Characterization of Edge Instabilities In the PEGASUS Toroidal Experiment

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PEGASUS Toroidal Experiment

Abstract

Field-aligned, rotating edge filamentary structures are observed on a routine basis in Pegasus Ohmic discharges. Imaging studies using a fast-framing camera indicate the filaments are large-scale, short-lived, coherent structures with an average lifetime varying between 10 and ~ 150 μs. Measurements using a pair of toroidally separated, radially scannable internal magnetic probes indicate that these structures are electromagnetic in nature. They are clearly distinguished from typical 2/1 tearing activity and appear as low amplitude, broadband (≤ 150 kHz) magnetic turbulence. These fluctuations are not observed on probes far from the plasma edge, suggesting high poloidal mode number. The high edge current density ($j_a \sim 100$ kA/m^2) and low toroidal field ($|B_{\varphi, a}| \sim 0.1$ T) typical in Pegasus may make the edge unstable to peeling modes. Additional magnetic probe arrays will be implemented, allowing a more accurate determination of *n* and *m*, as well as estimates of filament propagation velocity.

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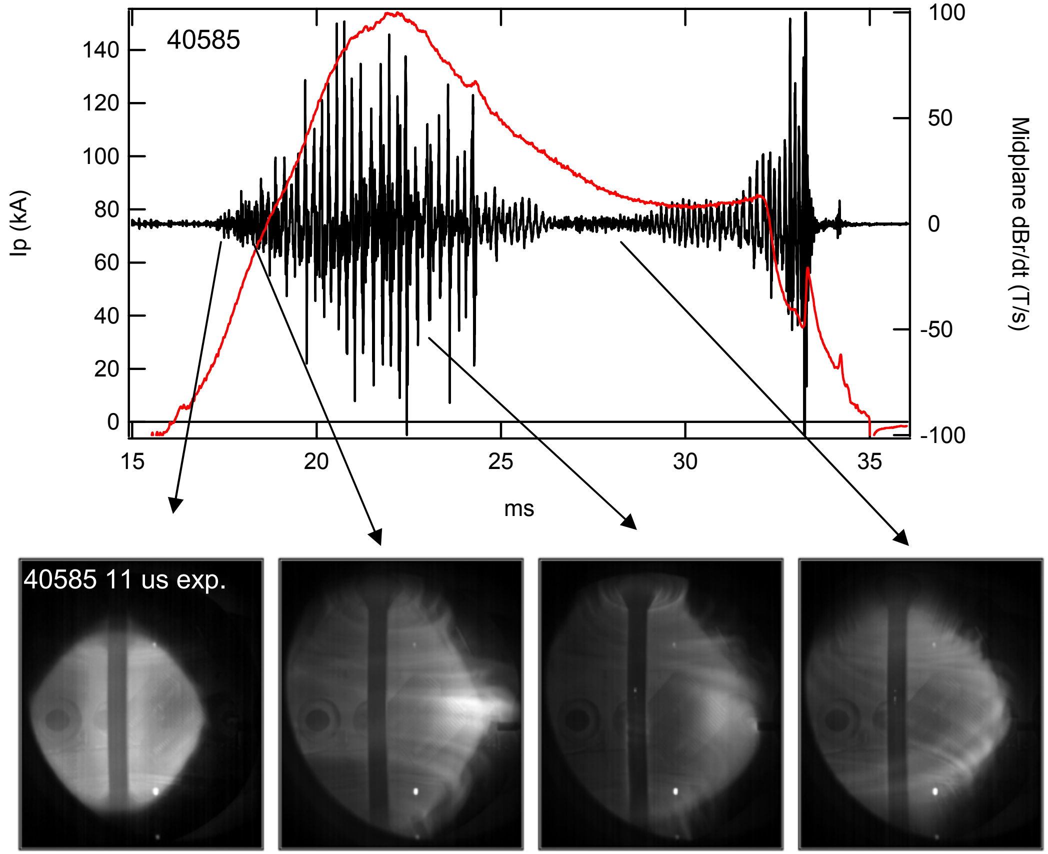
Motivation

- 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 structures/instabilities present
  - Visually similar to ELM bursts in other machines
  - Field-aligned, intermediate n
  - Varying lifetime $\tau \leq 150$ μs
- Research goal: Characterize instability in Pegasus
  - High-speed imaging
  - Magnetic characterization via internal magnetic probes
  - Electrostatic fluctuations via Langmuir probes

Three Distinct Phases in Fiducial Discharge

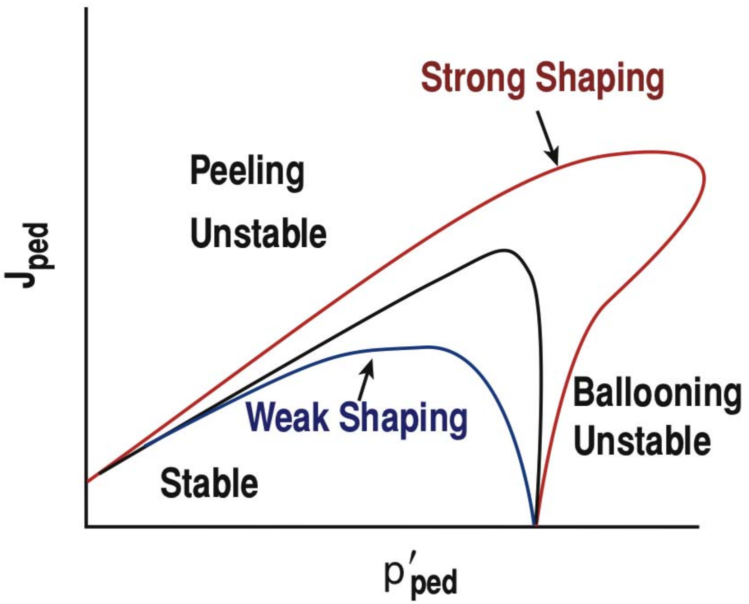
- Ip rampup
  - Filament triggering, rotation, radial propagation
- Peak Ip ~ 120-140 kA
  - m/n = 2/1 internal tearing mode dominant in addition to rampup filaments
- Ip rampdown
  - Tearing mode suppression
  - Short-lived, non-propagating, higher-n filaments
  - Consistent with L-mode ES turbulence



Rampup Pre-filament | Rampup Filamenting | 2/1 | Rampdown

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
  - Decouples current, shear



Snyder, Phys. Plasmas **12**, 056115, 2005

Peeling Mode Destabilized by Increased $(j_{||}/B)_{edge}$

- Necessary peeling stability criterion: (Review: Connor, PoP 5, 1998)

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

where

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

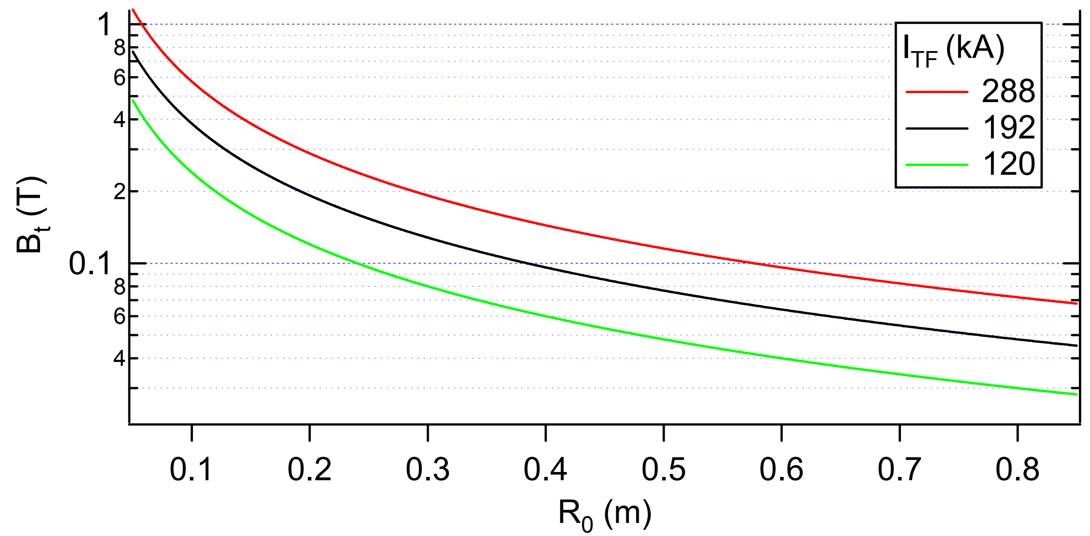
- Stability in high A, low-β, low ν, weak shaping limit:

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

with D_R (< 0) = GGJ resistive interchange coefficient

Pegasus: High $(j_{||}/B)_{edge}$ Typical

- Normal Operations:
  - Large $dI_p/dt \sim$ 25-100 MA/s
    - Strong j_{edge} drive
  - Low Toroidal Field
    - $|B_{\varphi,0}| \sim 0.1$ T
  - Strong Toridicity
    - $|B_{HFS}/B_{LFS}| > 10$

