EFFECT OF EDGE NEUTRAL SOUCE PROFILE ON H-MODE PEDESTAL HEIGHT AND ELM SIZE

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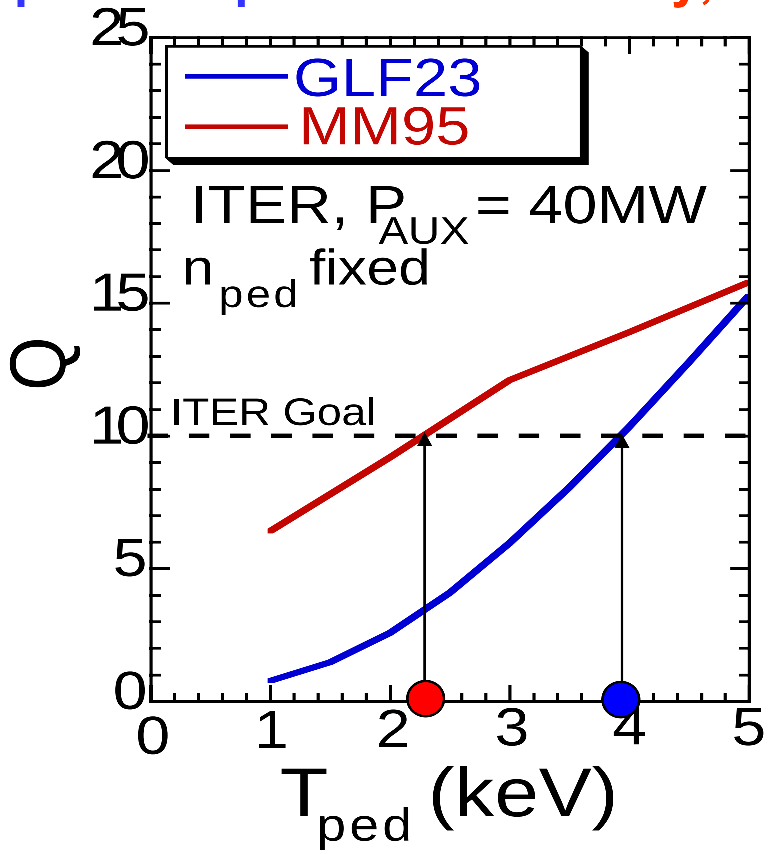
Summary

- **H-mode based tokamak reactors require large H-mode pedestal pressure, but ELM energy loss generally increases with p_{PED}. If ΔW_{ELM} is too large, divertor target can be quickly eroded**
- **ΔW_{ELM} might be reduced if the edge high pressure gradient region is moved outward within the edge transport barrier by controlling the edge particle source profile.**
  - ΔW_{ELM} is correlated with peeling/ballooning eigenmode width which is in turn set by width of high p′ region
  - Pedestal density profile appears to be controlled by edge particle source profile while ETB width (T profile) may be independent of particle source profile
  - Critical p′ for PB mode expected to increase with narrowed width and outward shift of high p′ region at low collisionality expected in reactor scale tokamaks.

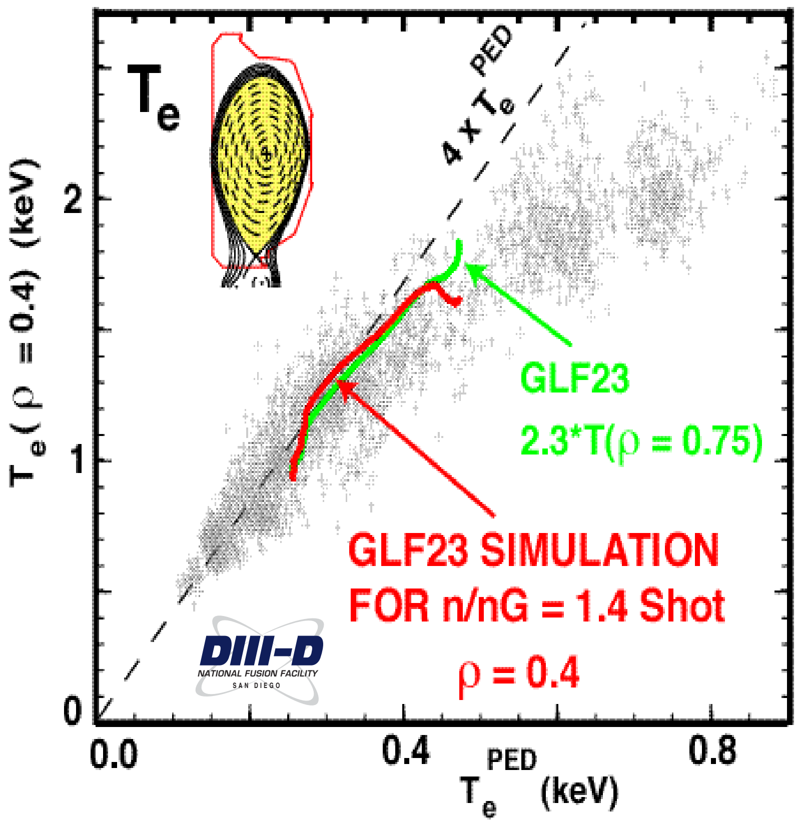
H-mode based tokamak reactors require high H-mode pedestal pressure

- Requirements of high $Q=P_{FUSION}/P_{HEATING}$ at high P_{FUSION} ⇒ large H-mode pedestal pressure in H-mode based tokamak reactor

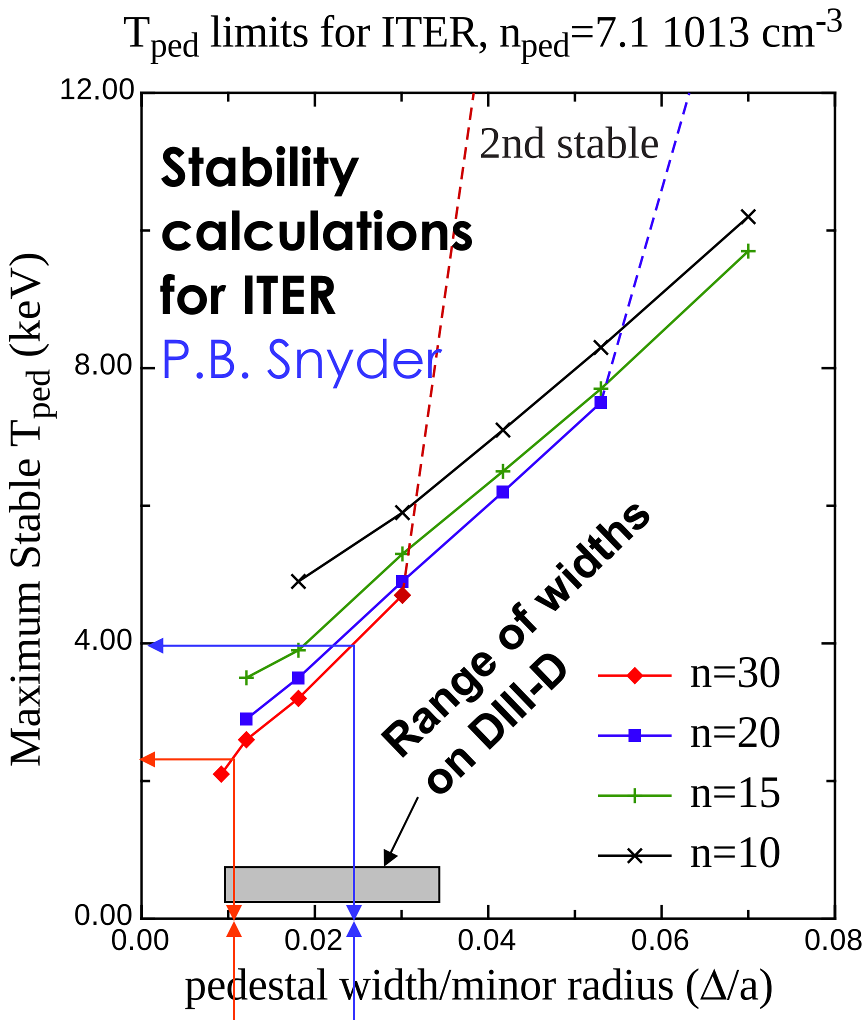
Temperature profile stiffness connects reactor performance strongly to pedestal pressure. J. Kinsey, IAEA 02



Evidence of temperature profile stiffness in DIII-D density scan



p_{PED} determined by physics of edge stability and the ETB width which are expected to be interdependent



- **ELITE code results for simplified ITER equilibrium**
  - Same width of steep gradient region in pedestal T and n and fixed density
  - **Sauter model j_{Boot}**
- **Stability + T_{PED} requirement for core confinement ⇒ minimum ETB width**
  - Experiments have widths in the required range
- **Curves are offset linear ⇐ p′ increases as small width**
- **Edge p′ affects the E_r well and thereby possibly the ETB structure**

STABILITY + GLF23 @ Q=10⇒ $\Delta_{MIDPLANE}/a$ = 2.5 %

STABILITY + MM @ Q=10 ⇒ $\Delta_{MIDPLANE}/a$ = 1 %

n_e pedestal structure may be set by structure of edge particle source

- **Engelhardt-Wagner model[1] extended by Mahdavi[2] to include poloidal variation in neutral source**

$$D/f(\theta)^2 d^2 n_e/d\xi^2 = \int n_n n_e \sigma V_e \, d\theta \qquad (1)$$

$$V_H/f(\theta)\,\partial n_n/\partial \xi = -n_n n_e \sigma V_e \qquad (2)$$

where $\xi = 1-\rho$ is the flux coordinate and

$f(\theta) = 1/d\xi/dx$ is the flux expansion

In scrape-off layer $(\xi \geq 0)\; n_e(\xi) = n_{sep}\exp[-\xi/\sqrt{D\tau_{\parallel}}]$

