H-mode and ELM Studies at Near-Unity Aspect Ratio

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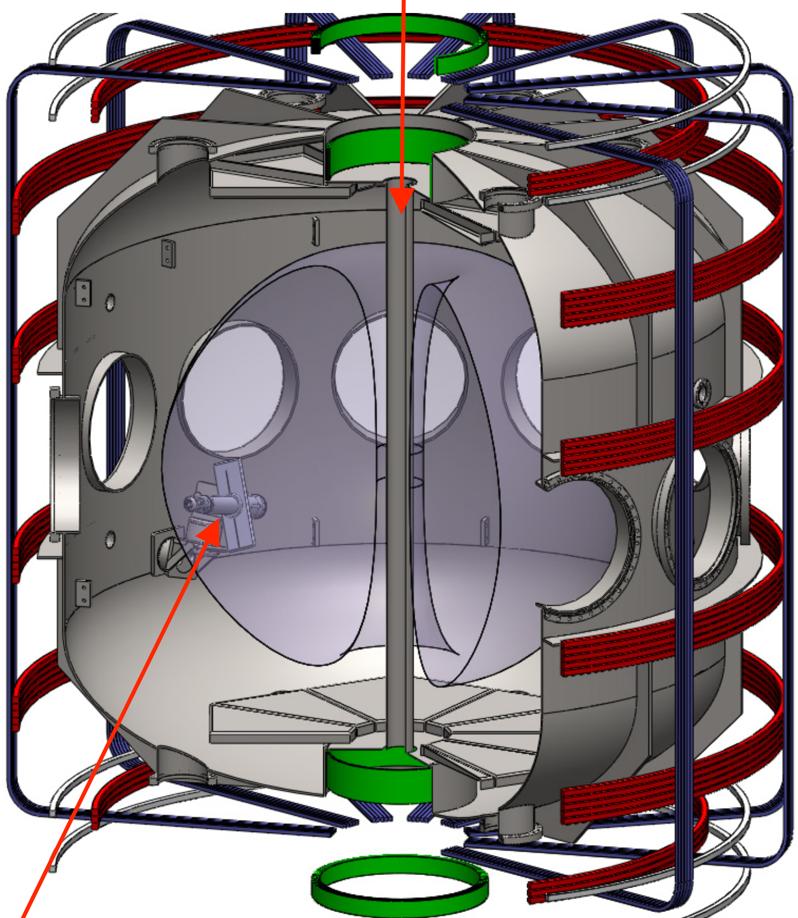
PEGASUS Toroidal Experiment

Studies Across Physics Regimes Are Crucial to Understanding H-mode and ELM Physics

- H-mode at low-*A* has similarities, differences with high-*A*
  - Important for testing, validating theories of H-mode and ELM behavior
- H-mode is readily attainable at *A* ~ 1
  - Low P_{LH} → OH access
- Some features are common between STs and ATs
  - Standard signatures seen
  - Improved confinement: $H_{98} \sim 1$
- Other characteristics differ with *A*
  - P_{LH}
  - ELM magnetic structure

PEGASUS is a Compact, Ultralow-*A* ST



Experimental Parameters

A	1.15 – 1.3
R (m)	0.2 – 0.45
I_p (MA)	$\leq$ 0.25
B_T (T)	< 0.2
Δt_{shot} (s)	$\leq$ 0.025

Major research thrusts:

- AT physics at small aspect ratio
- Non-inductive startup and growth

Recent upgrades for H-mode studies:

- HFS fueling
- New external divertor coils
- Radial field coils
- Edge current injection startup (LHI) for MHD control (future)

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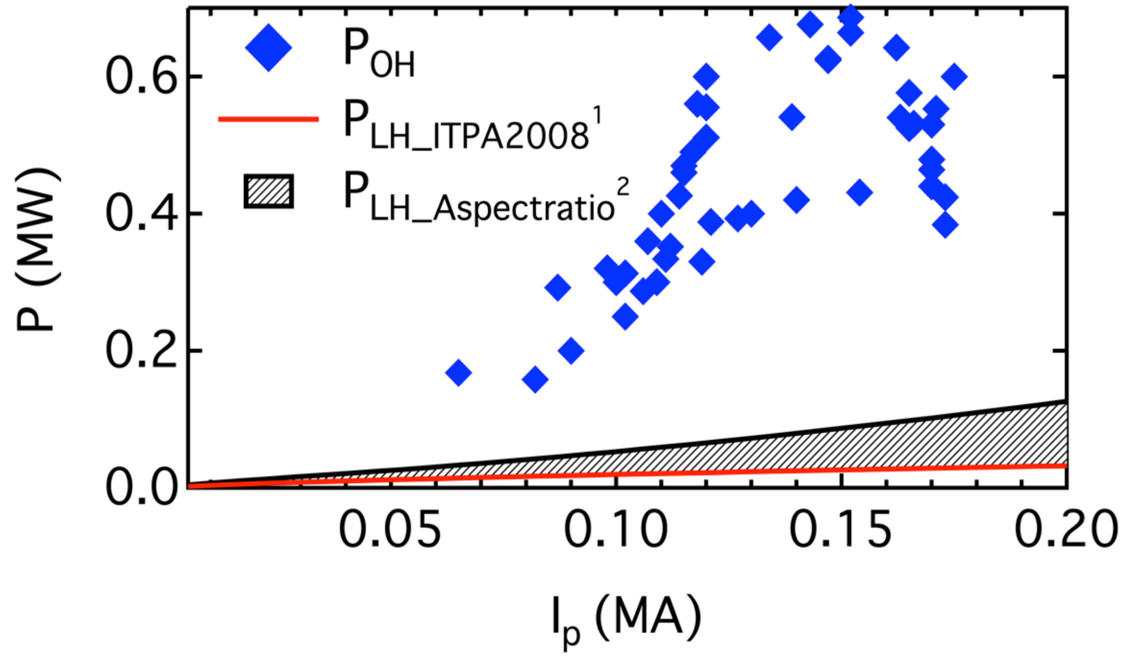
H-mode Readily Accessible at Near-Unity *A*

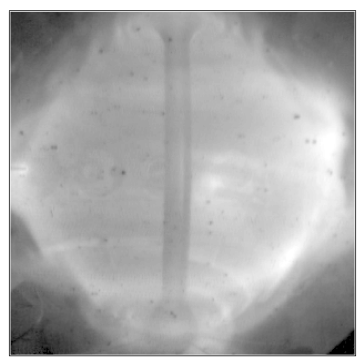
- $A \approx 1 \rightarrow$ low $B_T \rightarrow$ low P_{LH}

$$P_{LH} \sim n_e^{0.717} B_T^{0.803} S^{0.941}$$

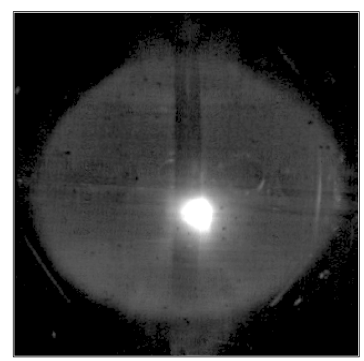


- H-mode achieved
  - HFS fueling
    - Similar to other STs
  - Limited or diverted plasmas

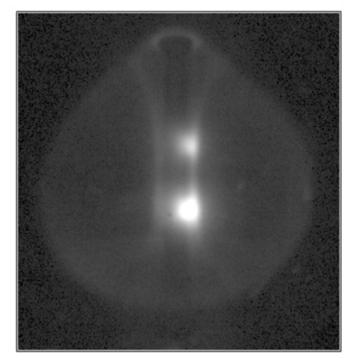
Limited L



Limited H



Diverted H



Fast visible imaging, $\Delta t \sim 30\ \mu s$

[1] *Journal of Physics: Conference Series*, **123**, 012033 (2008).
[2] *Plasma Phys. Control. Fus.*, **46**, A227 (2004).