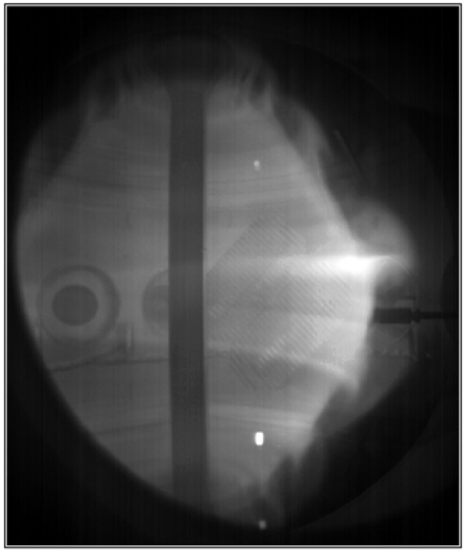


- $j_{||}/B$ Comparable to Larger Devices; strong peeling drive
  - Pegasus: $\langle j_{||}\rangle \sim 10^5$ A/m^2, $B_{\varphi,0} \sim 0.1$ T $\rightarrow j_{||}/B \sim 1\text{x}10^6$ A/(m^2-T)
  - DIII-D*: $\langle j_{||}\rangle \sim (1\text{-}2)\text{x}10^6$ A/m^2, $B_{\varphi,0} \sim 2$ T $\rightarrow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

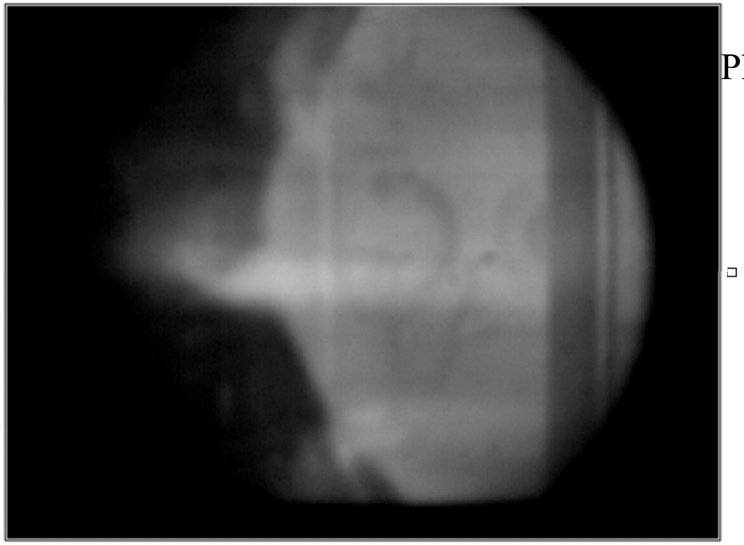
- Pegasus offers unique, university-scale opportunity for high $j_{||}/B$ experiments

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

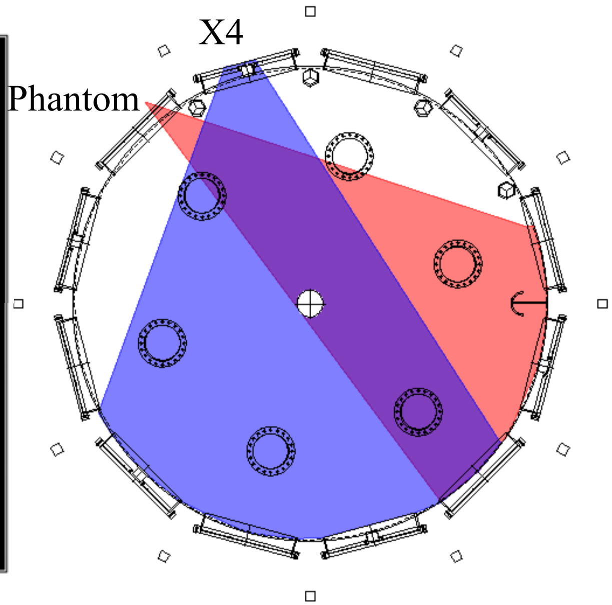
Characterization via High-speed Imaging



X4: 40271, 9 μs exposure



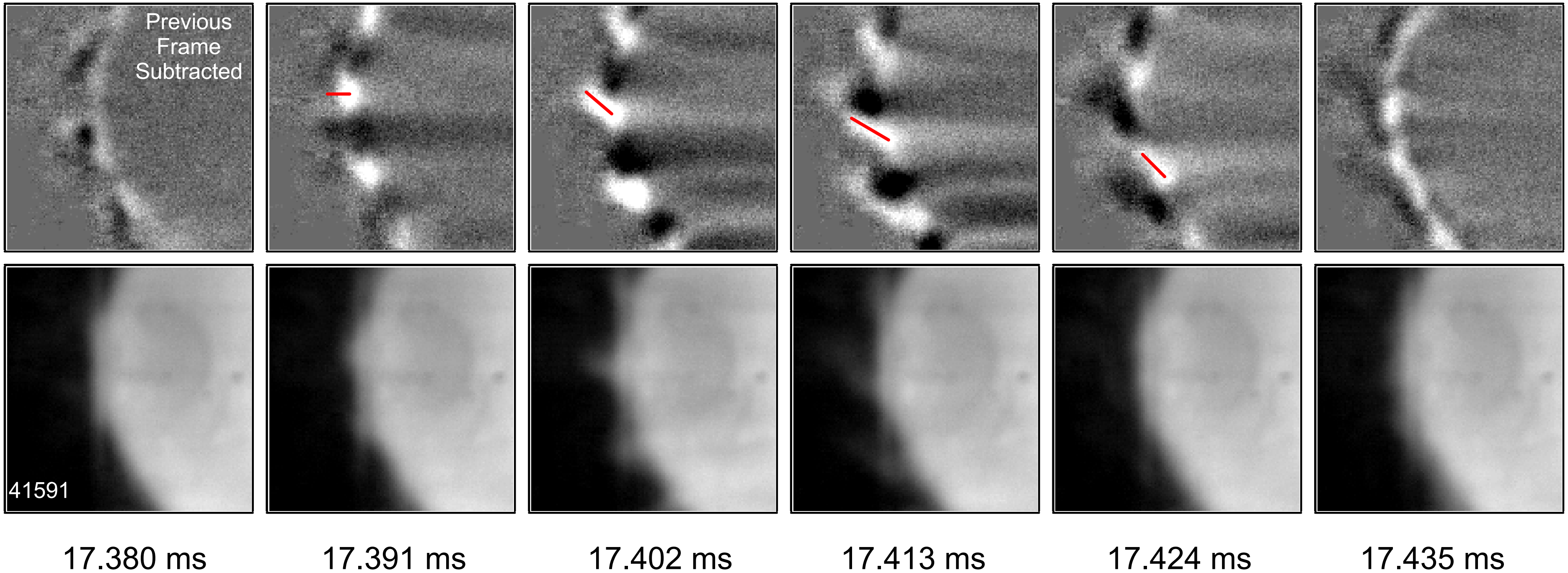
Phantom: 41583, 5 μs exposure



Viewing Ranges

- Red Lake X4
  - 5 kHz frame rate @ 512x512
  - Exposure times ~ 5-10 μs
  - Cross-sectional view
- PPPL: Phantom v7.3
  - 33 kHz frame rate @ 320x240
  - Useful frame rates ≤ 150 kHz at reduced resolution
  - Exposure times ~ 5-10 μs
  - Tangential view

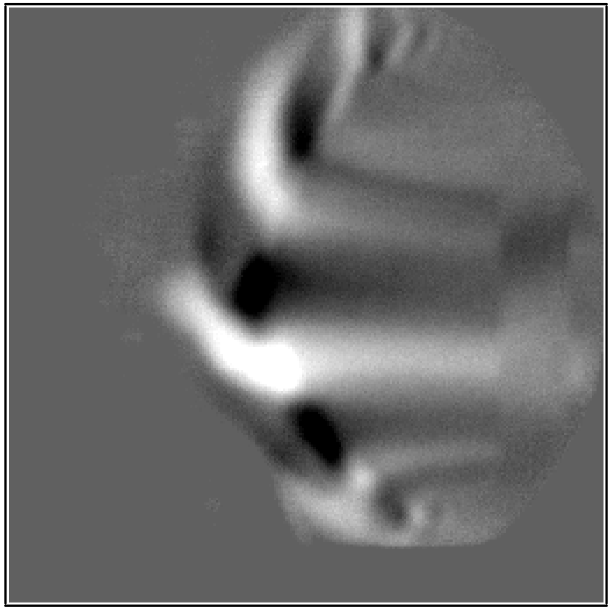
Rampup Imaging



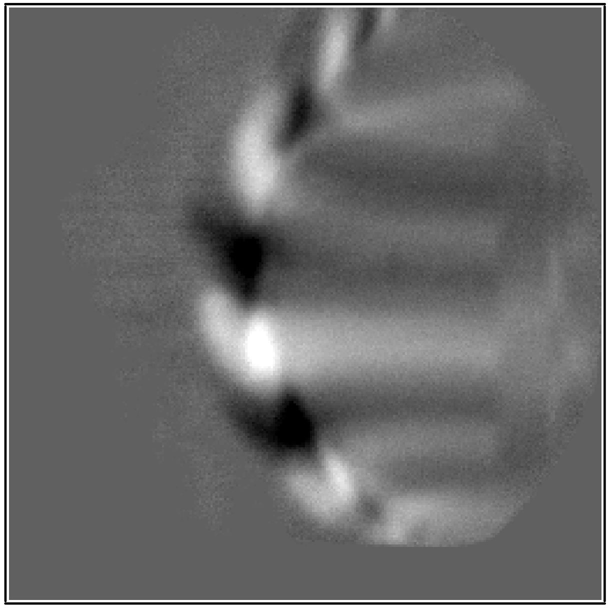
- 90 kHz framing (Δt = 11 μs)
- 9 μs exposure time
- Rotation in ion diamagnetic drift direction