Inside the separatrix $(\xi \leq 0)$,

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

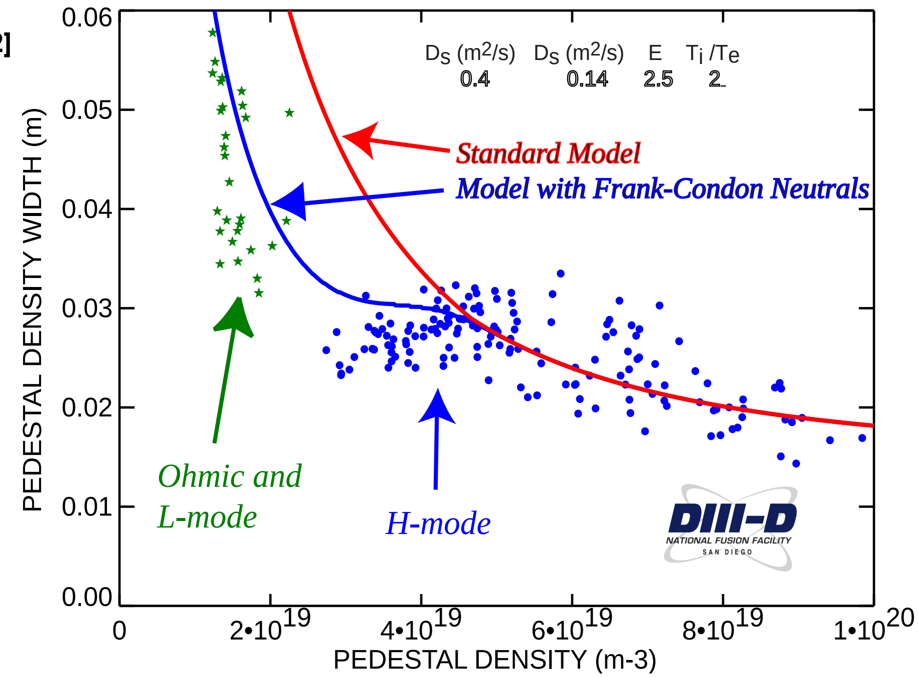
where $C \equiv 0.5\sinh^{-1}(U), U \equiv [(\sqrt{D\tau_{\parallel}})\sigma V_e/2V_H]\, f(\theta_0)\, n_{ped}$,

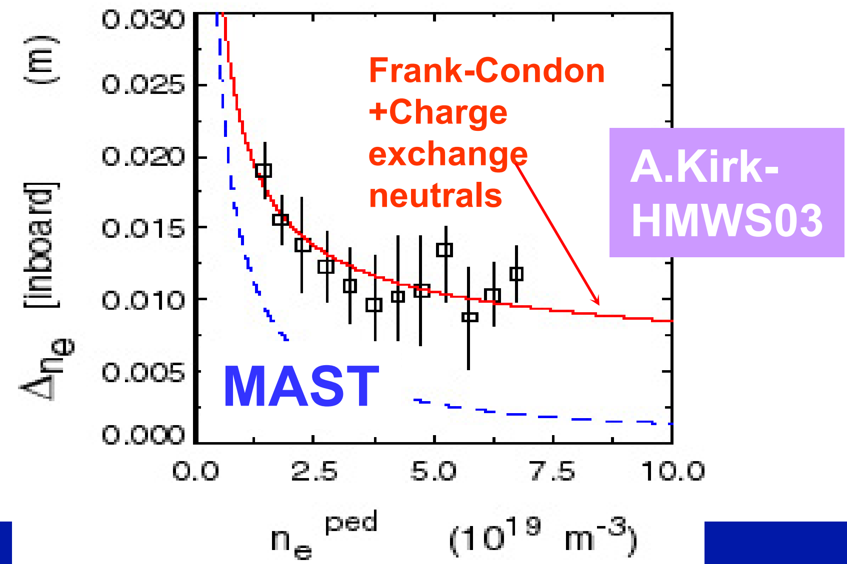
and $\tau_{\parallel}$ is particle confinement time in SOL

For $U \leq 1$, $n_{ped}/n_{sep} \propto 2/U \Rightarrow$

$$n_{ped}^2 \propto n_{sep}/f(\theta_0)$$

$$\Delta_{ne} \propto 1/n_{ped}$$





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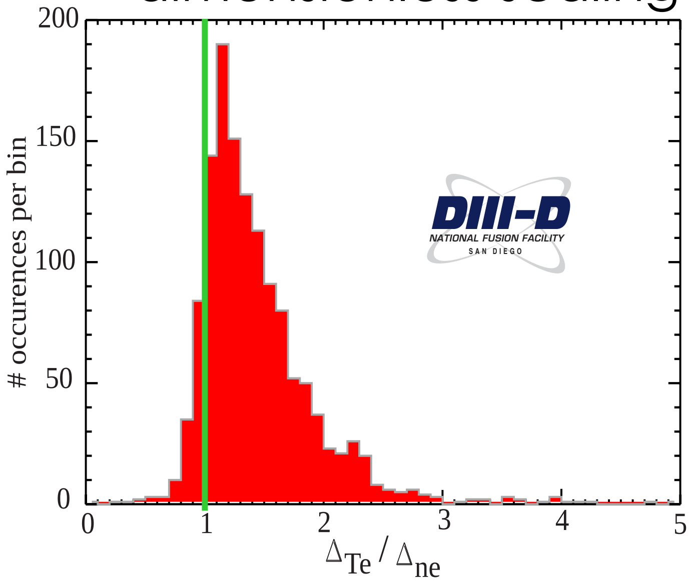
[1]W. Engelhardt, W. Fenenberg, J. Nucl. Mater. 76-77 (1978) 518.
[2]M.A. Mahdavi et al., "High Performance H-mode Plasmas at Densities above the Greenwald Limit", 2000 IAEA meeting, submitted to Nucl. Fusion

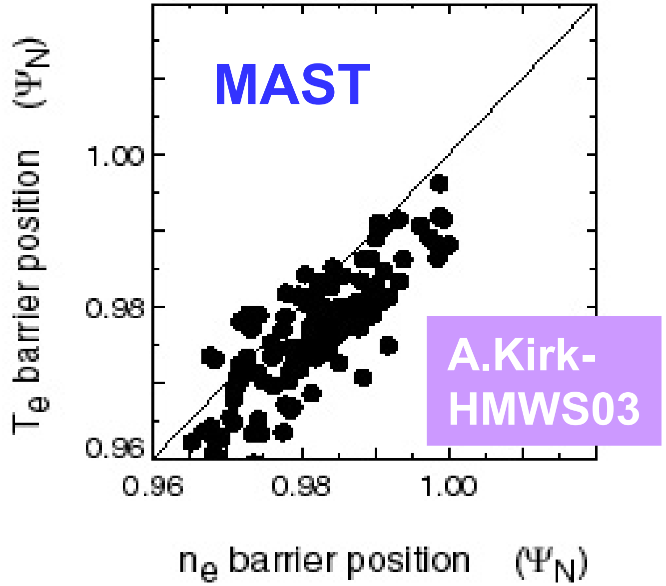
Can structure of pedestal n_e profile be set with particle source structure independent of ETB width ?

- **Hinton, Staebler[1]: Velocity shear can take on any value consistent with radial force balance ⇒ structure of particle and heat sources can control velocity shear and transport barrier width.**

$$\Delta \approx [2\lambda L_n^{Sep} \ln(c\Gamma_{Sep}Q_{Sep})]^{1/2}$$

- **Dimensionally identical experiments which match plasma shape and dimensionless parameters at top of pedestal in different size tokamaks, CMOD/DIII-D, CMOD/JET, JET/DIII-D, all give $\Delta_T \propto a$**
  - But using Engelhardt-Wagner-Mahdavi model in Hinton, Staebler formula gives $\Delta \approx 2V_H^{Sep}/(\sigma V_e n_e^{Ped})[\ln(c\Gamma_{Sep}Q_{Sep})]^{1/2}$ and then applying the dimensionless scaling constraints $n \propto a^{-2}$, $T \sim a^{-1/2}$ gives $\Delta \propto a^{7/4}$

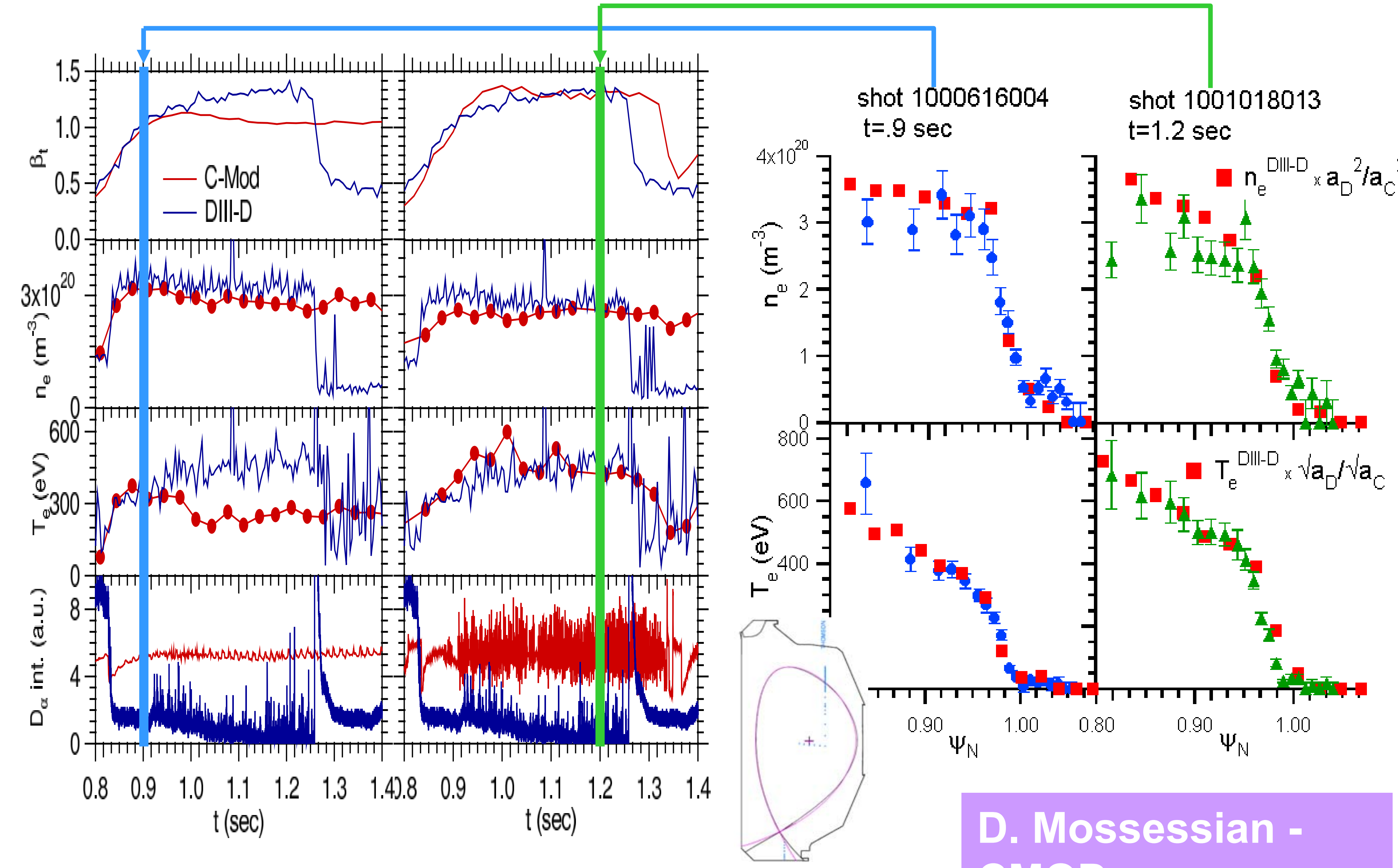




- **Δ_T and Δ_n correlated**
- **High ∇n_e narrower and outboard of high ∇T_e**
  - Consistent with edge particle source setting n_e profile if source lies within the ETB

