Edge Current Profile Measurements of Peeling-like Modes at High $\langle J_{edge}/B \rangle$ in PEGASUS

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University of Wisconsin-Madison

51st Annual APS-DPP

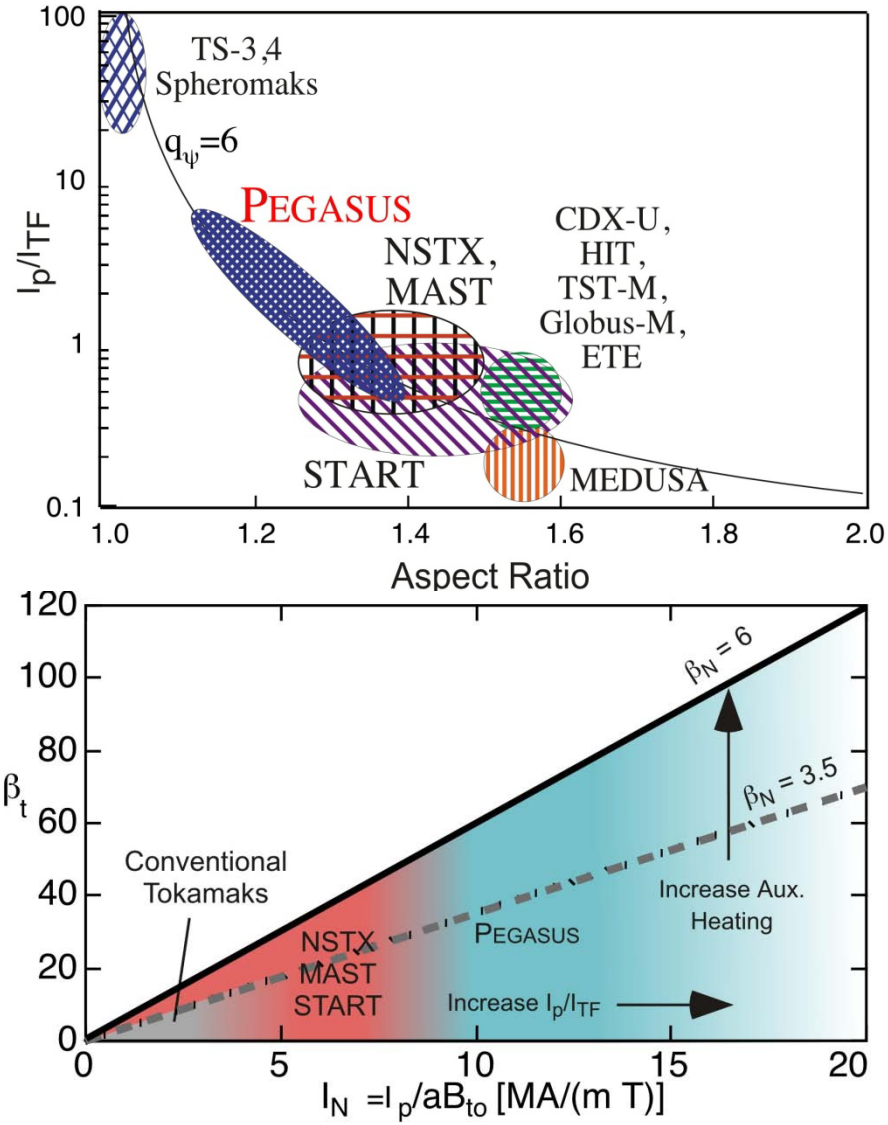
Atlanta, GA
November 3, 2009



PEGASUS
Toroidal Experiment

PEGASUS Mission: Physics of Low A → 1

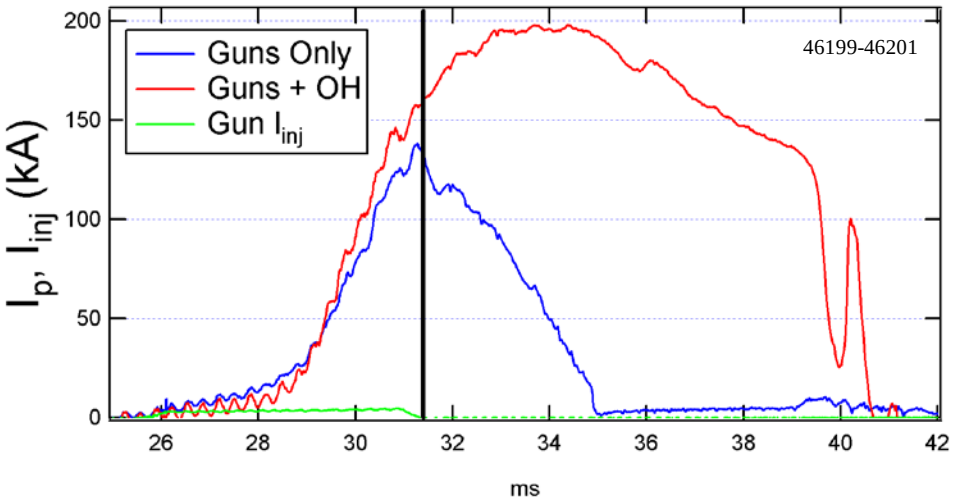
- University-scale, Low-A ST
  - $R_0 \leq 0.45$ m, a ~ 0.40 m
- Physics of High I_p/I_{TF}
  - Expand operating space of the ST
  - Study high β_t plasmas as A → 1

