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
- **ELMy H-mode physics**[1]
  - EPED Modeling on C-Mod

[1] JR 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**

[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.

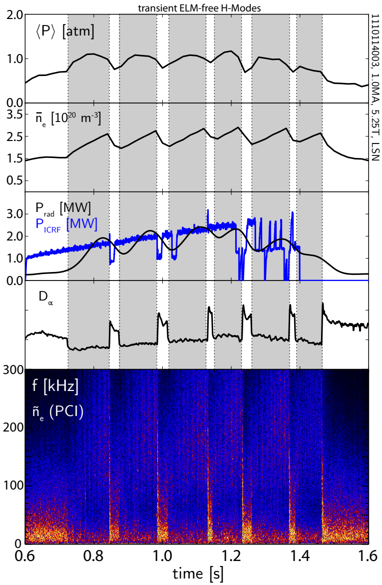
The solution?

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

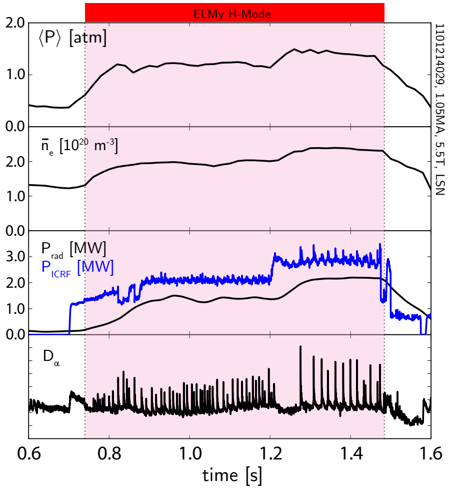


so, we need:

- 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



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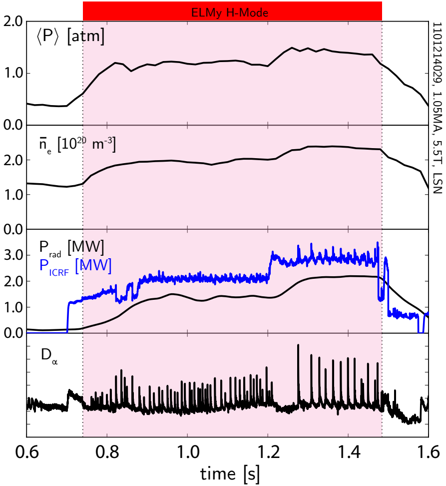
- large ELMs drive pulsed heat loads in excess of plasma-facing material tolerances



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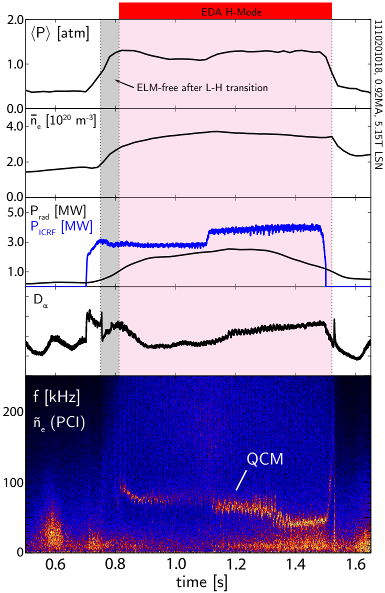
so, we need:

- 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)

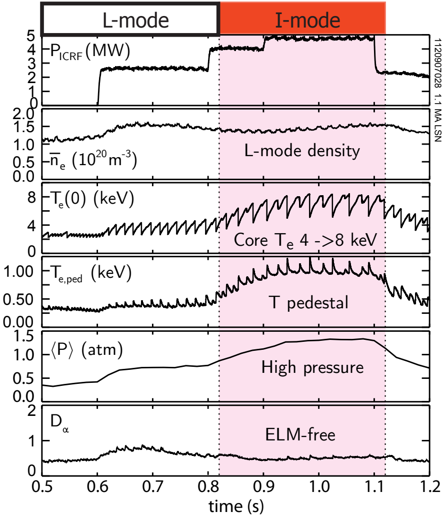
A number of fluctuation-regulated regimes have been observed:

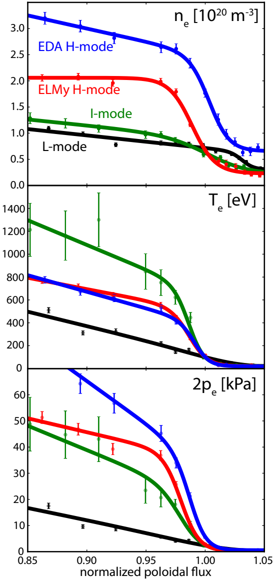
- EDA H-mode – Quasi-Coherent Mode (QCM) – C-Mod, AUG(?)
- Quiescent H-mode – Edge Harmonic Oscillator (EHO) – DIII-D, JET, AUG
- type-II, -III ELMy H-modes – various

