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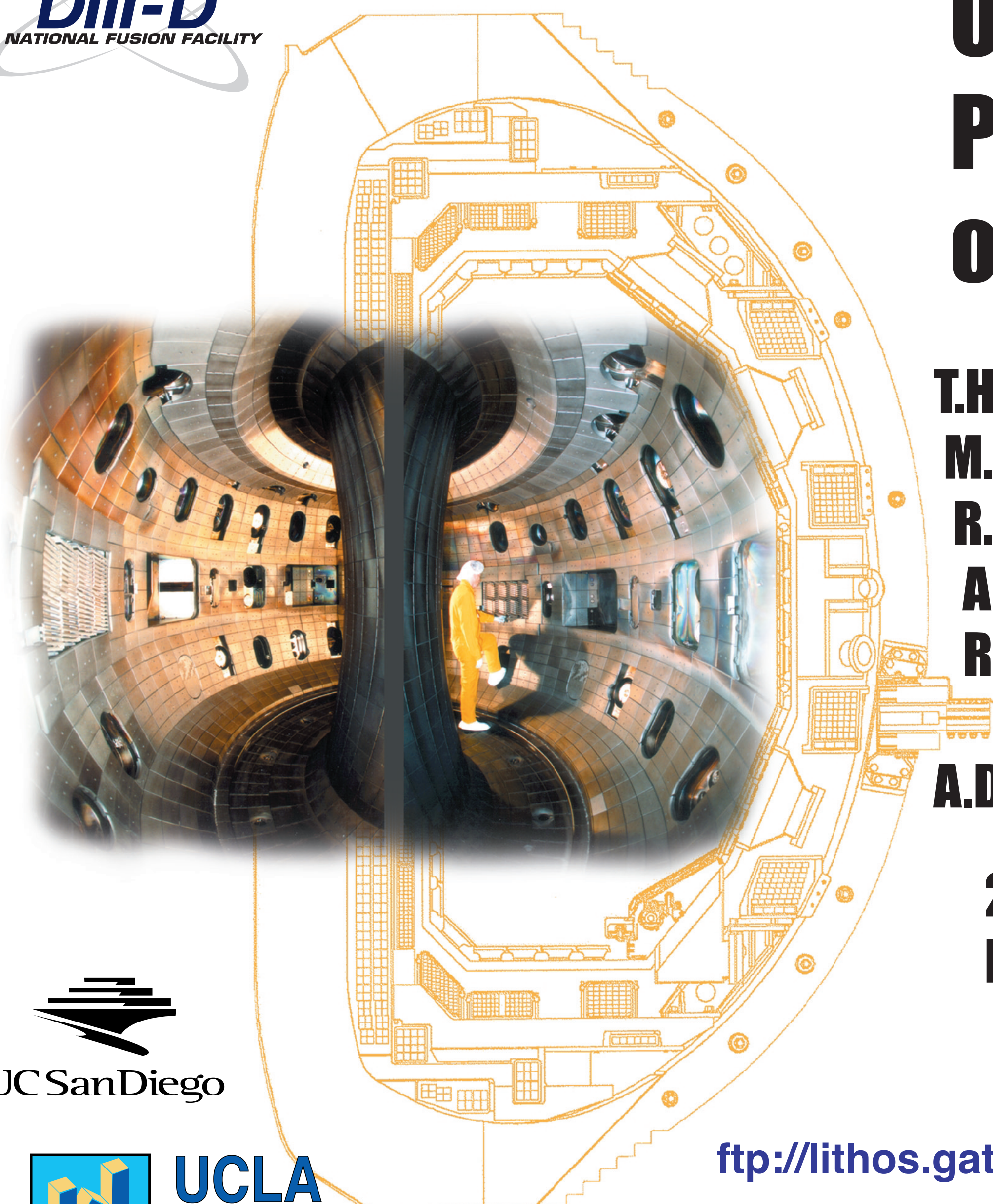

Overview of H-mode Pedestal Research on DIII-D

T.H. Osborne, K.H. Burrell, T.N. Carlstrom, M.S. Chance, M. Chu, E.Doyle, J.R. Ferron, R.J. Groebner, R. La Haye, L.L.Lao, A.W.Leonard, M.A. Mahdavi, G. McKee, R. Moyer, D. Mosesian, G. Porter, P.B. Snyder, G. Staebler, E.J. Strait, D.M. THomas, A.D. Turnbull, M.R. Wade, and the DIII-D Team

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Maderia, Portugal, 18 - 22 June 2001

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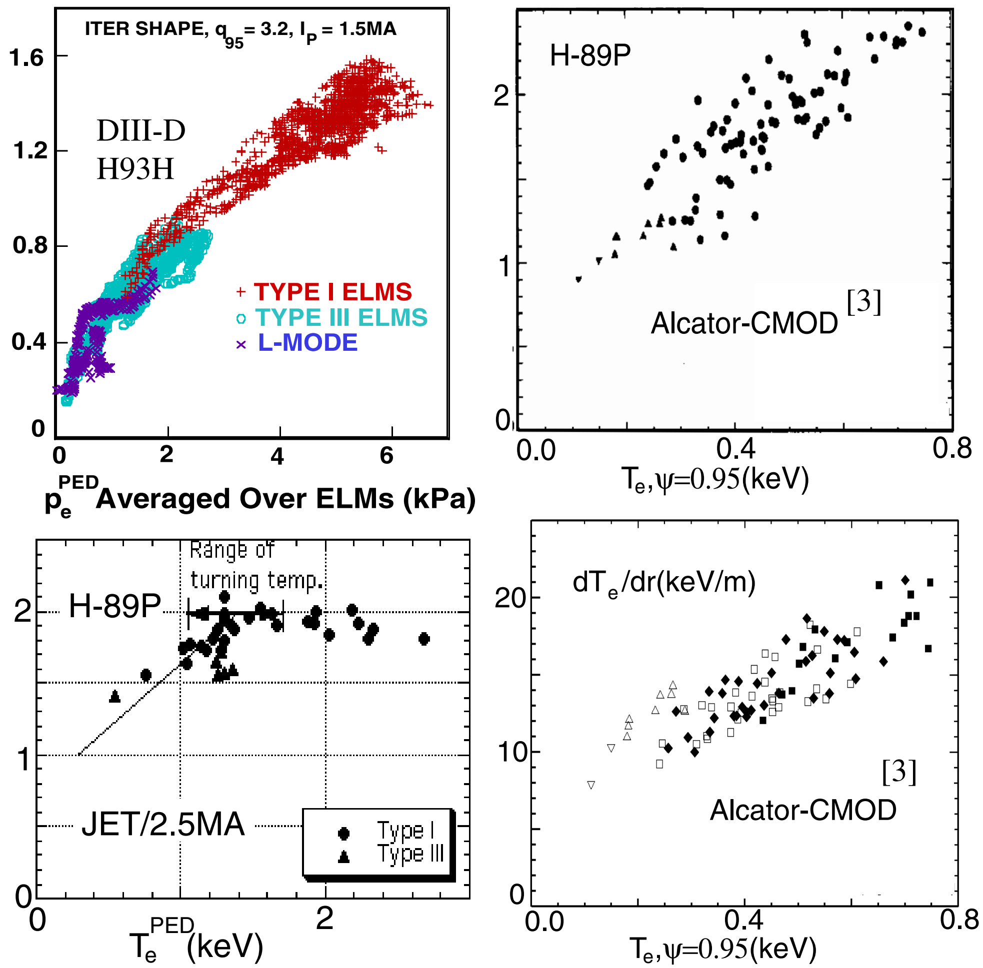
Motivation and Goals for H-mode Pedestal Studies

- Motivation
  - As a boundary condition for core kinetic profiles, H-mode transport barrier characteristics can strongly influence energy transport and β limit.
  - The ELM instability can negatively impact core performance and result in unmanageable divertor power loads.
- Goals
  - Develop a physics based predictive capability for the H-mode pedestal characteristics in the Type I ELM regime to be used as boundary conditions in core transport models, and for possible control of the pedestal parameters.
  - Develop a physics based predictive capability for the effects of Type I ELMs in the core and divertor, for possible mitigation of the negative effects of ELMs
  - Explore alternatives to the Type I ELM regime that may provide a path to high core performance without the negative ELM effects.

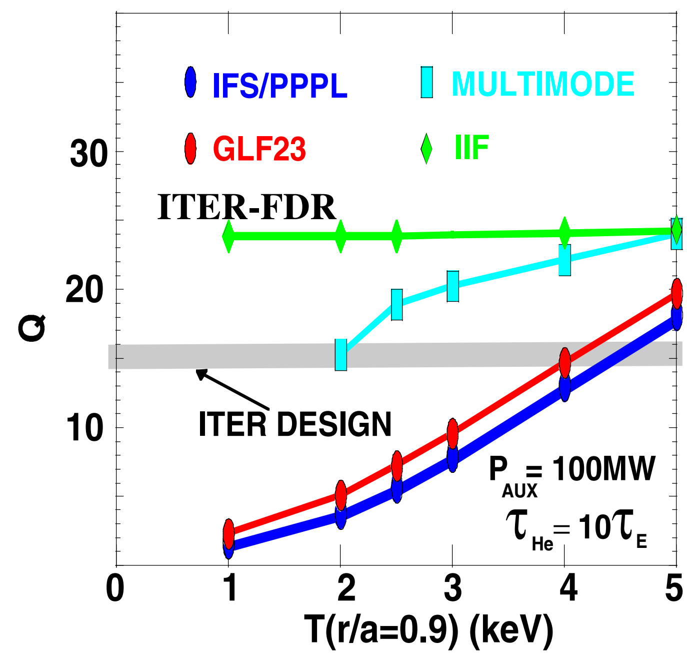
H-mode pedestal may impact H-mode based tokamak reactor performance through temperature profile stiffness.

- Maximum P_F and Q are obtained at min <T> for stable operation => $P_F/P_{LOSS} \sim H^2$

Effect of H-mode pedestal on H factor varies with tokamak possibly due to changes in turbulent transport process[2]



Turbulent transport simulations that predict stiff temperature profiles (ITG) show strong dependence of core on edge [1]



[1] J.E. Kinsey, et al., *Berchtesgarten EPS*, **III** 1081 (1997)

[3] M. Greenwald, et. al Nucl. Fus. **37** (1997) 793.

[2] G.Janeschitz, et.al Maastricht EPS, **23J** (1999) 1445.

H-mode pedestal pressure loss with stiff temperature profiles contribute to H reduction at high density on DIII-D

