Equilibrium and Stability Properties of Pegasus Edge Plasmas

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PEGASUS Toroidal Experiment

Abstract

ELM-like filamentary edge instabilities are observed under conditions of high $j_{||}/B$ ($\geq$ 1 MA/m^2T) in Pegasus. Their properties include: a high-*m*, low-*n* (1-5) electromagnetic signature, consistent with $m/n \approx q_a$; characteristic frequencies < 100 kHz; high poloidal coherence; rotation; and, explosive filament detachment followed by accelerating outboard radial propagation. Presently, these modes' dependence on the peeling instability parameter $j_{||}/B$ is being systematically studied through variation of dI_p/dt and I_{TF}. To date, all data indicate these instabilities lie in the peeling regime. The modest edge T_e and short pulse lengths of Pegasus afford direct diagnostic access to the edge via internal magnetic and Langmuir probe measurements. A novel edge probe utilizing a radial array of Hall-effect sensors* measures $B_z(R, t)$ with high spatial and ~ 50 μs temporal resolution, and provides strong experimental constraint on equilibrium reconstructions on ELM-relevant timescales. Initial magnetic equilibrium reconstructions and ideal stability analysis with DCON imply instability when edge filamentation occurs.

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

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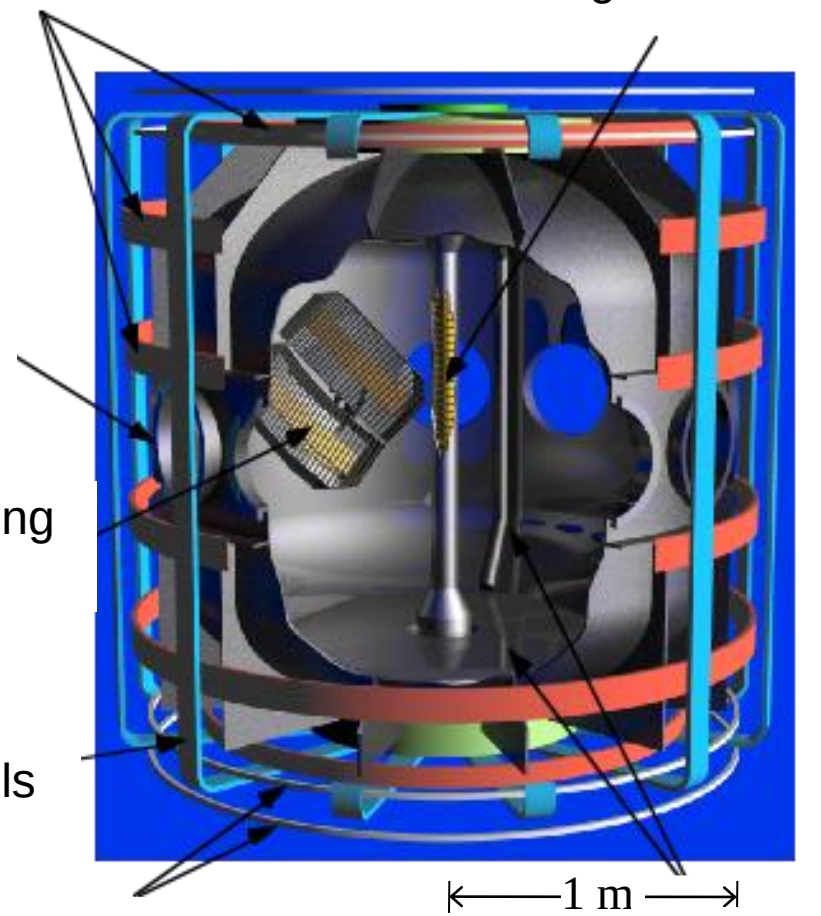
Overview and Motivation

- Edge stability critical to next-step devices
  - Edge localized mode (ELM) heat loads will damage plasma facing components
  - Validation of ELM physics necessary to devise effective mitigation techniques

- PEGASUS: ELM-like instabilities consistent with peeling modes
  - Edge localized, filamentary, field-aligned perturbations
  - High poloidal coherence
  - Intermediate n, high-m electromagnetic signature
  - Filament detachment, accelerating outboard radial propagation

- Systematic study conducted with respect to edge peeling drive
  - New edge current profile diagnostics measure J_{edge} dynamics

PEGASUS: A Mid-Size, Ultralow-A ST



Experimental Parameters

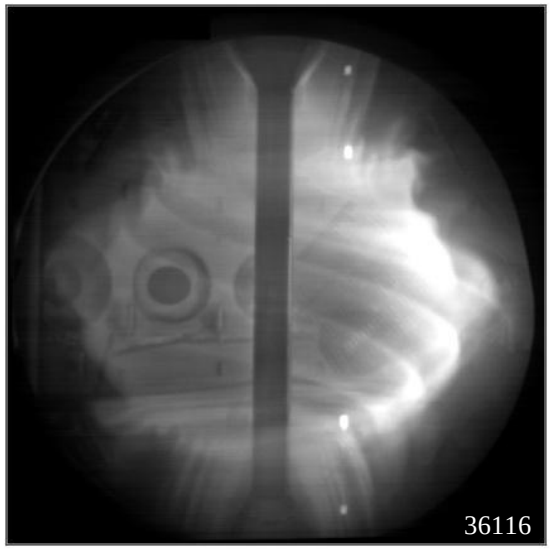
Parameter	To Date
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .22
I_N (MA/m-T)	6 – 12
ℓ_i	0.2 – 0.5
κ	1.4 – 3.7
τ_{shot} (s)	≤ 0.025
β_t (%)	≤ 25
P_{HHFW} (MW)	0.2



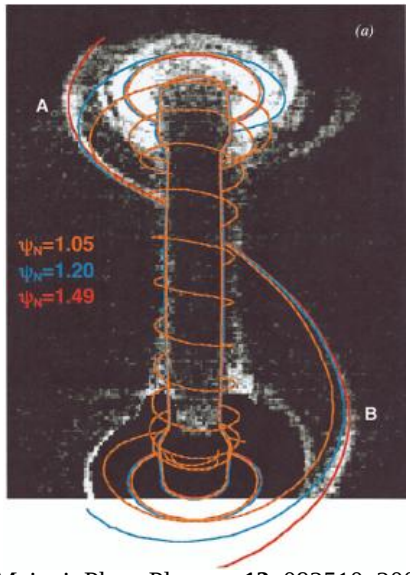
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ELM-like Structures Observed in PEGASUS

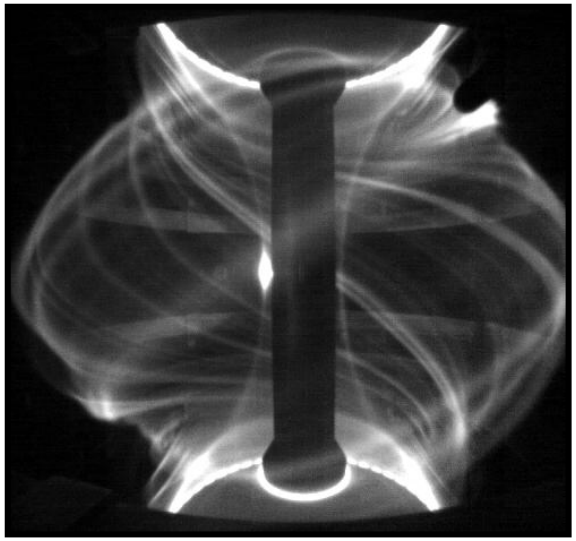


PEGASUS



Maingi, Phys. Plasmas **13**, 092510 ,2006

NSTX



Kirk, Plas. Phys. Controlled Fus. **49**, 2007

MAST

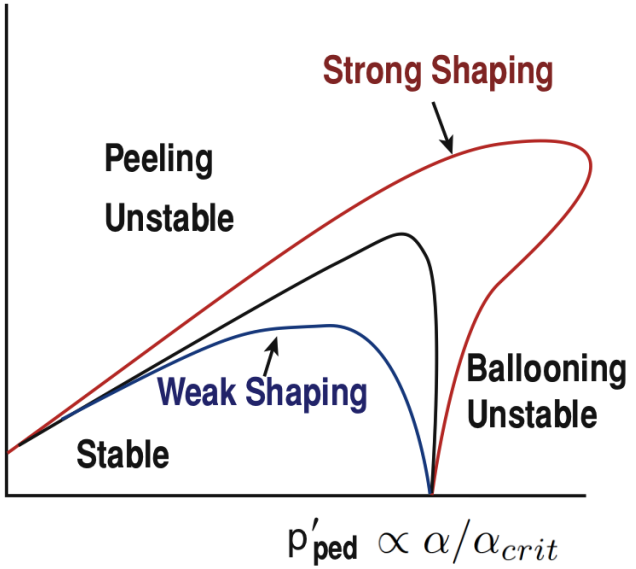
- ELM bursts take form of field-aligned filaments
  - Transient degradation of H-mode pedestal
  - Peeling-ballooning theory: trigger mechanism
- PEGASUS: L-mode edge assumed
  - Peeling instability candidate mechanism

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Candidate Instability: The Peeling Mode