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)

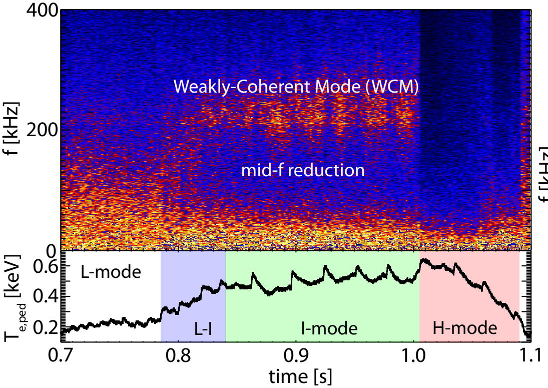
Can we do better?

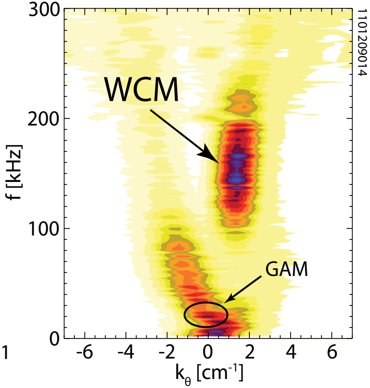
A challenger appears: the I-mode



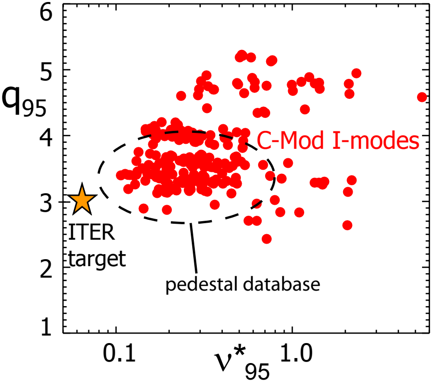


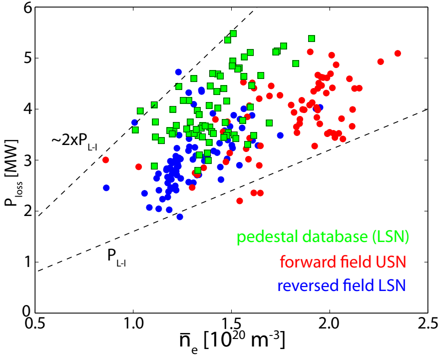
I-mode pedestal regulated by Weakly-Coherent Mode (WCM)





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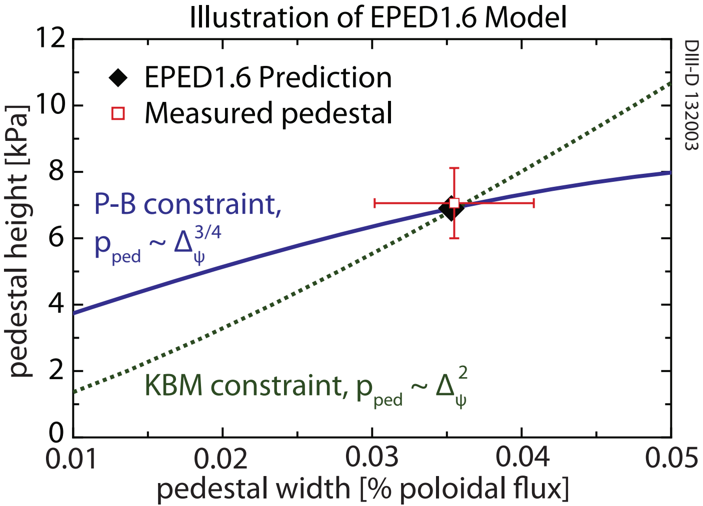
[1] JR Walk *et al.*, *Nuclear Fusion* **52** (2012)

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)