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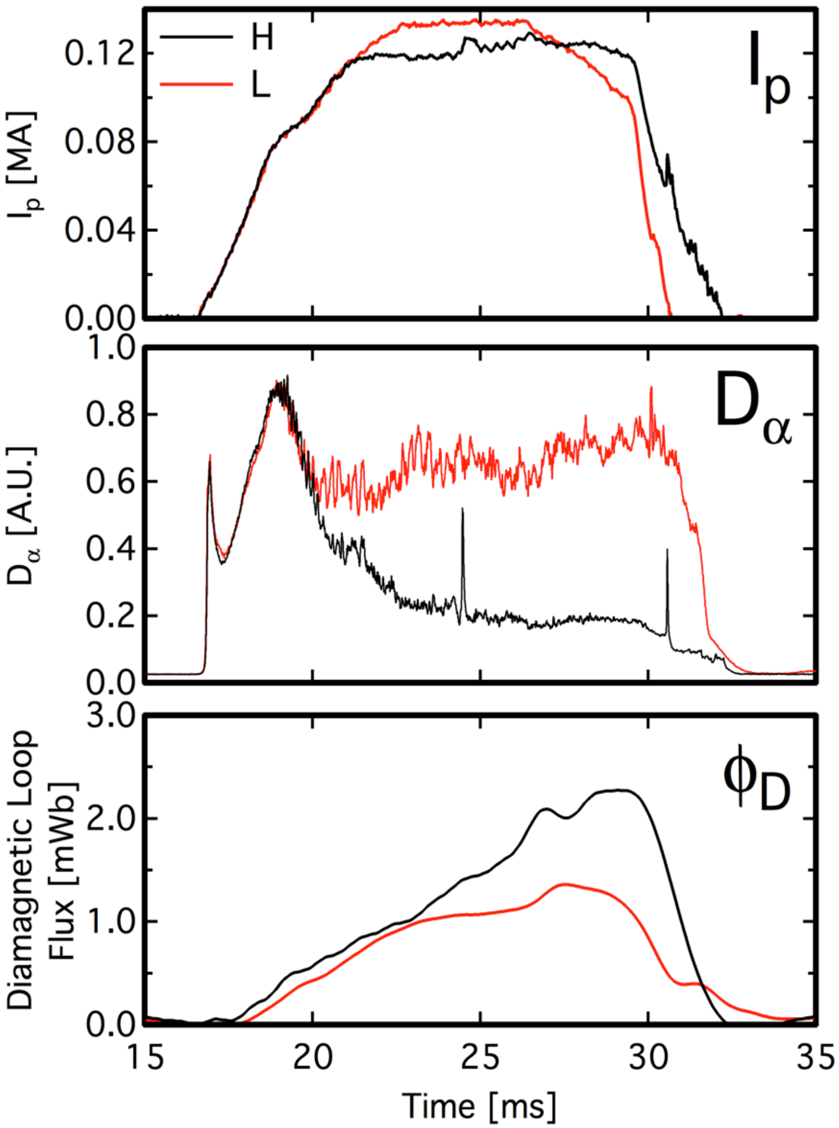
Standard Signatures in OH H-mode Plasmas

- Quiescent edge
  - Edge current and pressure pedestals
- Reduced D_α
- Large and small ELMs
- Bifurcation in ϕ_D
  - At $A \sim 1$, indicates current redistribution

