Peeling Instability in the PEGASUS ST

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University of Wisconsin-Madison

53rd Annual APS-DPP

Poster PP9.00003
Salt Lake City, UT
November 16, 2011



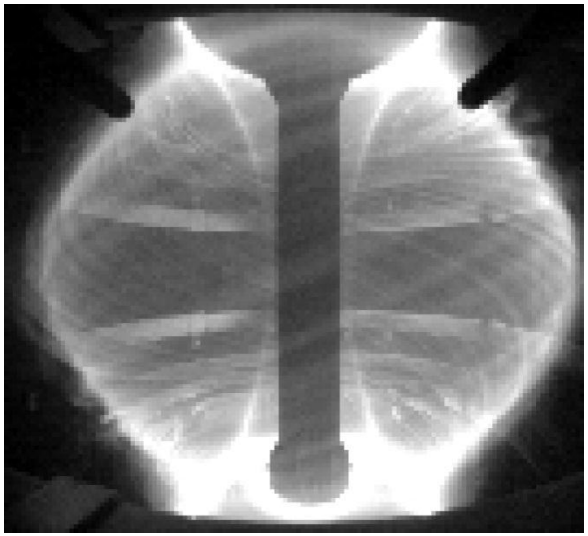
PEGASUS
Toroidal Experiment

Abstract

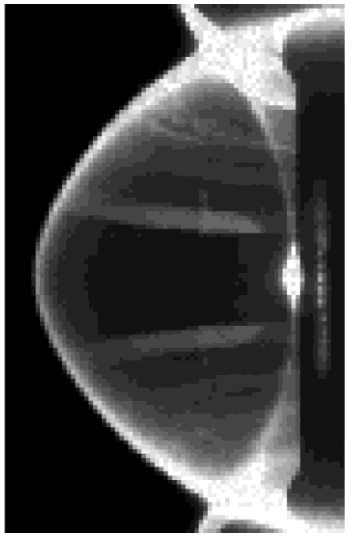
Ohmic plasmas in PEGASUS are often initially unstable to peeling modes, an instability underlying deleterious edge localized mode (ELM) activity in fusion-grade plasmas. These edge-localized instabilities are observed under conditions of high parallel edge current density ($J_{\|} \sim 0.1$ MA/m^2) and low magnetic field ($B \sim 0.1$ T) present at near-unity aspect ratio, corresponding to high peeling instability drive ($\propto J_{\|}/B$). They generate electromagnetic MHD activity with low toroidal mode numbers $n \leq 3$ and ELM-like, field-aligned edge filaments with high poloidal coherence that detach from the plasma and propagate outward. The modest edge temperatures and short pulse lengths of PEGASUS discharges permit time-resolved measurements of the edge current density profile J_{edge} using an insertable Hall probe. Peeling MHD fluctuation amplitudes scale strongly with measured $J_{\|}/B$, consistent with theory. Ideal stability analysis of Hall-constrained equilibrium reconstructions with DCON finds instability to peeling modes. Filaments form from an initial J_{edge} "current-hole" perturbation and carry currents ~100–250 A. Their radial trajectories feature transient acceleration due to magnetostatic repulsion followed by constant-velocity motion, consistent with models of ELM dynamics.

Work supported by U.S. DOE Grant DE-FG02-96ER54375

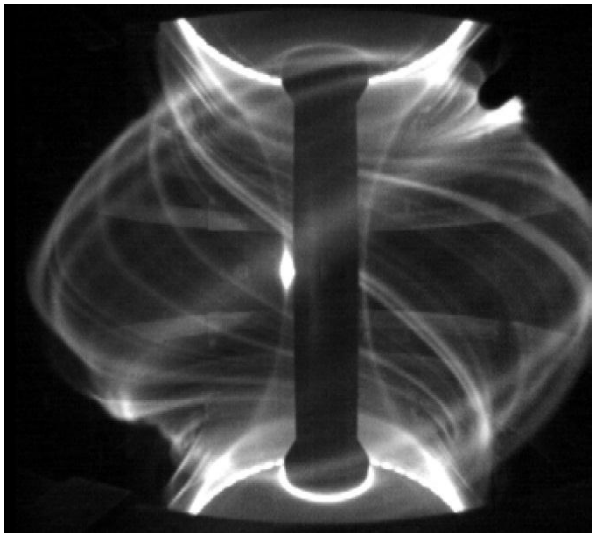
Edge Stability Critical to Next-Step Fusion Devices



MAST L-Mode*



H-Mode*



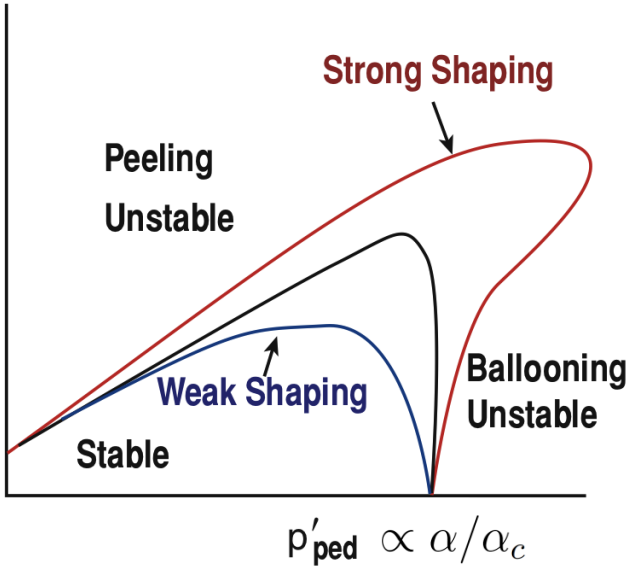
ELM**

- ITER and future fusion devices will operate in H-mode
  - Edge transport barrier enhances core pressure
- Pressure, current density gradients drive MHD instabilities
  - Edge Localized Modes (ELMs): periodic, transient release of stored energy
- Validated theory needed for effective ELM mitigation/control

*: Kirk *et al.*, Plasma Phys. Control. Fusion **48**, B433 (2006)
: Kirk *et al.*, Plasma Phys. Control. Fusion **49, 1259 (2007)

Peeling-Ballooning Model for ELM Onset

- Stability space determined by ideal MHD stability
  - Equilibrium-dependent boundaries $\propto \frac{qRJ_{\parallel}}{B}$ J_{ped}
- ∇p –driven ballooning modes
  - Short-wavelength; $n \geq 30$
- Current-driven peeling modes
  - Long-wavelength; $n \leq 3-5$
  - Analytic stability criterion:*



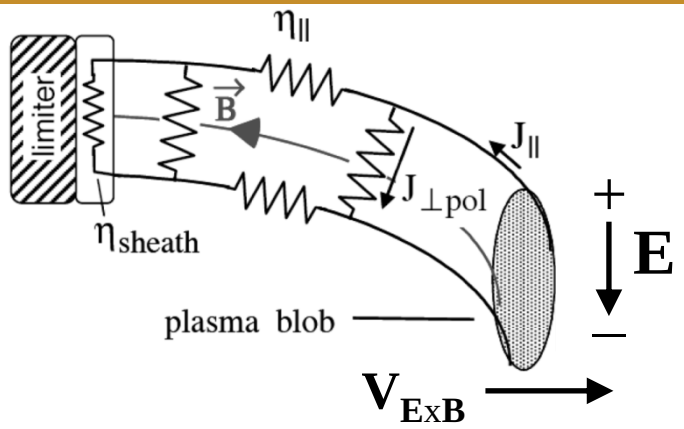
Snyder, Phys. Plasmas **12**, 056115 (2005);
see also Hegna, Phys. Plasmas **3**, 584 (1996)

$$\sqrt{1-4D_M} > 1 + \frac{1}{\pi q'} \oint \frac{\mu_0 J_{\parallel} B}{R^2 B_p^3}\, dl \sim \frac{Rq}{s}\left(\frac{\mu_0 \bar{J}_{\parallel}}{B}\right)$$

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

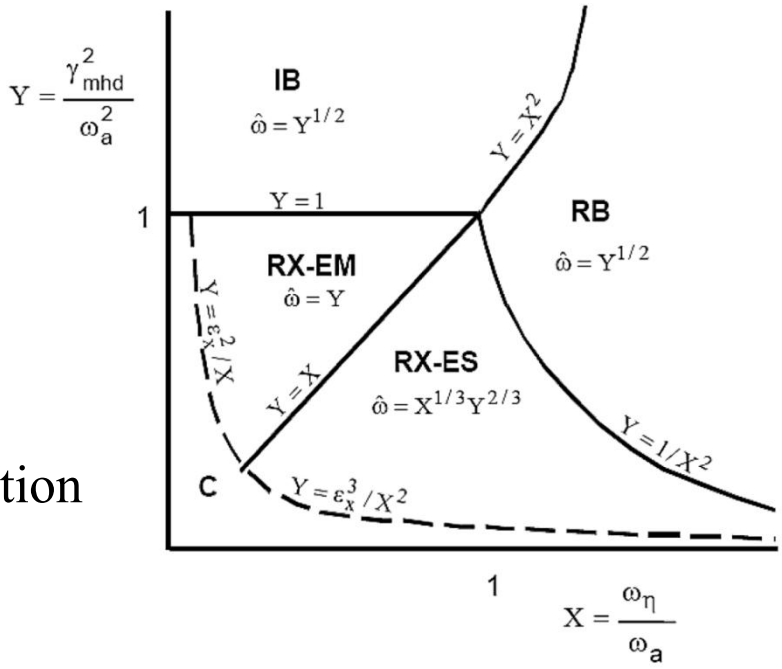
Electromagnetic Blob Transport Theory Being Extended to Treat ELM Filament Propagation

- Filamentary blob structures commonly observed in tokamaks
  - L-mode electrostatic turbulence
  - ELM-generated propagating filaments



- Blob-filament models imply radial propagation in a tokamak*
  - Effective gravity → Polarization Currents → **E** x **B** motion
  - V_R set by closures for $J_{||}$**

*: Krasheninnikov *et al.*, J. Plasma Physics **74**, 679 (2008)

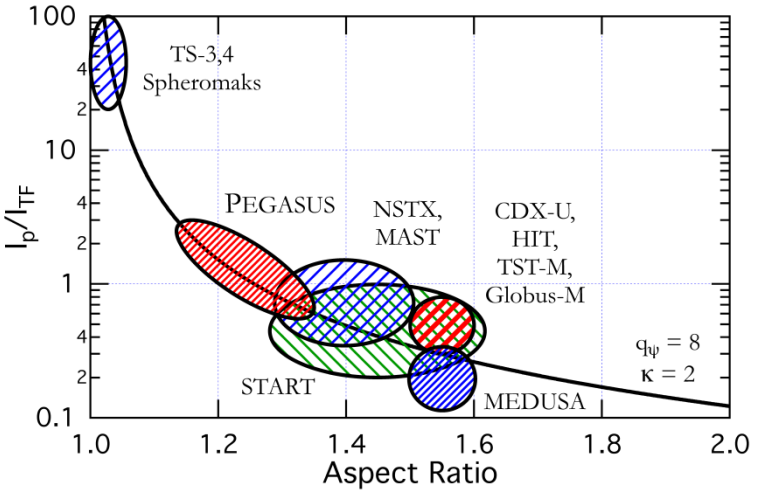


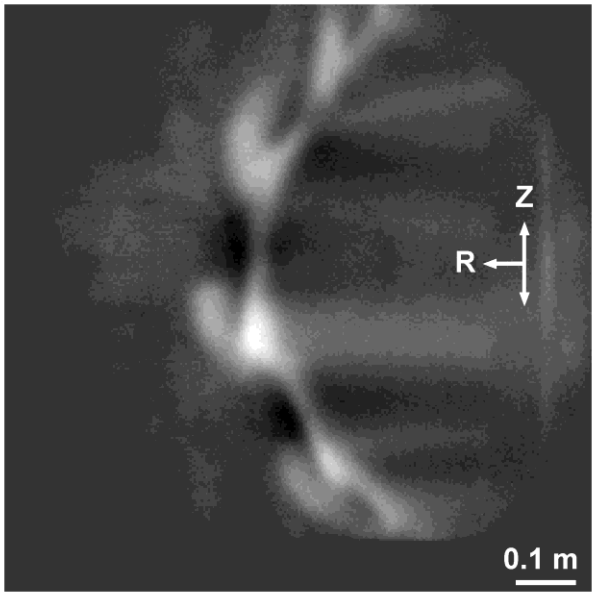
- Extensions treat ELM effects
  - Electromagnetic effects → transient acceleration
  - Little known experimentally (lack of J)

