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)

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?

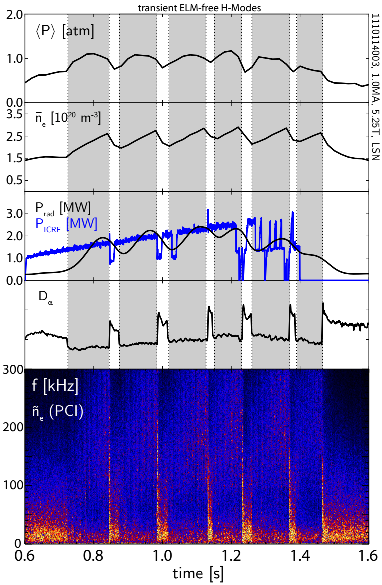
Under right conditions, plasma forms "transport barrier" in edge, with steep gradients in density and temperature – the *pedestal*
$\rightarrow$ plasma transitions to "high-confinement" or H-mode

- 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

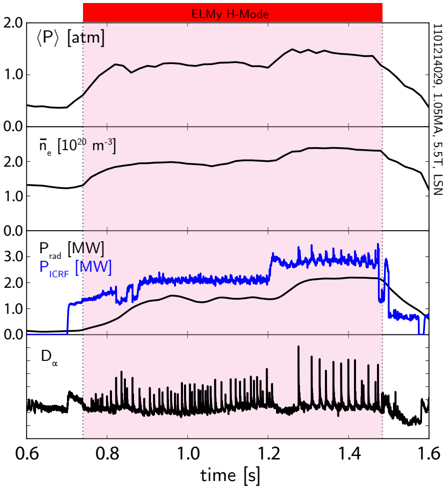


so, we need:

- 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



The solution? (part II)

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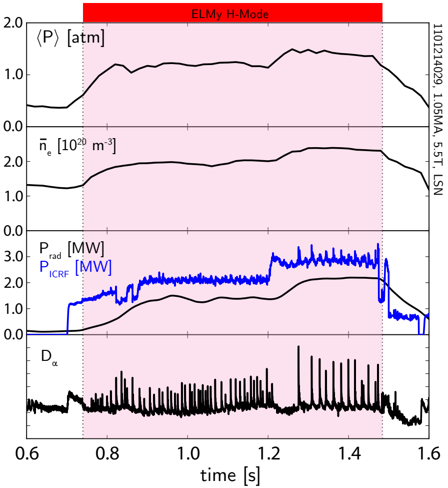
- large ELMs drive pulsed heat loads in excess of plasma-facing material tolerances



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- 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)

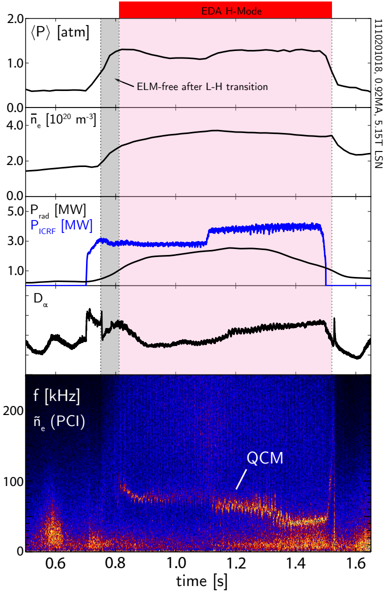
A number of fluctuation-regulated regimes have been observed:

- 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} $\rightarrow$ stationary operation possible with good performance

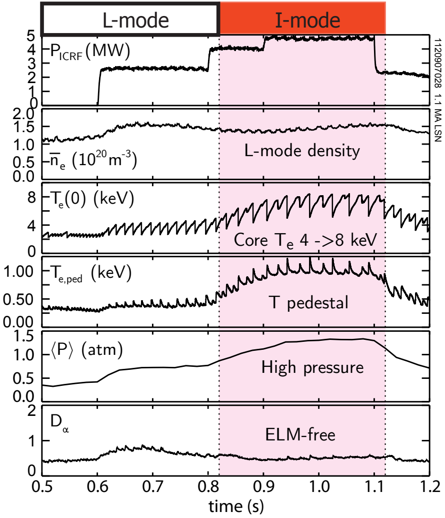


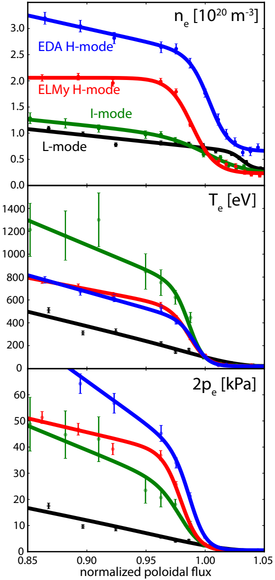
But each of these has drawbacks

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

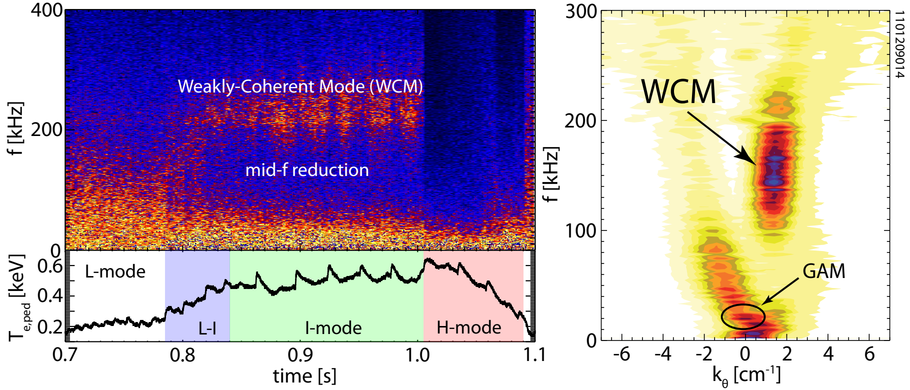
Can we do better?

A challenger appears: the I-mode

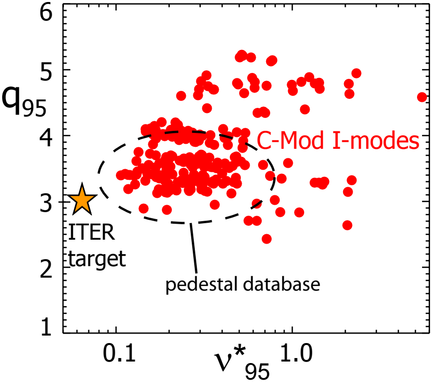


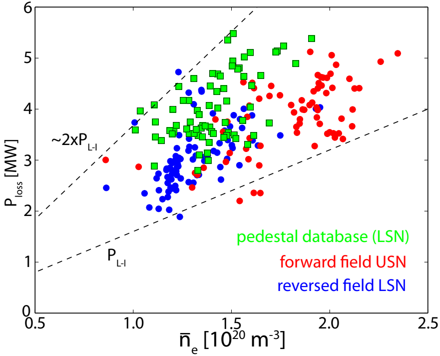


I-mode pedestal regulated by Weakly-Coherent Mode (WCM)



Robust I-mode access on C-Mod





- I-mode accessed over range of edge current profiles, low-mid collisionalities
- "Unfavorable" ∇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

last intro slide here

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ELMs associated with MHD instabilities

ideal edge MHD modes → sufficiently fast instability growth to drive explosive ELM transport

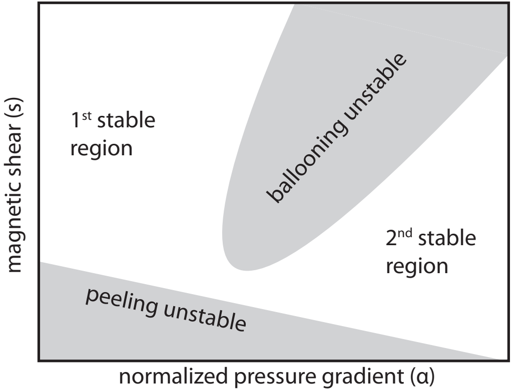
- ballooning mode: driven by pressure gradient, stabilized by magnetic shear, with drive term

$$\alpha_{MHD} = -2\frac{Rq^2}{B_T^2}\nabla p \sim \frac{d\beta_p}{d\psi}$$

- kink/peeling mode: driven by edge current and current gradient, stabilized by magnetic shear, pressure gradient

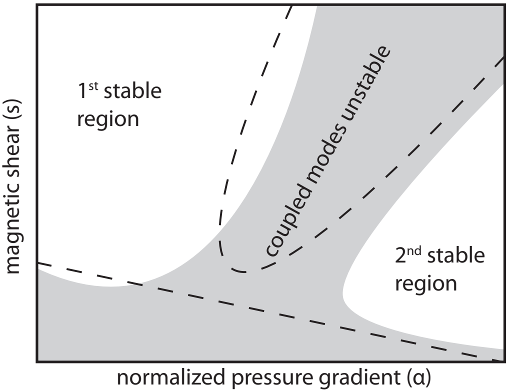
$$s = 2\left(1 - \frac{j_\parallel}{\langle j \rangle}\right)$$

ELMs associated with MHD instabilities



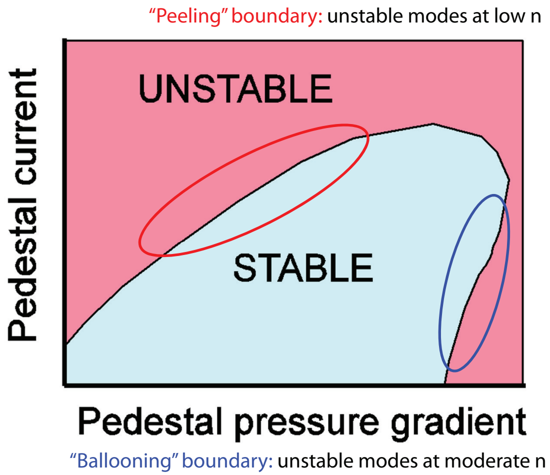
- in high-n limit modes are easily calculated: $s - \alpha$ stability contour
- at high α, second stability region opens – highly desirable for high-β operation
- magnetic shear stabilizing to both modes (in first-stable region)

At finite n, peeling + ballooning modes couple



- high-n modes stabilized by diamagnetic, FLR effects – most unstable modes in range $n \sim 5 - 40$
- coupling closes off access to second-stable regime – need strong magnetic well (best accomplished by aggressive plasma shaping) to decouple modes, reopen access

