Initial Investigations of H-mode Edge Dynamics in the PEGASUS Toroidal Experiment

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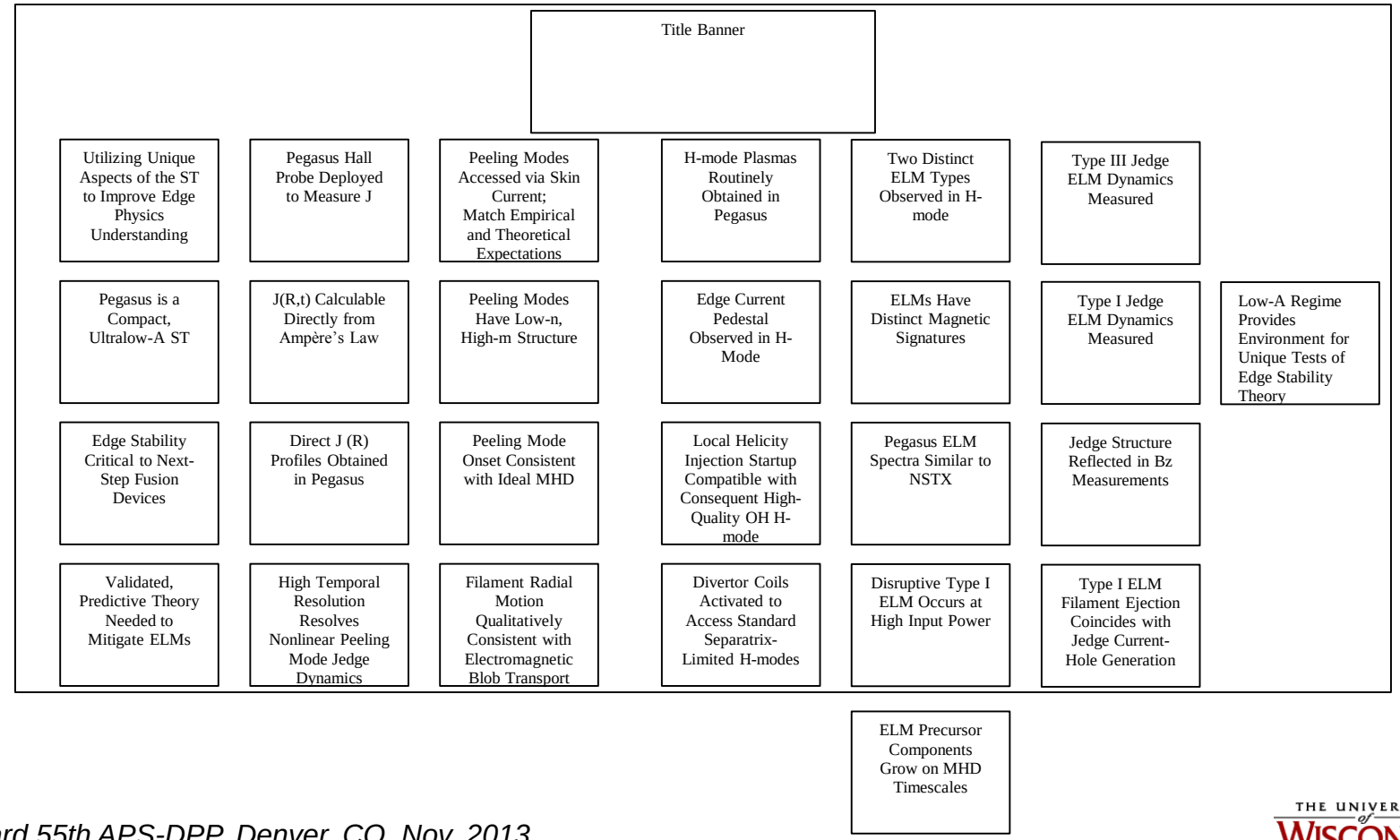


PEGASUS Toroidal Experiment

Layout

8.5” x 11”

8’ W x 4’ H

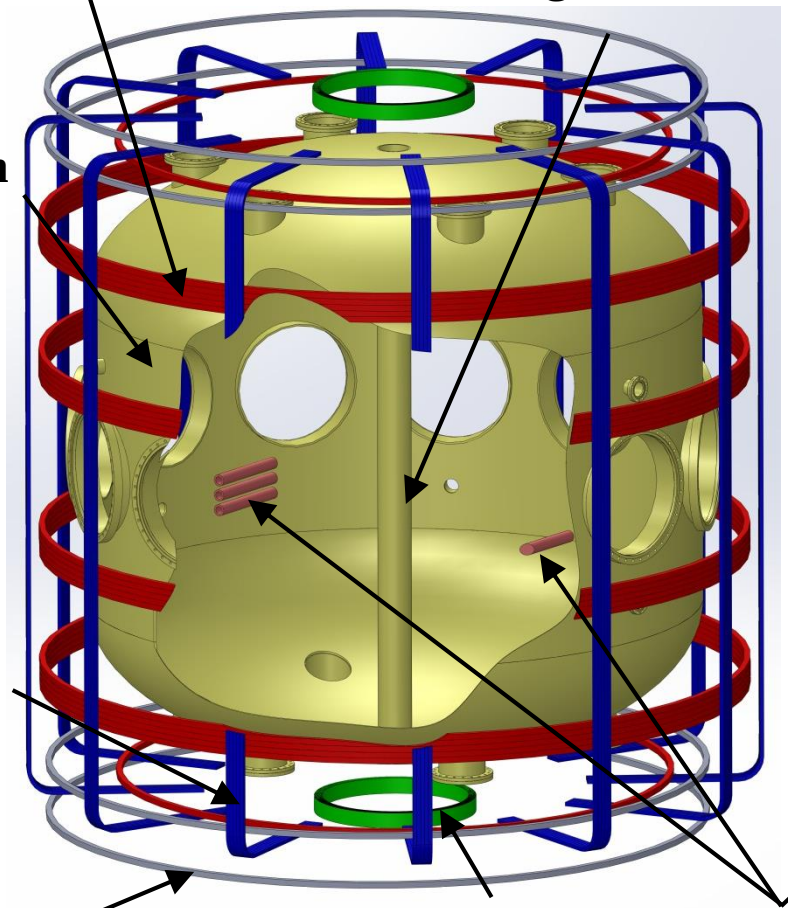


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Utilizing Unique Aspects of the ST to Improve Edge Physics Understanding

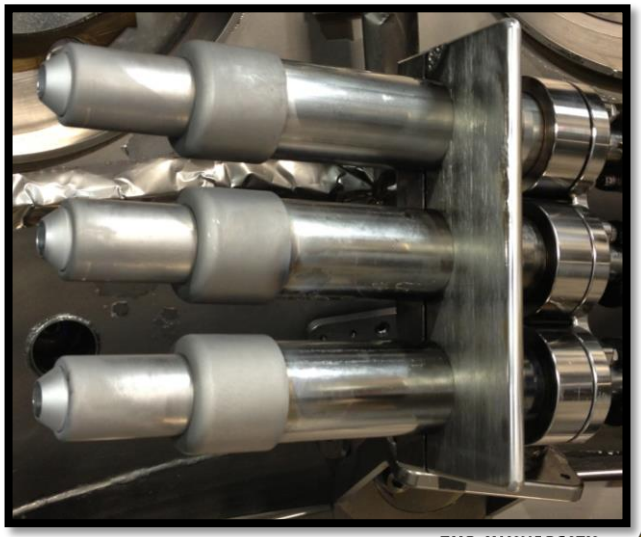
- Low A ST operation offers ready access to AT physics
  - Low H-mode P_{th}; strong neoclassical effects at low T_e
  - Peeling, peeling-ballooning mode edge physics
  - Simplified diagnostic access → unique $J_{edge}(t)$ measurements
- Peeling mode characterized in L-mode via skin current drive
  - Edge-localized, low-n, ideal MHD mode; onset consistent with ideal MHD
  - Nonlinear J_{edge} dynamics: Filament generation, expulsion, and propagation
- Extension to H-mode: Measurements of pedestal, ELM dynamics
  - Ohmic H-mode routinely accessed; limited and diverted magnetic topologies
  - Two ELM regimes suggested to date with differing toroidal mode spectra
  - $J_{edge}(R,t)$ measured throughout ELM crash

PEGASUS is a Compact, Ultralow-A ST



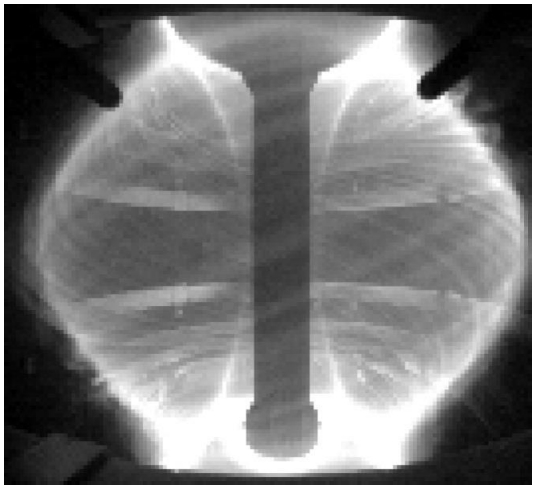
Experimental Parameters

Parameter	Achieved	Goals
A	1.15 – 1.3	1.12 – 1.3
R(m)	0.2 – 0.45	0.2 – 0.45
I_p (MA)	≤ .23	≤ 0.30
I_N (MA/m-T)	6 – 14	6 – 20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	≤ 0.025	≤ 0.05
β_t (%)	≤ 25	> 40

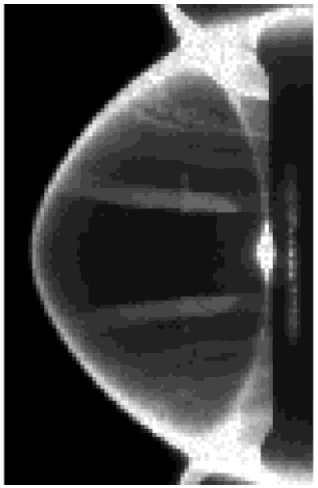


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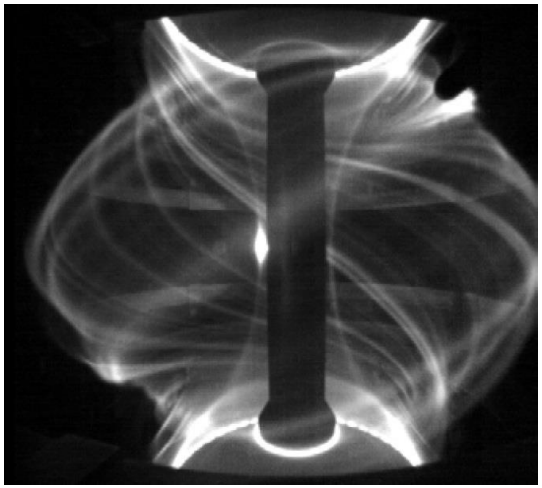
Edge Stability Critical to Next-Step Fusion Devices



MAST L-Mode*

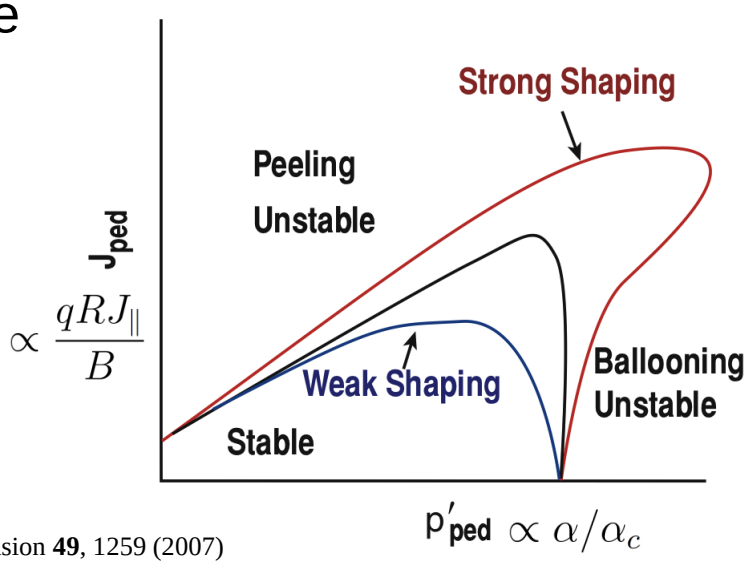


H-Mode*



ELM**

- Future fusion devices will operate in H-mode
  - Edge Localized Modes (ELMs) of concern
- Peeling-ballooning theory believed to underlie most damaging Type-I ELM
  - Pressure, current density gradients in edge drive ideal MHD instabilities
  - Detailed J_{edge} measurements needed