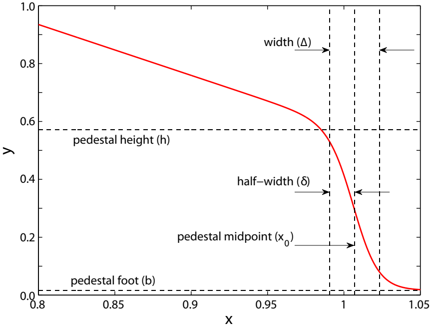
Pedestal Structure Definitions

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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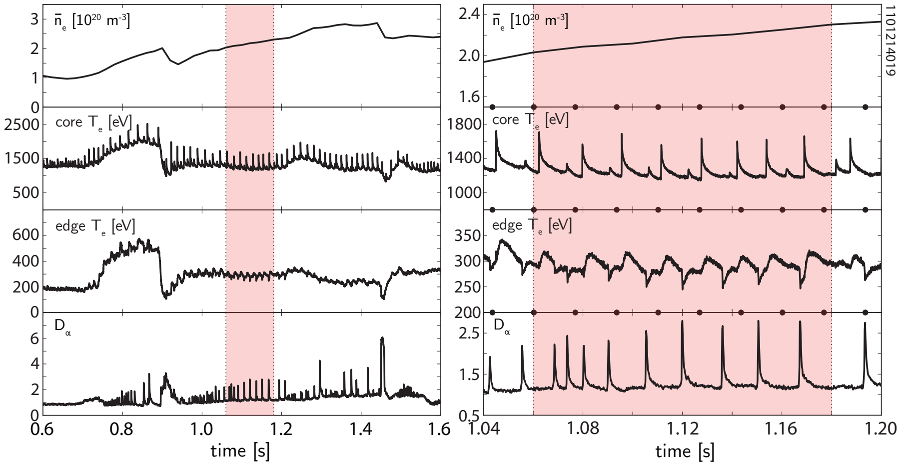
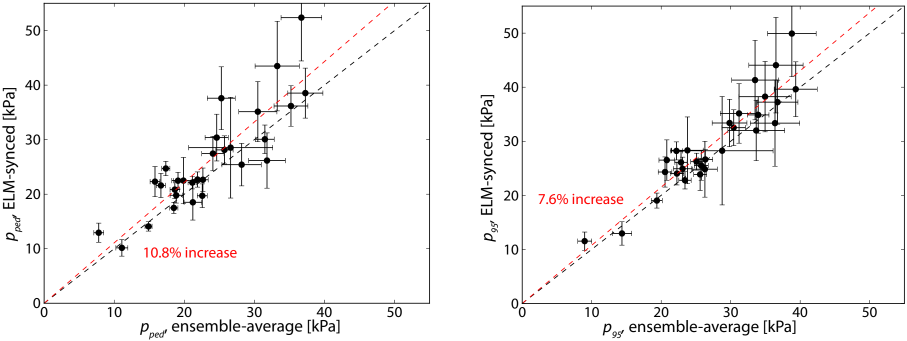
Target steady ELMy phases for study

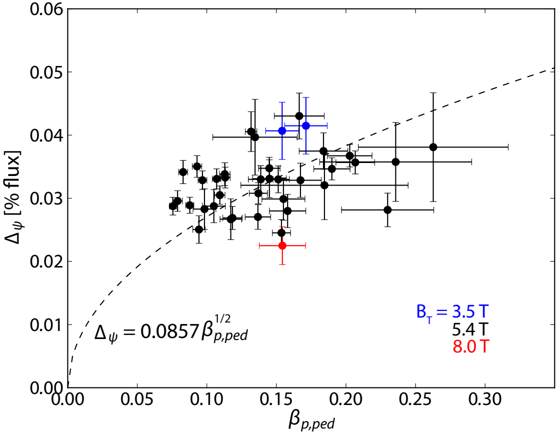


ELM cycle binning necessary to capture pedestal limit



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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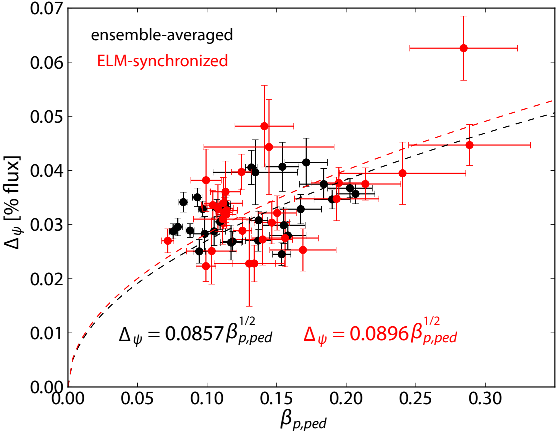