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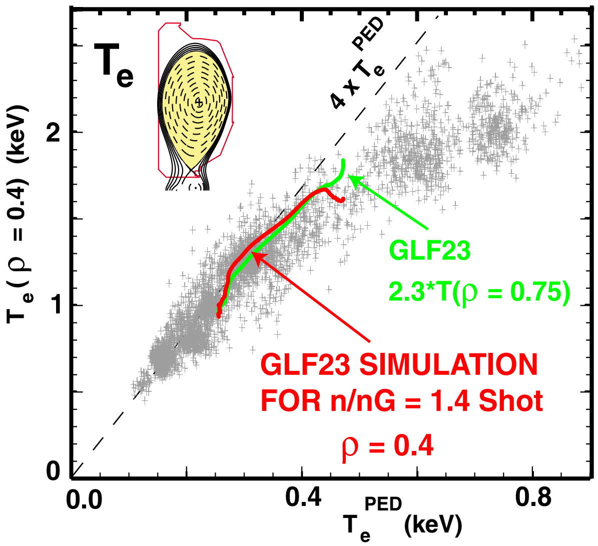
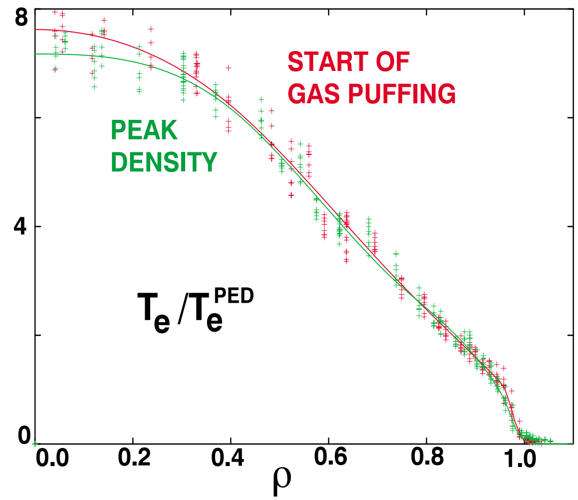
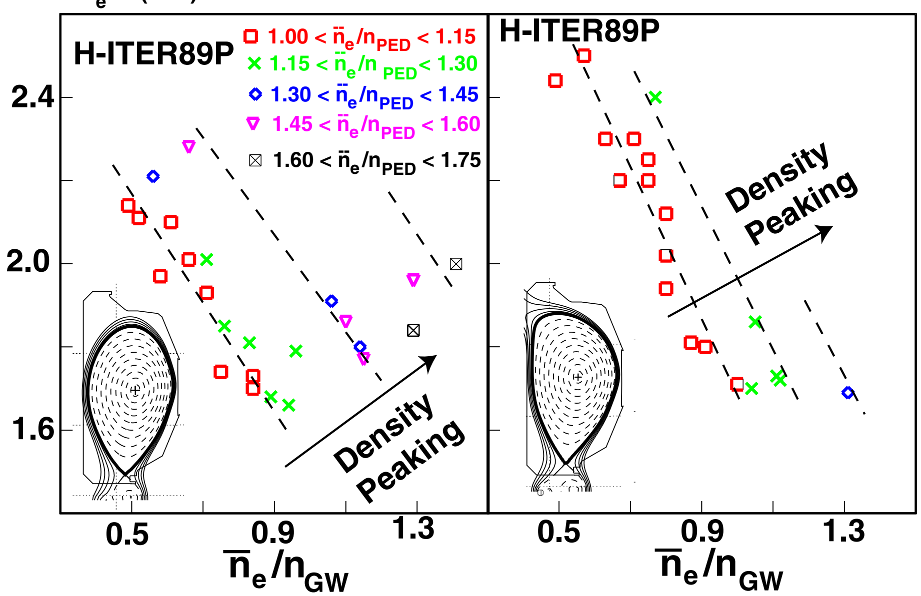
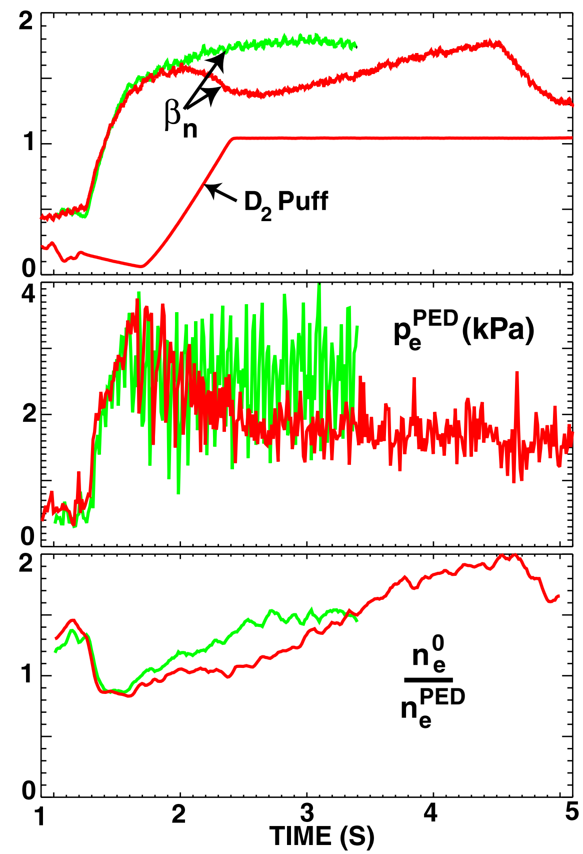
$$T(\rho) = T^{PED} f(\rho) \Rightarrow W_{Total} \propto p^{PED} g(n^0 / n^{PED})$$

- Stored energy loss at high density associated with loss of p^{PED} and stiff T profiles.
- Density profile peaking can compensate for reduced p^{PED}.



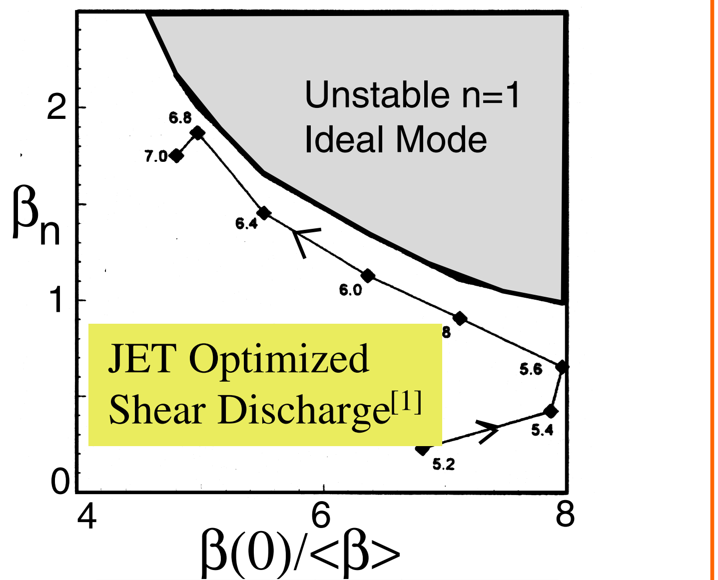


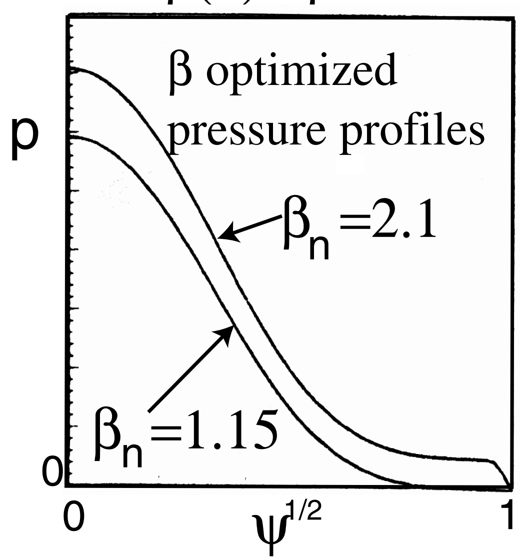




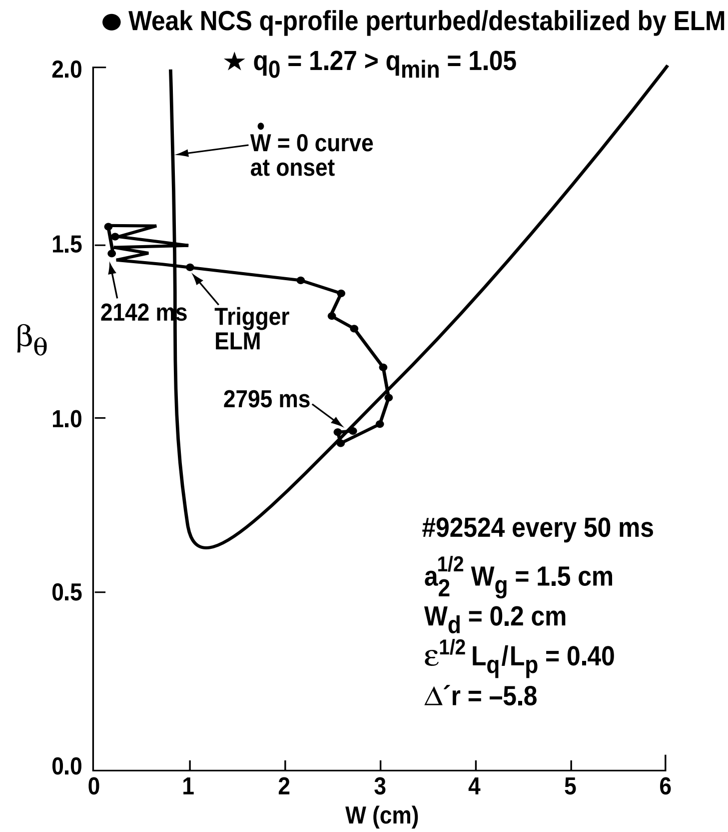
H-mode pedestal can impact core stability

Global β limit increases with p^{PED}



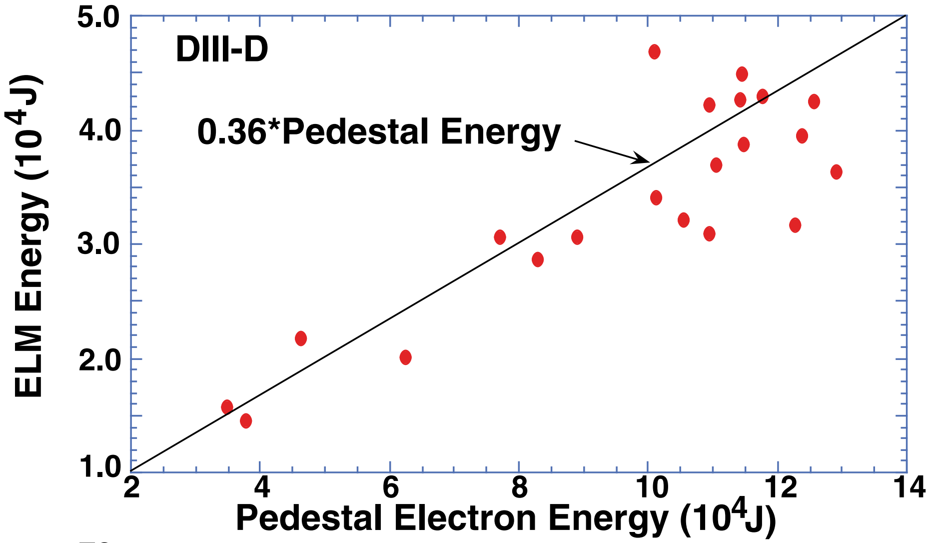


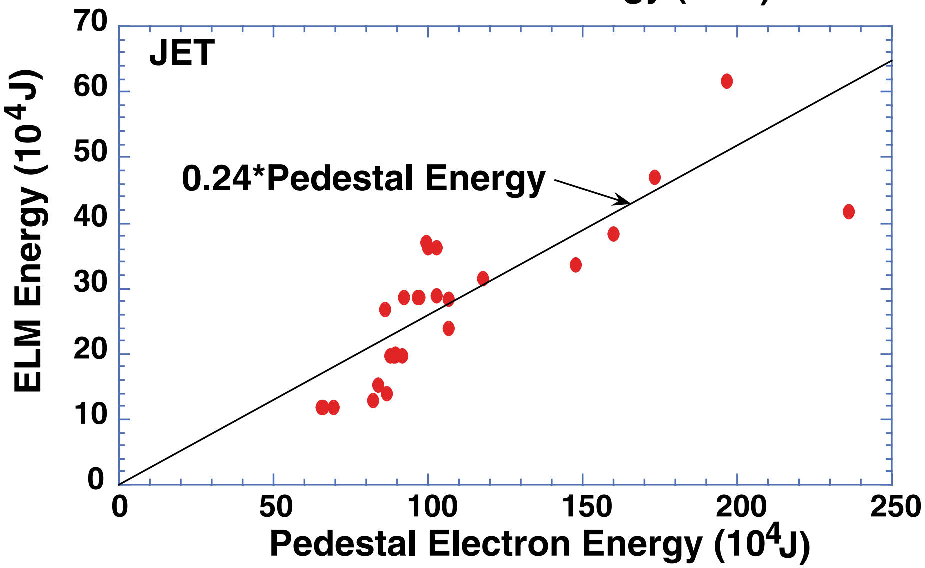
NTM can be triggered by ELM



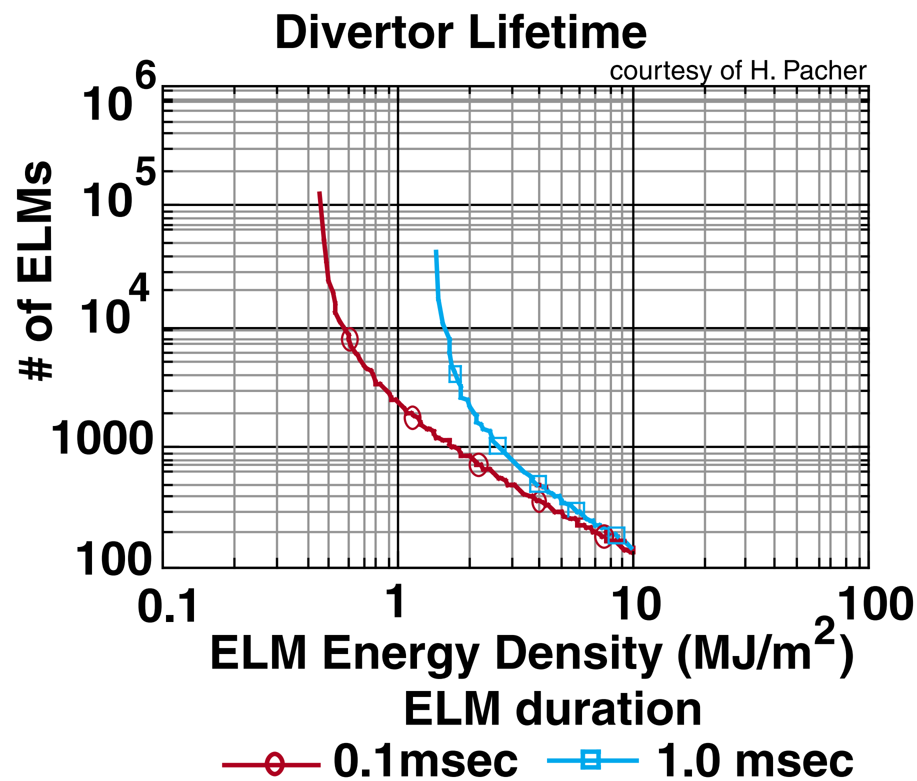
[1]G.T.A Huysmans, et.al, Berchtesgaden EPS, 1997, **21A**, 21.

