

ELM Suppression and Pedestal Structure in I-Mode Plasmas on Alcator C-Mod

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Thank you to...

- The thesis committee: JW Hughes, DG Whyte, AE White, JP Freidberg
- The I-mode crew: AE Hubbard, JL Terry, I Cziegler, A Dominguez, SG Baek, C Theiler, RM Churchill, ML Reinke, JE Rice...
- Physops: R Granetz, S Shiraiwa, S Wolfe, S Wukitch...
- C-Mod operations, engineering, researchers and techs
- PSFC grad students, past and present
- Family and friends
- the audience!

Outline

■ Context & Motivation

- ▶ High-performance regimes
- ▶ Pedestal physics
- ▶ Introduction to I-mode

■ Pedestal Modeling & Theory:

- ▶ Peeling-ballooning MHD stability
- ▶ Kinetic-ballooning mode turbulence

■ ELM My H-mode physics¹

- ▶ EPED Modeling on C-Mod

¹JR Walk *et al.*, *Nuclear Fusion* 52 (2012)

Outline

■ I-Mode Pedestals & Global Performance^{2,3}

- ▶ Pedestal response to fueling, heating power
- ▶ Pedestal widths and gradients
- ▶ Global performance and confinement scalings

■ I-Mode Pedestal Stability

- ▶ P-B MHD, KBM modeling
- ▶ ELM characterization

■ Summary, Future Work, & Questions

²JR Walk *et al.*, *Physics of Plasmas* **21** (2014)

³Invited talk, APS-DPP Nov. 2013

The problem...

By default (“L-mode”), rapid transport of energy and particles from plasma driven by turbulence

- and energy transport gets *worse* with more heating power!
- need very strong magnetic field and/or large machine size to overcome poor plasma performance

L-mode likely not suitable for (economical) power plant development.

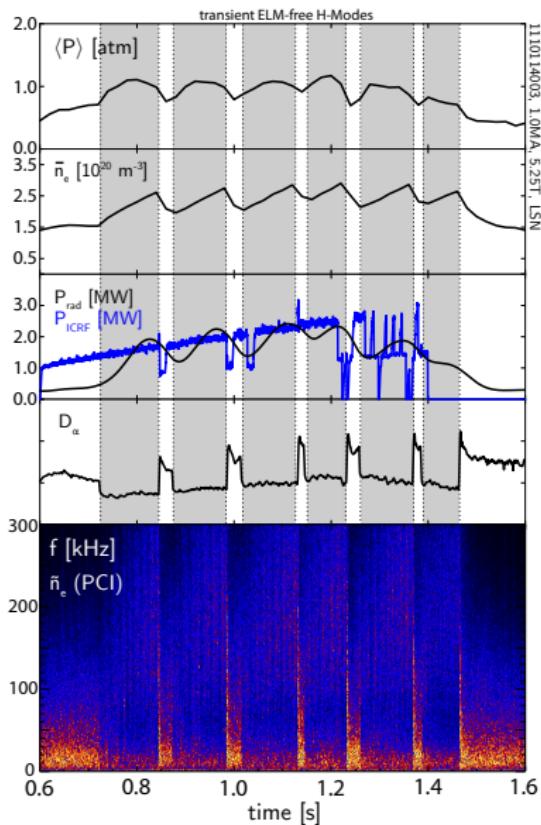
The solution?

Under right conditions, plasma forms “transport barrier” in edge, with steep gradients in density and temperature – the *pedestal*
→ plasma transitions to “high-confinement” or H-mode

- immediate factor of ~ 2 increase in energy confinement
- pedestal supports higher core pressures = fusion power density
- pedestal height sets strong constraint on global performance

...But this has problems of its own

- increased particle confinement
= plasma retains impurities as well as fuel ions
- radiated power ($\sim Z^2$ for a given impurity species) increases, overcomes heating power \rightarrow plasma drops back into L-mode
- inherently transient state

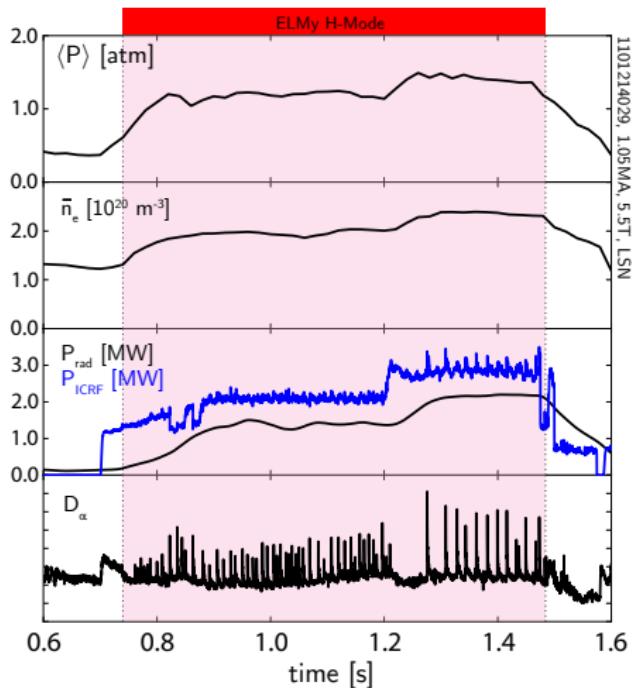


so, we need:

- high energy confinement
- low particle confinement (low enough, at least)
- ... and that's it, right?

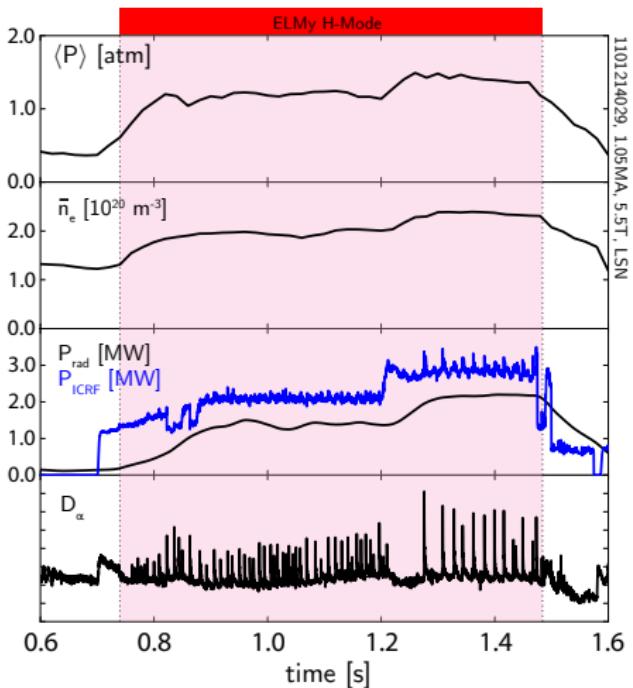
The solution? (part II)

- Edge-Localized Modes (ELMs)
 - instabilities that relax the pedestal, drive bursts of energy, particle transport, enough to prevent impurity accumulation



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- Edge-Localized Modes (ELMs)
 - instabilities that relax the pedestal, drive bursts of energy, particle transport, enough to prevent impurity accumulation
- large ELMs drive pulsed heat loads in excess of plasma-facing material tolerances



so, we need:

- high energy confinement
- low particle confinement (low enough, at least)
- avoid, mitigate, or suppress large ELMs

