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

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PEGASUS Toroidal Experiment

Abstract

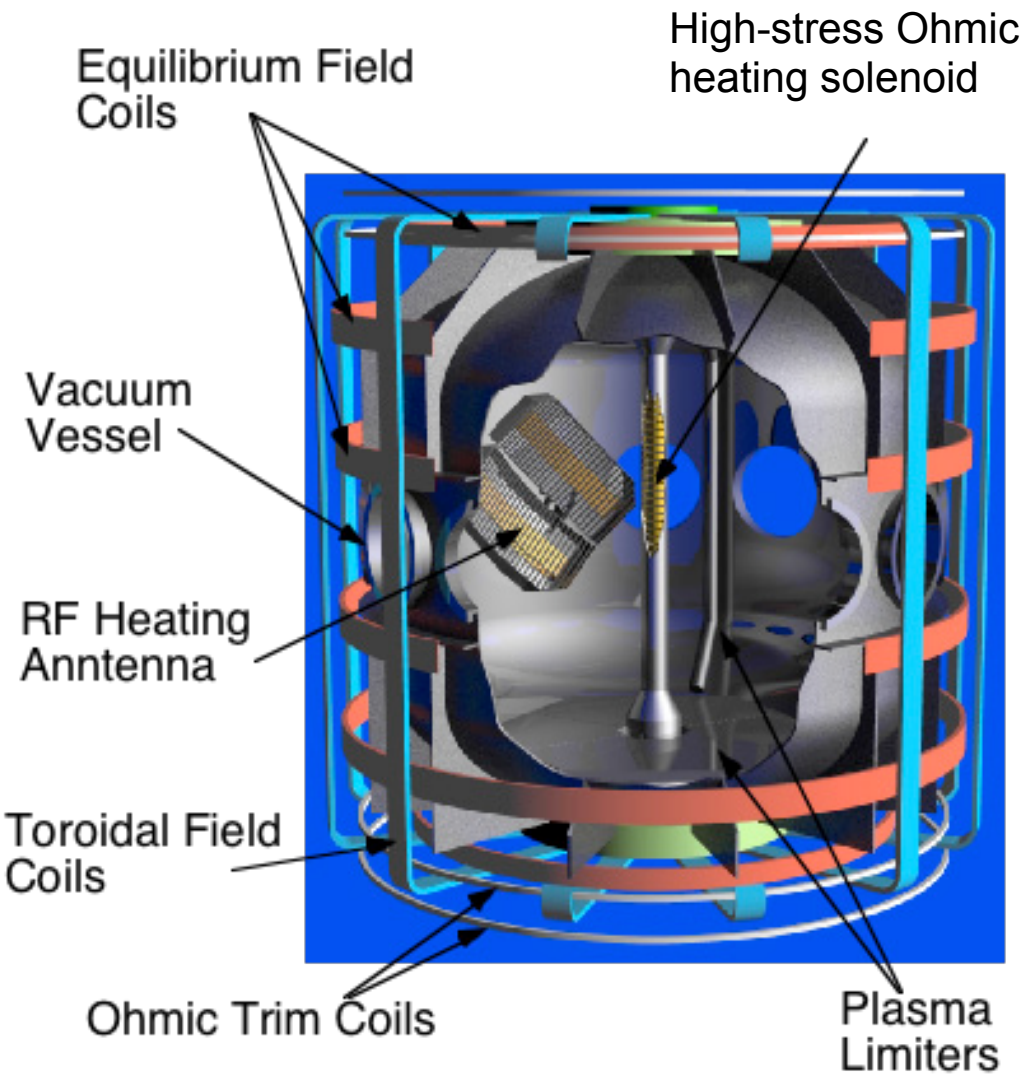
Large-scale, coherent, high-m filamentary edge instabilities are routinely observed under conditions of high edge current density in the PEGASUS Toroidal Experiment. These instabilities exhibit properties strikingly similar to Edge Localized Mode observations in large, high-performance advanced tokamak plasmas. In particular, the filaments are observed via high-speed imaging and local magnetic field fluctuation measurements to have low- to intermediate-*n*, large poloidal coherence lengths (over the majority of the poloidal cross-section), to rotate in the poloidal direction, and to explosively detach from the plasma edge region and propagate radially outward. Local edge measurements with scanning magnetic and electrostatic probes indicate these ELM-like structures have both magnetic and electrostatic turbulence properties. A coherent electromagnetic signature is particularly evident in the 100-200 kHz spectral range. This signature vanishes rapidly with distance from the last closed flux surface, consistent with a MHD origin and high *m*. These ELM-like structures may be explained by peeling-ballooning stability theory. The extremely low-**B** ($B_{t,0} \leq 0.1$ T at $R_0 = .45$ m) and high edge current density ($j_{edge} \approx 100$ kA/m^2) present in PEGASUS leads to high peeling instability drive, proportional to $\langle j_{edge}/B \rangle$, that is comparable to that achieved in H-mode operation on larger experiments. It is thus reasonable to expect peeling modes in PEGASUS, although the large relative $\langle j_{edge}/B \rangle$ is due to the naturally very low magnetic field and strong dI_p/dt (≤ 50 MA/s) driving j_{edge} as opposed to the presence of a strong pressure gradient and bootstrap current in the edge. PEGASUS, as a very low-field ST, offers a unique opportunity to study detailed properties of peeling-ballooning instabilities, in that the edge current and pressure profiles can readily be measured in detail via insertable probes. To that end, a new magnetic probe array and a scanning Langmuir probe assembly are being installed on PEGASUS. They will provide measurements of $P_e(R,t)$, $B_z(R,t)$ with high spatial and temporal resolution for comparison to peeling-ballooning stability theory with direct experimental constraint on both the edge current and pressure profiles in equilibrium reconstructions.

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

Motivation

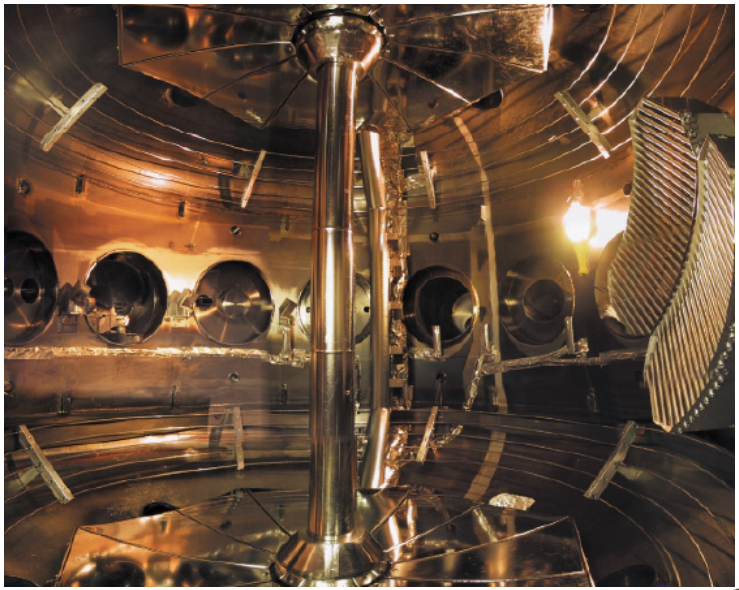
- Edge Stability Critical to Next-Step Devices
  - Transient ELM heat loads → PFC damage
  - Filamentary structures transiently studied during ELMs in large devices
- PEGASUS: Filamentary edge instabilities at high $\langle j_{edge}/B \rangle$
  - Visually similar to ELM bursts in other machines
  - Field-aligned, low to intermediate n, high m
  - Edge detachment and outboard radial propagation
  - Varying lifetime $\tau \leq 150$ μs
- Research goal: Characterize instability in PEGASUS
  - High-speed imaging
  - Magnetic characterization via external, internal magnetic probes
  - Electrostatic fluctuations via Langmuir probes

PEGASUS: A University Scale, Ultralow-A ST



Experimental Parameters

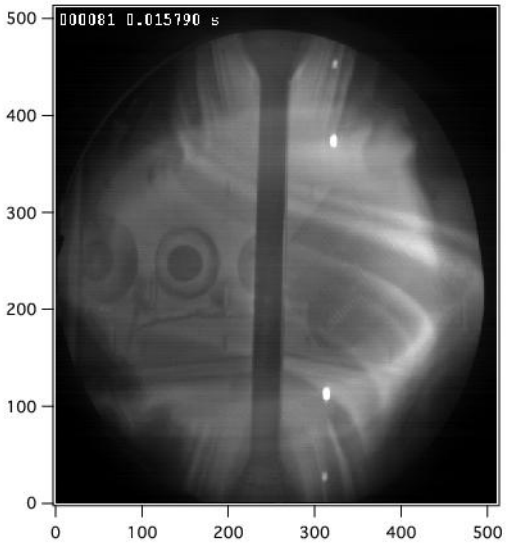
Parameter	Achieved	Goals
A	1.15-1.3	1.12-1.3
R (m)	0.2-0.45	0.2-0.45
I_p (MA)	≤ 0.18	≤ 0.30
I_N (MA/m-T)	6-12	6-20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4–3.7	1.4–3.7
τ_{shot} (s)	≤ 0.02	≤ 0.05
β_t (%)	≤ 25	> 40
P_{HHFW} (MW)	0.2	1.0



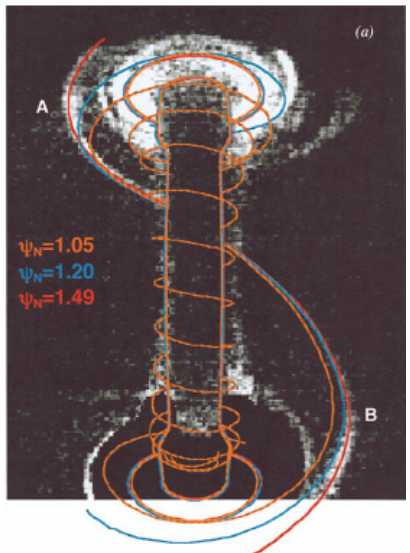
M.W. Bongard, H-Mode Wkshp, PPPL, 10/09

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PEGASUS: Edge Structures Similar to ELMs

