Abstract

The plasma edge region in the PEGASUS ST exhibits a range of fluctuation phenomena, from peeling-like modes at high $d(I_p)/dt$, to standard broadband electrostatic turbulence. Measurements of the edge region will support studies of its equilibrium and stability properties, and provide information for RF coupling (HHFW and EBW) for future heating and current drive studies. Langmuir probes are used to measure the edge pressure gradient with high temporal resolution. Together with measurements of the edge B_z profiles from a radial array of Hall probes, the derived p(r) and $j_{||}$ profiles will support detailed edge stability analyses. Peeling-like modes manifest as edge filamentary structures commonly observed in Ohmic discharges. Scanning Mirnov probes indicate broadband magnetic turbulence when this filamentation occurs. Peeling-mode theory predicts instability for large $< j_{||}/B >$, a condition that PEGASUS may satisfy (B_t = 0.1T, $j_{||}$ = 0.1MA). These measurements will enable determination of $<J_{||}/B>$ and p(r) at $r \approx a$ and offer unique tests of peeling-ballooning theory. Future studies will employ divertors to increase magnetic shear and influence edge turbulence.

Supported by U.S. DOE Grant DE-FG02-96ER54375

Abstract

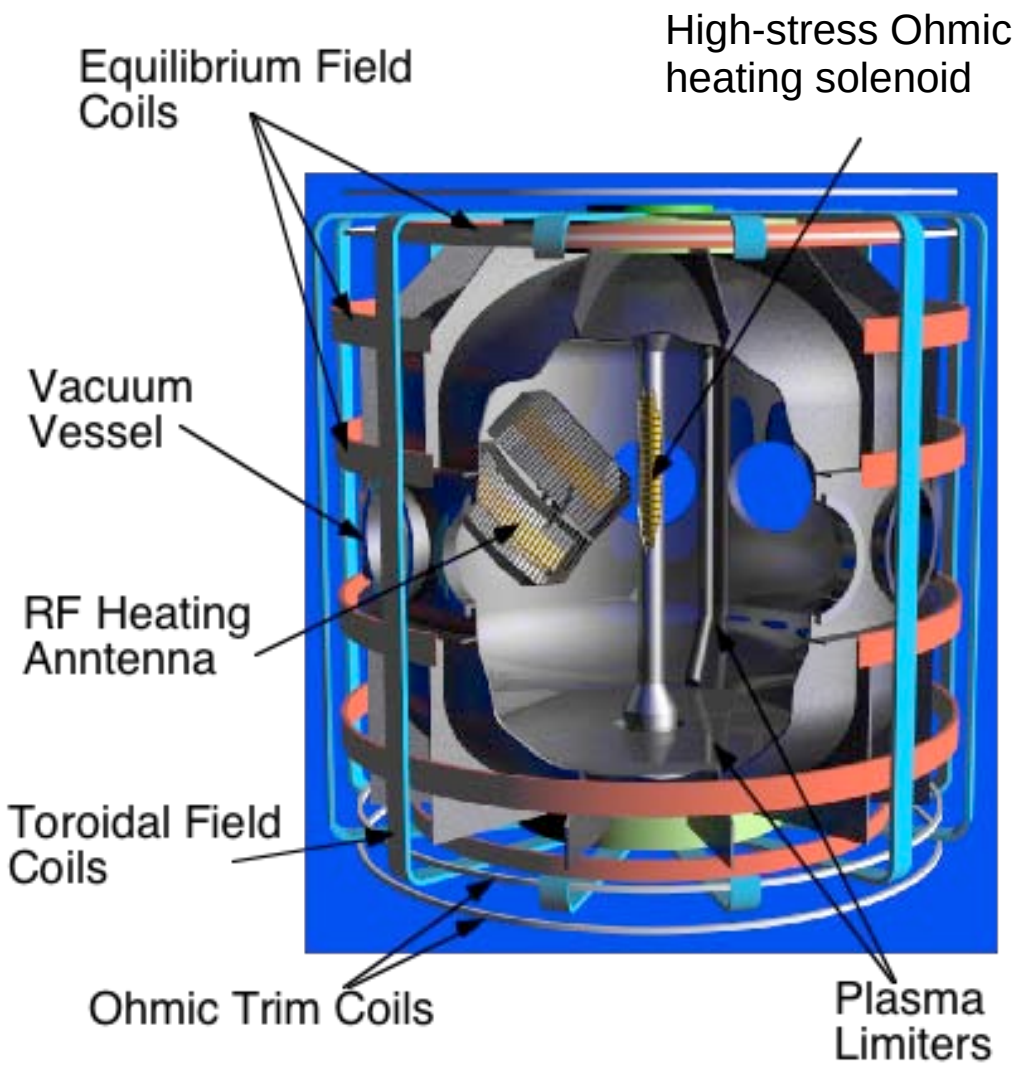
- The plasma edge region in the PEGASUS ST exhibits a range of fluctuation phenomena, including peeling-like modes at high $d(I_p)/dt$.
  - Peeling-like modes manifest as edge filamentary structures commonly observed in Ohmic discharges.

- Peeling-mode theory predicts instability for large $< j_{||}/B >$, a condition that PEGASUS satisfies ($B_t \approx 0.1$T, $j_{||} \approx 0.1$MA).

- Measurements of edge B_z profiles with a Hall probe array, together with measurements of p(r) from a pair of Langmuir triple probes will support detailed edge stability analyses.
  - These measurements will enable determination of j(r) and p(r) at r≈a and offer unique tests of peeling-ballooning theory.

Supported by U.S. DOE Grant DE-FG02-96ER54375

PEGASUS: A University Scale, Ultralow-A ST



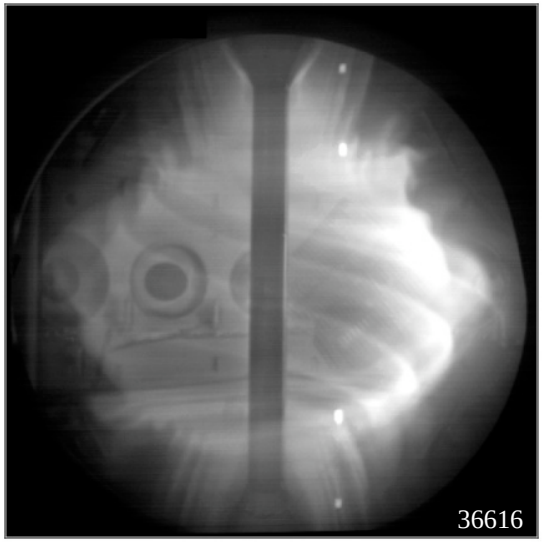
Experimental Parameters

Parameter	To Date
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	$\leq$ .21
I_N (MA/m-T)	6 – 12
ℓ_i	0.2 – 0.5
κ	1.4 – 3.7
τ_{shot} (s)	$\leq$ 0.025
β_t (%)	$\leq$ 25
P_{HHFW} (MW)	0.2

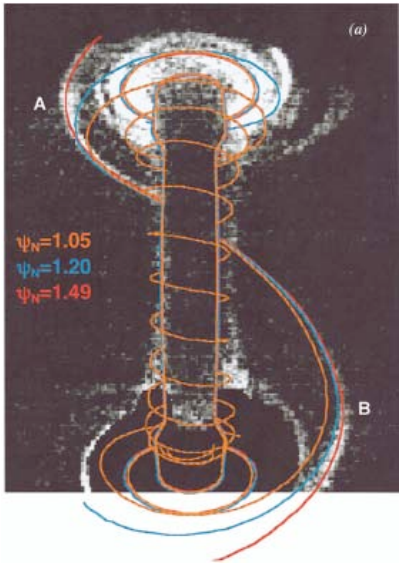


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PEGASUS: ELM-like Structures Observed

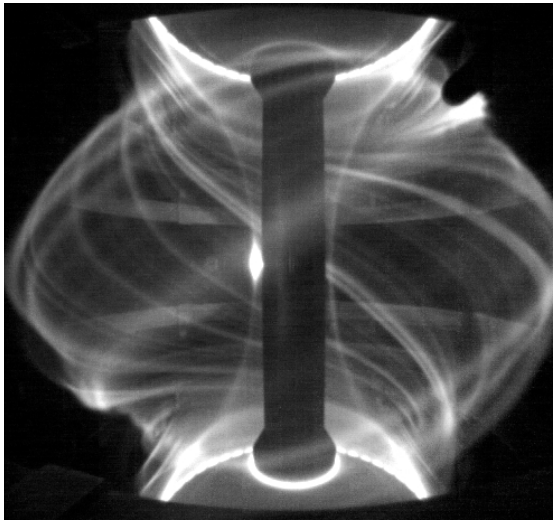


PEGASUS



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

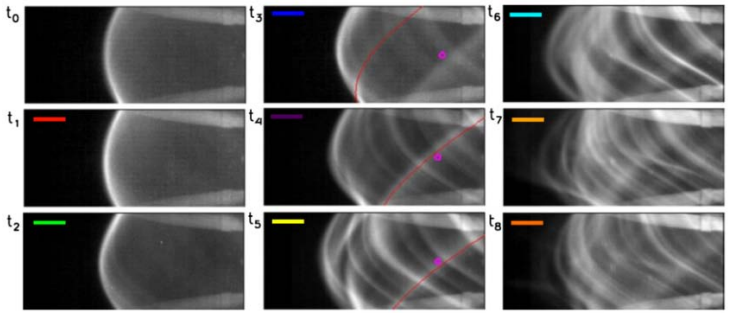
NSTX



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



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

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Distinct Edge Stability Phases Observed

