Pedestal Structure and Stability in High-Performance 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
- **ELMy H-mode physics**[1]
  - EPED Modeling on C-Mod

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

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- **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**

[2] JR Walk *et al.*, *Physics of Plasmas* **21** (2014)
[3] *Invited 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.

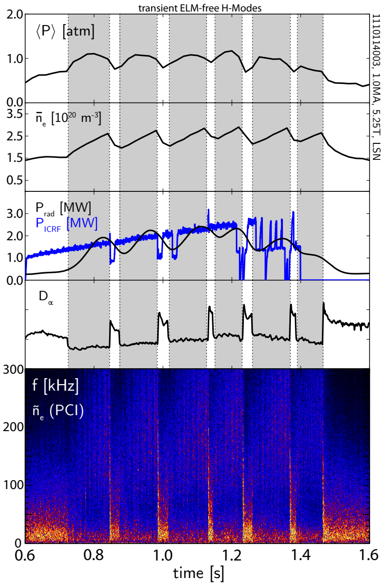
The solution?

Under right conditions, plasma forms “transport barrier” in edge, with steep gradients in density and temperature – the *pedestal*
$\rightarrow$ 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

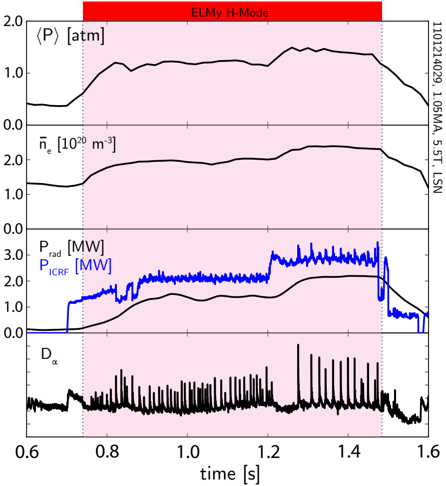


so, we need:

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

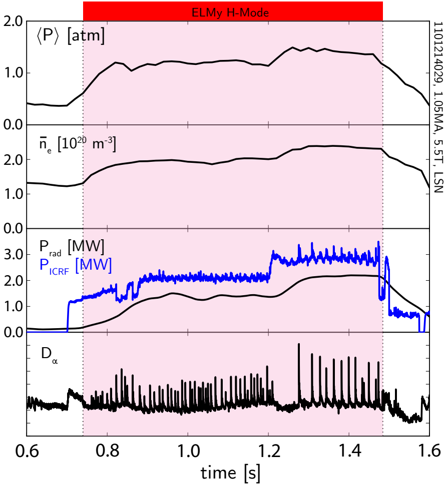
The solution? (part II)

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



The solution? (part II)

- 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



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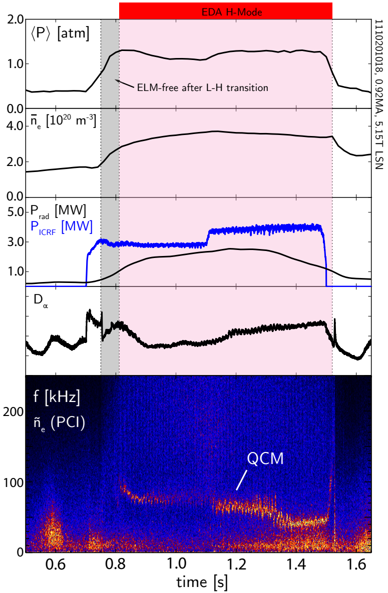
  - engineering solutions:
    pellet pacing, resonant magnetic perturbations

so, we need:

- high energy confinement
- low particle confinement (low enough, at least)
- 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)

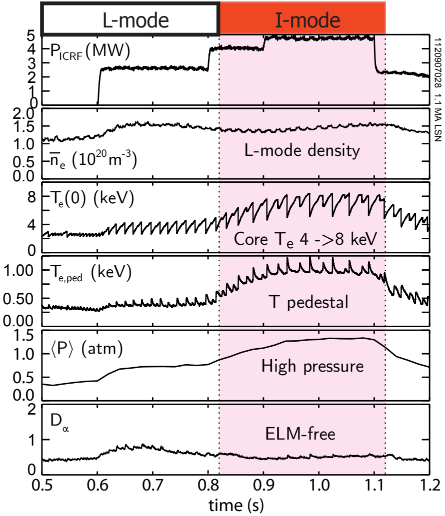
A number of fluctuation-regulated regimes have been observed:

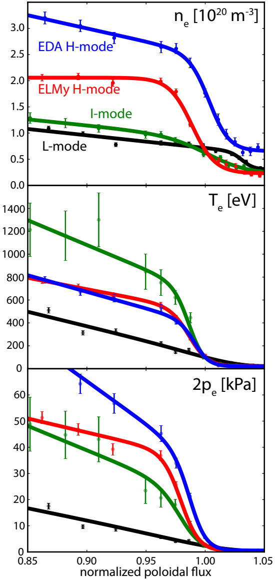
- EDA H-mode – Quasi-Coherent Mode (QCM) – C-Mod, AUG(?)
- Quiescent H-mode – Edge Harmonic Oscillator (EHO) – DIII-D, JET, AUG
- type-II, -III ELMy H-modes – various

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)

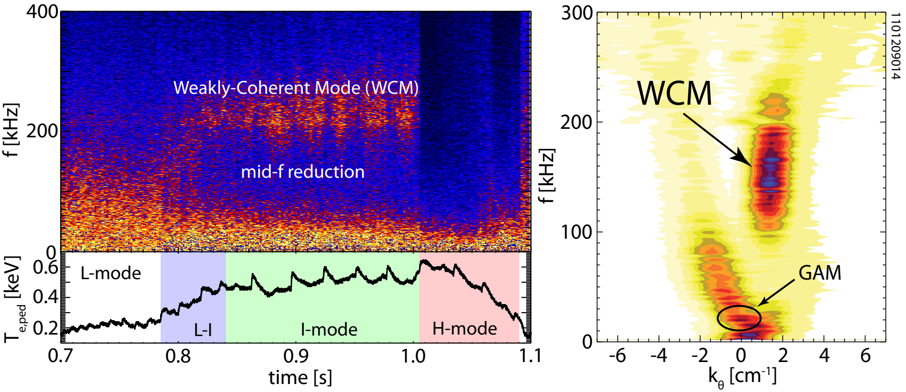
Can we do better?

A challenger appears: the I-mode

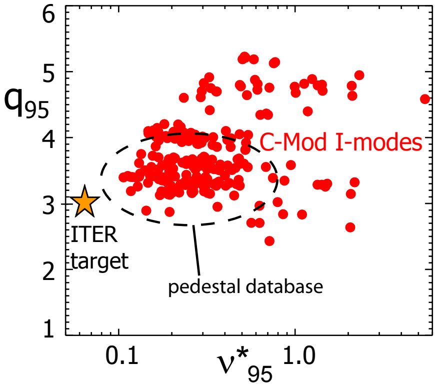


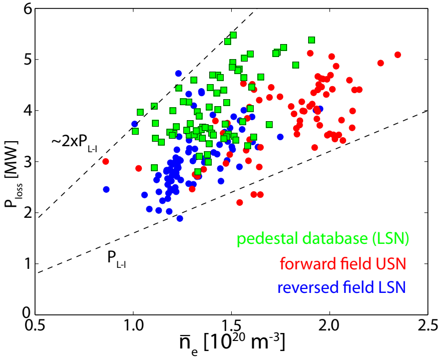


I-mode pedestal regulated by Weakly-Coherent Mode (WCM)



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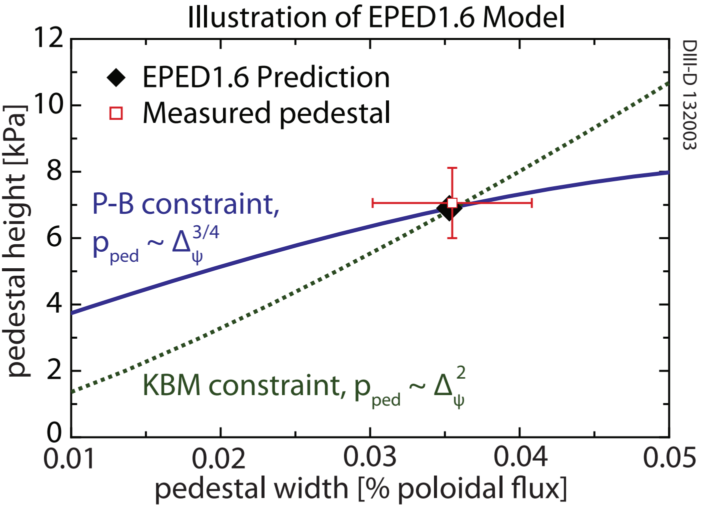
[1] JR Walk *et al.*, *Nuclear Fusion* **52** (2012)