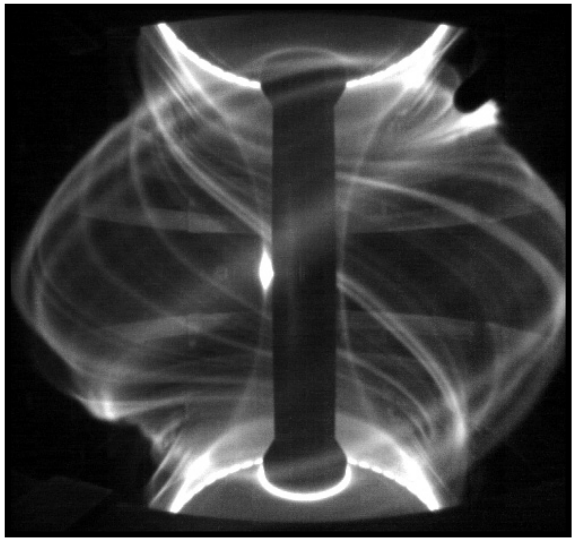


PEGASUS



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

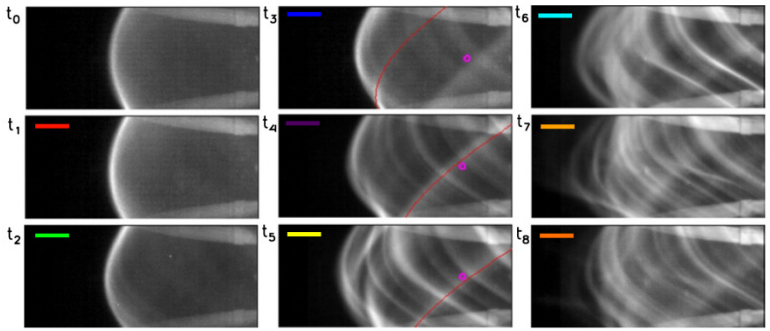
NSTX



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

MAST

- Filamentary, field-aligned structures
  - Present under conditions of high $\langle j_{edge}/B \rangle$
- PEGASUS: L-Mode edge assumed
  - Filamentation continuous in time, unlike strong ELM burst behavior

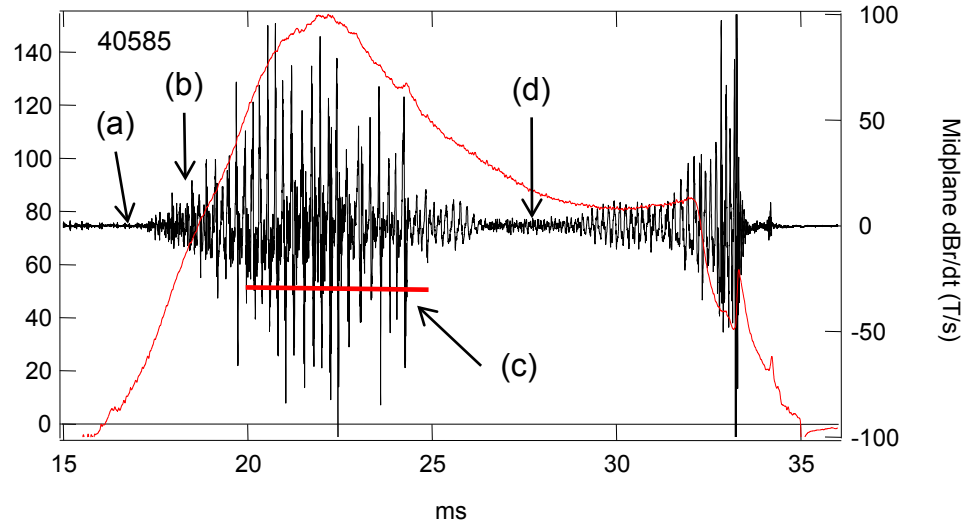


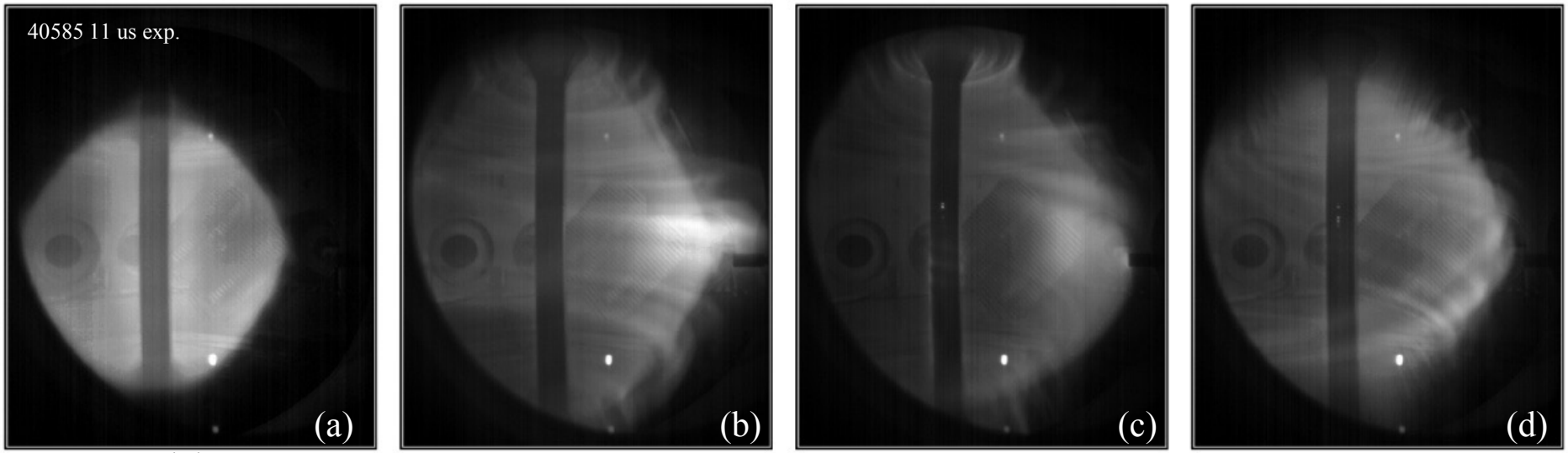
Scannell, Plas. Phys. Controlled Fus. **49**, 2007

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Distinct Edge Stability Phases Observed

- Breakdown/pre-filamentary
- Peeling-like
  - High m, low n; rotation, radial propagation
- m/1: Violent internal tearing
- MHD Quiescent L-mode



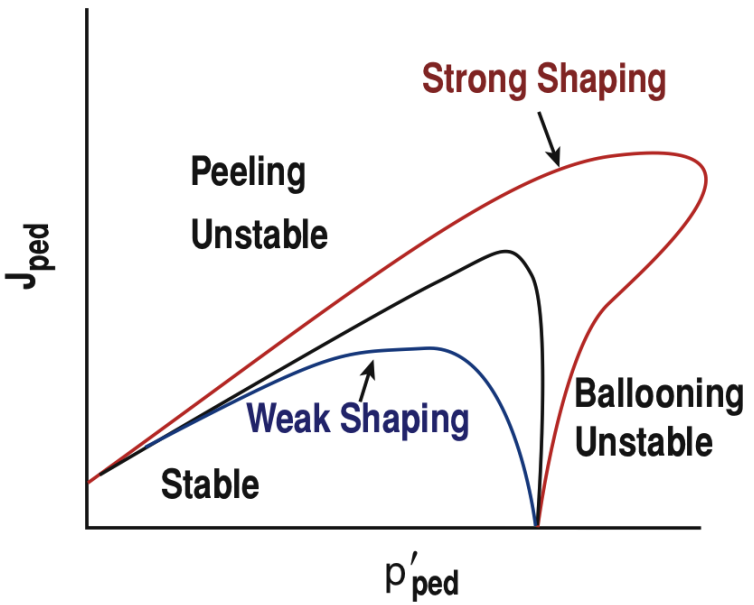


Breakdown | Peeling-like | m/1 | MHD Quiescent

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Candidate Instability: The Peeling Mode

- Peeling-ballooning theory is a proposed mechanism for ELMs
  - Localized MHD edge instability
- Peeling
  - Edge current, current gradient drive
  - Stabilized by pressure gradient
- Ballooning
  - Normal pressure gradient drive from H-mode pedestal
  - Stabilized by shear
- Strong stabilizing influence of shaping near high-n ballooning limit



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

Peeling Mode Destabilized by $\langle j_{edge}/B \rangle$

- Necessary peeling stability criterion*, valid for finite A:

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

where

  - $D_M \propto p'$ = Mercier coefficient (< 0; $D_I = D_M - 1/4$)
  - q' = Magnetic shear
  - $j_{\|}$ = Parallel edge current density

- Stability in high A, low-β, low ν, weak shaping limit:

$$-D_R > \frac{Rq}{s} \left(\frac{\bar{j}_{\|}}{B} \right)_{edge}, \quad s \equiv \frac{r}{q} \frac{dq}{dr}$$

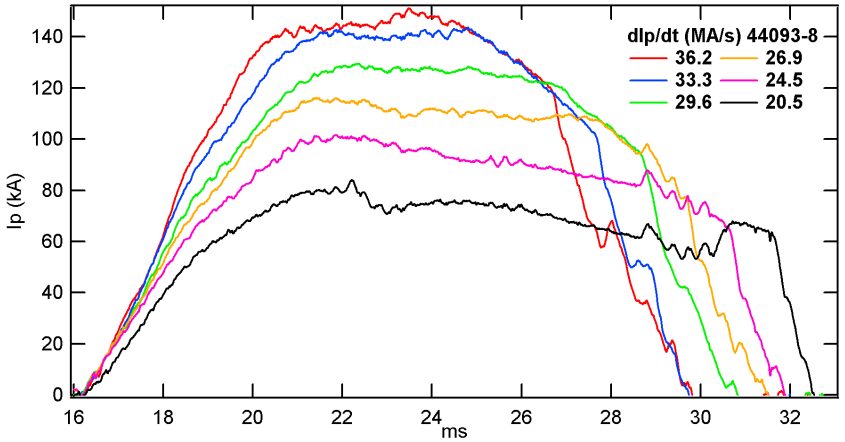
with D_R (< 0) = GGJ resistive interchange coefficient

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

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PEGASUS: Strong Peeling Drive Expected

- Normal Operations:
  - Large dI_p/dt (≤ 50 MA/s) $\rightarrow j_{edge}$ drive
  - Very low toroidal field: $|B_{\varphi,0}| \leq 0.1$ T



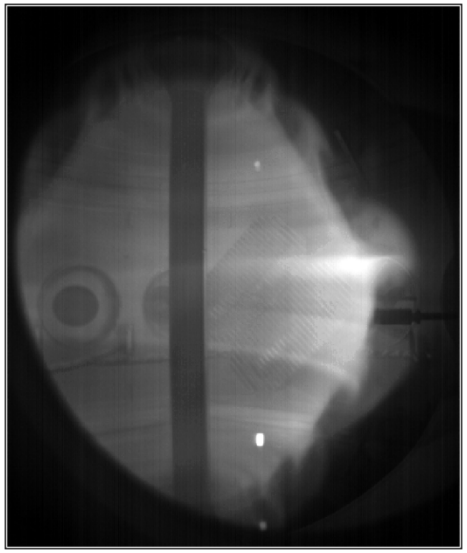
- <j/B> Comparable to Larger Devices; strong peeling drive
  - PEGASUS: $\langle j_{edge} \rangle \sim 10^5$ A/m^2, $B_{\varphi,0} \sim 0.1$ T $\rightarrow j_{edge}/B \sim 1$ MA/(m^2-T)
  - DIII-D*: $\langle j_{edge} \rangle \sim (1\text{-}2)\times 10^6$ A/m^2, $B_{\varphi,0} \sim 2$ T $\rightarrow j_{edge}/B \sim 0.5\text{-}1$ MA/(m^2-T)

- However, *source* of peeling drive different
  - Large machines: H-mode pedestal pressure gradient drives bootstrap current
  - PEGASUS: dI_p/dt drives skin current $\rightarrow$ hollow current profile ($l_i < 0.3$ typ.)

