Developing predictive capability for the tokamak pedestal: Experiment and modeling on Alcator C-Mod

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US Transport Task Force Workshop
Annapolis, MD
April 11, 2012

Alcator C-Mod

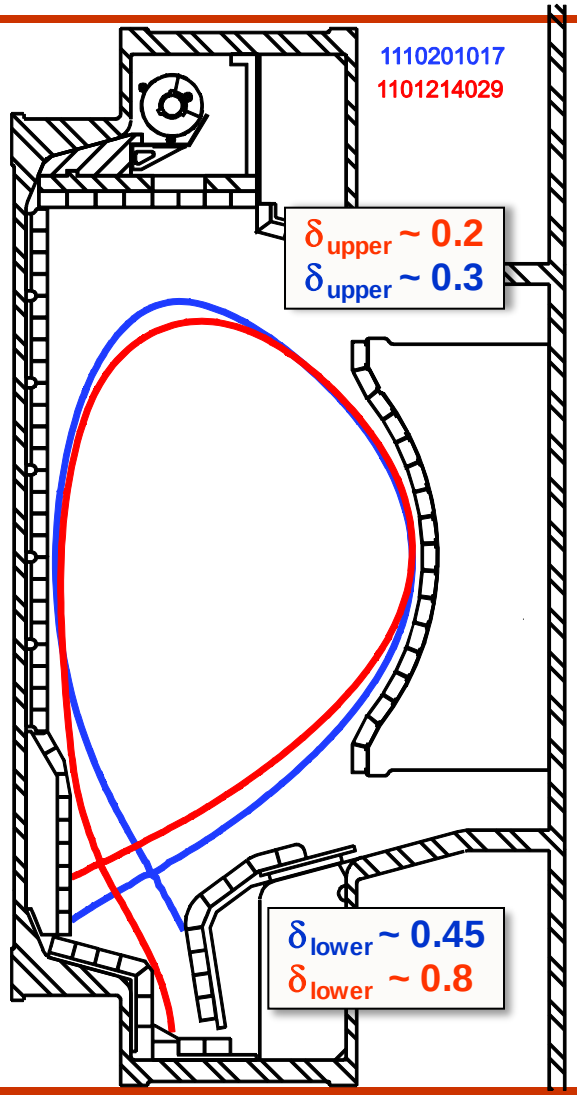
Find all C-Mod TTF contributions at: http://www.psfc.mit.edu/research/alcator/pubs/TTF/TTF_2012_abstracts.htm

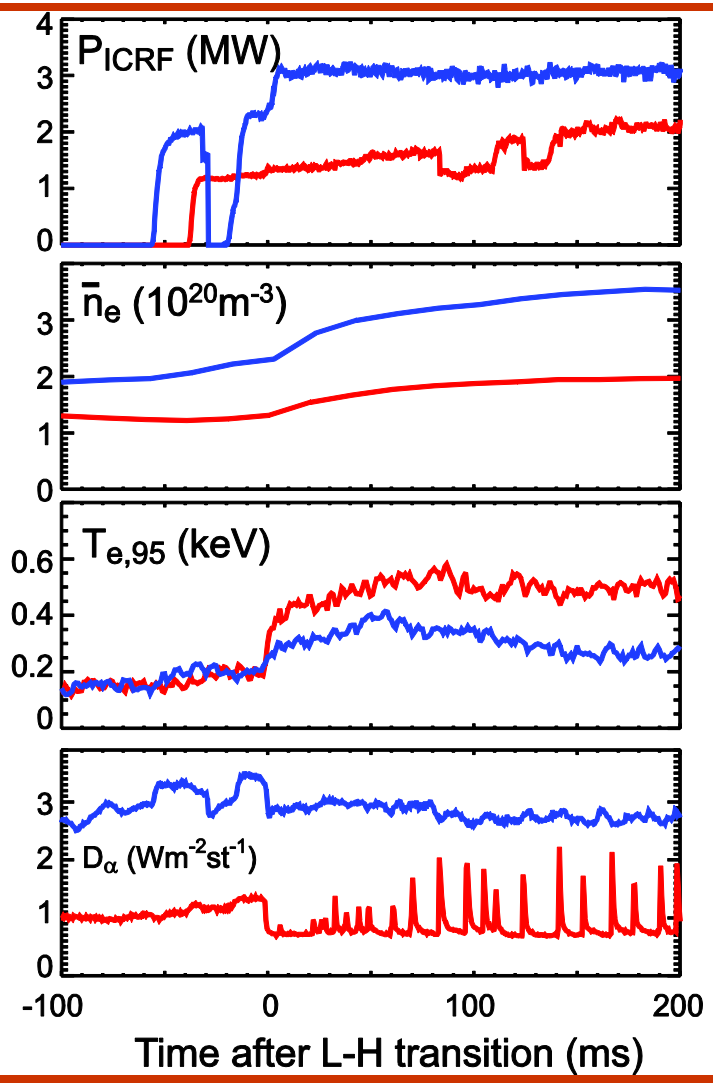
Goal: Better understanding of the edge pedestal through combined experiment and modeling

Alcator C-Mod

- Developing *predictive capability for the edge pedestal* in tokamaks is highly desirable to projecting performance on ITER
  - Focus of the FY11 FES Joint Research Target among US facilities, modeling groups
- Pedestal structure and relaxation mechanisms (ELMs, continuous modes) characterized in C-Mod high-performance plasmas
- Models for pedestal structure, stability are evaluated
- This talk will contrast:
  (a) *ELMy H-mode*
  (b) *Enhanced D-alpha (EDA) H-mode*
  (c) *I-mode*

Modified shaping promotes transition from *EDA* to *ELMy* H-mode on Alcator C-Mod