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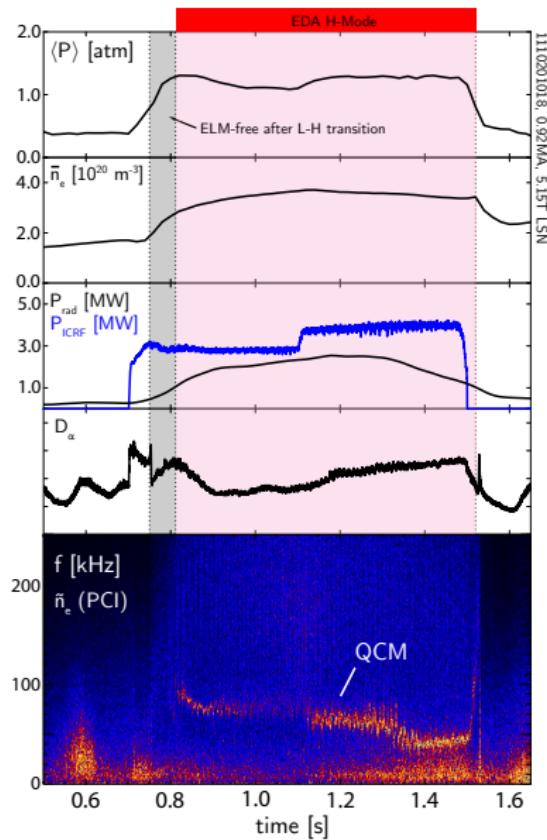
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 - ▶ engineering solutions:
pellet pacing, resonant magnetic perturbations

so, we need:

- high energy confinement
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- avoid, mitigate, or suppress large ELMs
 - ▶ engineering solutions:
pellet pacing, resonant magnetic perturbations
 - ▶ physics solutions:
pedestal regulation by fluctuations below ELM limit

EDA H-mode (on C-Mod and elsewhere)

- pedestal regulated by continuous edge fluctuation (QCM), rather than bursts of ELM transport
- steady density, $P_{rad} =$ stationary operation possible with good performance



The solution? (part III)

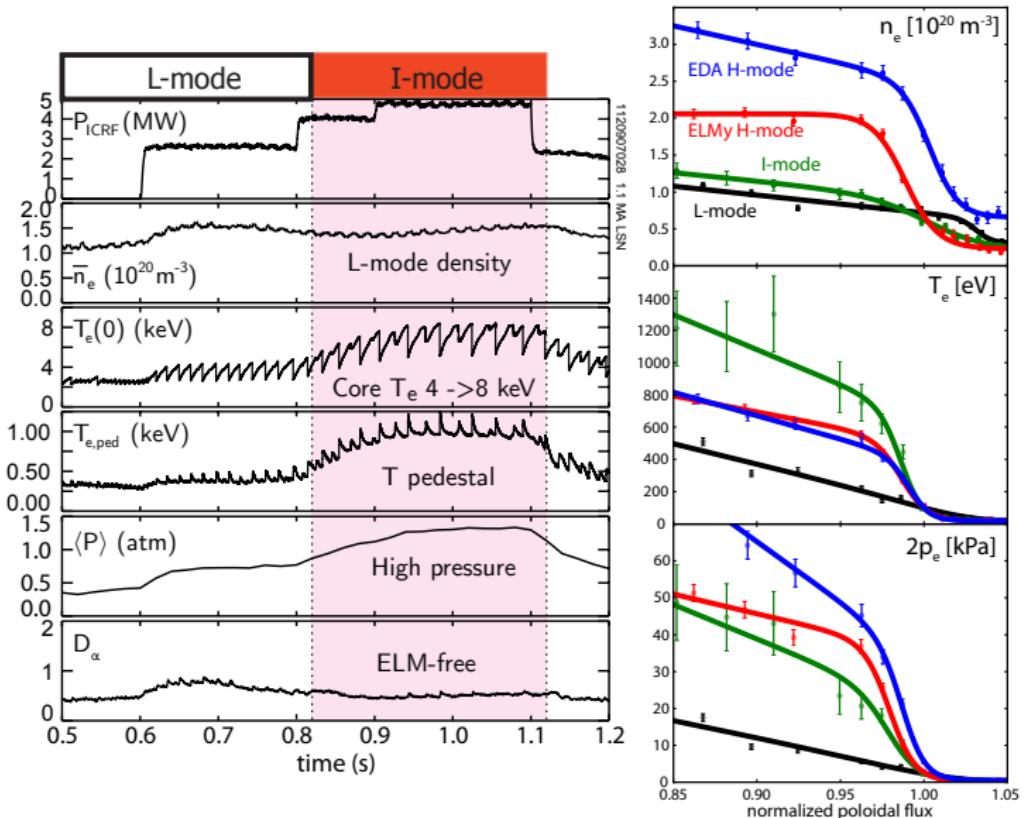
A number of fluctuation-regulated regimes have been observed:

- EDA H-mode – Quasi-Coherent Mode (QCM) – C-Mod, AUG(?)
- Quiescent H-mode – Edge Harmonic Oscillator (EHO) – DIII-D, JET, AUG
- type-II, -III ELMs H-modes – various

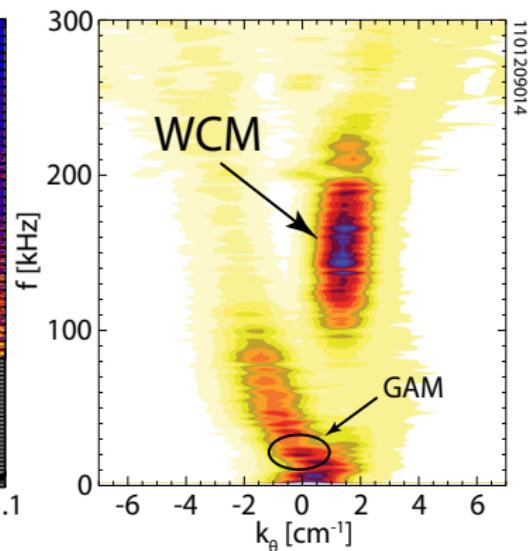
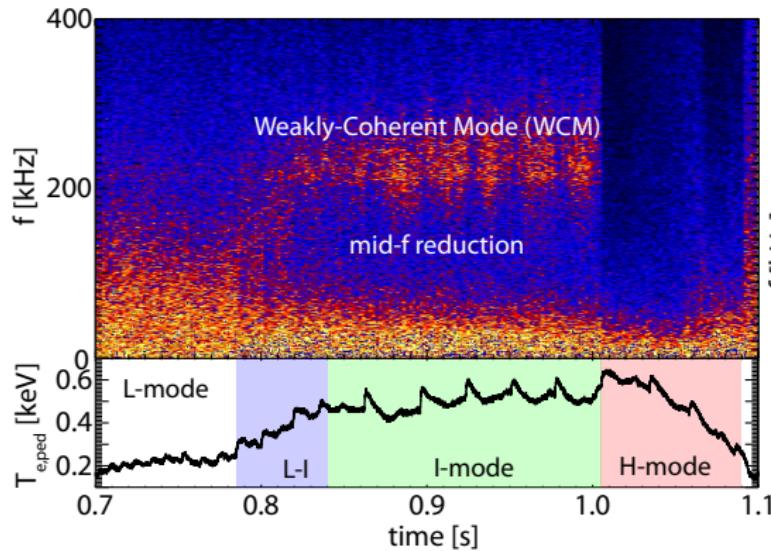
Each has drawbacks: engineering requirements (e.g., high beam torque for QH-mode), access limits (high collisionality for EDA H-mode, shaping requirements for type-II ELMs)

Can we do better?

