ELM Characterization and Dynamics at Near-Unity A in the Pegasus ST

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PEGASUS Toroidal Experiment

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Poster Layout

10:1 scale

US Legal
8.5 x 14”

US Letter
8.5 x 11”

Panel size: 190 x 120 cm

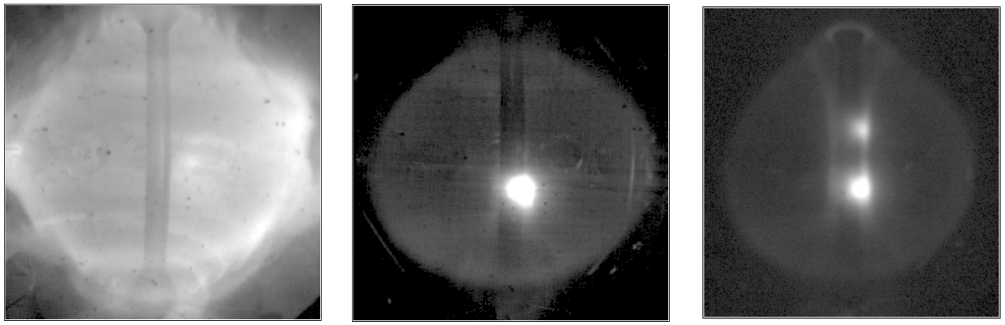
Title

H-mode Readily Accessed in A ~ 1 Pegasus ST	A~1 Regime Well-Suited for Studies of ELMs and their Nonlinear Dynamics	Current-Hole J_{edge} Perturbation Accompanies Edge Instability
Validated, Predictive Theory Needed to Mitigate ELMs	ELM Magnetic Structure Varies with A	Type I ELM $J_{edge}(R,t)$ Dynamics Measured Throughout Single ELM Event
H-Mode: Pedestal Formation, Increased Confinement	Nonlinear ELM Precursors Observable with Edge-Localized Mirnov Coil Array	Type I ELM Filament Ejection Coincides with J_{edge} Current-Hole Generation
P_{LH} Consistent with Global Parametric Scalings – But Significant Differences Arise at Low A	Pegasus Hall Probe Provides $J_{edge}(R,t)$ on Alfvénic Timescales Back: $J_{\phi}(r,t)$ Calculable Directly from Ampere's Law	Initial 3D Edge Current Injection Experiments Suggest Mitigation of Type III ELMs
Local Helicity Injection Startup Compatible with Access to High-Quality Ohmic H-mode	J_{edge} Structure Reflected in B_z Measurements	Low-A Regime Provides Environment for Unique Tests of Edge Stability Theory Back: Pegasus-U Supports Focused Physics Mission

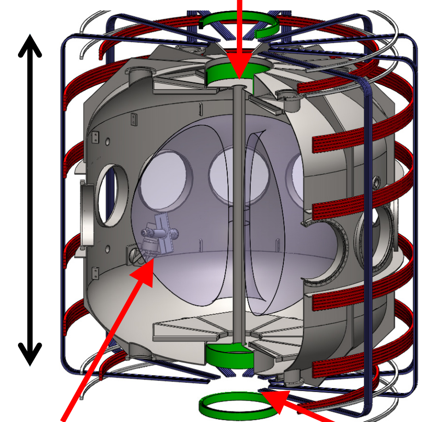
Recommended layout: 110 x 85 cm

H-mode Readily Accessed in A ~ 1 PEGASUS ST

Limited L | **Limited H** | **Diverted H**



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

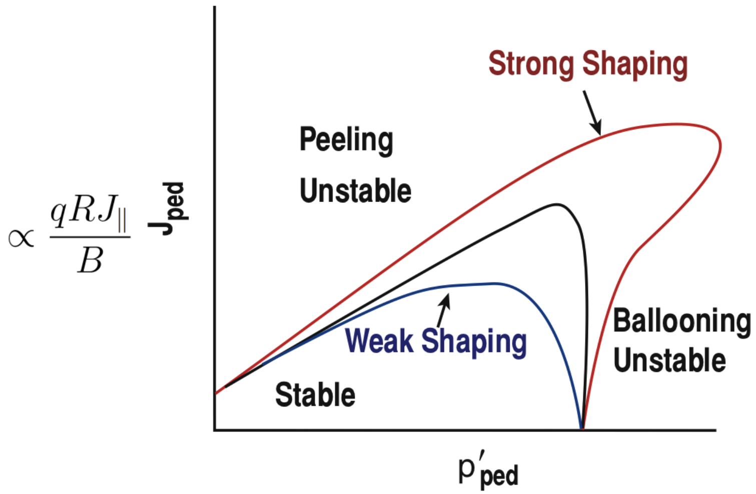
PEGASUS Toroidal Experiment

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

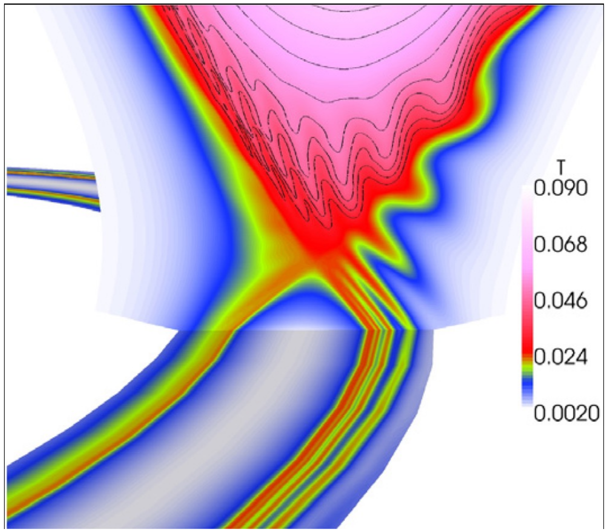
Thome et al., Nucl. Fusion ***57****, 022018 (2017)*

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
- Nonlinear extensions
  - More complete physical models
  - Evolution of P-B mode structures
  - Heat flux deposition projections
- Detailed measurements required to validate theory
  - P_{edge}, $J_{edge}(R,t)$ on ELM timescales