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

Low-A PEGASUS ST Provides Access to Peeling Instability and Conditions to Measure J

- Spherical tokamaks naturally provide strong peeling drive
  - Toroidal field utilization $I_p/I_{TF} \sim J_\parallel/B$
- PEGASUS accesses peeling modes
  - Strong $J_\parallel/B \sim 1$ MA/m^2-T at $A \leq 1.3$
  - Comparable to DIII-D in H-mode
- Machine parameters permit internal edge measurements
  - Short pulse lengths (< 50 ms)
  - Modest $T_e < 200$ eV

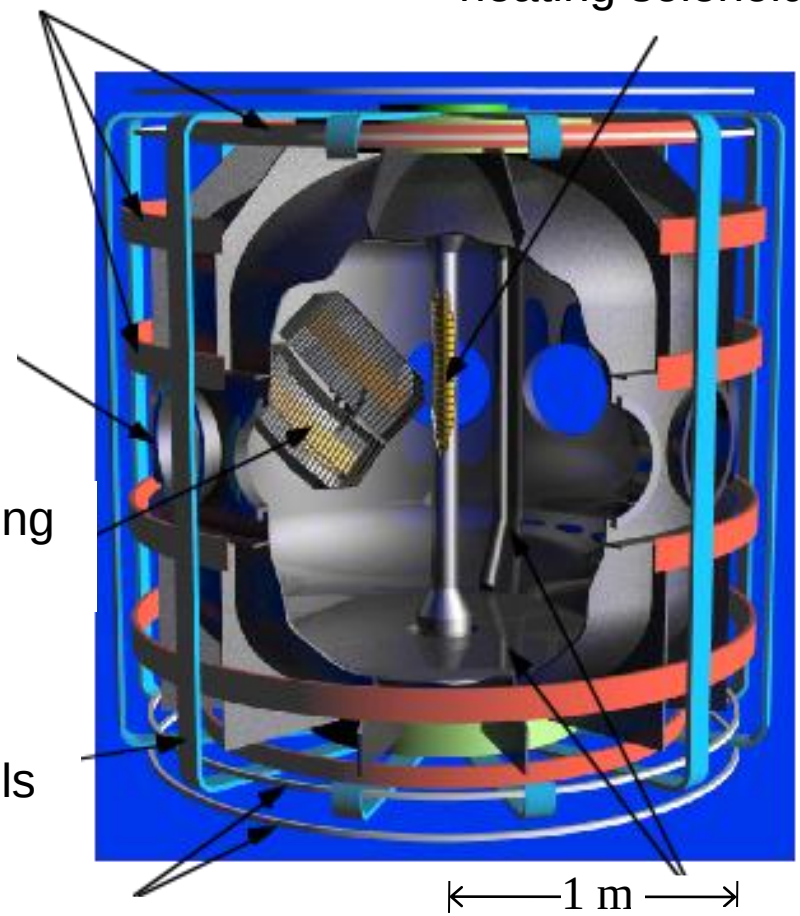




Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

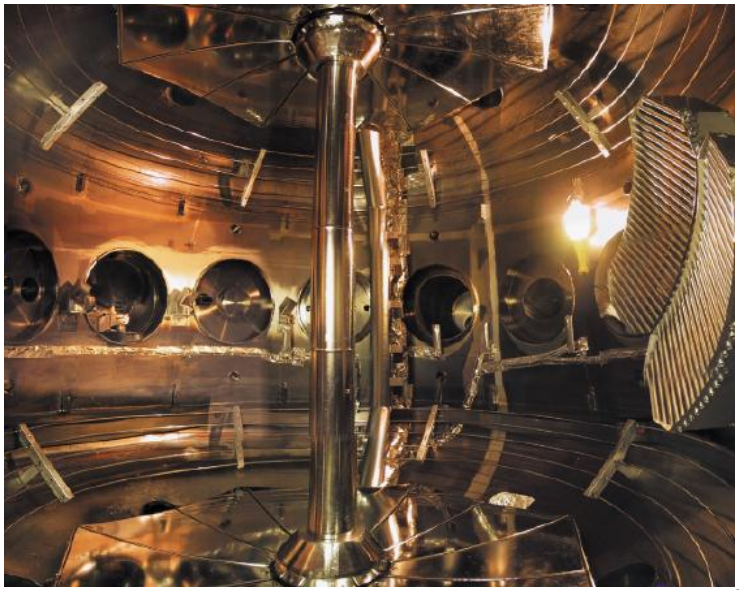
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PEGASUS: A Mid-Size, Ultralow-A ST



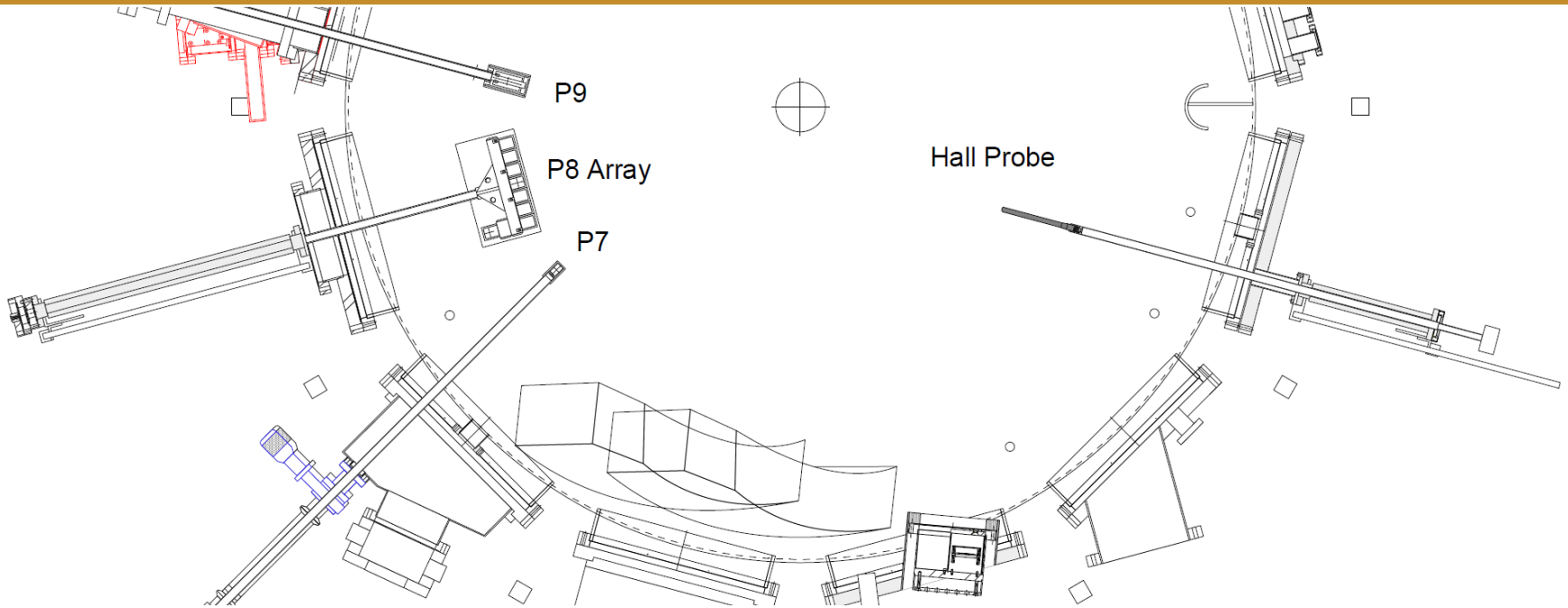
Experimental Parameters

Parameter	To Date
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .22
I_N (MA/m-T)	6 – 12
ℓ_i	0.2 – 0.5
κ	1.4 – 3.7
τ_{shot} (s)	≤ 0.025
β_t (%)	≤ 25
P_{HHFW} (MW)	0.2



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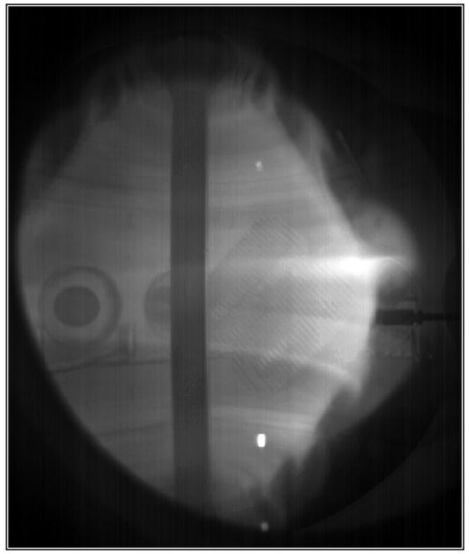
Radially Scanning Diagnostics Access Edge Region



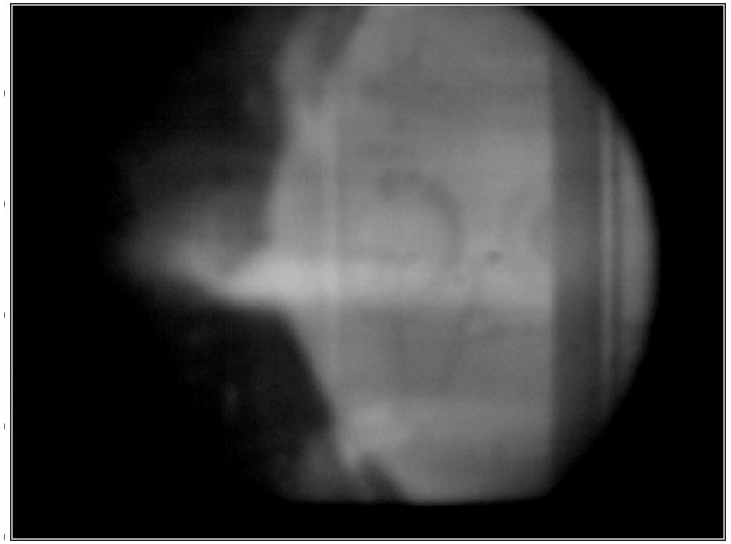
- PEGASUS edge region compatible with probes
  - Locations variable on shot-to-shot basis
- External Probes
  - Single-point Mirnov, Langmuir probes
  - Toroidal B_z array
- Internal Hall Probe
  - $B_z(R, t) \rightarrow J(R, t)$

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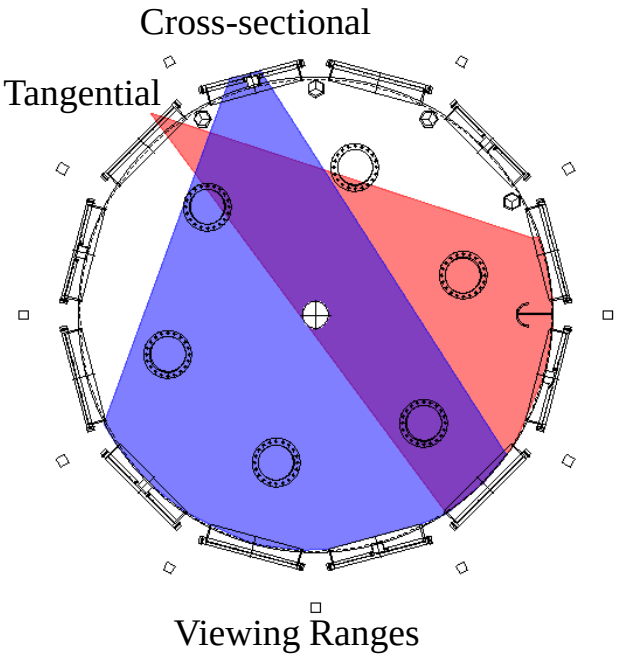
High-Speed Imaging Resolves Detailed Edge Structure