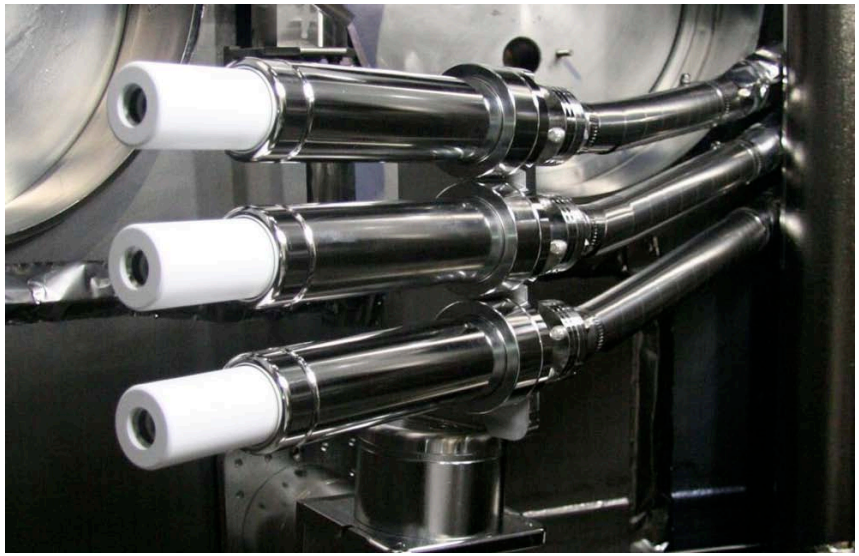


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PEGASUS Mission: Physics of Low A → 1

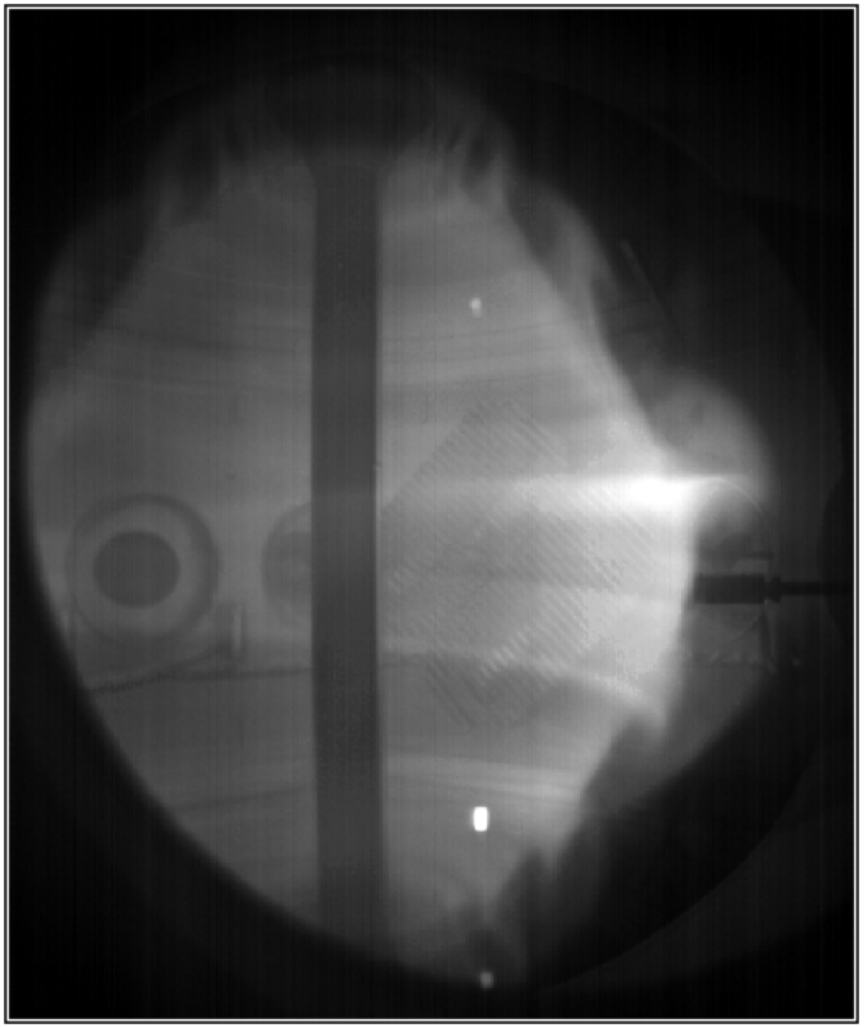
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  - Point Source DC Helicity Injection ("Plasma Guns")
  - Addressing critical ST physics of plasma initiation, growth