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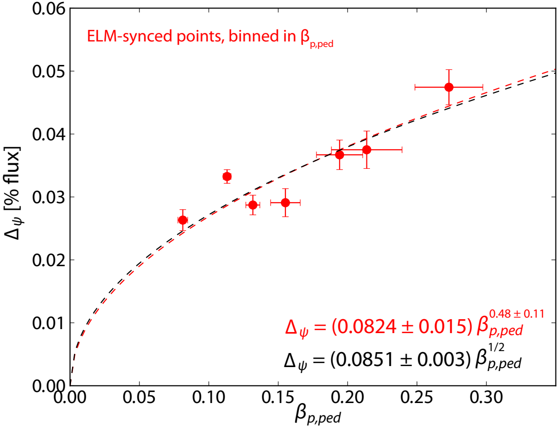
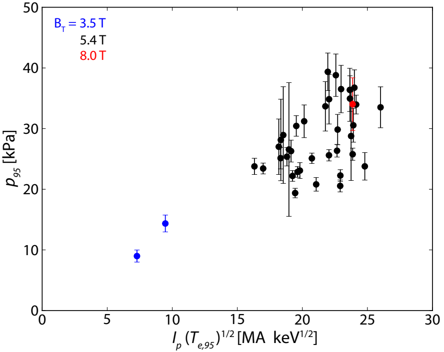
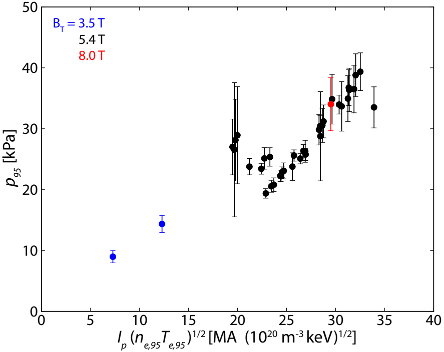


KBM limit predicts width $\Delta_\psi = G(\nu^*, \varepsilon, \ldots)\beta_{p,ped}^{1/2}$

Minimal dependence of width on other parameters

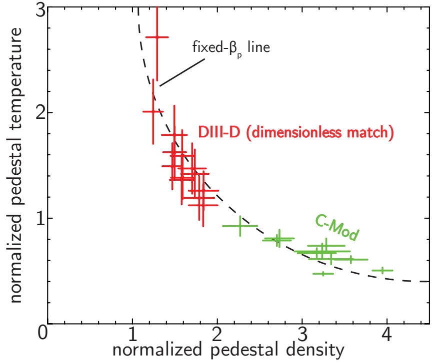
Pedestal height predicted by ballooning ∇p limit

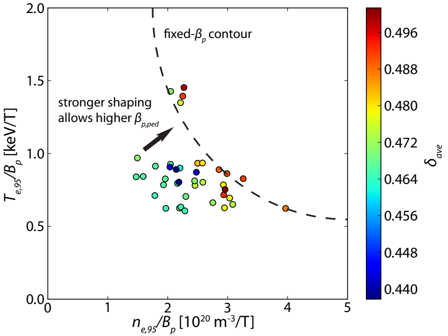




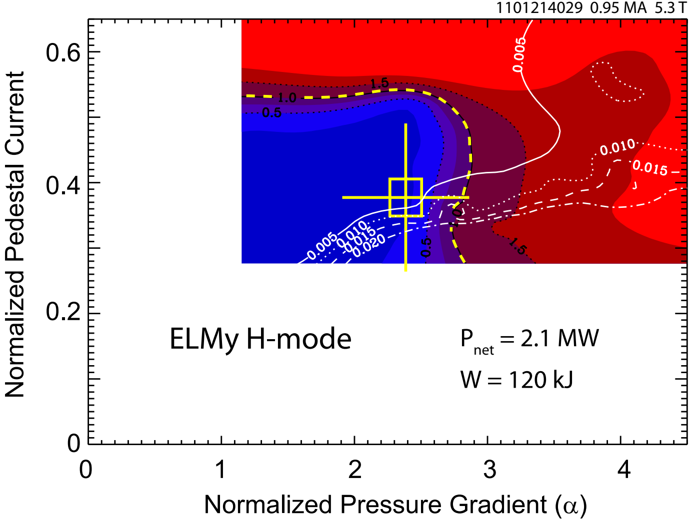
Pedestal height $p_{ped} \sim \nabla p \times \Delta_p \rightarrow \sim I_p^2 \Delta_p$ from ballooning MHD predicted well by $\Delta_p \sim \sqrt{\beta_{p,ped}}$, less so by $\Delta_p \sim \rho_{i,pol}$

