Probe Measurements in the H-mode Pedestal Region in the Pegasus Toroidal Experiment

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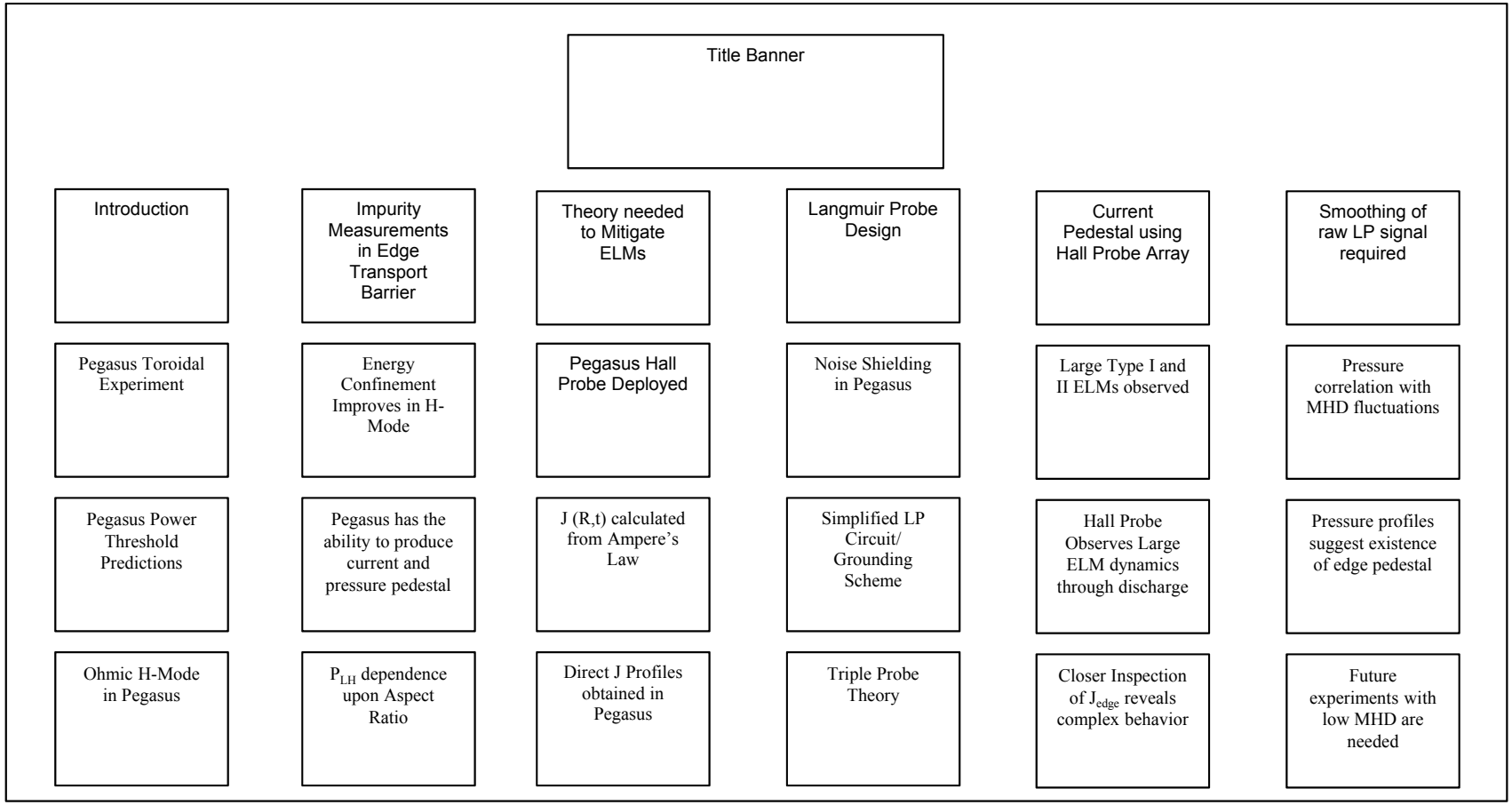
October 29, 2014

PEGASUS Toroidal Experiment

Layout

8.5” x 11”

8’ W x 4’ H

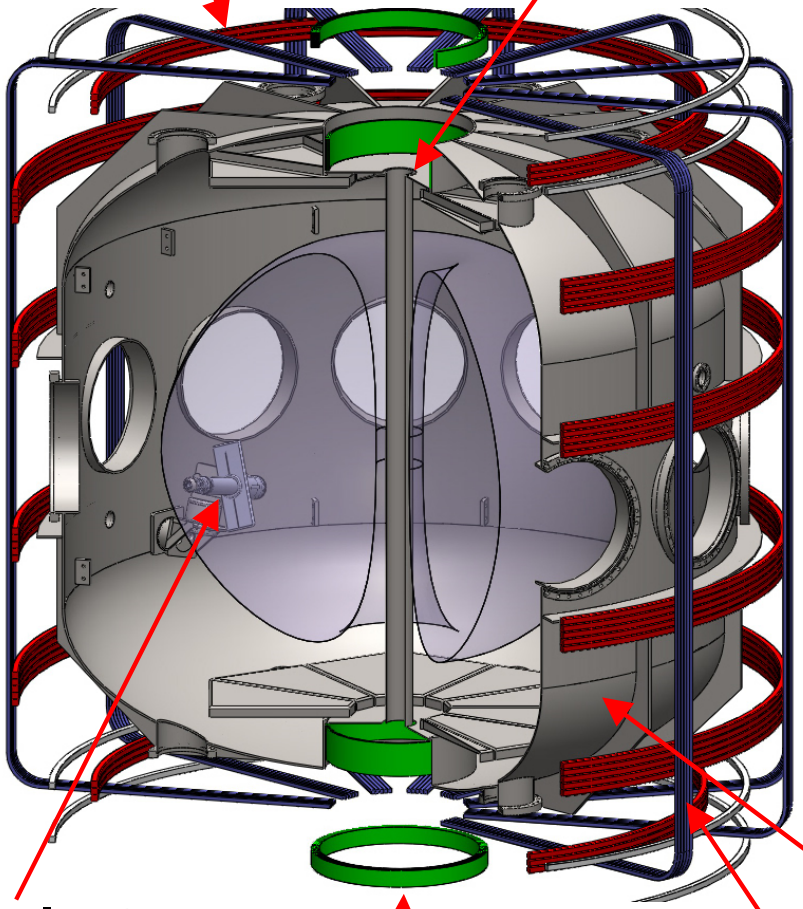


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Introduction

- H-mode is the presumed operating regime of ITER.
- An edge transport barrier is formed in H-mode. This barrier drives the ELM instability.
- No first-principles model currently exists for H-mode or ELMs. Thus, understanding the H-mode plasma edge is crucial to developing a model.
- A current pedestal is routinely measured on Pegasus using a Hall Probe.
- A Triple Langmuir Probe was implemented on Pegasus in order to investigate the feasibility of an edge profile measurement.

PEGASUS is a Compact, Ultralow-*A* ST



Experimental Parameters

Parameter	Achieved
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .25
K	1.4 – 3.7
$\Delta\tau_{shot}$ (s)	≤ 0.025
β_t (%)	≤ 25

Major research thrusts:

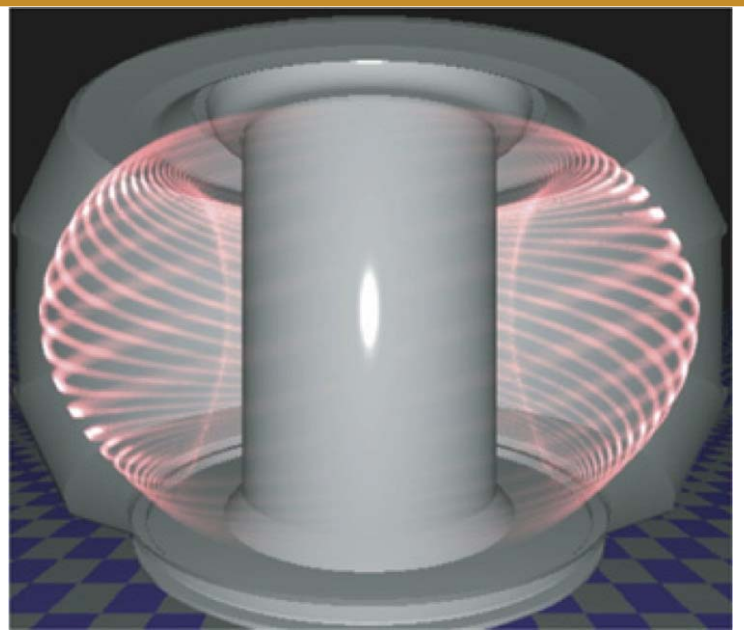
- Tokamak physics at small aspect ratio
- Non-inductive startup and growth

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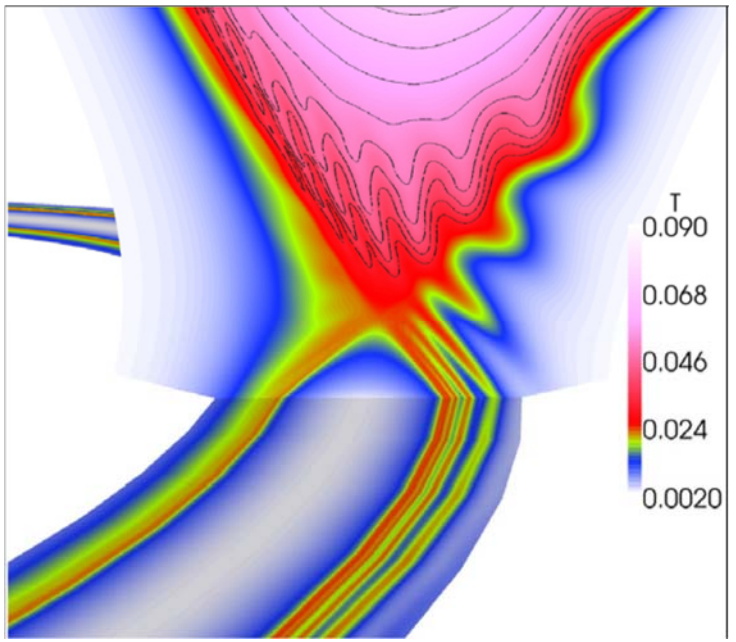
Validated, Predictive Theory Needed to Mitigate ELMs

