Characterization of Edge Stability and Ohmic H-mode in the PEGASUS Toroidal Experiment

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University of Wisconsin-Madison

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Kyushu University
Fukuoka, Japan
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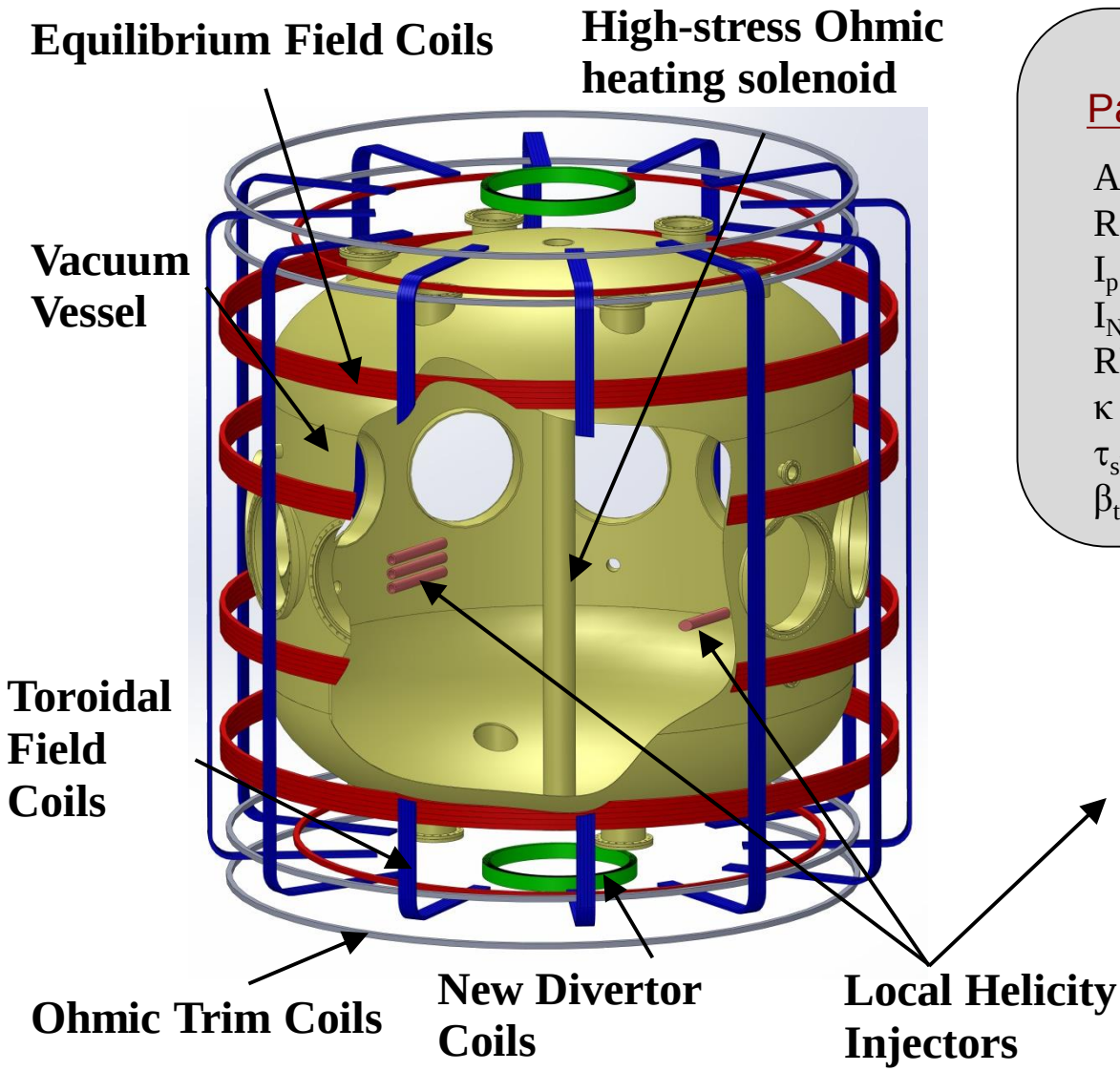


PEGASUS Toroidal Experiment

Utilizing Unique Aspects of the ST to Improve Edge Physics Understanding

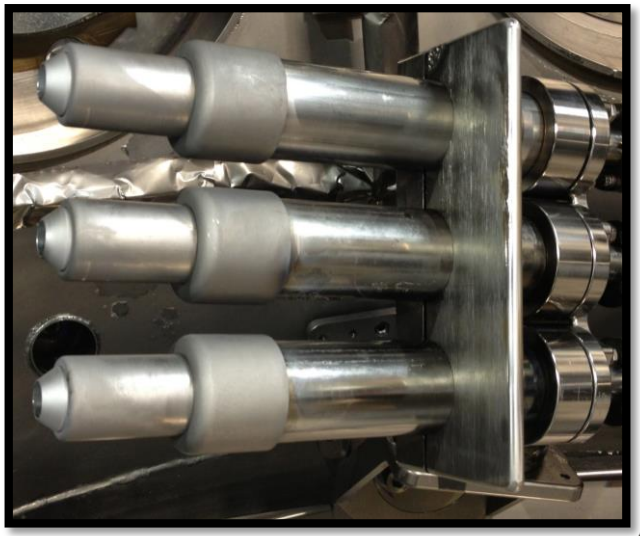
- Low A ST operation offers ready access to AT physics
  - Low H-mode P_{th}; strong neoclassical effects at low T_e
  - Peeling, peeling-ballooning mode edge physics
  - Simplified diagnostic access → unique $J_{edge}(t)$ measurements
- Peeling mode characterized in L-mode via skin current drive
  - 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

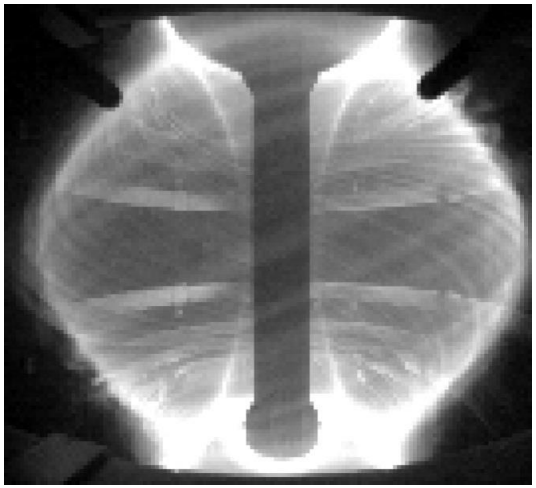
Parameter	Achieved	Goals
A	1.15 – 1.3	1.12 – 1.3
R(m)	0.2 – 0.45	0.2 – 0.45
I_p (MA)	≤ .23	≤ 0.30
I_N (MA/m-T)	6 – 14	6 – 20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	≤ 0.025	≤ 0.05
β_t (%)	≤ 25	> 40



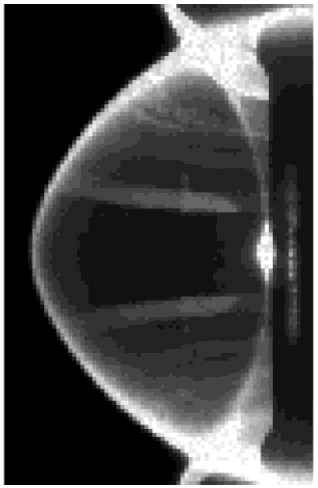
M.W. Bongard, 14th Int'l. H-mode Workshop, Fukuoka, Japan, Oct. 2013

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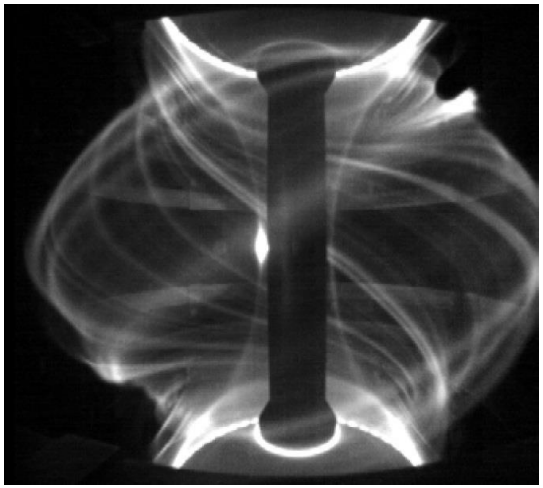
Edge Stability Critical to Next-Step Fusion Devices