X4: 40271, 9 μs exposure
Cross-sectional view



Phantom v7.3: 41583, 5 μs exposure
Tangential View

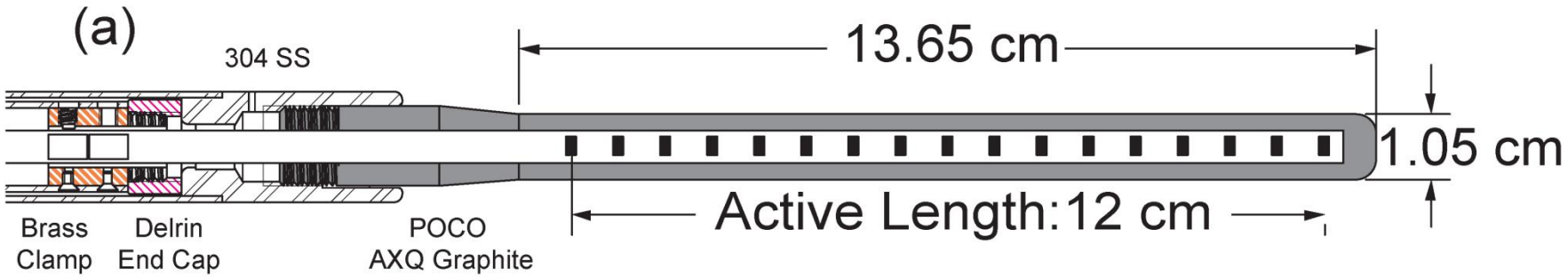


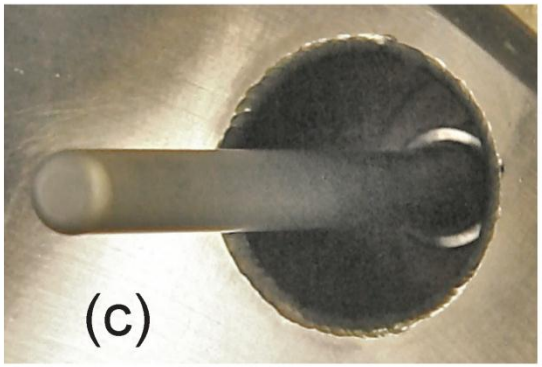
Viewing Ranges

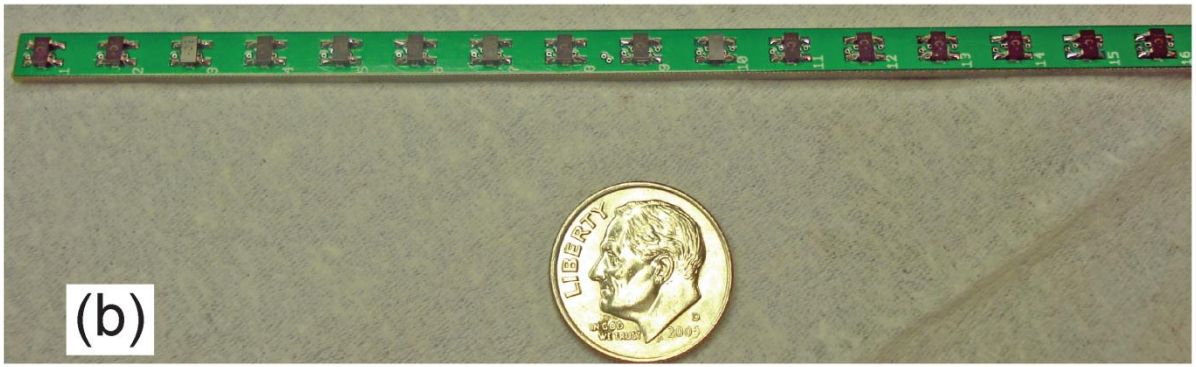
- IDT MotionPro X4
  - 8-bit, 5 kfps framing
  - 512x512 resolution
  - τ_{exp} ~ 5-10 μs
- VRI Phantom Series
  - v7.3: 14-bit, < 90–250 kfps framing
  - v12.0: 12-bit, < 1 MHz framing
  - Variable resolution/frame rates
  - τ_{exp} ~ 5-10 μs

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PEGASUS Hall Probe Deployed to Measure J





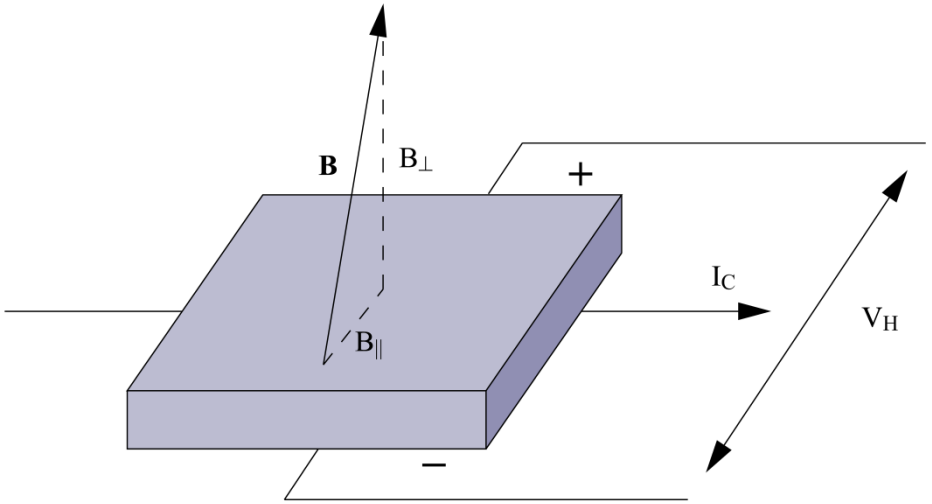


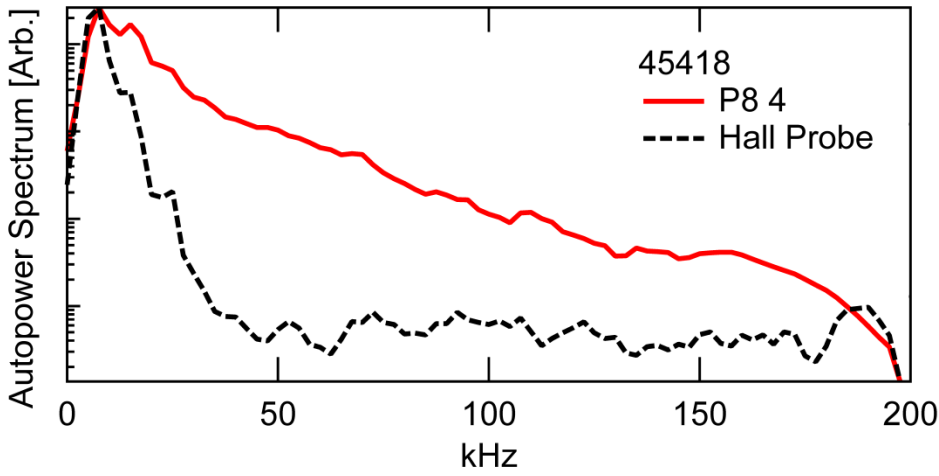
- Solid-state InSb Hall sensors
  - Sypris model SH-410
- Slim C armor as low-Z PFC
  - Minimizes plasma perturbation
- 16 channels, 7.5 mm radial resolution
- 25 kHz bandwidth

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

Solid-state Hall Sensors Sample **B** Directly

- Provides $V_H = G_H I_c B_\perp$
  - G_H combines all Hall physics effects; determined by calibration
  - Simple operation with constant control current I_c ~ mA
- High spatial, good temporal resolution
  - Sensor size: few mm
  - Bandwidth ~ 25 kHz
- Weak variance in G_H possible
  - Hall semiconductor, T_{sensor}, $B_\parallel$
  - Calibration corrects these effects

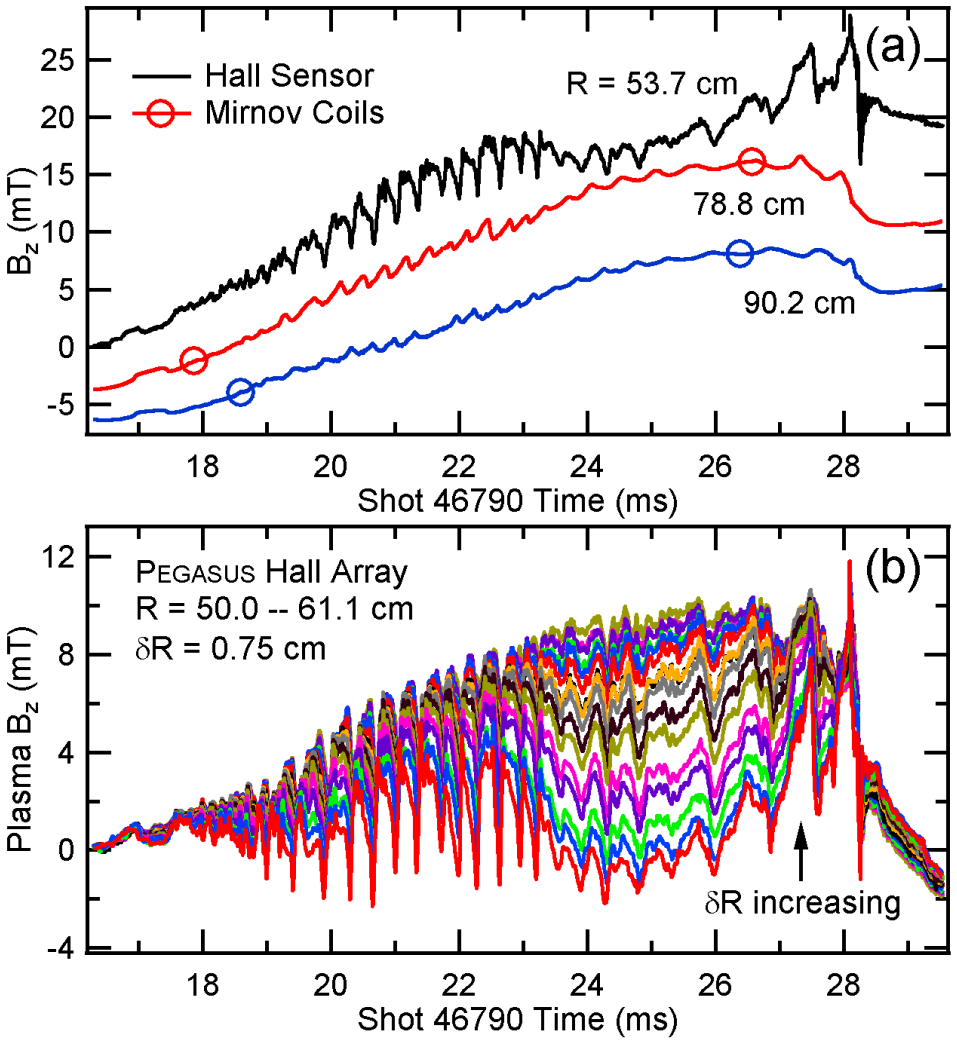




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Precision Internal B_z Measurements Attained

- Internal probing yields no measurable plasma perturbation, according to:
  - I_p evolution / sustaining V_{loop}
  - Achieved shape (ℓ_i evolution)
  - SPRED impurity spectroscopy
- Compares favorably with external Mirnov coils
  - $n = 1$ MHD well-resolved
- Full array yields spatially resolved $B_z(R,t)$



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:

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

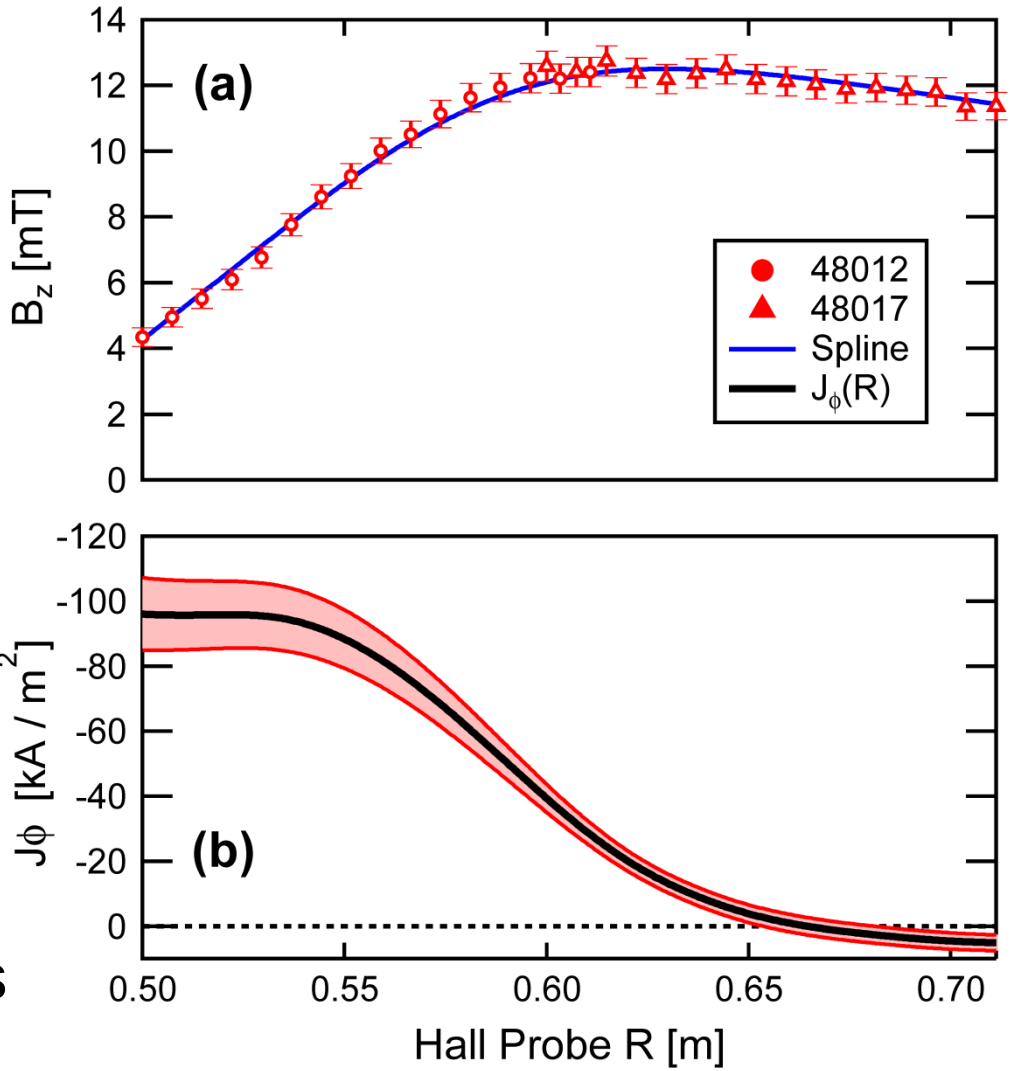
- Does not make assumptions on shape of J(R)

