Edge Stability Studies at High $\langle J_{edge}/B \rangle$ in the PEGASUS Toroidal Experiment

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PEGASUS Toroidal Experiment

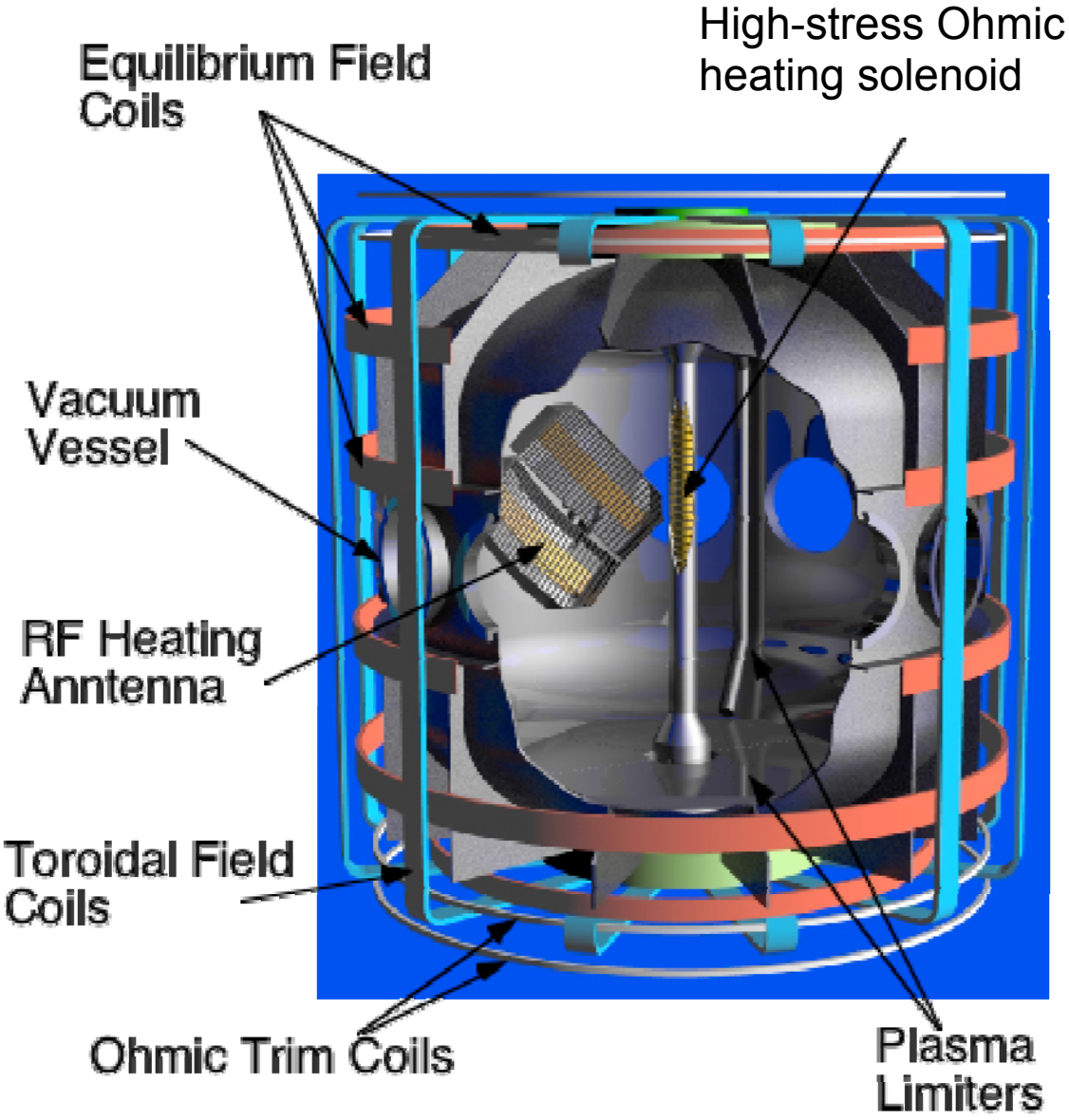
15th International Workshop on Spherical Tori

Madison, WI
October 23, 2009

Outline

- Introduction
- Filamentary Edge Instabilities in PEGASUS: Peeling Modes
- Characterization of Filaments
  - High-speed imaging
  - Magnetic, electrostatic measurements
- Experimental Current Profile Constraint via Hall Probes
- Summary / Conclusions

PEGASUS: A University Scale, Ultralow-A ST



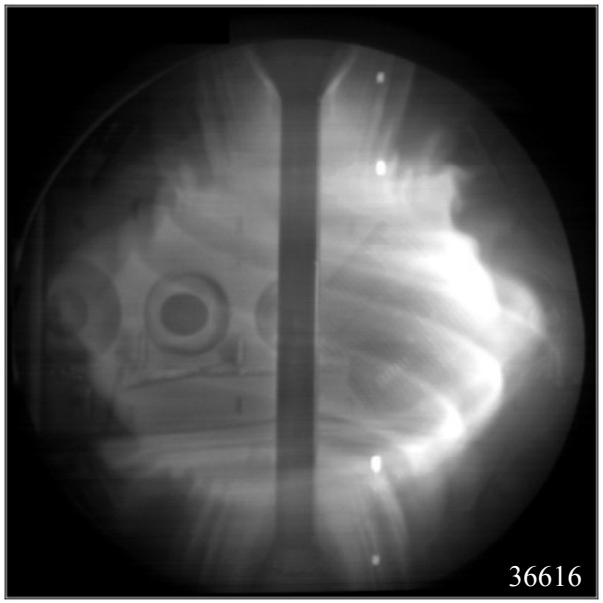
Experimental Parameters

Parameter	To Date
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .21
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

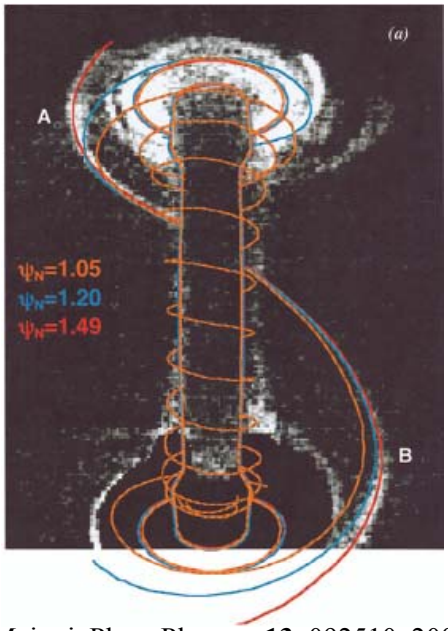


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PEGASUS: ELM-like Structures Observed

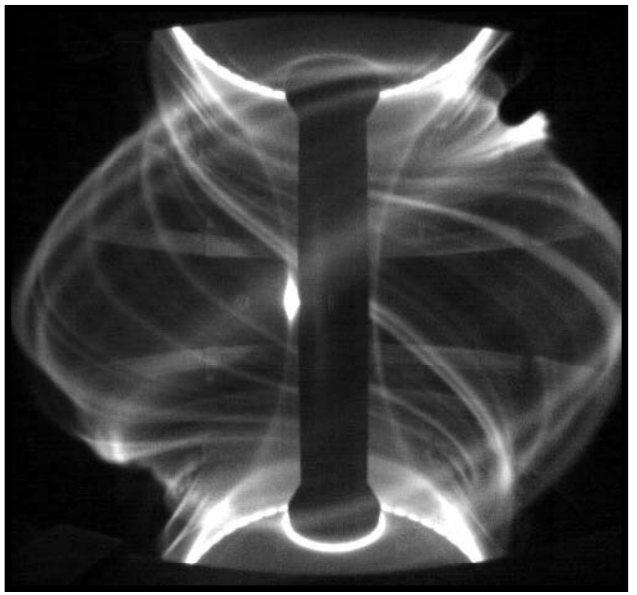


PEGASUS



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

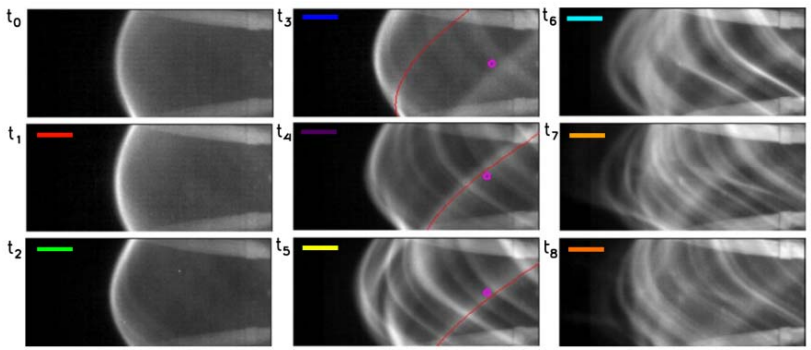
NSTX



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

MAST

- Filamentary, field-aligned structures
  - Found under conditions of high $\langle j_{edge}/B \rangle$
- Unlike ELMs, L-Mode edge assumed
  - However, may be same instability