- Peeling-ballooning model
  - Competing ideal MHD instabilities cause ELM onset
  - Current-driven peeling modes
  - Pressure-driven ballooning modes
- Nonlinear dynamics
  - More complete physical models
  - Evolution of P-B mode structures
  - Heat flux deposition projections
- Detailed measurements required to validate theory
  - P_{edge}, $J_{edge}(R,t)$ on ELM timescales[1]

[1]Maggi, Nucl. Fusion **50**, 066001 (2010)



Snyder *et al.*, Phys. Plasmas **12**, 056115 (2005)



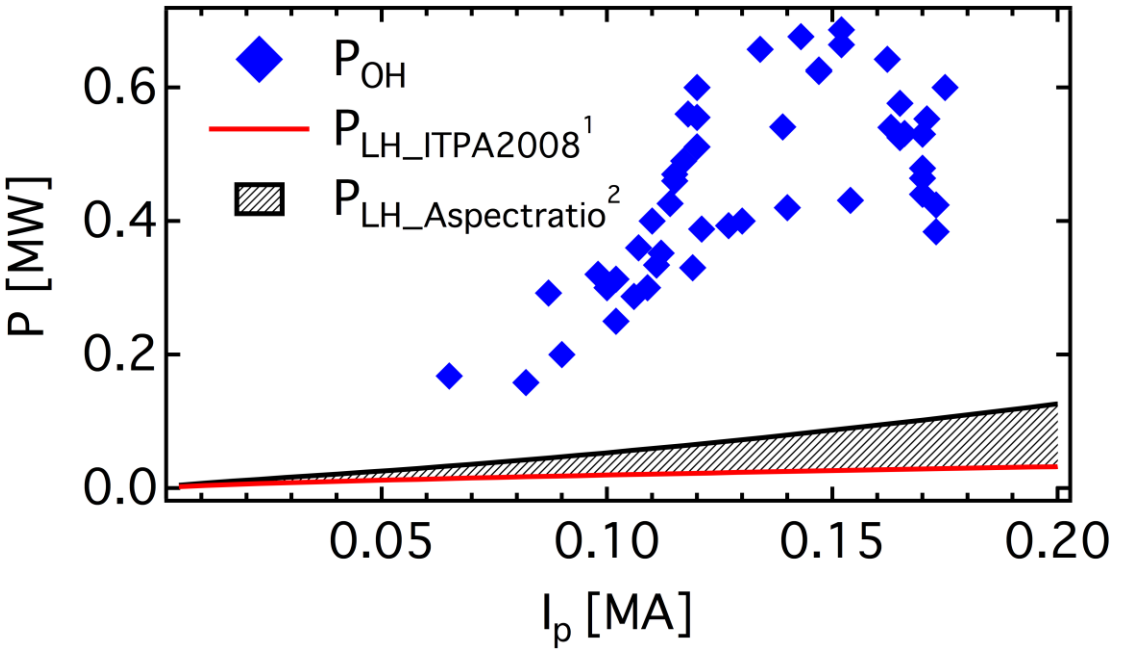
Huysmans *et al.*, Plasma Phys. Control. Fusion **51**, 124012 (2009)

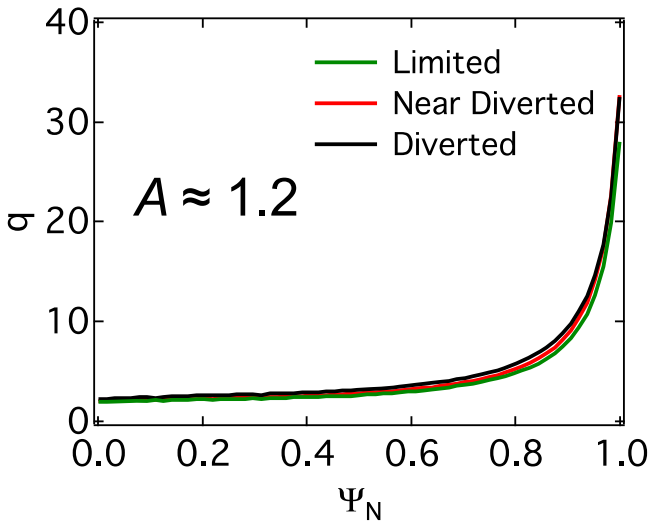
H-mode Readily Accessible at Near-Unity *A*

- H-mode accessed when $P_{OH} > P_{LH}$
- P_{LH} scalings strongly depend on B_T

$$P_{LH} \sim n_e^{0.7} B_T^{0.7} S$$

  - Low *A*, B_T: P_{LH} is low
- Magnetic profile similar in limited and diverted at *A≈1*
  - Edge shear equivalent between limited and diverted



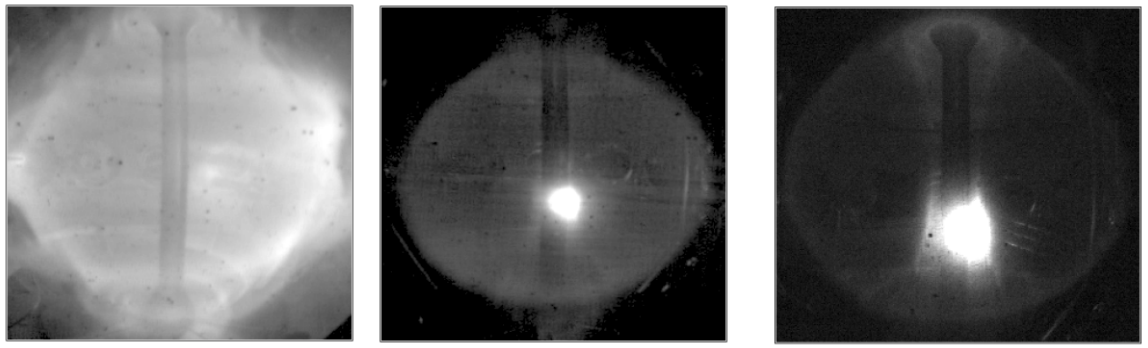


[1] *Nucl. Fus.*, **47,** S82 (2007)
[2] *Plasma Phys. Control. Fus.*, **46**, A232 (2004)

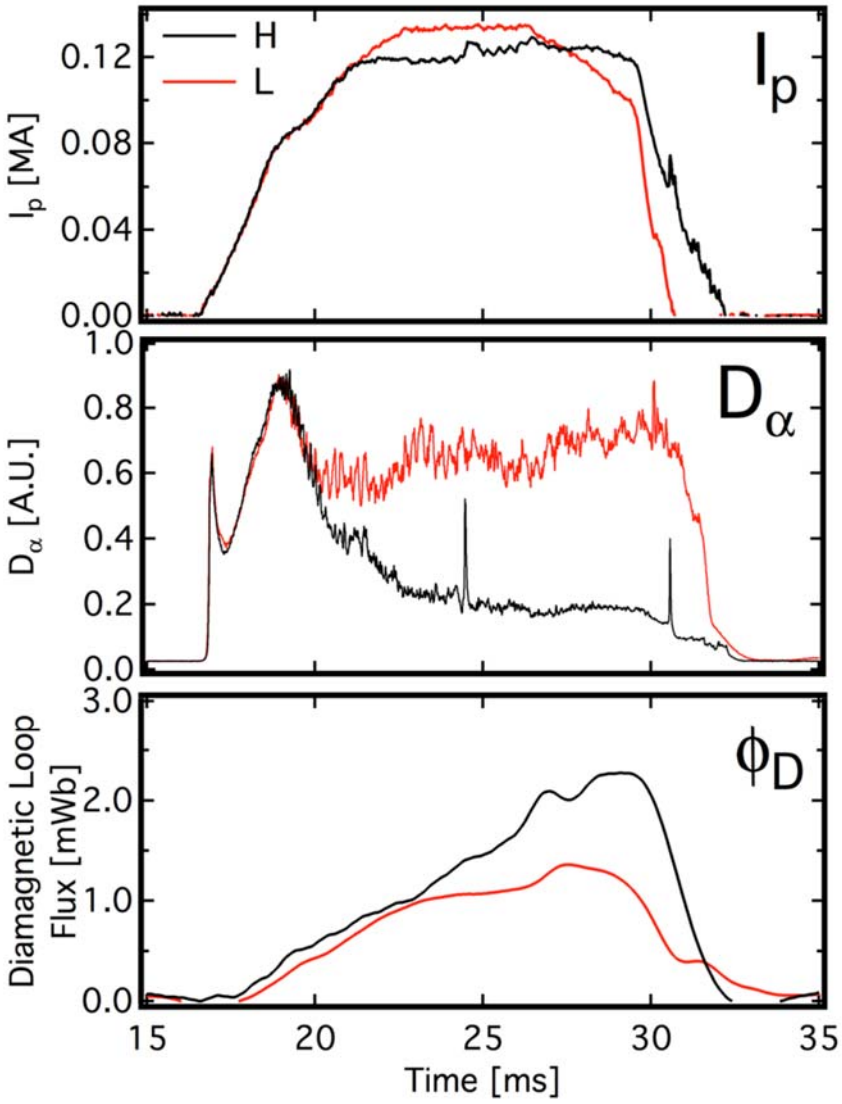
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Ohmic H-mode Plasmas have Standard Signatures

Limited L **Limited H** **Near-diverted H**

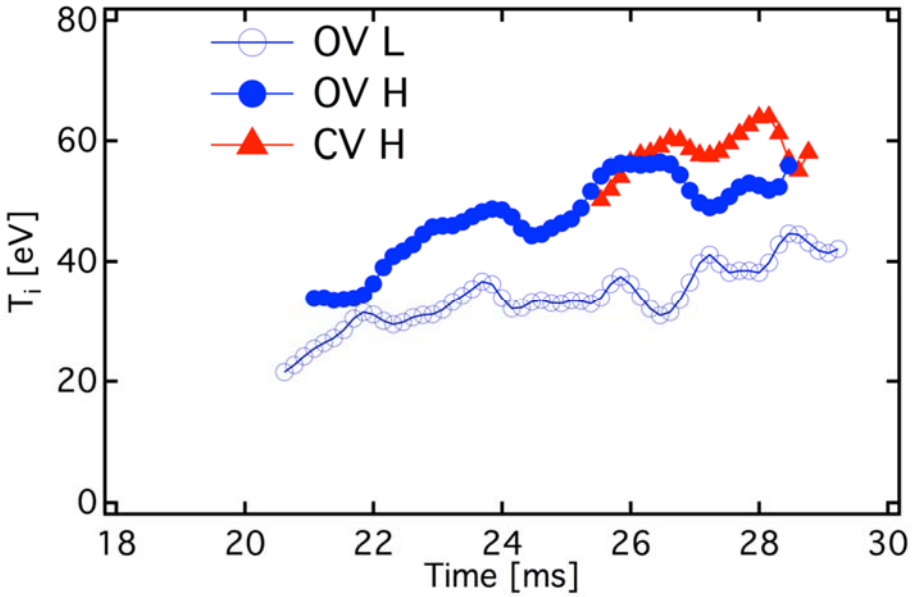


- H-mode achieved via HFS fueling
- Quiescent edge
- Reduced D_α, Increased ∇D_α
- Large and small ELMs
- Bifurcation in ϕ_D
  - Transport equilibrium not attained