*: 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

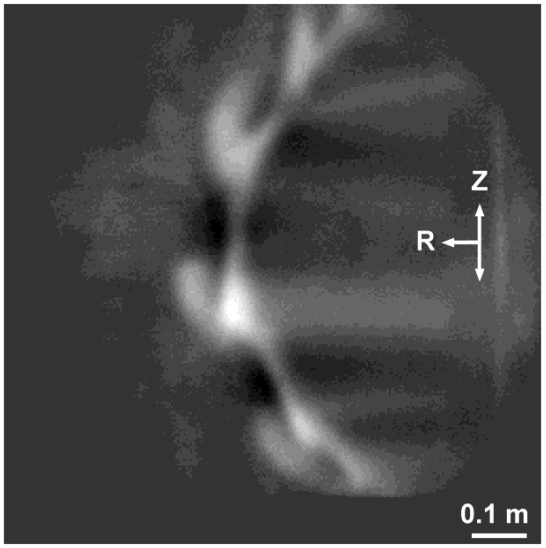


Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

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

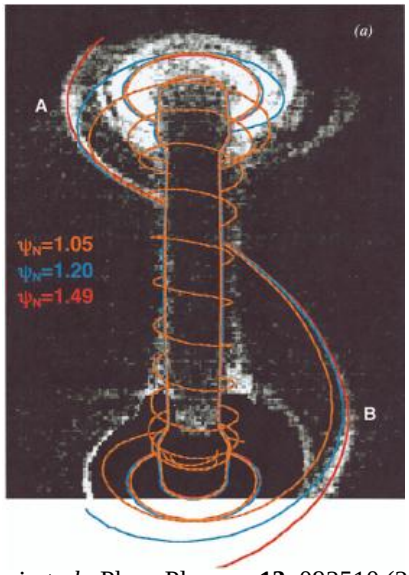
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Peeling Modes Create ELM-like Filaments



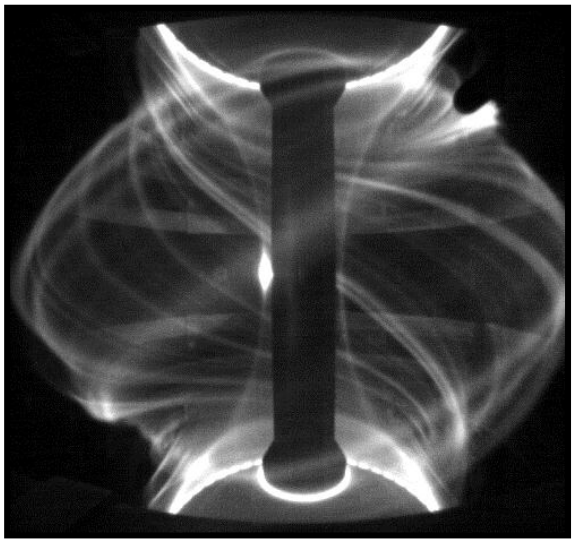
Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

PEGASUS



Maingi *et al.*, Phys. Plasmas **13**, 092510 (2006)

NSTX



Kirk *et al.*, Plasma Phys. Control. Fusion **49**, 1259 (2007)

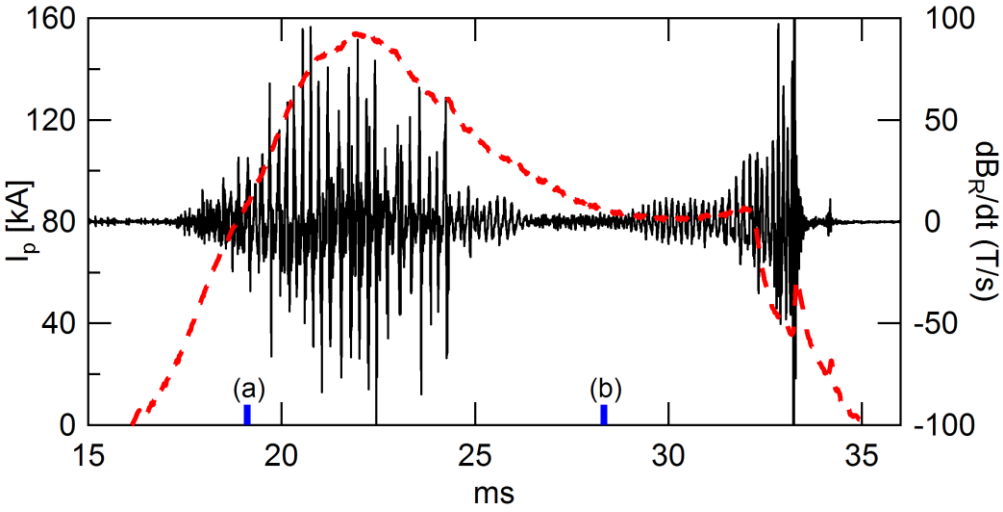
MAST

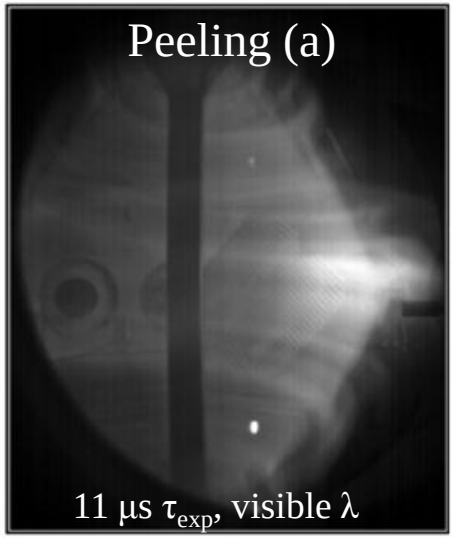
- Edge-localized, field-aligned, propagating filaments
  - Generated with strong J_{edge}/B
- Created by underlying low-n electromagnetic MHD

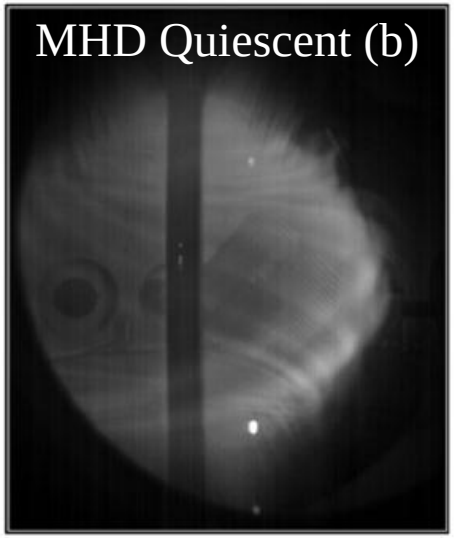
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Two Distinct Filament Classes Observable

- Peeling (a)
  - EM signature: high m, low n
  - Coherent spatial structure
  - Filament rotation
  - Detachment, outboard radial propagation, acceleration
- MHD Quiescent / L-mode (b)
  - No EM signature
  - Electrostatic turbulence: short-lived filaments observable when $\tau_{exp} \leq 20$ μs
  - No detachment, propagation

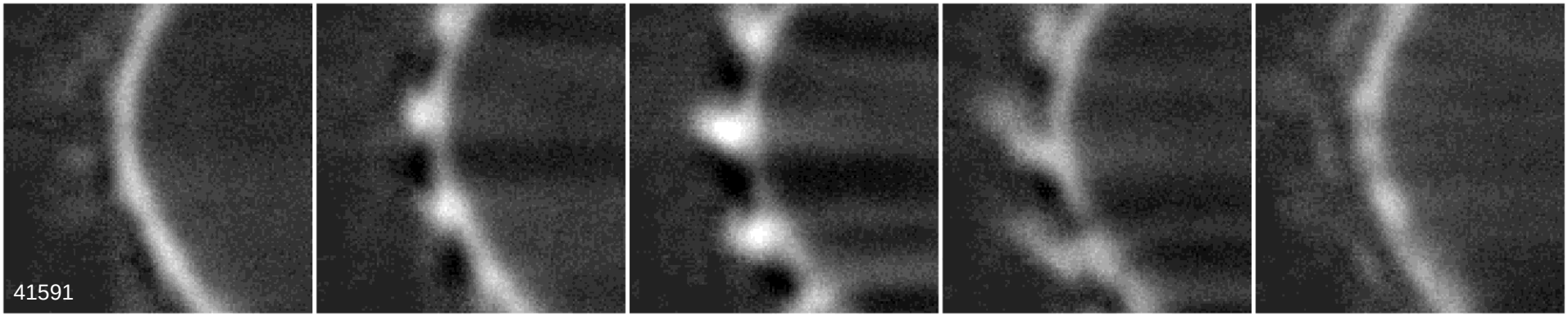






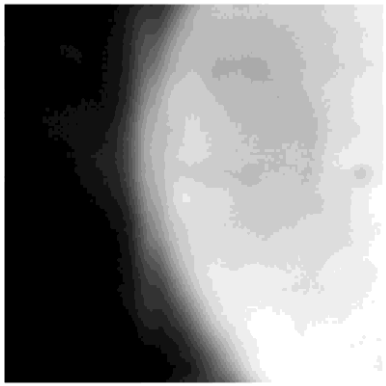
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Peeling Filaments Are Coherent Global Structures



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

- High poloidal coherence
  - Simultaneous growth, decay of high-m structures
- Short lifetime: ~ 55 μs
  - Resolvable with exposure times ≤ 30 μs
  - Larger exposures → conventional L-mode fuzzy edge
- Detachment, radial propagation