MAST L-Mode*

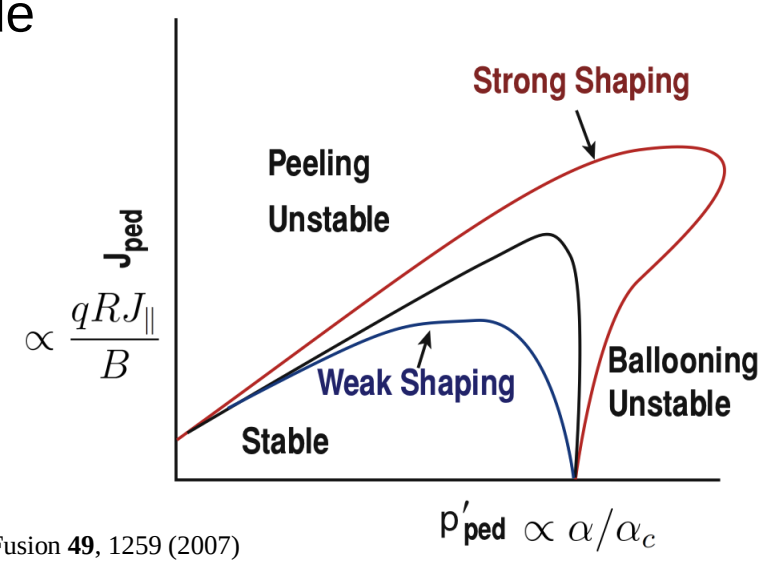


H-Mode*



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



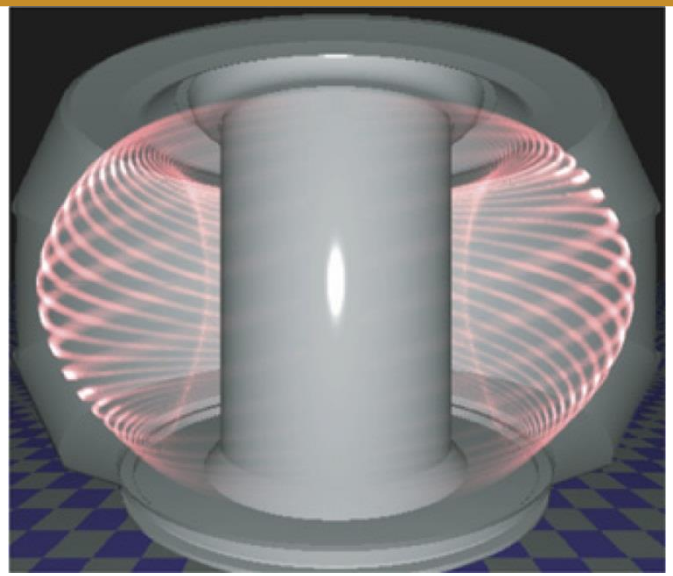
Stability Space***

*: 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)

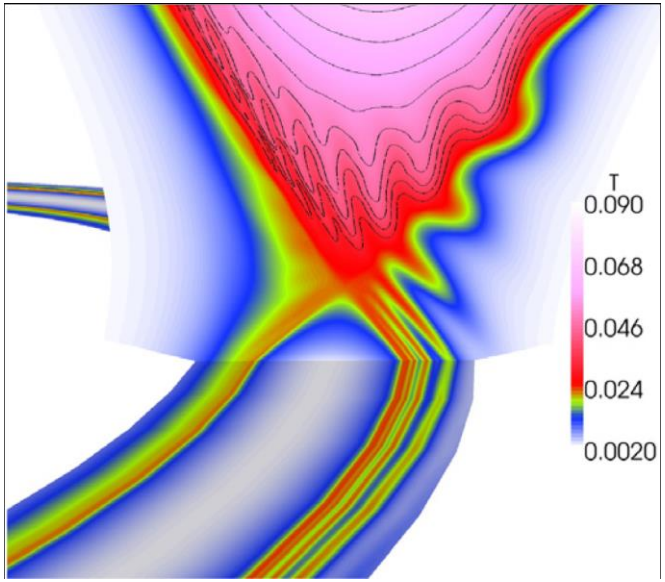
Validated, Predictive Theory Needed to Mitigate ELMs

- 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)

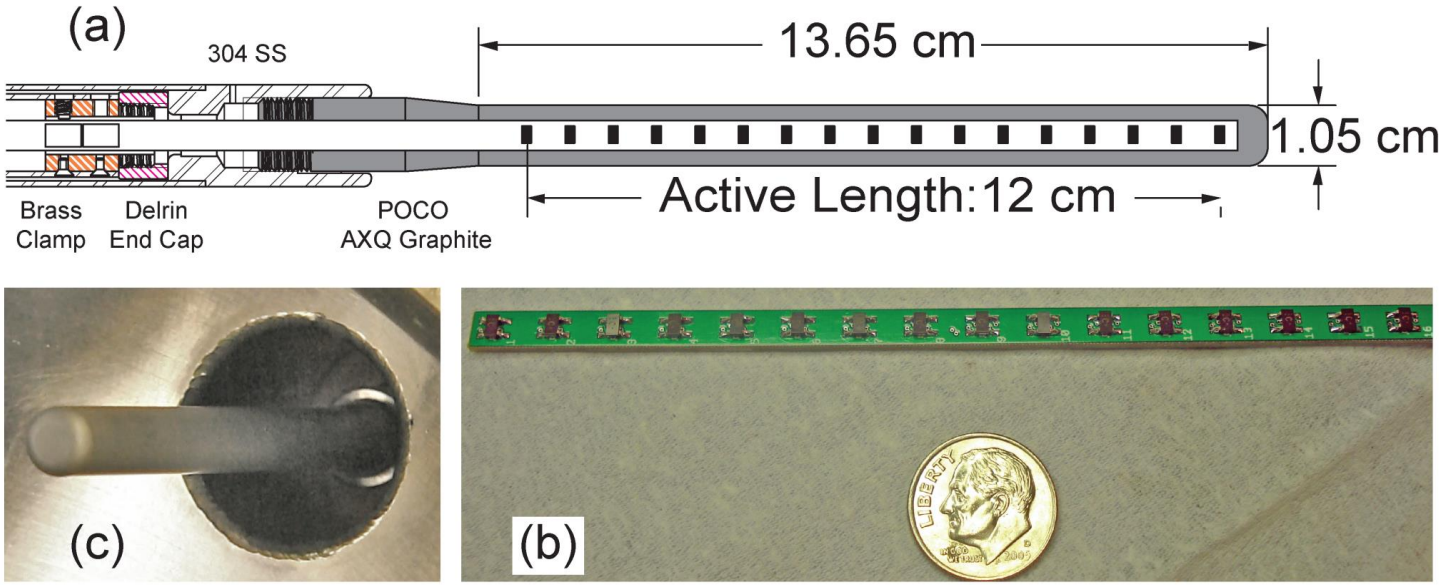


Snyder *et al.*, Phys. Plasmas **12**, 056115 (2005)



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

PEGASUS Hall Probe Deployed to Measure J



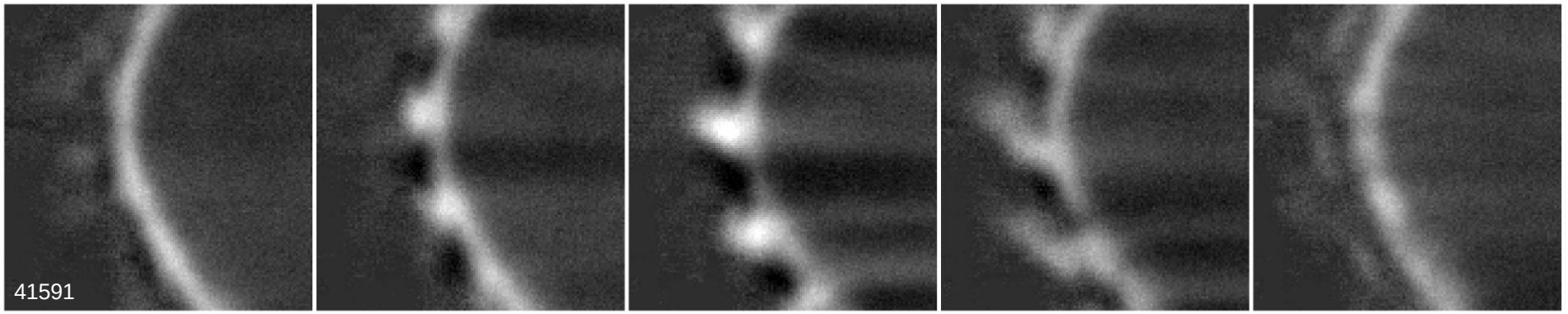
Bongard *et al.*, Rev. Sci. Instrum. **81**, 10E105 (2010)

- Precision $B_z(R, t)$ measurements
  - 16 solid-state InSb Hall sensors
  - 7.5 mm radial resolution
  - 25 kHz large-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

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

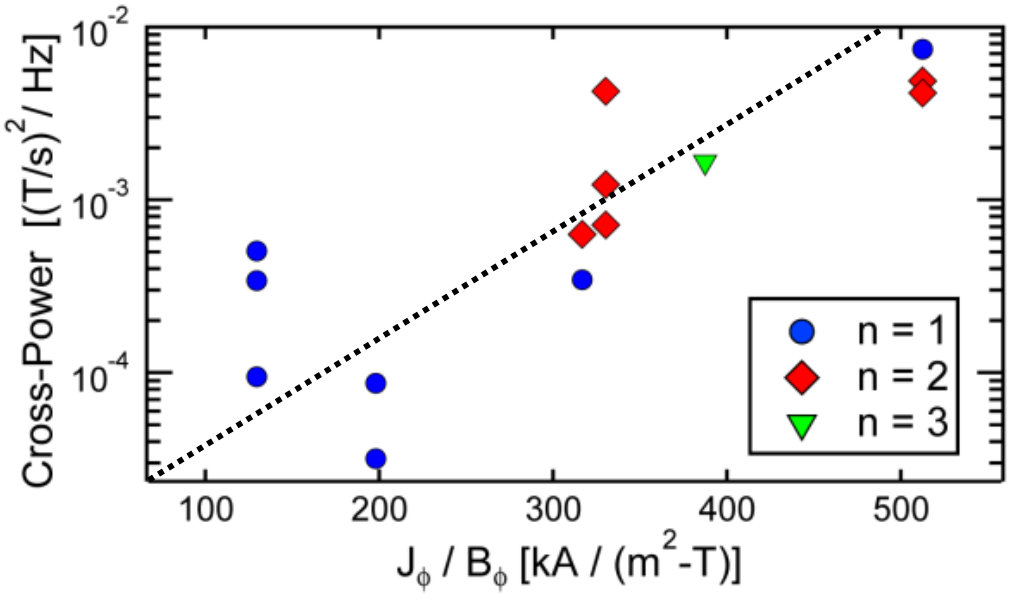
*: Petty, *et al.*, Nucl. Fusion **42**, 1124 (2002)

