Effect of Aspect Ratio on H-mode and ELM Characteristics

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PEGASUS
Toroidal Experiment

Layout

8.5” x 11”

8’ W x 4’ H

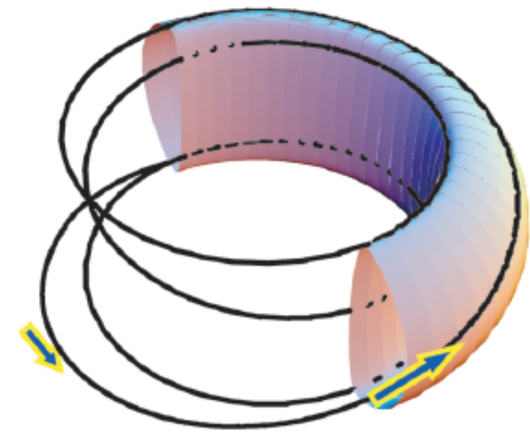
Title Banner

Motivation I	H-mode Characteristics I	H-mode Characteristics II	Power Threshold	ELMs	Future Work
Motivation II	Energy Confinement Improves in H-Mode	Pegasus Hall Probe Deployed	Noise Shielding in Pegasus	Large Type I and II ELMs observed	Pressure correlation with MHD fluctuations
Pegasus	Pegasus has the ability to produce current and pressure pedestal	J (R,t) calculated from Ampere’s Law	Simplified LP Circuit/ Grounding Scheme	Hall Probe Observes Large ELM dynamics through discharge	Pressure profiles suggest existence of edge pedestal
H-mode Upgrades	P_{LH} dependence upon Aspect Ratio	Direct J Profiles obtained in Pegasus	Triple Probe Theory	Closer Inspection of J_{edge} reveals complex behavior	Future experiments with low MHD are needed

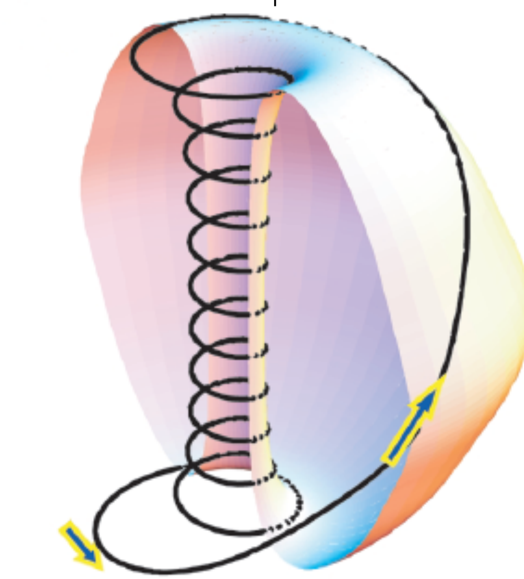
H-mode Studies Across Physics Regimes Crucial

- ITER will operate in H-mode
- Parameter variations critical to validate theories of H-mode and ELM behavior
- Toroidal aspect ratio *A* changes H-mode access, equilibrium, and stability
- Low-*A* H-mode differences
  - Fueling location importance
  - P_{LH} and ELM characteristics
  - Magnetic configuration effects

$A \geq 4,\ q_\psi \geq 4$



$A \geq 1.25,\ q_\psi \geq 12$

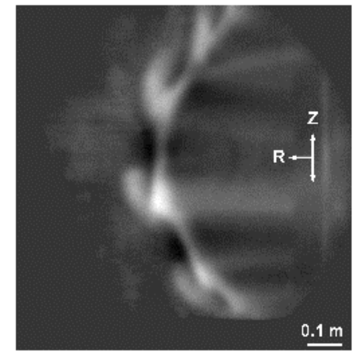


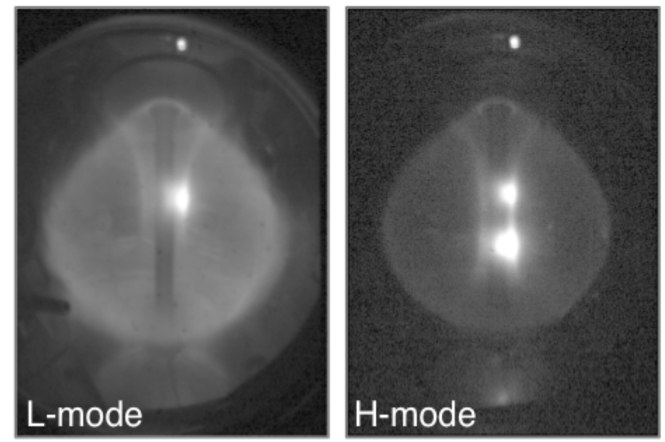
Peng, Phys. Plasmas, **7**, 1681 (2000).

A ~ 1 Operations Provide Access to AT Physics

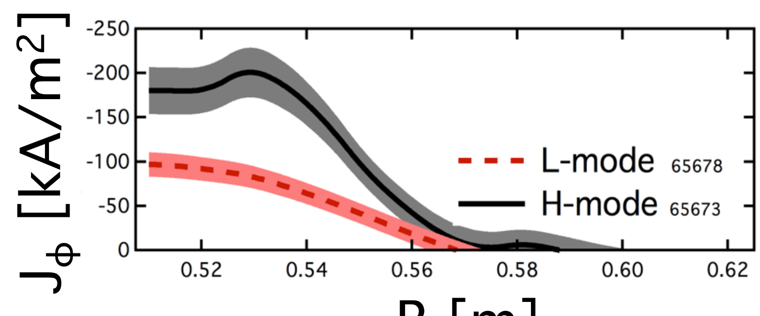
- *A* ~ 1 → high I_p at very low B_T
  - Excitation of peeling modes without J_{BS}[1,2]
  - Easy access to H-mode regime and ELMs
  - Neoclassical effects (resistivity enhancement)

PEGASUS





- Modest-sized plasma and relatively low T_e
  - Allows diagnostic access to pedestal
  - Pedestal $J_\phi(R, t)$, $p(R, t)$, and v_ϕ (R, t) via probes



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

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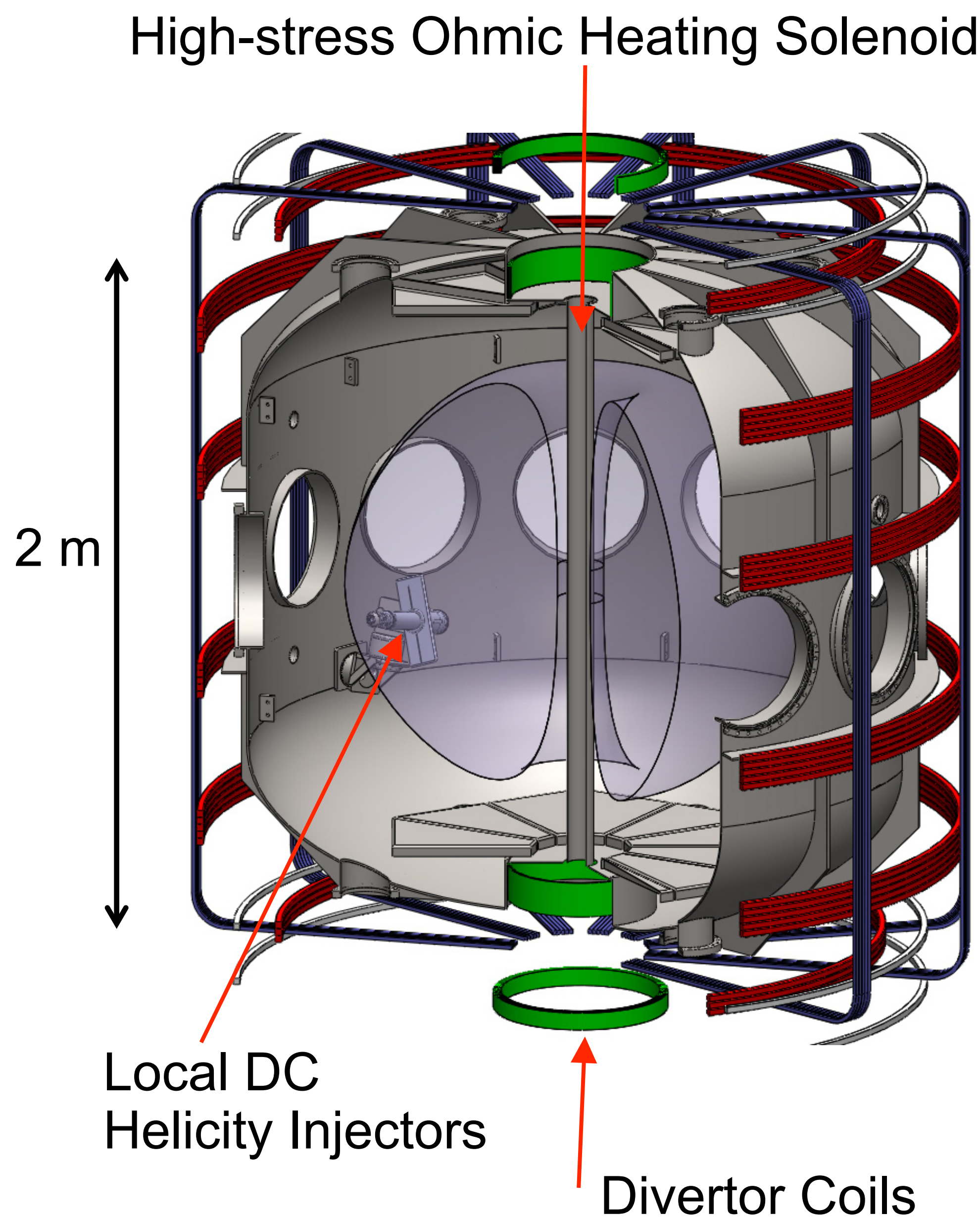
PEGASUS Provides H-mode Plasmas at Ultralow-A

