

# 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<sup>1</sup>

- ▶ EPED Modeling on C-Mod

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<sup>1</sup>JR Walk *et al.*, *Nuclear Fusion* **52** (2012)

# Outline

## ■ I-Mode Pedestals & Global Performance<sup>2,3</sup>

- ▶ 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

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<sup>3</sup>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.

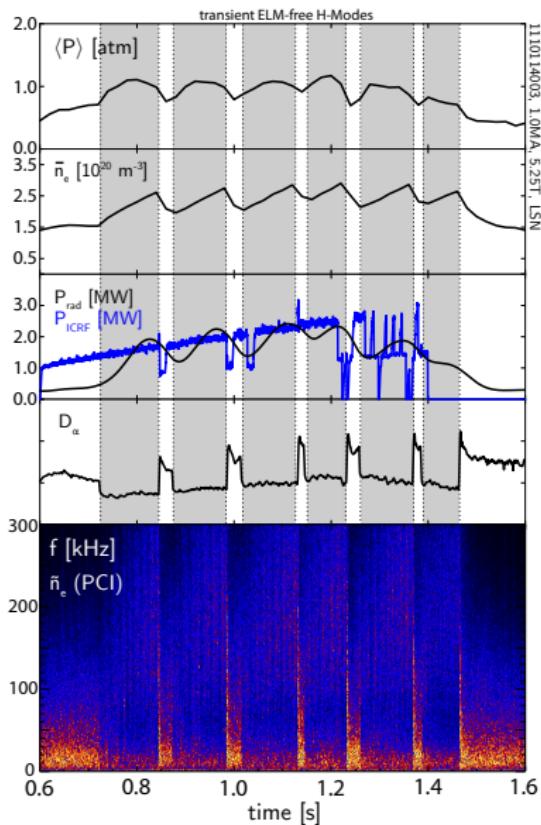
## The solution?

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

- immediate factor of  $\sim 2$  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

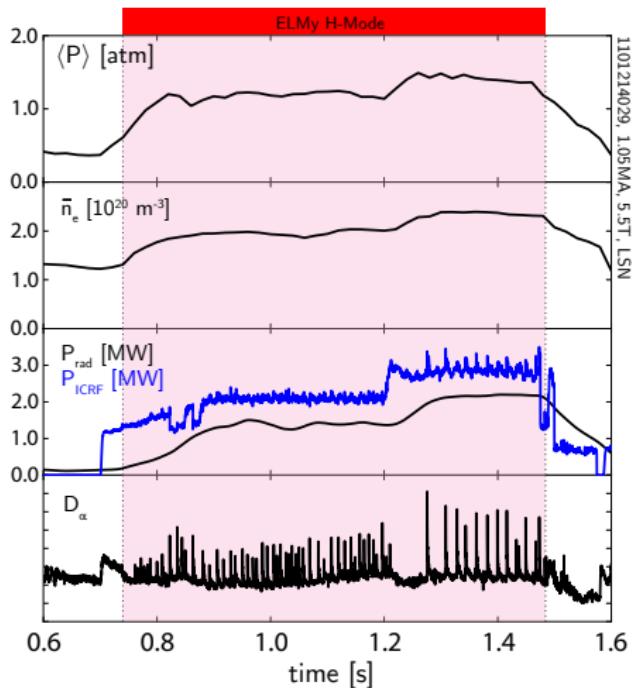


so, we need:

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

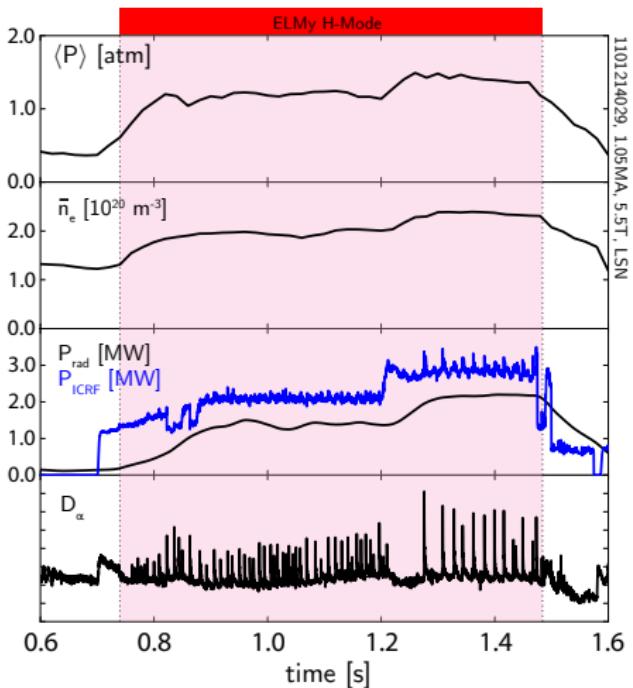
# The solution? (part II)

- 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



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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

## The solution? (part III)

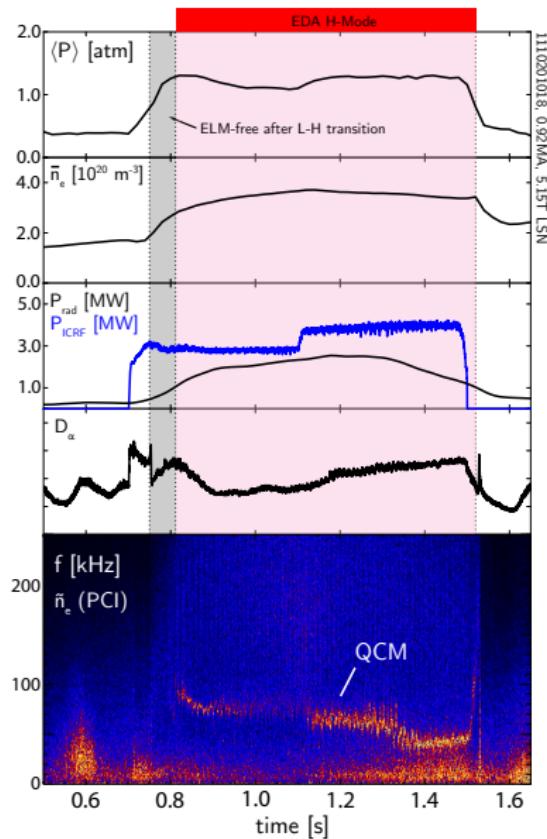
A number of fluctuation-regulated regimes have been observed:

- EDA H-mode  
Quasi-Coherent Mode (QCM) – C-Mod, AUG(?)
- Quiescent H-mode  
Edge Harmonic Oscillator (EHO) – DIII-D, JET, AUG
- High-Recycling Steady H-mode  
edge MHD fluctuations – JFT-2M
- type-II, -III ELMy H-modes  
small, rapid ELMs – various devices