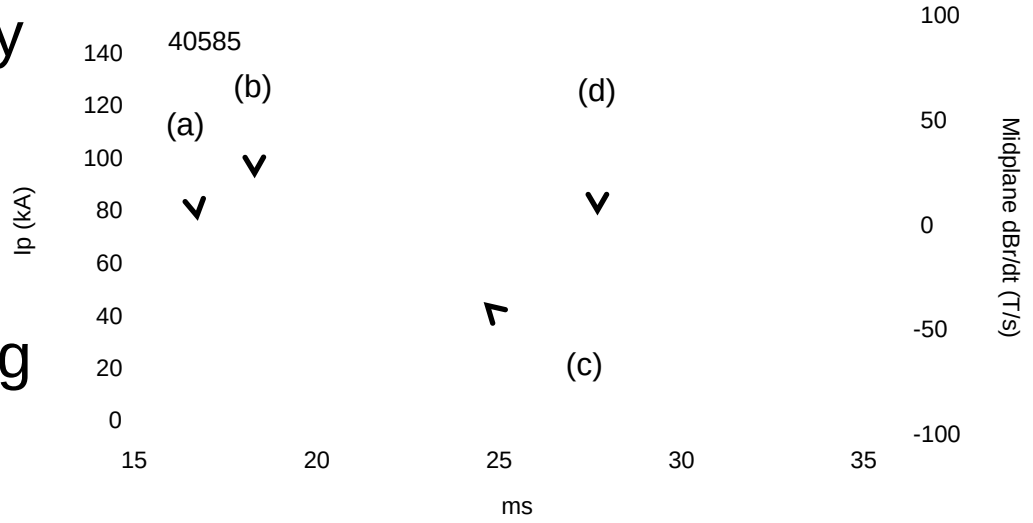
a.) Breakdown/pre-filamentary

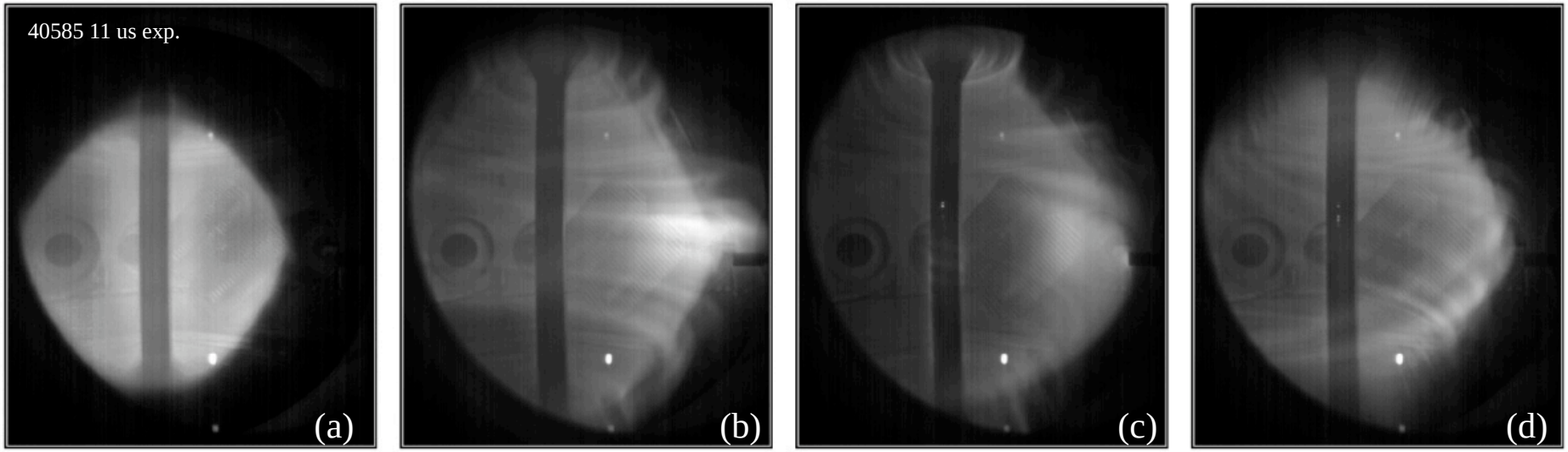
b.) Peeling-like

- High m, low n; rotation, radial propagation

c.) m/1: Violent internal tearing

d.) MHD Quiescent L-mode



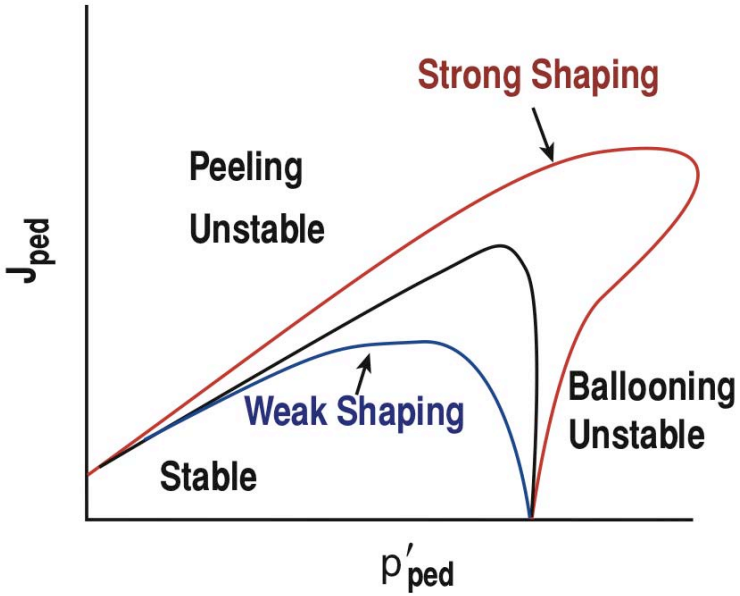


Breakdown | Peeling-like | m/1 | MHD Quiescent

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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:

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

where

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

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

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

with D_R (< 0) = GGJ resistive interchange coefficient

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

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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**

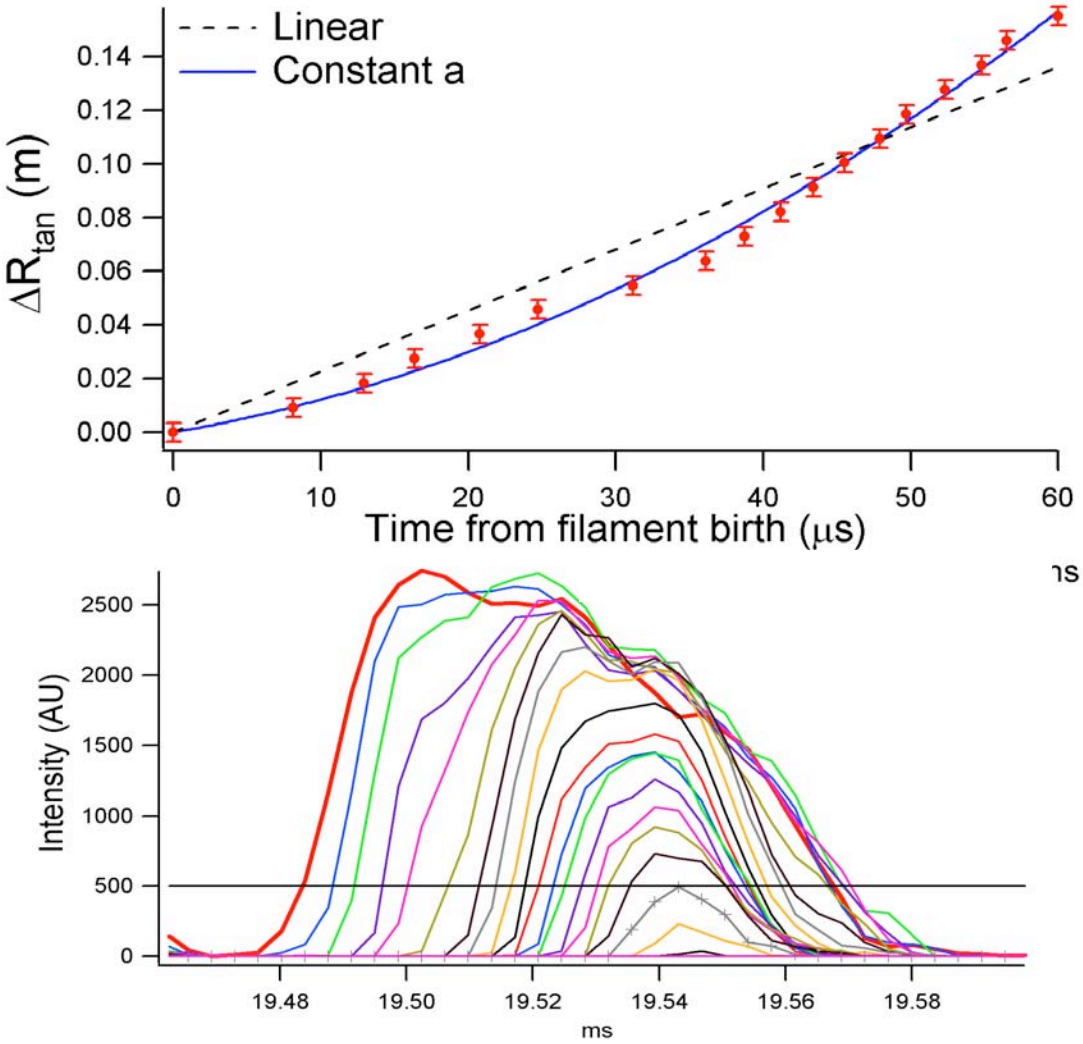
*: Thomas, Phys. Plasmas **12**, 056123 2005