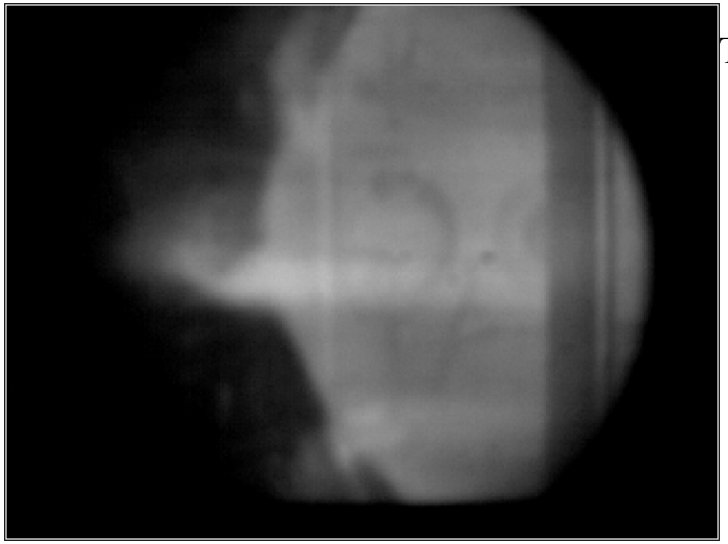
*: Thomas, Phys. Plasmas **12**, 056123 2005

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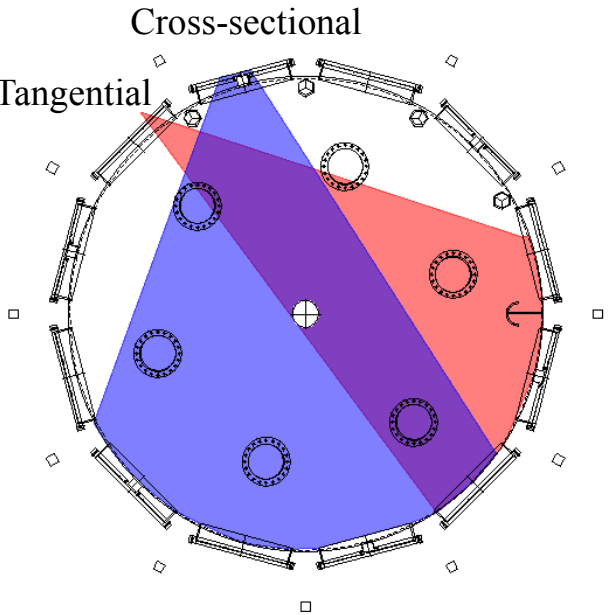
Characterization via High-Speed Imaging



X4: 40271, 9 μs exposure
Cross-sectional view



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

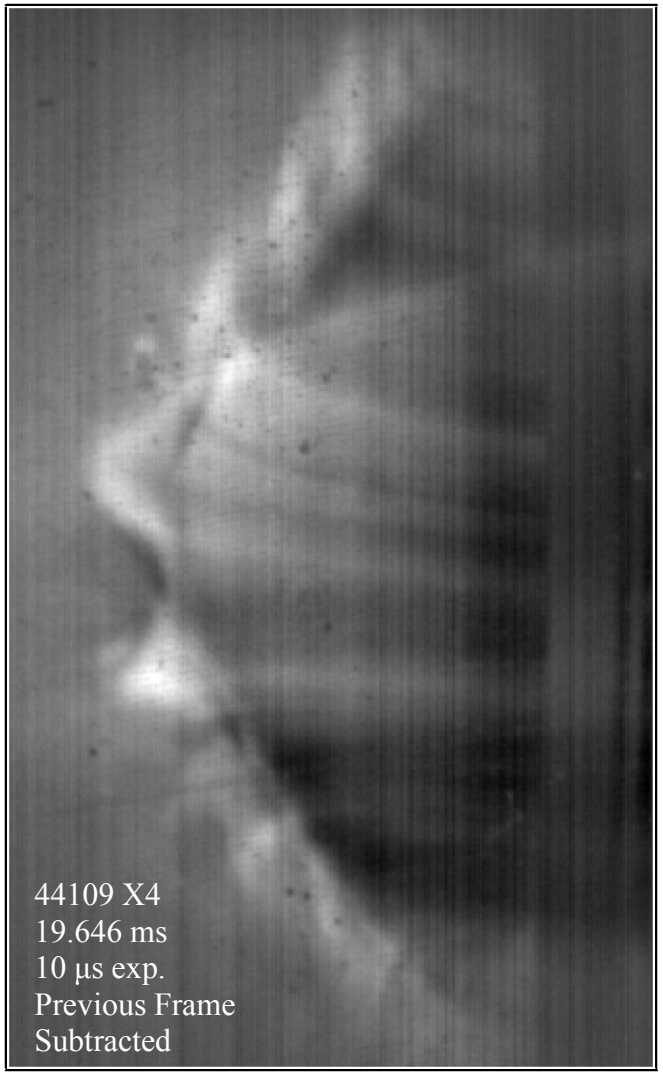


Viewing Ranges

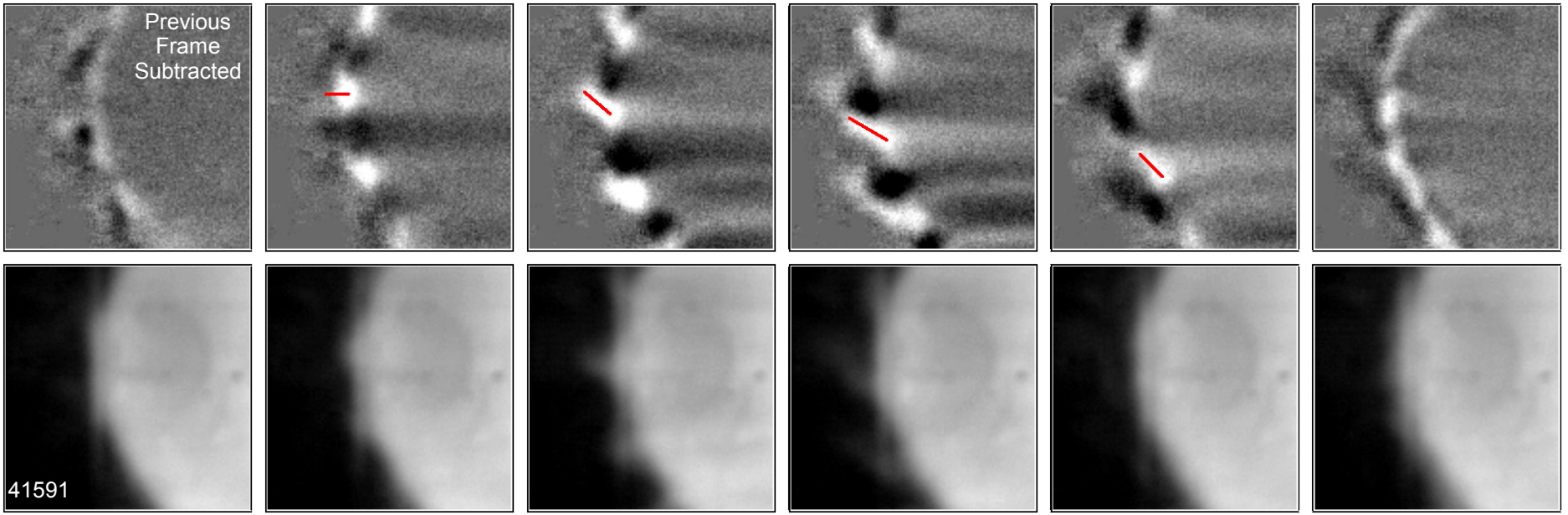
- Red Lake X4
  - 5 kHz frame rate @ 512x512
  - $\Delta t_{exp} \sim$ 5-10 μs
- Phantom v7.3 (PPPL loan)
  - 33 kHz frame rate @ 320x240
  - Frame rates $\leq$ 150 kHz at reduced resolution
  - $\Delta t_{exp} \sim$ 5-10 μs

Rampup: Peeling-like Filament Structure

- Peeling-like filaments observed during periods of high $\langle j_{edge}/B \rangle$
- Spatial coherence
  - Flute-like perturbations appear / decay simultaneously
- High-m structure visible over majority of poloidal cross-section



