

H-mode and Edge Physics on the PEGASUS ST: Progress and Future Directions

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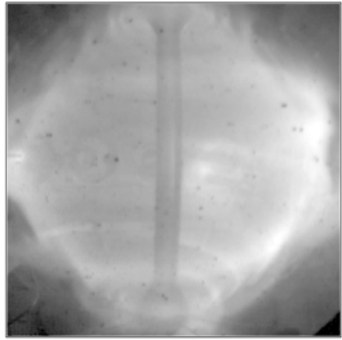


PEGASUS
Toroidal Experiment

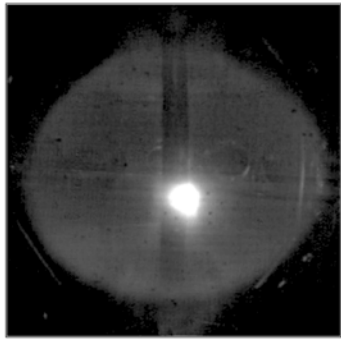


H-mode Readily Accessed in A ~ 1 PEGASUS ST

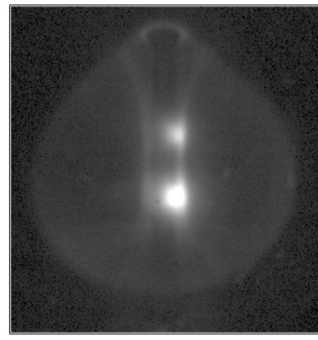
Limited L



Limited H

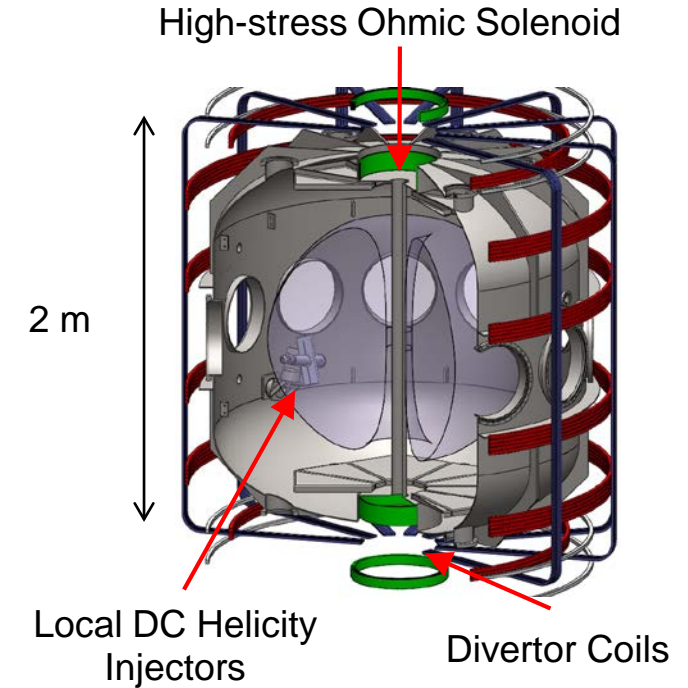


Diverted H



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

- Low B_T at $A \sim 1 \rightarrow$ low H-mode P_{LH}
 - $P_{OH} \gg P_{ITPA08} \sim B_T^{0.80} n_e^{0.72} S^{0.94}$
 - Limited or diverted topology
 - Facilitated by HFS fueling
- Standard H-mode features observed
 - Quiescent edge, improved τ_E , ELMs