- 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 : dI_p/dt ($\leq$ 50 MA/s) → transient skin current
- Low-A geometry enables ITER-relevant research

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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

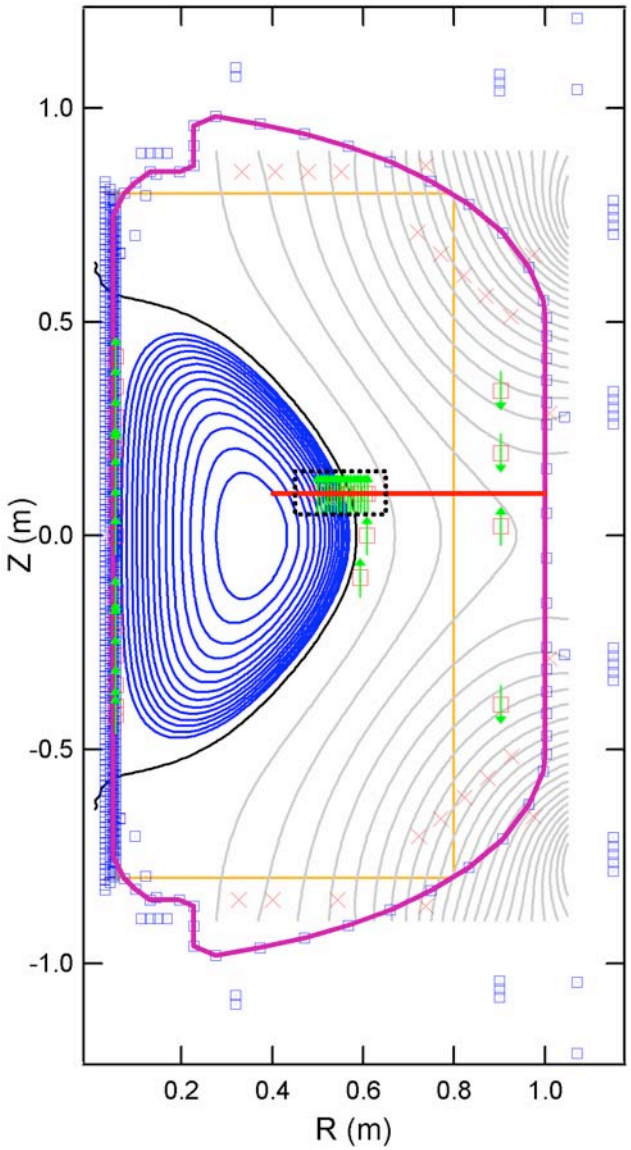


Time evolution of uniformly spaced R_{tan} viewing chords

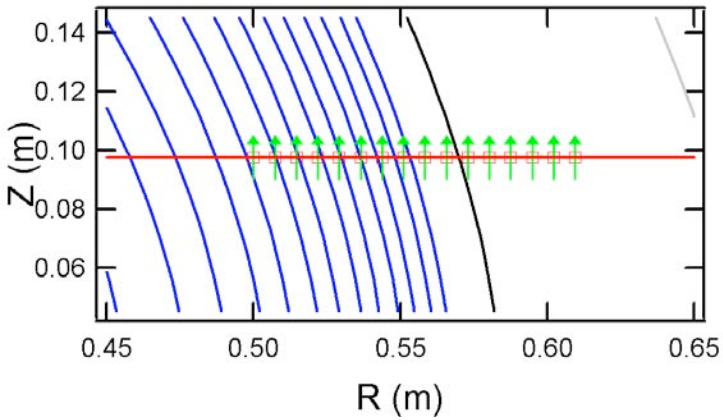
*Kirk, Plas. Phys. Controlled Fus. **49**, 2007

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Comparison of Peeling Theory to Experiment Requires Accurate Equilibrium Reconstructions



- Accurate equilibria depend crucially on accuracy of local measurements
  - E.g. Peeling-ballooning: edge $P(\psi)$, $j(\psi)$ profiles
- PEGASUS operating conditions allow for direct measurement of B_z and p
  - New probes provide strong experimental constraint on $j(\psi)$ and $p(\psi)$.

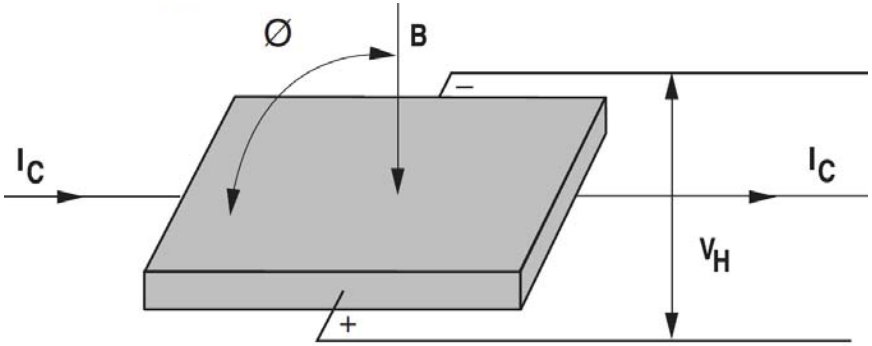


Hall probes positioned to strongly constrain current profile

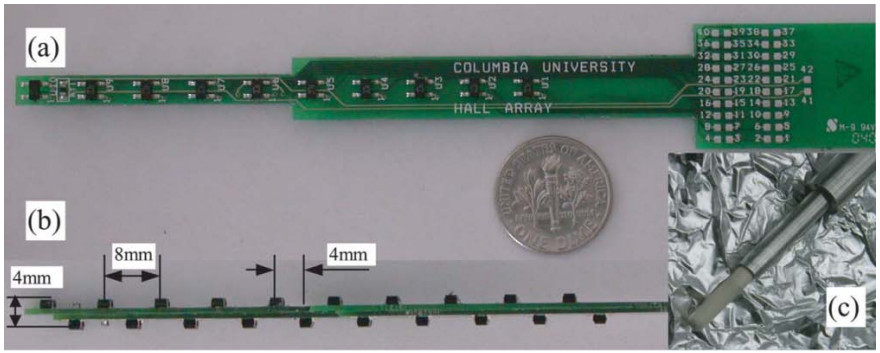
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In-situ Hall Probe Arrays Constrain J(ψ)

- 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 $B_z \rightarrow j(\psi)$

