H-mode and ELM Characteristics at Ultralow Aspect Ratio in the Pegasus Experiment

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University of Wisconsin-Madison

58th Annual APS-DPP Meeting

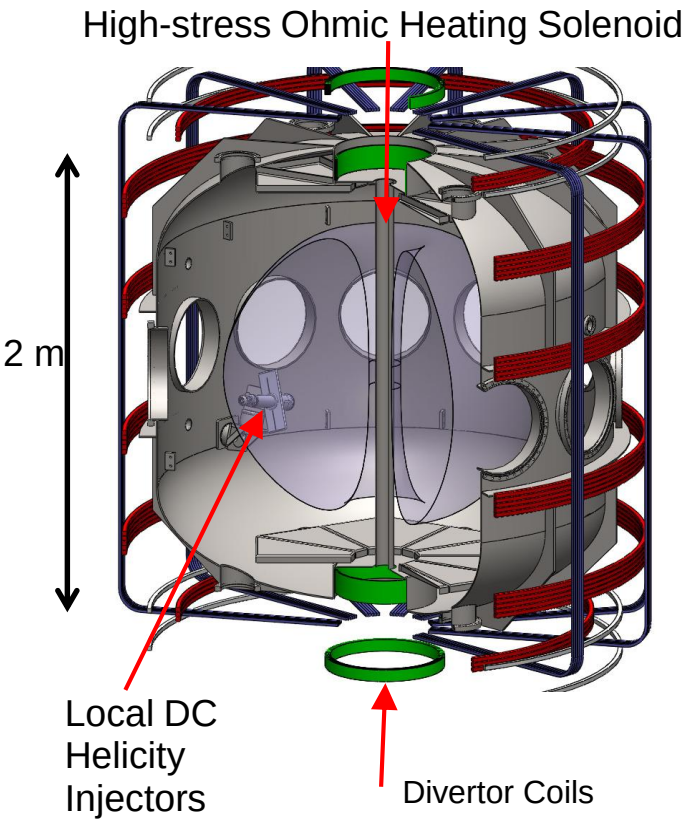
San Jose, CA

November 2, 2016

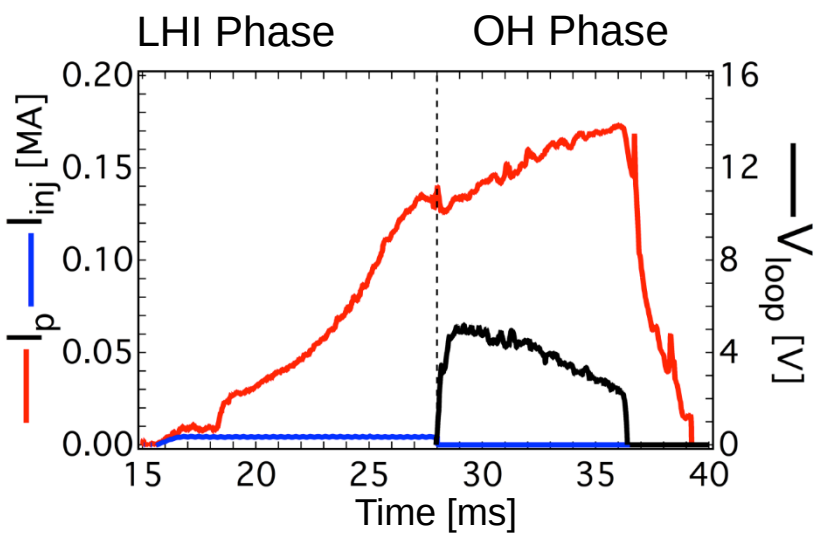


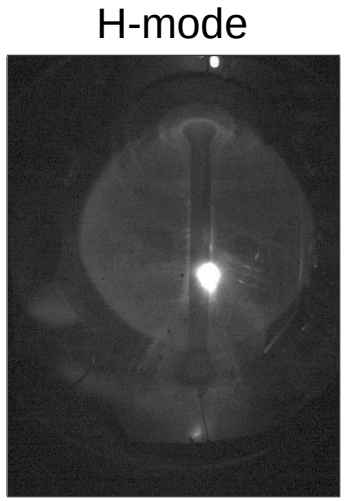
PEGASUS Toroidal Experiment

Pegasus ST at A~1 Facilitates AT Science Studies at Small Scale



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



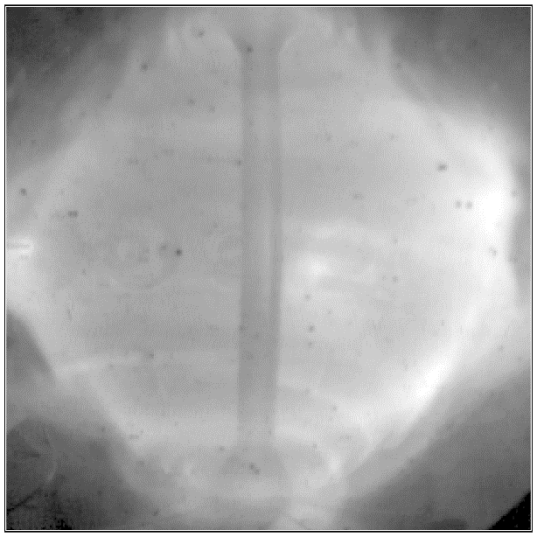


- Local Helicity Injection (LHI) for ST Startup
  - Inject current streams in plasma edge
- H-mode Physics at Ultralow-*A*
  - H-mode and ELM characteristics
- Access to high I_N > 10
  - Tokamak stability limits at A ~ 1

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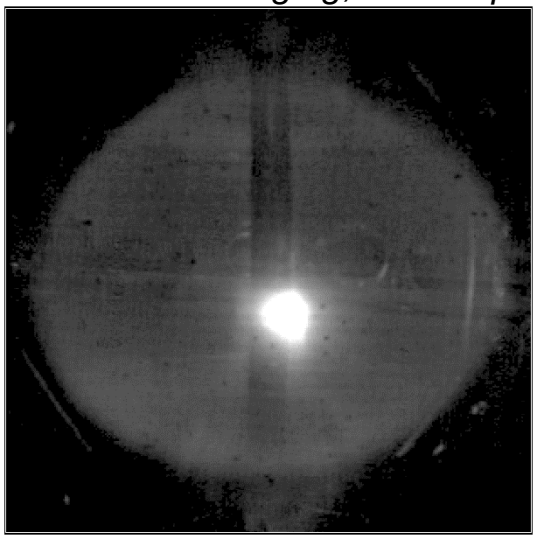
H-mode Readily Accessed at A ~ 1

Limited L

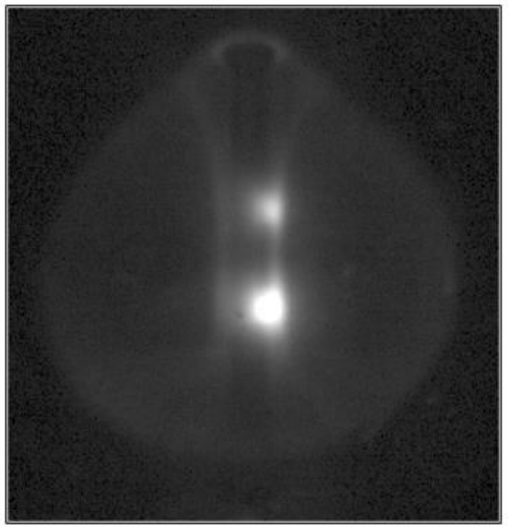


Limited H

Fast visible imaging, Δt ~ 30 μs



Diverted H



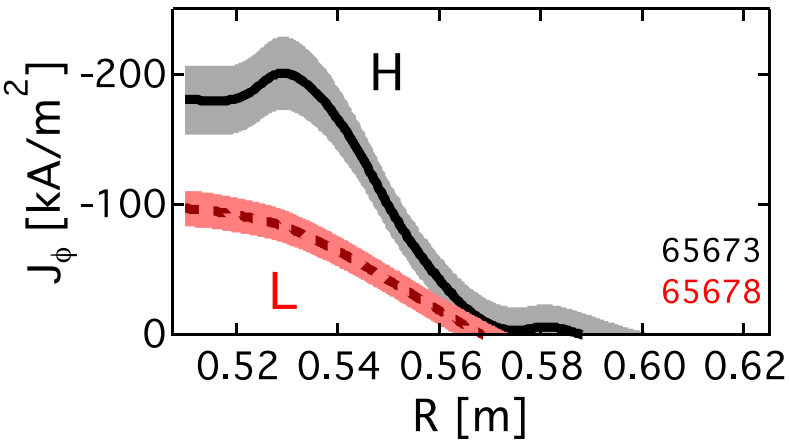
- Low B_T at A ~ 1 -> low H-mode P_{LH}
  - $P_{OH} >> P_{ITPA08} \sim B_T^{0.80} n_e^{0.72} S^{0.94}$
  - Limited or Diverted topology
- Standard H-mode features
  - Quiescent edge
  - Reduced H_α
  - Improved τ_E
  - Some differences compared to high-A

