Near-Unity Aspect Ratio H-mode and ELM Studies

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PEGASUS Toroidal Experiment

H-mode Workshop

IPP

Garching, Germany

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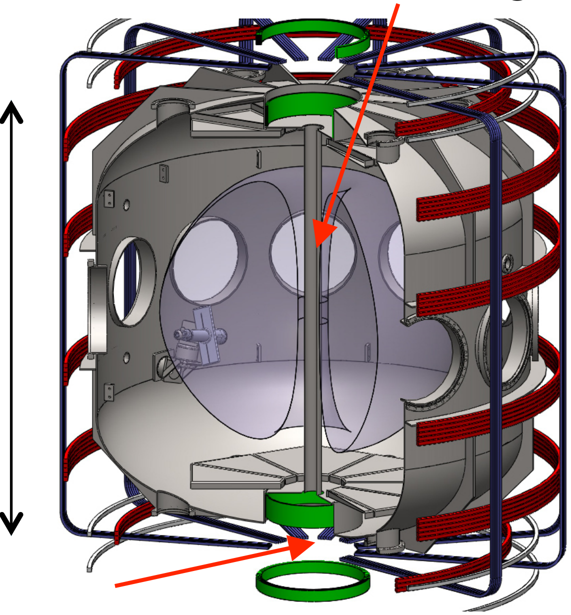
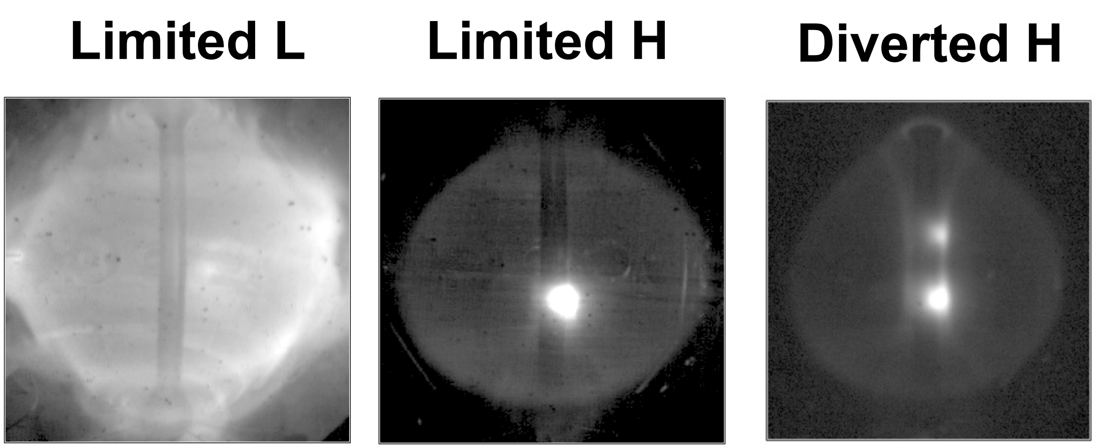
H-mode Readily Accessible at Near-Unity *A*



PEGASUS Toroidal Experiment

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



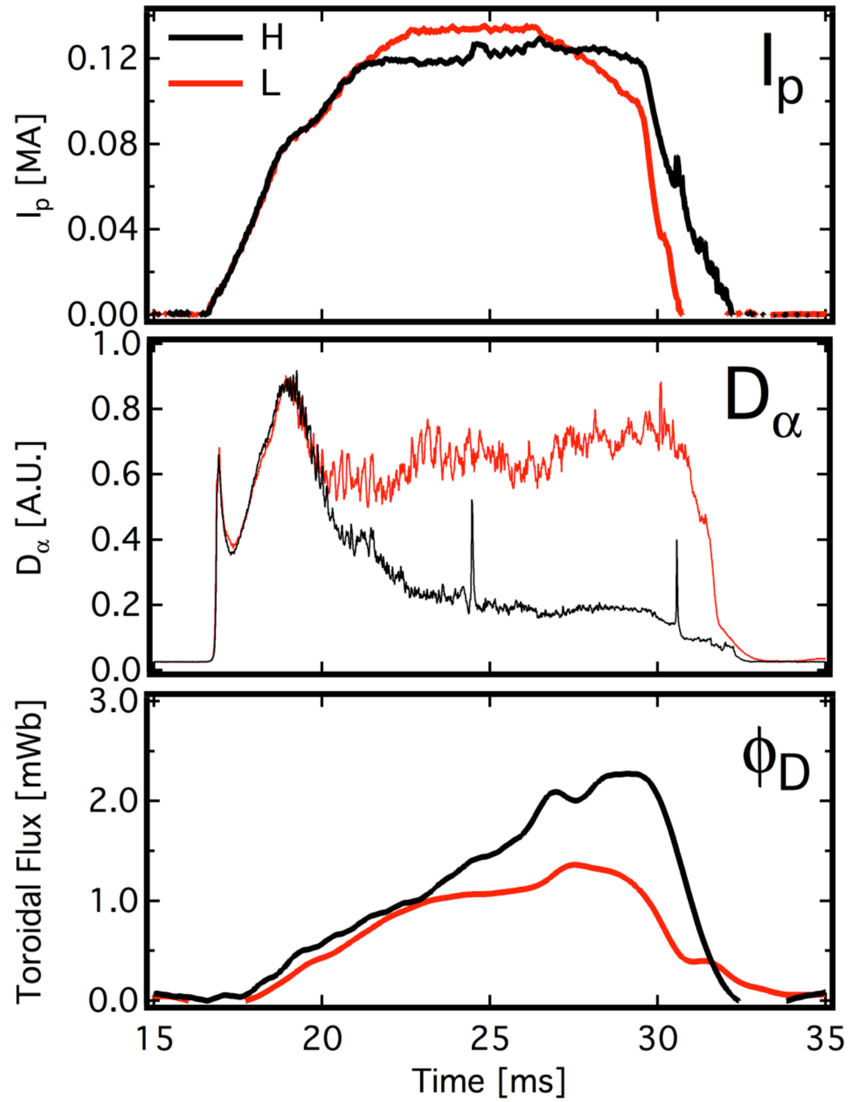
Fast visible imaging, $\Delta t \sim 30\ \mu s$

- H-mode achieved
  - $P_{OH} >> P_{ITPA08}$
  - Facilitated by HFS fueling
    - Similar to other STs[1]
  - Limited or diverted plasmas

[1]Field *et al.*, Plasma Phys. Control. Fusion. **46,** 981 (2004).