Coupled peeling-ballooning MHD modes calculated by ELITE code



- efficiently calculates moderate-n P-B MHD instability, growth rate
- calculate range of n to find most unstable mode on grid of pedestal pressure gradient and current $\rightarrow$ stability contour

Kinetic-ballooning mode (KBM) turbulence limits gradient

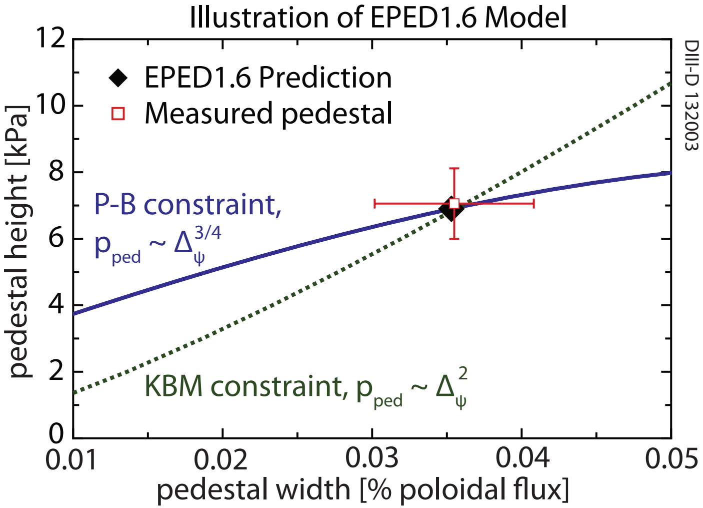
Predictive Model for ELMy H-modes – EPED[4]

Goal: predict pedestal width, height based on engineering target parameters, rather than reconstructed equilibria after-the-fact

- take inputs: R, a, κ, δ, I_p, B_T, $\langle\beta_N\rangle$, $n_{e,ped}$
  $\rightarrow$ construct analytic model equilibria
- ELITE calculation for peeling-ballooning MHD constraint
- width constraint from KBM, either by fitted analytic form (EPED1) or direct calculation of ballooning threshold (EPED1.6)

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

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



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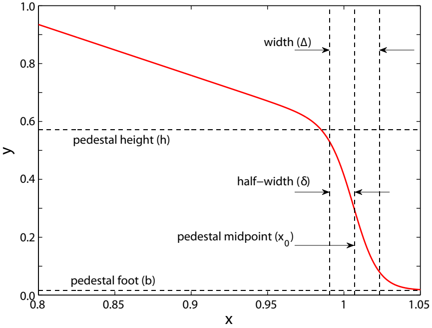
Pedestal Structure Definitions

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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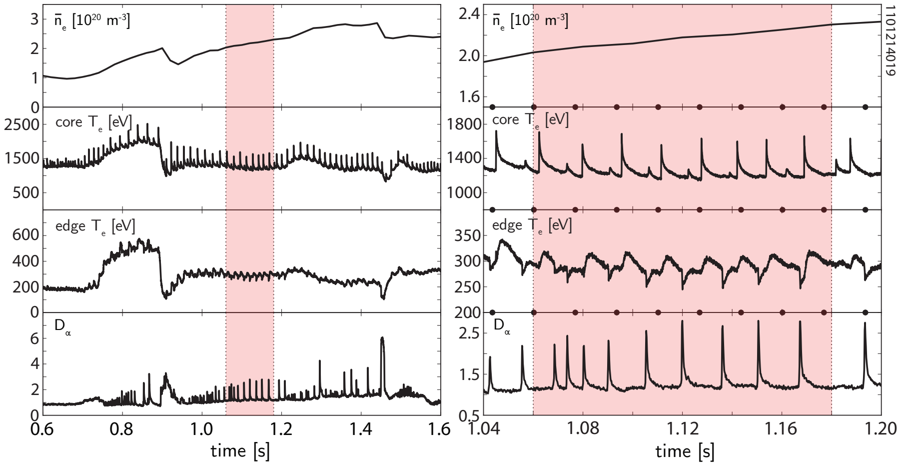
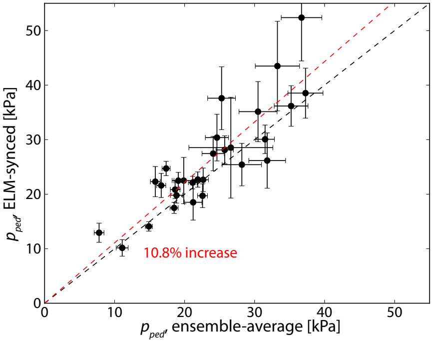
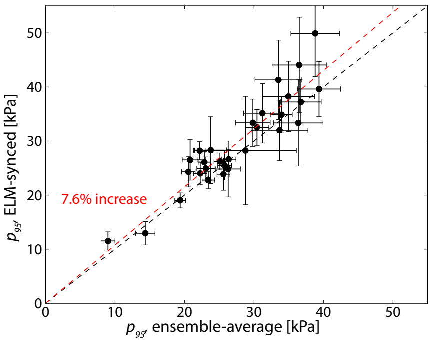
Target steady ELMy phases for study



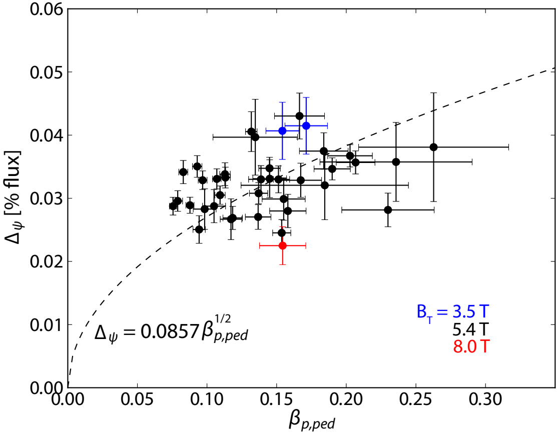
ELM cycle binning necessary to capture pedestal limit





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

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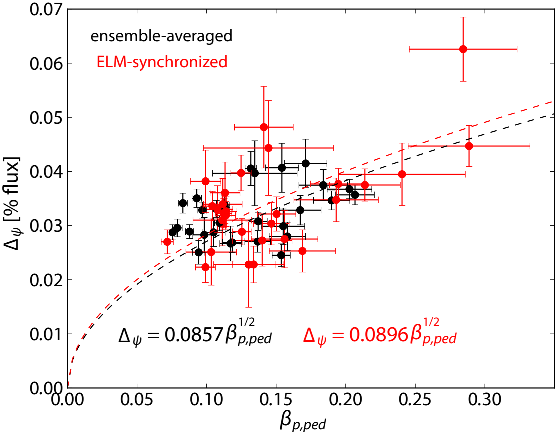

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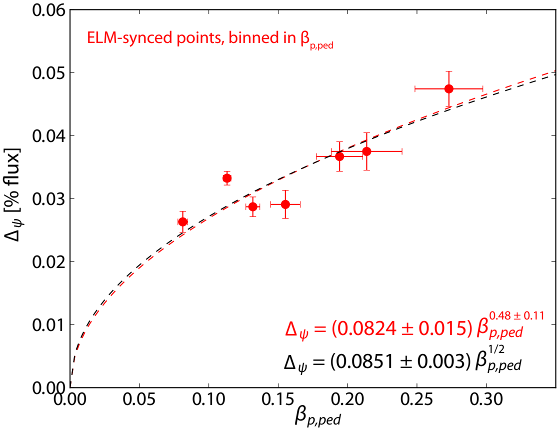
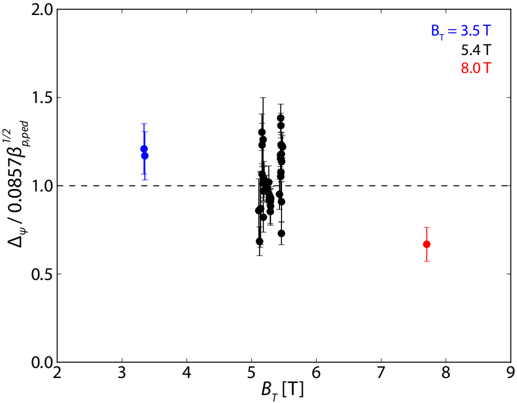


KBM limit predicts width $\Delta_\psi = G(\nu^*, \varepsilon, \ldots)\beta_{p,ped}^{1/2}$

Minimal dependence of width on other parameters

Secondary dependences via pedestal width normalized to $\beta_{p,ped}^{1/2}$ scaling



- broader pedestal at low field qualitatively ∼ some modeling efforts, but within spread at standard field, strong covariance with current
- no variation with collisionality, despite effects on edge current → magnetic shear
- no variation with gyroradius (expected as dependence in G)

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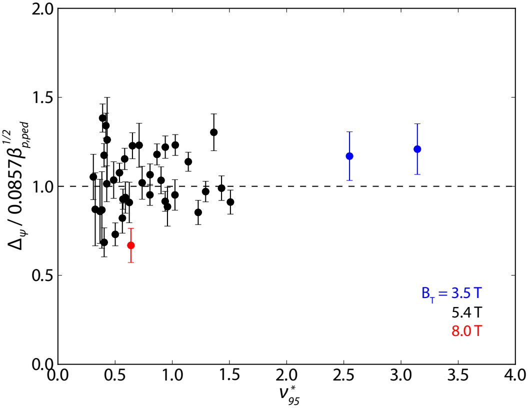
Secondary dependences via pedestal width normalized to $\beta_{p,ped}^{1/2}$ scaling



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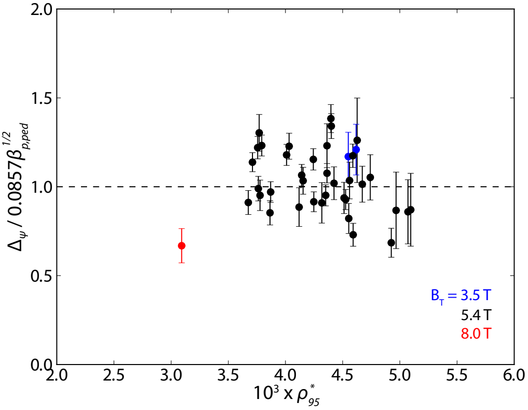