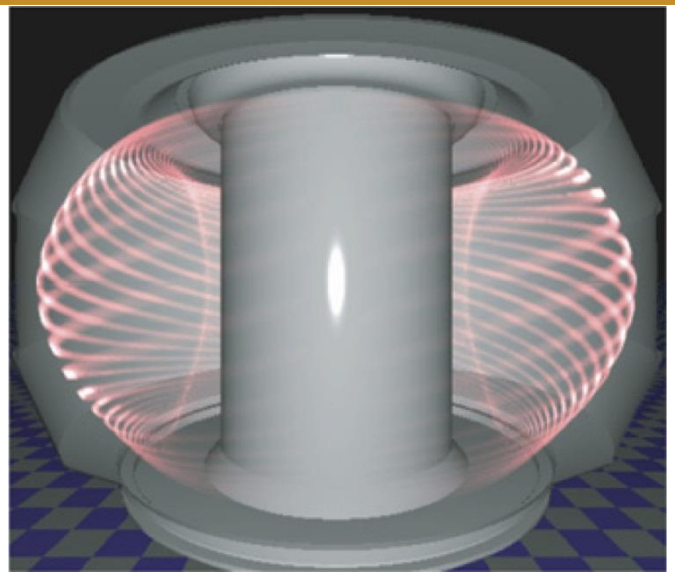
Stability Space***

*: Kirk *et al.*, Plasma Phys. Control. Fusion **48**, B433 (2006); **: Kirk *et al.*, Plasma Phys. Control. Fusion **49**, 1259 (2007)
***: Snyder, Phys. Plasmas **12**, 056115 (2005); Hegna, Phys. Plasmas **3**, 584 (1996)

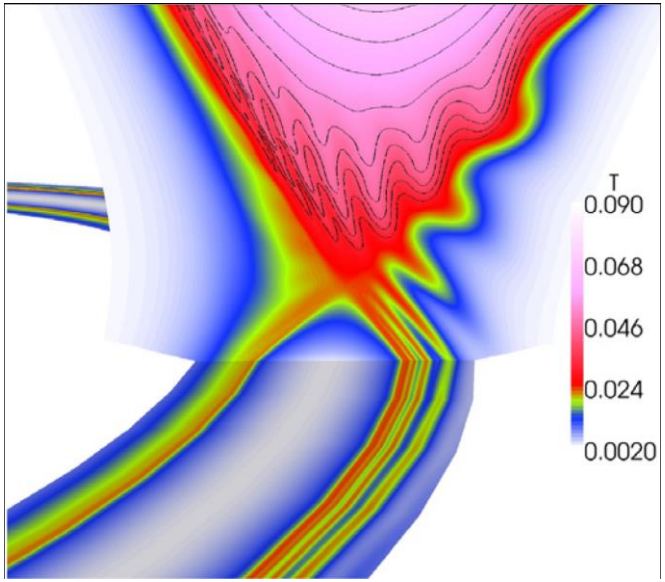
Validated, Predictive Theory Needed to Mitigate ELMs

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

*: Maggi, Nucl. Fusion **50**, 066001 (2010)

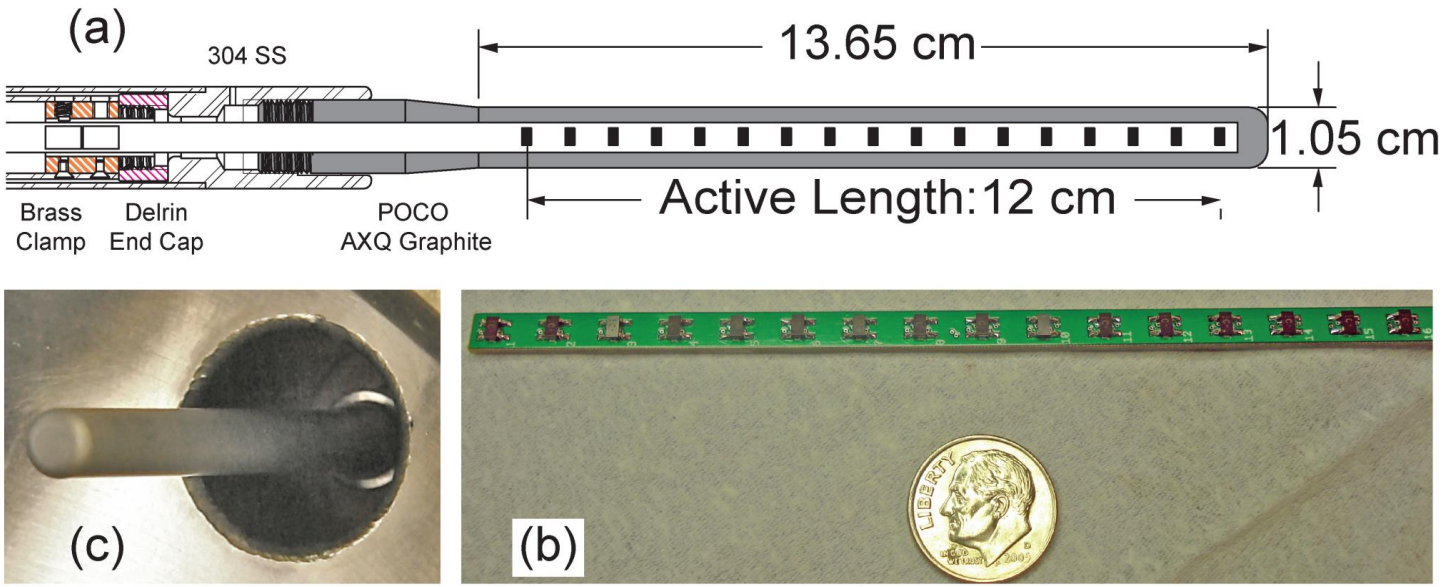


Snyder *et al.*, Phys. Plasmas **12**, 056115 (2005)

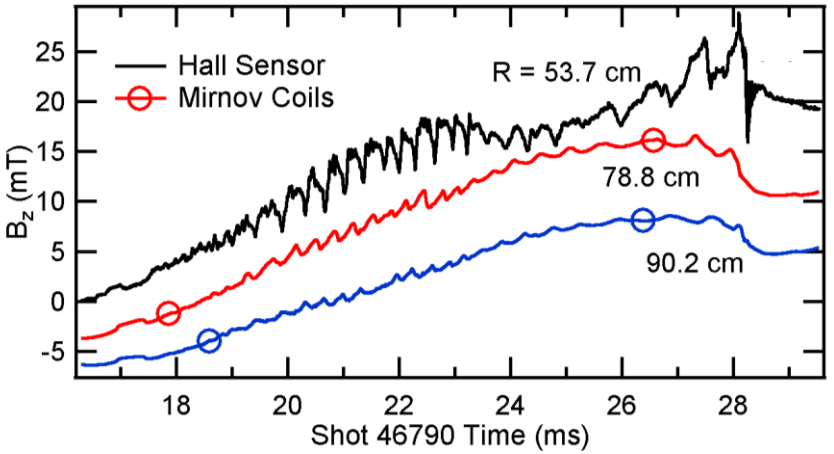


Huysmans *et al.*, Plasma Phys. Control. Fusion **51**, 124012 (2009)

PEGASUS Hall Probe Deployed to Measure J



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



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

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$J_\phi(R,t)$ 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:

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

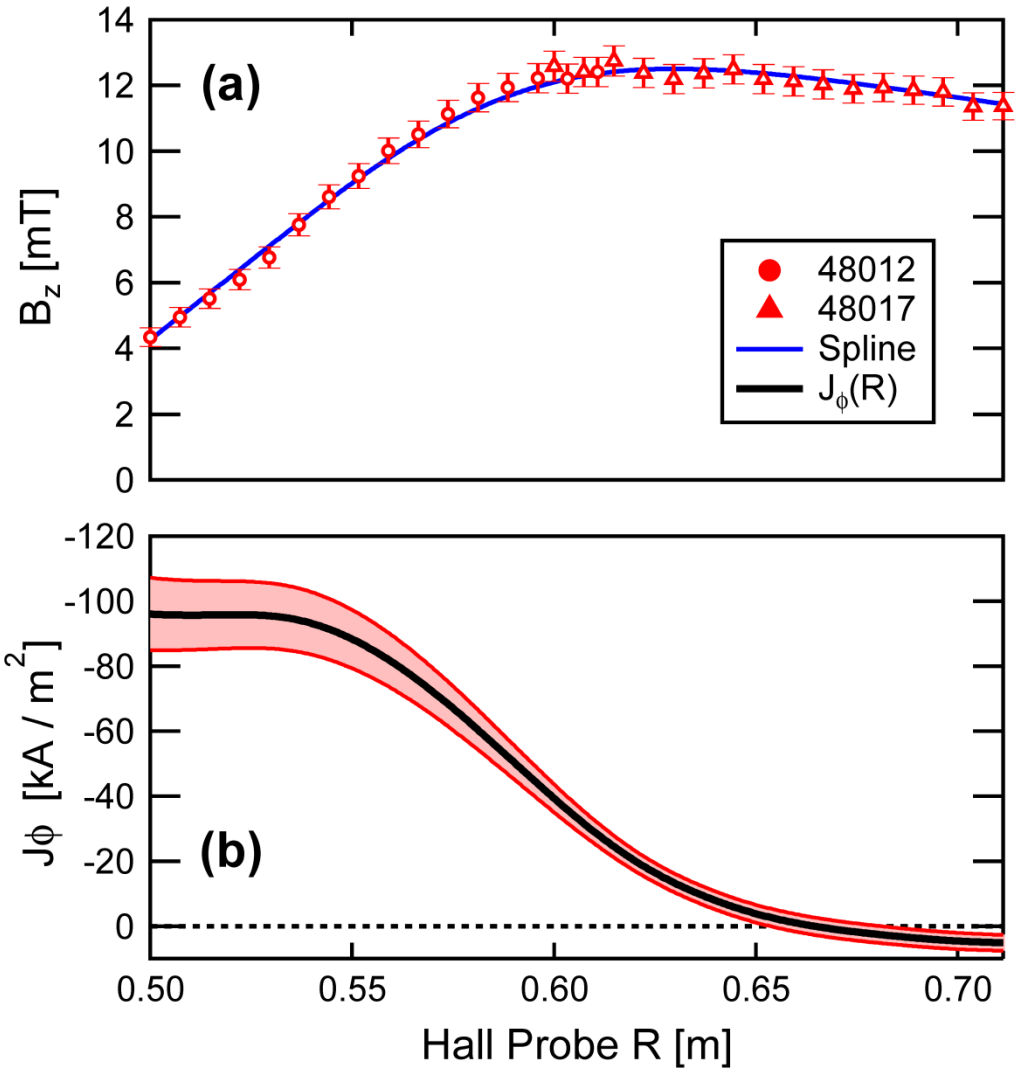
- Does not make assumptions on shape of J(R)

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

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Direct $J_\phi(R)$ Profiles Obtained in PEGASUS

- Straightforward J estimation
  - Obtain Hall Probe $B_z(R,t)$
  - Compute dB_Z/dR using interpolated smoothing spline*
  - Compute $J_\phi(R,t)$ given geometry
- Resultant $J_\phi(R,t)$ consistent with I_p, MHD evolution
- Radial span extendible with multi-shot averaging
- Higher-order shaping effects negligible within errors



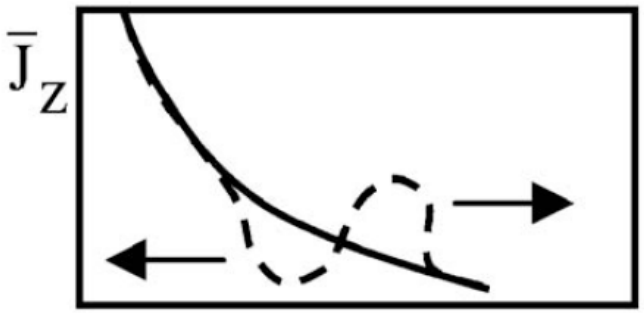
Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