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



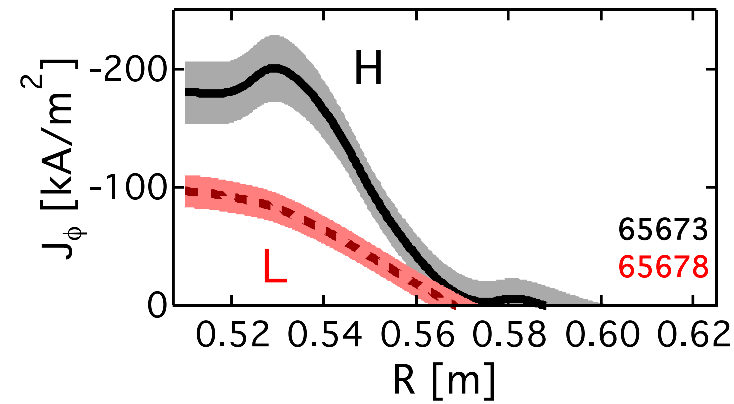
Huysmans et al., Plasma Phys. Control. Fusion ***51****, 124012 (2009)*

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

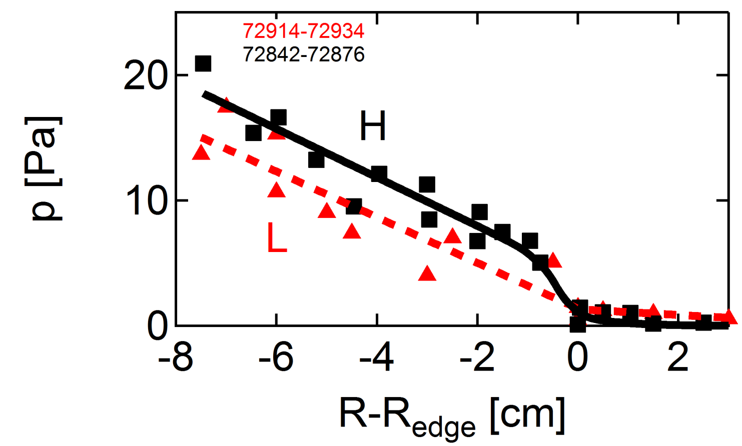
H-mode: Pedestal Formation, Increased Confinement

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



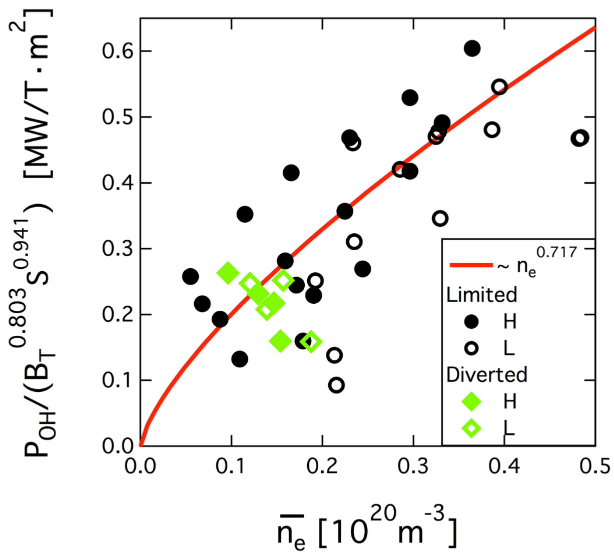
Multi-shot average



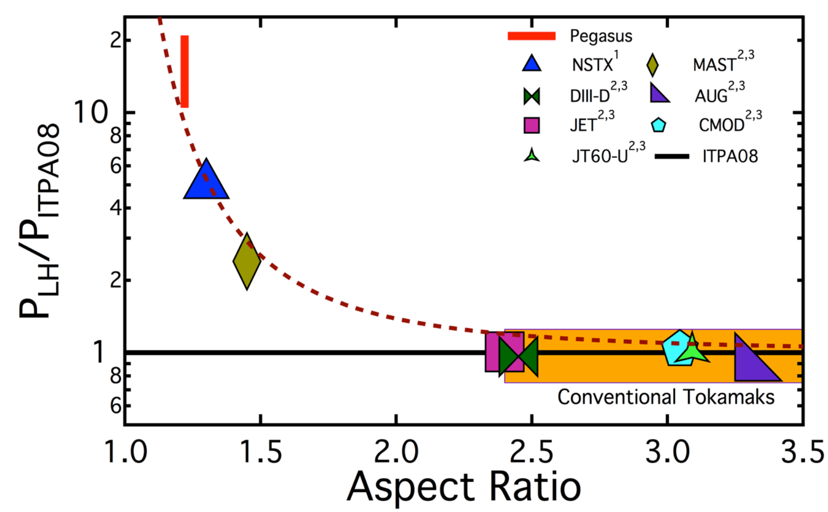
*Bongard et al., Rev. Sci. Instrum. **81**, 10E105 (2010)*
*Bongard et al., Phys. Rev. Lett. **107**, 035003 (2011)*
*Thome et al., Phys. Rev. Lett. **116**, 175001 (2016)*
*Thome et al., Nucl. Fusion **57**, 022018 (2017)*

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

Normalized P_{LH} vs. Density



Normalized P_{LH} vs. Aspect Ratio



- $P_{LH}(n_e)$ follows ITPA scaling
  - FM³ model: minimum $P_{LH}(n_e) \sim 1\times10^{18}$ m^{-3}
- Magnetic topology independence
  - Diverted, limited edge topology similar
  - FM³: $P_{LH}^{LIM}/P_{LH}^{DIV} \sim (q_\star^{LIM}/q_\star^{DIV})^{-7/9}$
- At low A, $P_{LH} >> P_{ITPA08}$
  - P_{LH} increasingly diverges from expectations as A → 1
  - $P_{LH}/P_{ITPA08} \sim 15$ at A ~ 1.2

*Fundamenski et al., Nucl. Fusion **52**, 062003 (2012)*
*Thome et al., Phys. Rev. Lett. **116**, 175001 (2016)*