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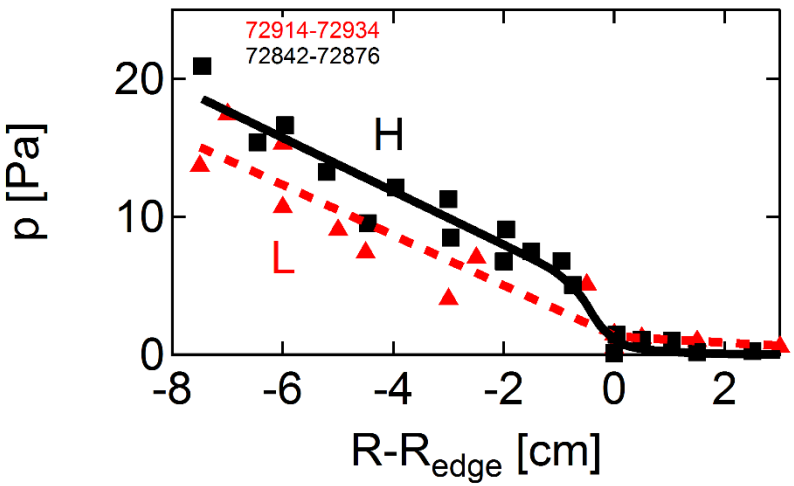
H-mode: Pedestal Formation, Increased Confinement

- Short pulse, low $T_{e,edge}$
- **Simple probe access across pedestal**
- J_ϕ, P pedestals in H-phase
  - $J_\phi(R,t)$: multichannel Hall probe
  - p(R): triple Langmuir probe
- Confinement increases 2x
  - Requires time-evolving reconstructions
  - L: $H_{98} \sim 0.5 \pm 0.2$
  - H: $H_{98} \sim 1.0 \pm 0.2$

Single-shot, $\Delta t = 6\ \mu s$



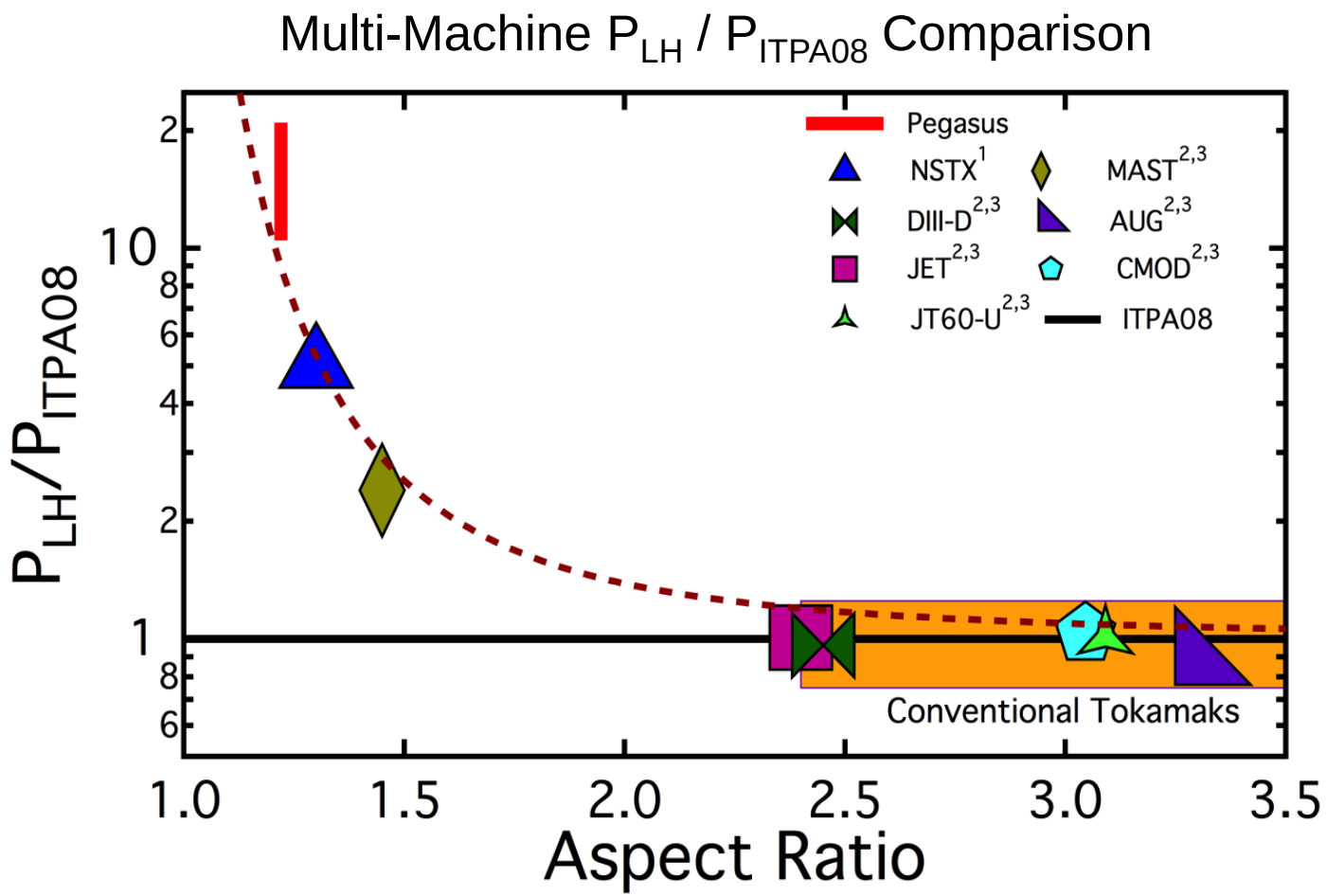
Multi-shot average



Bongard et al., Rev. Sci. Instrum. ***81****, 10E105 (2010)*
Bongard et al., Phys. Rev. Lett. ***107****, 035003 (2011)*
Thome et al., Phys. Rev. Lett. ***116****, 175001 (2016)*
Thome et al., Nucl. Fusion ***57****, 022018 (2017)*

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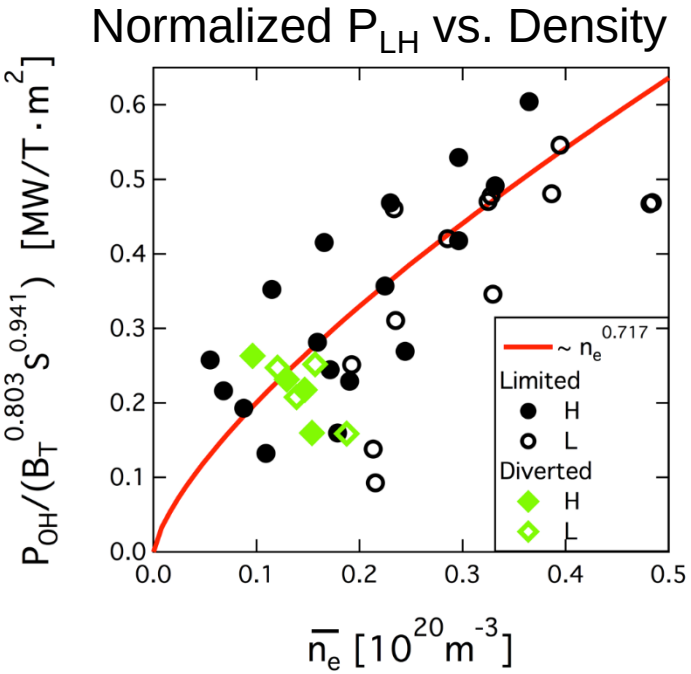
At Low A, $P_{LH} \gg P_{ITPA08}$

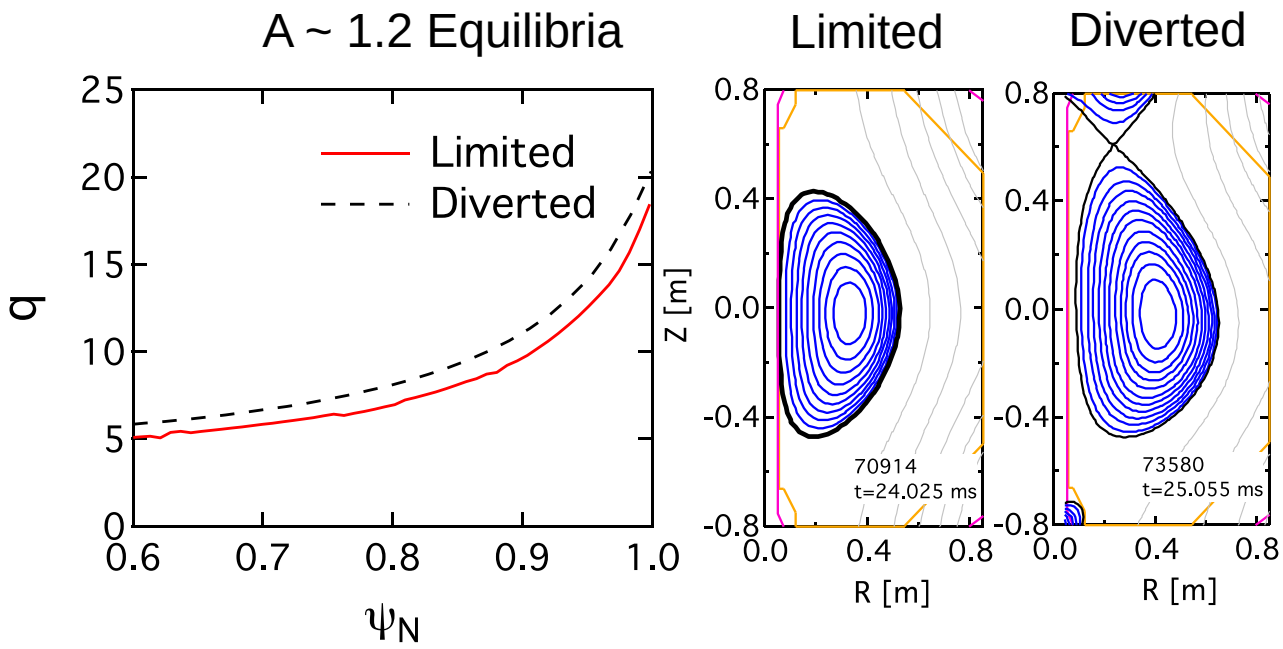


[1]*Maingi et al., Nucl. Fusion* ***50****, 064010 (2010)*
[2]*Martin et al., J. Phys.: Conf. Ser.* ***123****, 012033 (2008)*
[3]*Wesson, Tokamaks, 4th ed. (2011), p. 630*