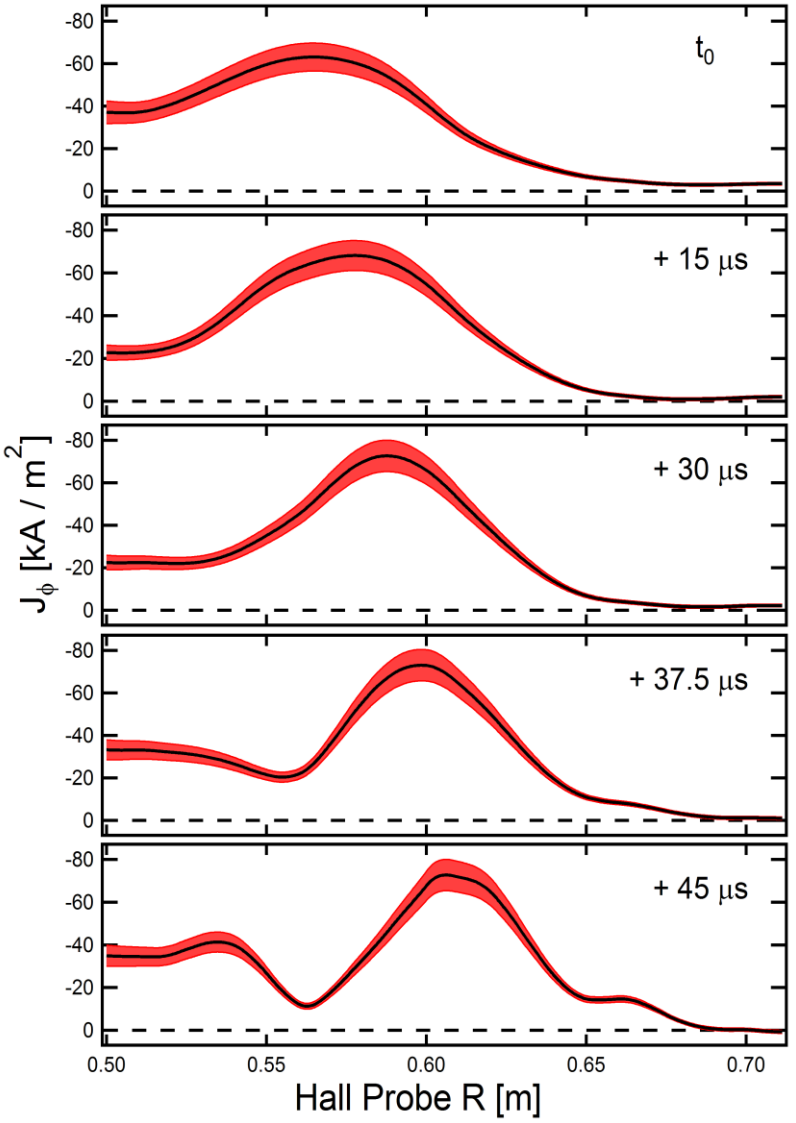
*: Reinsch, Numerische Mathematik **10**, 177 (1967)

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High Temporal Resolution Resolves Nonlinear Peeling Mode J_{edge} Dynamics

- Pure peeling modes accessed in L-mode via transient skin current drive
- Radially-propagating filaments form from initial "current-hole" J_{edge} perturbation*
  - Validates formation mechanism hypothesized by EM blob transport theory**
- Filaments carry current I_f ~ 100-220 A
  - I_f < 0.2 % of I_p, similar to MAST ELMs

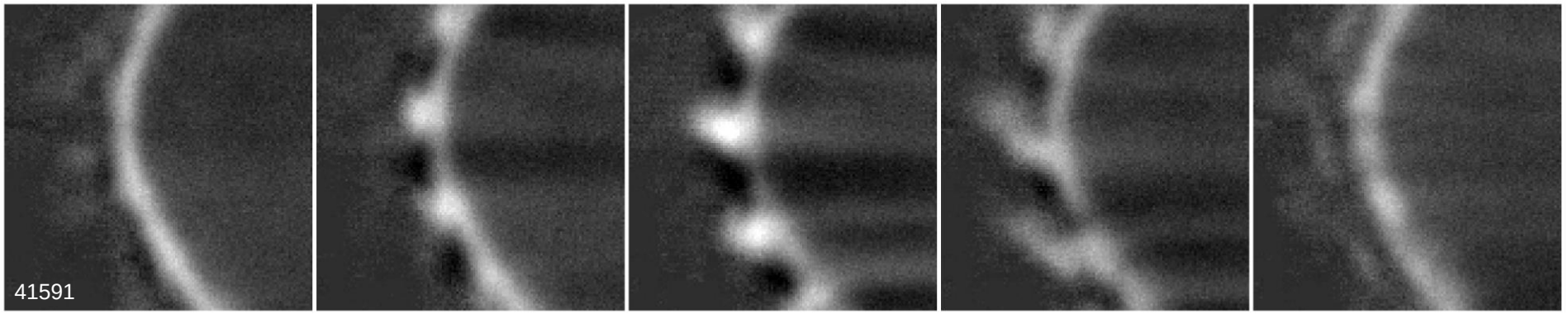




: Myra, Phys. Plasmas **14, 102314 (2007)

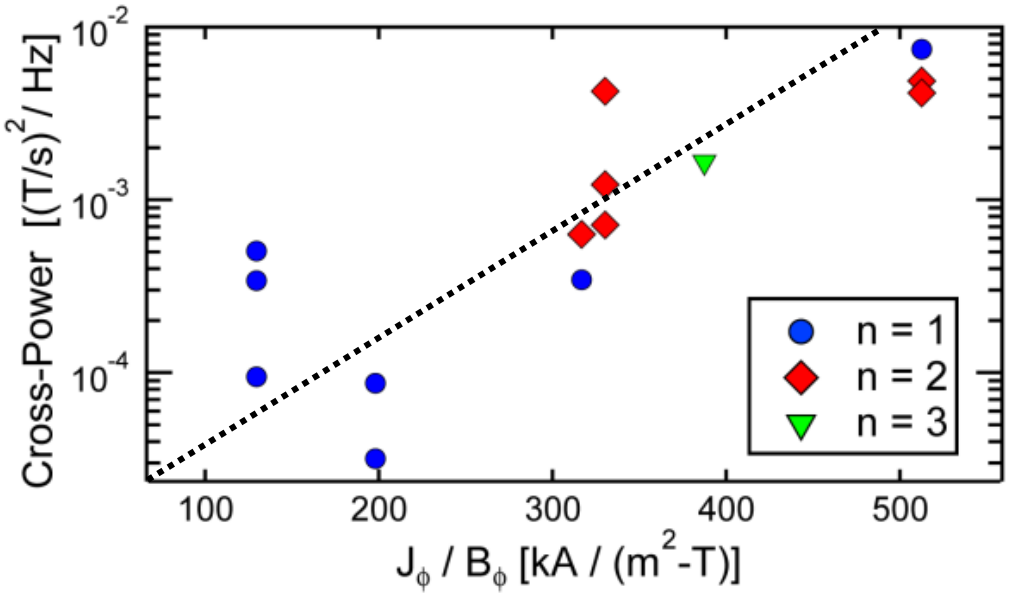
*: Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

Peeling Modes Accessed via Skin Current; Match Empirical and Theoretical Expectations



0-9 μs 11-20 μs 22-31 μs 33-42 μs 44-53 μs

- Short lifetimes with high poloidal coherence
- Detachment, radial propagation of filaments
- High-m, low-n structure
- Mode amplitude increases with measured J/B theoretical drive

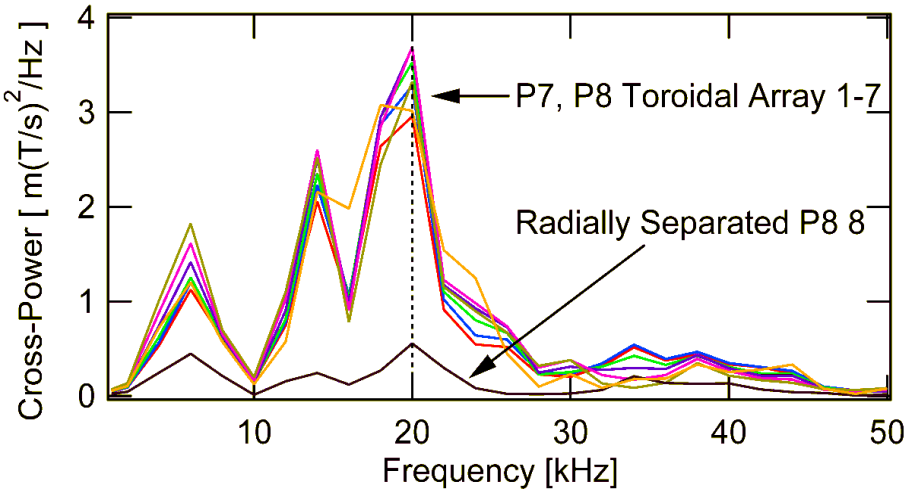


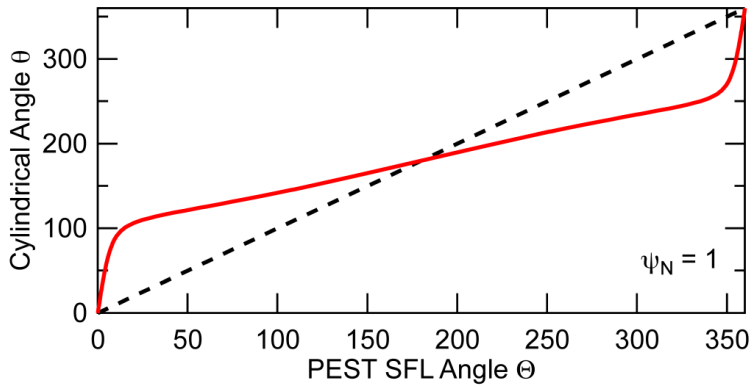
Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

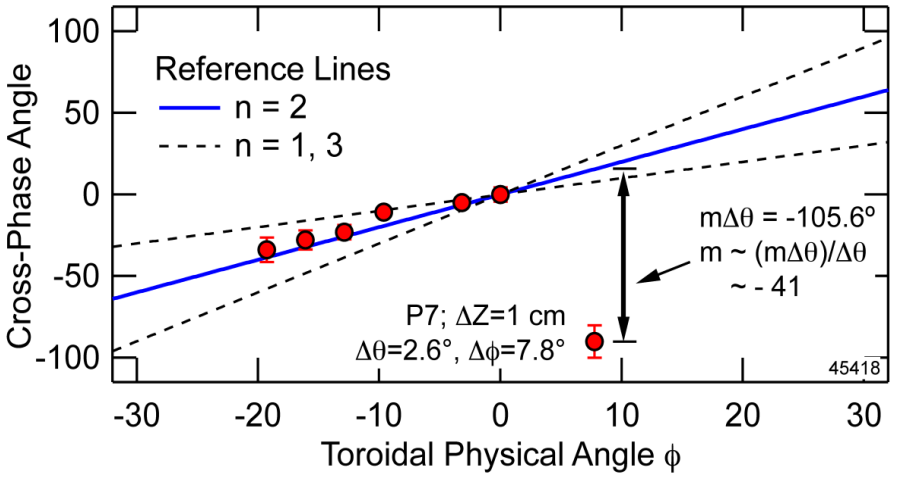
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Peeling Modes Have Low-n, High-m Structure

- Dominant toroidal n ≤ 3 strictly observed
  - Only detectable near edge
  - n = 2 depicted here
- Lower limit on m via cylindrical mode analysis
  - Poloidal cross-phase: $m_{lab} \approx 41$
  - P8 Radial decay rate: $m_{lab} \approx 42$
- More accurate m via straight field line mapping
  - PEST transform large at A ~ 1
  - m ~ 3–7 m_{lab} for this case