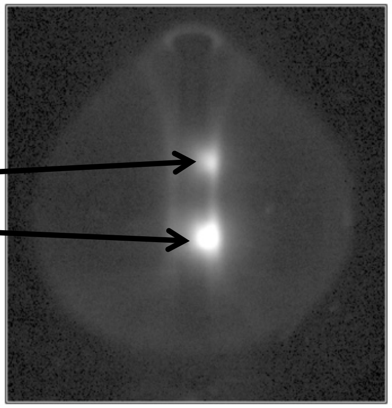


Experimental Parameters

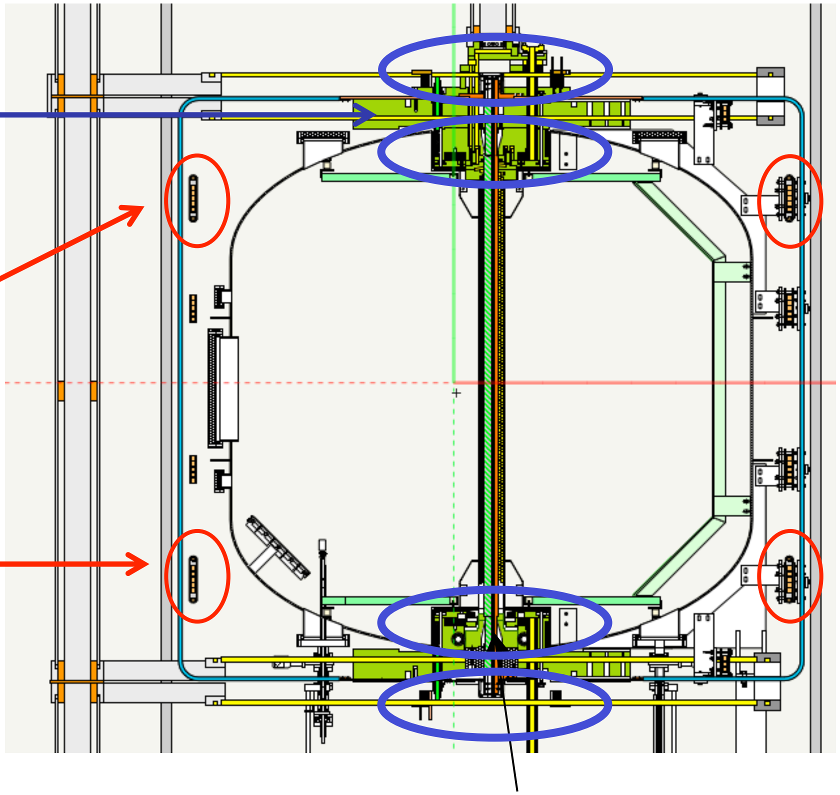
A	1.15 – 1.3
R (m)	0.2 – 0.45
I_p (MA)	$\leq$ 0.25
B_T (T)	< 0.2
Δt_{shot} (s)	$\leq$ 0.025
Z_{eff}	~ 1
Recycling Coefficient	< 0.7

Recent Upgrades for H-mode Studies

- High-field-side (HFS fueling)
  - Two valves (top and bottom)
  - Improved density control



- Augmented divertor coils
  - New external divertor set
  - Allows SN, DN operation
- Radial field coils
  - Vertical position control

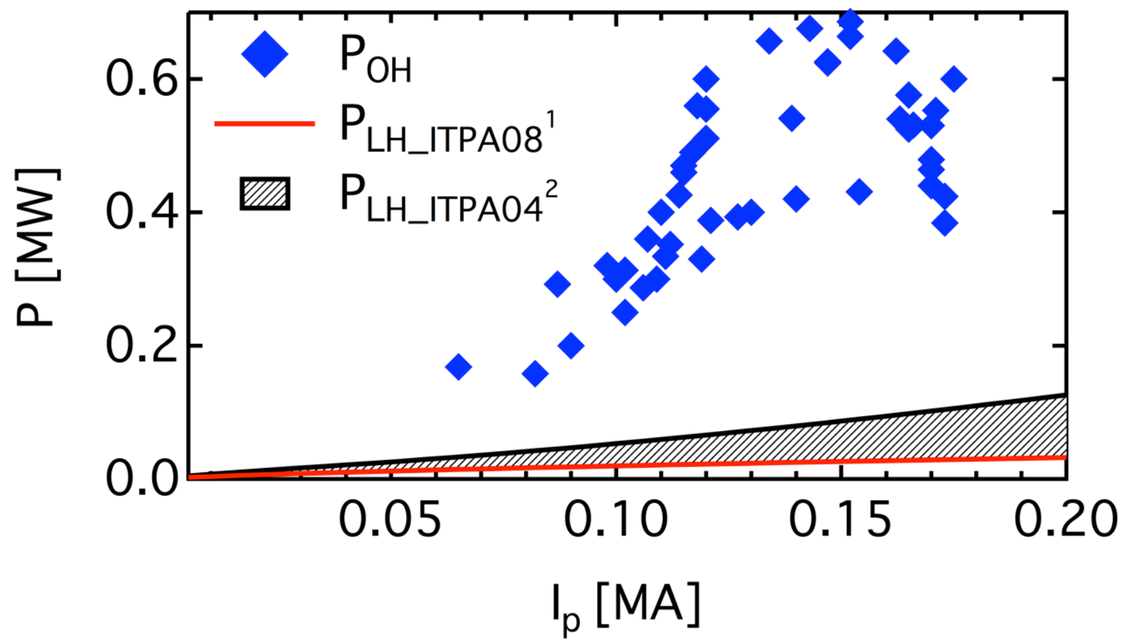


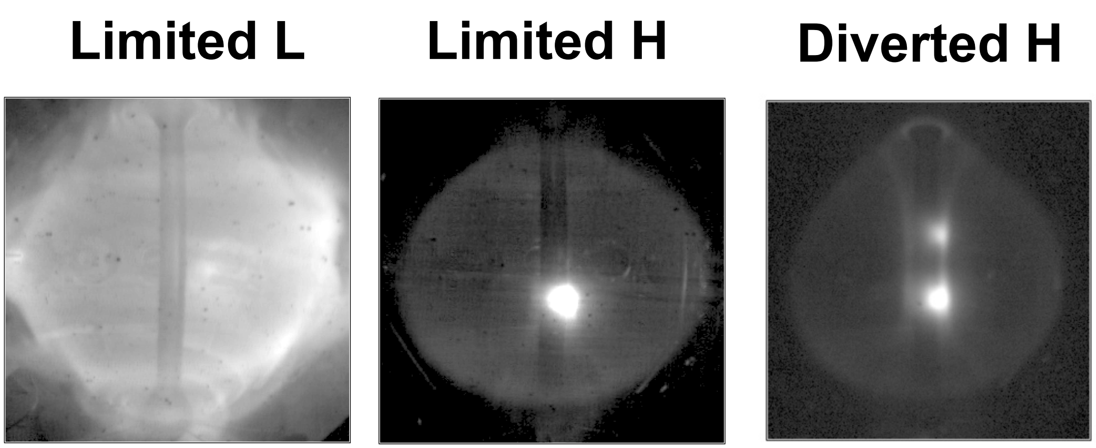
H-mode Readily Accessed at Near-Unity A

- $A \approx 1 \rightarrow$ 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 neutral fueling
    - Similar to other STs
  - Limited or diverted plasmas