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 theoretical drive J/B

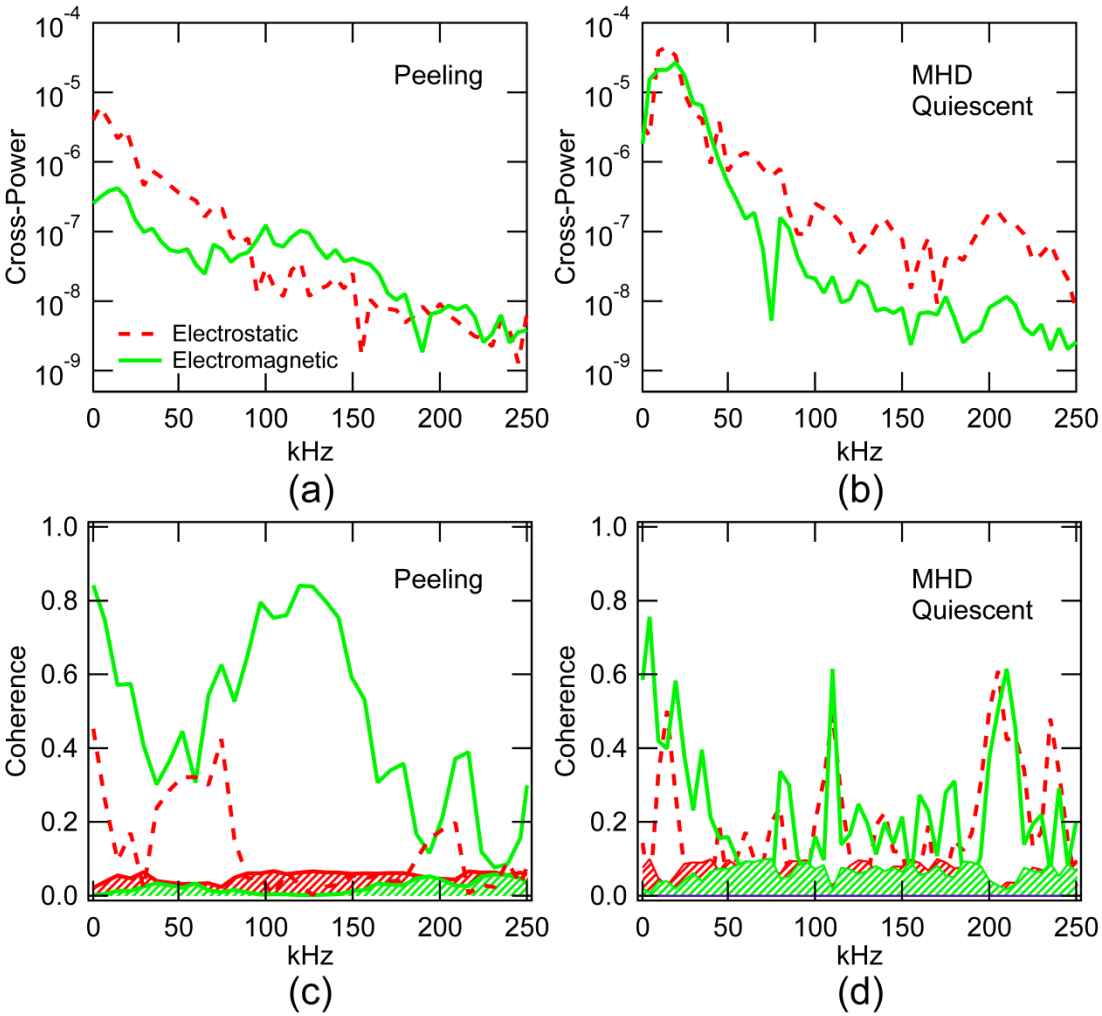


Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

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Peeling Filaments Have Electromagnetic Origin

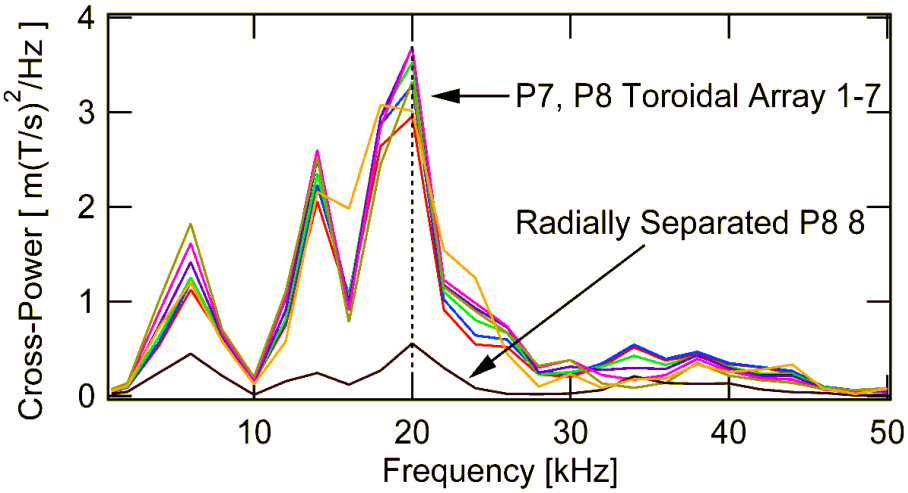
- Magnetic, Langmuir probes placed at plasma edge
- Peeling modes produce coherent electromagnetic activity
  - Uncorrelated with electrostatic LP fluctuations
- No EM signature in MHD quiescent phase
  - Consistent with electrostatic L-mode turbulence

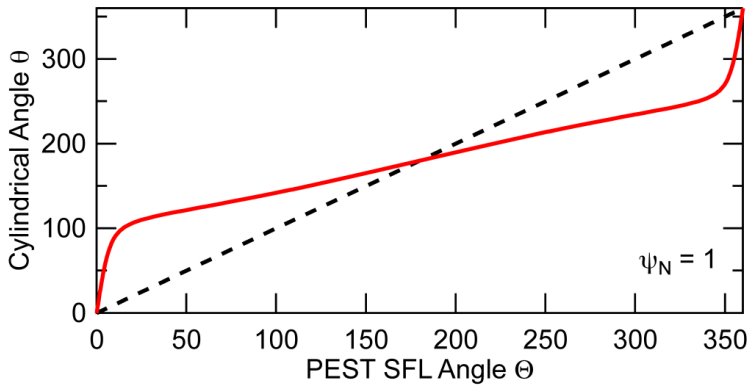


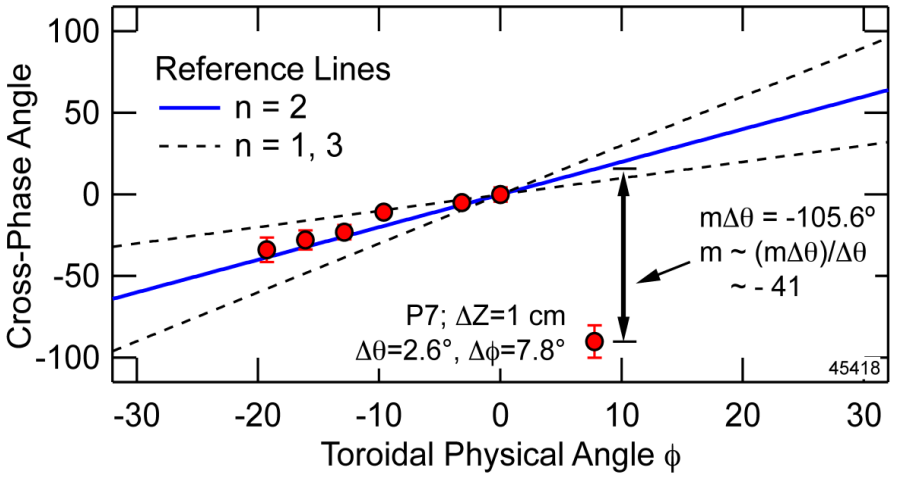
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Peeling Modes Have Low-n, High-m Structure

- 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



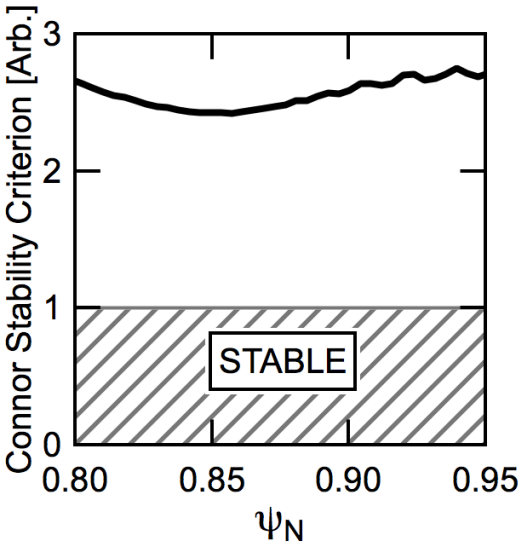


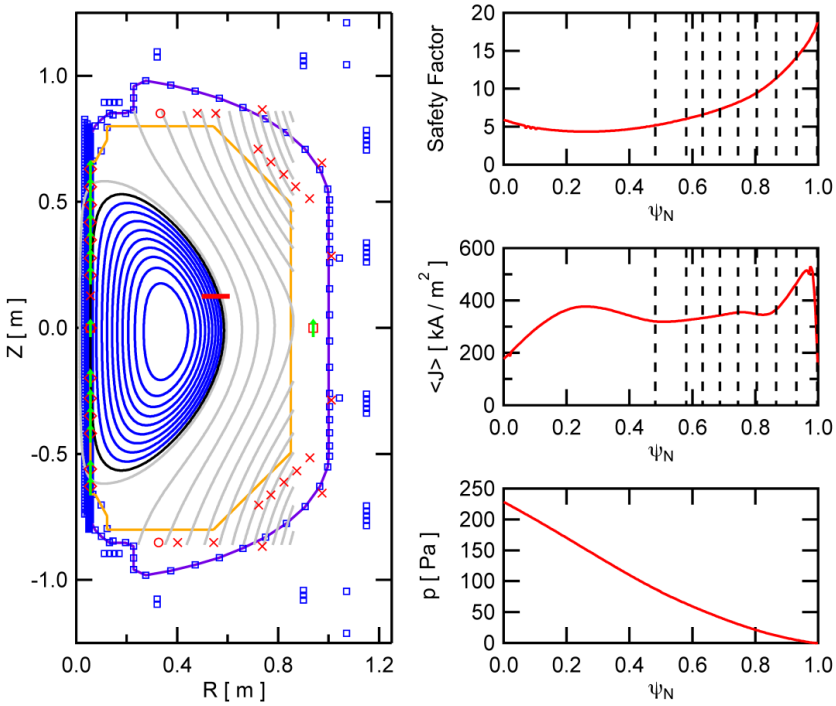


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Peeling Mode Onset Consistent with Ideal MHD