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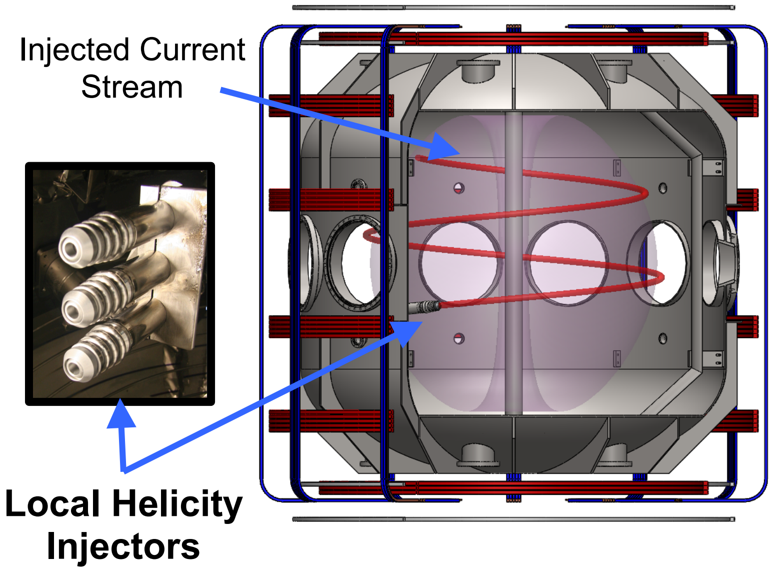
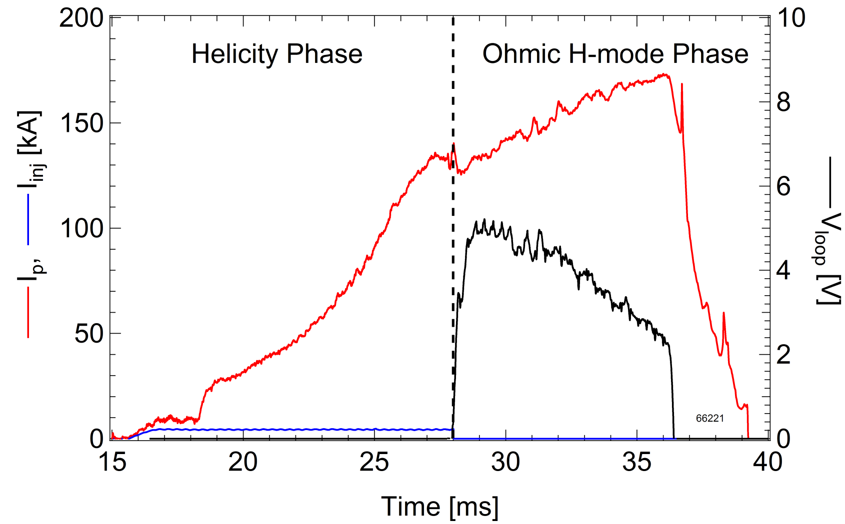
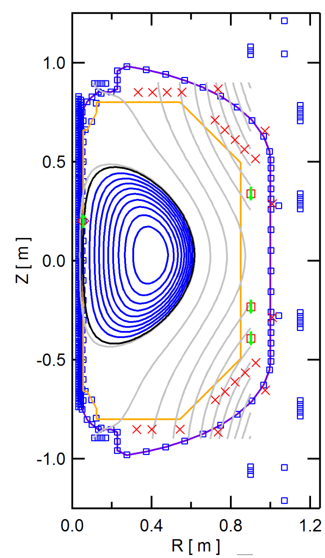
Local Helicity Injection Startup Compatible with Access to High-Quality Ohmic H-mode





- 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

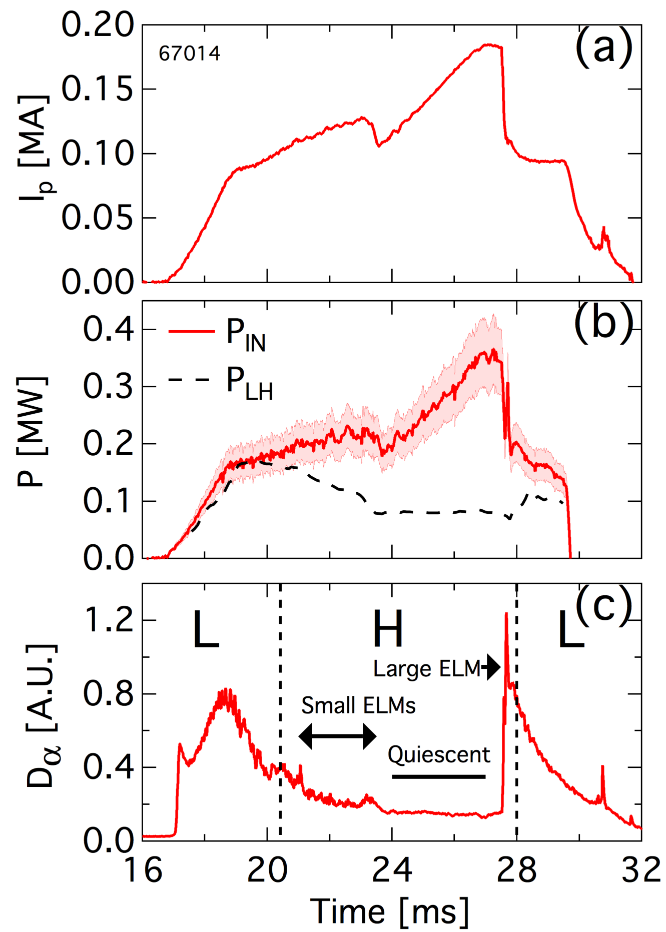
I_p	169 kA	R_0	0.336 m
β_t	0.081	a	0.281 m
ℓ_i	0.42	A	1.20
β_p	0.31	κ	1.6
W	2101 J	δ	0.44
B_{T0}	0.179 T	q_{95}	9.92

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

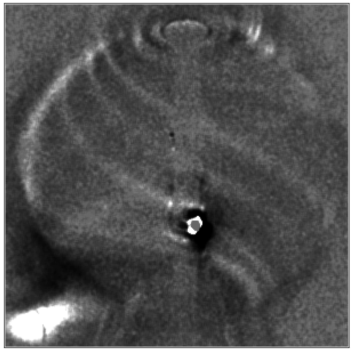
A ~ 1 Regime Well-Suited for Studies of ELMs and their Nonlinear Dynamics

