H-mode and ELM Dynamics Studies at Near-Unity Aspect Ratio in the PEGASUS Toroidal Experiment and their Extension to PEGASUS-Upgrade

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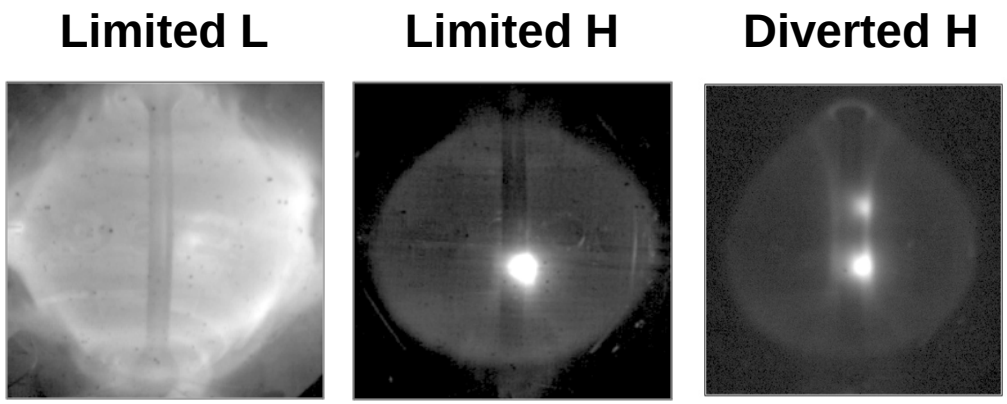
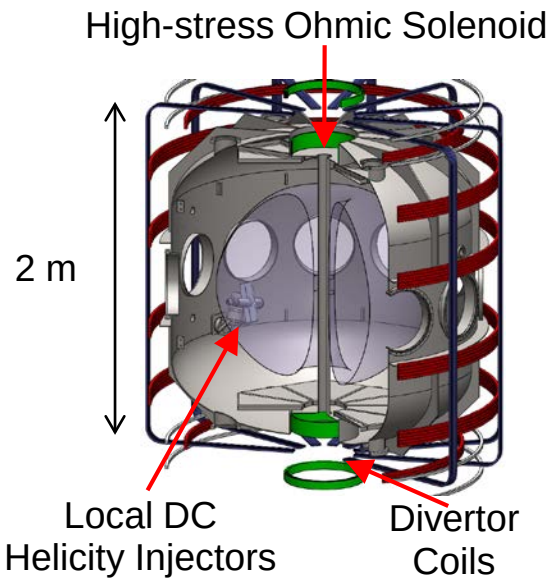
PEGASUS Toroidal Experiment

H-mode Readily Accessed in A ~ 1 PEGASUS ST



Fast visible imaging, Δt ~ 30 μs



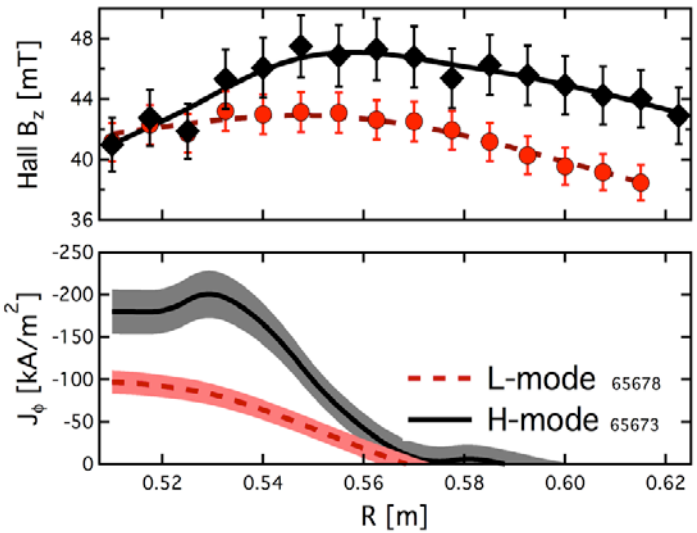
- Low B_T at A ~ 1 → low H-mode P_{LH}
  - $P_{OH} >> P_{ITPA08} \sim B_T^{0.80} n_e^{0.72} S^{0.94}$
  - Limited or diverted topology
  - Facilitated by HFS fueling
- Standard H-mode features observed
  - Unique edge diagnostic access

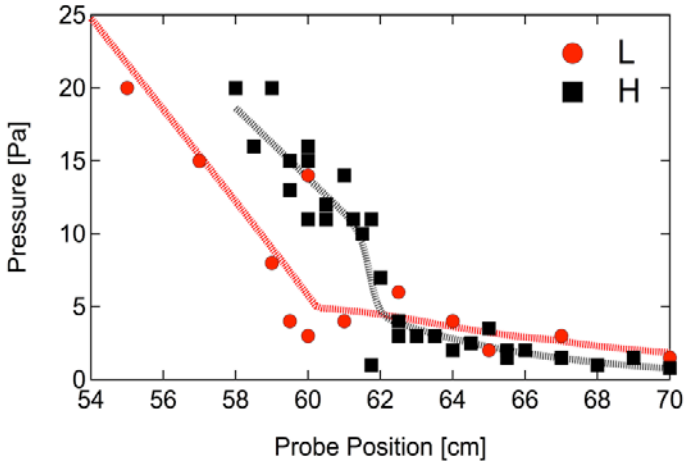
PEGASUS Toroidal Experiment

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 → H scale lengths: 4 → 2 cm
- Multi-shot Langmuir probe scans indicate pressure pedestal
  - Some edge distortion present from MHD





[1] M.W. Bongard *et al.*, *Rev. Sci. Instrum.* **81**, 10E105 (2010)
[2] M.W. Bongard *et al.*, *Phys. Rev. Lett.* **107**, 035003 (2011)