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P_{LH} Consistent with Global Scalings, but Low-A Differences





- Follows ITPA n_e scaling
  - FM^3: min $n_e \sim 1\times10^{18}$ m^{-3}

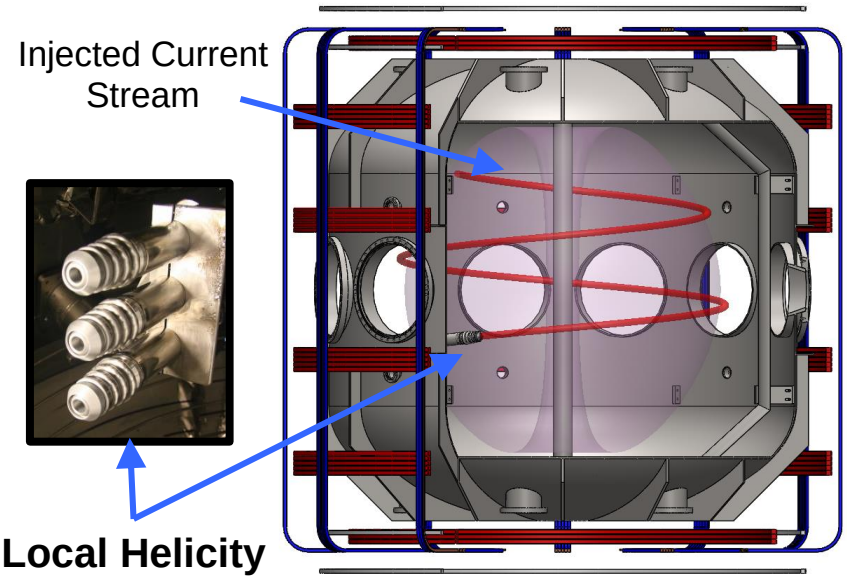
- Magnetic topology independence
  - Diverted, limited edge q(ψ) similar
  - FM^3 model:

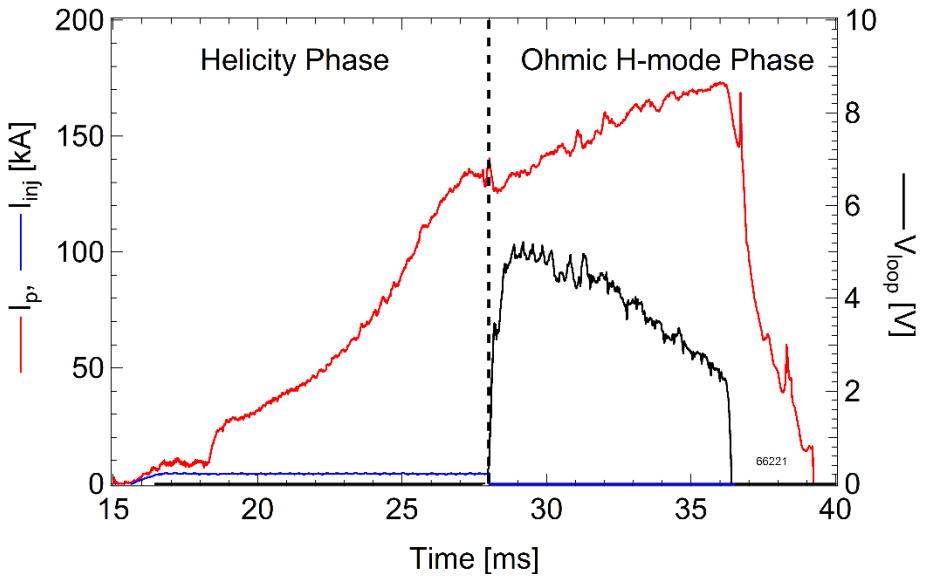
$$(P_{LH}^{LIM}/P_{LH}^{DIV}) \sim (q_\psi^{LIM}/q_\psi^{DIV})^{-7/9} \sim 1$$

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

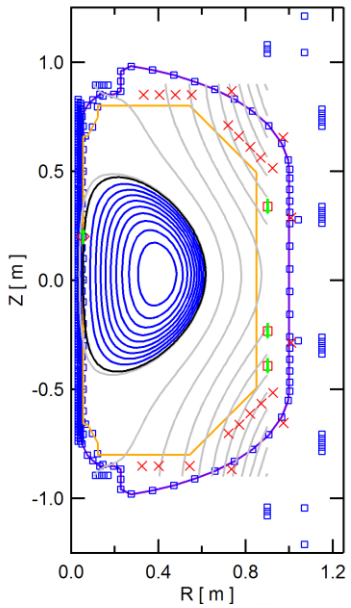
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Local Helicity Injection Startup Compatible with Access to High-Quality Ohmic H-mode





- High-I_p, long-pulse H-mode plasmas desirable
  - Confinement, edge stability studies; attaining high β_T
- LHI creates tokamak plasmas via edge current drive
  - Taylor relaxation, helicity balance
- No fundamental obstacles to H-mode access from LHI physics



Equilibrium Parameters
Shot 66221, 34.80 ms

I_p	169 kA	R_0	0.336 m
β_t	0.081	a	0.281 m
ℓ_i	0.42	A	1.20
β_p	0.31	κ	1.6
W	2101 J	δ	0.44
B_{T0}	0.179 T	q_{95}	9.92

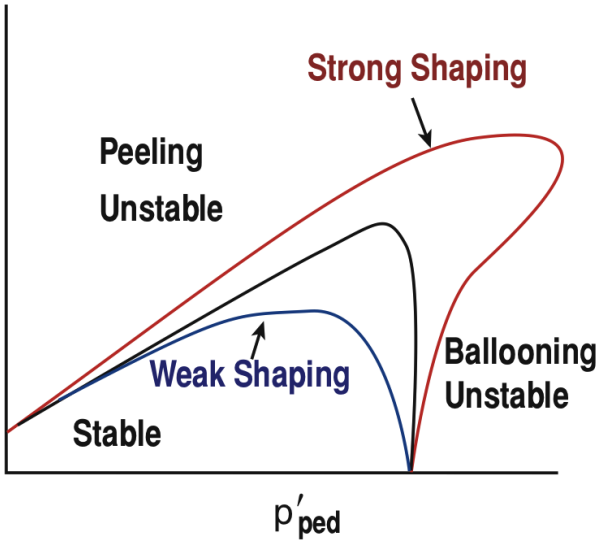
*Battaglia et al., Nucl. Fusion **51**, 073029 (2011)*
*Thome et al., Nucl. Fusion **57**, 022018 (2017)*

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Validated, Predictive Theory Needed to Mitigate ELMs

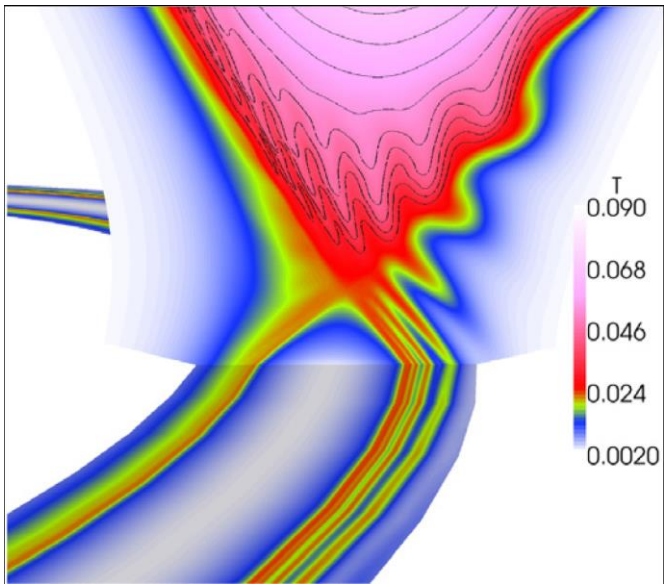
- Peeling-ballooning model
  - Competing ideal MHD instabilities cause ELM onset
  - Current-driven peeling modes
  - Pressure-driven ballooning modes

$$\propto \frac{qRJ_{\parallel}}{B}$$ J_{ped}



*Snyder et al., Phys. Plasmas **12**, 056115 (2005)*
*Hegna, Phys. Plasmas **3**, 584 (1996)*

- Nonlinear extensions
  - More complete physical models
  - Evolution of P-B mode structures
  - Heat flux deposition projections