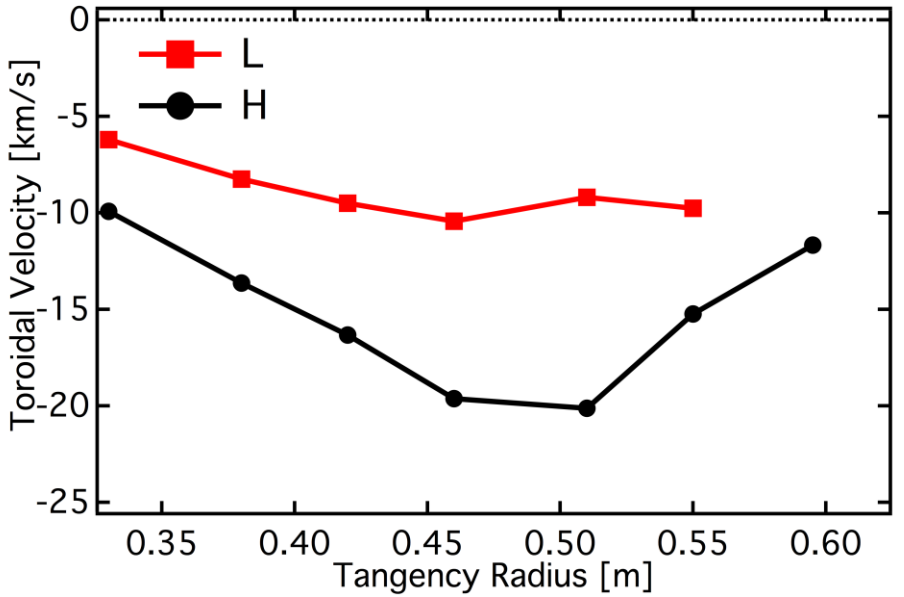


$T_i(0)$ and Edge Shear Increase in H-mode

- Impurity $T_i(0)$ doubles
  - CV only seen in core H-mode plasmas
  - Transport equilibrium not attained



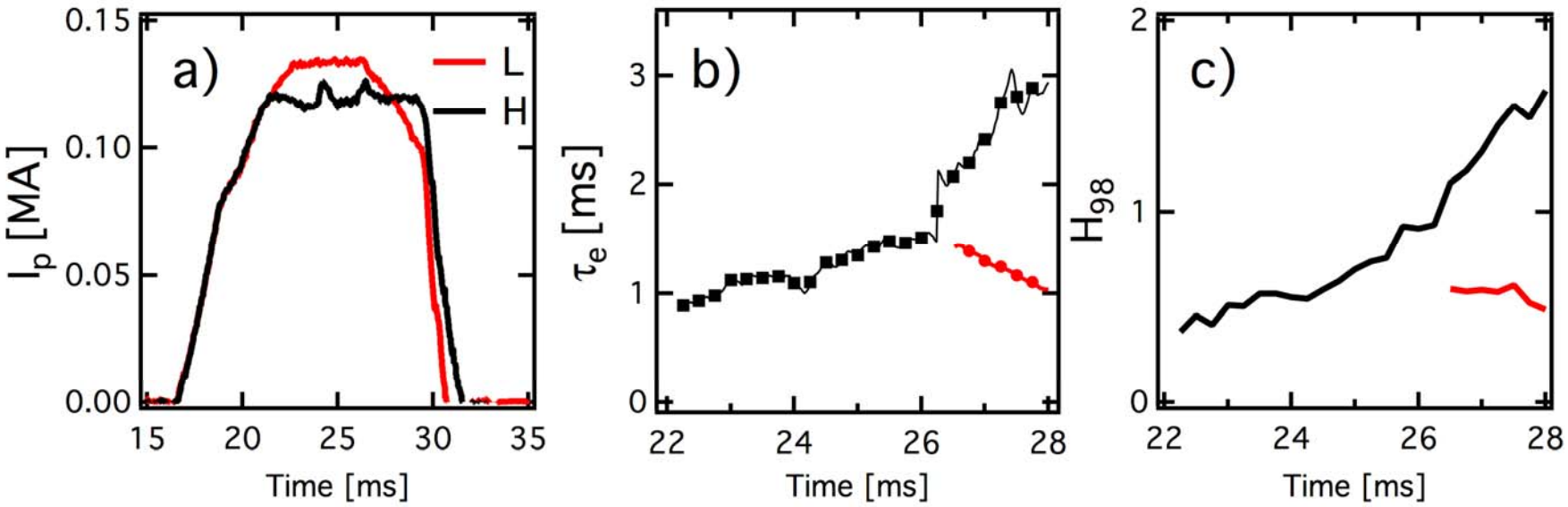
- Chordally-integrated velocity profiles show increased shear in the outer region in H-mode
  - Indirect evidence of E_r well



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Energy Confinement Improves in H-mode

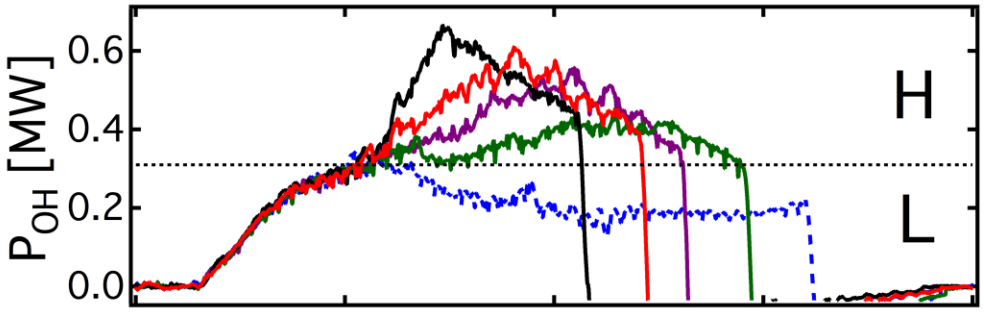
- τ_e from time-evolving magnetic reconstructions
- L-mode: $\tau_e \sim 1.5$ ms, $H_{98} \sim 0.5$
- H-mode: $\tau_e \sim 3$ ms, $H_{98} > 1$
  - Due to short pulse — not in transport equilibrium



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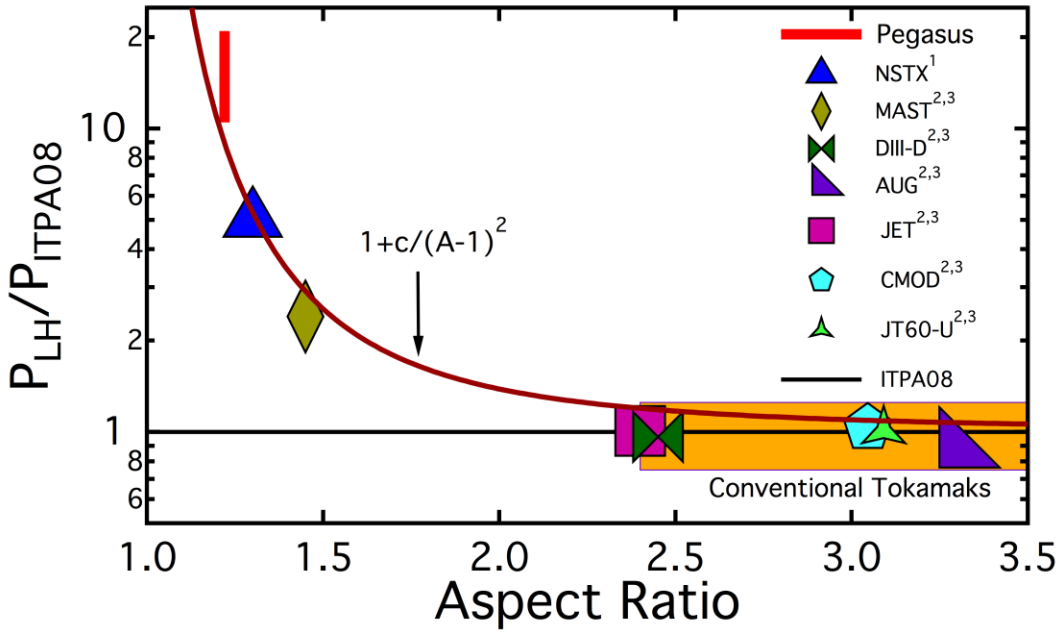
P_{LH} Increasingly Diverges from Expectations as $A \rightarrow 1$

- P_{LH} studied by varying P_{OH}, n_e
  - n_e dependence observed
  - Near-diverted P_{LH} similar to limited



- PEGASUS $P_{LH}/P_{ITPA08} \approx 10$

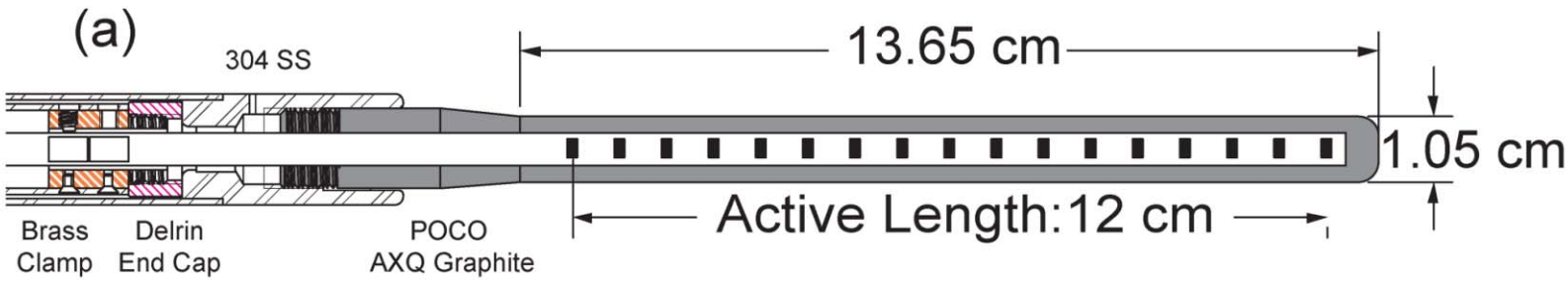
- P_{LH}/P_{ITPA08} continues to increase as A $\rightarrow$1
  - Similar to dependence with q_{edge}, β_T