generally capable of stationary high performance without large ELMs

# 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

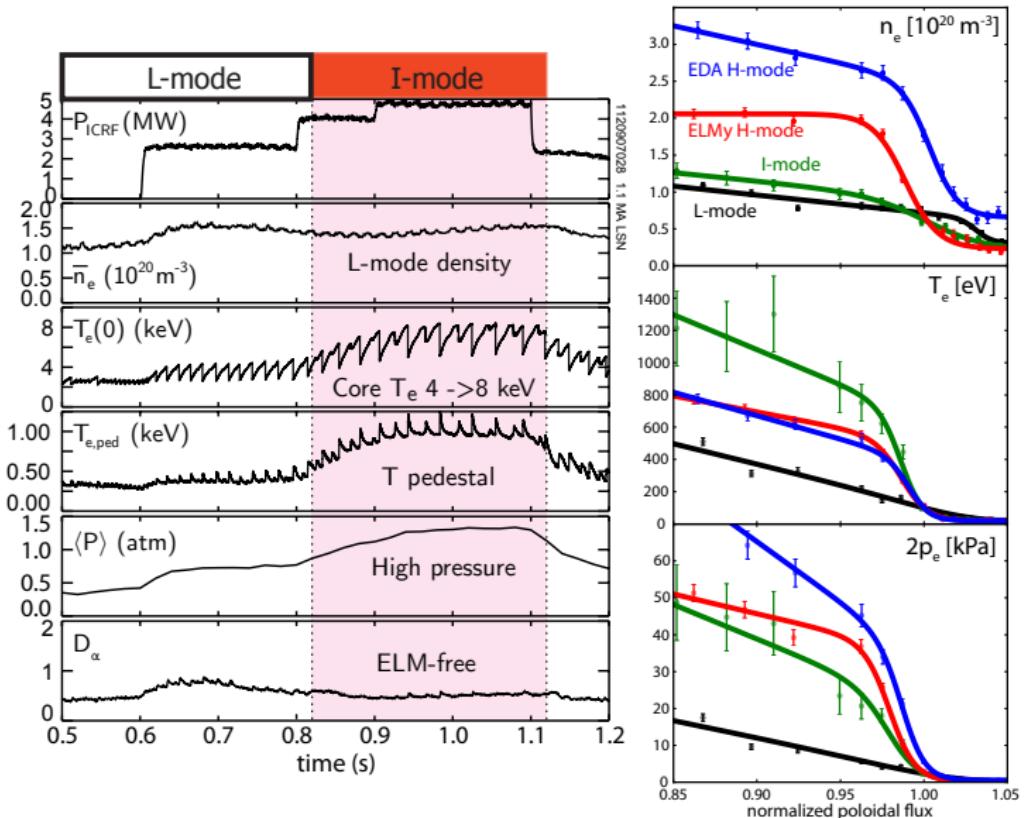


## But each of these has drawbacks

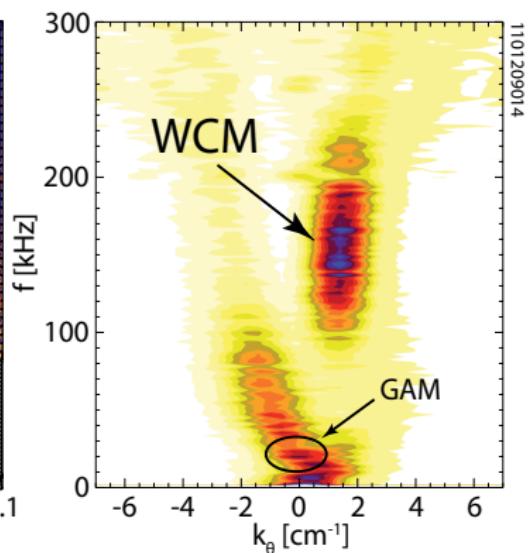
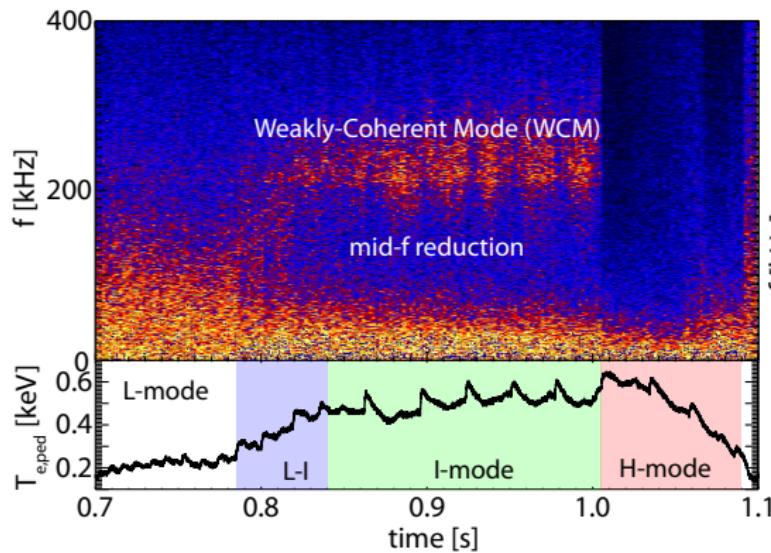
- engineering requirements, e.g. high beam torque for QH-mode
- access limits: high collisionality for EDA, shaping for type-II ELMs

Can we do better?

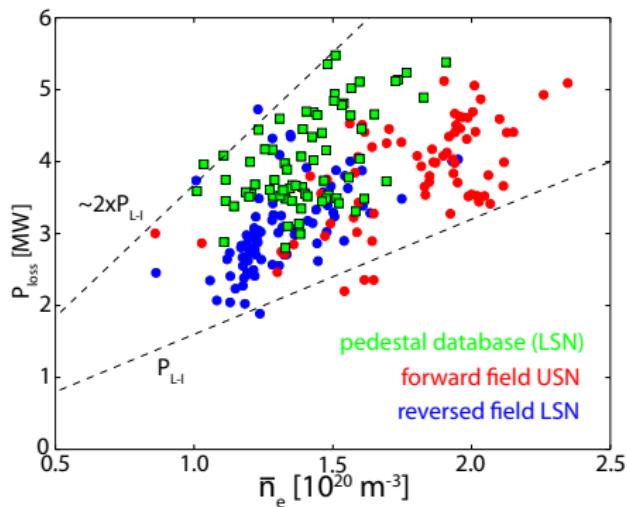
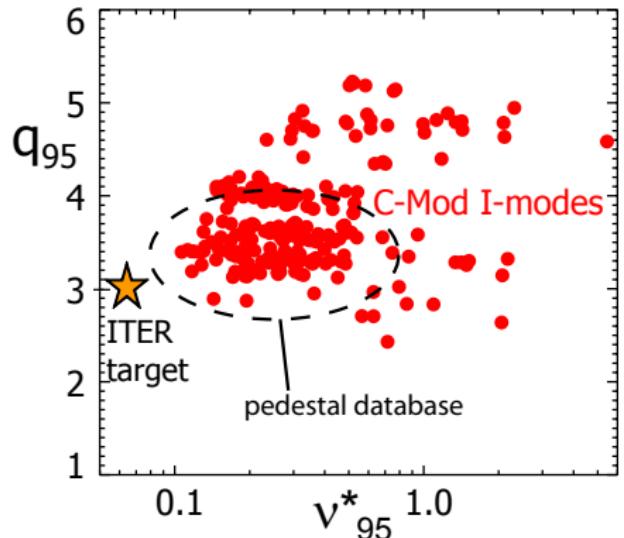
# A challenger appears: the I-mode



# 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”  $\nabla B$  orientation (ion  $\nabla B$  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 physics<sup>1</sup>

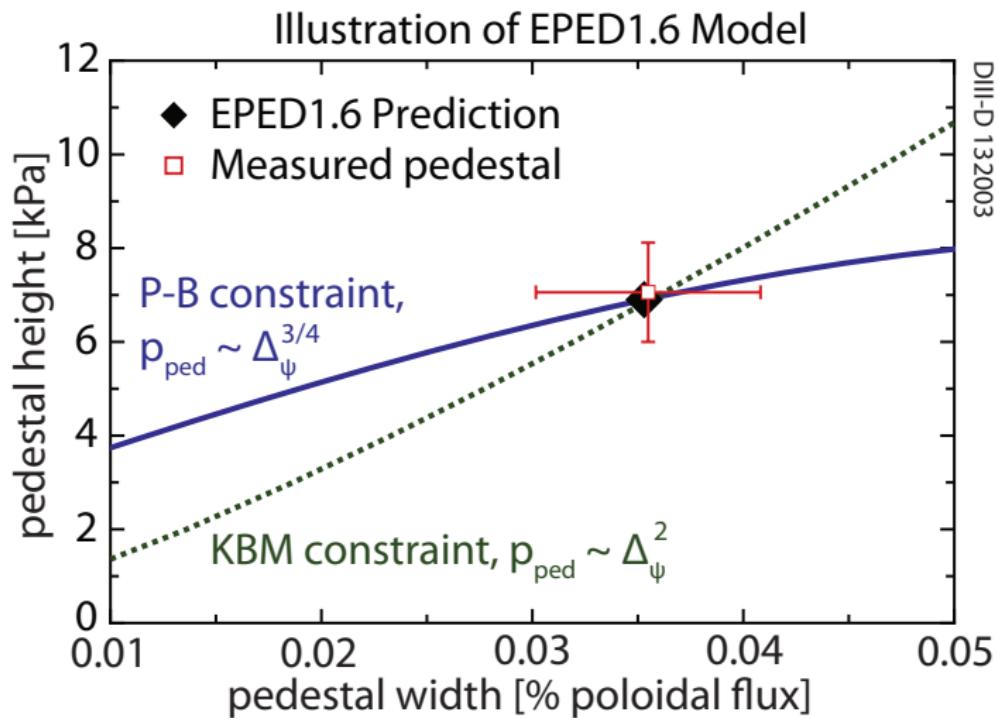
- ▶ EPED Modeling on C-Mod

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<sup>1</sup>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<sup>4</sup>



<sup>4</sup>PB Snyder *et al.*, Nuclear Fusion **51** (2011)