- Spatially Coherent
  - Flute-like perturbation rises and falls simultaneously
- Lifetime ~ 55 μs

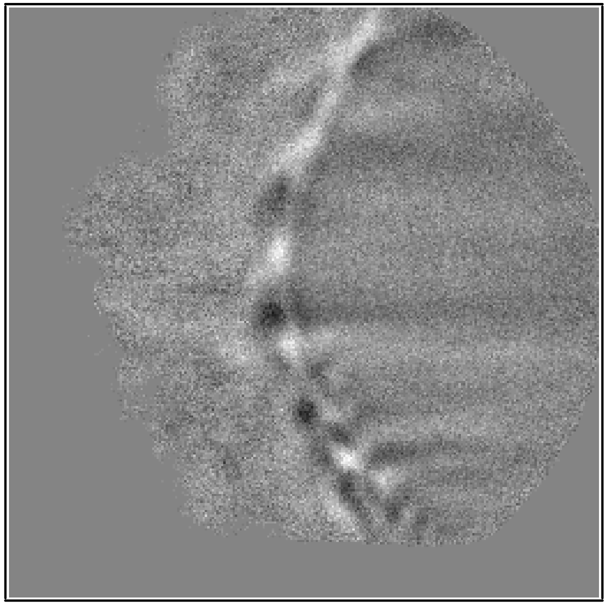
Rampup Edge Structures ~ 1/B



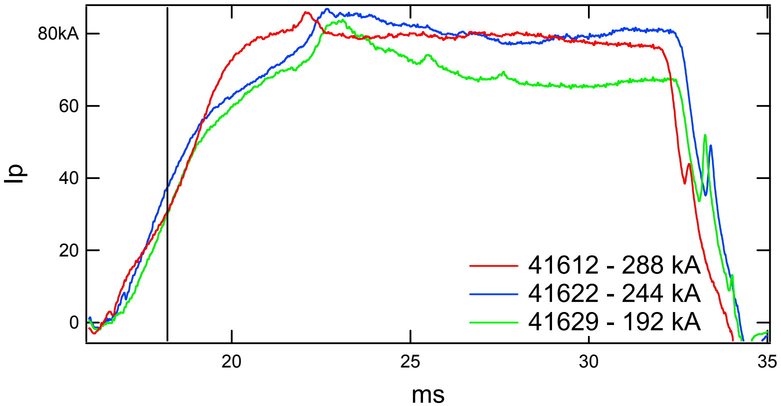
41629, 192 kA, 18.198 ms



41622, 244 kA, 18.198 ms

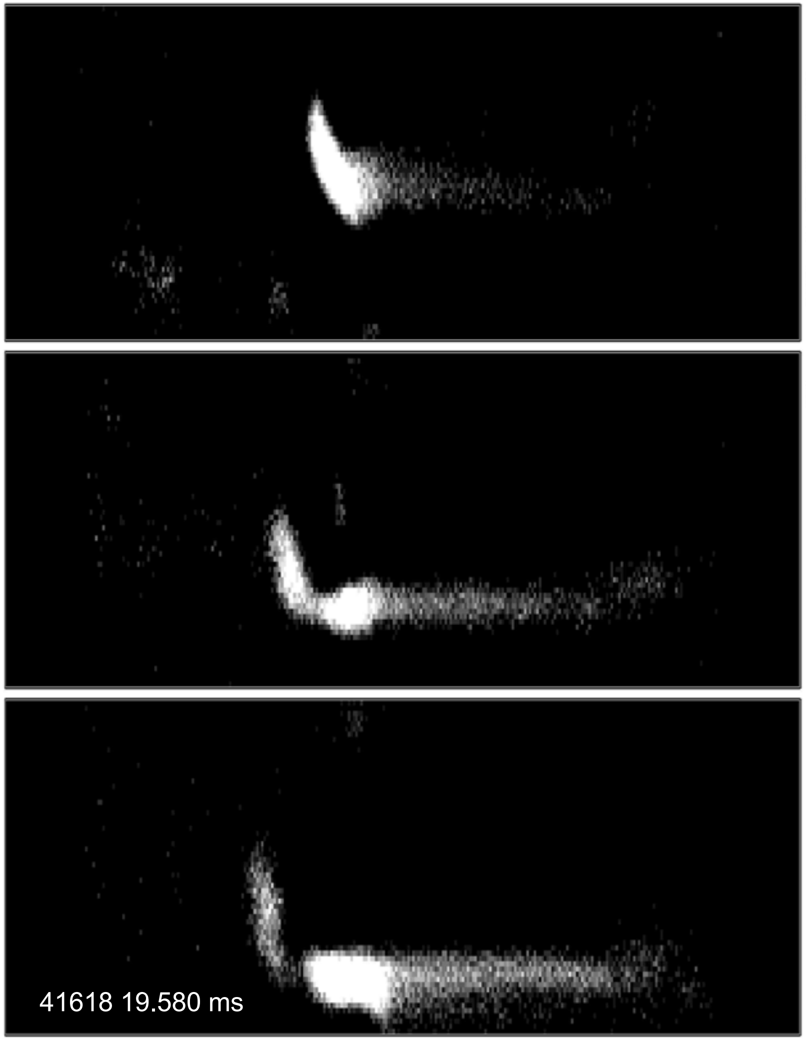


41612, 288 kA, 18.198 ms

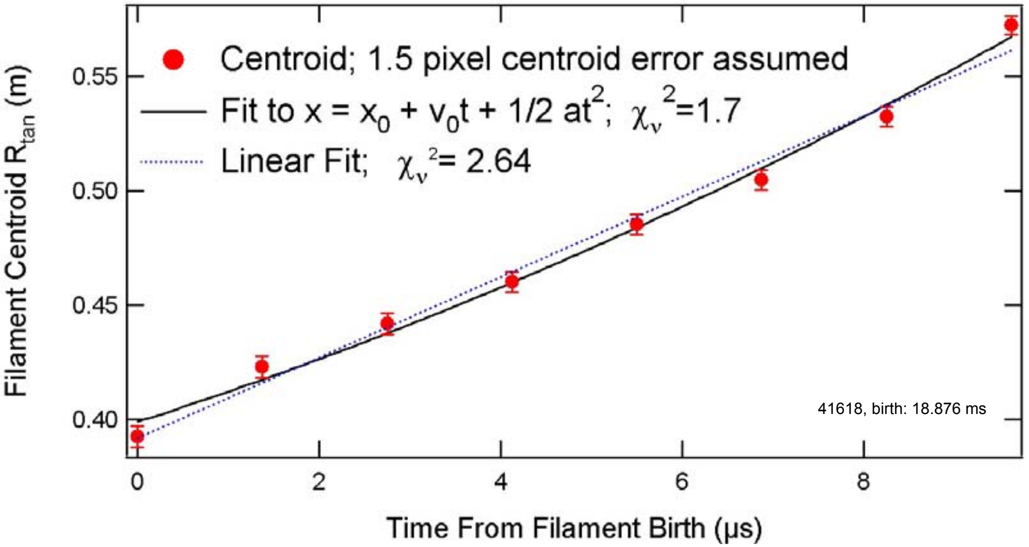


- TF Varied with dI_p/dt, geometry, V_{loop}, fueling held constant
- Edge perturbation size decreases with increasing B_φ