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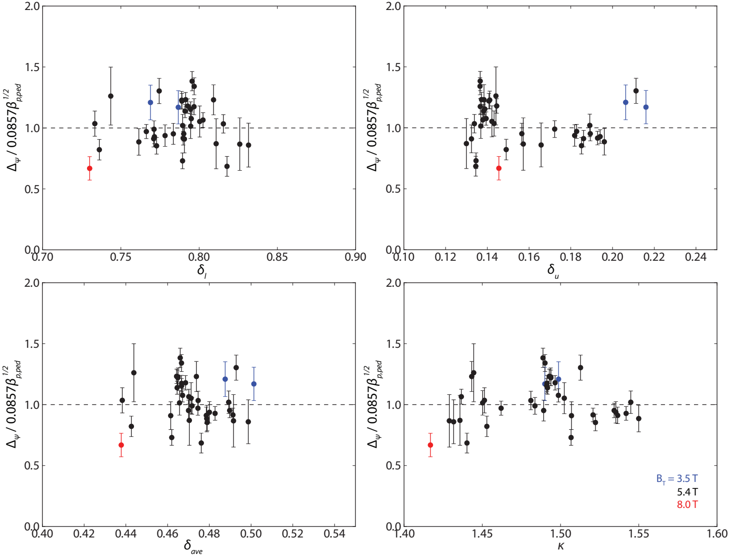
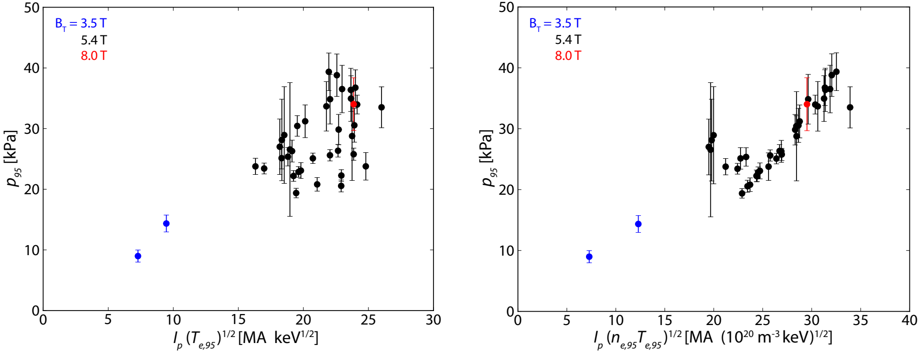
Minimal dependence of normalized width on shaping

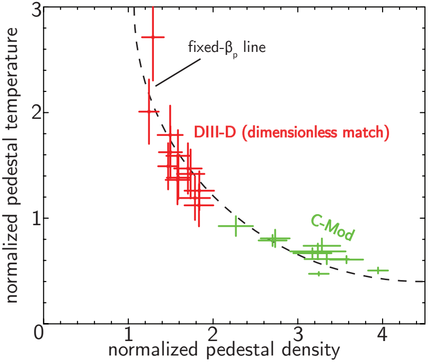


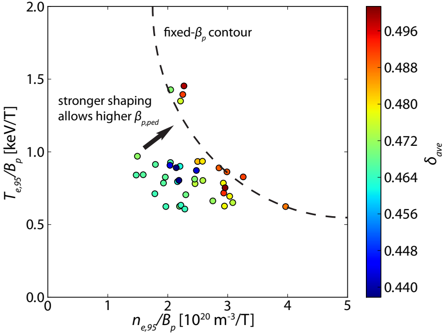
Pedestal height predicted by ballooning ∇p limit



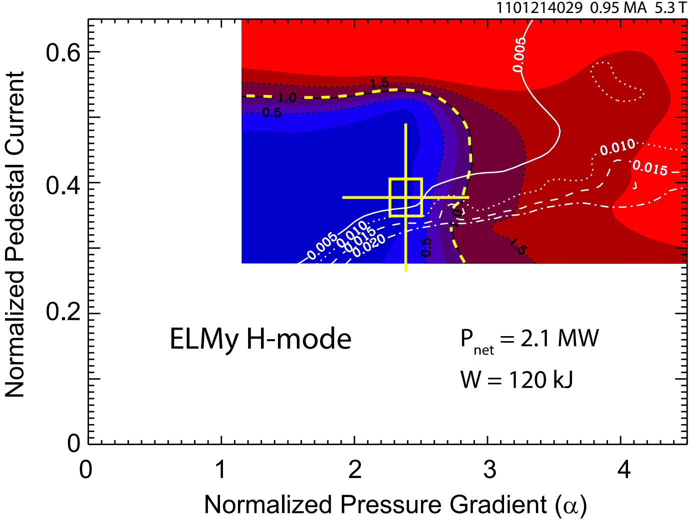
Pedestal height $p_{ped} \sim \nabla p \times \Delta_p \rightarrow \sim I_p^2 \Delta_p$ from ballooning MHD predicted well by $\Delta_p \sim \sqrt{\beta_{p,ped}}$, less so by $\Delta_p \sim \rho_{i,pol}$

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

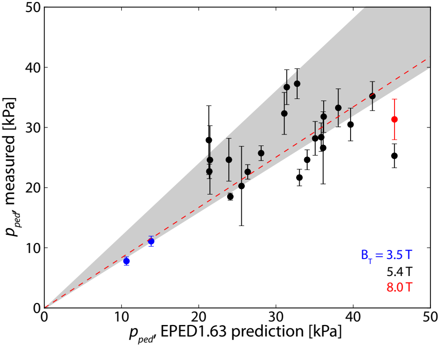


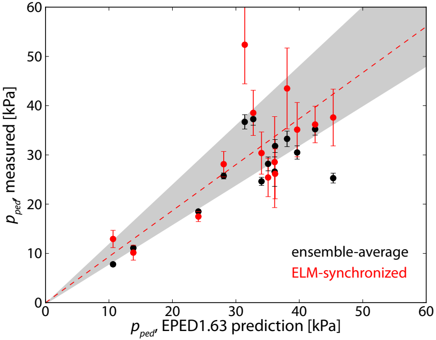


Computational modeling of P-B MHD, KBM captures ELMy pedestal



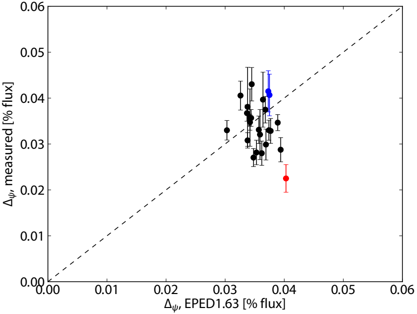
EPED predicts pedestal height for ELM-binned pedestals

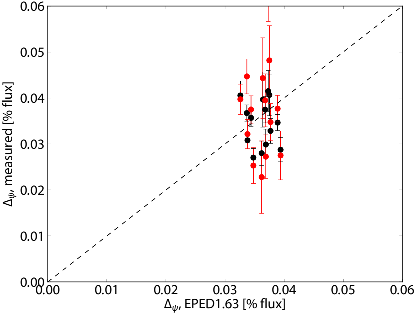




measured to predicted ratio of 0.835 ± 0.036 for ensemble-averaged data, 0.934 ± 0.066 for ELM-synced pedestals, well within expected $\pm 20\%$ accuracy for EPED predictions

Width varies over narrow range, hard to predict

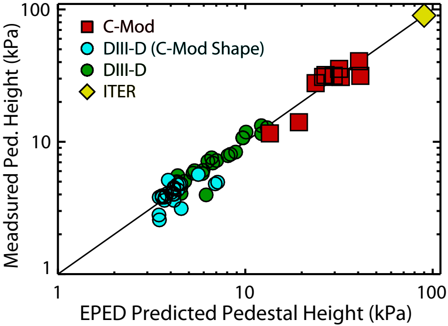




Pedestal width varies little over range of $3-5\%$ of poloidal flux, difficult to extract trend – EPED reproduces robust width to within $\pm 20\%$ uncertainty

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, motivates development of EPED to higher collisionality, density
- reliable physics-based understanding of H-mode pedestal limits



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

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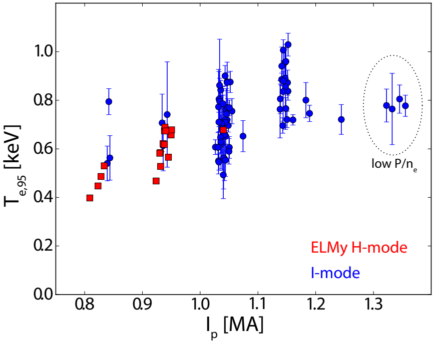
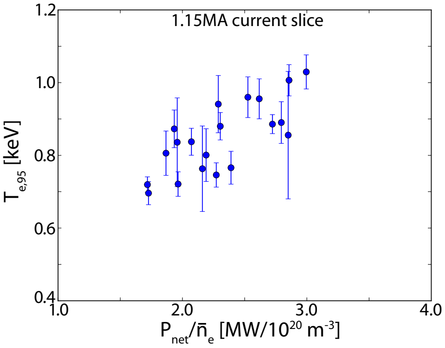
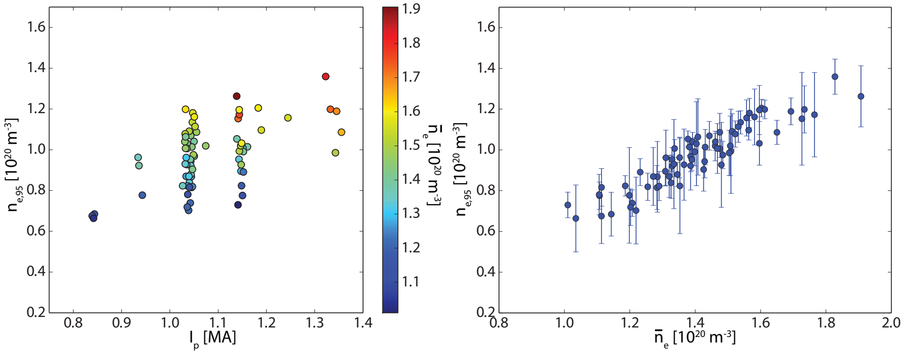
Temperature pedestal H-mode-like, set by plasma current, heating power