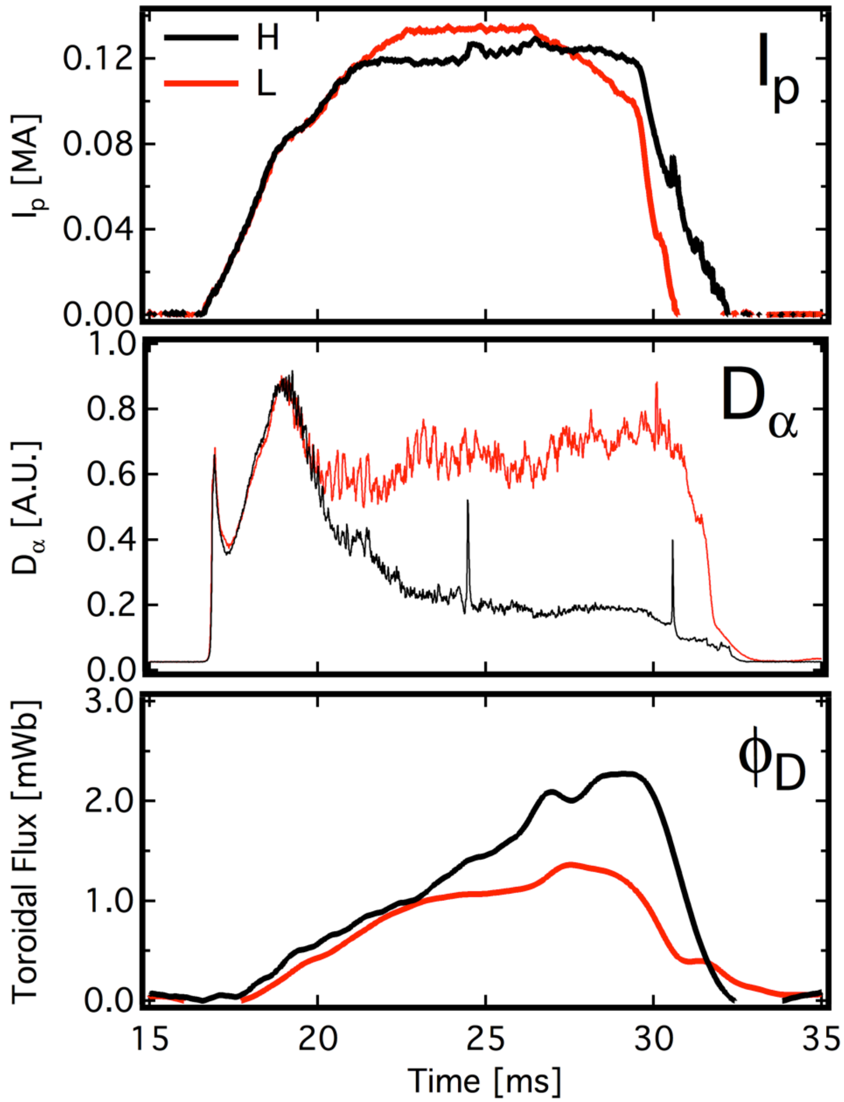


Fast visible imaging, $\Delta t \sim 30$ μs

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

Standard Signatures Observed in OH H-mode

- 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

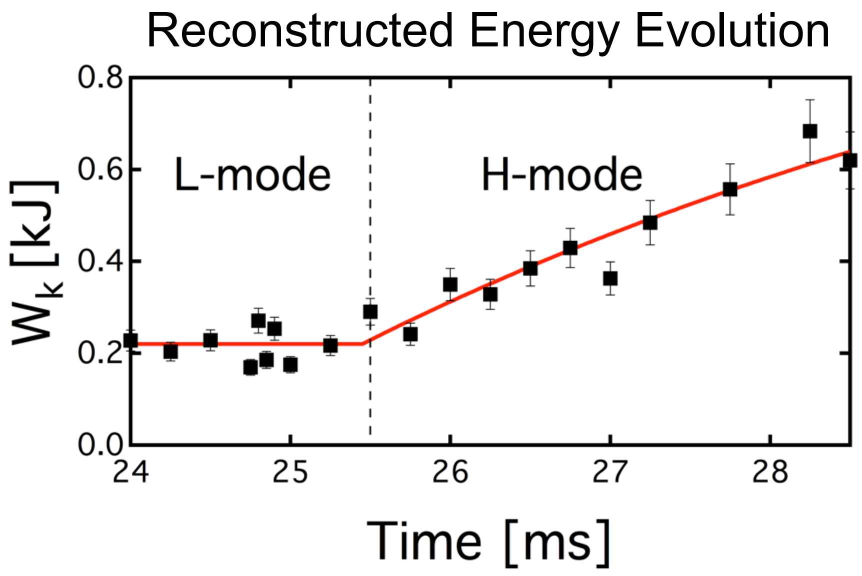


Energy Confinement Improves in H-mode

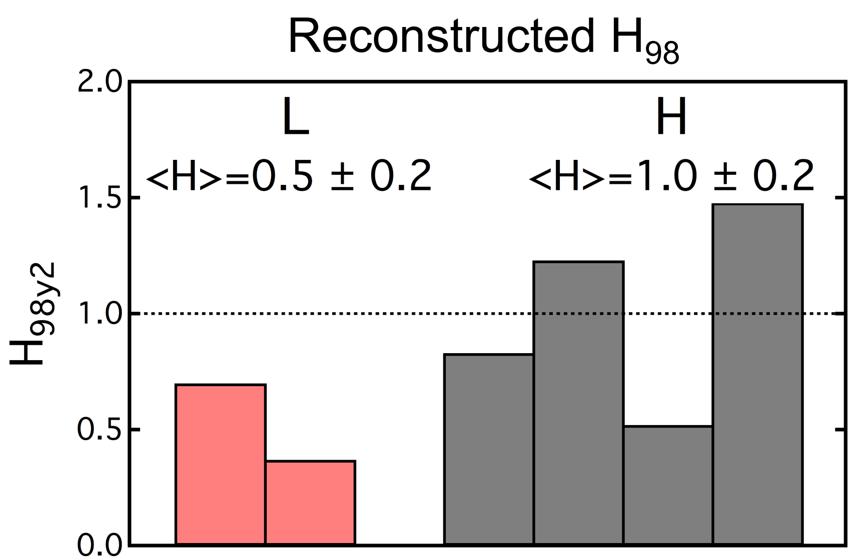
- Equilibrium reconstructions yield τ_e

$$\tau_e = \frac{W_k}{P_{in} - dW/dt - P_{RAD}}$$

  - 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

Full Virial Analysis is Required as A → 1

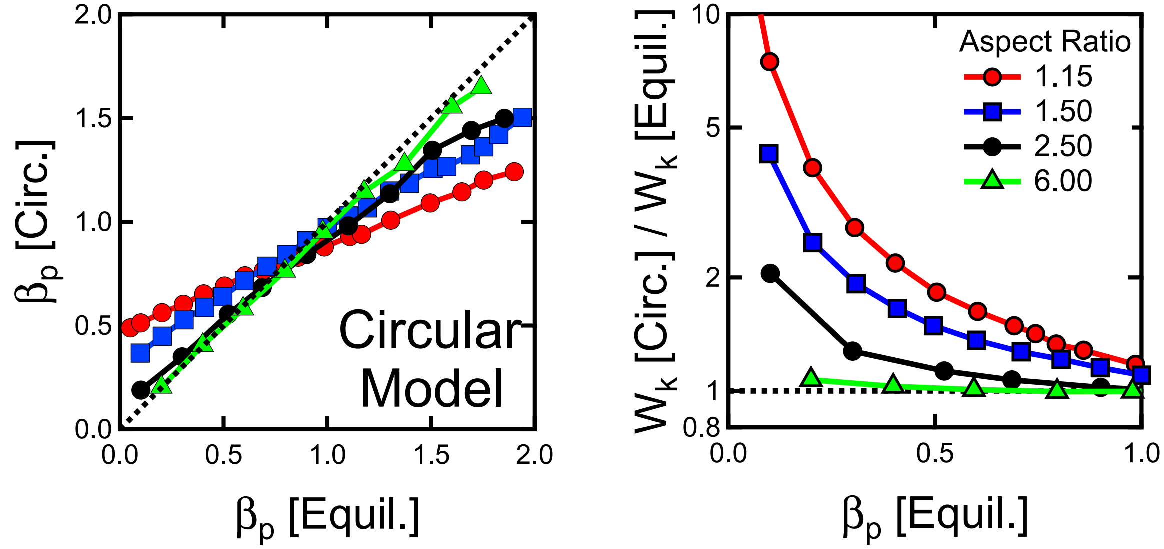
- Provides magnetics based β_p, W_k, and τ_e[1]

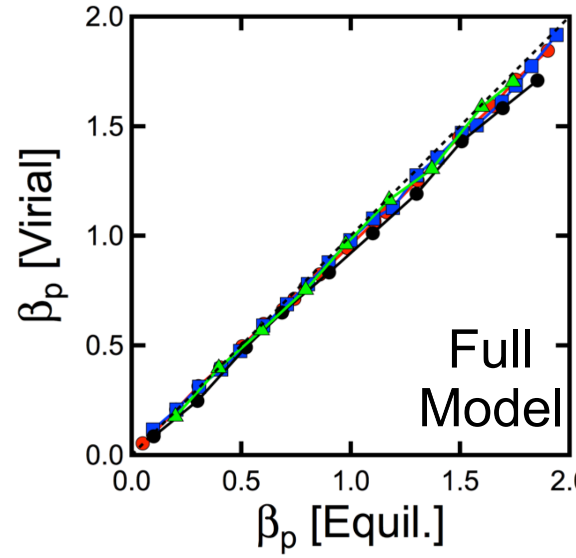
- High-*A*: $\beta_{p,circ} \approx 1 + \mu$
  - Overestimates β_p, W_k at low-*A*
  - $\mu = 4\pi B_{T0} R_0 \Delta\Phi / B_{pa}^2 \Omega$

- Low-*A*: $\beta_p = S_1/2 + S_2/2(1 - R_T/R_0) + \mu$
  - Full treatment accurately determines β_p, W_k

- In progress: fast boundary reconstruction code for full treatment at *A* ~ 1

Comparison of Virial Analyses with Model Equilibria





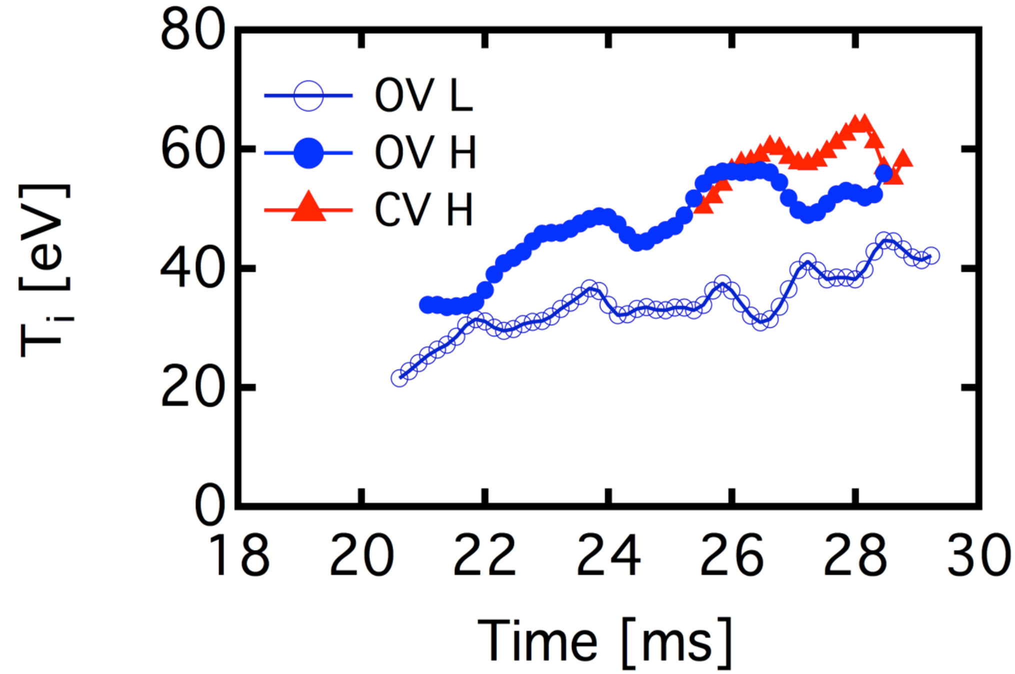
[1] Lao *et al.*, Nucl. Fusion **25**, 1421 (1985).