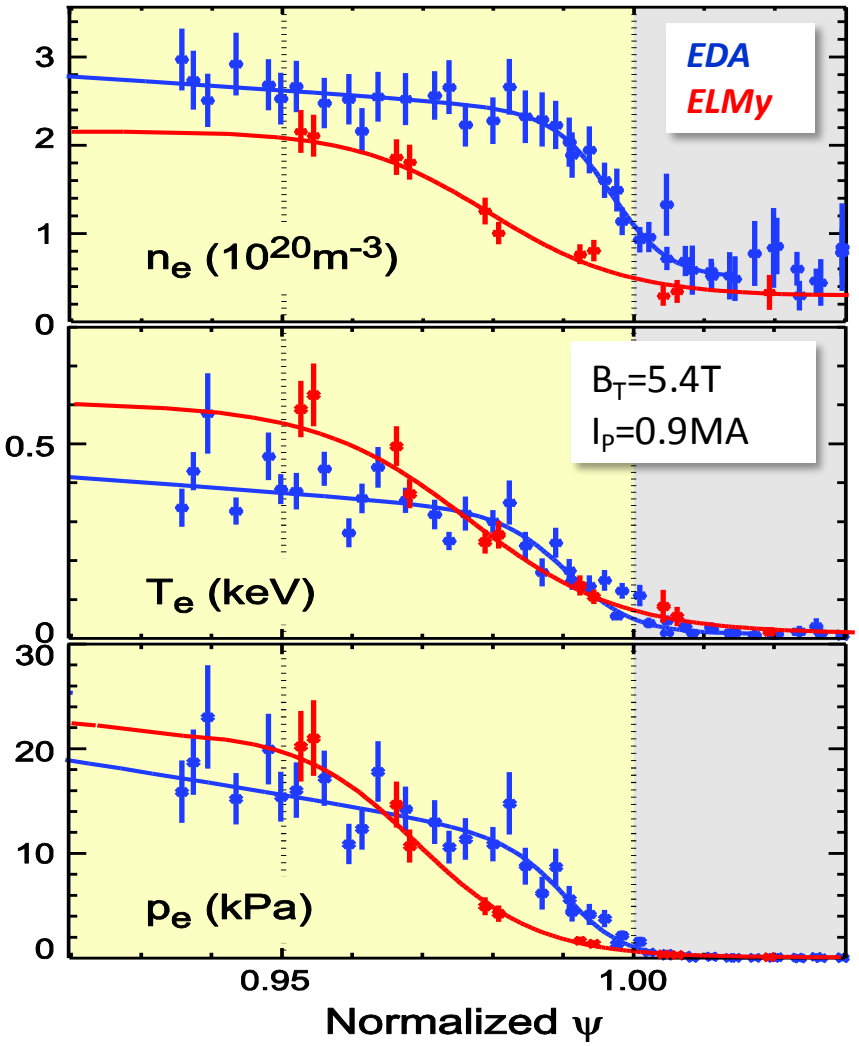


B_T=5.4T
I_P=0.9MA

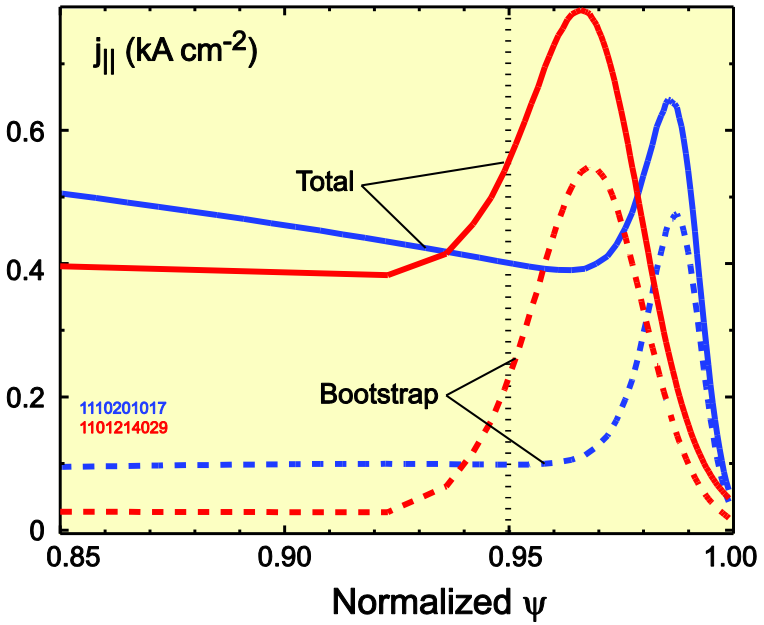
Both EDA and ELMy H-modes relatively stationary

Edge relaxation very different

Transition from EDA to ELMs associated with collisionality reduction + *wider pedestal*



- H-modes with similar performance compared
- Modeled current profile similar in peak value, but with greater radial extent in ELMy case



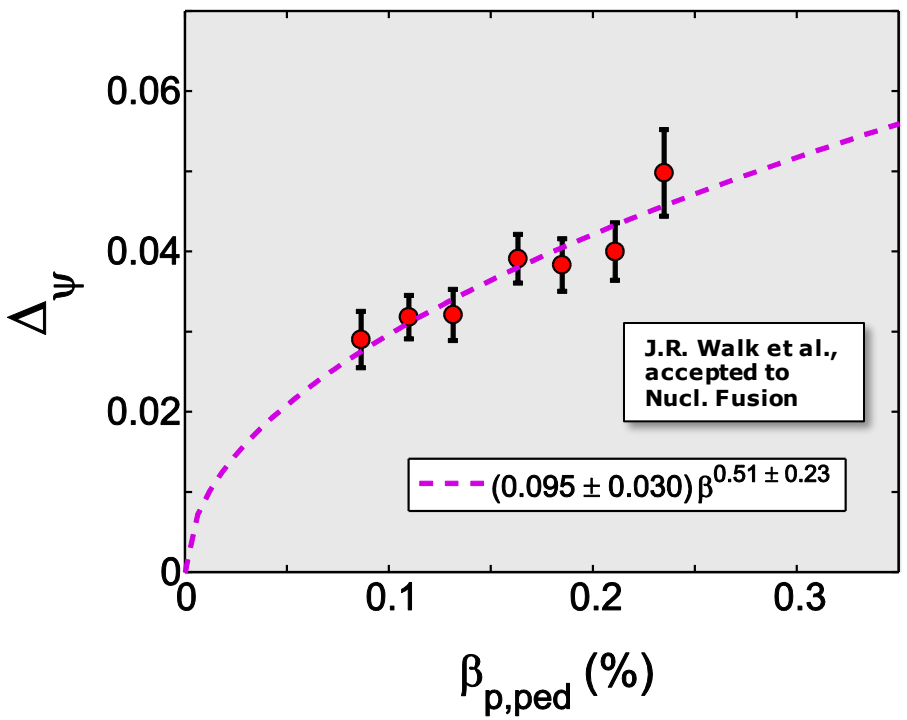
Recent experiments have expanded ELMy H-mode operating space on Alcator C-Mod

- Prior studies mostly restricted to 5.4T, 0.9MA, low elongation
- New data: $0.45<I_p[MA]<1.05$
  $3.5<B_T[T]<8.0$
  $1.42<\kappa<1.56$

- Width data consistent with $\beta_p^{1/2}$ scaling, with little or no trend on other parameters
  - *Consistent with trends observed on DIII-D, JET, NSTX, MAST*
  - *Consistent with a pedestal limited by kinetic ballooning mode (KBM) stability*

- Need additional physical mechanism to limit total pedestal pressure

Mean of T_e, n_e widths in flux space *vs.* pedestal poloidal beta

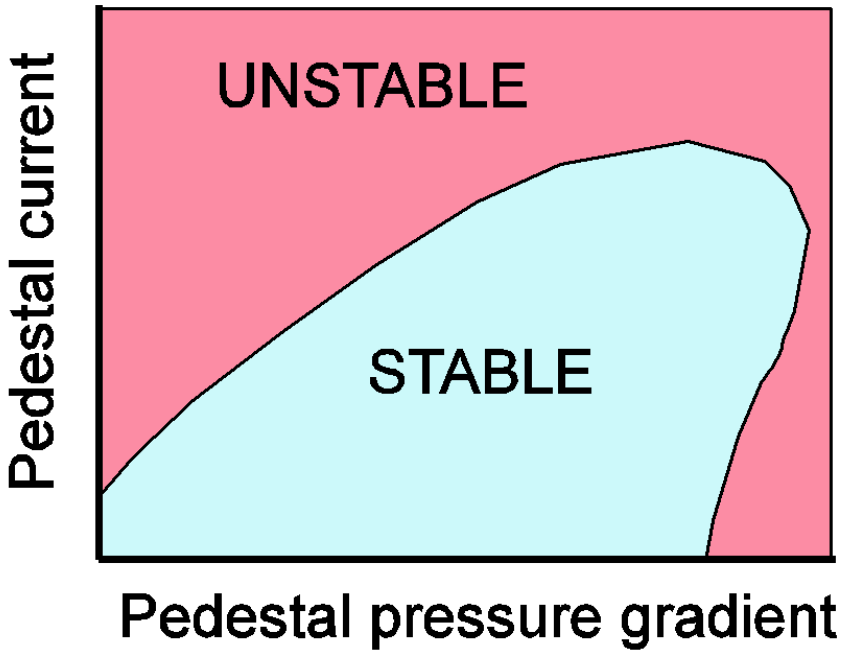


J.R. Walk, Thurs AM Edge session

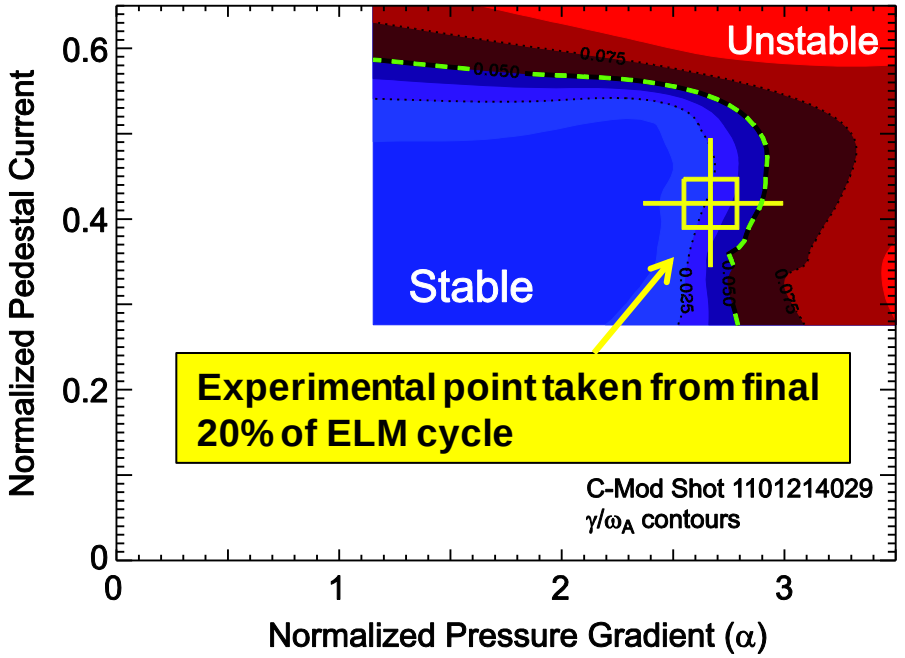
ELITE: C-Mod ELMs associated with peeling-ballooning instability

- Coupled pressure gradient and edge current driven instabilities, seen to be linearly unstable before Type-I ELMs on a number of devices