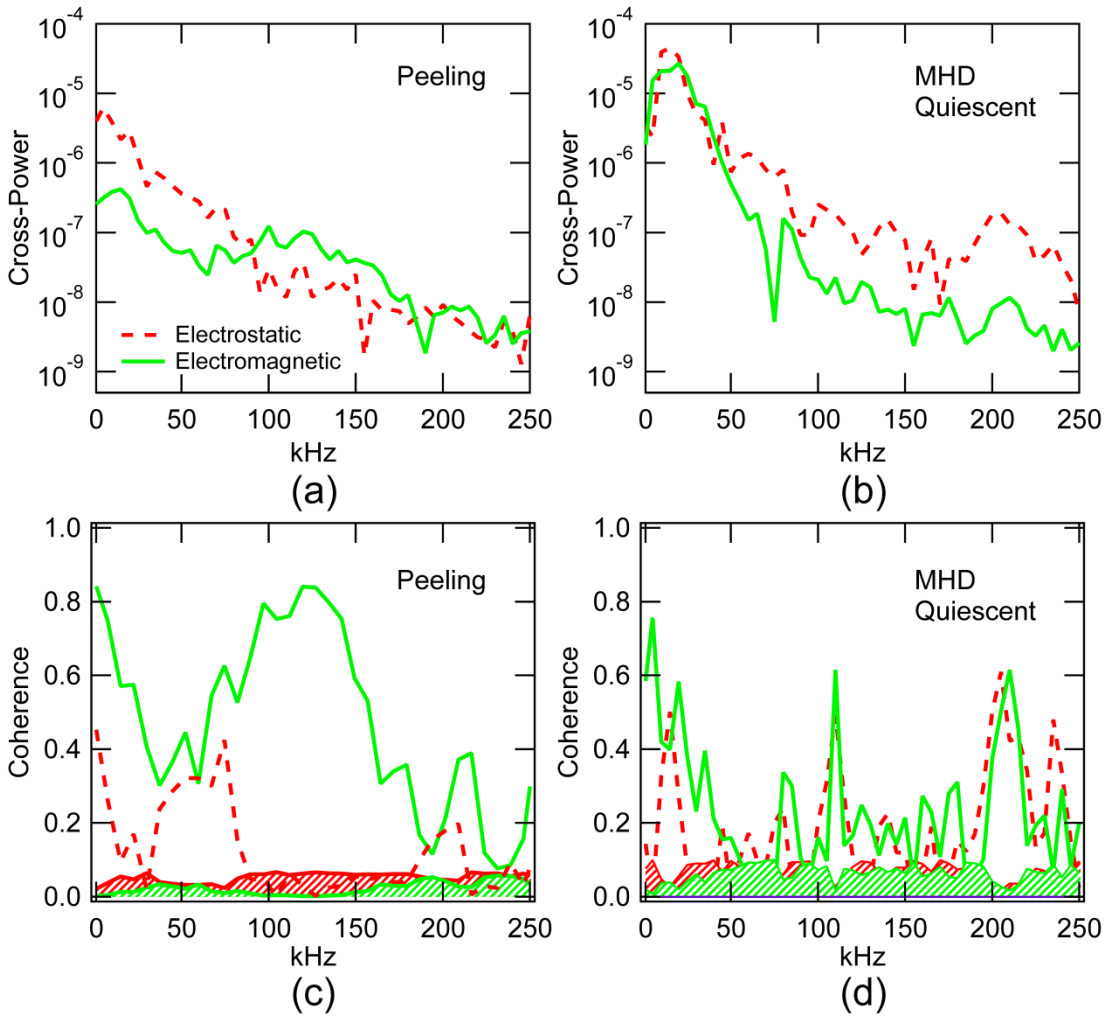


Average

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Peeling Filaments Have Electromagnetic Origin

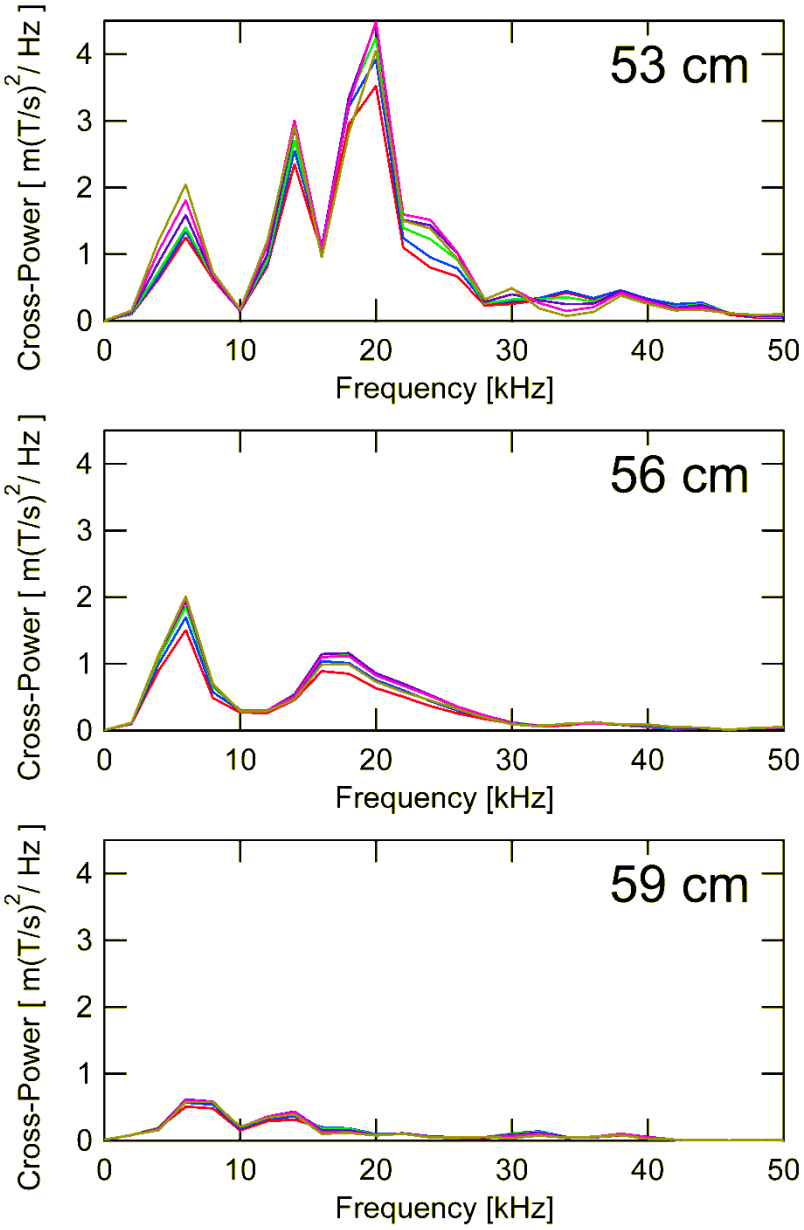
- Magnetic, Langmuir probes placed at plasma edge
- Peeling modes produce coherent electromagnetic activity
  - Uncorrelated with electrostatic LP fluctuations
- No EM signature in MHD quiescent phase
  - Consistent with electrostatic L-mode turbulence



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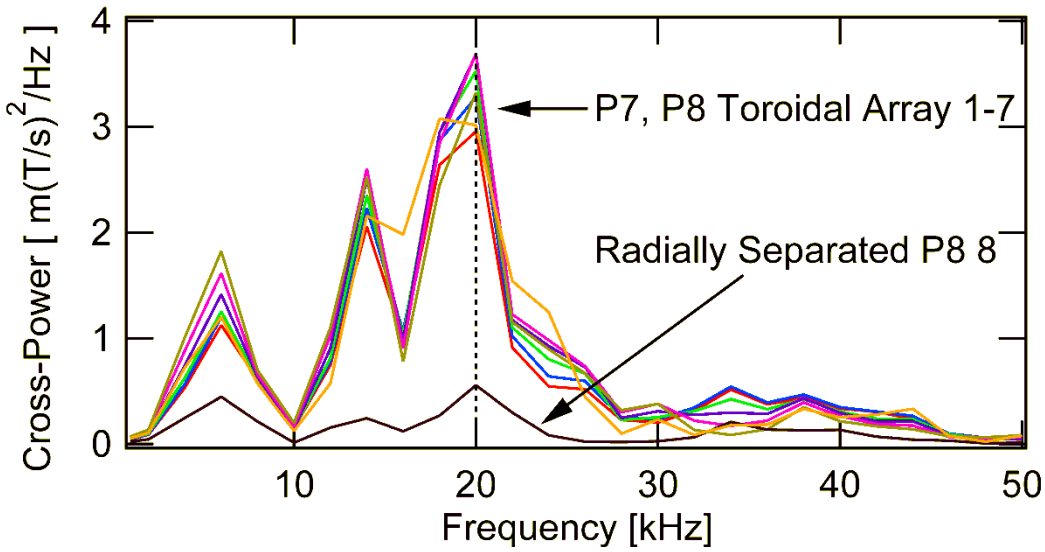
Peeling MHD Only Detectable Near Edge

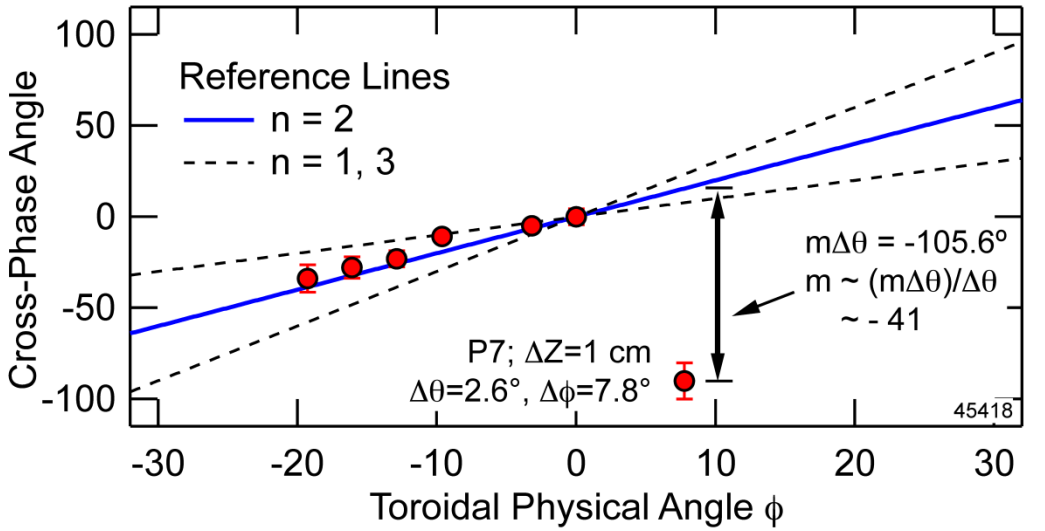
- Radial scan of magnetic probe array profiled spatial dependence of peeling MHD
- Dominant 20 kHz spectral peak vanishes rapidly from edge
- Signature undetectable on Mirnov coils near R ~ 90 cm
- Implies underlying activity has high poloidal mode number m



Spectral Analysis Finds Low-n, High-m MHD

- Dominant cross-power Fourier component used for mode identification
- Toroidal cross-phase analysis finds n = 2
- Lab-space poloidal mode estimation (cylindrical limit)
  - Poloidal cross-phase: $m_{lab} \approx 41$
  - P8 Radial decay rate: $m_{lab} \approx 42$
- Accurate m estimation requires straight field line coordinate transformation

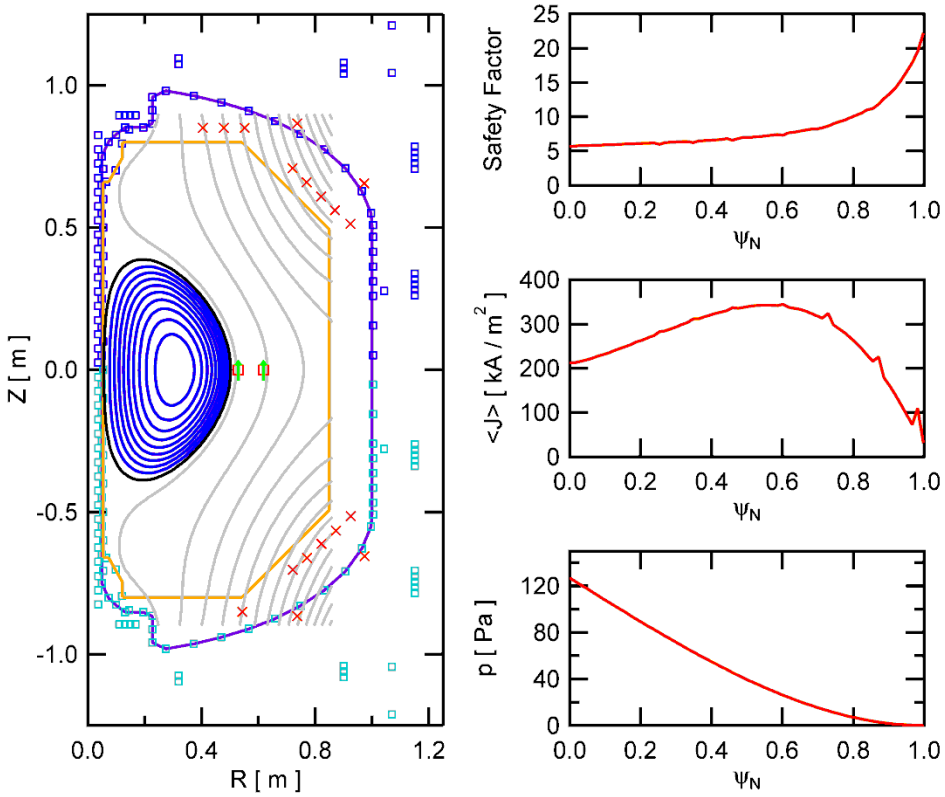




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Reconstructions Spatially Localize MHD to Edge