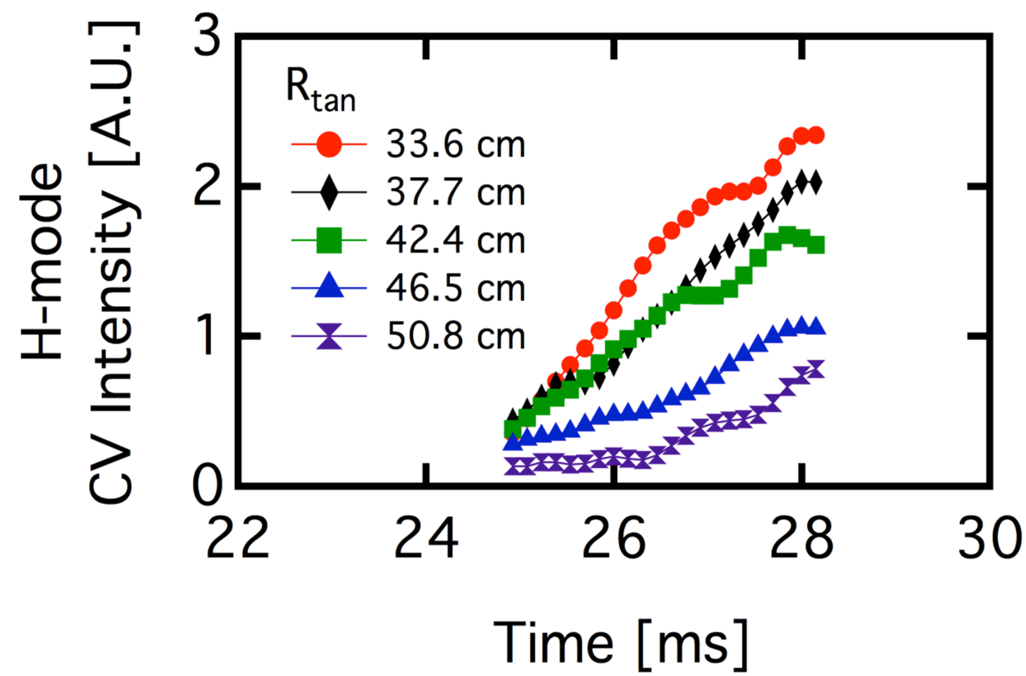
T_i and T_e Increase in H-mode

- OH plasmas: $T_i \ll T_e$

- Impurity T_i doubles

- Increasing $T_e(0)$
  - Increasing, peaking CV emission observed in H-mode





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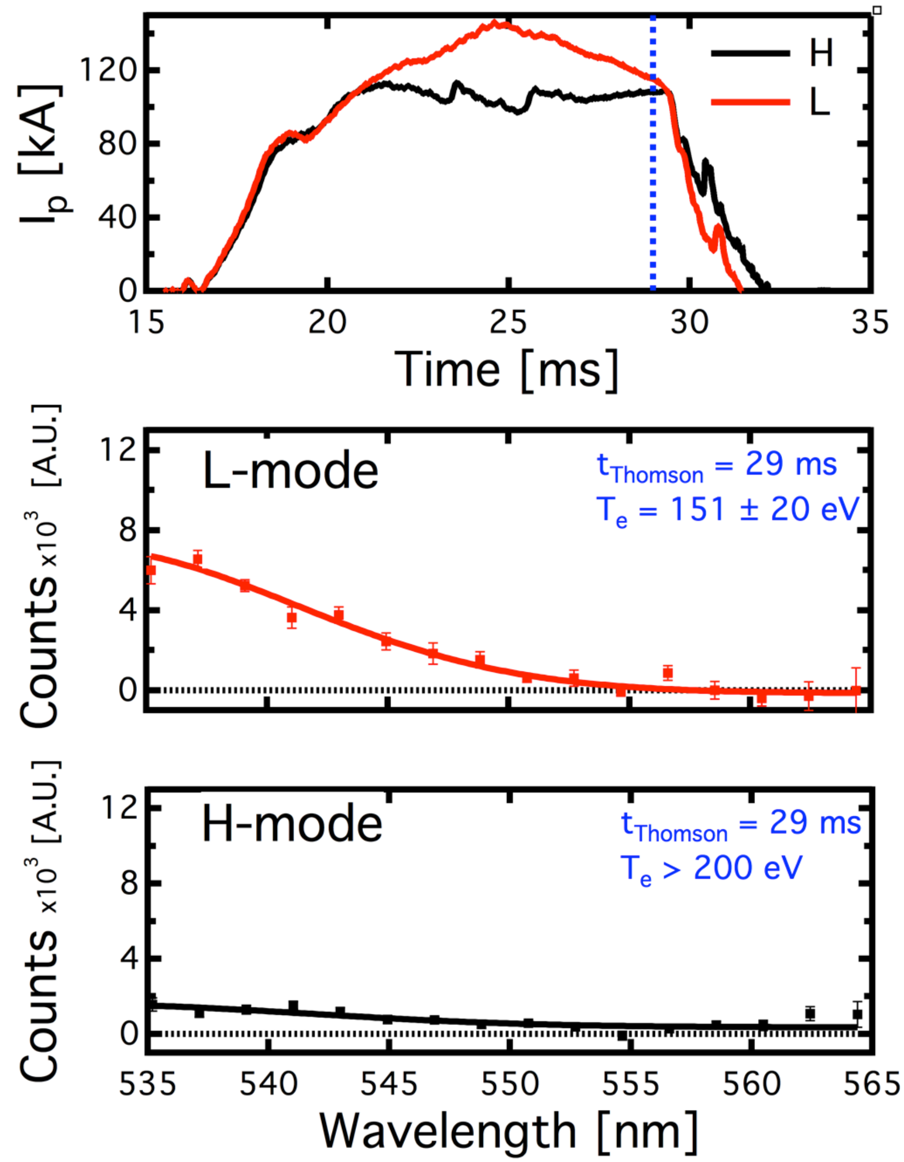
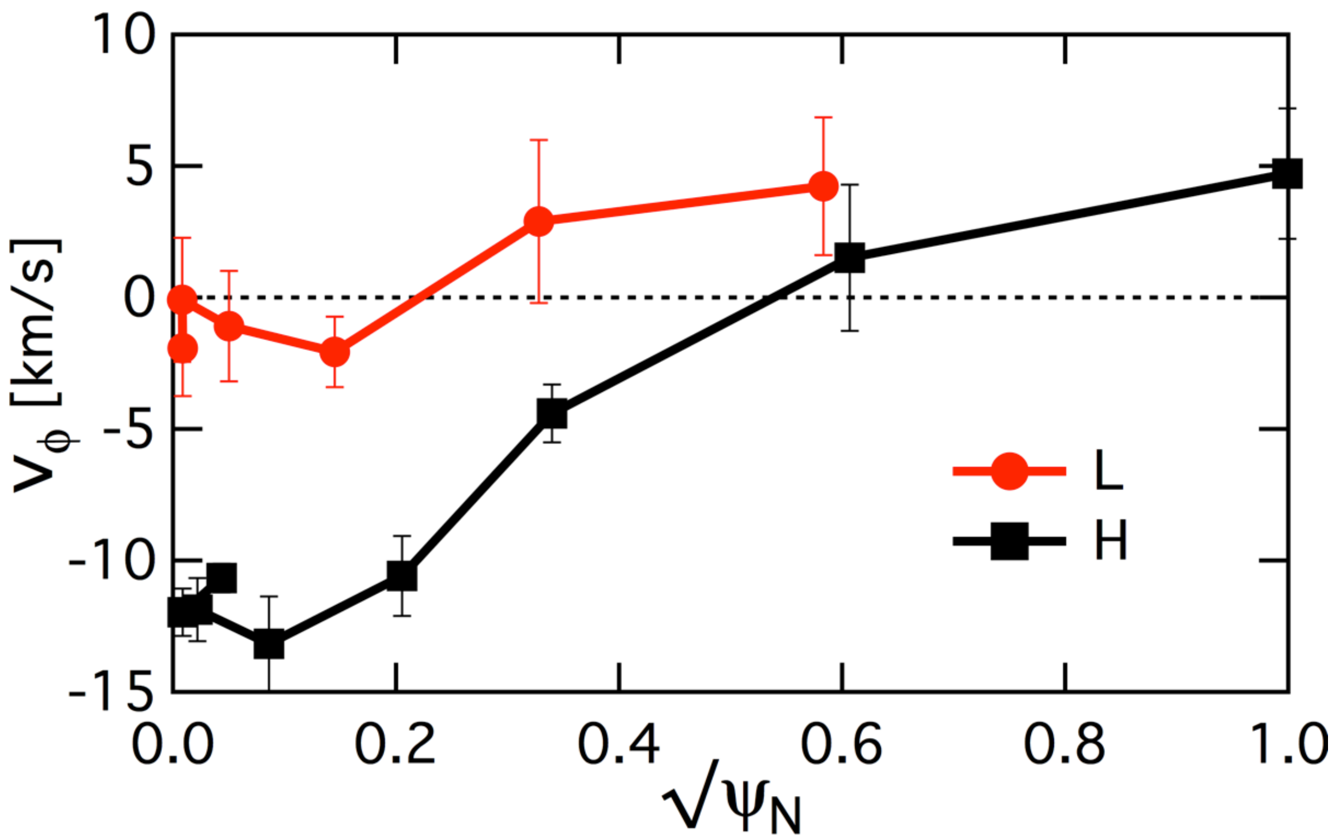
Thomson Scattering Indicates Higher H-mode T_e

- Initial measurements
  - Grating optimized: $T_e \leq 100$ eV
- L-mode: $T_e(0) \sim 150$ eV
- H-mode: $T_{e,H}(0) > T_{e,L}(0)$
  - Spectrum broadened off low T_e grating
  - Comparable n_e, but lower peak emission
- Diagnostic upgrades improve spatial and T_e resolution
  - Alternate grating: $T_e \leq 1$ keV



*See posters 118 and 119 for more detail

Strengthened Core Rotation in H-mode



- No external momentum input — intrinsic rotation
- Chordally-integrated velocity profiles show low rotation in L-mode