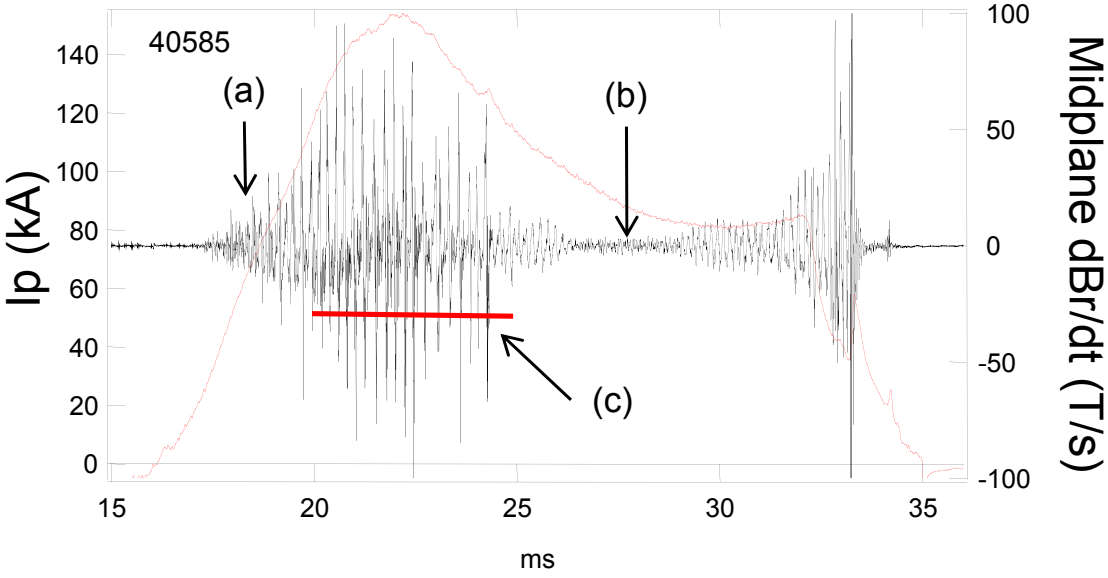


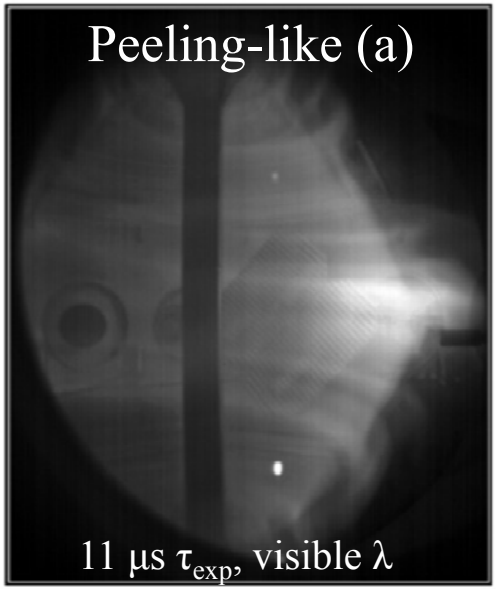
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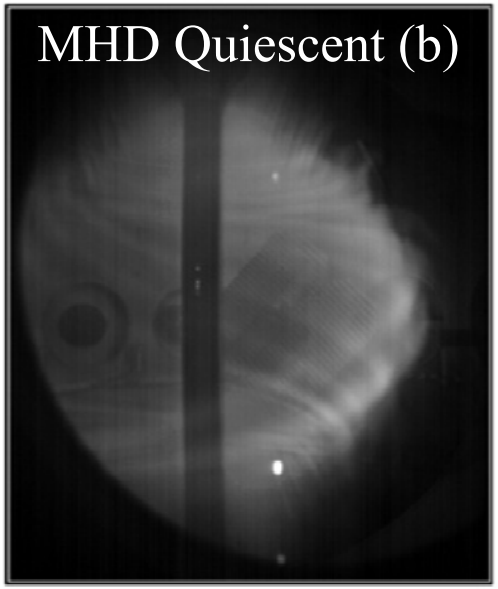
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Two Distinct Filament Classes Observed

- Peeling-like (a)
  - EM signature: high m, low n
  - Coherent spatial structure
  - Filament rotation
  - Detachment, radial propagation
- 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)



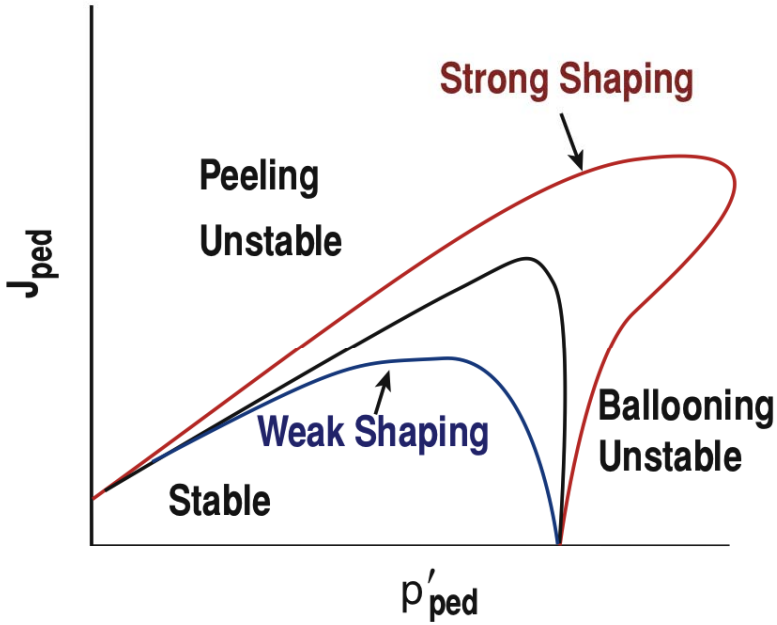




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Candidate Instability: The Peeling Mode

- 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



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

- Qualitative guide: analytic peeling stability criterion*

$$2\sqrt{-D_I} = \sqrt{1 - 4D_M} > 1 + \frac{2}{2\pi q'} \oint \frac{\mu_0 j_{\parallel} B}{R^2 B_p^3} dl$$

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

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Near-unity A Maximizes Peeling Drive

Device	J_{edge} (MA/m^2)	$B_{\varphi,0}$ (T)	J_{edge}/B
PEGASUS	~ 0.1 – 0.2	0.1	**~ 1**
DIII-D*	1 – 2	2	**0.5 – 1**

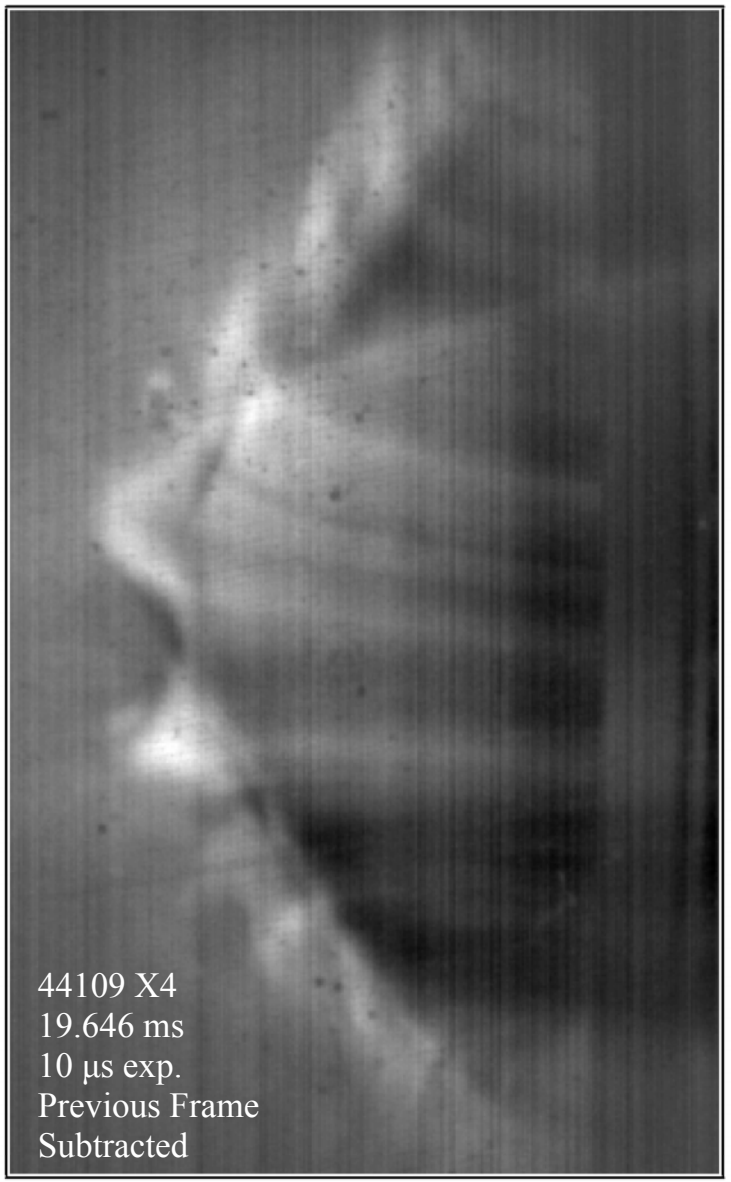
*: Thomas, Phys. Plasmas **12**, 056123 2005

