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

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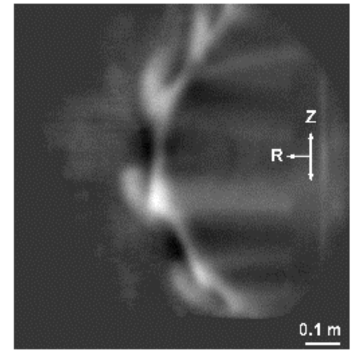
PEGASUS Toroidal Experiment

Outline

- Motivation and Introduction to PEGASUS
- Standard H-mode Characteristics
- Power Threshold
- ELM Characteristics and Dynamics
- Conclusion

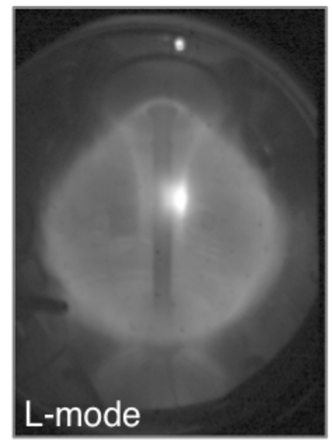
Understanding H-mode Physics is Critical to the Viability of Fusion Reactors

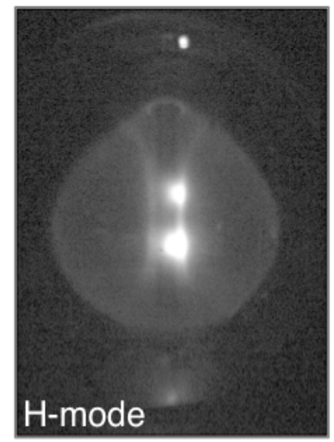
PEGASUS Peeling Modes



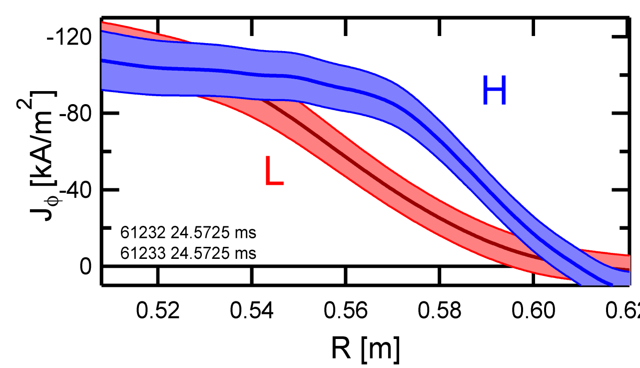
- Equilibrium, stability properties documented
  - No accepted first-principles model, knowledge empirical

- Parameter variations critical to test, validate theories of H-mode, ELM behavior
  - *A* changes H-mode access, equilibrium, and stability
  - Low-*A* H-mode similar, differs with high-*A*





- *A* ~ 1 operations → AT physics
  - High I_p at very low B_T
  - Modest-sized plasma and relatively low T_e
    - Allows diagnostic access to pedestal



Bongard *et al.*, Phys. Rev. Lett **107**, 035003 (2011).
Bongard *et al.*, Nucl. Fusion **54**, 114008 (2014).

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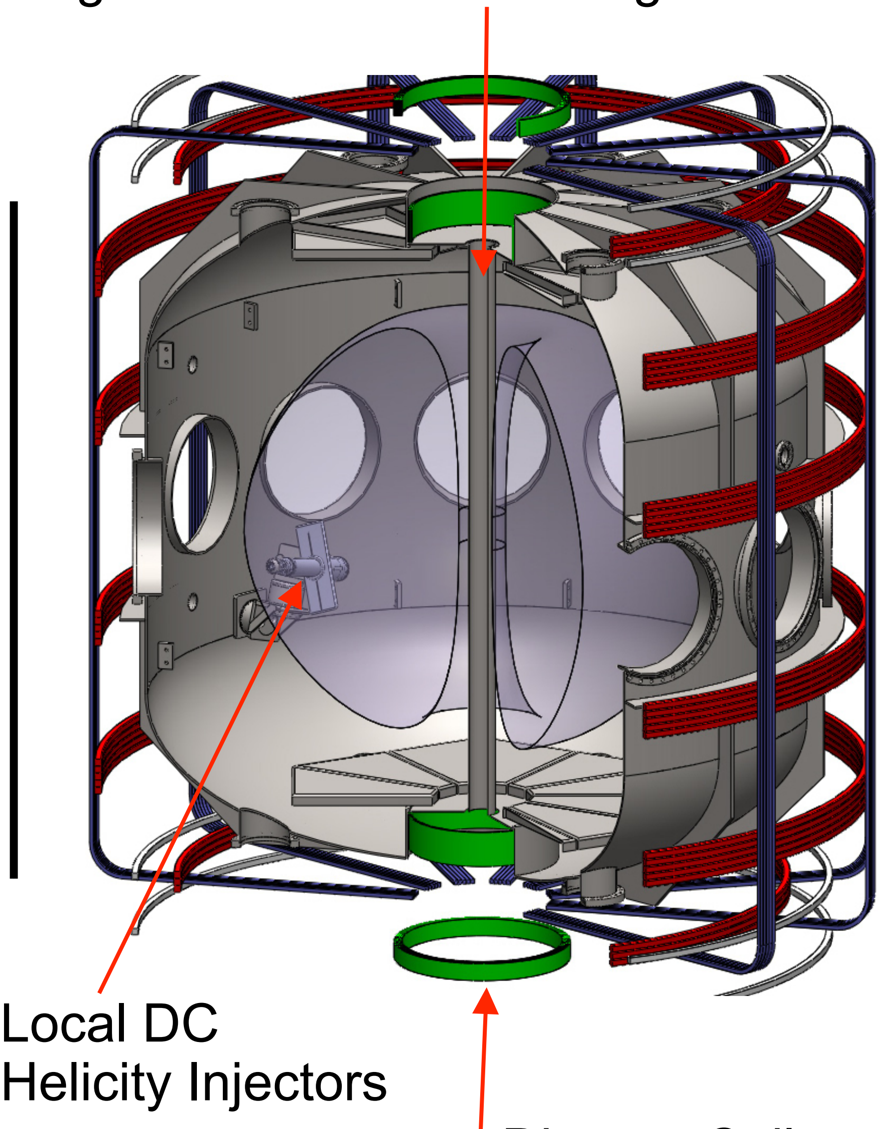
PEGASUS is a Compact, Ultralow-*A* ST



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
Z_{eff}	~ 1
Recy. Coeff.	<< 0.7

Recent upgrades for H-mode studies:

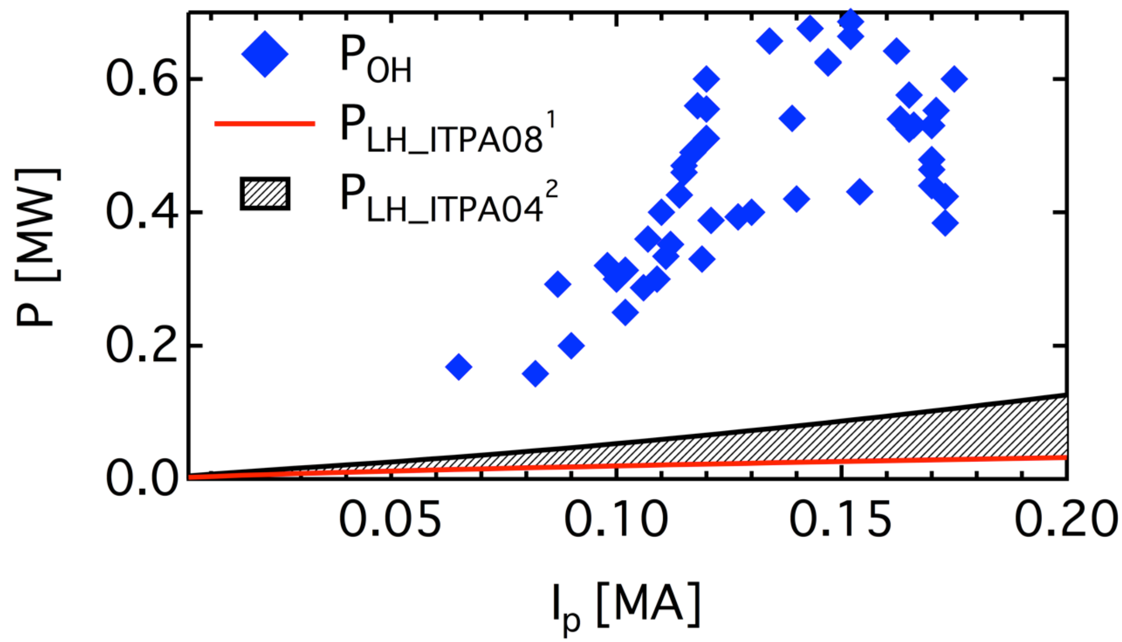
- HFS fueling
- New external divertor coils
- Radial field coils
- Edge current injection startup (LHI) for MHD control (future)