*Huysmans et al., Plasma Phys. Control. Fusion **51**, 124012 (2009)*

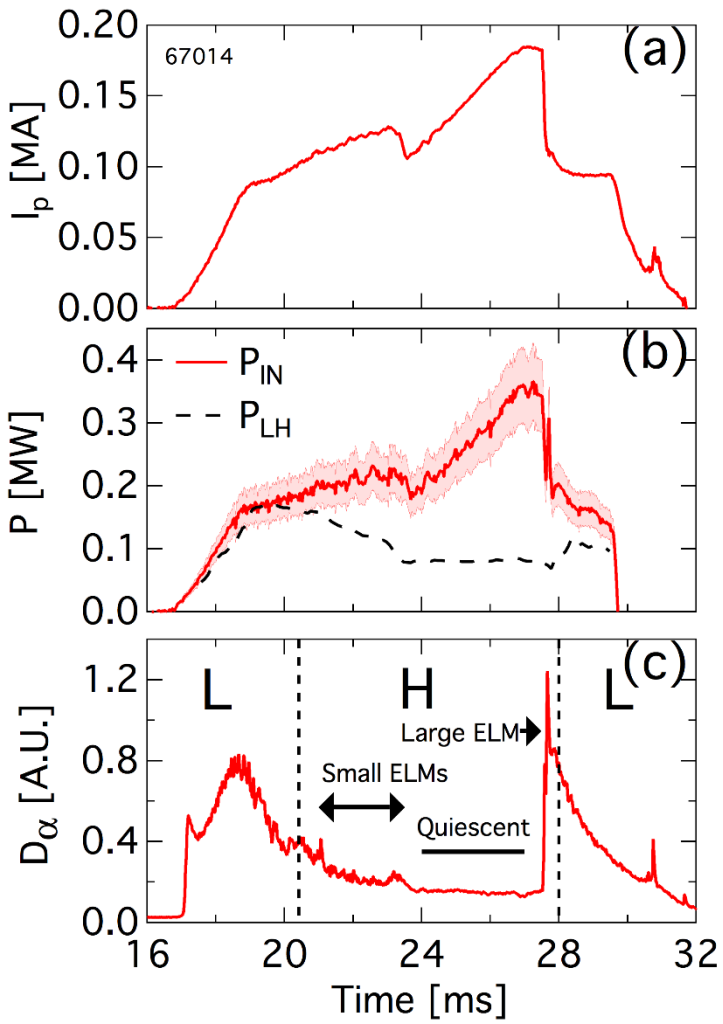
- Detailed measurements required to validate theory
  - P_{edge}, $J_{edge}(R,t)$ on ELM timescales

*Maggi, Nucl. Fusion **50**, 066001 (2010)*
*Huijsmans et al., Phys. Plasmas **22**, 021805 (2015)*

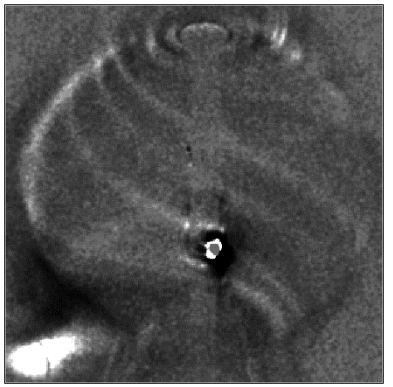
A ~ 1 Regime Well-Suited for Studies of ELMs and their Nonlinear Dynamics

- ELMs create 3D filaments
  - Coincident with D_α bursts
- Small ("Type III"):
  - Low-n, peeling-like
  - Observed at $P_{OH} \sim P_{LH}$
- Large ("Type I")
  - Intermediate n
  - Observed at $P_{OH} >> P_{LH}$

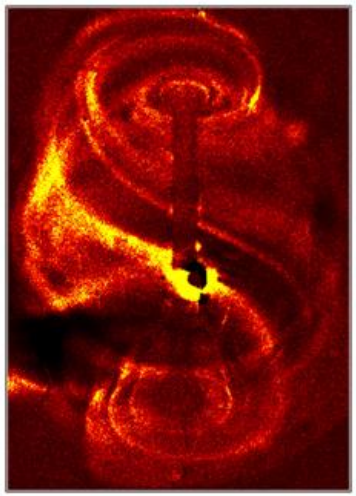
Evolution of Discharge with Small, Large ELMs with P_{OH} ramp



Small (Type III) ELM



Large (Type I) ELM



*Thome et al., Nucl. Fusion **57**, 022018 (2017)*

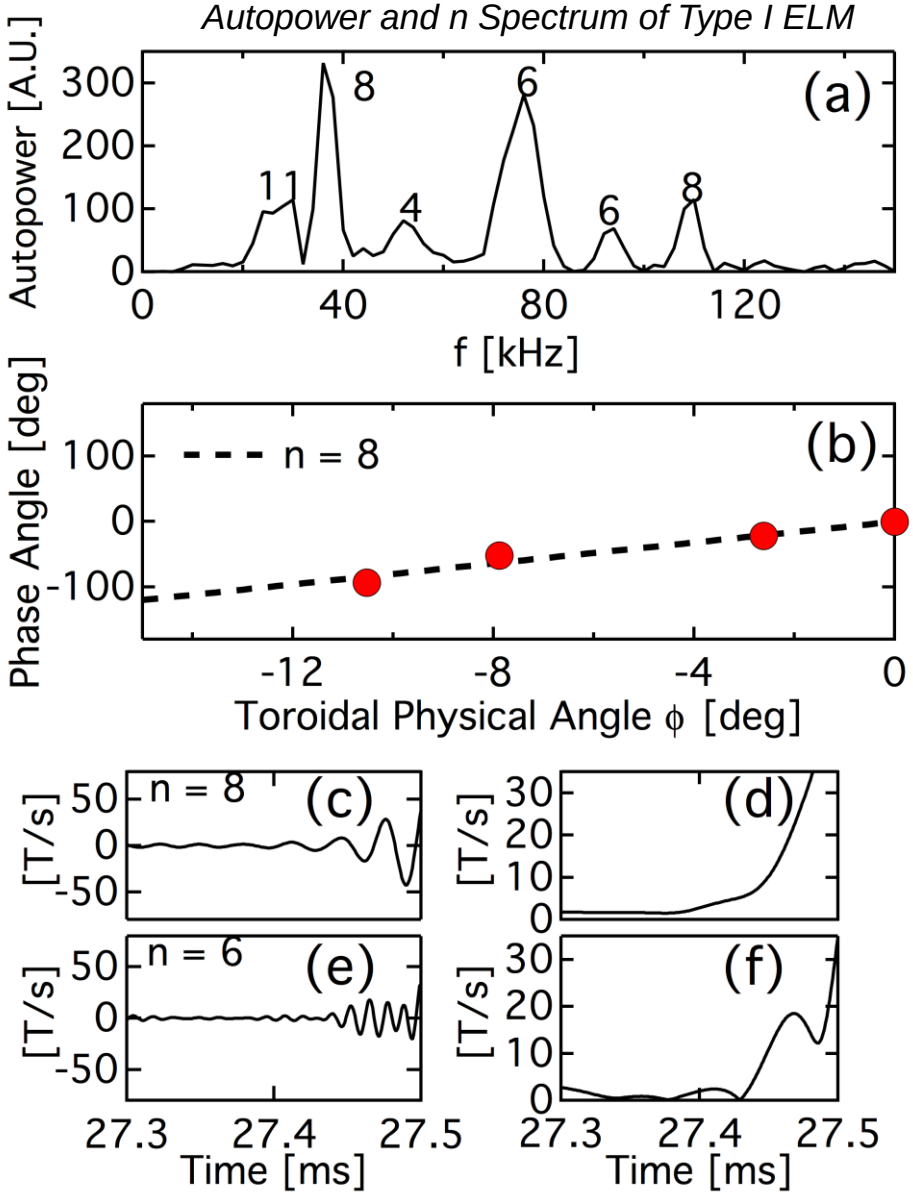
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Nonlinear ELM Precursors Observable with Edge-Localized Mirnov Coil Array

Fast Visible Imaging Across Type I ELM



Autopower and n Spectrum of Type I ELM



- Simultaneously unstable n during ELM
  - Detectable only within ~ cm of LCFS
  - Nonlinear energy exchange
- Modes grow on MHD timescales
  - n = 8 grows continuously
  - n = 6 fluctuates prior to crash

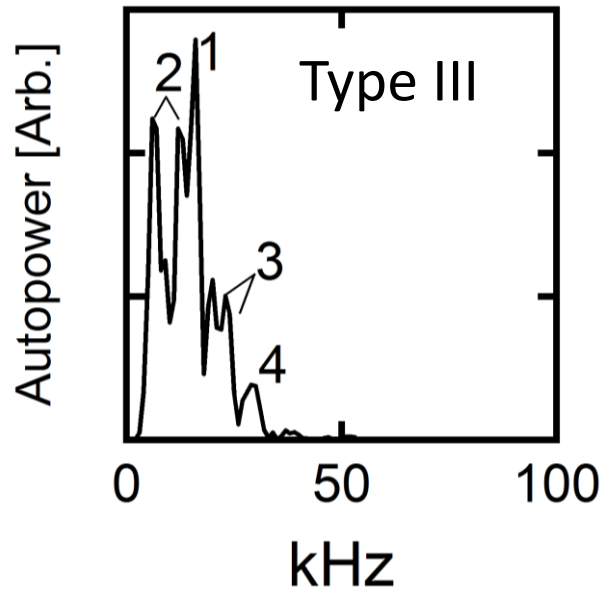
Thome et al., Nucl. Fusion **57**, *022018 (2017)*