Sketch of expected p.b. stability

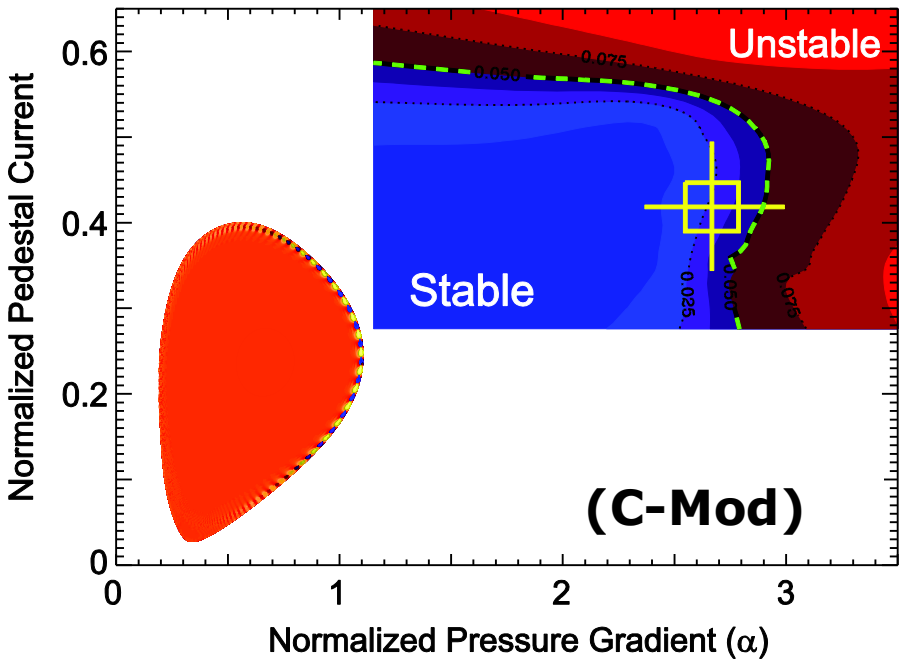


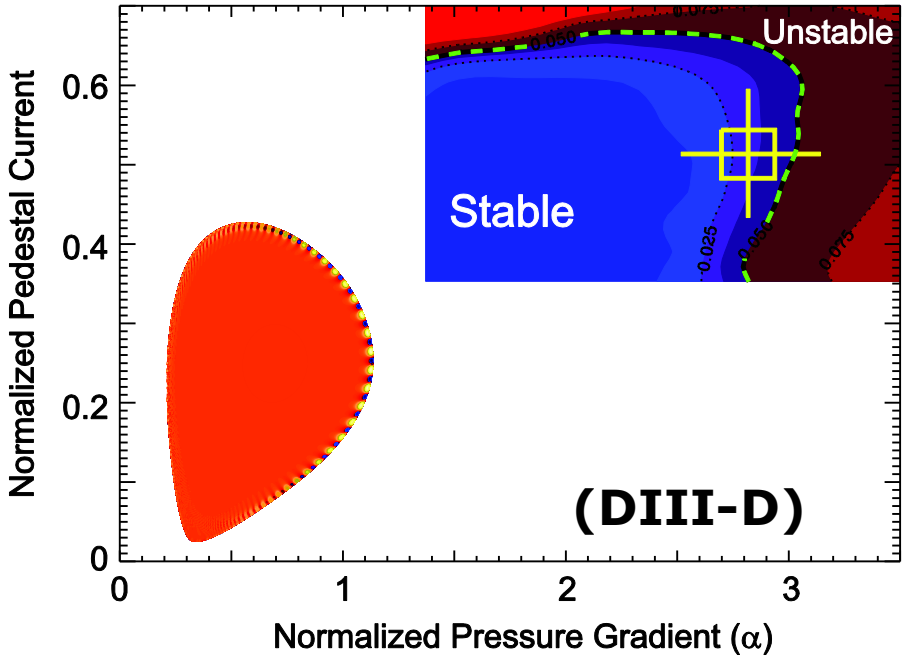
Calculated contours of p.b. growth rate



Pedestal profile and turbulence evolution during ELM cycle a topic of ongoing investigation!

Stability calculation confirmed with similar *ELMy H-modes* on DIII-D

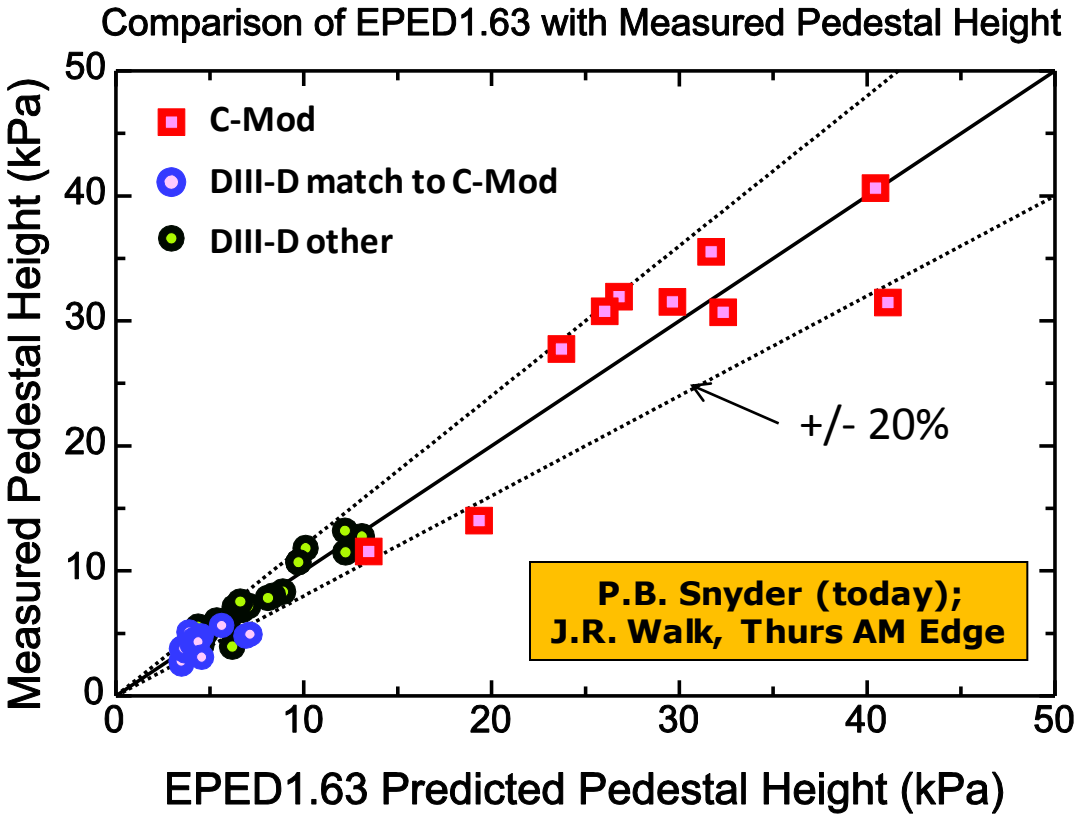




- Recent experiment on DIII-D to match C-Mod non-dimensional parameters at pedestal top: β, ν^*, ρ^*
- Similarities observed in experimental ELM signatures, inter-ELM fluctuations
- Stability diagrams, edge mode structure, and experimental operating point all similar

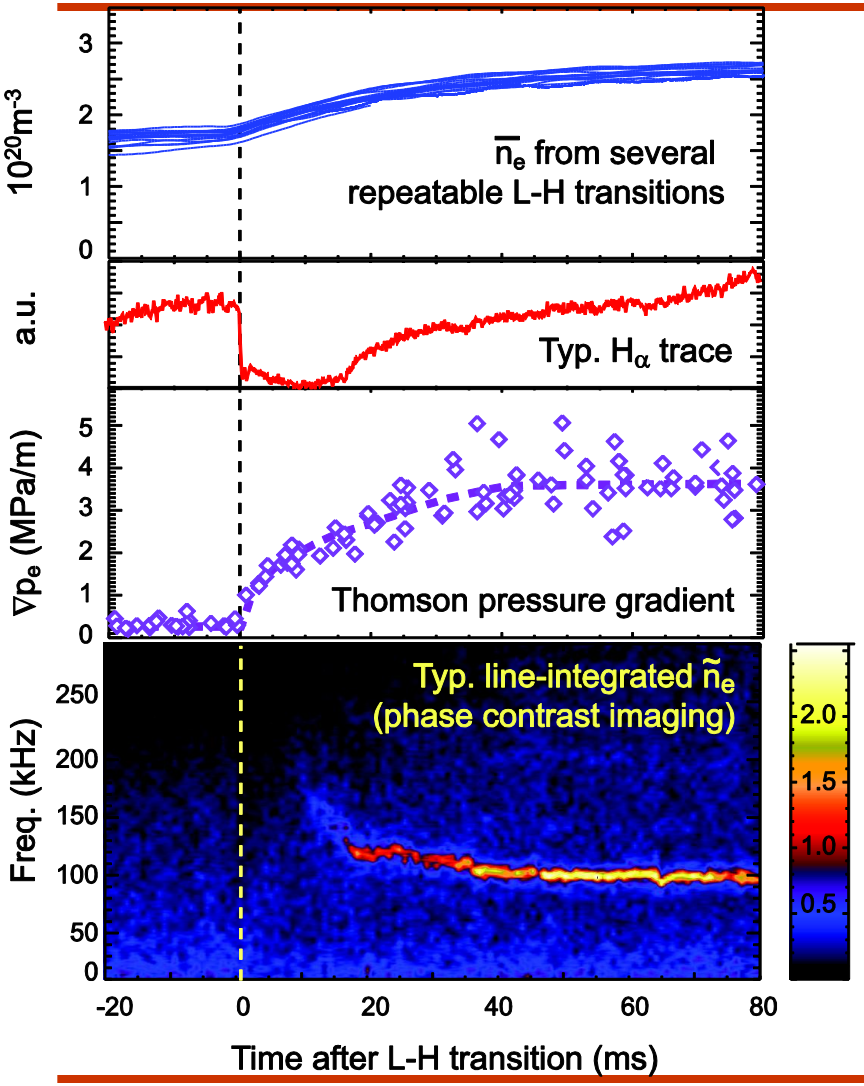
EPED model reproduces ELMy H-mode pedestal structure on C-Mod