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

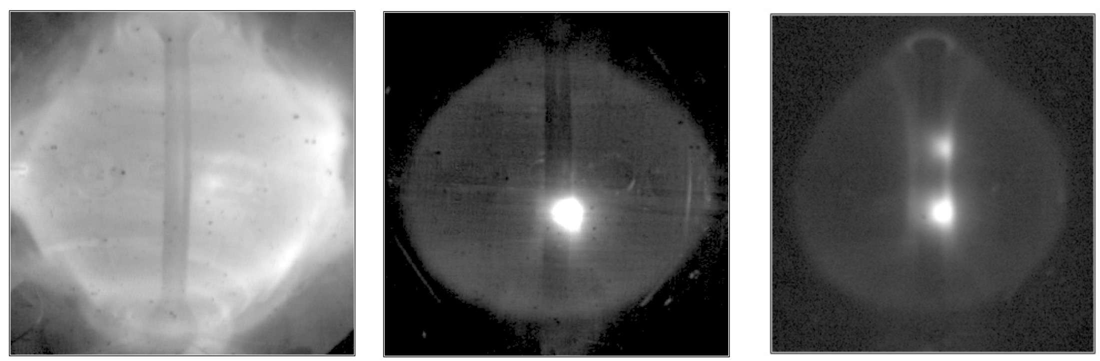
- $A \approx 1$ → low B_T → low P_{LH}

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

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



Limited L Limited H Diverted H

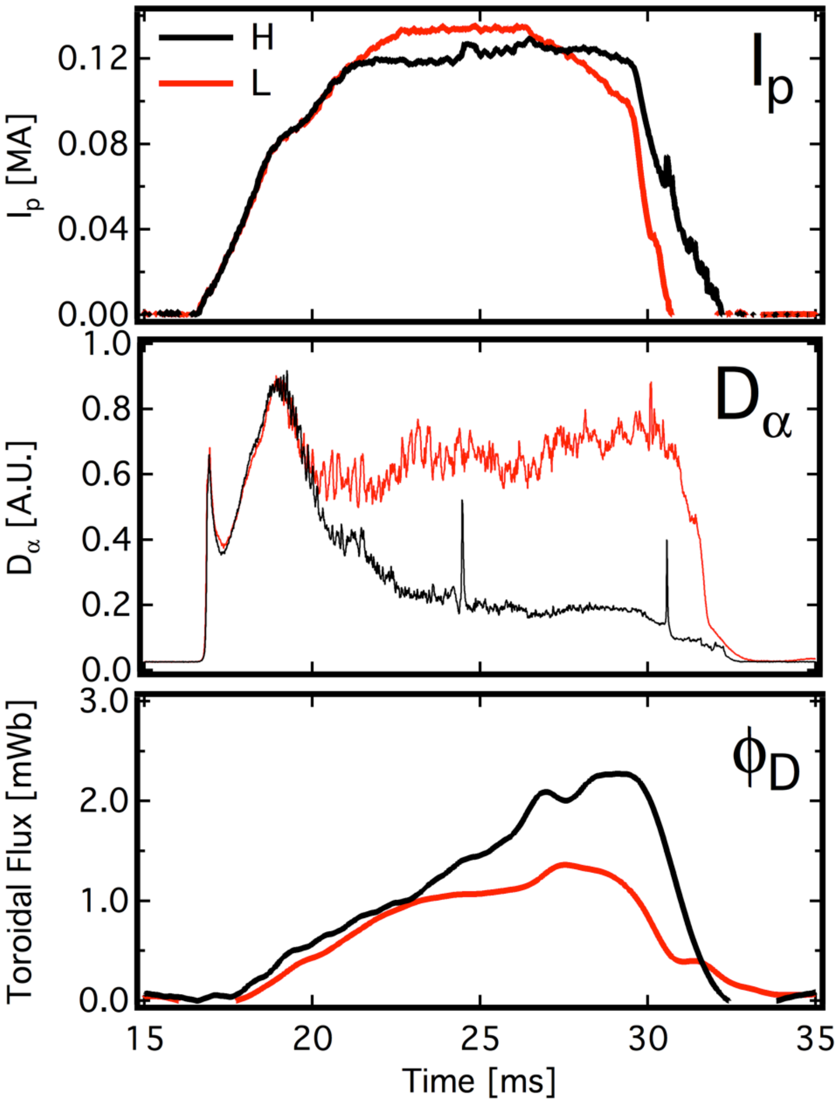


Fast visible imaging, $\Delta t \sim 30$ μs

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

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



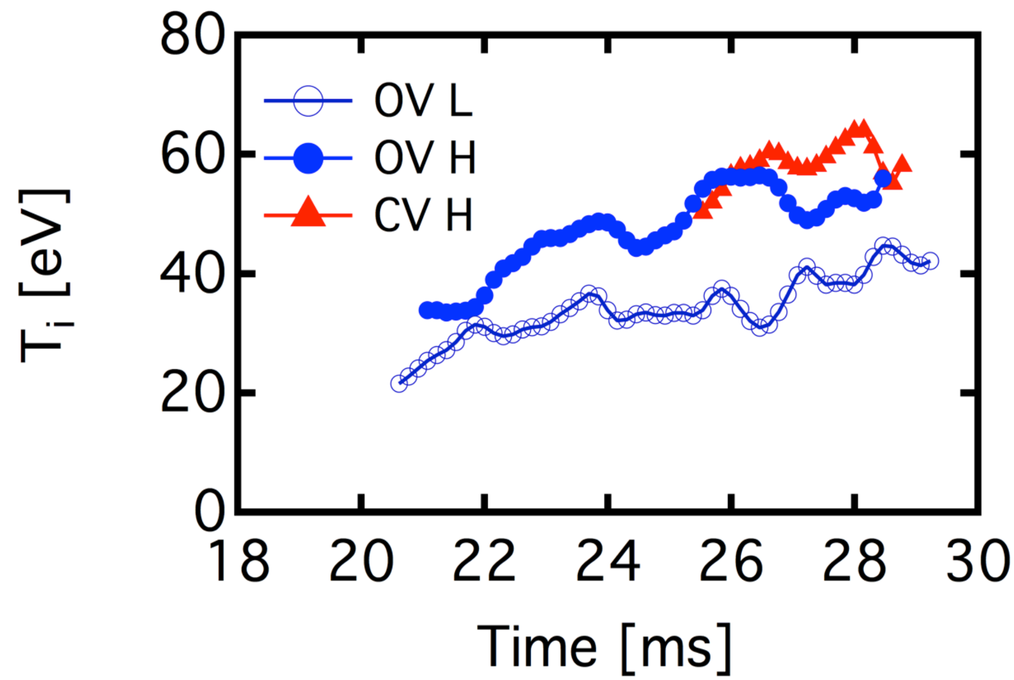
Energy Confinement Improves in H-mode

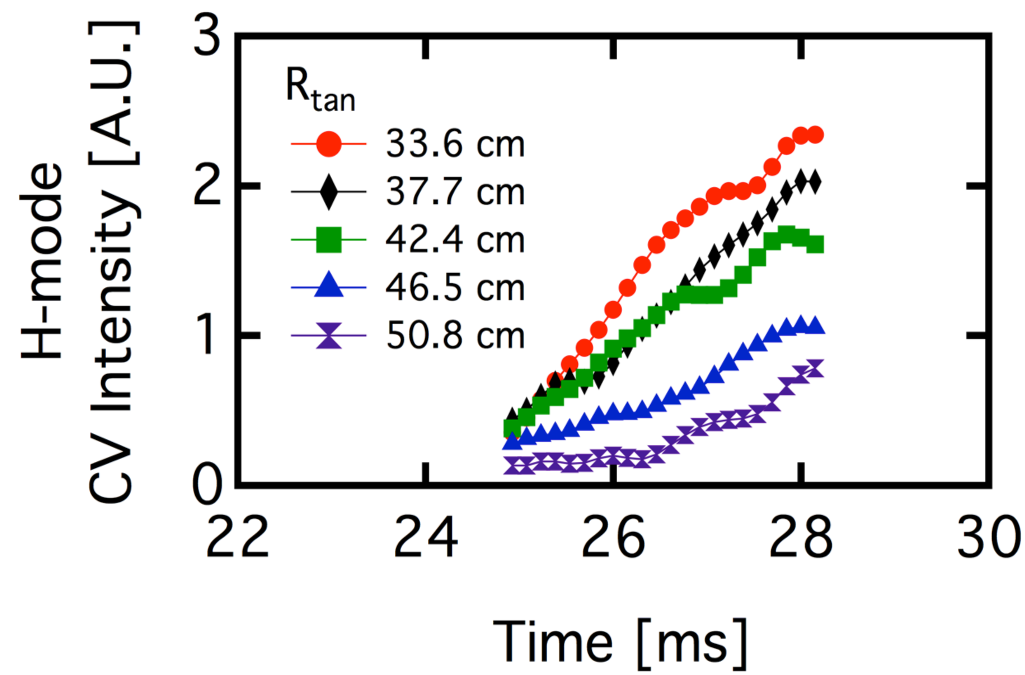
- At A~1.2, high-A cylindrical approximations not valid
  - Virial integrals S_1, S_2, $R_t/R_0 \neq 1$
  - Overestimates β_{pol}, W_k
- Equilibrium reconstructions necessary to calculate τ_e
  - Needed for W_k and dW/dt
    - dW/dt ~ 30% P_{OH}
  - Short pulse, not in transport equilibrium
- Established H-mode plasmas H_{98}~1
- Pegasus-U = transport equilibrium

	τ_E (ms)	H_{98}
Limited L-mode	1.5	~0.5
Limited H-mode	2 – 3	~1
Diverted H-mode	3	~1

T_i and T_e Increases Indicated in H-mode

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

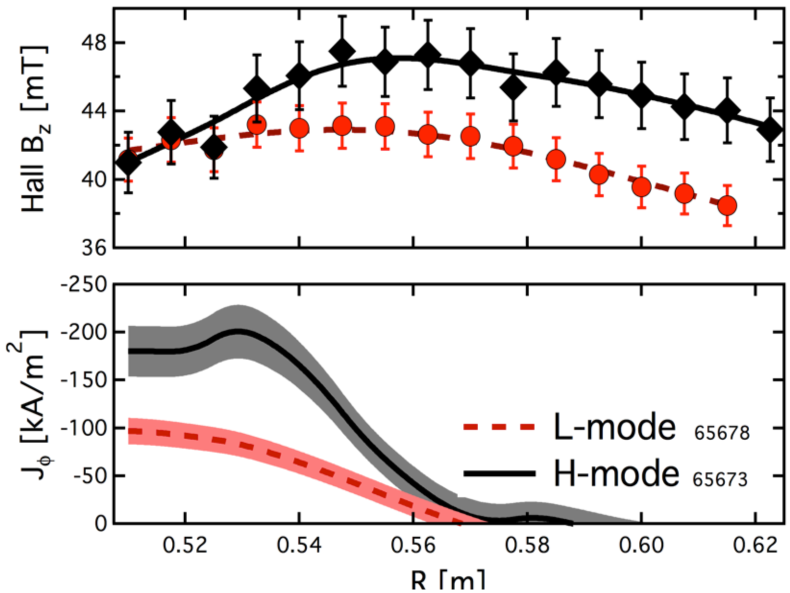


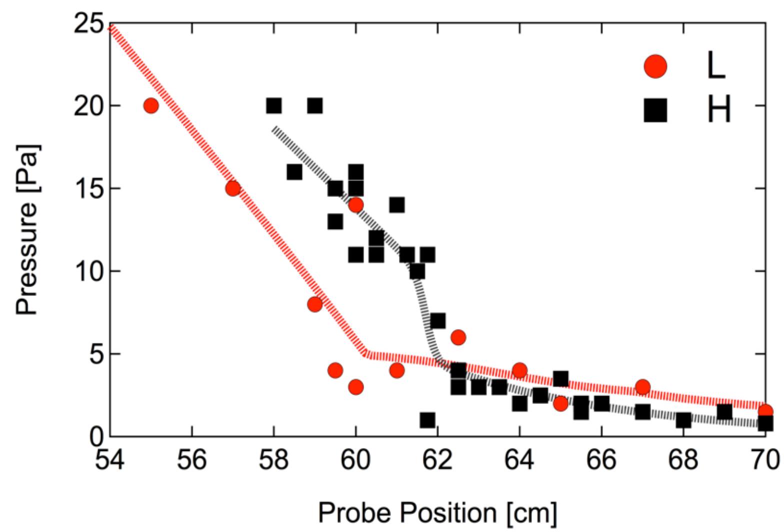


Edge Pedestals Measured with Probes

- Current pedestal observed
  - Measured with Hall Probe[1,2] array
  - L → H: 4 → 2 cm

