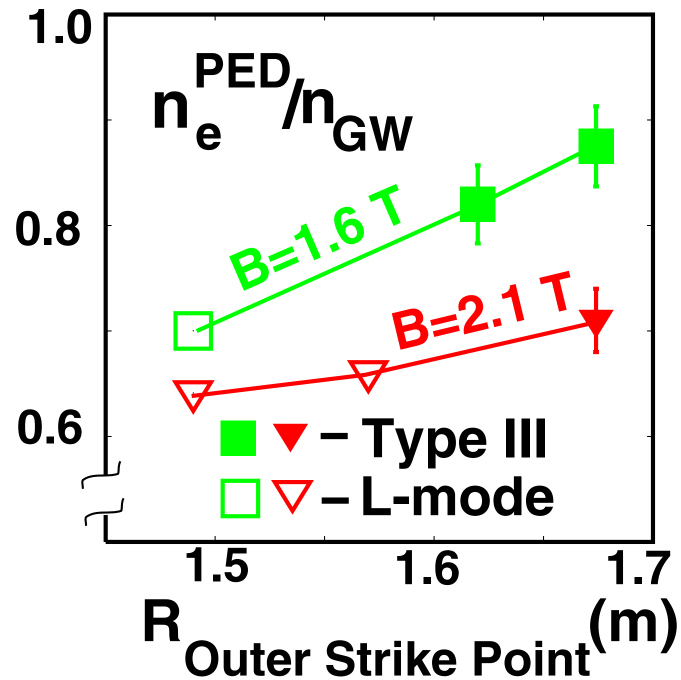




Achievable H-mode pedestal density increases at low x-point triangularity and low B_T

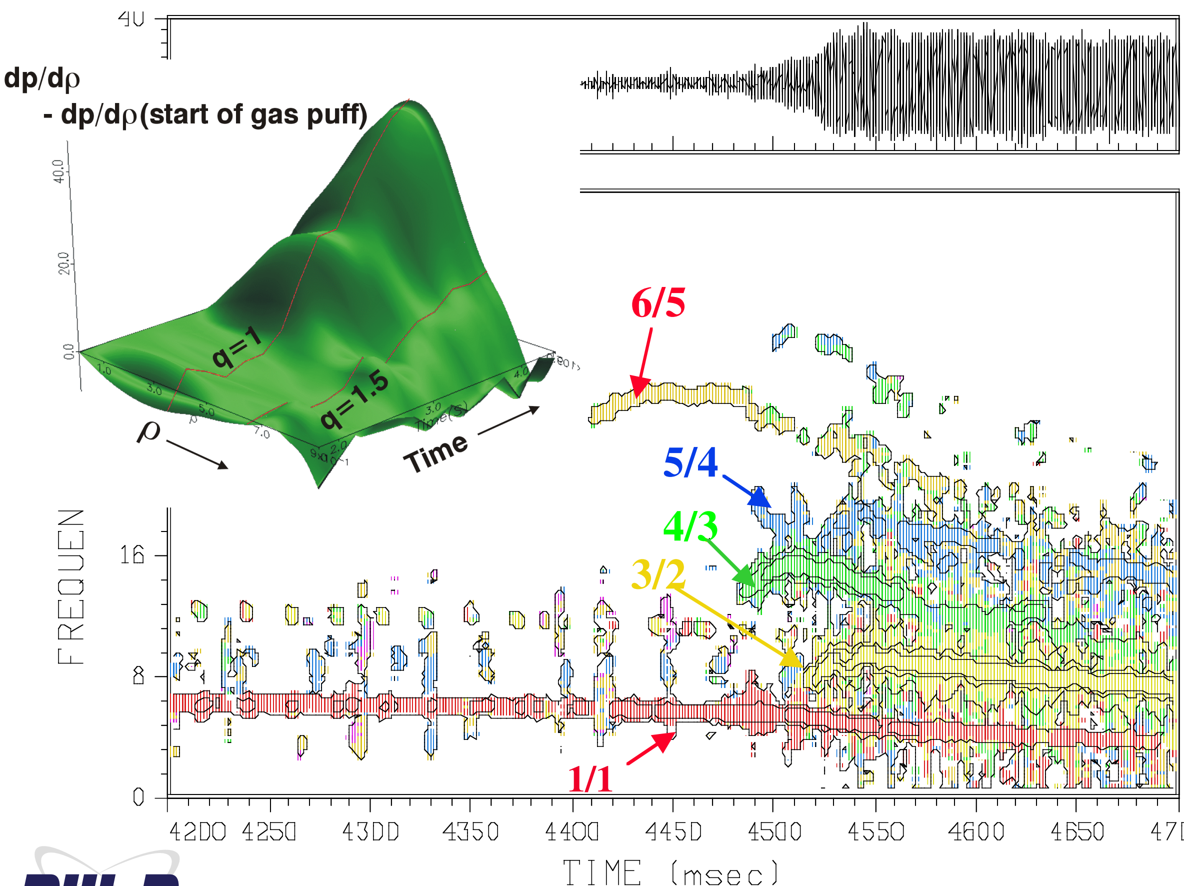
- Transition condition to L-mode or Type III dependent on triangularity at X-point and B_T