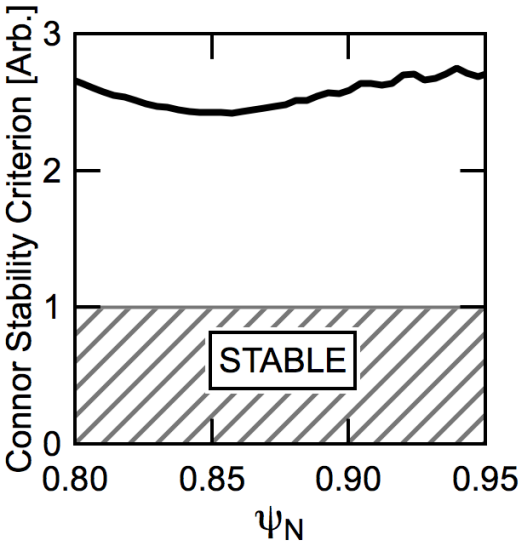




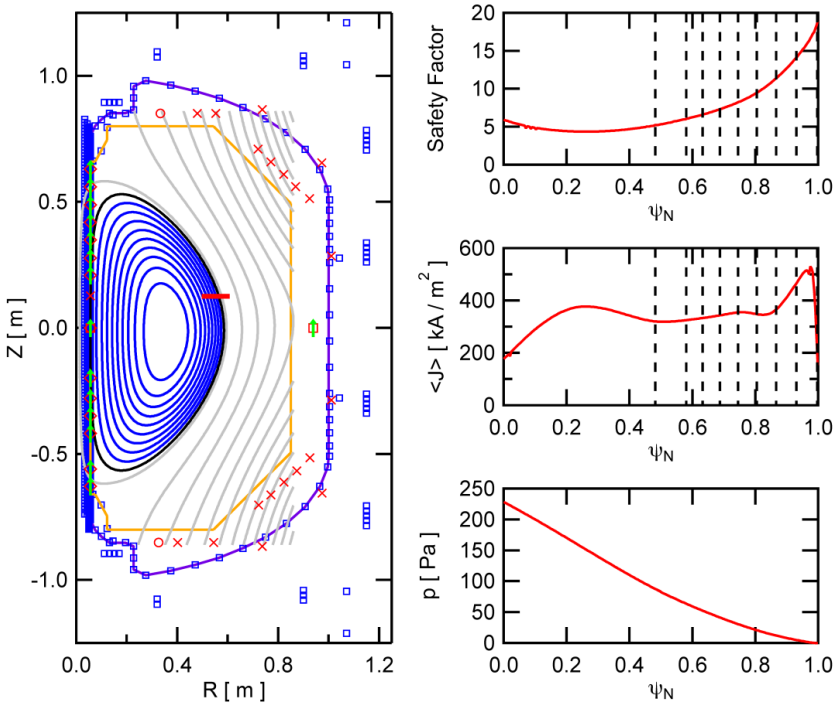
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Peeling Mode Onset Consistent with Ideal MHD

- High-performance discharge with peeling activity analyzed
  - $\langle J_\phi \rangle_{edge}(\psi) \sim 500$ kA/m^2 from reconstruction with Hall data
- Analytic peeling criterion*, DCON stability analysis indicate instability



Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)



Equilibrium Parameters
Shot 49507, 21.56 ms

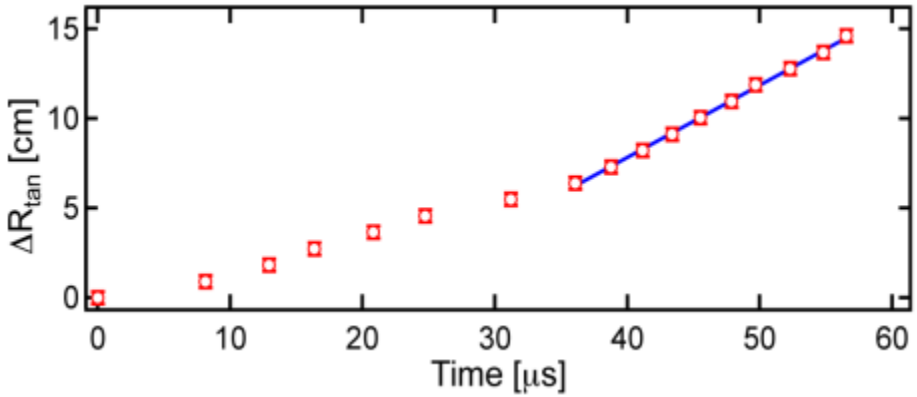
I_p	175 kA	R_0	0.320 m
β_t	0.0079	a	0.264 m
ℓ_i	0.26	A	1.21
β_p	0.030	κ	2.1
W	807 J	δ	0.53
B_{T0}	0.180 T	q_{95}	15.2

*: Connor *et al.*, Phys. Plasmas **5**, 2687 (1998)

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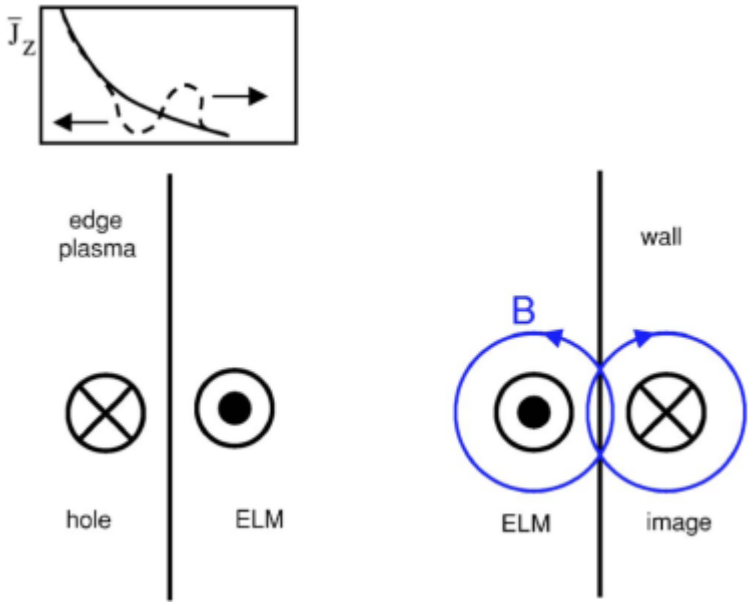
Filament Radial Motion Qualitatively Consistent with Electromagnetic Blob Transport

- Trajectory of detached peeling filament tracked with 275 kHz imaging



Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

- Magnetostatic repulsion* plausibly contributes to dynamics
  - Current-hole $\boldsymbol{J} \times \boldsymbol{B}$ drives a_R
  - Transition at ~ 35 μs comparable to healing time of current-hole



- Measured V_R comparable to available EM blob models**
  - V_R ~ 4 km/s; $V_{R,IB}$ ~ 8 km/s
  - Agrees to O(1) accuracy of theory

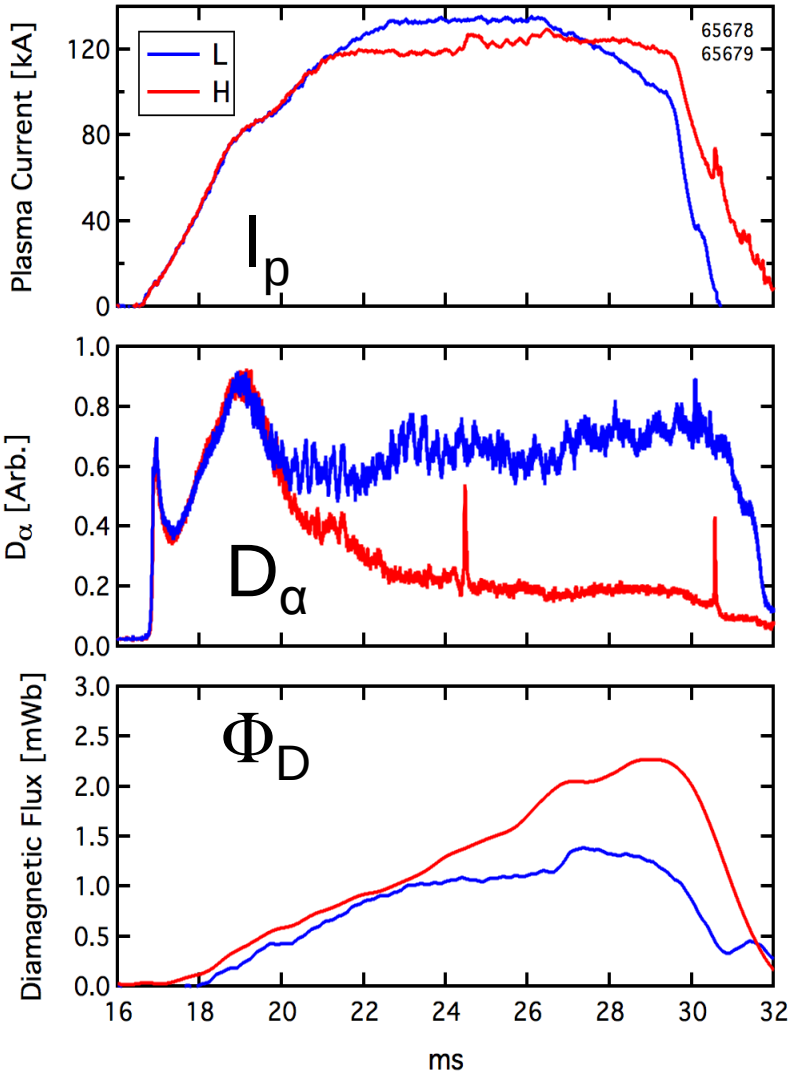
*: Myra, Phys. Plasmas **14**, 102314 (2007)

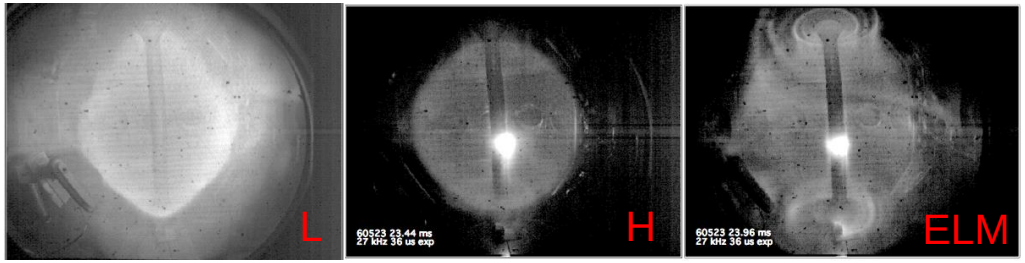
: Myra *et al.*, Phys. Plasmas **12, 092511 (2005)

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H-mode Plasmas Routinely Obtained in PEGASUS

- Obtained with centerstack fueling
  - Ohmically heated
  - Limited or diverted topology
- Standard H-mode signatures
  - Quiescent edge
  - Reduced D_α emission
  - T_e, T_i increase
  - Large, small ELMs suggested
  - Bifurcation in Φ_D
  - Toroidal flow reversal



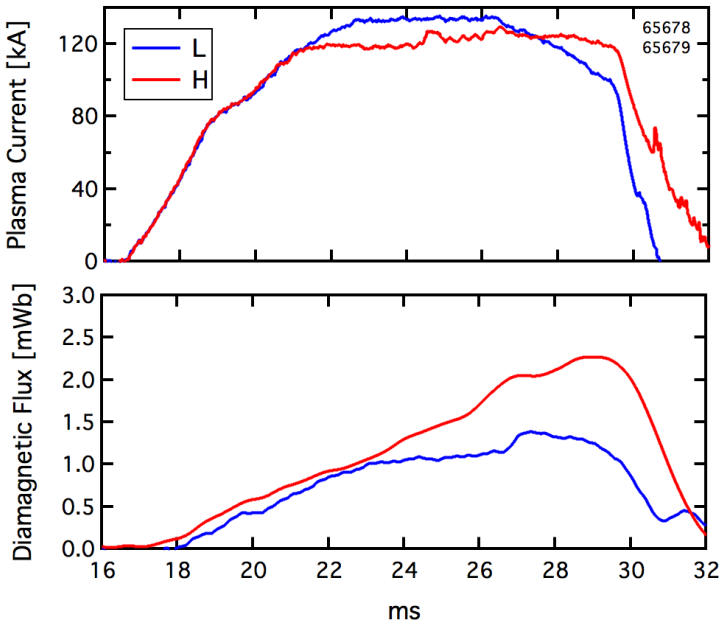


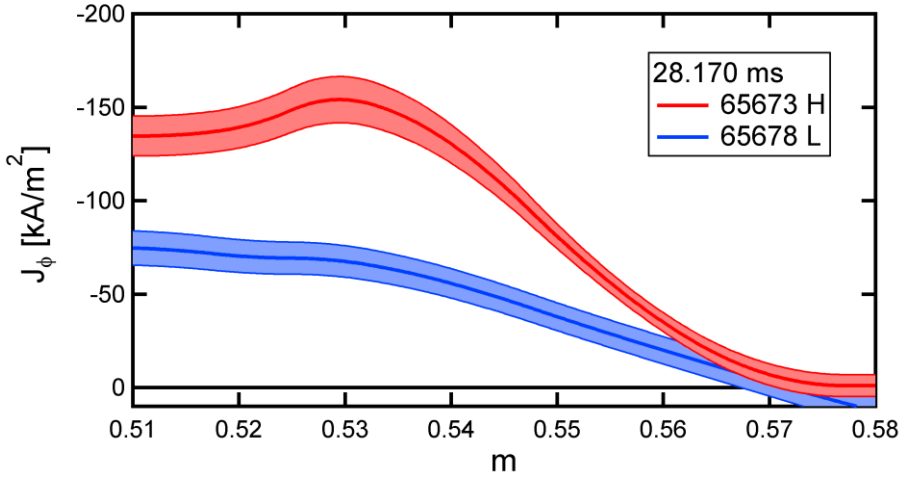
M.W. Bongard,55th APS-DPP, Denver, CO, Nov. 2013