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



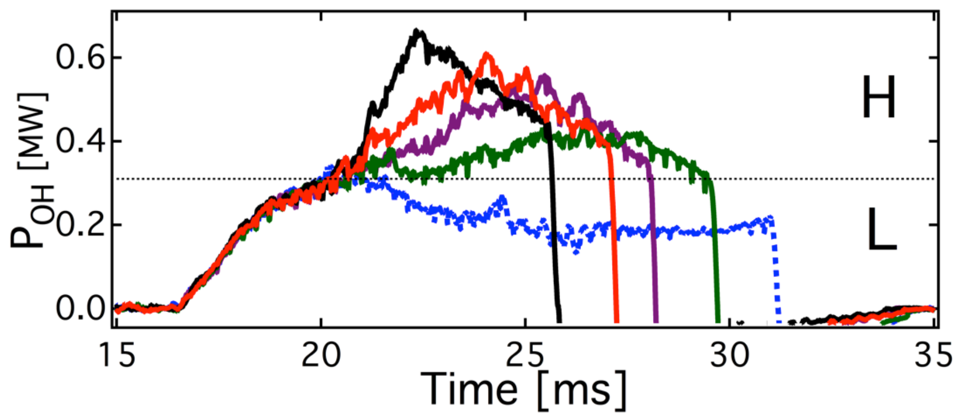


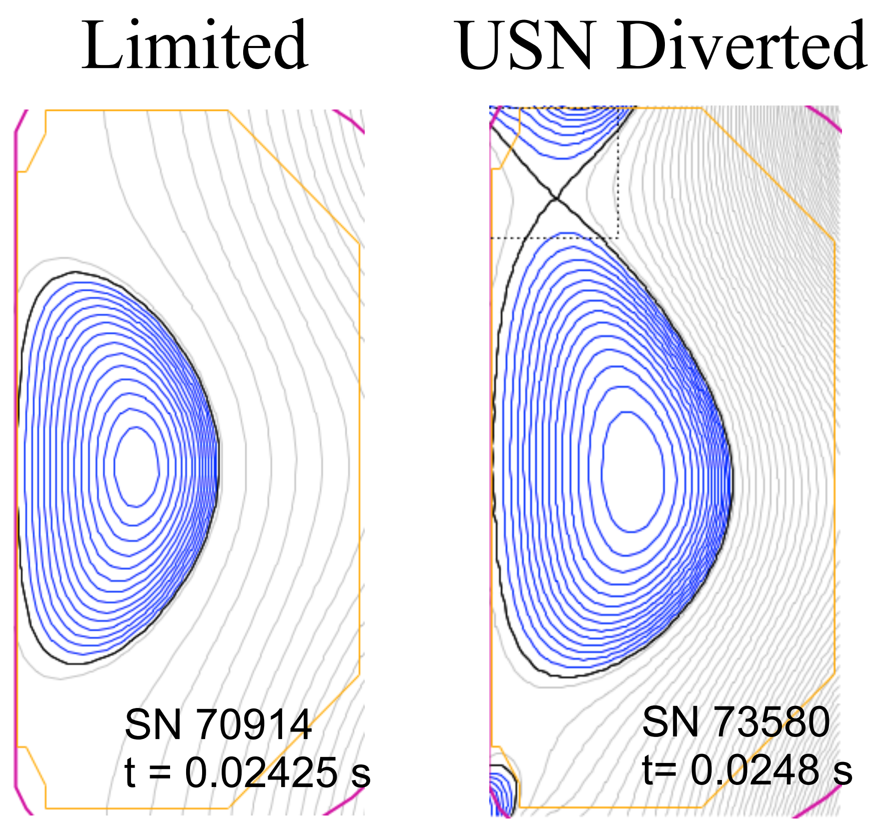
[1] PRL **107**, 035003 (2011).
[2] Petty *et al.* Nucl. Fusion **42**, 1124 (2002).

P_{LH} Measured in PEGASUS at $A \approx 1.2$

- P_{LH} from varying P_{OH}
  - Transition time from ϕ_D bifurcation
  - Wide parameter range
    - $P_{OH} = 0.1 – 0.6$ MW
    - $n_e = 0.5 – 4 \times 10^{19}$ m^{-3}
    - Limited: Centerstack
    - Diverted: USN (favorable ∇B)