- 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 $P_{OH} >> P_{LH}$

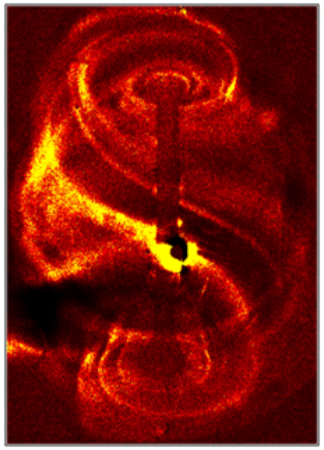
Evolution of Discharge with Small, Large ELMs with P_{OH} ramp



Small (Type III) ELM



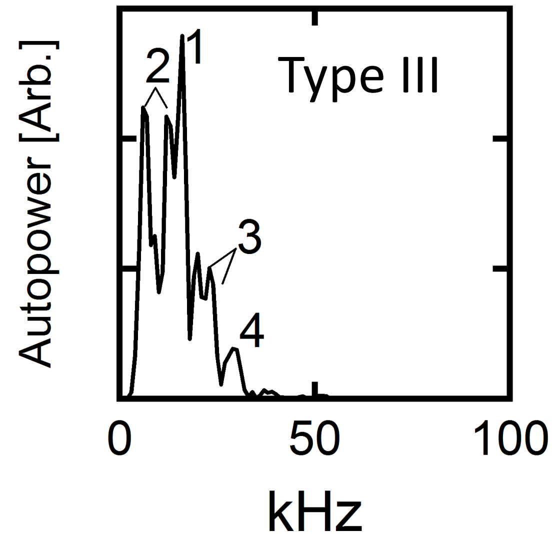
Large (Type I) ELM

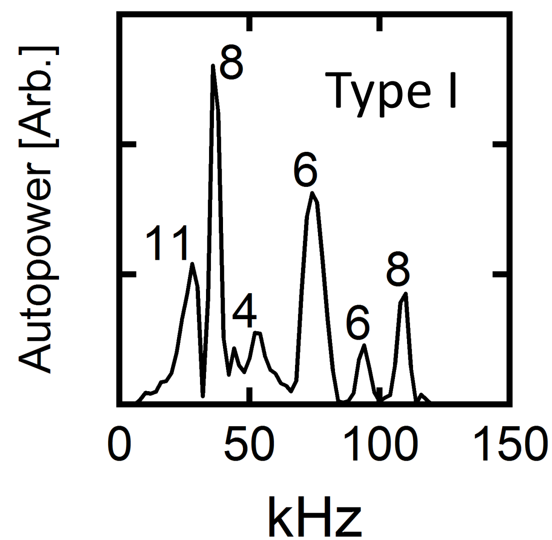


*Thome et al., Nucl. Fusion **57**, 022018 (2017)*

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 → lower n



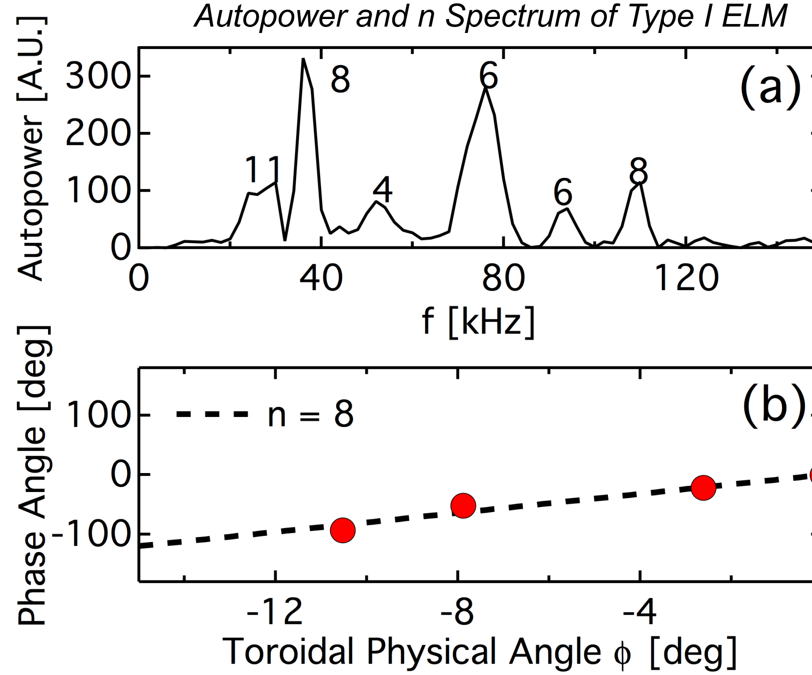


*Maingi et al., Nucl. Fusion **45**, 1066 (2005); Kass et al., Nucl. Fusion **38**, 111 (1998) Perez et al., Nucl. Fusion **44**, 609 (2004); Thome et al., Phys. Rev. Lett. **116**, 175001 (2016)*