Energy Confinement Improves in H-mode

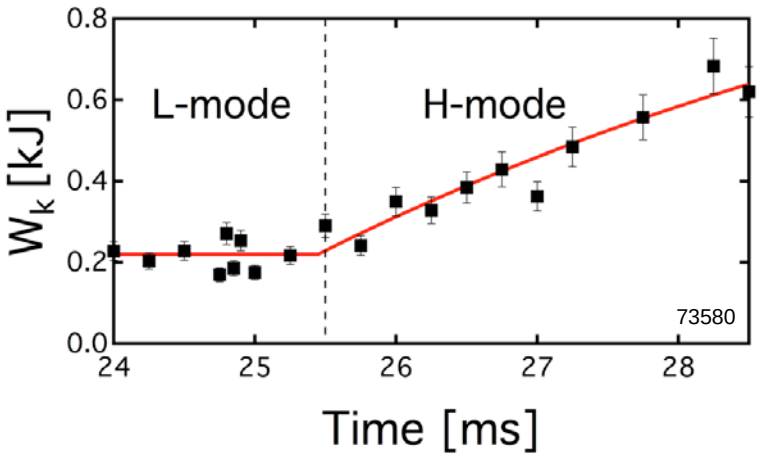
- Equilibrium reconstructions yield τ_e

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

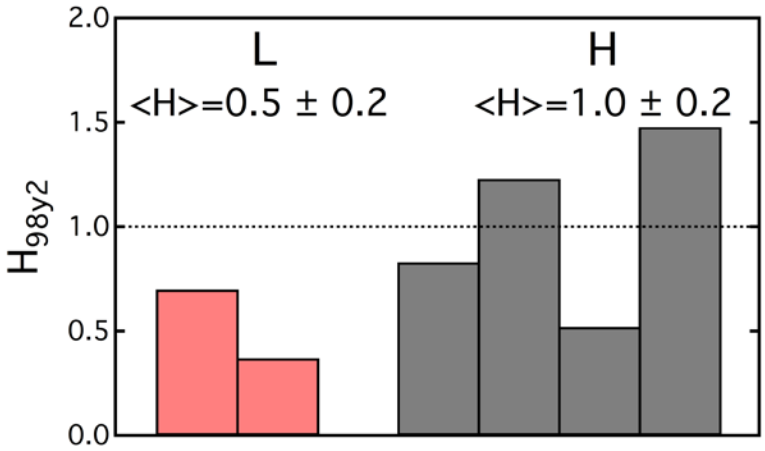
  - Challenges: short pulse, MHD, $I_{wall}(t)$
  - Significant dW/dt

- W_k (τ_e) increases after L-H transition
- H_{98} increases from 0.5 to 1.0
- Ongoing: virial analysis for fast τ_e

Reconstructed Stored Energy Evolution



Reconstructed H_{98}



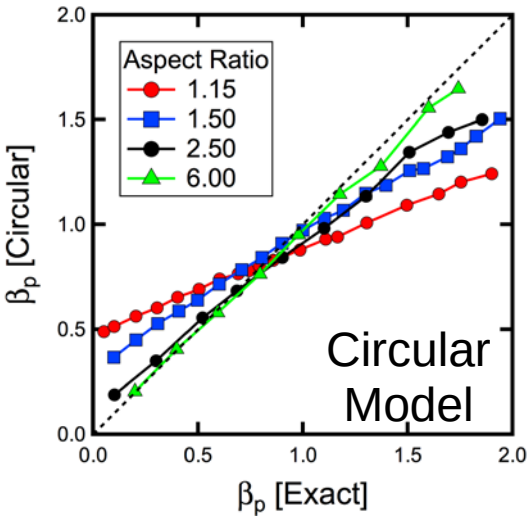
Full Virial Analysis is Required as A → 1

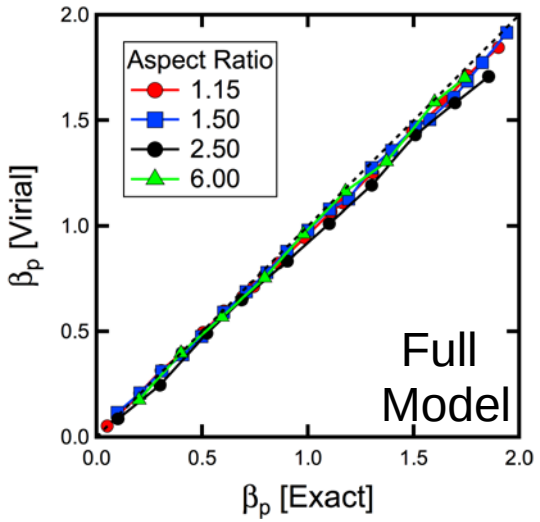
- Technique gives magnetics based β_p, W_K, and τ_e[1]

$$\beta_p = S_1/2 + S_2/2(1 - R_T/R_0) + \mu$$

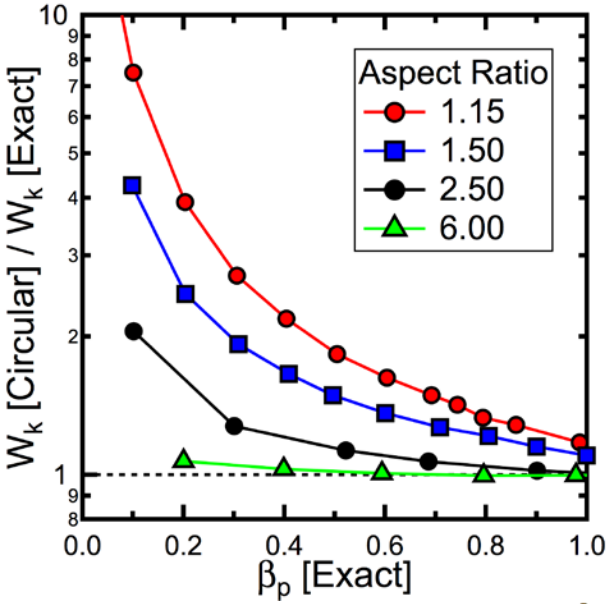
$$W_K = \frac{3}{2}\beta_p \, B_{pa}^2 \, \Omega \; / \; 2\,\mu_0$$

$$\mu_{expt} = 4\pi B_{T0} R_0 \Delta\phi \; / \; B_{pa}^2 \Omega$$





- Model equilibria at varied A, β_p highlight breakdown of high-A approximations
  - $\beta_{p,circ} = 1 + \mu$ significantly overestimates W_K (τ_e) in paramagnetic regime