Standard Signatures in OH H-mode Plasmas

- Quiescent edge
- Reduced D_α
- Large and small ELMs
- Bifurcation in $\phi_D(t)$
- Core impurity T_i increases
- Increased core T_e indicated
  - CV only observed in H-mode (E_{ion}=392 eV)
  - Thomson $T_{eH}(0) > T_{eL}(0)$
- Increased core rotation



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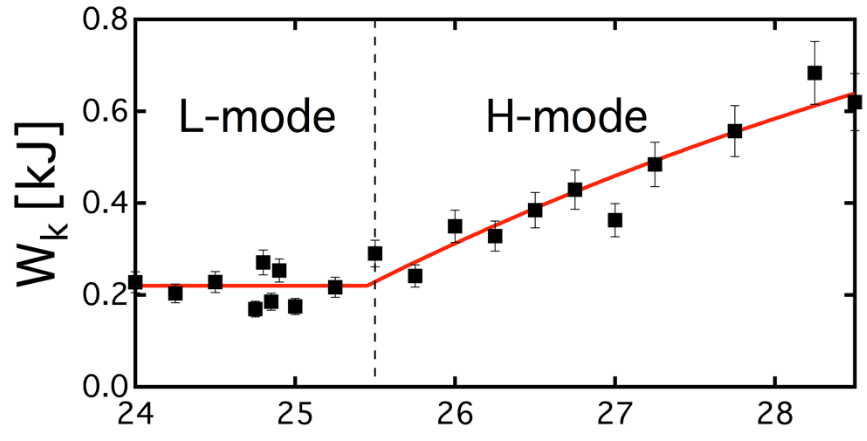
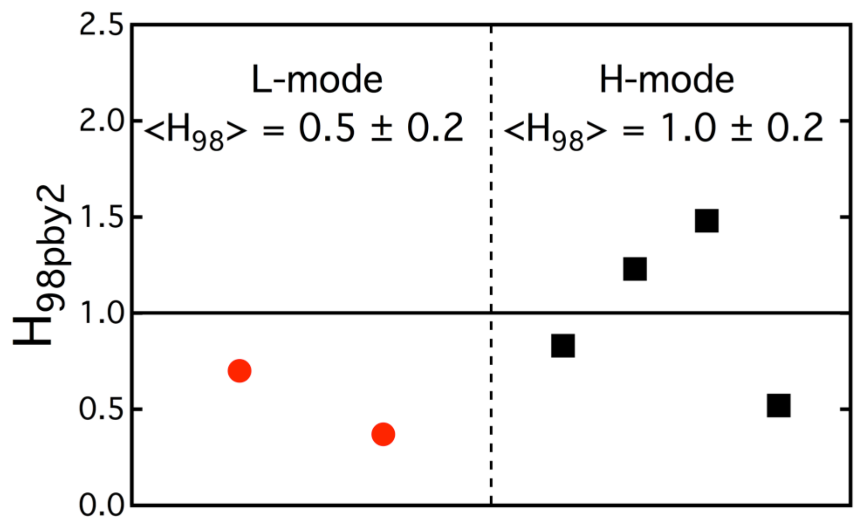
Energy Confinement Improves in H-mode

- Time-evolving magnetic equilibrium reconstructions used to calculate τ_e
  - Challenges: short pulse, MHD, I_{wall}
  - 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 β_p with fast boundary reconstruction code
  - $\beta_p \neq 1+\mu$ at low-A
    - Grossly overestimates β_p, W_k
  - At low-A need to calculate integrals