- PEGASUS operations at A → 1 lead to naturally high j_{edge}/B
  - Comparable to larger machines in H-mode
- However, *source* of peeling drive different
  - Large machines: H-mode p' → j_{BS}
  - PEGASUS: Large dI_p/dt (≤ 50 MA/s) → transient skin current
- Low-A geometry enables ITER-relevant research

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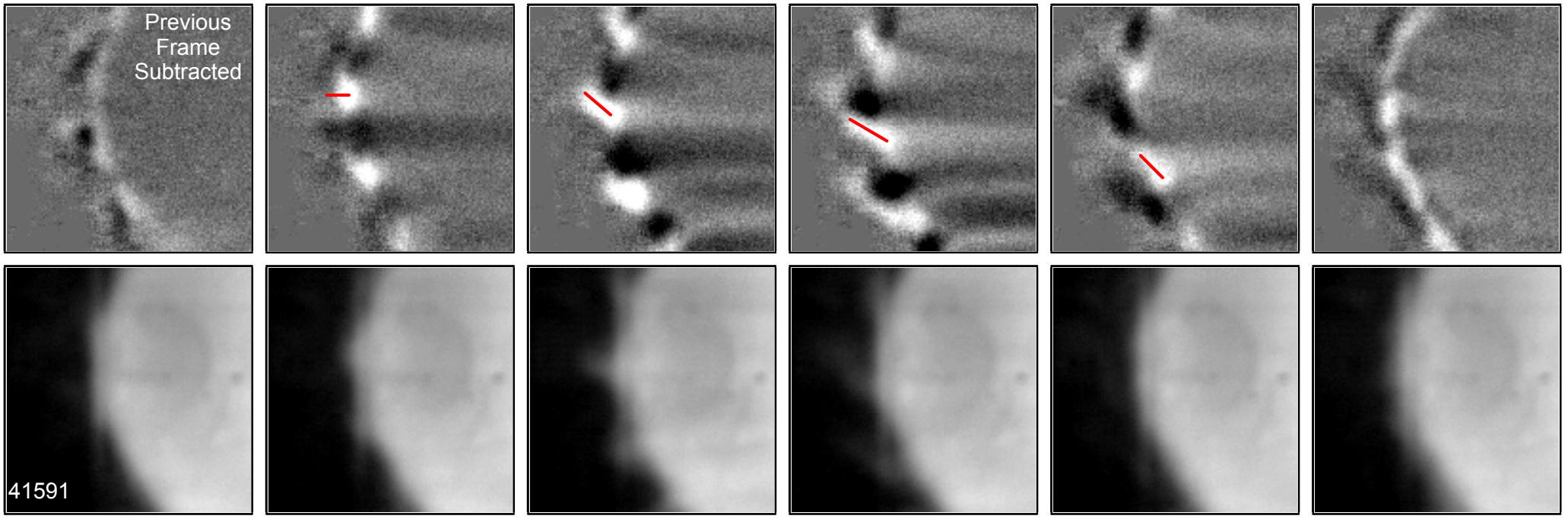
Peeling-like Filaments Observed During Periods of High $\langle j_{edge}/B \rangle$

- Spatially coherent
- High-m structure visible over majority of poloidal cross-section



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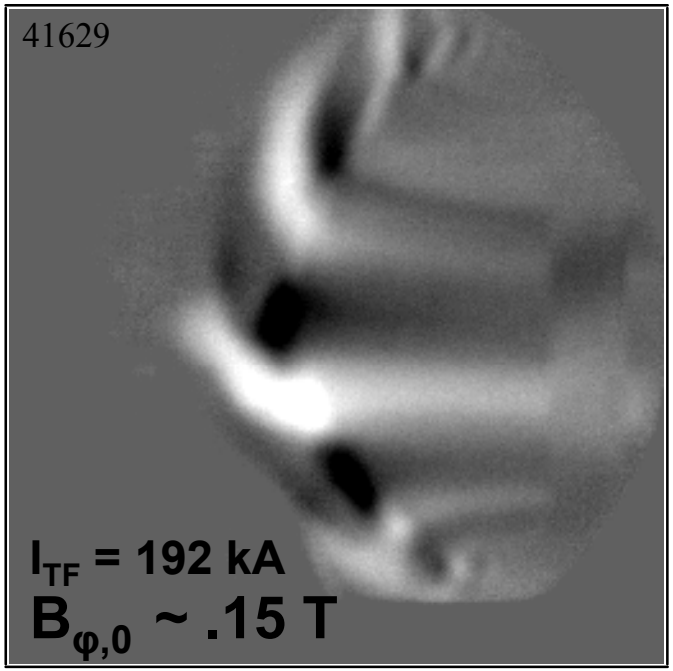
Fast Imaging: High Poloidal Coherence

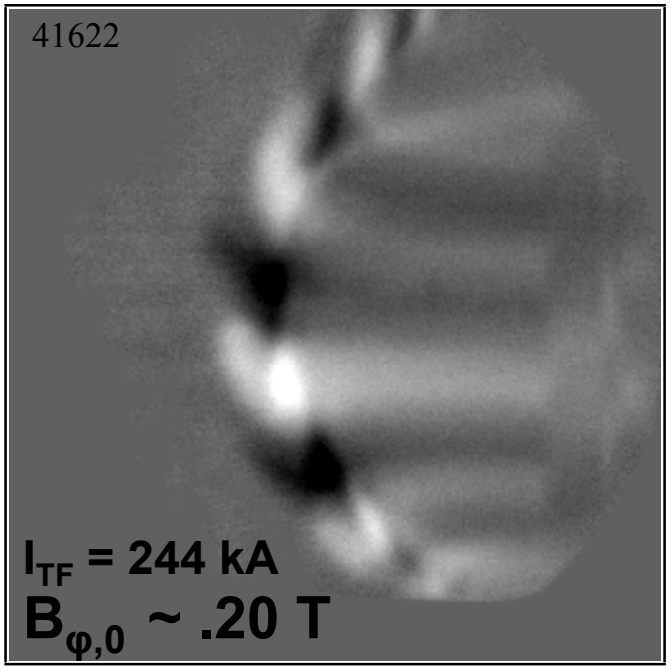


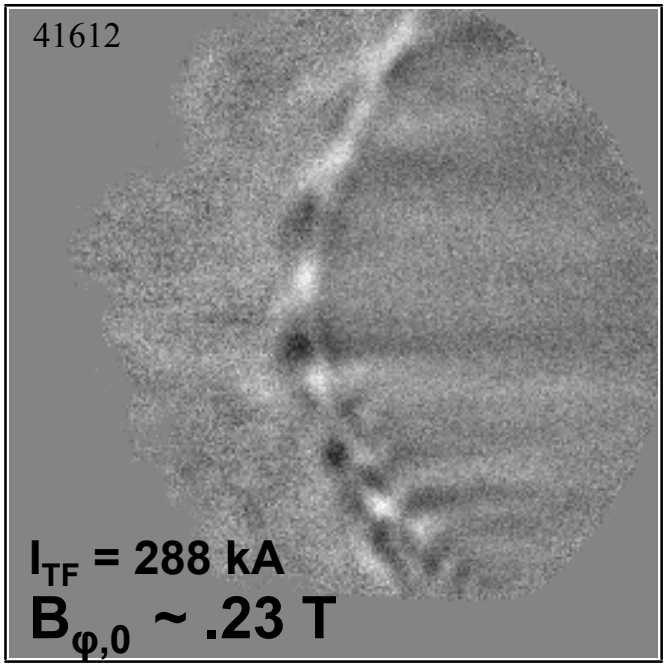
- Poloidal filamentary structures grow and decay simultaneously
- Mean lifetime ~ 55 μs
- Bulk filament rotation appears to be in ion diamagnetic drift direction

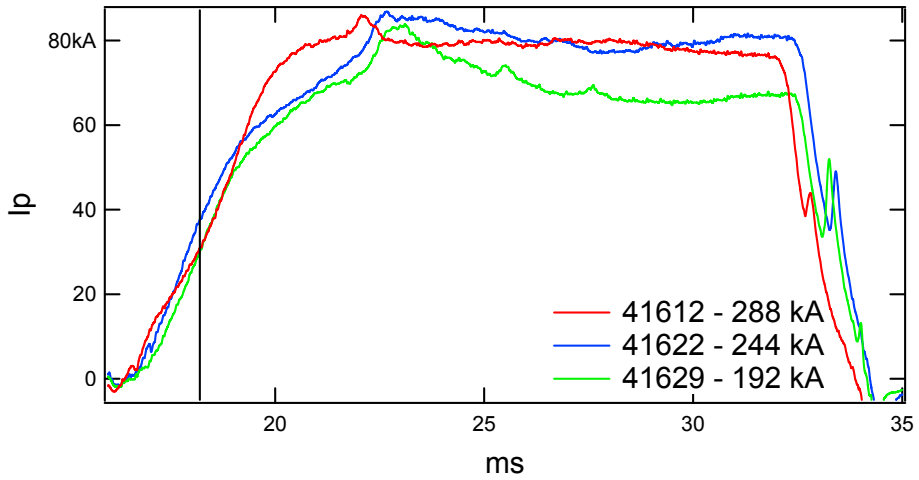
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Edge Perturbation Scale, Amplitude Decrease with Increased B