Rampup Filaments Propagate Radially



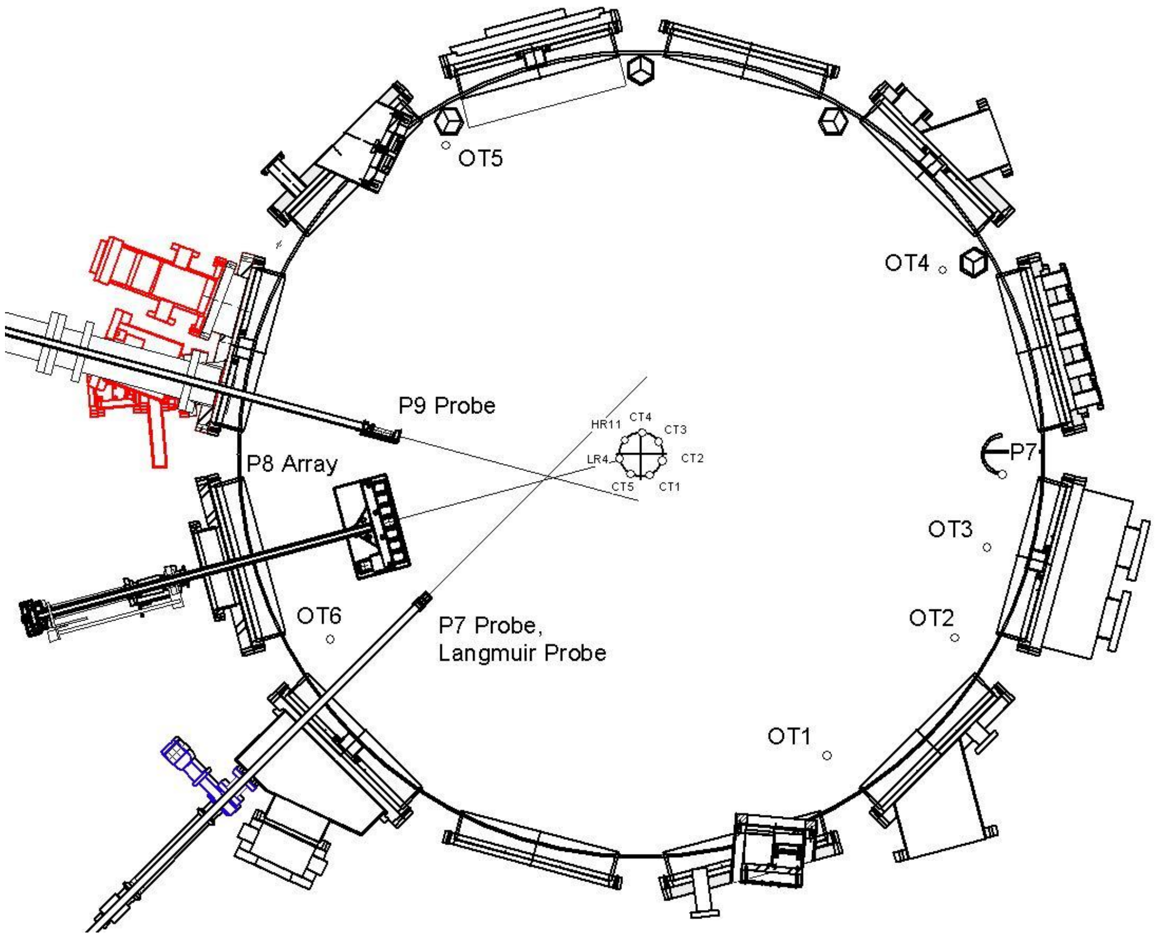
Example of filament detatchment and propagation



- Filaments observed to detach later in rampup phase
- Preliminary analysis:
  - Centroid tracked frame to frame via 90 kHz Phantom imaging
  - Exclusion of acceleration term in fit yields increased reduced χ^2, but inconclusive for definitive value of $a_{r,filament}$.

Fluctuation Characterization via Probes

- Low Te, short pulse length allows use of internal probes
  - Radially scannable shot to shot
- Variety of probes deployed:
  - P9: Br, Bz
  - P7: Bz; separate triple Langmuir probe
  - P8 Array: Bz with low toroidal angular spacing
- Magnetic probes complement existing internal diagnostics



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 $\hat{P}_{xy} = \left|\hat{G}_{xy}\right|$ with 1-σ random error

$$\sigma_{\hat{P}_{xy}} = \begin{cases} \dfrac{1}{\sqrt{n_d}} & x = y \\ \dfrac{1}{\left|\hat{\gamma}_{xy}(f)\right| \sqrt{n_d}} & x \neq y \end{cases}$$

Cross-phase $\hat{\theta}_{xy} = \arctan\left(\dfrac{\mathscr{I}\left(\hat{G}_{xy}\right)}{\mathscr{R}\left(\hat{G}_{xy}\right)}\right)$

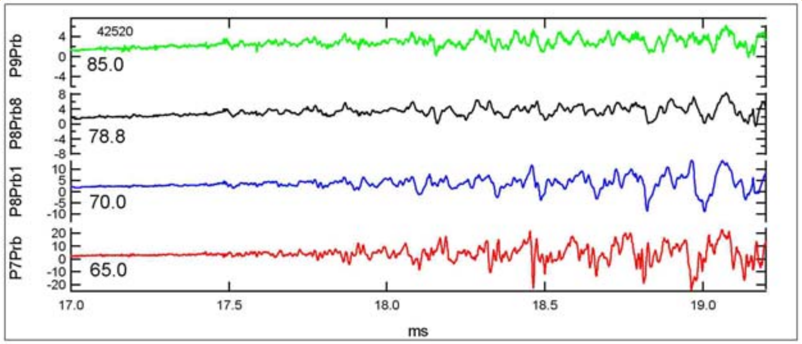
$$\sigma_{\hat{\theta}_{xy}} = \frac{\sqrt{1 - \hat{\gamma}_{xy}^2(f)}}{\left|\hat{\gamma}_{xy}(f)\right| \sqrt{2 n_d}}$$

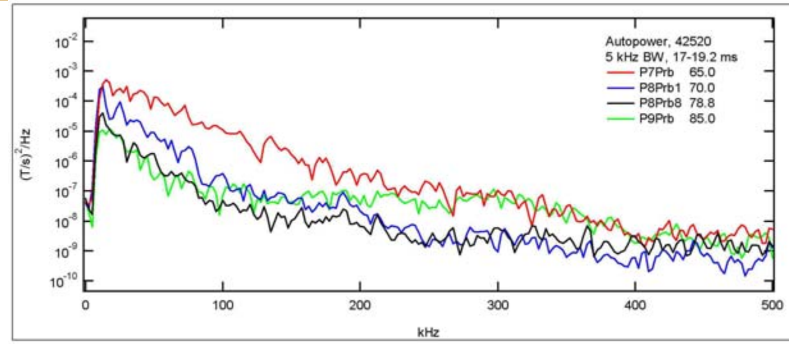
Coherence $\hat{\gamma}_{xy}^2 = \dfrac{\left|\hat{G}_{xy}\right|^2}{\hat{G}_{xx} \hat{G}_{yy}}$