Nonlinear ELM Precursors Observable with Edge-Localized Mirnov Coil Array

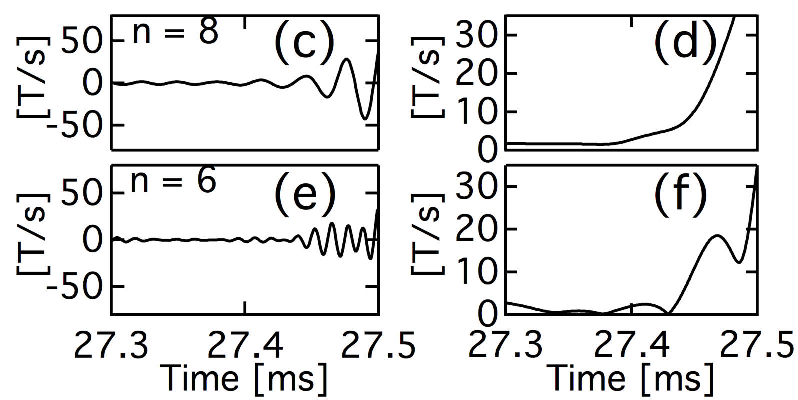
Fast Visible Imaging Across Type I ELM

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



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

M.W. Bongard, IAEA FEC 2016

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

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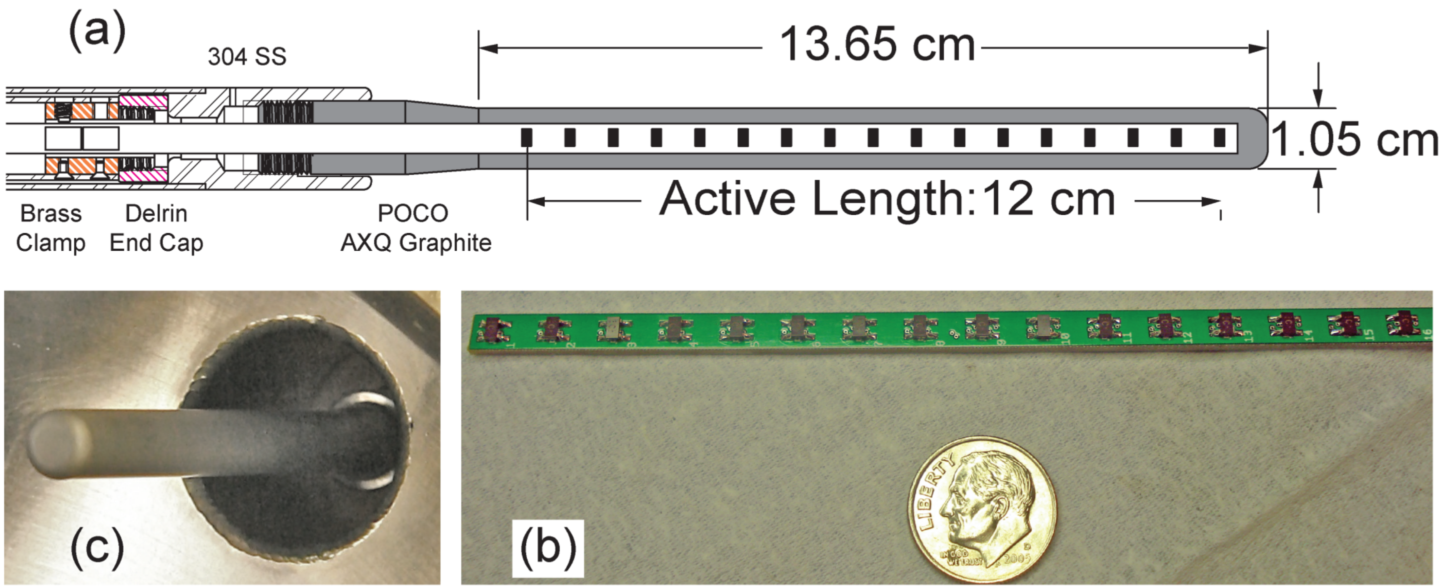
PEGASUS Hall Probe Provides $J_{edge}(R, t)$ on Alfvénic Timescales



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)*

$J_\phi(R,t)$ Calculable Directly from Ampère's Law

$$\mu_0 J_\phi = (\nabla \times \mathbf{B})_\phi = \frac{\partial B_R}{\partial Z} - \frac{\partial B_Z}{\partial R}$$

- Simplest test follows from $B_R(Z)$ or $B_Z(R)$ measurements
- Petty solves for an off-midplane $B_Z(R)$ measurement set and an elliptical plasma cross-section:

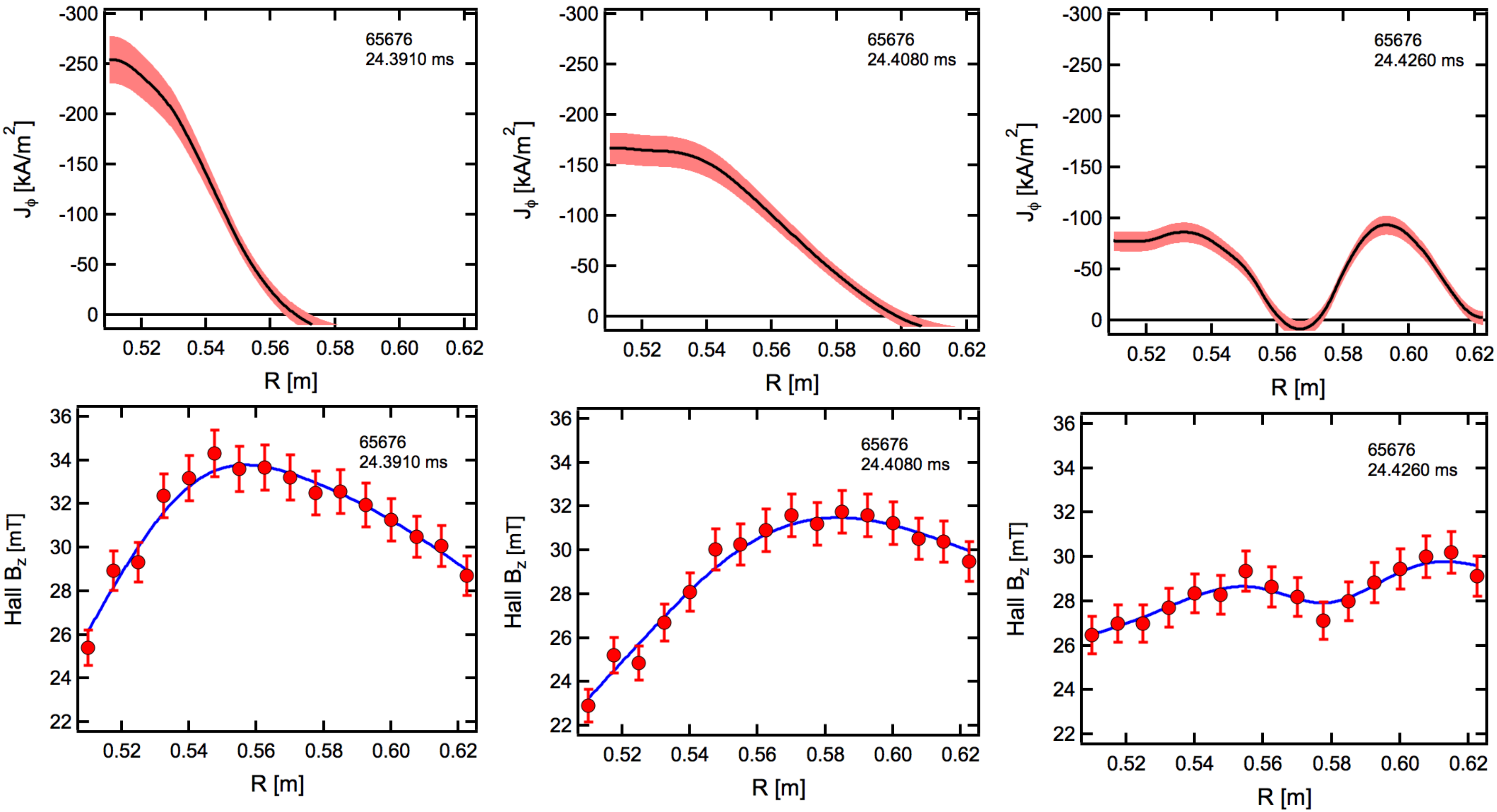
$$\mu_0 J_\phi = -\frac{B_Z}{\kappa^2 (R - R_0)}\left(1 - \frac{Z^2 R_0}{\kappa^2 R (R - R_0)^2}\right) - \frac{dB_Z}{dR}\left(1 + \frac{Z^2}{\kappa^4 (R - R_0)^2}\right)$$