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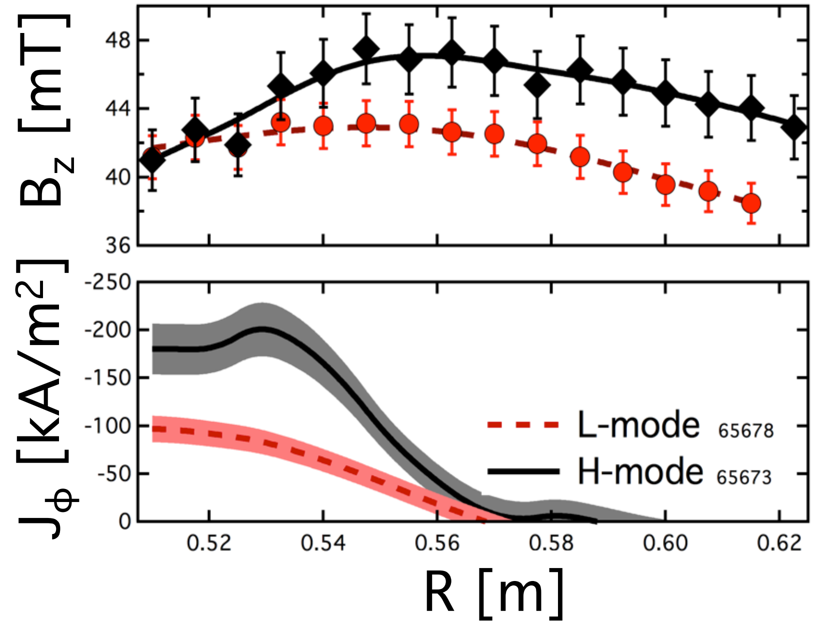
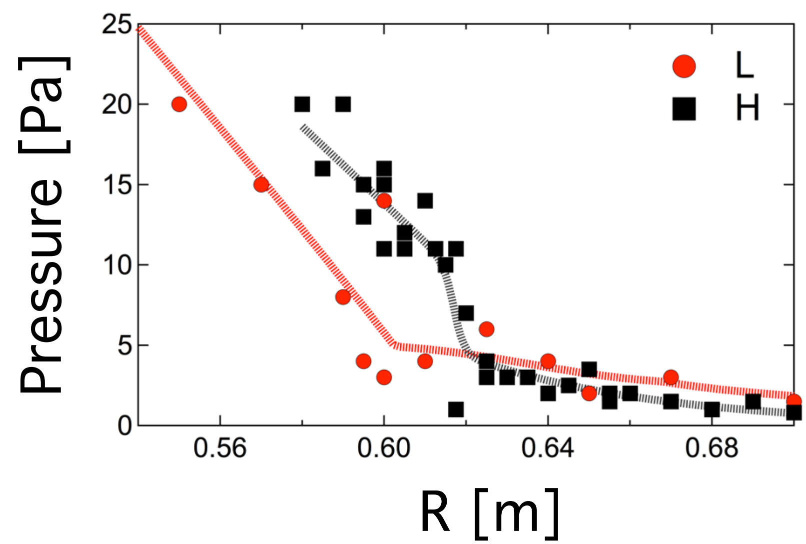
Edge Pedestals Measured with Probes

- *A* ~ 1: very low $B_T \rightarrow$ low T_e
  - Unique pedestal access with probes
- Inter-ELM current pedestal formation
  - Measured with Hall probe array[1,2]
  - Scale length: 4 → 2 cm L to H
- Pressure pedestal observed
  - Multi-shot scan with triple Langmuir probe
  - Edge distortion effects removed
    - See poster 120 for more information

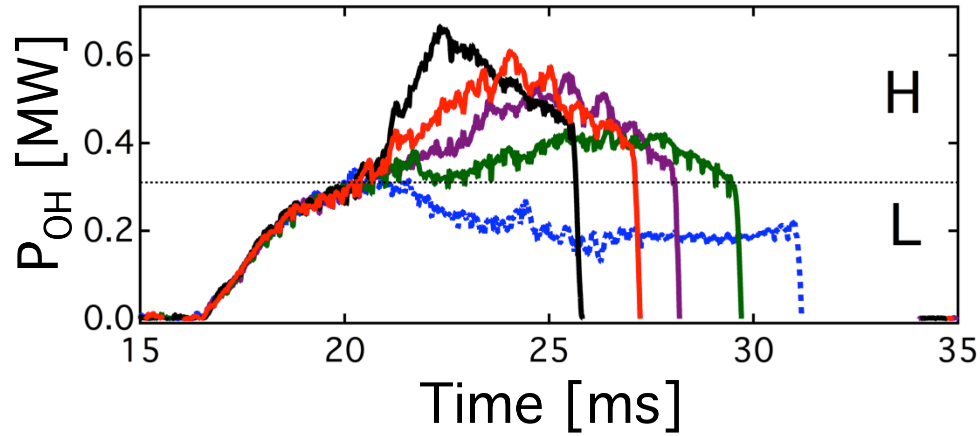


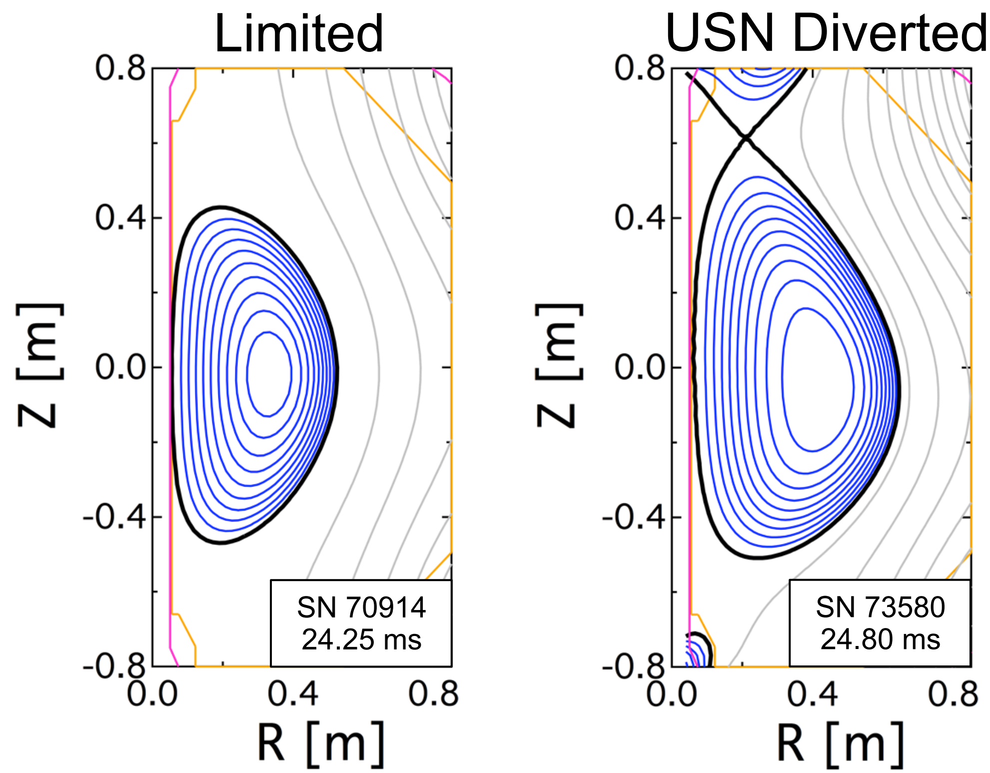


[1] Bongard *et al.*, Phy. Rev. Lett. **107**, 035003 (2011).
[2] Petty *et al.* Nucl. Fusion **42**, 1124 (2002).

L-H Power Threshold Determined at $A \approx 1.2$

- Extends P_{LH} to $A \sim 1$ regime
- 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}
    - Limited: Centerstack
    - Diverted: USN (favorable ∇B)
- $P_{LH,exp} = P_{OH} - dW/dt$
  - dW/dt by magnetic reconstruction
  - ~ 30% correction