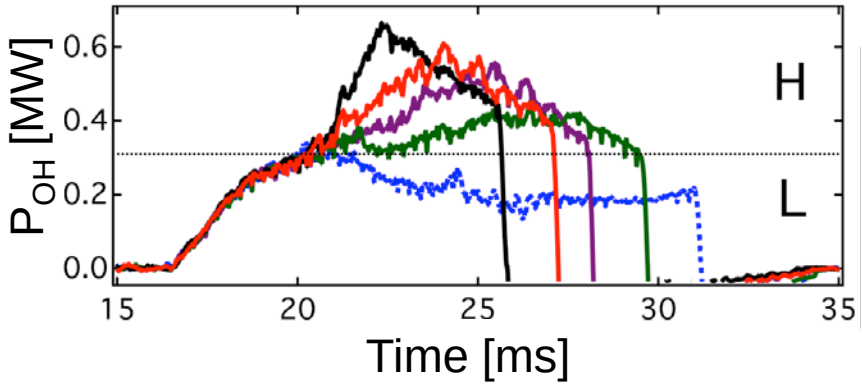
- Developing fast boundary reconstruction code to provide full treatment at A ~ 1

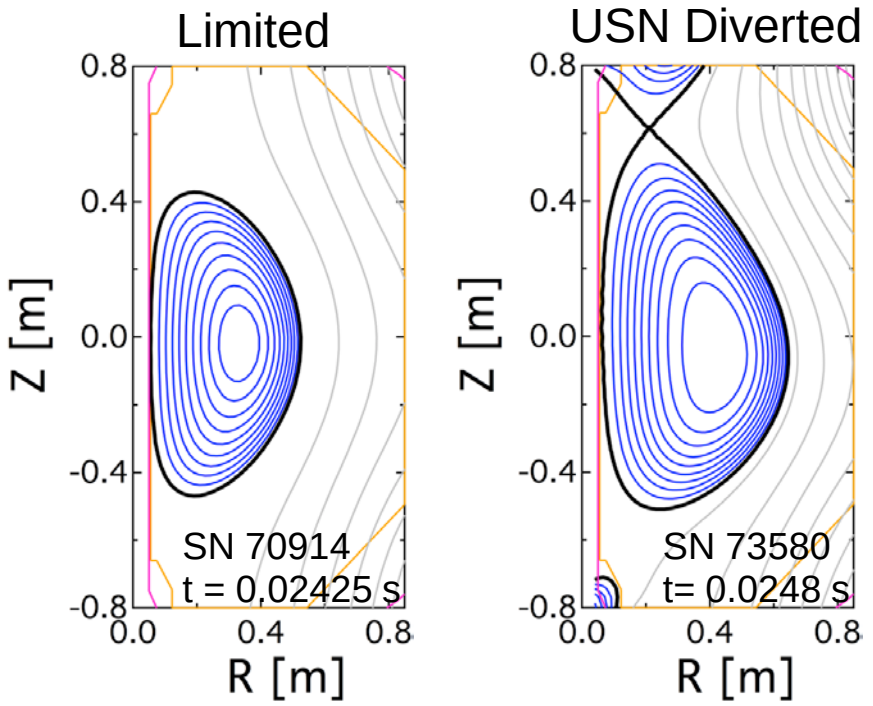
[1] Lao *et al.*, Nucl. Fusion **25**, 1421 (1985)

P_{LH} Measurements Extended to A ~ 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 – 4x10^{19} m^{-3}
    - Inner wall limited
    - Diverted: USN (favorable ∇B)

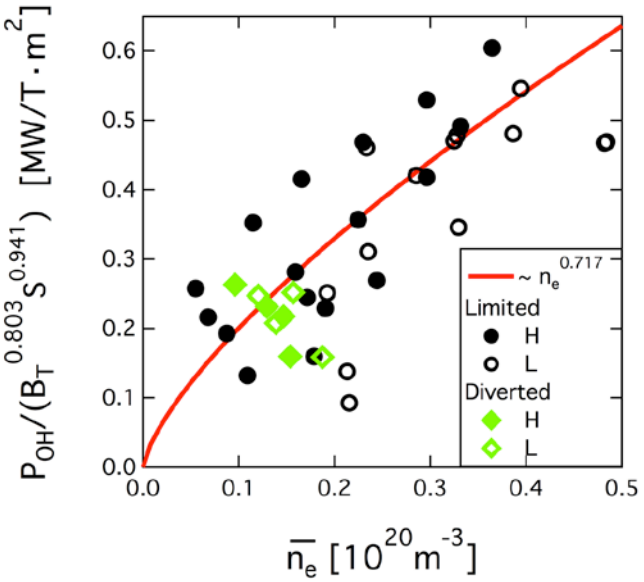
- $P_{LH,exp} = P_{OH} - dW/dt$
  - dW/dt from magnetic reconstructions
  - ~ 30% correction