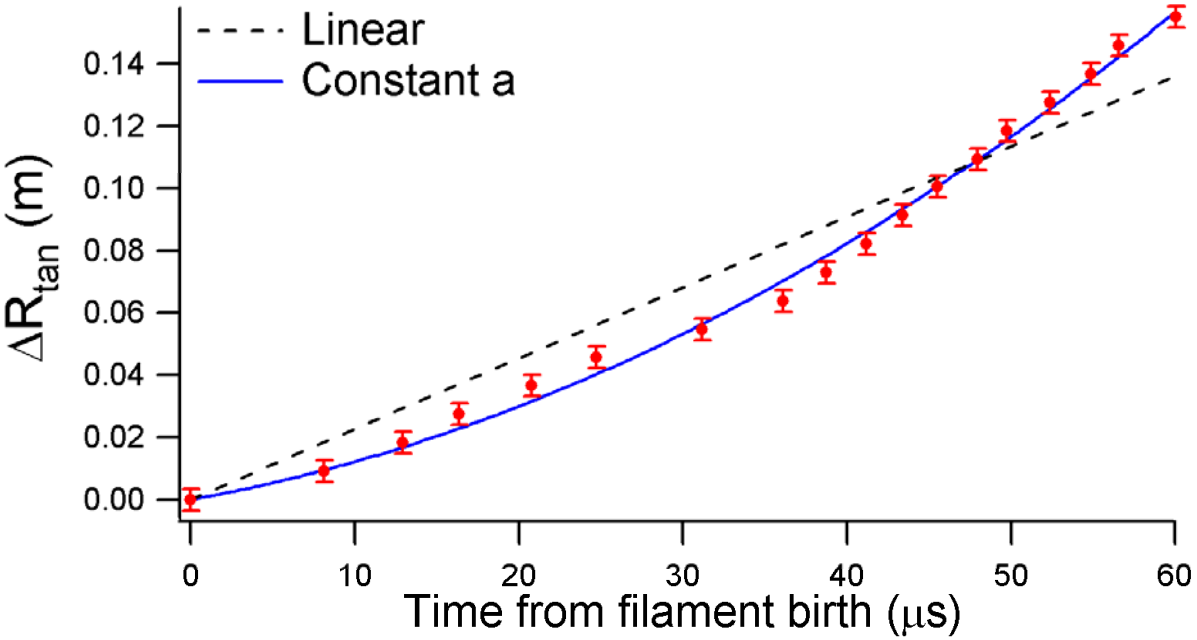


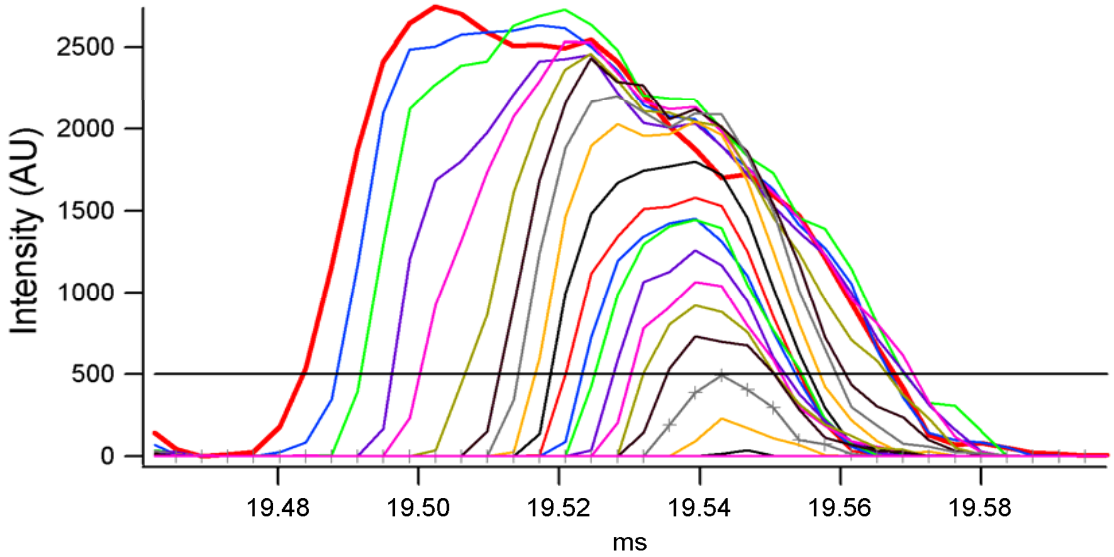
- Modes more virulent at reduced Bφ
  - dI_p/dt, shape, V_ℓ, fueling held constant to identify B dependence

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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



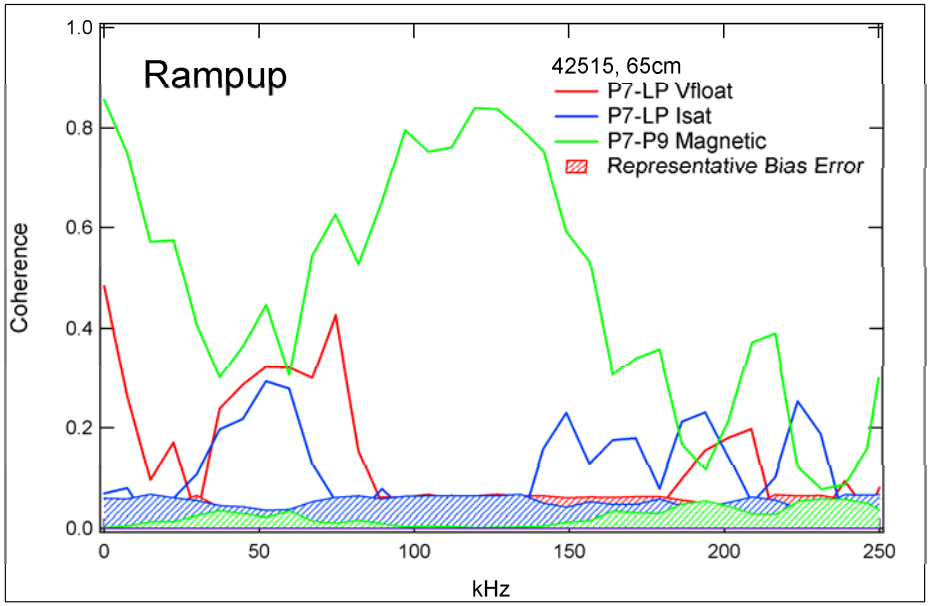


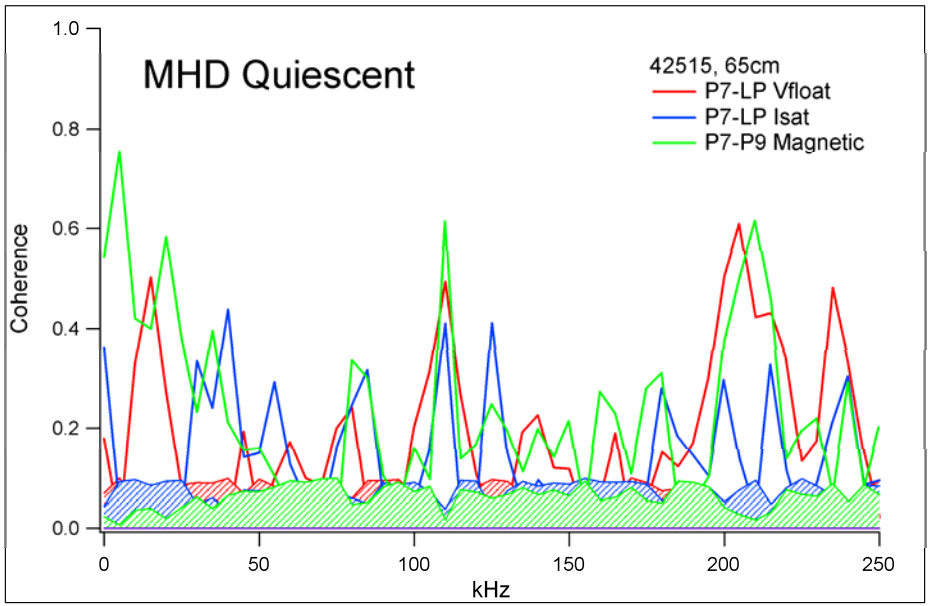
Time evolution of uniformly spaced R_{tan} viewing chords

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

Peeling-like 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 electrostatic L-mode turbulence