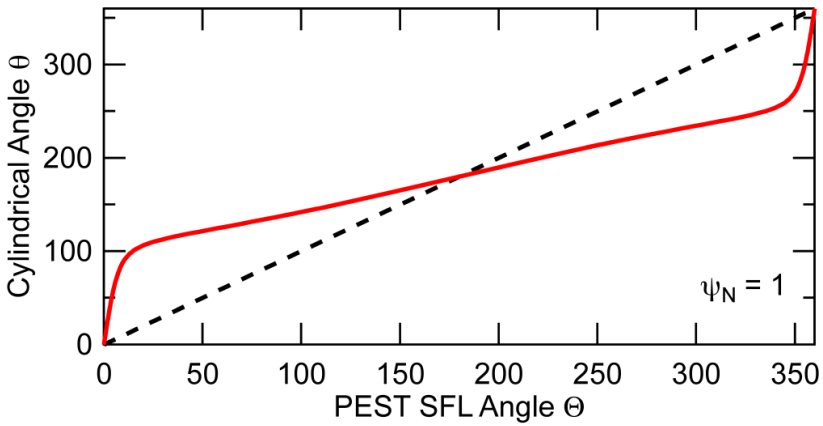
- Equilibrium reconstruction performed to localize peeling resonant q surface
  - $\sum I_{WALL}/I_p = 1.9$
- Cylindrical mode analysis found dominant m_{lab} / n = 20.5
- This q surface clearly lies in the edge region
  - $q = 20.5$ at $\psi_N = 0.98$

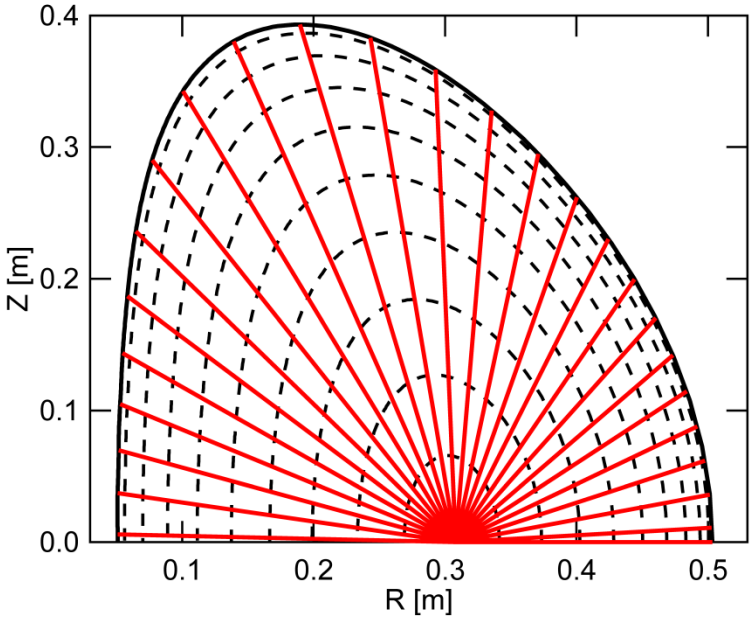


Equilibrium Parameters
Shot 45418, 19.50 ms

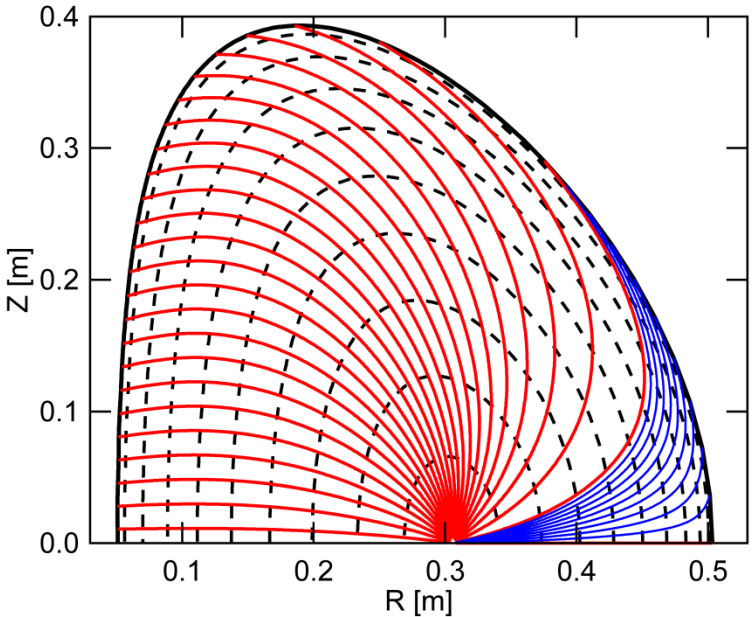
I_p	88.3 kA	R_0	0.280 m
β_t	0.0030	a	0.222 m
ℓ_i	0.40	A	1.27
β_p	0.047	κ	1.7
W	223 J	δ	0.38
B_{T0}	0.221 T	q_{95}	16.5

Straight Field Line Transform Further Localizes MHD





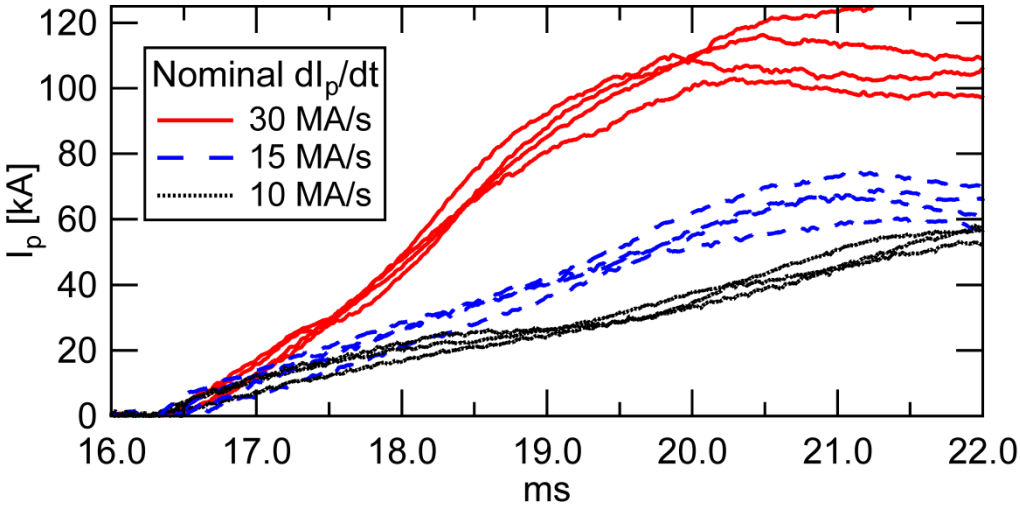
- PEST SFL coordinates* can convert m_{lab} to the plasma frame
  - $m = f(q)m_{lab}$; $f(q)$ ~ 3–7 here
  - θ overestimates Θ at outboard midplane, implying $m_{lab} \leq m$
- Application places true resonance at or exterior to edge
  - Consistent with peeling mode external kink structure

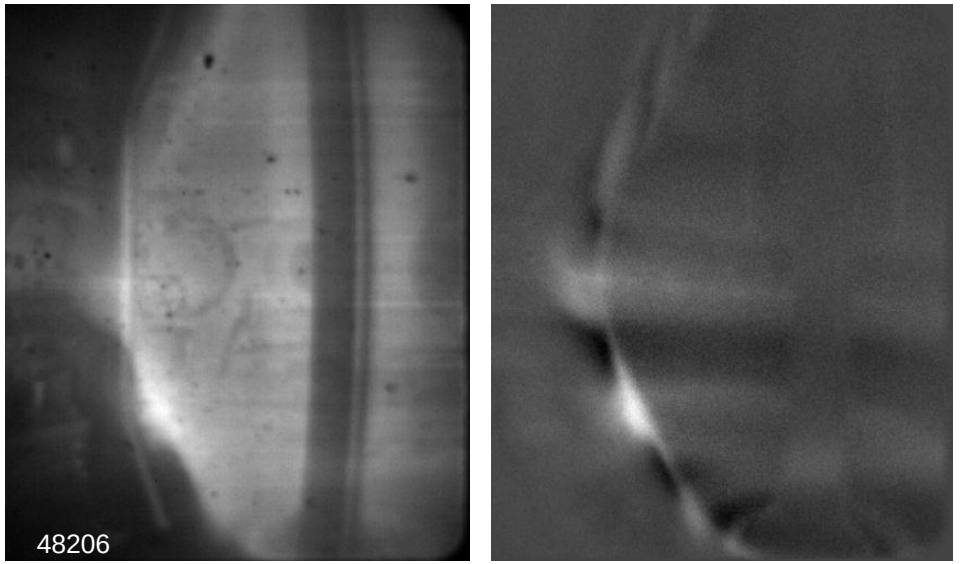


*: D'haeseleer, *et al.*, Flux Coordinates and Magnetic Field Structure, 1991

Experiment Tests MHD Dependence on J/B Drive

- Peeling drive varied systematically in I_p ramp
  - Shape well-matched
- Experimental proxies:
  - $dI_p/dt \sim J_{edge}$; $I_{TF} \sim B$
  - 11 combinations dI_p/dt, I_{TF}
- Uniform edge diagnosis
  - Hall, edge magnetic probes
  - 27 kHz fast imaging
- Equilibrium reconstructions
  - Spatial localization of MHD



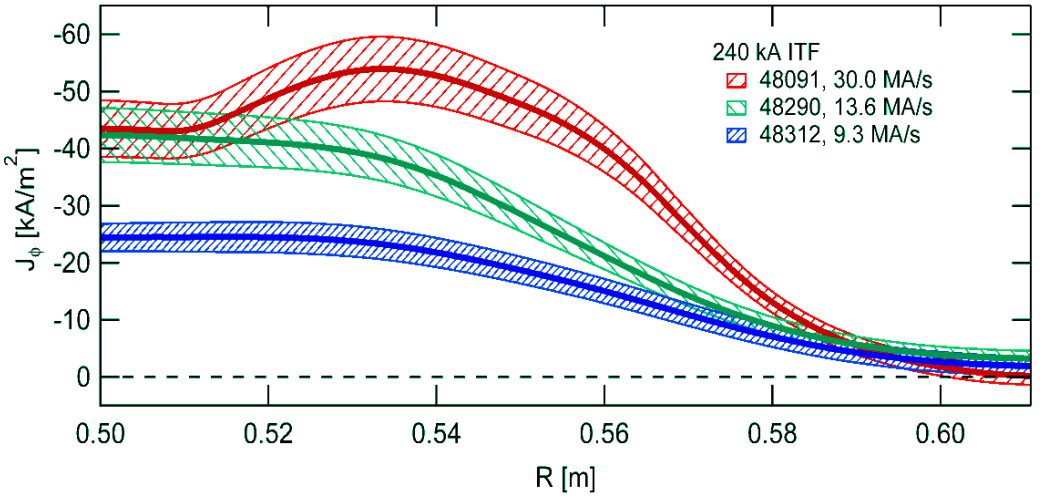


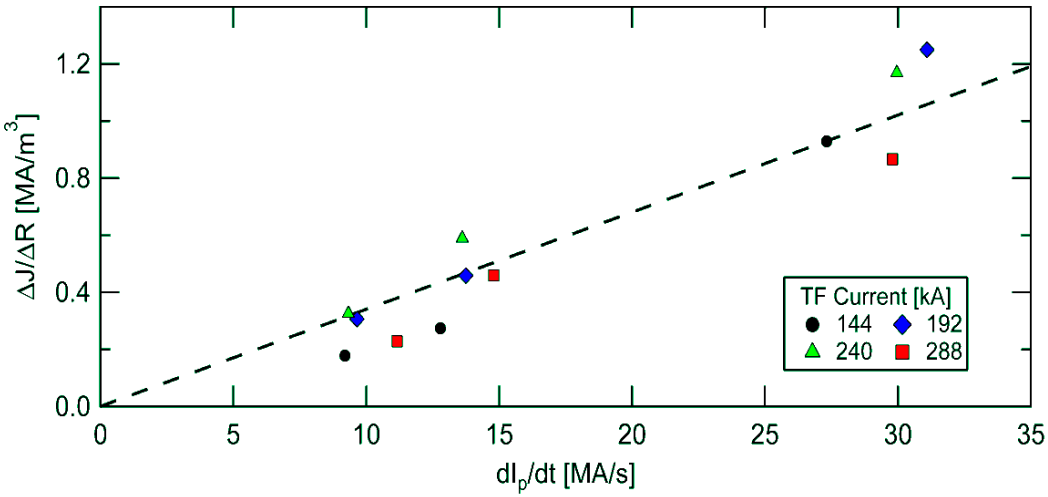
Phantom Imaging:
Original; 270 μs average subtracted