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

Predictive Model for ELMy H-modes – EPED[4]



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

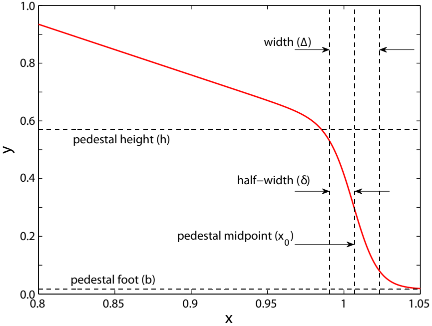
Pedestal Structure Definitions

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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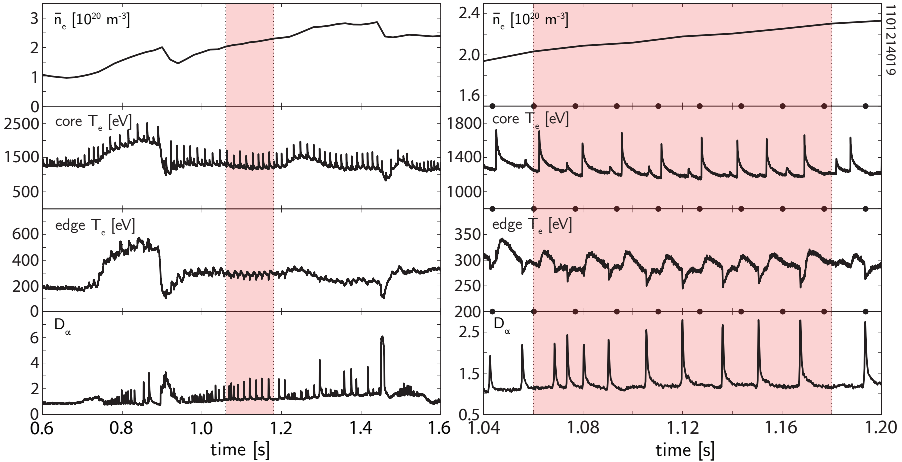
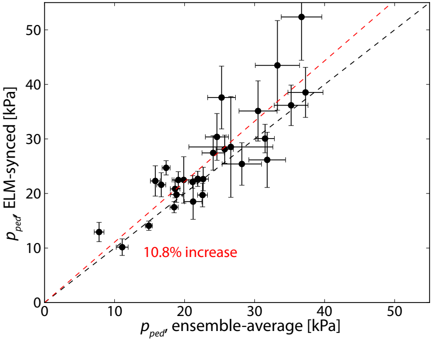
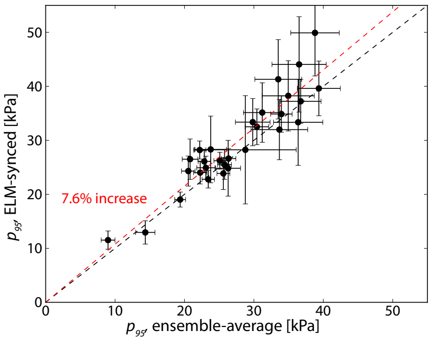
Target steady ELMy phases for study



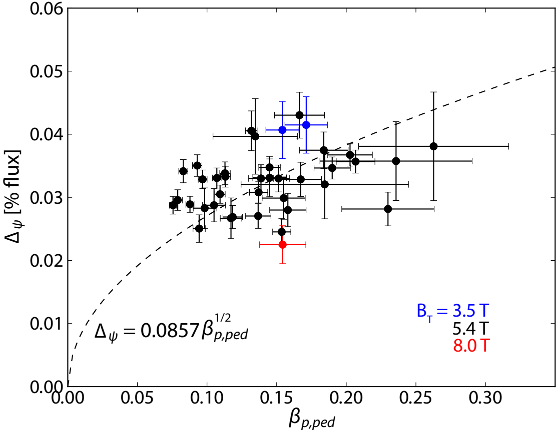
ELM cycle binning necessary to capture pedestal limit