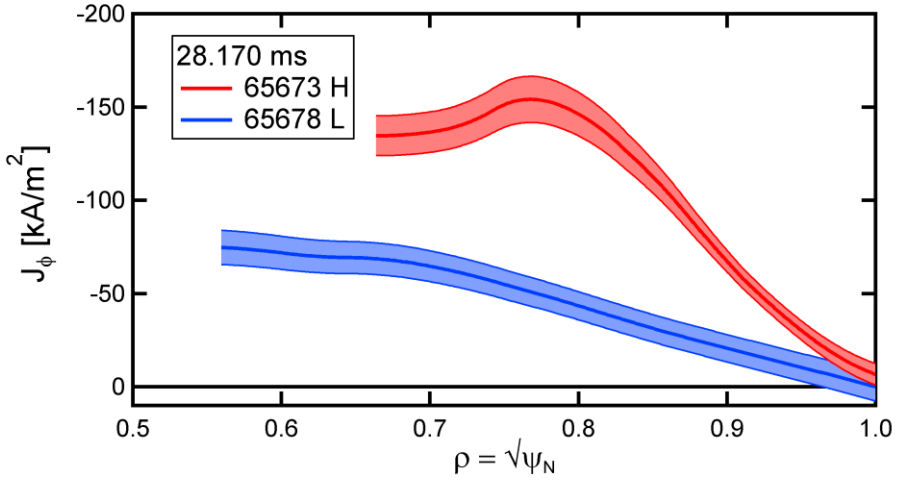
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Edge Current Pedestal Observed in H-Mode

- Internal B measurements from Hall array* yield local $J_\phi(R,t)$**
  - Map to ψ_N only approximate
- Current gradient scale length reduced in H-mode



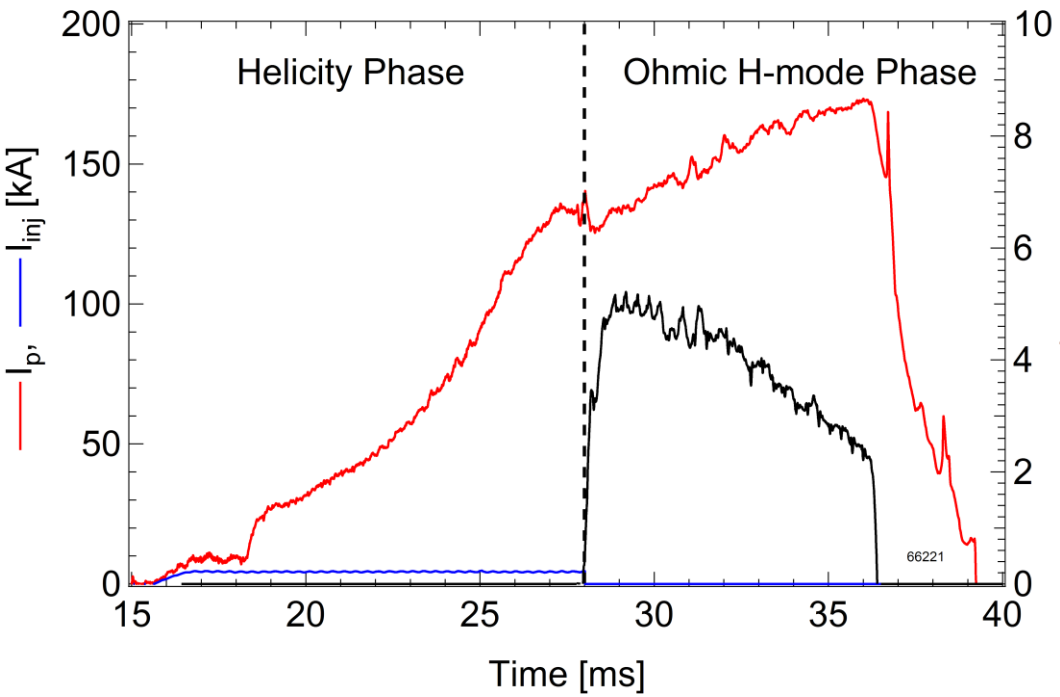


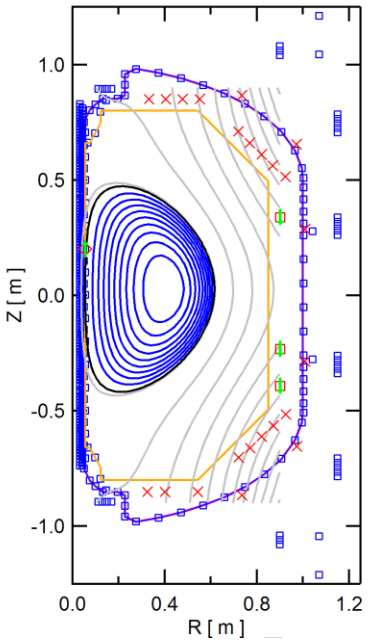


*: M.W. Bongard *et al.*, Rev. Sci. Instrum. **81**, 10E105 (2010)
: C.C. Petty *et al.*, Nucl. Fusion **42, 1124 (2002)

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Local Helicity Injection Startup Compatible with Consequent High-Quality OH H-mode





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

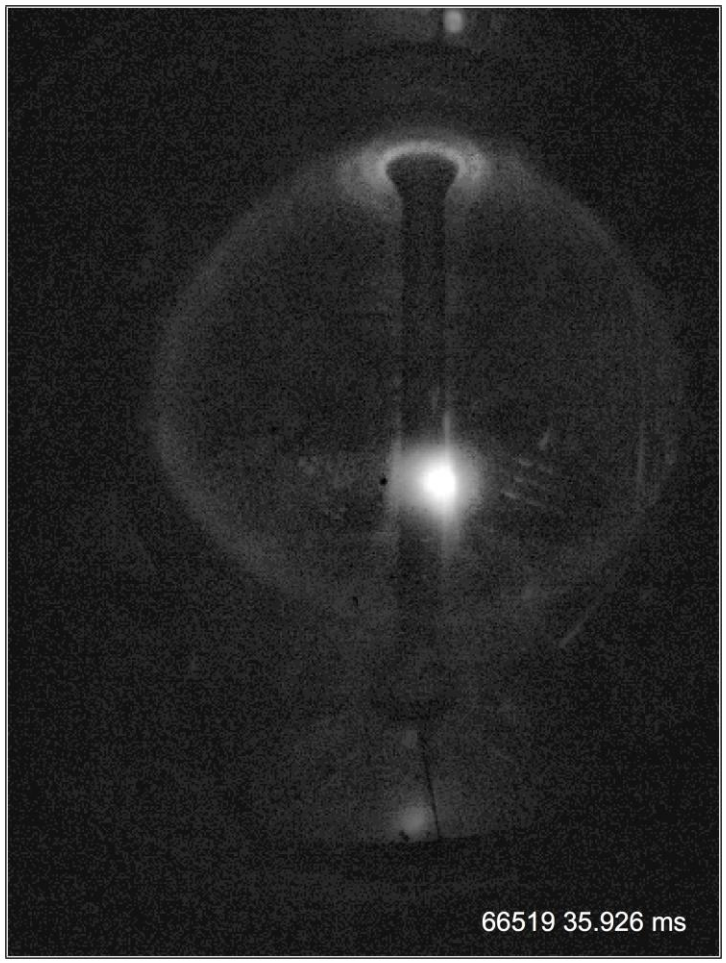
- High-I_p, long-pulse H-mode plasmas desirable for PEGASUS goals
  - Confinement and edge stability studies; attaining high β_T regime
- V-s savings provided by LHI support H-mode research
  - I_p > 150 kA, limited and diverted; highest H-mode I_p to date
  - No fundamental obstacle to H-mode access from LHI physics

*: Battaglia *et al.*, Nucl. Fusion **51**, 073029 (2011)

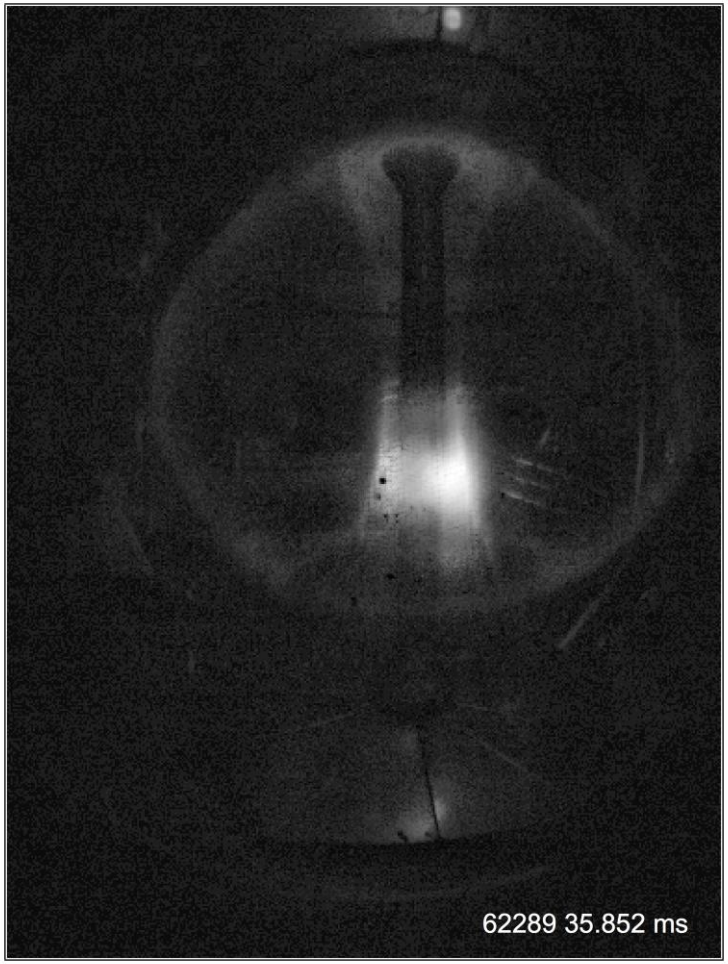
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Divertor Coils Activated to Access Standard Separatrix-Limited H-modes