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

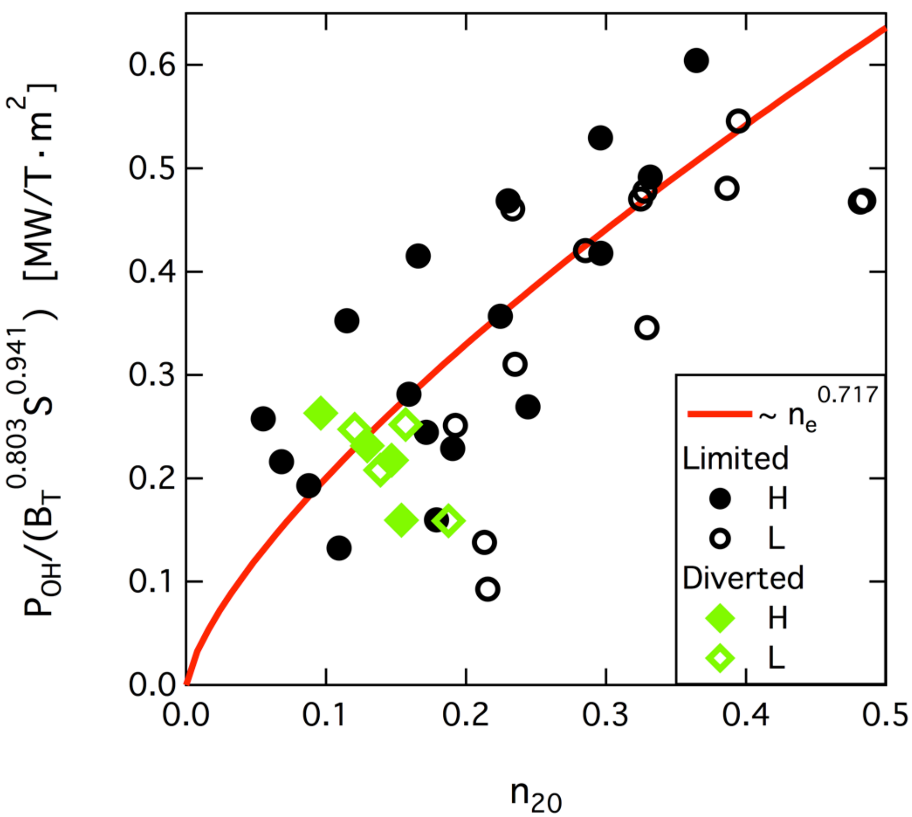




P_{LH} Shows Strong Density Dependence

Threshold Power vs. Density

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

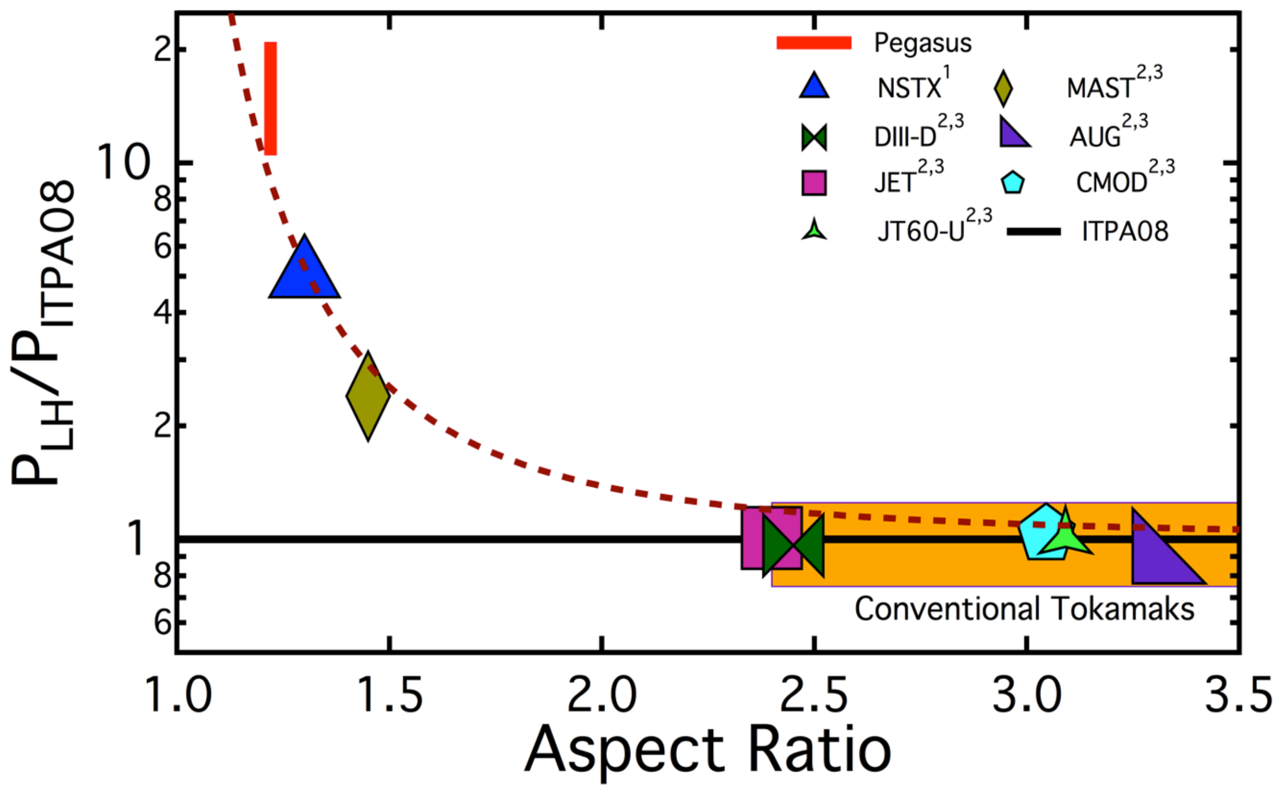


- Shot survey of L and H-mode plasmas at different P_{OH} and n_e

- Density minimum not apparent

- Diverted and limited P_{LH} similar
  - Comparable topology: *e.g.* $q_{lim}(\psi) \approx q_{div}(\psi)$

At low *A*, $P_{LH} >> P_{LH\_ITPA08}$



- P_{LH} increasingly diverges from expectations as *A* → 1
- Discrepancy may hint at additional physics

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

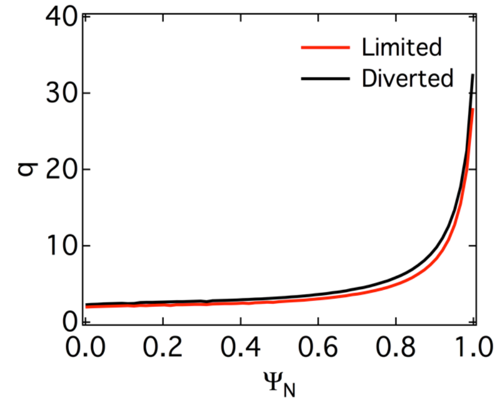
Some Results Consistent with FM^3 Model

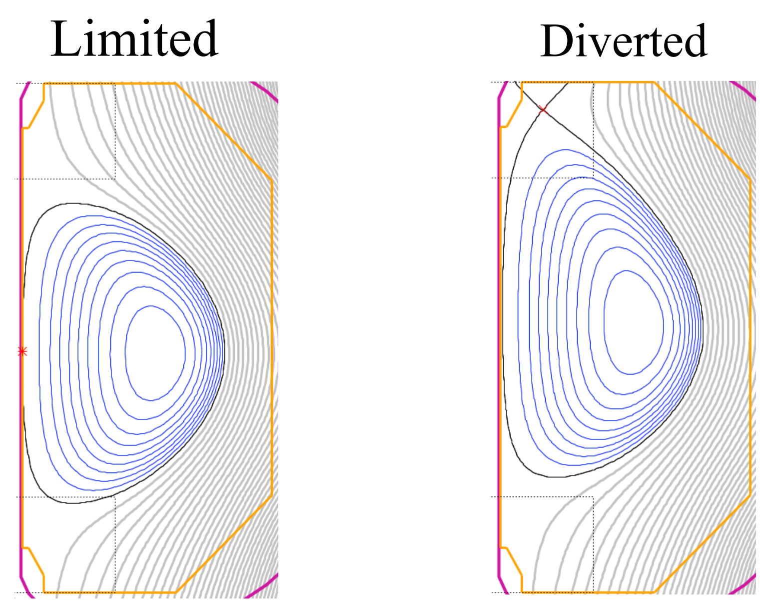
- FM^3: Predicts P_{LH} minimum for PEGASUS at n_e ~ 1 x10^{18} m^{-3}
  - n_e/n_G<<0.1, inaccessible due to runaways
- P_{LH} topology independence: self-similar q profiles at *A* ~1

$$\frac{P_{L-H}^{lim}}{P_{L-H}^{div}} \approx \left(\frac{q_*^{lim}}{q_*^{div}}\right)^{-7/9} \quad \begin{matrix} \gg 1 \text{ @ } A\sim 3 \\ \rightarrow 1 \text{ @ } A\sim 1 \end{matrix}$$

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

Predictive Equilibrium @ $A \approx 1.2$



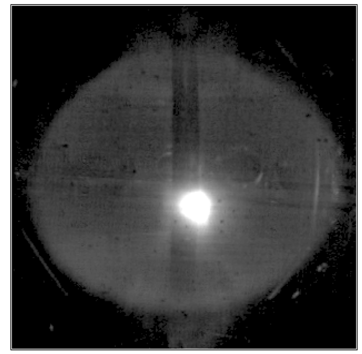


[1] Fundamenski W., Militello D., Moulton D., McDonald D.C., Nucl Fusion **52**, 062003 (2012).