- 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





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

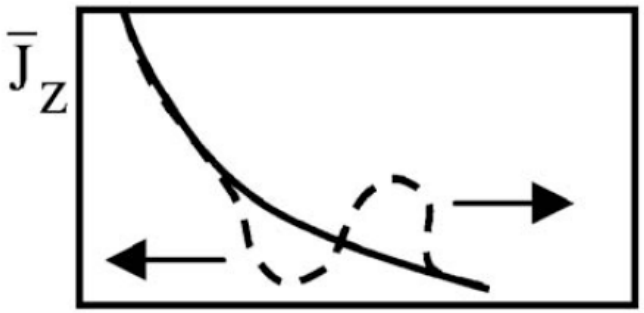
Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

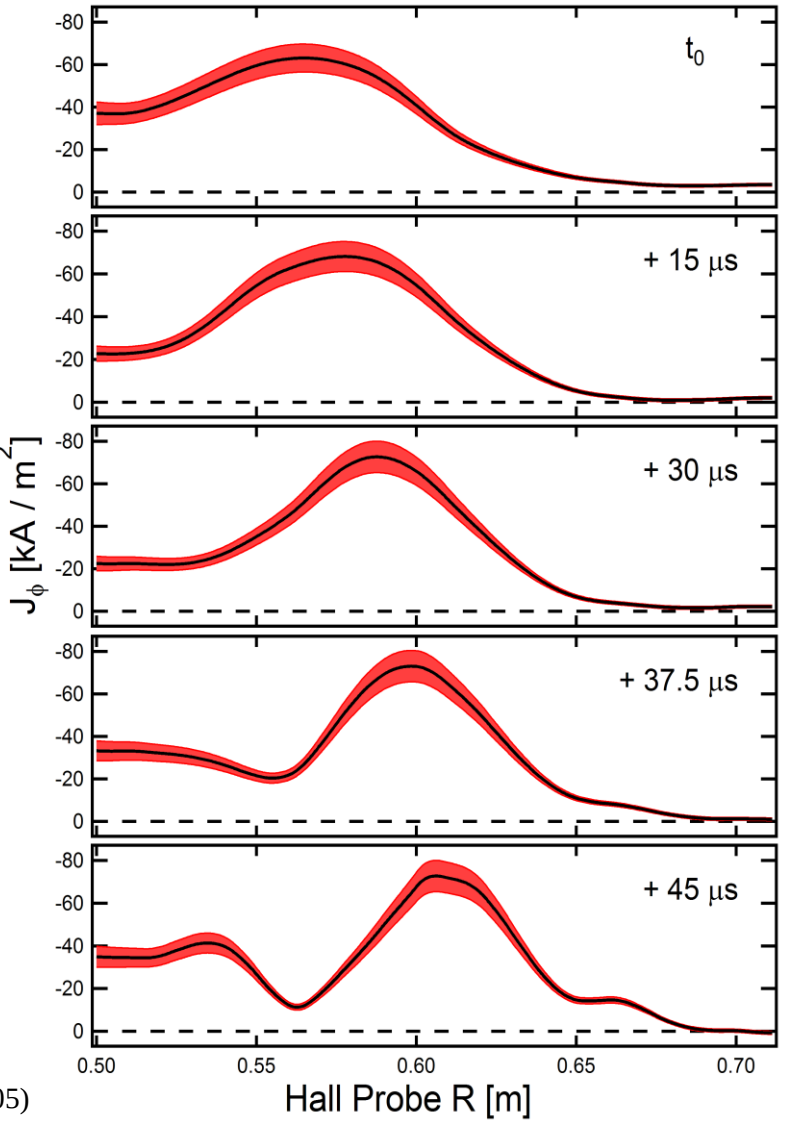
*: Connor *et al.*, Phys. Plasmas **5**, 2687 (1998)

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J_{edge} Dynamics Measured on ELM Timescales

- Peeling mode filament forms 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



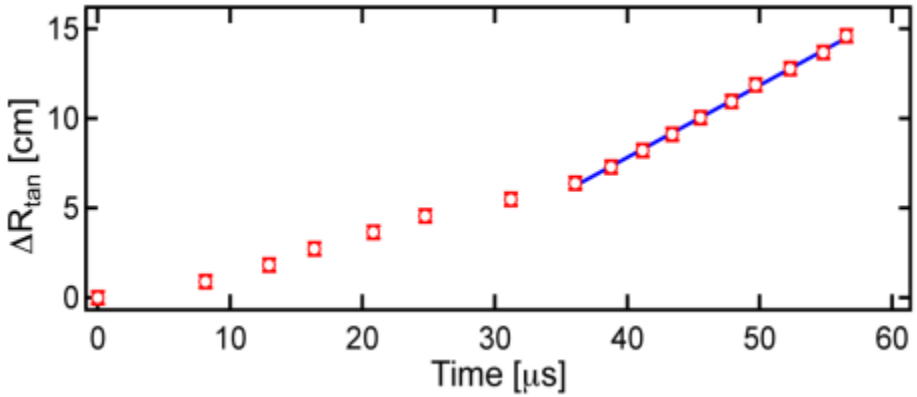


: Myra, Phys. Plasmas **14, 102314 (2007); ***: Myra *et al.*, Phys. Plasmas **12**, 092511 (2005)

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

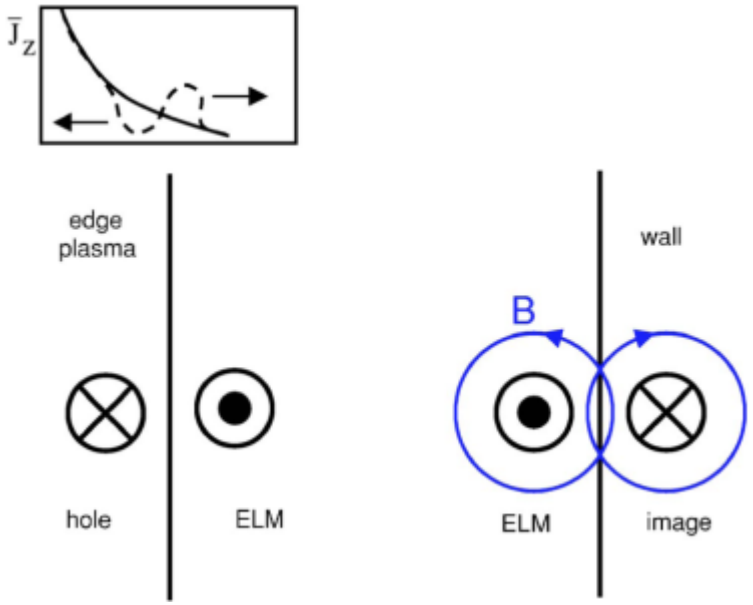
Filament Radial Motion Qualitatively Consistent with Electromagnetic Blob Transport

- 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

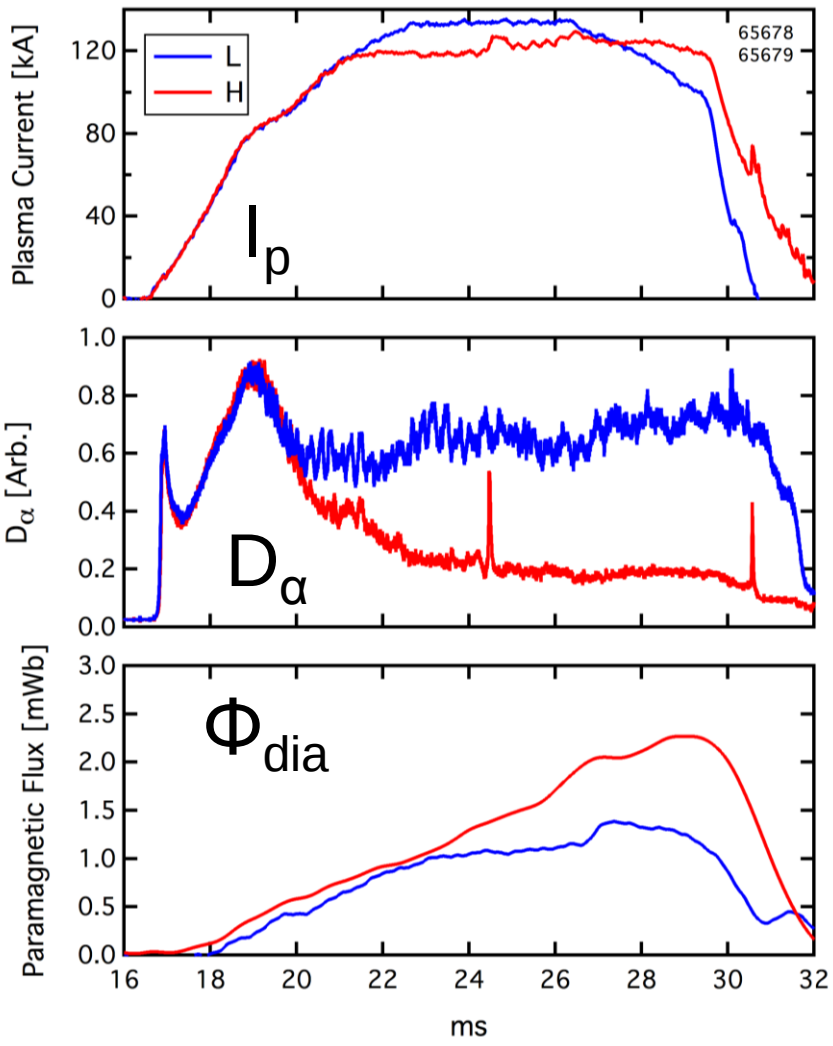
*: Myra, Phys. Plasmas **14**, 102314 (2007)