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

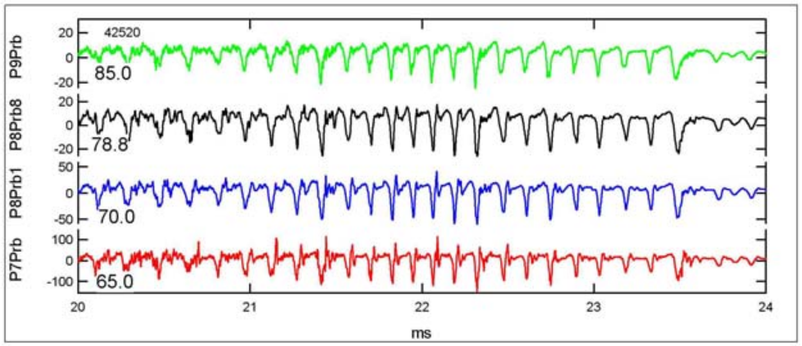
Additional Spectral Content Near Edge

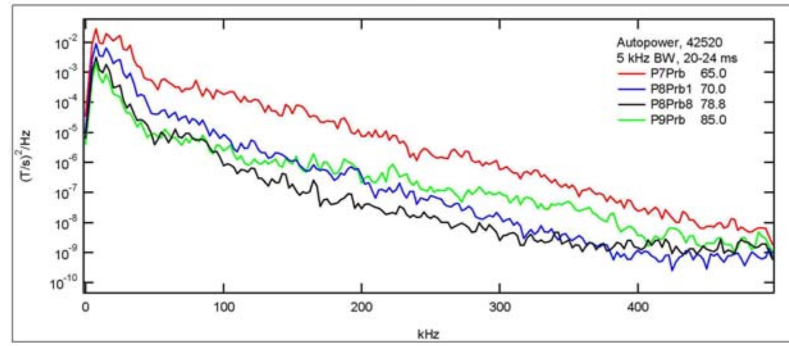
Rampup



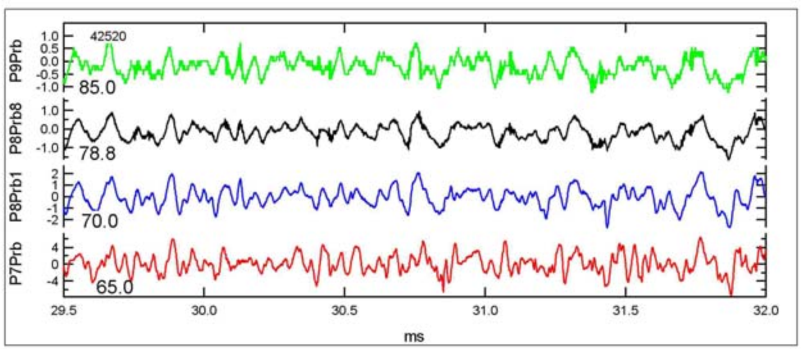


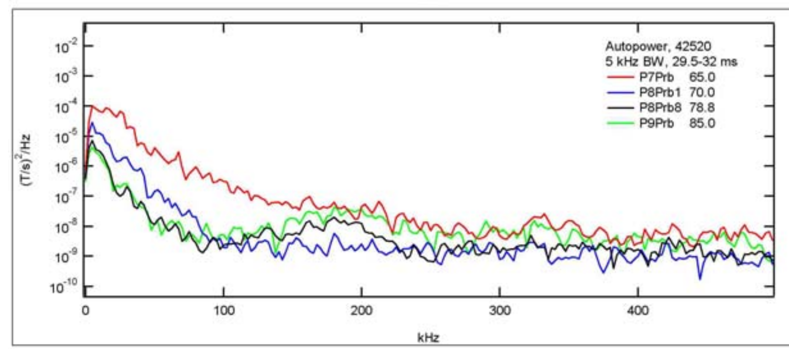
2/1





Rampdown





Radially staggered magnetic probes: simultaneous dB_z/dt (R)

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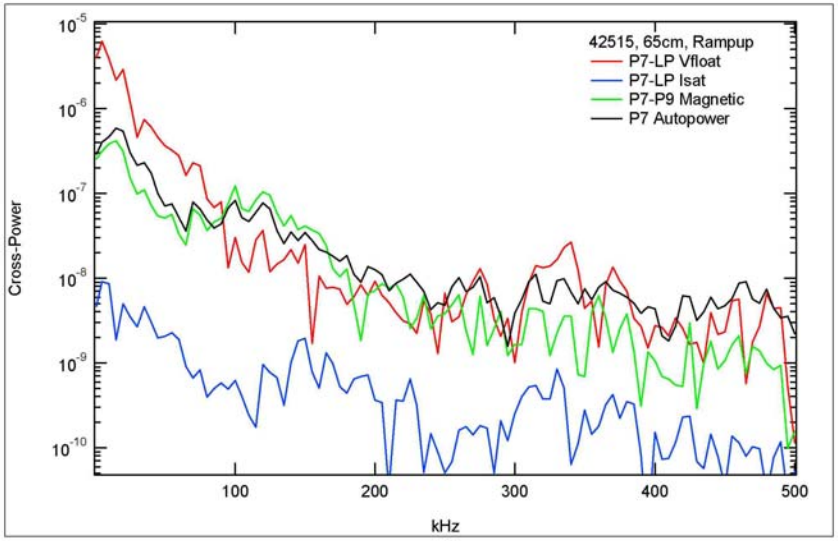
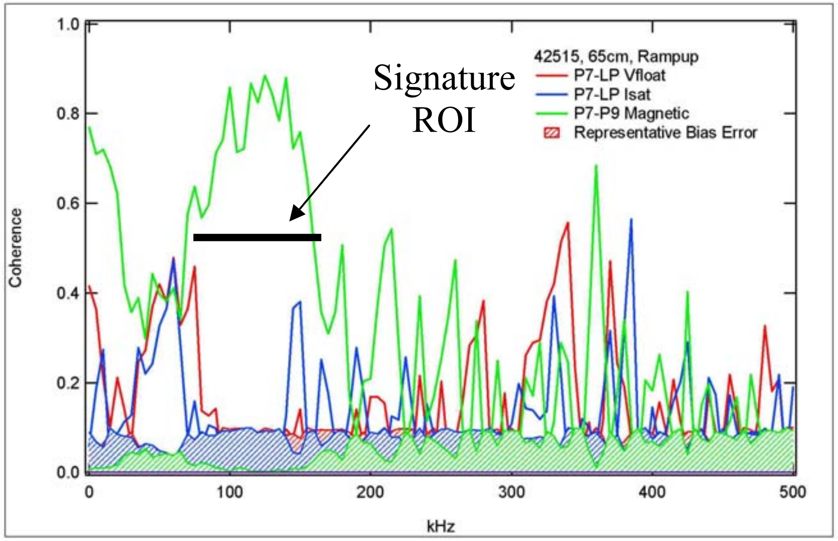
Rampup: Electromagnetic Signature Present

- Langmuir, magnetic probes held at same R
- Coherent magnetic signature for f < 150 kHz
- Spectral band 100 – 150 kHz simultaneously coherent magnetcially, incoherent with Langmuir measurements
  - Not present in subsequent phases
- Suggests source is not electrostatic in nature





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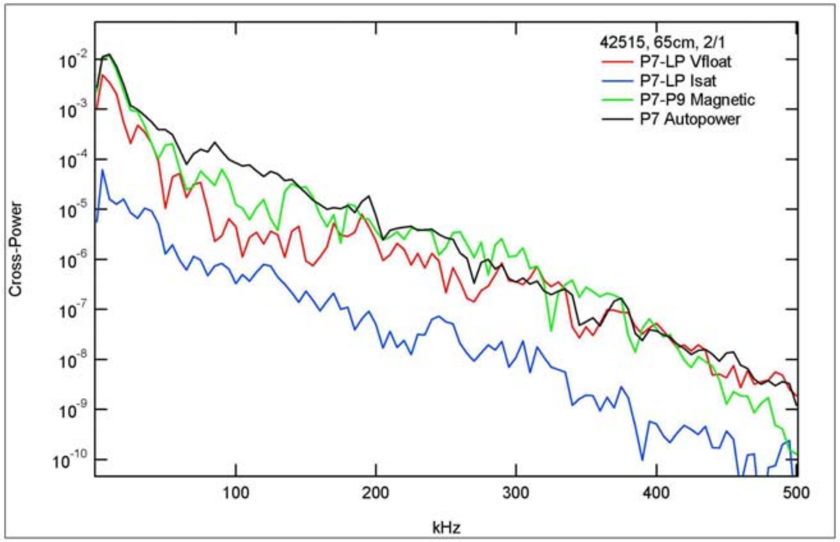
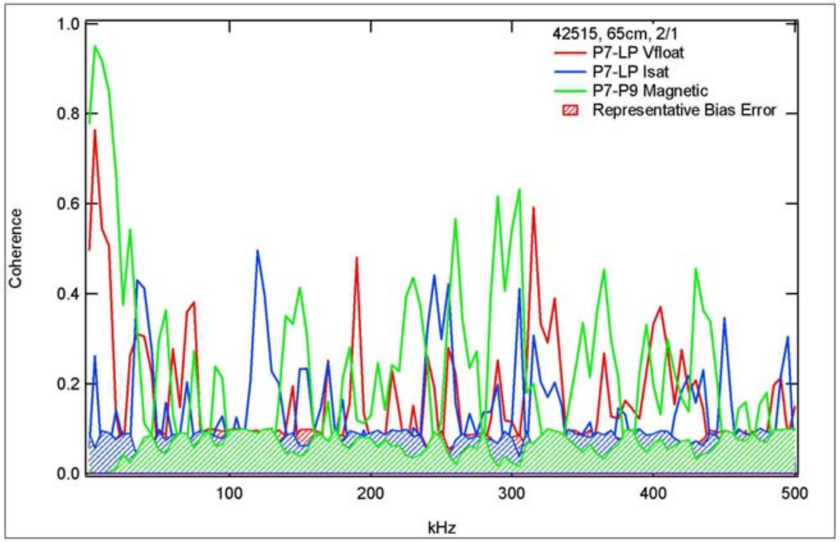
2/1 Dominates Probe Spectra

- Strong internal MHD clearly distinguished on Langmuir, magnetic probes

- Low-frequency coherece of magnetic, temperature, density fluctuations
  - Consistent with observed visible distortion of plasma column