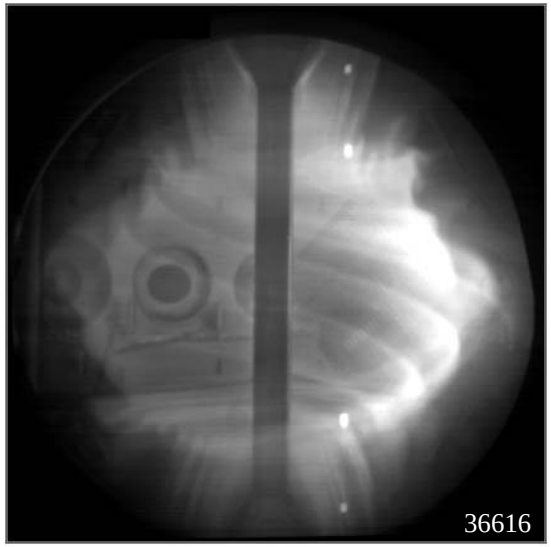


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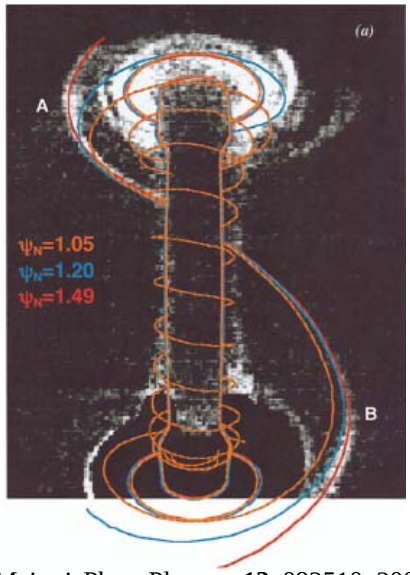
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  - Point Source DC Helicity Injection ("Plasma Guns")
  - Addressing critical ST physics of plasma initiation, growth
- Edge Stability Physics
  - Peeling modes at high $\langle j_{edge}/B \rangle$



PEGASUS: ELM-like Structures Observed

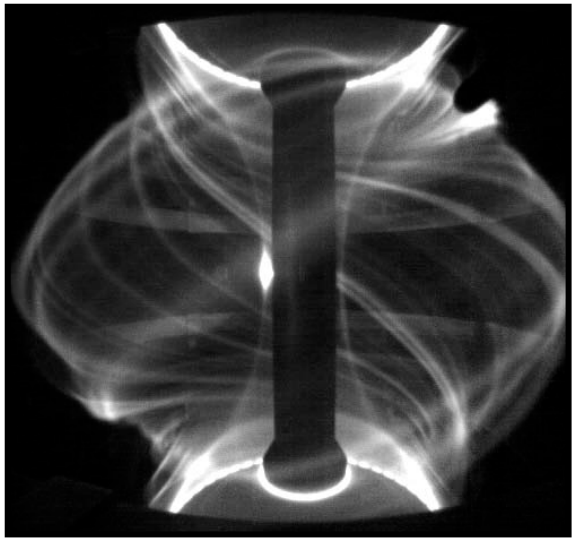


PEGASUS



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

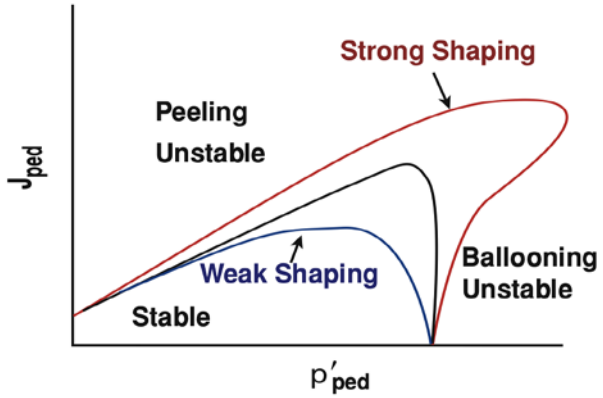
NSTX



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

MAST

- ELMs take form of filamentary, field-aligned structures
  - Peeling-ballooning theory: trigger mechanism
- PEGASUS: L-mode edge assumed
  - Peeling instability candidate mechanism



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

Near-unity A: Naturally Strong Peeling Drive

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

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

- j_{edge}/B is a figure of merit for quantifying peeling drive
- 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 ($\leq$ 50 MA/s) → transient skin current

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Near-unity A: Naturally Strong Peeling Drive

Device	J_{edge} (MA/m²)	$B_{\varphi,0}$ (T)	J_{edge}/B
PEGASUS	~ 0.1 – 0.2	0.1	**~ 1**
DIII-D*	1 – 2	2	**0.5 – 1**

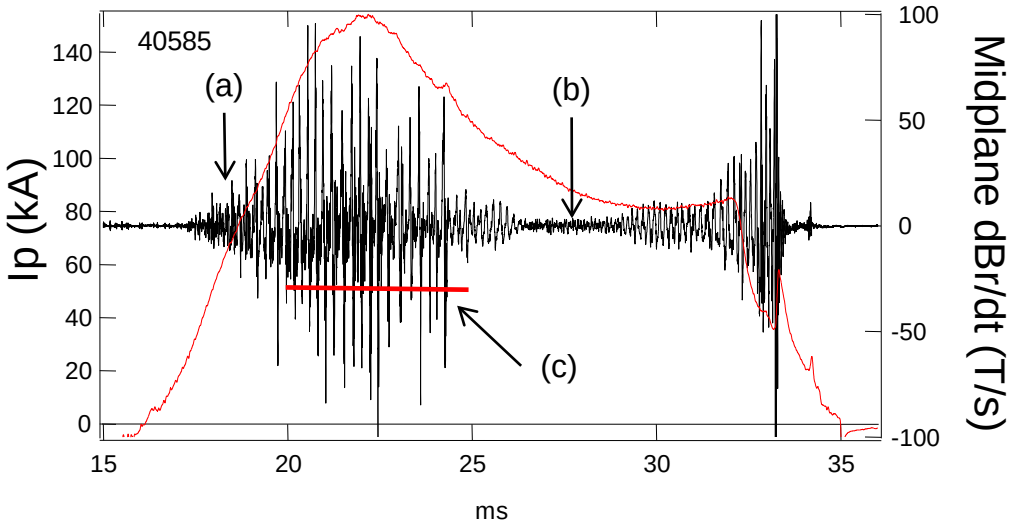
*: Thomas, Phys. Plasmas **12**, 056123 2005