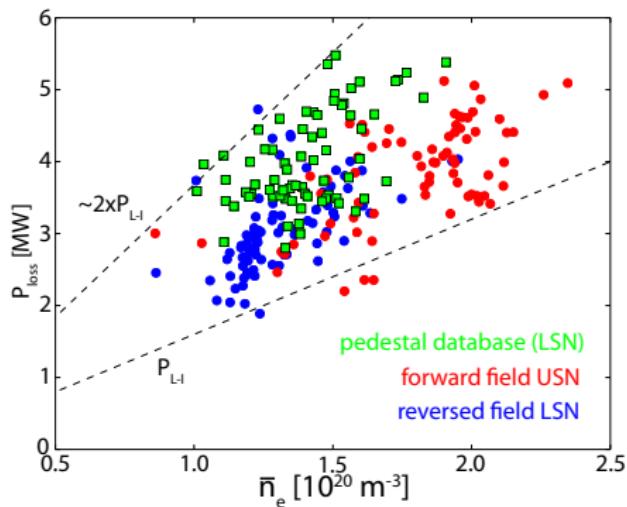
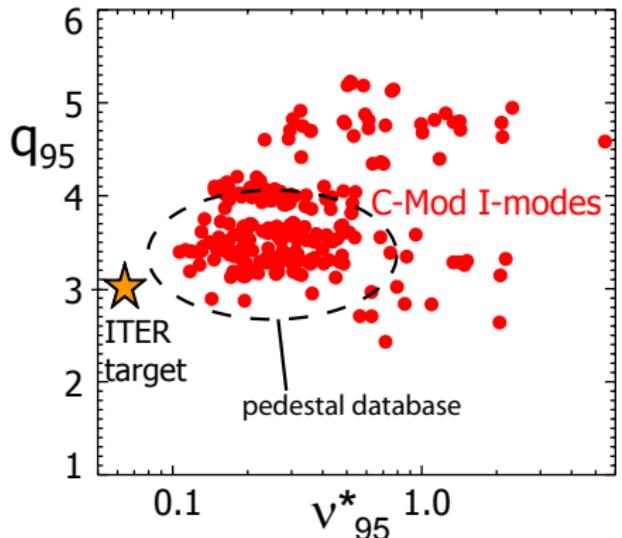
A challenger appears: the I-mode



I-mode pedestal regulated by Weakly-Coherent Mode (WCM)



Robust I-mode access on C-Mod



- I-mode accessed over range of edge current profiles, low-mid collisionalities
- “Unfavorable” ∇B orientation (ion ∇B drift away from primary X-point) – forward-field upper-null or reversed-field lower-null operation
- Sustain mode with heating power up to $\sim 2\times$ above L-I threshold

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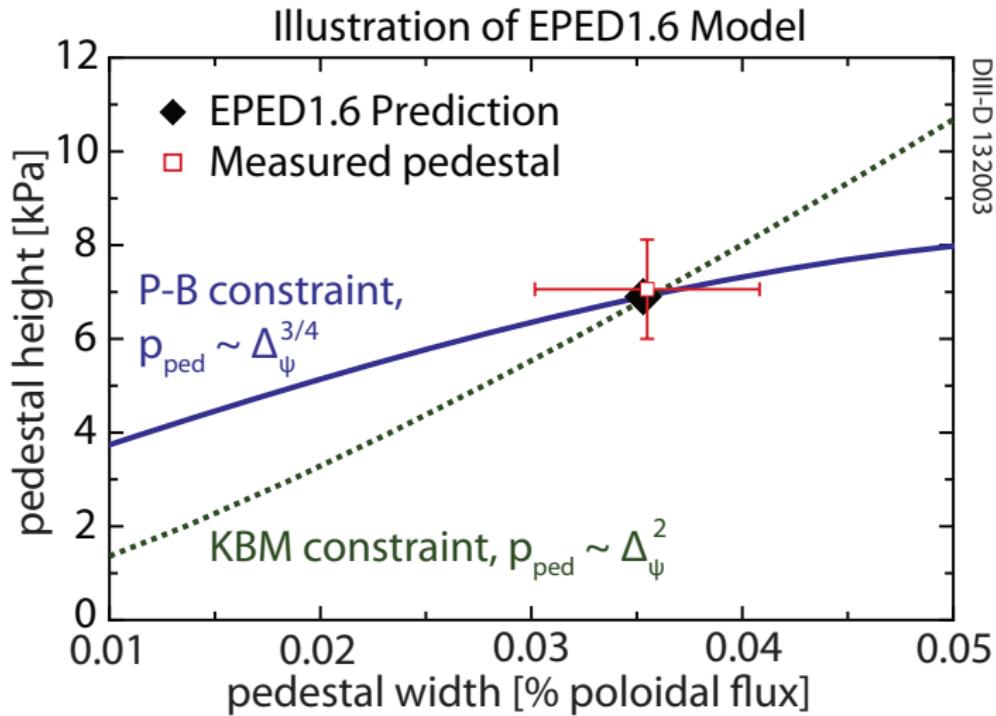
■ ELMy H-mode physics¹

- ▶ EPED Modeling on C-Mod

¹JR Walk *et al.*, *Nuclear Fusion* 52 (2012)

how much detail here for modeling, vs in extra slides?

Predictive Model for ELMy H-modes – EPED⁴



⁴PB Snyder *et al.*, Nuclear Fusion 51 (2011)

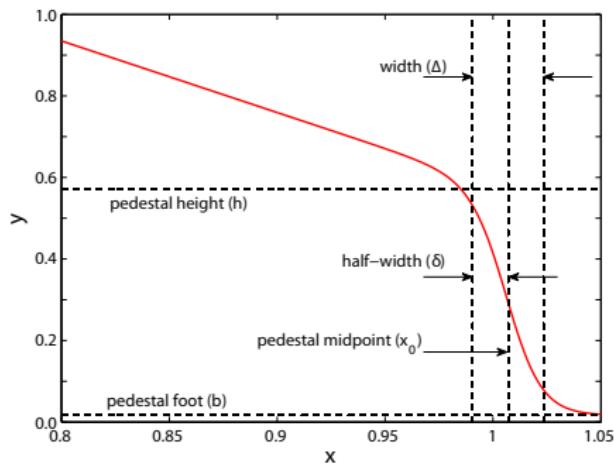
Pedestal Structure Definitions

pedestals fitted by

$$z = \frac{x_0 - x}{\delta}$$

$$mtanh(\alpha, z) = \frac{(1 + \alpha z)e^z - e^{-z}}{e^z + e^{-z}}$$

$$y = \frac{h + b}{2} + \frac{h - b}{2} mtanh(\alpha, z)$$



rigorous definition for pedestal width $\Delta = 2\delta$, continuous and differentiable throughout pedestal profile