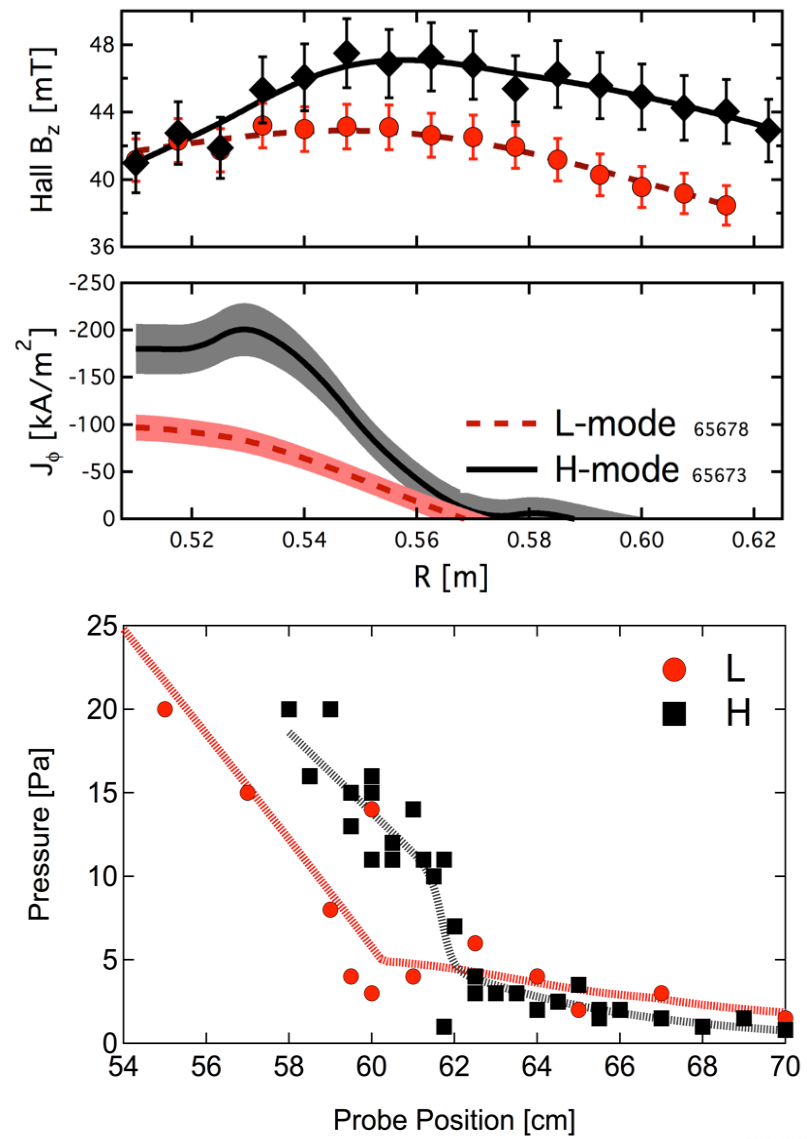
PEGASUS Toroidal Experiment

A	1.15 – 1.3
R (m)	0.2 – 0.45
I_p (MA)	≤ 0.25
B_T (T)	< 0.2
$\Delta\tau_{shot}$ (s)	≤ 0.025
Wall Type	SS + Ti getter



Edge Pedestals Present Between ELMs in H-mode

- Short pulse, low edge T_e permit detailed edge measurements
 - $J_\phi(R,t)$ via multichannel Hall probe^{1,2}
 - High spatial, temporal resolution
 - $p(R)$ via triple Langmuir probe
 - Single point, high temporal resolution
- Clear current pedestal observed
 - L \rightarrow H scale lengths: 4 \rightarrow 2 cm
- Multi-shot Langmuir probe scans indicate pressure pedestal
 - Some edge distortion present from MHD



¹ Bongard *et al.*, Rev. Sci. Instrum. **81**, 10E105 (2010)

² Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

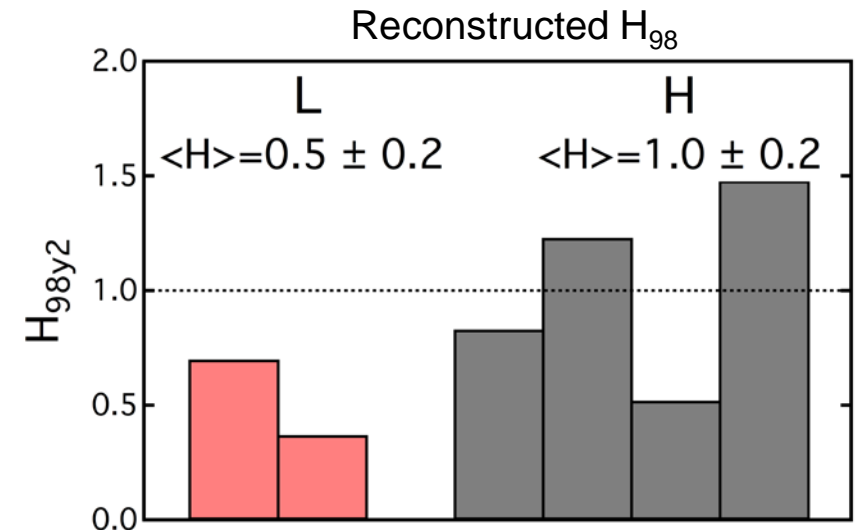
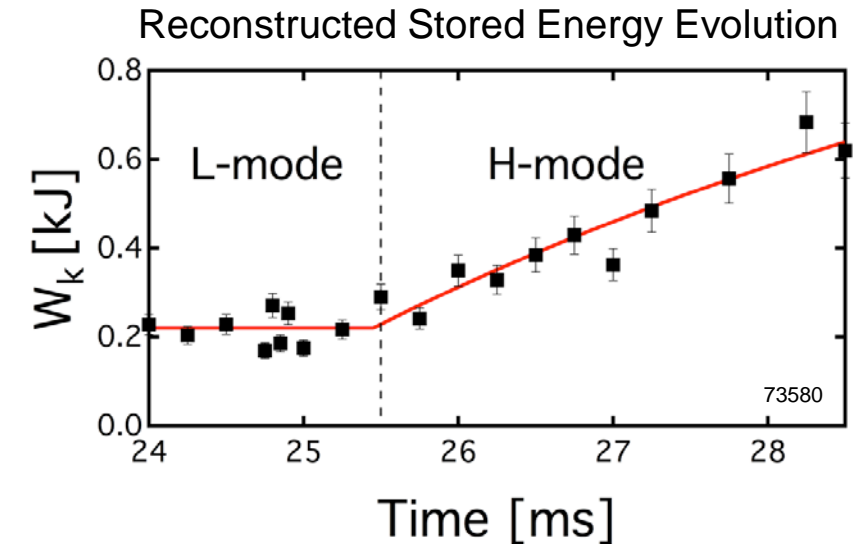