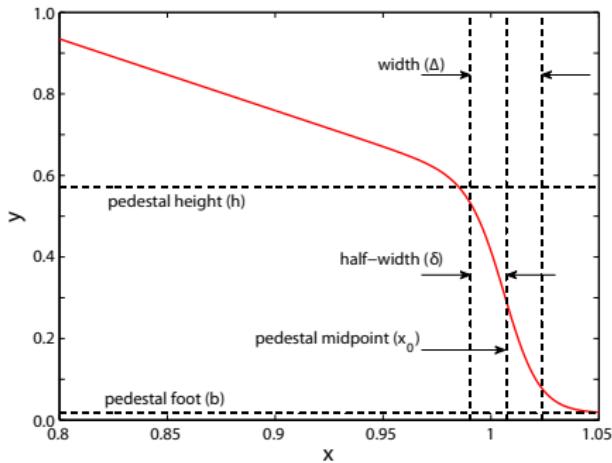
# Pedestal Structure Definitions

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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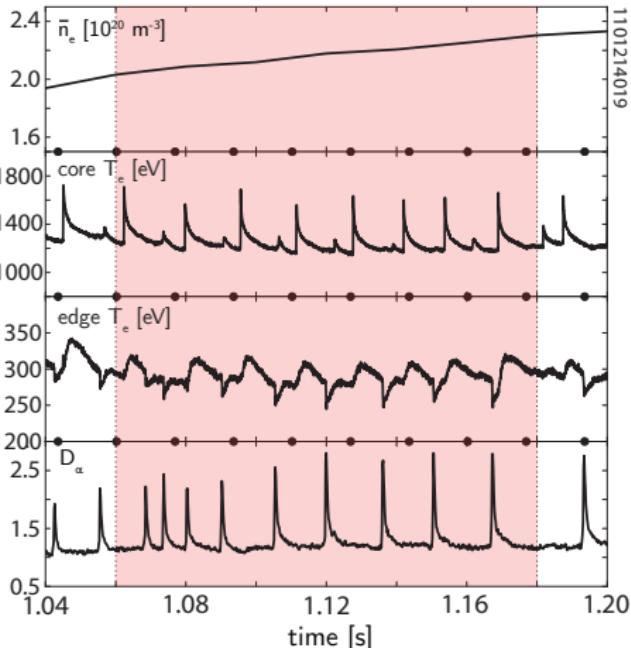
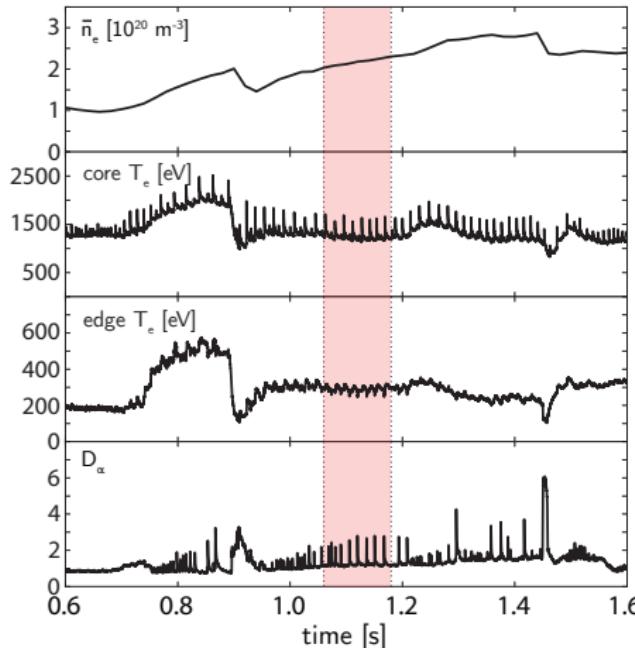
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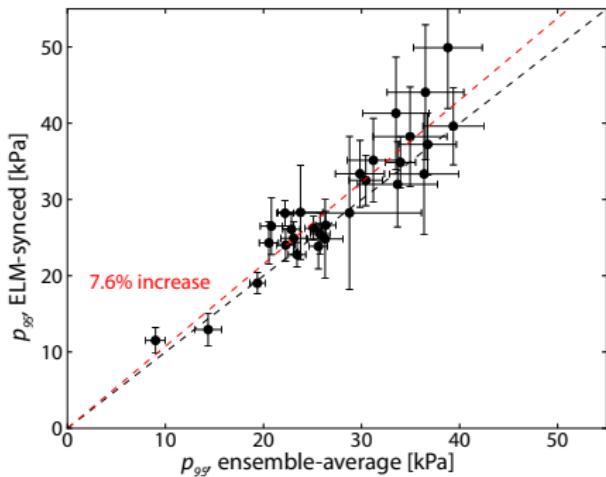
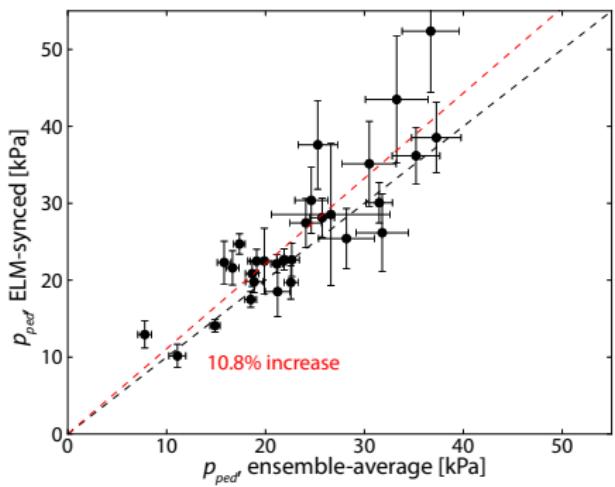
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# Target steady ELM phases for study

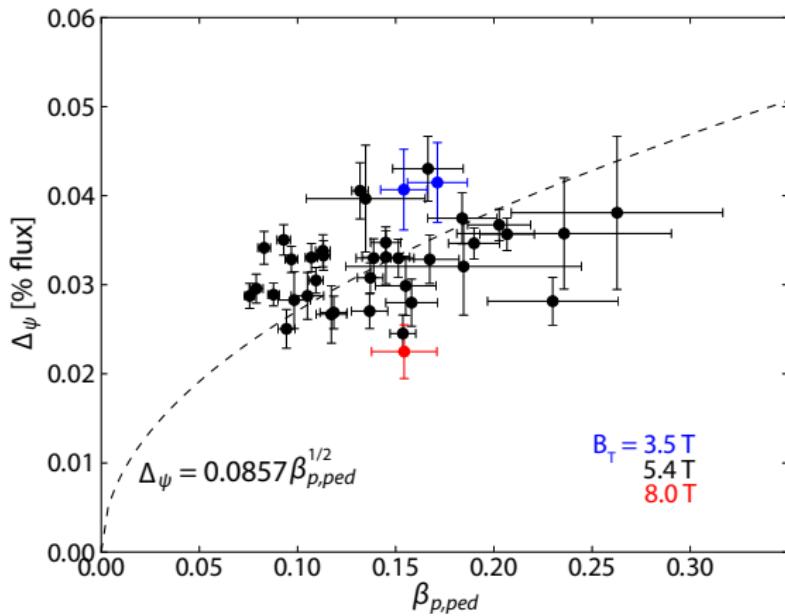


# ELM cycle binning necessary to capture pedestal limit



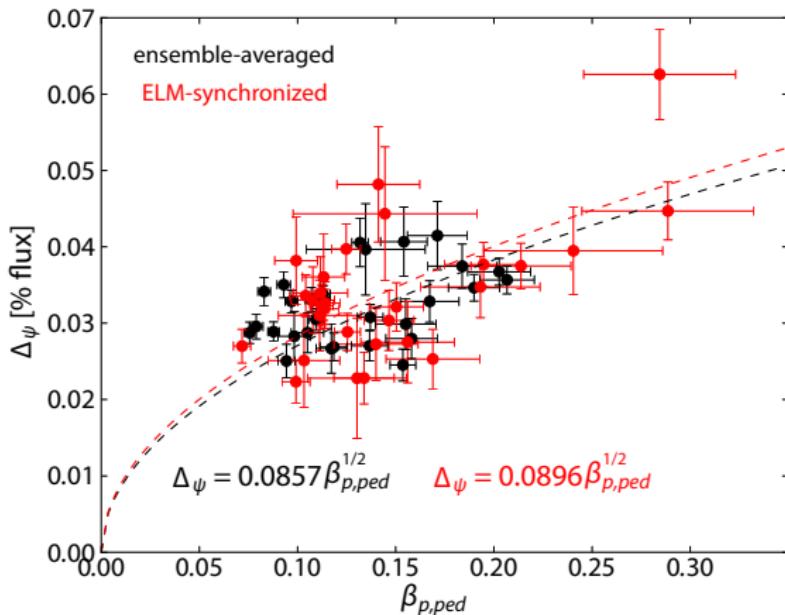
Take profile data immediately preceding ELM crash (typically last 20% of ELM cycle) for pedestal structure at point of instability – necessary, but difficult given ELM frequency on C-Mod (subset of data prepared thus).