Type I ELM energy loss increases with H-mode pedestal energy. ELM divertor heat loads can be a problem for reactor scale device





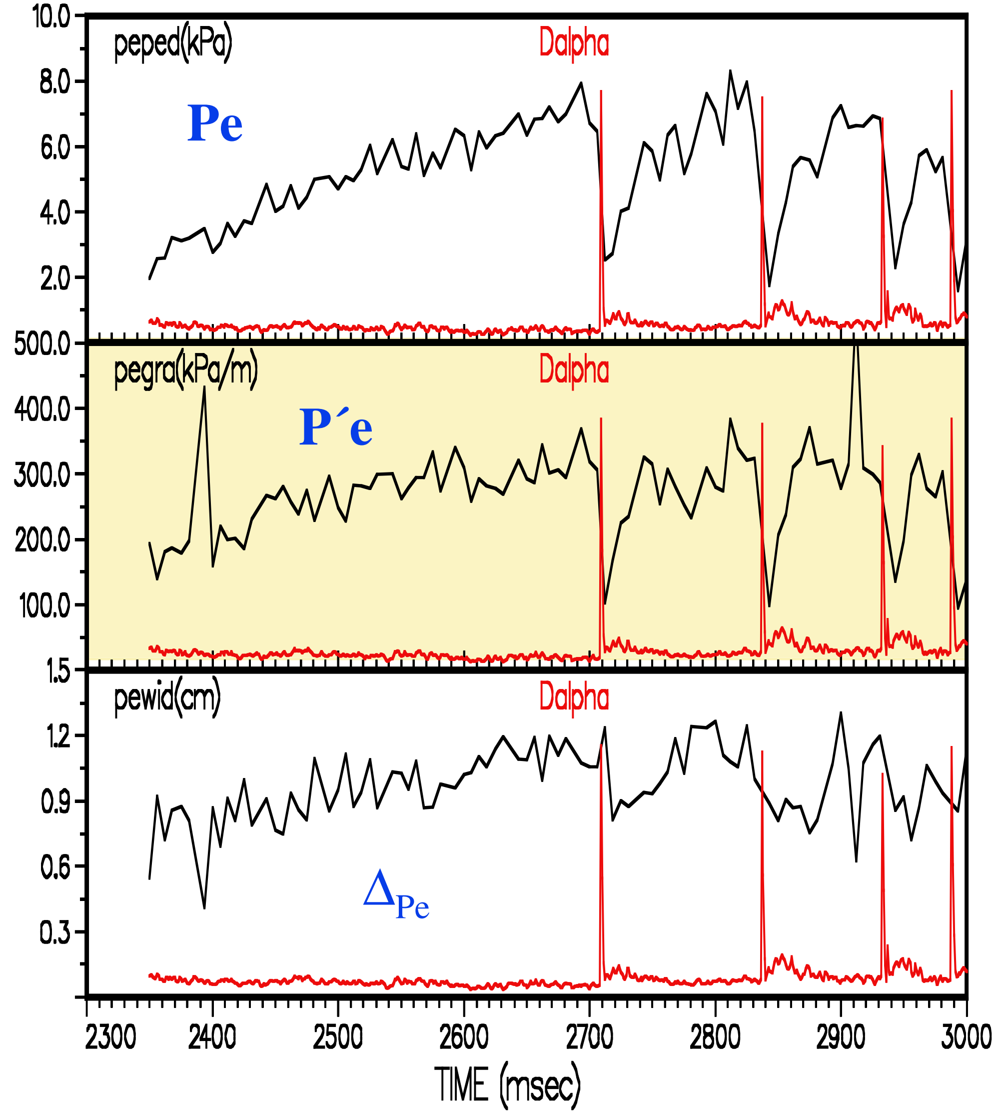
- $\Delta W \sim$ 1/3 of E_{ped} for DIII-D and 1/4 of E_{ped} for JET.
- Assuming $\Delta W_{ELM}/p^{PED}$ is the same for DIII-D and ITER gives for ITER $\Delta W_{ELM}=8\ T^{PED}$MJ/keV



Edge Stability

- Determining a scaling for p^{PED} or T^{PED} is separated into a study of the H-mode transport barrier width, Δ, and pressure gradient, p′
- p′ may be set by the ELM instability.
- Δ may be set by the physics of turbulence suppression.
- Stability work has concentrated on Type I ELM regime which has high energy confinement over a wide range of conditions.
- Comparison of conditions just before an ELM with theory:
  - GATO, 1<n<11 ideal modes in real geometry with wall
  - BALOO, n=∞ ideal ballooning modes
  - ELITE, intermediate n pealing/ballooning modes

Pedestal Parameter Evolution in Type I ELM Discharge



Future work on edge stability: Li Beam Diagnostic

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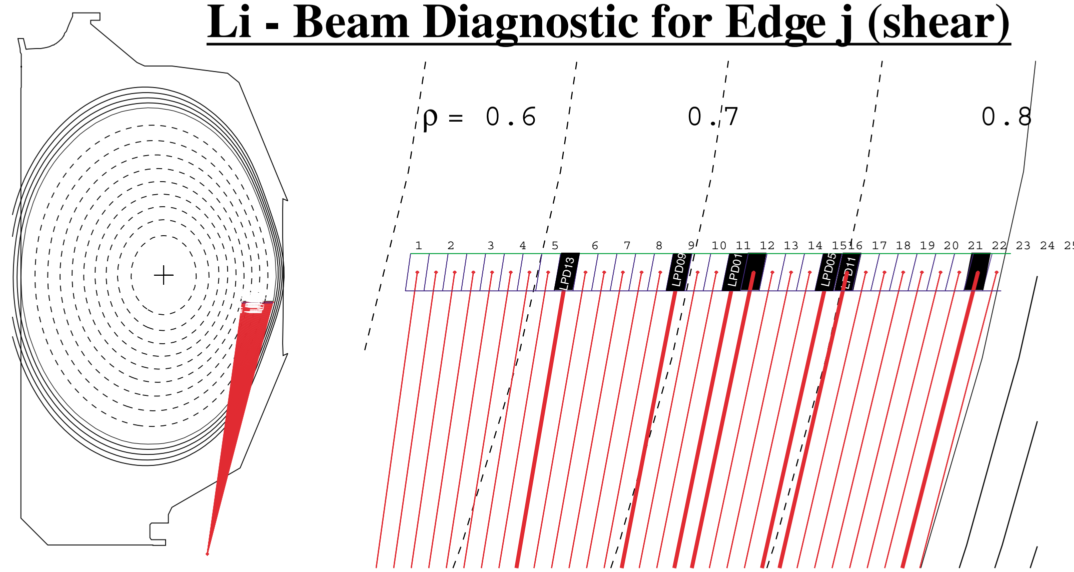
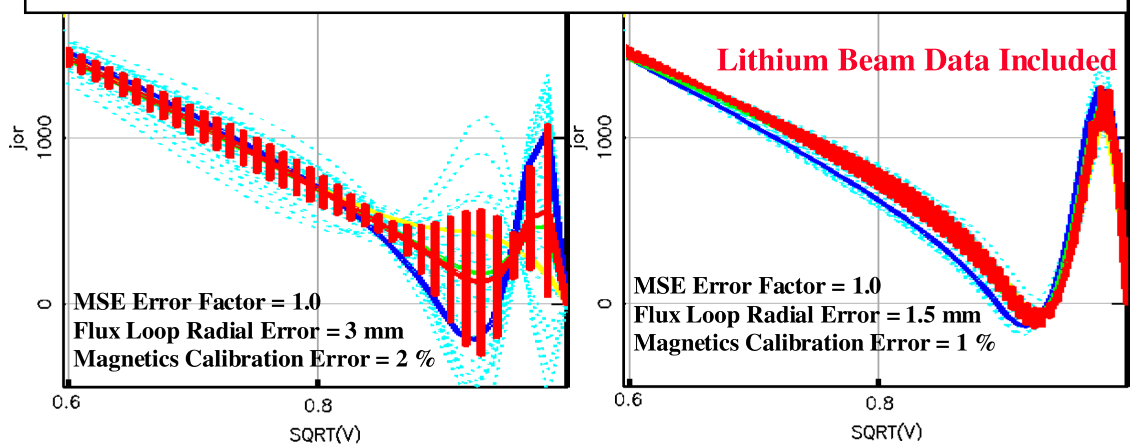
- Lithium Beam Diagnostic (D.M. Thomas[1]): high spatial resolution Zeeman effect measurement of edge magnetic field
  - **Diagnostic is installed on DIII-D and taking preliminary data.**
  - Will allow quantitative comparison between theory and experiment

Li - Beam Diagnostic for Edge j (shear)



Expected reduction in uncertainty in j^{EDGE} from inclusion of LiB data and reduction in magnetic diagnostic error



[1] D.M Thomas, et.al, Rev. Sci. Inst. 72 1023 (2001).

Ballooning mode model for ELM cannot account for edge p′; second stability plays a role.

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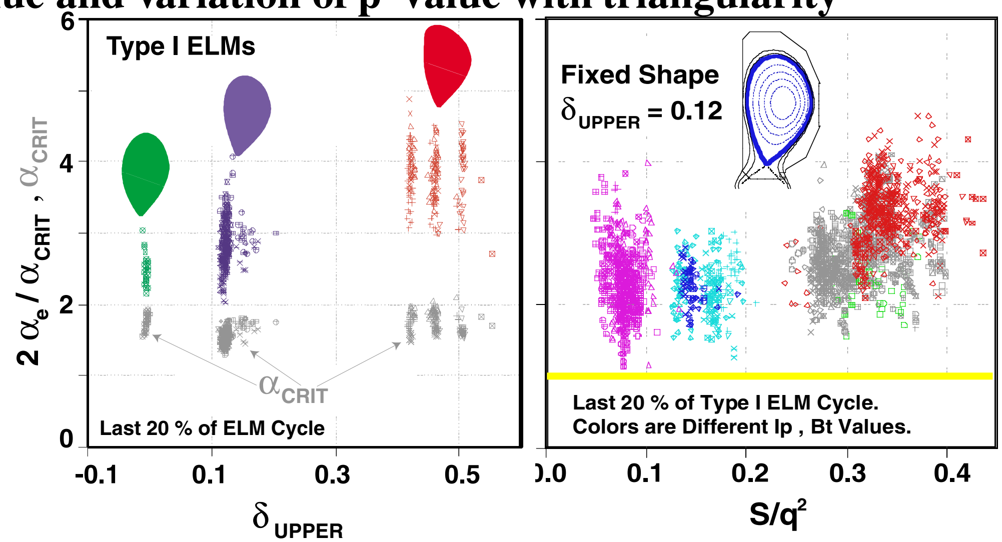
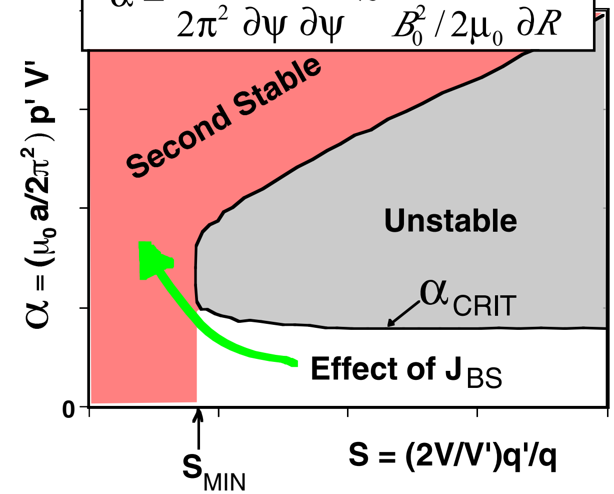
Ballooning mode model for ELM is inconsistent with high p′ value and variation of p′ value with triangularity