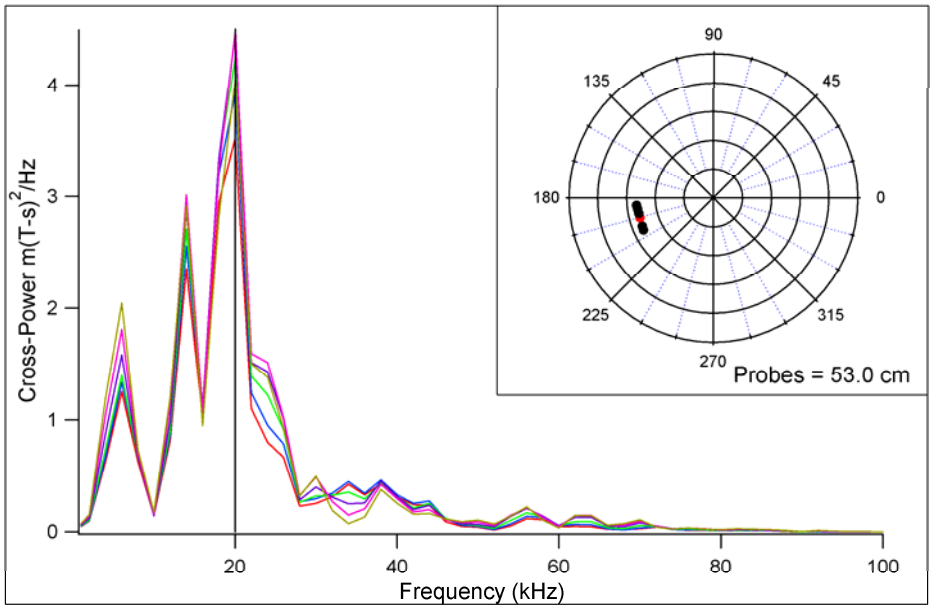


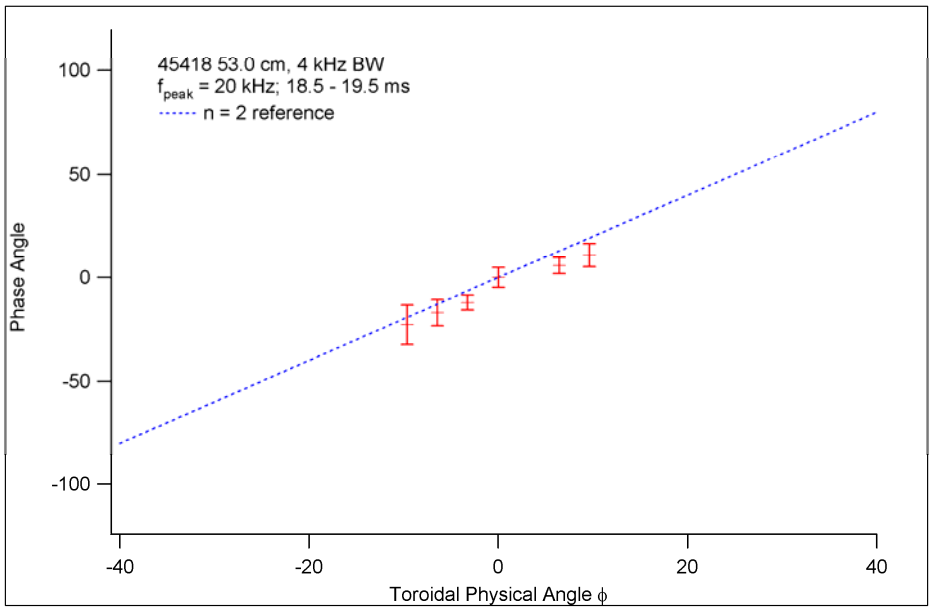


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Peeling-like Filaments Have Low- to Intermediate-n

- High-resolution magnetic probe array placed at edge (R_a + 3 cm)
- n = 2 mode helicity measured during I_p ramp
  - n < 5 commonly present
- 20 kHz peak spectral power consistent with O(50 μs) fast imaging results

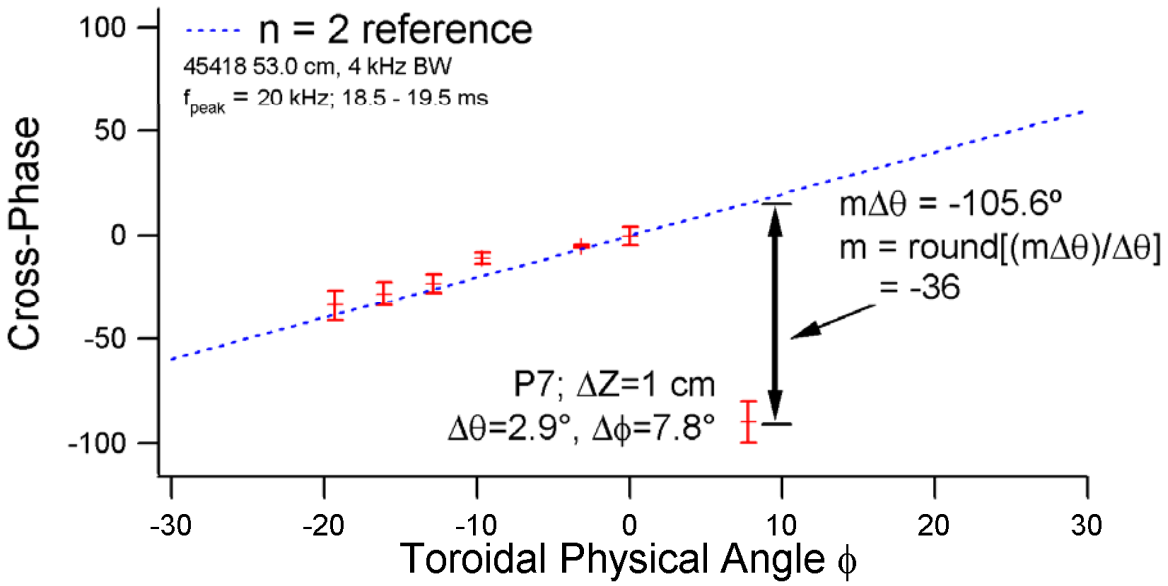


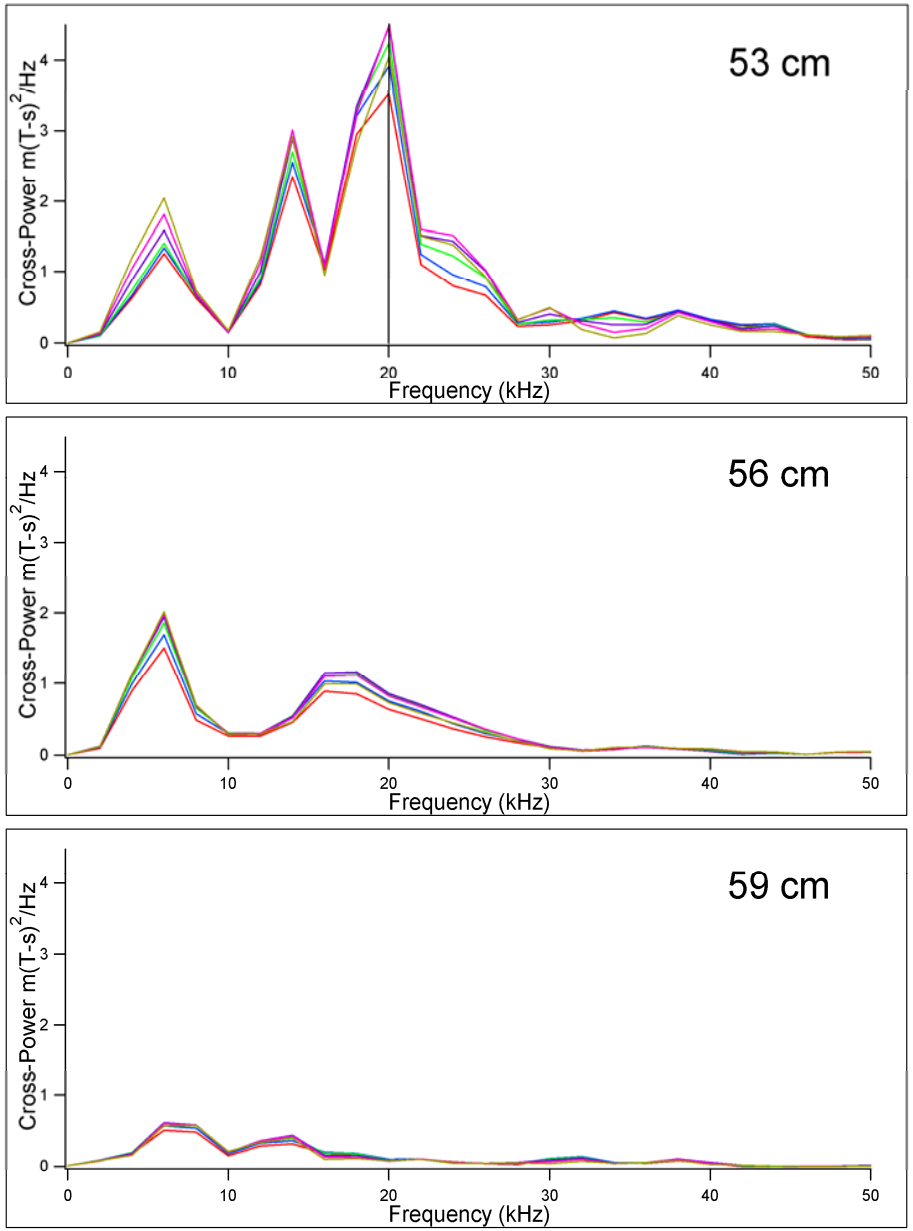


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Peeling EM Signature Consistent with High m