- Peeling-ballooning theory is a proposed mechanism for ELMs
  - Localized MHD edge instability
- Ballooning
  - p' drive from H-mode pedestal
- Peeling
  - Edge current, current gradient drive

$$\propto \frac{qRj_{\|}}{B} \quad J_{ped}$$



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

- Qualitative guide: analytic peeling stability criterion*

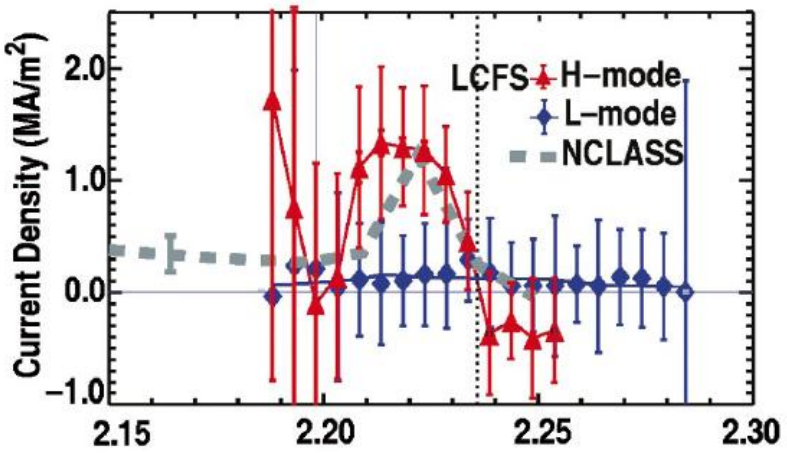
$$\sqrt{1-4D_M} > 1 + \frac{2}{2\pi q'} \oint \frac{\mu_0 j_{\|} B}{R^2 B_p^3} dl \sim \frac{Rq}{s} \left(\frac{\mu_0 \bar{j}_{\|}}{B} \right)$$

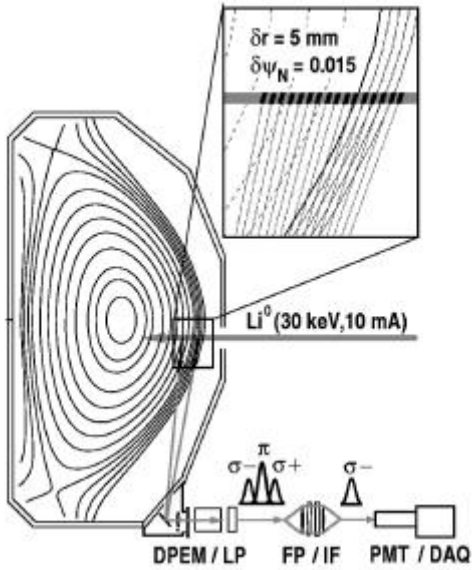
*Review: Connor *et. al.*, Phys. Plasmas **5**, 2687,1998

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Improved J_{edge} Measurements Desirable

- p(ψ) typically constrained via multichannel Thomson Scattering
  - PEGASUS system under design; see Schlossberg, CP9.00071
- Edge J(ψ) equally important to validate theory*; rarely measured
  - Extremely challenging measurement on high-temperature ATs
  - Results to date: DIII-D Li beam polarimetry**
- Typical alternative: compute J
  - Calculates J_{BS} given experimental p(Ψ)
  - Questionable assumptions in edge





*: Maggi, Nucl. Fusion **50**, 066001, 2010
: Thomas, Phys. Plasmas **12, 056123, 2005

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Near-unity A Enhances Peeling Drive

Device	J_{edge} (MA/m^2)	$B_{\varphi,0}$ (T)	J_{edge}/B	R_0 (m)	q_{95}
PEGASUS	~ 0.1 – 0.2	0.1	**~ 1**	**~ 0.45**	**< 25**
DIII-D	1 – 2*	2	**0.5 – 1**	**~ 1.50**	**< 5**

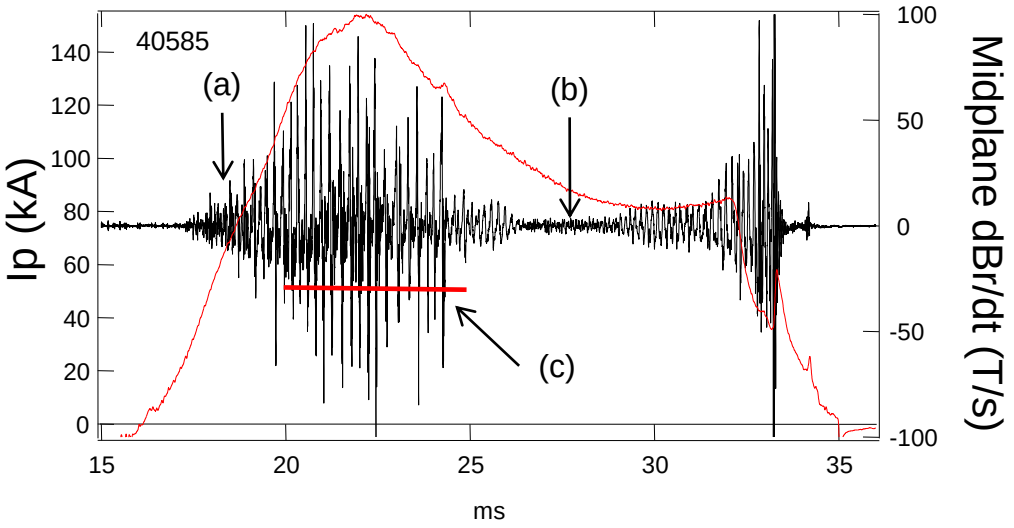
*: Thomas, Phys. Plasmas **12**, 056123 2005

- PEGASUS operations at A → 1 lead to naturally high J_{edge}/B
- However, *source* of J_{edge} differs
  - Large machines: H-mode p' → J_{BS}
  - PEGASUS: Large dI_p/dt ($\leq$ 50 MA/s) → transient skin current
- Additional geometric effects: modest drive from Rq_a possible
  - Increased edge shear competes with this effect

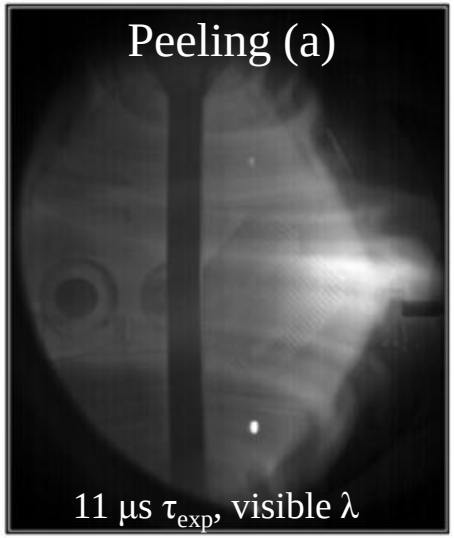
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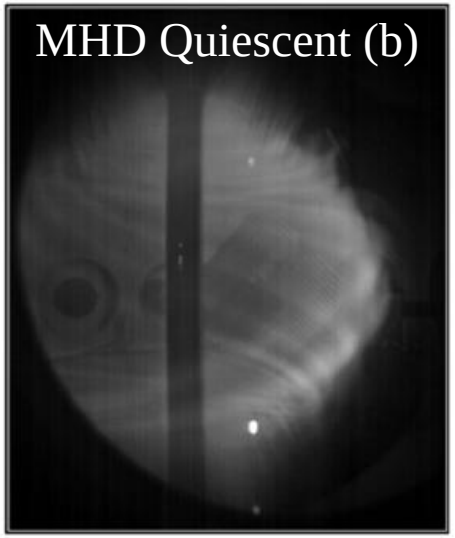
Two Distinct Filament Classes Observed

- 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 $\tau_{exp} \leq 20\ \mu s$





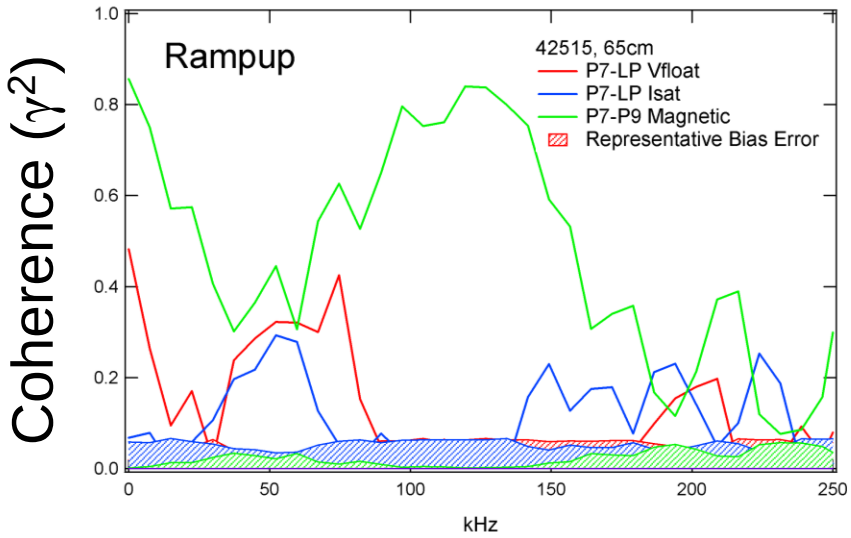
- Separated by n=1 internal tearing phase (c)

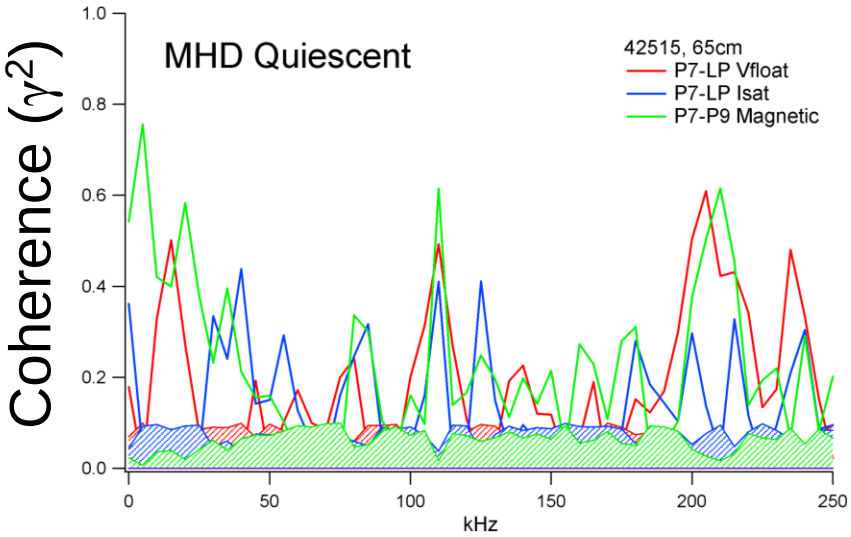
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Peeling Filaments are Electromagnetic