# Pedestal width described well by KBM limit



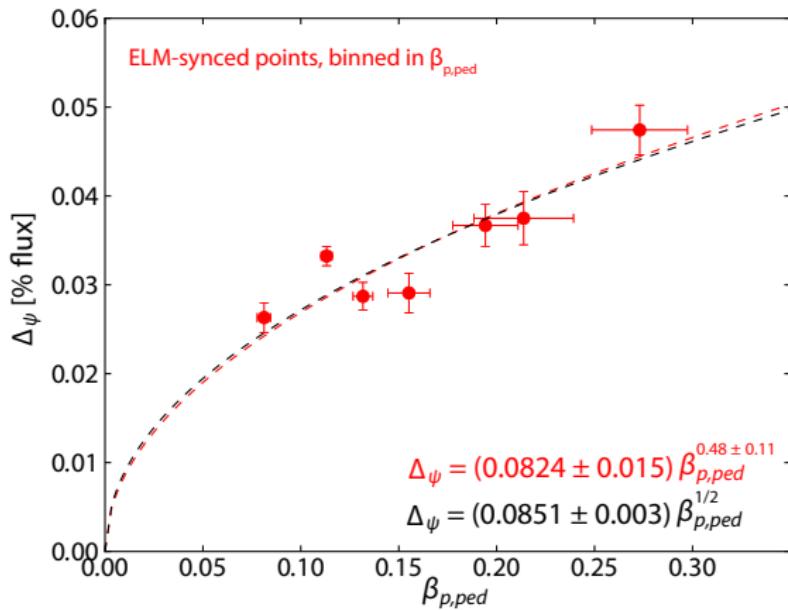
KBM limit predicts width  $\Delta_\psi = G(\nu^*, \varepsilon, \dots) \beta_{p,ped}^{1/2}$

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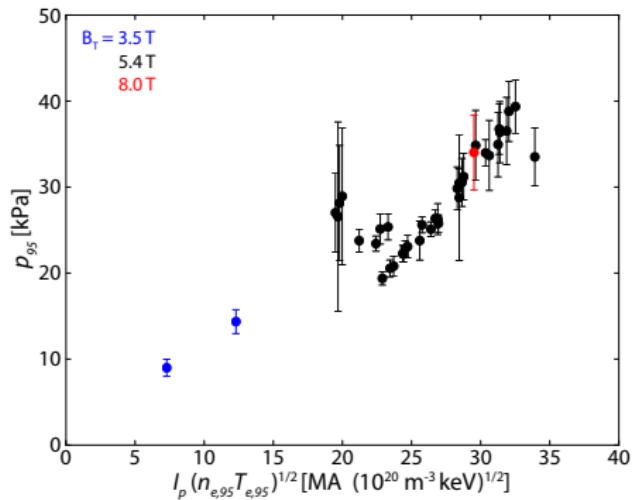
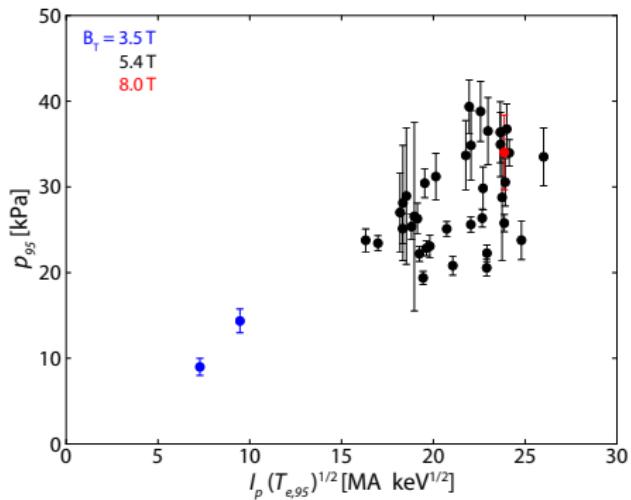
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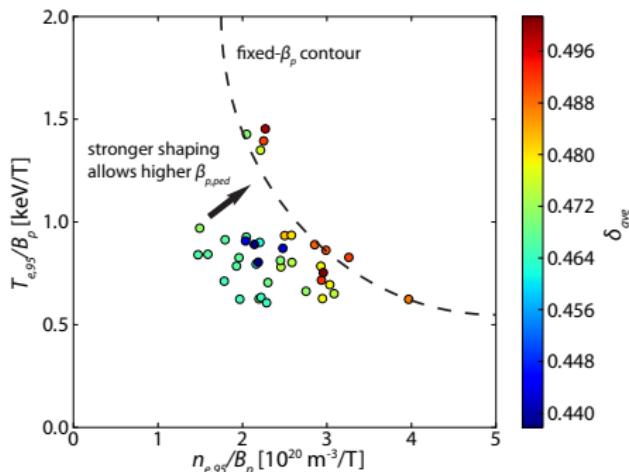
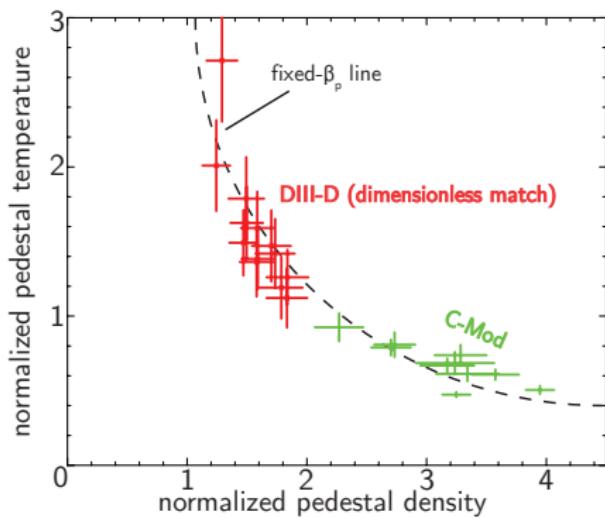
# Minimal dependence of width on other parameters

# Pedestal height predicted by ballooning $\nabla p$ limit

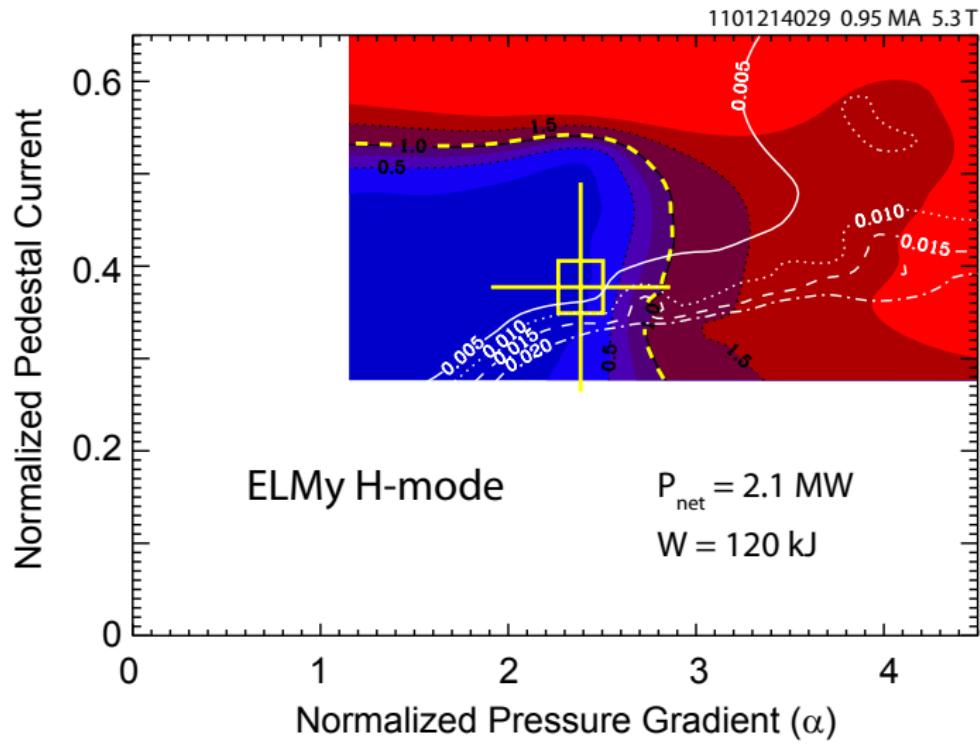


Pedestal height  $p_{ped} \sim \nabla p \times \Delta_p \rightarrow \sim I_p^2 \Delta_p$  from ballooning MHD  
predicted well by  $\Delta_p \sim \sqrt{\beta_{p,ped}}$ , less so by  $\Delta_p \sim \rho_{i,pol}$