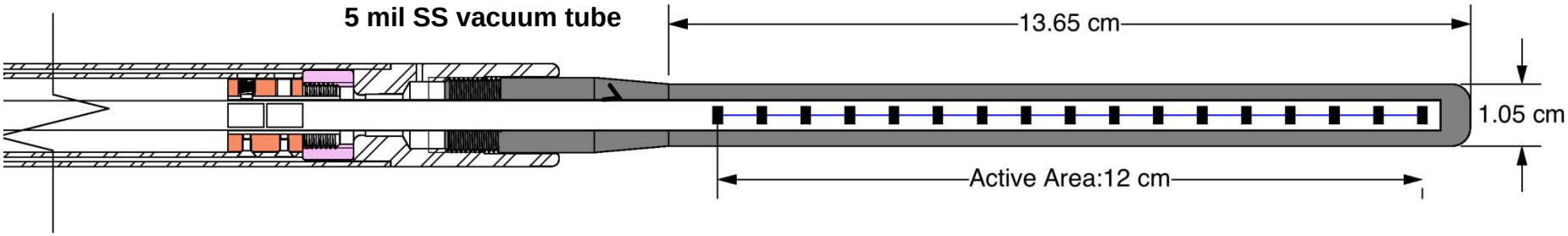


HBT-EP Hall Probe Array**

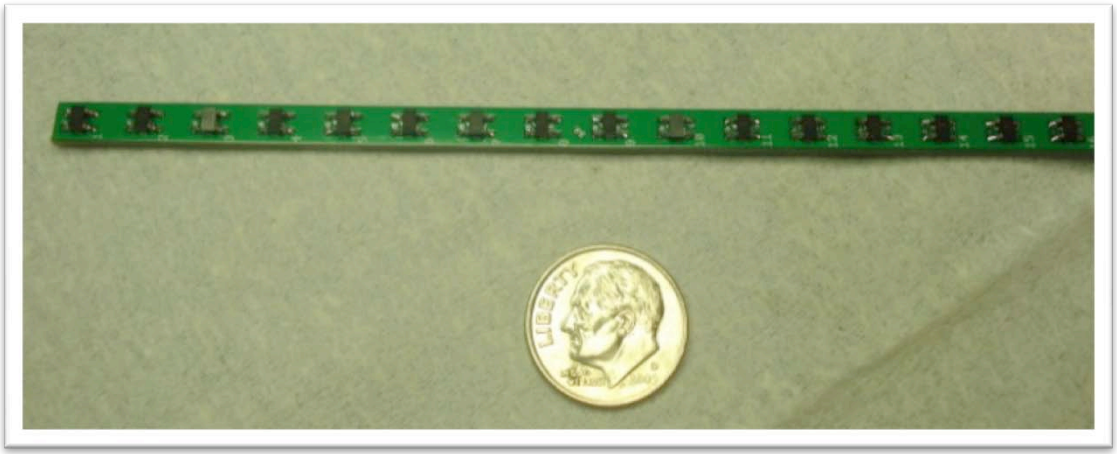
*: Ďuran, et. al., Rev. Sci. Instrum. **73**, 10, 3482, 2002
: Liu, et. al., Rev. Sci. Instrum. **76, 093501, 2005

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1st Generation Hall Probe Deployed



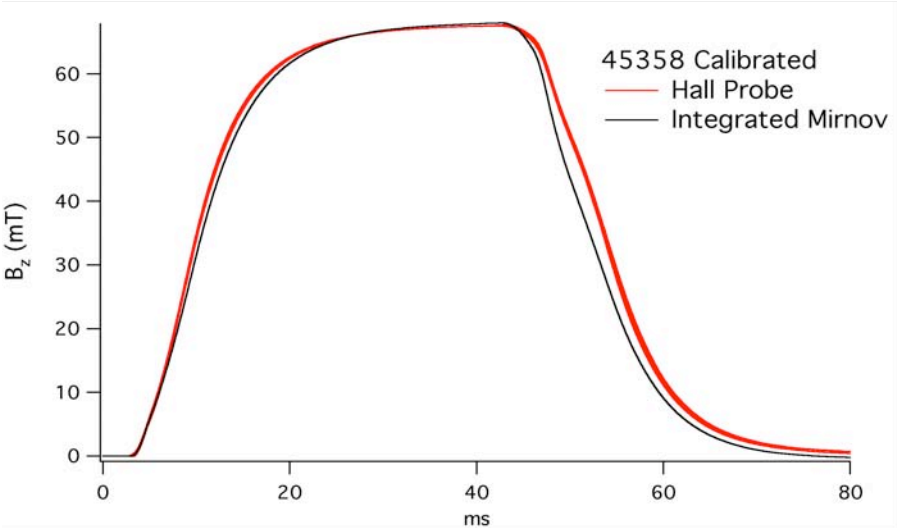
- Solid-state InSb Hall sensors
  - Sypris model SH-410
- 16 channels, 7.5mm center-center spacing
- C armor as low-Z PFC



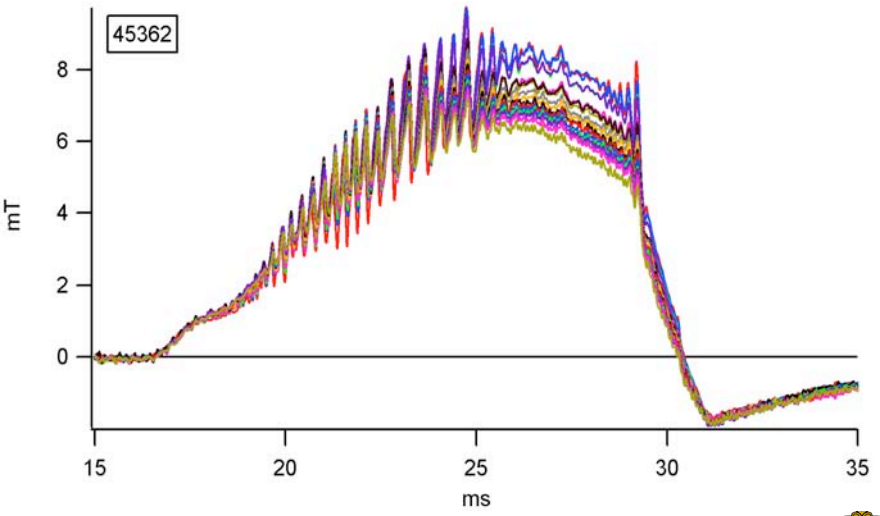
- Slim profile minimizes plasma perturbation

Initial Hall Probe Data Obtained

- Cross-calibration performed using existing Mirnov coils
  - Weak dependence of G_H on temperature observed
- Frequency response: ≤ 25 kHz
  - Suitable for equilibrium reconstructions



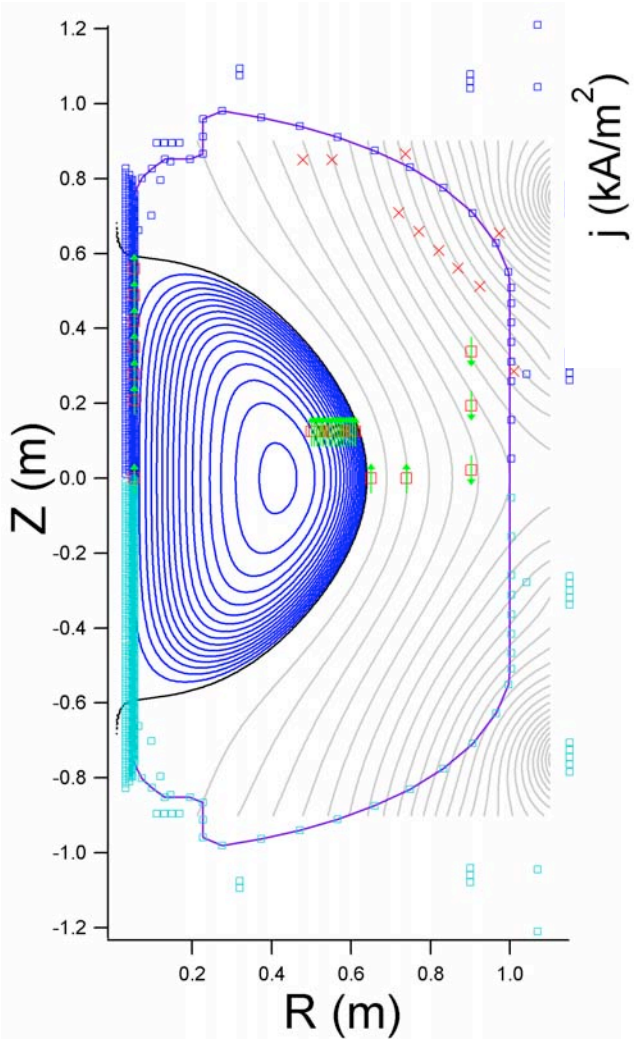
Time Response in EF-Only Calibration Pulse