- Magnetic, Langmuir probes placed at edge of plasma
- Coherent electromagnetic signature present in I_p ramp
  - Anticorrelated with electrostatic LP fluctuation measurements
- No EM signature in MHD quiescent phase
  - Consistent with interpretation of electrostatic L-mode turbulence

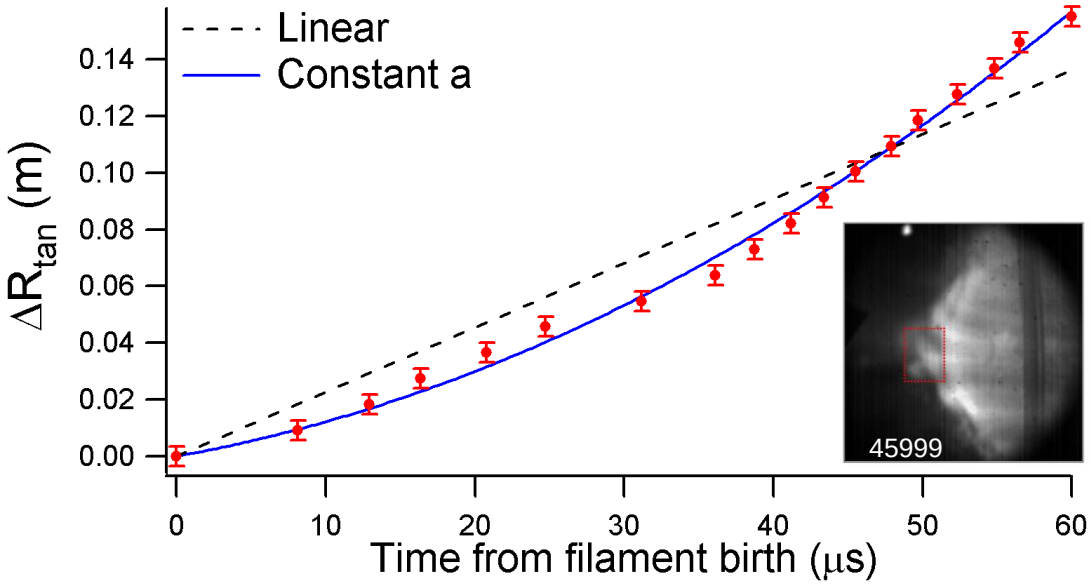


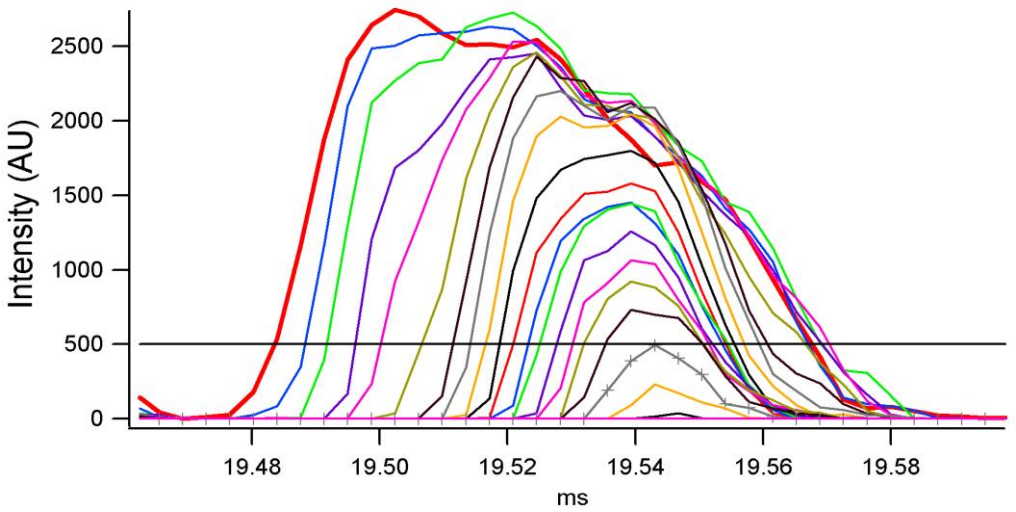


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Peeling Filaments Accelerate Radially

- Filaments detach from edge, propagate radially outboard
- Significant a_r measured
  - $a_r = 2.8 \times 10^7$ m/s^2
  - v_r: 1 → 4 km/s over 60 μs
- MAST*: Type-I ELM filaments accelerate radially



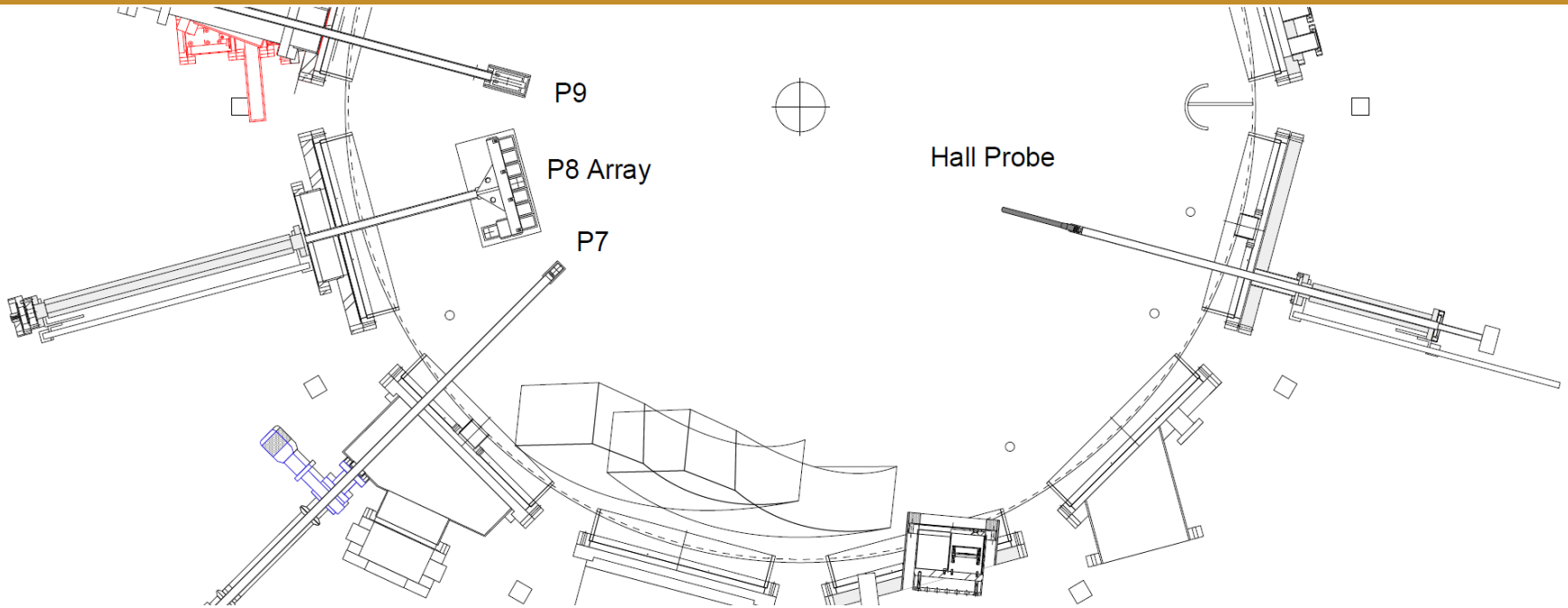


Time evolution of uniformly spaced R_{tan} viewing chords; 270 kHz fast imaging

*Kirk, Plas. Phys. Controlled Fus. **49**, 2007

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Probe-based Diagnostics Characterize Edge



- PEGASUS edge, SOL compatible with probes
  - Low T_e, short τ_{pulse}
  - Locations variable on shot-to-shot basis
- External Probes
  - Single-point Mirnov
    - dB_r/dt, dB_z/dt
  - Toroidal B_z array
    - Int. to high-n
- Internal Probes
  - Hall Probe
    - $B_z(R, t) \rightarrow J(R, t)$
  - Langmuir Probes
    - n_e, $T_e \rightarrow p_e$

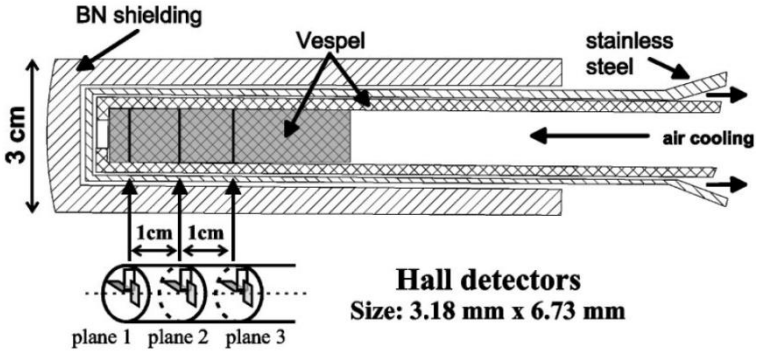
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J Determined by **B**(R, t)