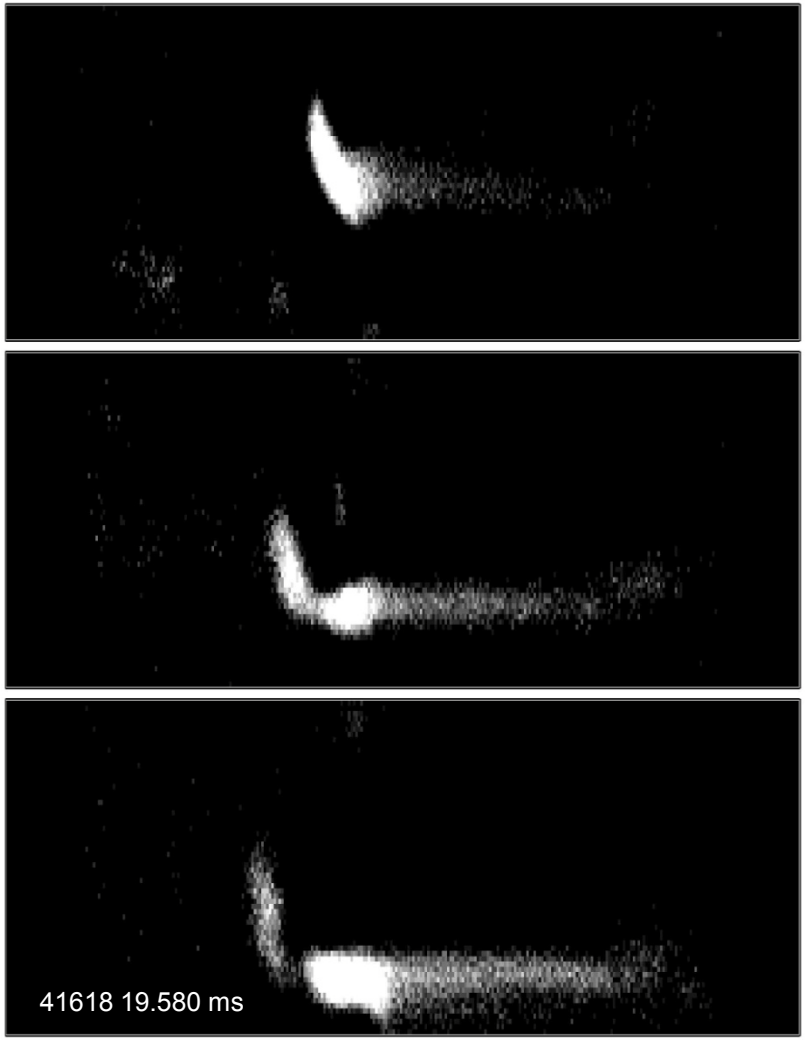
Fast Imaging Aids Mode Characterization



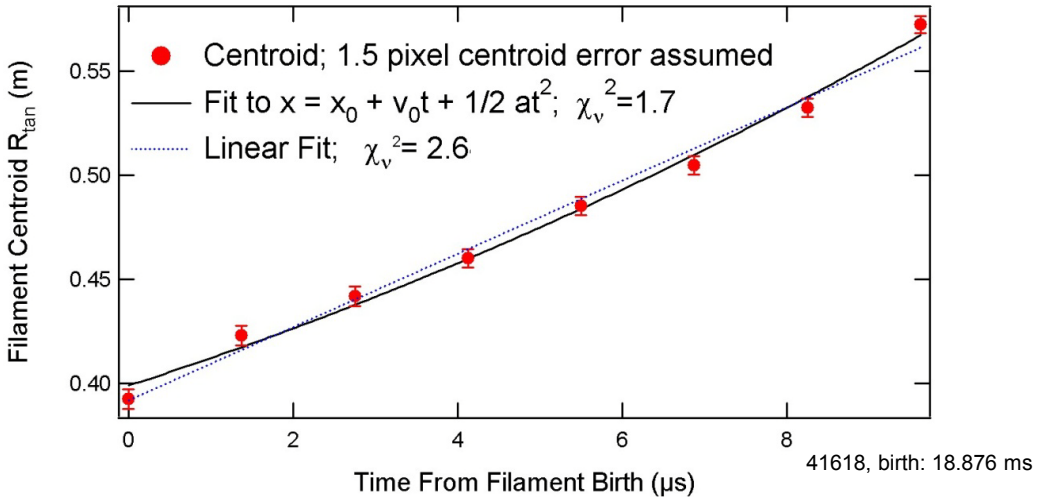
- 90 kHz framing (Δt = 11 μs)
- 9 μs exposure time
- Lifetime ~ 55 μs
- Rotation appears to be in ion diamagnetic drift direction

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Peeling Filaments Propagate Radially



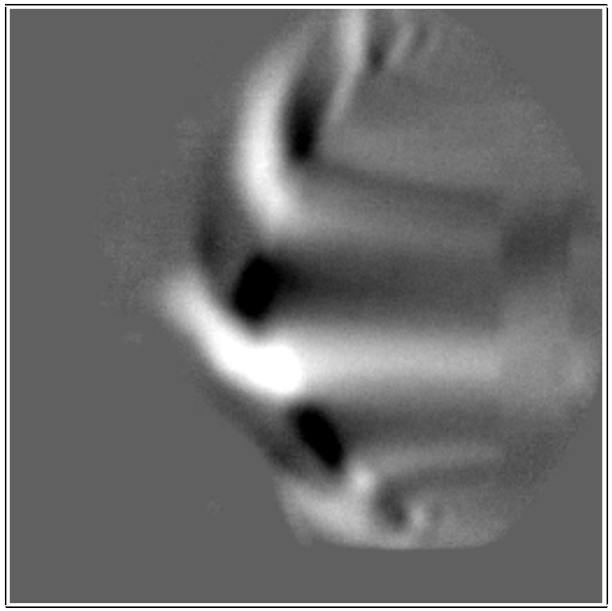
Example of filament detachment and propagation



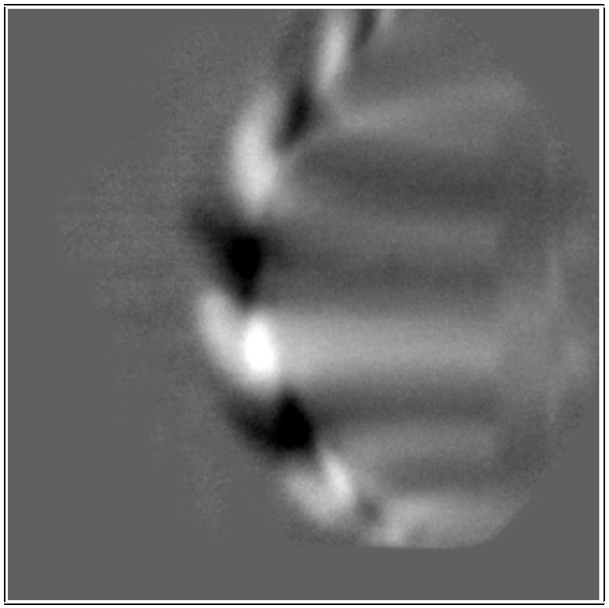
- Filaments detach, propagate radially outboard
- Preliminary analysis:
  - Data best fit with non-zero a_r term
  - Inconclusive for definitive value of a_r
    - Spatial calibration, longer time record required

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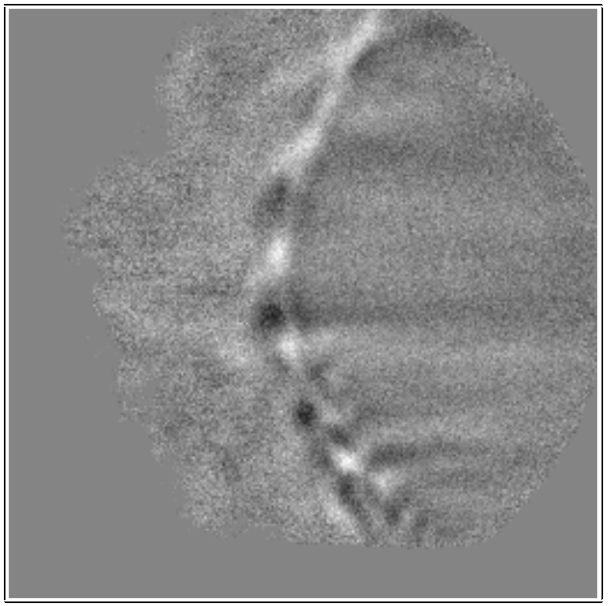
Edge Structures Decrease with B



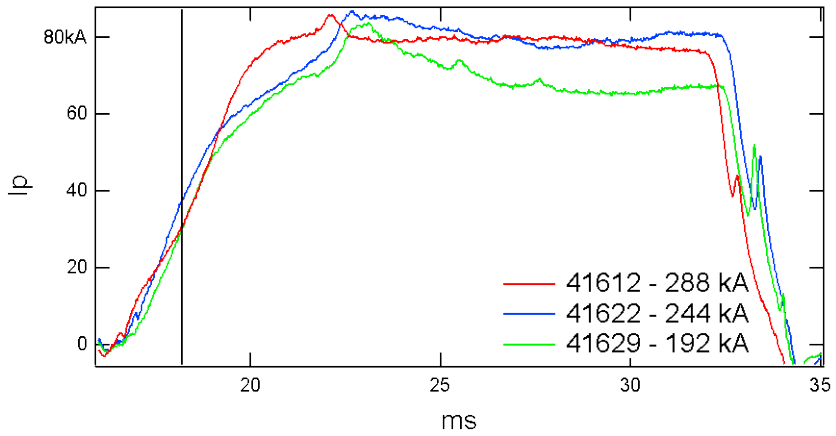
41629, 192 kA, 18.198 ms



41622, 244 kA, 18.198 ms



41612, 288 kA, 18.198 ms



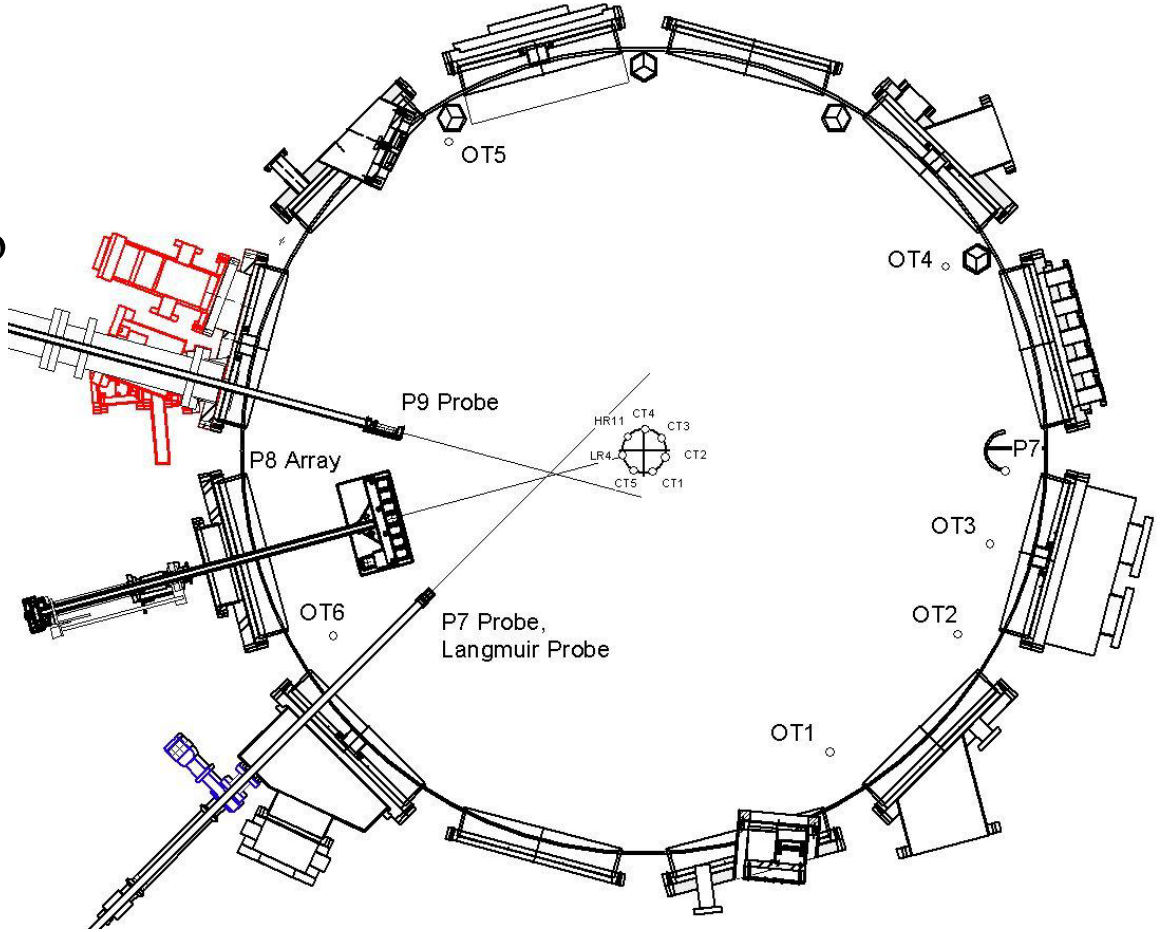
- TF Varied with dI_p/dt, geometry, V_{loop}, fueling held constant
- Edge perturbation size decreases with increasing B_φ