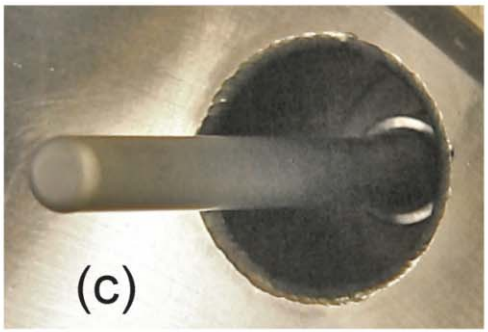


[1] *Nucl. Fusion.*, **50**, 064010 (2010)
[2] Journal of Physics: Conference Series, **123**, 012033 (2008)
[3] Tokamaks, 4th ed. (2011), p 630

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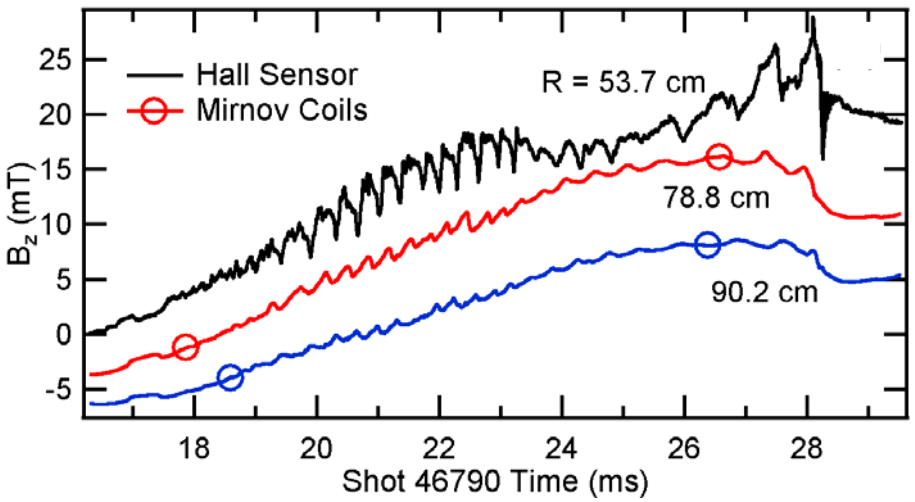
PEGASUS Hall Probe Deployed to Measure J







- Precision $B_z(R, t)$ measurements
  - 16 solid-state InSb Hall sensors
  - 7.5 mm radial resolution
  - 25 kHz large-signal bandwidth
- Carbon Armored
  - Compatible with L, H-mode to date



Bongard *et al.*, Rev. Sci. Instrum. **81**, 10E105 (2010)

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$J_\phi(R,t)$ Calculable Directly from Ampère's Law

$$\mu_0 J_\phi = (\nabla \times \mathbf{B})_\phi = \frac{\partial B_R}{\partial Z} - \frac{\partial B_Z}{\partial R}$$

- Simplest test follows from $B_R(Z)$ or $B_Z(R)$ measurements
- Petty[1] solves for an off-midplane $B_Z(R)$ measurement set and an elliptical plasma cross-section:

$$\mu_0 J_\phi = -\frac{B_Z}{\kappa^2 (R - R_0)} \left(1 - \frac{Z^2 R_0}{\kappa^2 R (R - R_0)^2} \right) - \frac{dB_Z}{dR} \left(1 + \frac{Z^2}{\kappa^4 (R - R_0)^2} \right)$$

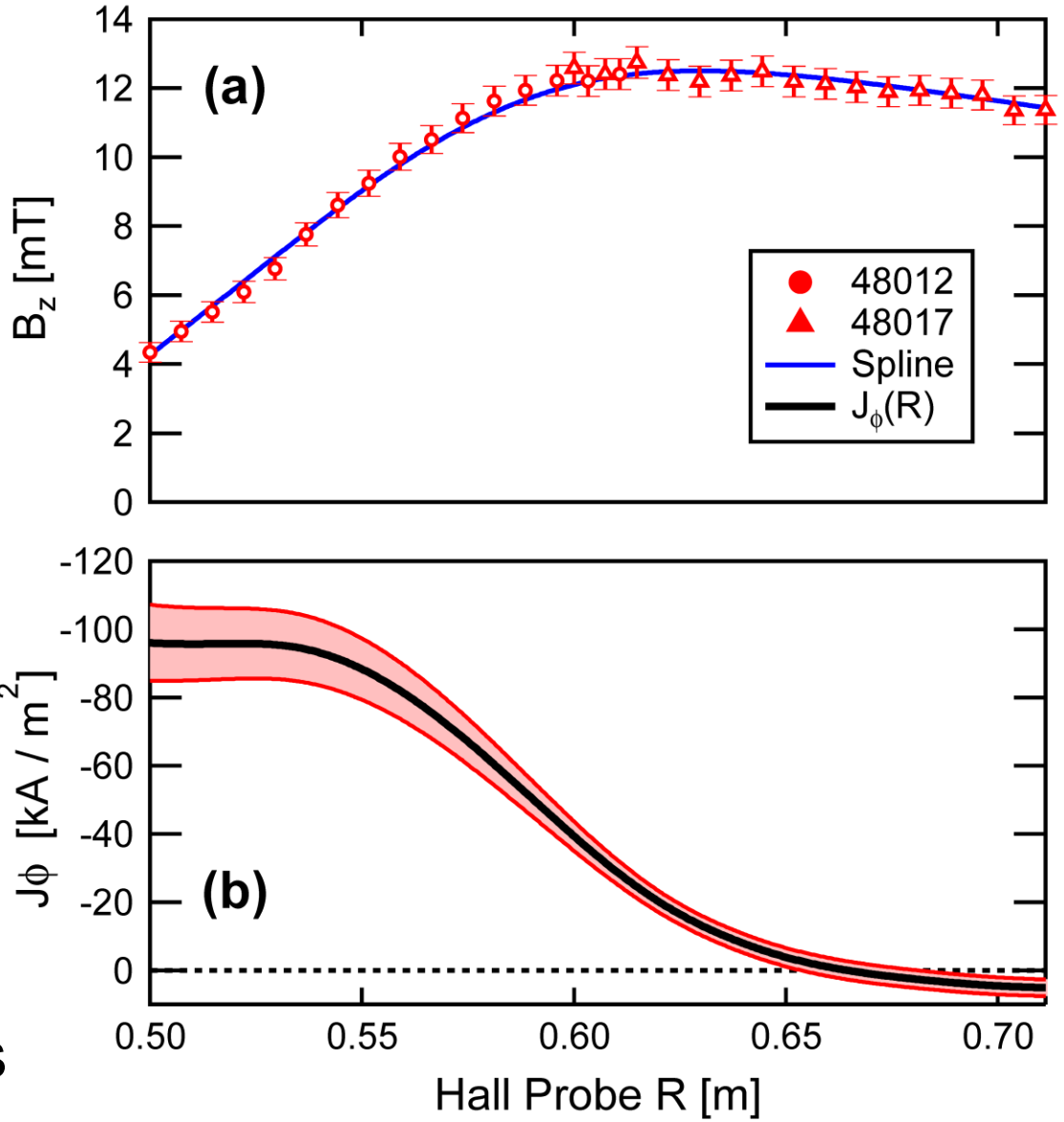
- Does not make assumptions on shape of J(R)

[1]Petty, *et al.*, Nucl. Fusion **42**, 1124 (2002)

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Direct $J_\phi(R)$ Profiles Obtained in PEGASUS

- Straightforward J estimation
  - Obtain Hall Probe $B_z(R,t)$
  - Compute dB_Z/dR using interpolated smoothing spline[1]
  - Compute $J_\phi(R,t)$ given geometry
- Resultant $J_\phi(R,t)$ consistent with I_p, MHD evolution
- Radial span extendible with multi-shot averaging
- Higher-order shaping effects negligible within errors



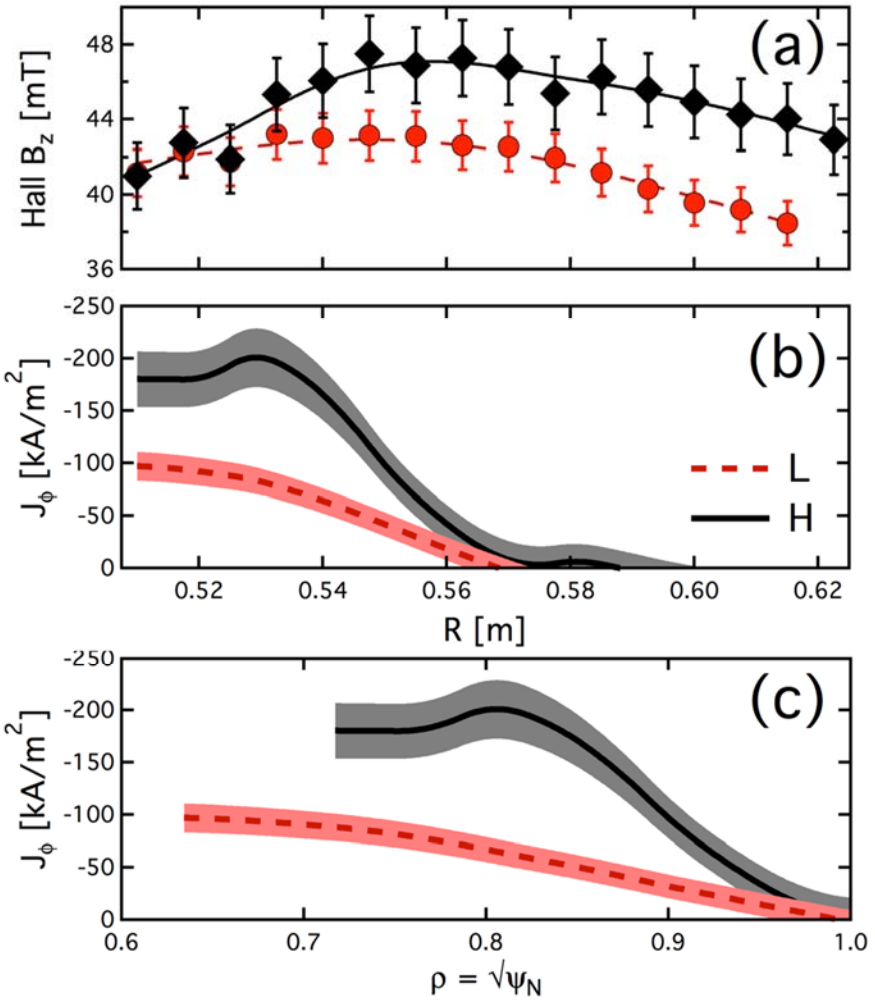
Bongard *et al.*, Phys. Rev. Lett. **107**, 035003 (2011)