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 $\Delta_\psi = G(\nu^*, \varepsilon, \ldots)\beta_{p,ped}^{1/2}$

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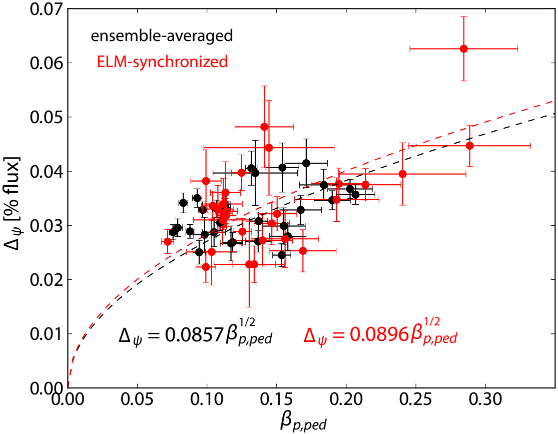

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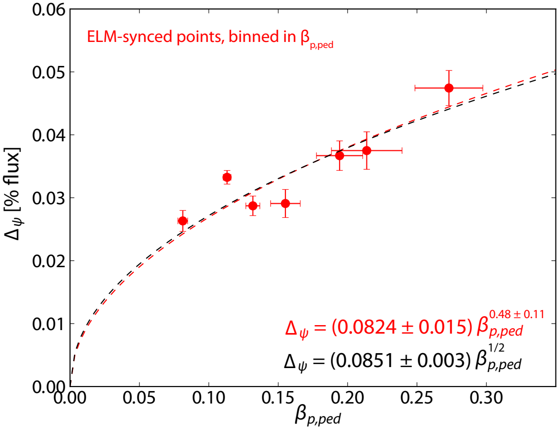
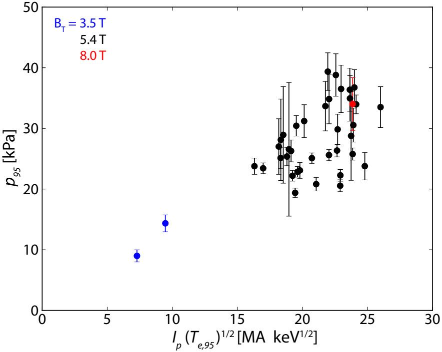
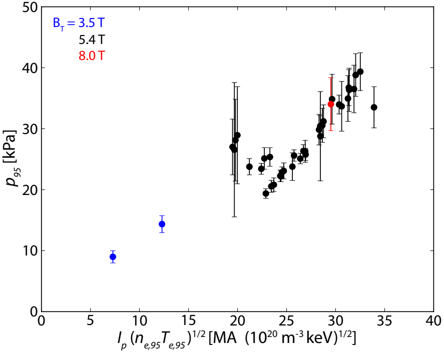


KBM limit predicts width $\Delta_\psi = G(\nu^*, \varepsilon, \ldots)\beta_{p,ped}^{1/2}$

Minimal dependence of width on other parameters

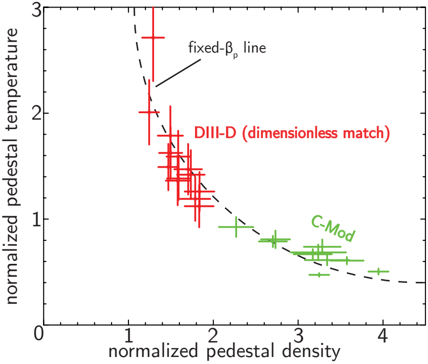
Pedestal height predicted by ballooning ∇p limit