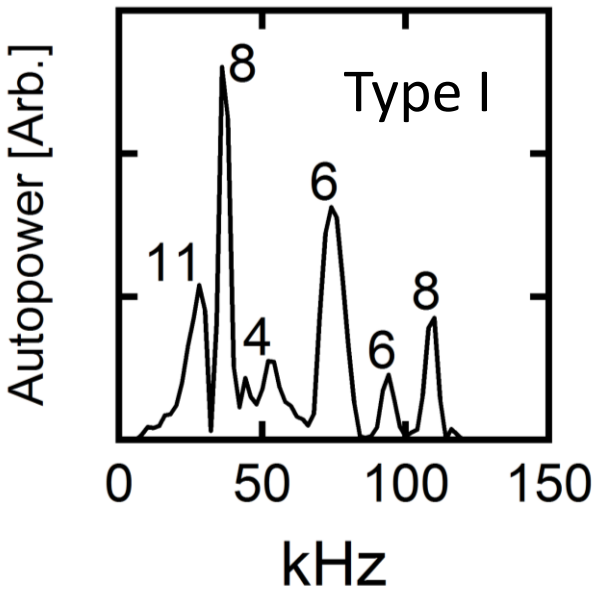
Bandpass filtered dBz/dt (c), (e) and amplitudes (d),(f) of n = 8, n = 6 modes

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ELM Magnetic Structure Varies with *A*

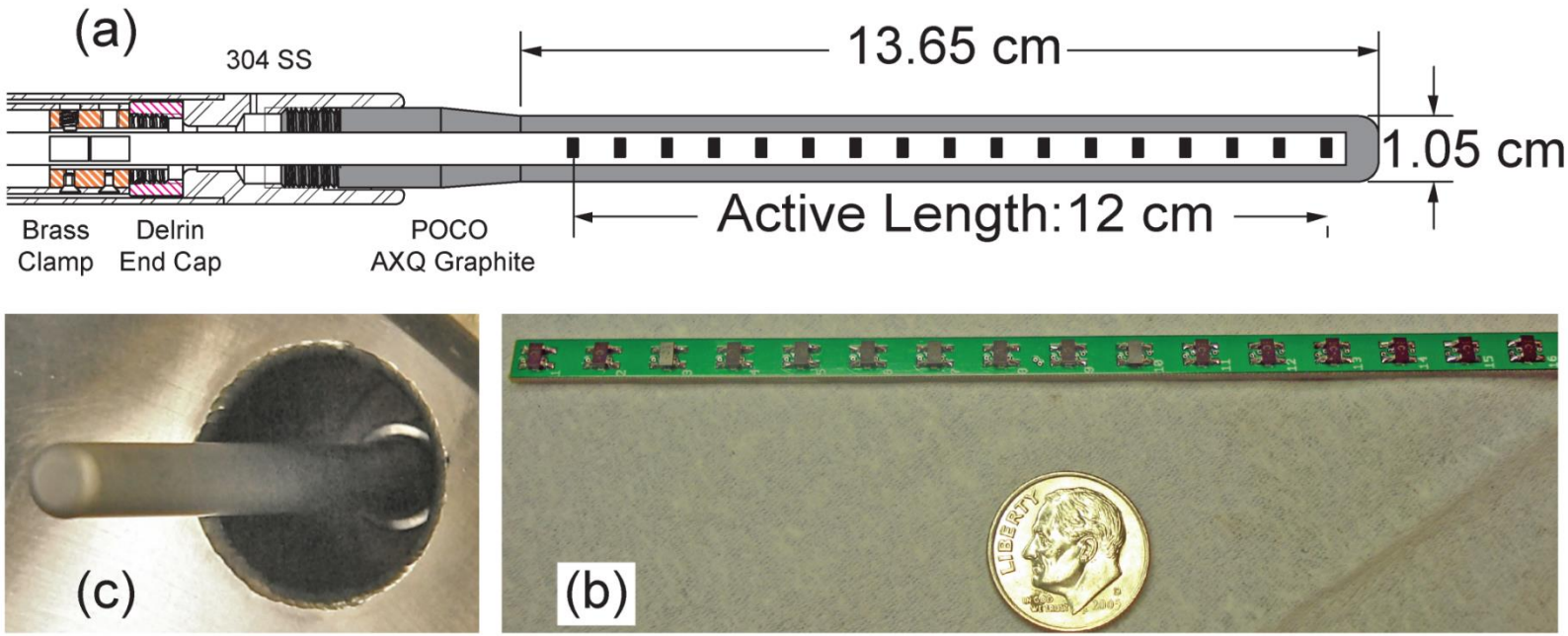
- Edge Mirnov array measures ELM toroidal mode spectrum
  - $n \leq 20$ resolved by multipoint cross-phase analyses
- Type III: *A* dependent
  - Low $A \leq 1.4$: $n \leq 1 - 4$
    - PEGASUS, NSTX
  - Conventional $A \sim 3$: n > 8
- Type I: *A* independent
  - Intermediate-*n*
  - Low-*A* devices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





*Maingi et al., Nucl. Fusion **45**, 1066 (2005); Kass et al., Nucl. Fusion **38**, 111 (1998)*
*Perez et al., Nucl. Fusion **44**, 609 (2004); Thome et al., Phys. Rev. Lett. **116**, 175001 (2016)*

PEGASUS Hall Probe Provides $J_{edge}(R, t)$ on Alfvénic Timescales



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

- Precision $B_z(R, t)$ measurements
  - 16 solid-state InSb Hall sensors
  - 7.5 mm radial resolution
  - 75 kHz large-signal bandwidth
  - 175 kHz small-signal bandwidth
- Carbon Armored
  - Compatible with L, H-mode to date

- J_ϕ obtained directly via Ampère's Law
  - Assumes local tokamak equilibrium
  - No profile parameterization constraint

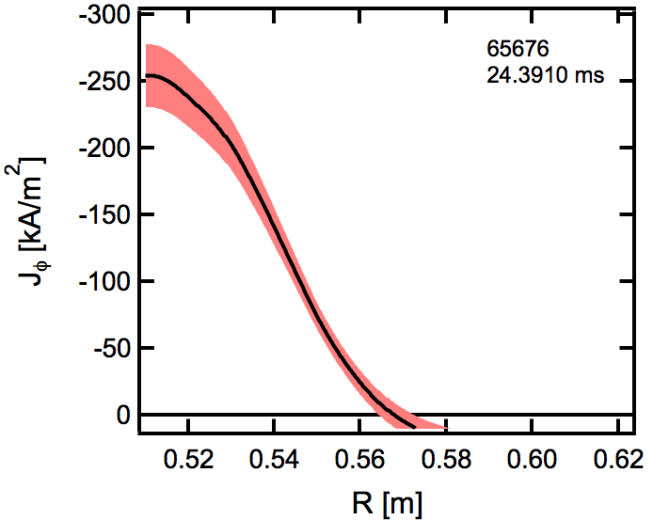
$$\mu_0 J_\phi = -\frac{B_Z}{\kappa^2 (R-R_0)}\left(1-\frac{Z^2 R_0}{\kappa^2 R (R-R_0)^2}\right)-\frac{dB_Z}{dR}\left(1+\frac{Z^2}{\kappa^4 (R-R_0)^2}\right)$$

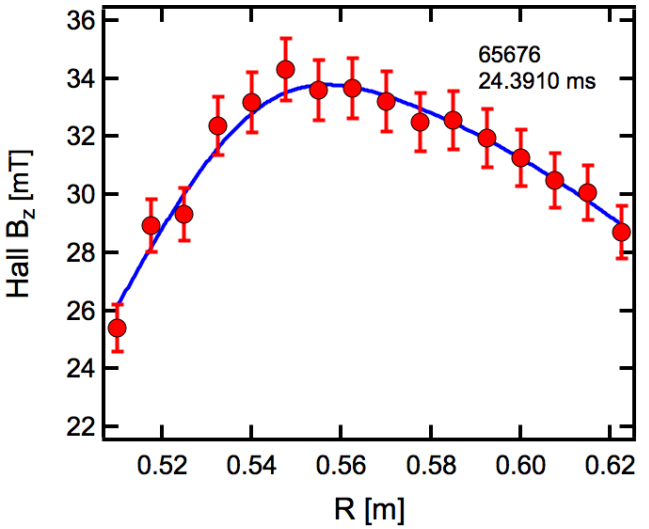
Petty et al., Nucl. Fusion ***42****, 1124 (2002)*

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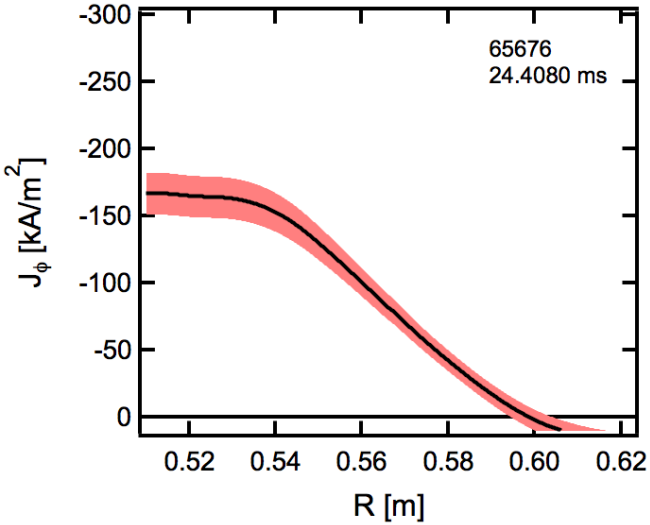
J_{edge} Structure Reflected in B_z Measurements