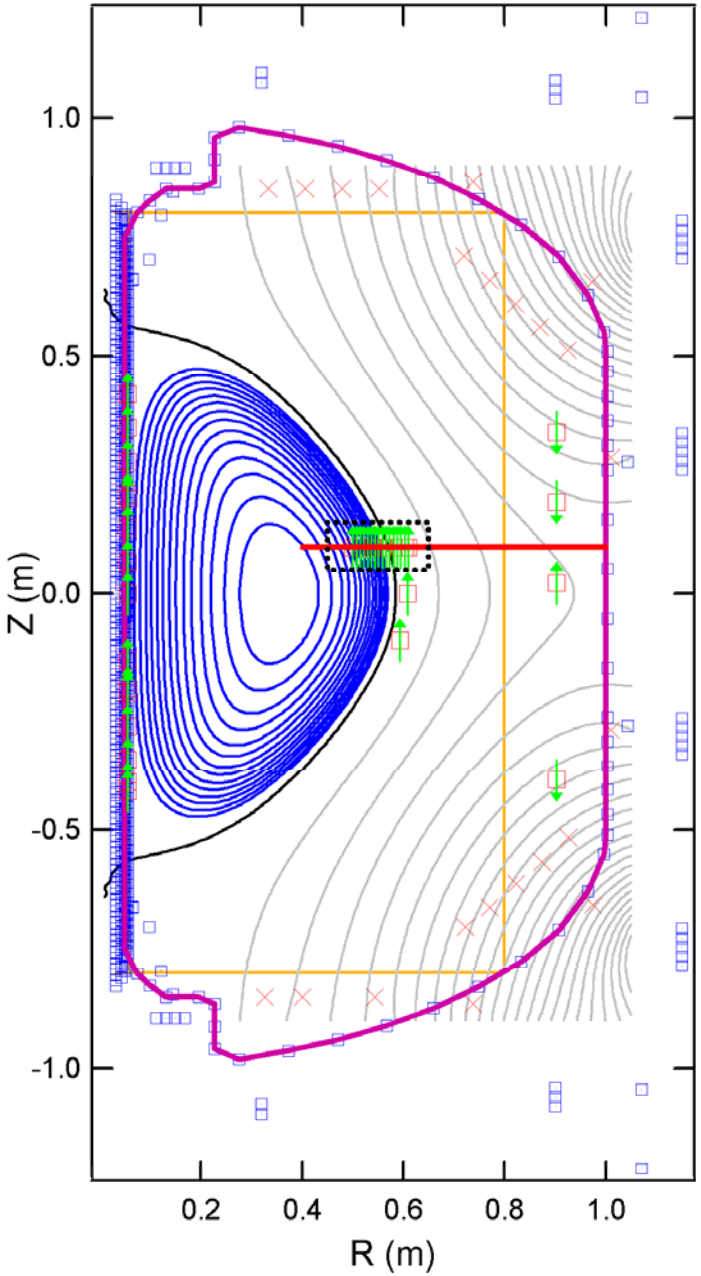
- Peeling cross-power spectral peak vanishes rapidly from edge
- 2-point m identification: m ~ -36
  - Approximate; need full magnetic geometry correction for accurate m
  - Consistent with reconstructed $q_a \sim 18$



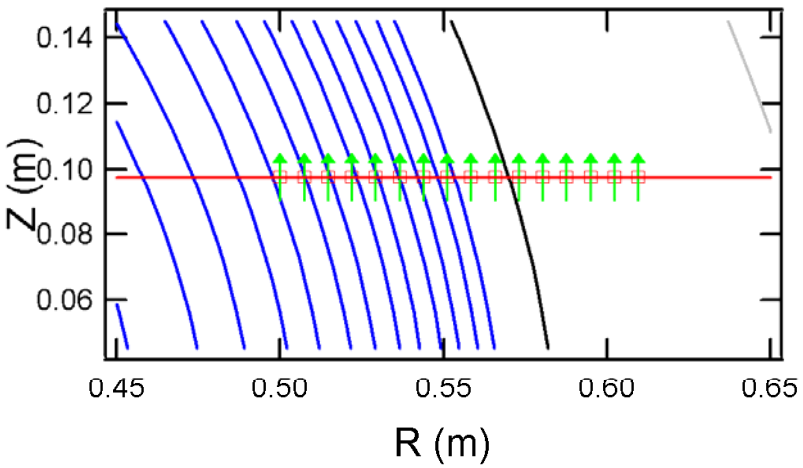


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Stability Analysis Requires Local Measurements



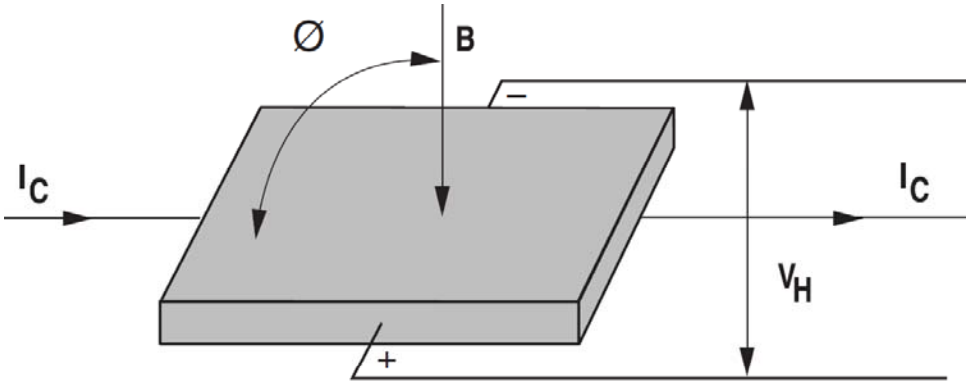
- Utilization of experimental equilibria in stability analysis depends crucially on accuracy of reconstructions
  - E.g. Peeling-ballooning: edge p(ψ), **j(ψ)** profiles
- PEGASUS: Operating conditions allow for direct measurement of *internal* B_z
  - New diagnostic capability provides strong experimental constraint on j(ψ)



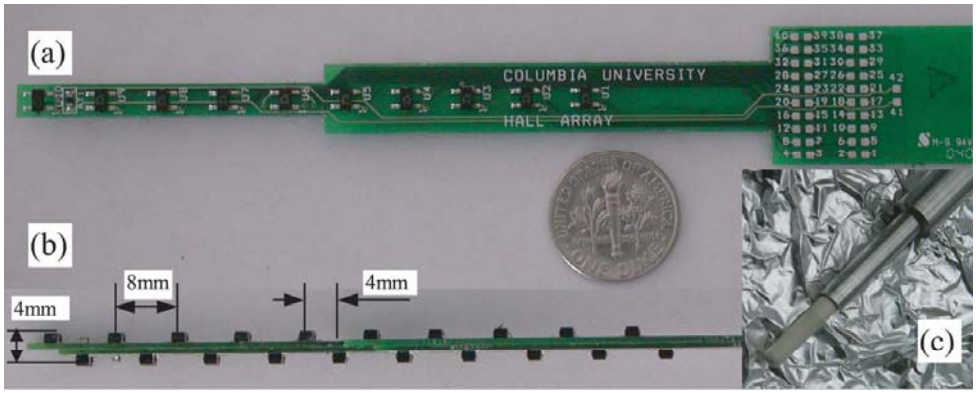
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In-situ Hall Probe Arrays Constrain J(ψ)

- Solid-state magnetic sensors afford an excellent means to sample **B** with good spatial and temporal resolution
  - $V_H = I_c G_H B \sin\varphi$, where G_H is primarily determined by sensor material
  - Very small size; O(mm)



- Deployed on several tokamaks:
  - TEXTOR* : ext. B_z fluctuations
  - HBT-EP**: dB_z/dt, internal B_z
  - PEGASUS: Internal $B_z \rightarrow j(\psi)$

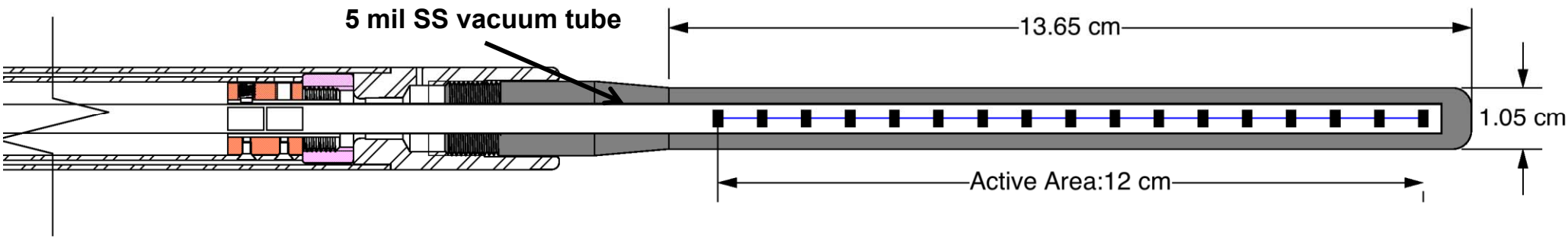


HBT-EP Hall Probe Array**

*: Ďuran, et. al., Rev. Sci. Instrum. **73**, 10, 3482, 2002
: Liu, et. al., Rev. Sci. Instrum. **76, 093501, 2005