- EPED model simultaneously solves:
  - *(a)* Pedestal width constrained by kinetic ballooning modes ($\Delta \sim p_{ped}^{1/2}$)
  - *(b)* Pedestal height limited by PBMs ($p_{ped} \sim \Delta^{3/4}$)
- (a), (b) appear well satisfied in C-Mod, as on other devices
- Height/width predictions agree over a wide range of experimental conditions



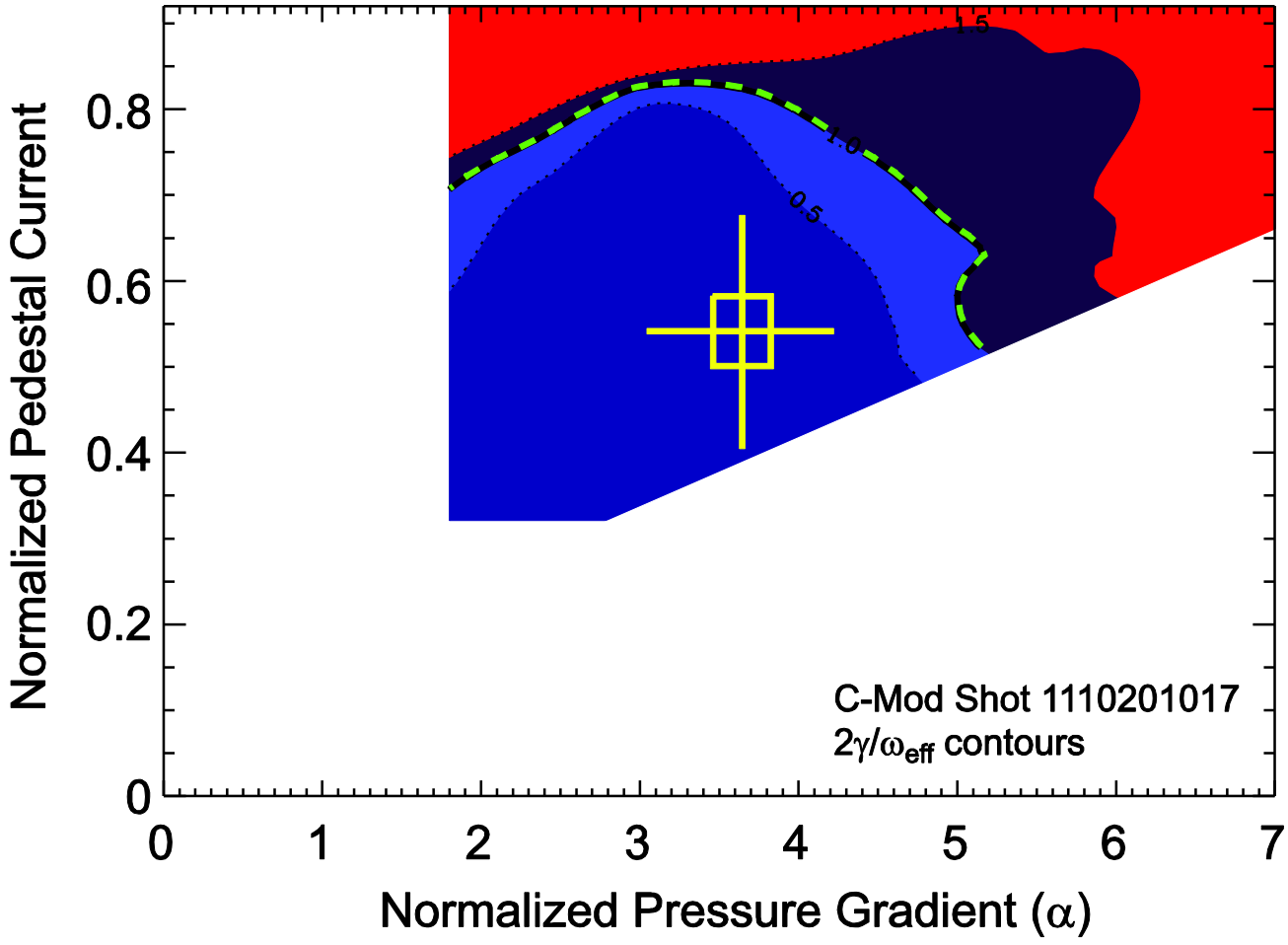
C-Mod significantly extends the range of validation of EPED predictive capability

Natural ELM-suppression with continuous pedestal regulation: EDA H-mode



- Pedestal saturation and stationary H-mode established typically in <100ms
- Enhanced D_α; no ELMs needed to regulate particles/impurities
- Pressure pedestal saturation accompanied by onset and growth of fluctuation in edge density, magnetic field:
- quasi-coherent mode (QCM)
  - f~50—100kHz, n~10—25, k_{pol}~1.5cm
- *Small ELMs are observed in EDA H-modes at sufficiently high power, but these cases are not considered here*