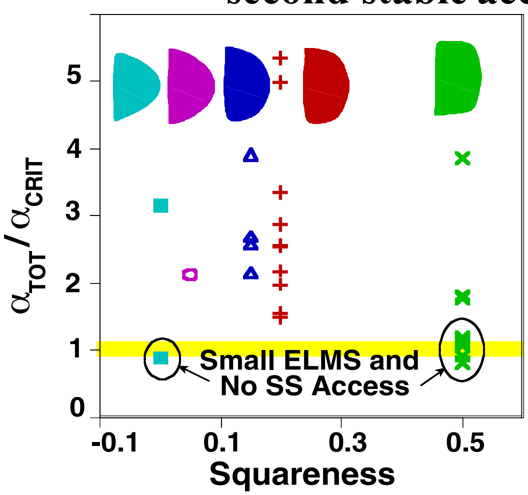


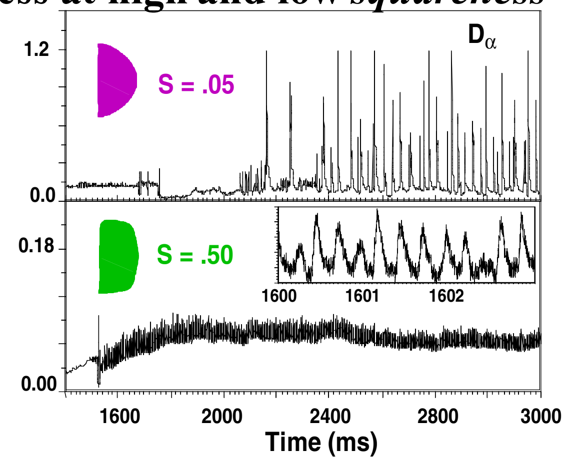
$$\alpha = \frac{\mu_0 a}{2\pi^2}\frac{\partial p}{\partial \psi}\frac{\partial V}{\partial \psi} \approx \frac{R_0 q^2}{B_0^2/2\mu_0}\frac{\partial p}{\partial R}$$

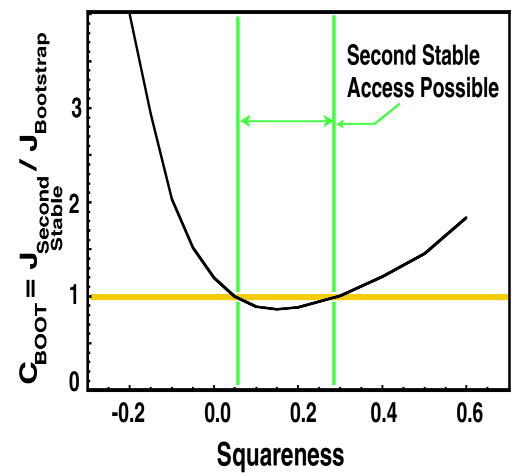


$j_{\parallel BS} \approx C_{BS}\,\varepsilon^{1/2}\,Rp'$, $\Delta S_{BS} \approx -C_{BS}\,\varepsilon^{-1/2}\,\Delta\alpha$

¥ Qualitative change in ELM behavior is consistent with loss of second stable access at high and low *squareness*



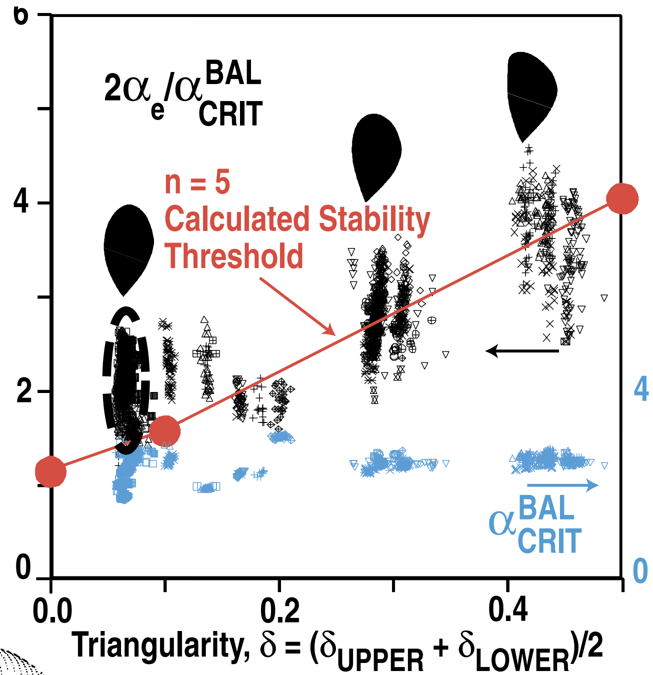


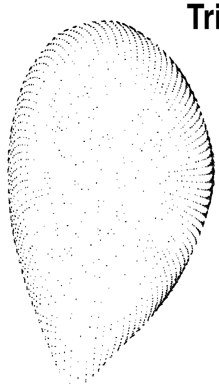


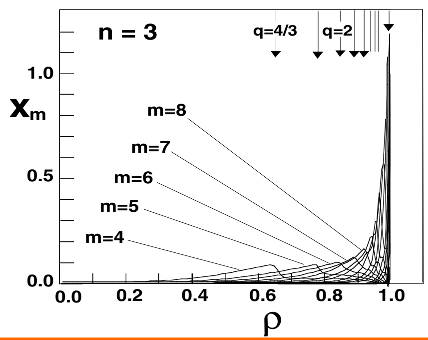
R.Miller, et. al, Plasma Phys. and Cont. Fusion **40** (1998) 753.

Observations are consistent with low n, ideal, edge localized, kink/ballooning as mode associated with the Type I ELM

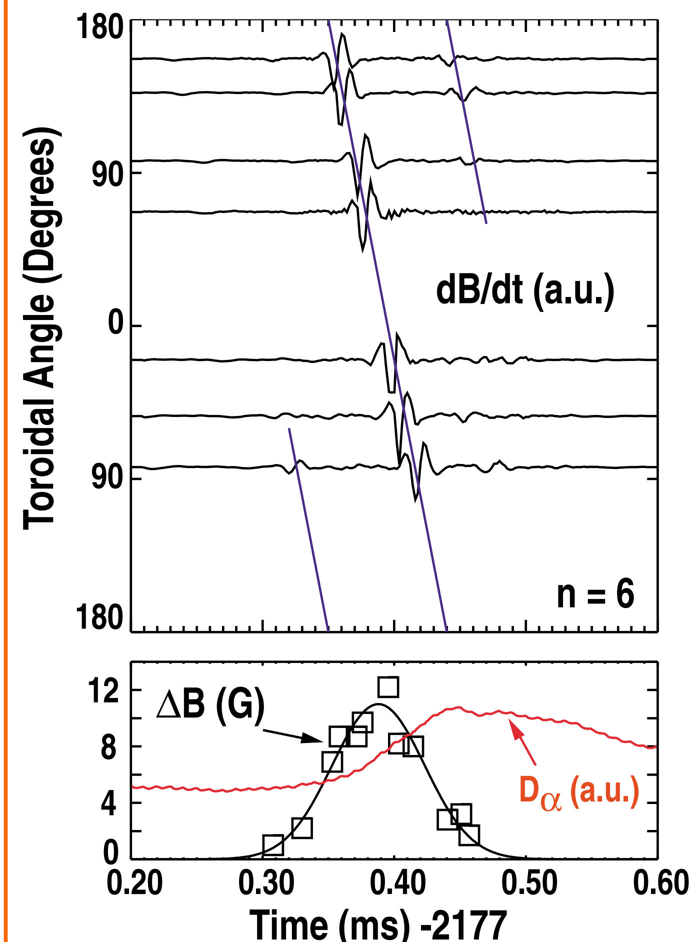
p′ variation with shape is consistent with low n edge localize kink/ballooning stability





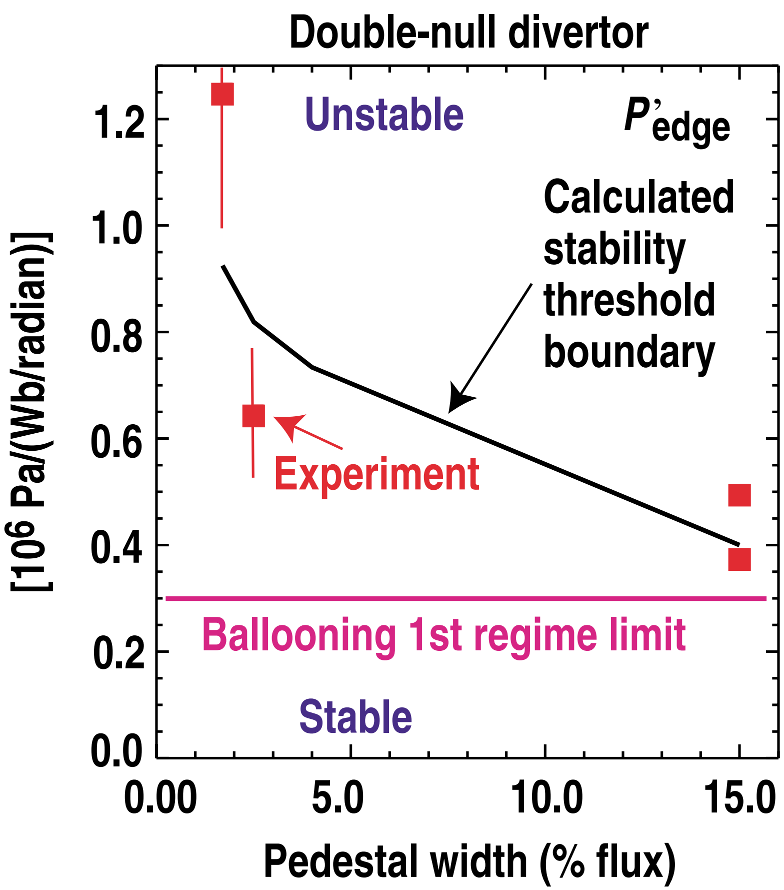


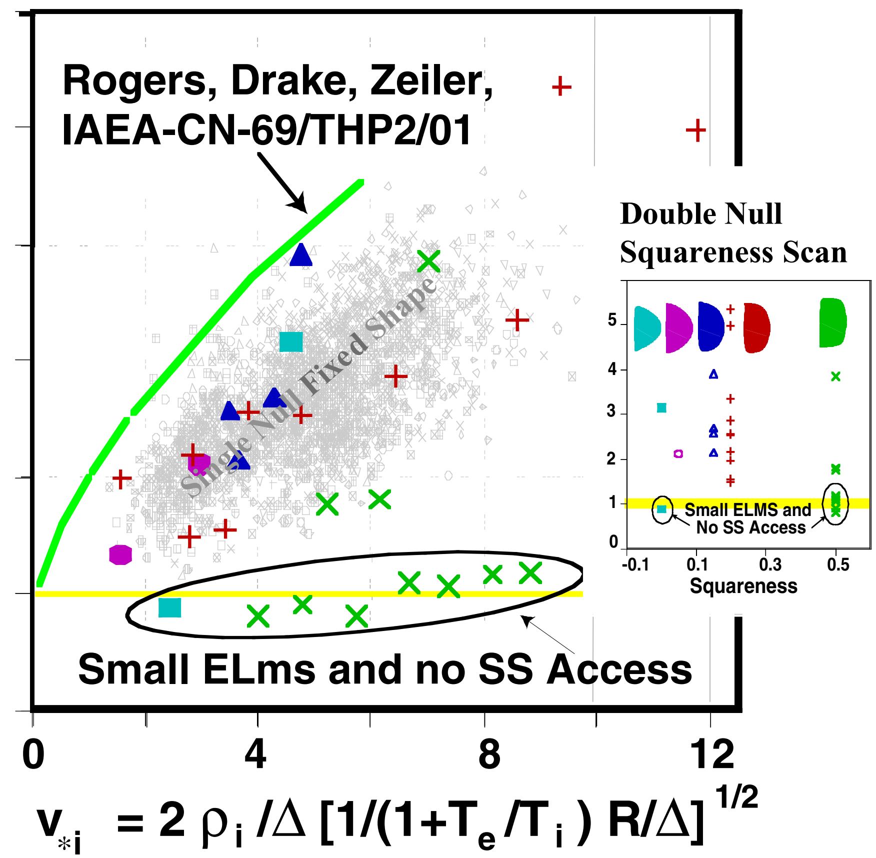
Fast growing low (1 < n < 10) toroidal mode number mode is observed as Type I ELM precursor



H-mode transport barrier width and stability limit are coupled for lower n modes.