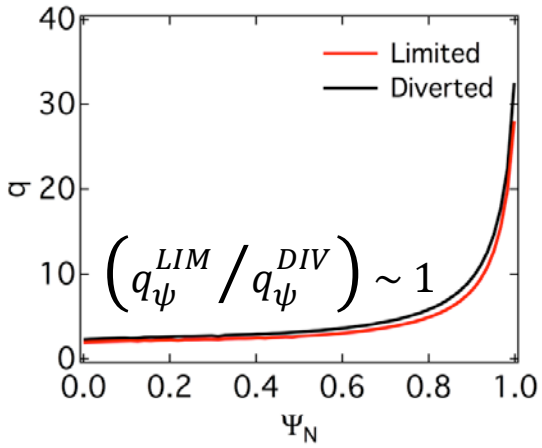


P_{LH} Consistent with Global Parametric Scalings—But Differences Arising at Low A

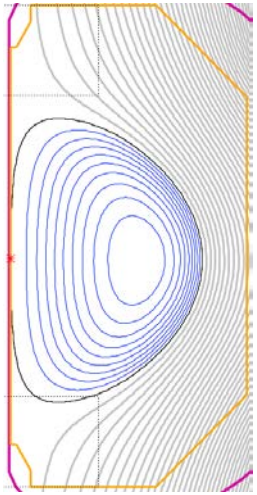
Normalized P_{LH} vs. Density



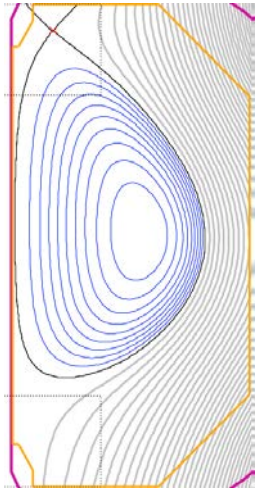
A ~ 1.2 Equilibria



Limited



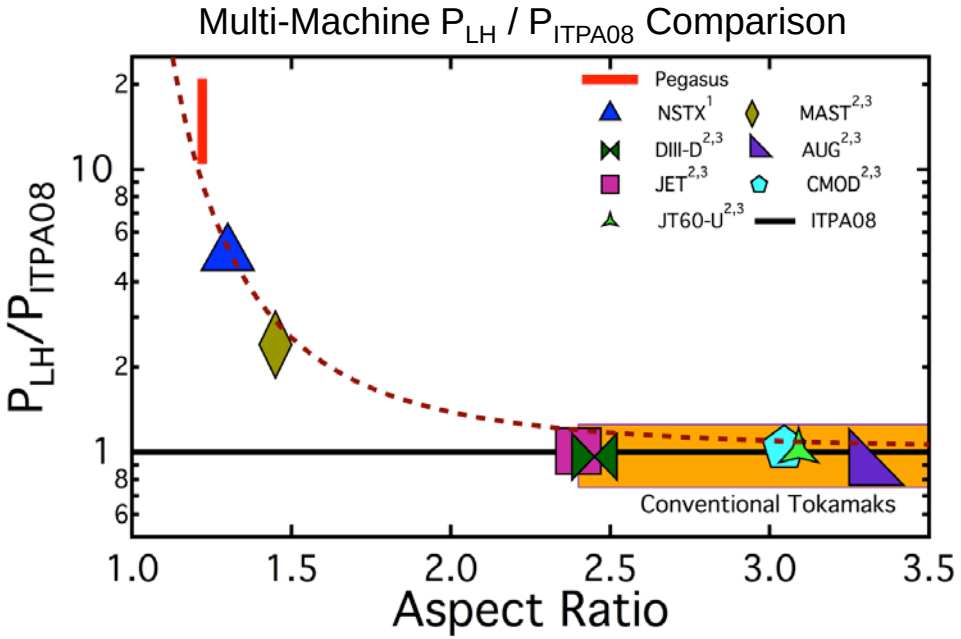
Diverted



- $P_{LH}(n_e)$ consistent with ITPA scaling
  - FM^3 model[1]: minimum $P_{LH}(n_e) \sim 1\times10^{18}$ m^{-3}
- Magnetic topology independence
  - Diverted, limited edge topology similar
  - FM^3: $P_{LH}^{LIM}/P_{LH}^{DIV} \sim \left(q_\psi^{LIM}/q_\psi^{DIV}\right)^{-7/9}$

[1] Fundamenski *et al.*, Nucl. Fusion **52**, 062003 (2012)