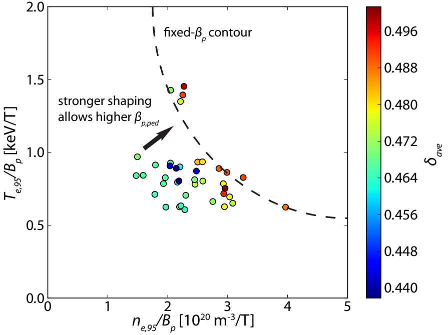




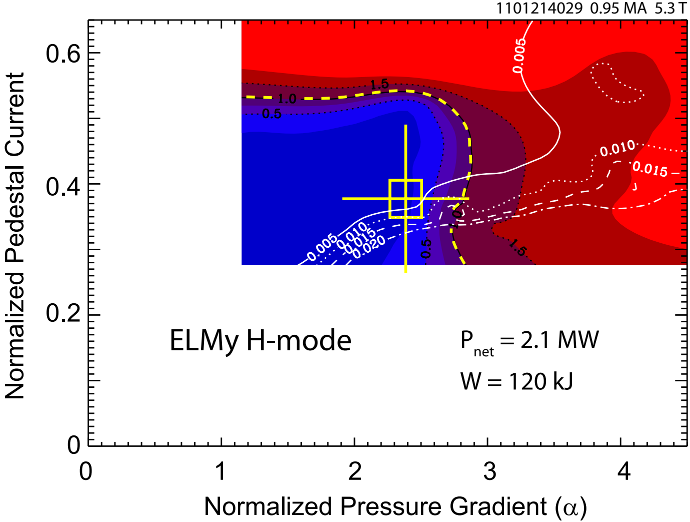
Pedestal height $p_{ped} \sim \nabla p \times \Delta_p \rightarrow \sim I_p^2 \Delta_p$ from ballooning MHD predicted well by $\Delta_p \sim \sqrt{\beta_{p,ped}}$, less so by $\Delta_p \sim \rho_{i,pol}$

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

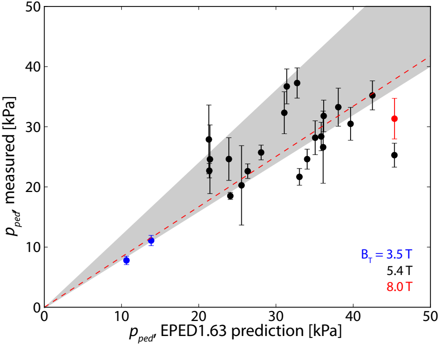


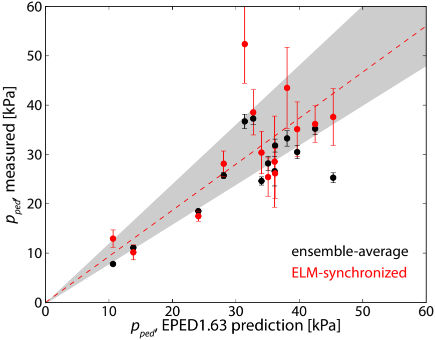


Computational modeling of P-B MHD, KBM captures ELMy pedestal



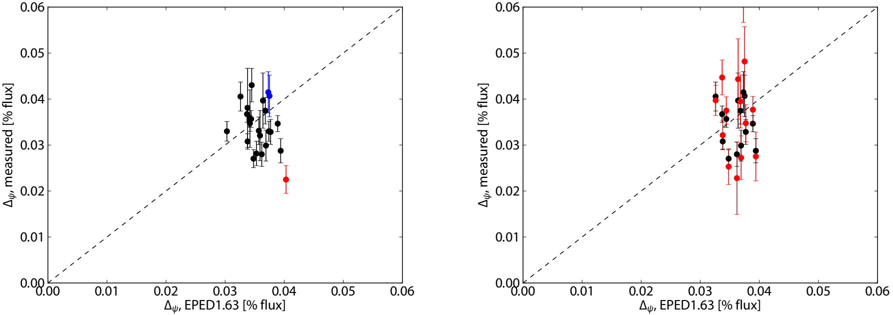
EPED predicts pedestal height for ELM-binned pedestals





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

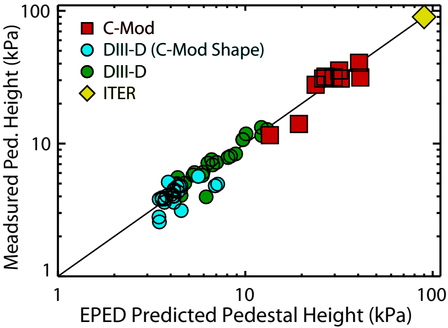
Width varies over narrow range, hard to predict