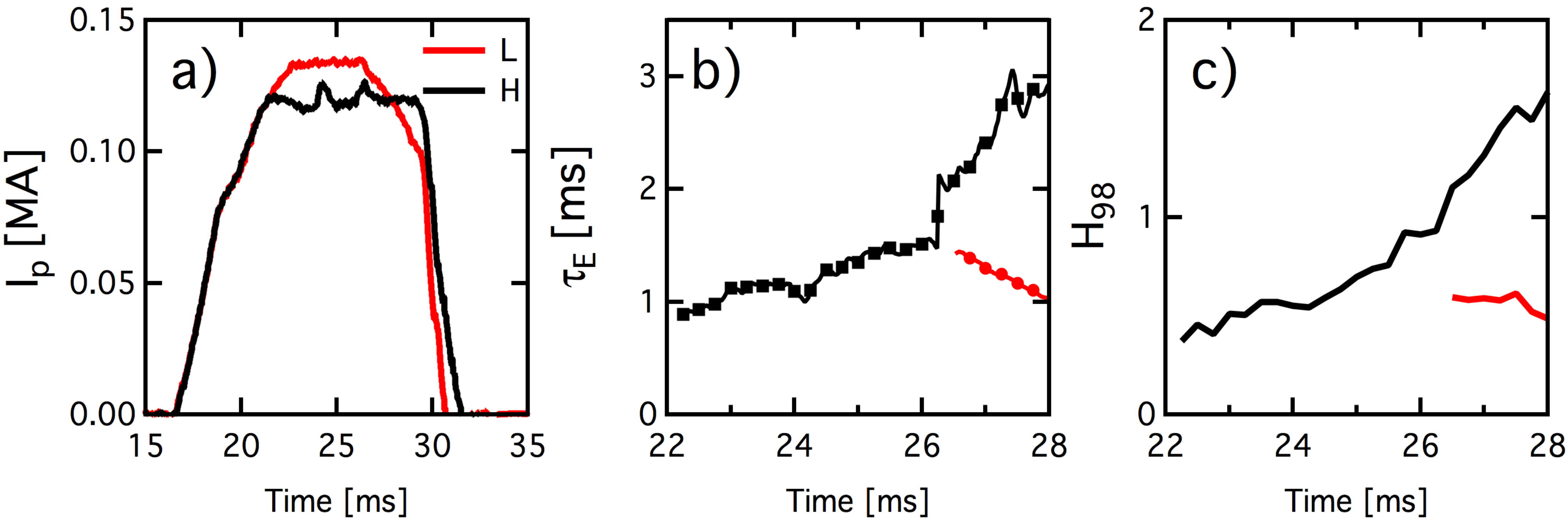


Energy Confinement Improves in H-mode

- τ_E from time-evolving magnetic reconstructions

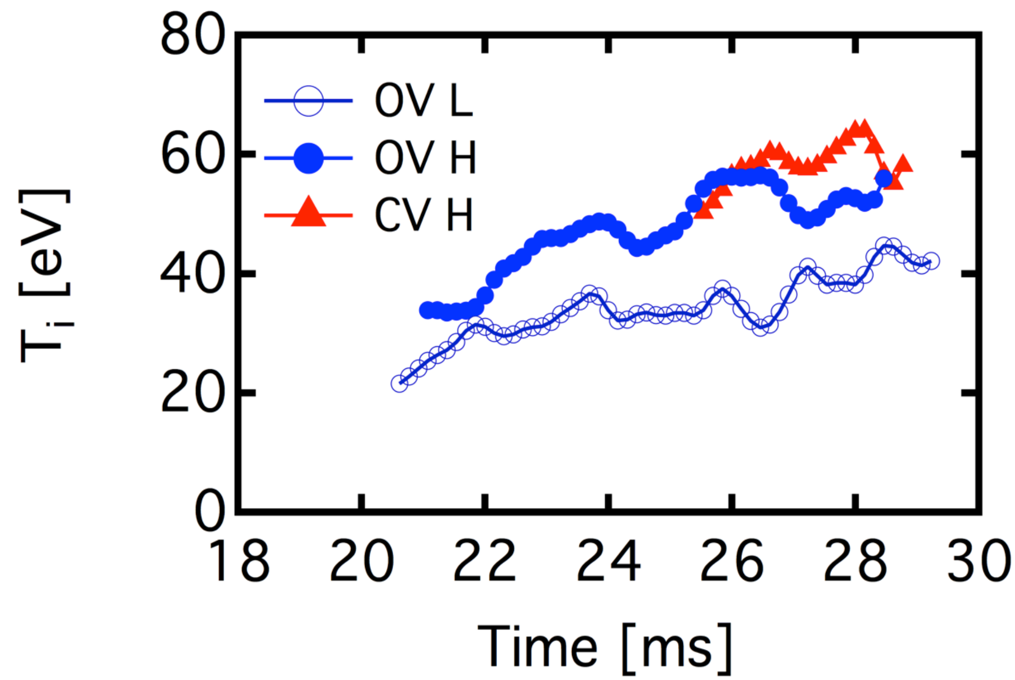
- H-mode: τ_E increases throughout
  - No transport equilibrium — short pulse

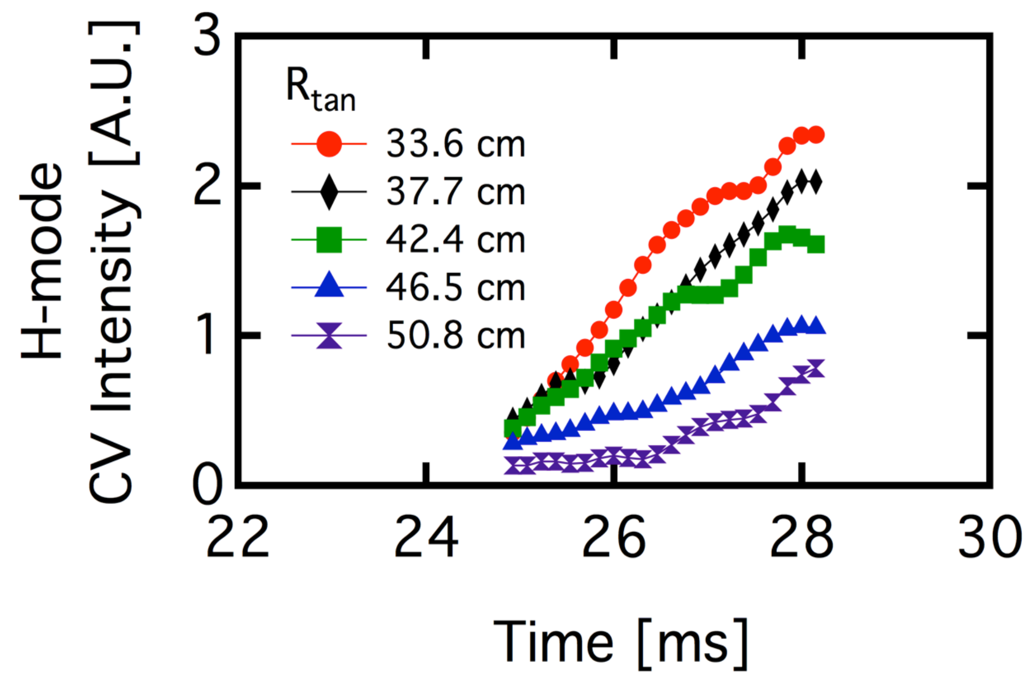
	τ_E (ms)	H_{98}
L-mode	1.5	0.5
H-mode	3	>1



T_i and T_e Increases Indicated in H-mode

- OH plasmas: $T_i << T_e$
- Impurity T_i doubles
- Increasing $T_e(0)$ indicated
  - Increasing, peaking CV emission
  - Preliminary Thomson scattering
    - L-mode: $T_e(0)$ ~ 160 eV
    - H-mode: $T_{e\_H}(0) > T_{e\_L}(0)$





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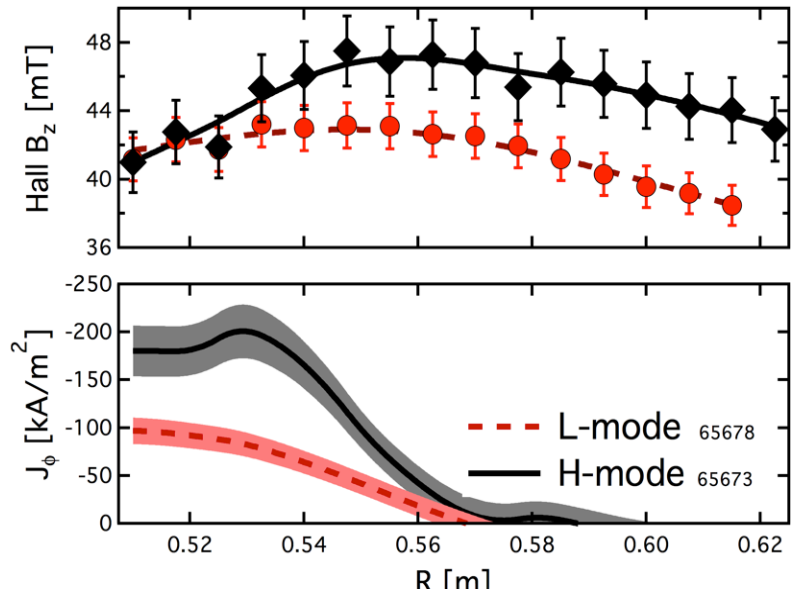
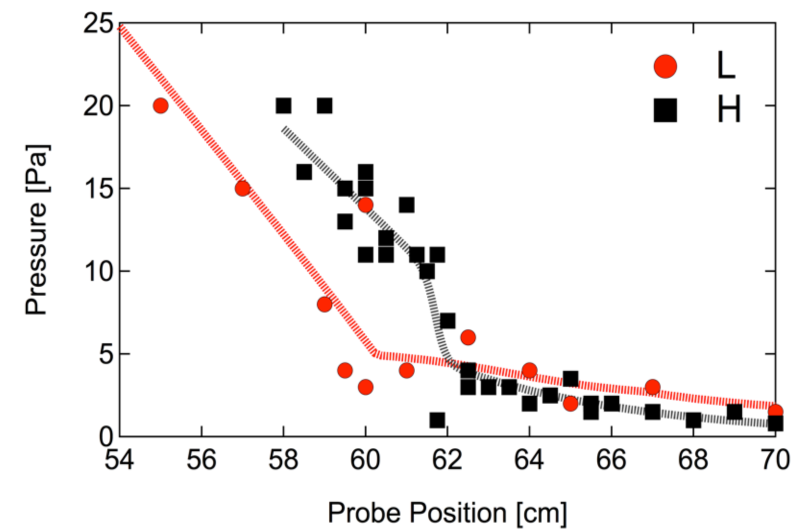
Edge Pedestals Measured with Probes

- Current pedestal observed
  - Measured with Hall Probe array



- Preliminary Langmuir probe scans indicate pressure pedestal
  - Single-point, multi-shot profile
  - Some edge distortion present from MHD



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[1]PRL **107**, 035003 (2011).