M.W. Bongard, H-Mode Wkshp, PPPL, 10/09

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Fluctuations Characterized via Probes

- Low T_e, short pulse length allows use of internal probes
  - Radially scannable shot to shot
- Variety of probes deployed:
  - P9: B_r, B_z
  - P7: B_z; separate triple Langmuir probe
  - P8 Array: B_z with low $\Delta\varphi$
- Magnetic probes complement existing internal diagnostics



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Spectral Analysis Tools

Cross-spectral density of signals x(t), y(t) over time interval $n_d T$:

$$\hat{G}_{xy} = \frac{2}{n_d T} \sum_{k=1}^{n_d} X_k^*(f,T) Y_k(f,T),$$

where X(f), Y(f) are the Fourier transforms of x,y

Cross-power $\hat{P}_{xy} = |\hat{G}_{xy}|$ with 1-σ random error $\sigma_{\hat{P}_{xy}} = \begin{cases} \frac{1}{\sqrt{n_d}} & x = y \\ \frac{1}{|\hat{\gamma}_{xy}(f)|\sqrt{n_d}} & x \neq y \end{cases}$

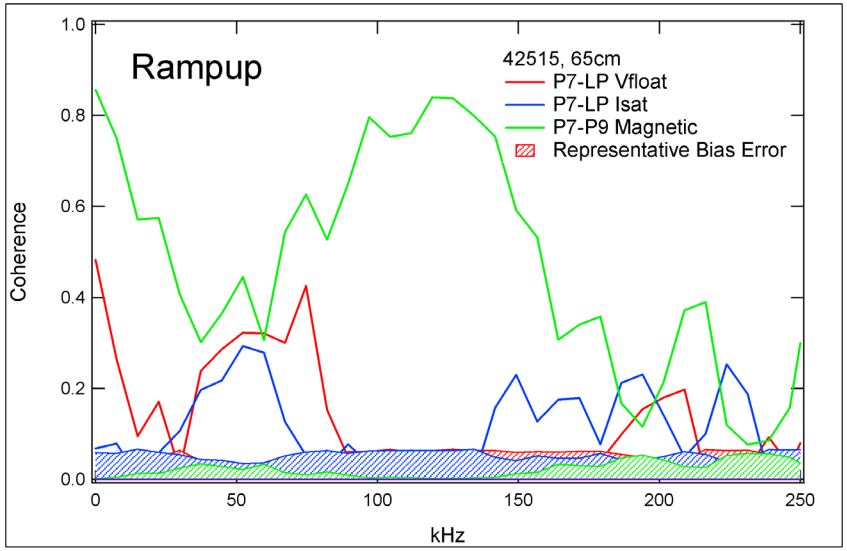
Cross-phase $\hat{\theta}_{xy} = \arctan\left(\frac{\mathcal{I}(\hat{G}_{xy})}{\mathcal{R}(\hat{G}_{xy})}\right)$ $\quad \sigma_{\hat{\theta}_{xy}} = \frac{\sqrt{1-\hat{\gamma}_{xy}^2(f)}}{|\hat{\gamma}_{xy}(f)|\sqrt{2n_d}}$

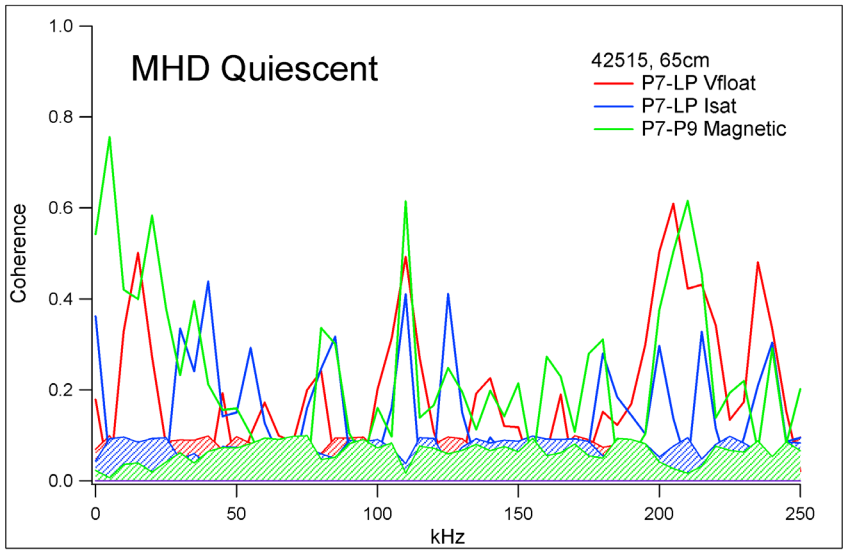
Coherence $\hat{\gamma}_{xy}^2 = \frac{|\hat{G}_{xy}|^2}{\hat{G}_{xx}\hat{G}_{yy}}$ $\quad \sigma_{\hat{\gamma}_{xy}^2} = \frac{\sqrt{2}\left[1-\hat{\gamma}_{xy}^2(f)\right]}{|\hat{\gamma}_{xy}(f)|\sqrt{n_d}}$

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EM Signature Uniquely Present in Rampup

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





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Mode Identification Methods

- Two-point method:*

$$n \approx \frac{\hat{\theta}_{xy,\phi}}{\Delta\phi} \quad m \approx \frac{\hat{\theta}_{xy,\theta}}{\Delta\theta}$$

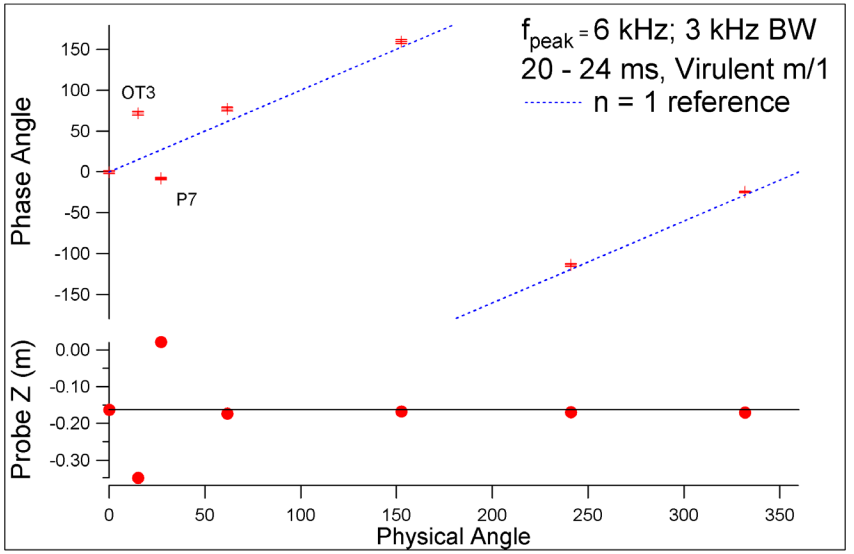
where Δ{φ,θ} are the physical angular separation of the probes

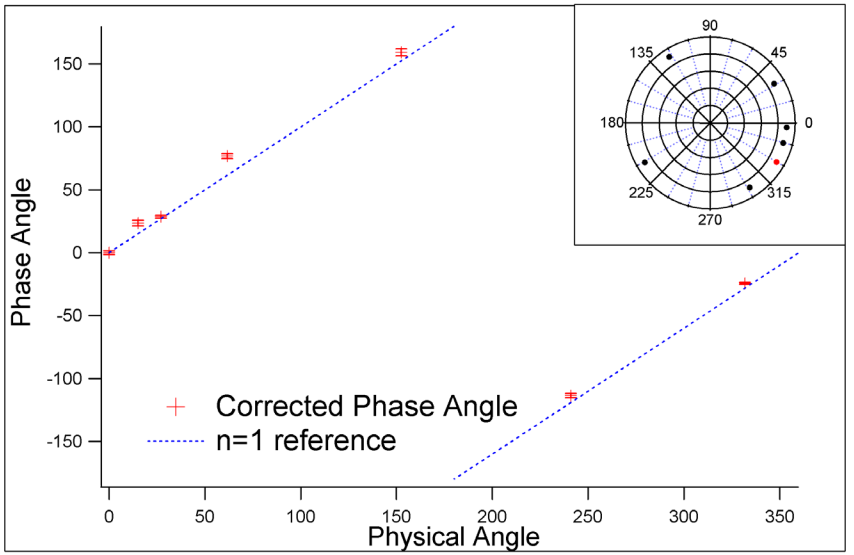
- Phase-slope (P-S)
  - Plot of $\hat{\theta}_{xy}$ vs Δ{φ,θ} for multiple measurements about a narrow spectral band
  - Best-fit n, m is slope of measured phase shift
  - Advantage: Allows multiple measurements to be incorporated into the fit

*Ferron, Rev. Sci. Instrum, 62, 4799, 1992

Non-Planarity Correction for P-S Analysis

- These techniques assume all probes lie in a plane of constant physical angle
  - However, cross-phase techniques measure total phase = nφ + mθ
- For non-planar coils, this leads to a phase discrepancy from the nφ reference, proportional to mθ
  - Given physical angles, this discrepancy may be subtracted away – or used as a simple method for determining m
  - Example: two non-planar coils during virulent n=1 internal tearing activity