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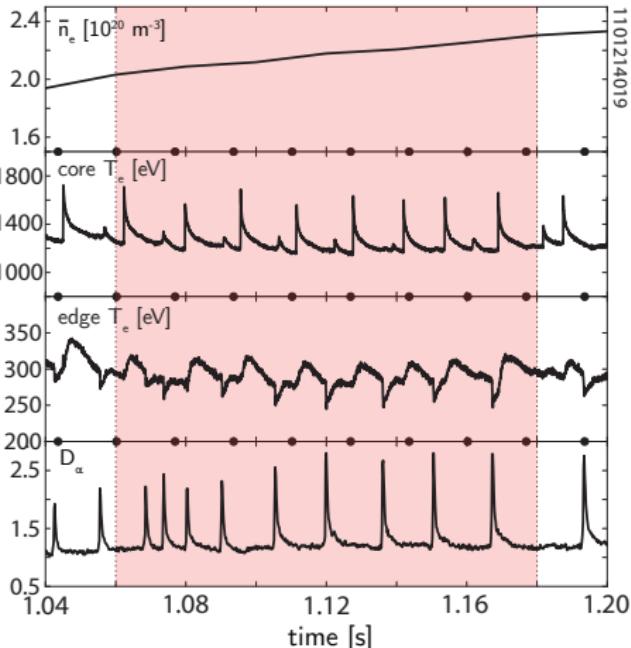
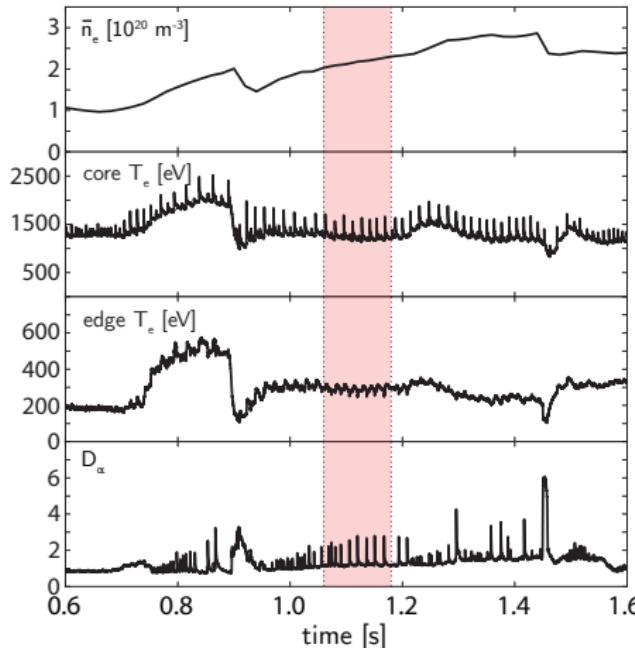
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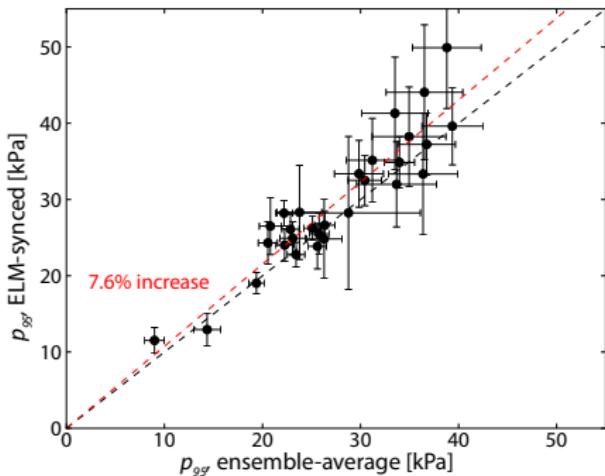
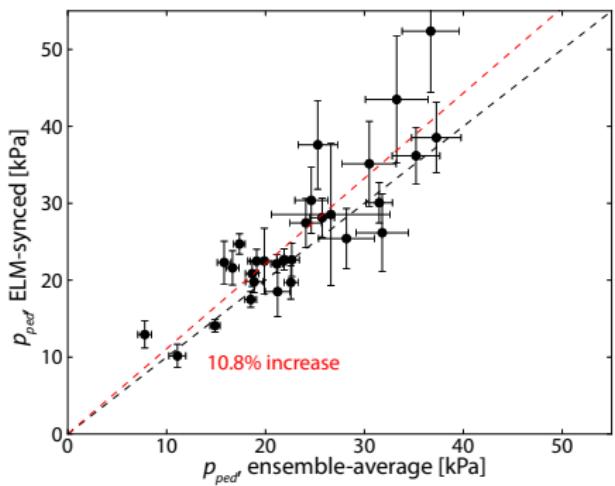
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Target steady ELM phases for study

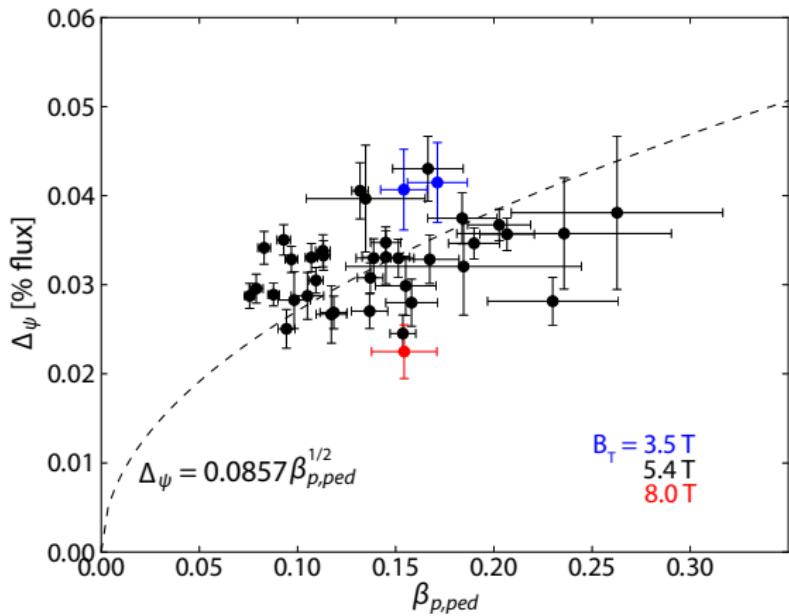


ELM cycle binning necessary to capture pedestal limit



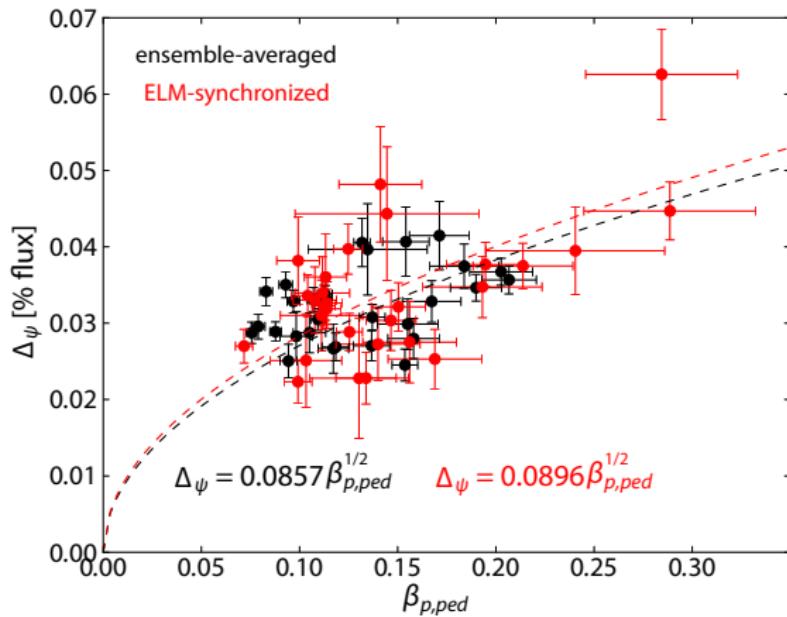
Take profile data immediately preceding ELM crash (typically last 20% of ELM cycle) for pedestal structure at point of instability – necessary, but difficult given ELM frequency on C-Mod (subset of data prepared thus).