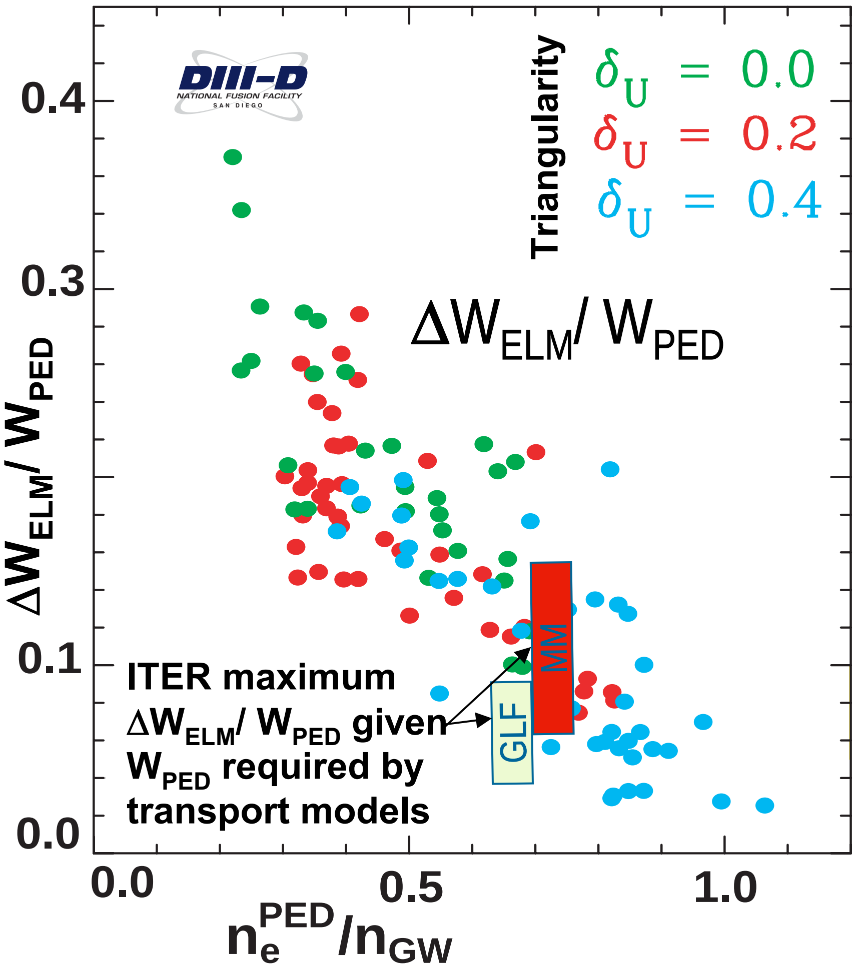
[1] Hinton, F.L., Staebler, G.M., Phys. Fluids B **5** , (1993), 1281.

Δ/a, β_T, ELM behavior all match under dimensionally identical pedestal conditions in CMOD/DIII-D comparison experiment

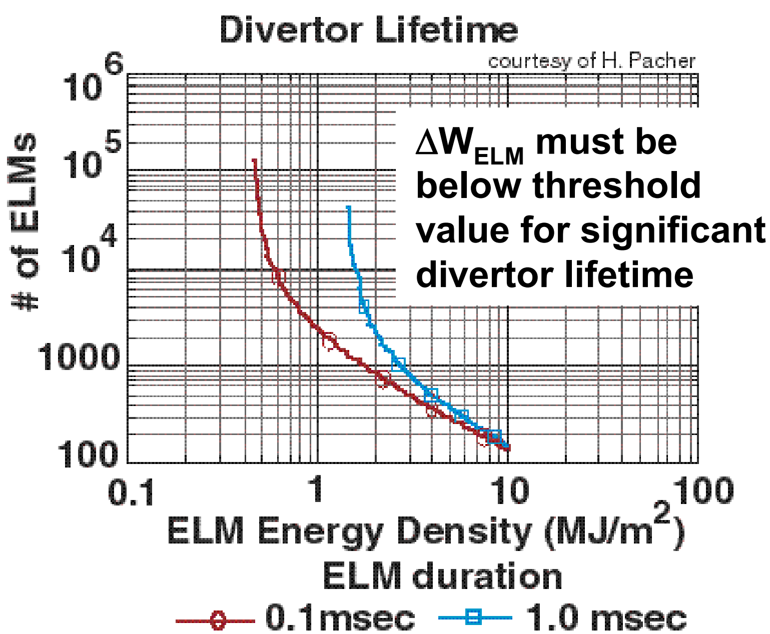


D. Mossessian - CMOD

A technique for significantly reducing ELM size is required for H-mode based tokamak reactor (ITER)

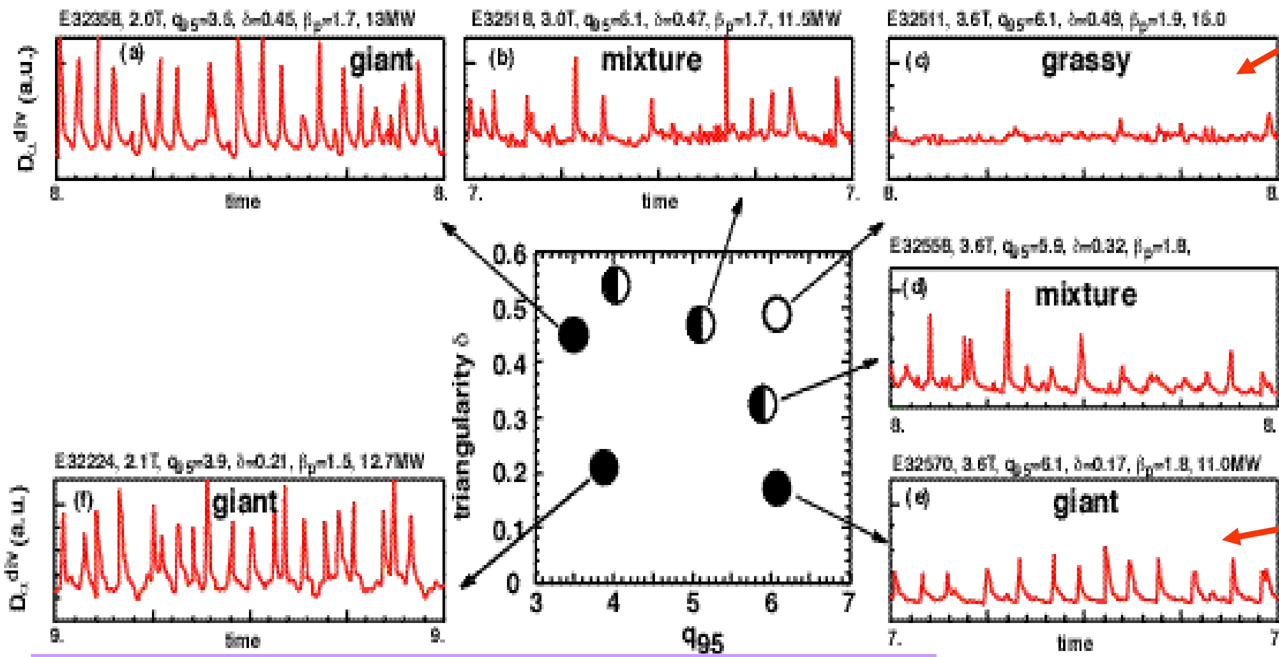


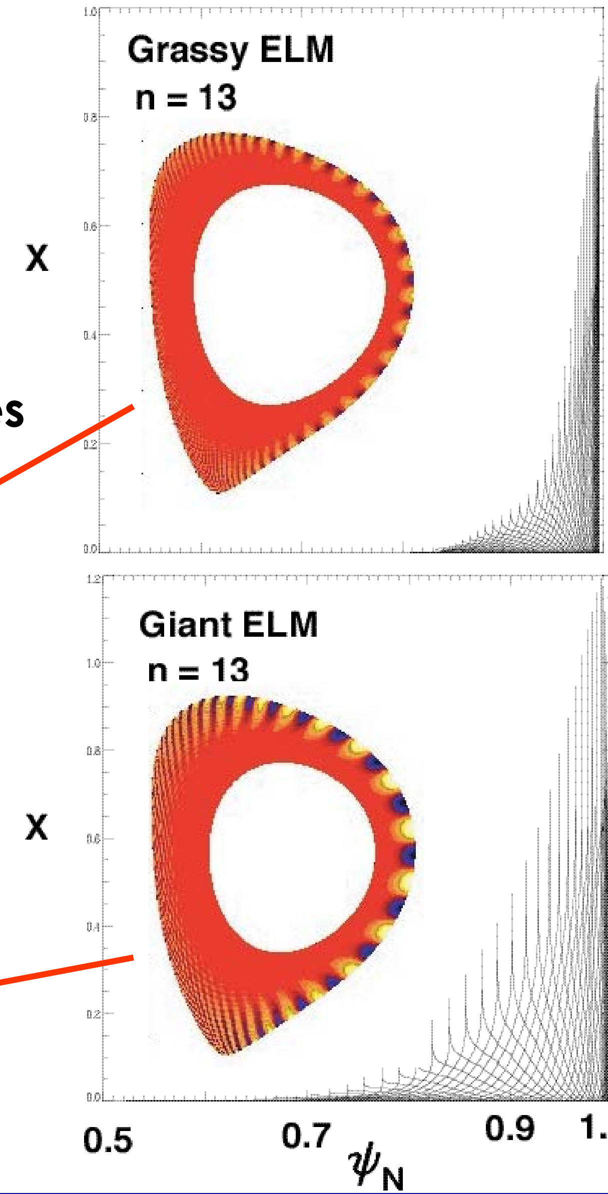
- Divertor target lifetime in ITER would be strongly reduce below a threshold ELM energy loss.
- Type I ELM energy loss is normally proportional to p_{PED} as p_{PED} varies with I_P and shape, but decreases as the density is raise with gas puffing
- Scaling of ΔW_{ELM} from present tokamaks gives ELM size for ITER that is marginal at best.