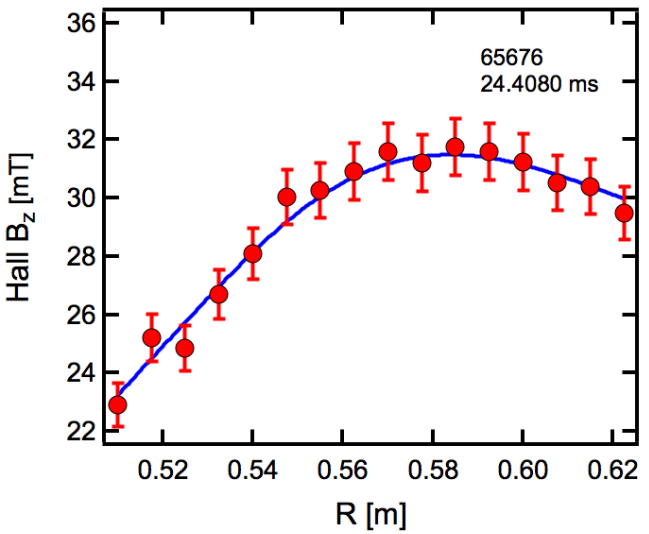
Type I Peak



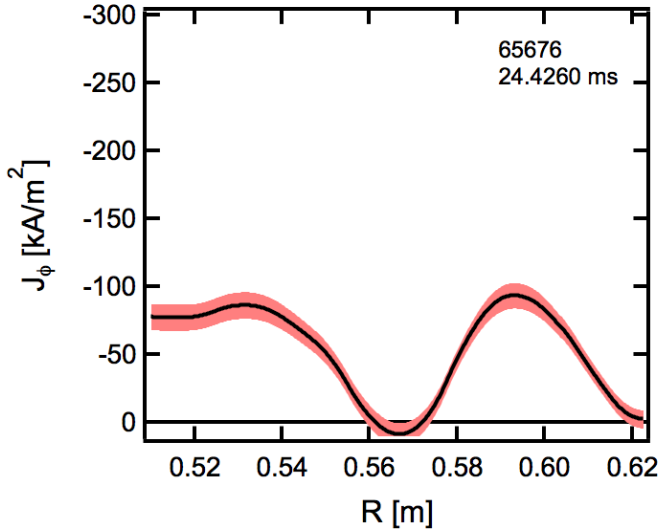


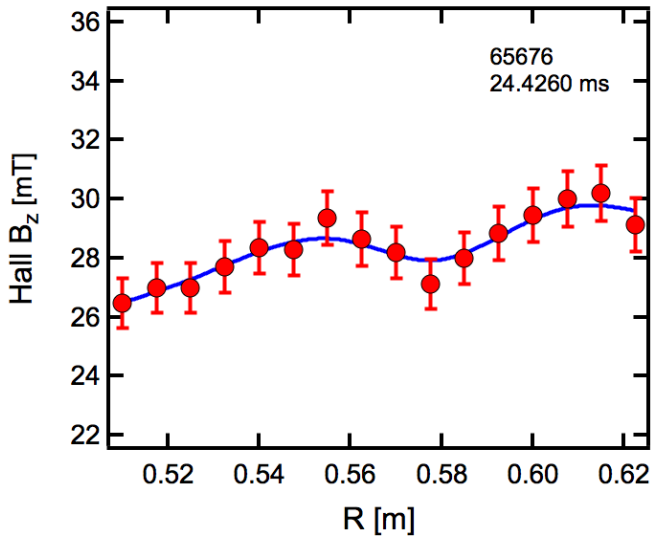
Type I Mid-Crash





Filament Expulsion

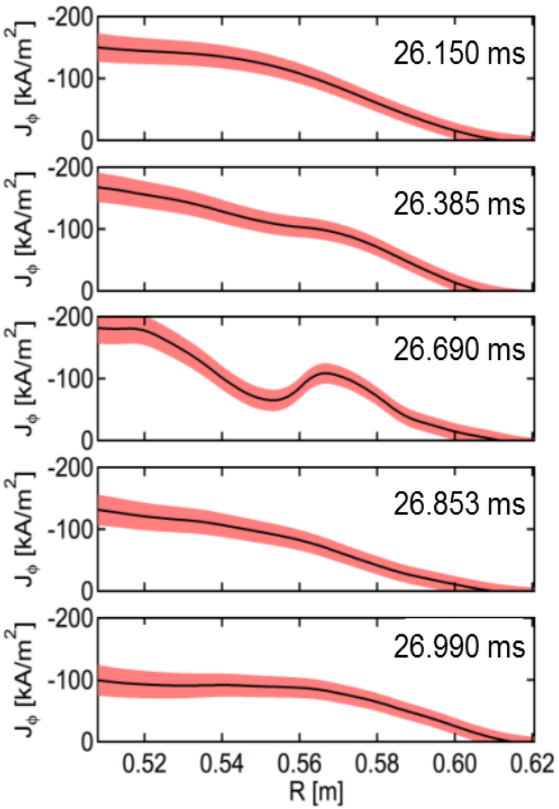




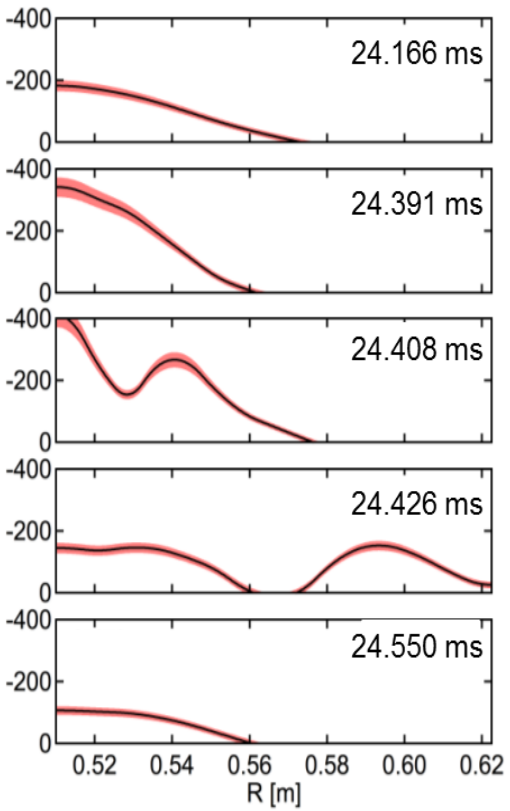
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Current-Hole J_{edge} Perturbation Accompanies Edge Instability

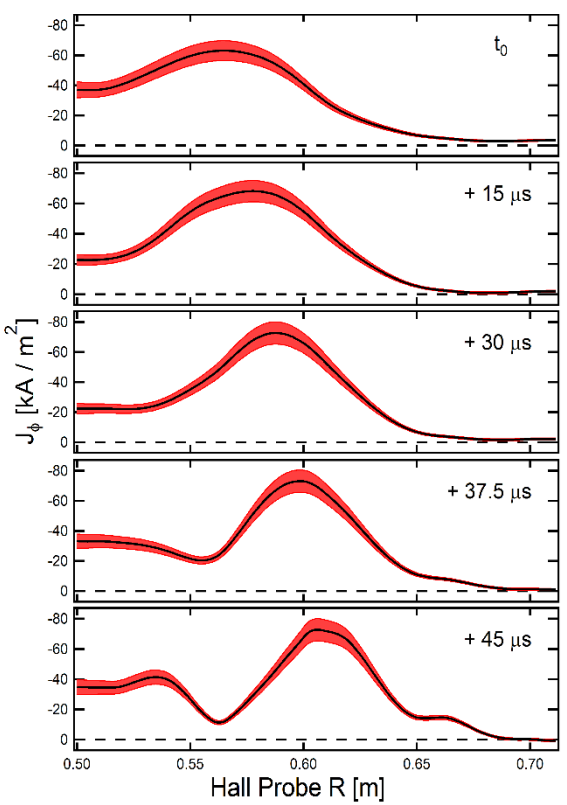
Type III ELM



Type I ELM

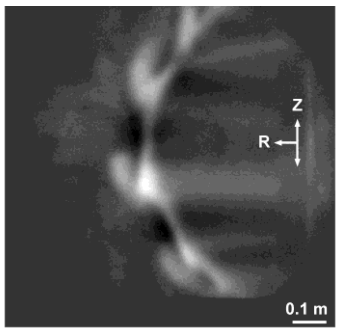


Nonlinear Peeling Mode (L-mode)

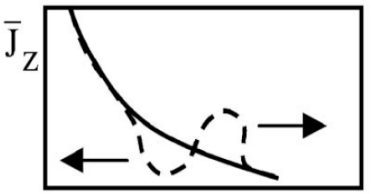


- Feature observed during ELMs and peeling modes
  - Validates mechanism hypothesized by EM blob transport theory
  - Type III ELM: smaller perturbation, slower, no filament evident
  - Type I: larger, faster, filament expulsion