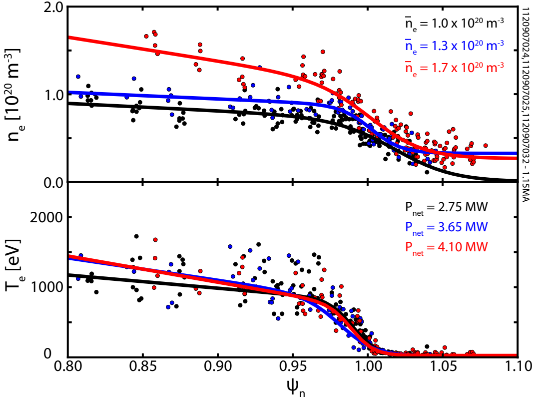
- pedestal T_e shows positive trending $T_e \sim I_p$, spread at given current due to heating power
- input power strongly affects pedestal temperature as with EDA H-mode – more properly, power per particle sets pedestal temperature at fixed current

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



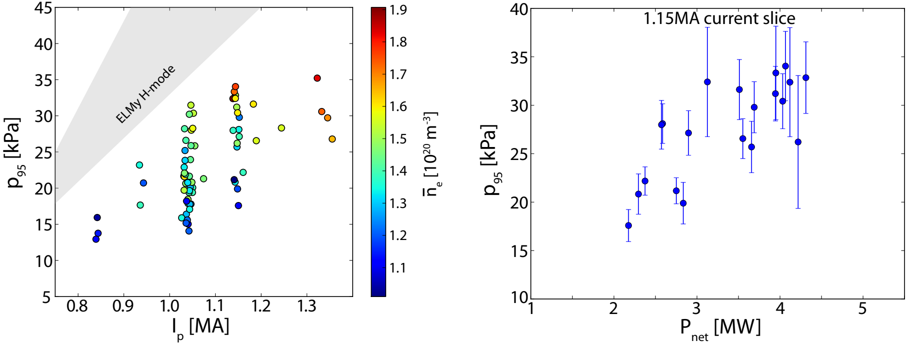
Plasma current a poor predictor of pedestal density, in contrast to transport-limited EDA H-modes – easy density control

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

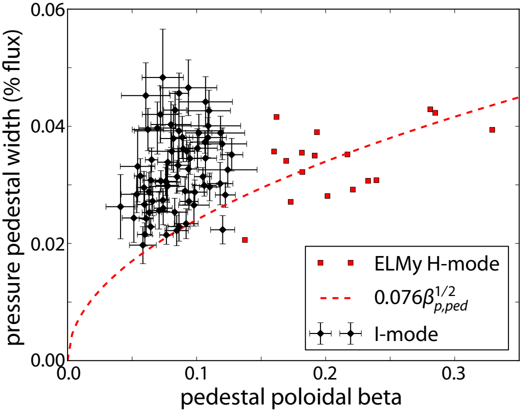
What does this get us?

- Independent determination of density profile (via fueling), temperature profile (via heating power) – operator control, rather than physics limits, sets pedestal
- path to strongly improved performance in I-mode – matched increases in fueling, heating power strongly increase pedestal pressure at same size, current, field
- Good for ITER access as well: sidestep high power threshold by accessing at low density, step up to $Q = 10$ scenario with matched density, power increase
- L-mode density profile $\rightarrow$ fuel core via turbulent particle pinch, despite neutral-opaque SOL: desirable for ITER

Pedestal widths & gradients

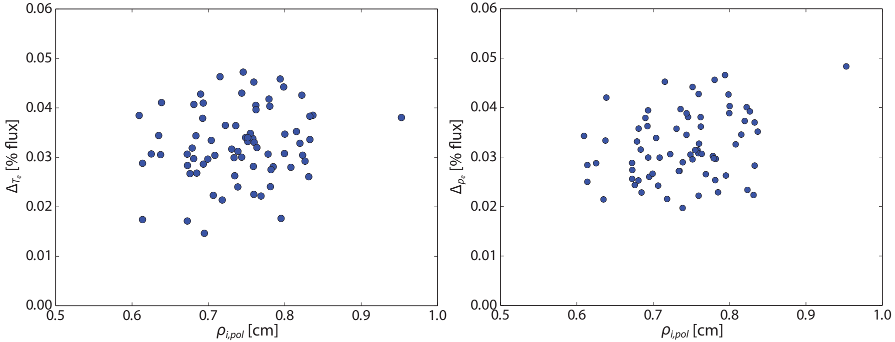
- pedestal structure typically constrained by gradient limits $\rightarrow$ need to understand pedestal width to predict height, performance
- small spatial scales $\rightarrow$ accurate measurement historically difficult

Pedestal width uncorrelated with $\beta_{p,ped}$, contrary to KBM limit



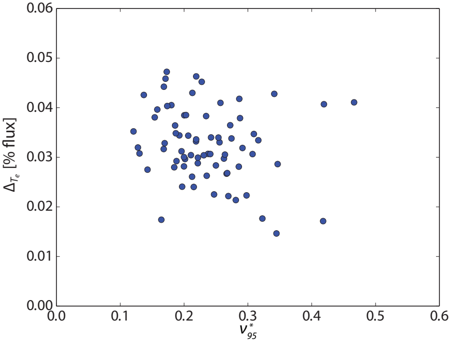
- I-mode pedestal width shows no trend with $\beta_{p,ped}$, consistently broader than predicted by EPED1-like KBM limit $\Delta_\psi = 0.076\beta_{p,ped}^{1/2}$
- intuitively, pedestal ∇p insufficient to drive ballooning-like instabilities

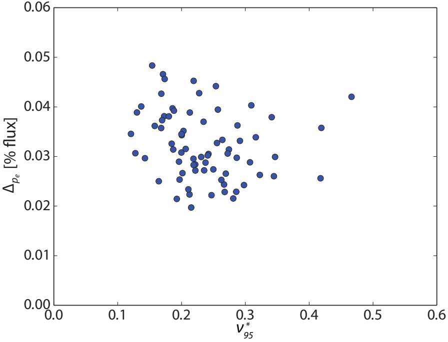
I-mode temperature, pressure pedestal widths uncorrelated with physics parameters



$\rho_{i,pol} \rightarrow$ ion-orbit-loss models for E_r well width

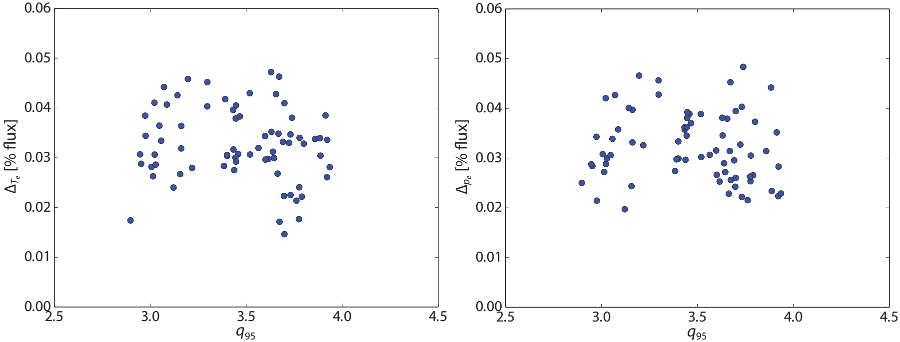
I-mode temperature, pressure pedestal widths uncorrelated with physics parameters





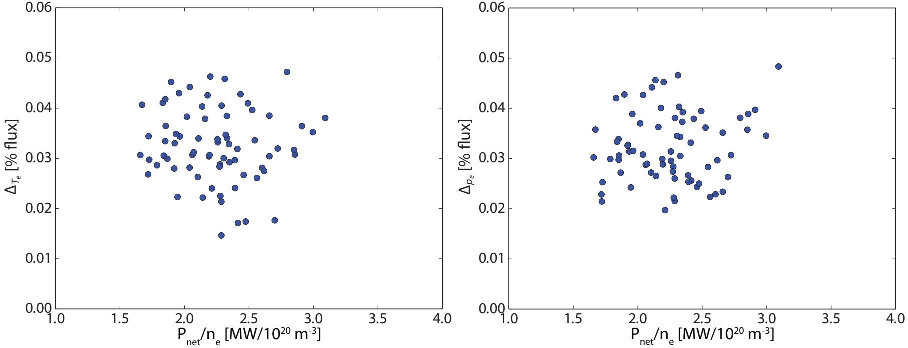
edge collisionality $\rightarrow$ bootstrap current instability drive

I-mode temperature, pressure pedestal widths uncorrelated with physics parameters



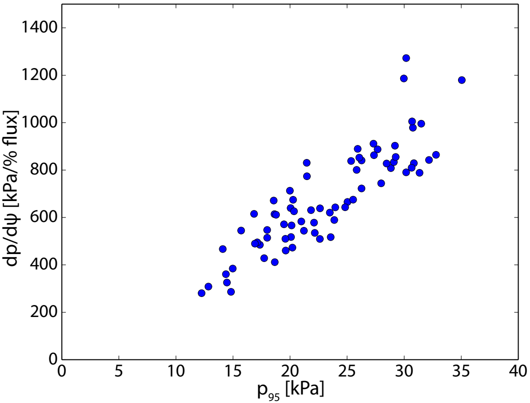
edge safety factor → magnetic shear, ballooning stabilization

I-mode temperature, pressure pedestal widths uncorrelated with physics parameters



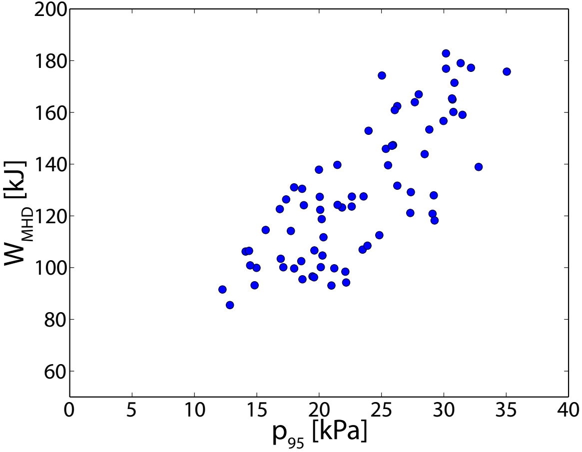
heating power per particle $\rightarrow$ heat flux through temperature pedestal