EDA H-mode tends to operate in a region stable to peeling-ballooning modes



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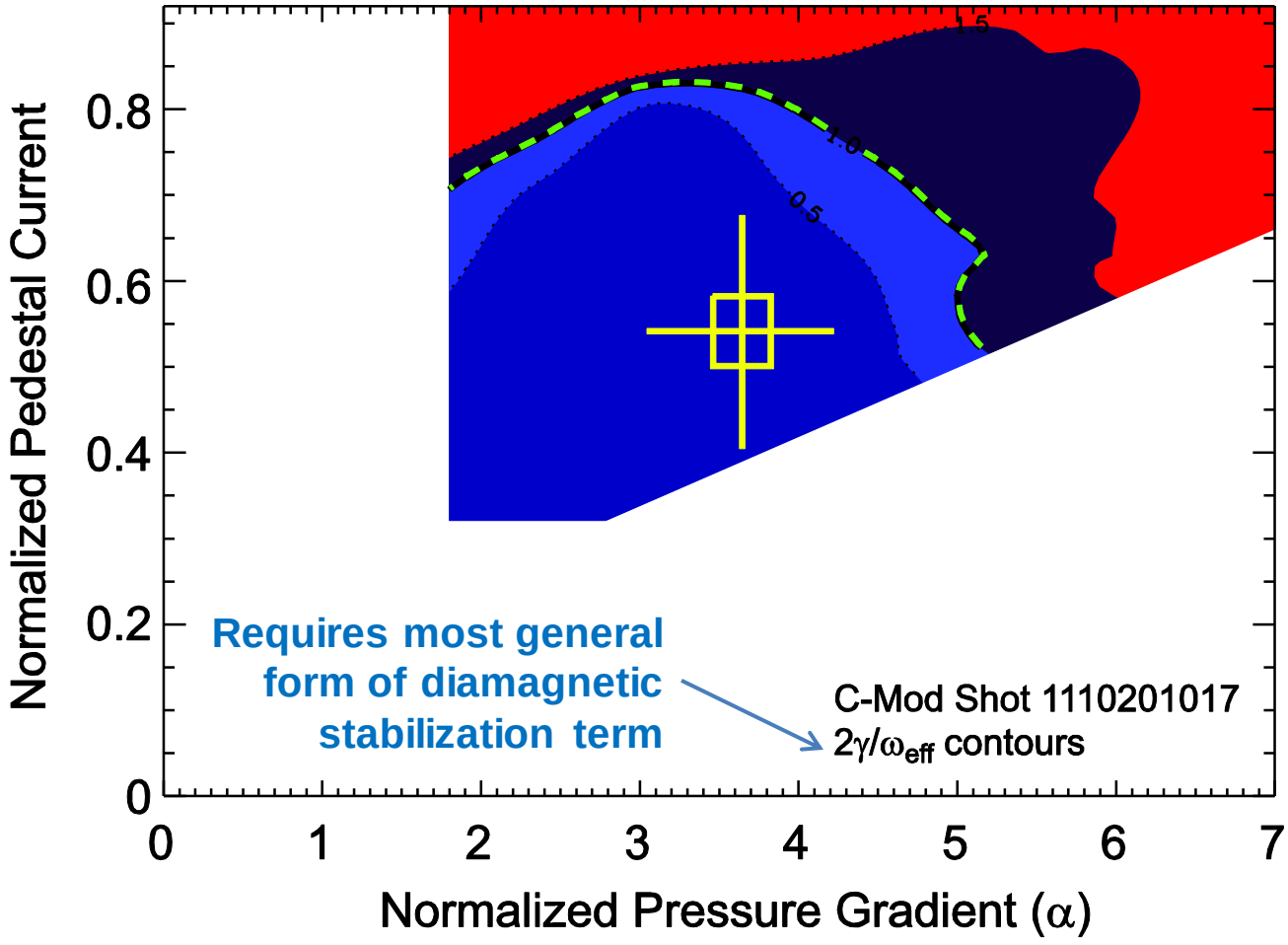
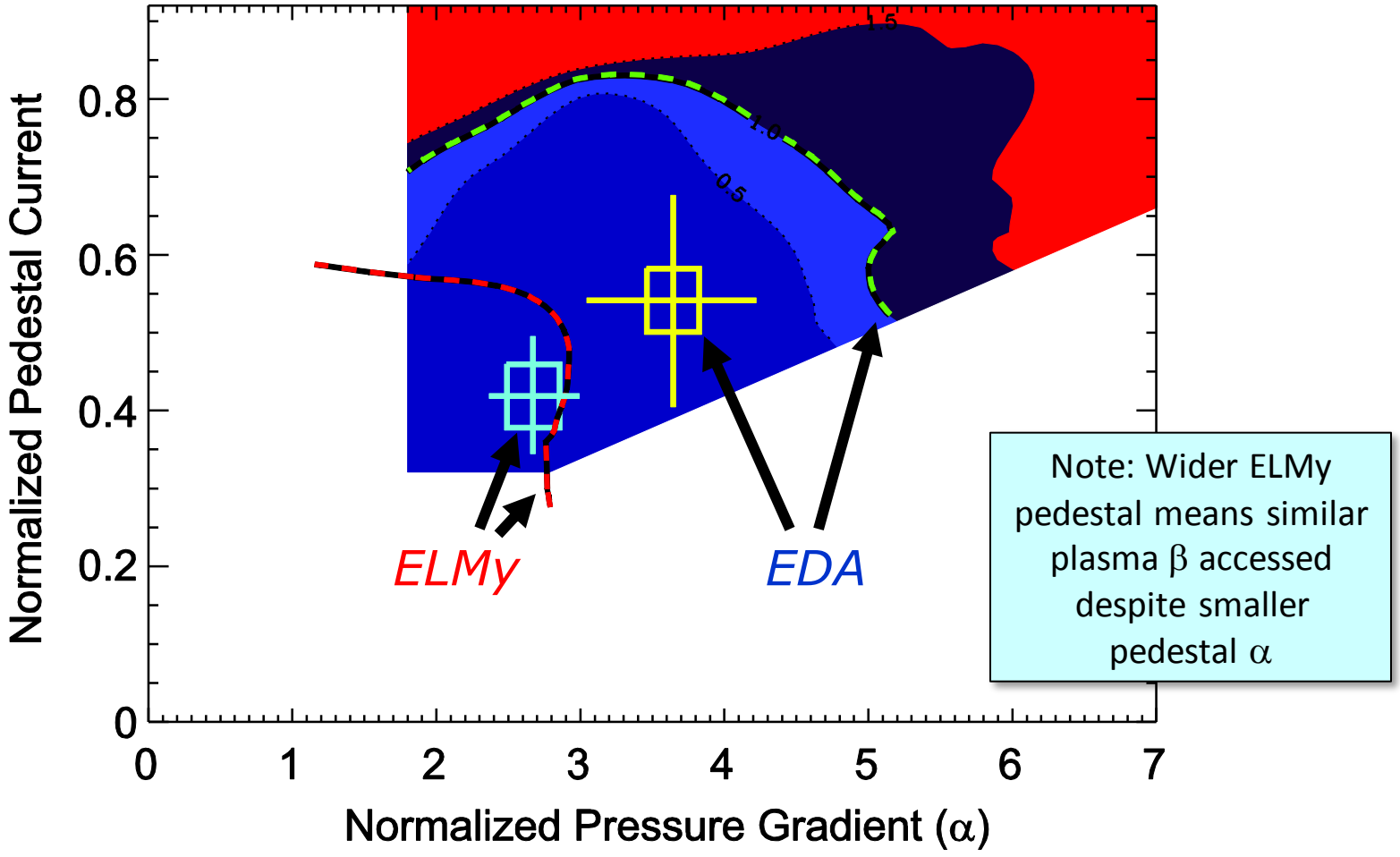
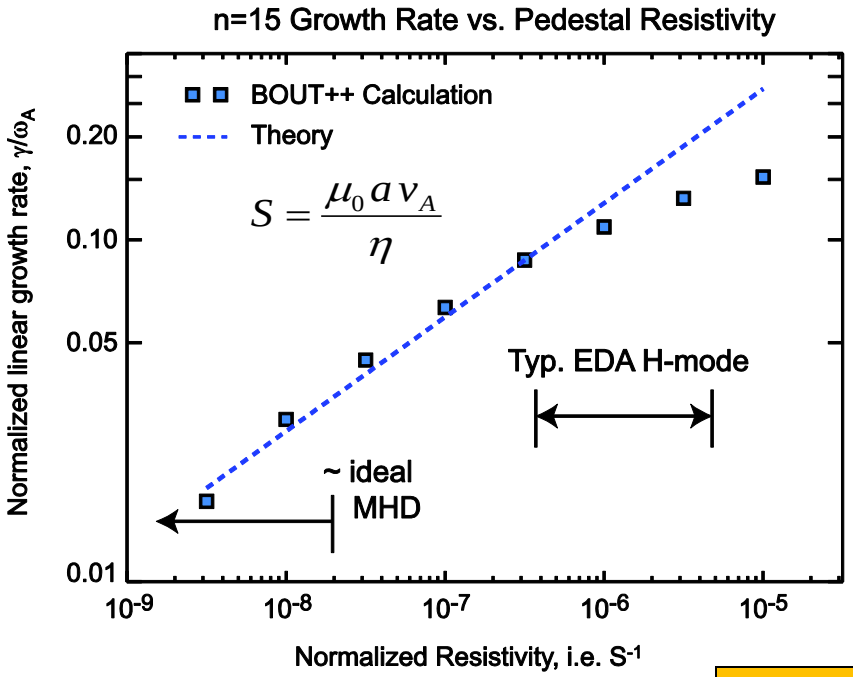


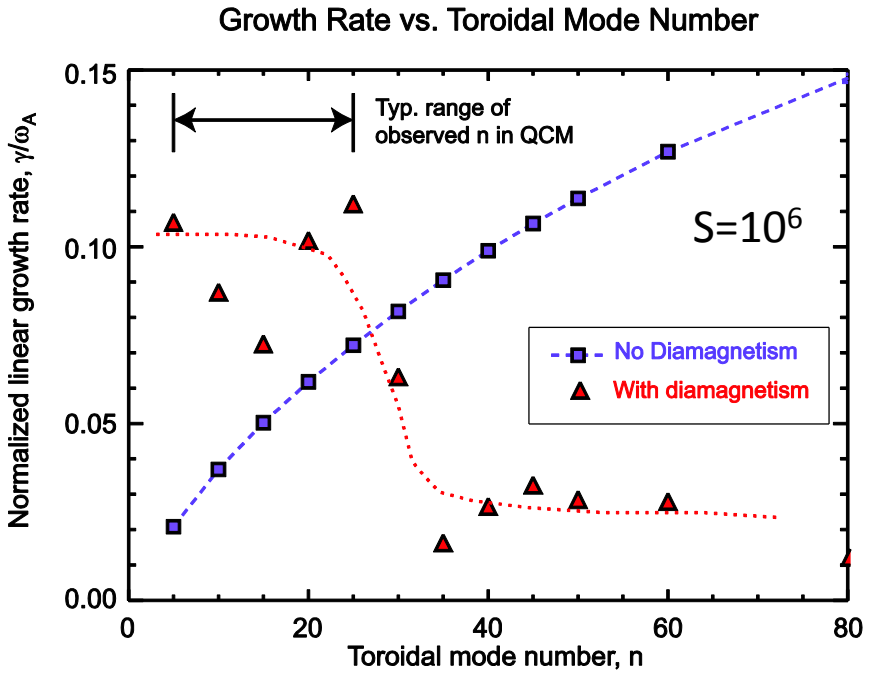
Stability window significantly reduced in *differently shaped* ELMy target