Diverted Equilibrium Reconstruction

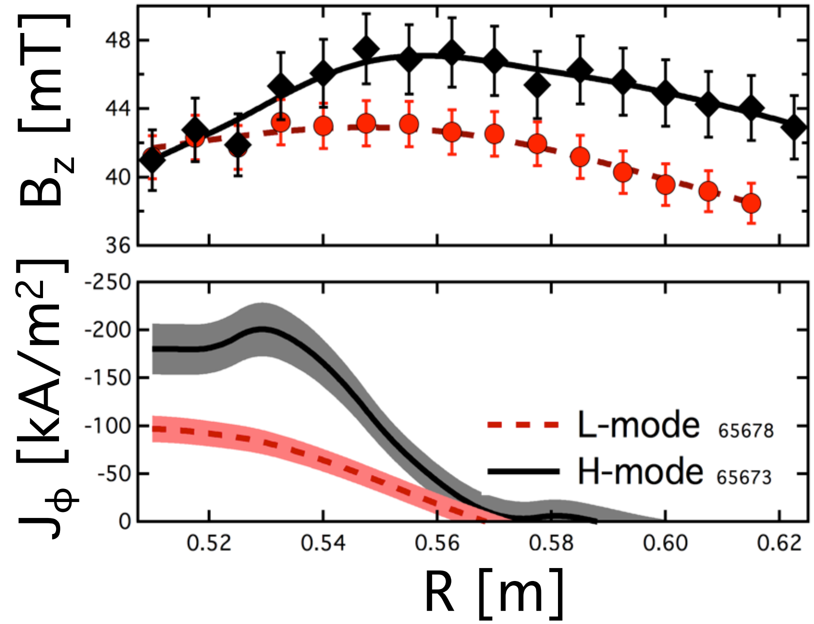


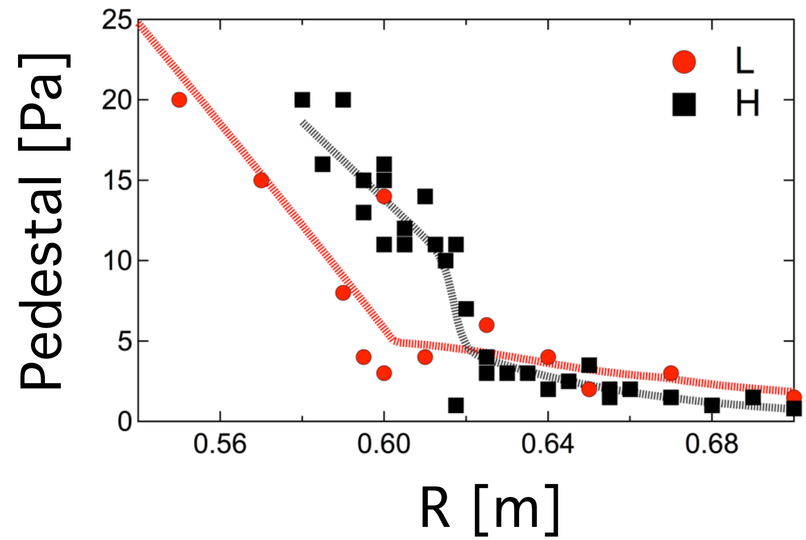
H_{98} Summary



Edge Pedestals Measured with Probes

- *A* ~ 1: very low B_T → low T_e
  - Unique pedestal measurements using insertable probes
- Current pedestal observed
  - Measured with Hall Probe[1,2] array
  - Scale length: 4 → 2 cm L to H
- Preliminary Langmuir probe scans indicate pressure pedestal
  - Single-point, multi-shot profile
  - Some edge distortion present from MHD





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

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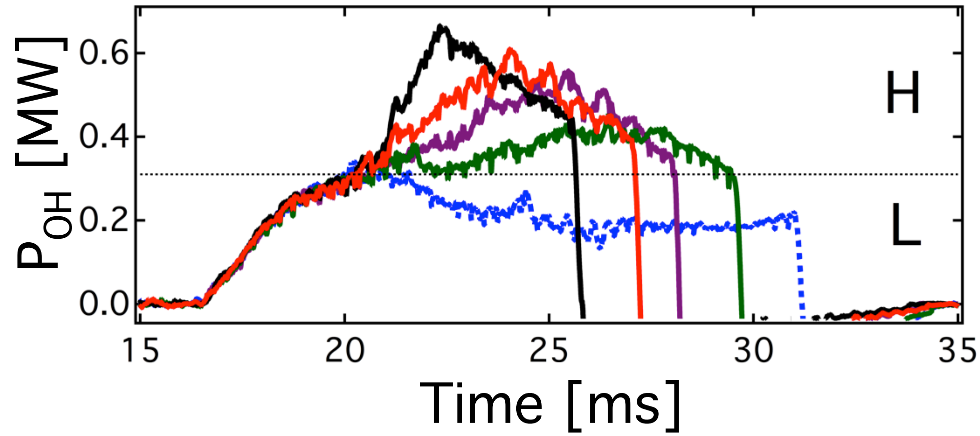
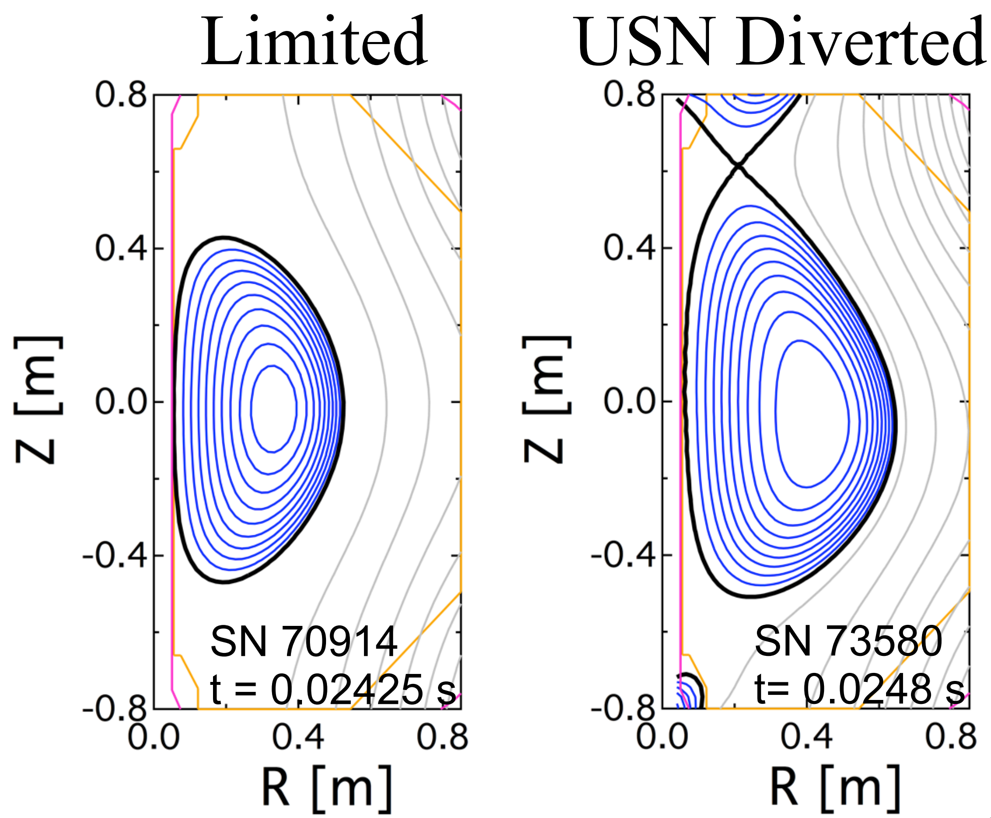
P_{LH} Measured in PEGASUS at $A\approx1.2$

- Vary P_{OH} with power scan
  - Transition time from ϕ_D bifurcation
  - Wide parameter range
    - $P_{OH} = 0.1 – 0.6$ MW
    - $n_e = 0.5 – 4\times10^{19}$ m^{-3}
    - Limited: Centerstack
    - Diverted: USN (favorable ∇B)