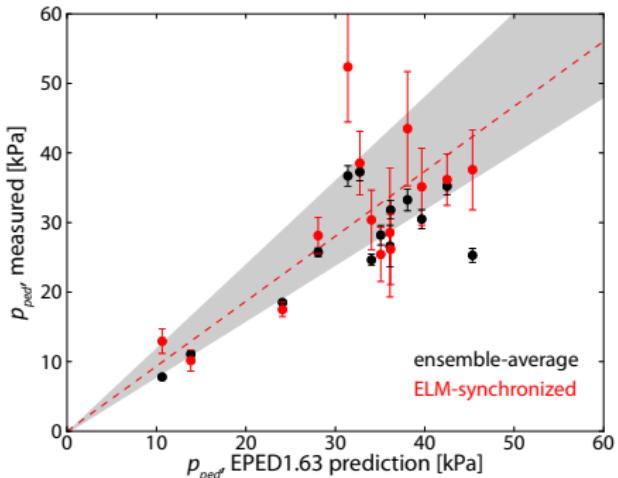
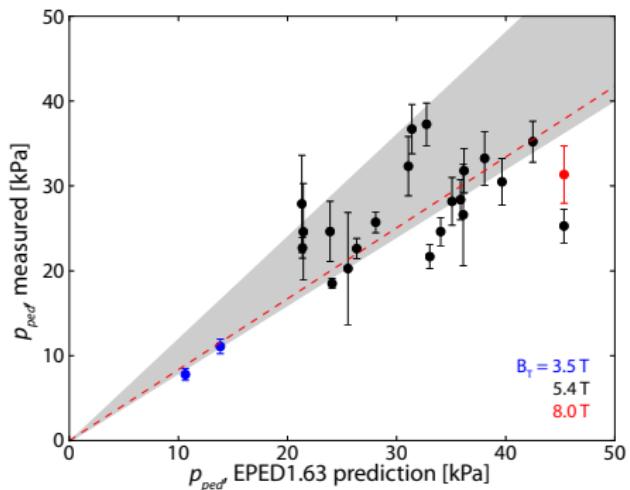
# Robust width, gradient limit = attainable $\beta_{p,ped}$ limited in ELM My H-mode



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

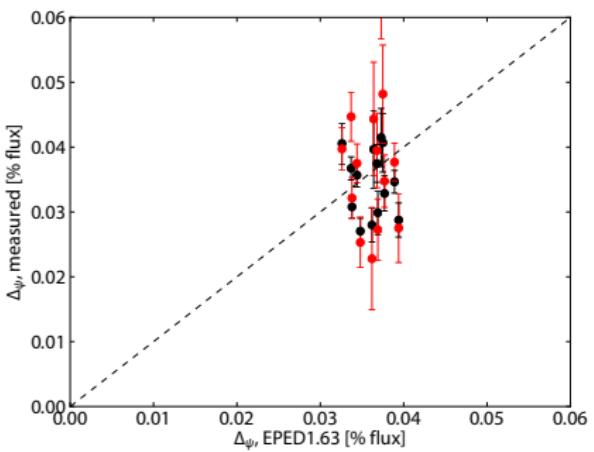
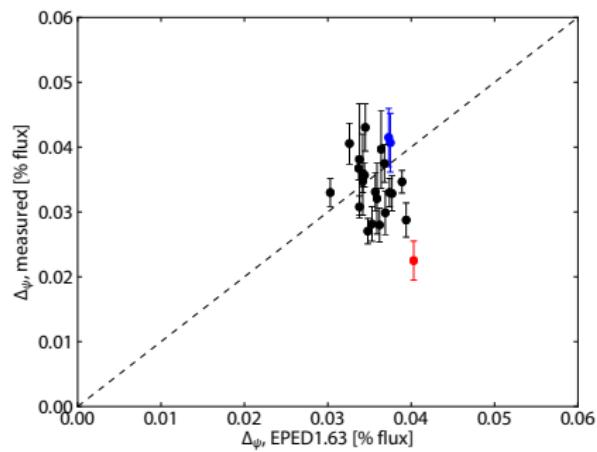


# EPED predicts pedestal height for ELM-binned pedestals



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

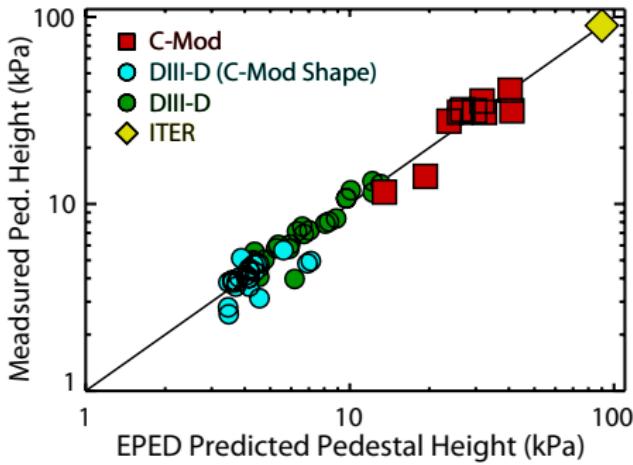
## Width varies over narrow range, hard to predict



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<sup>5</sup>

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



<sup>5</sup>RJ Groebner et al., Nuclear Fusion 53 (2013)

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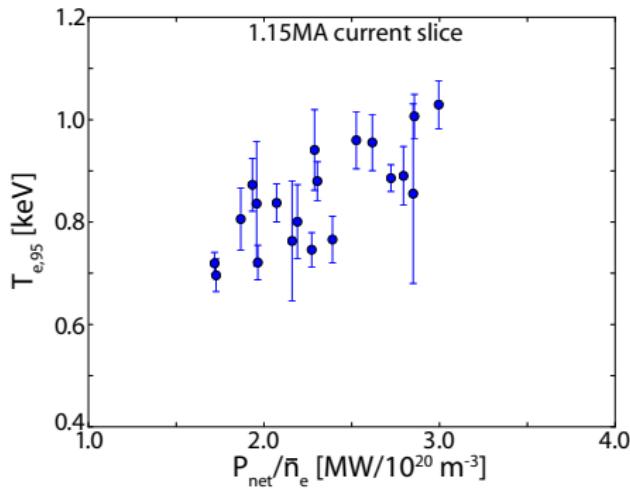
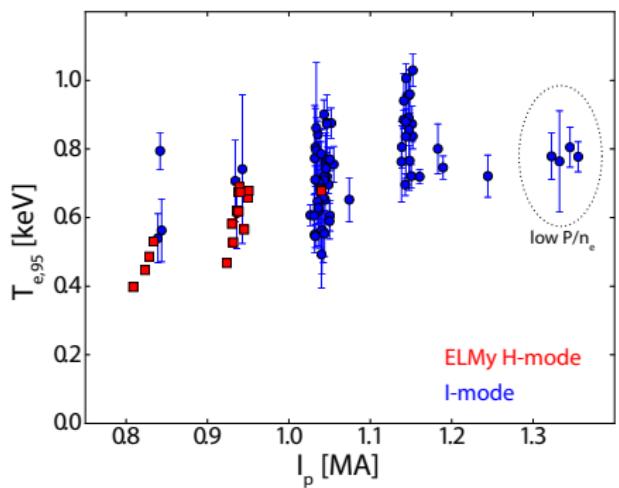
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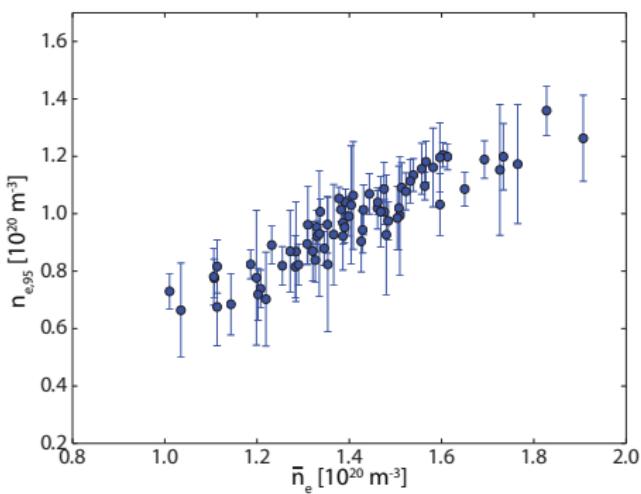
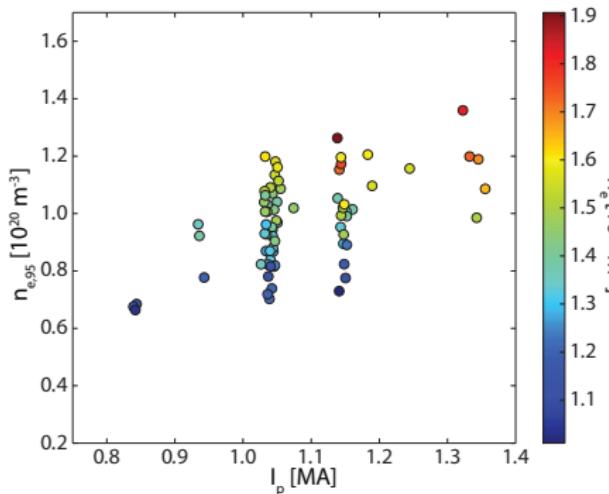
<sup>3</sup>Invited talk, APS-DPP Nov. 2013