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

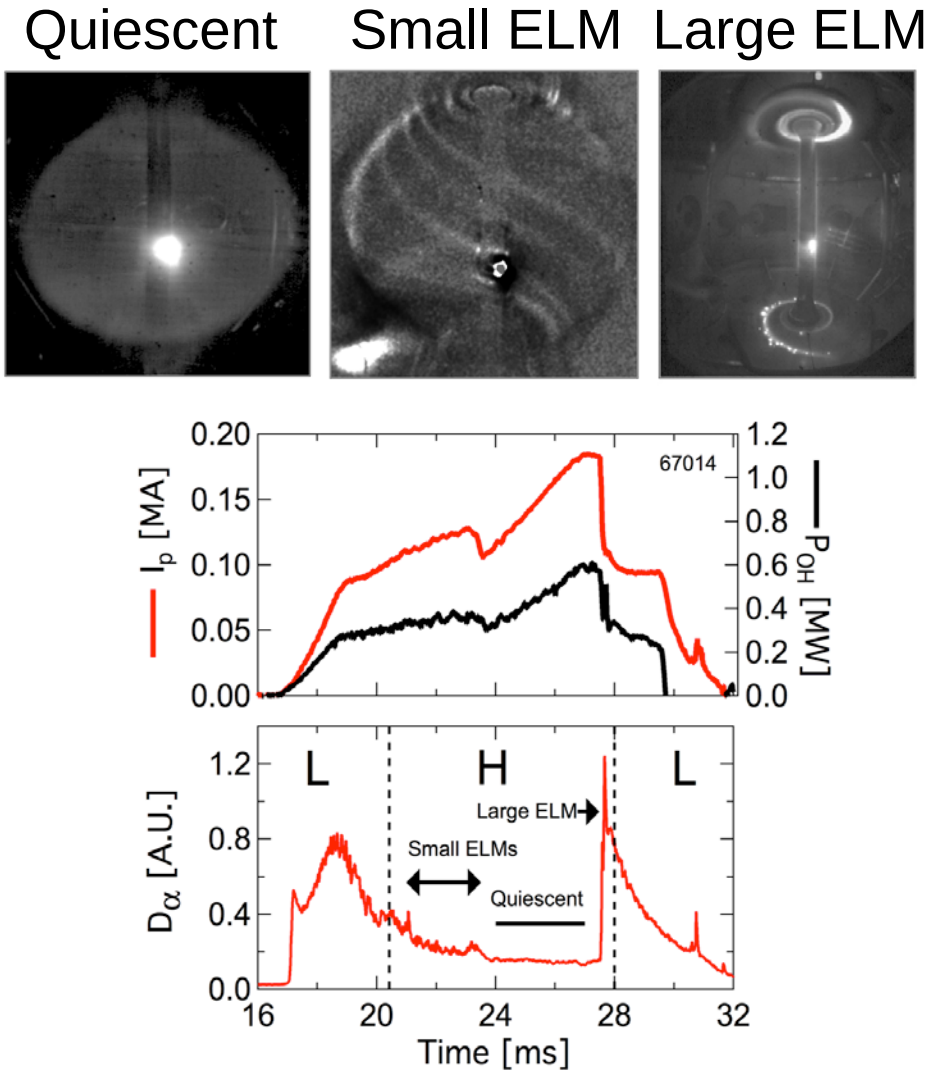


- P_{LH} increasingly diverges from expectations as $A \rightarrow 1$
  - PEGASUS $P_{LH} / P_{ITPA08} \geq 10$–$20$
  - Confirms trend from NSTX, MAST
- Discrepancy may hint at additional physics

[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

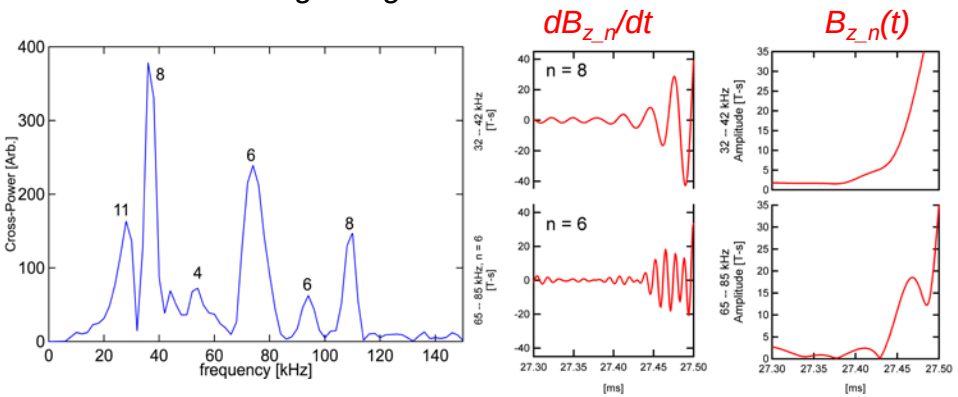
- Filament structures observed
  - Coincident with D_α bursts
- Small ("Type III") ELMs ubiquitous, less perturbing
  - $P_{OH} \sim P_{LH}$
  - Low n
- Large ("Type I") ELMs infrequent, violent
  - $P_{OH} >> P_{LH}$
  - Intermediate n
  - Can cause H-L back-transition



Details of Nonlinear ELM Behavior Emerging

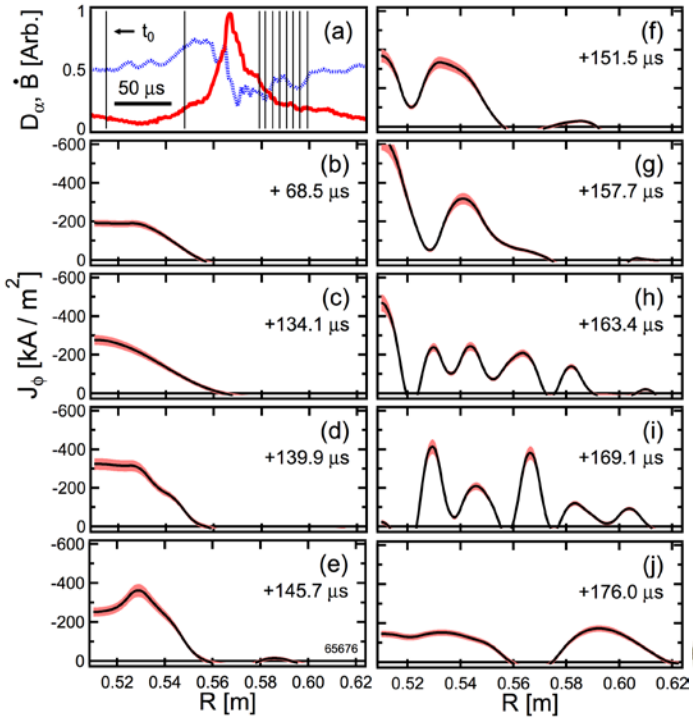
- Simultaneously unstable toroidal modes present during ELM
  - Detectable only within ~ cm of LCFS
  - Nonlinear energy exchange

Edge Magnetic Probes on PEGASUS:



Large ELM Magnetic Structure *ELM mode growth*

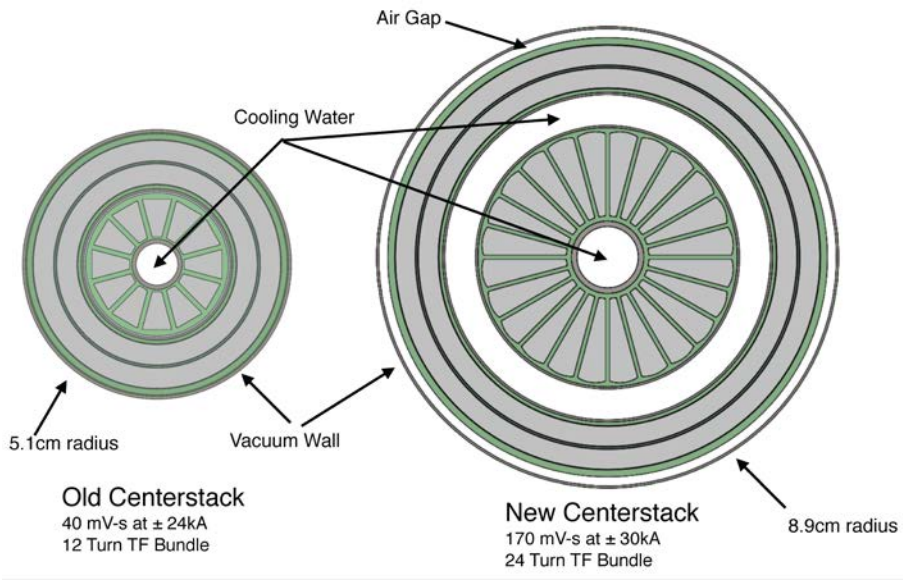
- Complex, multimodal $J_{edge}(R, t)$ collapse
  - High $\Delta t \sim 6$ μs through single large ELM
  - Current filament ejection

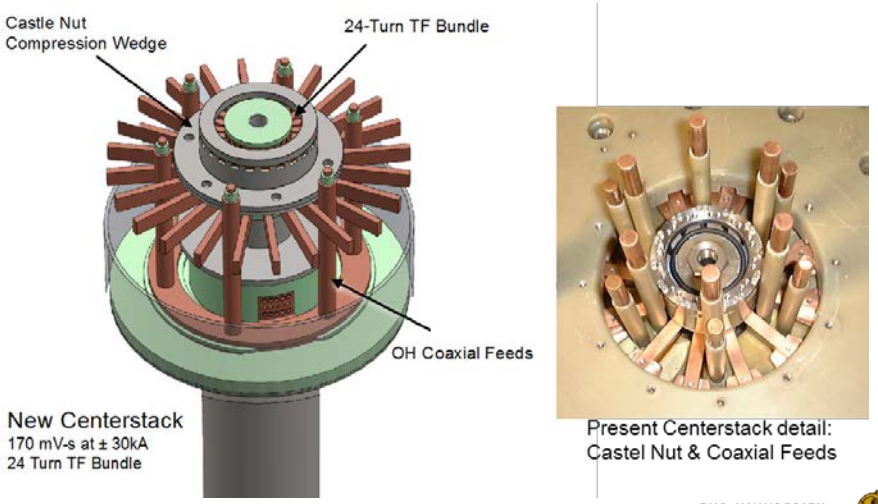


- **Challenge:** studies of nonlinear ELM dynamics at Alfvénic timescales

Results Motivate PEGASUS-U Upgrade Proposal

- New centerstack assembly
  - OH solenoid via PPPL collaboration
    - $\Delta\Phi_{OH}$: 40 → 170 mV-s
  - TF bundle: 0.15 → 0.40 T
  - Pulse length: 15 → 50–100 ms
- Power system, control upgrades
  - New TF power supply
    - I_{TF} × 3–4
  - Upgraded OH power supply
    - Improved V_{loop} control
- Comprehensive 3D-Magnetic Perturbation System
- Longer-term: ECH auxiliary heating
  - In discussion with ORNL

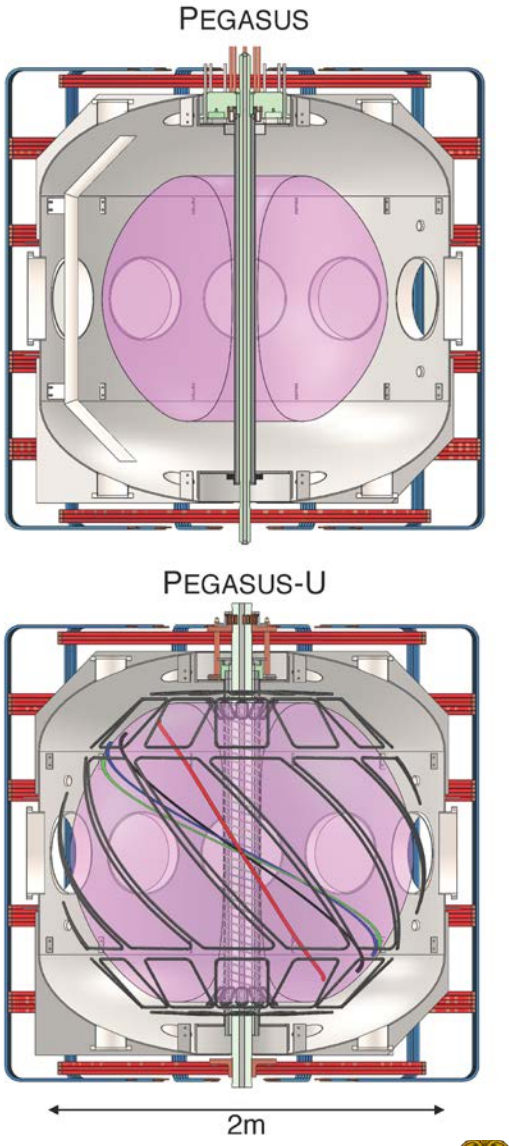




"Castle Nut" compression wedge in proposed, present assemblies.