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





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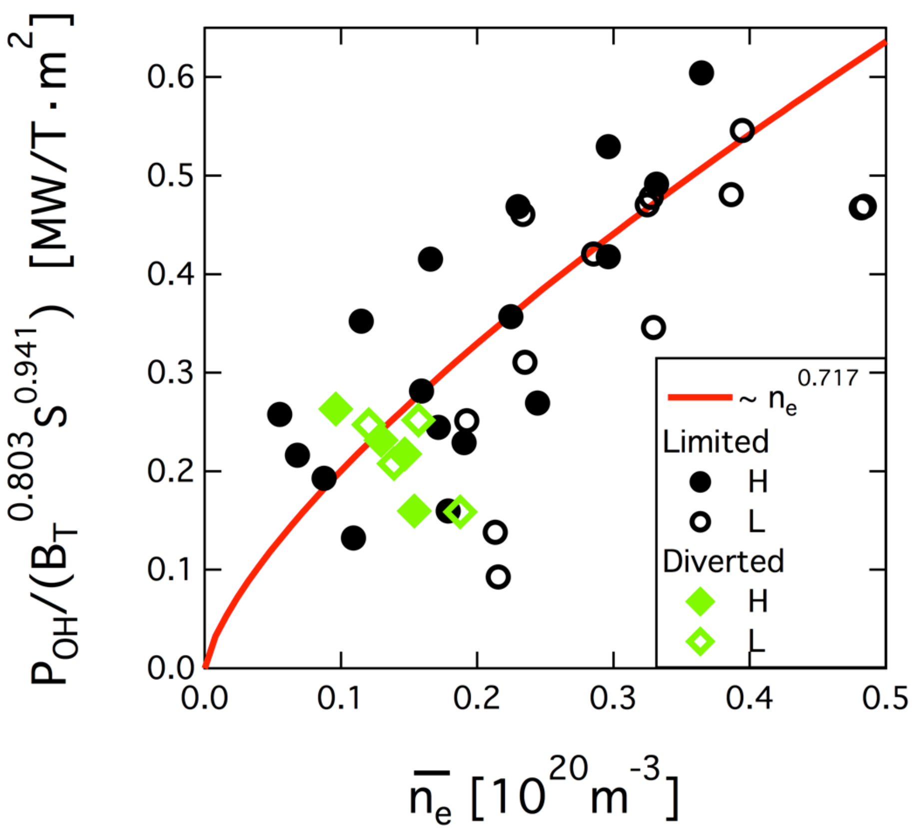
P_{LH} Shows Strong Density Dependence

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

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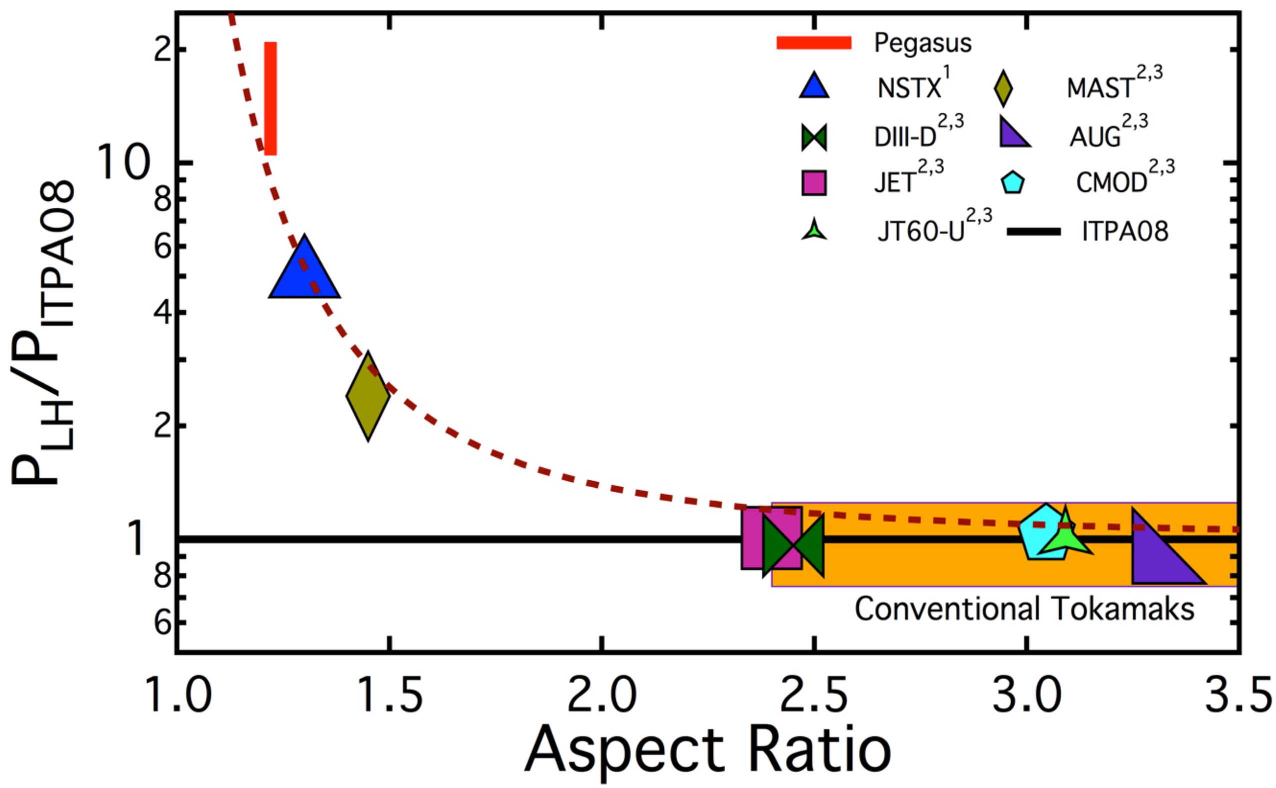
At low A, $P_{LH} >> P_{ITPA08}$



- 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

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

- FM^3 model reproduces P_{ITPA08} scaling

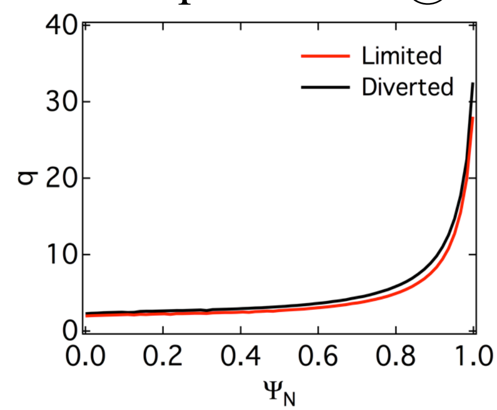
- FM^3: Predicts P_{LH} minimum for PEGASUS at $n_e \sim 1 \times 10^{18}\ m^{-3}$
  - $n_e/n_G \ll 0.1$, inaccessible due to runaways