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

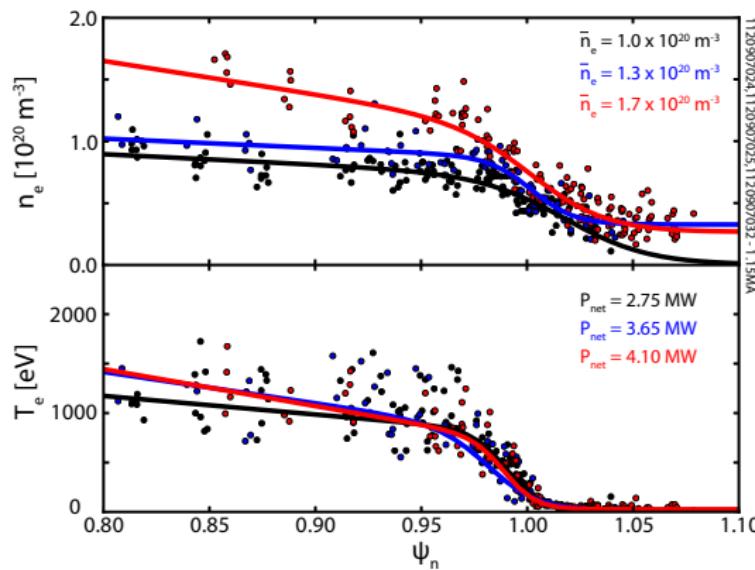


- pedestal  $T_e$  shows positive trending  $T_e \sim I_p$ , spread at given current due to heating power
- input power strongly affects pedestal temperature as with EDA H-mode – more properly, **power per particle sets pedestal temperature** at fixed current

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

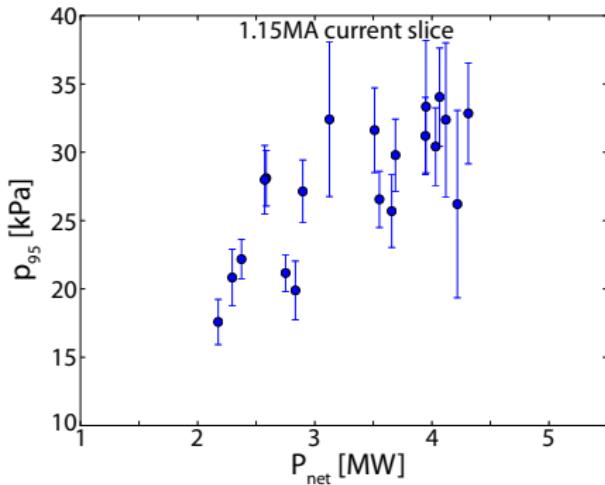
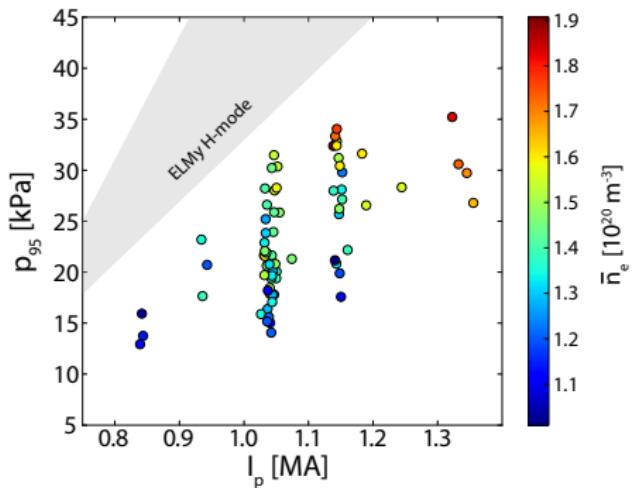


# Pedestal density separately controlled from temperature, independent of MHD limits



- with sufficient power to maintain  $P_{\text{net}}/\bar{n}_e$ , 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

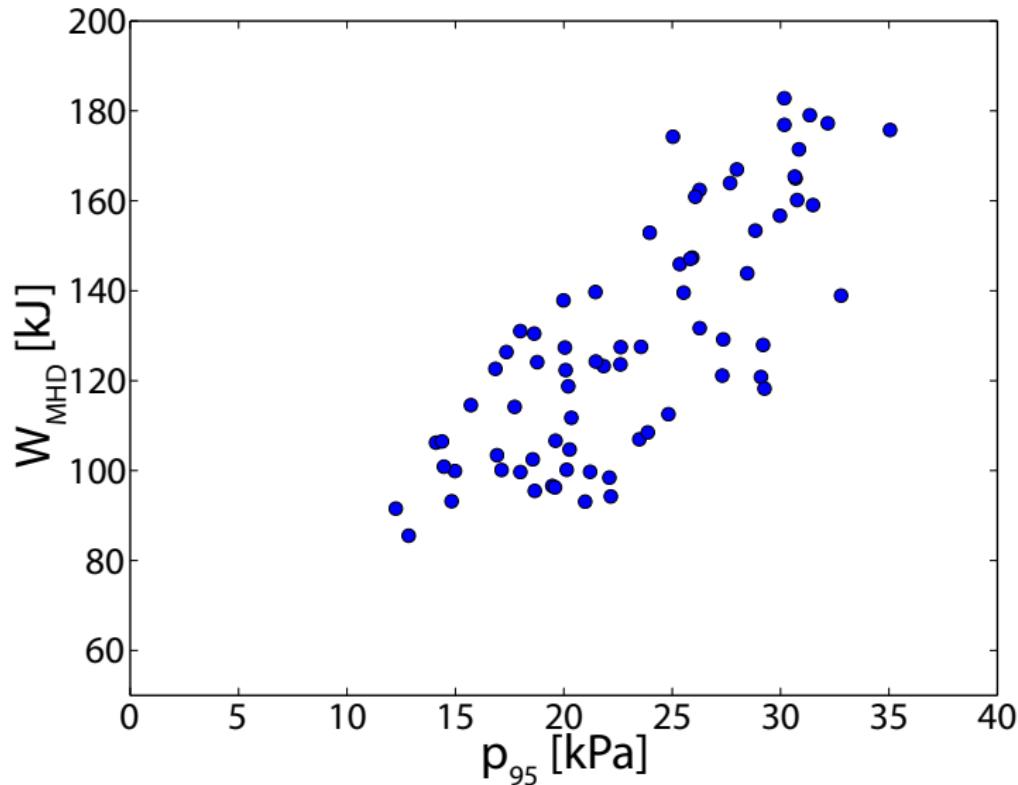
# I-mode pedestal pressure scales with current, heating power, fueling, competitive to H-mode



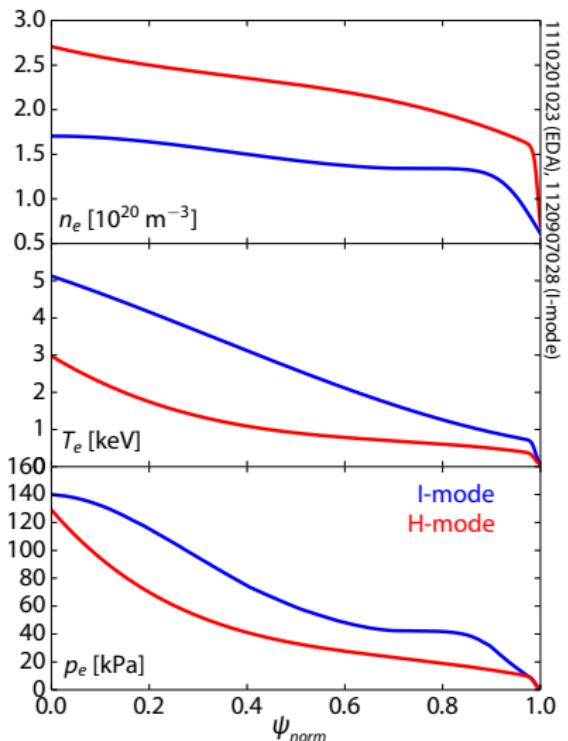
- Pedestal pressure increases at least as  $p_{ped} \sim I_p$ , due to increased  $T_e \sim I_p$  and more fueling (fixed  $f_{Gr}$ ) at higher current
- Pedestal pressure at fixed current  $\sim P_{net}$  (consistent with  $T_e \sim P/n_e$ ), corresponds to favorable scaling of energy confinement with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