[1]Reinsch, Numerische Mathematik **10**, 177 (1967)

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Current Pedestal Measured with High Time and Space Resolution

- Short pulse, low T_e allow detailed J_{edge} and p_{edge} profiles
  - $J_\phi(R,t)$ from Hall Probe B_z measurements[1,2]
  - p(R,t) will be obtained with Langmuir probes
- Clear current pedestal observed
  - H scale length ~ 2 cm
  - L scale length ~ 4 cm

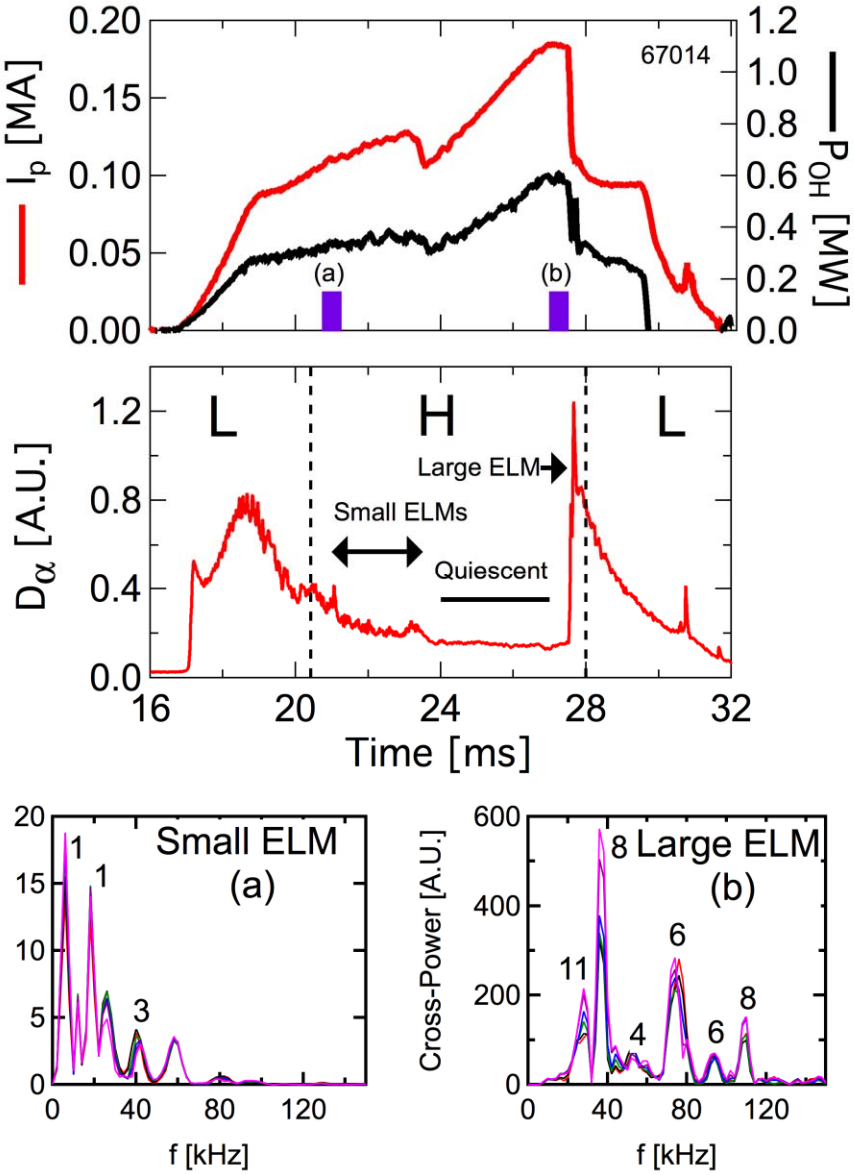


[1] *Rev. Sci. Instrum.* **81**, 10E105 (2010)
[2] *Phys. Rev. Lett.* **107**, 035003 (2011)

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Type I (Large) and Type III (Small) ELMs are Seen

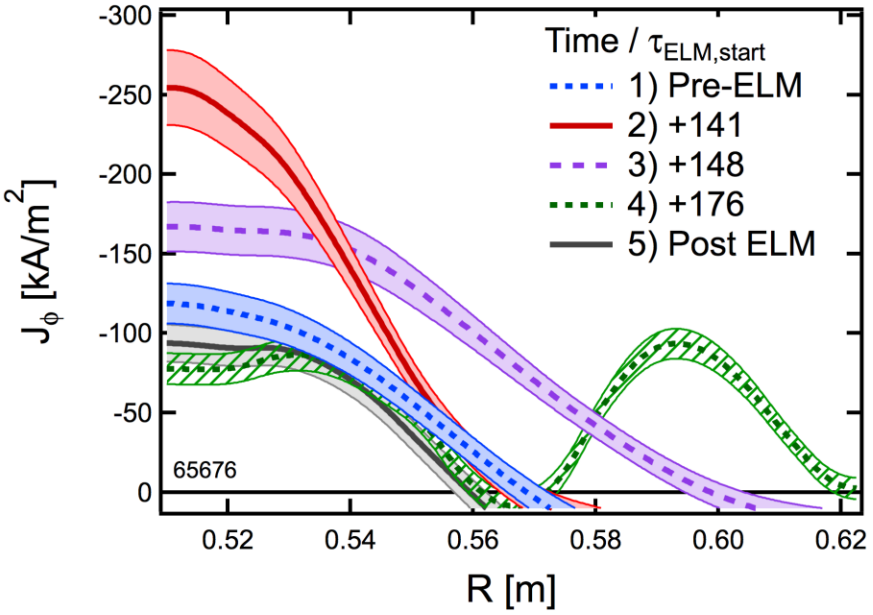
- STs magnetic structure opposite of ATs
  - Large ("Type I"): intermediate-n
    - Infrequent, violent, $P_{OH} >> P_{LH}$
  - Small ("Type III"): low-n
    - common, less perturbing, $P_{OH} \sim P_{LH}$
- Precursors grow on MHD times (10's μs)
  - Simultaneously unstable modes
  - Dominant n = 8 grows continuously
  - Non-dominant components fluctuate prior to crash



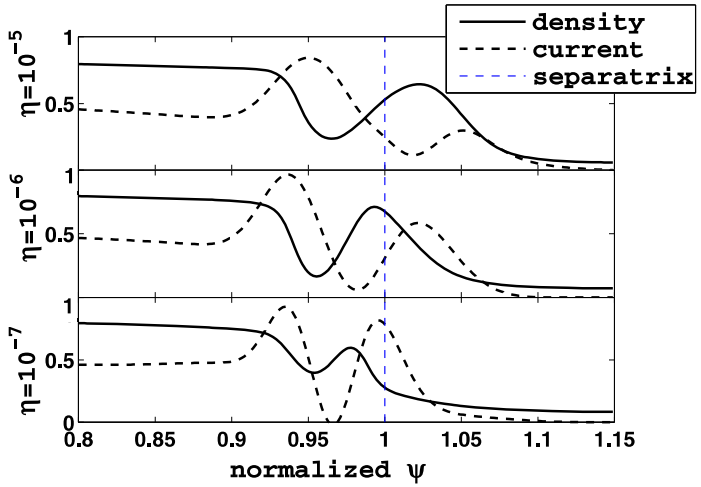
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Large ELM $J_{edge}(R,t)$ Dynamics Measured Throughout Single ELM Cycle

- Complex $J_{edge}(R,t)$ evolution
  1) Modest but steep pedestal
  2) Rapid buildup until crash
  3) Collapse with wider pedestal gradient
  4) Current-hole filament ejection
  5) Recovery: lower than pre-ELM pedestal



- $J_{edge}(R,t)$ evolution similar to that seen in JOREK MHD[1] simulations
  - Potential for unique simultaneous measurements of $J_{edge}(R,t)$ and $p_{edge}(R,t)$