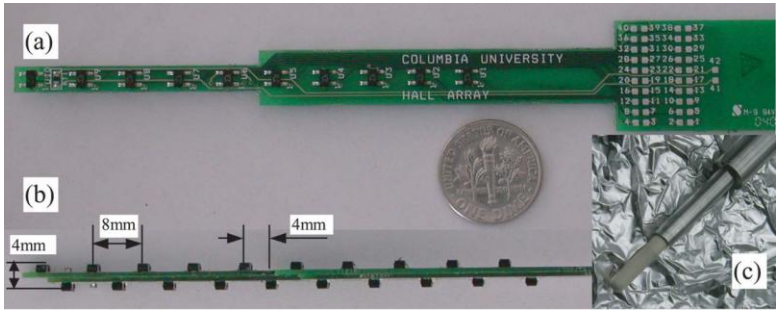
- Internal **B** constrains **J** through Ampere's law: $\frac{1}{\mu_0}\nabla \times \mathbf{B} = \mathbf{J}$
  - Requires spatially localized measurements
  - Edge stability theory validation demands time resolution ~ $\tau_{ELM} \leq 100$ μs
- J(ψ) must be obtained through equilibrium reconstruction
- Successful approaches to measuring J(R,t) employ B_p(R,t)
  - Beam-based methods: Localized, but poor- to moderate time resolution
    - Motional Stark Effect spectroscopy: core J
    - Li beam polarimetry: edge J
  - Faraday rotation polarimetry: good time response, but chordal
  - Direct probes: Localized, good time response, but incompatible with high T plasmas

Hall Arrays Provide Local B(t) in Tokamaks

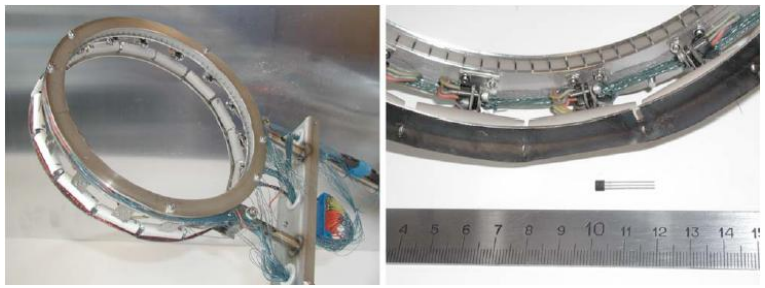
- TEXTOR*
  - External B_R, B_z fluctuations
- HBT-EP**
  - dB_z/dt, internal B_z
- CASTOR***
  - External $B_z \rightarrow$ plasma position
- PEGASUS****
  - Internal $B_z \rightarrow J(R), J(\psi)$



TEXTOR Hall Probe*



HBT-EP Hall Probe Array**

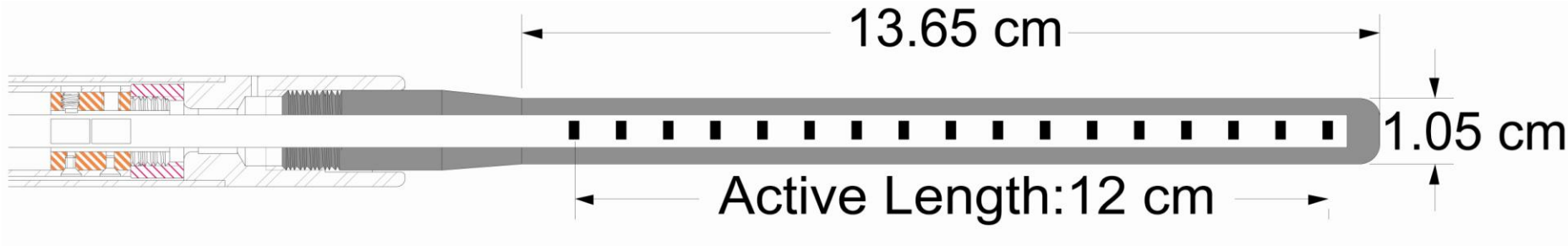


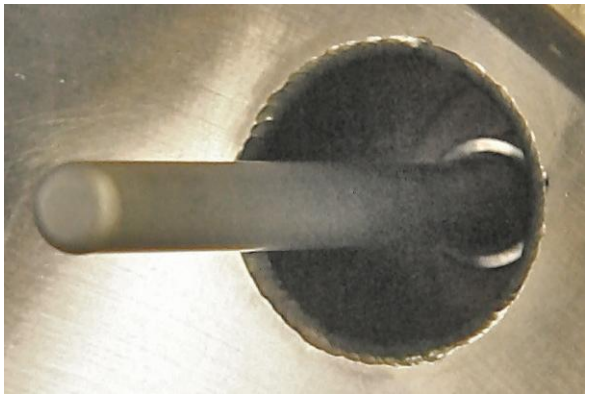
CASTOR Hall Array***

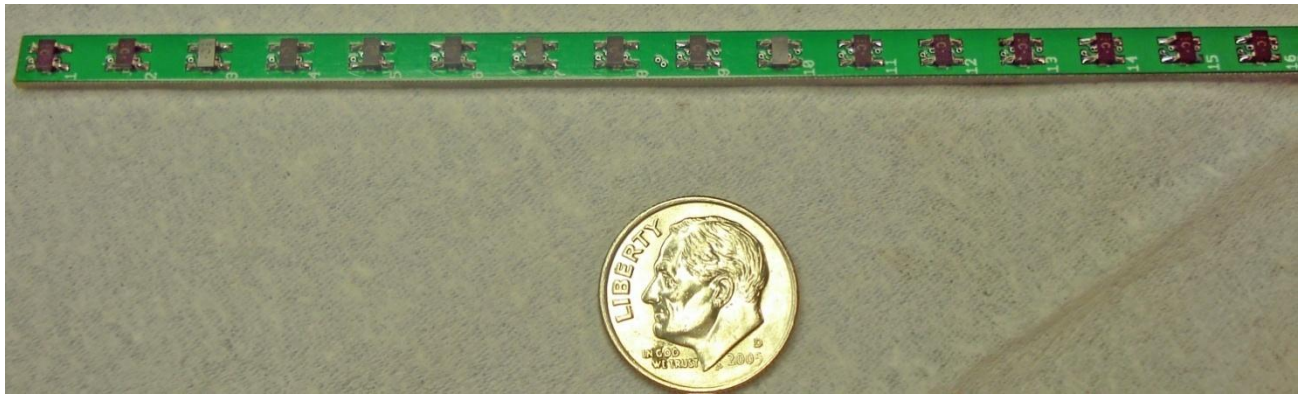
*: Ďuran, *et al.*, Rev. Sci. Instrum. **73**, 3482, 2002
: Liu, *et al.*, Rev. Sci. Instrum. **76, 093501, 2005
***: Ďuran, *et al.*, Rev. Sci. Instrum. **79**, 10F123, 2008
****: Bongard, *et al.*, Rev. Sci. Instrum. **81**, 10E105, 2010

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PEGASUS Hall Probe Deployed





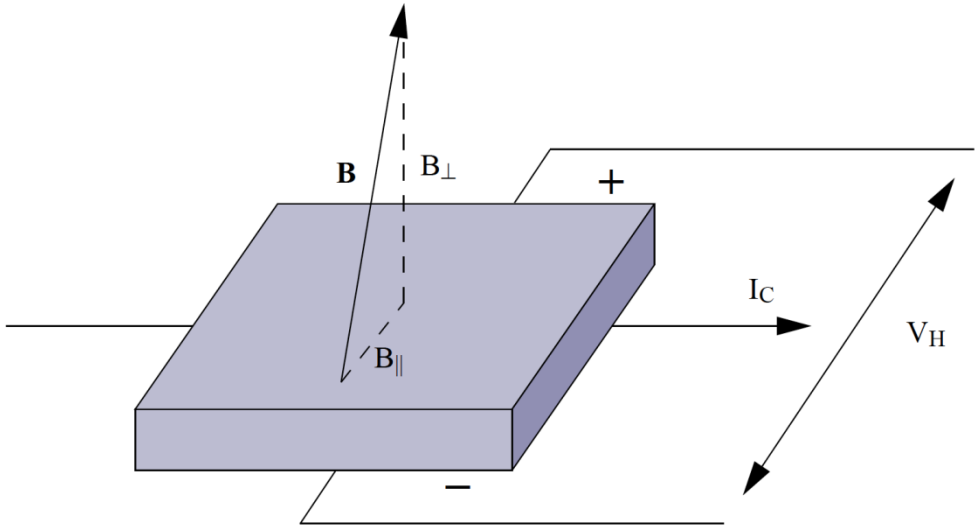


- Solid-state InSb Hall sensors
  - Sypris model SH-410
- 16 channels, 7.5 mm radial resolution
- Slim C armor as low-Z PFC
  - Minimizes plasma perturbation
- 25 kHz bandwidth