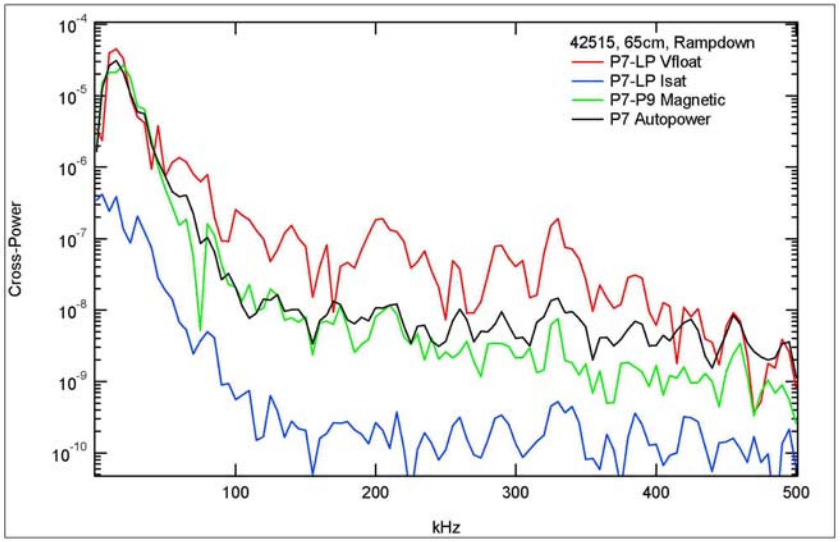
- No clear EM component

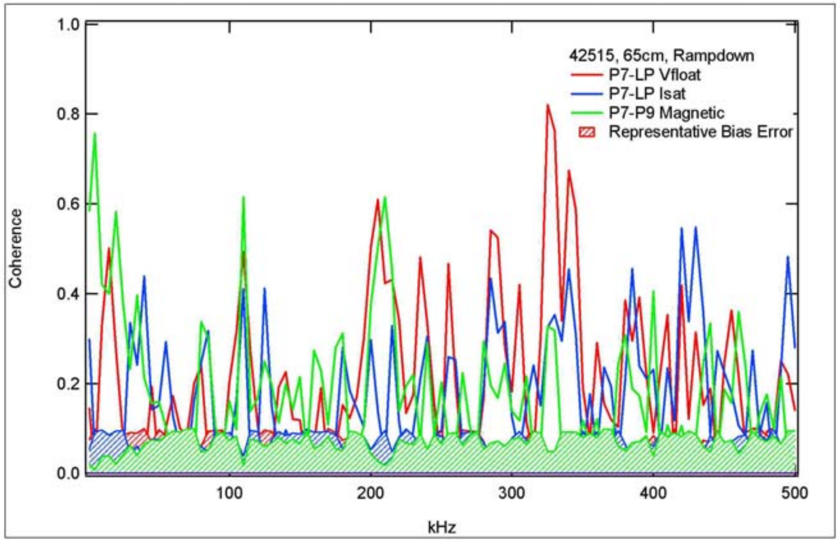




Rampdown Phase: L-mode turbulence?

- 2/1 magnetic signature dramatically reduced
  - No meaningful magnetic signature above f > ~ 150 kHz; hits noise floor of measurement system
- Power spectra for Langmuir, magnetic measurements appear turbulent
  - Spikes in magnetic coherence correlate with ES activity on the Langmuir probes



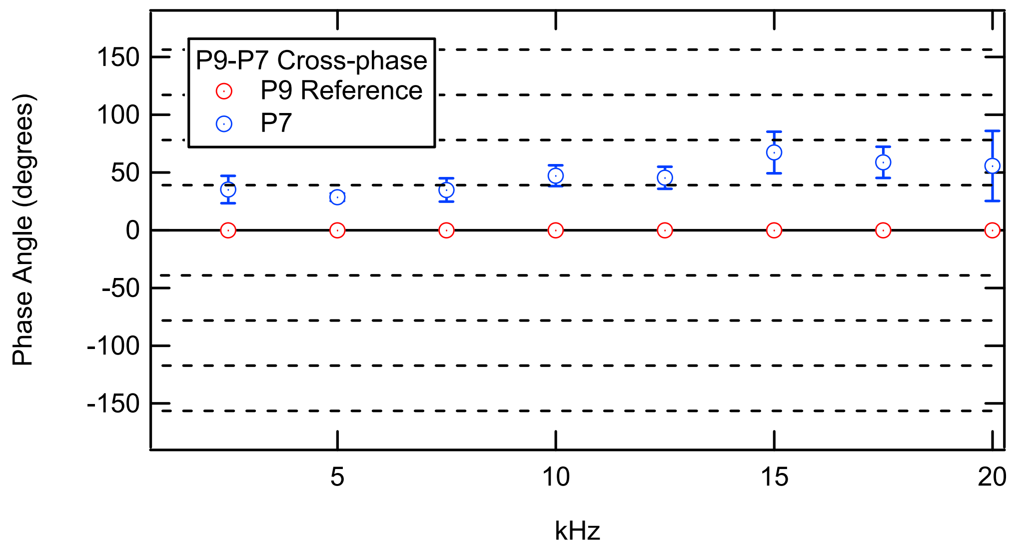


n Identification Methods

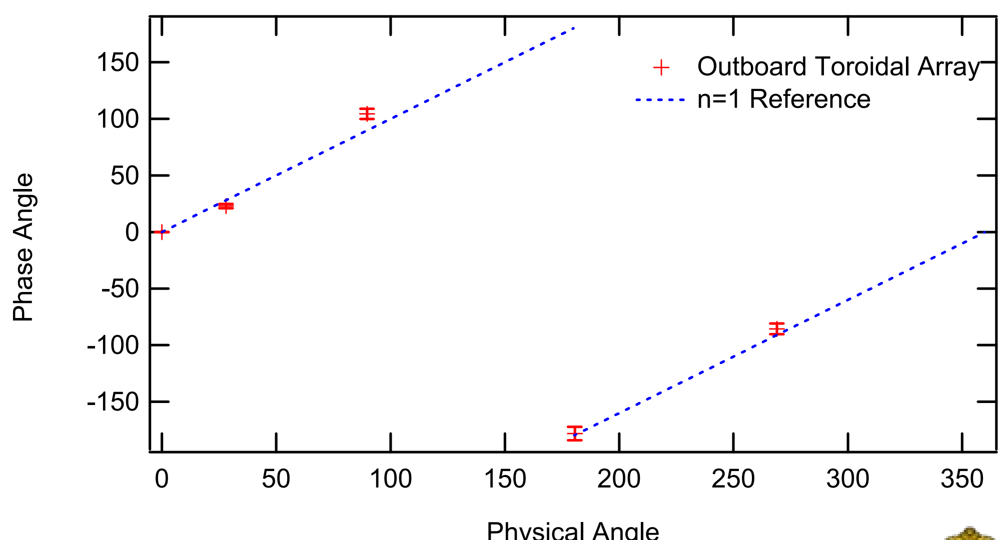
- 2-probe Cross-phase:

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

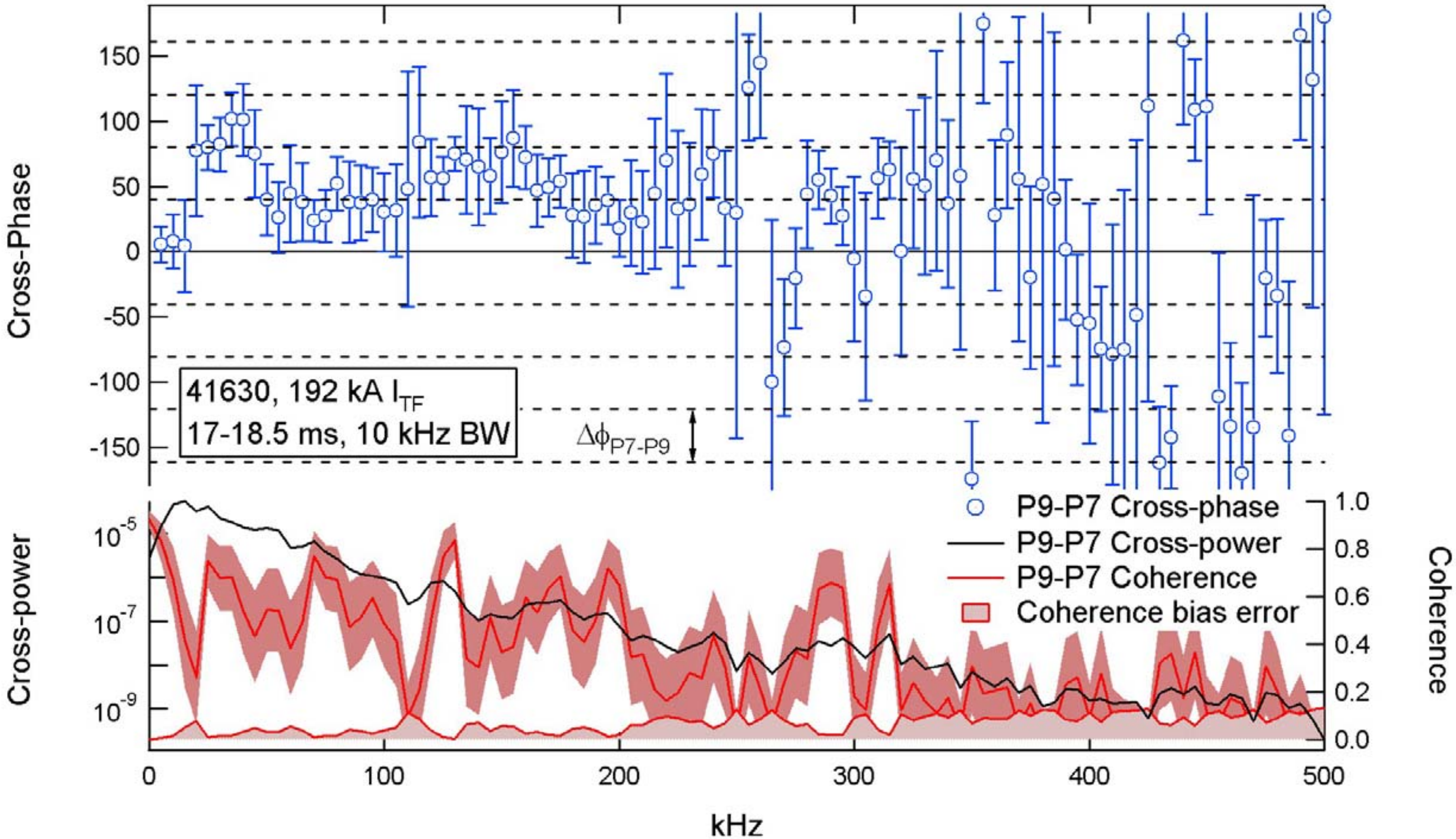
where Δφ is the physical separation of the probes