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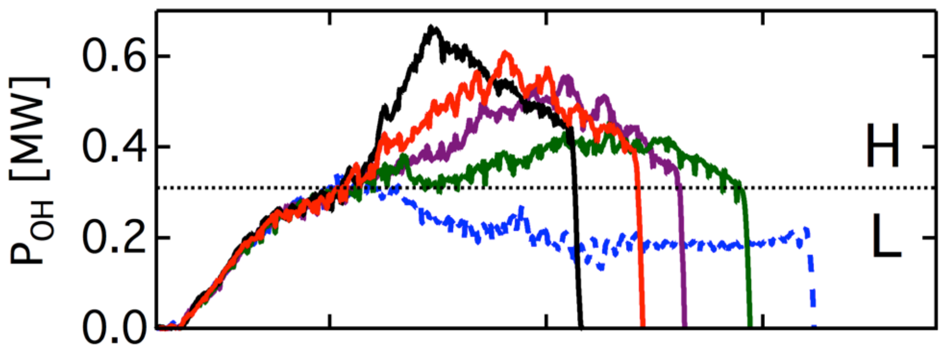
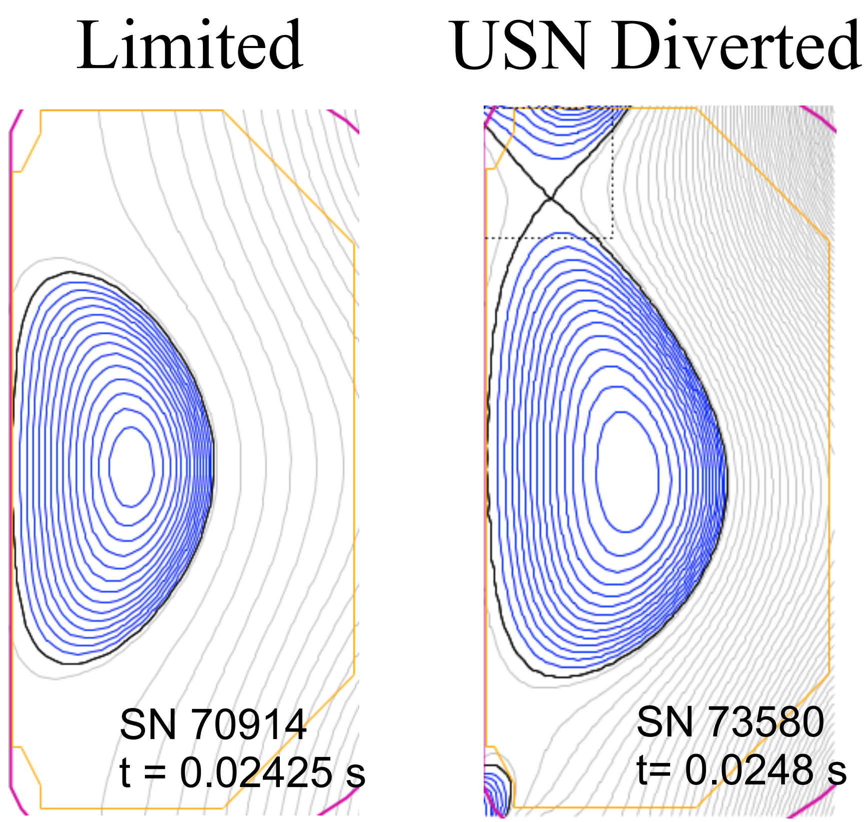
P_{LH} Measured in Limited & Diverted Plasmas

- P_{LH} from varying P_{OH}
  - Transition time from ϕ_D bifurcation
  - Wide parameter range
    - P_{OH} = 0.1 – 0.6 MW
    - n_e = 0.5 – 4x10^{19} m^{-3}
    - Limited: Centerstack
    - Diverted: USN (favorable ∇B)

- $P_{LH\_exp} = P_{OH}$ - dW/dt
  - dW/dt by magnetic reconstruction
  - ~ 30% correction