BOUT++ simulation finds edge resistivity important for stability in *EDA H-mode*

- BOUT++ is an initial value code capable of calculating non-linear fluid edge turbulence → can investigate effects of resistivity, diamagnetism on pedestal stability
  - EDA H-mode found ideally stable, but increased η increases linear growth rates
  - Diamagnetism stabilizes higher n modes





E. Davis, P11 today

Additional effort needed to understand turbulence and transport in EDA pedestal

- BOUT++ results suggestive of resistive ballooning modes with 5<n<25 being a dominant pedestal relaxation mechanism in the EDA H-mode
- Would be consistent with empirical observations
  - QCM activity favored by higher ν^*, q, m_i
  - EDA can sometimes be "burned through" at high power to yield ELMs → transition to ideal instability
- Analysis of fully non-linear calculations with BOUT++ is ongoing: fully developed turbulence and flux drive computable

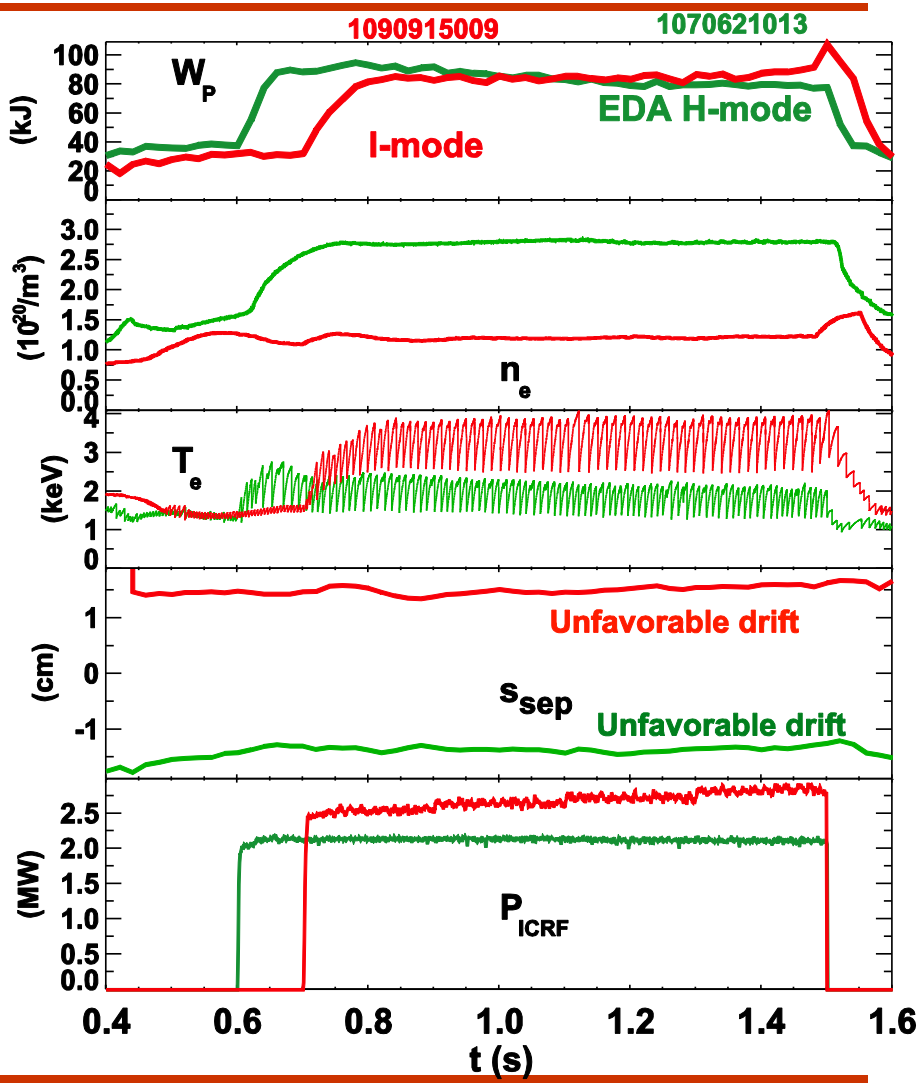
- *Improved understanding of pedestal stability, turbulence-driven transport → an EPED-like model for pedestal structure in ELM-suppressed H-mode?*

- Simulations of EDA H-modes with additional codes (SOLT, 2DX, M3D) are being pursued
  - e.g. D. Russell, Thurs PM Edge-IV

I-mode regime: an ELM-suppressed regime with reduced collisionality

- I-modes at similar parameters to EDA H-modes can have *higher T, lower density, similar stored energy*
- Stationary!

- EDA: QCM provides particle + impurity transport to regulate pedestal, but does not fully relax the density pedestal*
- In I-mode, particle transport is sufficiently high that density barrier never forms



*Greenwald, Fusion Sci. Technol. **51** 266 (2007); Hughes, Fusion Sci. Technol. **51** 317 (2007)

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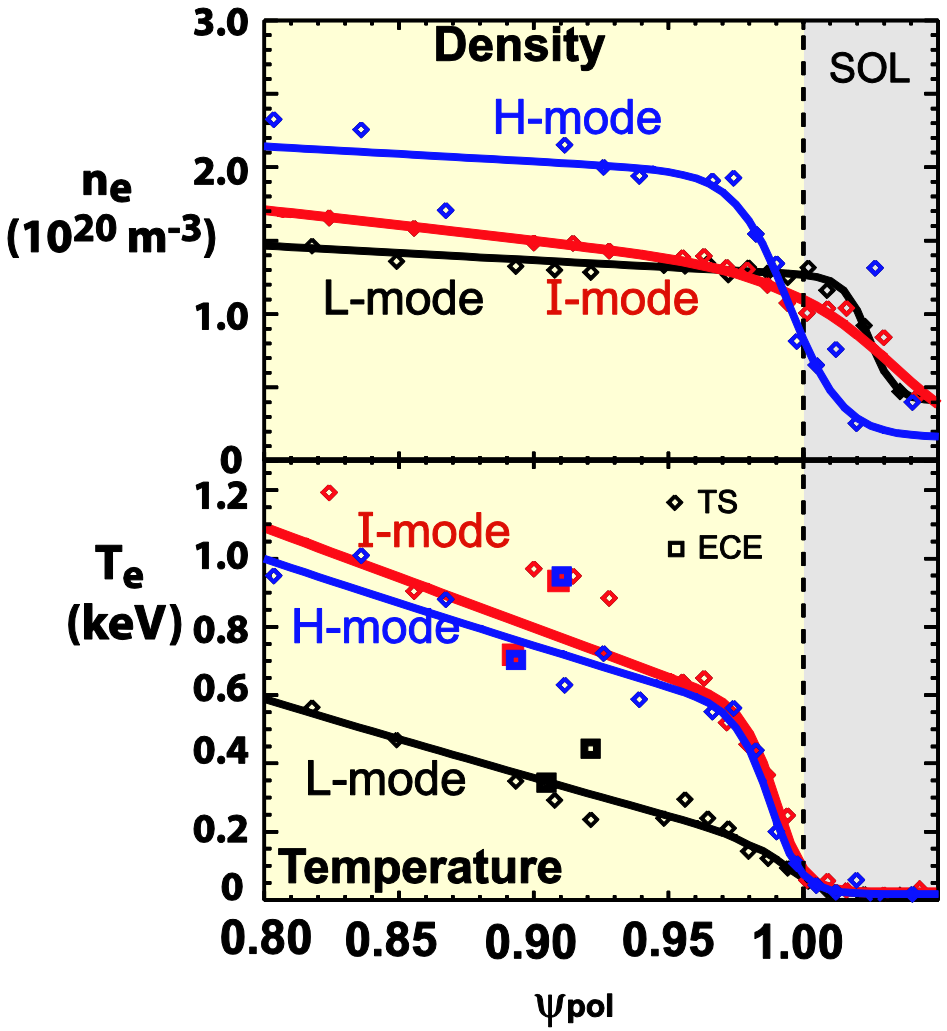