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



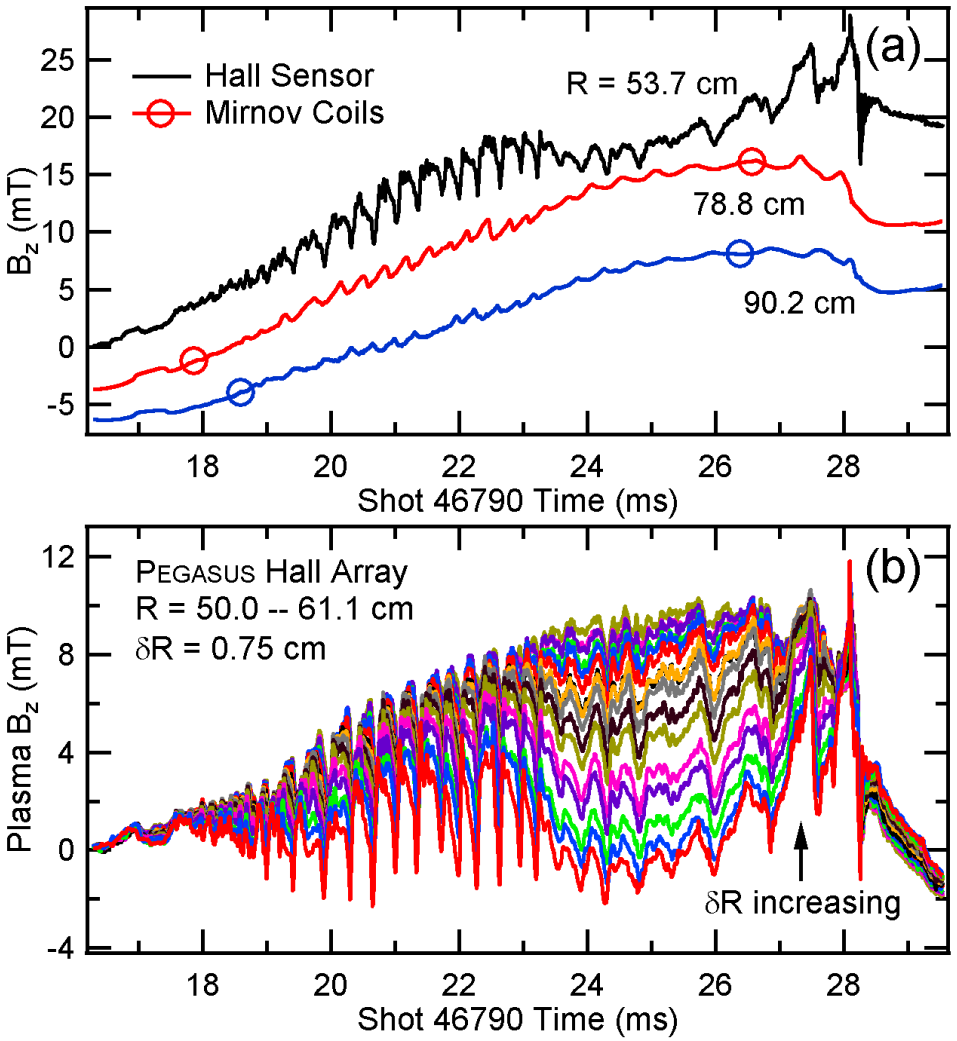
- High spatial, good temporal resolution
  - Sensor size: few mm
  - Bandwidth ~ 10–30 kHz
- Simple operation
  - Control current I_c ~ mA

- Provides $V_H = G_H I_c B_\perp$
  - G_H combines all Hall physics effects; determined by calibration
- Weak variance in G_H possible
  - Hall semiconductor, T_{sensor}, $B_\parallel$
  - Calibration corrects these effects

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Initial Tests Yield Precision B_z Measurements

- 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 $B_z(R,t)$



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$J_\varphi(R,t)$ Calculable Directly from Ampere'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:

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

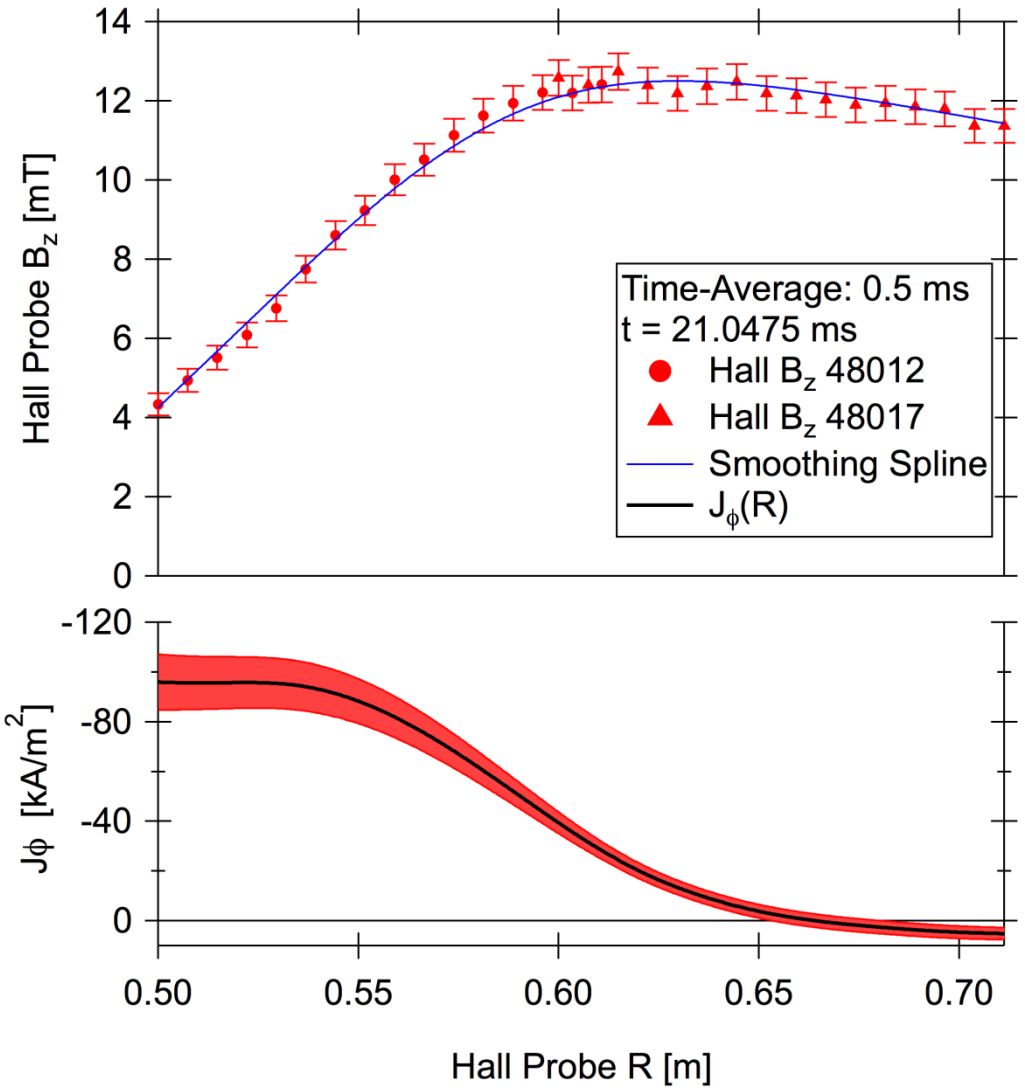
- Does not make assumptions on shape of J(R)

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

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Application to J(R) in PEGASUS

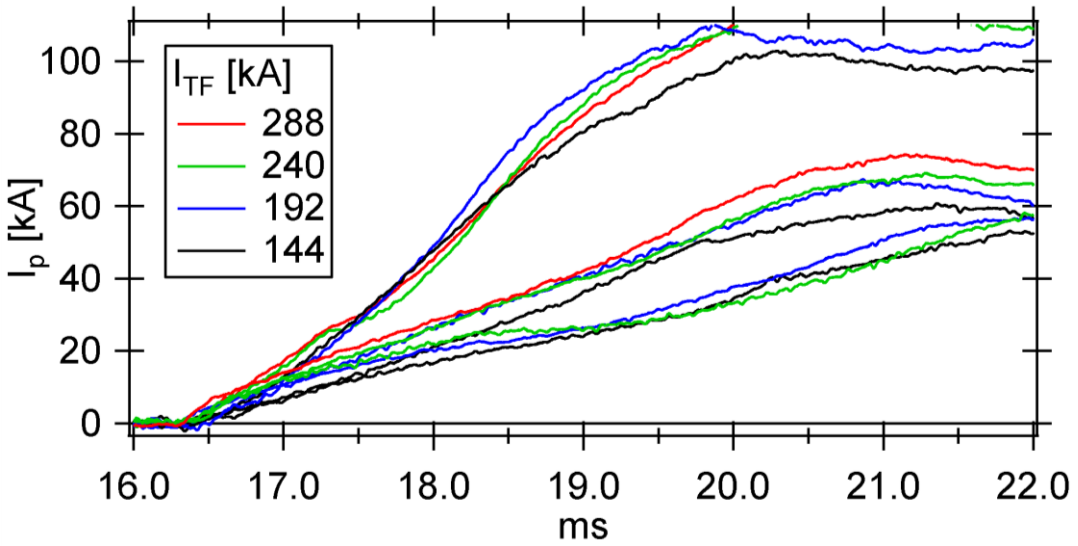
- Computational method:
  - Obtain Hall Probe $B_z(R,t)$
  - Construct interpolated $B_Z(R)$ with smoothing spline*
  - Compute dB_Z/dR from spline
  - Compute $J_\varphi(R,t)$ given geometry
- J(R,t) show features of I_p, MHD evolution
- Radial span extendible with multi-shot averaging
  - Requires mild time averaging; MHD is out-of-phase in general