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

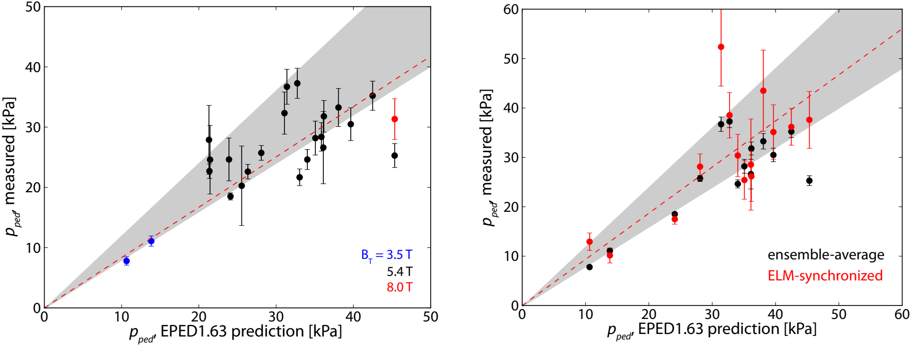




Computational modeling of P-B MHD, KBM captures ELMy pedestal

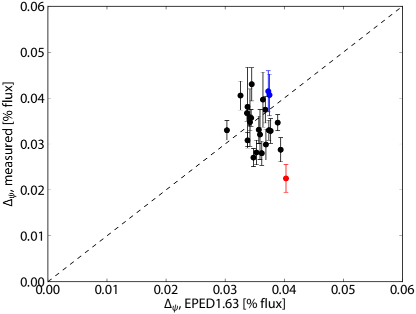


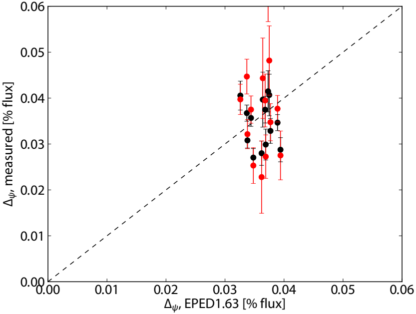
EPED predicts pedestal height for ELM-binned pedestals



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

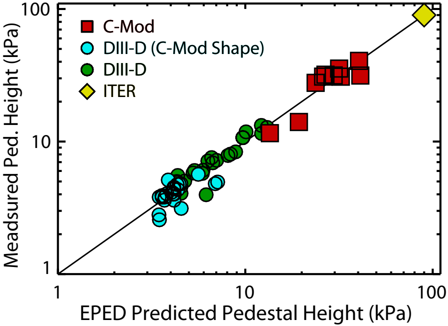




Pedestal width varies little over range of $3 - 5\%$ of poloidal flux, difficult to extract trend – EPED reproduces robust width to within $\pm 20\%$ uncertainty

Experiments expand parameter space tested in EPED[5]

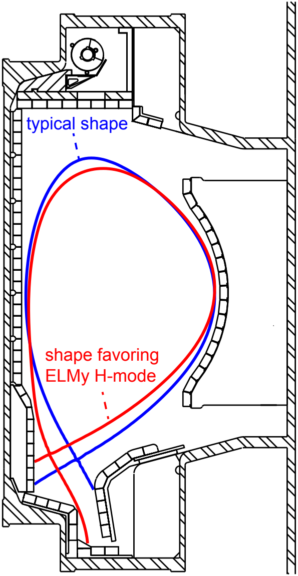
- reach highest field (8 T), highest thermal pressure, within factor of ~ 2 of ITER pedestal target
- C-Mod contribution to multi-machine Joint Research Target
- reliable physics-based understanding of H-mode pedestal limits



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

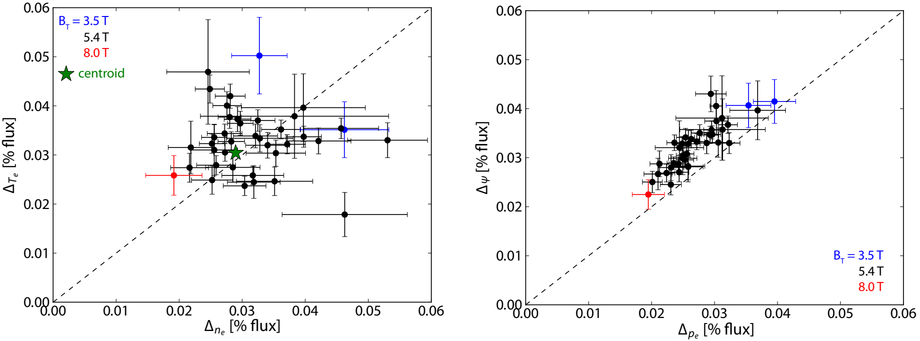
Supplemental Slides

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}