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 EPED[5]

- 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



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

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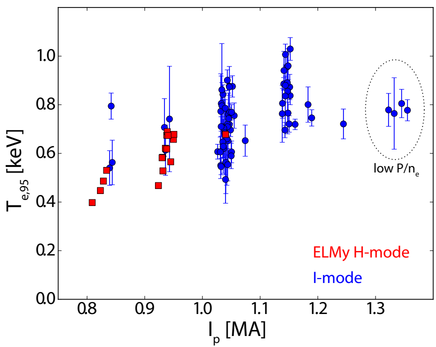
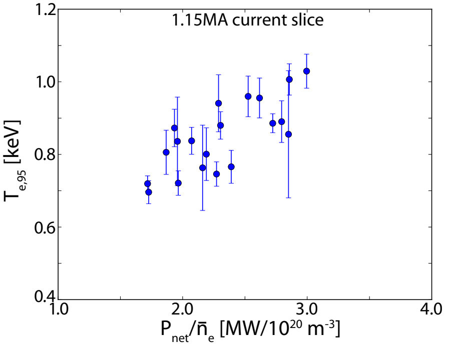
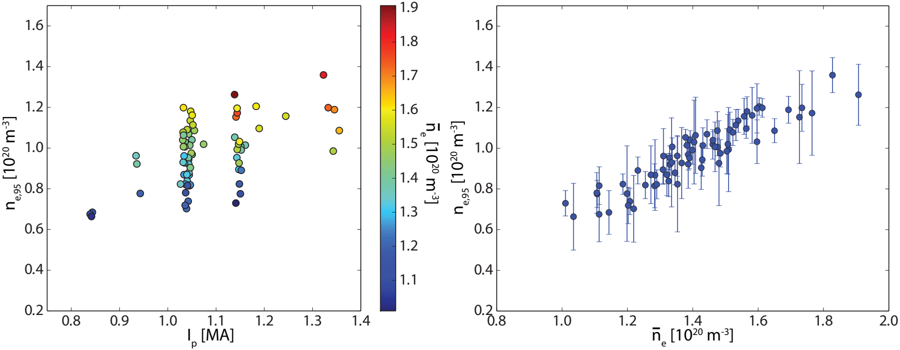
Temperature pedestal H-mode-like, set by plasma current, heating power



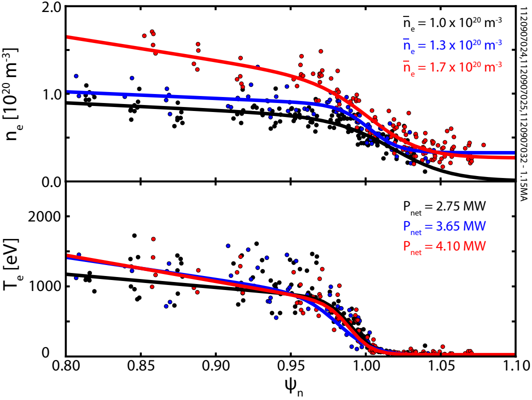


- pedestal T_e shows positive trending $T_e \sim I_p$, spread at given current due to heating power
- input power strongly affects pedestal temperature as with EDA H-mode – more properly, power per particle sets pedestal temperature at fixed current

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

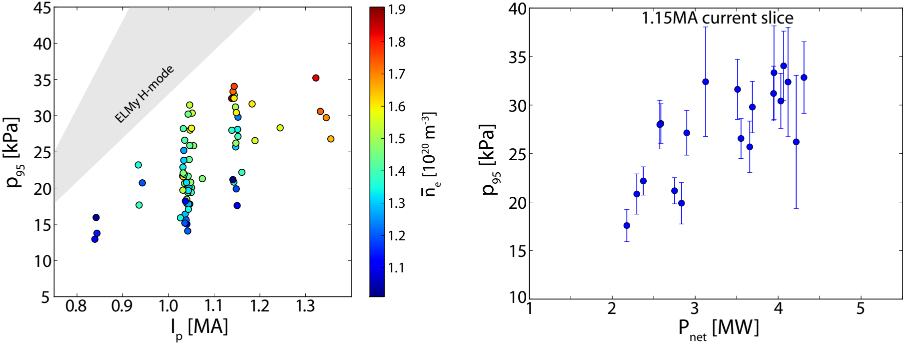


Pedestal density separately controlled from temperature, independent of MHD limits