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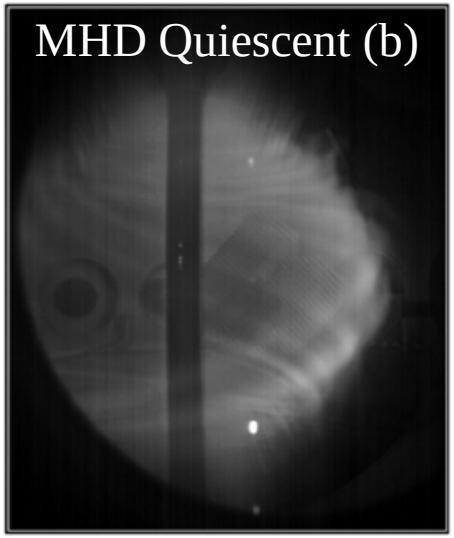
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Two Distinct Filament Classes Observed

- 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 $\tau_{exp} \leq 20$ μs
- Separated by n=1 internal tearing phase (c)



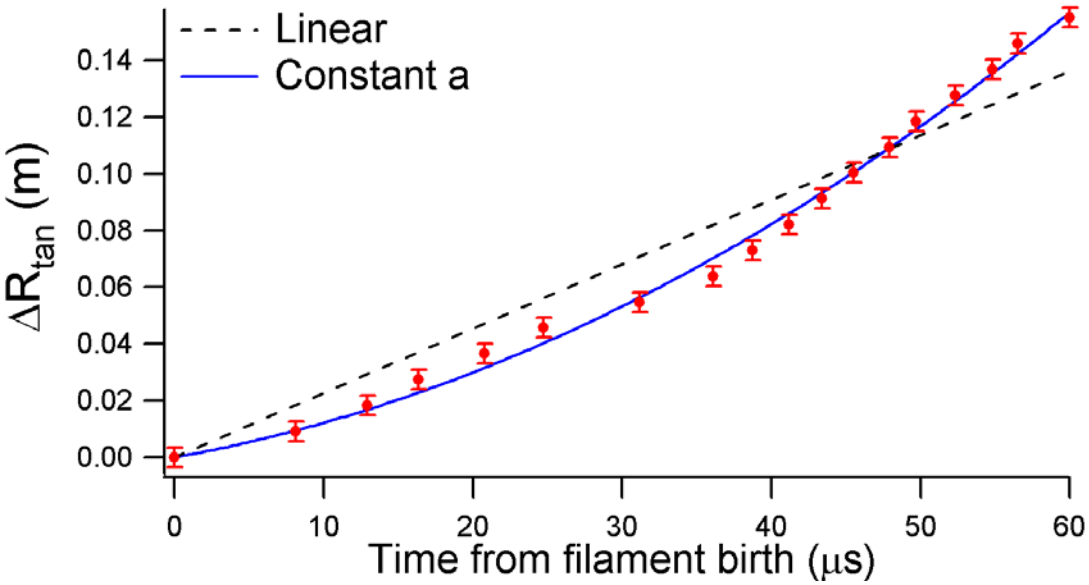


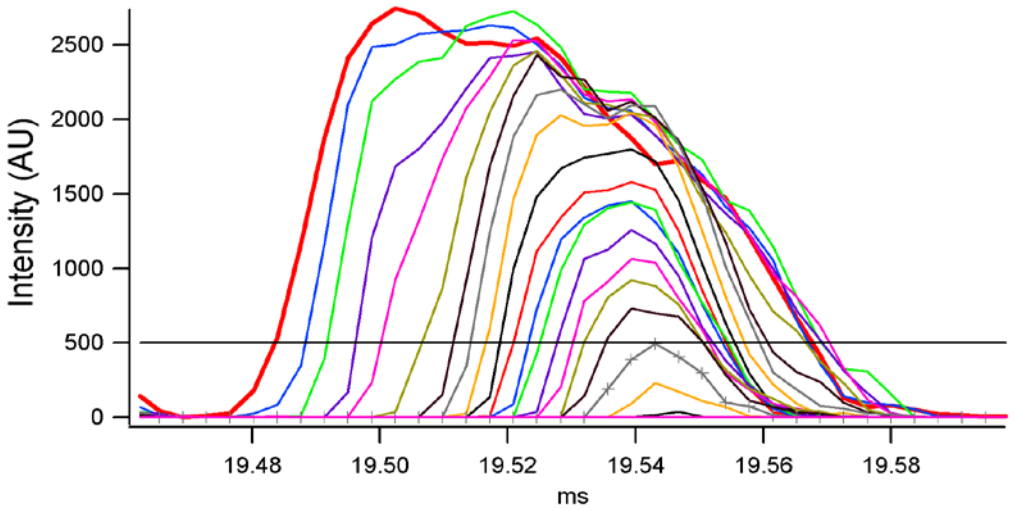


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Peeling-like Filaments Accelerate Radially