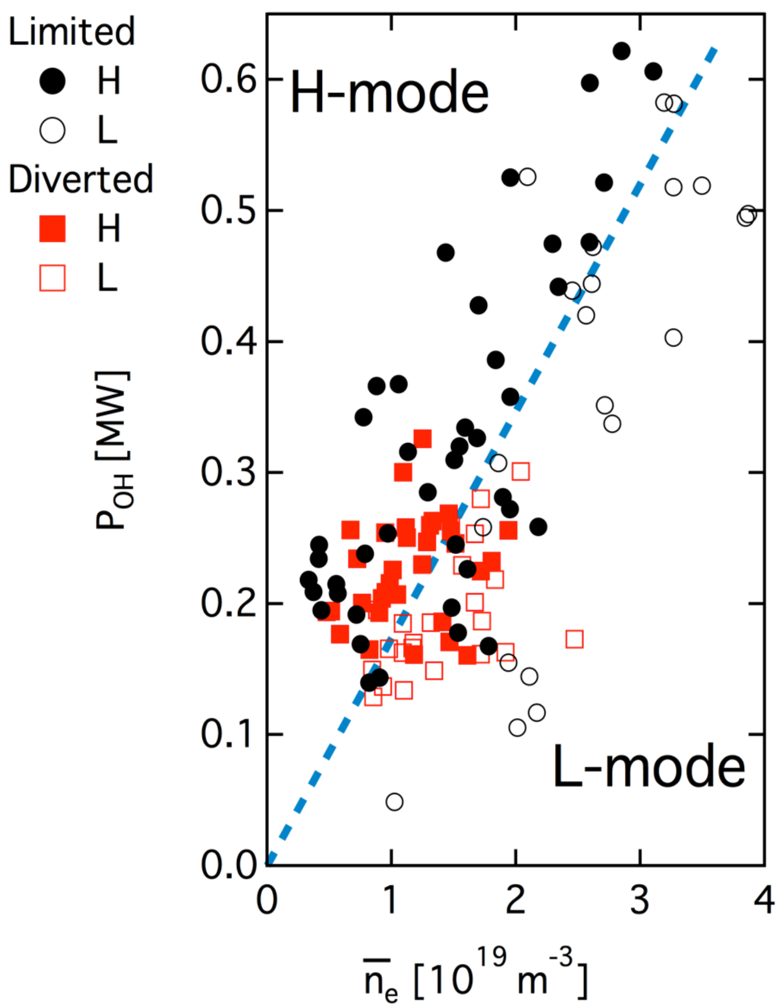




P_{LH} Shows Strong Density Dependence

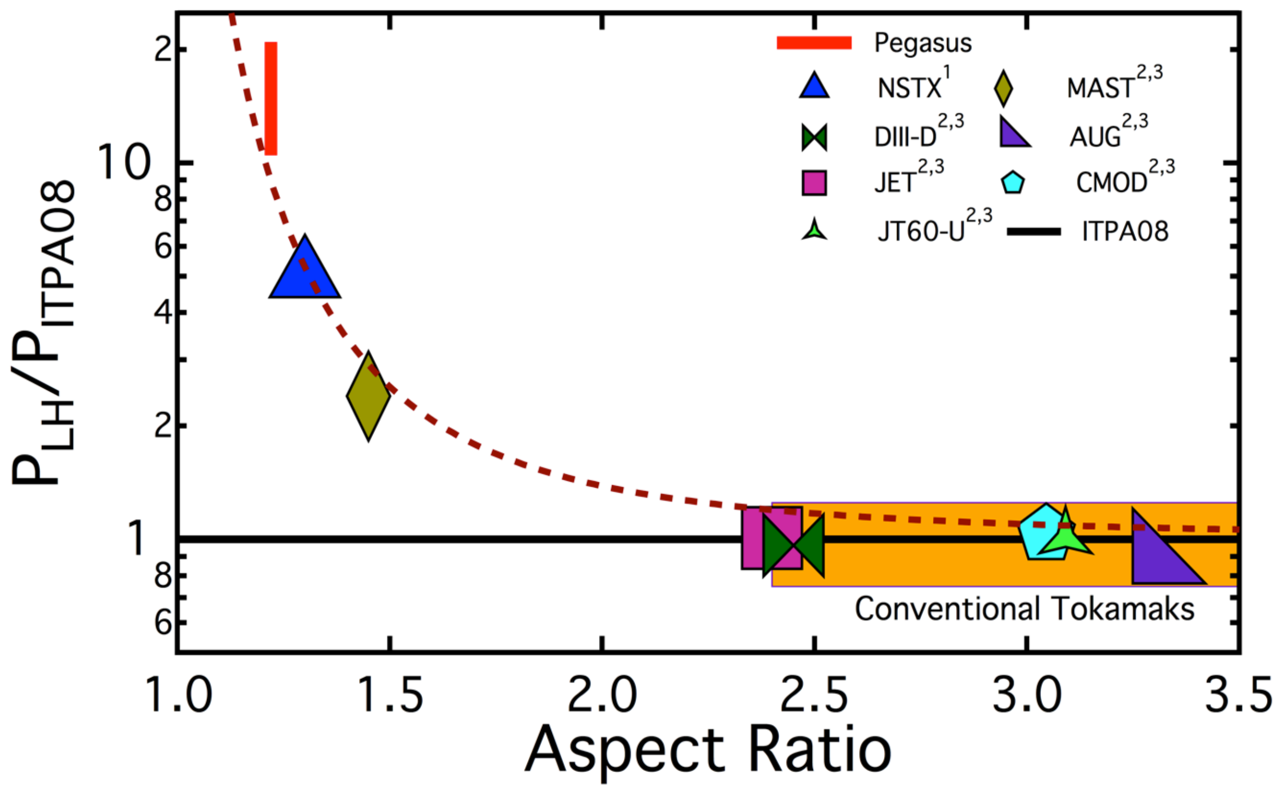
Threshold Power vs. Density

$$P_{LH\_exp} \approx 0.7 P_{OH}$$



- No observed density minimum in this operational range
- No difference between diverted P_{LH} and limited P_{LH}
  - Note: generally similar topology: *e.g.* $q_{lim}(\psi) \approx q_{div}(\psi)$

At low A, $P_{LH} >> P_{ITPA08}$



- P_{LH} increasingly diverges from expectations as $A \rightarrow 1$
- Discrepancy in comparison to ITPA scalings not yet explained

[1] *Nucl. Fusion,* **50**, 064010 (2010).
[2] *Journal of Physics: Conference Series*, **123**, 012033 (2008).
[3] Tokamaks, 4th ed. (2011), p 630

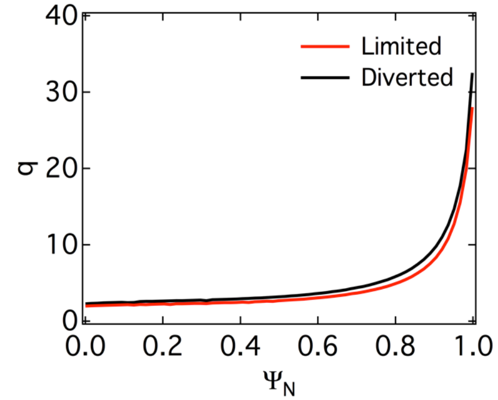
FM^3 Model Consistent with PEGASUS Results

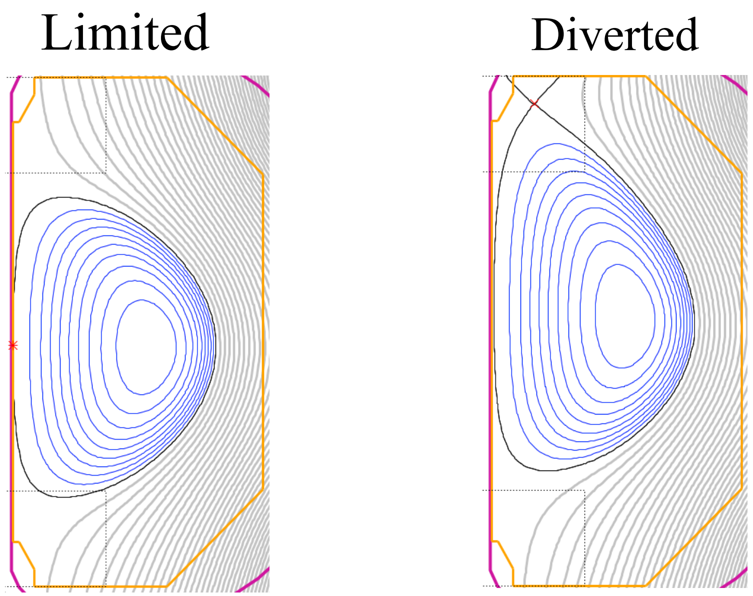
- Predicts P_{LH} minimum for PEGASUS at n_e ~ 1 x10^{18} m^{-3}
  - Below operational space
- P_{LH} topology independence: self-similar q profiles at *A* ~1

$$\frac{P_{L-H}^{lim}}{P_{L-H}^{div}} \approx \left(\frac{q_*^{lim}}{q_*^{div}}\right)^{-7/9} \quad \begin{matrix} >>1 \ @ \ A\sim3 \\ \rightarrow 1 \ @ \ A\sim1 \end{matrix}$$

- Model does not explain strong P_{LH} dependence on *A*
  - Multi-Machine P_{LH} Studies Proposed (NSTX-U, DIII-D, PEGASUS)

Predictive Equilibrium @ $A \approx 1.2$





[1] Fundamenski W., Militello D., Moulton D., McDonald D.C., Nucl Fusion **52**, 062003 (2012).