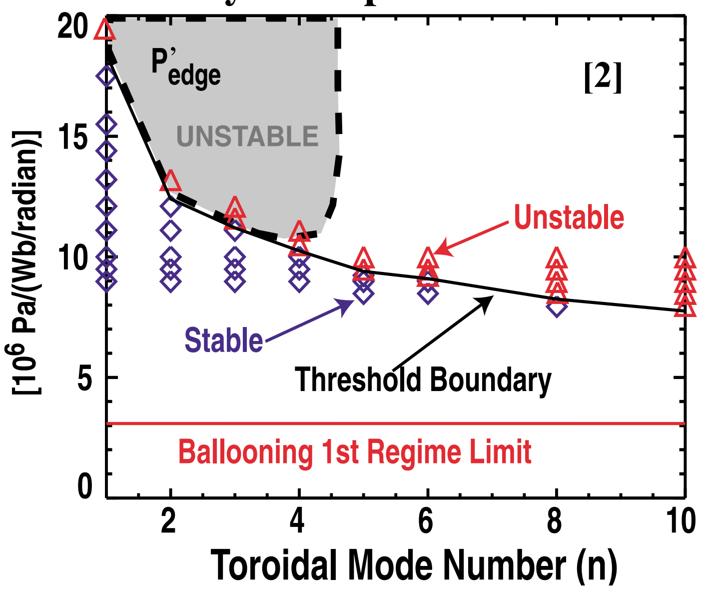
- Improved Stability for narrow H-mode barrier width predicted in GATO runs for n=5 and by Rodgers, Drake, Zeiler theory.
- Effect of barrier width for higher n modes (no SS access to ballooning) predicted by RDZ theory does not appear to be present.



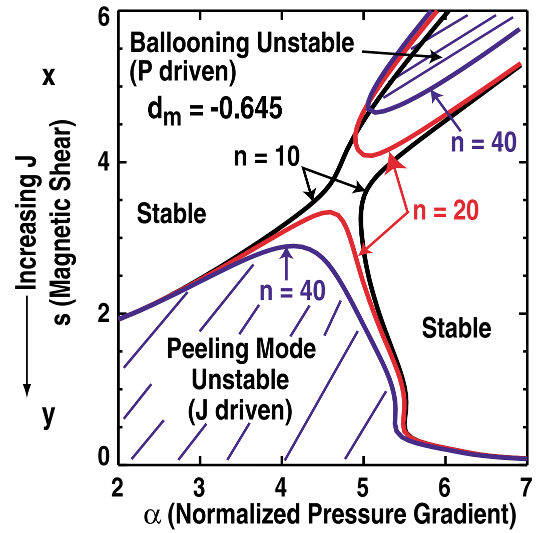


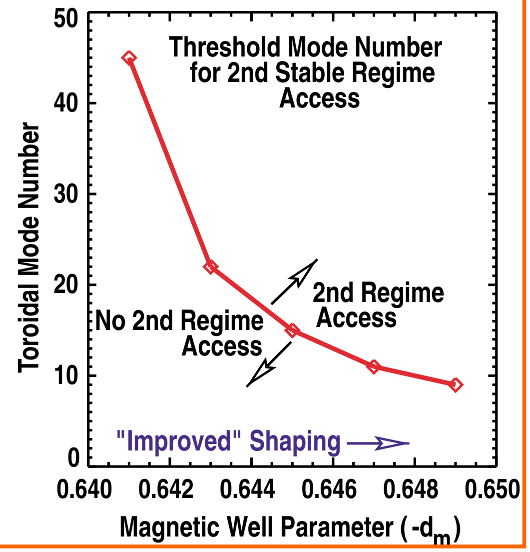
ELM mode may be the highest n ideal mode without access to second stability and consistent with FLR stabilization

- p′ limit decreases with increasing n (GATO calculation for wall=1.5a, self consistent j_{BOOT})
- First mode without second stable access may be responsible for ELM



- Second stability occurs for lower n modes
- First mode without second stable access may be a function shape (shifted circle calculation)[1]

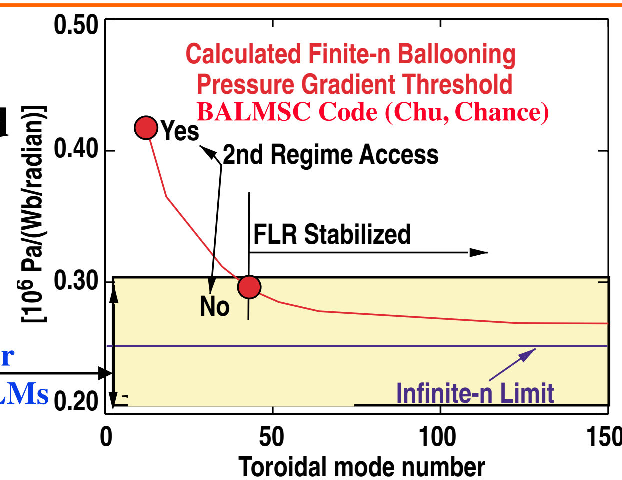




¥ Maximum n limited to < 40 by FLR

$k_\perp \rho_i > 0.5$

Pressure gradient range for High Squareness, small ELMs



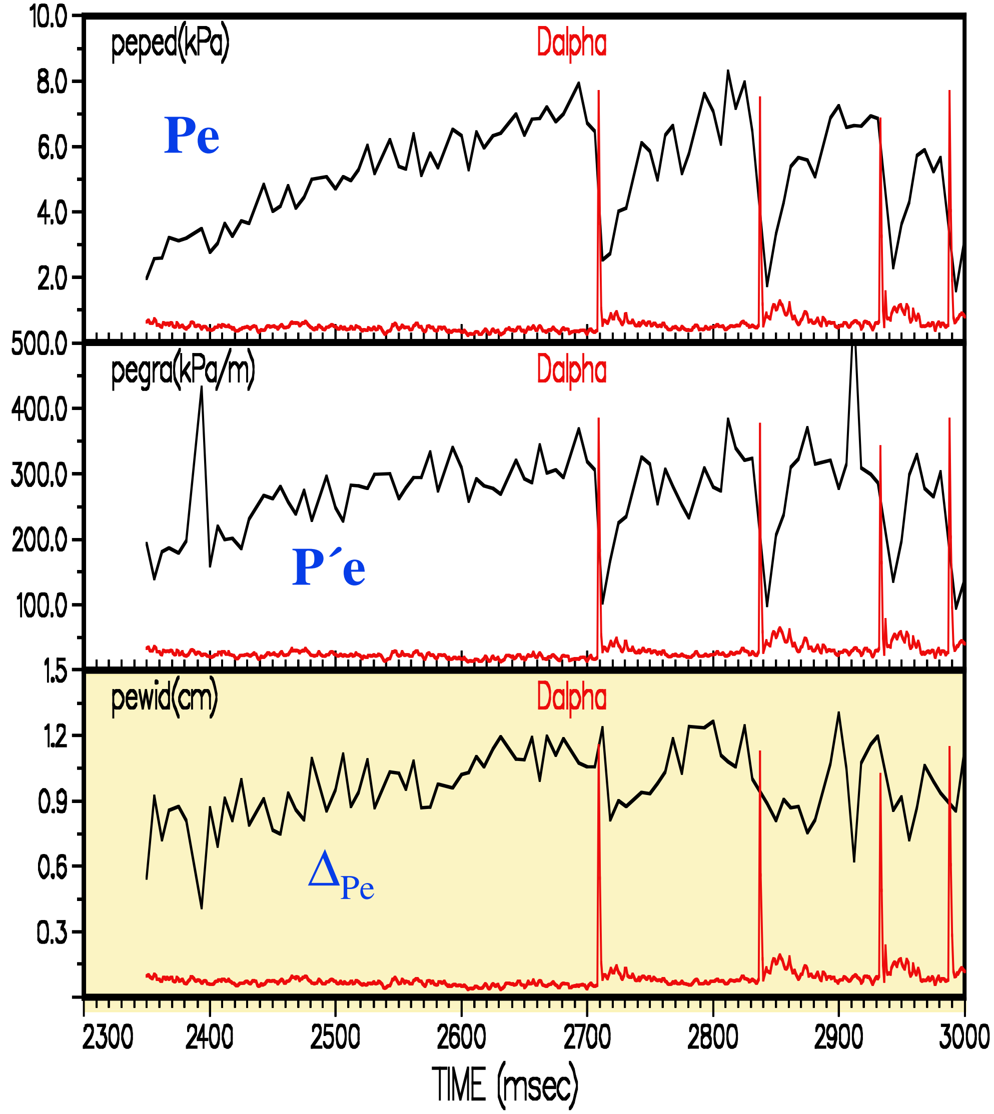
[1]H.R. Wilson, R.L. Miller, Phys. Plasmas 6, 873 (1999) extended by P. Snyder

[2]J.R. Ferron, *et al.*, Phys. Plasmas 7 1976 (2000).

H-mode Transport Barrier Width

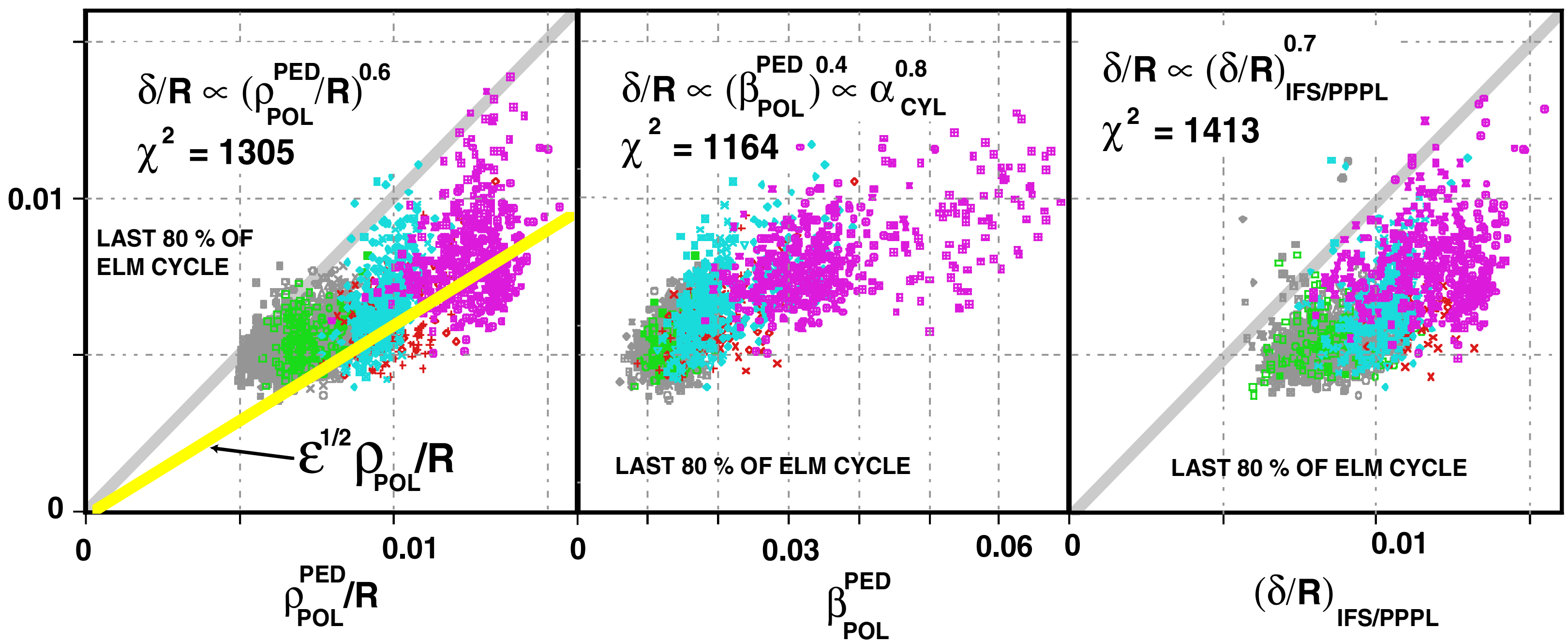
- Derivation of barrier width scaling form data base of discharges.
- Testing of derived scaling with specific experiments.
- Dimensionally similar comparison with CMOD discharges.
- Role of neutrals model for in determining the density pedestal.
- Future Work
  - Hopefully more direct inter-machine comparisons
  - Development of a coupled turbulent transport and stability code for the edge (underway).