I-mode pressure pedestal width robust across dataset

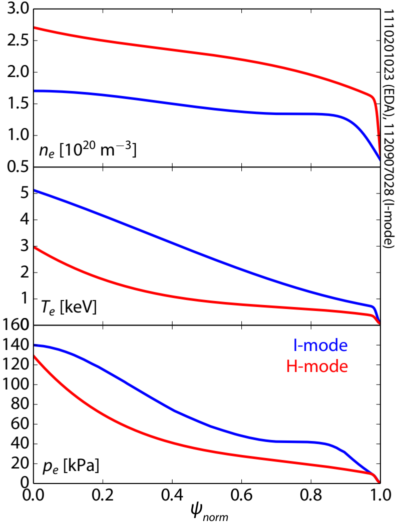


- width robust across dataset, $\nabla p \sim p_{95}$
- suggests with increasing pressure, ballooning ∇p boundary could be exceeded $\rightarrow$ ELMs
- independent density, temperature profile control = approach, but not exceed, limit

Pedestal impacts core, global performance

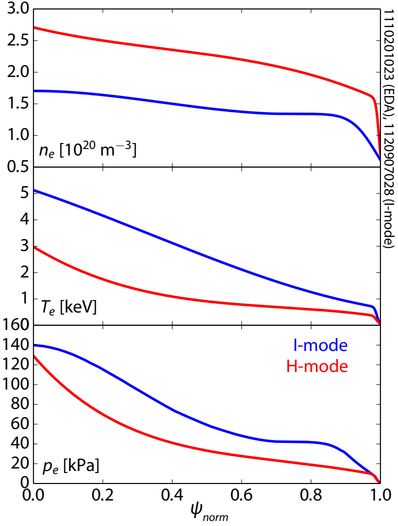


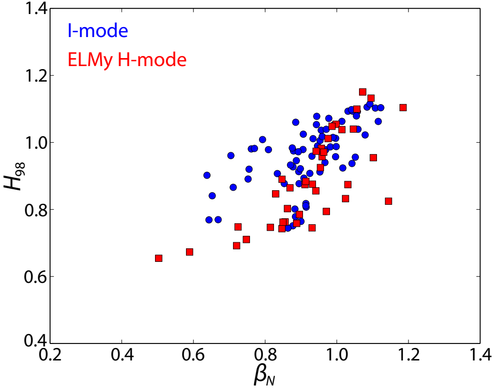
Strong temperature pedestal supports high core temperature, pressure



- stiff ($R/L_{T_e} \sim$ fixed) temperature profiles $\rightarrow$ higher T_{ped} supports greatly increased core temperatures
- provided moderate 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

Strong temperature pedestal supports high core temperature, pressure

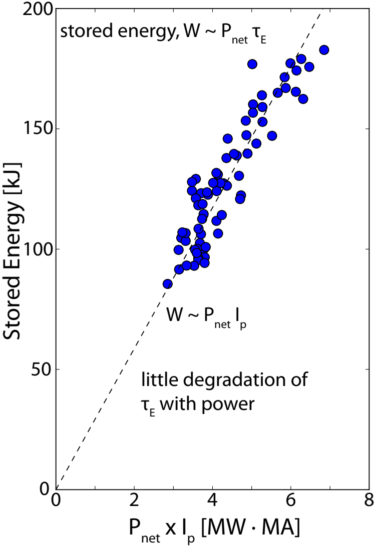




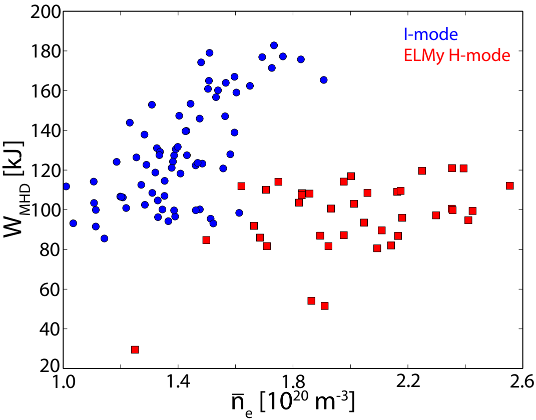
$\rightarrow$ same $\langle \beta_N \rangle$, normalized confinement to ELMy H-mode

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 τ_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
- ELMy H-mode stored energy set by pedestal β_p, limited by MHD constraint – mainly increase pedestal β_p with stronger shaping, flat relation with fueling

First pass at an I-mode confinement scaling

Following practice in ITER89,ITER98 scalings, express I-mode energy confinement as a power law of the form

$$\tau_E = C\ I_p^{\alpha_{I_p}}\ B_T^{\alpha_{B_T}}\ \overline{n}_e^{\alpha_{n_e}}\ R^{\alpha_R}\ \varepsilon^{\alpha_\varepsilon}\ \kappa^{\alpha_\kappa}\ P_{loss}^{\alpha_P}$$

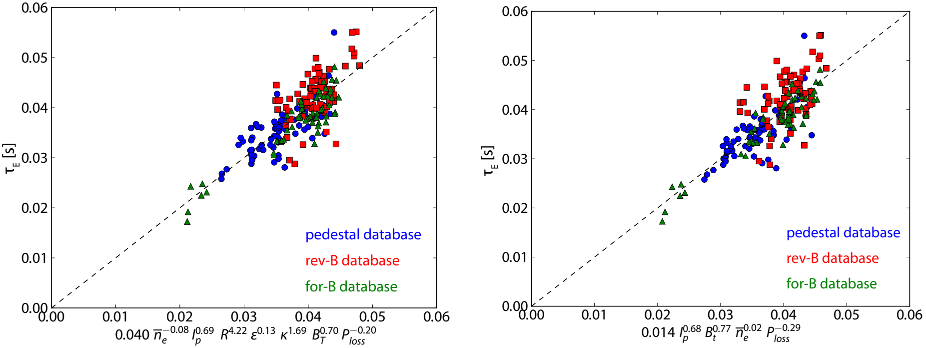
Using high-res pedestal database plus older forward- and reversed-field datasets for expanded parameter range

Reduced fitting parameter set captures I-mode physics

	(a)	(b)	(c)
C	0.040 ± 0.066	0.014 ± 0.002	0.056 ± 0.008
I_p	0.686 ± 0.074	0.685 ± 0.076	0.676 ± 0.077
B_T	0.698 ± 0.075	0.768 ± 0.072	0.767 ± 0.072
$\overline{n}_e$	-0.077 ± 0.055	0.017 ± 0.048	0.006 ± 0.048
R	4.219 ± 4.623		2^*
ε	0.127 ± 1.144		0.5^*
κ	1.686 ± 0.398		
P_{loss}	-0.197 ± 0.048	-0.286 ± 0.042	-0.275 ± 0.042
r^2	0.713	0.685	0.683

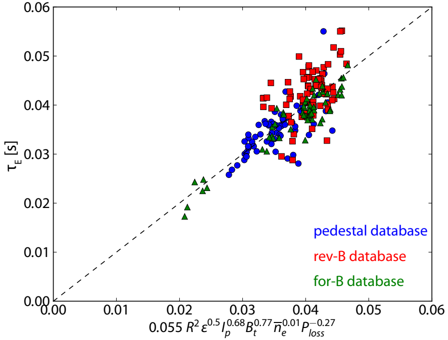
poor fitting in R, ε, κ due to restricted range in dataset

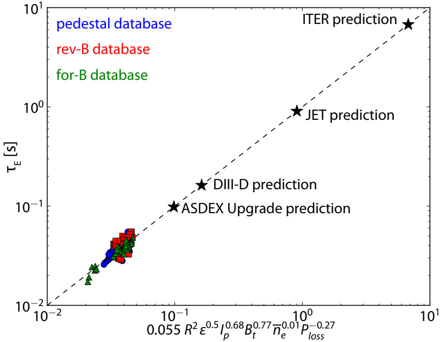
Reduced fitting parameter set captures I-Mode physics



Both fits capture weak degradation of τ_E with heating power, strong response to current, field

Thought experiment: apply ITER98-like size dependence to I-mode scaling, extrapolate to larger machines?





Apply fixed $R^2\sqrt{\varepsilon}$ size scaling – does not impact C-Mod data fit. Weak degradation $\tau_E \sim P_{loss}^{-0.27}$ extrapolates highly favorably to large devices – $\tau_E \sim 8\,\mathrm{s}$ for ITER!

I-mode behavior beneficial for global performance, confinement

- high temperature pedestal supports steep core ∇T, comparable pressure and confinement despite relaxed pedestal
- stored energy responds strongly to heating power, fueling, consistent with pedestal response
  - good news: in burning plasma, alpha heating power $\sim n_e^2$

First-pass confinement scaling laws consistent with observed behaviors

- single-machine scaling captures strong response to current, field, weak degradation with heating power ($\tau_E \sim P^{-\alpha}$, $\alpha < 0.3$)
  - consistent with assumptions in ITER simulations leading to $Q = 10$ scenario[6]
- extrapolates to $\tau_E \sim 8\,\mathrm{s}$ for ITER(!)