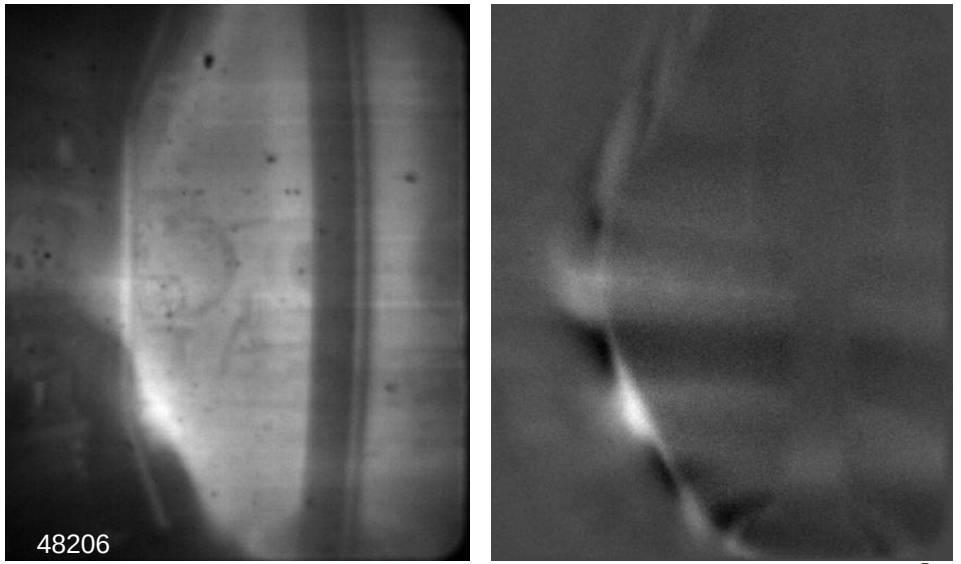


*: Reinsch, C., Numerische Mathematik **10**, 177, 1967

Peeling Instability Drive Scan Conducted

- Peeling drive varied systematically in I_p ramp
  - Shape well-matched
- Experimental proxies:
  - $dI_p/dt \sim J_{edge}$; $I_{TF} \sim B$
- Uniform edge diagnosis
  - Hall, edge magnetic probes
  - 27 kHz fast imaging
- 11 combinations dI_p/dt, I_{TF}
  - I_{TF} = {144, 192, 240, 288} kA
  - dI_p/dt = {30, 15, 10} MA/s



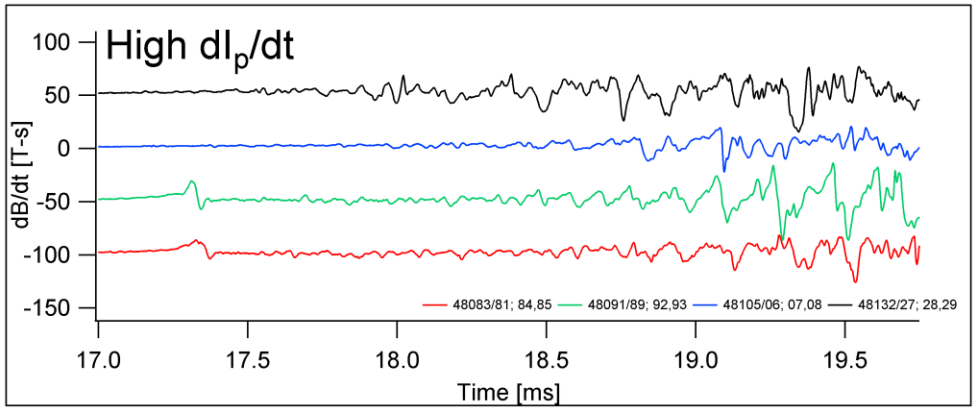


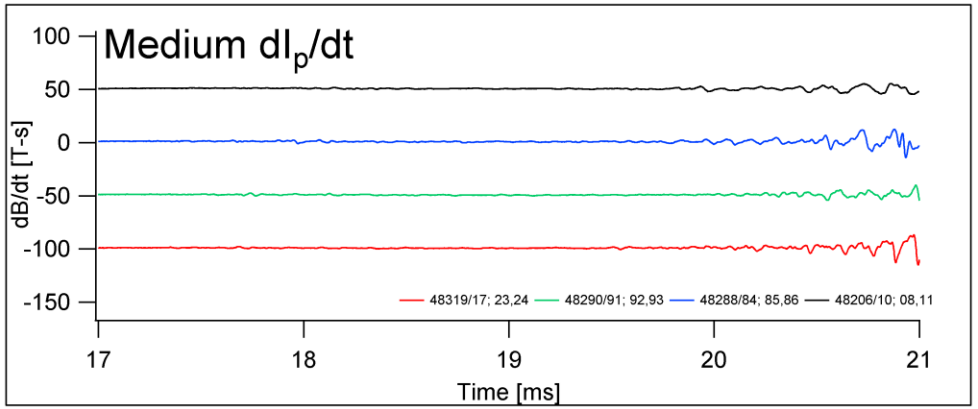
Phantom Imaging:
Original; 270 μs average subtracted

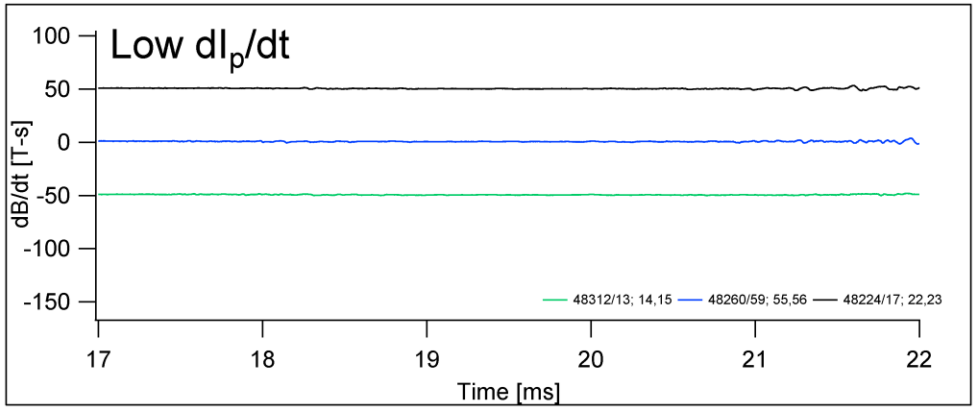
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Peeling Instability Mitigated via Lower Drive

- High-n Toroidal Probe Array used to characterize filament EM signature
- Observed dB/dt signal onset concurrent with edge filament detachment
- Peeling suppression achieved at lowest dI_p/dt
- Mitigation effectiveness increases with reduced J/B
  - Reduced virulence; delayed onset

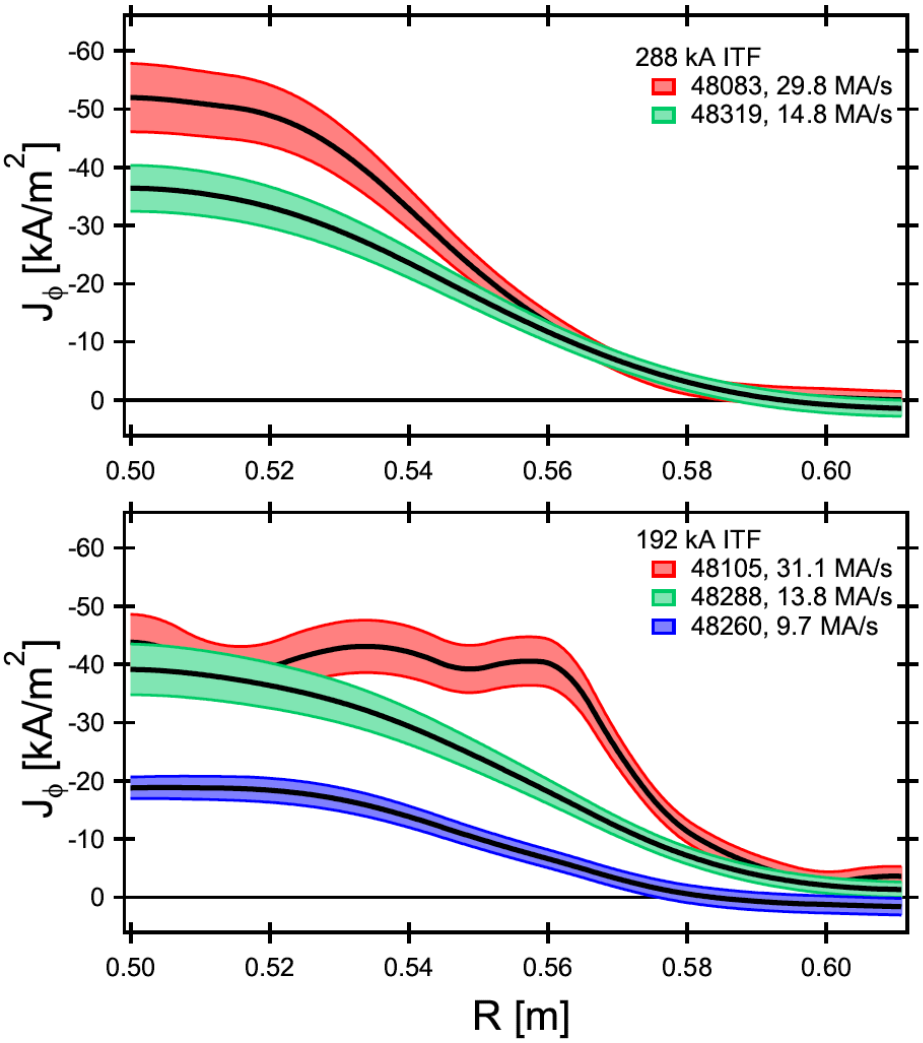






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J(R) Structure Strongly Influenced by dI_p/dt