ELM size (energy loss) correlated with peeling-ballooning eigenmode width in JT-60U high triangularity discharges

- Giant ELMs ~ 100 Hz, small amplitude "grassy" ELMs ~ 500-1000 Hz
- At intermediate δ and q_{95} mixtures of giant and grassy ELMs
- Unstable edge modes in grassy elm discharges have narrow radial mode width (ELITE Code).
- Changes in radial width related to difference in q profiles





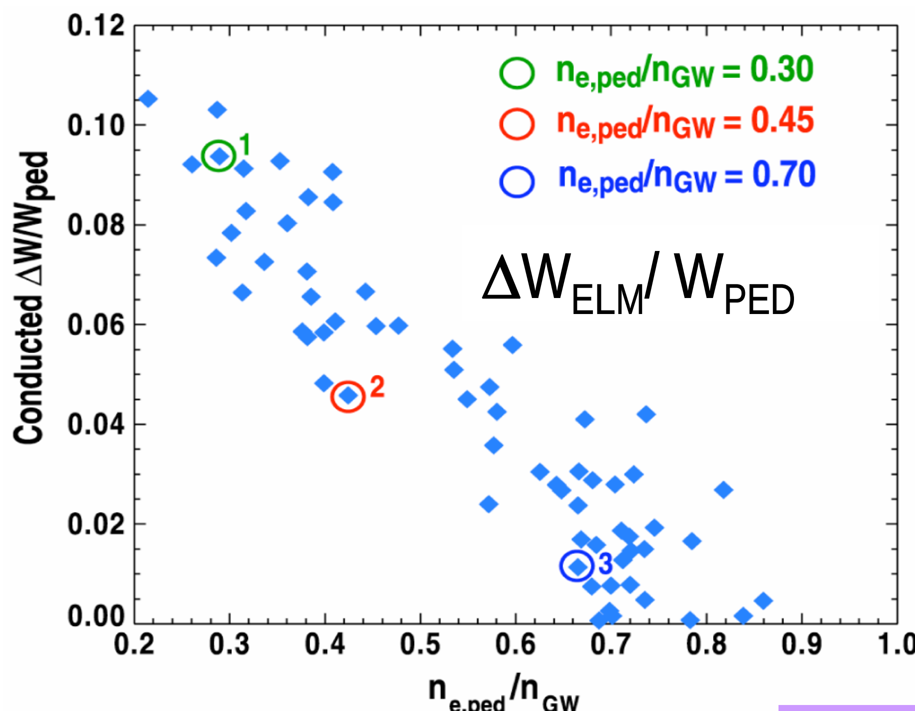
LL. Lao, et. al, Nucl. Fusion, 41 295 (2001).

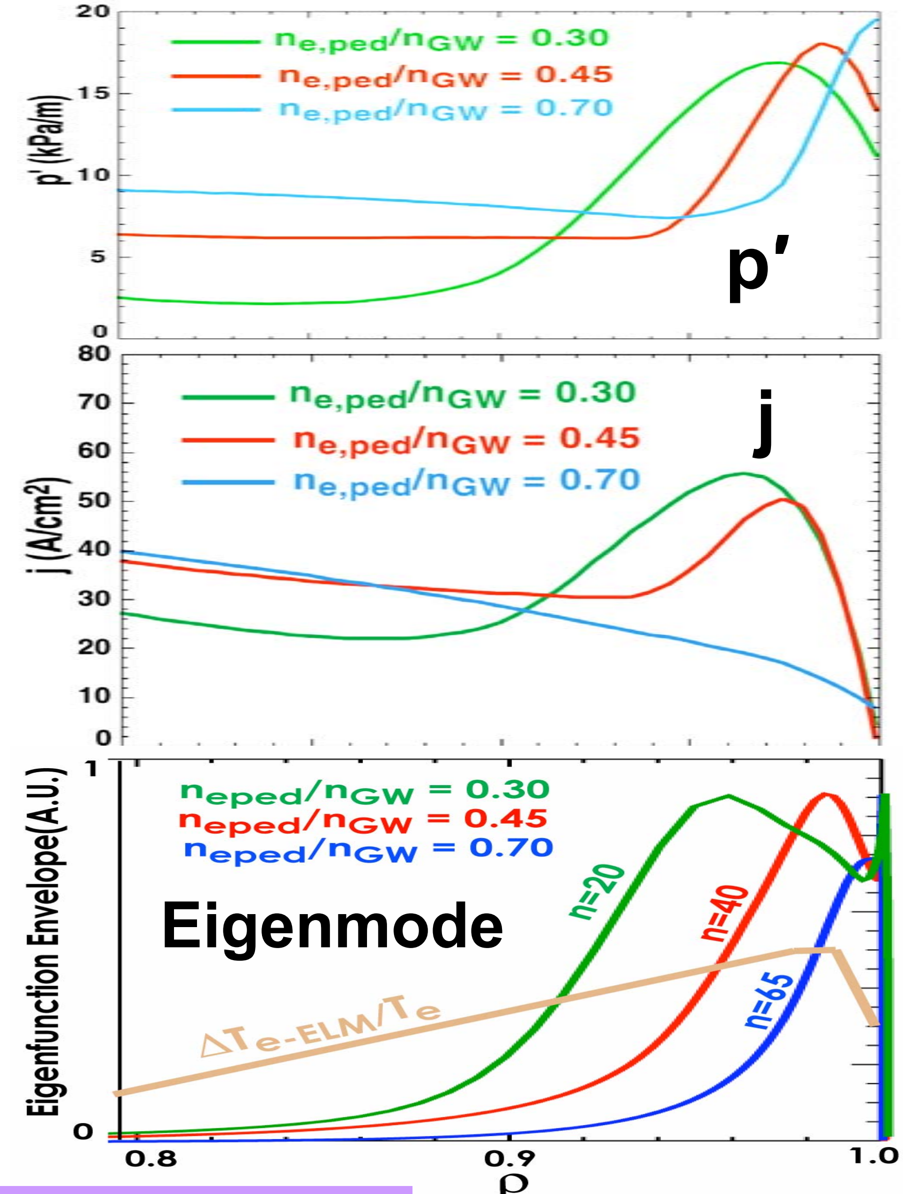
A path to small ELMs with large p_{ped} ?

- **Control particle source to move steep gradient region in density toward separatrix ⇒ narrowed steep gradient region in pressure ⇒ narrowed PB eigenmode width ⇒ smaller ELMs**
- **Improved stability on more strongly shaped surfaces near separatrix + increased p′ at reduced width for PB modes may make up for the reduced pressure width thus keeping pressure more constant**
  - Increasing collisionality near separatrix should reduce the bootstrap current in detriment to p′
- **Will ETB width (Temperature profile) be effected ?**

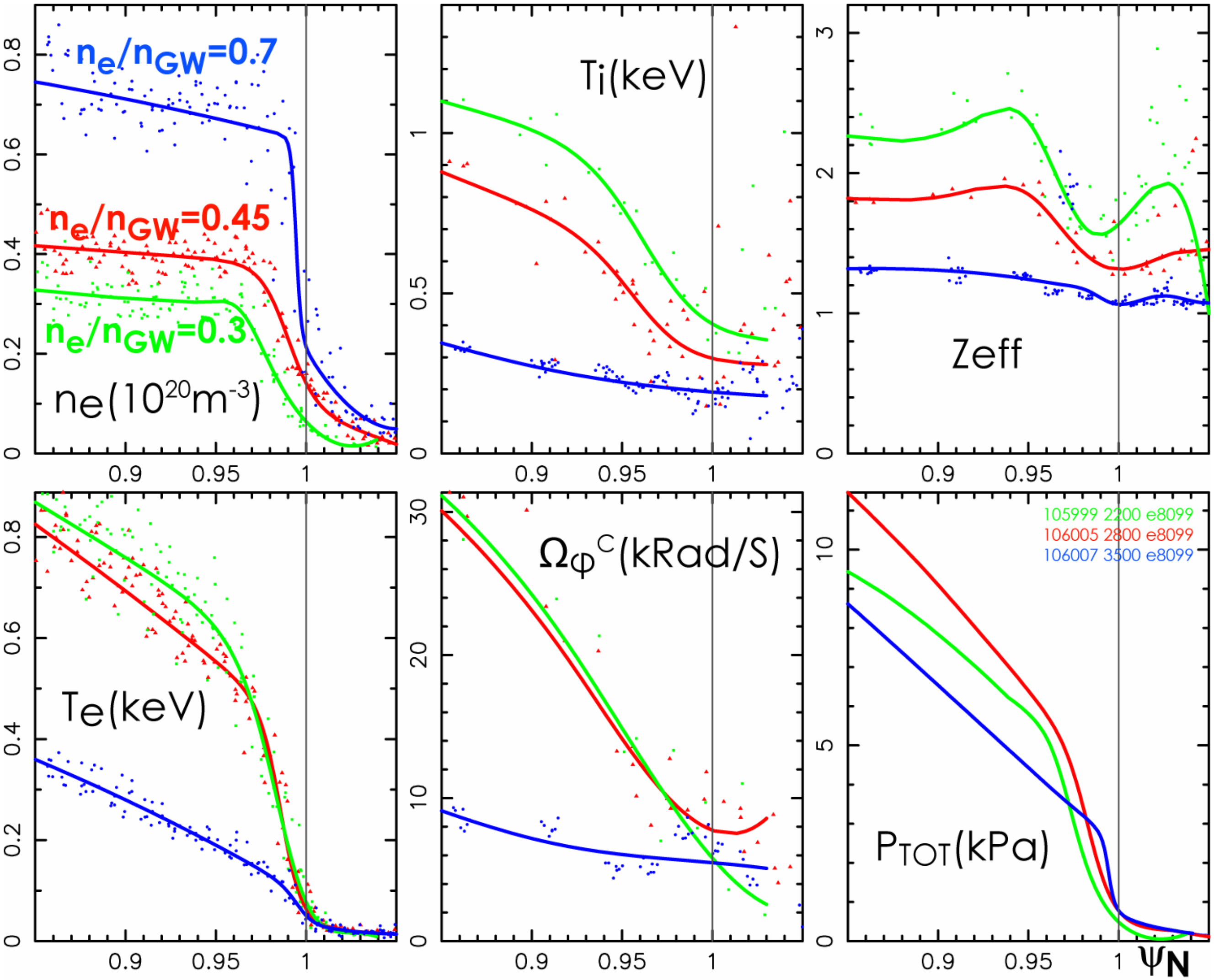
ELM size and PB eigenmode width decrease as extent of high p′ region is reduced with increased n_e