Energy Confinement Improves in H-mode

- Equilibrium reconstructions yield τ_E

$$\tau_E = \frac{W_K}{P_{in} - dW/dt - P_{rad}}$$

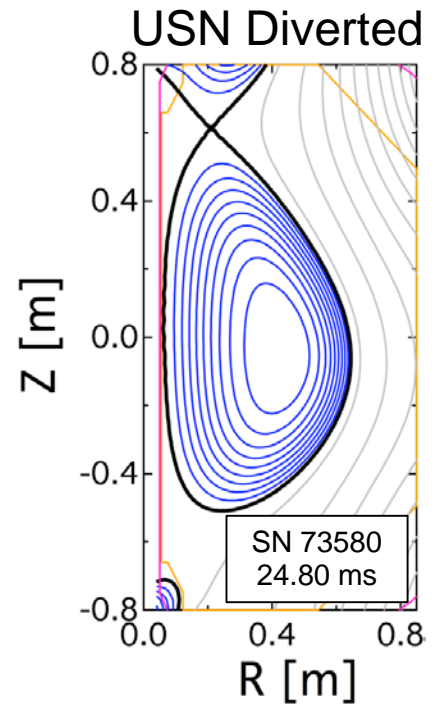
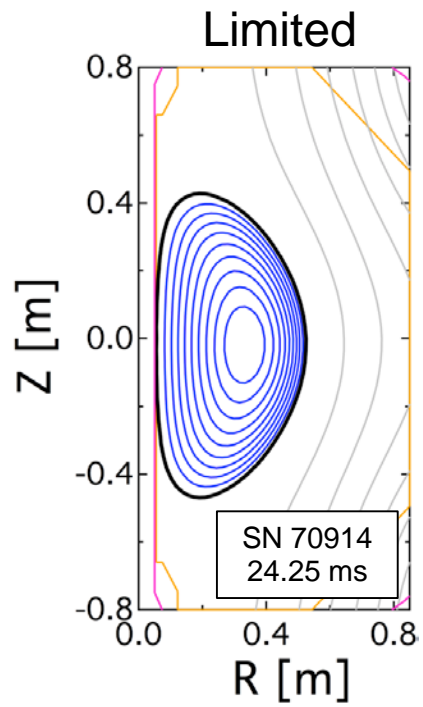
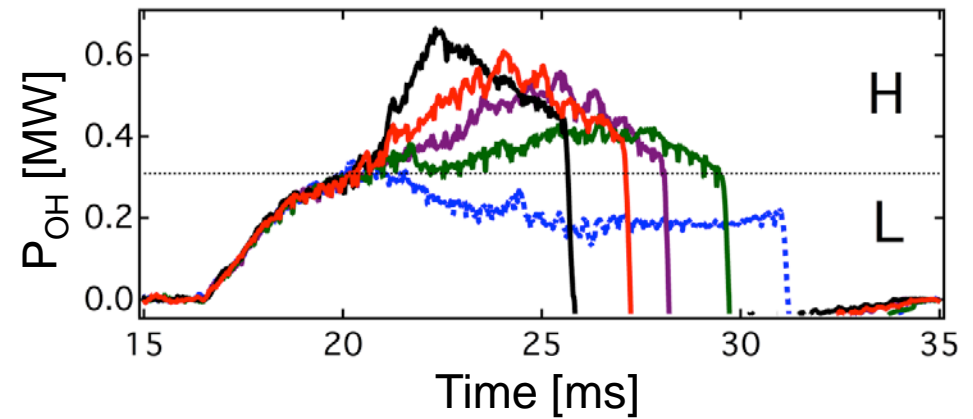
- Challenges: short pulse, MHD, $I_{wall}(t)$
- Significant dW/dt
- $W_K(\tau_E)$ increases after L-H transition
- H_{98} increases from 0.5 to 1.0
- Virial analysis ongoing for τ_E database