- 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





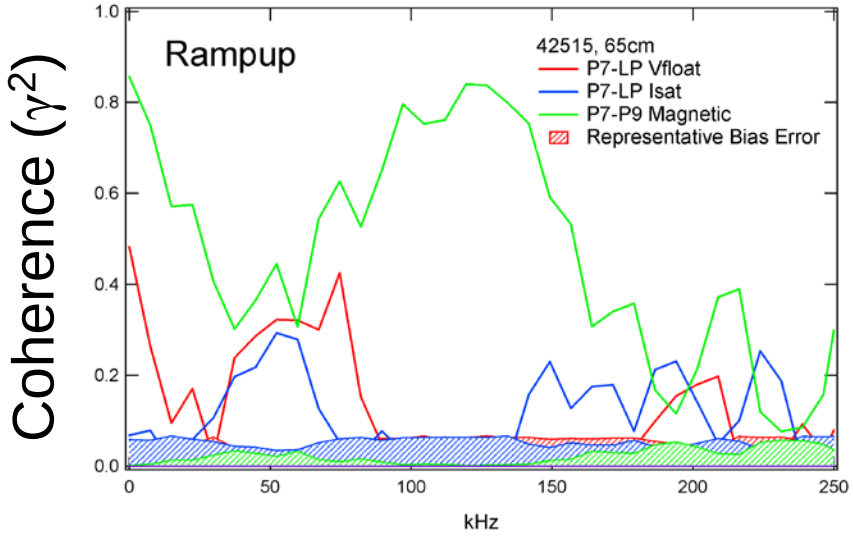
Time evolution of uniformly spaced R_{tan} viewing chords

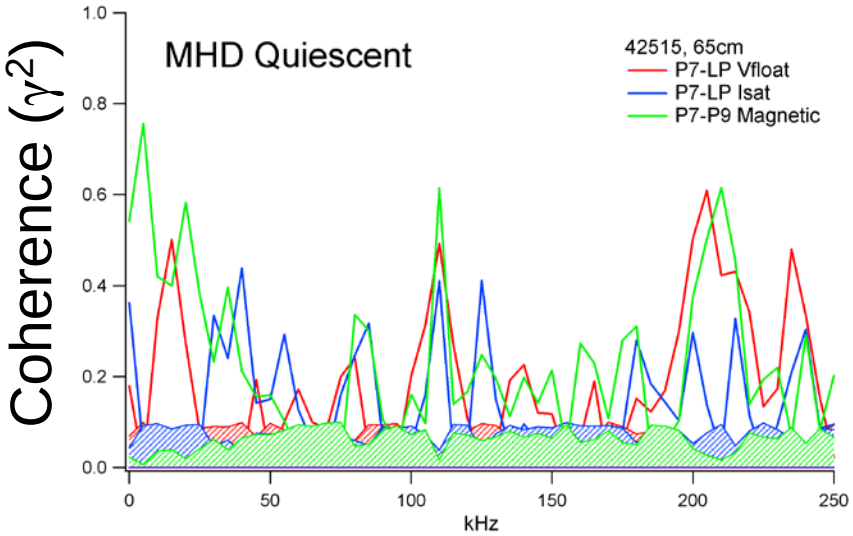
*Kirk, Plas. Phys. Controlled Fus. **49**, 2007

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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

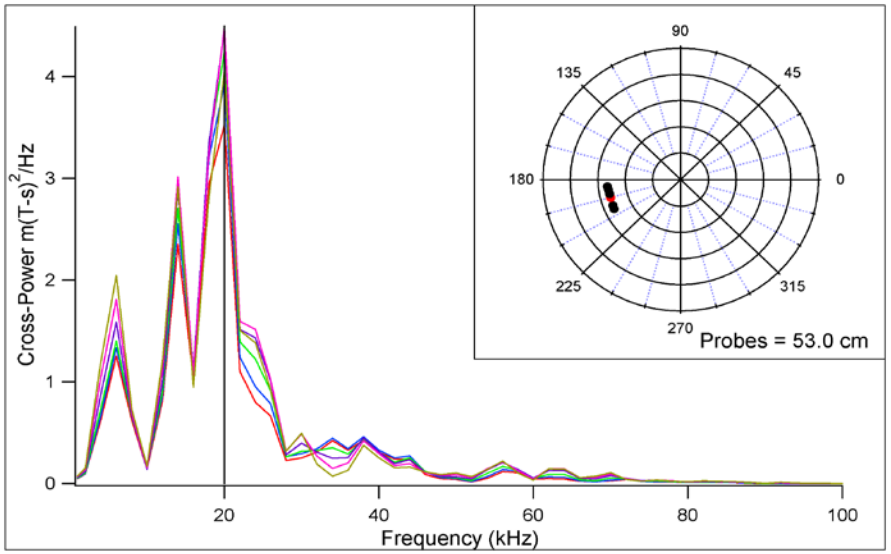


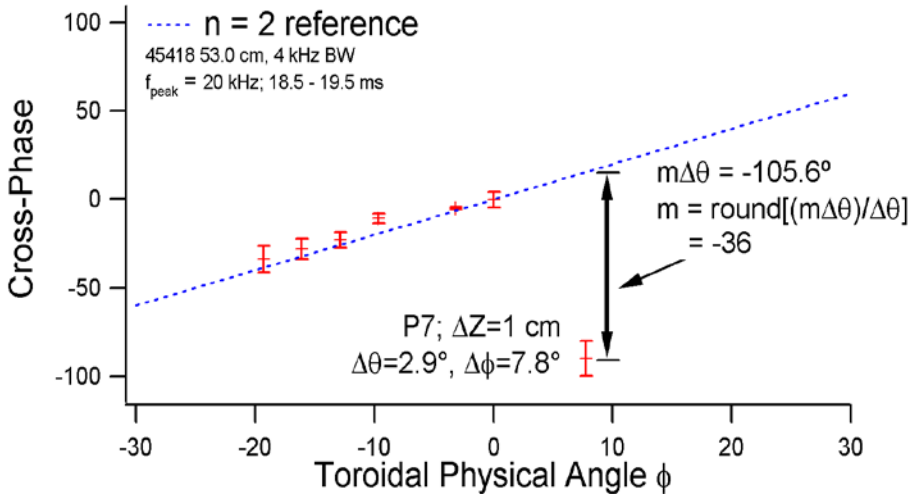


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Peeling-like Filaments Are Low-n, High-m