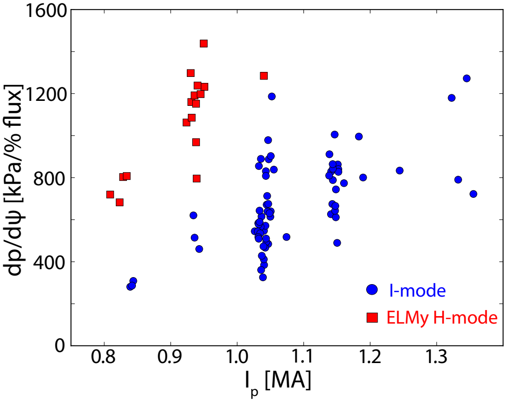
[6] DG Whyte, APS-DPP Nov. 2011

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**

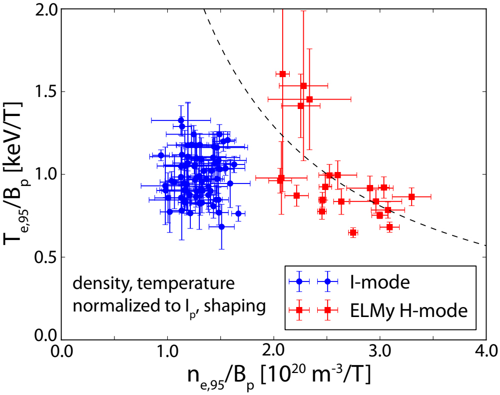
[2] JR Walk *et al.*, *Physics of Plasmas* **21** (2014)
[3] *Invited talk*, APS-DPP Nov. 2013

Pedestal pressure gradient suggests MHD stability, headroom for performance improvement



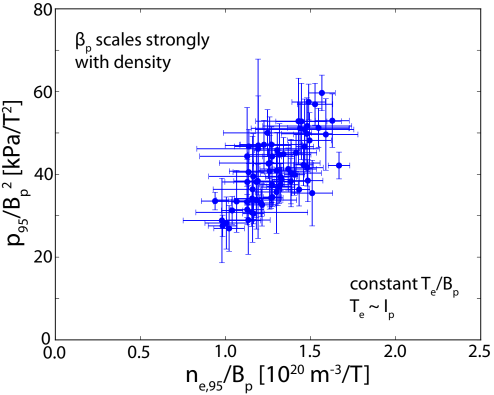
- Pedestal ∇p shallower at given I_p than ELMy H-mode due to lack of density pedestal
- Gradients scale more weakly than $\nabla p \propto I_p^2$ from ballooning MHD (critical-gradient) stability boundary

I-mode pedestal scalings consistent with stability against peeling-ballooning MHD



- ballooning stability, to lowest order, limits pedestal β_p in ELMy H-mode; I-mode n_e, T_e independent, rather than fixed $n_e T_e$
- Pedestal β_p scaling with density consistent with constant $T_{e,95}/B_p \rightarrow T_e \sim I_p$, rather than $T_e \sim 1/n_e$

I-mode pedestal scalings consistent with stability against peeling-ballooning MHD



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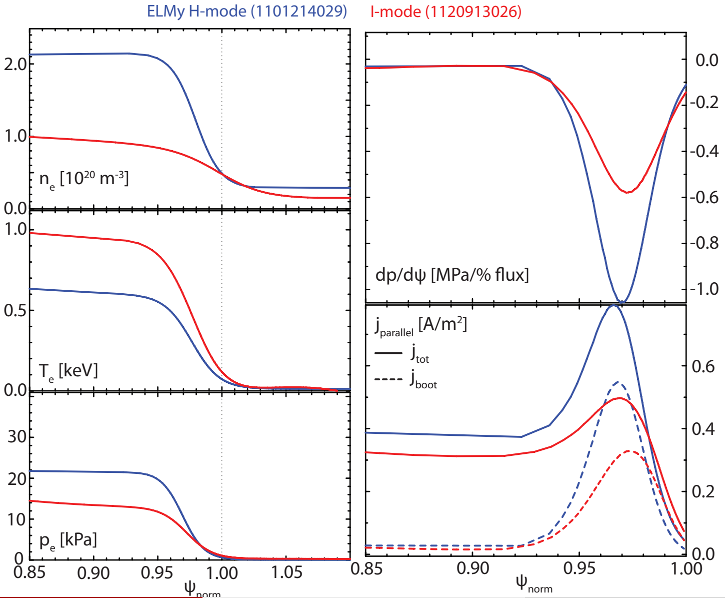
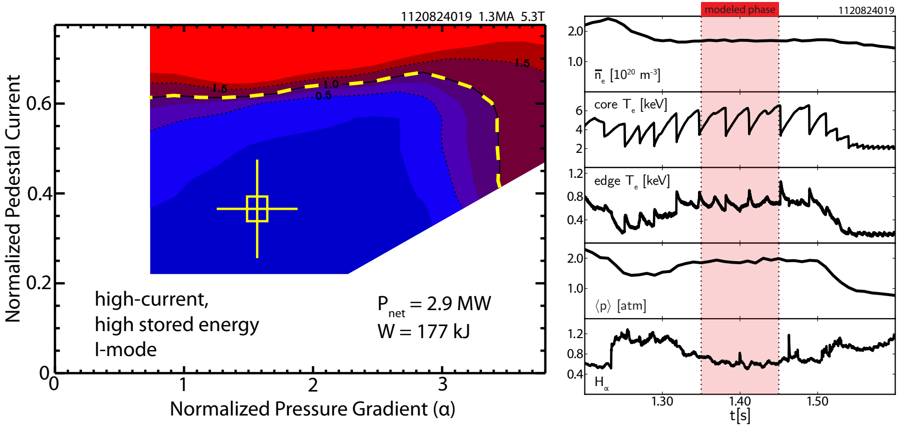
- Pedestal β_p scaling with density consistent with constant $T_{e,95}/B_p \rightarrow T_e \sim I_p$, rather than $T_e \sim 1/n_e$

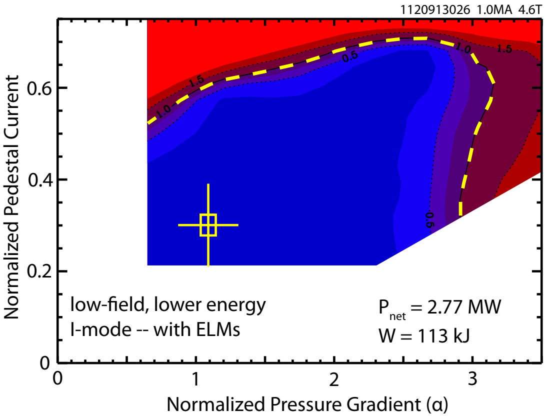
Stability is self-enforcing for I-mode pedestals

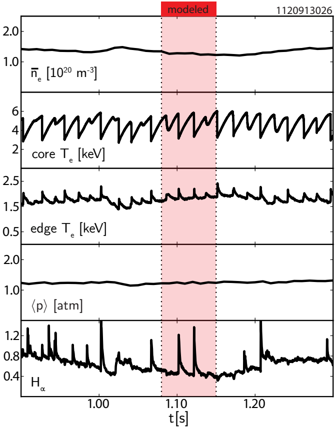


I-mode pedestal strongly stable against peeling-ballooning MHD, KBM turbulence

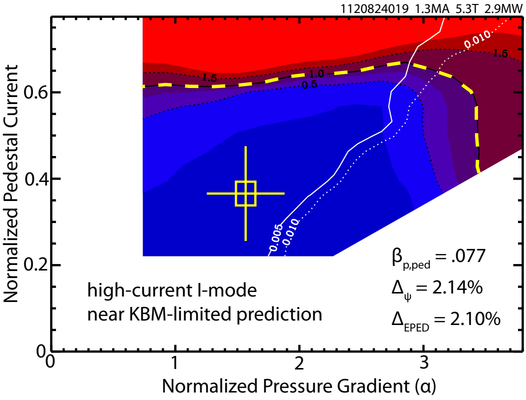


Including in low-field, low-energy cases exhibiting apparent ELMs



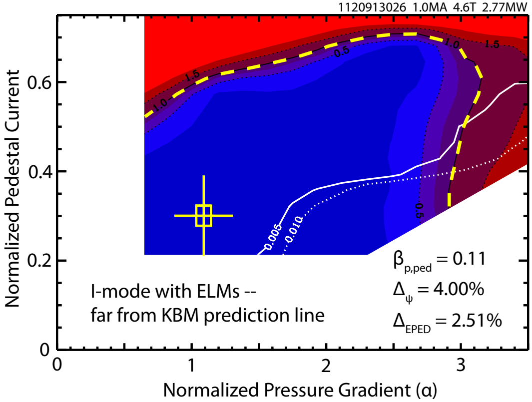


I-mode pedestal modeled to be below KBM threshold as well, including cases with ELMs



- KBM-limited (EPED1) prediction for width, $\Delta_{EPED} = 0.076\beta_{p,ped}^{1/2}$
- BALOO calculates width of pedestal locally beyond threshold – mode onset when half of pedestal is unstable
- I-mode cases spanning width range modeled below threshold

I-mode pedestal modeled to be below KBM threshold as well, including cases with ELMs



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- I-mode cases spanning width range modeled below threshold

EPED physics assumptions alone are not capturing all observed edge behavior in I-mode

I-mode pedestal is stable against identified ELM triggers – however, in minority of cases (12 time windows / 10 unique shots, out of dataset of 72 time windows / 52 shots), particularly at low field ($\sim 4.6\,\mathrm{T}$) exhibit small, intermittent events that appear to be ELMs.

$\rightarrow$ need to more carefully characterize these events!

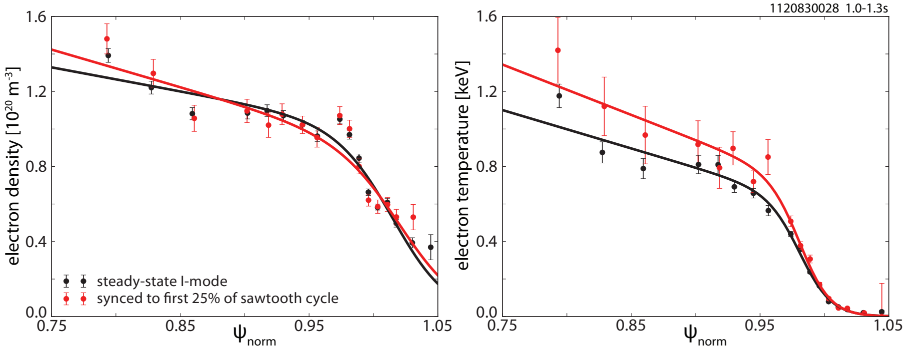
What is an ELM?

ELMs denoted by:

- burst of ionization in edge $\rightarrow$ spike in H_α light
- "explosive" crash in pedestal, both temperature and pressure
- unstable fluctuation leading up to ELM (P-B MHD instability, magnetic precursors, turbulent fluctuations...)

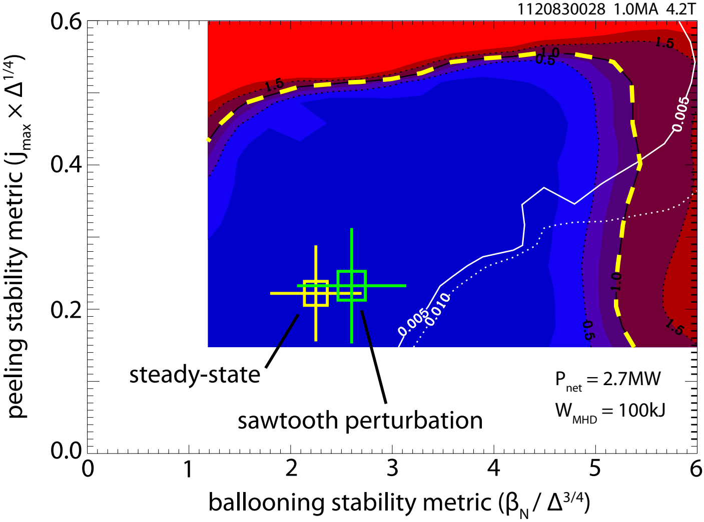
observations of ELMs in I-mode based on H_α spikes, in most cases ($\sim$ 70%) tied to the sawtooth heat pulse reaching the edge – good place to begin!