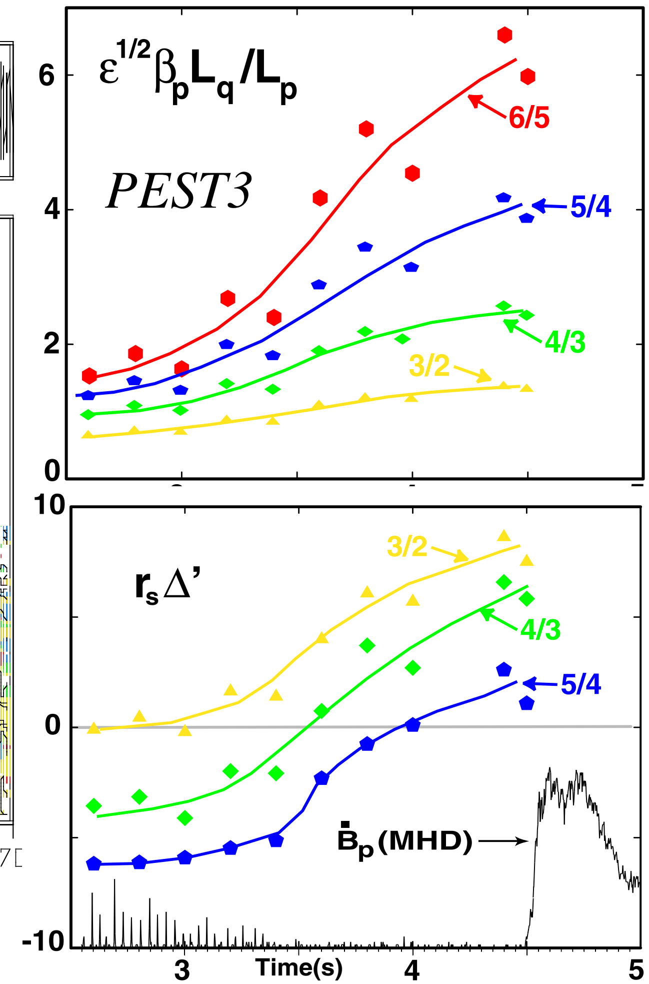




Rising core p′ may trigger MHD that ends good confinement phase of high density discharges

- Modes in region $1 < q < 1.5$, $m/n = 3/2, 4/3, 5/4, 6/5$.
- Both classical, $\Delta' r_s$, and neoclassical, $\varepsilon^{1/2}\beta_P L_q/L_p/(r_s/w)$, tearing mode drives increase as p′ increases due to n_e profile peaking





Summary, Conclusions

- ELMing H-mode discharges with good energy confinement, H_{89P} = 2 well above the Greenwald density, n/n_G = 1.4, were obtained with gas puffing
  - Limited by core MHD rather than transport or divertor effects
- Density profile peaking is important in obtaining high H factor
  - Peaking is enhanced under conditions that reduce central temperature.
  - He transport studies indicate an anomalous inward pinch
  - Neoclassical pinch would be very weak in a reactor scale tokamak however scaling of anomalous pinch is not known
- Confinement degradation at high density on DIII-D is related to the reduction in H-mode pedestal pressure.
  - Edge pressure gradient may be reduced at increased collisionality through loss of edge second stability at reduced bootstrap current.
    - Should not be important in a reactor scale tokamak

Summary, Conclusions

- Low triangularity of the x-point or low toroidal field increases the H-mode pedestal density that can be obtained without transition to a regime of reduced energy confinement.
- Termination event is possibly a NTM triggered by an increase in the pressure and density profile peaking.

Related Presentations

MO1.011 M.A. Mahdavi, *Confinement and Stability of H-mode Discharges above the Greenwald Limit*

GP1.135 A. Leonard, *Edge Pedestal and ELM Scaling with Density in DIII-D*

GP1.136 T. Petrie, *Recent High Density Experiments in Open and Closed Divertors in DIII-D*