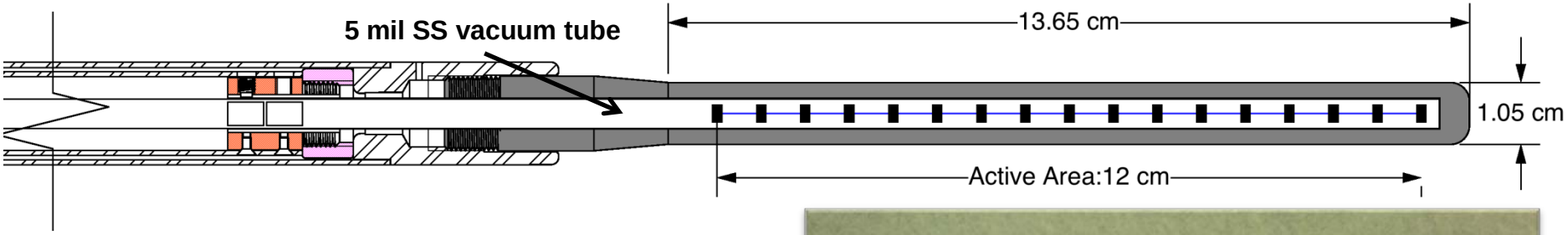
- High-resolution magnetic probe array placed at edge (R_a + 3 cm)
- n = 2 mode helicity measured during I_p ramp
  - n < 5 commonly present
- 20 kHz peak spectral power consistent with O(50 μs) fast imaging results
- 2-point m ID: m ~ -36
  - Consistent with reconstructed q_a~18





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PEGASUS Hall Probe To Constrain J(ψ)

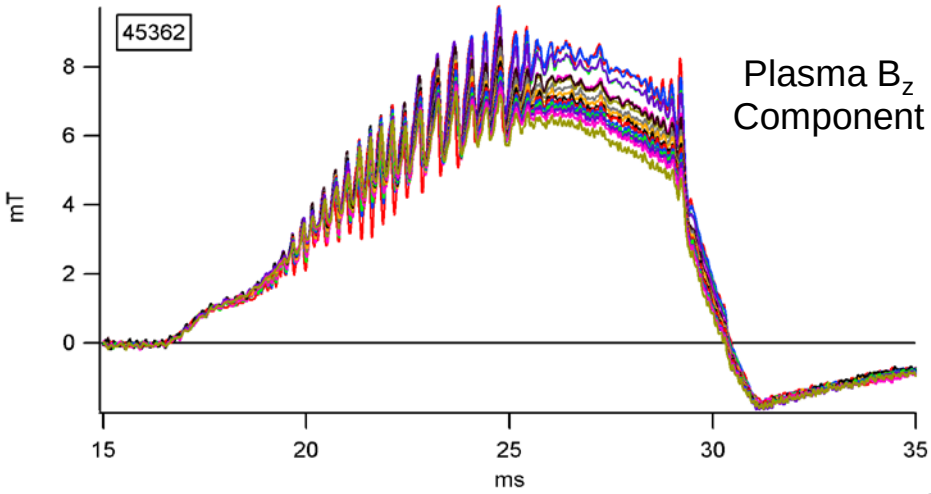


- Diagnostic Capability: $B_z(R,t)$
  - 16 Sypris SH-410 Hall detectors
  - 7.5 mm channel spacing
  - C armor: Low-Z PFC



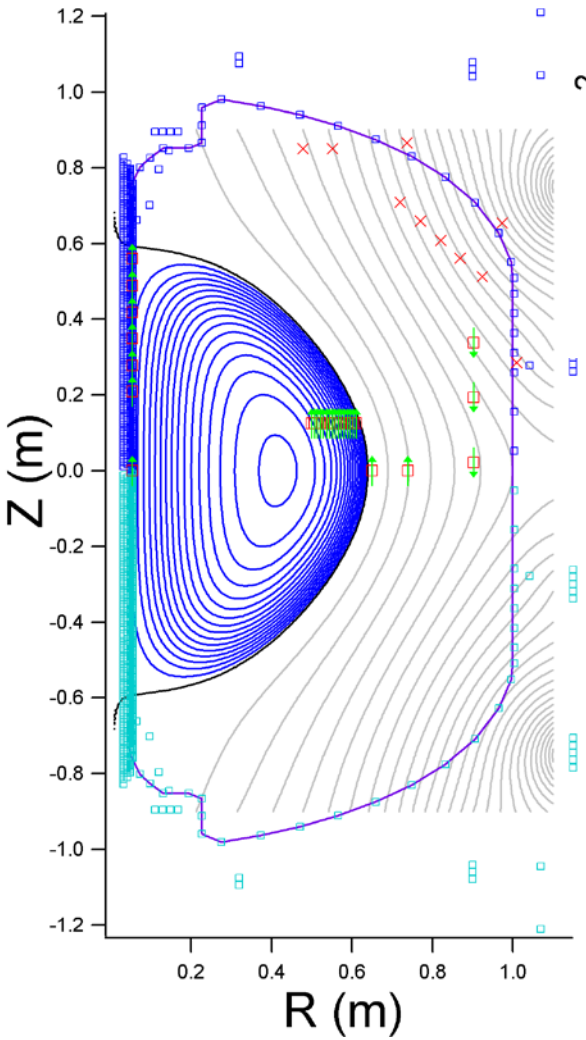
- Good Temporal Resolution
  - Frequency response: ≤ 25 kHz