Non-diverted: Centerstack Limited



Diverted: Separatrix Limited

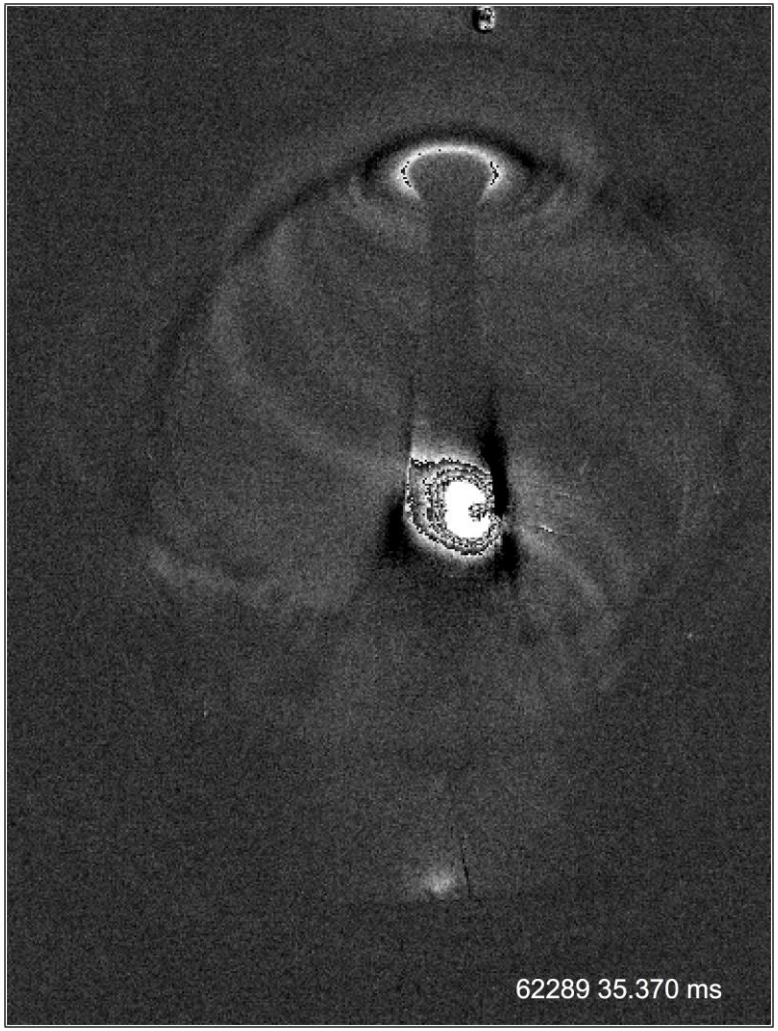


- Initial results show no significant difference between topologies

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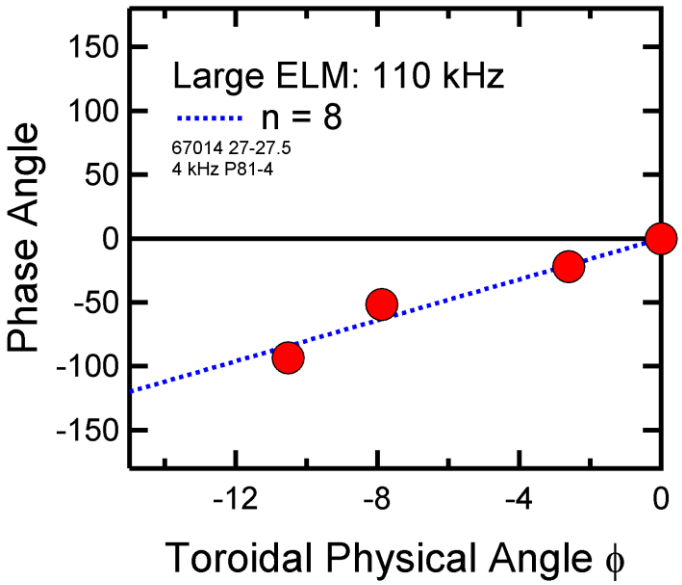
Two Distinct ELM Types Observed in H-mode

- Conventional identification complicated by lack of P_{aux} and modest pulse length
  - Large, Type I-like ELMs are infrequent and violent
    - Can cause H-L back-transition
    - Occur at high P_{OH}
  - Small, Type III-like more ubiquitous, less perturbing
    - Occur at lower P_{OH}
- Temporally coincident with D_α bursts
- Standard filamentary structures observed during ELM crash

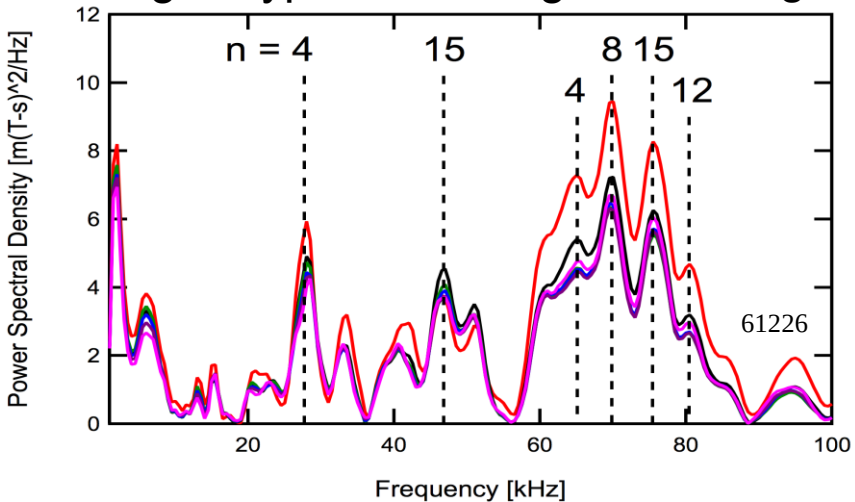


ELMs Have Distinct Magnetic Signatures

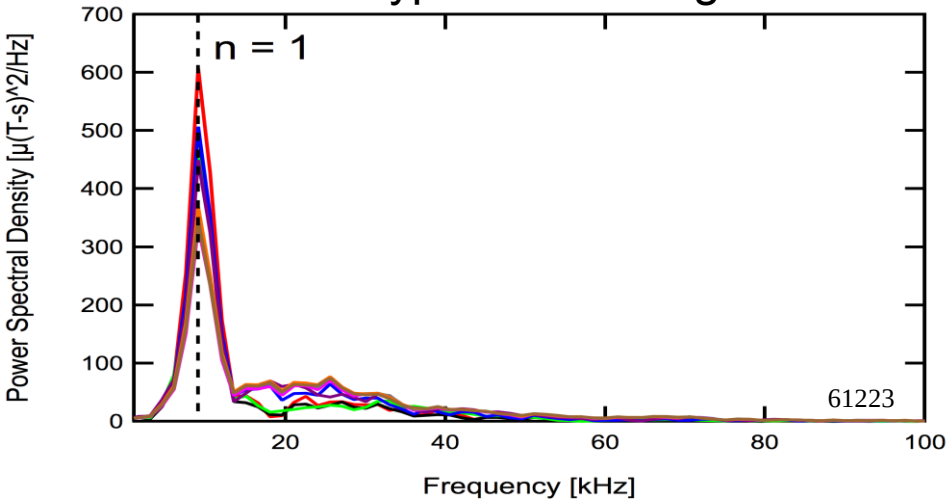
- High-n Mirnov coil array placed at edge
  - Resolves n < 20 without phase wrapping
- n spectra imply different MHD modes at play
  - n manifold used to tentatively classify ELMs



Large "Type I:" Peeling-Ballooning?

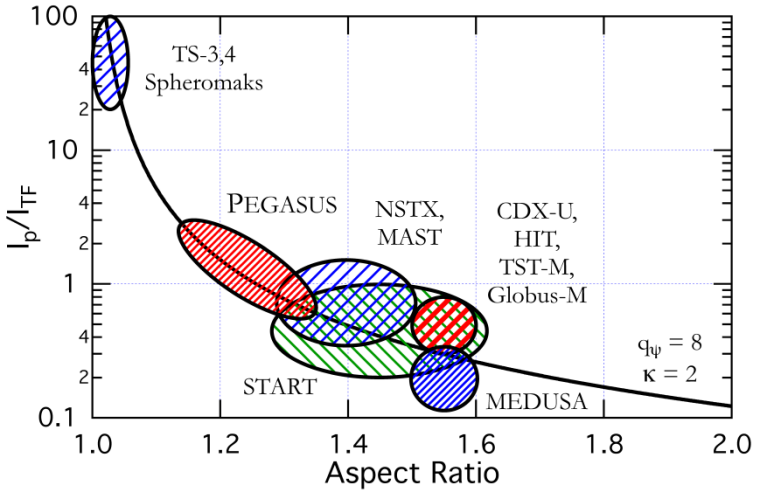


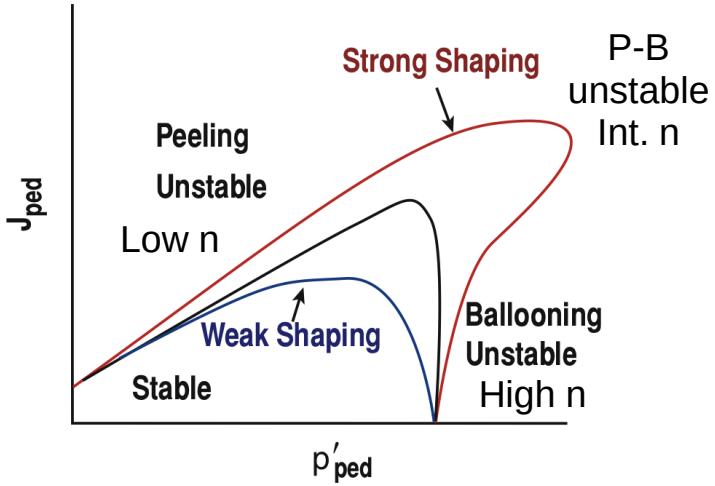
Small "Type III:" Peeling-like?



PEGASUS ELM Spectra Similar to NSTX

- PEGASUS: ELM types have distinct n
  - Large ("Type I"): intermediate $5 < n < 15$
  - Small ("Type III"): low $n \leq 3$
- Similar n ranges reported for NSTX*
  - Type I: intermediate $5 \leq n \leq 8$
  - Type III: low $n \leq 3$
- Differences in machines' ELM toroidal mode spectra attributable to A effects?
  - Conventional AT Type I ELMs at higher n**
    - But, at low ν^* ($\rightarrow$ higher J_{BS}) n can fall
  - ST's naturally provide strong peeling drive
    - Toroidal field utilization $I_p/I_{TF} \sim J_{\|}/B$

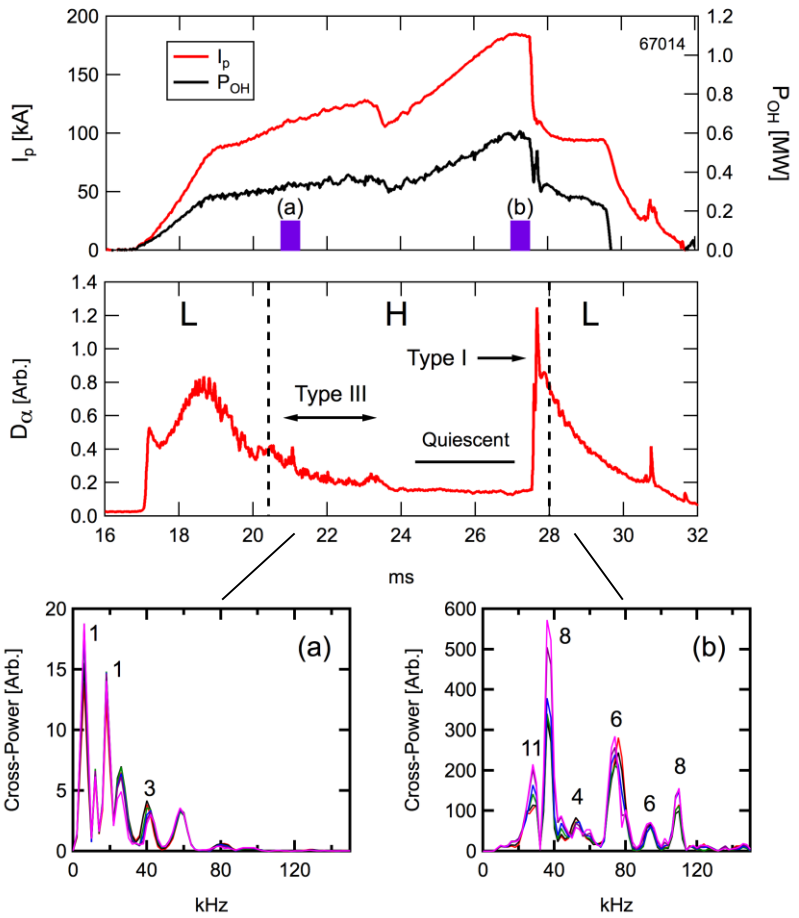




*: Maingi *et al.*, Nuclear Fusion 45, 1066 (2005)
: Example: Perez *et al.*, Nuclear Fusion **44, 609 (2004)