- P_{LH} topology independence: self-similar q profiles at $A \sim 1$

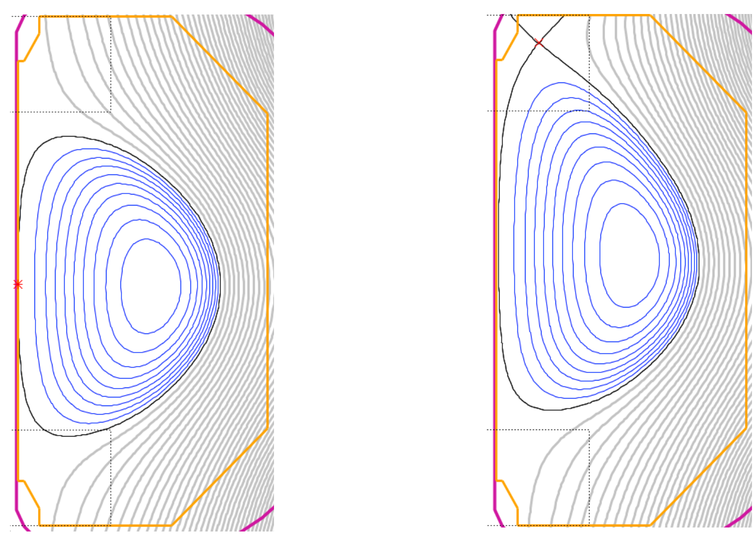
$$\frac{P_{L-H}^{lim}}{P_{L-H}^{div}} \approx \left(\frac{q_*^{lim}}{q_*^{div}}\right)^{-7/9} \qquad \begin{array}{l} \gg 1 \text{ @ } A\sim 3 \\ \rightarrow 1 \text{ @ } A\sim 1 \end{array}$$

- Model does not explain strong P_{LH} dependence on A
  - Multi-Machine P_{LH} studies in progress/ proposed (NSTX-U, PEGASUS, DIII-D)

Predictive Equilibrium @ $A \approx 1.2$



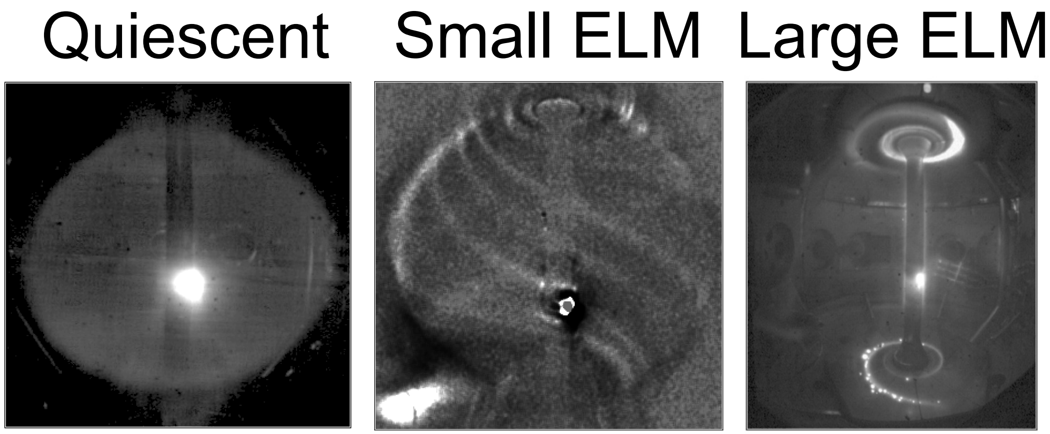
Limited Diverted

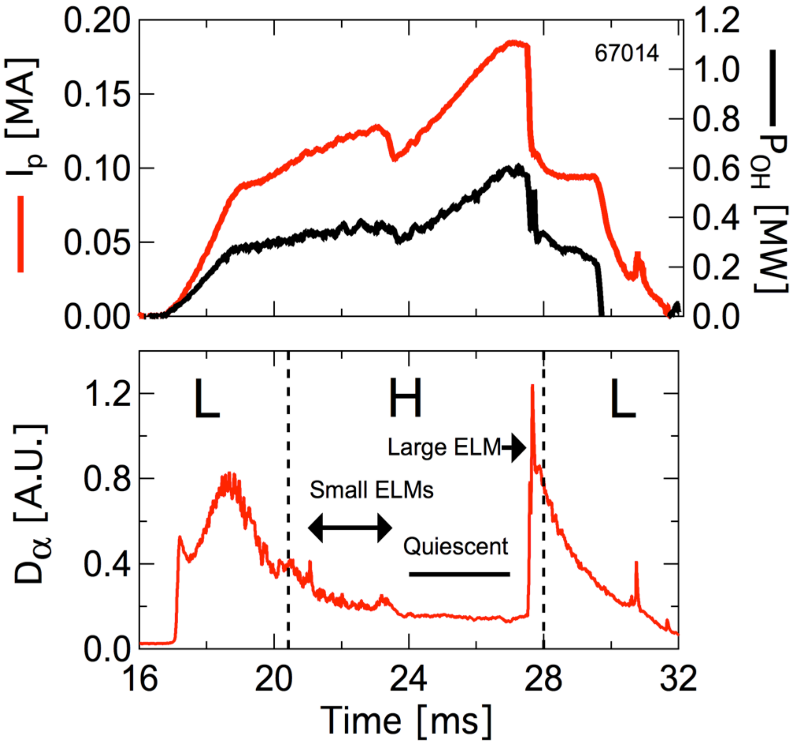


[1] Fundamenski *et al.*, Nucl. Fusion **52**, 062003 (2012).