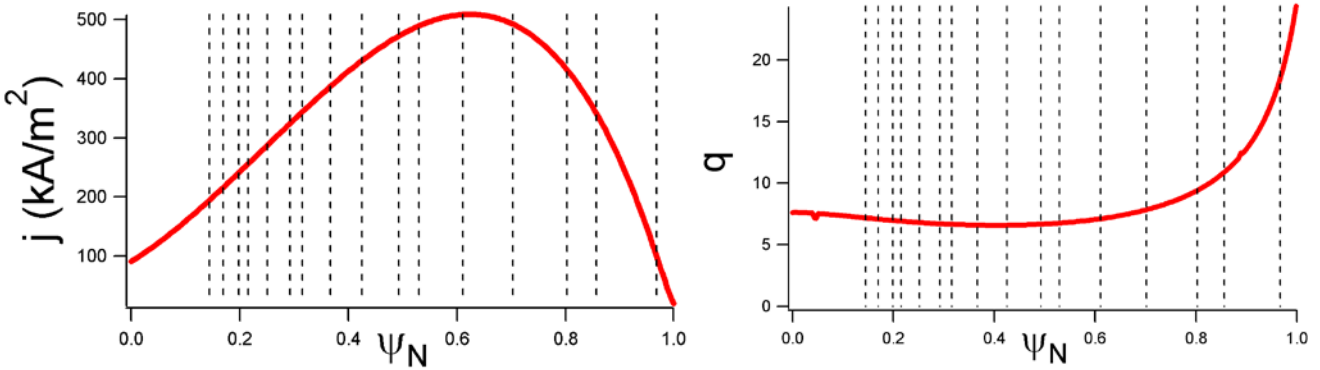
- Negligible plasma perturbation



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Hall Probes Constrain J(ψ)