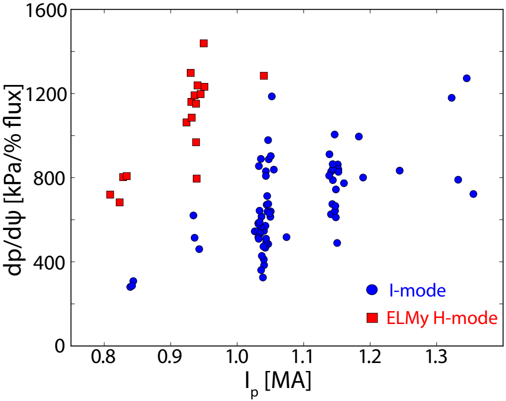
- with sufficient power to maintain $P_{net}/\overline{n}_e$, temperature pedestal matched across range of fueling
- Contrasts to MHD-limited pedestals (fixed $\beta_{p,ped} \rightarrow$ limit on $n_e T_e$) – path to strongly increase pedestal beta

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

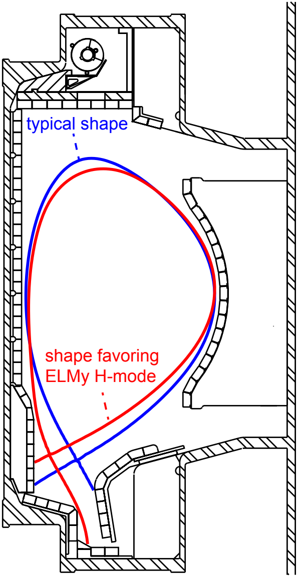
Pedestal pressure gradient suggests MHD stability, headroom for performance improvement



- 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

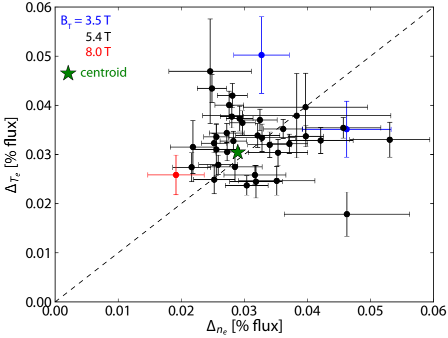
Supplemental Slides

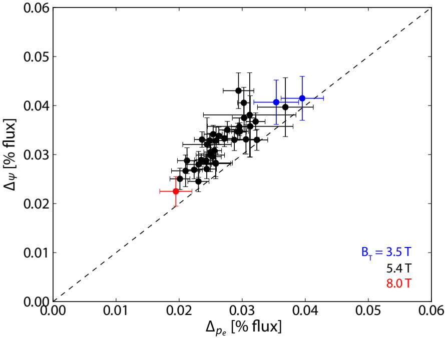
Plasma shaping in C-Mod operation



- I-mode operates at typical shaping for C-Mod plasmas (with reversed I_p, B_T for unfavorable ∇B drift)
- ELMy 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





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

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

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

$$\delta W_F = \frac{1}{2}\int_P d^3\vec{r}\left[\frac{|\vec{Q}|^2}{\mu_0} + \frac{B^2}{\mu_0}\left|\nabla\cdot\vec{\xi}_\perp + 2\vec{\xi}_\perp\cdot\vec{\kappa}\right|^2 + \gamma p\left|\nabla\cdot\vec{\xi}\right|^2 \right.$$

$$\left. - 2\left(\vec{\xi}_\perp\cdot\nabla p\right)\left(\vec{\kappa}\cdot\vec{\xi}^*_\perp\right) - j_\parallel\left(\vec{\xi}^*_\perp\times\vec{b}\right)\cdot\vec{Q}_\perp\right]$$

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

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

$$X = RB_p\xi_\psi$$

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

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

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

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

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