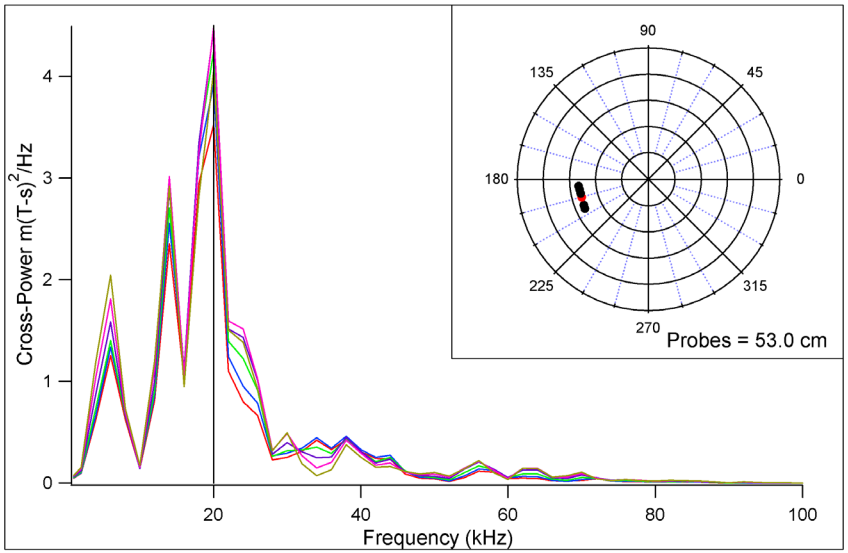


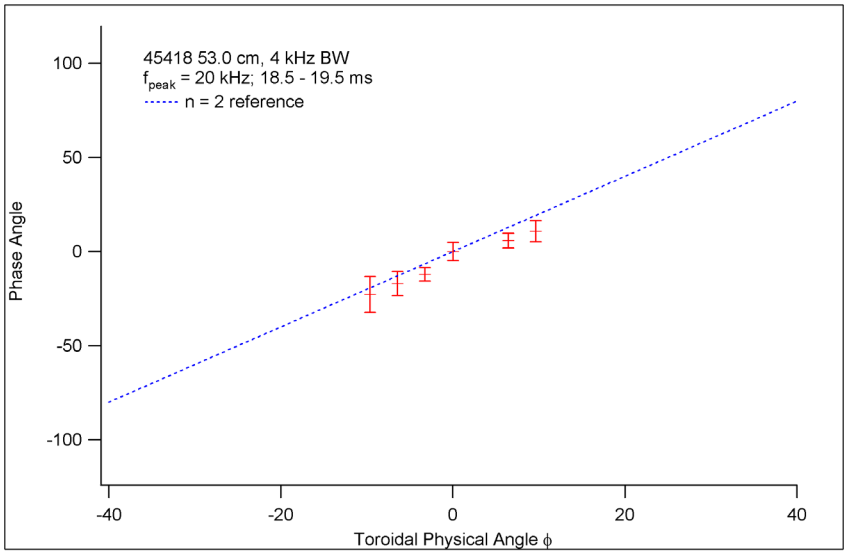


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Filament Helicities Have Low n

- 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

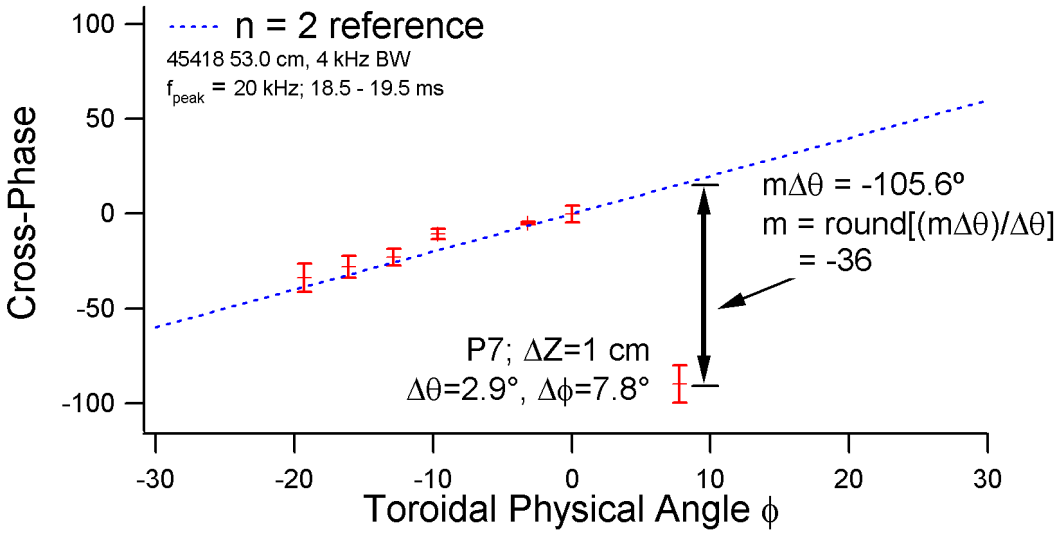


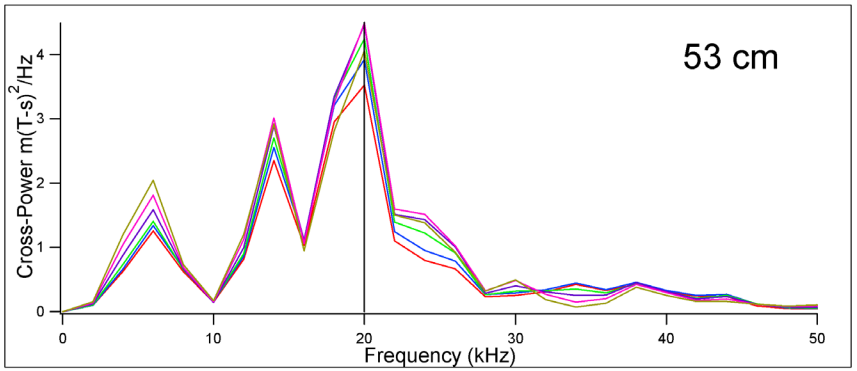


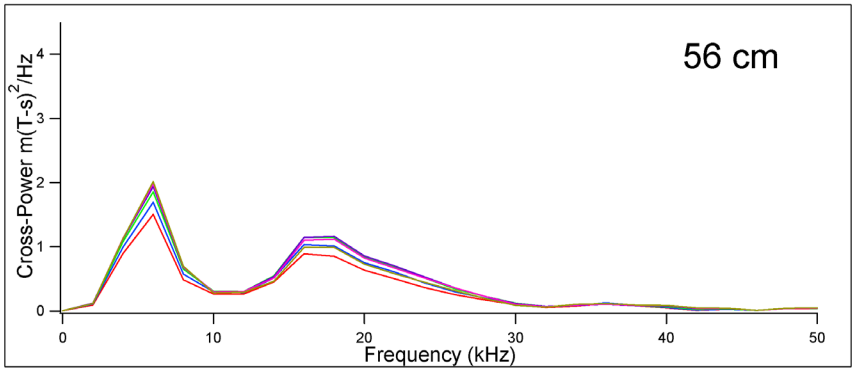
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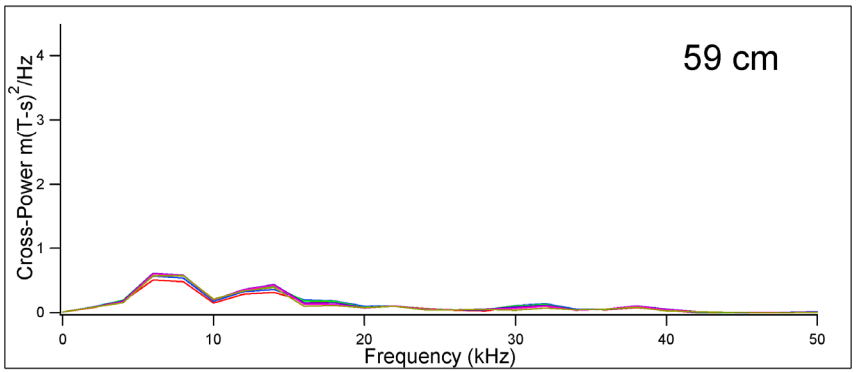
Peeling EM Signature Consistent with High m

- Peeling cross-power spectral peak vanishes rapidly from LCFS
- 2-point m identification: m ~ -36
  - Approximate; need full magnetic geometry correction for accurate m



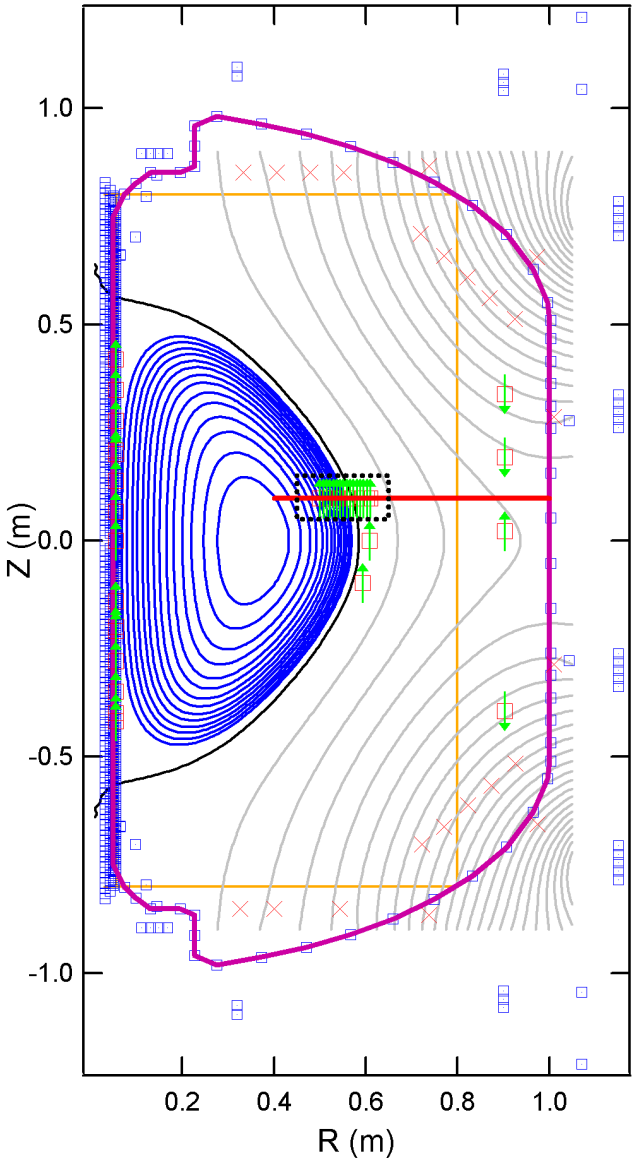




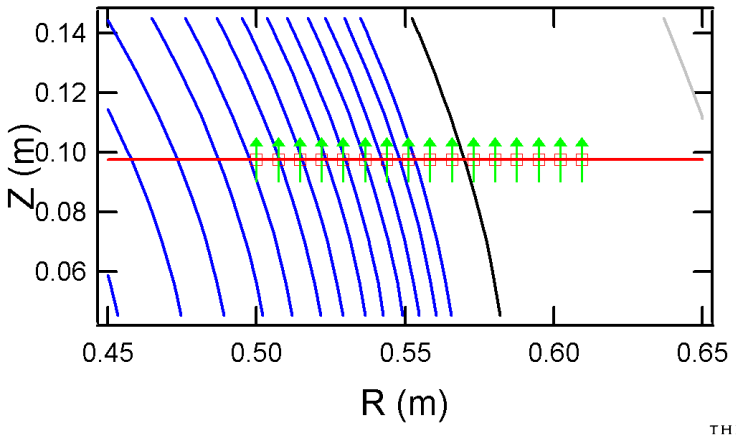


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Stability Analysis Requires Local Measurements