- Phase-slope
  - Plot of $\hat{\theta}_{xy}$ vs Δφ for multiple measurements about a narrow spectral band
  - Best-fit n is slope of measured phase shift



Two-probe Data Consistent with Low n



- n = 1, 2 measured in rampup
- Toroidal angle spacing of ~ 40^{o} insufficient to discriminate against possiblitiy of higher-n due to spatial aliasing

Midplane Probe Array to Clarify n

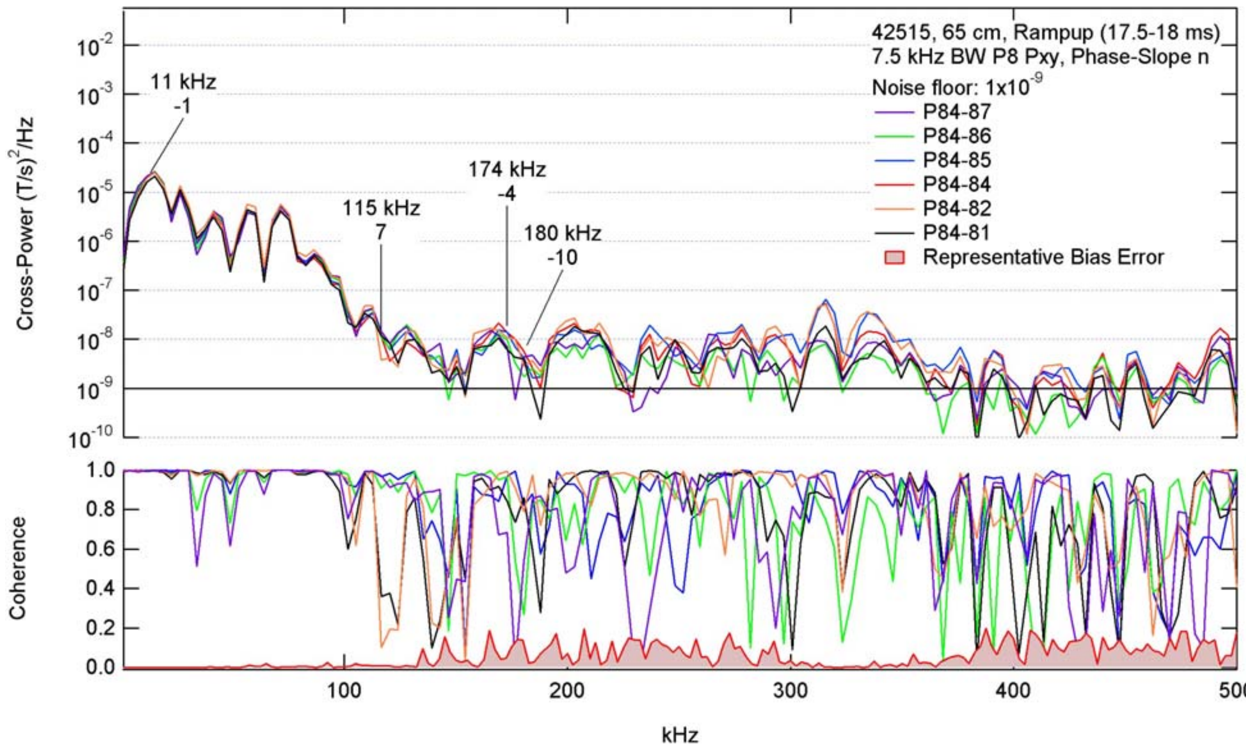
- Port 8 Bz array installed late October with intermediate $\Delta\varphi_{phys}$
  - 6 coils at approximately same major radius ($\delta R_{coil} < 0.5$ cm)
  - 21 cm physical size; 3 cm coil-coil spacing
  - Radial midplane insertion path
  - Spans $\Delta\varphi \sim 10^o$ to increase n resolution capabilities

- Preliminary results: rampup filament magnetic signature is consistent with low- to intermediate n

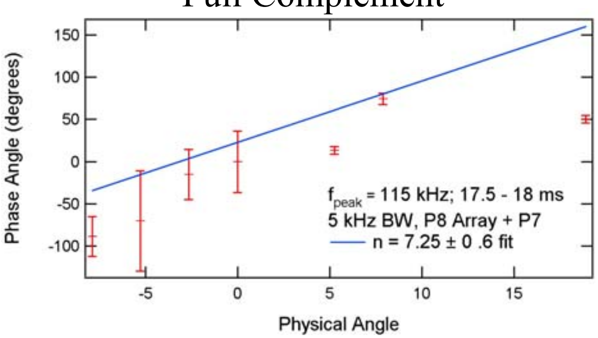
- Exact identification complicated by coupling of poloidal contributions to cross-phase near plasma edge
  - Resulting from systemic errors, e.g. slight tilt of array → small ΔZ_{coil}
  - Coil-coil averaging found useful in averaging out phase error; used to obtain phase-slope mode ID
  - Continued analysis ongoing

Preliminary: Intermediate n Present in Rampup

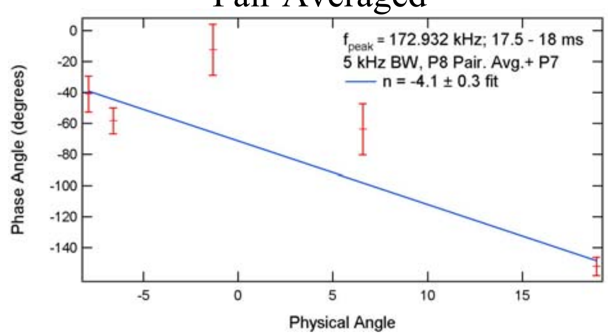
- P8 Array, P7 midplane B_z coils near plasma edge
  - $\Delta\varphi_{coil,\ center\text{-}center} \sim 18^o$
  - P9 coil omitted due to severe poloidal θ_{xy} contamination
- Intermediate |n| < 10 present