PEGASUS-U Supports Focused Physics Mission

- Nonlinear pedestal and ELM studies
  - Simultaneous measurements of p(R,t), J(R,t), v_ϕ (R,t)
    - New edge diagnostics (probe arrays, DNB)
  - Tests of Sauter neoclassical bootstrap model
- ELM Modification and Mitigation
  - Novel 3D-MP coil array
    - LFS array: 12 toroidal × 7 poloidal
    - Helically-wound HFS coils
  - LHI current injectors in divertor, LFS regions
- Physics of Local Helicity Injection Startup[1]
  - High I_p, long-pulse startup
  - Projections to NSTX-U



1: J.A. Reusch, Session O6, Friday

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; $H_{98} \sim 1$
- Features unique to low-*A* emerging
  - Strong P_{LH} threshold scaling with *A*
  - Insensitivity to magnetic topology
- Operating regime allows detailed ELM studies
  - Nonlinear ELM dynamics on Alfvénic timescales
- PEGASUS-U planned to address critical physics, technology issues
  - Nonlinear ELM, pedestal physics with local edge diagnostics
  - Comprehensive 3D-MP and J_{edge} injection for ELM migitation / control
  - Tests of LHI at NSTX-U relevant field, pulse length

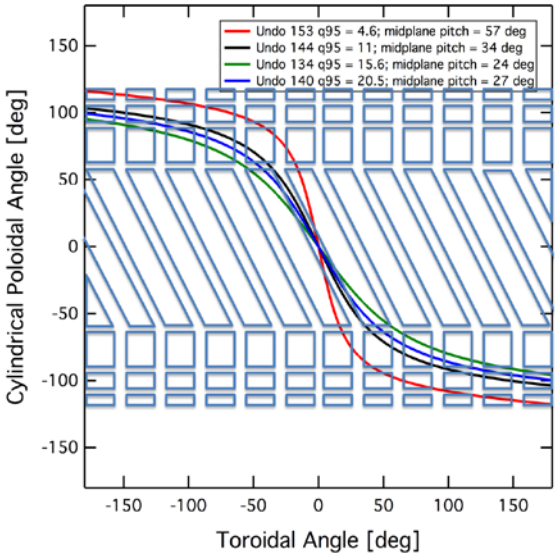
BACKUP

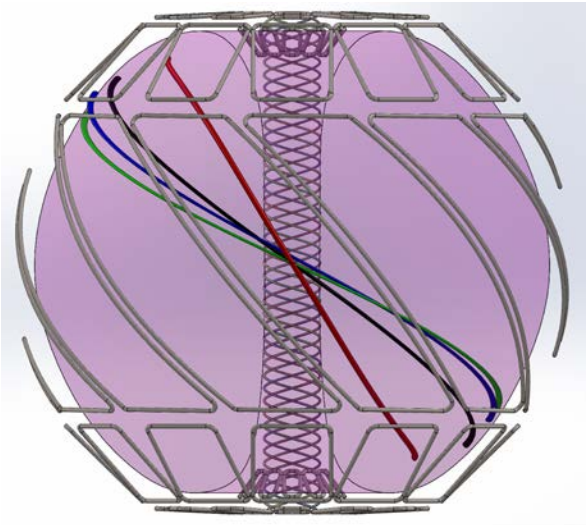
3D-Magnetic Perturbation System Proposed

- Design study, fabrication as proposed work

- Comprehensive 3D-MP system
  - LFS coils, spaced with ~equal-PEST angle from model equilibria
    - 12 toroidal x 7 poloidal array
    - Initial DC power systems for n=3 control
  - HFS 4-fold helical coil set

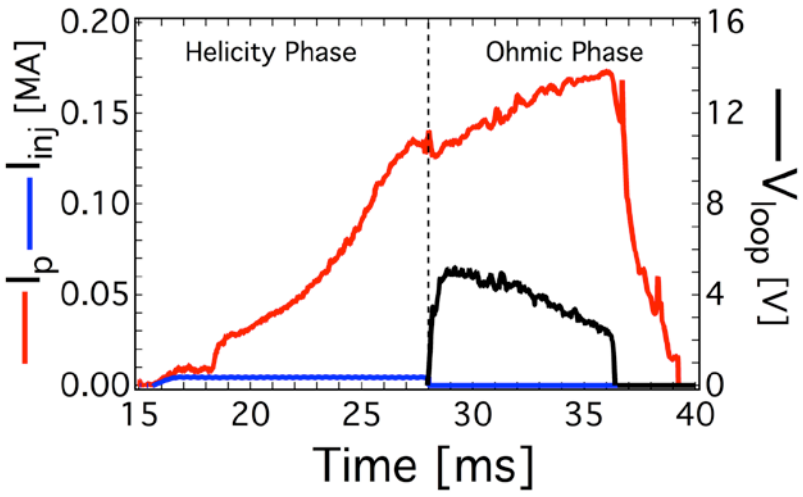
- Uniqueness
  - Wide spectral range
  - Local pedestal plasma response measurements



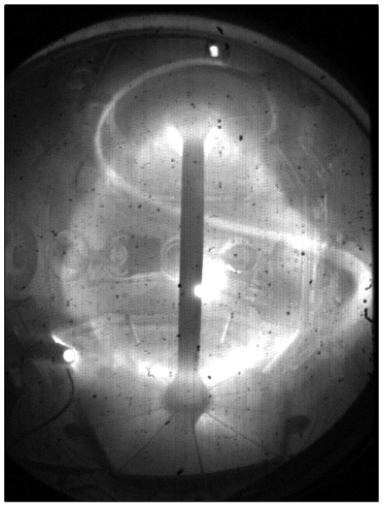


3D Edge Current Injectors Support ELM Studies

- Local helicity injection system provides 3D SOL current injection
  - $I_{inj} \leq 5$ kA, J_{inj} ~1 kA/cm^2
- LHI use with H-mode studies
  - Pulse extension and J(R) control