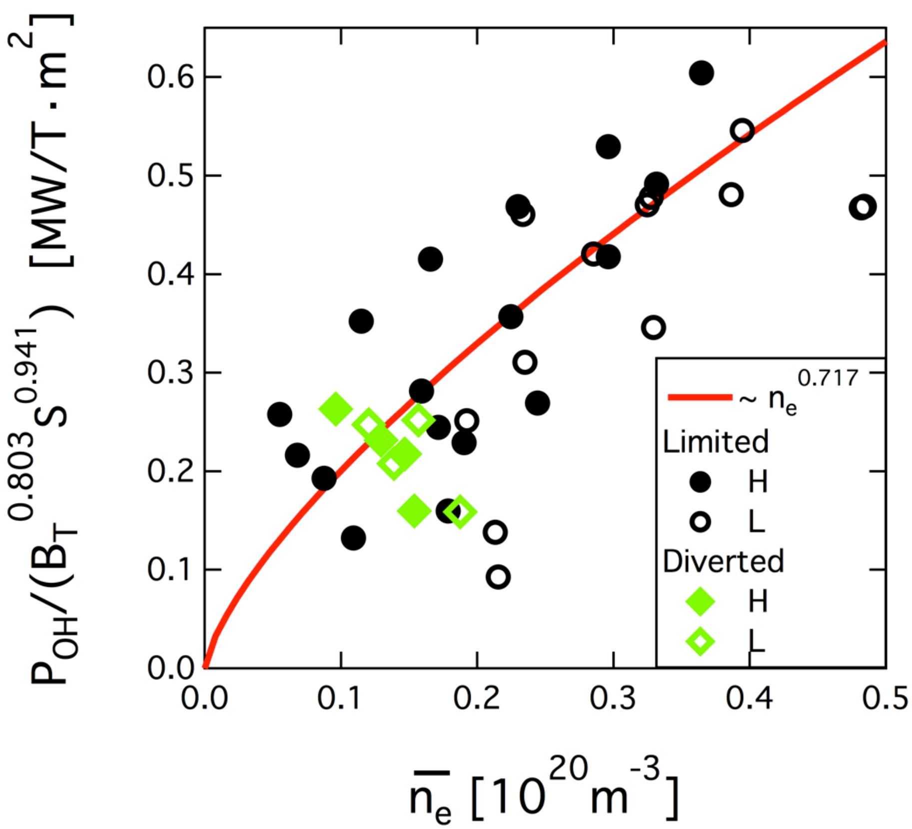




P_{LH} Shows Strong Density Dependence

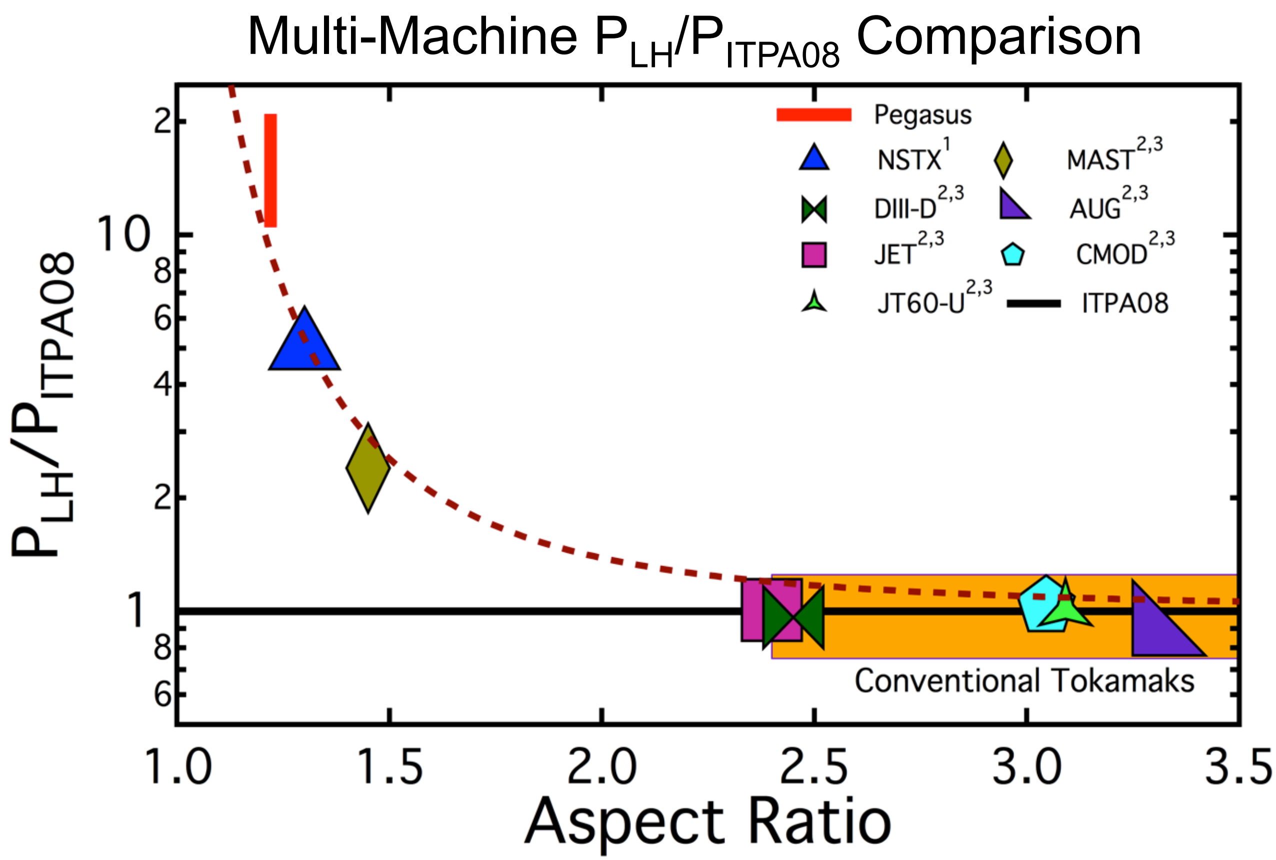
Threshold Power vs. Density

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



- Survey of L and H-mode plasmas at different P_{OH} and n_e
- P_{LH} increases with n_e
  - n_e dependence consistent with scalings
  - Density minimum not apparent
- Topology independent
  - Diverted and limited P_{LH} similar

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



- P_{LH} increasingly diverges from expectations as $A \rightarrow 1$
- 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.

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Some P_{LH} Results Consistent with FM^3 Model

- FM^3 model reproduces P_{ITPA08} scaling

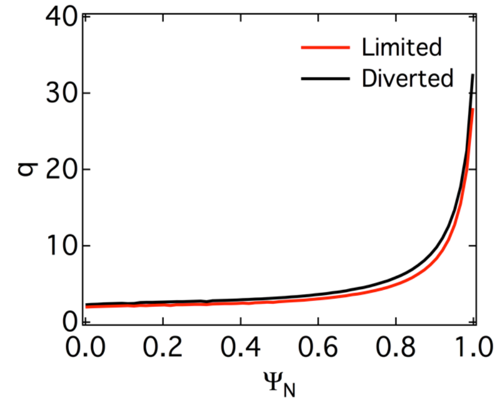
- FM^3: $P_{LH}(n_e)$ minimum ~ 1 x10^{18} m^{-3}
  - n_e/n_G<<0.1, inaccessible due to runaways

- P_{LH} topology independence

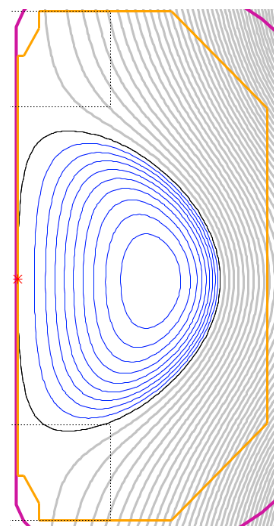
$$\frac{P_{L-H}^{lim}}{P_{L-H}^{div}} \approx \left(\frac{q_*^{lim}}{q_*^{div}}\right)^{-7/9} \qquad \begin{array}{l} >>1 \;@\; A\sim 3 \\ \rightarrow 1 \;@\; A\sim 1 \end{array}$$

- Strong $P_{LH}(A)$ not understood
  - Multi-machine P_{LH} studies in progress/ proposed (NSTX-U, PEGASUS, DIII-D)

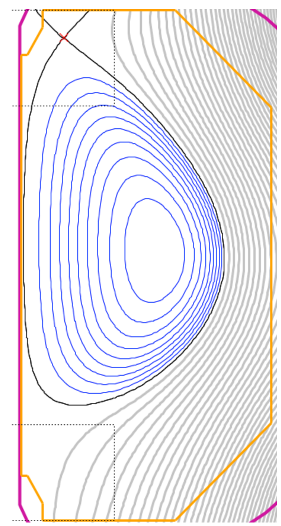
Predictive Equilibria @ $A \approx 1.2$



Limited



Diverted

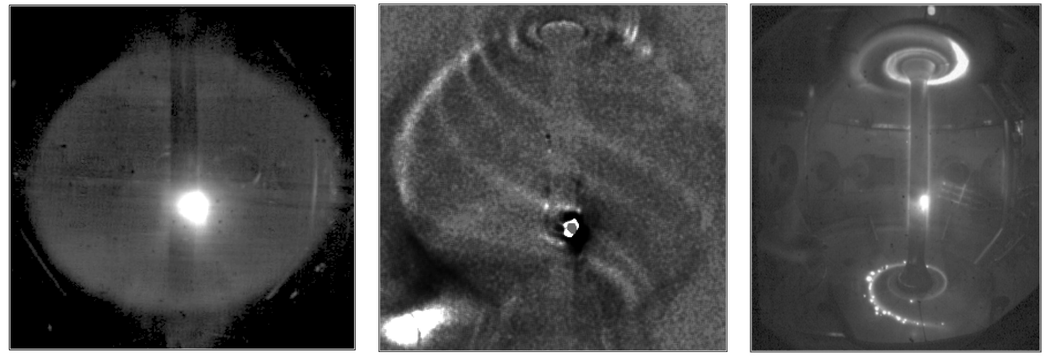


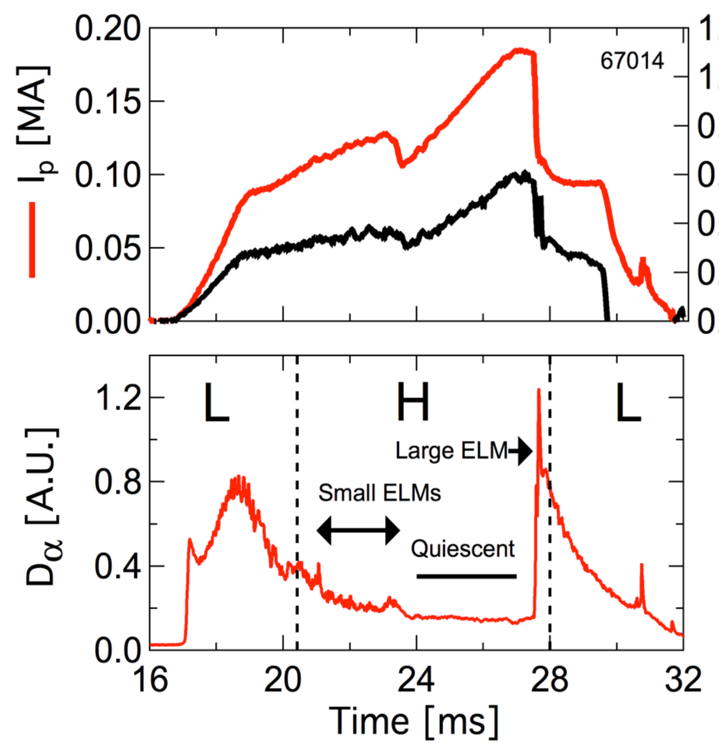
[1] Fundamenski *et al.*, Nucl. Fusion **52**, 062003 (2012).