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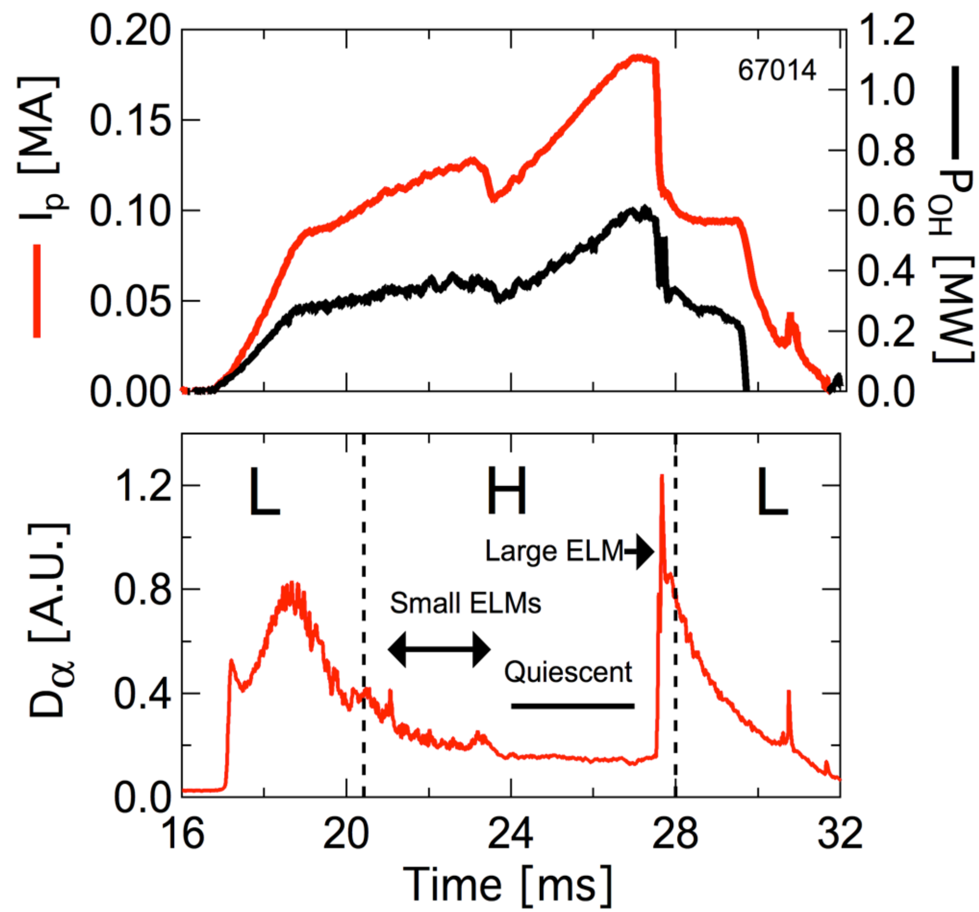
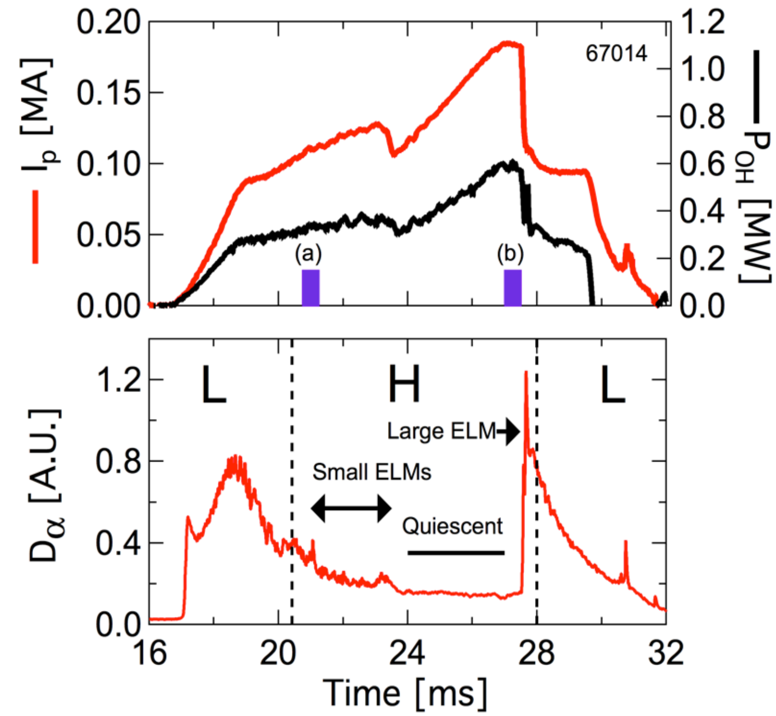
Small and Large ELMs are Seen

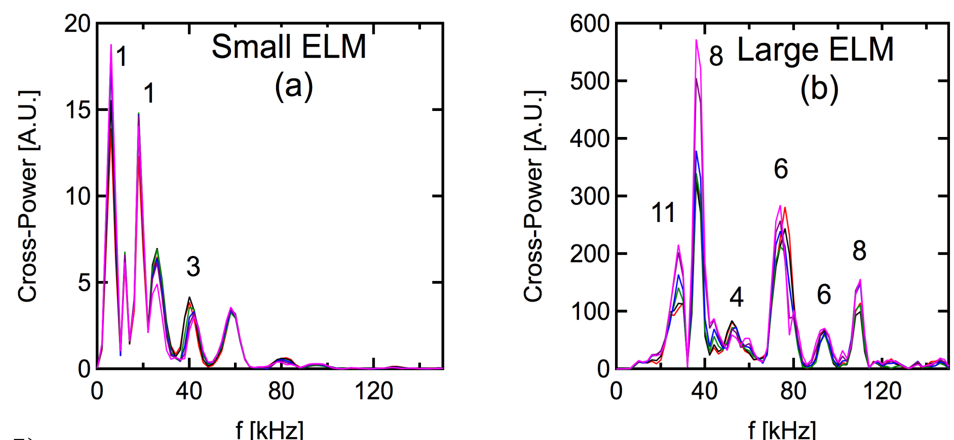
- Small ("Type III") ELMs ubiquitous, less perturbing
  - $P_{OH} \sim P_{LH}$
- Large ("Type I") ELMs infrequent, violent
  - $P_{OH} >> P_{LH}$
  - Can cause H-L back-transition
- Filament structures observed
  - Coincident with D_α bursts



Small ELM Magnetic Structure Varies with *A*

- Type III: *A* dependent
  - $A \leq 1.4$: $n \leq 1 - 3$
    - Pegasus and NSTX
    - Increased peeling drive at low *A* (higher J_{edge}/B)
  - $A \sim 3$: $n > 8$
- Type I: *A* independent
  - Intermediate-n, $n \sim 4 - 12$
  - Low and high-*A* similar





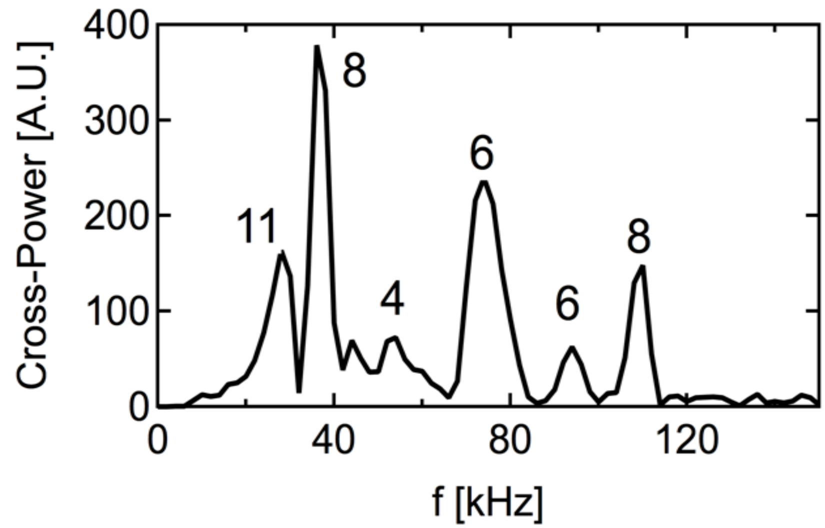
[1] Nucl. Fusion **45**, 1066 (2005).
[2] Nucl. Fusion **38**, 111 (1998).
[3] Nucl. Fusion **52**, 609 (2004).