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1st Generation Hall Probe Deployed



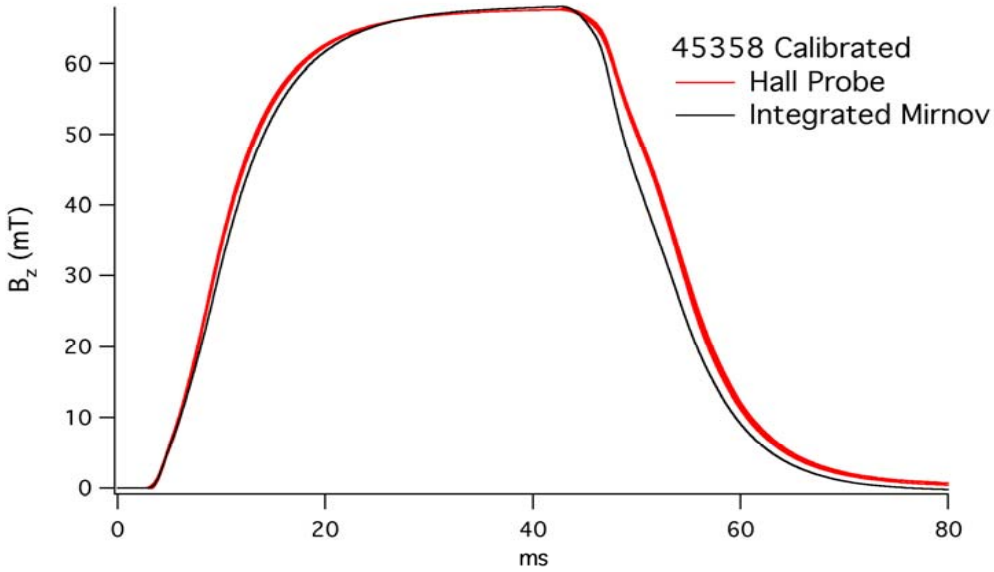
- Solid-state InSb Hall sensors
  - Sypris model SH-410
- 16 channels, 7.5mm center-center spacing
- C armor as low-Z PFC
- Slim profile minimizes plasma perturbation



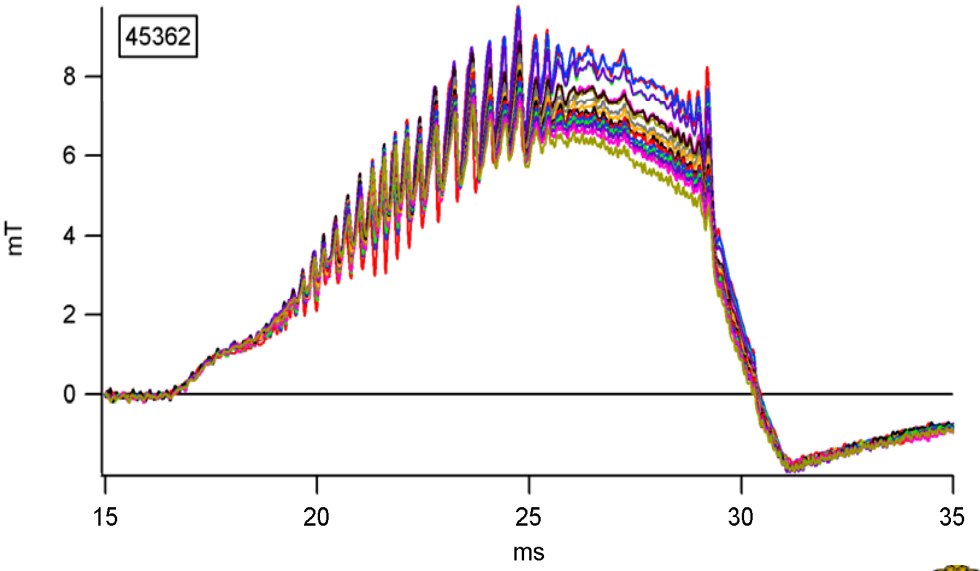
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Initial Hall Probe Data Obtained

- Cross-calibration performed using existing Mirnov coils
  - Weak dependence on $G_H(T)$ observed
- Frequency response: ≤ 25 kHz
  - Suitable for equilibrium reconstructions

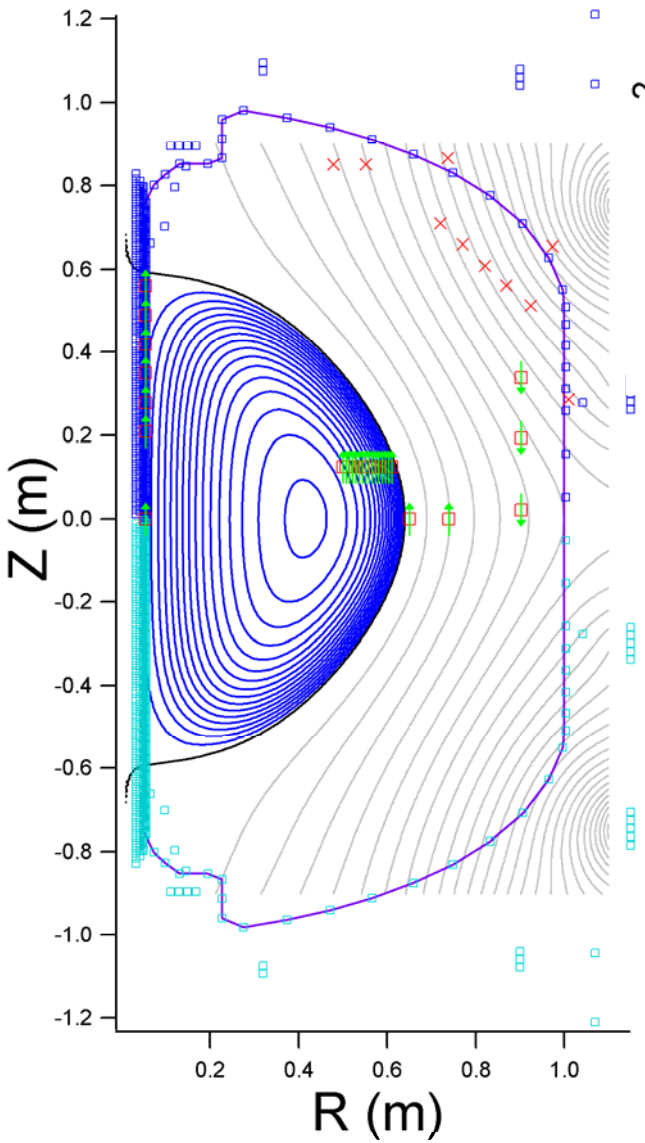


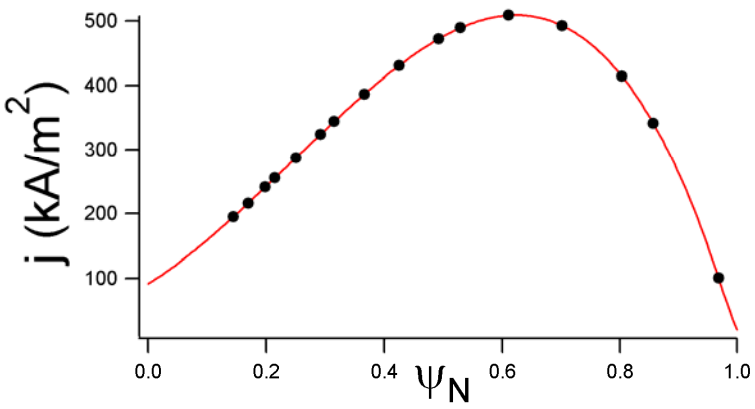
Time Response in EF-Only Calibration Pulse

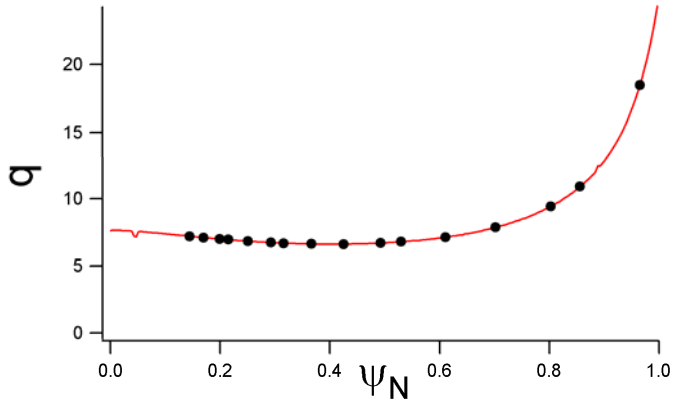


Plasma Component

HP Can Strongly Constrain J(ψ)