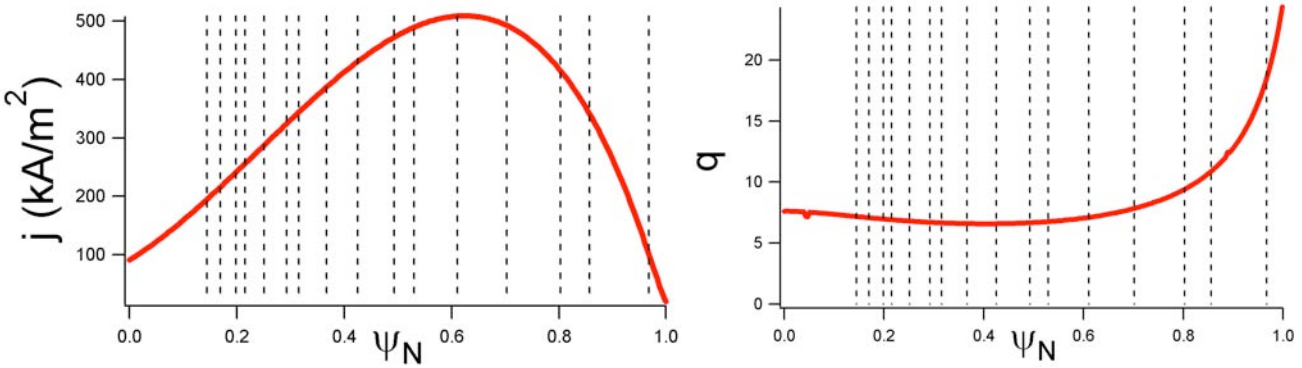


Plasma Component

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Hall Probes Constrain J(ψ)



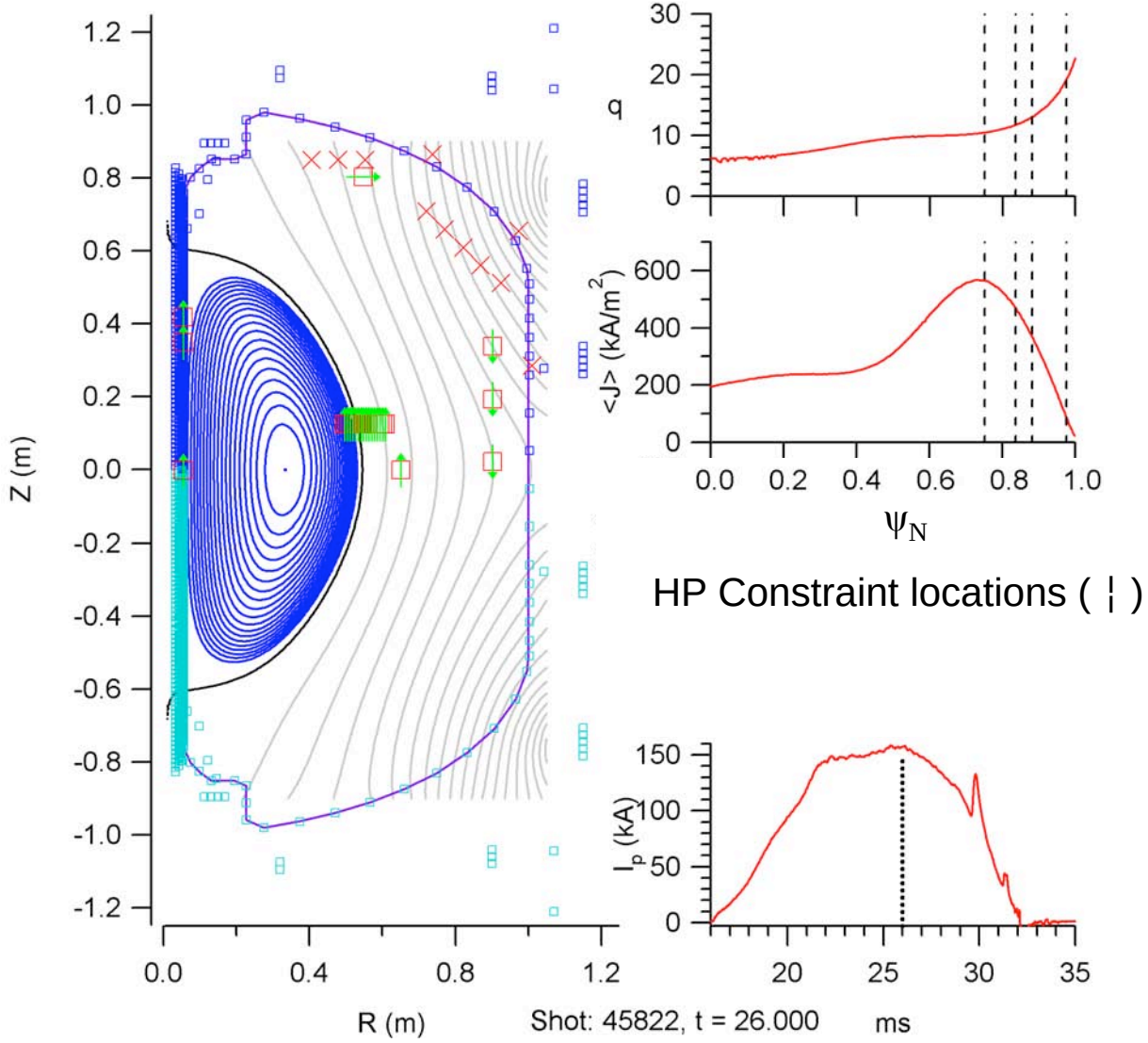


Representative profiles using 3-term polynomial fit

- 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

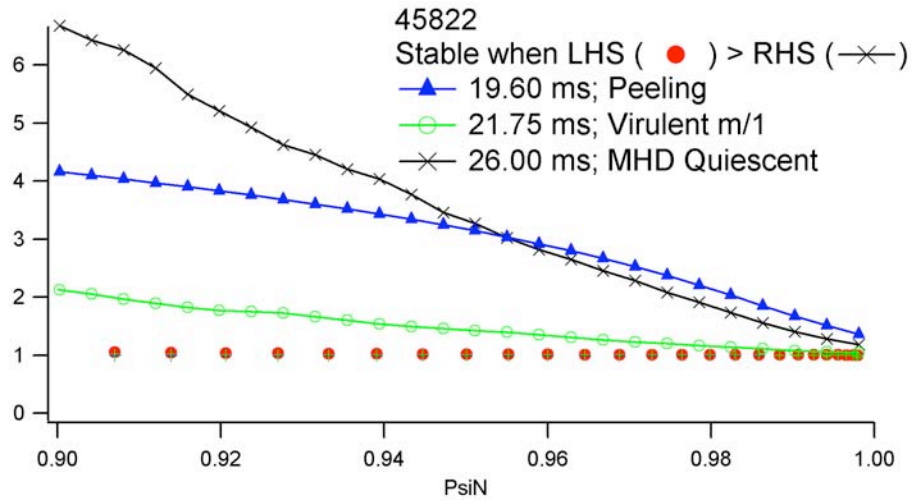
*Sontag, A, Nuclear Fusion, **48,** 095006 , 2008

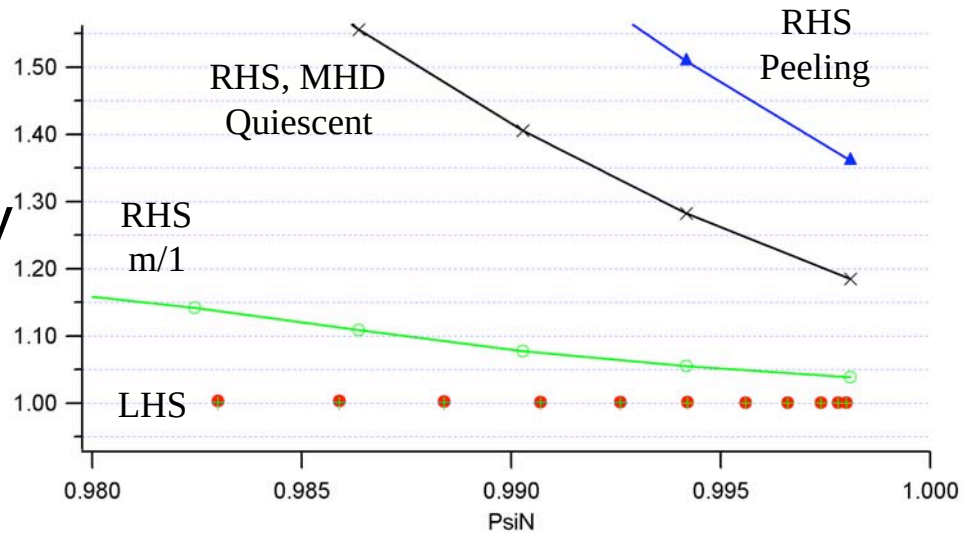
I_p	157 kA
R_0	.30 m
a	.24 m
A	1.2
κ	2.2
ℓ_i	.25
β_p	.10
β_t	.02
q_0	6.1
q_{95}	17

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Filament Appearance Consistent with Peeling Stability Criterion

- Connor's peeling stability criterion computed from initial equilibria
  - 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
  - Numeric stability analysis of accurate j(ψ) equilibria via DCON, ELITE