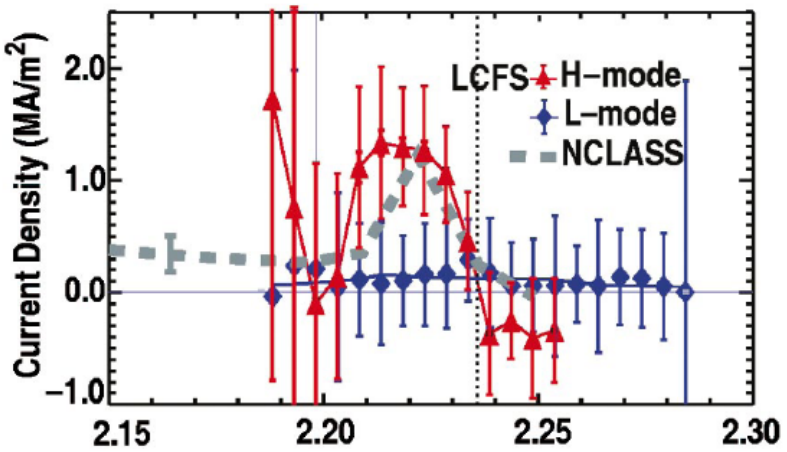
- Comparison of experimental equilibria with a stability analysis depends crucially on accuracy of reconstructions
  - E.g. Peeling-ballooning: edge $P(\psi)$, $j(\psi)$ profiles
- PEGASUS: Operating conditions allow for direct measurement of *internal* B_z
  - New diagnostic capability provides strong experimental constraint on $j(\psi)$

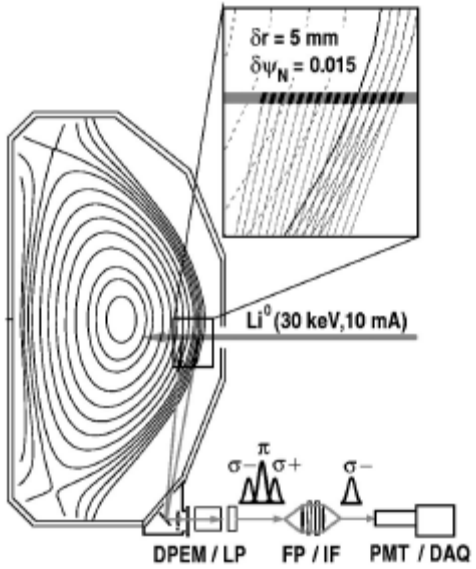


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Experimental J Measurement Desirable

- p(ψ) typically constrained via multichannel TS
  - Currently unavailable on PEGASUS
- J(ψ) equally important to confront theory
  - Extremely challenging measurement on high-temperature ATs
  - Best results to date: DIII-D Li beam polarimetry
- Typical alternative: compute J
  - Assumes bootstrap current drive
  - Questionable assumptions in edge



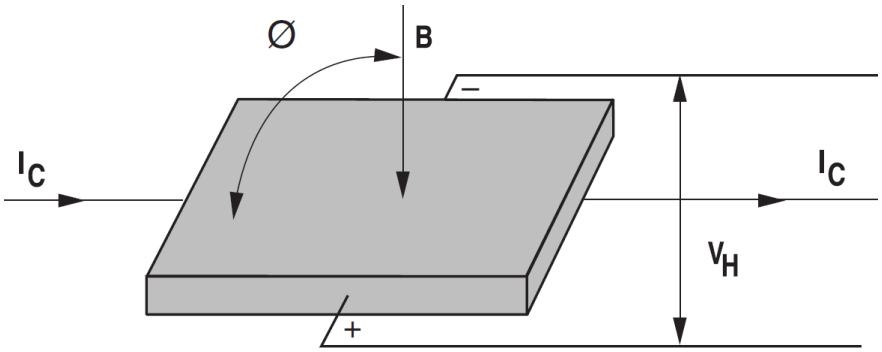


Thomas, Phys. Plasmas **12**, 056123, 2005

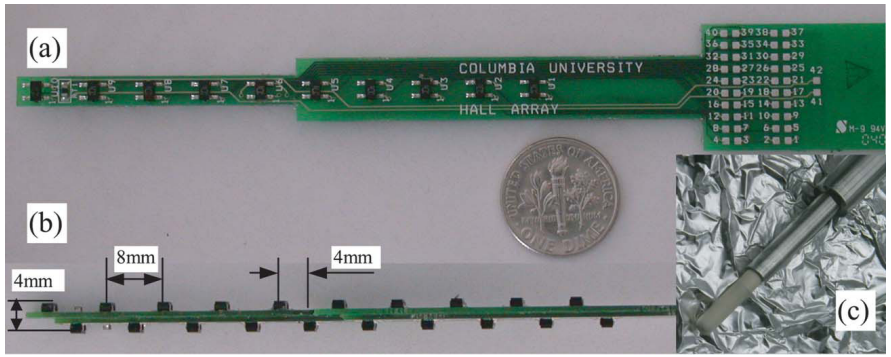
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In-situ Hall Probe Arrays Constrain J(ψ)

- 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)



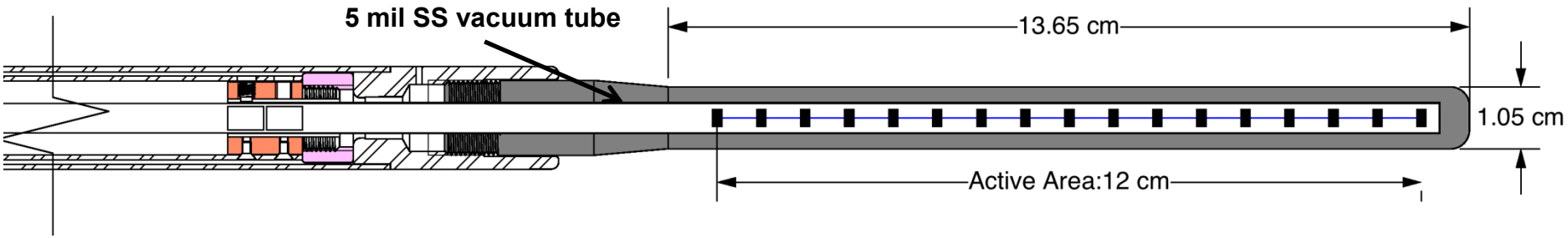
- Deployed on several tokamaks:
  - TEXTOR* : ext. B_z fluctuations
  - HBT-EP**: dB_z/dt, internal B_z
  - PEGASUS: Internal $B_z \rightarrow j(\psi)$



HBT-EP Hall Probe Array**

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

1st Generation Hall Probe Deployed



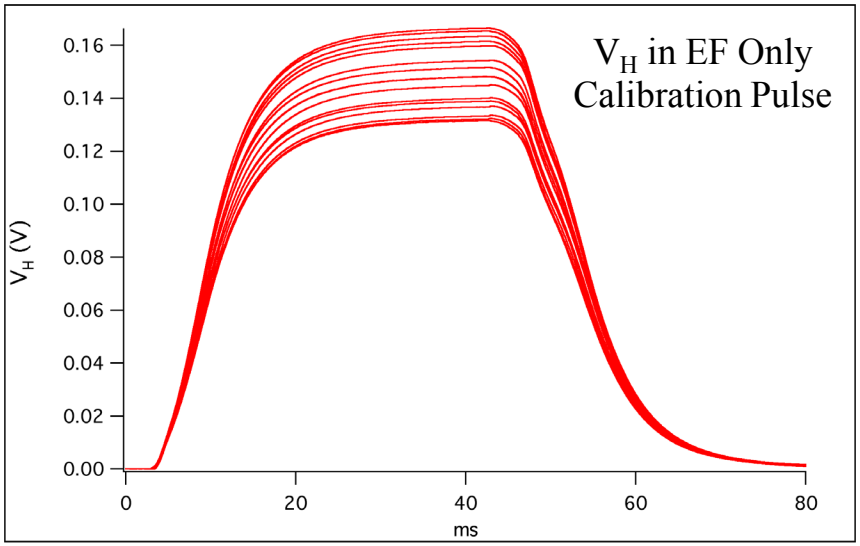
- Solid-state InSb Hall sensors
  - Sypris model SH-410
- 16 channels, 7.5mm center-center spacing
- C armor as low-Z PFC
- Slim profile minimizes plasma perturbation

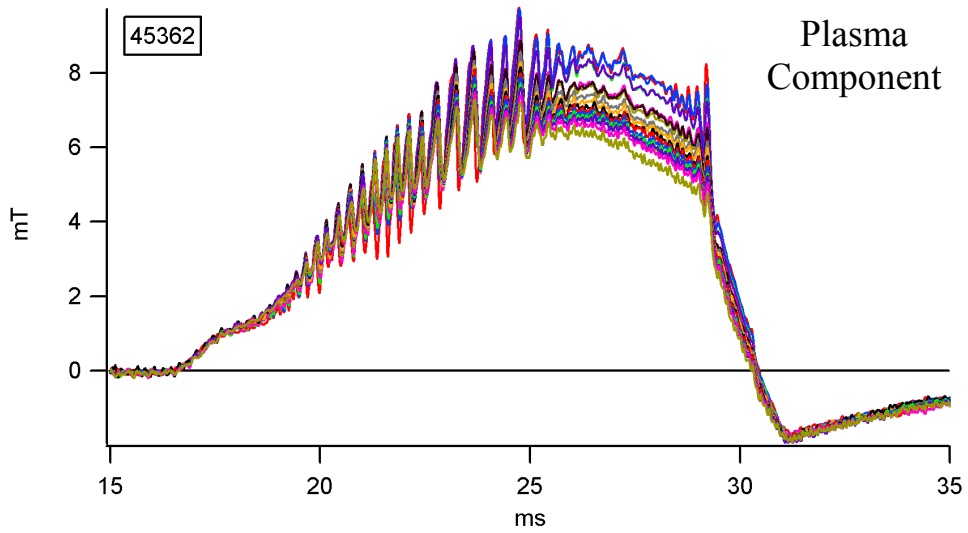


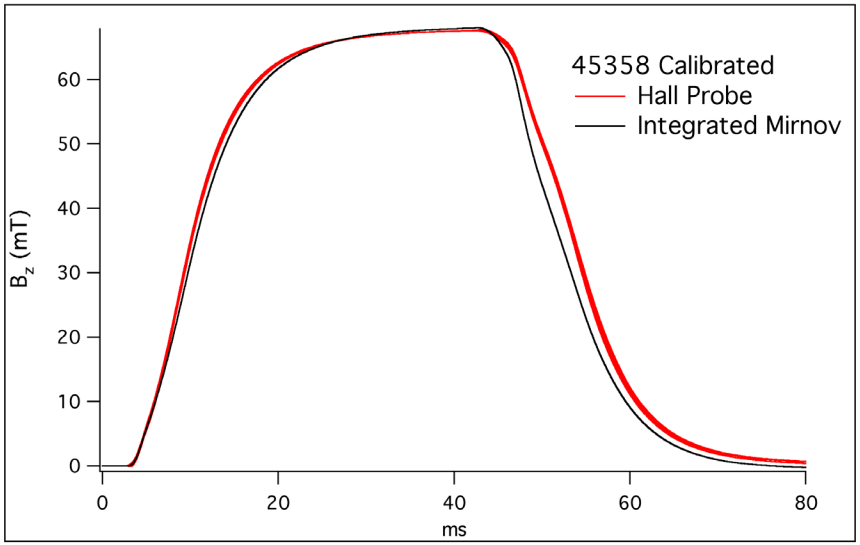
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Initial PEGASUS Hall Data