Pedestal width described well by KBM limit



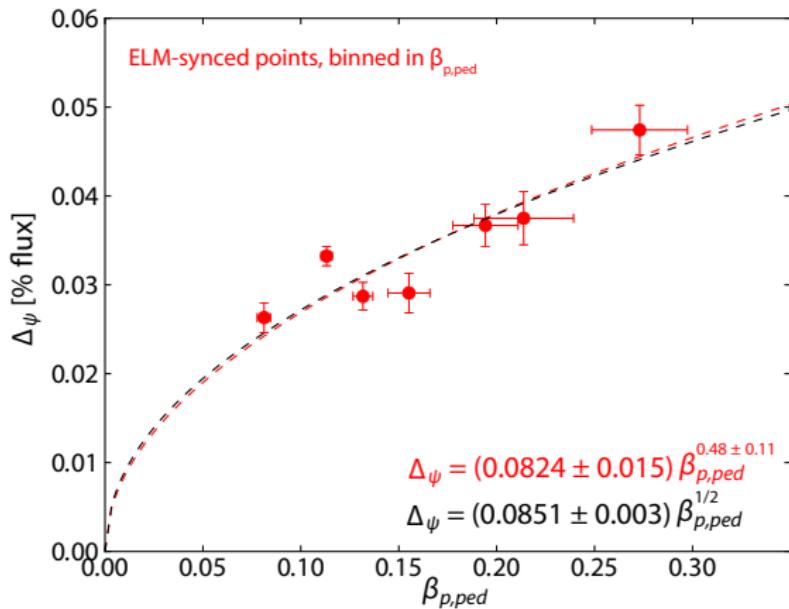
KBM limit predicts width $\Delta_\psi = G(\nu^*, \varepsilon, \dots) \beta_{p,ped}^{1/2}$

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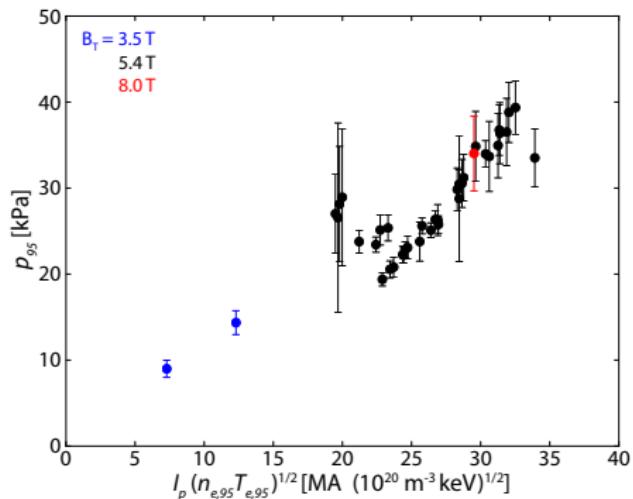
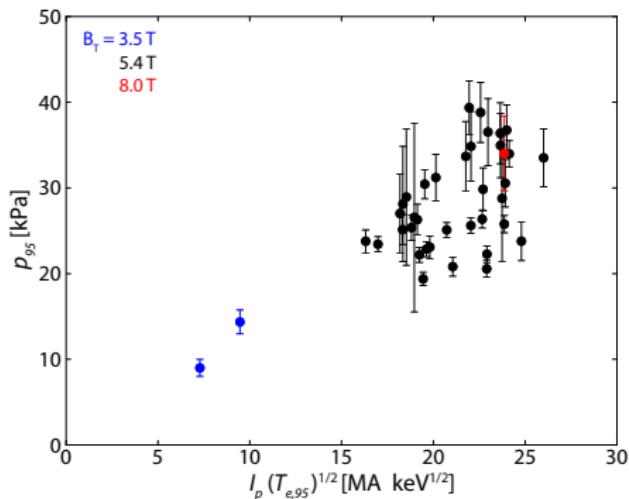
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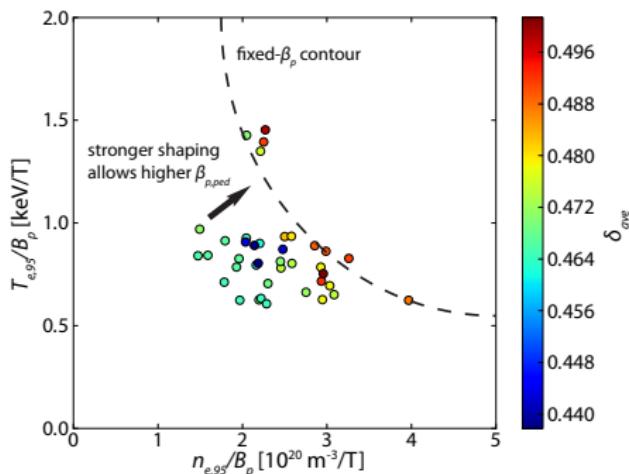
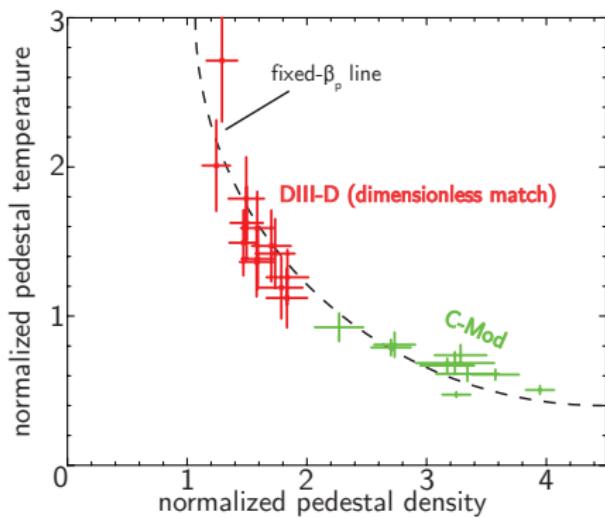
Minimal dependence of width on other parameters

Pedestal height predicted by ballooning ∇p limit

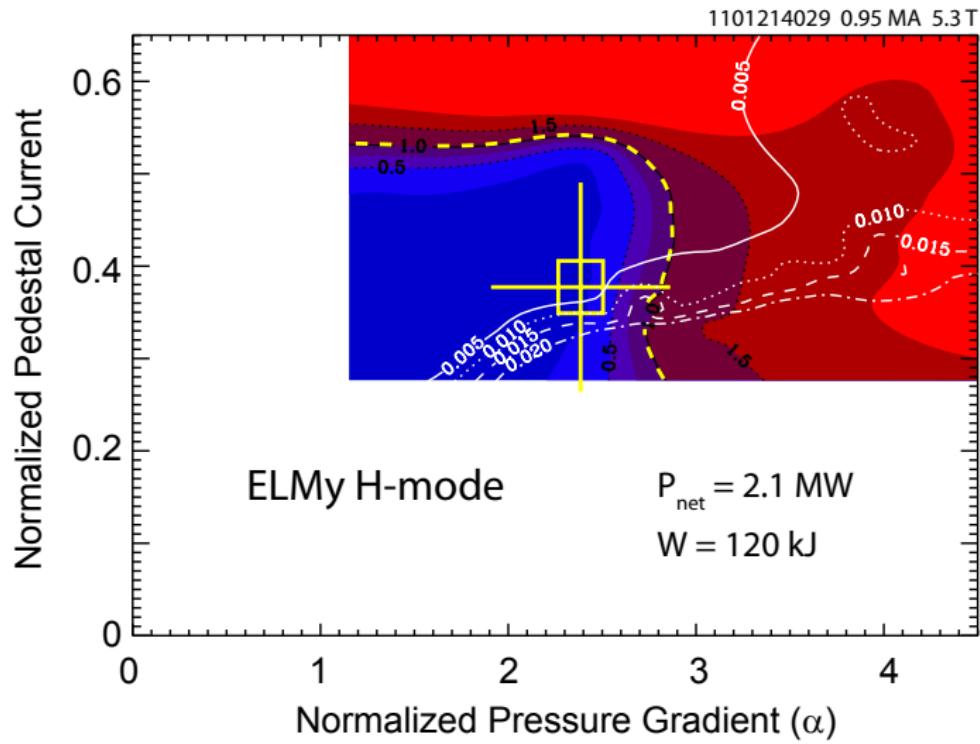


Pedestal height $p_{ped} \sim \nabla p \times \Delta_p \rightarrow \sim I_p^2 \Delta_p$ from ballooning MHD
predicted well by $\Delta_p \sim \sqrt{\beta_{p,ped}}$, less so by $\Delta_p \sim \rho_{i,pol}$