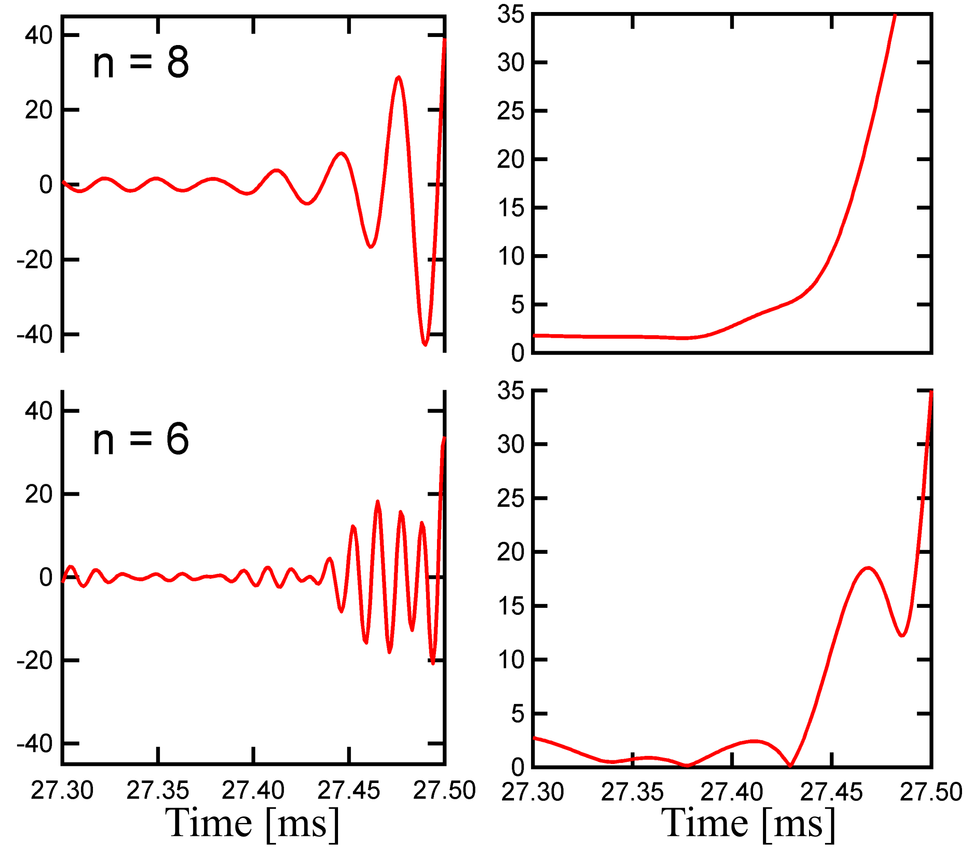
Nonlinear ELM Precursors Observed

- Measured with near-edge magnetics probe

- Magnetic signature of ELMs have multiple n components
  - Simultaneously unstable modes

- Modes show different time evolutions
  - n = 8 grows continuously
  - n = 6 fluctuates prior to crash





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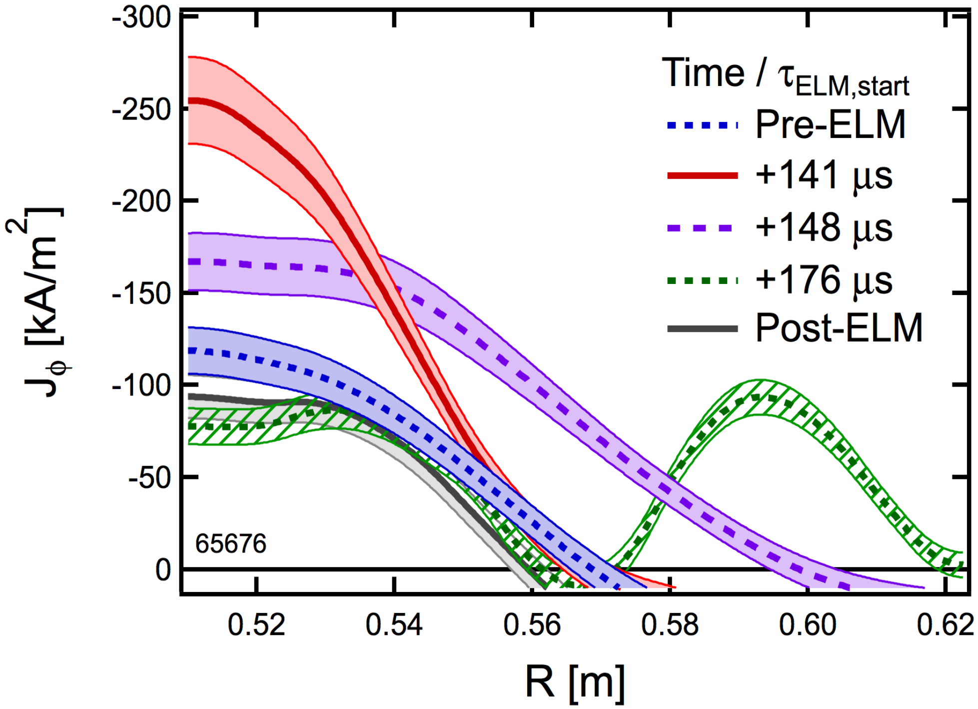
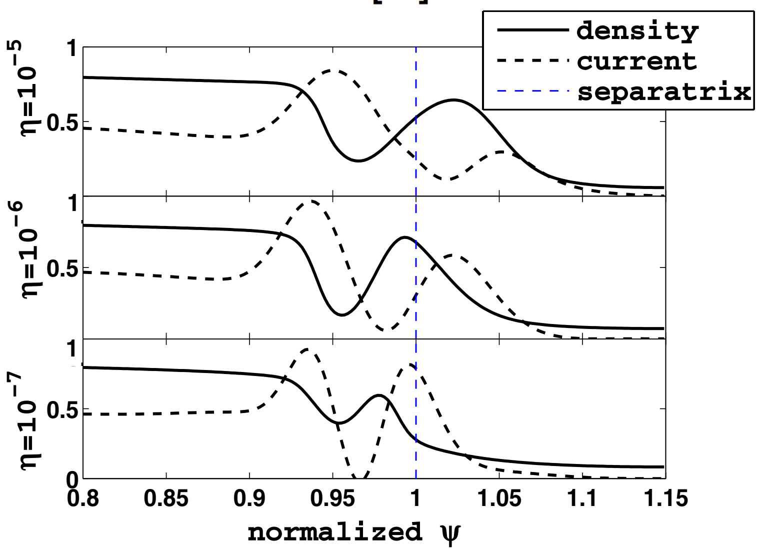
Large ELM J_{edge}(R,t) Dynamics Measured Throughout Single ELM Cycle

- Complex J_{edge}(R,t) evolution
  1) Modest but steep pedestal
  2) Rapid buildup until crash
  3) Collapse: wider pedestal
  4) Current-hole filament ejection
  5) Recovery: After ELM



- J_{edge}(R,t) measurements similar to JOREK MHD[1] simulations



[1] *Plasma Physics Control. Fusion.* **53**, 054014 (2011).