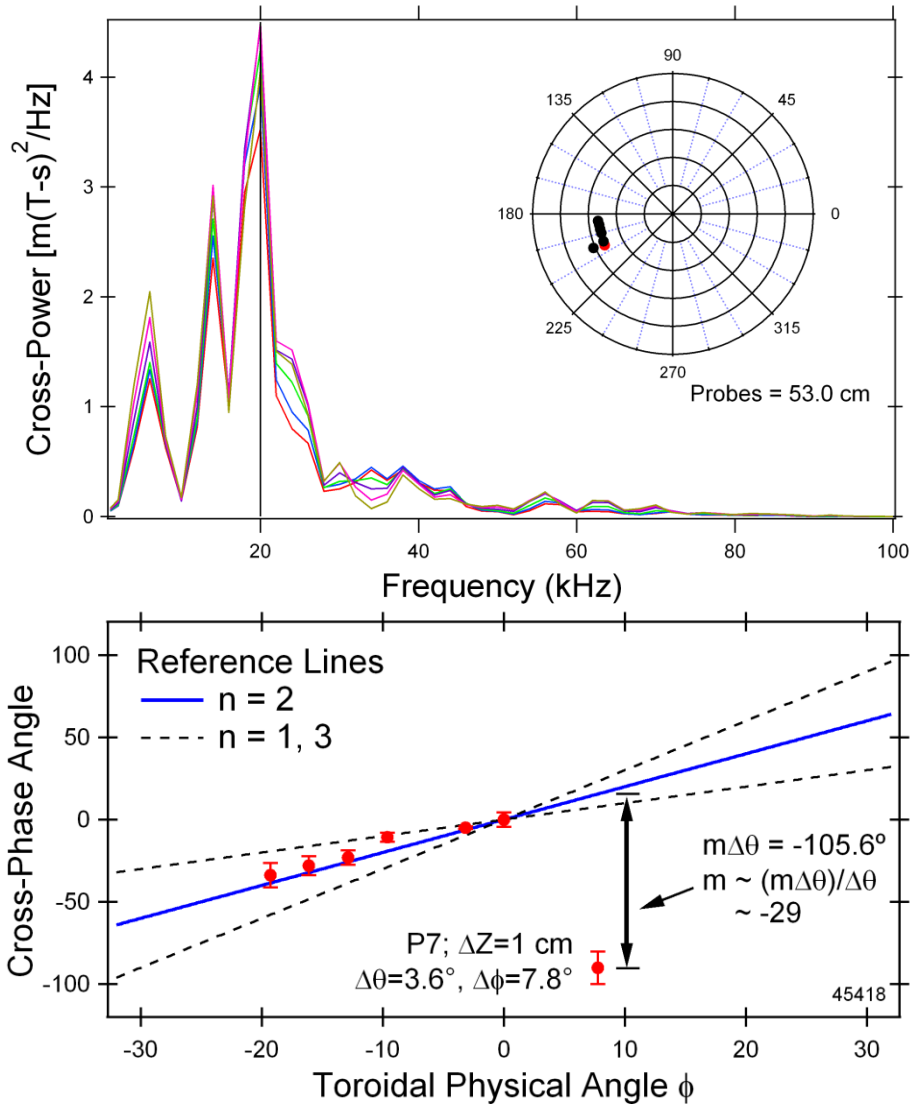


- Data supports hypothesis of skin current drive

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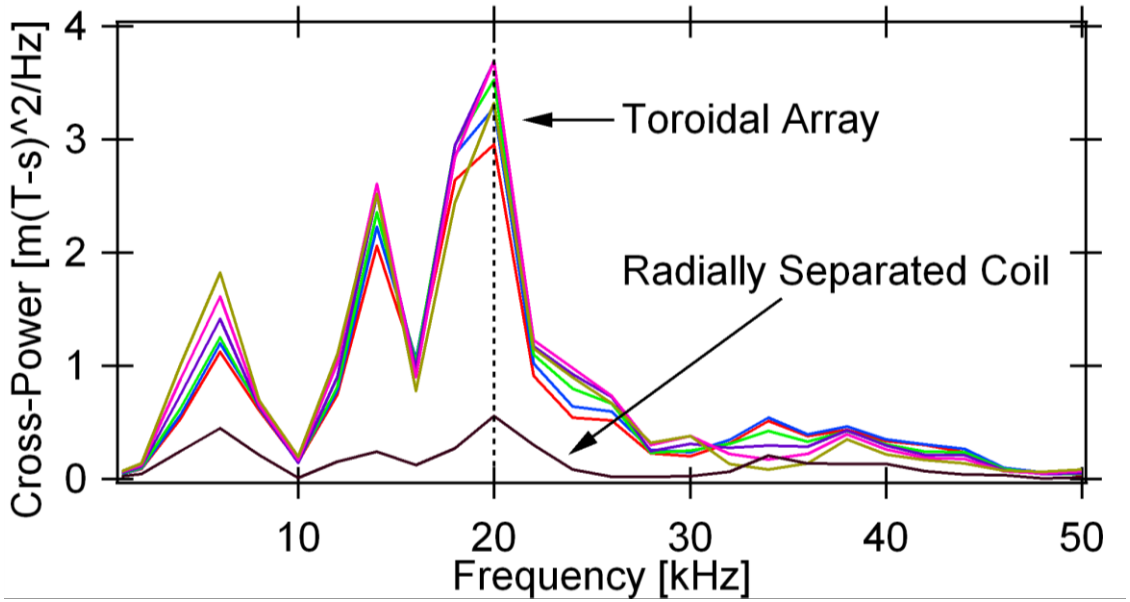
Diagnosis of Peeling EM Signatures

- High-m, low-n EM signature found in peeling phase
- n determined by standard cross-phase analysis
- High-m found in dedicated experiments with high-n probe array and a poloidally separated probe
  - Case shown: $m \approx -29 \pm 3$
- Data set used to benchmark new m estimation technique



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m Also Approximated via Radial Decay Rate



$$|m| \approx -\frac{\log A_2/A_1}{\log R_2/R_1} = -2\frac{\log \hat{P}_2/\hat{P}_1}{\log R_2/R_1}$$

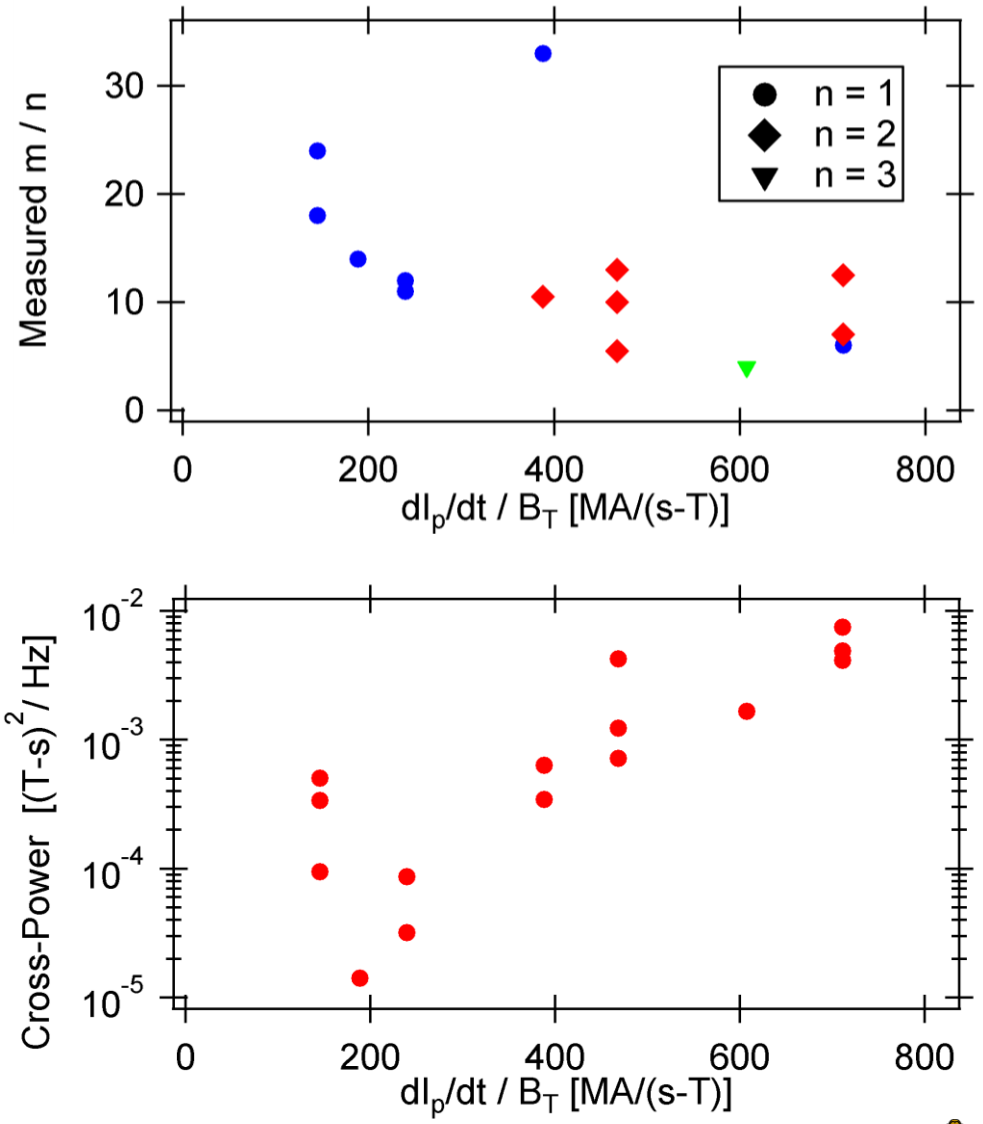
for fluctuation amplitudes A, power spectral density $P_{1,2}(f)$ at $R_{surf} < R_1 < R_2$