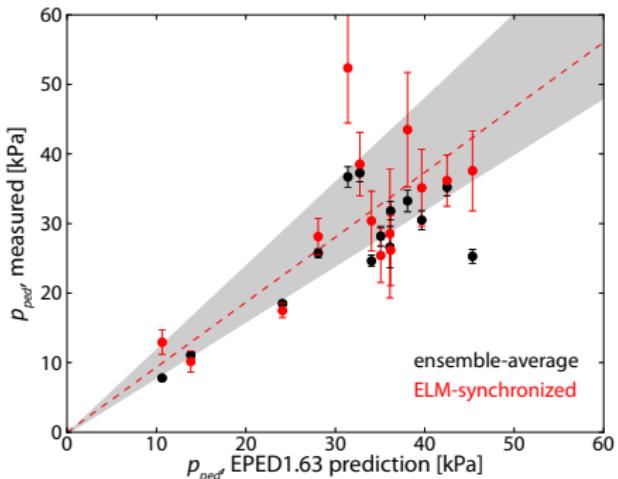
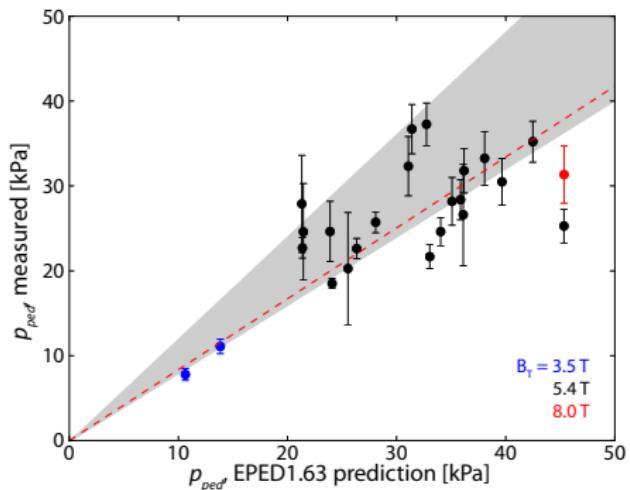
Robust width, gradient limit = attainable $\beta_{p,ped}$ limited in ELM My H-mode



Computational modeling of P-B MHD, KBM captures ELMy pedestal

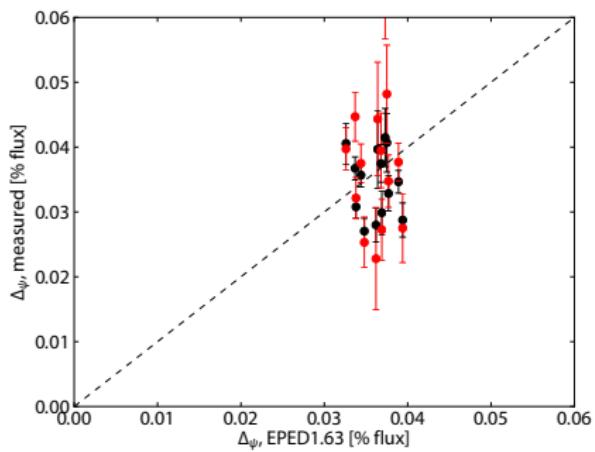
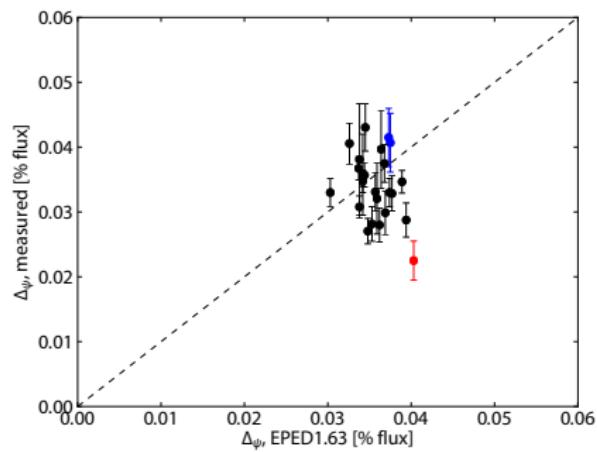


EPED predicts pedestal height for ELM-binned pedestals



measured to predicted ratio of 0.835 ± 0.036 for ensemble-averaged data, 0.934 ± 0.066 for ELM-synced pedestals, well within expected $\pm 20\%$ accuracy for EPED predictions

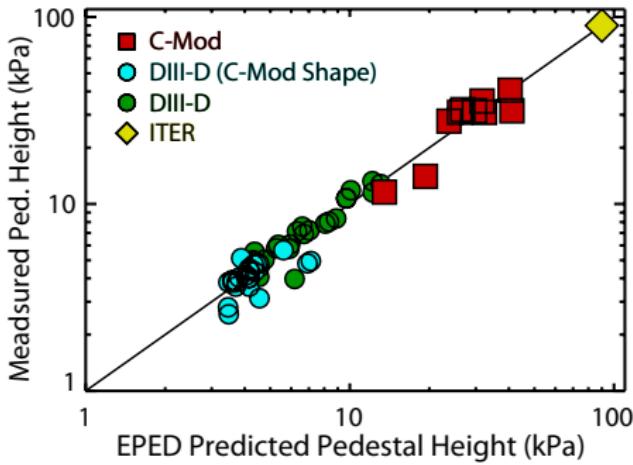
Width varies over narrow range, hard to predict



Pedestal width varies little over range of 3 – 5% of poloidal flux, difficult to extract trend – EPED reproduces robust width to within $\pm 20\%$ uncertainty

Experiments expand parameter space tested in EPED⁵

- reach highest field (8 T), highest thermal pressure, within factor of ~ 2 of ITER pedestal target
- C-Mod contribution to multi-machine Joint Research Target
- reliable physics-based understanding of H-mode pedestal limits



⁵RJ Groebner et al., Nuclear Fusion 53 (2013)

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■ I-Mode Pedestal Stability

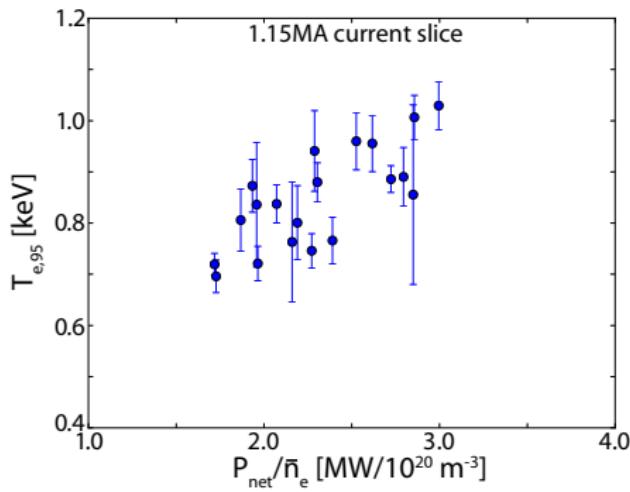
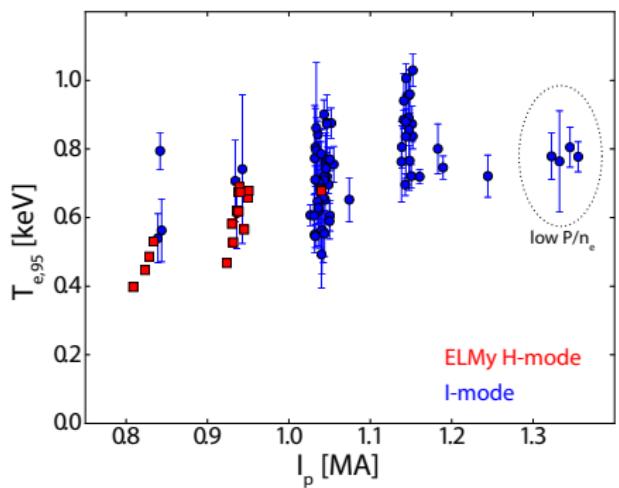
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²JR Walk *et al.*, *Physics of Plasmas* 21 (2014)