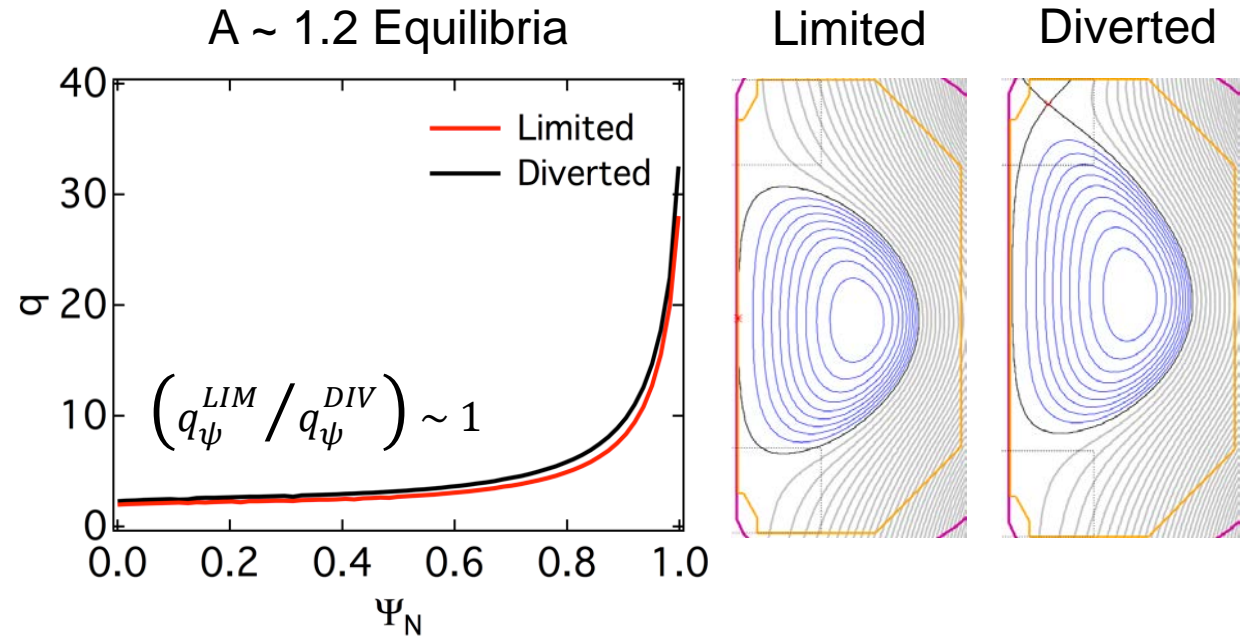
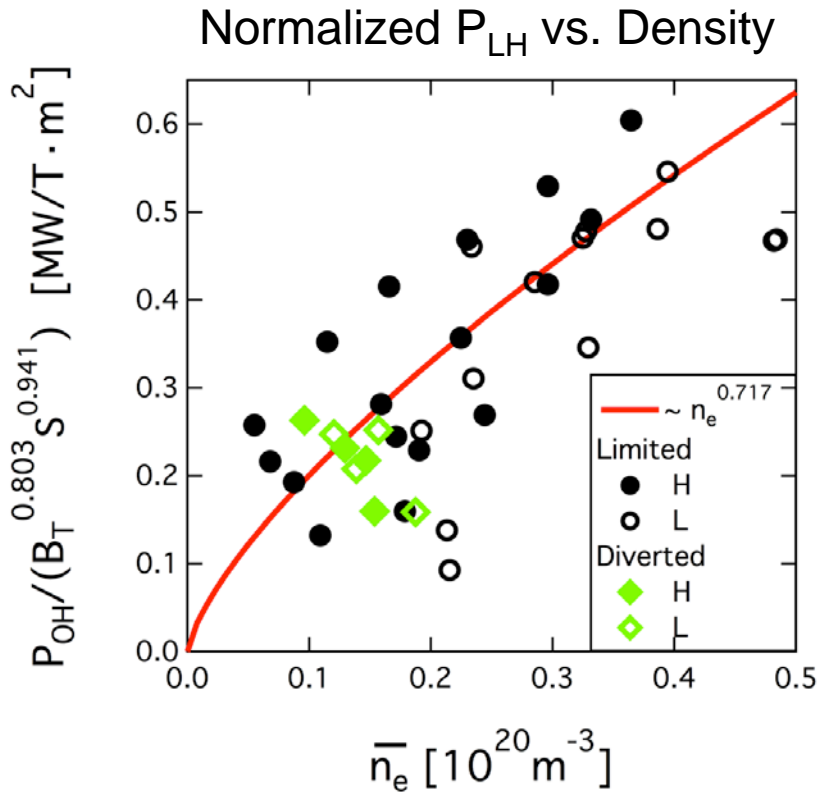
P_{LH} Measurements Extended to $A \sim 1.2$ in PEGASUS

- Vary P_{OH} with power scan
 - Transition time from ϕ_D bifurcation
 - Wide parameter range
 - $P_{OH} = 0.1 - 0.6$ MW
 - $n_e = 0.5 - 4 \times 10^{19} \text{ m}^{-3}$
 - Inner wall limited
 - Diverted: USN (favorable ∇B)
- $P_{LH,exp} = P_{OH} - dW/dt$
 - dW/dt from magnetic reconstructions
 - $\sim 30\%$ correction