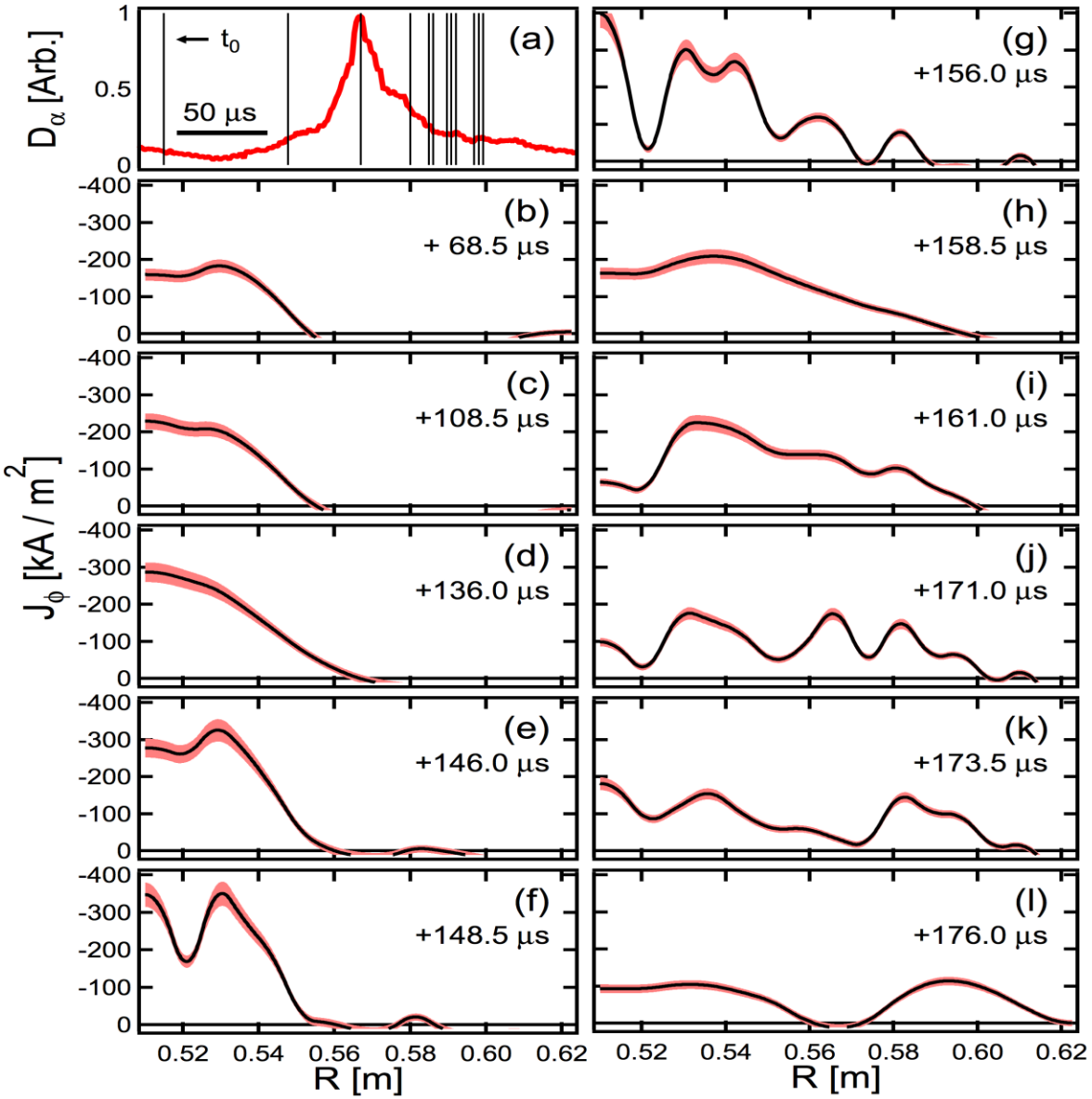


[1] *Plasma Physics Control. Fusion.*, **53**, 054014 (2011)

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Closer Inspection of J_{edge} Reveals Complex Dynamic Behavior

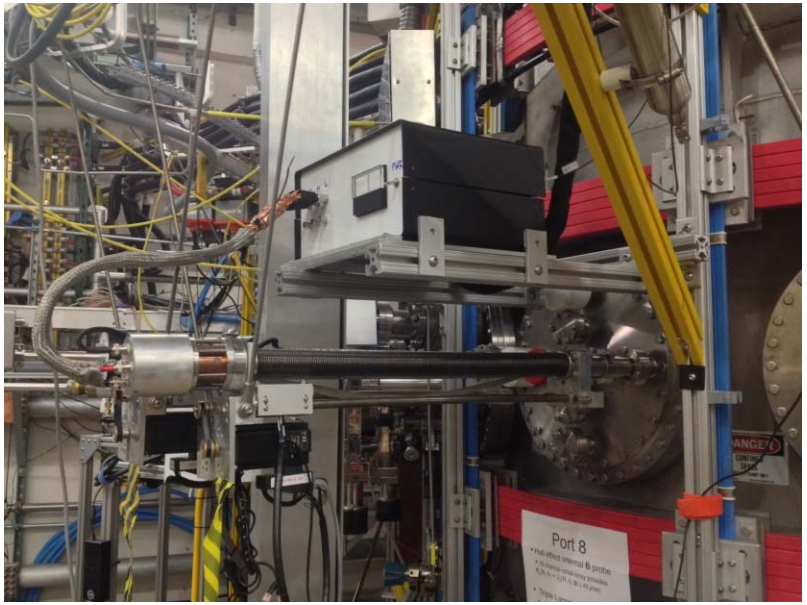
- Current profile evolution through ELM cycle shows complex multimodal behavior
- Opportunities for detailed comparisons to nonlinear MHD simulations
  - E.g. NIMROD, JOREK, BOUT

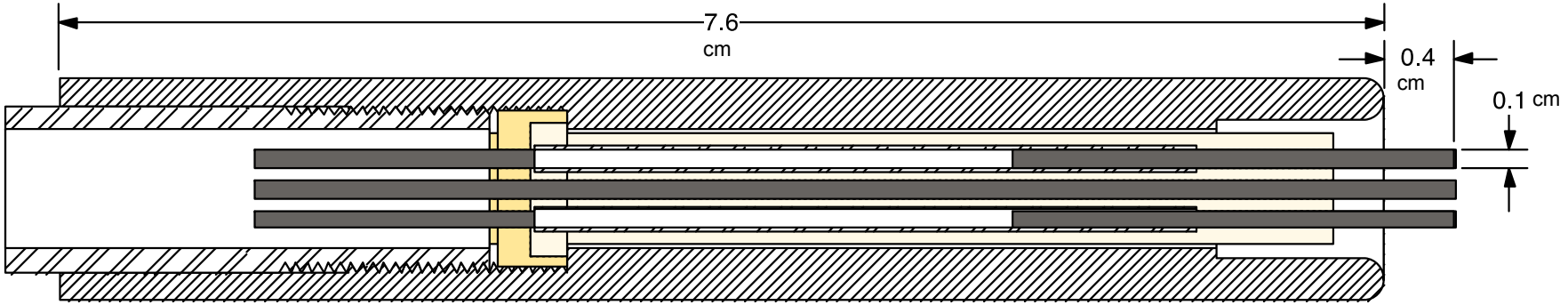


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Triple Langmuir Probe Design and Implementation

- Three 1mm W probe tips with 3 mm spacing
- Tips epoxied to PEEK spacer
- BN guide faces plasma
- Graphite shield covers leading 43 cm
- Circuit upgrade: initial bias set to 150 V, capable of 300V
- Arcus DMX-ETH 23 stepper motor for remote operation



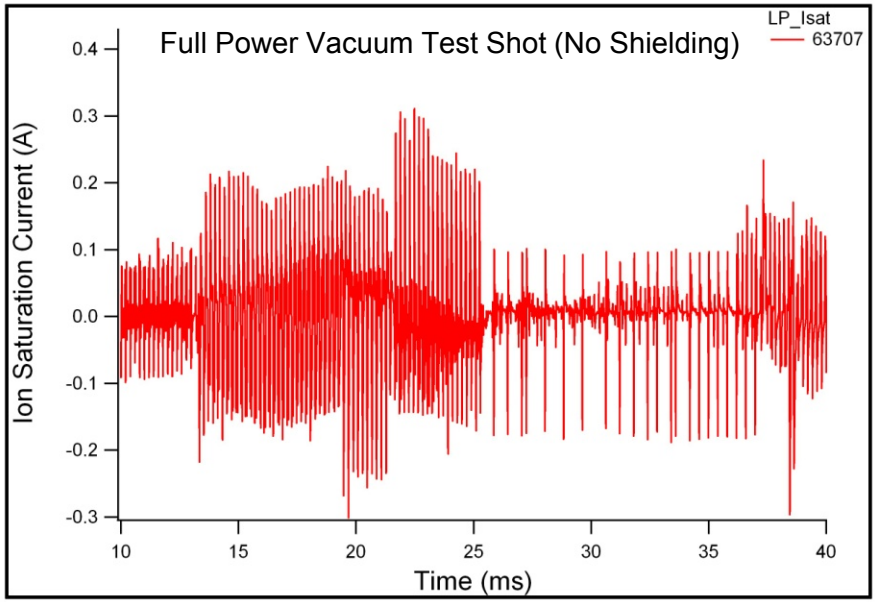


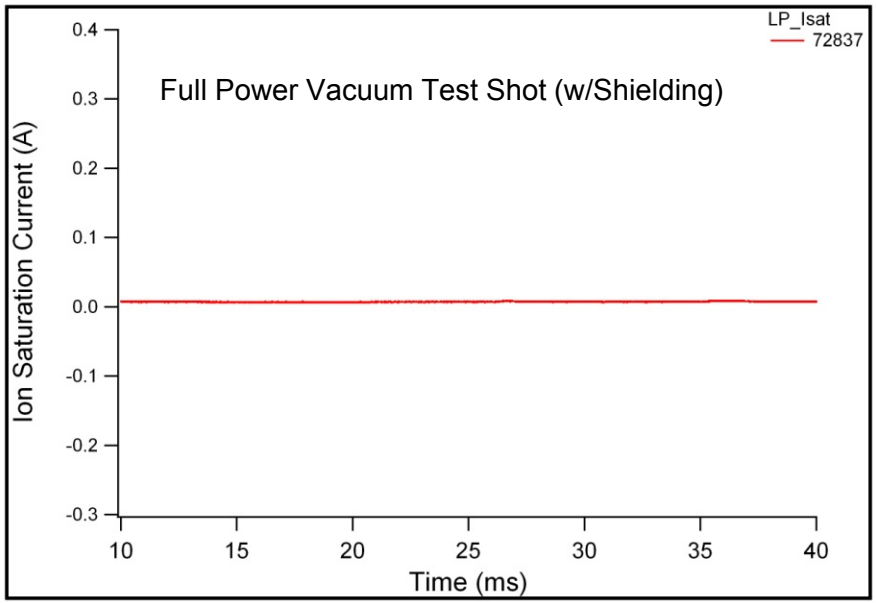
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Switching Power Supplies Require Proper Shielding Techniques

- PEGASUS diagnostics require careful shielding and isolation techniques
  - Triaxial shielding
  - Local differential line drivers
  - Optical triggering