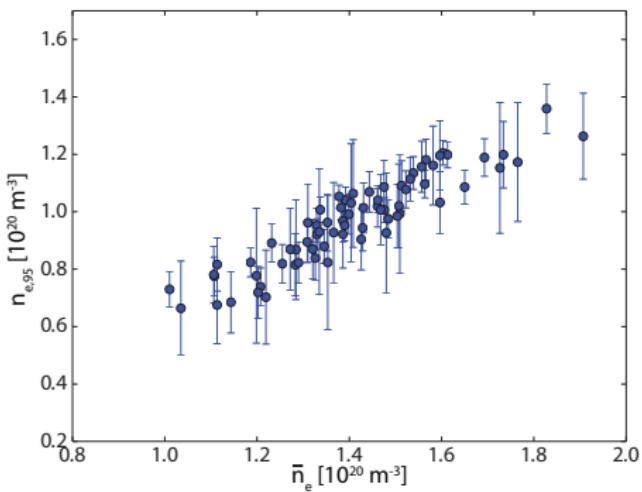
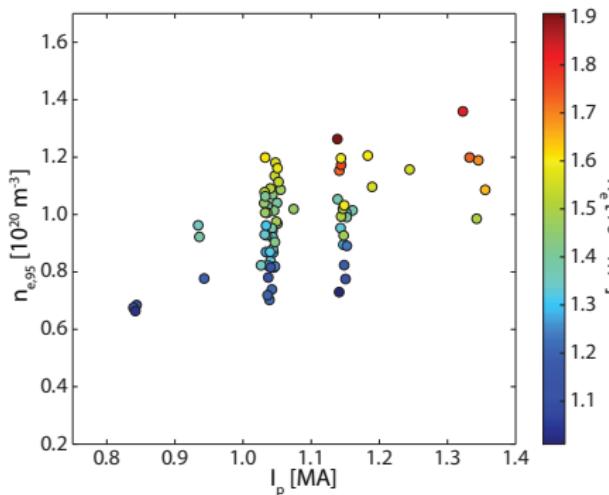
³Invited talk, APS-DPP Nov. 2013

Temperature pedestal H-mode-like, set by plasma current, heating power

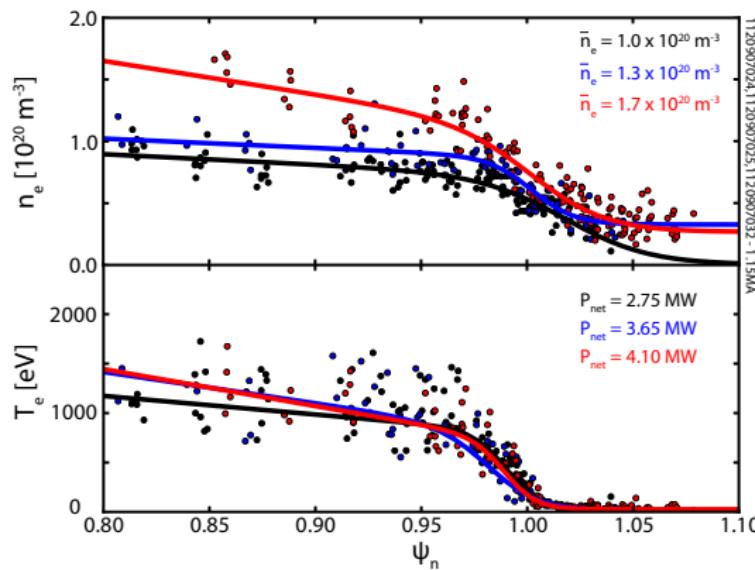


- pedestal T_e shows positive trending $T_e \sim I_p$, spread at given current due to heating power
- input power strongly affects pedestal temperature as with EDA H-mode – more properly, **power per particle sets pedestal temperature** at fixed current

In contrast, density set by operator fueling, with L-mode-like profile

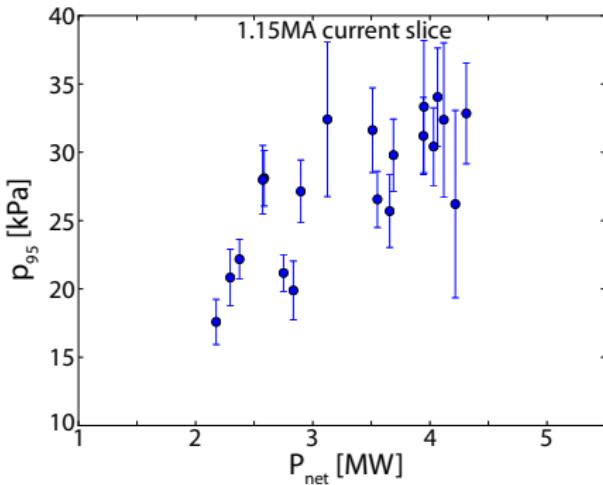
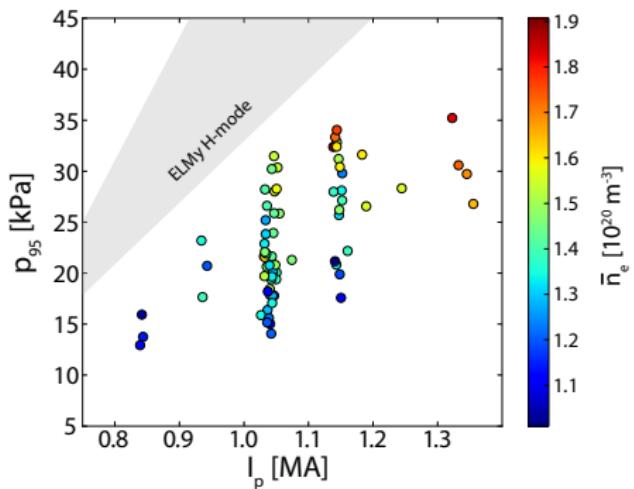


Pedestal density separately controlled from temperature, independent of MHD limits



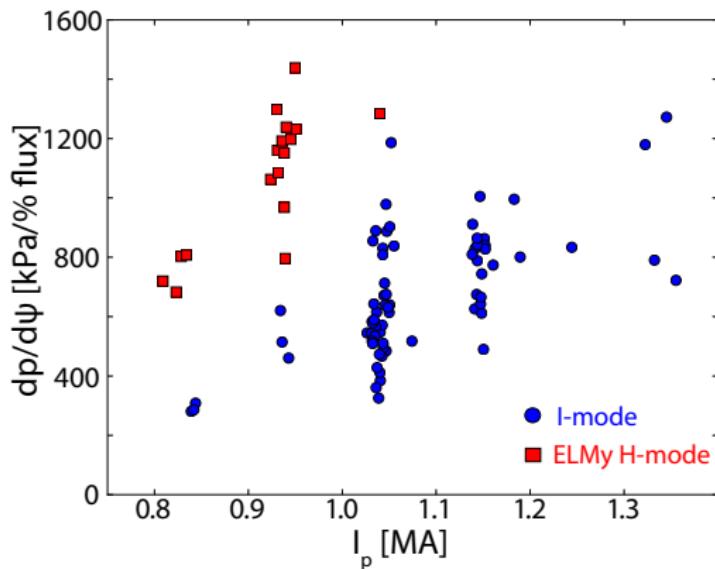
- with sufficient power to maintain P_{net}/\bar{n}_e , temperature pedestal matched across range of fueling
- Contrasts to MHD-limited pedestals (fixed $\beta_{p,ped} \rightarrow$ limit on $n_e T_e$) – path to strongly increase pedestal beta