P_{LH} Consistent with Global Scalings—But Low-A Differences Arising



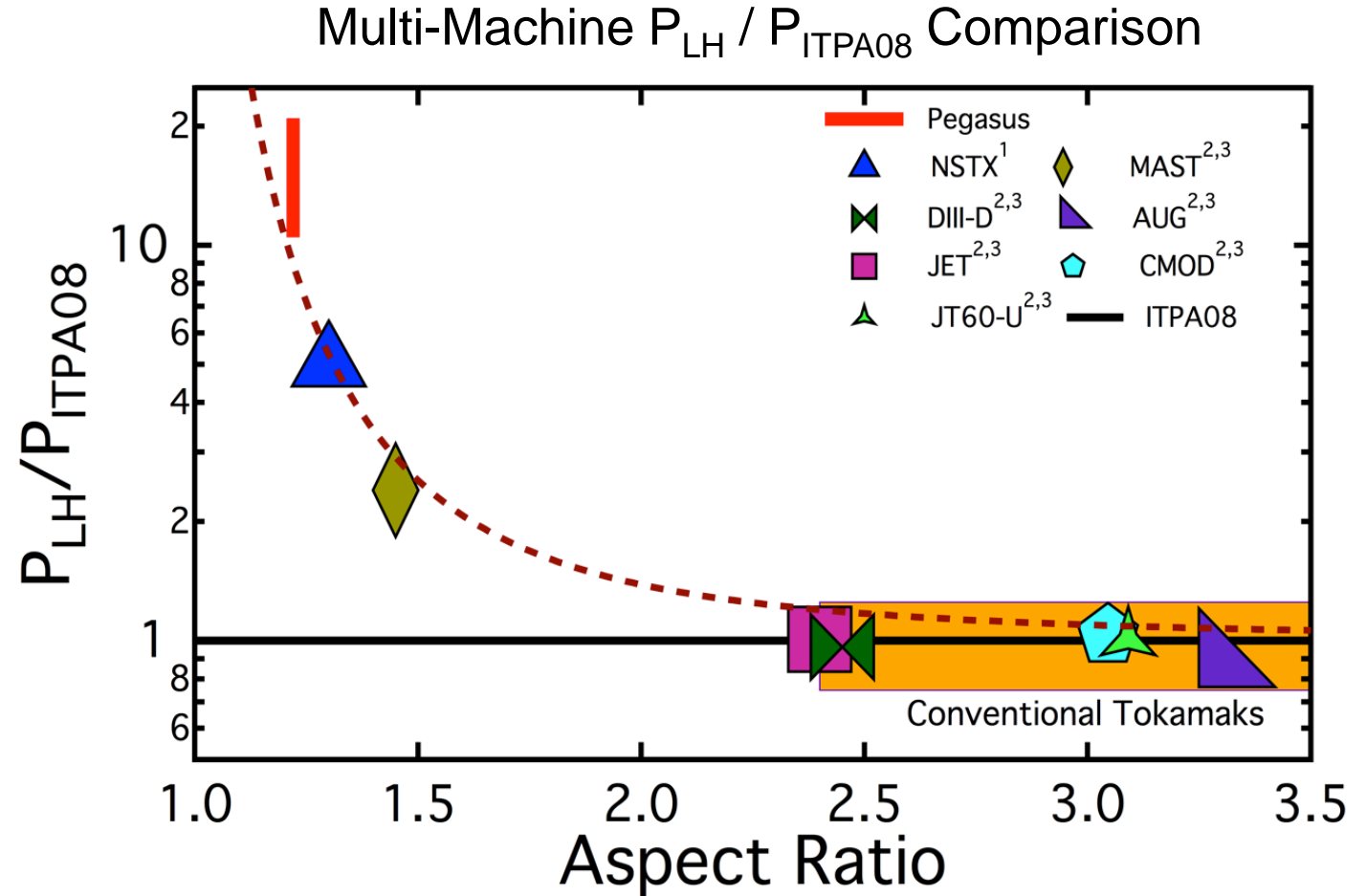
- $P_{LH}(n_e)$ consistent with ITPA scaling
 - FM³ model¹: minimum $P_{LH}(n_e) \sim 1 \times 10^{18} \text{ m}^{-3}$

- Magnetic topology independence
 - Diverted, limited edge topology similar
 - FM³: $P_{LH}^{LIM} / P_{LH}^{DIV} \sim (q_{\psi}^{LIM} / q_{\psi}^{DIV})^{-7/9}$



At Low A, $P_{LH} \gg P_{ITPA08}$

- P_{LH} increasingly diverges from expectations as $A \rightarrow 1$
 - PEGASUS $P_{LH} / P_{ITPA08} \geq 10-20$
 - Confirms trend from NSTX, MAST
- Discrepancy may hint at additional physics



¹ Maingi *et al.*, Nucl. Fusion **50**, 064010 (2010)