A ~ 1 Enables Nonlinear ELM Studies

- 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

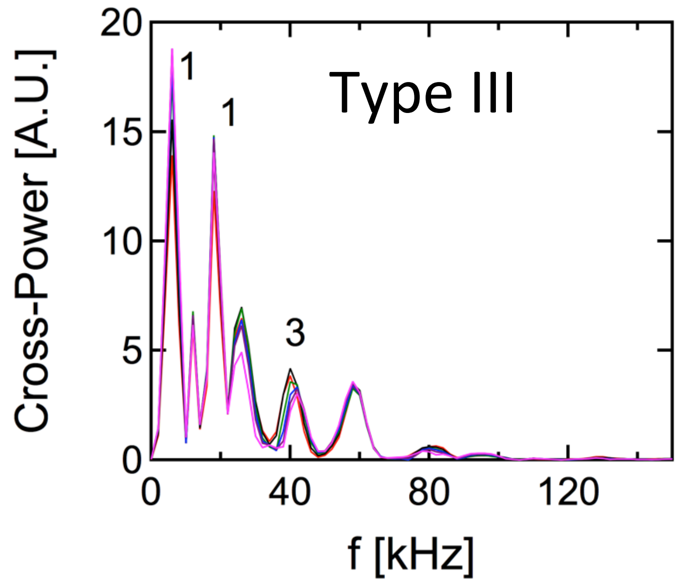
Quiescent Small ELM Large ELM

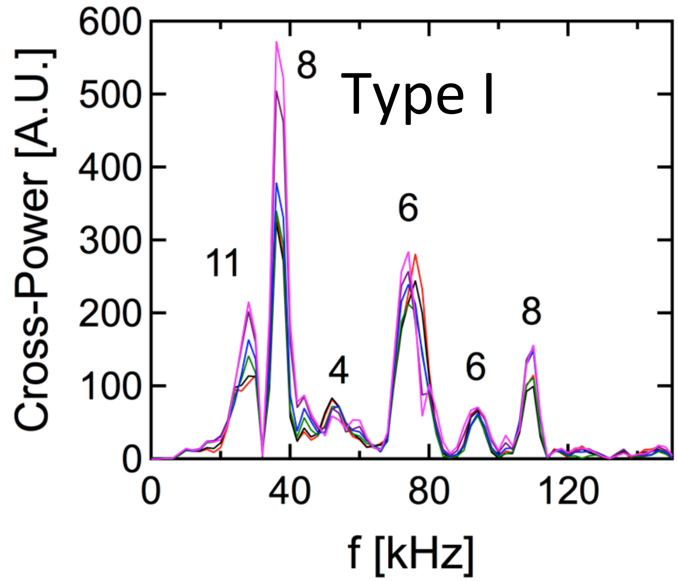




ELM Magnetic Structure Varies with *A*

- Edge Mirnov array measures ELM toroidal mode spectrum
  - $n \leq 20$ resolved by cross-phase analyses
- Type III: *A* dependent
  - $A \leq 1.4$: $n \leq 1 - 4$
    - PEGASUS and NSTX[1]
  - $A \sim 3$: $n > 8$[2]
- Type I: *A* independent
  - Intermediate-*n*[2,3]
  - Low-*A* devices have lower *n*
- Increased peeling drive at low-*A*
  - Higher J_{edge}/B → lower *n*



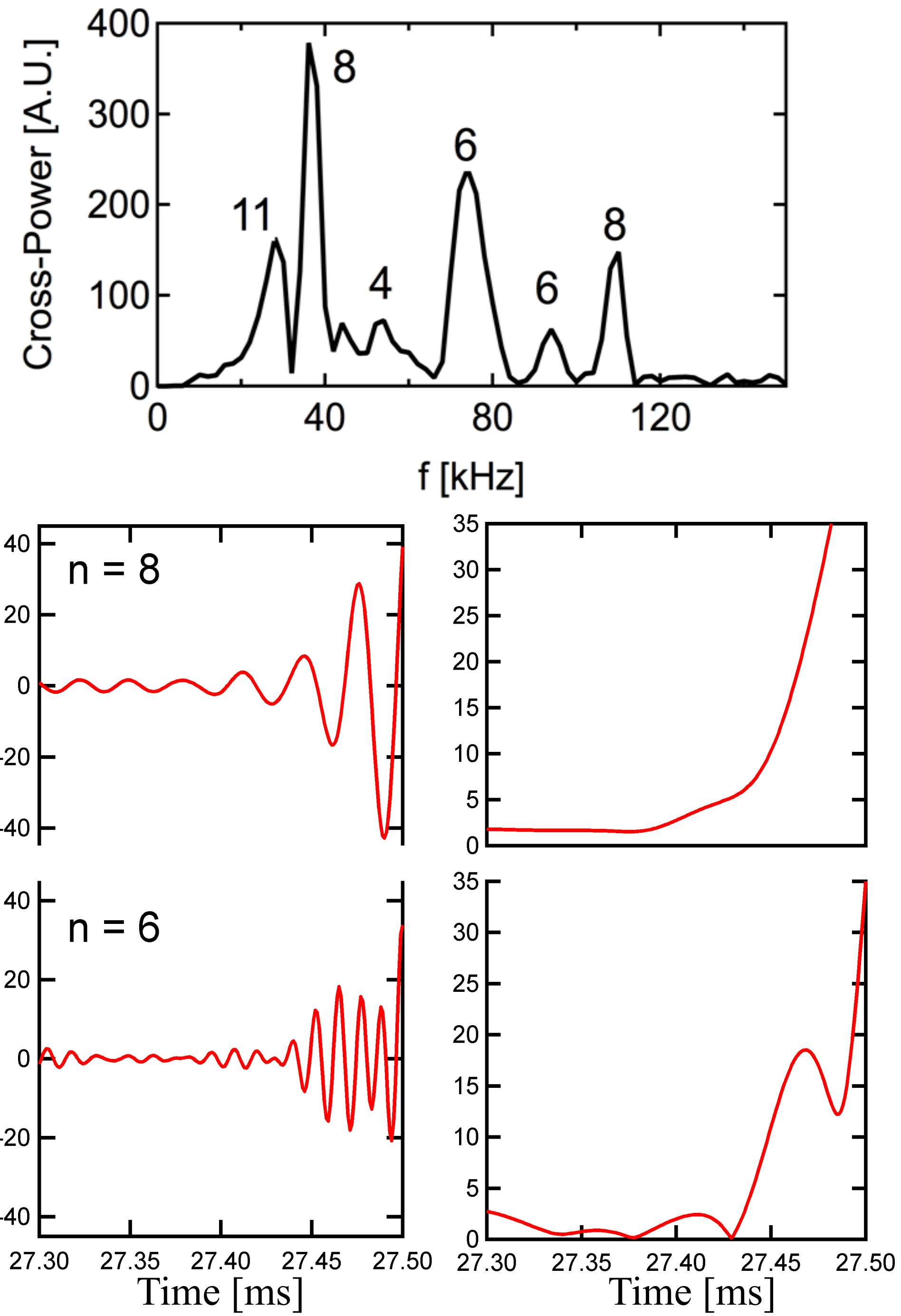


[1] Maingi *et al.*, Nucl. Fusion **45**, 1066 (2005).
[2] Kass *et al.*, Nucl. Fusion **38**, 111 (1998).
[3] Perez *et al.*, Nucl. Fusion **44**, 609 (2004).

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



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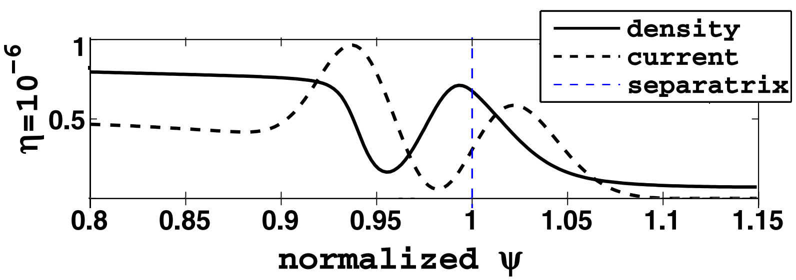
Complex Evolution of $J_{edge}(R,t)$ During ELMs