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

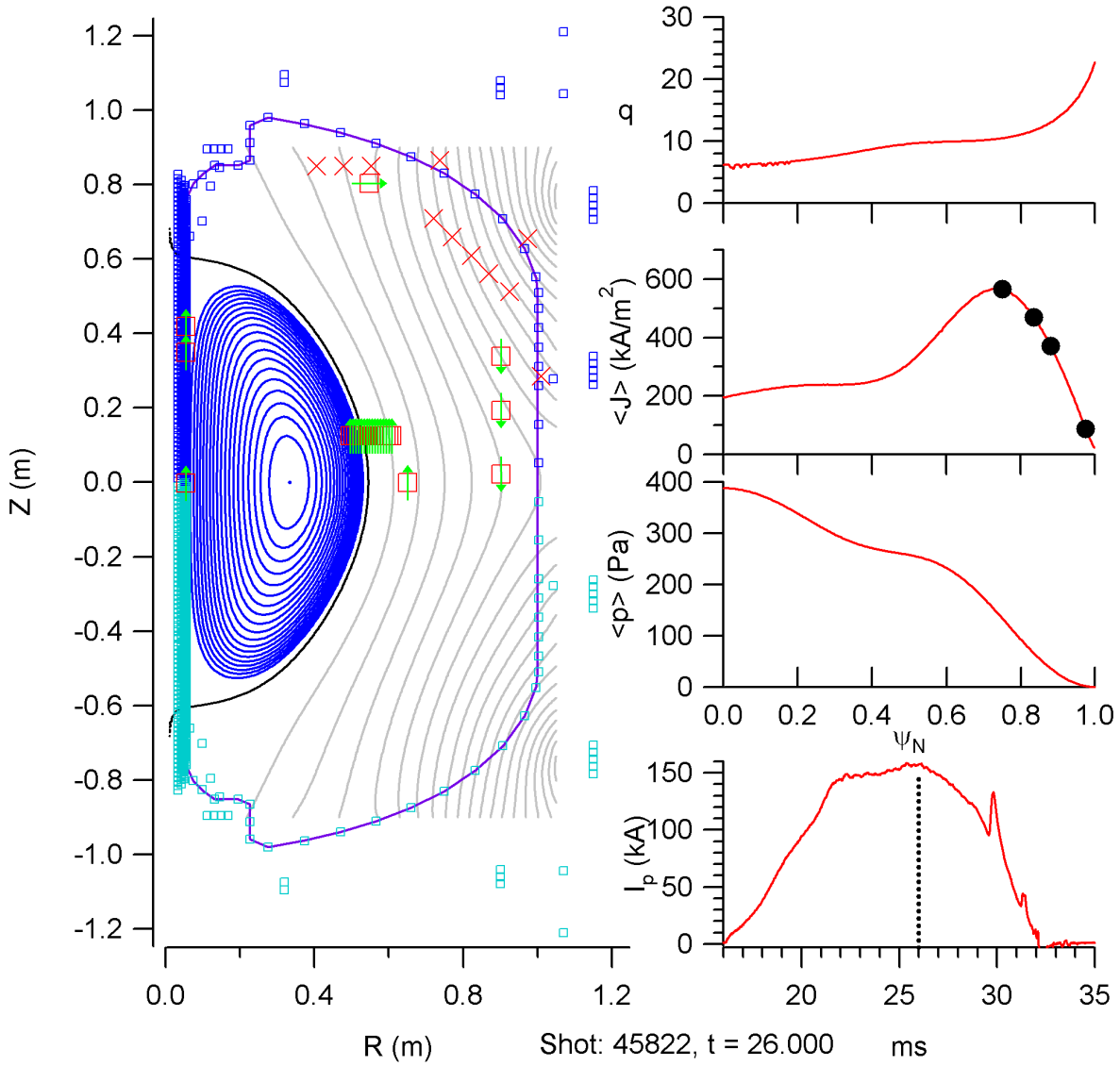






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Initial Internally Constrained Equilibrium



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

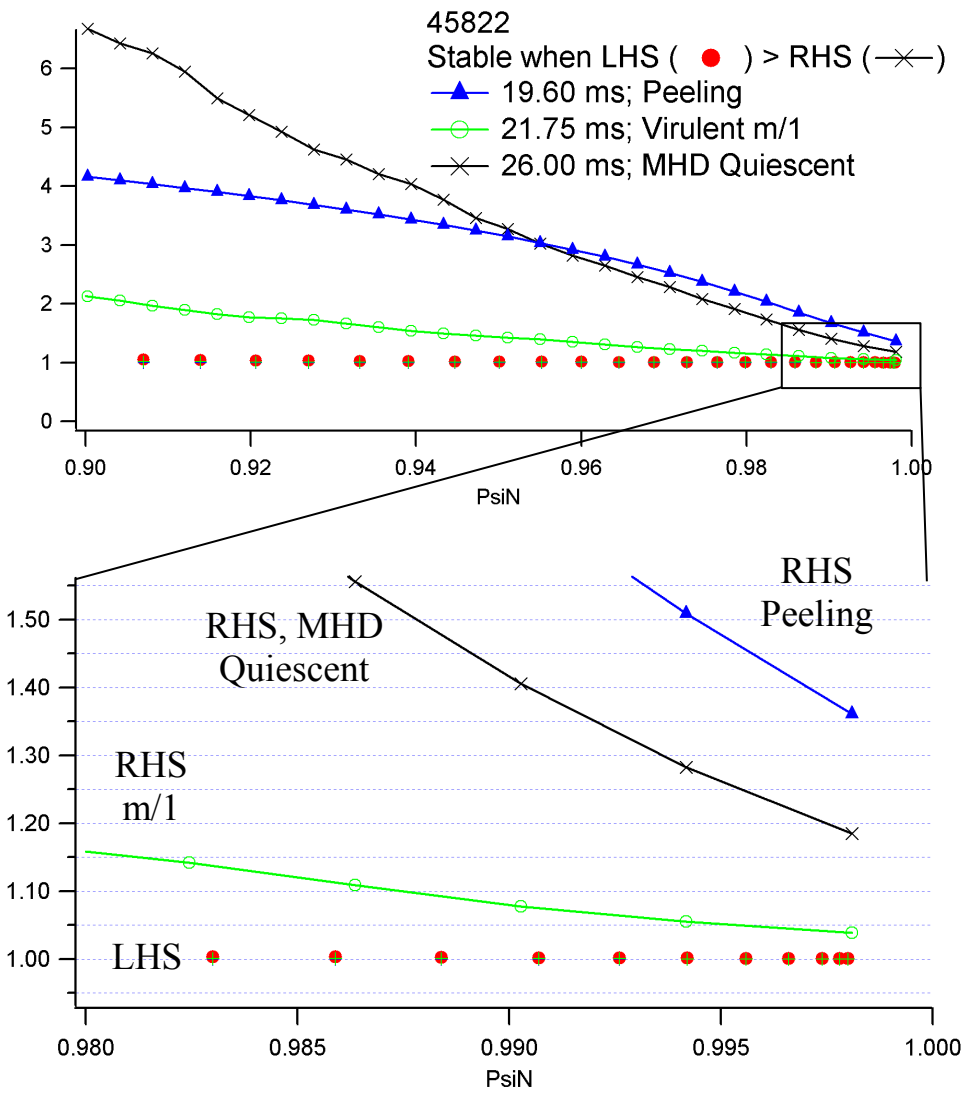
*Sontag, A., et. al., Nuclear Fusion, **48,** 095006 , 2008

I_p	157 kA
R_0	.296 m
a	.242 m
A	1.22
κ	2.20
l_i	.250
β_p	.102
β_t	.017
q_0	6.14
q_{95}	16.9

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Initial Comparison With Peeling Stability

- Connor's peeling stability criterion computed w/ DCON
  - RHS from equilibrium fit
- Peeling appears unstable at all times
  - Not observed; however, peeling phase *is* least stable of all phases
- Critical Issue: How well is j(ψ) determined at edge?
  - Initially employed spline model is relatively coarse; may significantly underestimate dj/dψ in edge
  - Precise test requires improved j(ψ) determination and full uncertainty analysis



Unstable if RHS > LHS

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Future Work

- Equilibrium and stability studies with accurate j(ψ)
  - Enhancements to KFIT to accommodate diagnostic capabilities
- Deployment of Langmuir probe arrays for internal T_e,n_e
  - Affords $p_e(\psi)$ constraint
- Additional filament characterization via high-speed imaging
  - Phantom v12.0 camera coming online 4Q 2009
- Possible development of Hall Probe arrays
  - Improved spatial resolution for stronger j(ψ) constraint
  - Improve S/N, possibly frequency response

Summary

- Localized filamentary edge instabilities present in PEGASUS consistent with peeling drive
  - Triggered during conditions of high $\langle j_{edge}/B \rangle$
  - Electromagnetic signature with low n, high m
  - Nonlinear phase: explosive detachment and radial propagation
- Measurement capabilities deployed to directly constrain $j(\psi)$
  - Results demonstrate capability to measure $B_z(R,t)$ at edge and inward
  - Initial analysis with relatively smooth $j(\psi)_{edge}$ model suggests stronger peeling drive at time of observation
    - Expansion of equilibrium parameterization and coupling to DCON will provide more rigorous comparison with peeling theory
- Future: extend operations to peeling-ballooning regime?
  - Requires high-β_t operations

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Reprints of this and other PEGASUS presentations are available at

http://pegasus.ep.wisc.edu/Technical_Reports