- Eigenmode width tracks p′ width
- Bootstrap current reduced at high n
- ELM effect extends radially inward beyond eigenmode width
- Radial extent of ELM effected region does not vary with n_e , only amplitude

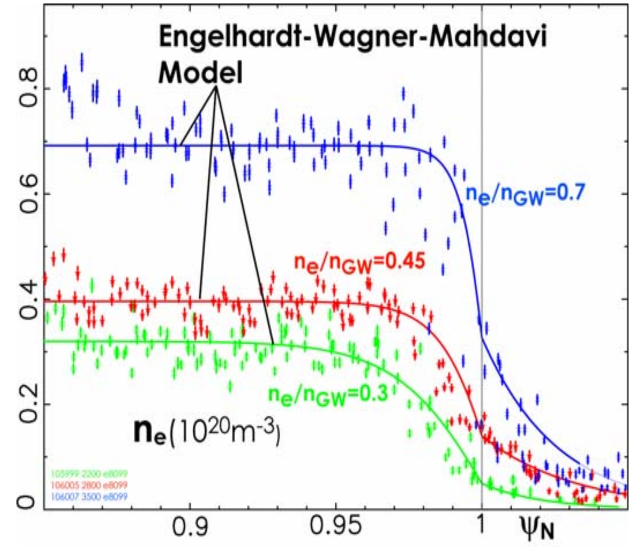




Steep gradient regions in both n_e and T_e are reduced in width with D_2 gas puffing to high density

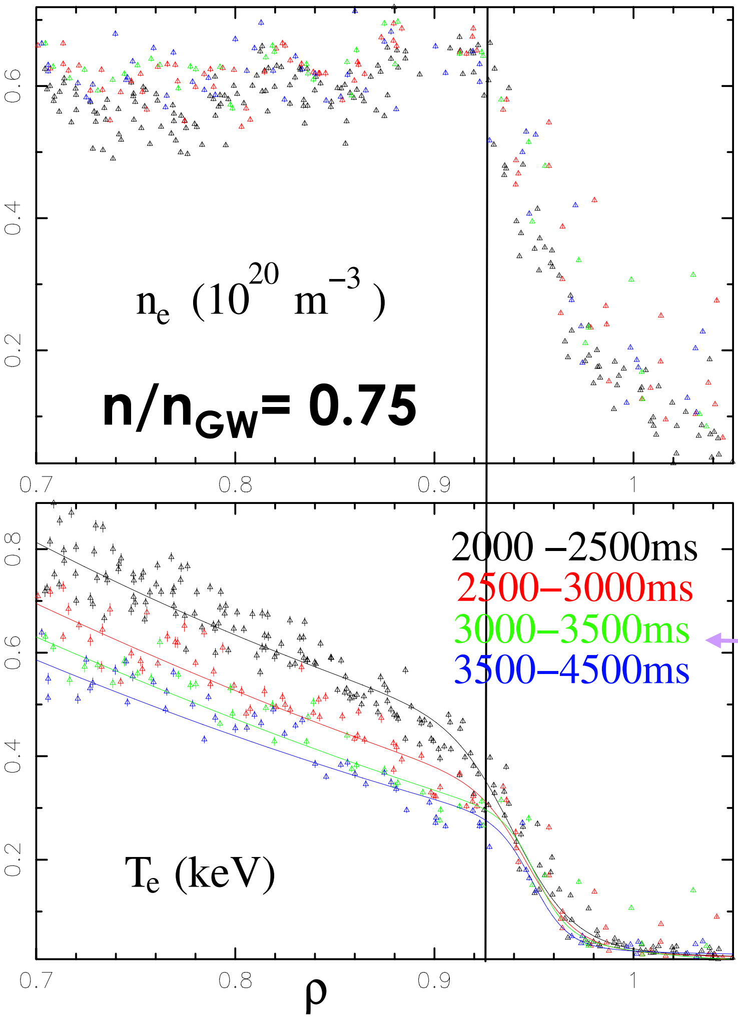


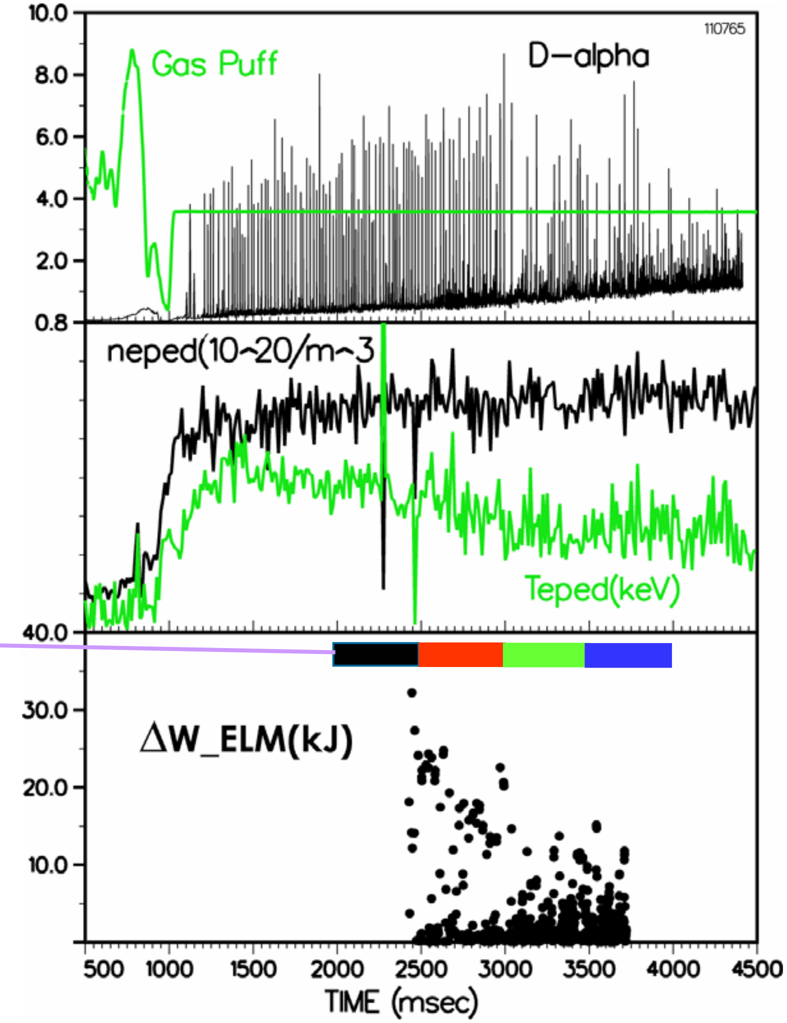
- **Steeping of n_e profile at high density is consistent with neutral penetration model**



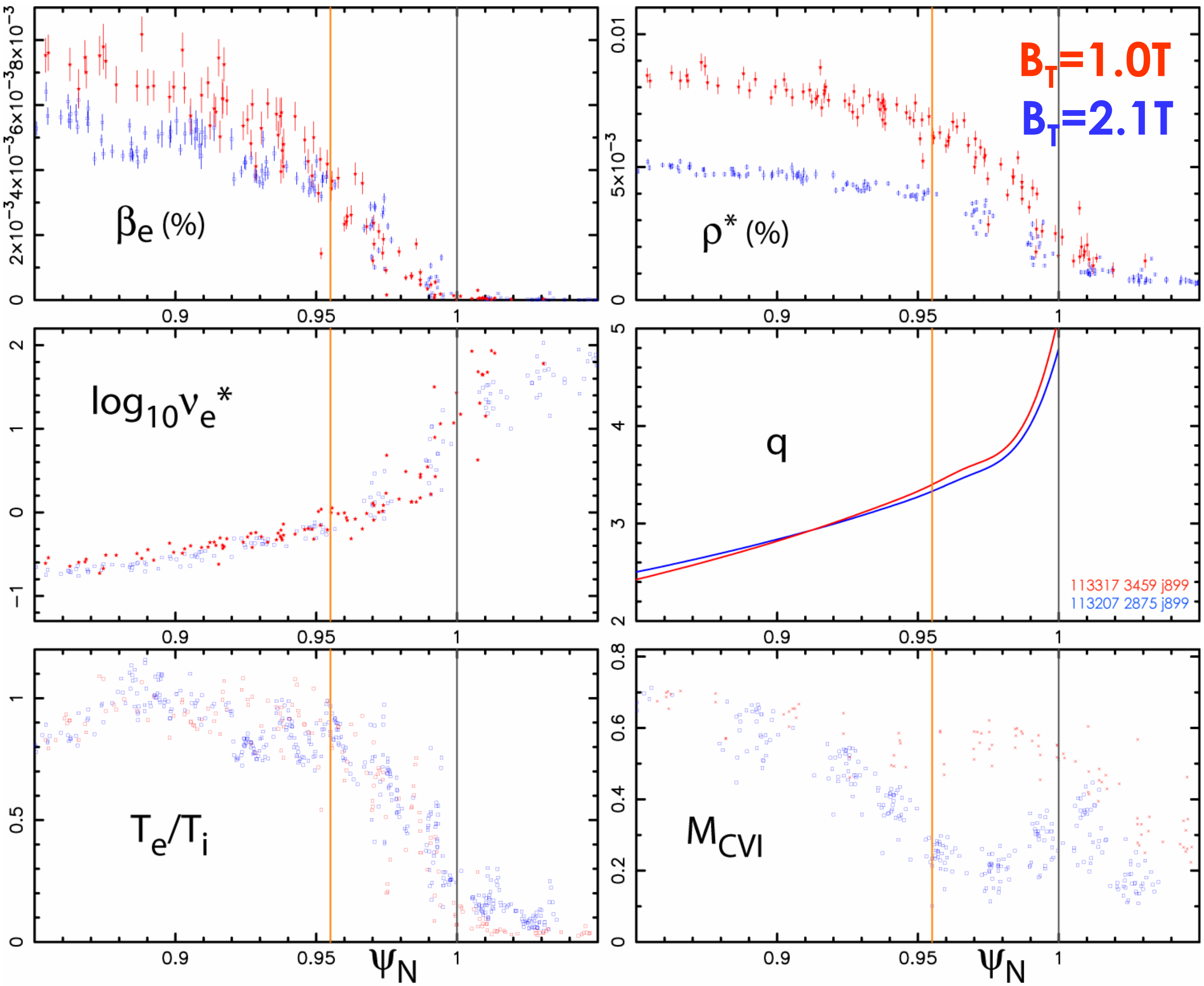
Steep gradient region in T_e narrows and ELM size is reduce with D_2 gas puffing