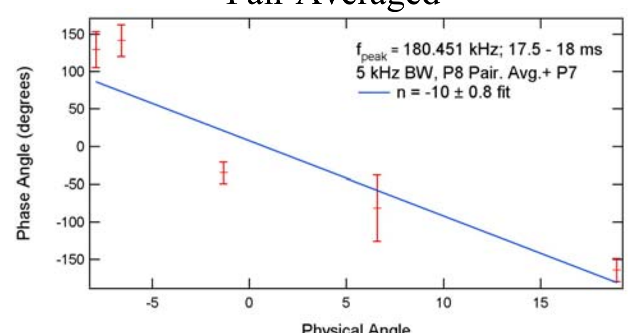
Full Complement



Pair Averaged

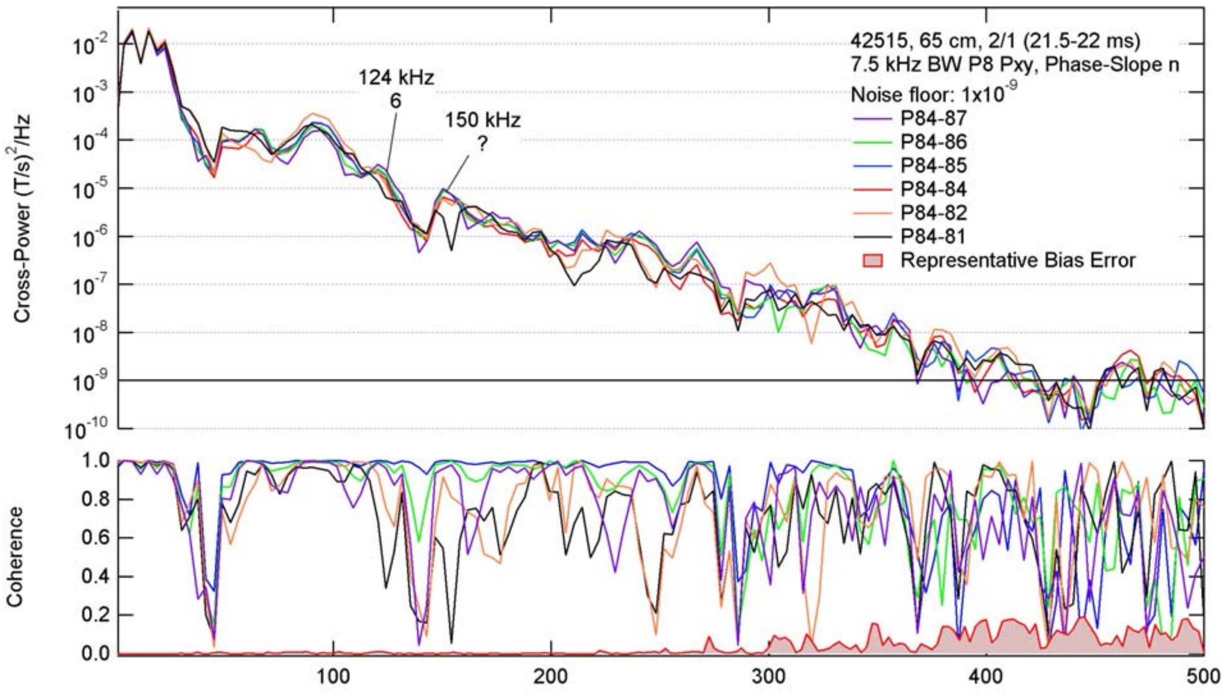


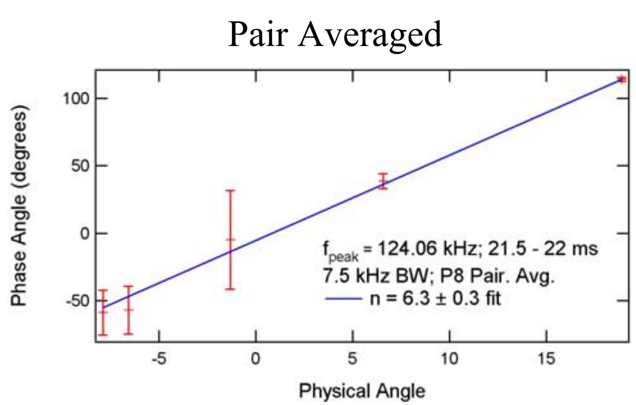
Pair Averaged

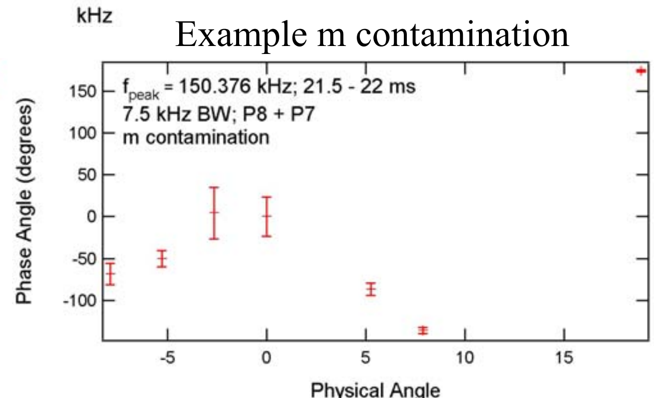


Preliminary: Intermediate n in 2/1 phase

- Intermediate n observed in addition to virulent low frequency n=1 activity
- Phase mixing makes mode ID difficult
  - Intrinsic tradeoff: bandwidth vs averaging time







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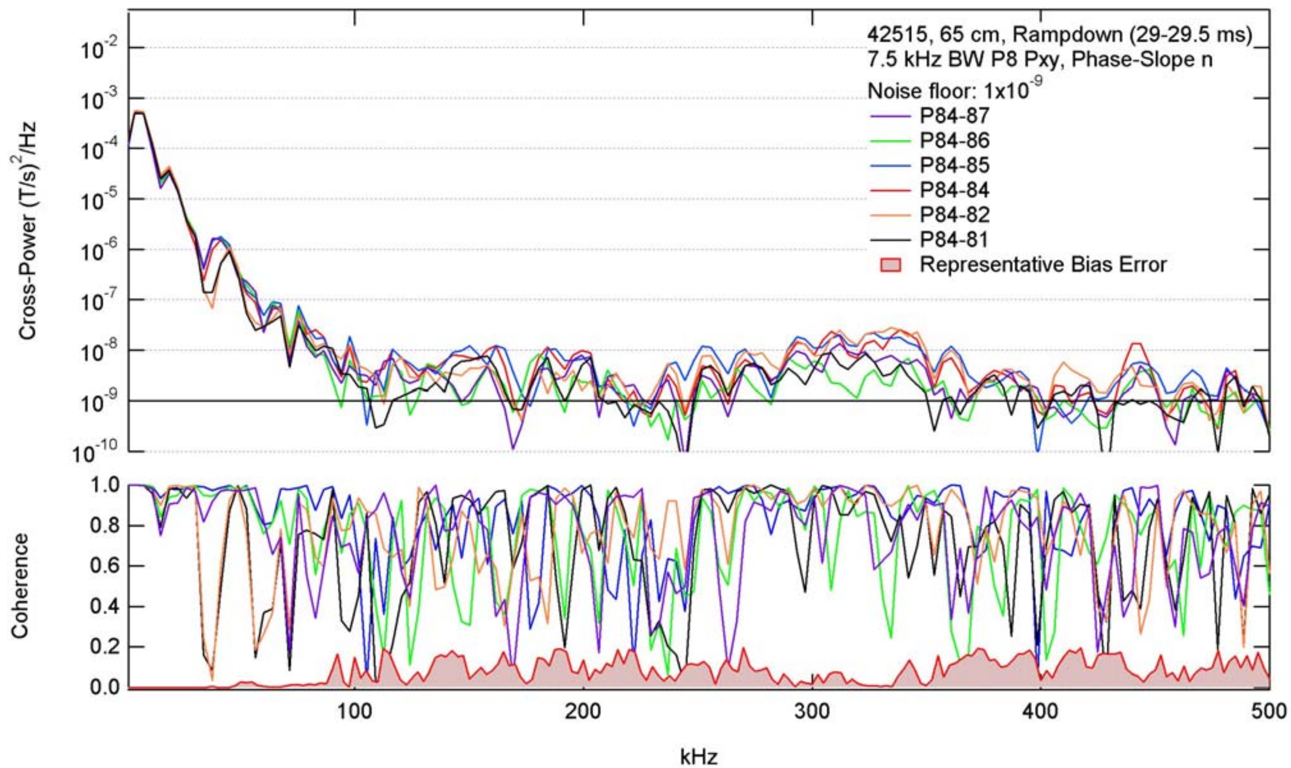
Rampdown: No clear EM Signature

- Rapid falloff in power spectra yields no data above 100 kHz
  - Consistent with magnetic-LP comparison
- No consistent phase-slope ID possible for f < 100 kHz



Edge Profiles Can Be Measured With Probes in Pegasus

- Meaningful stability analysis will require strong experimental constraints on input equilibrium reconstructions
- Short pulse, low T_e of Pegasus discharges compatible with insertable probes for direct measurement of edge profiles
  - Existing probes designed only for external plasma measurements; physical size, PFCs significantly perturbative
- Future work: Internal magnetic, Langmuir probe arrays
  - Slim profile, BN PFC to reduce high-Z impurities, plasma perturbation
  - Direct measurement of $B_\theta \rightarrow$ edge $J(\psi)$ constraint
  - n_e, $T_e \rightarrow p_e(\psi)$ in lieu of multichannel TS
  - Magnetic probe array for determination of poloidal structure

Summary

- Characteristics of rampup filaments consistent with peeling mode
  - Pegasus' characteristic high edge current, low |B| suggest strong peeling drive
  - Spatially coherent filaments with rotation, detatchment and radial propagation
  - Electromagnetic signature; low- to intermediate |n|
    - Work ongoing for more precise determination of n
  - Suppression with reduced $j_{||}$; increase in structural size with reduced |B|

- Rampdown filaments consistent with ES turbulence
  - Short lifetime; non-propagating
  - Trace magnetic signature coherent with LP fluctuations

- Future work: Internal magnetic, ES probes to constrain reconstruction, allow for meaningful stability analysis

Acknowledgements

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Reprints of this and other Pegasus presentations are available at

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