Pedestal Parameter Evolution in Type I ELM Discharge



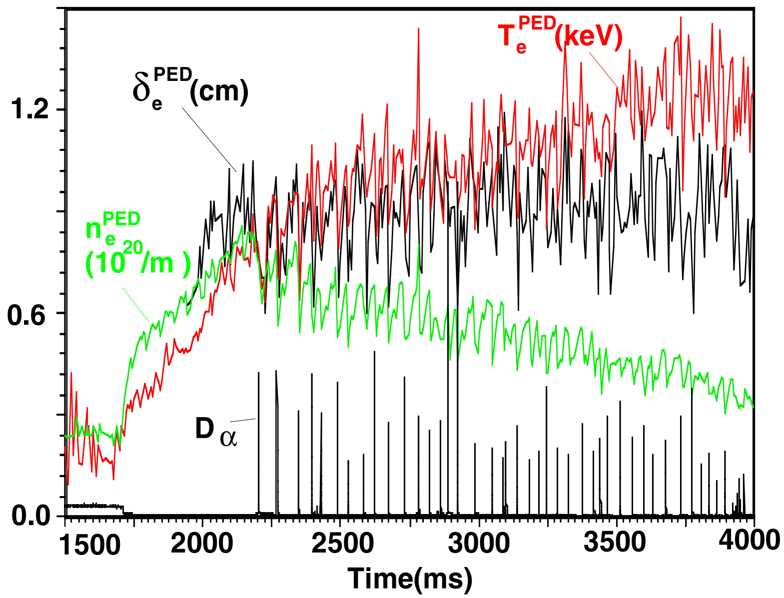
H-mode transport barrier width scaling

- Empirical scaling: only I_P, p_e^{PED}, T_e^{PED} are strongly correlated with Δ:
  $\Delta \propto (p_e^{PED})^{0.52}/B_P^{0.94} \approx (\beta_P^{PED})^{1/2}$ or $\Delta \propto (T_e^{PED})^{0.36}/B_P^{0.44} \approx (\rho_P^{PED})^{1/2}$
- Shaing[1]: Ion obit loss $\Rightarrow E_R$, $\omega_{ExB} \Rightarrow$ turbulence suppression
  $\Delta/R \approx (\varepsilon/s)^{1/2}\rho_P/R$, where s=orbit squeezing.
  $s=|1-dE_R/dR/(B_P\,\Omega_P)| \approx |1+(\rho_P^{\,2}/(\delta L_{Ti})| \approx 1 \Rightarrow \delta_{SHAING}/R \approx 0.6\rho_P/R$
- IFS-PPPL[2]: ITG and TEM turbulence, nonlinear simulations indicate turbulence is suppressed when $\omega_{ExB} > \gamma_L \Rightarrow \Delta_{IFS\text{-}PPPL}/R \approx 4\,\rho_i/R\,(T_i/T_e)\,(1+f(q))/(1+f(\varepsilon))$ $[\times S^x]$[3]

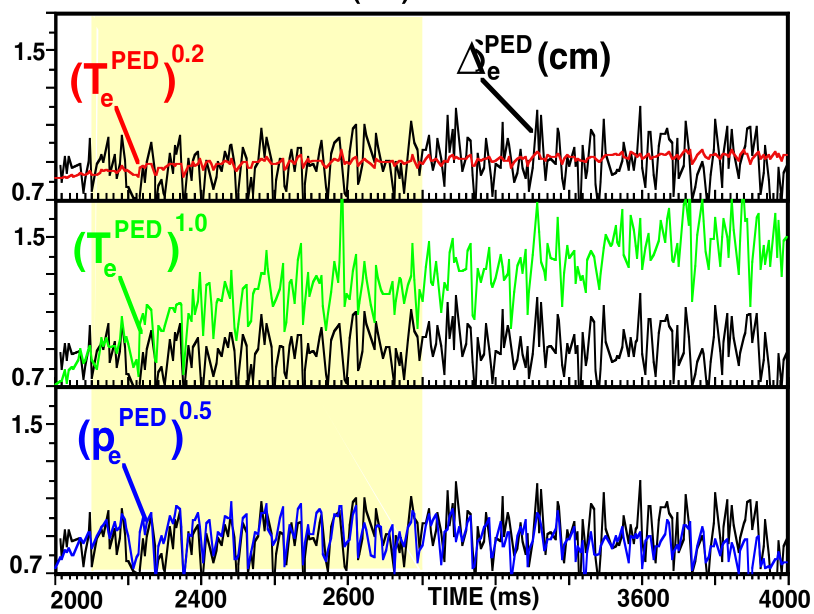


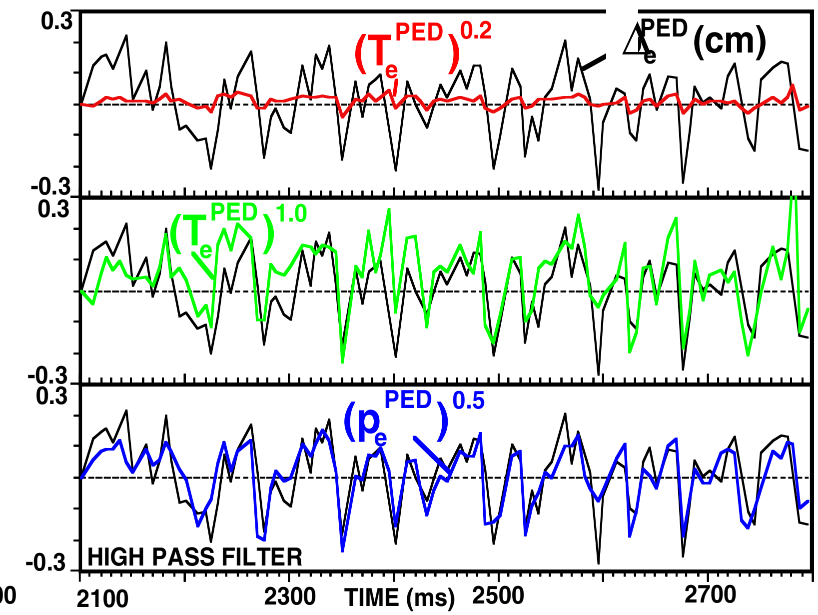
[1]K.C. Shaing, *Phys. Fluids B* **4,** 290 (1992)
[2]W. Dorland, et. al, ISPP-17, *Theory of Fusion Plasma s,* SFI Bologna 185 (1996)
[3]M. Sugihara, et. al, 2000 EPS.

Divertor pumping experiment appears to rule out the T^{PED} as a controlling parameter for H-mode transport barrier width



- To match the variation of Δ just before the ELM (or for time average) with divertor pumping requires $\Delta \propto (T_e^{PED})^{0.2}$ while to match the variation of Δ between ELMs requires $\Delta \propto (T_e^{PED})^{1.0}$
- $\Delta \propto (p_e^{PED})^{0.5}$ is a better match to the overall and between ELM Δ variation.

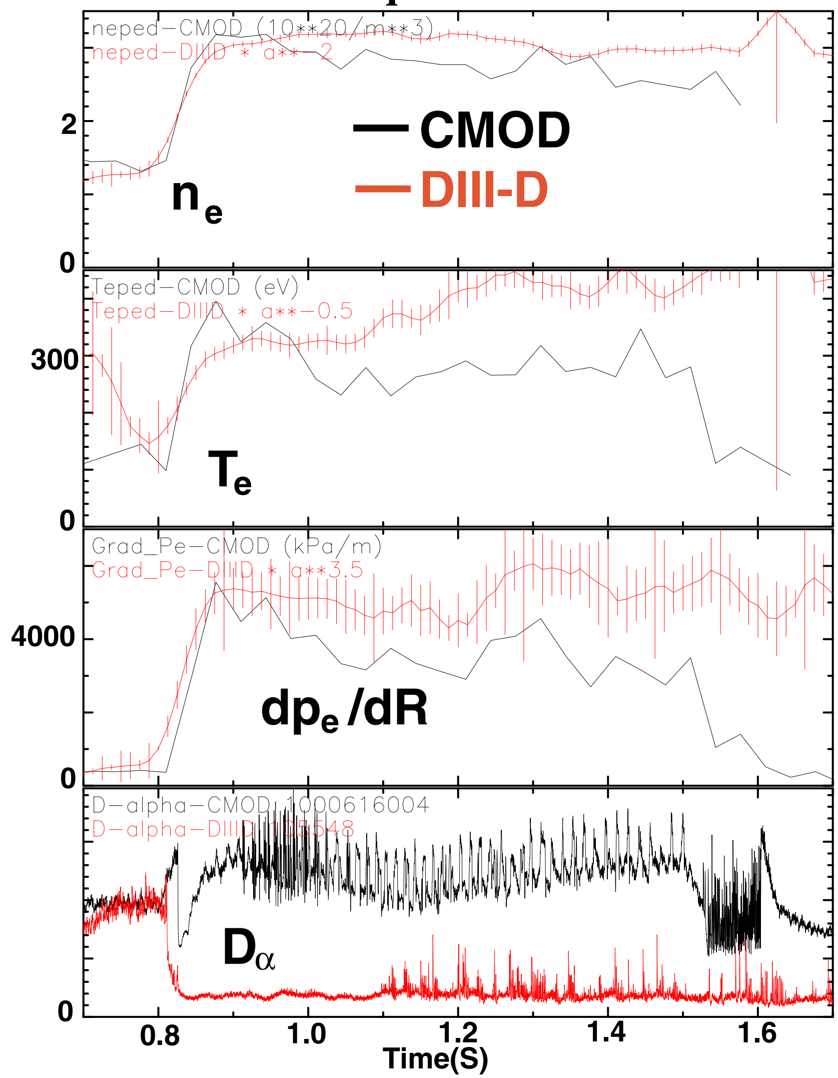




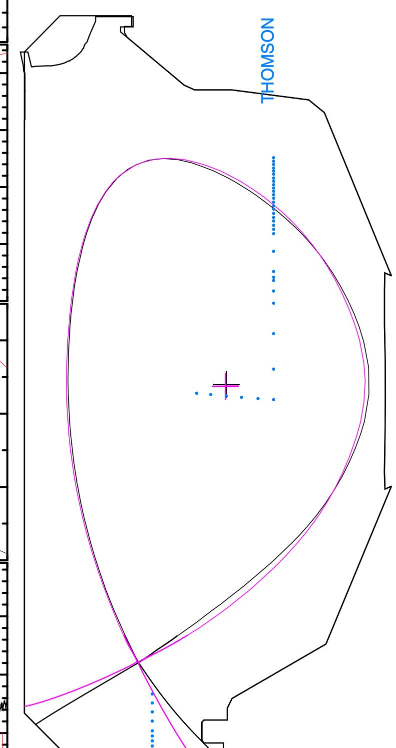
Pedestal dimensionless scaling experiment in collaboration with Alcator-CMOD Group

- Can dimensionless scaling be applied to H-mode transport barrier width (or is atomic physics important) ?
- Match plasma shape, q; scale T_e^{PED}, n_e^{PED} to maintain ν^*, ρ^*, β fixed
- Data still being analyzed but possible quasi-coherent mode observed in DIII-D
- Future direct comparisons between machines of this type could be very helpful.

T_e^{PED} and n_e^{PED} were scaled to keep dimensionless quantities fixed.