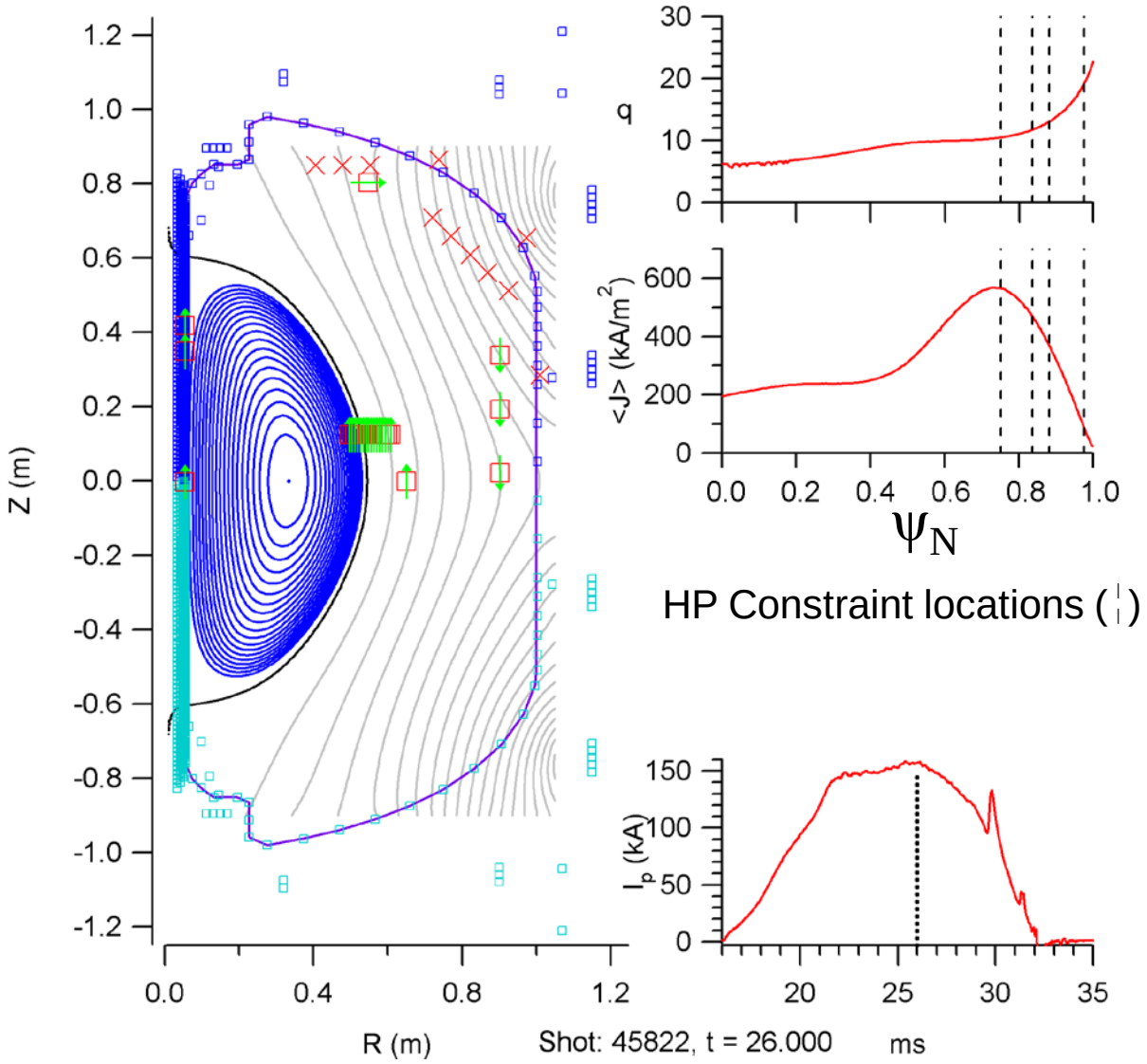


Representative profiles using 3-term polynomial fit

- Strong constraint over full ψ_N possible
  - Constraint locations ( ) vary in time due to evolution of plasma over fixed location of probes
- Polynomial parameterization inadequate to accurately fit internal data
  - Additional parameterizations in development

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Improving Models to Determine $J_{edge}(\psi)$



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

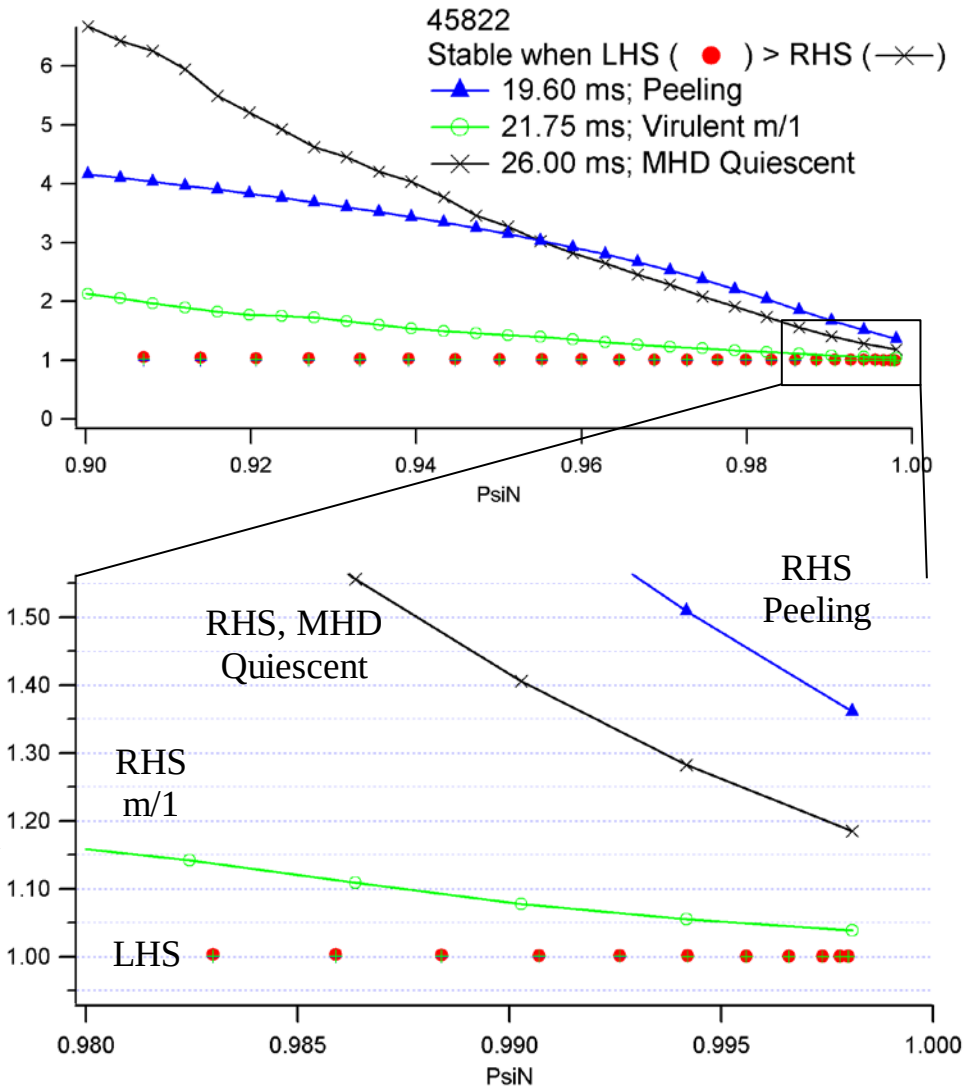
*Sontag, A, Nuclear Fusion, **48,** 095006 , 2008

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

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Filament Appearance Consistent with Peeling Stability Criterion

- Connor's peeling stability criterion computed
  - KFIT spline fits coupled to DCON
- Peeling calculated unstable at all times (not observed)
  - However, peeling phase *is* least stable of all phases
- Future: Detailed comparison with peeling-ballooning theory
  - Stability analysis via DCON, ELITE



Unstable if RHS > LHS

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Summary

- Localized filamentary edge instabilities 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

- 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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See Also

Later This Session:

- A.J. Redd, JO4.00012
  - Point-source helicity injection for ST plasma startup in PEGASUS

Poster Session PP8, Wednesday PM:

- R.J. Fonck, PP8.00085
  - The PEGASUS Toroidal Experiment Program
- D.J. Schlossberg, PP8.00086
  - Non-solenoidal startup and low-β operations in PEGASUS
- E.T. Hinson, PP8.00087
  - Edge current and pressure measurements of plasma equilibrium and stability properties in PEGASUS