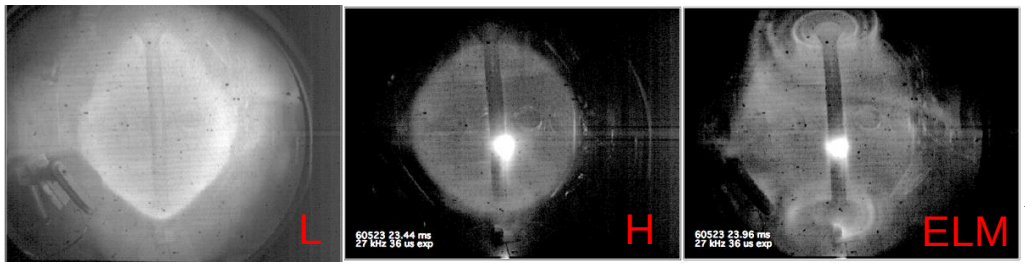
: Myra *et al.*, Phys. Plasmas **12, 092511 (2005)

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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
  - Reduced D_α emission
  - Edge current pedestal between ELMs
  - Type I, III ELMs suggested
  - ~ Doubling of stored energy
  - Toroidal flow reversal
  - T_e, T_i increase



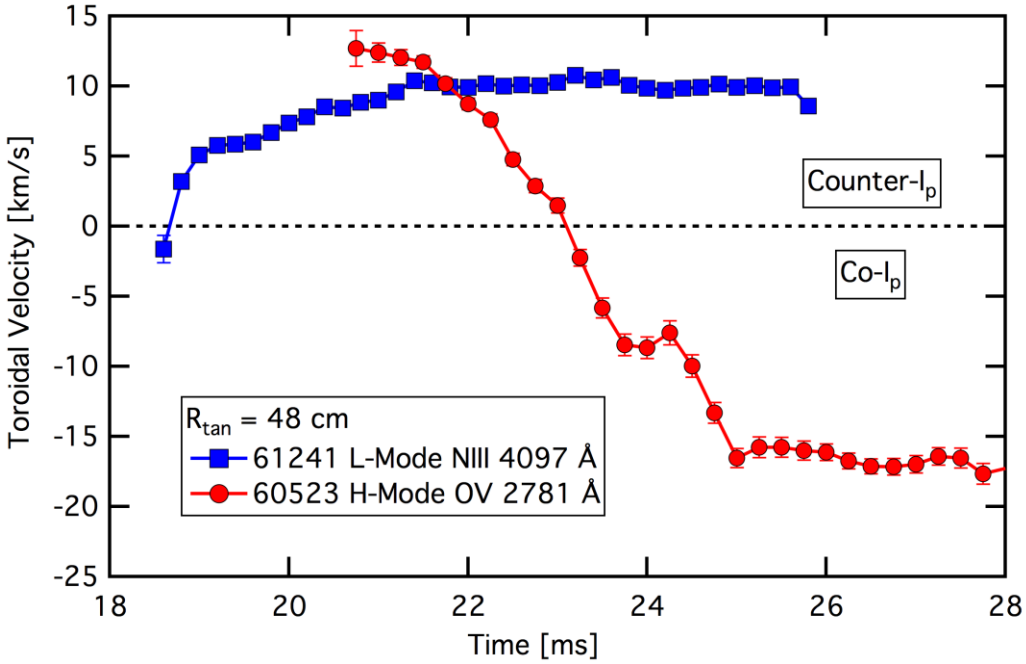


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Toroidal Flow Reverses at L–H Transition

- Toroidal rotation measured via T_i spectrometry* in L, Ohmic H-mode discharges
  - No external momentum input
- L-mode flows are in the counter-current direction
- H-mode shots reverse rotation at L → H transition
  - Effect seen on MAST** and NSTX during HFS fueling

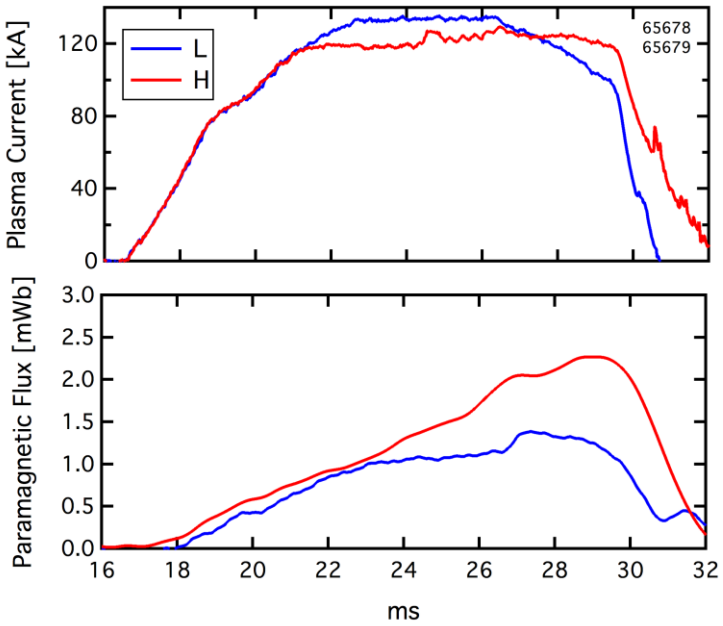


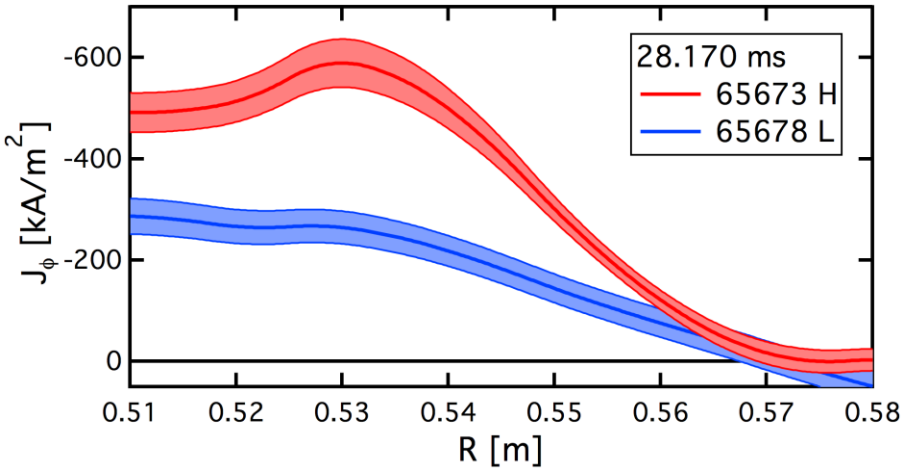
*: Burke *et al.*, Rev. Sci. Instrum. **83**, 10D516 (2012)

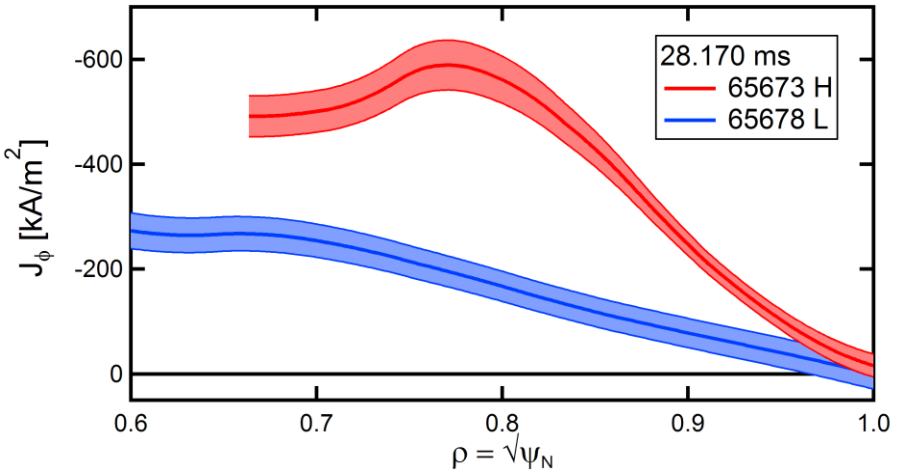
: Meyer *et al.*, J. Phys.: Conf. Ser. **123, 012005 (2008)

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 significantly reduced in H-mode