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





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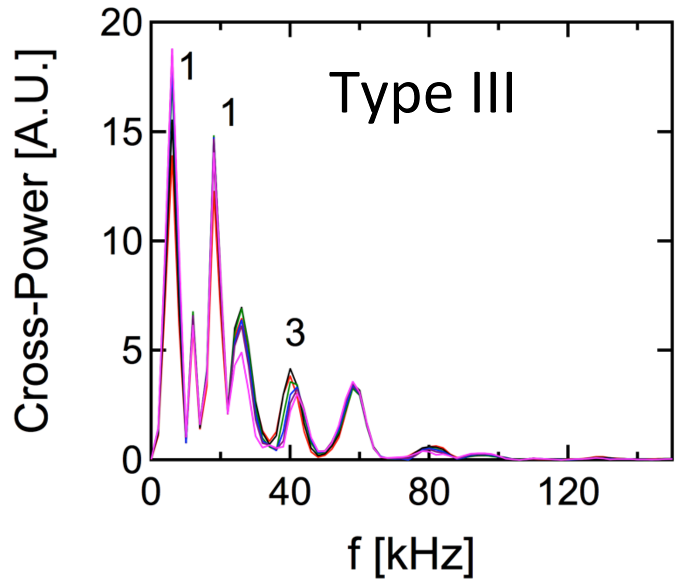
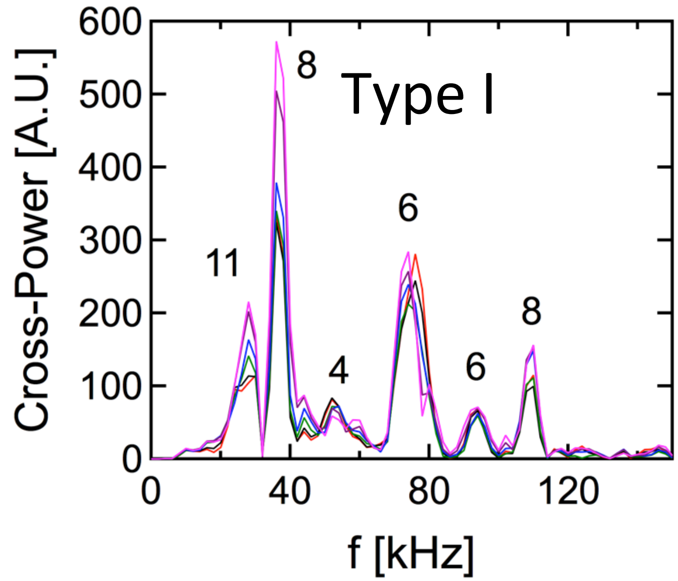
ELM Magnetic Structure Varies with *A*

- Measured with near-edge magnetics probe
- Type III: *A* dependent
  - $A \leq 1.4$: $n \leq 1 - 3$
    - PEGASUS and NSTX[1]
  - $A \sim 3$: $n > 8$[2]
- Type I: *A* independent
  - Intermediate-n, $n \sim 4 - 12$[2,3]
  - Low and high-*A* similar, but low-*A* lower *n*
- Increased peeling drive at low *A*
  - Higher $J_{edge}/B \rightarrow$ lower *n*





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[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).

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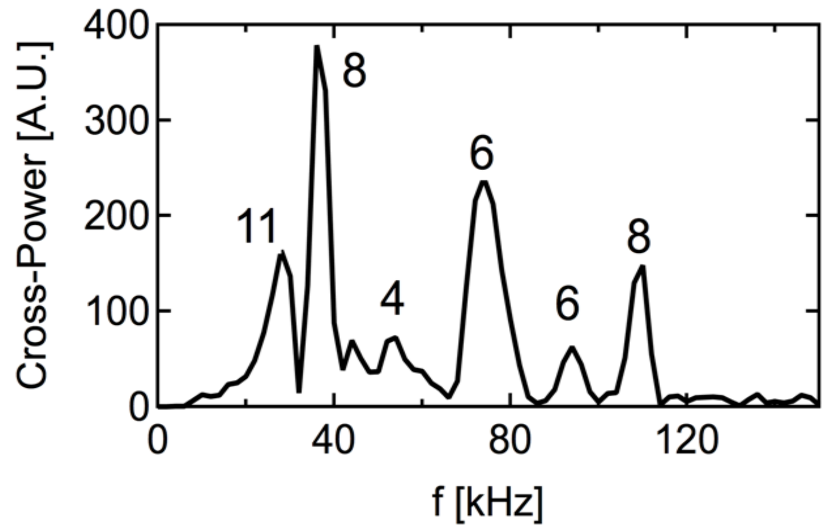
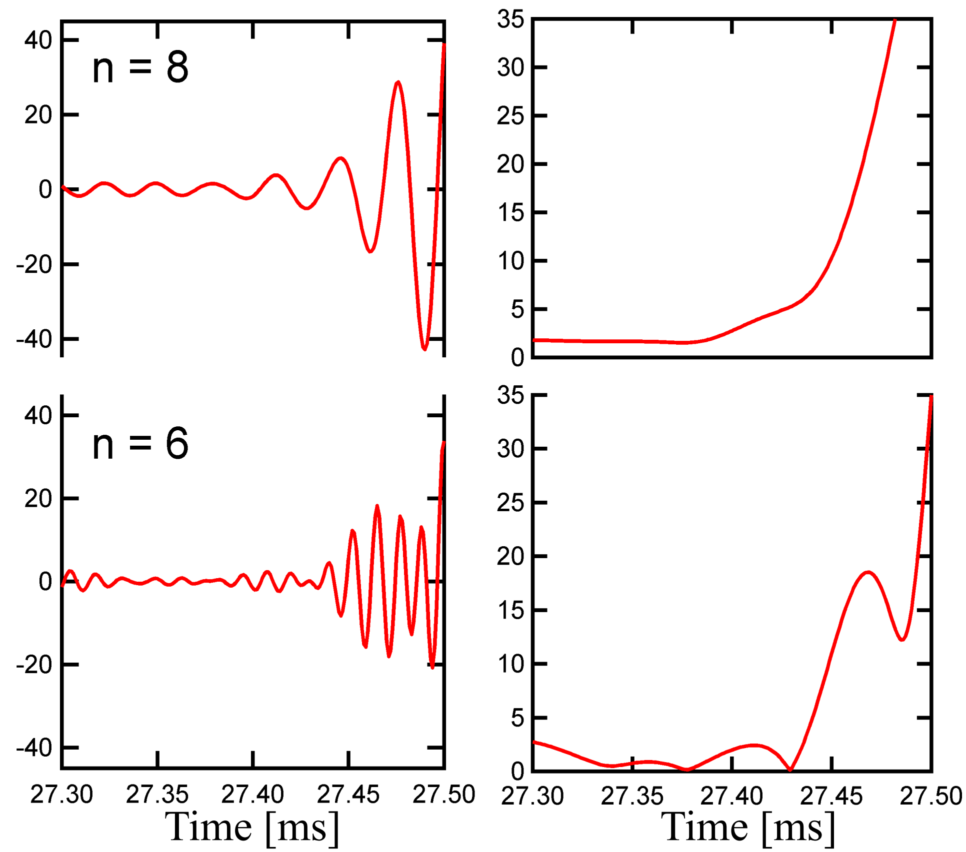
Nonlinear ELM Precursors Observed