Sawtooth heat pulse modifies temperature pedestal, little impact on density profile

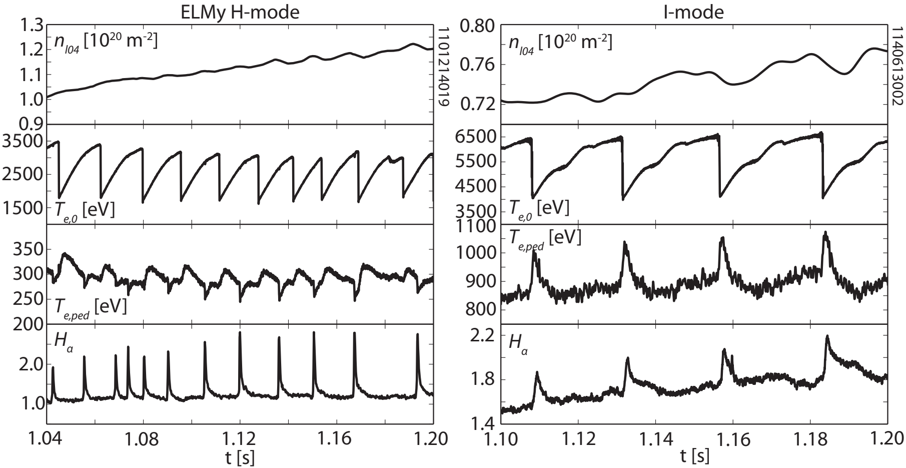


prepare data by masking TS frames to first 25% of sawtooth cycle (immediately following heat pulse reaching edge) – similar to ELM-binning technique used for ELMy H-mode

Sawtooth measurably perturbs pedestal in stability space, but insufficient to reach ELM threshold



I-mode sawtooth H_α events (mostly) do not exhibit characteristic temperature crash expected for ELMs



These events do not appear to be ELMs

Given the lack of a temperature pedestal crash and the computed stability against known ELM triggers, these events appear to not be instability-driven ELMs at all – best described simply as "sawtooth-driven H_α bursts."

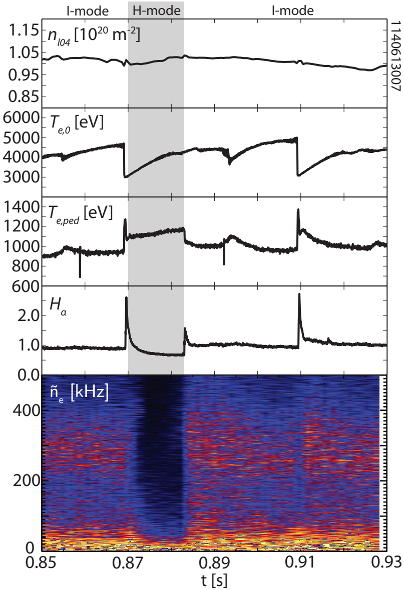
possible explanations:

- ionization front impacting neutrals in SOL?
- density transport effect from sawtooth interaction with WCM?

which raise questions:

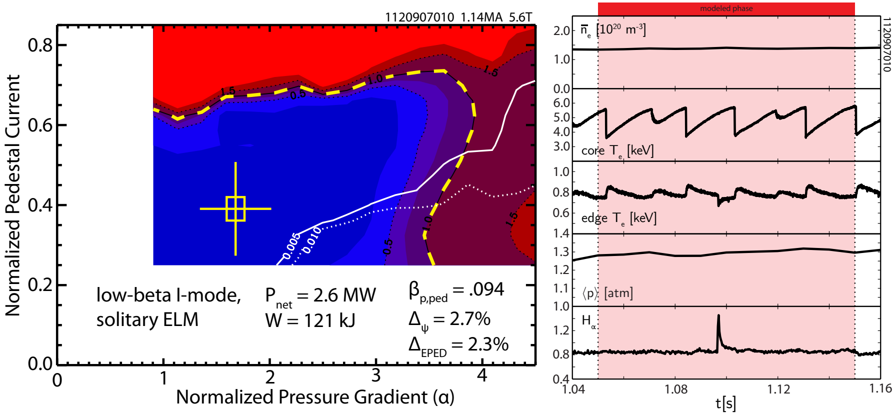
- why are these sometimes triggered – field, shaping, density effects?
- under comparable conditions, why are H_α spikes inconsistently triggered by similarly-sized sawteeth?

Minority of H_α spikes do appear to be ELMs, however



- Few events (10 out of 37 total events) do exhibit observable drop in edge T_e with spike, are not necessarily triggered by sawteeth
- suggests these are "true" ELMs – but perturbation is still small, $<1\%$ stored energy drop, T_e crash on sawtooth-triggered ELMs insufficient to overcome T_e increase from heat pulse

Stationary pedestal structure around intermittent ELMs still stable to P-B MHD, KBM threshold



- H_α spikes (putative ELMs) in minority of I-mode cases (12 out of 72 time windows)
- Majority ($\sim 70\%$, $27/37$) of identified events do not appear to be ELMs at all, consistent with computed stability and observed pedestal behavior – rather, are benign H_α pulses triggered by sawteeth
- a few do exhibit ELM behavior, not necessarily triggered on sawteeth – but these are rare, small
  - stationary pedestal structure still stable – transient modifications to hit stability boundary?

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ELMy H-mode

ELMy H-mode pedestal well-described by EPED physics assumptions

- width set by KBM limit, $\Delta_\psi \sim \beta_{p,ped}^{1/2}$
- pressure pedestal height limited by peeling-ballooning MHD, $p_{ped} \sim \Delta_\psi^{3/4}$; particularly, ballooning limit $\nabla p \sim I_p^2$
- EPED accurately predicts pedestal width, height, within $\pm 20\%$ systematic expected error

C-Mod results motivate further development to EPED

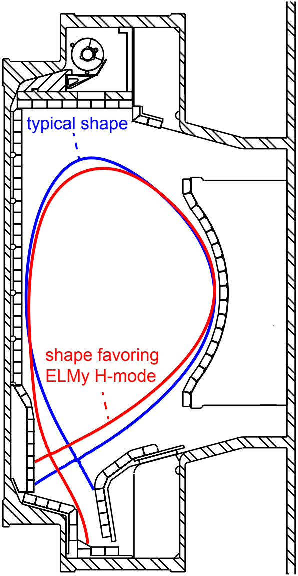
- careful treatment of diamagnetic stabilization necessary for high-collisionality C-Mod pedestals
- extend model to handle more general equilibria

I-mode pedestals & performance

I-mode stability & ELM characterization

Supplemental Slides

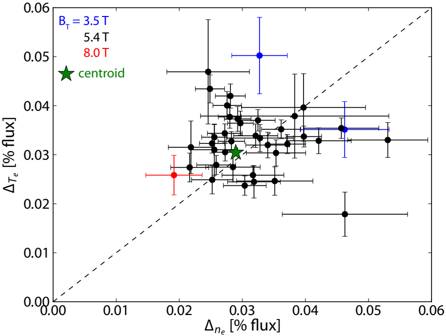
Plasma shaping in C-Mod operation

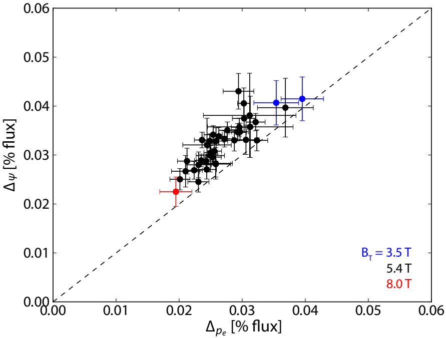


- I-mode operates at typical shaping for C-Mod plasmas (with reversed I_p, B_T for unfavorable ∇B drift)
- ELMy H-mode on C-Mod requires special shaping with low elongation, upper triangularity, high lower triangularity – in normal shaping in forward field, reach ELM-free H-mode (low ν^*) or EDA H-mode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

ELMy H-mode

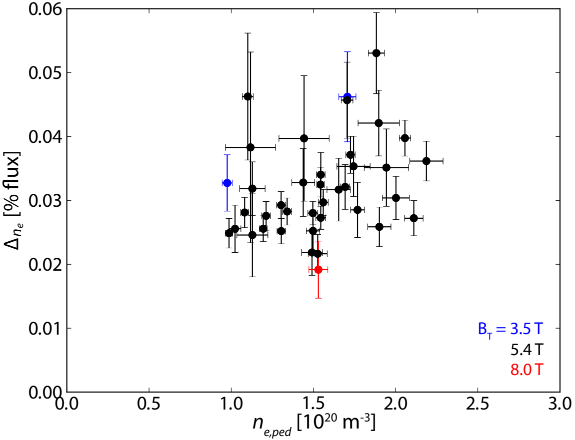
Density, temperature, and pressure widths in ELMy H-mode





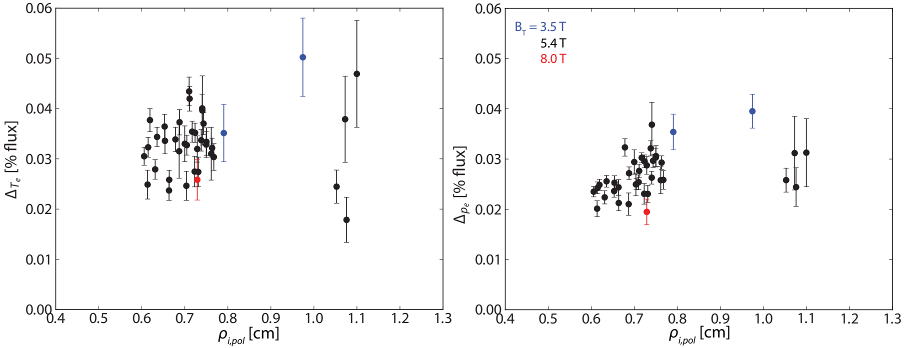
$\Delta_\psi = (\Delta_{n_e} + \Delta_{T_e})/2$, tracks with directly-measured Δ_{p_e}