- Does not make assumptions on shape of J(R)

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

J_{edge} Structure Reflected in B_z Measurements

Type I Peak | Type I Mid-Crash | Filament Expulsion



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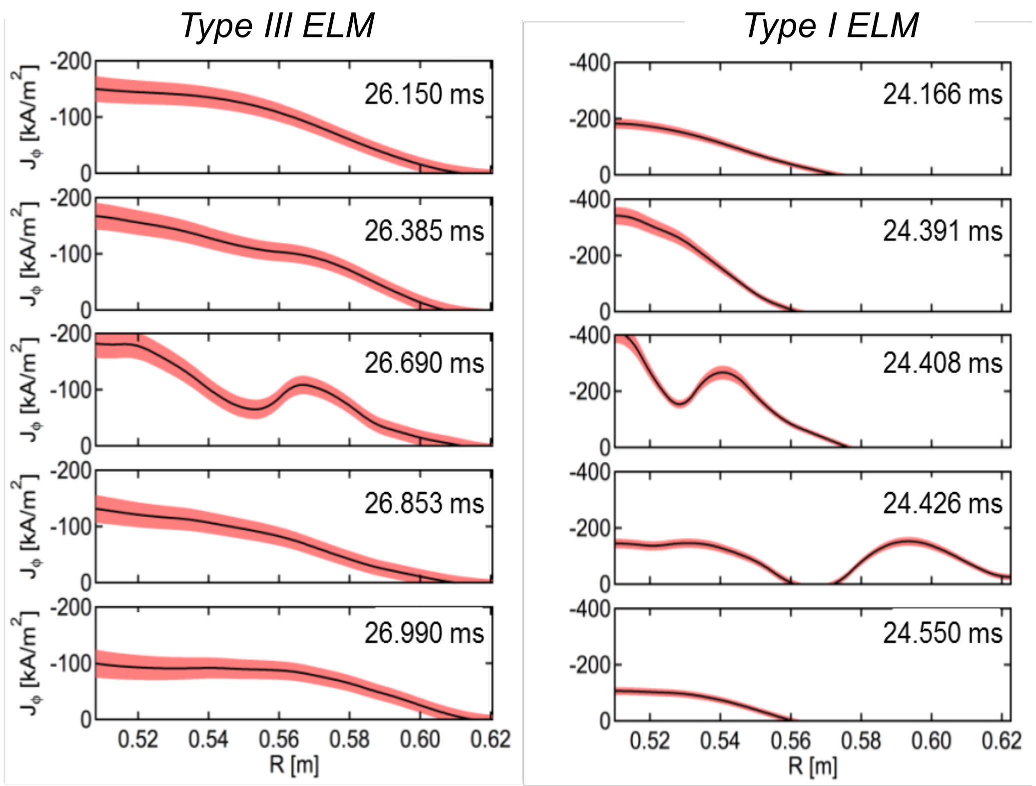
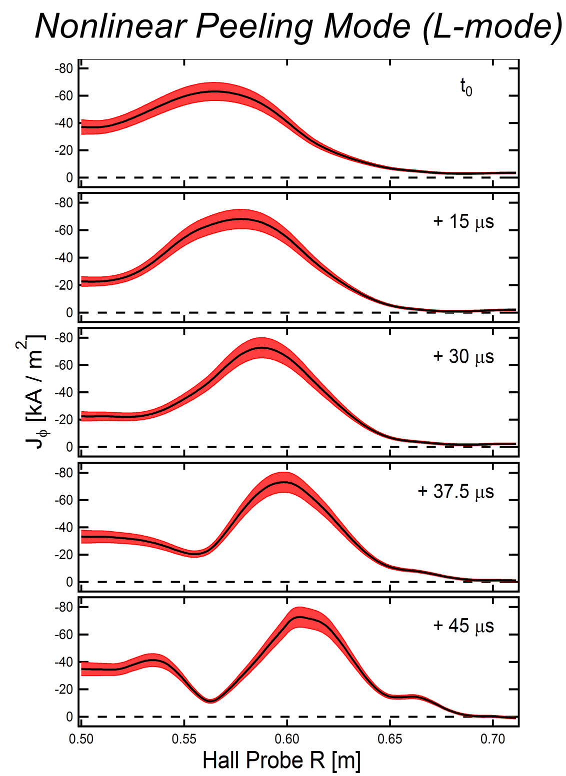
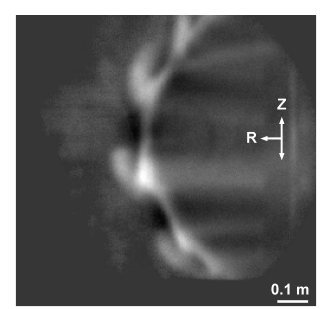
Current-Hole J_{edge} Perturbation Accompanies Edge Instability



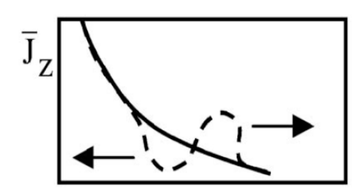


- Feature observed during ELMs and peeling modes
  - Validates mechanism hypothesized by EM blob transport theory
  - Type III ELM: smaller perturbation, slower, no filament evident
  - Type I: larger, faster, filament expulsion