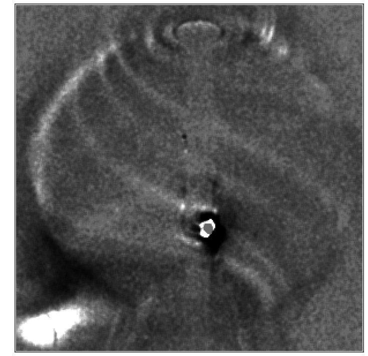
Small and Large ELMs are Seen

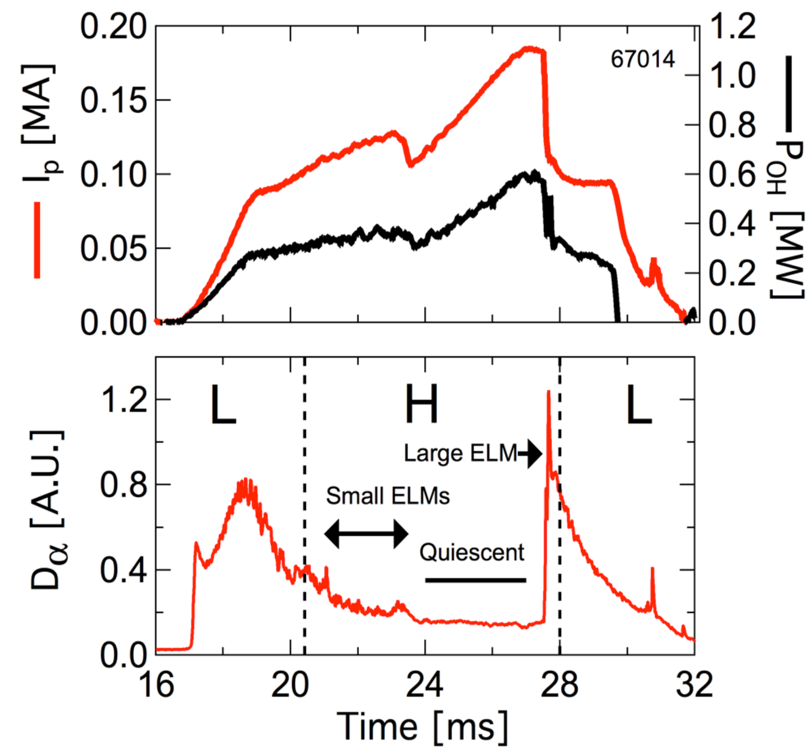
- Filament structures observed
  - Coincident with D_α bursts
- Small ("Type III") ELMs ubiquitous, less perturbing
  - $P_{OH} \sim P_{LH}$
- Large ("Type I") ELMs infrequent, violent
  - $P_{OH} >> P_{LH}$
  - Can cause H-L back-transition

Quiescent



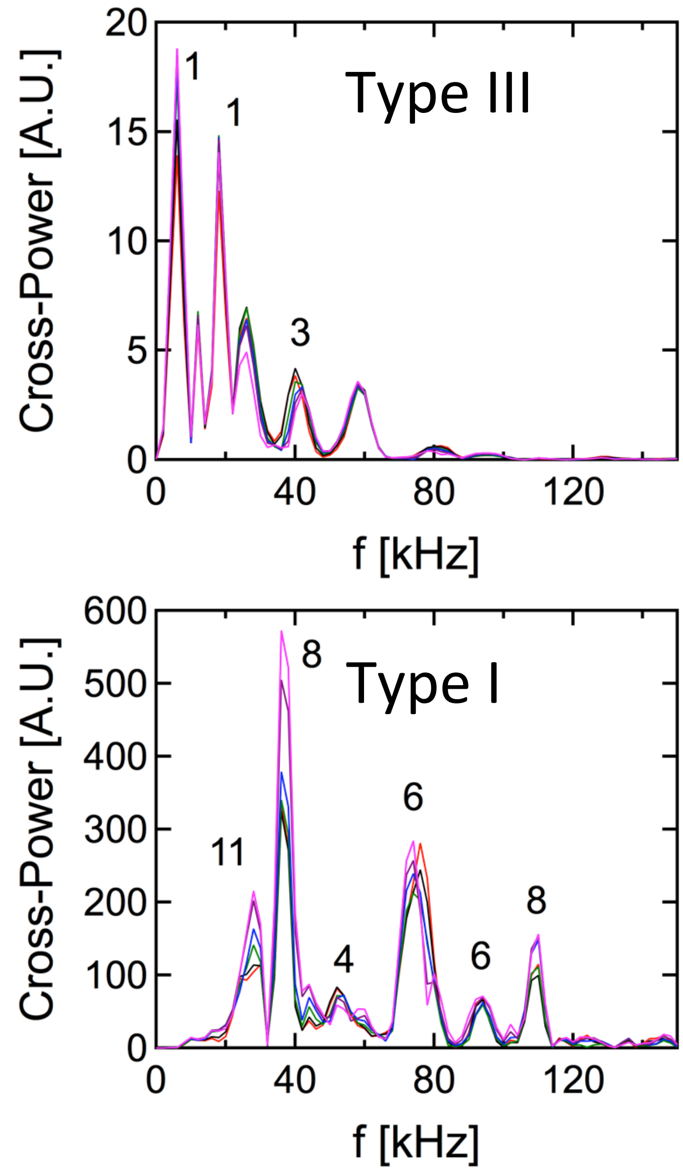
ELM





ELM Magnetic Structure Varies with *A*

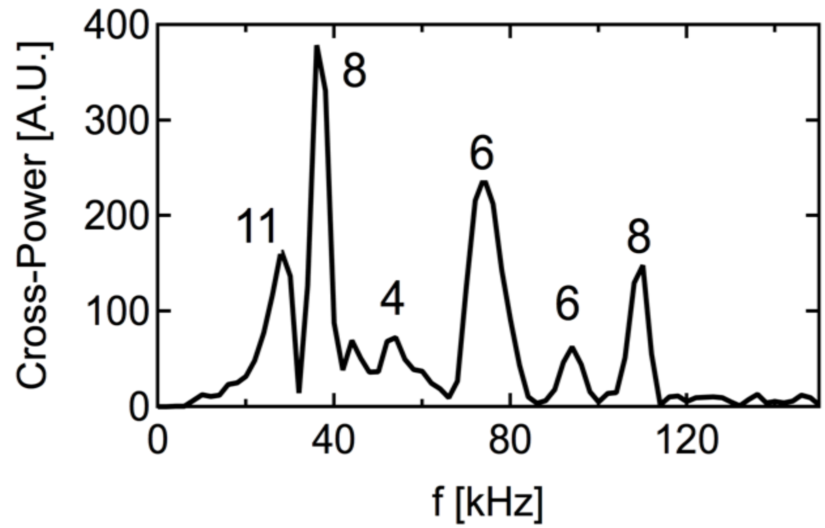
- Measured with near-edge magnetics probe
- Type III: *A* dependent
  - $A \leq 1.4$: $n \leq 1 - 3$
    - PEGASUS and NSTX
  - $A \sim 3$: $n > 8$
- Type I: *A* independent
  - Intermediate-n, $n \sim 4 - 12$
  - Low and high-*A* similar, but low-*A* lower *n*
- Increased peeling drive at low *A* (higher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