Density pedestal width in ELMy H-mode inconsistent with neutral-penetration model



as expected from high-density, neutral-opaque SOL on C-Mod

Temperature, pressure pedestal widths not well-described by gyroradius scaling

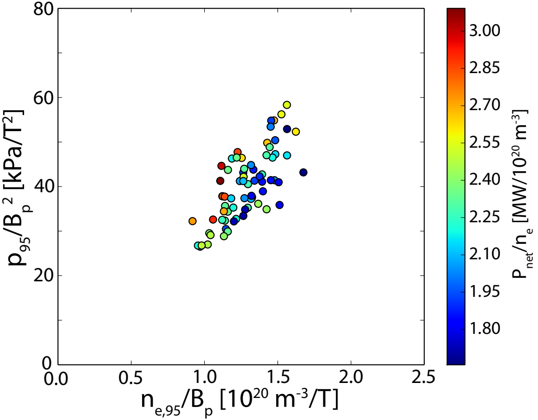


T_e pedestal width uncorrelated; p_e pedestal width trend due to covariance between $\rho_{i,pol} \sim \sqrt{T_{e,ped}}/I_p$ and $\sqrt{\beta_{p,ped}} \sim \sqrt{n_{e,ped}T_{e,ped}}/I_p$

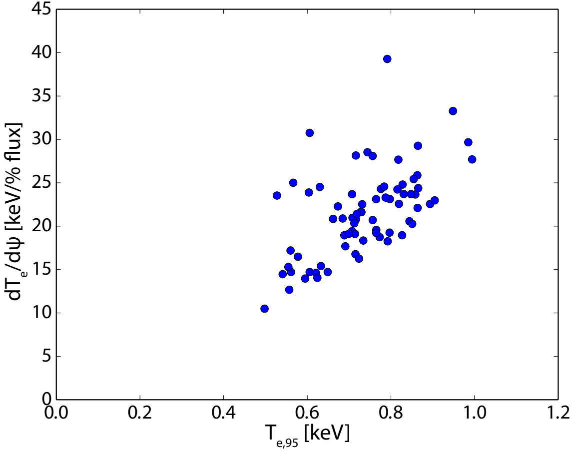
I-mode pedestals

$\beta_{p,95}$ scaling with norm. density in addition to heating-power response

- $P_{net}/\overline{n}_e$ sets slope of T_e/B_p line – response of pedestal temperature at fixed current
- pressure responds to fueling, provided sufficient power to maintain the pedestal

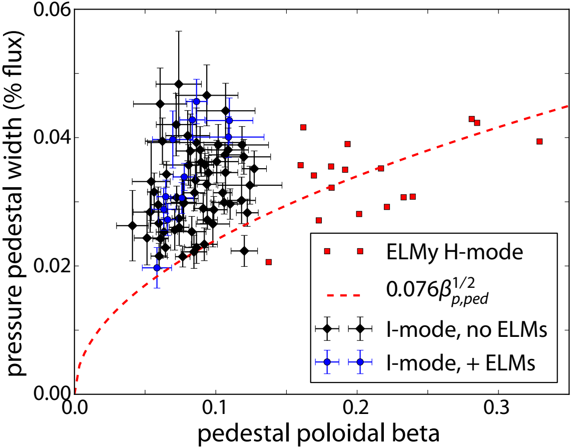


I-mode temperature pedestal width also robust, though less strictly than pressure pedestal



I-mode stability & ELM characterization

I-modes exhibiting edge H_α spikes / ELMs typically at lower β_p range



MHD stability analysis

$$
\begin{aligned}
\vec{Q} &= \nabla \times \left(\vec{\xi} \times \vec{B}\right) \\
\delta W &= \delta W_F + \delta W_S + \delta W_V \\
\delta W_F &= \frac{1}{2}\int_P d^3\vec{r}\left[\frac{|\vec{Q}|^2}{\mu_0} + \frac{B^2}{\mu_0}\left|\nabla\cdot\vec{\xi}_\perp + 2\vec{\xi}_\perp\cdot\vec{\kappa}\right|^2 + \gamma p\left|\nabla\cdot\vec{\xi}\right|^2\right. \\
&\qquad \left. - 2\left(\vec{\xi}_\perp\cdot\nabla p\right)\left(\vec{\kappa}\cdot\vec{\xi}^*_\perp\right) - j_\parallel\left(\vec{\xi}^*_\perp \times \vec{b}\right)\cdot\vec{Q}_\perp\right] \\
\delta W_S &= \frac{1}{2}\int_S dS\left|\hat{n}\cdot\vec{\xi}_\perp\right|^2 \hat{n}\cdot\left[\nabla\left(p + \frac{B^2}{2\mu_0}\right)\right] \\
\delta W_V &= \frac{1}{2}\int_V d^3\vec{r}\frac{\left|B_1\right|^2}{\mu_0}
\end{aligned}
$$

$$X = RB_p\xi_\psi$$

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

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

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

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

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

magnetic line bending: stabilizing

ballooning drive

kink drive

magnetic curvature: stabilizing inboard, destabilizing outboard

surface term: peeling drive

$$\delta W = \pi \iint d\psi d\chi \left\{ \boxed{\frac{JB^2}{R^2 B_p^2} \left| k_\parallel X \right|^2 + \frac{R^2 B_p^2}{JB^2} \left| \frac{1}{n} \frac{\partial}{\partial \psi} \left(JB k_\parallel X \right) \right|^2} \right.$$

$$\boxed{- \frac{2J}{B^2} \frac{dp}{d\psi}} \boxed{\left[|X|^2 \frac{\partial}{\partial \psi} \left(p + \frac{B^2}{2} \right) - \frac{iF}{JB^2} \frac{\partial}{\partial \chi} \left(\frac{B^2}{2} \right) \frac{X^*}{n} \frac{\partial X}{\partial \psi} \right]}$$

$$\boxed{- \frac{X^*}{n} JB k_\parallel \left(X \frac{d\sigma}{d\psi} \right)} + \frac{1}{n} \left[PJBk_\parallel^* Q^* + P^* JB k_\parallel Q \right]$$

$$\left. + \boxed{\frac{\partial}{\partial \psi} \left[\frac{\sigma}{n} X^* JB k_\parallel X \right]} \right\}$$

ELITE solves this for given n by encoding the poloidal angle χ in a straight-line coordinate via the "ballooning transform,"

$$\omega = \frac{1}{q}\int^{\chi} \nu \, d\chi$$

(note $2\pi q = \oint \nu \, d\chi$) and decomposing the displacement X into poloidal harmonics

$$X = \sum_m u_m(\psi) e^{-im\omega}$$

centered on the (m, n) rational surface. Define a "fast" radial variable

$$x = m_0 - nq$$
$$m_0 = \mathrm{Int}(nq_a) + 1$$

readily convertible between x and ψ.

Euler-Lagrange equation minimizing the energy may be expressed in this harmonic expansion by a set of coupled equations[7]

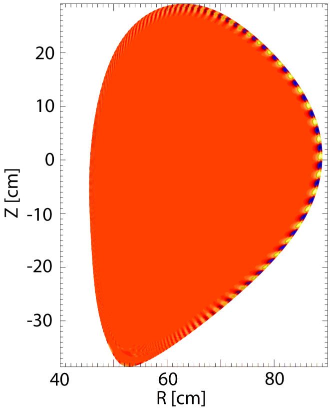
$$A^{(2)}_{m,m'}\frac{d^2 u_m}{d\psi^2} + A^{(1)}_{m,m'}\frac{du_m}{d\psi} + A^{(0)}_{m,m'}u_m = 0$$

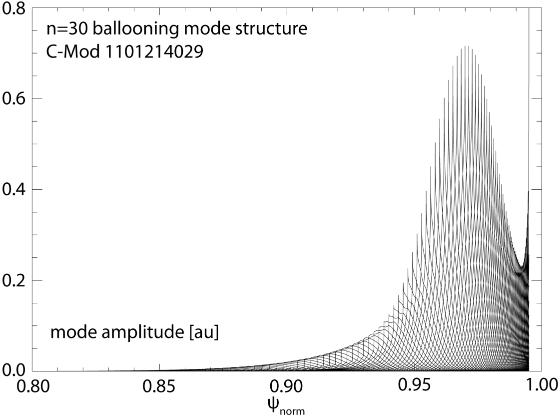
describing coupling between harmonics m, m', with matrix elements A calculated from the equilibrium describing the mode amplitudes. Features:

- u_m varies rapidly ($\sim x$, comparable to spacing between rational surfaces), needs fine mesh; A set by equilibrium parameters, varies more slowly, can be calculated on coarse mesh for numerical efficiency
- modes only couple to few nearest neighbors, so most $A_{m,m'}$ may be ignored
- can quickly calculate "fictitious eigenvalue" for stable/unstable determination, or true eigenvalue γ^2 for mode growth rate when inertial terms included (modifications to matrix elements A)

[7] HR Wilson *et al.*, *Physics of Plasmas* **9** (2002)

ELITE radial, poloidal mode structure for $n = 30$ ballooning mode





BALOO solves simplified version of ballooning energy formulation, in the $n \to \infty$ limit: reduces to 1-D eigenvalue equation,

$$(L_0 + \omega^2 M_0) f = 0$$
$$X = f(\psi, y) e^{-in \int \nu \, dy}$$

for displacement X and ballooning-transformed angle y, given by

$$L_0 f = \frac{\partial}{\partial y} \left\{ \frac{1}{JR^2 B_p^2} \left[1 + \left(\frac{R^2 B_p^2}{B} \int^y \frac{d\nu}{d\psi} dy \right)^2 \right] \frac{\partial f}{\partial y} \right\}$$
$$+ f \left\{ \frac{2J}{B^2} \frac{dp}{d\psi} \frac{\partial}{\partial \psi} \left(p + \frac{B^2}{2} \right) - \frac{F}{B^4} \frac{dp}{d\psi} \left(\int^y \frac{d\nu}{d\psi} dy \right) \frac{\partial B^2}{\partial y} \right\}$$
$$M_0 f = \frac{J}{R^2 B_p^2} \left[1 + \left(\frac{R^2 B_p^2}{B} \int^y \frac{d\nu}{d\psi} dy \right)^2 \right] f$$