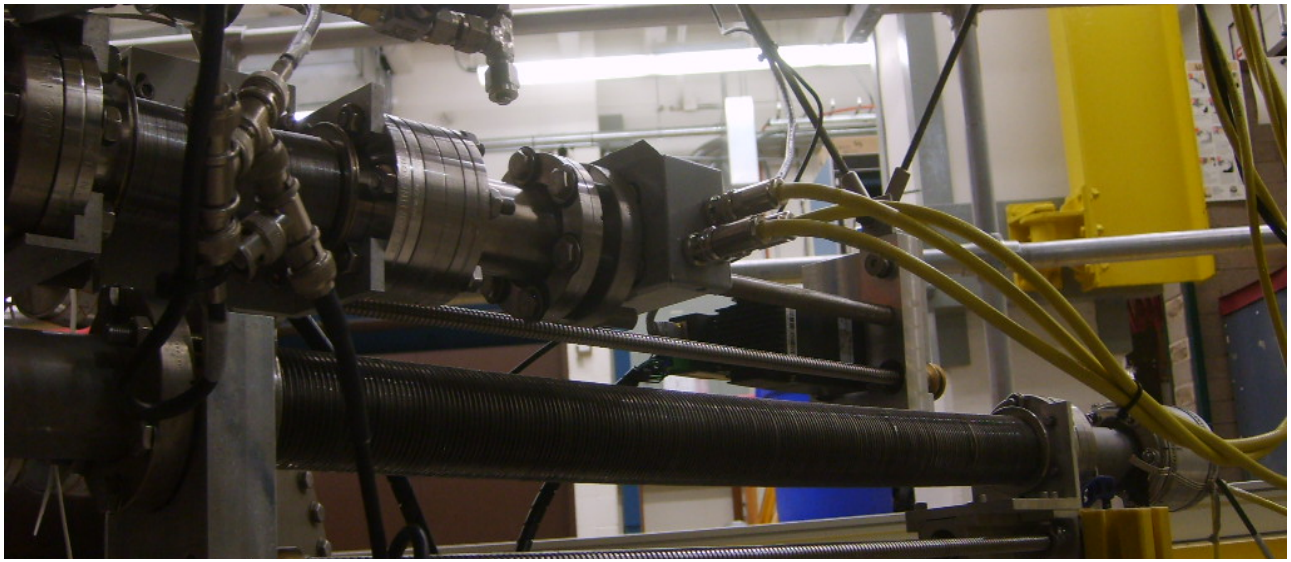




Unstable if RHS > LHS

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Langmuir Triple Probes Deployed on PEGASUS to Constrain p(ψ)



- Langmuir triple probes pair constructed to provide edge pressure profiles for equilibrium reconstructions.

- Probes are radially-scanning, with -3dB corner frequency ~10-40kHz.

Langmuir Probe Theory*

- Measures local T_e and n_e in cold, low-density plasmas
- Biasing used to control collected fraction of $f_{Boltzmann}(v)$.
- Integrating ion and electron Maxwellian velocity distributions gives a general expression for probe current I_P:

$$I_P = -I_{sat}^{e} e^{\frac{e(V_{Bias}-V_P)}{kT}} + I_{sat}^{i}$$

$$\text{where} \quad I_{sat}^{e} = A_p n_e e \left(\frac{k_B T_e}{2\pi m_e}\right)^{\frac{1}{2}} \quad \text{and} \quad I_{sat}^{i} = \exp\left(-\frac{1}{2}\right) A_p n_e e \left(\frac{k_B T_e}{m_i}\right)^{\frac{1}{2}}$$

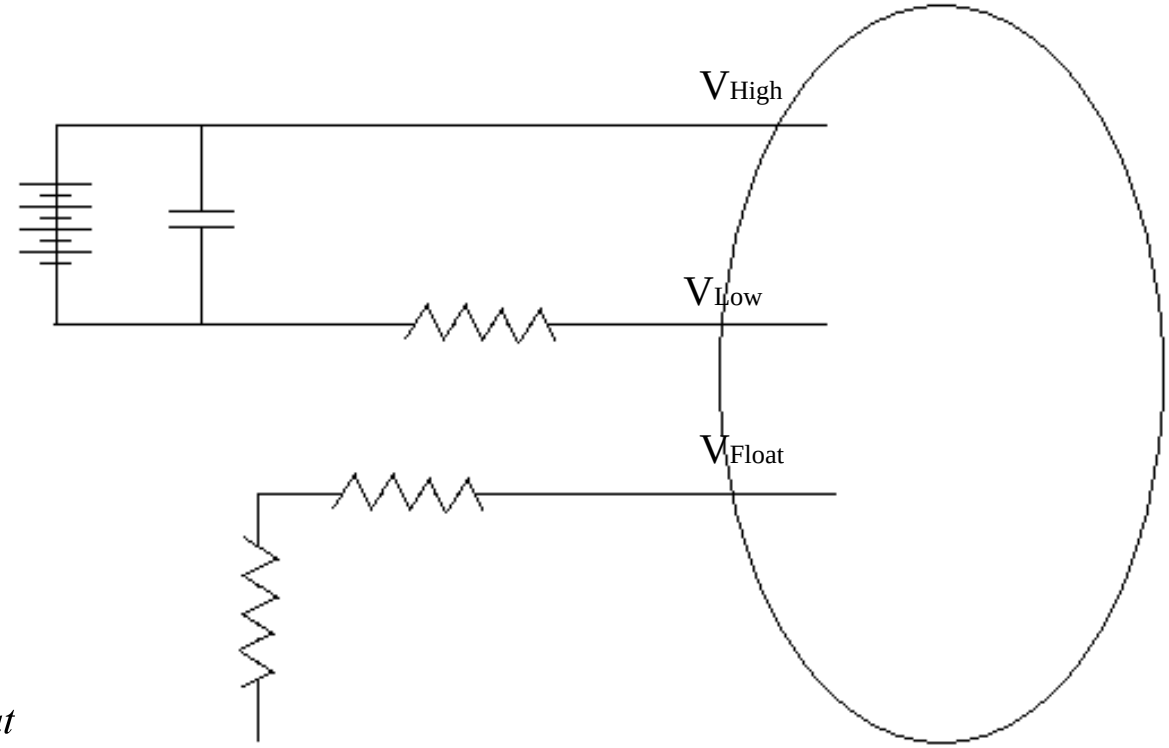
- The ion saturation current equation yields density immediately:

$$n_e = \left(\frac{m_i}{k_B T_e}\right)^{\frac{1}{2}} \frac{I_{sat}^{ion}}{Ae} \exp\left(\frac{1}{2}\right)$$

*Sin-Li Chen and T. Sekiguchi, J. Applied Phys. 36, 2363 (1965)

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Triple Probe Theory



For each probe in the triple probe setup, one has:

$$I_H = -I_{sat}^{e} e^{\frac{e(V_H - V_P)}{kT}} + I_{sat}^{i}$$

$$I_L = -I_{sat}^{e} e^{\frac{e(V_L - V_P)}{kT}} + I_{sat}^{i} = -I_H$$

$$I_F = -I_{sat}^{e} e^{\frac{e(V_F - V_P)}{kT}} + I_{sat}^{i} = 0$$

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Triple Probe Temperature Measurements

Making use of the expression for the current to each probe we consider the quantity $\frac{I_H - I_F}{I_H - I_L}$.

The simplification of this quantity at right allows for a solution for T_e.

$$\frac{I_H - I_F}{2I_H} = \frac{I_H - I_F}{I_H - I_L}$$

$$\frac{1 - I_F / I_H}{2} = \frac{1 - I_F / I_H}{1 - I_L / I_H}$$

$$\frac{1}{2} = \frac{1 - I_F / I_H}{1 - I_L / I_H}$$

$$\frac{1 - e^{\frac{e(V_{Float} - V_{High})}{k_B T_e}}}{1 - e^{\frac{e(V_{Low} - V_{High})}{k_B T_e}}} = \frac{1}{2}$$

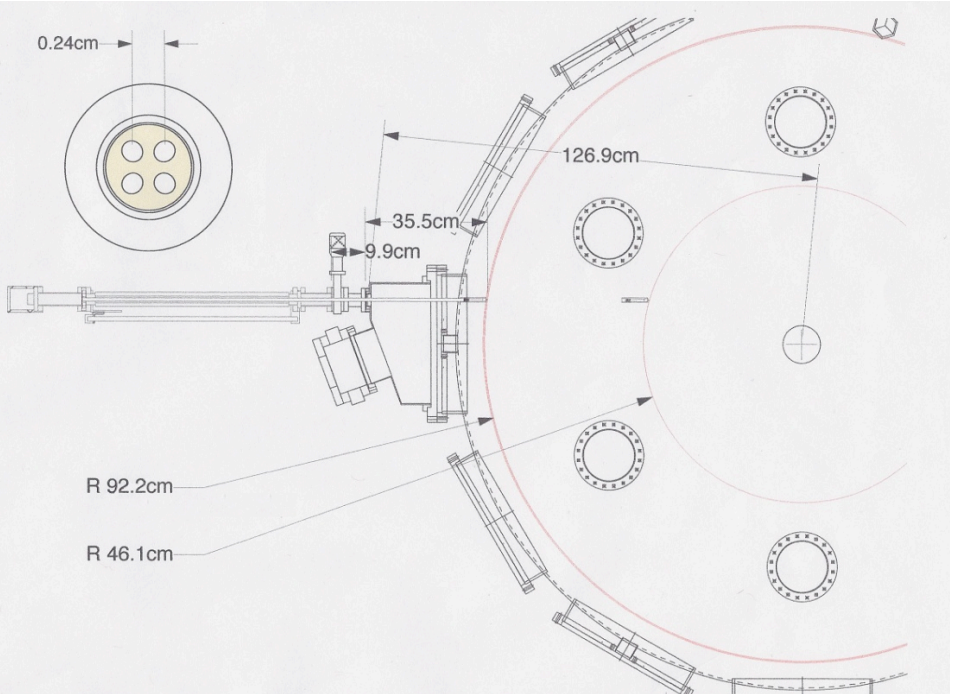
Which in the limit $eV_{Bias} >> k_B T_e$ reduces to:

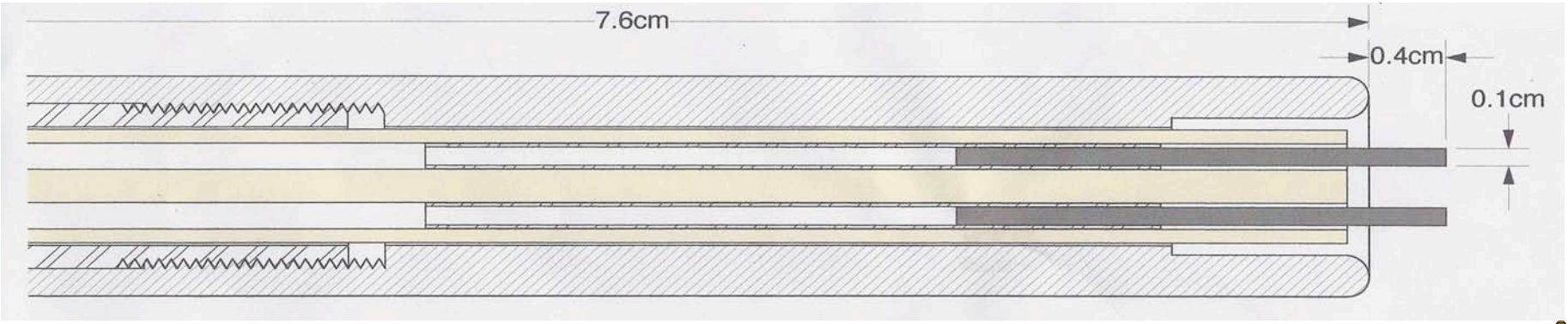
$$\frac{(V_{High} - V_{Float})}{\ln(2)} = T_e (eV)$$

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Langmuir Probes mounted on PEGASUS

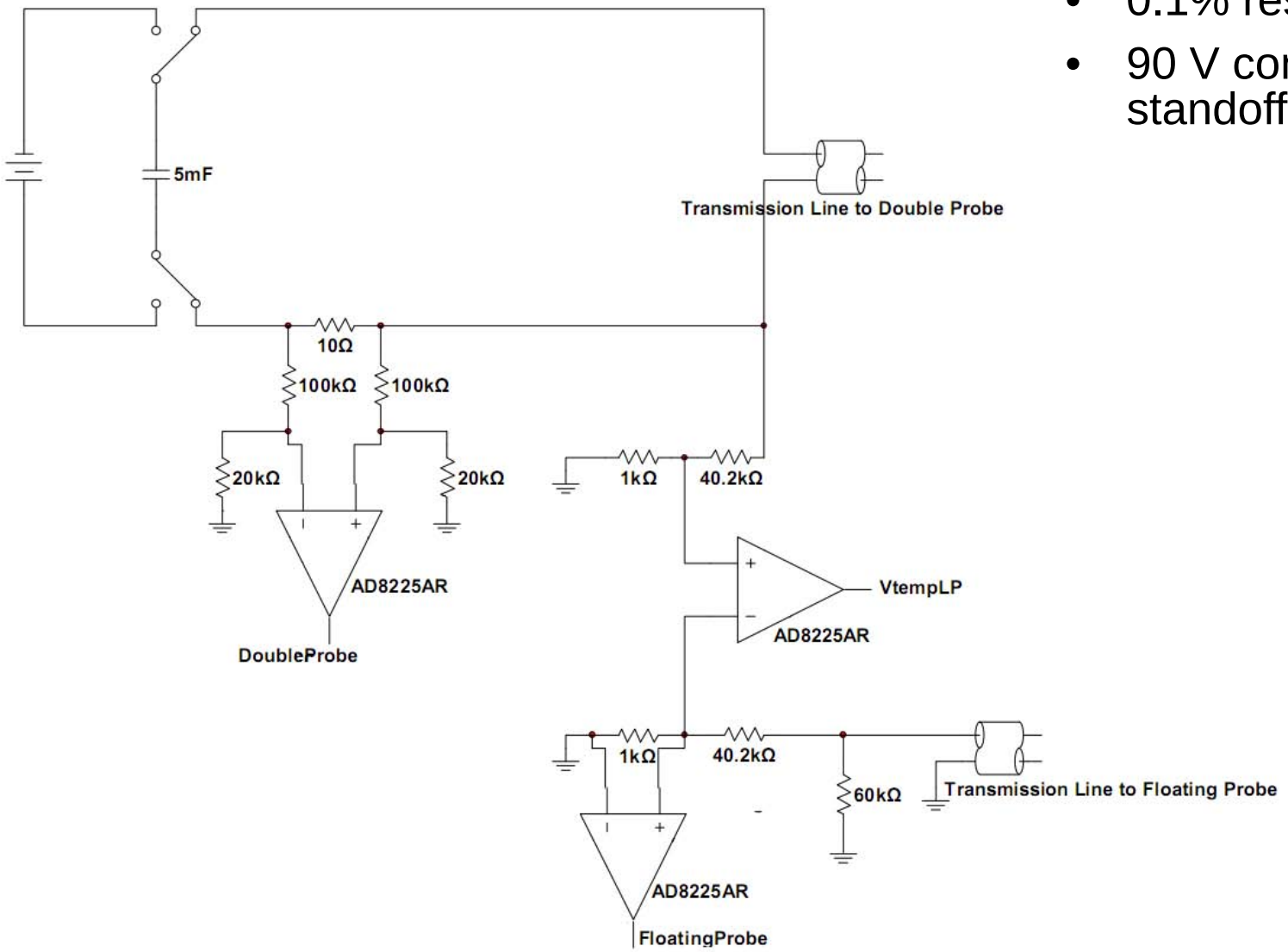
- 4 Tungsten tips per probe
- Probes at z = -7.5 cm, 1.0 cm
- Graphite/Alumina insulation
- Stepper-motor scanning
  - Currently on mid-plane probe only





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Probe Circuit

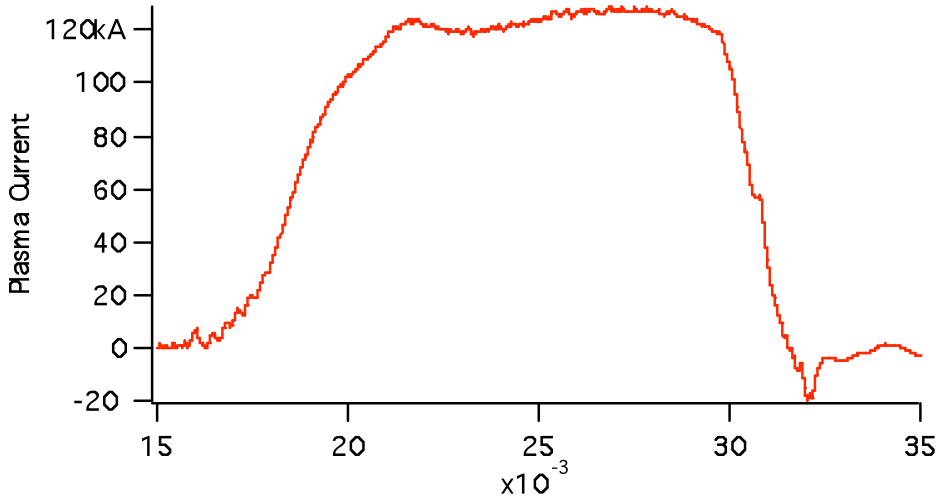


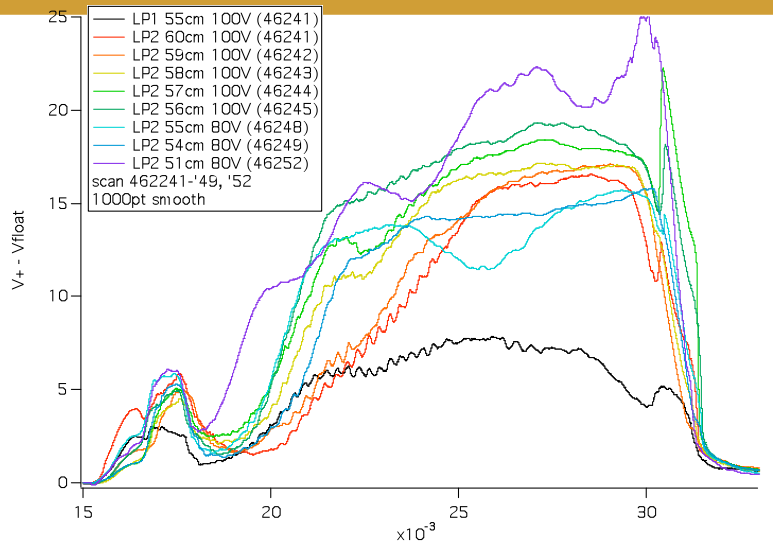
- 0.1% resistors
- 90 V common mode standoff