# What does this get us?

## Pedestal impacts core, global performance

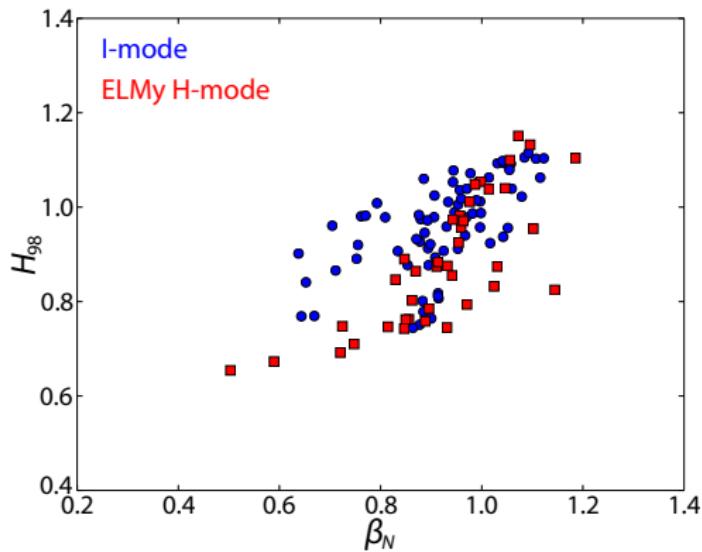
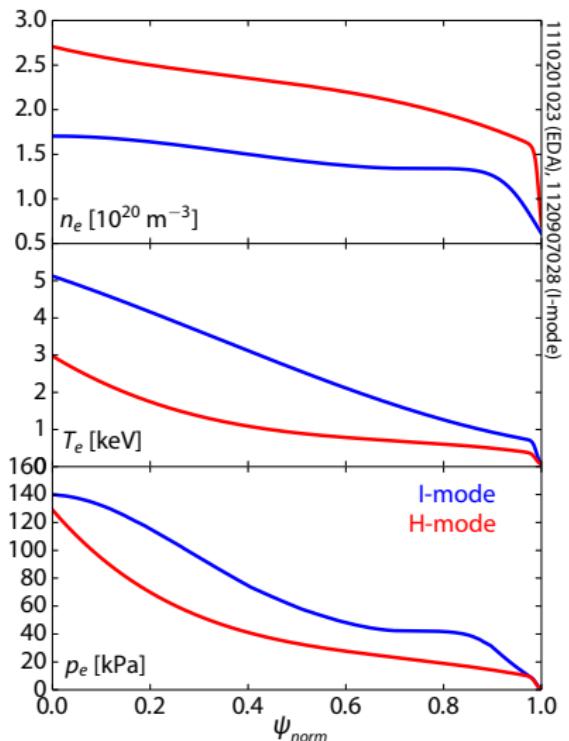


# Strong temperature pedestal supports high core temperature, pressure



- stiff ( $R/L_{T_e} \sim \text{fixed}$ ) temperature profiles  $\rightarrow$  higher  $T_{ped}$  supports greatly increased core temperatures
- provided moderated density peaking ( $n_{e,0}/\langle n_e \rangle \sim 1.1 - 1.3$  in I-mode), reaches comparable core, vol-average pressure despite relaxed  $p_{ped}$
- fusion-reactive plasma where  $T_e > 4 \text{ keV}$ , high  $T_{ped}$  maximizes fusing volume

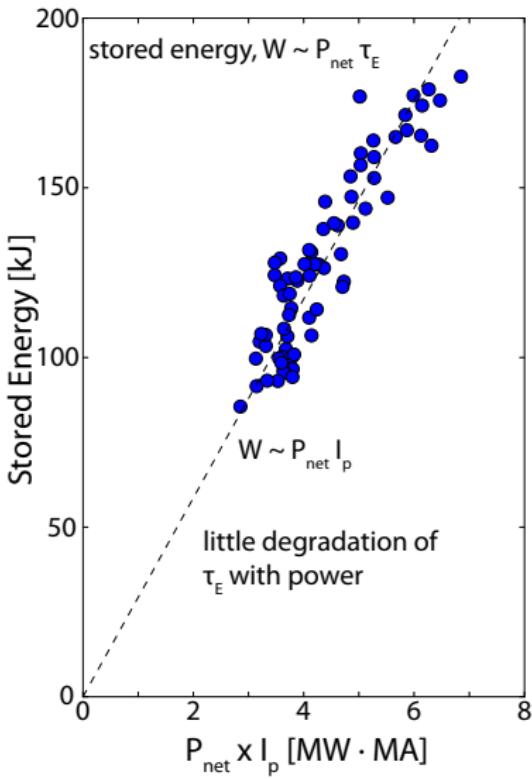
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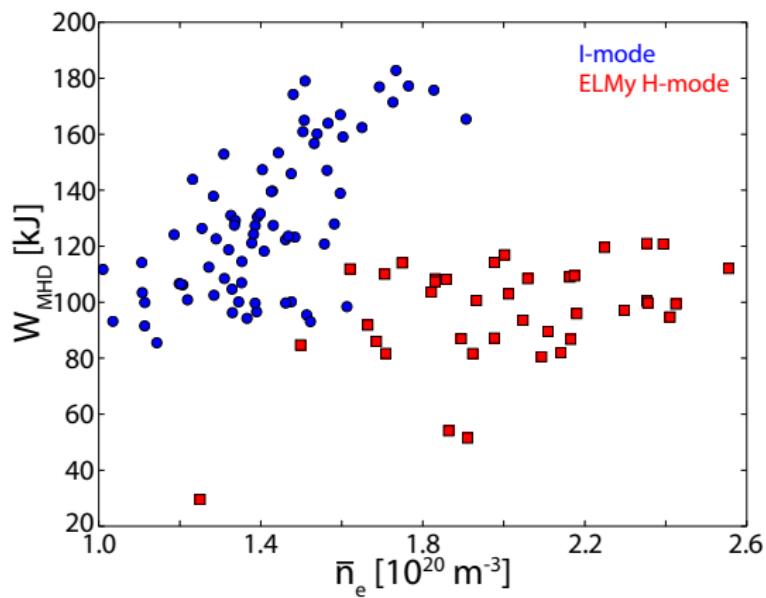
→ same  $\langle \beta_N \rangle$ , normalized confinement to ELM-My H-mode

# Energy confinement lacks degradation with heating power

- Stored energy  $W \sim P\tau_E$
- for H-mode, expect  $\tau_E \sim I_p$ , with power degradation  $\tau_E \sim P^{-0.7}$  thus  $W \sim I_p P^{0.3}$
- I-mode stored energy  $W \sim I_p P_{net} \rightarrow$  little/no degradation of  $\tau_E$  with heating power
- reflects lack of MHD limit on pedestal



## ...As well as with fueling



- I-mode stored energy set by pedestal pressure, responding strongly to fueling
- ELM My H-mode stored energy set by pedestal  $\beta_p$ , limited by MHD constraint – mainly increase pedestal  $\beta_p$  with stronger shaping, flat relation with fueling