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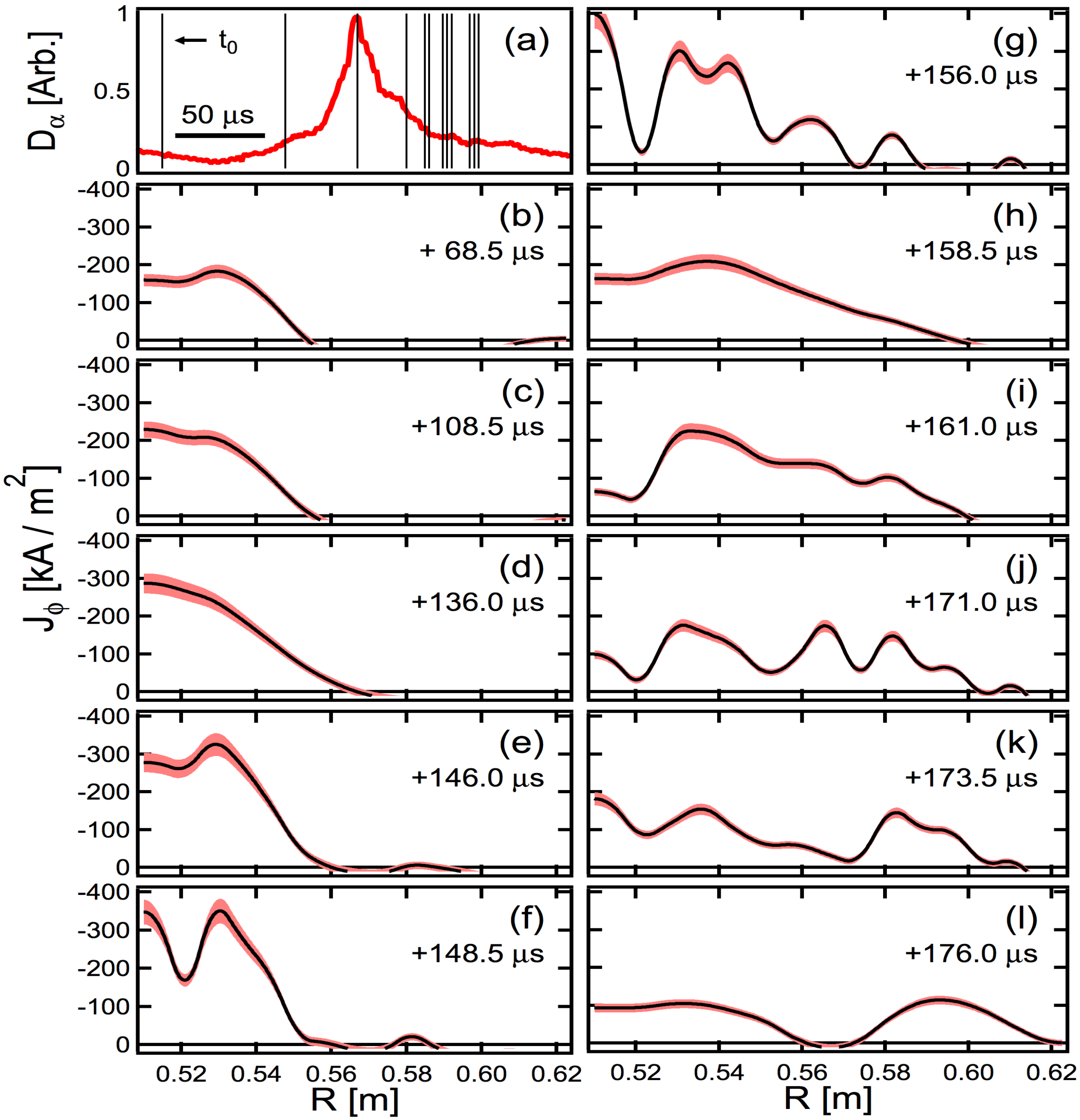
Closer Inspection of J_{edge} Reveals Complex Dynamic Behavior

- $J_{edge}(R,t)$ evolution through ELM cycle shows complex multimodal behavior

- Challenge: study nonlinear ELM dynamics at Alfvénic timescales



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Upgraded PEGASUS Can Provide Access to Nonlinear ELM Studies and H-mode Physics

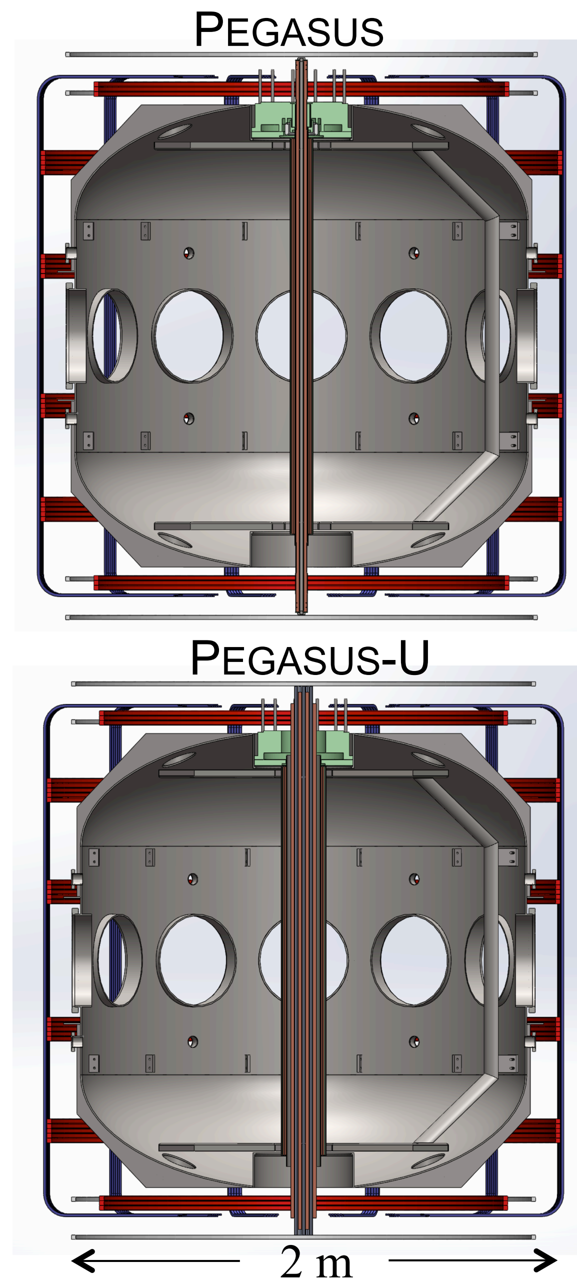
- Unique opportunities for nonlinear pedestal and ELM studies
  - Simultaneous measurements of p(R,t), J(R,t), v_φ(R,t) through ELM cycles
  - Compare to and help validate nonlinear simulations
    - NIMROD, JOREK, BOUT++
- ELM modification and mitigation
  - Vary J_{edge}(r), modify edge v_φ and shear, apply 3D field perturbation via LHI
  - C-pellet injection for tests of models for ELM-pacing (w/ ?)
- Integrating with ELM studies on NSTX-U, DIII-D (BES)

PEGASUS-Upgrade Proposed to Support Study of H-mode and ELMs

- New centerstack assembly
  - B_T increases 2 – 5x
  - $\Delta t_{pulse} \sim 100$ ms
  - V-sec increases 6x (PPPL)
  - Improved separatrix operation

- NSTX-U relevant LHI injector arrays

- Diagnostics: multipoint TS; CHERS via DNB; edge probe arrays



H-mode and ELM Characteristics Show a Strong *A* Dependence

- H-mode achieved in plasma with simple diagnostic access
  - Standard characteristics: pedestal; low D_α; increased τ_e; $H_{98} \geq 1$; etc.
- Features unique to low-*A* emerging
  - Strong P_{LH} threshold scaling with *A*
  - Little to no difference between limited and diverted H-modes
- Operating regime allows detailed studies of ELMs
  - Small ELM Mode numbers at low-*A* opposite that of high-*A*
  - $J_{edge}(R,t)$ through ELM cycle shows some correspondence with simulations
- Overall, complements experiments on larger fusion facilities
  - Detailed measurements can elucidate more limited results on larger facilities