- **Width of Te steep gradient region is narrowed with D_2 gas puffing even though pedestal n_e does not increase**





In ρ_* scaling experiment n_e and neutral penetration are varied with B (fixed q) without additional gas puff



- **Maintaining q, β, and ν_* fixed as B is varied at fixed plasma shape requires**

$$n \sim B^{4/3}, \quad T \sim B^{2/3}$$

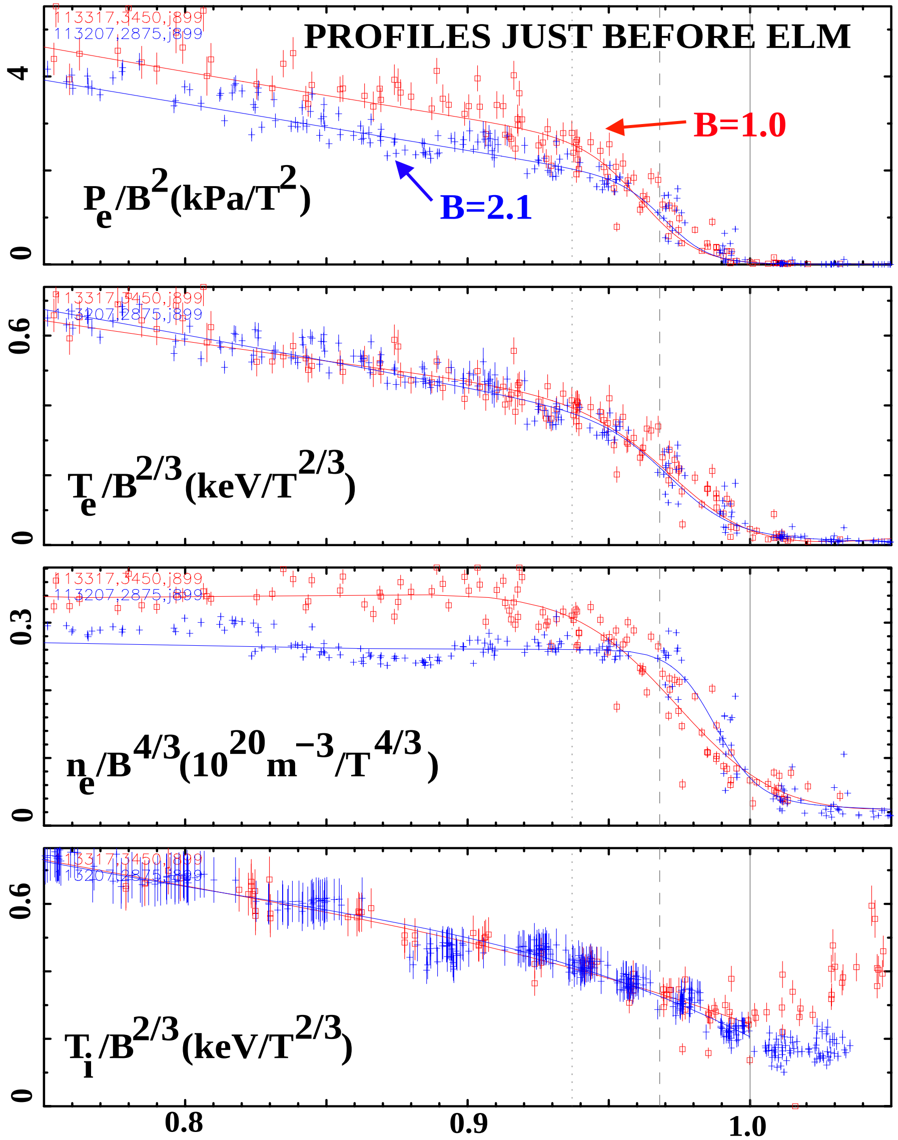
ρ_* then varies as

$$\rho_* \sim B^{-2/3}$$

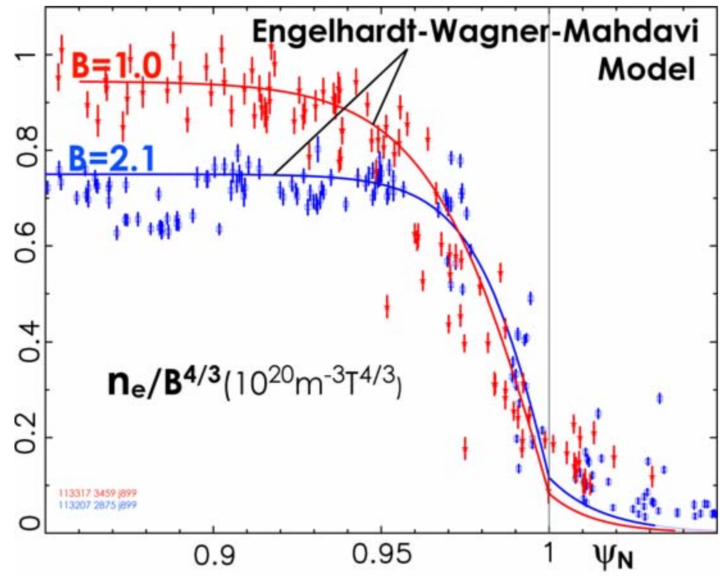
- **Neutral penetration increases with ρ_***

$$\hat{\Delta}_n \sim \rho_*^2 \sim B^{-4/3}$$

In ρ* scaling experiment ETB width remained fixed as reduced neutral penetration at high B reduced the p′ width

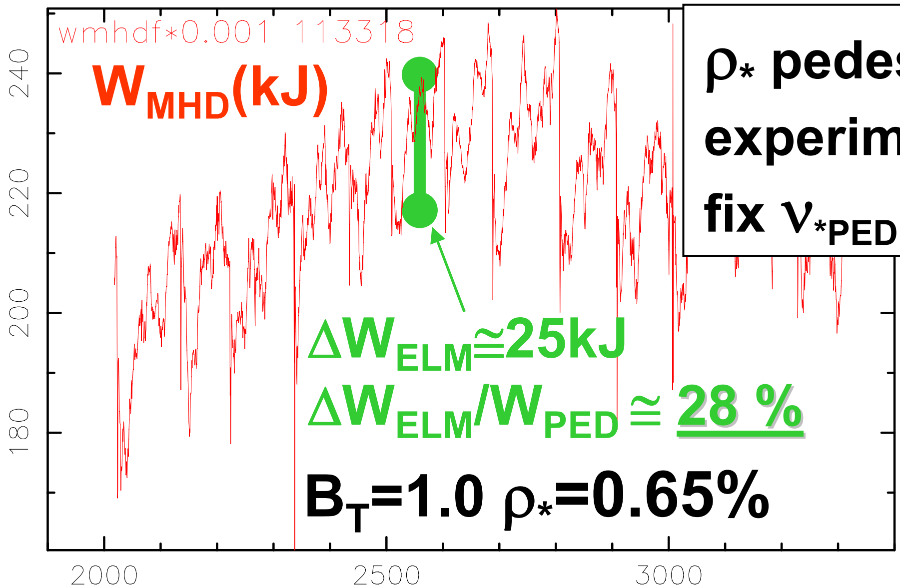


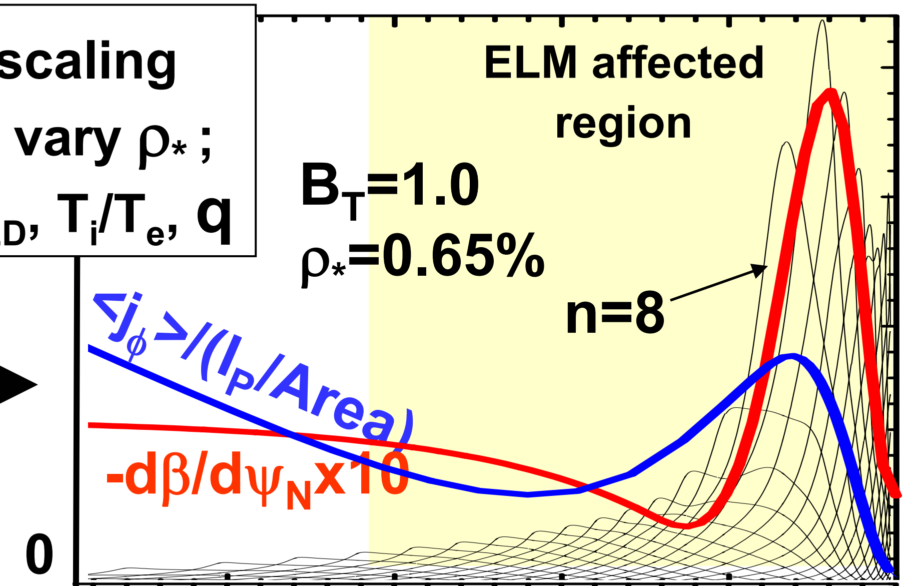
- **At the high B, high n_e, point in ρ* scan, n_e profile is shifted outward relative T_e profile, and relative to n_e profile in low B, low n_e , high ρ* discharge**
  - High p′ region shifted outward but p′ was fixed ⇒ β_{PED} reduced