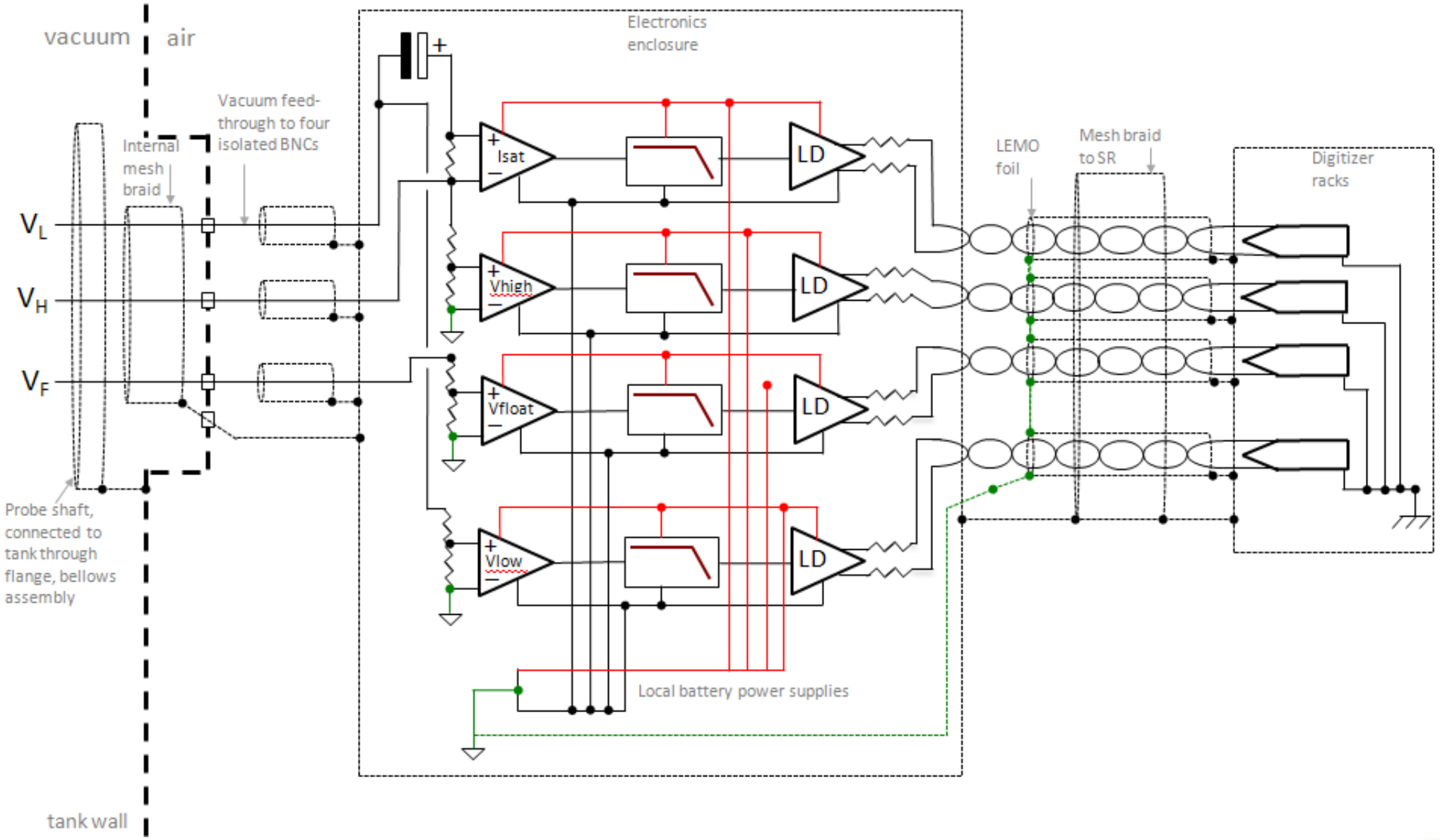
- High bandwidth requires local signal processing / power supplies
  - 200V EMCO ULP05 DC-DC converter provides high voltage probe bias
  - Anti-aliasing board as well as optical triggering components are powered using a series of 9V batteries





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Langmuir Probe Circuit and Noise Shielding Diagram



G.M. Bodner, APS-DPP 2014

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Triple Probe Theory

- Bias voltage is manually set: $V_B = V_H - V_L$

$$\frac{1 - \exp[e(\Phi_f - V_H)/k_B T_e]}{1 - \exp(-eV_B/k_B T_e)} = \frac{1}{2}$$

- If $eV_B \gg k_B T_e$

$$\longrightarrow T_e[eV] = \frac{V_H - \Phi_f}{\ln 2}$$

- Density is calculated from the ion saturation current

$$I^i_{sat} = A_p n_e e \left(\frac{k_B T_e}{m_i}\right)^{1/2} \exp(-1/2)$$

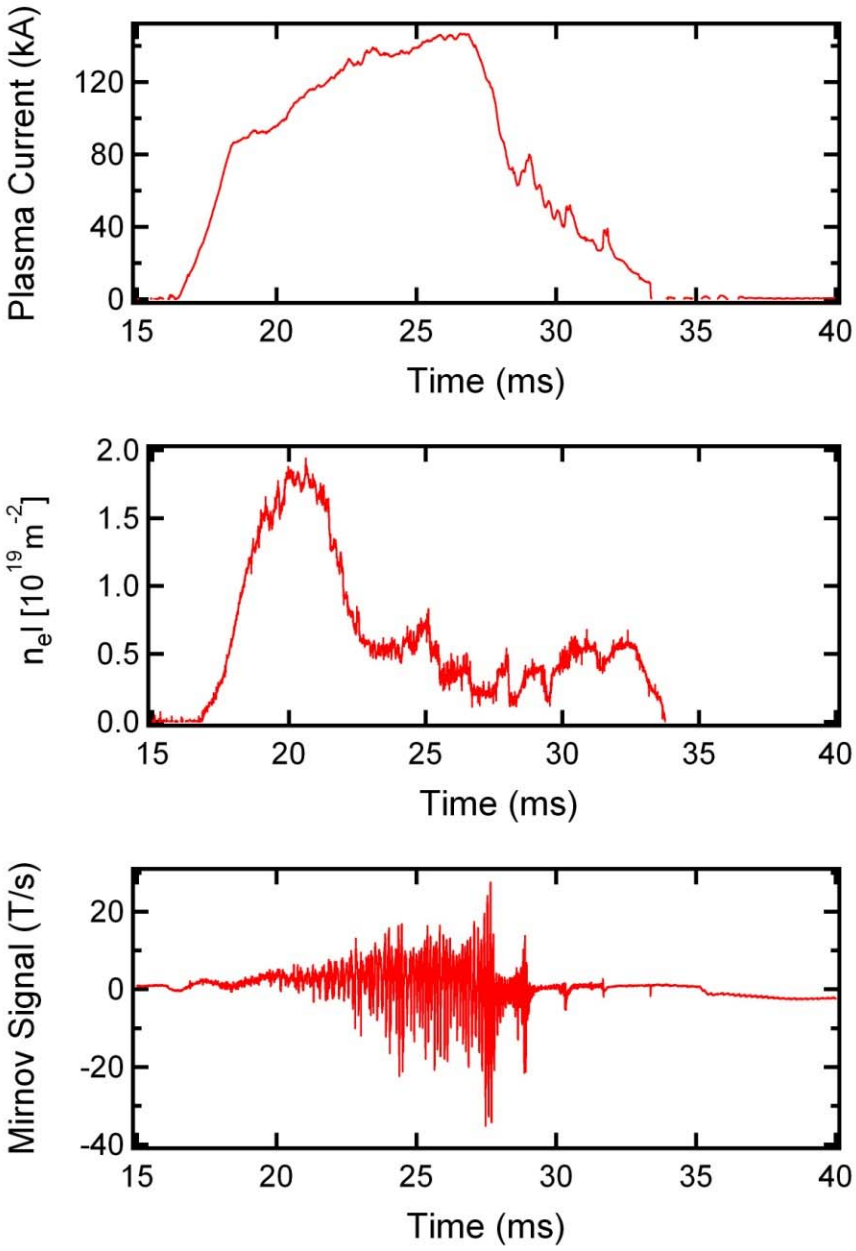
- With a small correction for impurities

$$n_e = \frac{I^i_{sat}}{A^i_p e}\left(\frac{m_p}{k_B T_e}\right)^{1/2} \bar{Z}^* \exp(1/2)$$

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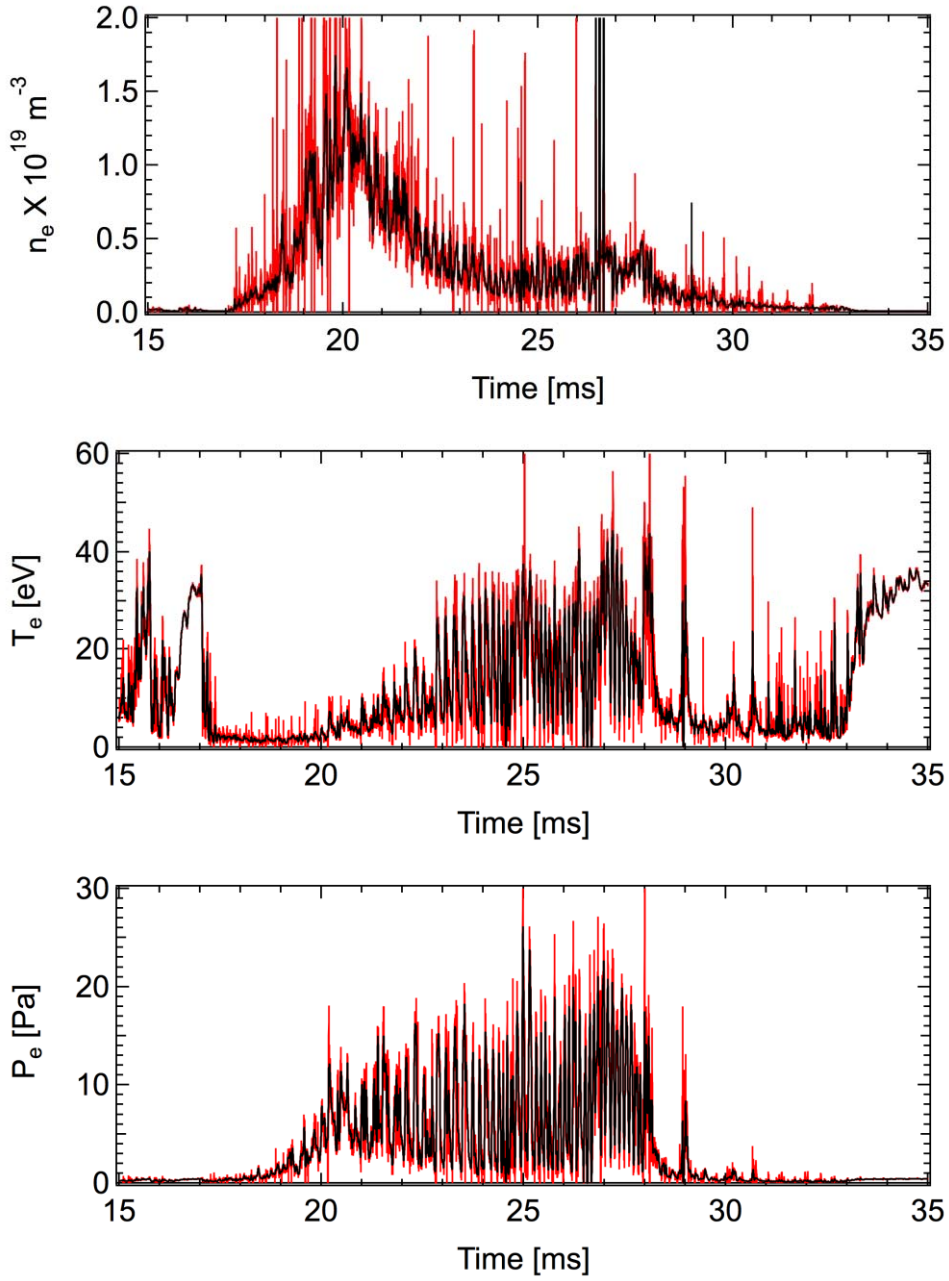
H-mode Plasma Scanned with Langmuir Probe

- Langmuir probe was inserted into a repeatable target discharge with I_p ~ 140 kA.
- Langmuir Probe was radially scanned from SOL (~70 cm) to top of the pedestal (~58 cm).
- Insertion of the Langmuir Probe was limited by flaring at the probe tips.