Shapes were well matched



Density pedestal may be determined by charge exchange penetration of neutrals

- 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 $(\xi \geq 0)$ $n_e(\xi) = n_{sep}\exp[-\xi/\sqrt{D\tau_{\|}}]$

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

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

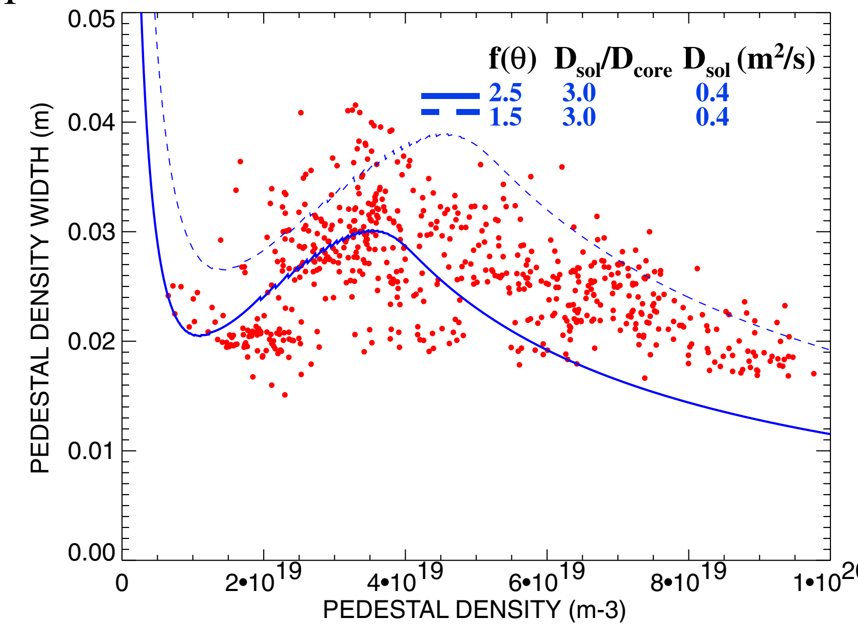
where $C \equiv 0.5\sinh^{-1}(U)$, $U \equiv [(\sqrt{D\tau_{\|}})\sigma V_e/2V_H]f(\theta_0)n_{ped}$,

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

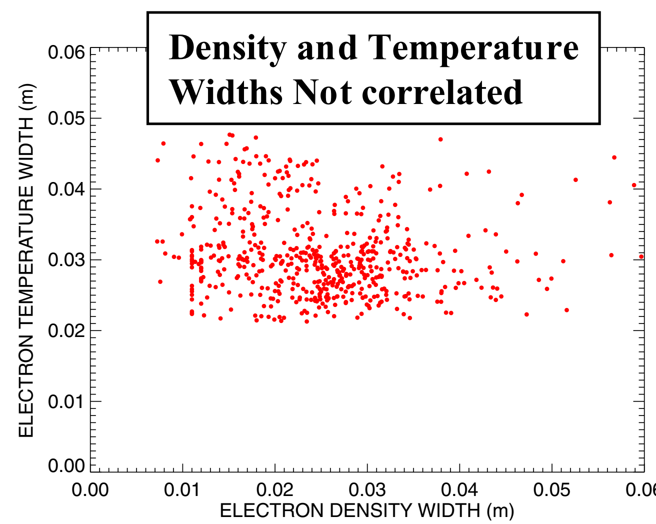
For $U \leq 1$, $n_{ped}/n_{sep} \propto 2/U \Rightarrow$

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

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



Although neutral penetration may set the Δ_{ne} the transport barrier may be controlled by other physics

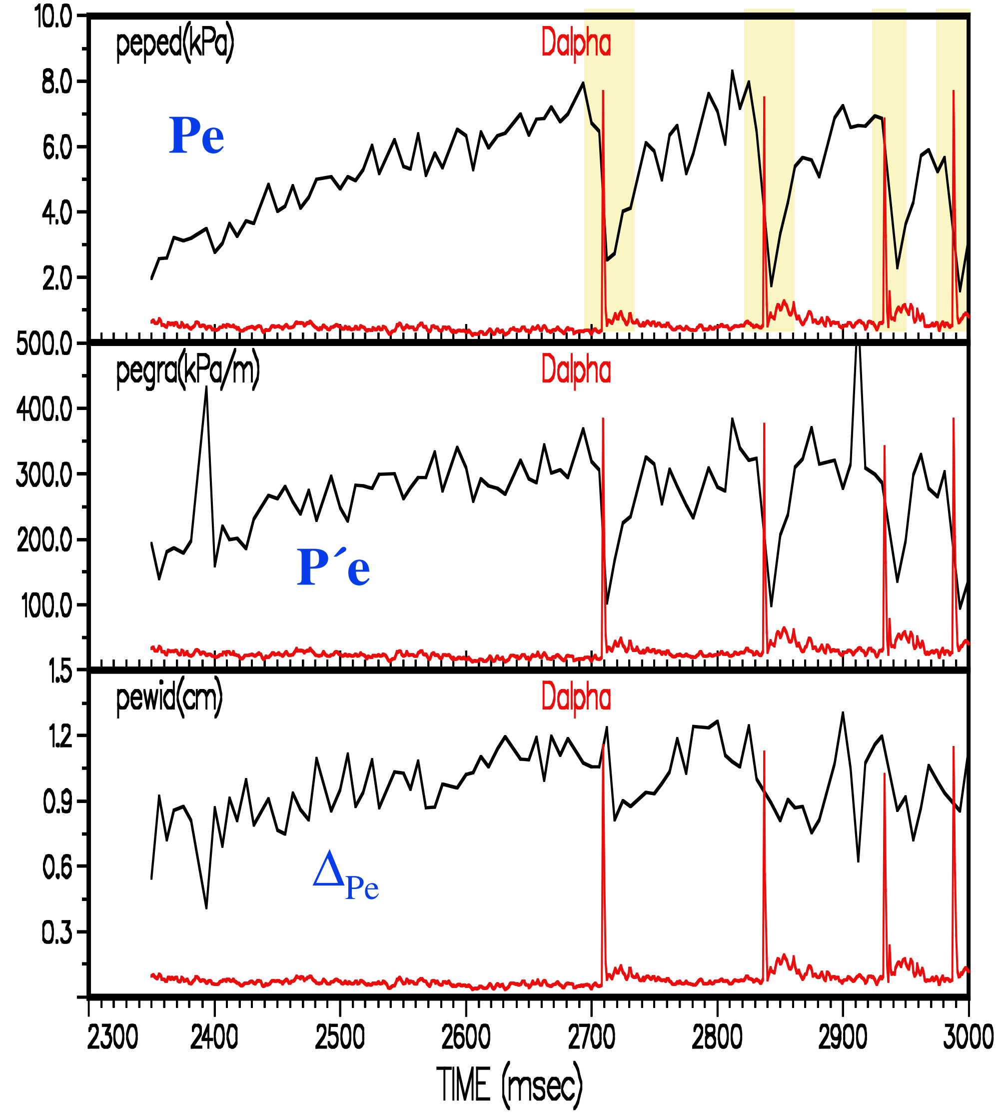


[1]W. Engelhardt, W. Fenenberg, J. Nucl. Mater. 76-77 (1978) 518.
[2]M.A. Mahdavi et al., "High Performance H-mode Plasmas at Densities above the Greenwald Limit", 2000 IAEA meeting, submitted to Nucl. Fusion

ELM effects

- Radial extent of the ELM instability eigenmode correlated with ELM size.
- **Quiescent H-mode**: high energy confinement ELM free regime without the problems of ELM free H-mode (density and impurity accumulation, large edge current and resulting instability).
- Future work.
  - Other models for the Type I ELM energy loss mechanism ?
    - Coupling of edge kink/ballooning to core ?
    - Response of stiff temperature profile ?
    - Inward propagation of the instability ?

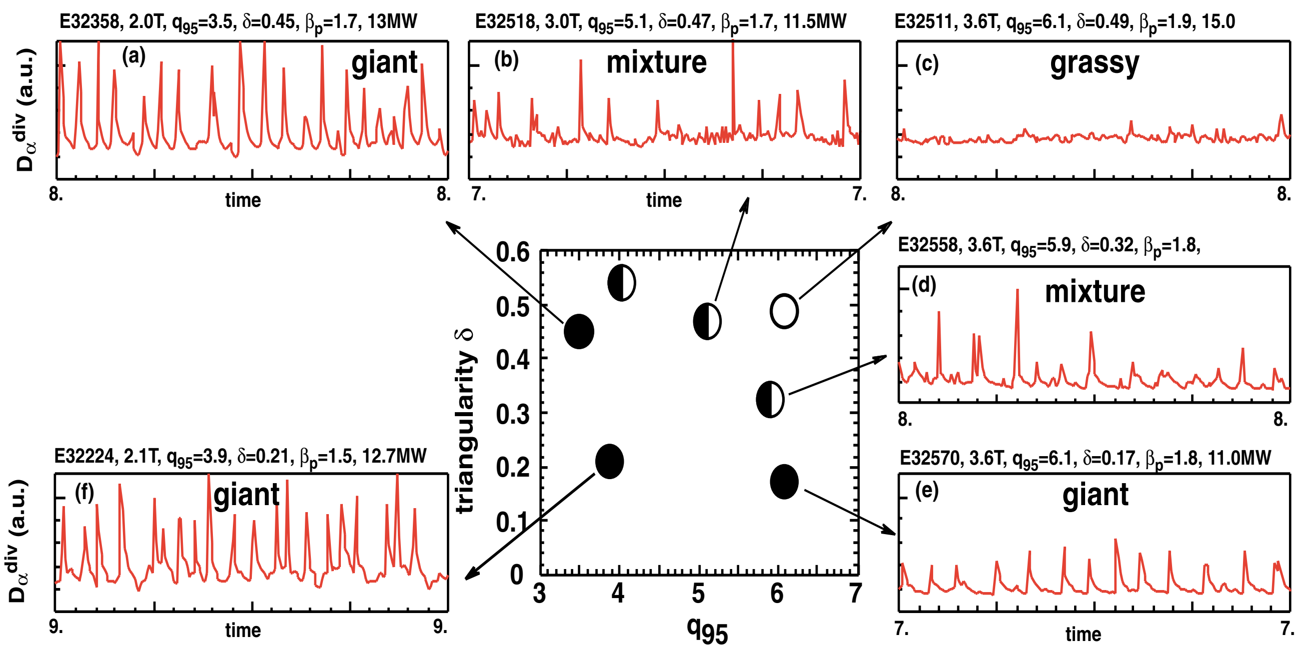
Pedestal Parameter Evolution in Type I ELM Discharge

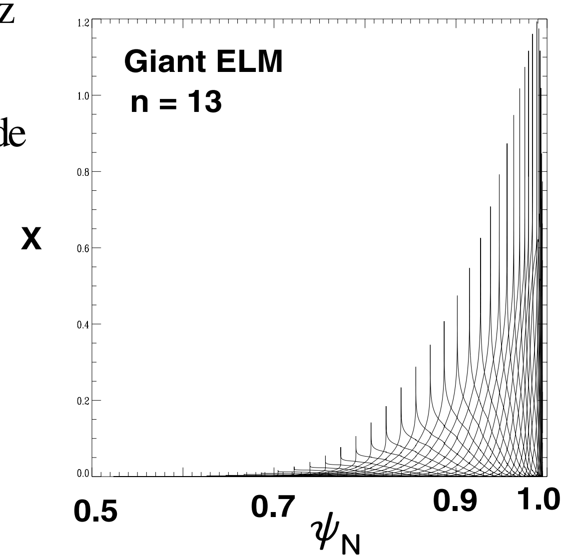


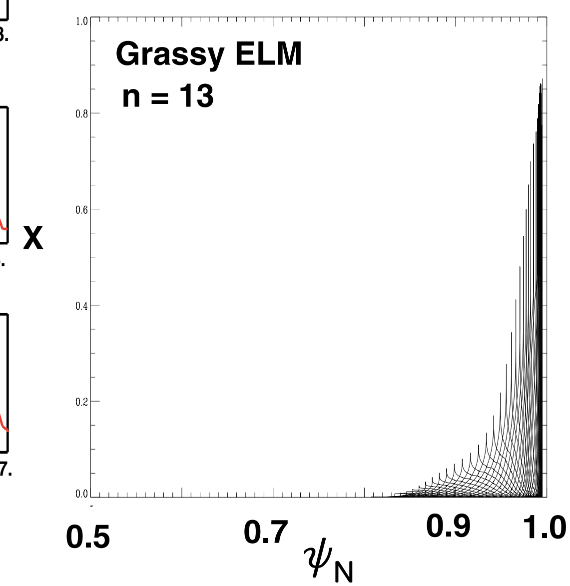
Change in ELM size with shape and q may be related to change in radial mod width of associated instability (JT-60U discharges[1]).