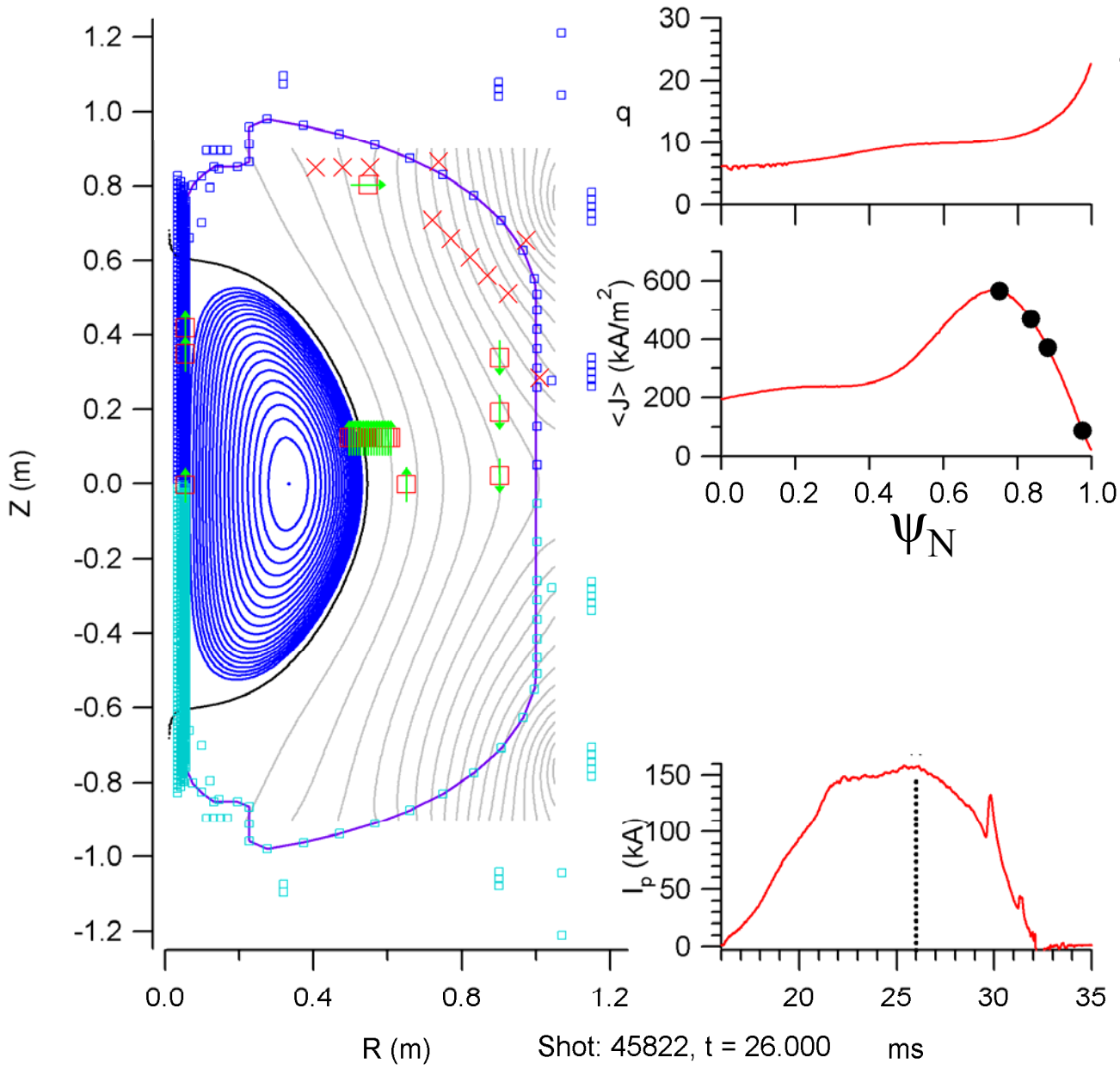


Representative profiles using 3-term polynomial fit

- Strong constraint over full ψ_N possible
  - Constraint locations (●) can vary in time due to evolution of plasma over fixed spatial location of probes
- Simple polynomial parameterization insufficient to represent full internal detail
  - Additional parameterizations in development

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Initial Internally Constrained Equilibrium



- 5-knot cubic spline parameterization using KFIT* Grad-Shafranov solver

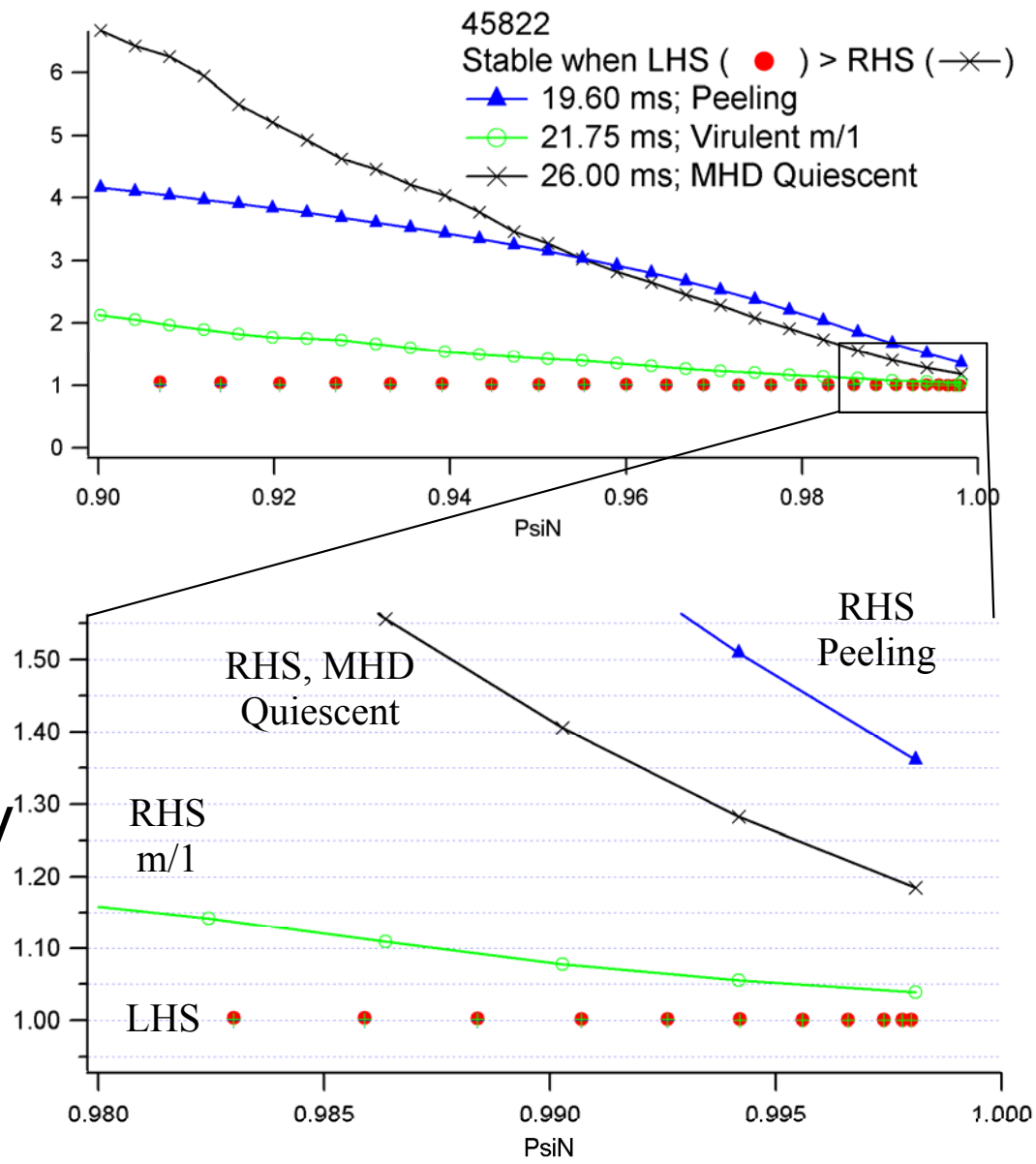
I_p	157 kA
R_0	.30 m
a	.24 m
A	1.2
κ	2.2
ℓ_i	.25
β_p	.10
β_t	.02
q_0	6.1
q_{95}	17

*Sontag, A., et. al., Nuclear Fusion, **48,** 095006 , 2008

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Filament Appearance Consistent with Peeling Stability Criterion

- Connor's peeling stability criterion computed from initial equilibria
  - KFIT spline fits coupled to DCON
- Peeling appears unstable at all times
  - Not observed; however, peeling phase *is* least stable of all phases
- Future: Rigorous comparison with peeling-ballooning theory
  - Numeric stability analysis of accurate j(ψ) equilibria via DCON, ELITE



Unstable if RHS > LHS

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Summary

- Localized filamentary edge instabilities present in PEGASUS consistent with peeling drive
  - Triggered during conditions of naturally high $\langle j_{edge}/B \rangle$
  - Electromagnetic signature with low n, high m
  - Nonlinear phase: radial propagation, acceleration
- Low-A, modest plasma parameters of PEGASUS afford unique laboratory to confront key ELM-relevant physics
- Measurement capabilities deployed to directly constrain $j(\psi)$
  - Demonstrated capability to measure internal $B_z(R,t)$
  - Initial analysis with relatively smooth $j(\psi)_{edge}$ model: strongest peeling drive when observed in experiment
  - Improvements to equilibrium parameterization and coupling to DCON, ELITE will provide more rigorous comparison with peeling theory

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