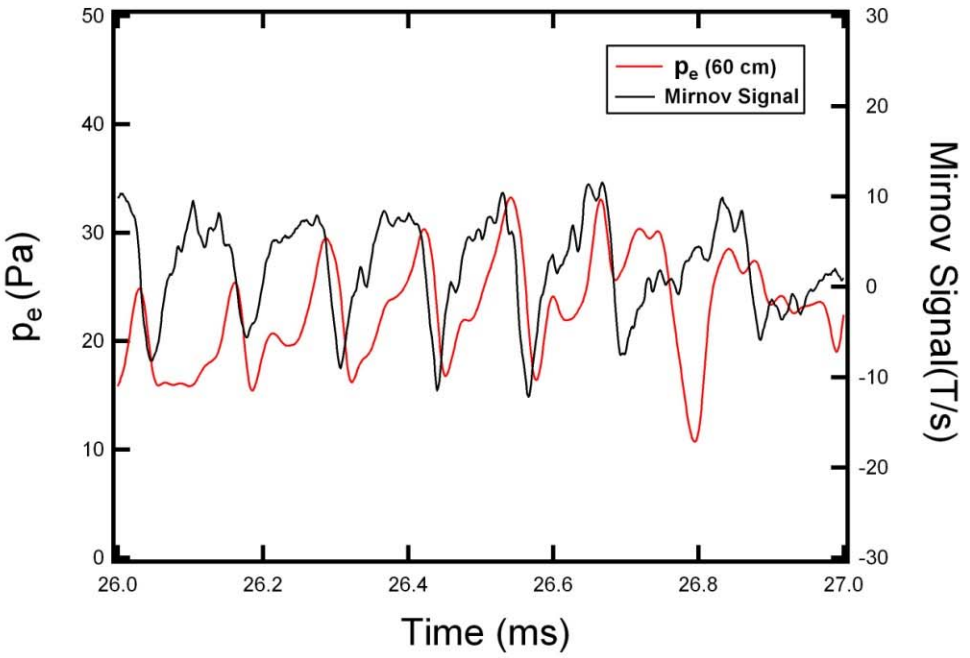
Smoothing Techniques used to Filter Raw LP Signals

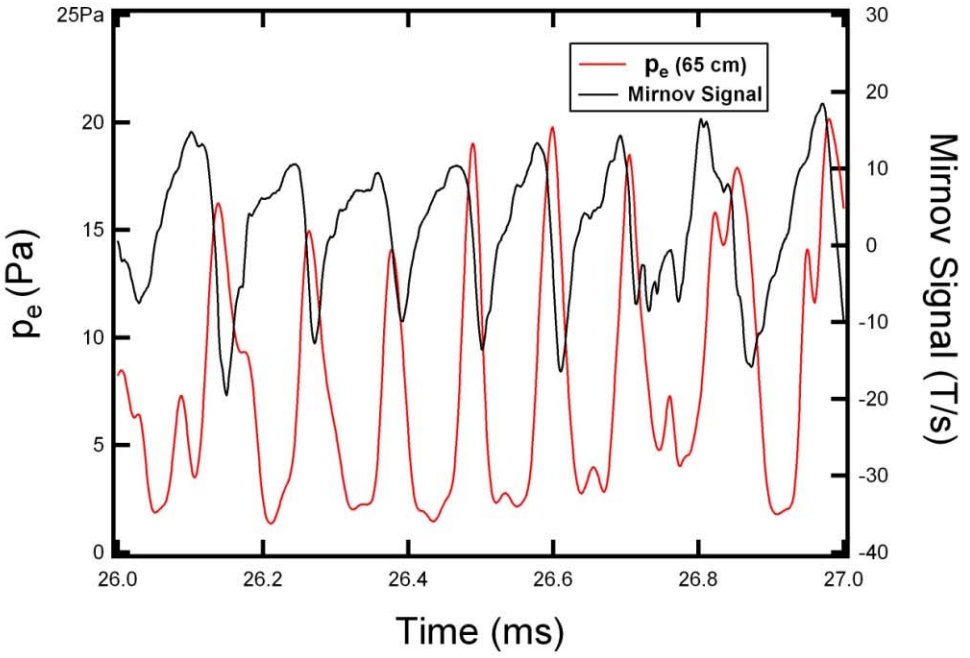
- Initial measurements have high frequency signal variation.
  - Due to edge turbulence and effects of MHD/edge deflection
- A 10 kHz Gaussian smoothing eliminated high frequency characteristics, while maintaining the measurement integrity.



$p_e(R,t)$ Shows a Strong Correlation to MHD Fluctuations

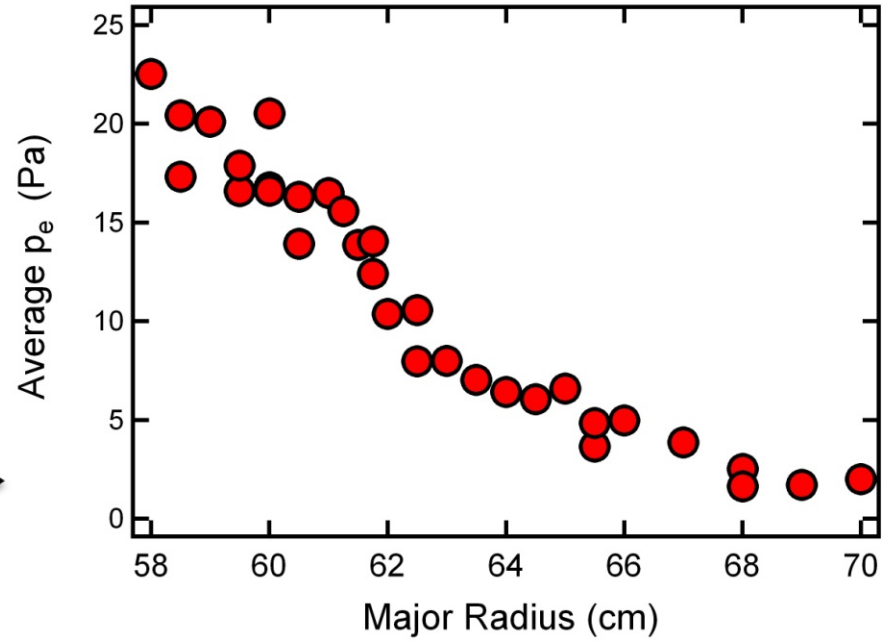
- A phase relationship exists between the p_e signal and the MHD activity.
- The drop in Mirnov signal represents a plasma edge growth, while the rise represents a plasma edge shrinkage.
- This MHD activity creates fluctuations in the p_e (R,t) profile and distorts the pedestal measurements.



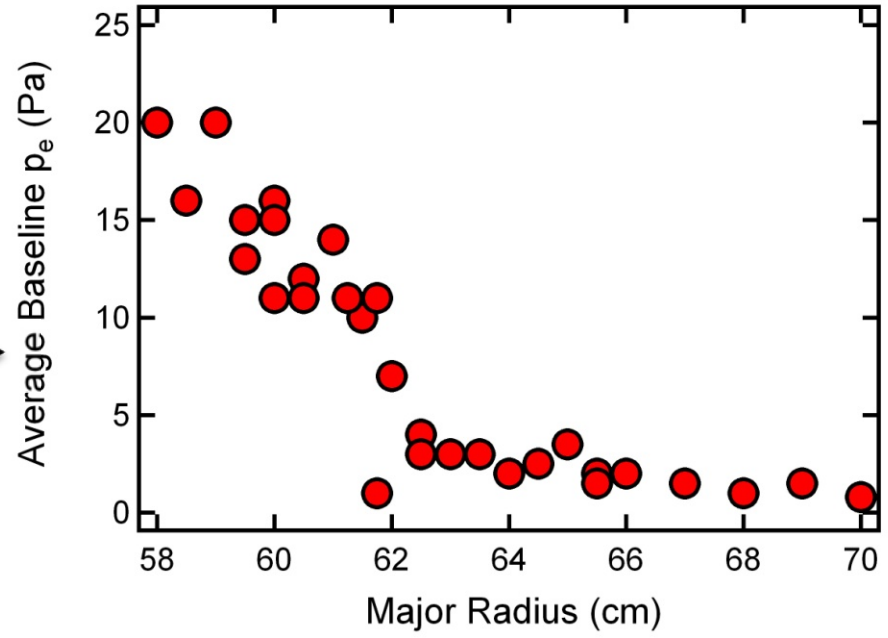


Analysis Suggests Evidence of Pedestal Structure in the Pressure Profile

- p_e profiles at maximum I_p (t = 26-27ms)
- Average of the total p_e signal



- Average of the $p_{e,baseline}$ signal
  - Mitigate effects of MHD-induced movement



Summary

- Probe measurements represent a feasible strategy to support edge pedestal investigations.
- Magnetic Hall Probe provides a detailed evolution of J_{edge}
- Eliminated ubiquitous switching noise in LP signals.
- Initial Langmuir Probe scans suggest a pressure pedestal in the edge region of H-Mode discharges.
- Future Work:
  - Employ LHI startup to provide MHD-quiescent Ohmic H-mode
  - Deploy a multiple triple probe array to complement the Hall Probe array

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