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Edge Current Profile Manipulated with dI_p/dt

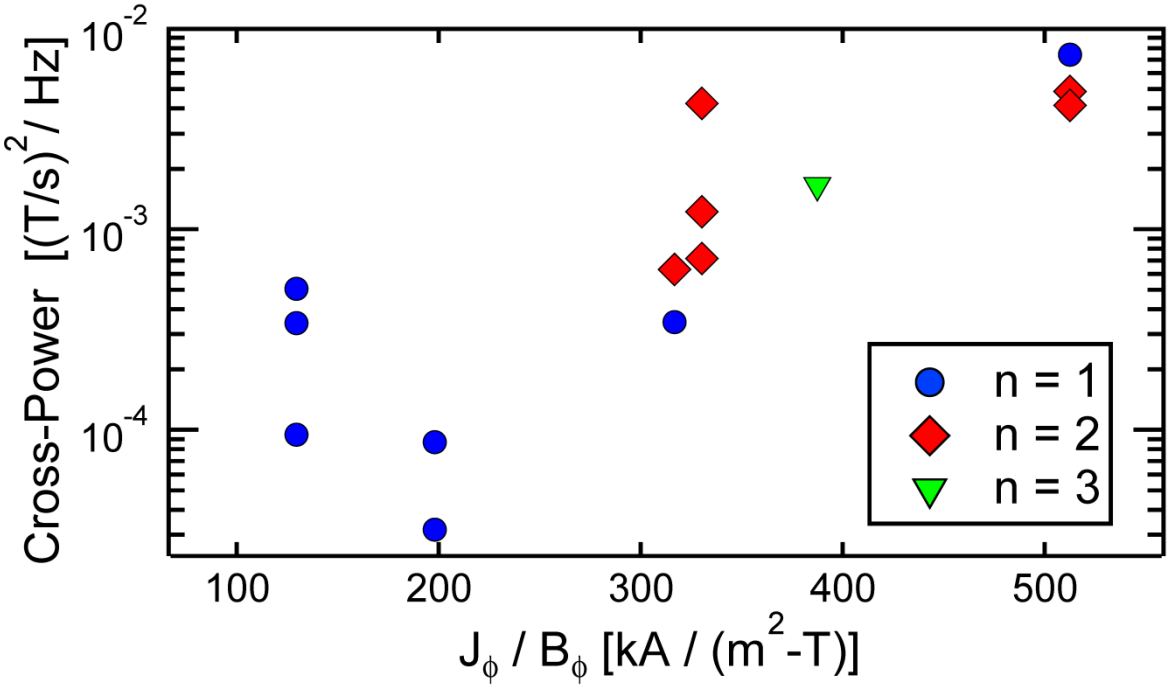
- Direct Hall analysis used to obtain $J_\phi(R)$ in scan discharges
- $J_{||}/B$ estimated from experiment by $\Delta J_\phi/B_\phi$
  - Linear trend in edge current gradient $\Delta J_\phi / B_\phi$
  - Increasing ΔJ_ϕ
  - Reduced gradient scale length
- Trends independent of B_ϕ





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Peeling MHD Strongly Scales with Theoretical Drive



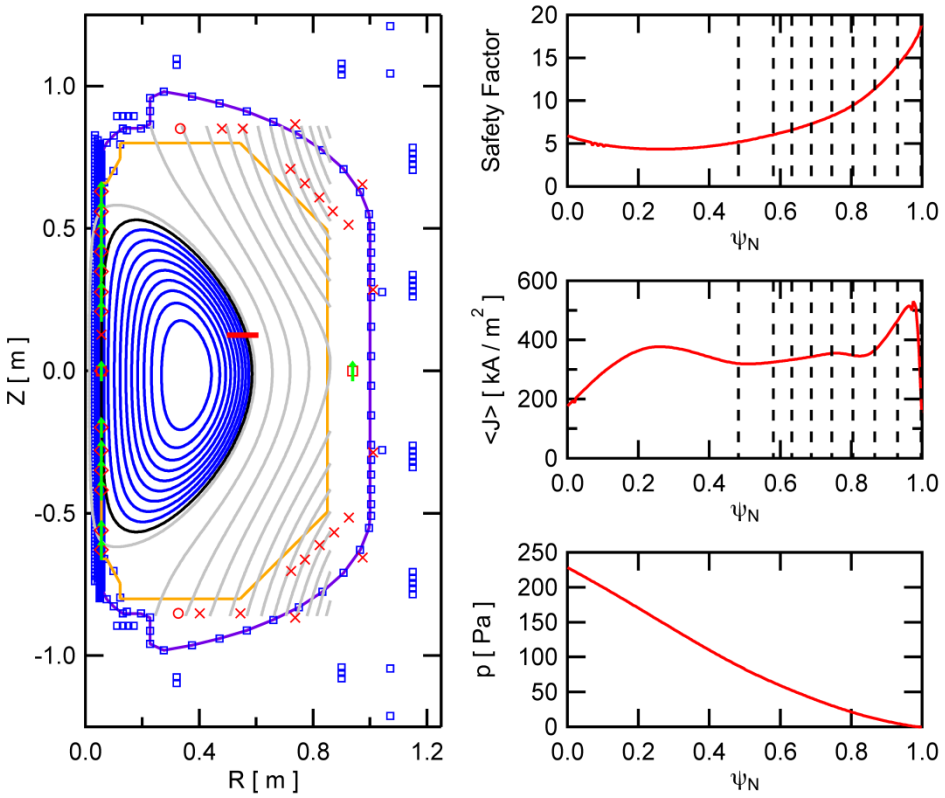
- Mode helicities estimated from port 8 Mirnov array
  - $n < 3$ via cross-phase analysis
  - $m_{lab} \geq 10$ via radial decay rate
  - $10 \leq m_{lab} / n \leq 30$ ($\psi_N > 0.9$)
- MHD power spans two orders of magnitude with factor-of-five variation in J/B

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

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Hall-Constrained Equilibrium Obtained During Peeling Activity

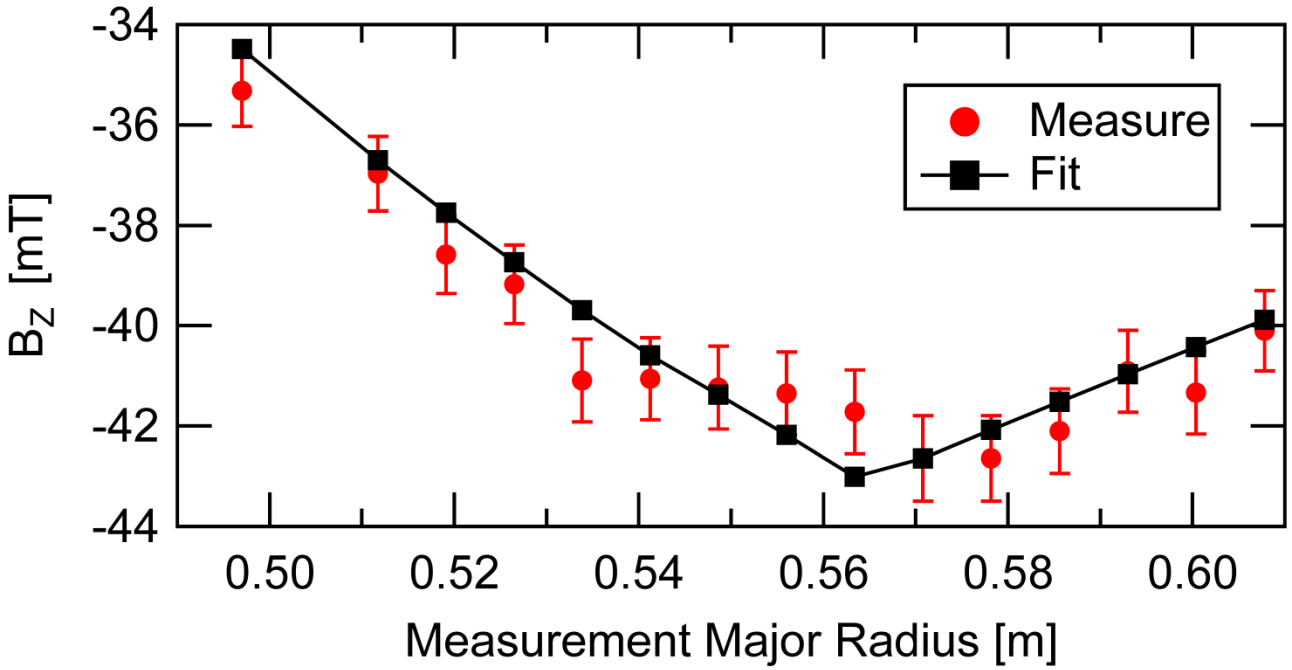
- High-performance discharge with peeling activity
- $\langle J_\phi \rangle(\psi)$ determined by reconstruction with Hall data
  - $\psi_N > 0.5$ constrained
  - $\langle J_\phi \rangle \sim 500$ kA/m^2 in edge
- New KFIT tools applied
  - Akima spline parametrization
  - Fine-spaced 256x256 grid
  - $\delta R = 3.3$ mm, $\delta Z = 6.72$ mm
  - $\sum I_{WALL}/I_p = 1.1$



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

Reconstructed $B_Z(R)$ Reasonably Matches Hall Data

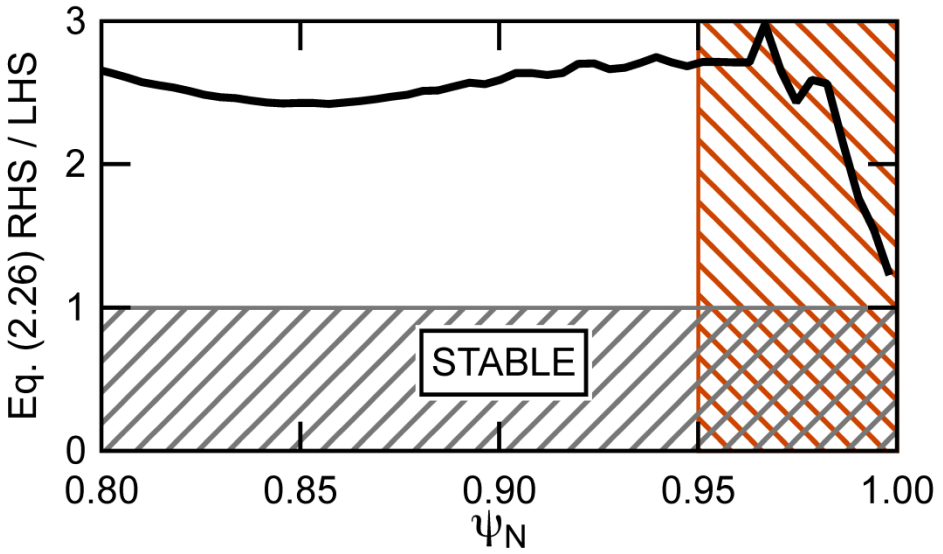


- Good agreement internal, external to plasma boundary
- Disagreement in vicinity near R = 0.565 m equates to region $0.95 < \psi_N \leq 1$

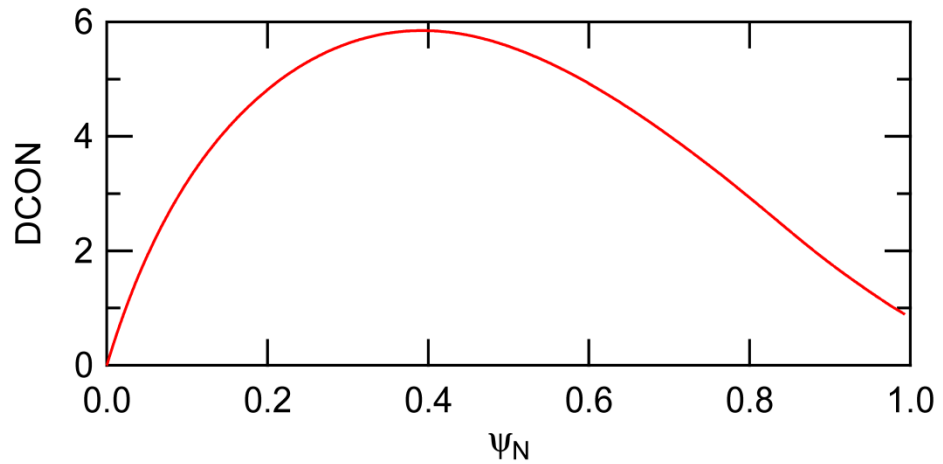
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Stability Analysis Confirms Peeling Instability