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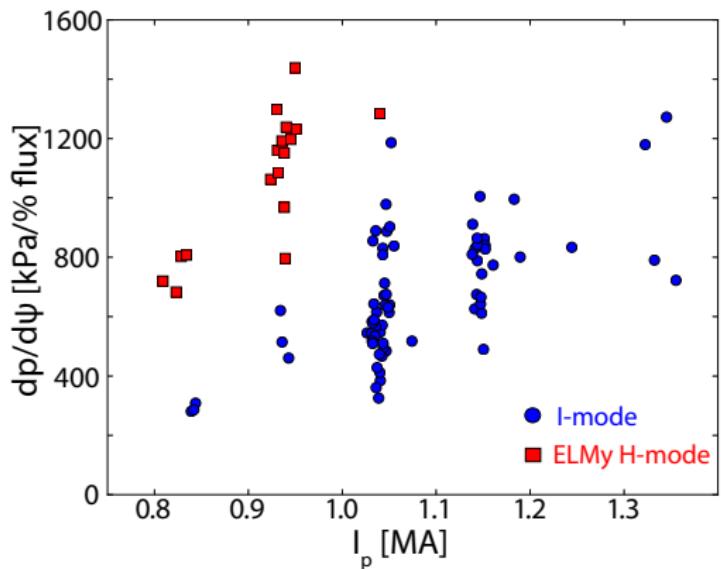
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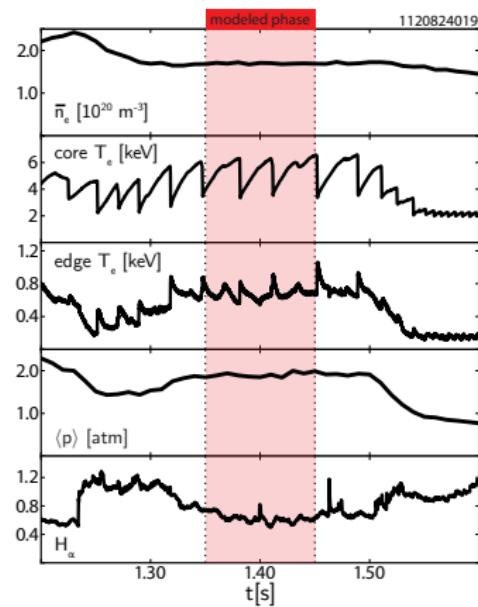
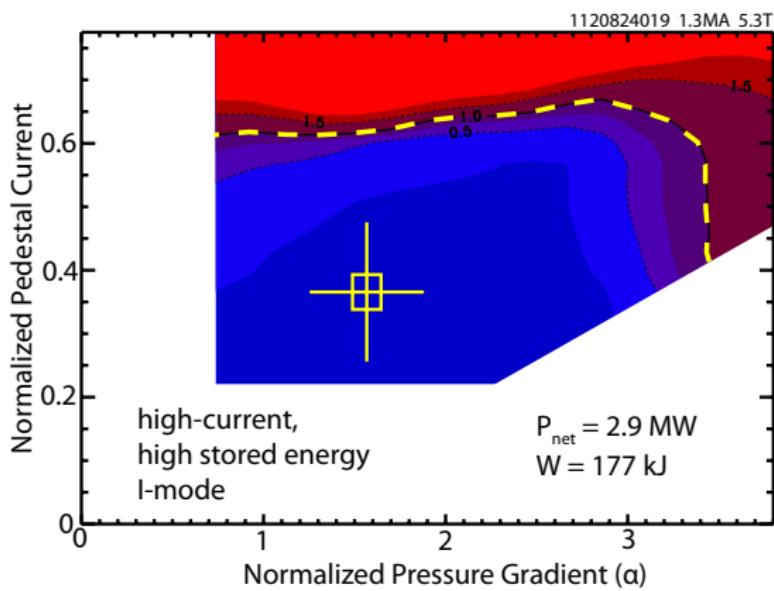
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# Pedestal pressure gradient suggests MHD stability, headroom for performance improvement

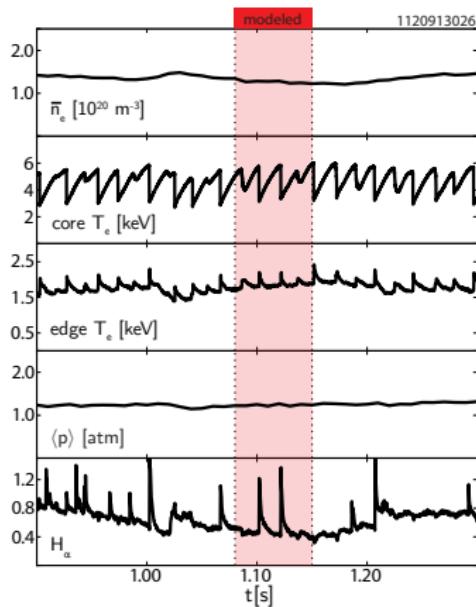
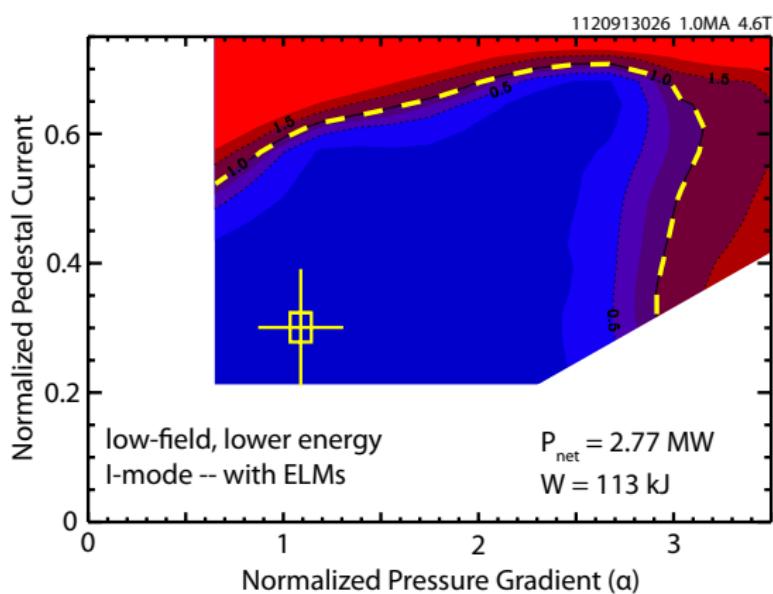


- Pedestal  $\nabla p$  shallower at given  $I_p$  than ELMy H-mode due to lack of density pedestal
- Gradients scale more weakly than  $\nabla p \propto I_p^2$  from ballooning MHD (critical-gradient) stability boundary

# I-mode pedestal strongly stable against peeling-balloonning MHD, KBM turbulence



# Including in low-field, low-energy cases exhibiting apparent ELMs



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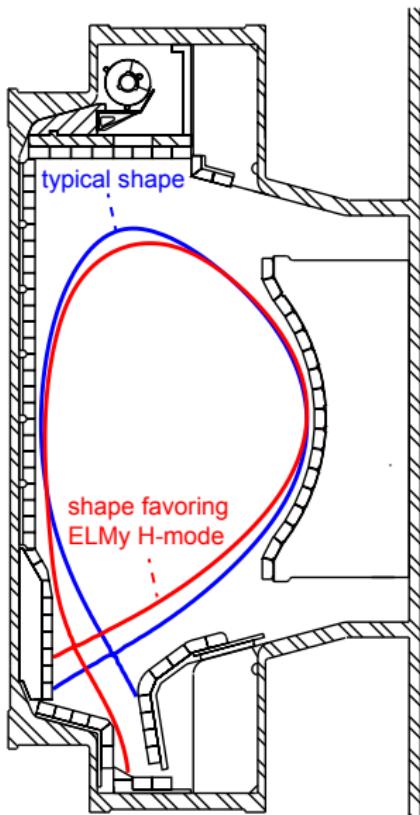
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# Supplemental Slides

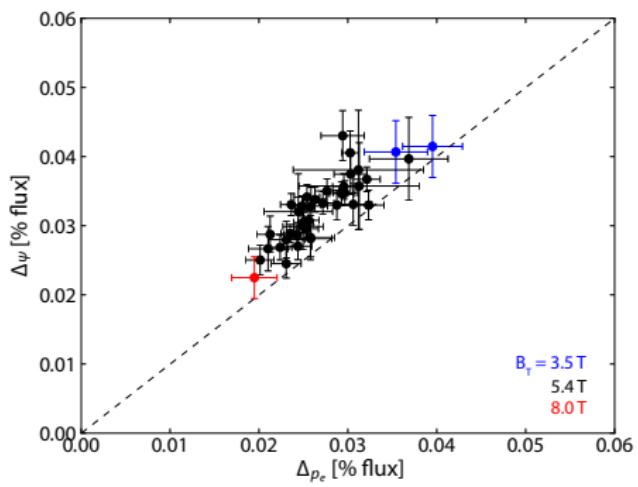
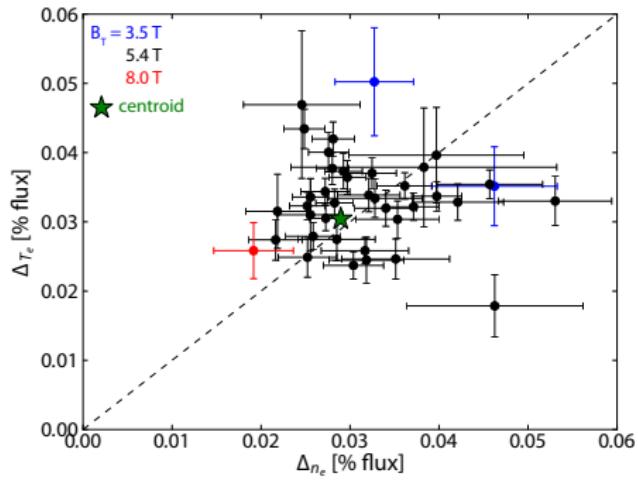


# Plasma shaping in C-Mod operation



- I-mode operates at typical shaping for C-Mod plasmas (with reversed  $I_p$ ,  $B_T$  for unfavorable  $\nabla B$  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  $\nu^*$ ) or EDA H-mode (high  $\nu^*$ )

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



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

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

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

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

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

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

$$X = RB_p \xi_\psi$$

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

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

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

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

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