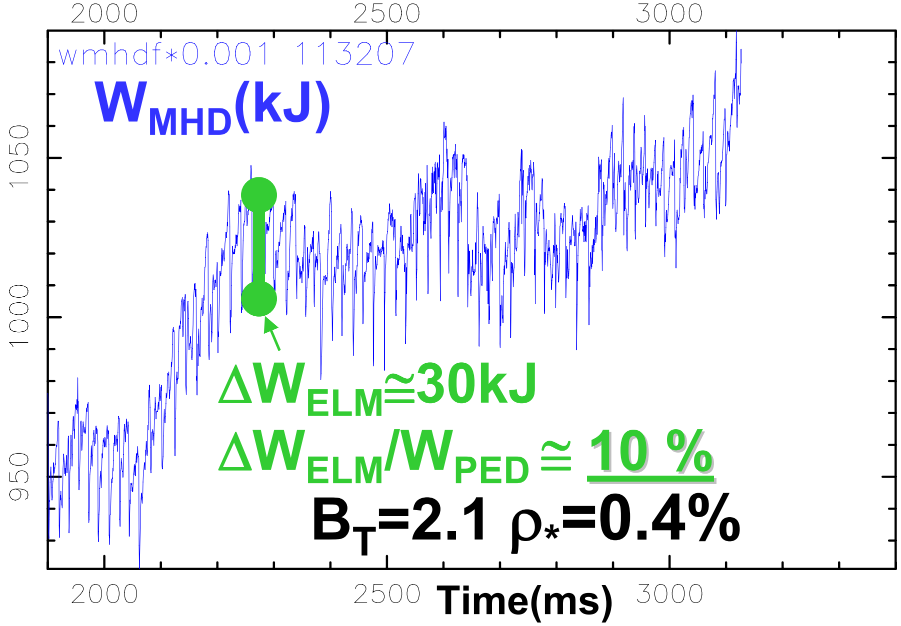


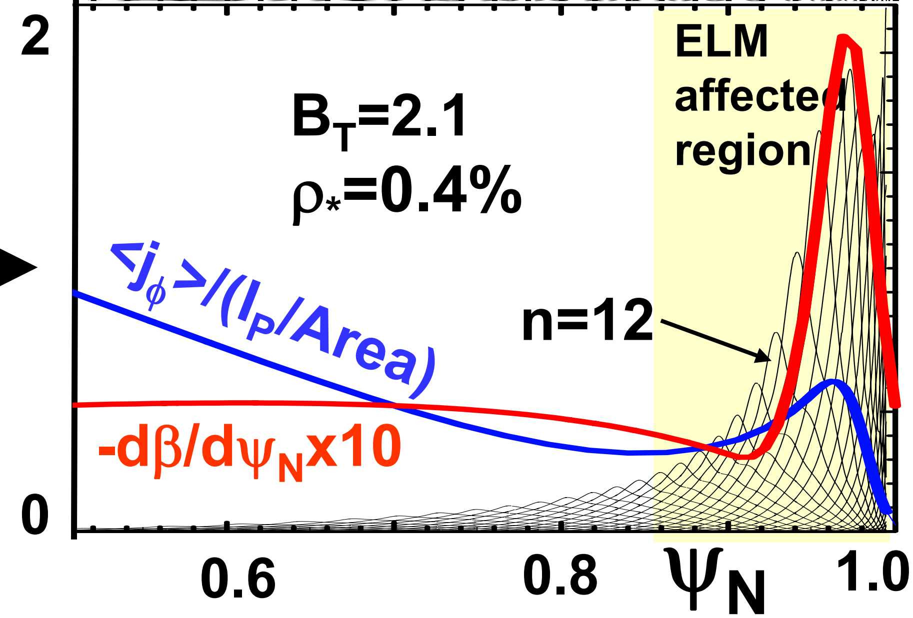
ELM size and PB eigenmode width decrease as extent of high p′ region is reduced at reduced ρ_* (increasing n_e)

ρ_* pedestal scaling experiment: vary ρ_* ; fix ν_{*PED}, β_{PED}, T_i/T_e, q

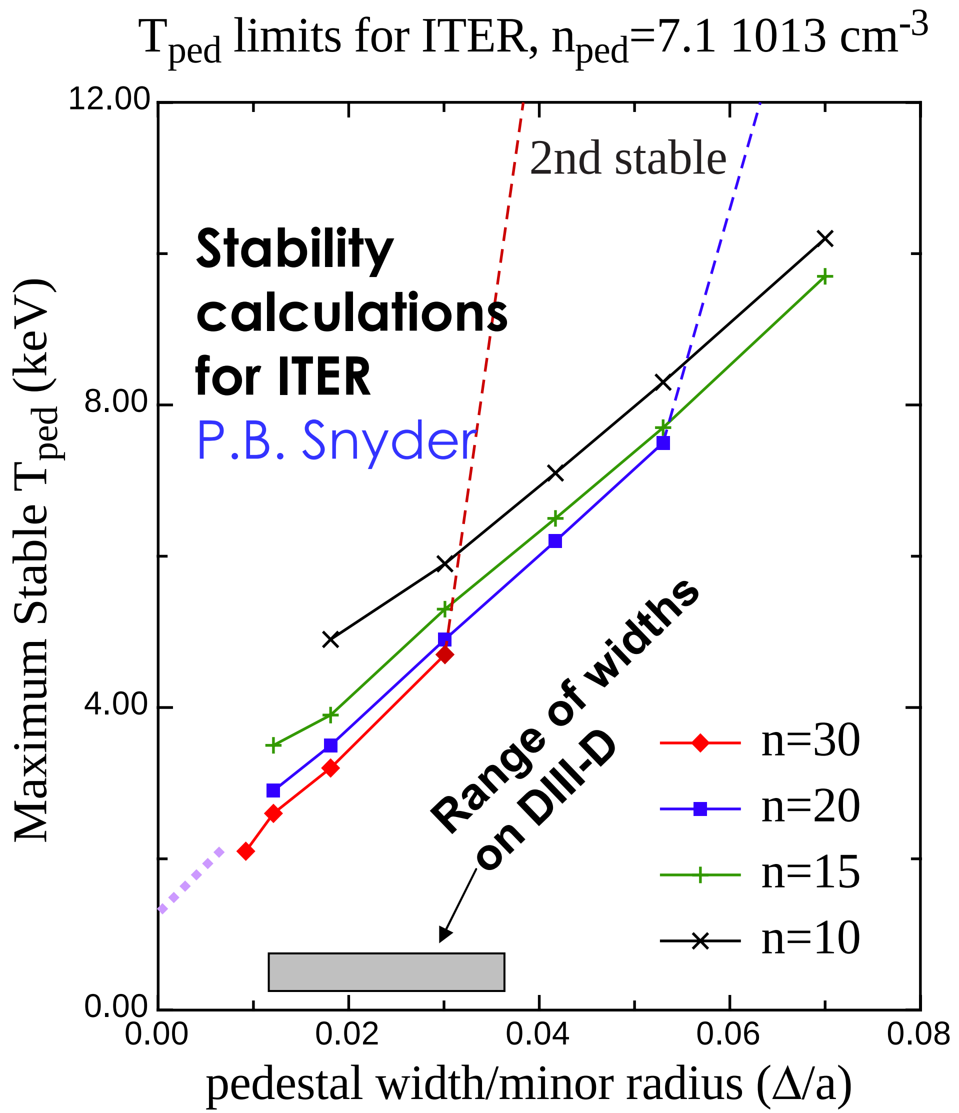








Calculations for ITER indicate pedestal p' should increase at small widths

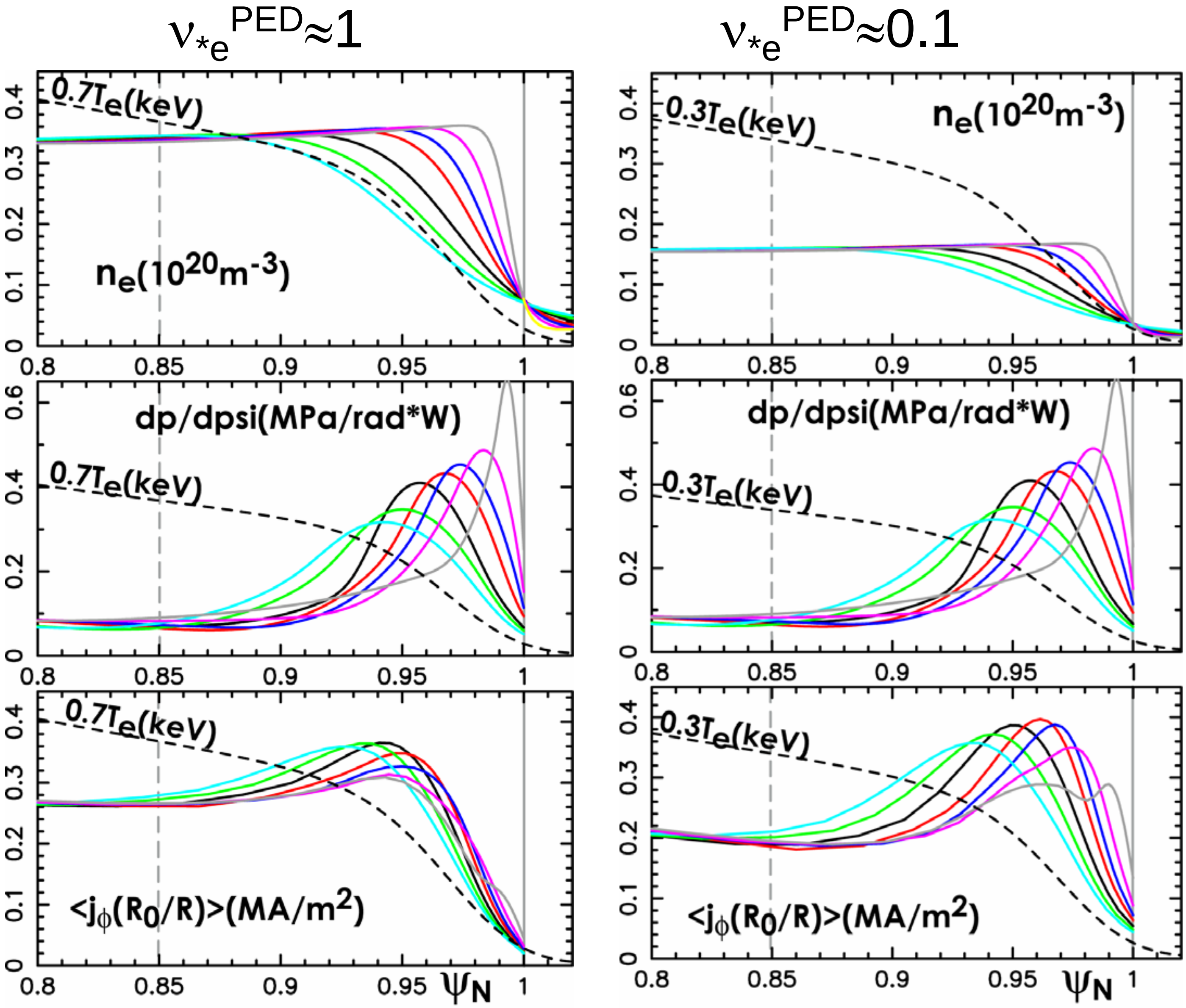


- Curves are offset linear ⇐ p' increases as small width
- Difference in ITER might be lower collisionality allowing bootstrap current to maintain second stable access as steep p' region shifts toward separatrix and lower temperature.