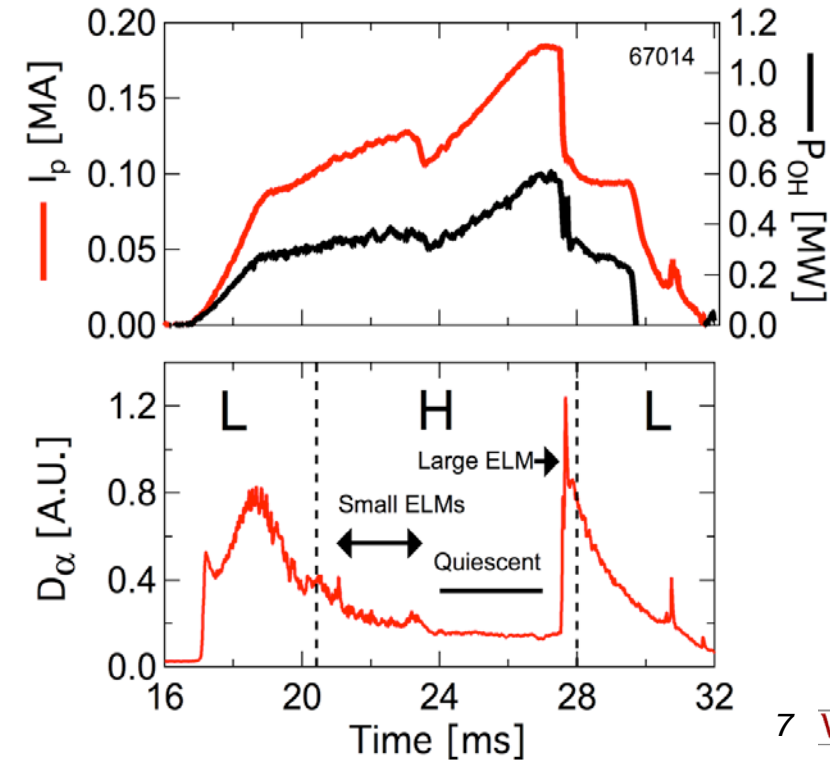
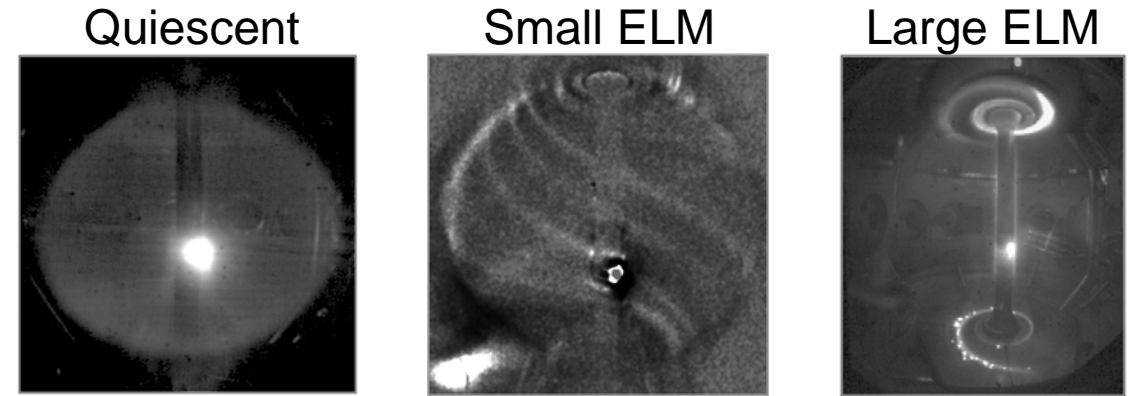
² Martin *et al.*, J. Phys.: Conf. Ser. **123**, 012033 (2008)

³ Wesson, *Tokamaks*, 4th ed. (2011), p. 630



A ~ 1 Regime Well-Suited for Studies of ELMs and their Nonlinear Dynamics

- Filament structures accompany ELMs
- Small (“Type III”) ELMs ubiquitous, less perturbing
 - $P_{OH} \sim P_{LH}$
 - Low n
- Large (“Type I”) ELMs infrequent, violent
 - $P_{OH} \gg P_{LH}$
 - Intermediate n
- ELM magnetic structure varies with A
 - Type III: A-dependent
 - Pegasus, NSTX: $n \leq 4$
 - A ~ 3: $n > 8$
 - Type I: A independent, but ST’s report lower n in range
 - Strong peeling drive in ST → lower n