- MHD vacuum perturbation amplitude decays with R, m*
  - Approximately as $(R\text{-}R_{surf})^{-|m|}$
- Power spectral density ratio allows course estimation of m
  - This case: $m \approx 25 \pm 2$ at 20 kHz
- High-n probe array has two coils separated purely by R
- Technique allows estimation of m with probe array alone

*: Wesson, Tokamaks, 3rd Ed., 6.7

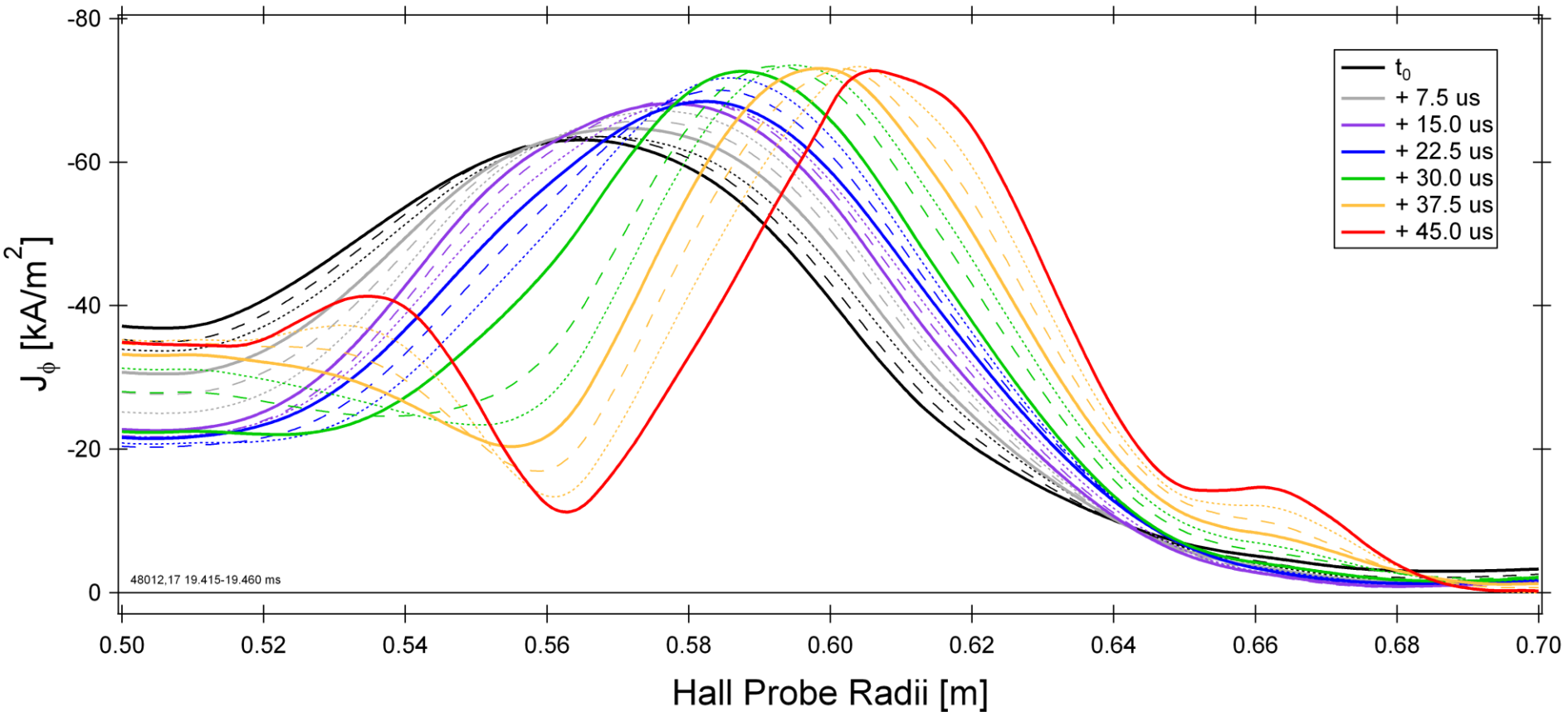
Filament MHD Has Peeling Characteristics

- Toroidal mode analysis, m estimation performed on peeling signatures from dI_p/dt, I_{TF} scan
- Low n, high m observed
  - $n < 3$; 1–2 typical
  - $m \geq 10$ for most modes
- m/n ~ q_a, implying edge localization
- Fluctuation power strongly increases with J/B



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J_{edge} Dynamics Resolved on ELM Timescales

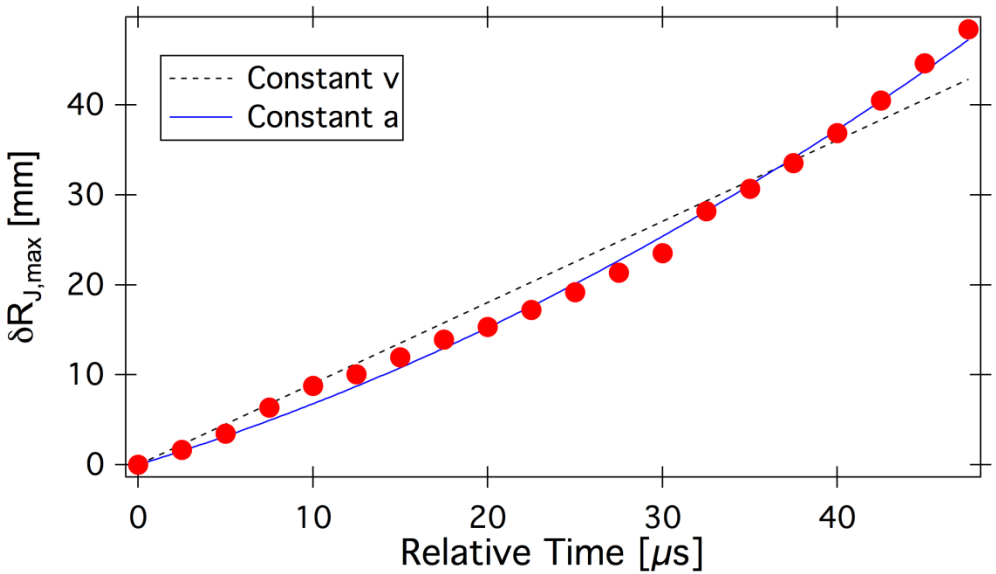


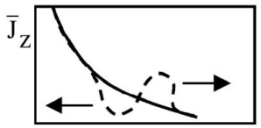
- J(R) evolution tracked over filament burst
- Filament carries $|J_{edge}|$ prior to instability outward
- Outboard δJ acceleration, radial localization

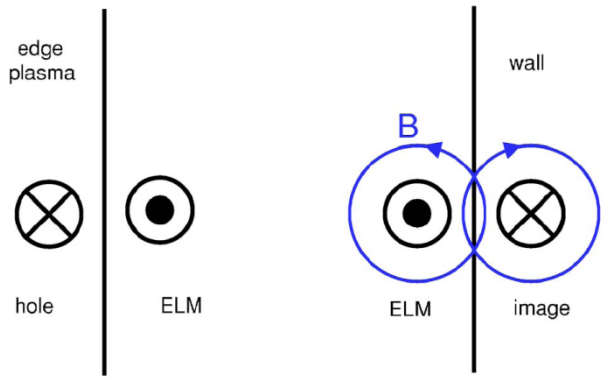
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Edge Dynamics Consistent with ELM models

- Tracking $J_{max}(R,t)$ allows determination of filament velocity, acceleration
- This particular filament has
  - $v_{r,0} \sim 600$ m/s, $a_r \sim 1.7 \times 10^7$ m/s^2
  - Fast imaging results comparable
- Filament / Hole creation, propagation qualitatively consistent with ELM dynamics models*
  - Current-carrying ELM filaments repelled by magnetostatic forces







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

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Equilibrium and Stability Analysis

- Equilibrium analysis of peeling unstable shots is challenging
- Peeling instability when wall currents dominate internal B(R,Z)
  - Peeling unstable $I_p \sim 50–80$ kA $< \sum I_{wall} \sim 150$ kA
  - Typical PEGASUS reconstructions attained when $I_p \geq \sum I_{wall}$
- Wall modeling and equilibrium code improvements underway
  - Recalibration of wall resistance distribution
  - Exploring minimization of weighted χ^2 functional to emphasize Hall data
  - Applying direct $J_\varphi(R)$ estimates as experimental fit constraint
- Due to low-n nature of observed modes, ideal stability analysis with DCON is appropriate means to test theory
  - If future experiments find intermediate n > 5, ELITE becomes applicable

Future Investigative Directions

- Equilibrium, stability studies with internal profile constraints
  - Hall Probe for J(ψ)
  - Thomson Scattering for p(ψ)
  - Enhancements to KFIT to accommodate diagnostic capabilities
- Investigation of J(R, t) in non-inductively produced plasmas
- Planned machine upgrades to enable diverted operations, feedback control
  - Affords investigation of shear effects on edge stability
  - Possibility of H-mode access

Summary

- Edge instabilities in PEGASUS consistent with peeling modes
  - Present under conditions of naturally high J_{edge}/B as $A \rightarrow 1$
  - Low-n, high-m electromagnetic signature with $m/n \sim q_a$
  - Edge detachment, radial outboard acceleration
  - MHD virulence correlated with peeling drive
- New Hall probe allows diagnosis of J_{edge} dynamics
  - Precision, internal $B_z(R,t)$ obtained without plasma perturbation
  - Radially accelerating filaments qualitatively consistent with ELM model
- Peeling stability to be evaluated with DCON as reliable edge reconstructions are obtained
  - Present challenge: accurate reconstruction in presence of large wall currents

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