- Analytic peeling criterion computed from Hall-constrained equilibrium indicates instability
  - More than factor of two in region of optimal $\langle J_\phi \rangle$ constraint
- Free-boundary ideal stability analysis performed with DCON
  - Indicates instability to m/n = 19/1 external kink
- Both methods agree with experiment



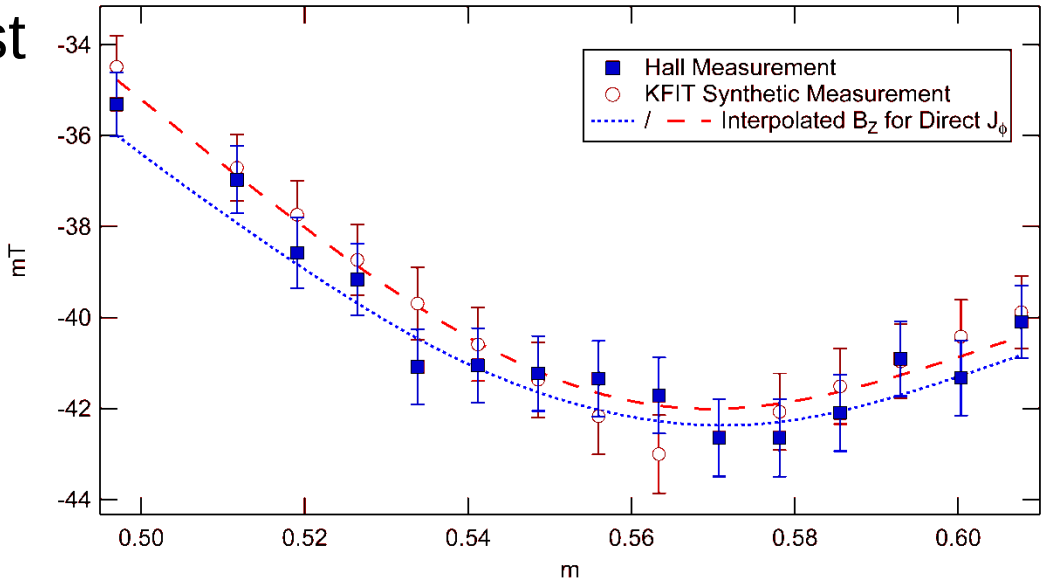
Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

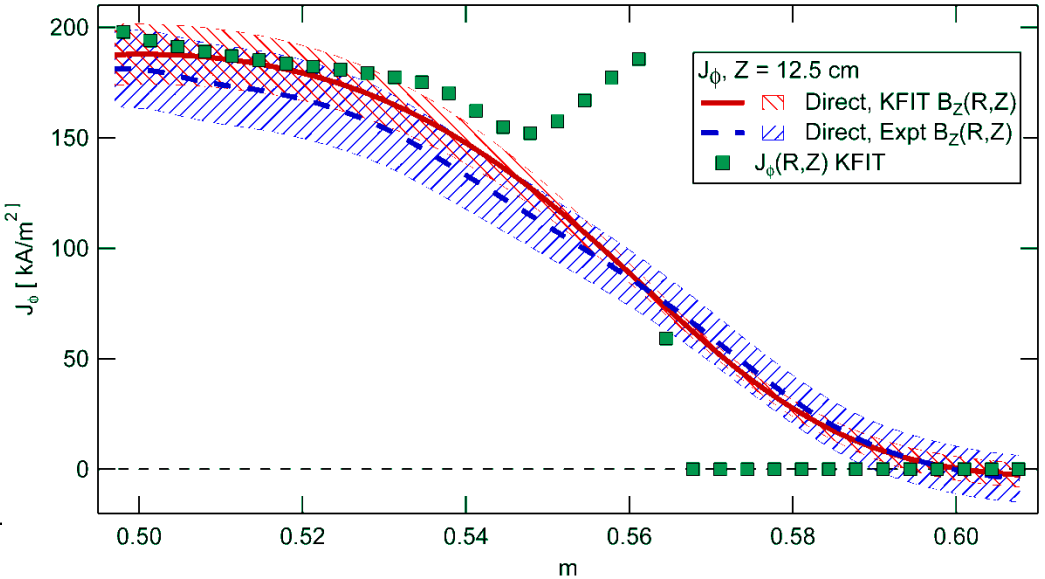


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Synthetic Diagnostic Tests Direct J_ϕ Method

- Hall equilibrium used to test direct, reconstructed J(R)
  - Direct method applied to synthetic $B_Z(R)$ fit by KFIT
- Direct, synthetic J(R) profiles agree within error
  - Reconstructed J(R) disagrees with direct in vicinity of LCFS
- Slight open field line currents indicated
  - ~ 100 A; < 0.1% of I_p
  - KFIT profile parametrizations cannot place J outside LCFS

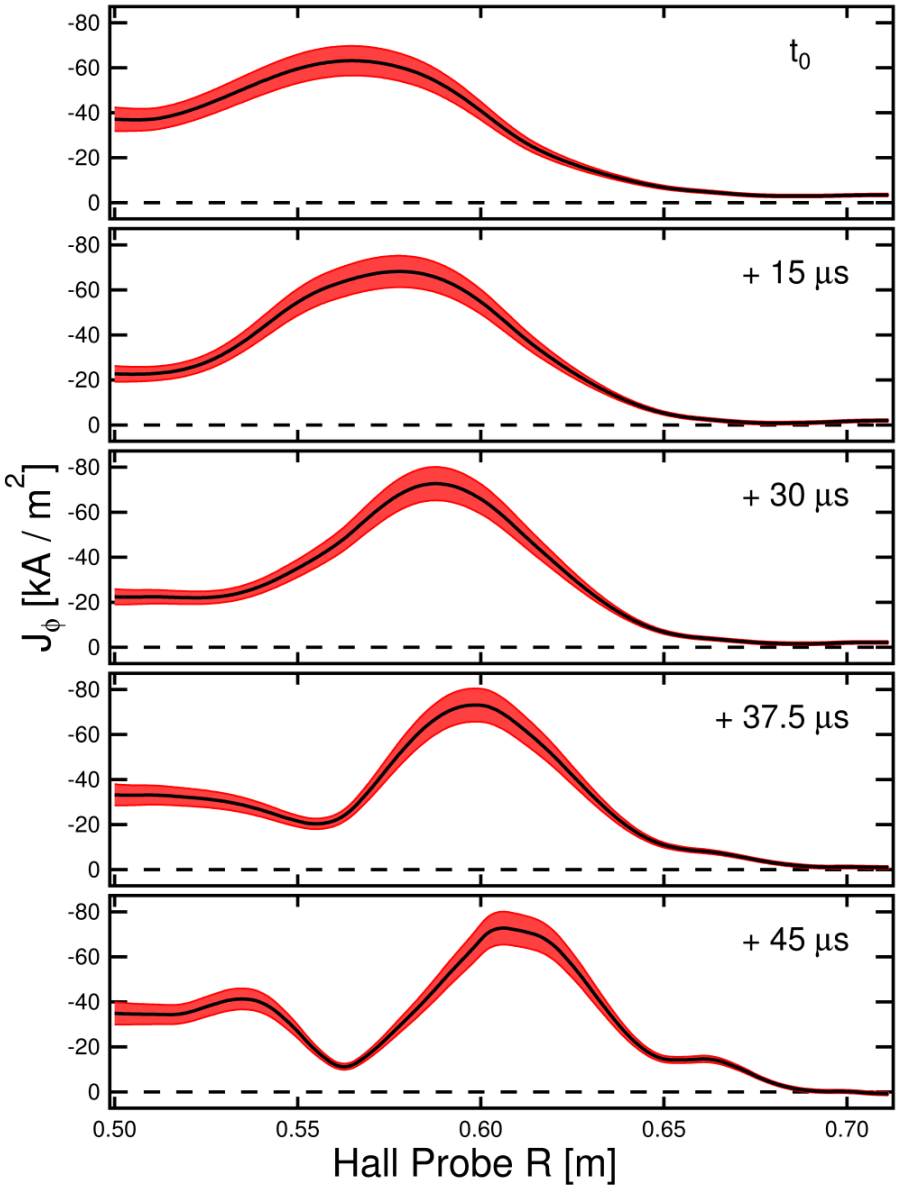




M.W. Bongard,53rd APS-DPP, Salt Lake City UT, Nov. 201.

J_{edge} Dynamics Measured on ELM Timescales

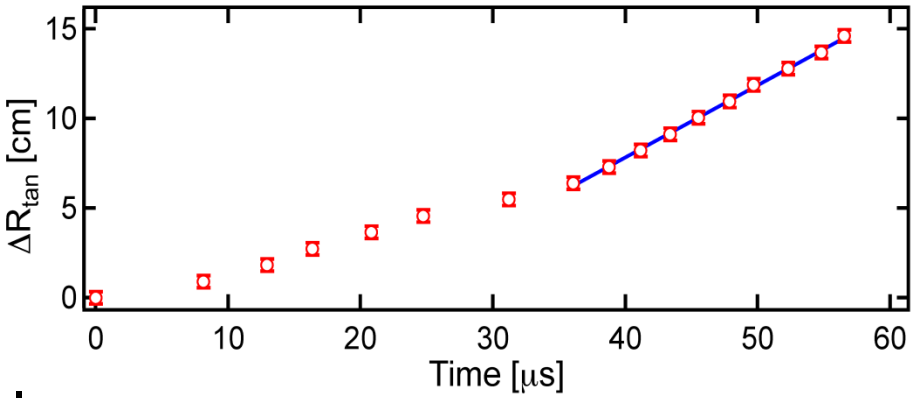
- J_{edge} resolved during peeling filament generation
- Propagating filament forms from initial "current-hole" J_{edge} perturbation
  - Validates formation mechanism hypothesized by EM blob transport theory
- Filament carries toroidal current I_f ~ 100–220 A
  - Comparable to MAST ELM estimates
  - $I_f < 0.2$ % of I_p



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

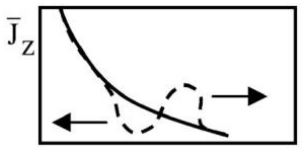
Filament Radial Motion Qualitatively Consistent with Electromagnetic Blob Transport

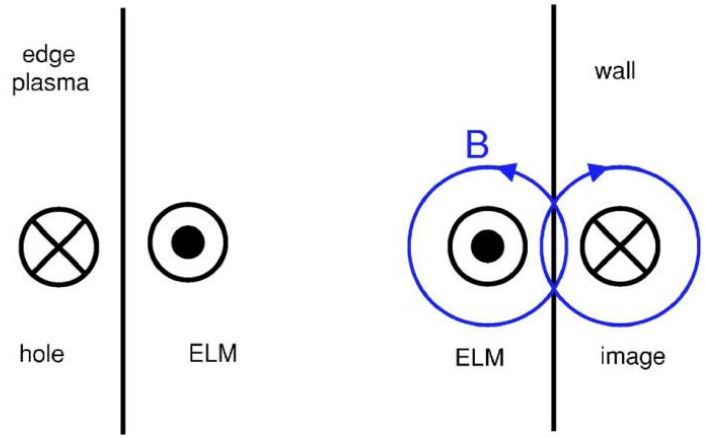
- Trajectory of detached filament tracked with 275 kHz imaging
  - Radially accelerates, followed by constant velocity motion



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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Conclusions

- Direct measurements of J_{edge} conducted with Hall probe
  - Direct analysis, equilibrium reconstruction
  - J_{edge} controllable with dI_p/dt
- Characteristics of peeling modes consistent with theory
  - Macroscopic features: Low-n, high-m external kink
  - Onset consistent with ideal MHD, analytic peeling stability theories
  - Observed MHD scales with measured J/B peeling drive
  - Coherent, propagating filaments
- J_{edge} dynamics supports current-hole & EM blob hypotheses
  - Nonlinear filaments generated from current-hole J_{edge} perturbation
  - Transient magnetostatic repulsion
  - Constant-V_R propagation in agreement with available EM blob theory

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