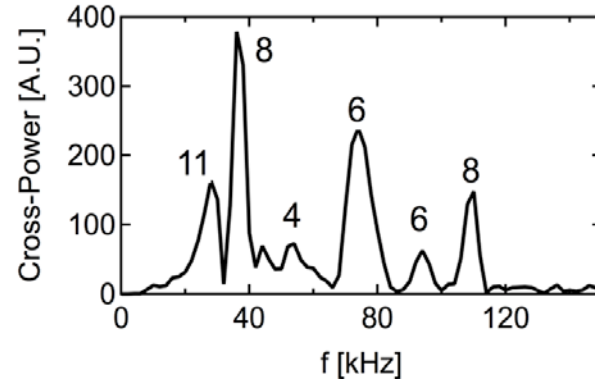




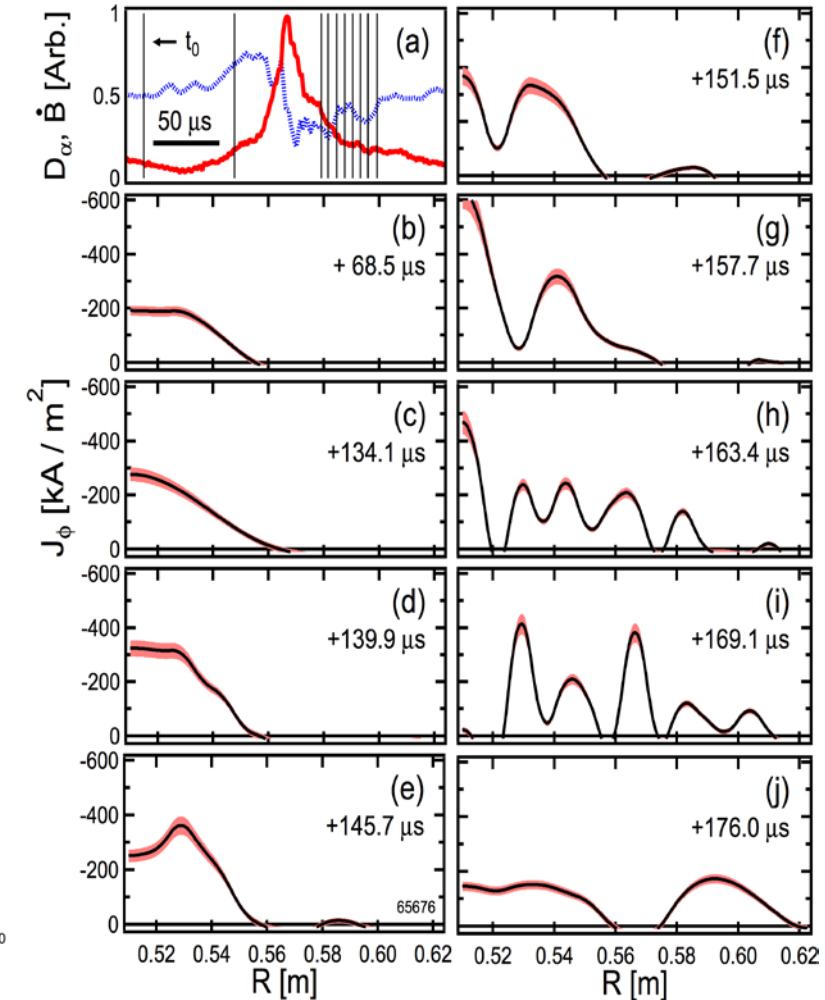
Details of Nonlinear ELM Behavior Emerging

- Simultaneously unstable toroidal modes present during ELM
 - Detectable only within \sim cm of LCFS
 - Nonlinear energy exchange
- Complex, multimodal $J_{\text{edge}}(R, t)$ collapse
 - High $\Delta t \sim 6 \mu\text{s}$ through single large ELM
 - Current filament ejection
- **Challenge:** studies of nonlinear ELM dynamics at Alfvénic timescales