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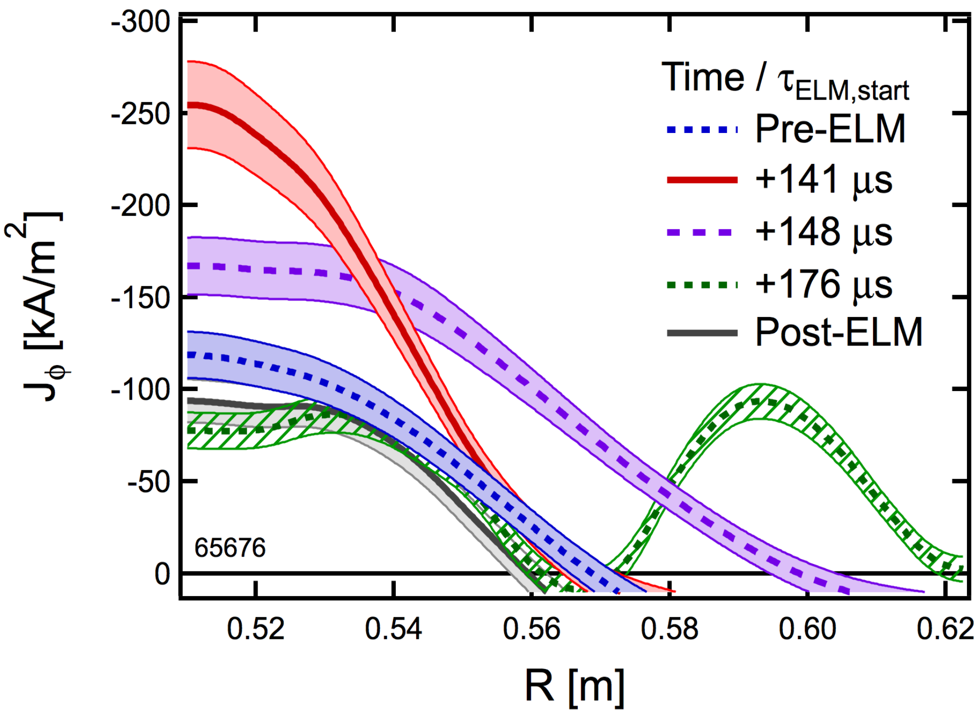
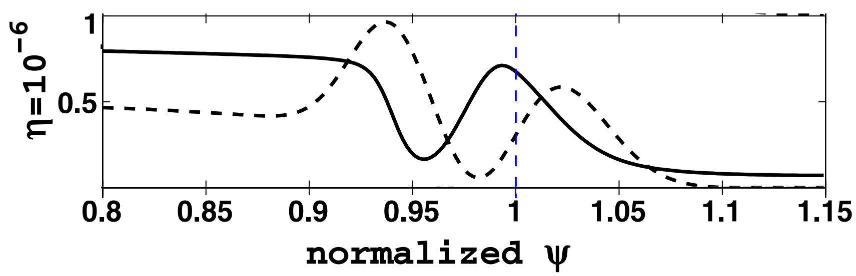
Complex Evolution of $J_{edge}(R,t)$ During ELMs

- Challenge: study nonlinear ELM dynamics at Alfvénic timescales

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

Type I ELM Evolution





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

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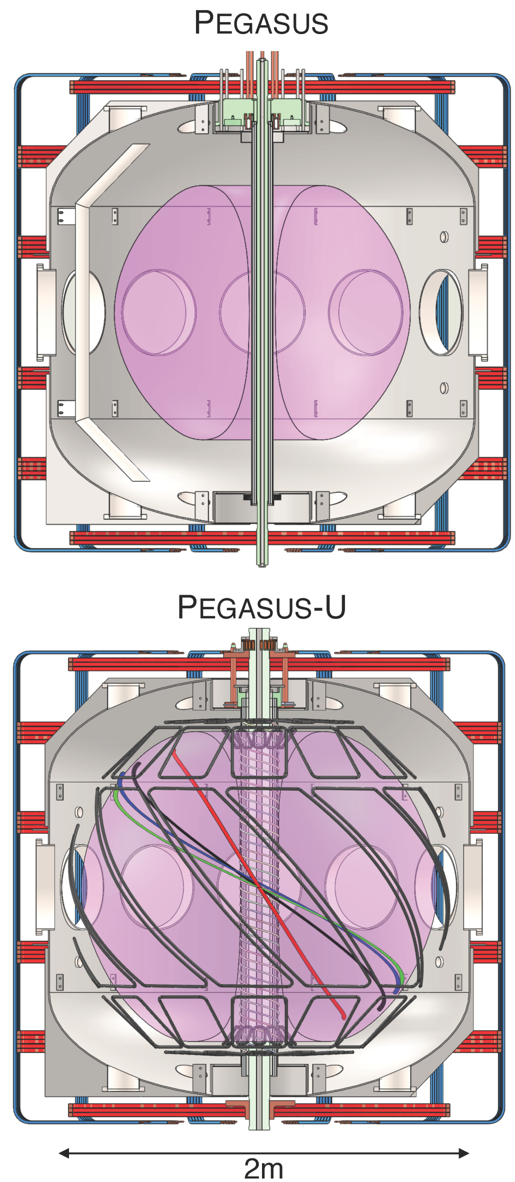
Motivates PEGASUS-Upgrade Proposal