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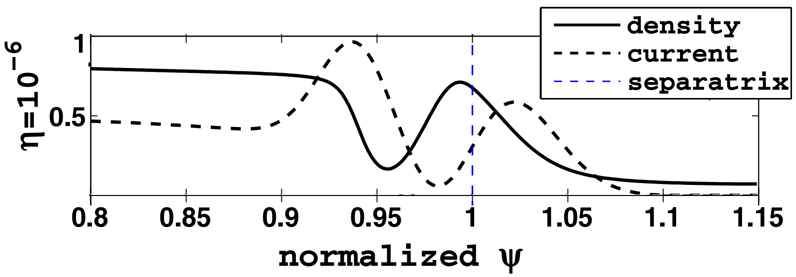
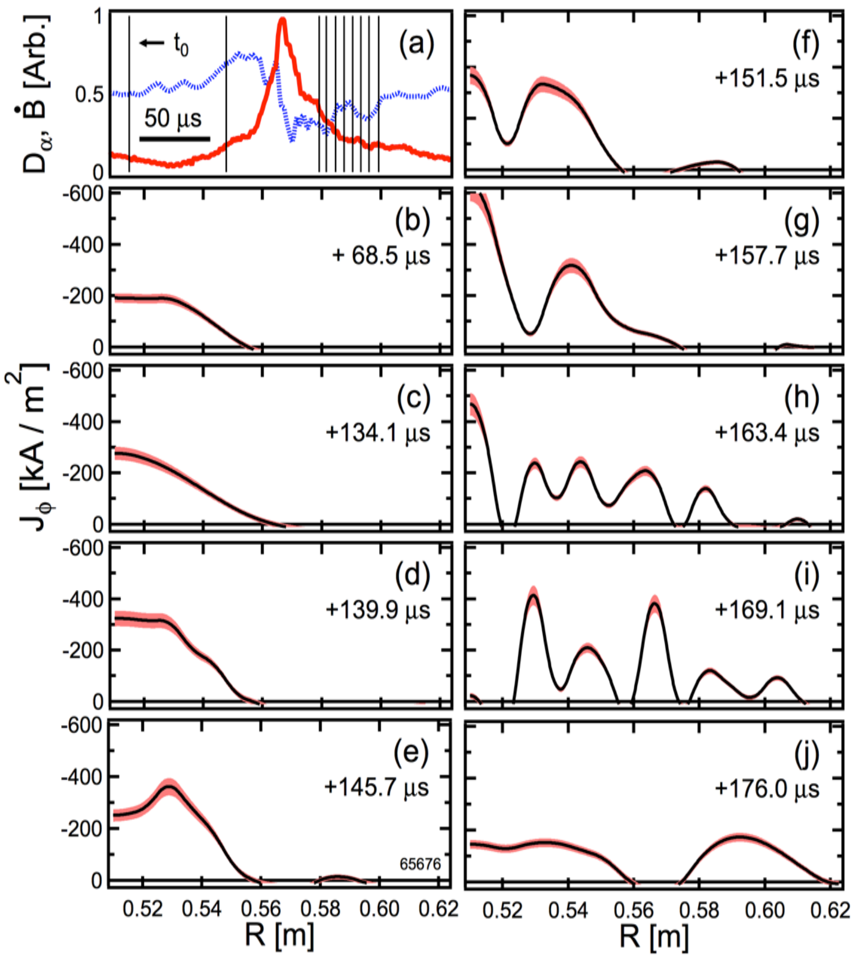
Type I ELM $J_{edge}(R,t)$ Dynamics Measured Throughout Single ELM Event

- **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++



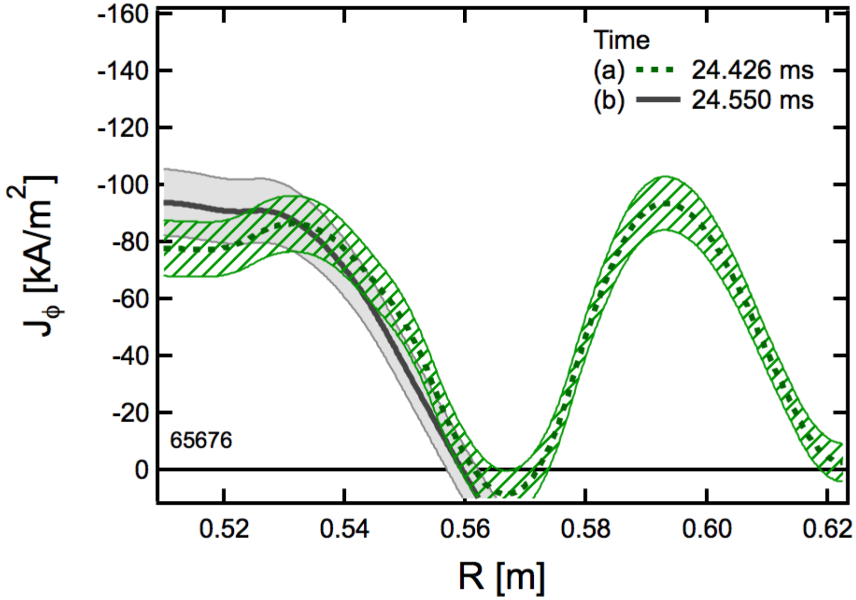
Pamela et al., Plasma Phys. Control. Fusion ***53****, 054014 (2011)*