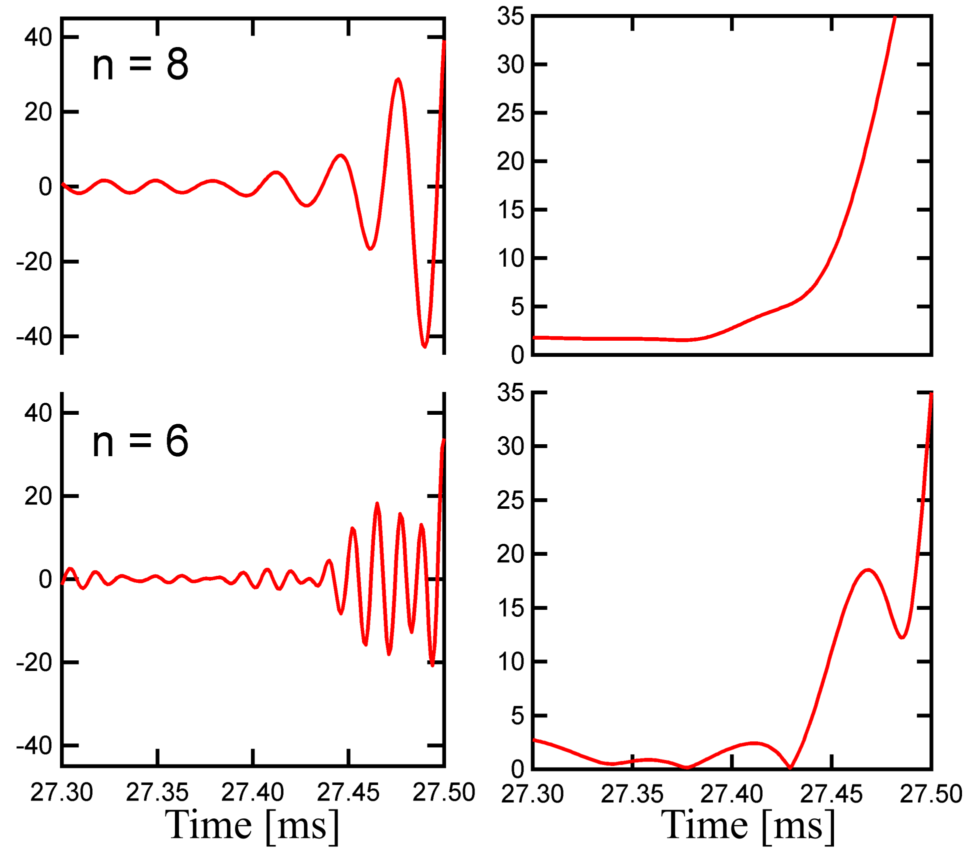
[1] Nucl. Fusion **45**, 1066 (2005).
[2] Nucl. Fusion **38**, 111 (1998).
[3] Nucl. Fusion **52**, 609 (2004).

Nonlinear ELM Precursors Observed

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

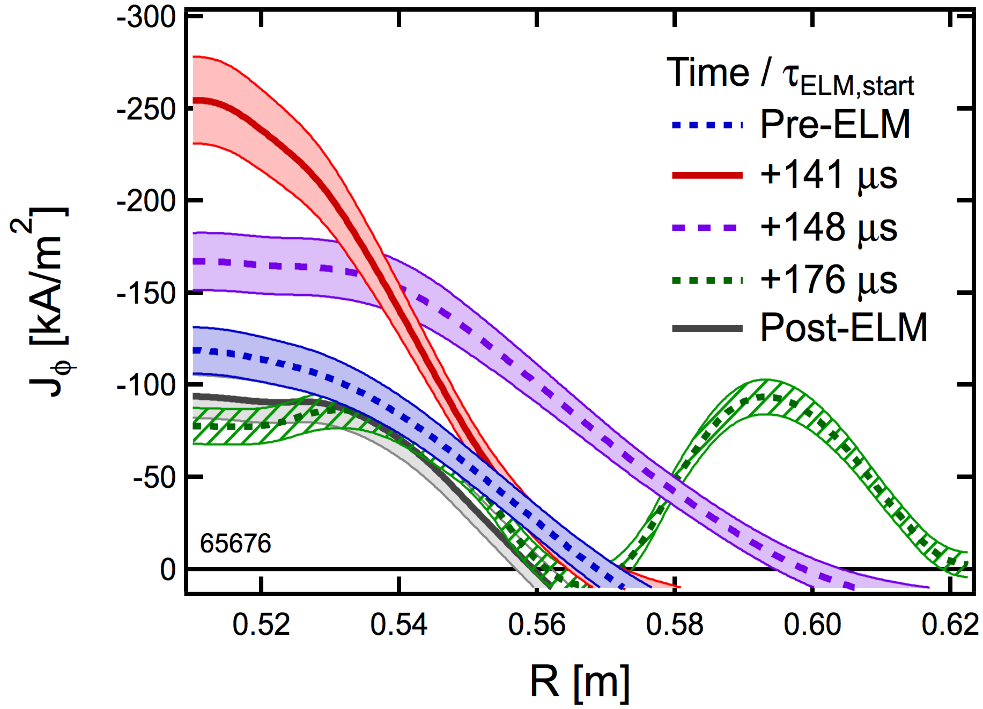


- Modes show different time evolutions (isolated with bandpass filter)
  - n = 8 grows continuously
  - n = 6 fluctuates prior to crash