	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

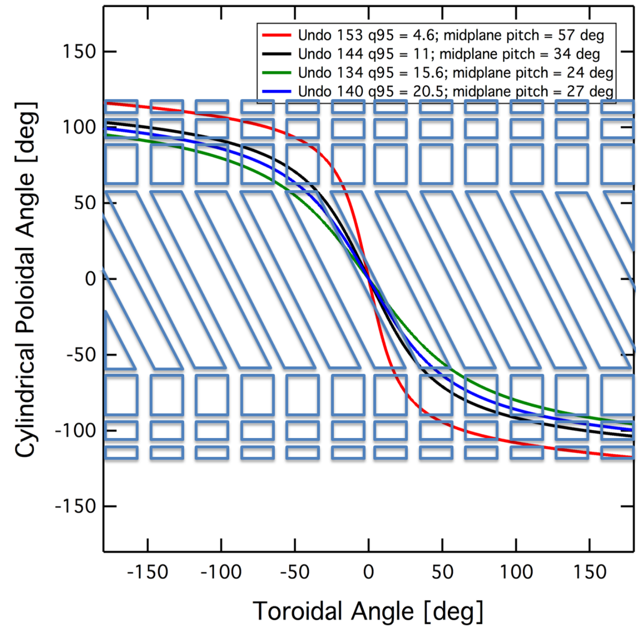


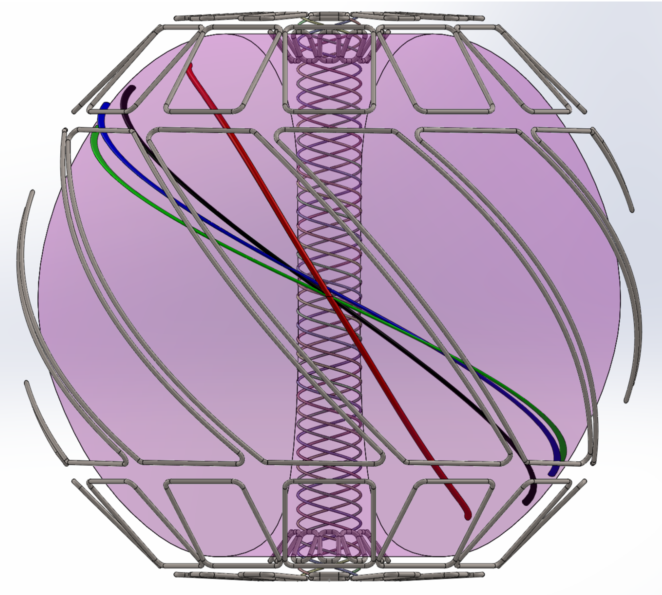
- Nonlinear pedestal and ELM studies
  - Simultaneous measurements of p(R,t), J(R,t), v_φ(R,t)
    - New edge diagnostics (probe arrays, DNB)
  - Tests of Sauter neoclassical bootstrap model

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

3D-Magnetic Perturbation System Proposed

- Design study, fabrication
- 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





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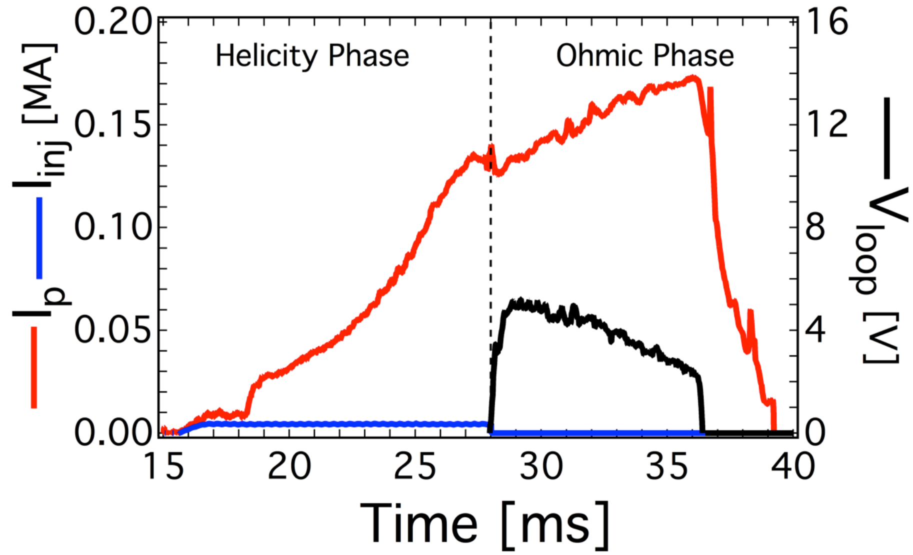
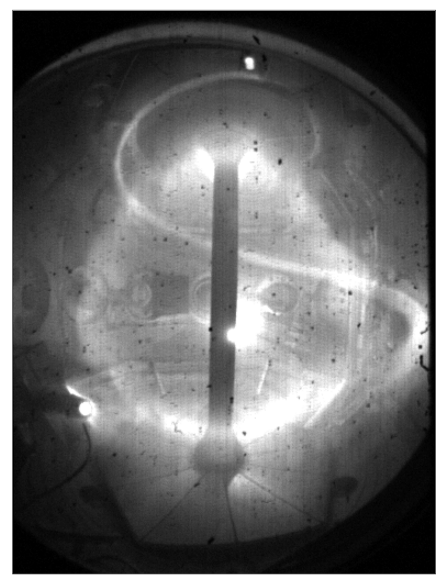
3D Edge Current Injectors Support ELM Studies

- 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.
- 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
- Complements experiments on larger fusion facilities
  - Detailed measurements can elucidate more limited results on larger facilities
  - Proposed upgrade allows detailed study of nonlinear ELMs and pedestal physics