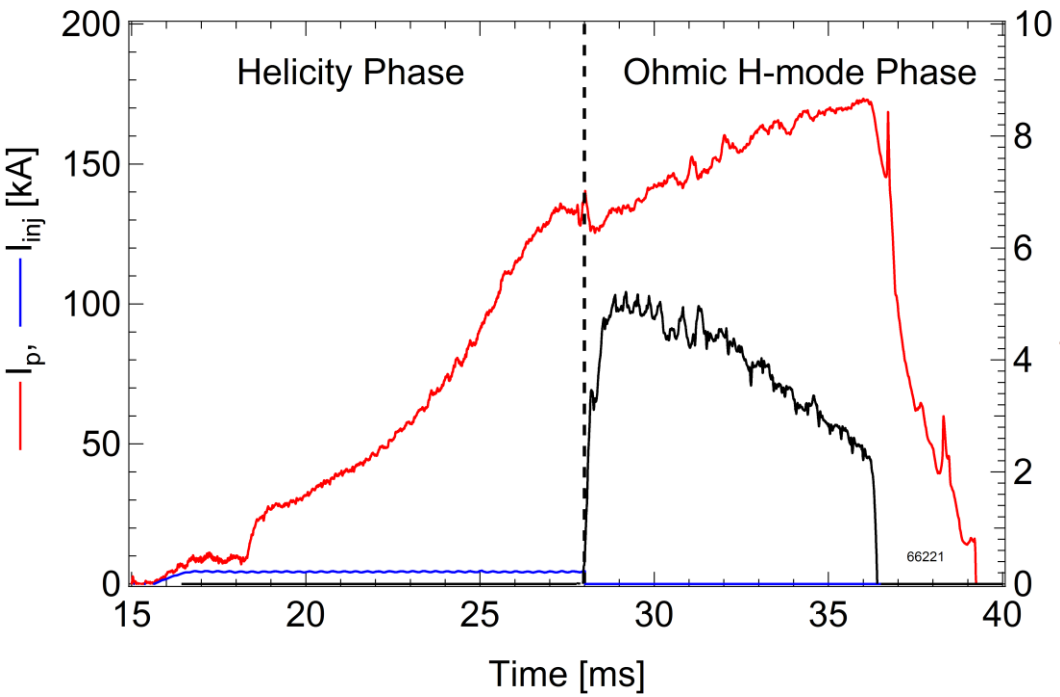


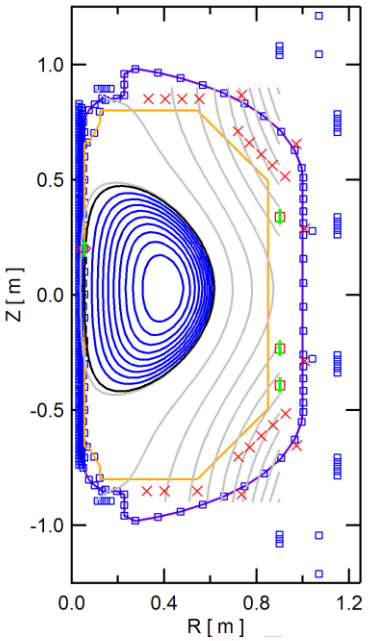


*: M.W. Bongard *et al.*, Rev. Sci. Instrum. **81**, 10E105 (2010)
: C.C. Petty *et al.*, Nucl. Fusion **42, 1124 (2002)

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





Equilibrium Parameters
Shot 66221, 34.80 ms

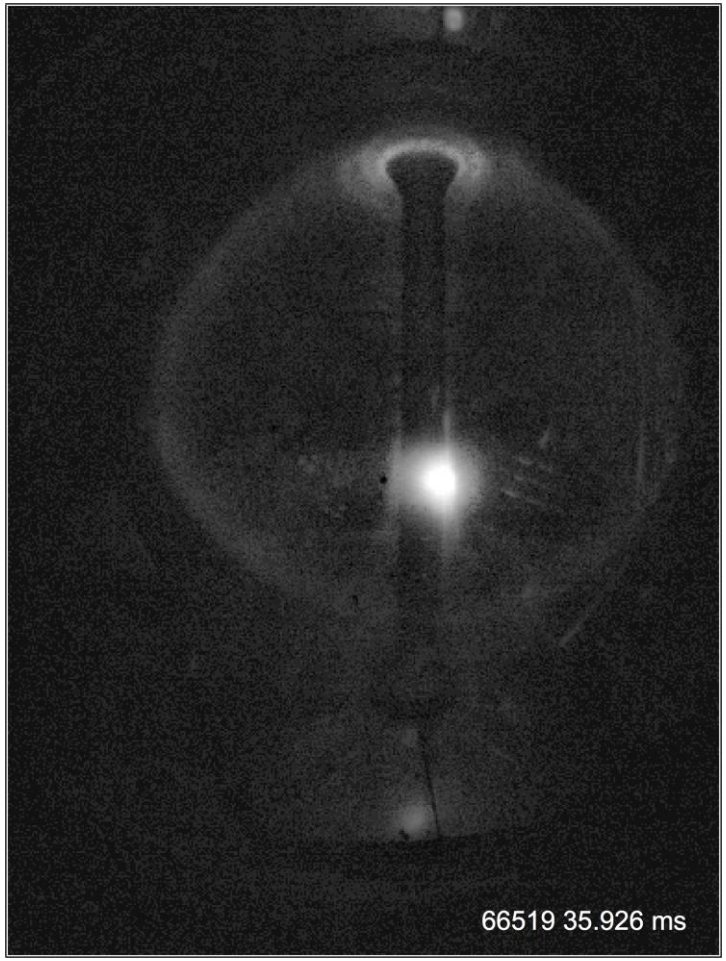
I_p	169 kA	R_0	0.336 m
β_t	0.081	a	0.281 m
ℓ_i	0.42	A	1.20
β_p	0.31	κ	1.6
W	2101 J	δ	0.44
B_{T0}	0.179 T	q_{95}	9.92

- 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

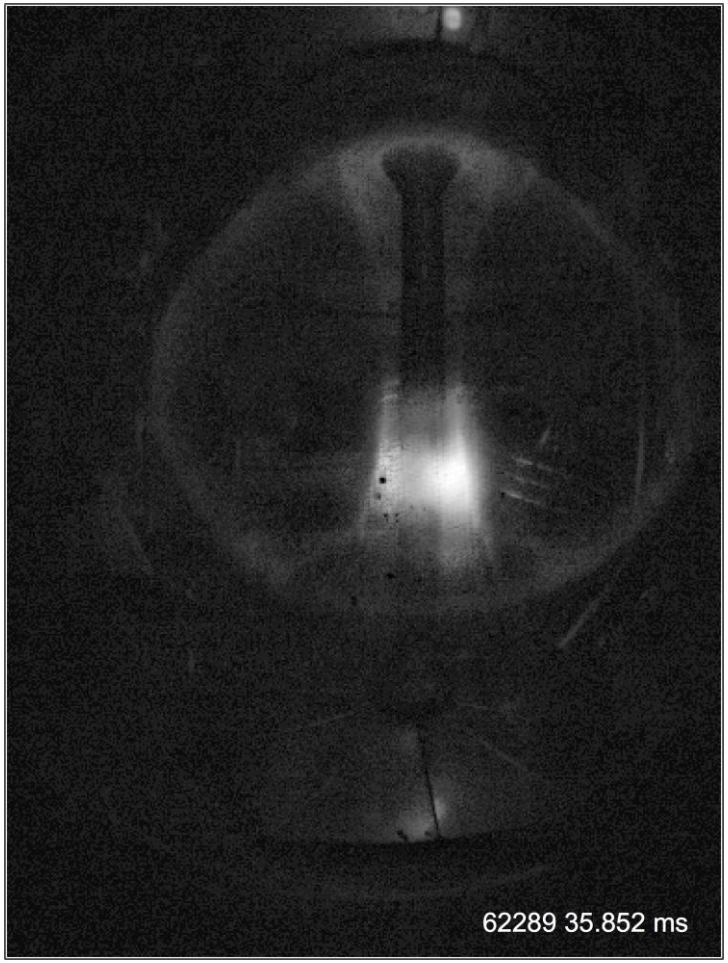
 *: Battaglia *et al.*, Nucl. Fusion **51**, 073029 (2011)

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

Non-diverted: Centerstack Limited



Diverted: Separatrix Limited



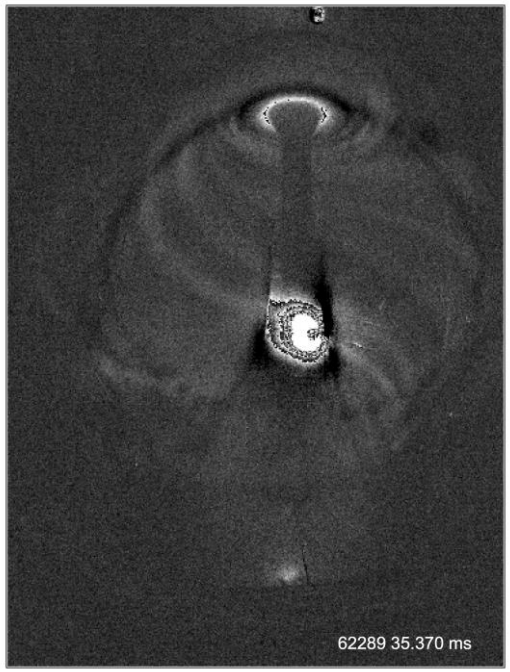
- Initial results show no significant difference between topologies