Analysis of the effects of pedestal density profile shape on achievable β_{PED} and PB eigenmode width.

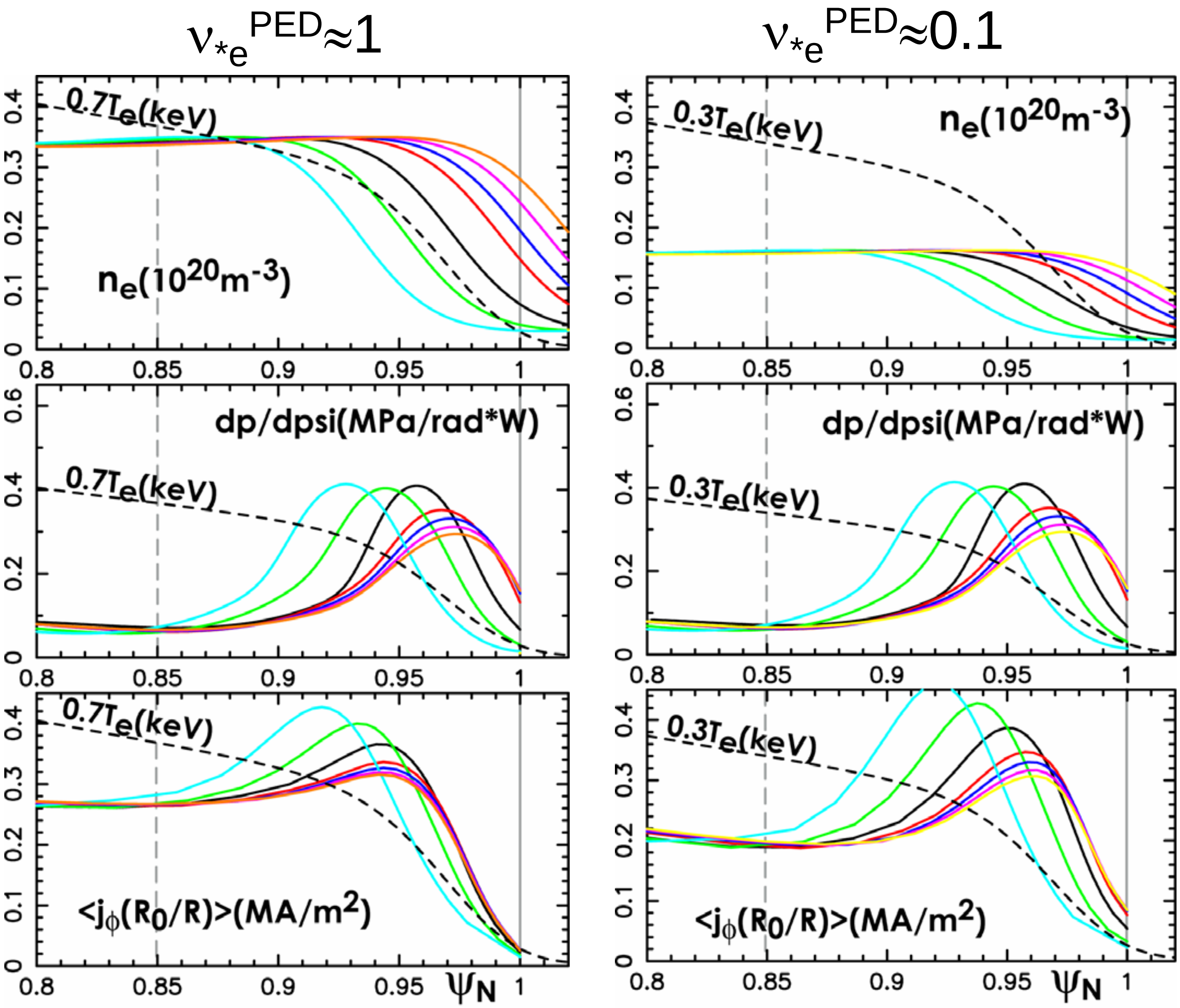
- **Begin with equilibrium for high ρ_* discharge in ρ_* scan.**
- **At fixed pedestal n_e, vary n_e profile. Two methods:**
  - Compress against separatrix ⇒ varied n_e gradient and relation to T_e profile
  - Rigid shift ⇒ varied n_e relation to T_e profile
- **Increase T_{PED} at fixed T profile shape until PB mode becomes unstable ($\gamma > \omega_{*e}/2$) ⇒ maximum β_{PED}**
  - Current distribution in pedestal determined self consistently by running a transport simulations with ONETWO code
    - Both bootstrap (Sauter model) and Ohmic current
- **Width of steep p′ region taken to be PB mode width (can be confirmed in the future)**

Pedestal density profile scan to determine effect of n_e profile on achievable β_{PED} 1: compress against separatrix



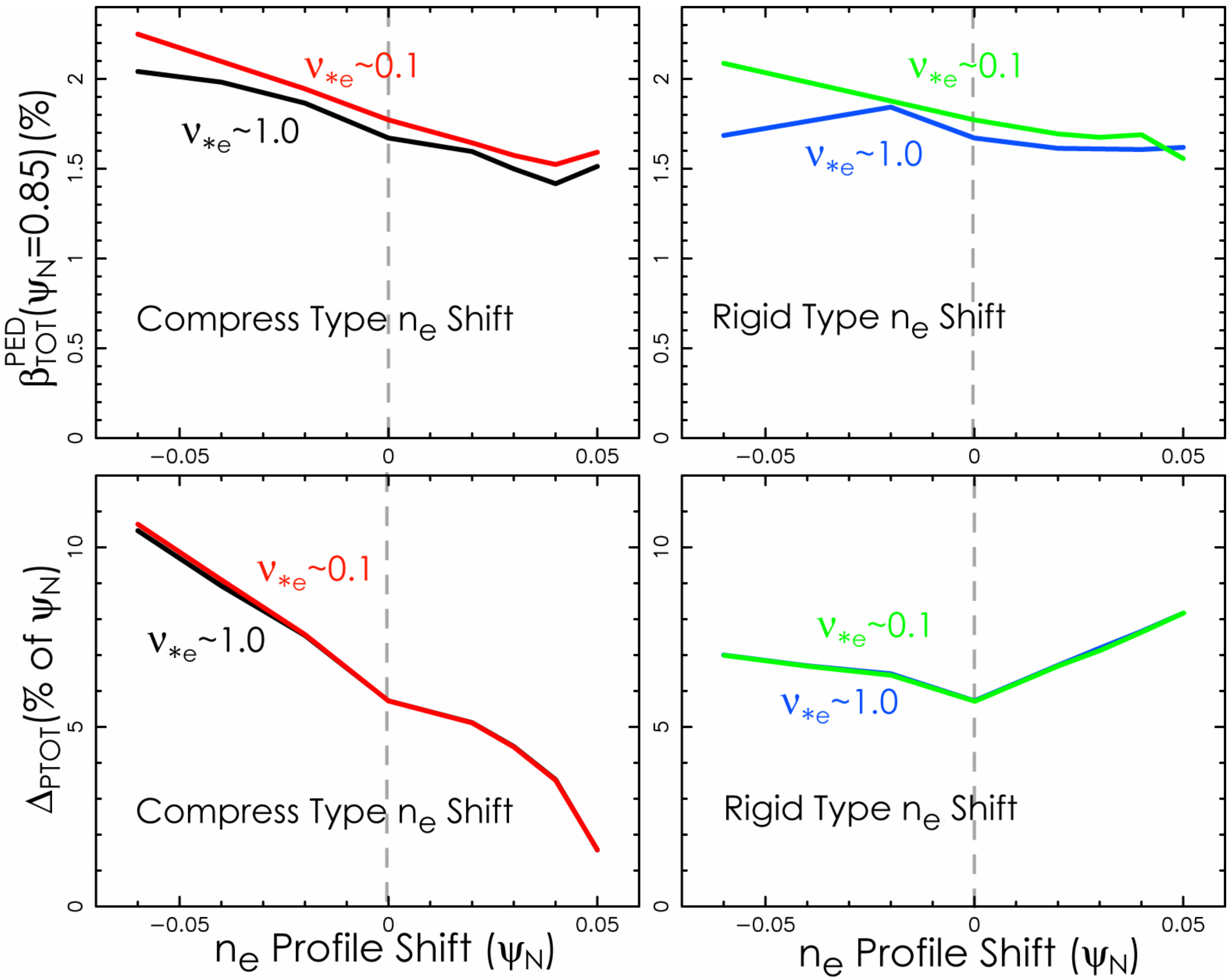
- **Pedestal n_e and shape of T profiles fixed**
- **n_e^{SEP} fixed and n_e compressed against separatrix**
- **T_{PED} increased until PB mode becomes unstable, $\gamma > \omega_{*e}/2$, to determine maximum pedestal pressure**
- **Higher collisionality case has reduced current near the separatrix**

Pedestal density profile scan to determine effect of n_e profile on achievable β_{PED} 2: simple rigid shift



- Pedestal n_e and shape of T profiles fixed
- n_e shifted relative to T profile
- T_{PED} increased until PB mode becomes unstable, $\gamma > \omega_{*e}/2$, to determine maximum pedestal pressure
- Width of high p′ not strongly affected by shift
- Higher collisionality case has reduced current near the separatrix

β_{PED} only weakly reduced with narrowing of the n_e steep gradient region in simulation while PB mode (p') width strongly reduced



- **Strongest effect for compression type shift**
- **Only a small difference for different collisionalities**

Conclusions

- **If the n_e profile in the pedestal region can be steepened and moved toward the separatrix without the ETB itself being narrowed, the resulting pressure profile may result in small ELMs while still keeping β_{PED} high**
  - Independence of pedestal T profile from n profile and particle source structure suggested by but still not confirmed by experiments
  - Relation between linear PB eigenmode width and ELM size not understood
- **Need to examine expected density profiles for pellet injection in ITER**
  - Pellet size, velocity, or aiming might be adjusted to produce pedestal n_e profiles with small p′ width but high β_{PED} resulting in small ELMs