Nonlinear Peeling Mode Filaments



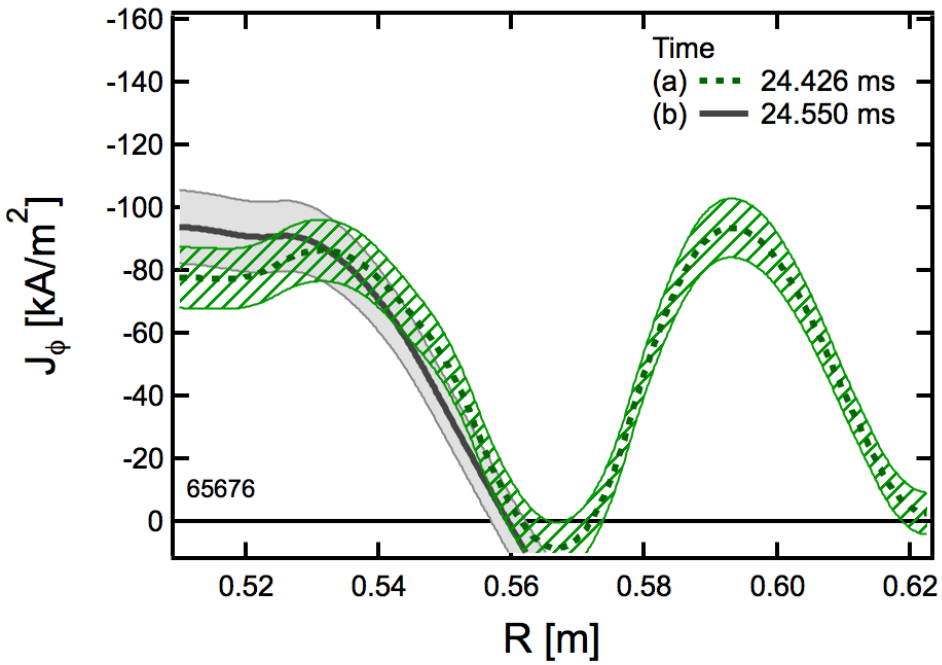
Model of "Current-Hole" Filament Ejection

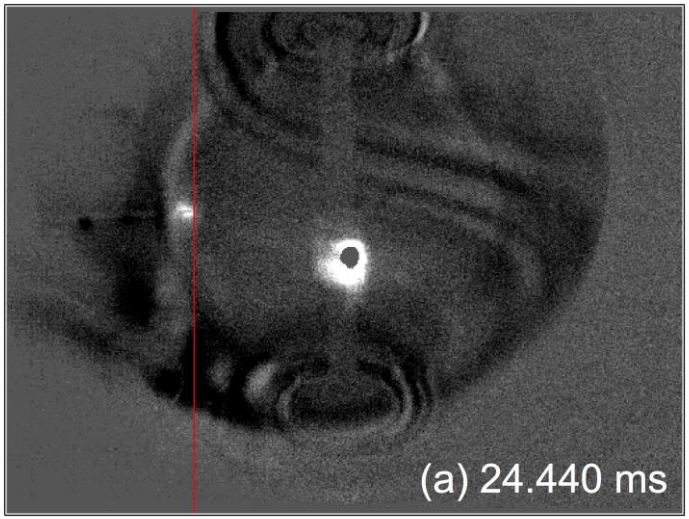


*Myra, Phys. Plasmas **14**, 102314 (2007)*
*Bongard et al., Phys. Rev. Lett. **107**, 035003 (2011)*
*Thome et al., Nucl. Fusion **57**, 022018 (2017)*

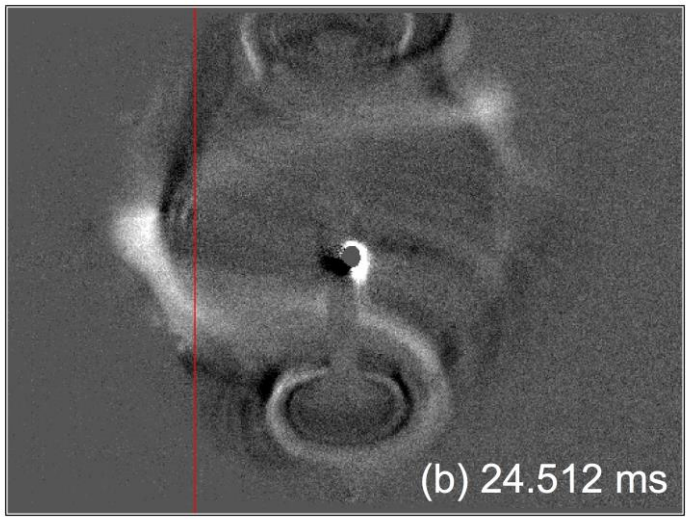
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Type I ELM Filament Ejection Coincides with J_{edge} Current-Hole Generation





Nearest Imaging Times; Prior Frame Subtracted

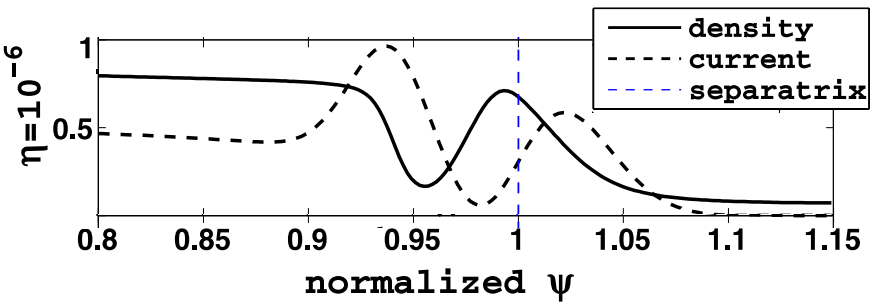


- Outwardly-propagating filament observed with high-speed visible imaging in ELM crash

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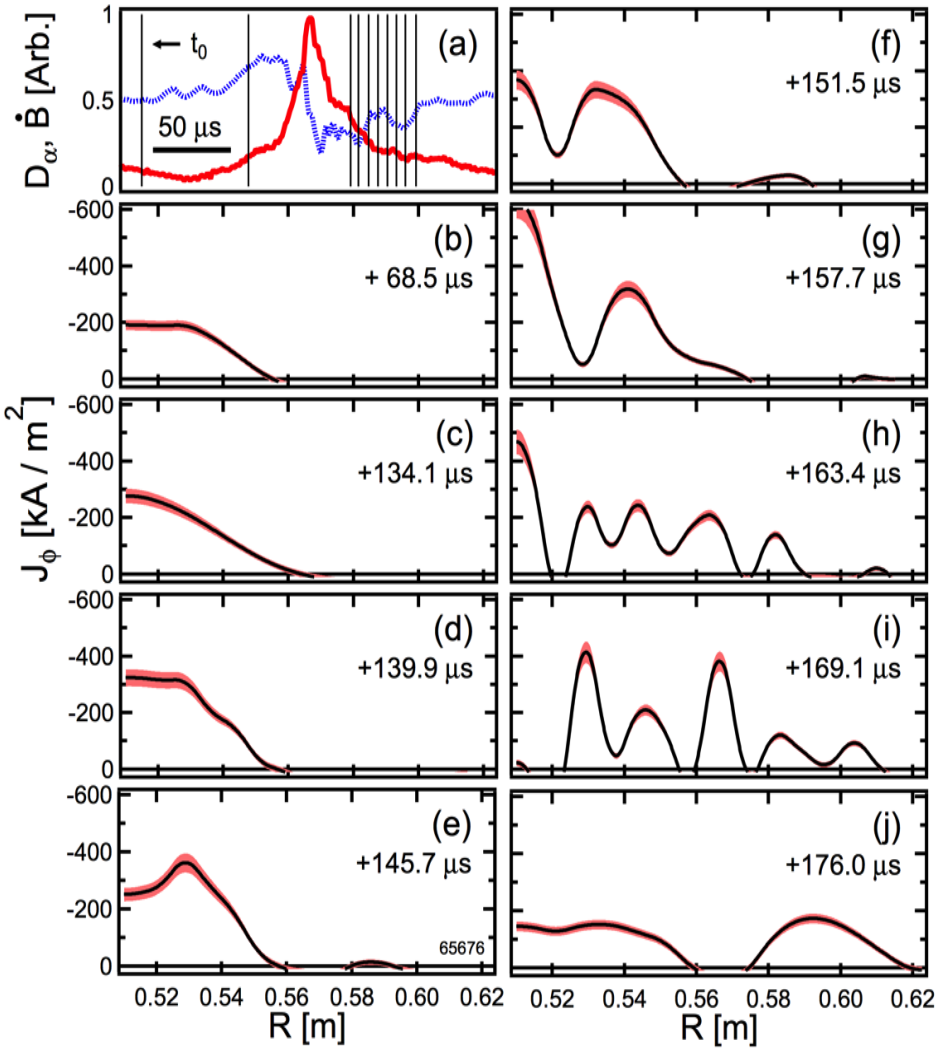
Type I ELM $J_{edge}(R,t)$ Dynamics Measured Throughout Single ELM Event

- **Challenge:** nonlinear ELM dynamics at Alfvénic timescales
- Current profile evolution through ELM cycle shows complex multimodal behavior
  - Less spatial smoothing employed in Hall probe analysis
- Opportunities for detailed comparison to nonlinear MHD simulations
  - *e.g.* NIMROD, JOREK, BOUT++