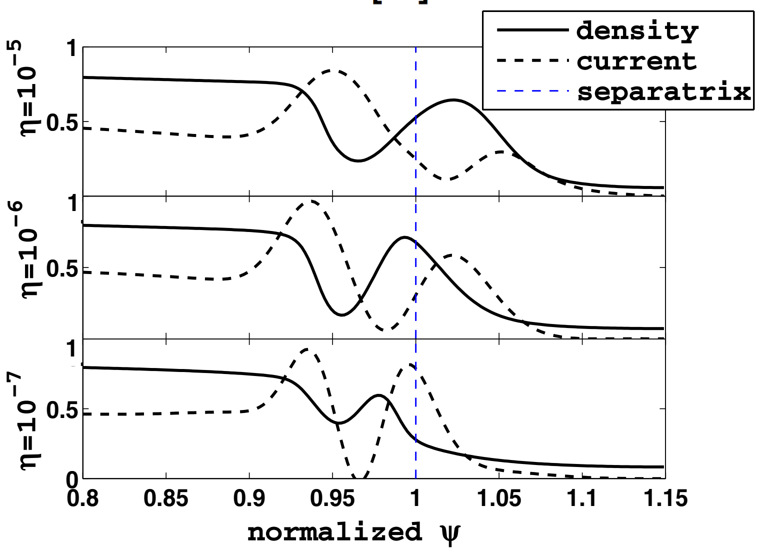


Type I ELM $J_{edge}(R,t)$ Dynamics Measured Throughout Single ELM Cycle

- 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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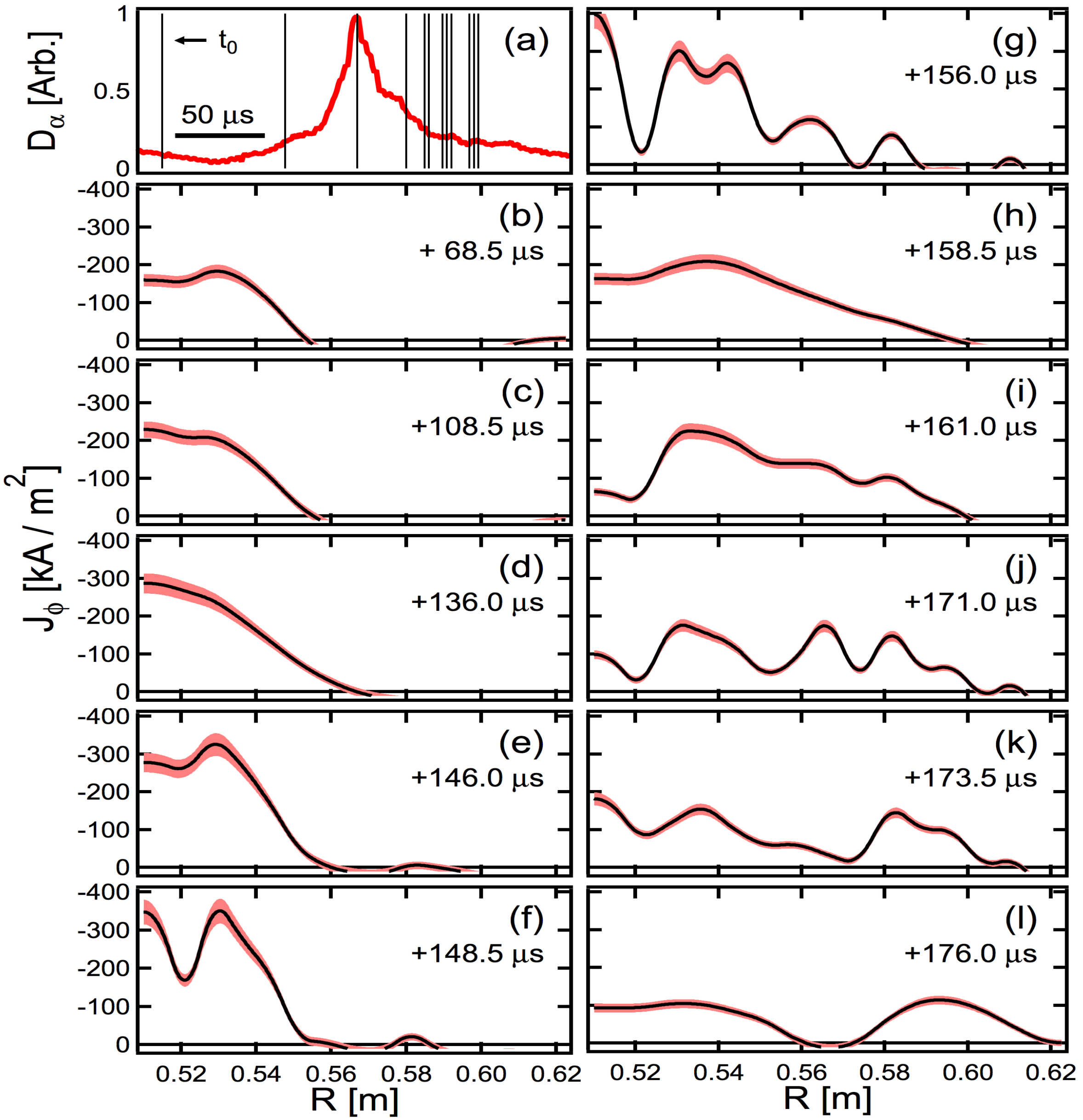
Closer Inspection of J_{edge} Reveals Complex Dynamic Behavior

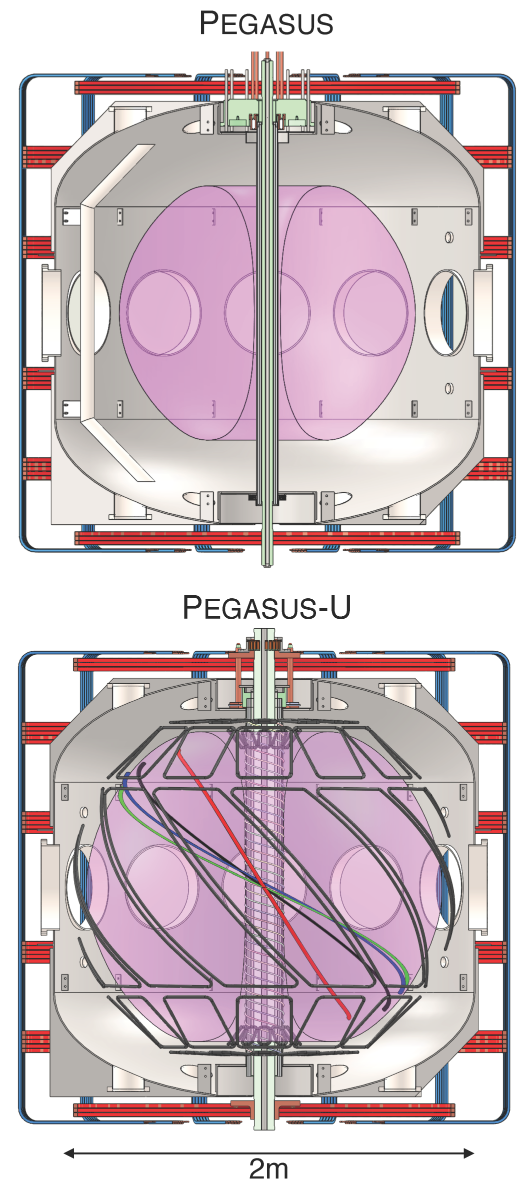
- With less spatial smoothing, $J_{edge}(R,t)$ evolution through ELM cycle shows complex multimodal behavior

- Challenge: study nonlinear ELM dynamics at Alfvénic timescales



These Exploratory H-mode Studies Provide Motivation for Upgraded PEGASUS

- 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
- ELM modification and mitigation
  - LHI, 3D-Magnetic Perturbation
- Upgrade
  - New Centerstack = longer pulse, higher B_T
  - Comprehensive 3D Magnetic Perturbation
  - Edge Diagnostics with high spatiotemporal resolution



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
  - ELM Mode numbers at low-*A* systematically lower than high-*A*
  - $J_{edge}(R,t)$ through ELM event shows some correspondence with simulations
- Overall, complements experiments on larger fusion facilities
  - Detailed measurements can elucidate more limited results on larger facilities