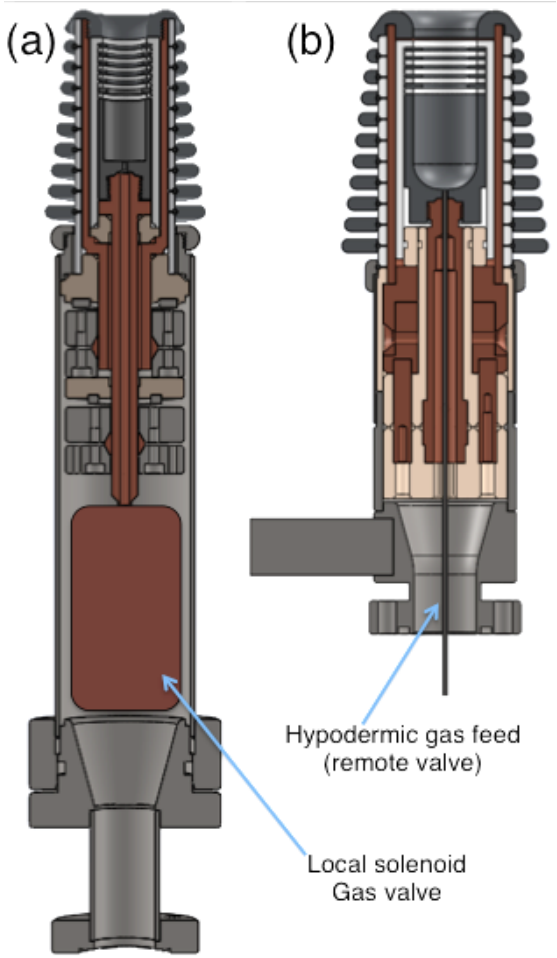


- LHI system affects edge plasma
  - Strong 3D edge current perturbation
    - Similar to LHCD on EAST[1]
  - Edge biasing to modify rotation profiles

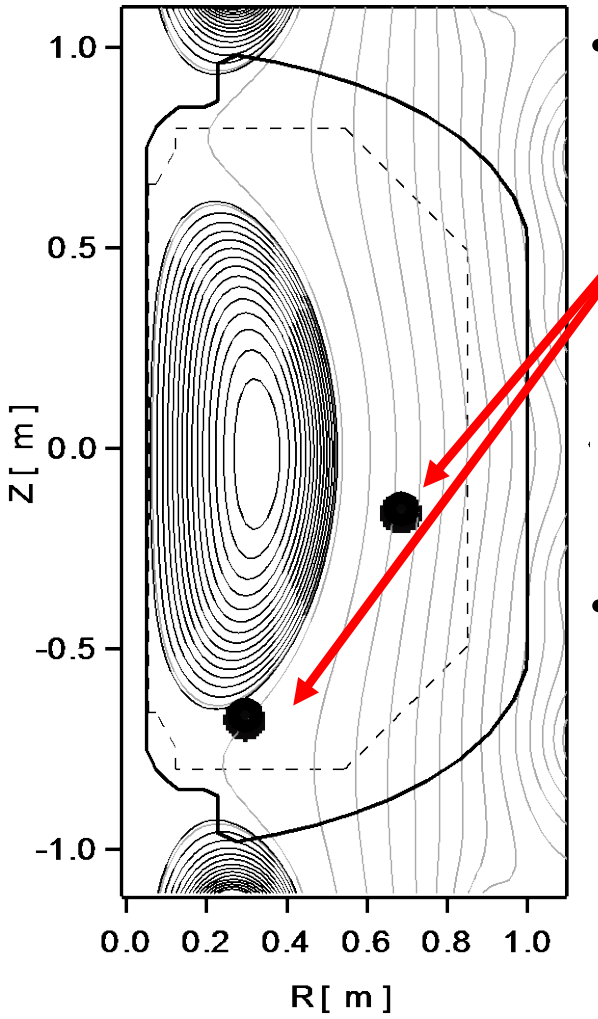


1: Liang *et al.*, Phys. Rev. Lett. **110**, 235002 (2013)

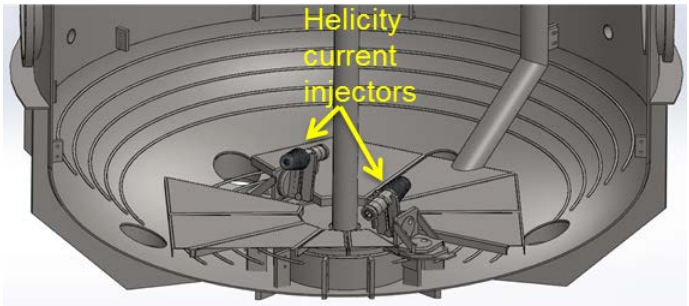
Pegasus-U LHI Injector Configuration



(a) Present injector cross-section; (b) proposed new injector design.



- Four, large-A_{inj} injectors
  - 2 cm^2 → 4 cm^2
  - LFS, HFS locations
  - Modest P/S devel. for long-pulse
    - *e.g.* cathode-spot quench interrupter circuit
- Supports confinement, scaling studies for NSTX-U



Ohmic H-mode Plasmas Have Standard Signatures

- Quiescent edge
  - Edge current, pressure pedestals
- Reduced D_α emission
- Large and small ELMs
- Bifurcation in ϕ_D
  - Correlates with improving τ_e