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

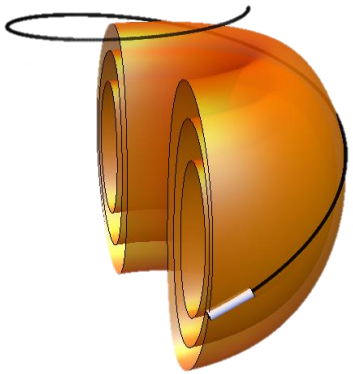
Type I ELM Evolution

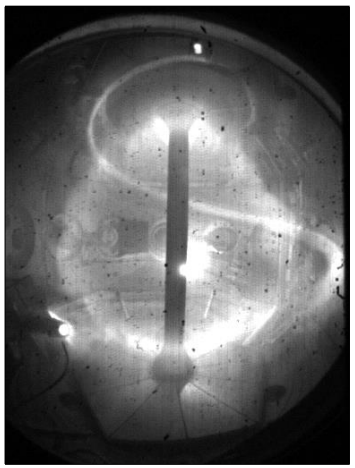


Thome et al., Phys. Rev. Lett. ***116****, 175001 (2016)*

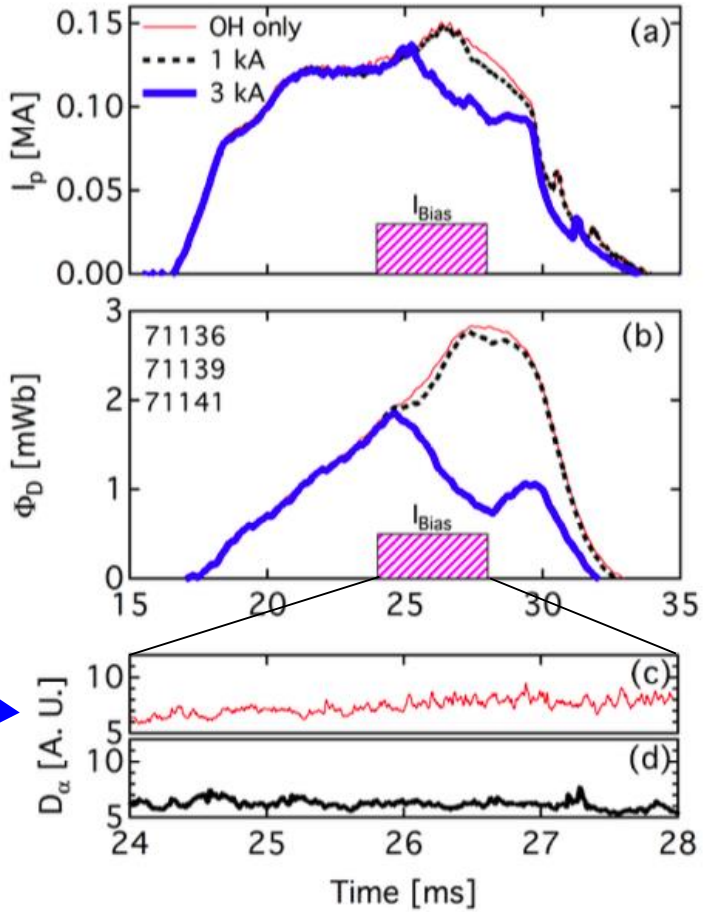
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3D Edge Current Injection May Influence ELM Stability





- LHI system affects edge plasma
  - $I_{inj} \leq 5$ kA, J_{inj} ~1 kA/cm^2
  - Strong 3D edge current perturbation
    - Similar to LHCD on EAST[1]
  - Edge biasing; modify rotation
- J_{edge} injection in H-mode suggests ELM suppression
  - Low I_{inj} = ELM suppression
  - High I_{inj} = edge, discharge degradation



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

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Low-A Regime Provides Environment for Unique Tests of Edge Stability Theory

H-mode Physics with Pedestal Diagnostic Access

- Standard features: J, p pedestals; low D_α, increased τ_e
- Strong P_{LH} threshold dependence on A
- Insensitivity to magnetic topology

ELM Regimes Identified with Differing n Spectra

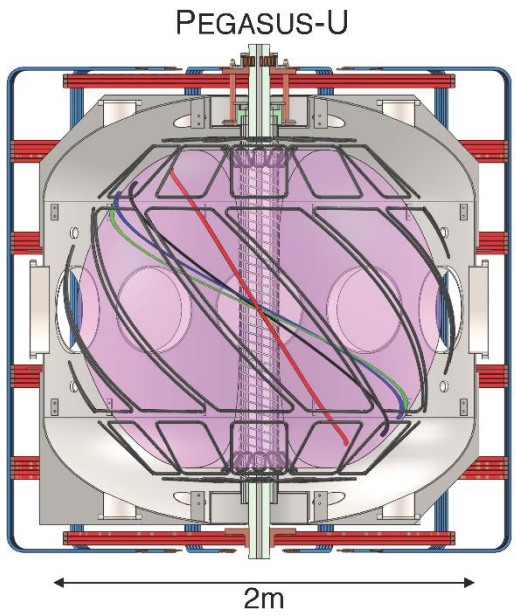
- Large, Type I-like: intermediate n
- Small, Type III-like: low n
- Strong peeling drive @ low A
- Simultaneous spectrum of n present during crash

Nonlinear ELM Dynamics on Alfvénic Timescales

- Nonlinear energy exchange in n modes prior to crash
- Fast $J_{edge}(R, t)$: current-hole perturbation, filament expulsion

Helical Edge Current Injection Affects Type III ELMs

- Potential dual use of LHI injectors as ELM control actuator



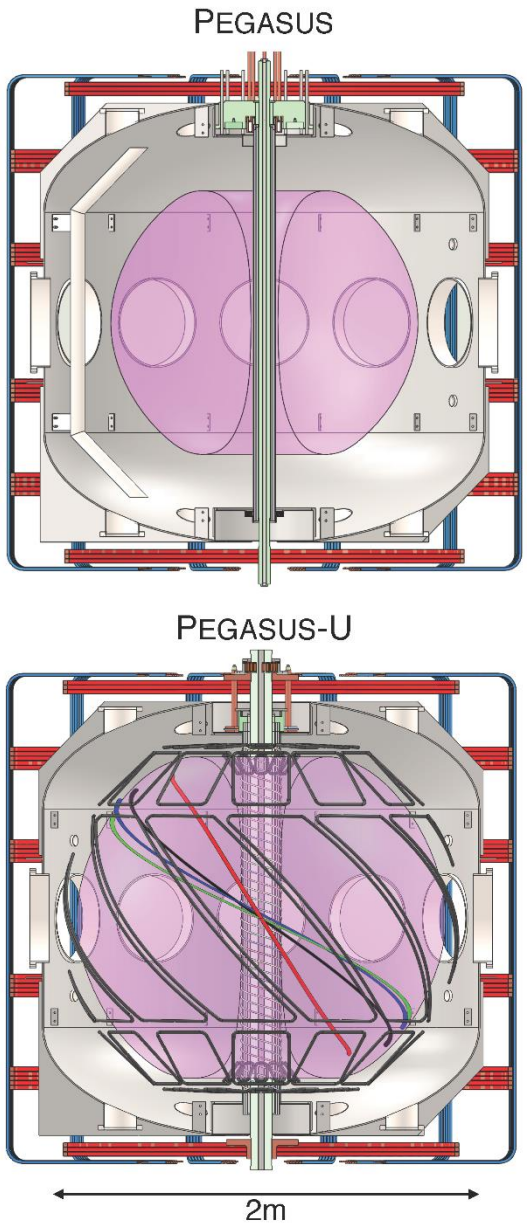
Proposed Upgrades:

- Pedestal physics, nonlinear ELM physics and mitigation
- Local Helicity Injection in NSTX-U relevant conditions

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PEGASUS-U Supports ELM Physics Mission

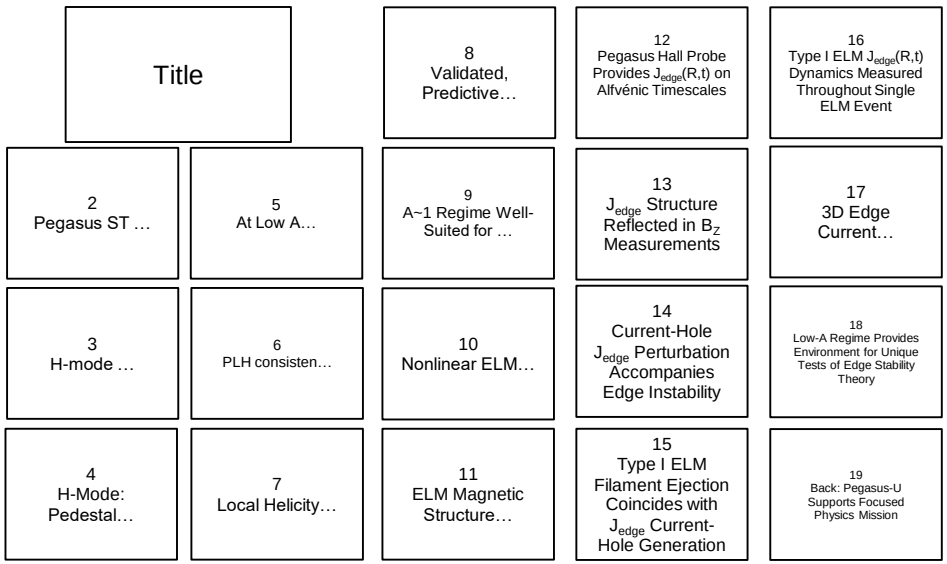
- Nonlinear pedestal and ELM studies
  - Simultaneous measurements of p(R,t), J(R,t), v_ϕ(R,t)
    - New edge diagnostics (probe arrays, DNB)
  - Tests of Sauter neoclassical bootstrap model
- ELM Modification and Mitigation
  - Novel 3D-Magnetic Perturbations coil array
    - LFS array: 12 toroidal × 7 poloidal
    - Helically-wound HFS coils
  - LHI current injectors in divertor, LFS regions



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Poster Layout

US Letter
8.5 x 11”



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