I-mode pedestal pressure scales with current, heating power, fueling, competitive to H-mode



- Pedestal pressure increases at least as $p_{ped} \sim I_p$, due to increased $T_e \sim I_p$ and more fueling (fixed f_{Gr}) at higher current
- Pedestal pressure at fixed current $\sim P_{net}$ (consistent with $T_e \sim P/n_e$), corresponds to favorable scaling of energy confinement with heating power
- Fueling (with sufficient power to maintain temperature pedestal) strongly increases pedestal pressure

Pedestal pressure gradient suggests MHD stability, headroom for performance improvement

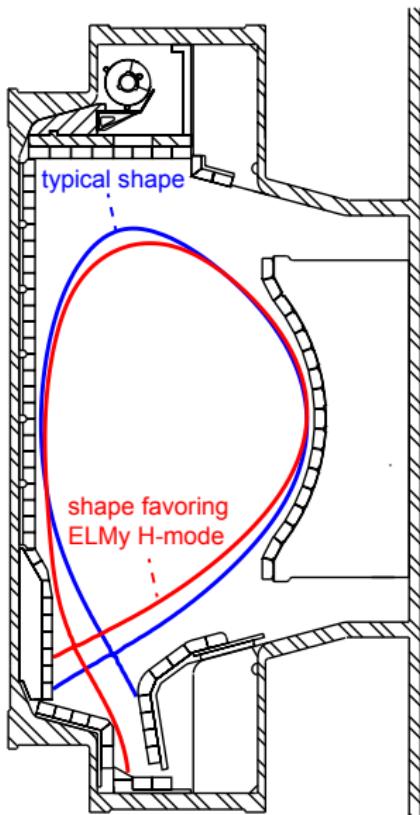


- Pedestal ∇p shallower at given I_p than ELMy H-mode due to lack of density pedestal
- Gradients scale more weakly than $\nabla p \propto I_p^2$ from ballooning MHD (critical-gradient) stability boundary

Supplemental Slides

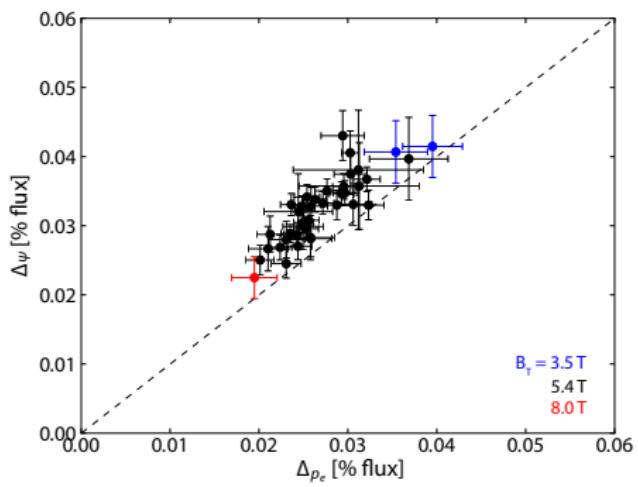
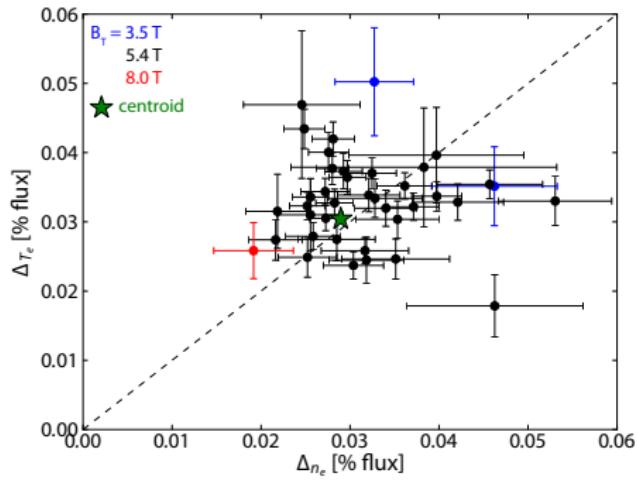


Plasma shaping in C-Mod operation



- I-mode operates at typical shaping for C-Mod plasmas (with reversed I_p , B_T for unfavorable ∇B drift)
- ELMMy H-mode on C-Mod requires special shaping with low elongation, upper triangularity, high lower triangularity – in normal shaping in forward field, reach ELM-free H-mode (low ν^*) or EDA H-mode (high ν^*)

Density, temperature, and pressure widths in ELMy H-mode



$$\Delta_\psi = (\Delta n_e + \Delta T_e)/2, \text{ tracks with directly-measured } \Delta p_e$$

$$\vec{Q} = \nabla \times (\vec{\xi} \times \vec{B})$$

$$\delta W = \delta W_F + \delta W_S + \delta W_V$$

$$\begin{aligned}\delta W_F = & \frac{1}{2} \int_P d^3 \vec{r} \left[\frac{|\vec{Q}|^2}{\mu_0} + \frac{B^2}{\mu_0} \left| \nabla \cdot \vec{\xi}_\perp + 2\vec{\xi}_\perp \cdot \vec{\kappa} \right|^2 + \gamma p \left| \nabla \cdot \vec{\xi} \right|^2 \right. \\ & \left. - 2 \left(\vec{\xi}_\perp \cdot \nabla p \right) \left(\vec{\kappa} \cdot \vec{\xi}_\perp^* \right) - j_{||} \left(\vec{\xi}_\perp^* \times \vec{b} \right) \cdot \vec{Q}_\perp \right]\end{aligned}$$

$$\delta W_S = \frac{1}{2} \int_S dS \left| \hat{n} \cdot \vec{\xi}_\perp \right|^2 \hat{n} \cdot \left[\nabla \left(p + \frac{B^2}{2\mu_0} \right) \right]$$

$$\delta W_V = \frac{1}{2} \int_V d^3 \vec{r} \frac{|B_1|^2}{\mu_0}$$

$$X = RB_p \xi_\psi$$

$$ik_{\parallel} = \frac{1}{JB} \left(\frac{\partial}{\partial \chi} + i n \nu \right) \quad \quad \nu = JB_T / R$$

$$P = \sigma X + \frac{B_p^2}{\nu B^2} \frac{F}{n} \frac{\partial}{\partial \psi} (JBk_{\parallel})$$

$$Q = \frac{X}{B^2} \frac{dp}{d\psi} + \frac{F^2}{\nu R^2 B^2} \frac{1}{n} \frac{\partial}{\partial \psi} (JBk_{\parallel} X)$$

$$\sigma = - \frac{F}{B^2} \frac{dp}{d\psi} - \frac{dF}{d\psi} = - \frac{j_{\parallel}}{B}$$

$$\delta W = \pi \iint d\psi d\chi \left\{ \frac{JB^2}{R^2 B_p^2} |k_{\parallel} X|^2 + \frac{R^2 B_p^2}{JB^2} \left| \frac{1}{n} \frac{\partial}{\partial \psi} (JBk_{\parallel} X) \right|^2 \right. \\ - \frac{2J}{B^2} \frac{dp}{d\psi} \left[|X|^2 \frac{\partial}{\partial \psi} \left(p + \frac{B^2}{2} \right) - \frac{iF}{JB^2} \frac{\partial}{\partial \chi} \left(\frac{B^2}{2} \right) \frac{X^* \partial X}{n} \right] \\ - \frac{X^*}{n} JBk_{\parallel} \left(X \frac{d\sigma}{d\psi} \right) + \frac{1}{n} [P J B k_{\parallel}^* Q^* + P^* J B k_{\parallel} Q] \\ \left. + \frac{\partial}{\partial \psi} \left[\frac{\sigma}{n} X^* J B k_{\parallel} X \right] \right\}$$