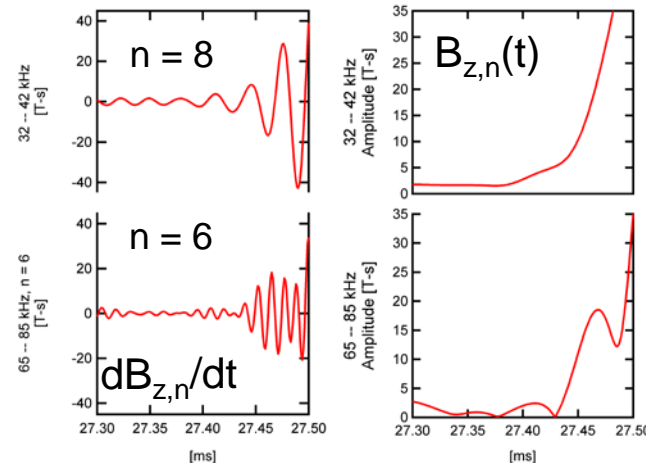
Large ELM Magnetic Structure



$J_{\text{edge}}(R, t)$ Through Large ELM



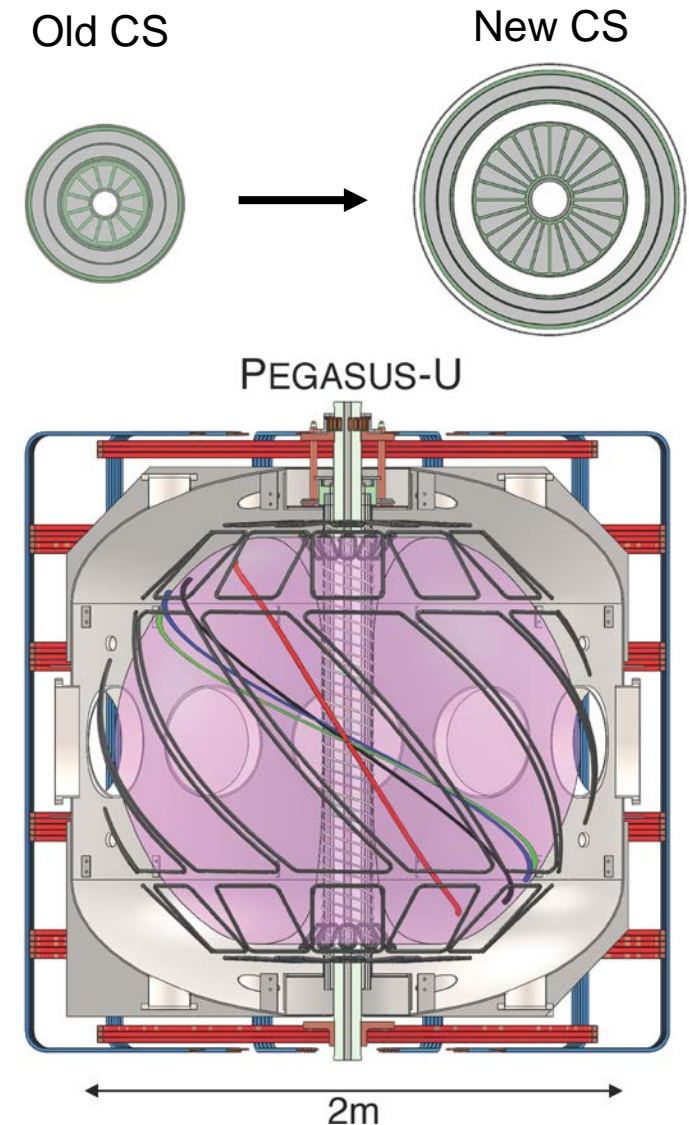
ELM Mode Growth





Results Motivate PEGASUS-U Upgrade Proposal

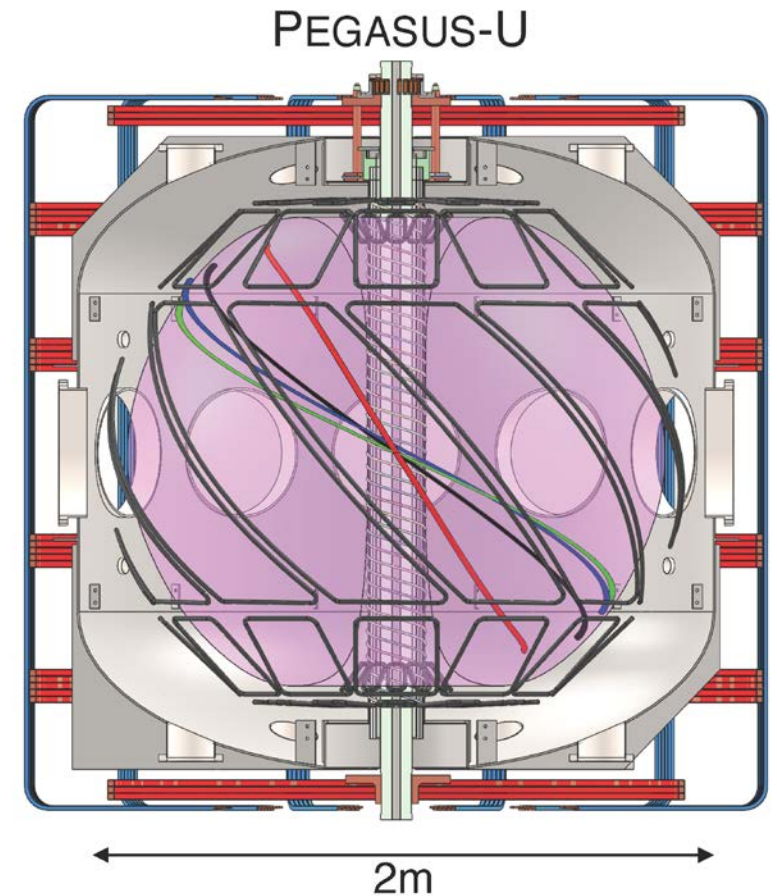
- Centerstack upgrade: new capabilities at $A \sim 1.2$
 - B_T increases $2-5\times$
 - Pulse length ~ 100 ms
 - V_s increases by $> 4\times$ (PPPL collaboration)
- Focused Physics Mission
 - Nonlinear pedestal and ELM studies
 - Simultaneous measurement of $p(R,t)$, $J(R,t)$, $v_\phi(R,t)$
 - New edge diagnostics (probe arrays, DNB)
 - ELM Modification and Mitigation
 - Novel 3D-MP coil array
 - LHI current injectors in divertor, LFS regions
 - Physics of Local Helicity Injection Startup
 - High I_p , long-pulse startup
 - Projections to NSTX-U





Unique Studies of H-mode Physics at $A \sim 1$

- H-mode plasmas with pedestal diagnostic access
 - Standard characteristics: pedestal; low D_α ; increased τ_e ; $H_{98} \sim 1$
- Low- A P_{LH} features emerging
 - P_{LH} threshold strongly increases as $A \rightarrow 1$
 - Insensitivity to magnetic topology
- Operating regime allows detailed ELM studies
 - Nonlinear ELM dynamics on Alfvénic timescales
- PEGASUS-U addresses critical physics, technology issues
 - Nonlinear ELM, pedestal physics with local edge diagnostics
 - Comprehensive 3D-MP and J_{edge} injection for ELM control
 - Tests of LHI at NSTX-U relevant field, pulse length



[Supporting Posters This Meeting](#)

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