- 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

JT-60U Results







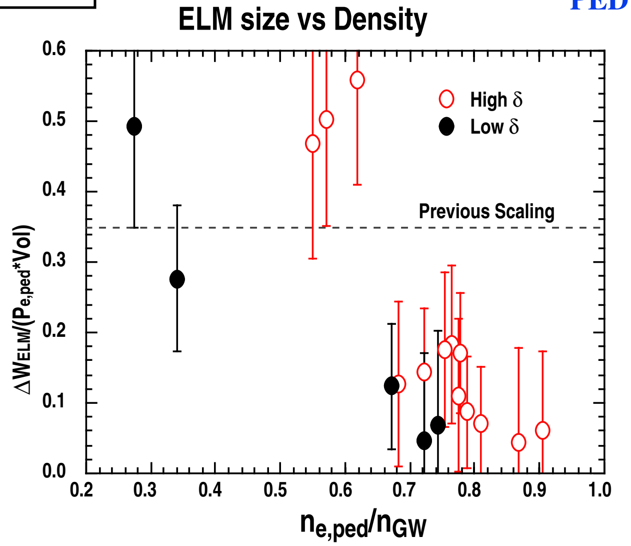
[1]LL. Lao, et. al, Nucl. Fusion, 41 295 (2001).

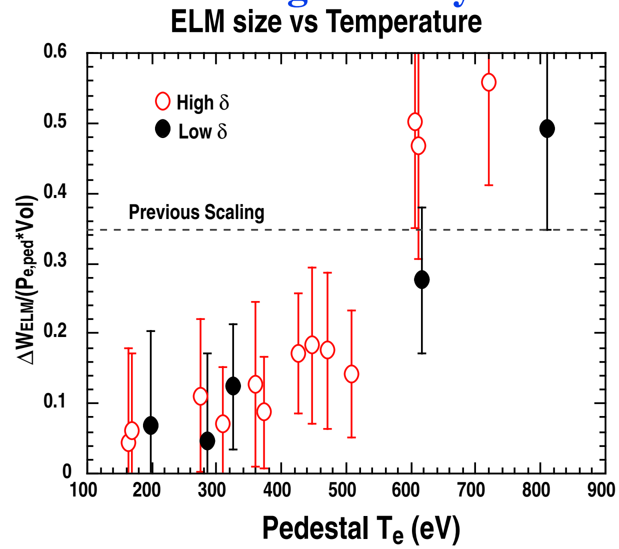
Reduction in ELM size at high density may be due to reduced mode number at higher collisionality

With increasing n_e^{PED} or $\nu^* \propto n/T^2$.

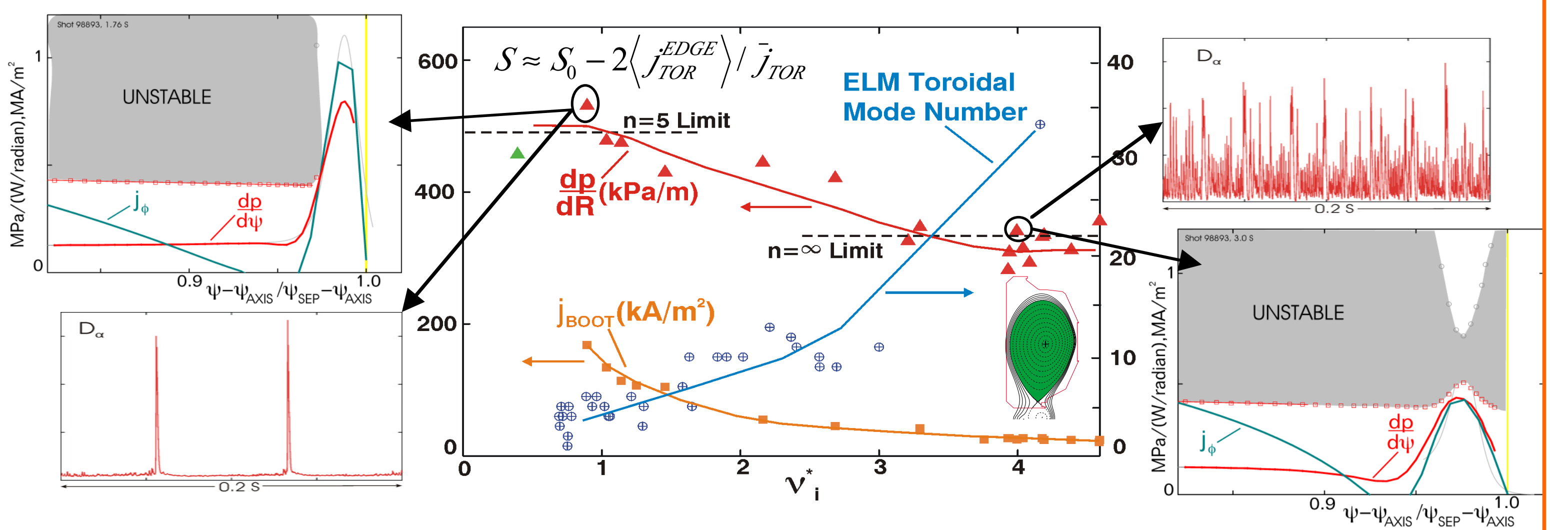
- $\Delta W^{ELM}/W^{PED}$ decreases
- ELM mode increases in n
- Calculated j_{BOOT} decreases $\Rightarrow$ edge magnetic shear increases $\Rightarrow$ SS access lost
- ∇p is reduced from calculated n=5 limit (GATO) to ideal nigh n ballooning mode limit (BALOO).

ELM size relative to W_{PED} is reduced at high density

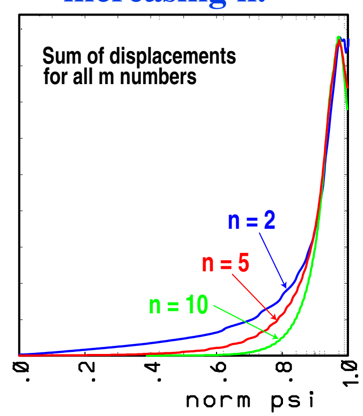




n number of ELM mode increases with n_e perhaps due to loss of second stability

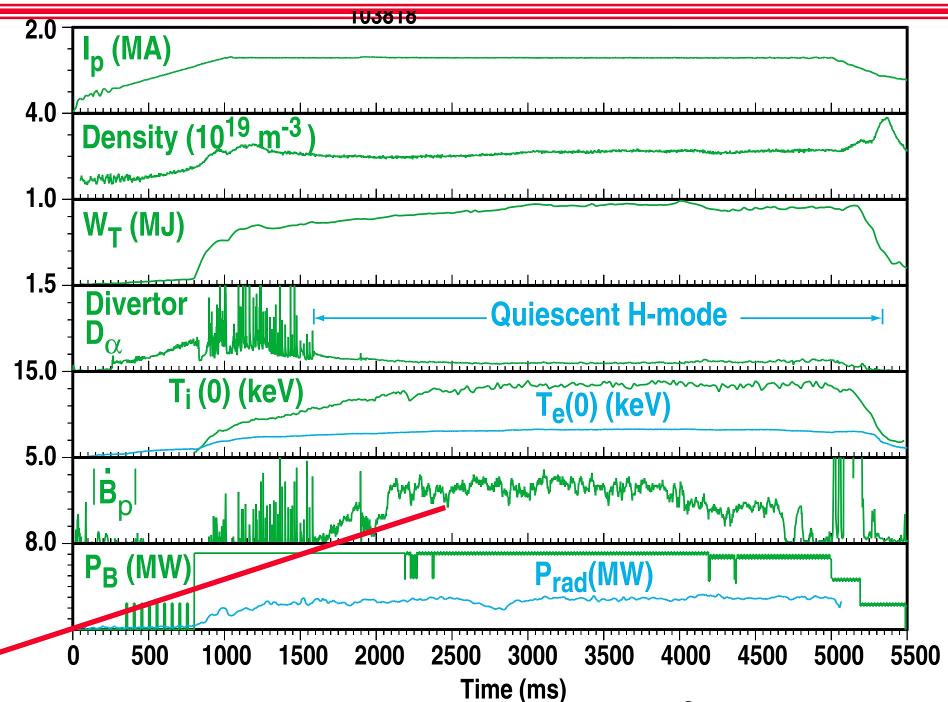


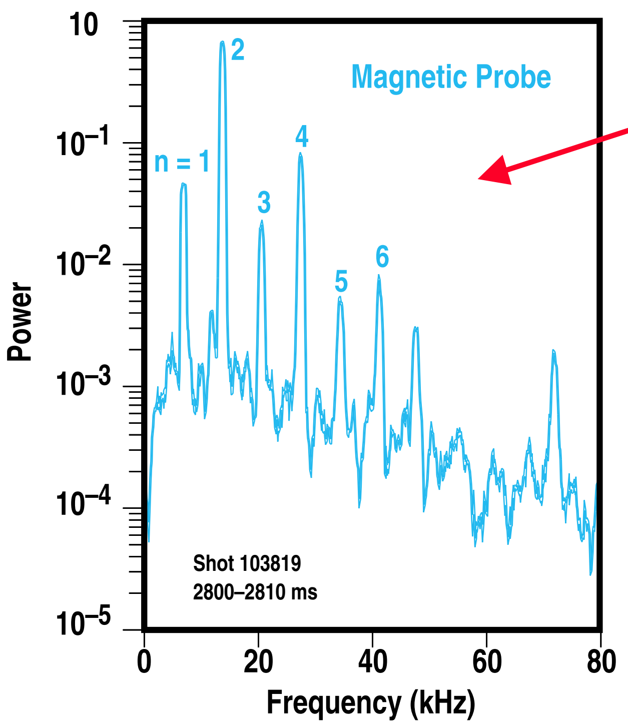
Mode width decreases with increasing n.

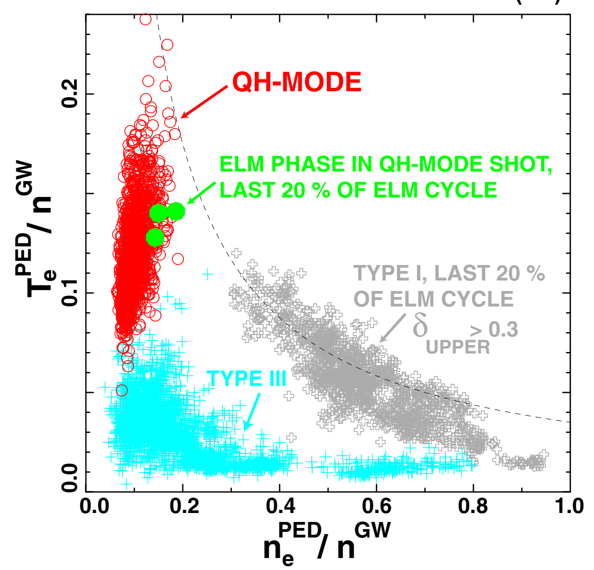


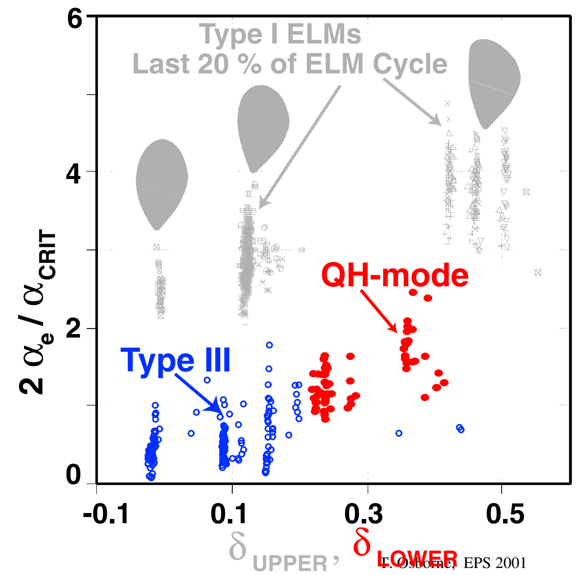
ELM free H-mode with edge harmonic oscillation (EHO) has high H and no density accumulation.

- Counter Injection
- Low density with divertor pumping
- Large outer gap
- H89P to 2.4
- β_N to 2.9
- β_NH to 7









Conclusions

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

- Edge Stability
  - Low - medium n edge localized kink/ballooning mode is good candidate for Type I ELM instability
    - Quantitative comparison between theory and experiment will be possible with Li-Beam edge current density diagnostic.
    - Extension of intermediate n theory
  - MHD associated with QH-mode still not understood
- Transport barrier width
  - DIII-D - CMOD comparison may indicate dimensionless scaling applies to the edge but need more inter-machine comparisons to settle this and to derive the scaling laws.
  - Need to develop a model for the edge including both transport and stability since these effects are coupled
- ELM Effects
  - ELM size may be related to low-medium n mode radial extent
  - Other possibilities (e.g stiff profiles) should be tested