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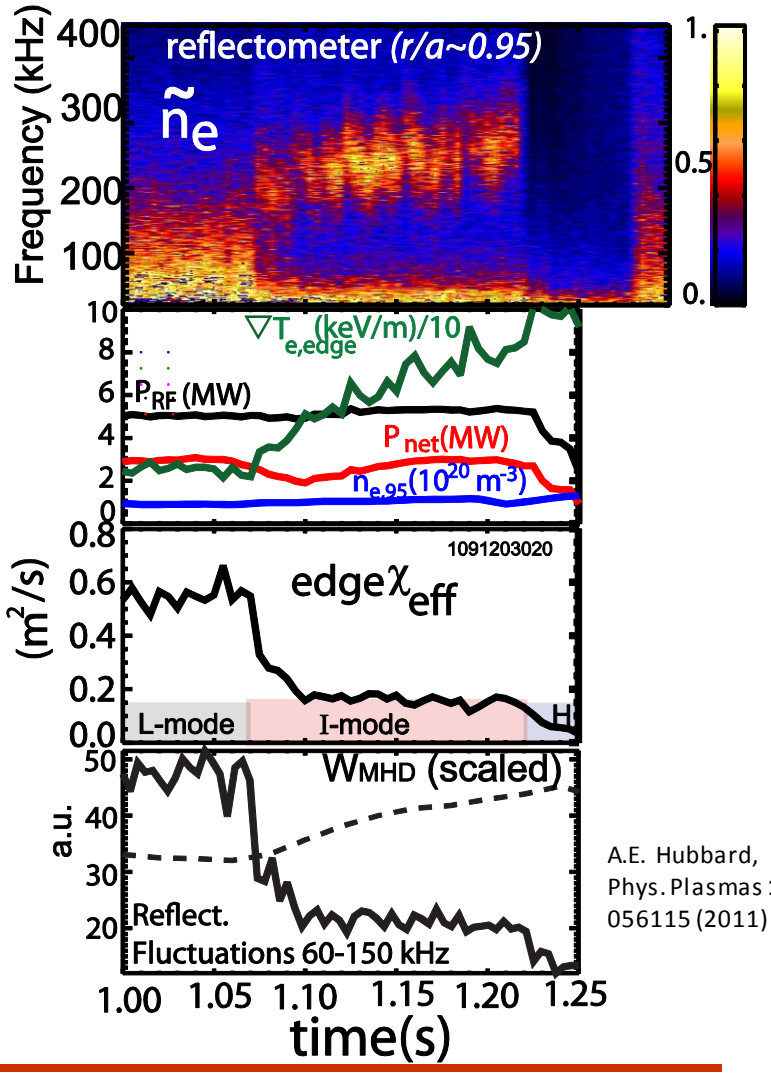
I-mode pedestal associated with *selective* turbulence suppression

- L→I transition associated with simultaneous drop in pedestal χ_{eff}, mid-f turbulence. (~60-150kHz)
- Persistent turbulence at ~200—300kHz = weakly coherent mode (WCM)
  - n~10—25 , k_{pol}~1.5cm
  - Significant $\tilde{n}$, $\tilde{B}$; $\tilde{T}/T = 1 - 2\%$
  - Fluctuations: White, P18, Tues.
- I-mode particle/impurity transport remains at L-mode levels
- Does WCM regulate the particle transport?



A.E. Hubbard, Phys. Plasmas **18** 056115 (2011)

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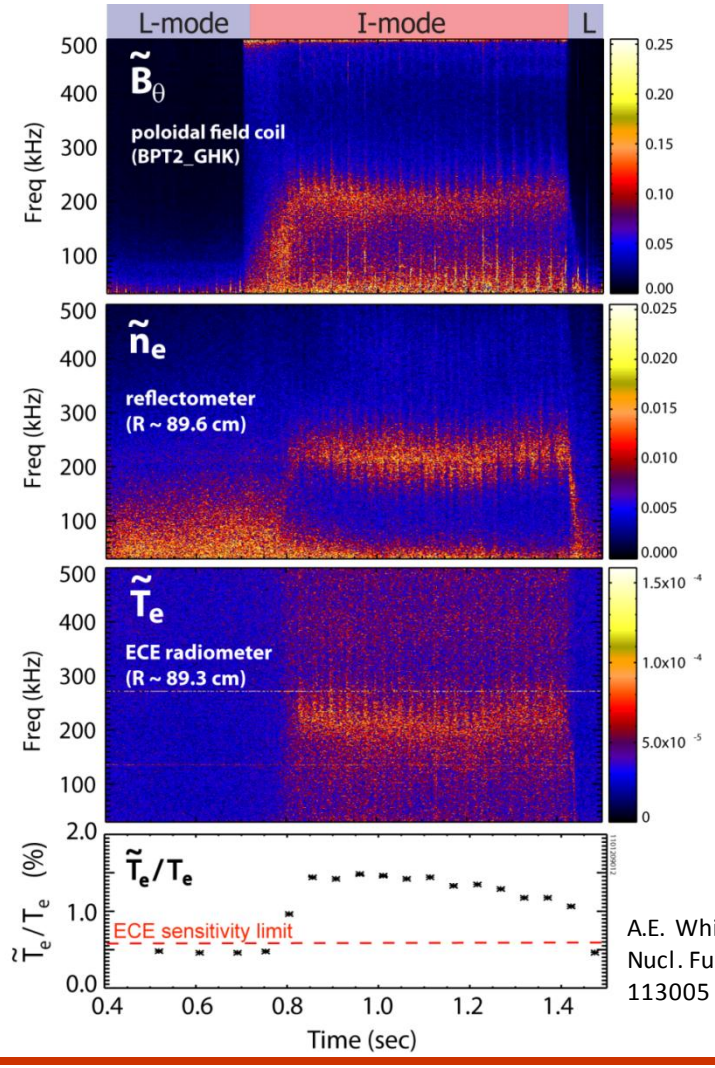

A.E. White, Nucl. Fusion **51** 113005 (2011)

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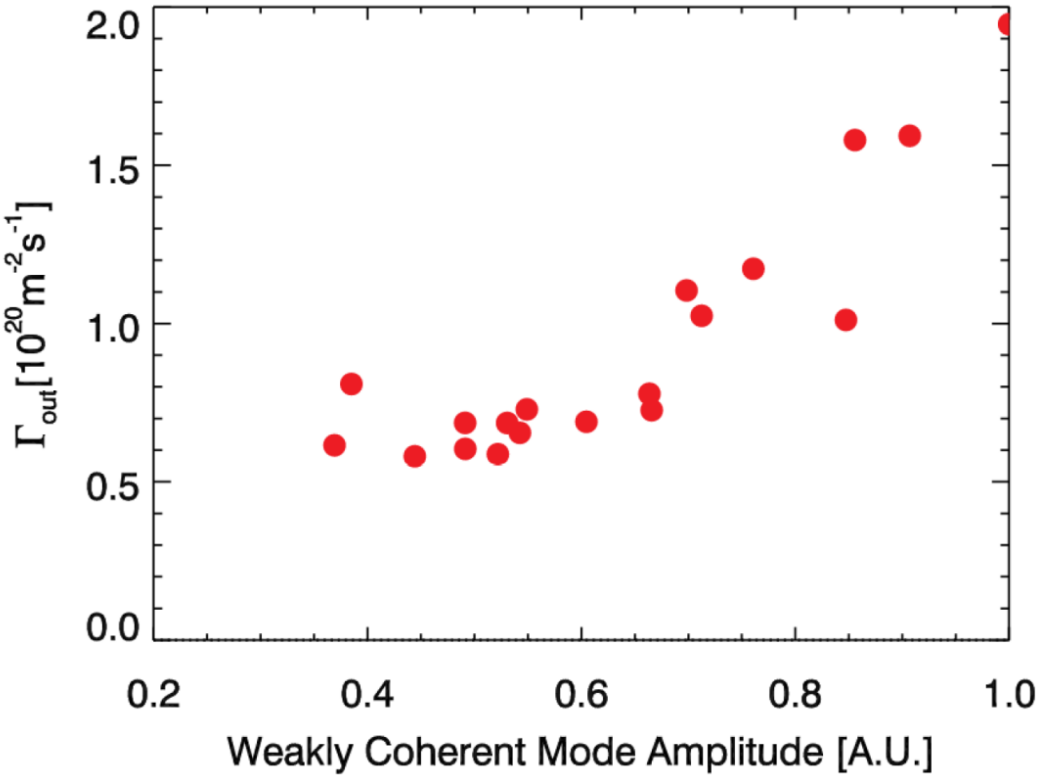
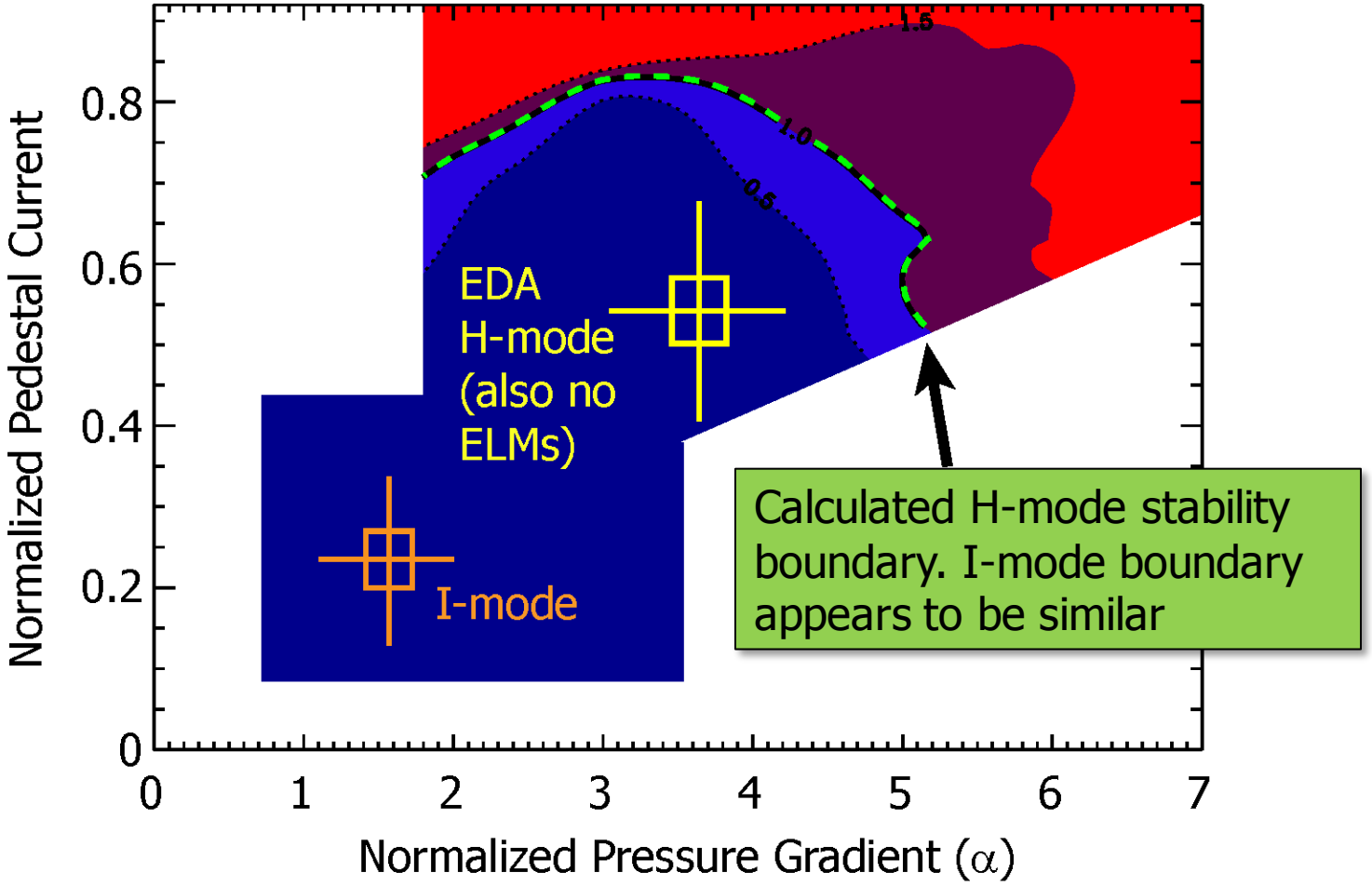