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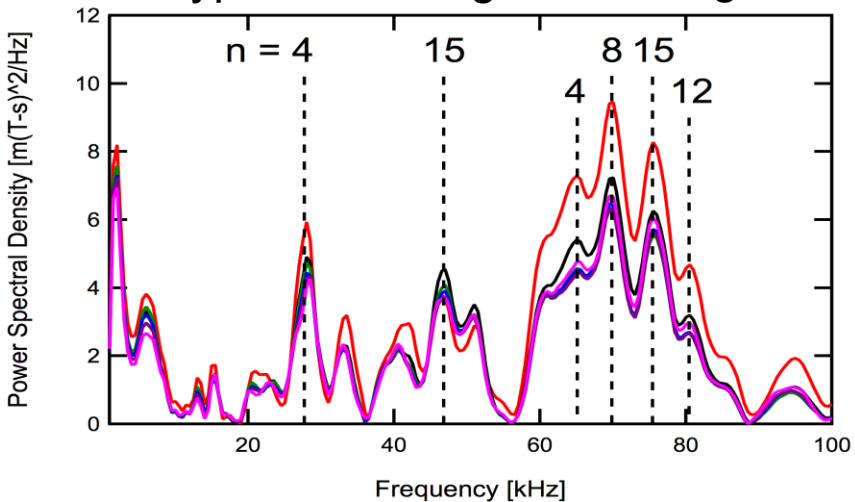
Two Distinct ELM Types Observed in H-mode with Differing Magnetic Signatures

- Conventional identification complicated by lack of P_{aux} and modest pulse length
  - Type I-like ELMs are infrequent and violent
  - Type III-like more ubiquitous, less perturbing
  - Standard filamentary structures observed

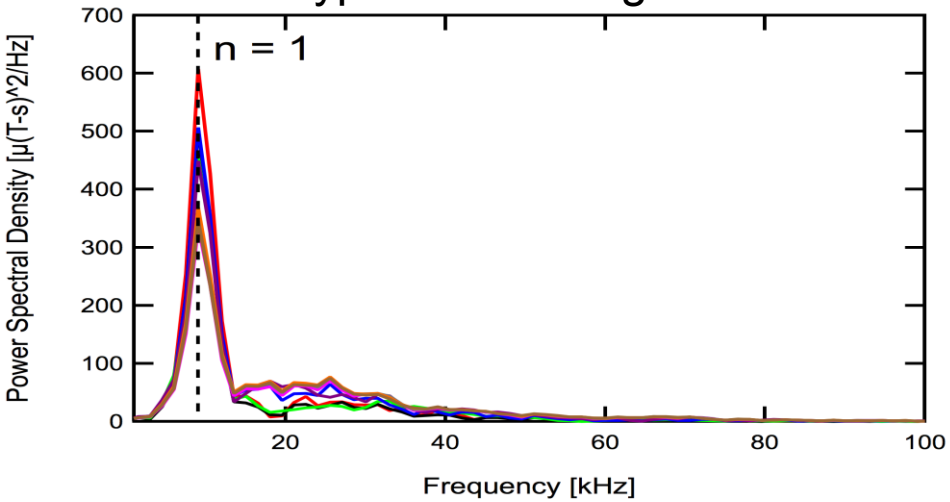
- Toroidal mode spectra suggest different MHD modes at play
  - n manifold used to tentatively classify ELMs here



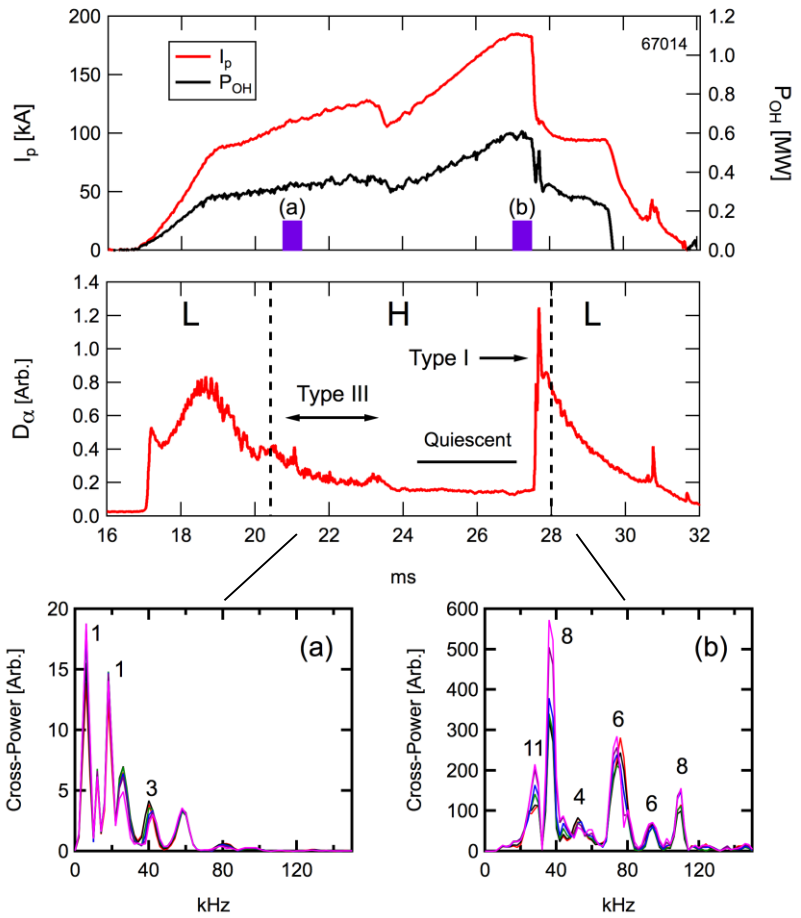
"Type I:" Peeling-Ballooning?



"Type III:" Peeling-like?

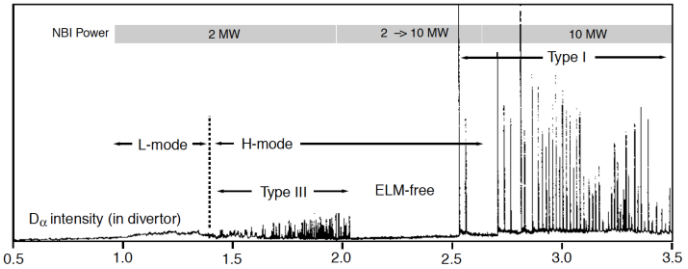


Disruptive Type I ELM Occurs at High Input Power





Spiraling heat deposition on lower divertor plate from large ELM



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

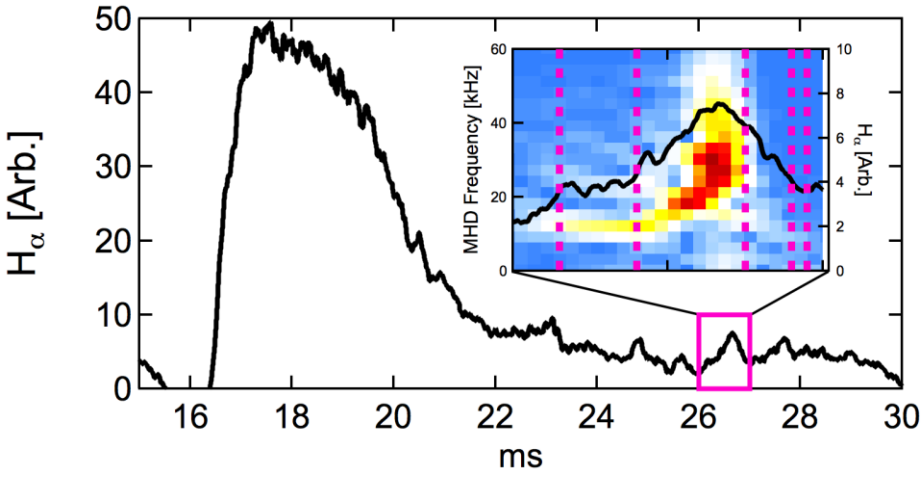
- Large Type I ELM after quiescent period
  - Large ELM induces back-transition, terminates discharge
  - Similar to large tokamaks with auxiliary heating

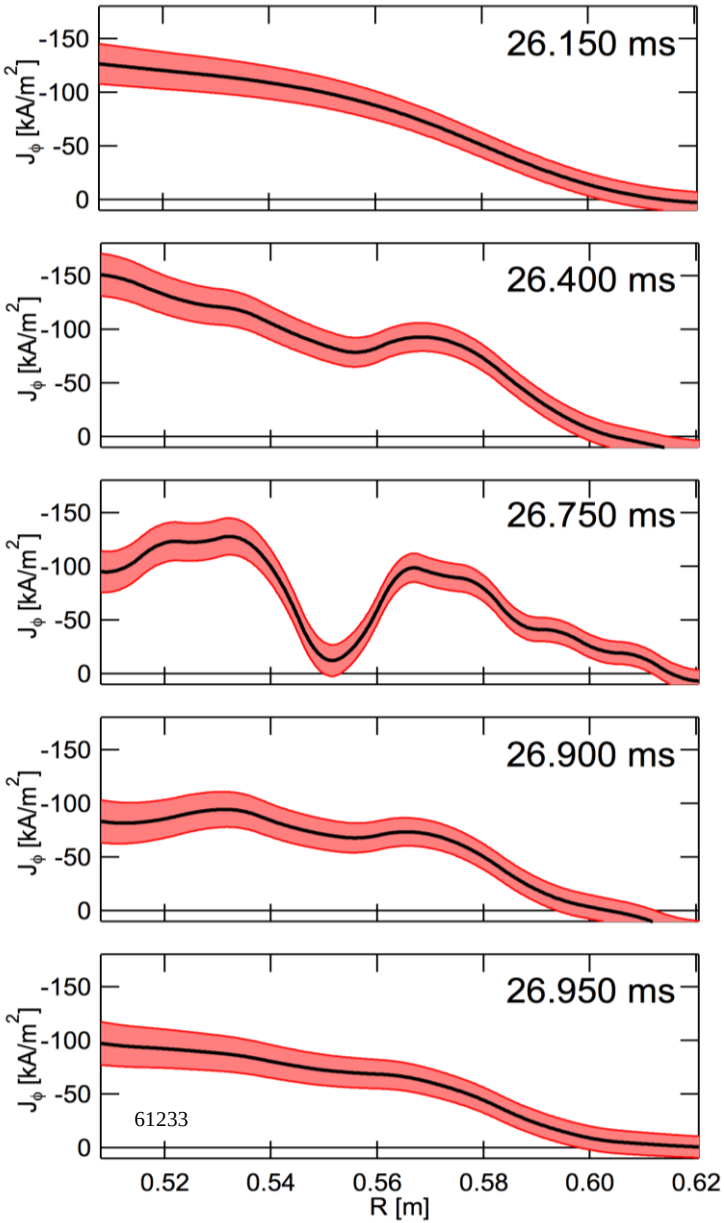
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Type III J_{edge} ELM Dynamics Measured