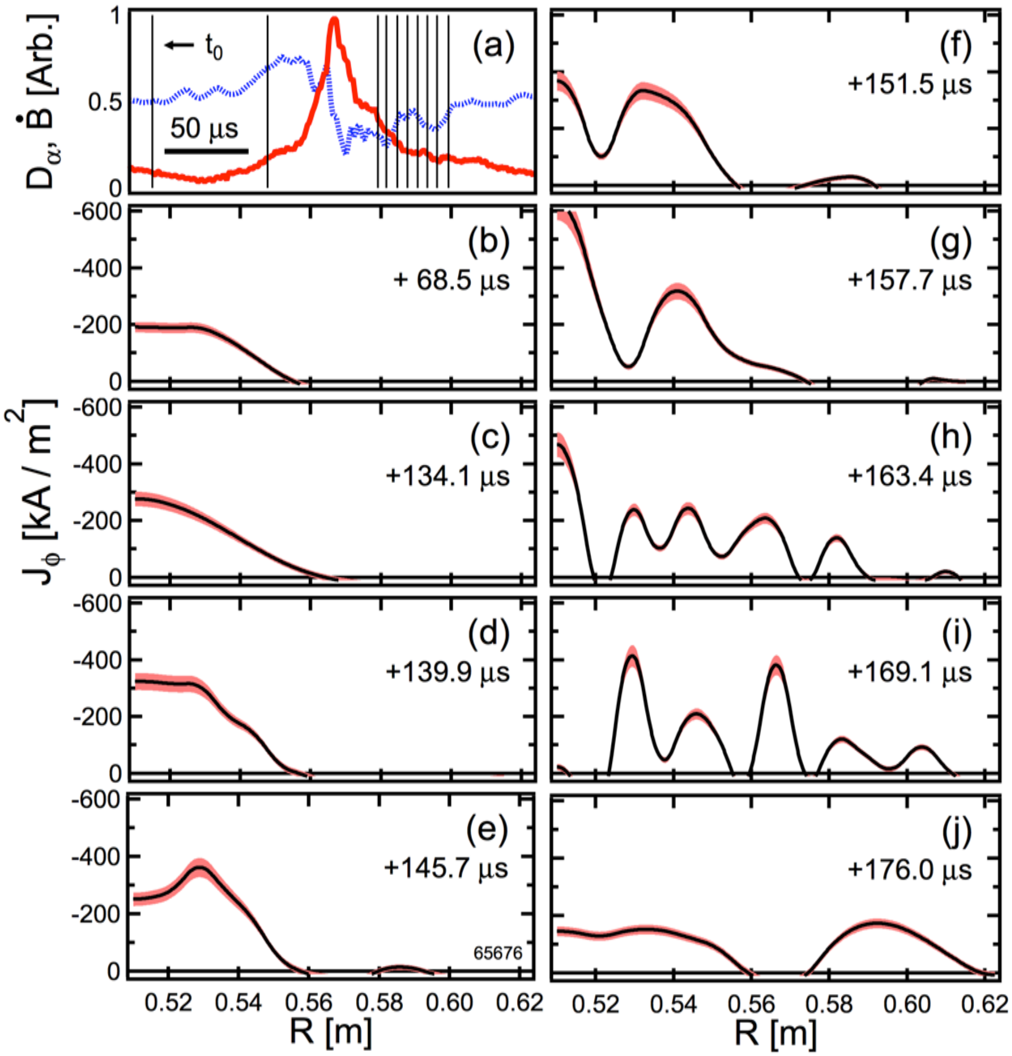
Type I ELM Evolution

- Challenge: study nonlinear ELMs at Alfvénic timescales

- Complex behavior with current-filament ejection
  - Time-averaged data qualitatively similar to JOREK[1]

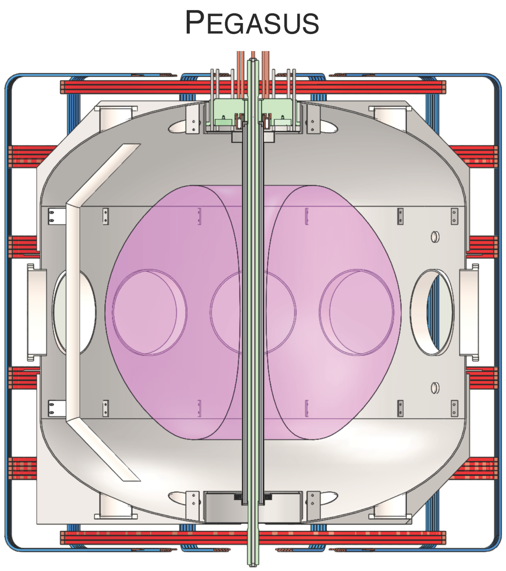


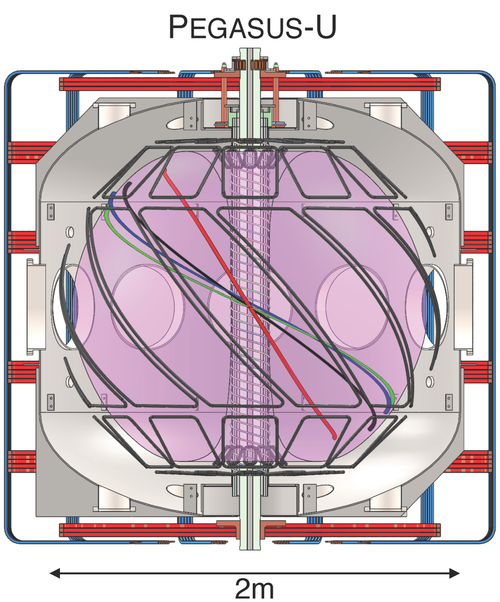
[1] Pamela *et al.*, Plasma Phys. Control. Fusion **53**, 054014 (2011).



Results Motivate Proposed PEGASUS-Upgrade

	PEGASUS	PEGASUS-U
ψ_{SOL} (mWb)	40	138 / 170
$B_{T,max}$ (T) at R_0	0.14	~ 0.4
$I_{p,max}$ (MA)	0.15	0.3
Δt (ms)	15	> 50
A	1.15	1.22





- 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 neoclassical physics
- ELM Modification and Mitigation
  - Novel 3D-MP coil array
  - LHI current injectors in divertor, LFS regions

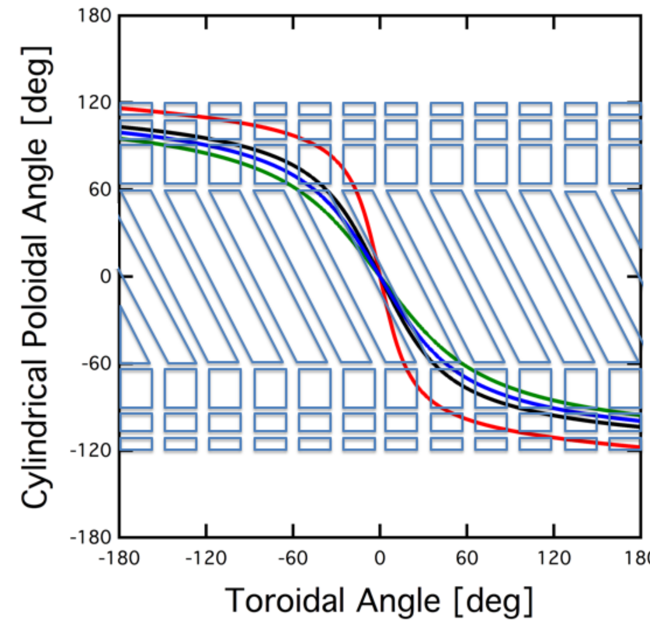
3D-Magnetic Perturbation System Proposed

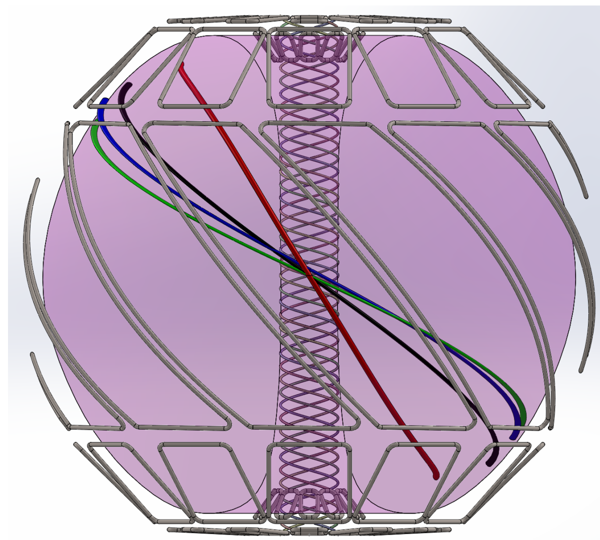
- Full design study planned
  - Proposal includes initial tests

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

- Uniqueness
  - Wide spectral range
  - Measure internal plasma response

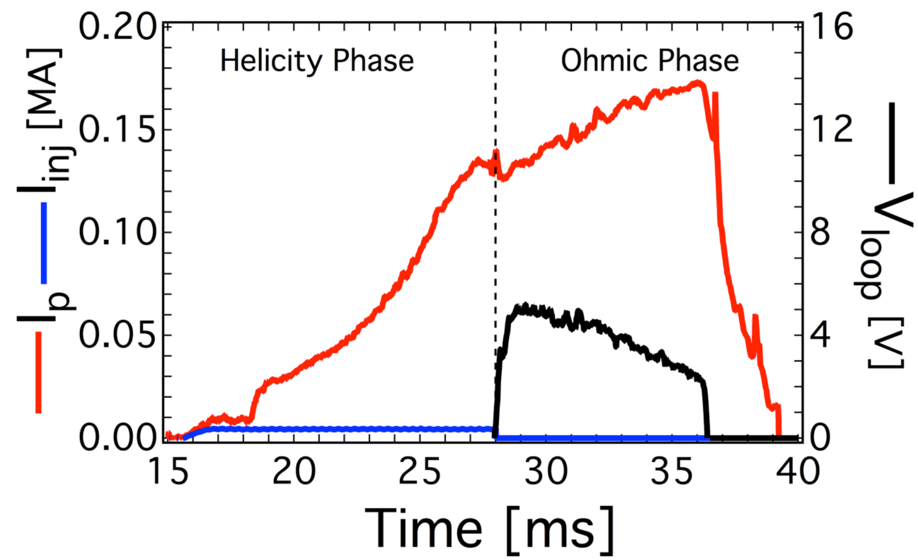
3D-MP Conceptual Design





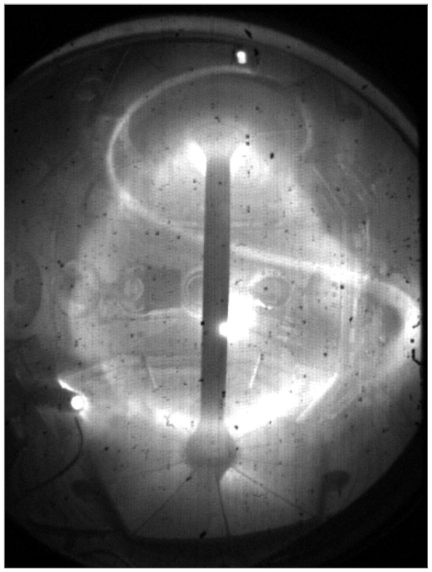
3D Edge Current Injectors Support ELM Studies

- Local helicity injection system provides 3D SOL current injection
  - $I_{inj} \leq 5$ kA, $J_{inj} \sim 1$ 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
  - Edge biasing to modify rotation profiles
  - Similar to LHCD on EAST[1]



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

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Unique Studies of H-mode Physics at *A*~1

- H-mode achieved in plasma with pedestal diagnostic access
  - Standard characteristics: pedestal; low D_α; increased τ_e; $H_{98} \sim 1$; etc.

- P_{LH} 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*
  - Nonlinear ELM dynamics measured at Alfvénic timescales

- Upgrade allows detailed study of nonlinear ELMs, pedestal physics
  - Complements experiments on larger fusion facilities
  - Detailed measurements can elucidate more limited results on larger facilities