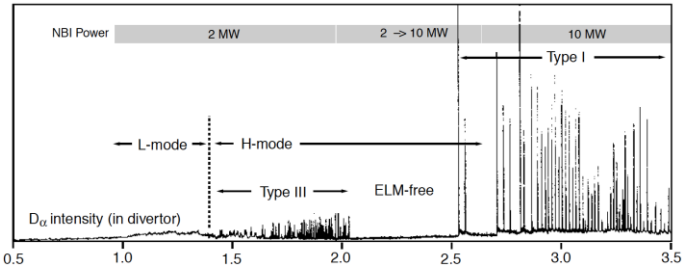
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Disruptive Type I ELM Occurs at High Input Power





Spiraling heat deposition on lower divertor plate from large ELM



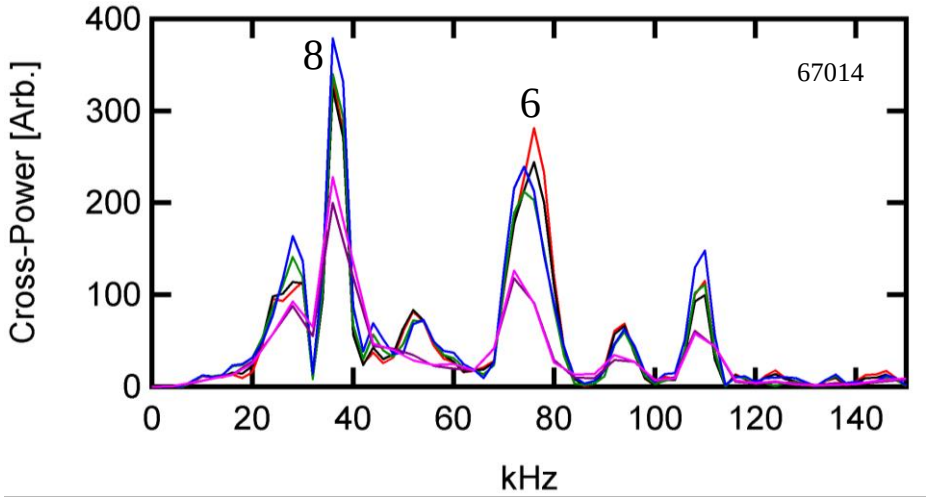
ITER Physics Basis, Nucl. Fusion **39** 2251 (1999)

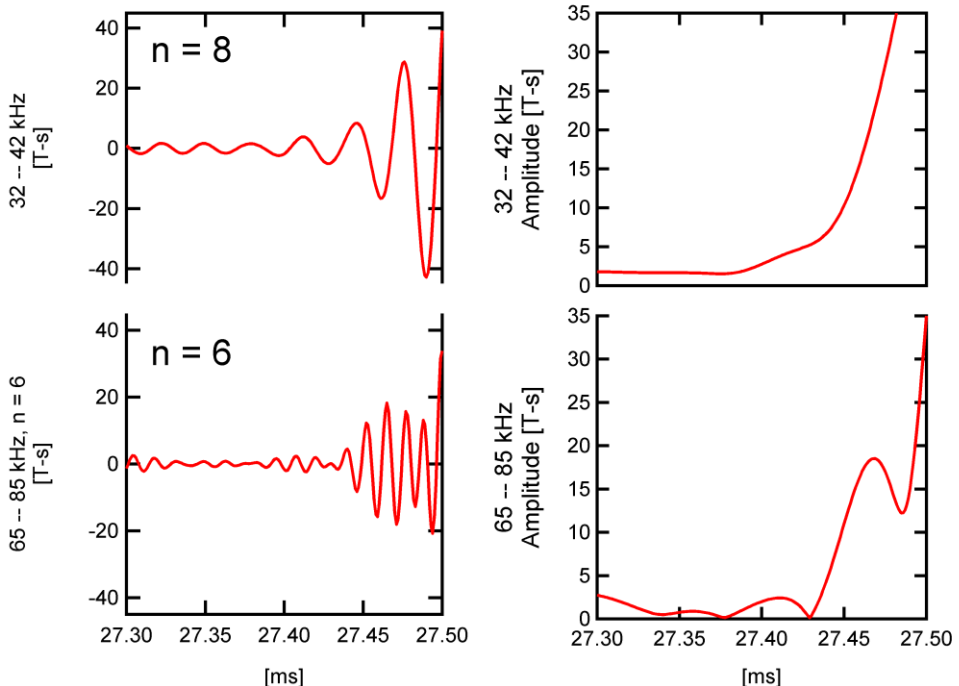
- Large Type I ELM after quiescent period
  - Large ELM induces back-transition, terminates discharge
  - Similar to large tokamaks with auxiliary heating

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ELM Precursor Components Grow on MHD Timescales

- Magnetic signature of ELMs have multiple n components
  - Simultaneously unstable modes
- Example: Large ELM signature
  - Immediately prior to D_α rise
- Bandpass-filtered Mirnov components: different growth rates present
  - Timescale: < 10's μs
  - Dominant n = 8 grows continuously
  - n = 6 component grows and decays prior to crash

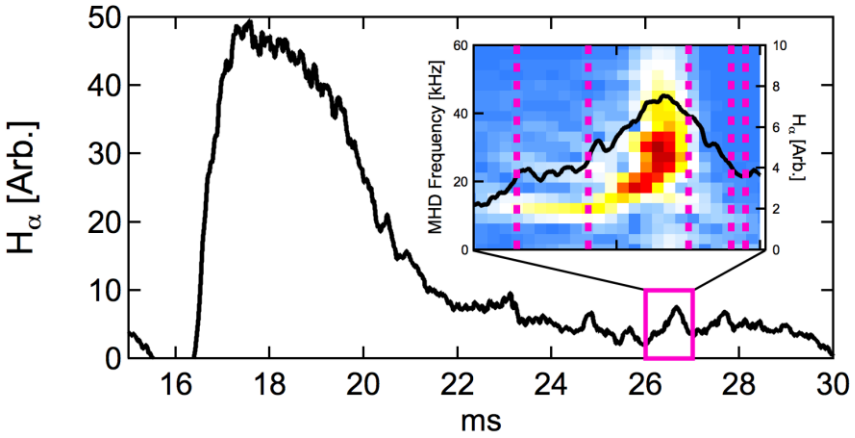


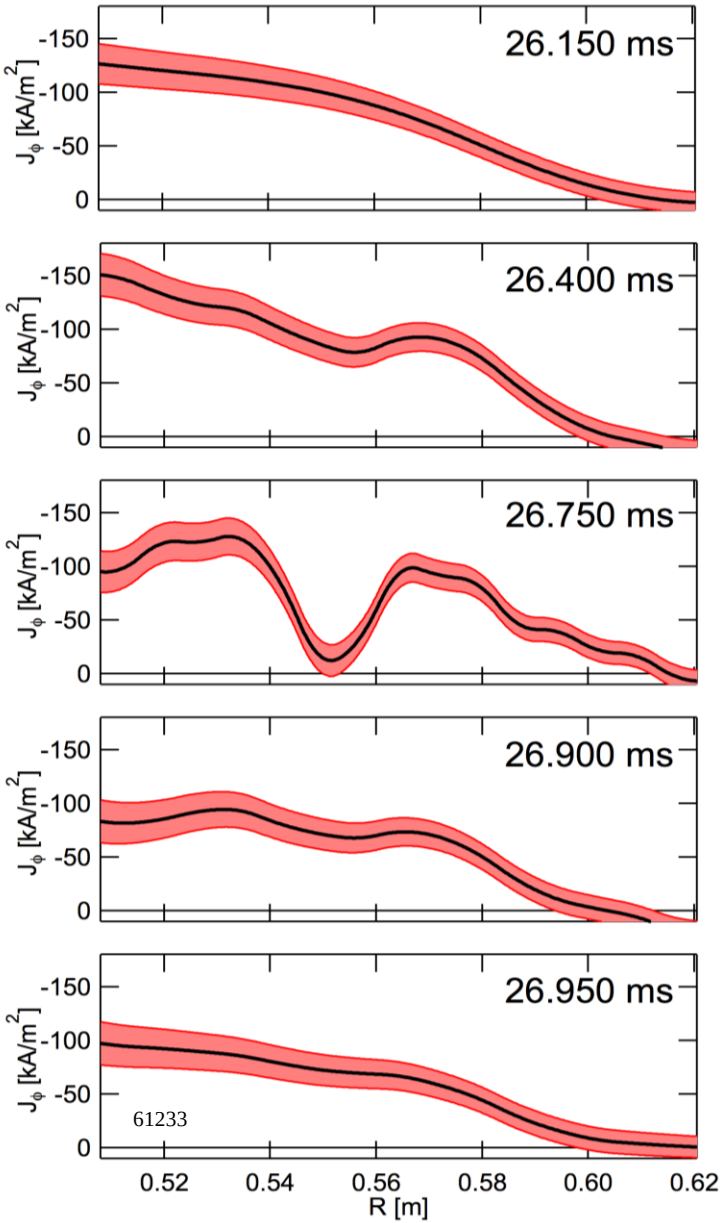


M.W. Bongard, 55th APS-DPP, Denver, CO, Nov. 2013

Type III J_{edge} ELM Dynamics Measured

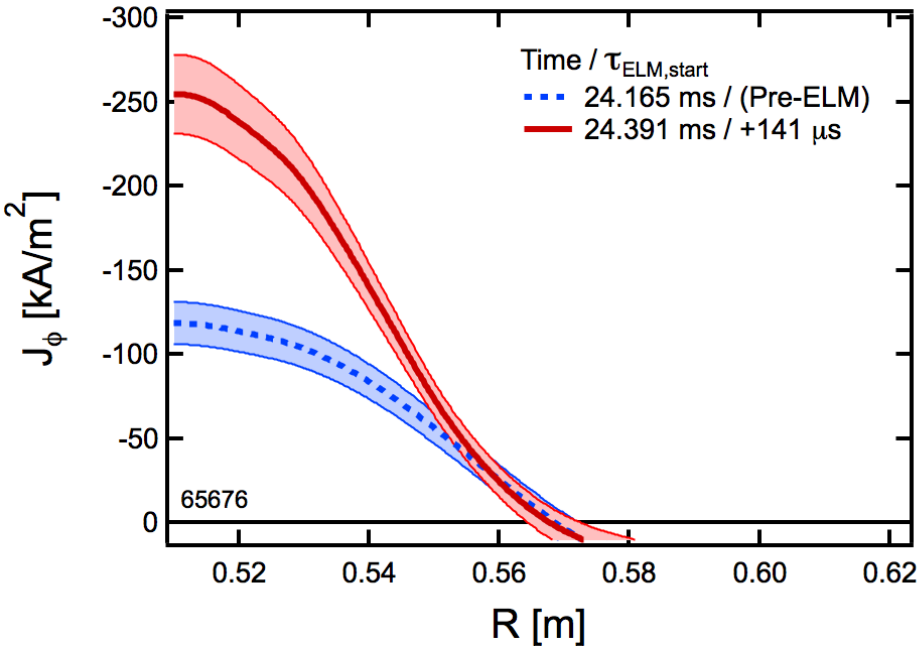
- J(R,t) profiles measured throughout single Type III small ELM
  - n = 1 precursor
- Current-hole perturbation accompanies pedestal crash
  - Similar to peeling modes in PEGASUS
- Rapid recovery of H-mode pedestal