Increase in radial particle flux correlates strongly with WCM mode amplitude from reflectometry

A. Dominguez, paper in progress

- Does WCM regulate the particle transport? Evidence: *YES*

I-mode pedestals maintained well below peeling-ballooning stability boundary



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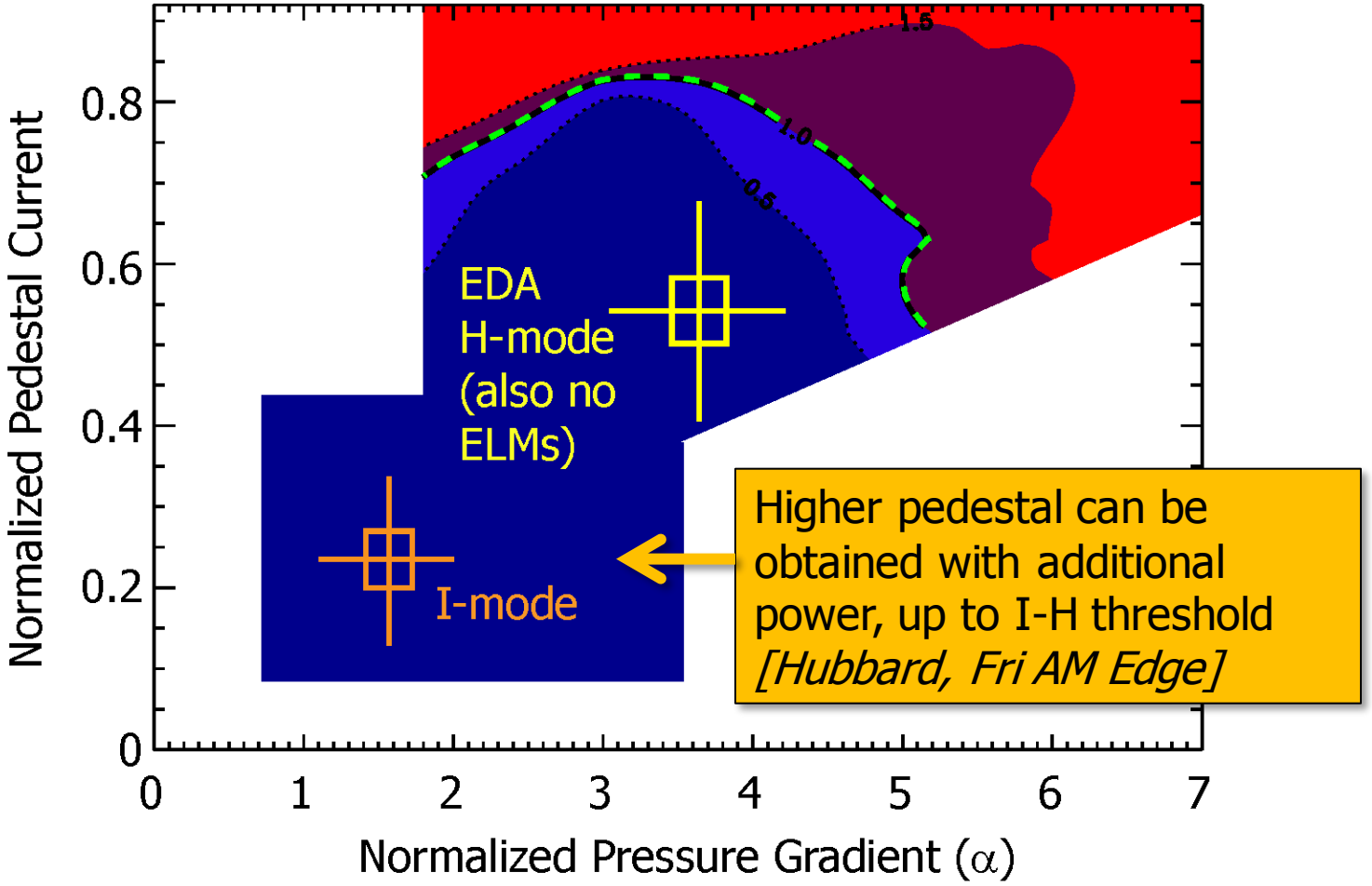

Key results and *plans* (I)

- Tests of EPED model successfully extended using C-Mod ELMy pedestal data
  - Pedestal scalings agree with expectations from limits imposed by mix of KBMs, PBMs
  - *New experiments are proposed to study inter-ELM evolution, seek signatures of KBM in fluctuations*

- Linear peeling-ballooning mode calculations show proximity to stability boundary in ELMy discharges, operation in stable region in EDA H-mode, I-mode
  - Need an understanding of what limits pedestal growth in absence of ELMs

- BOUT++ resistive calculation yields finite linear growth rates and shows promise of capturing QCM physics

Key results and *plans* (II)

- I-mode: documented reductions in pedestal thermal transport while maintaining L-mode levels of particle/impurity transport
  - Correlated with clear changes in edge turbulence $\tilde{n}$, $\tilde{B}$, $\tilde{T}$
  - *New information coming to light about WCM fluctuations: amplitude, phase velocity, poloidal distribution*
  - *May be a good candidate for simulation with GK codes (large L_n, low ν^*)*
- *Non-linear simulations with BOUT++, M3D are ongoing for EDA, planned for I-mode → guide understanding of fluctuation origin, turbulence-driven transport*
- *Ongoing: pedestal control and attainment of benign edge relaxation*
  - Pedestal modification using RF tools [Hughes, NF 2010]
  - Direct drive with short wavelength MHD antenna ("shoelace" antenna): first results in 2012

C-Mod is a unique and essential component of US pedestal research effort

- Novel pedestal regimes which provide high confinement with ELMs *naturally mitigated or fully suppressed*
- A *powerful diagnostic set* is in place for measuring high-resolution plasma profiles, pedestal/edge turbulence
- Auxiliary systems being implemented for *active pedestal control*
- *Engaged with theory and modeling community* to understand the physics governing pedestal transport and microstability → generic predictive capability