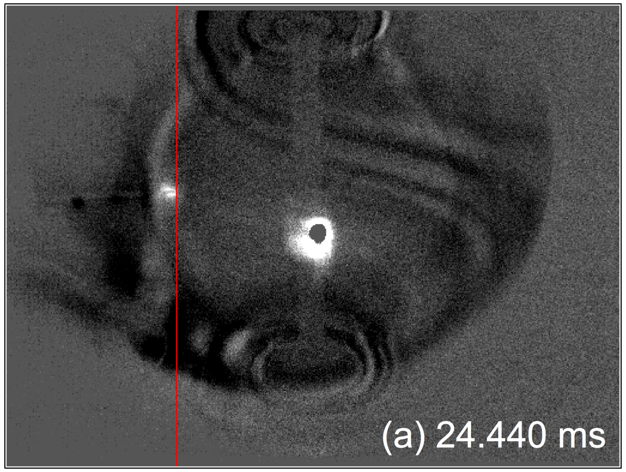
Type I ELM Evolution



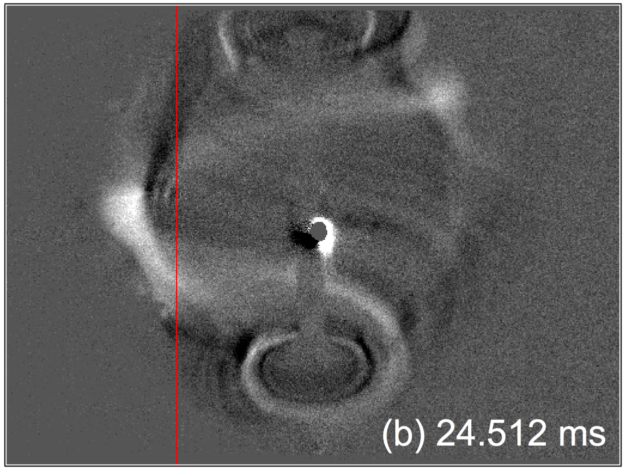
Thome et al., Phys. Rev. Lett. ***116****, 175001 (2016)*

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



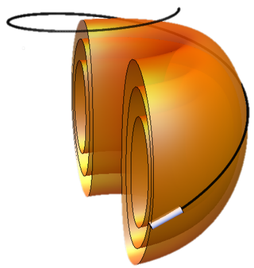


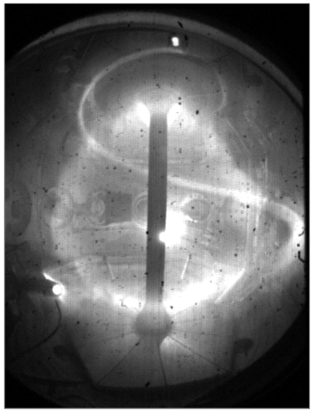
Nearest Imaging Times; Prior Frame Subtracted



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

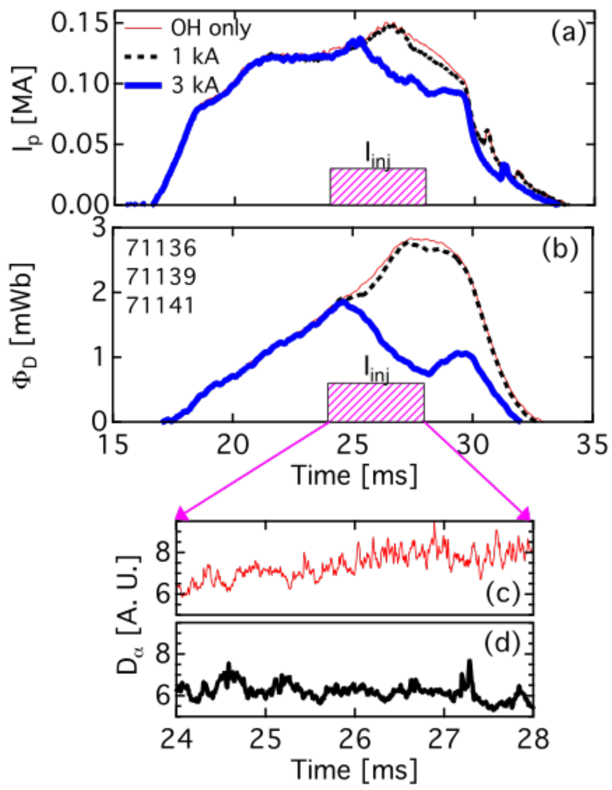
Initial 3D Edge Current Injection Experiments Suggest Mitigation of Type III ELMs





- Local helicity injection system provides 3D SOL current injection
  - $I_{inj} \leq 5$ kA, $J_{inj} \sim 1$ kA/cm^2
  - Strong 3D edge current perturbation
    - Similar to LHCD on EAST
  - Edge biasing: modify rotation

- Low levels of J_{edge} injection into H-mode reduce ELM activity
  - Low I_{inj} = ELM suppression
  - High I_{inj} = edge, shot degradation



Liang et al., Phys. Rev. Lett. ***110****, 235002 (2013)*
Thome et al., Nucl. Fusion ***57****, 022018 (2017)*

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
- Features unique to low-*A* emerging: P_{LH} threshold

ELM Regimes Identified with Differing n Spectra

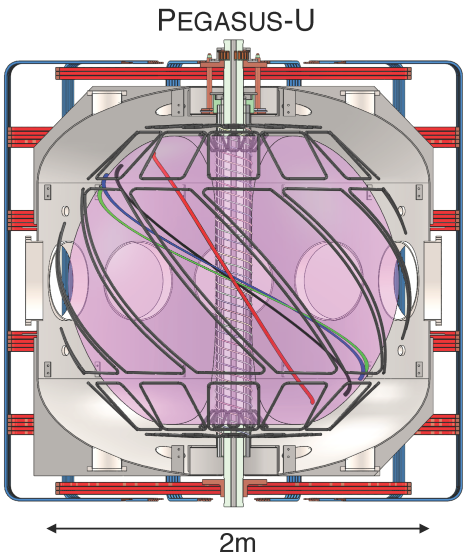
- Large, Type I-like: intermediate n
- Small, Type III-like: low n
- Simultaneous spectrum of n present during crash

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

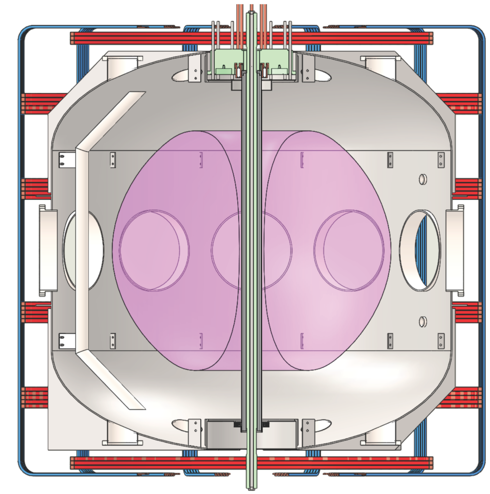
PEGASUS-U Supports Focused Physics Mission

- 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 $\times$ 7 poloidal
    - Helically-wound HFS coils
  - LHI current injectors in divertor, LFS regions

- Physics of Local Helicity Injection Startup
  - High I_p, long-pulse startup
  - Projections to NSTX-U

PEGASUS



PEGASUS-U