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.

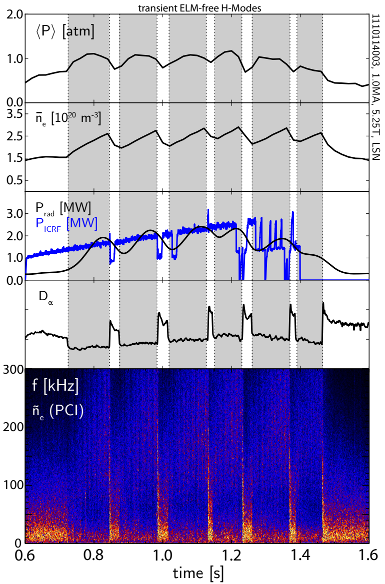
The solution?

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

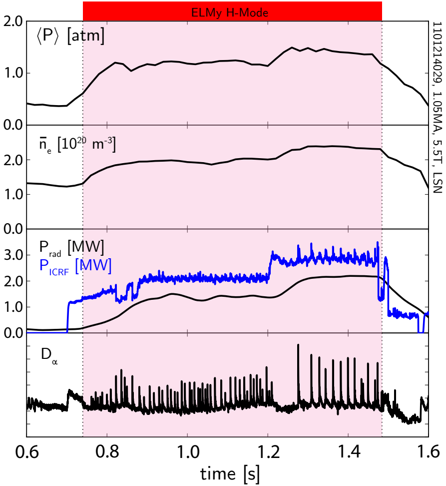


so, we need:

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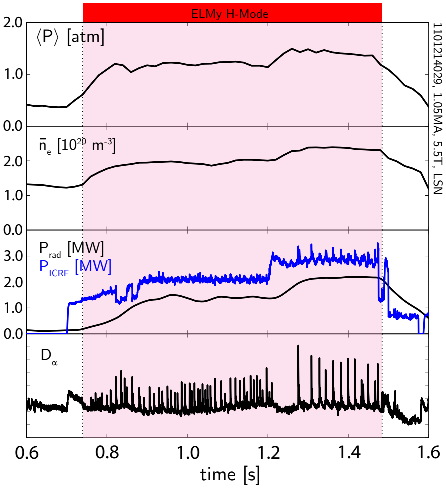
- large ELMs drive pulsed heat loads in excess of plasma-facing material tolerances



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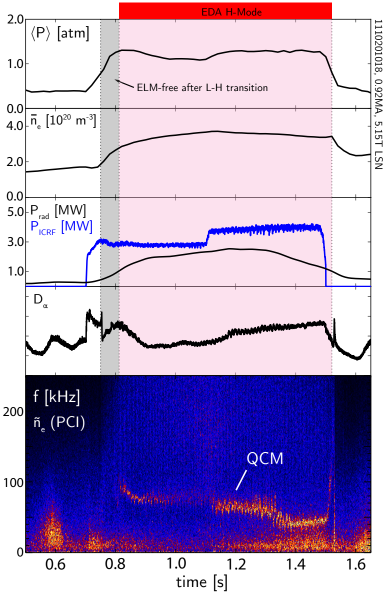
- high energy confinement
- low particle confinement (low enough, at least)
- avoid, mitigate, or suppress large ELMs
  - engineering solutions:
    pellet pacing, resonant magnetic perturbations
  - physics solutions:
    pedestal regulation by fluctuations below ELM limit

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)

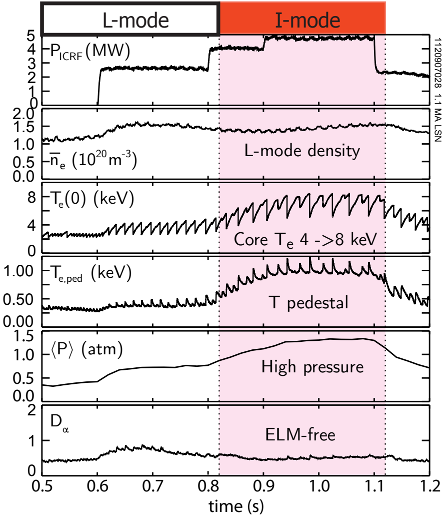
A number of fluctuation-regulated regimes have been observed:

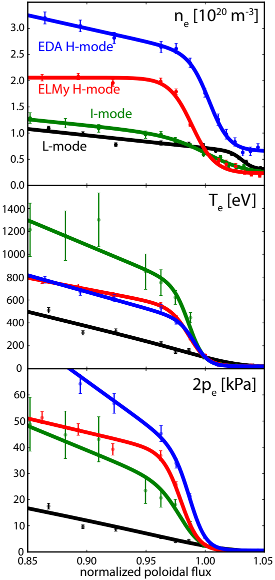
- EDA H-mode – Quasi-Coherent Mode (QCM) – C-Mod, AUG(?)
- Quiescent H-mode – Edge Harmonic Oscillator (EHO) – DIII-D, JET, AUG
- type-II, -III ELMy H-modes – various

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)

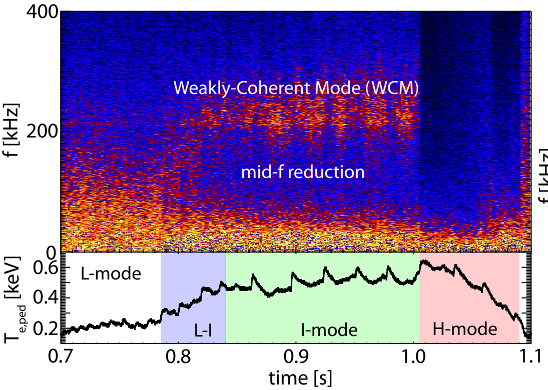
Can we do better?

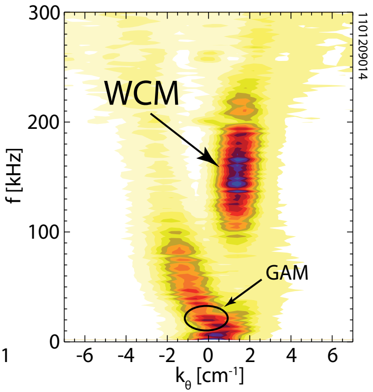
A challenger appears: the I-mode



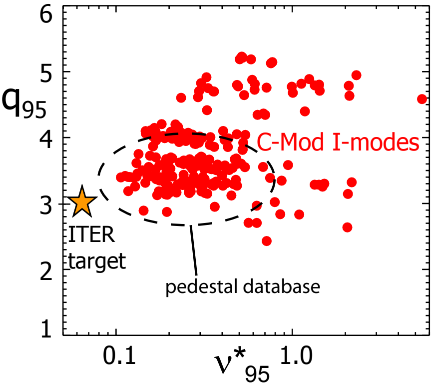


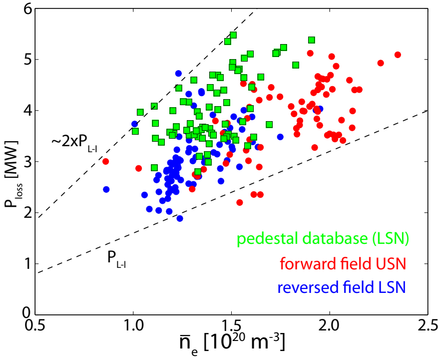
I-mode pedestal regulated by Weakly-Coherent Mode (WCM)





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

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