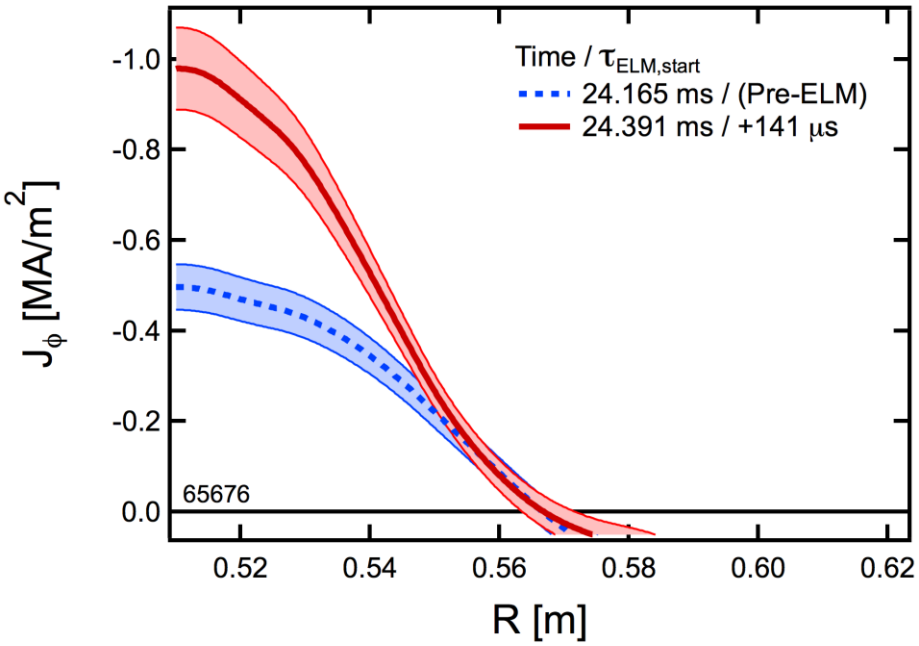
- J(R,t) profiles measured throughout single Type III ELM
  - n = 1 EM precursor
  - ~10% I_p loss, negligible $\Delta\Phi$
- Current-hole perturbation accompanies pedestal crash
  - Similar to peeling modes in PEGASUS
- Rapid recovery of H-mode pedestal

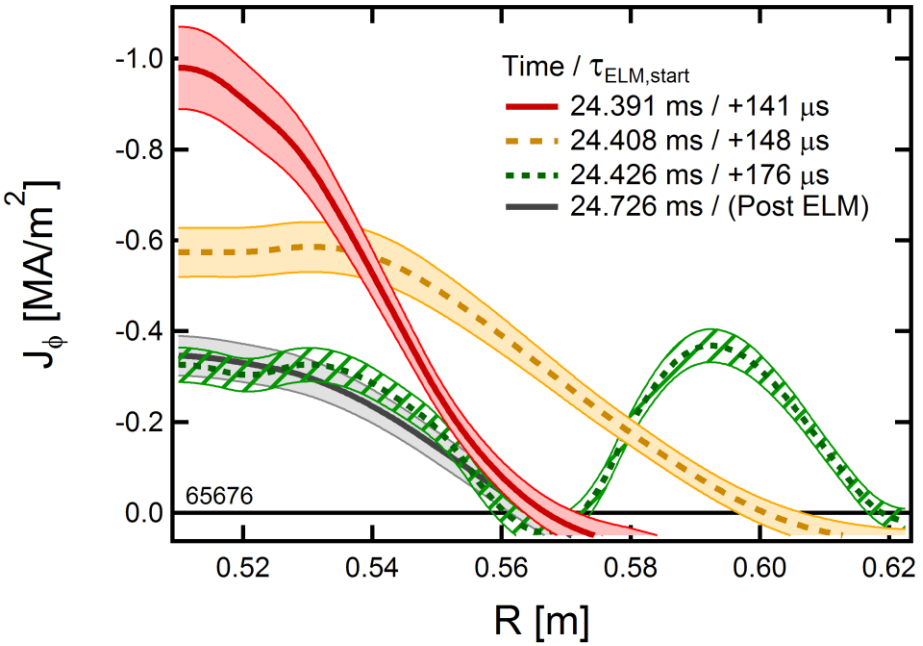




M.W. Bongard, 14th Int'l. H-mode Workshop, Fukuoka, Japan, Oct. 2013

Type I J_{edge} ELM Dynamics Measured



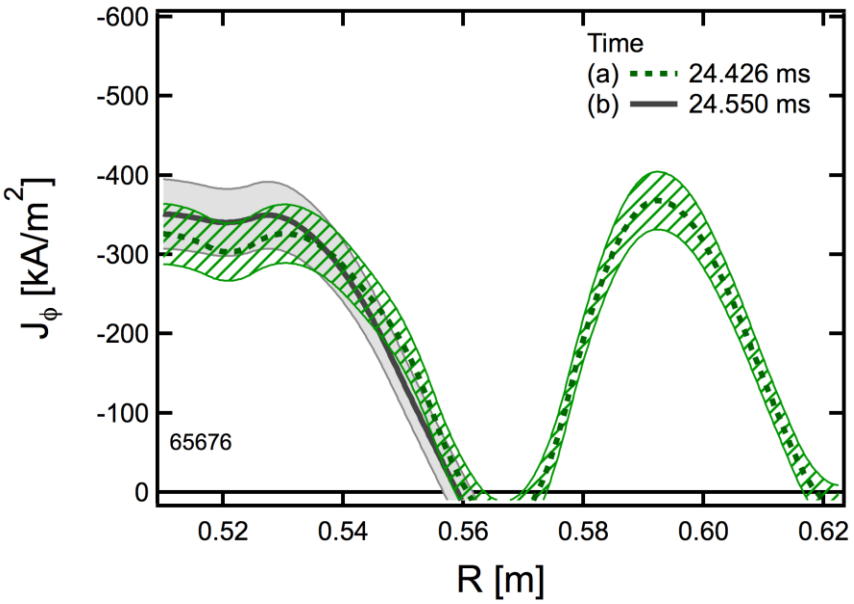


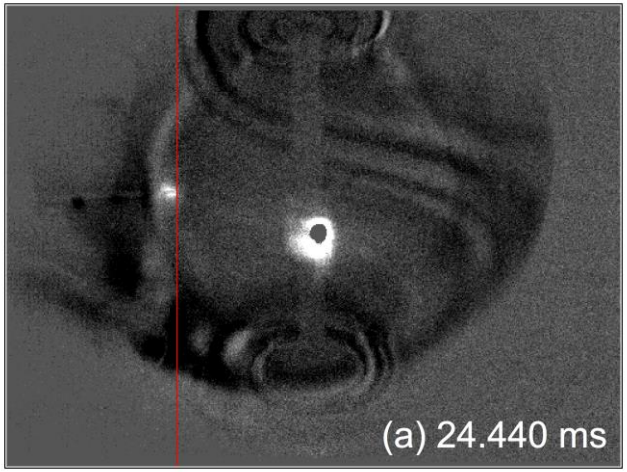
- J(R,t) profiles resolved throughout single Type I ELM cycle
  - No clear EM precursor
- J_{edge} builds to ~ 2x pre-ELM value
- Crash phase resembles L-mode
  - Reduction in gradient scale length
  - Intermediate n = 6 – 9 MHD present
- Filament generation suggested
  - Post-ELM J_{edge} attained by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

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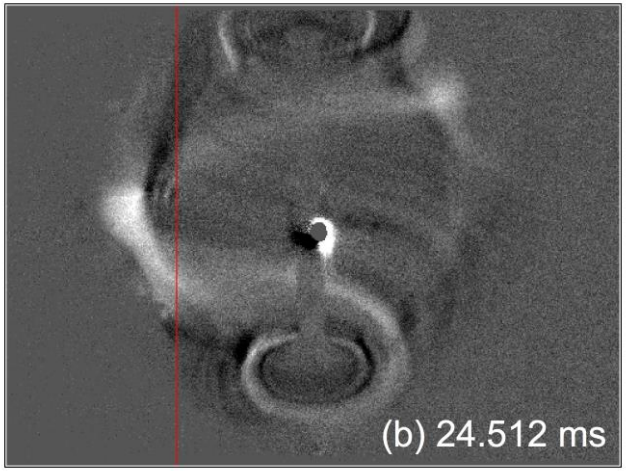
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Type I ELM Filament Ejection Coincides with J_{edge} Current-Hole Generation





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
- First measurements of J_{edge} dynamics throughout ELM crash
  - Type I, III ELMs tentatively identified
    - Marked differences in toroidal mode number spectrum; virulence
  - $J_{edge}(R,t)$ current-hole perturbations and current-carrying filament expulsion
  - ITER-relevant ELM stability tests of peeling-ballooning modes