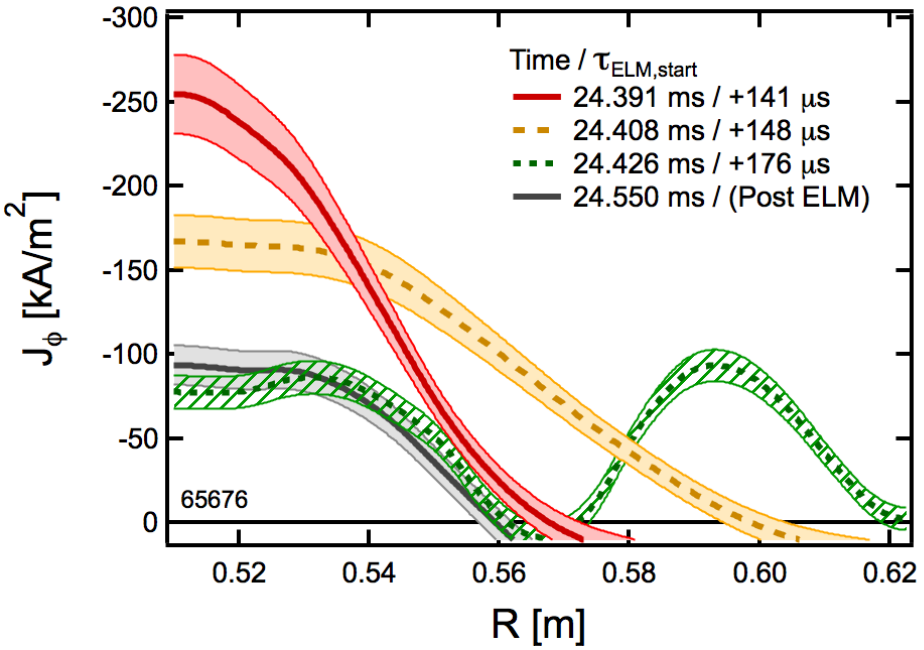




M.W. Bongard,55th APS-DPP, Denver, CO, Nov. 2013

Type I J_{edge} ELM Dynamics Measured



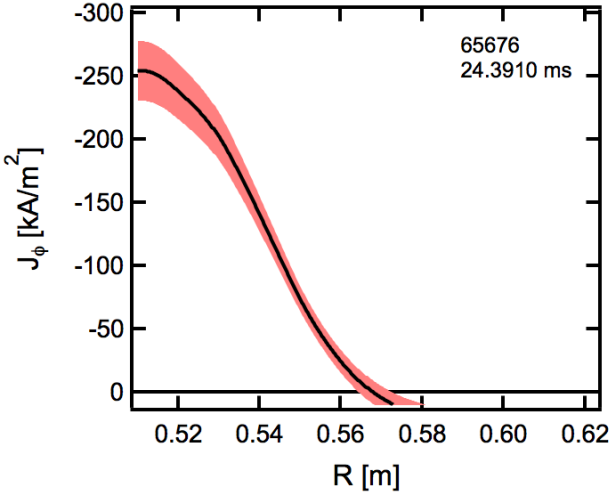


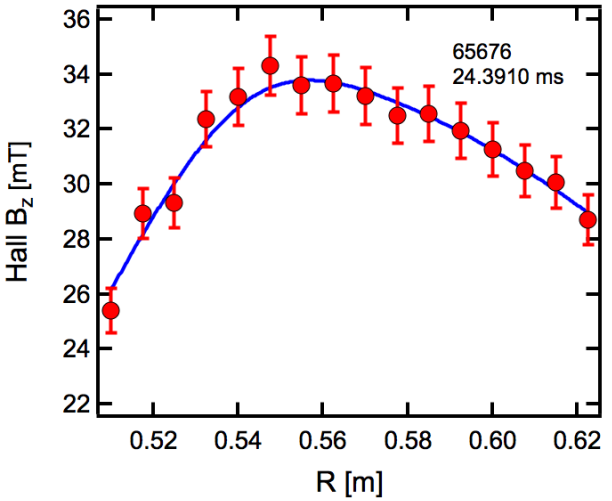
- J(R,t) profiles resolved throughout single Type I ELM cycle
  - No clear EM precursor
- J_{edge} builds to ~ 2x pre-ELM value
- Crash phase resembles L-mode
  - Reduction in gradient scale length
  - Intermediate n = 6 – 9 MHD present
- Filament generation suggested
  - Post-ELM J_{edge} attained by current-hole expulsion

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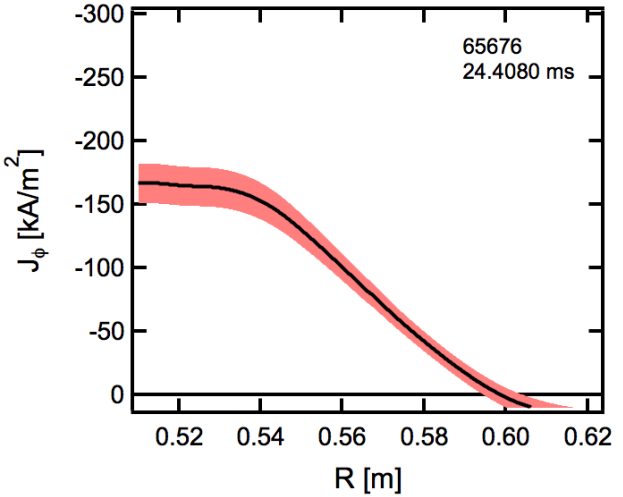
J_{edge} Structure Reflected in B_z Measurements

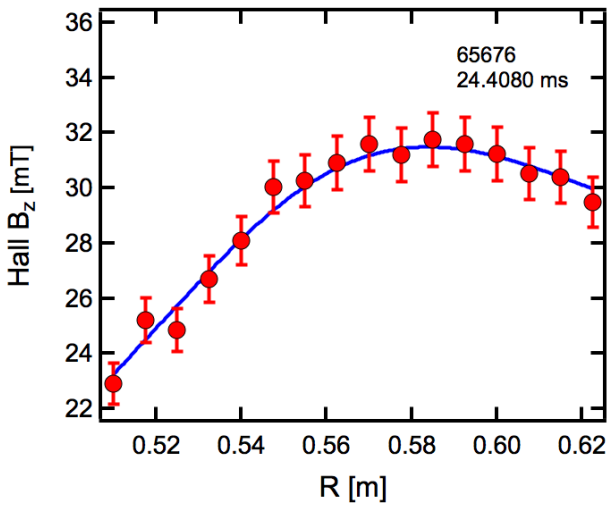
Type I Peak



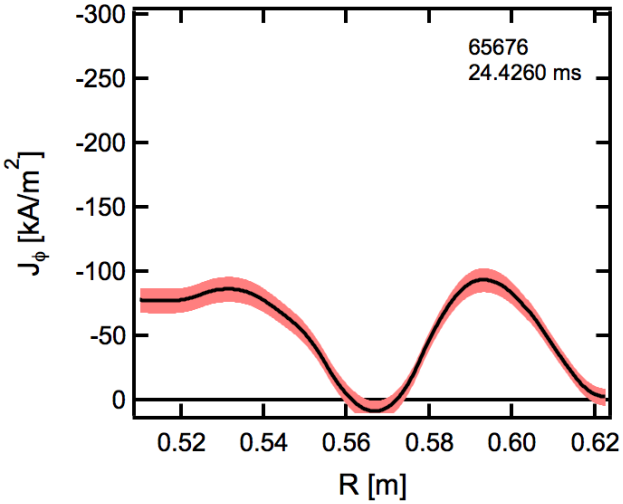


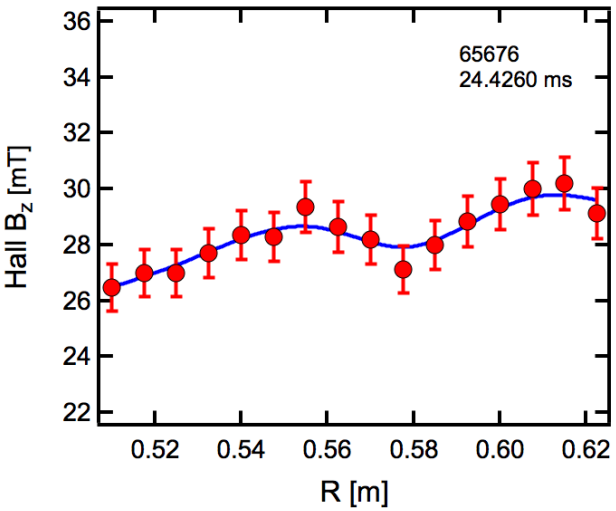
Type I Mid-Crash





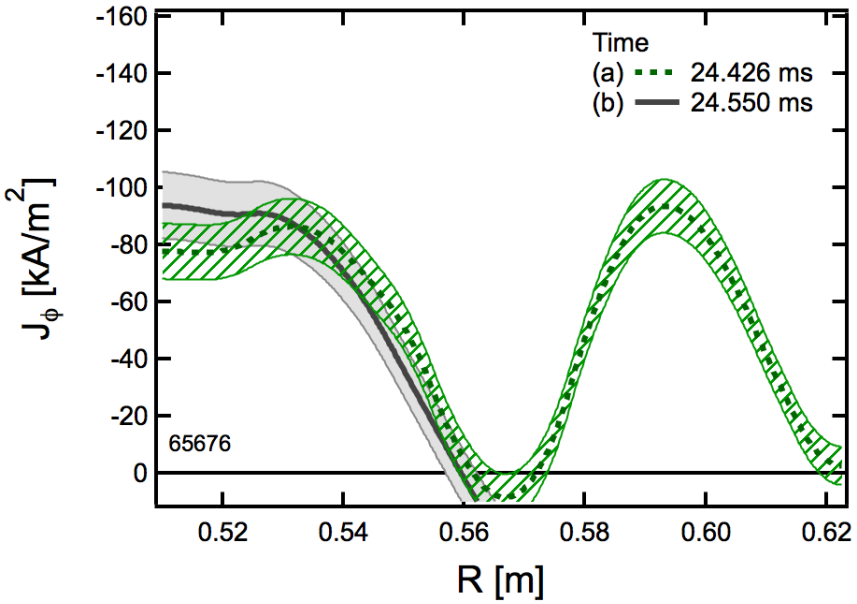
Filament Expulsion

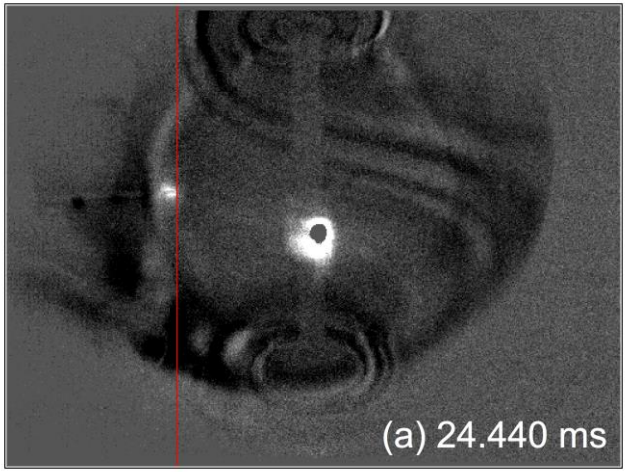




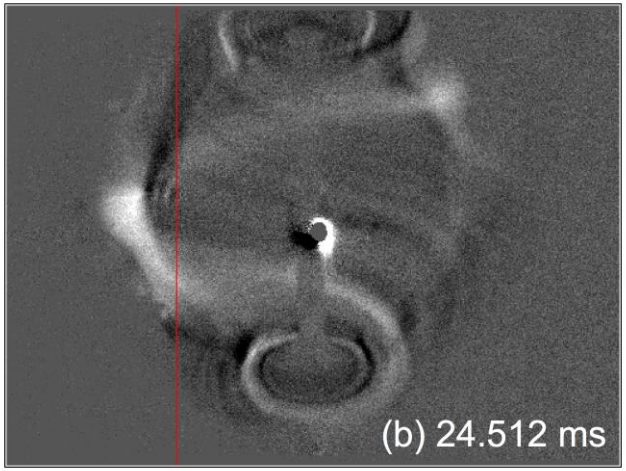
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Type I ELM Filament Ejection Coincides with J_{edge} Current-Hole Generation





Nearest Imaging Times; Prior Frame Subtracted



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

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

- Peeling mode characteristics consistent with theory
  - Onset, spatial structure, MHD virulence consistent with ideal MHD
  - Nonlinear dynamics: filament creation / propagation from J_{edge} current-hole
- Ohmic H-mode routinely accessed at $A \rightarrow 1$
  - Standard features observed in limited and diverted topologies
  - Compatible with non-solenoidal local helicity injection startup
- Two ELM regimes identified with differing toroidal mode spectra
  - Large, Type I-like: intermediate n
  - Small, Type III-like: low n
  - Observations similar to NSTX results
- J_{edge} dynamics measured throughout ELM crash
  - J_{edge} pedestal present in H-mode
  - $J_{edge}(R,t)$ current-hole perturbations and current-carrying filament expulsion