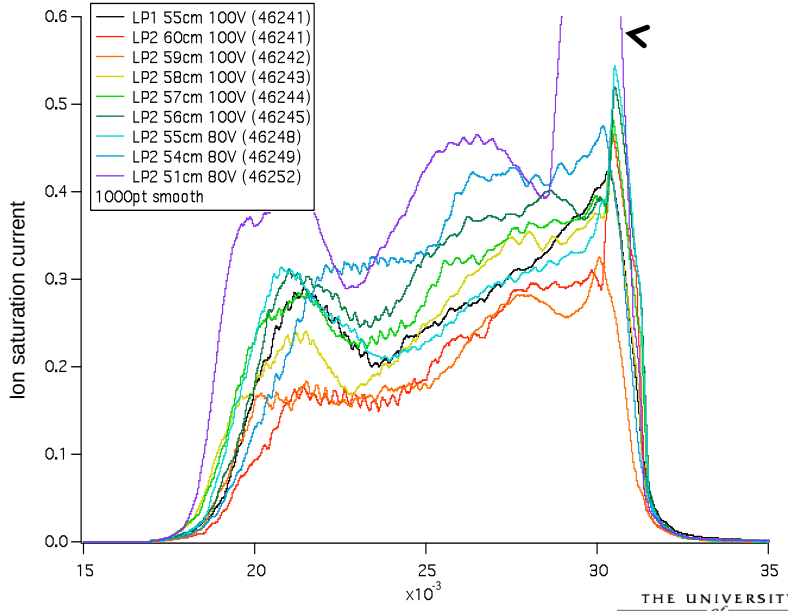
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Initial measurements obtained

- Initial data gathered
  - Plasma R≈35cm, a≈30cm
- Drive-mounted probe scanned from R=60-50 cm
- Manual probe at R=55 cm



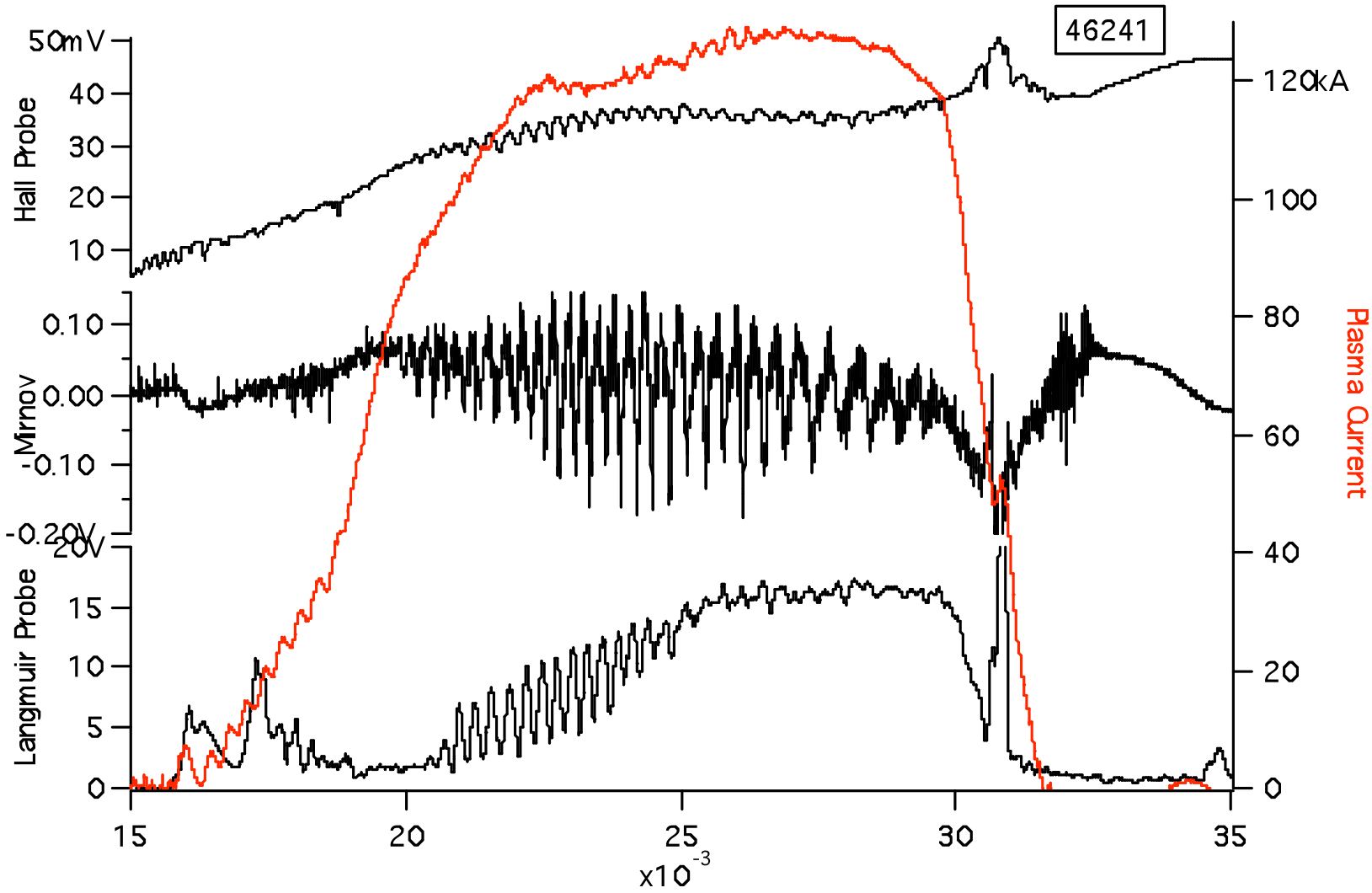




Arc

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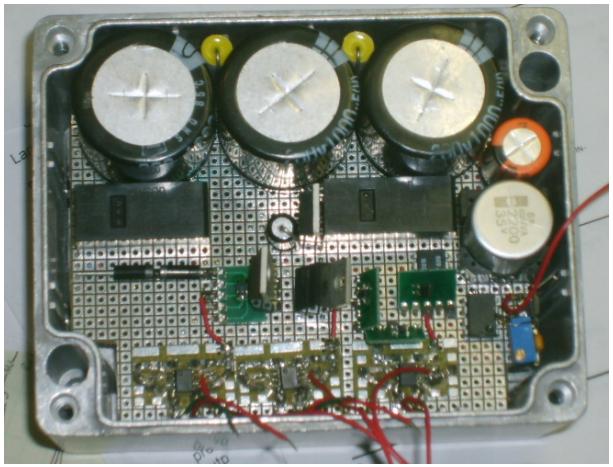
MHD modes visible in Langmuir Data



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Future Work

- Langmuir Triple Probe
  - Determine adequate bias voltage
  - Investigate shielding method of non-scanning probe
  - Deploy electronics at end of probe stalk, reducing capacitance from ~5nF to 400pF
  - Do systematic edge plasma studies



- Equilibrium and stability studies with accurate $j(\psi),p(\psi)$
  - Enhancements to KFIT to accommodate diagnostic capabilities

- Deployment of Langmuir probe arrays for internal T_e,n_e

Summary

- Filamentary structures observed in PEGASUS consistent with peeling mode drive
  - PEGASUS' <j/B> peeling drive comparable to larger devices in H-mode
  - Filaments observed during conditions of high dI_P/dt
- $B_z(r)$, p(r) required for accurate equilibrium reconstructions
  - PEGASUS plasma conditions allow use of probes
  - j, p, can be obtained with Hall probe, Langmuir triple probes
- Hall probe implemented
  - Frequency response ≤ 25kHz
- Langmuir triple probe pair recently deployed

Reprints

Contact: ehinson@wisc.edu

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