A Hall Sensor Array for Internal Current Profile Constraint

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PEGASUS Toroidal Experiment

Abstract

Measurements of the internal distribution of **B** in magnetically confined plasmas are required to obtain current profiles via equilibrium reconstruction with sufficient accuracy to challenge stability theory. A 1D, 16-channel array of InSb Hall effect sensors with 7.5 mm spatial resolution has been constructed to directly measure internal $B_z(R,t)$ for determination of $J(\psi,t)$ associated with edge-localized peeling mode instabilities in the Pegasus Toroidal Experiment. The diagnostic is mounted in an electrically isolated vacuum assembly which presents a slim, cylindrical profile (~1 cm OD) to the plasma, using graphite as a low-Z PFC. Absolute calibration of the sensors is determined via *in situ* cross-calibration against existing magnetic pick-up coils. Present channel sensitivities are of order .25 mT. Internal measurements with bandwidth $\leq$ 25 kHz have been obtained without measurable plasma perturbation. They resolve n=1 internal MHD and indicate systematic variation in $J(\psi)$ under different stability conditions.

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

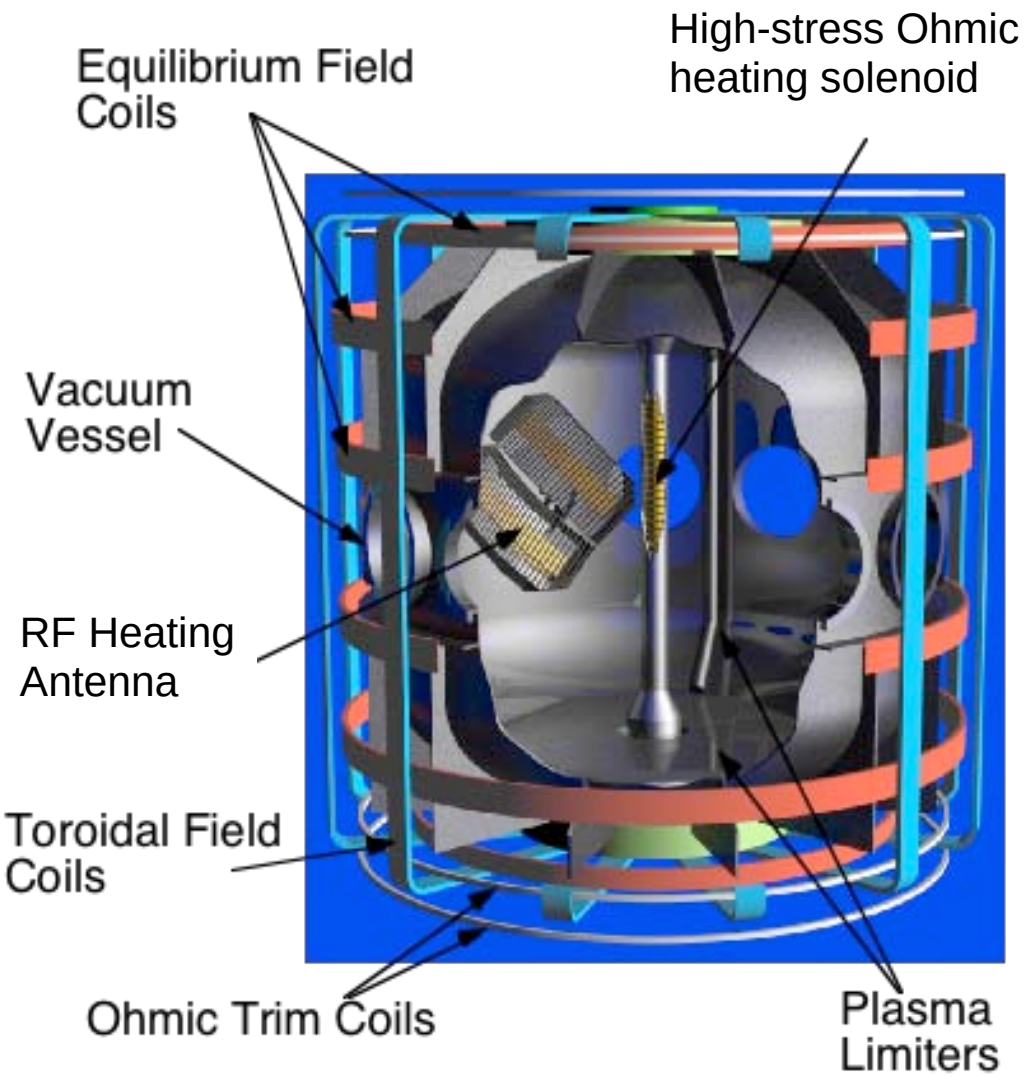
Diagnostic Motivation

- Edge stability critical to next-step devices
  - Transient ELM heat loads → PFC damage in ITER-scale facility

- PEGASUS: ELM-like edge instabilities at high $\langle j_{edge}/B \rangle$
  - Field-aligned filaments similar to ELM bursts in other machines
  - Electromagnetic signature with low- to intermediate-n, high m
  - Edge detachment, outboard radial propagation, and acceleration
  - Consistent with peeling drive

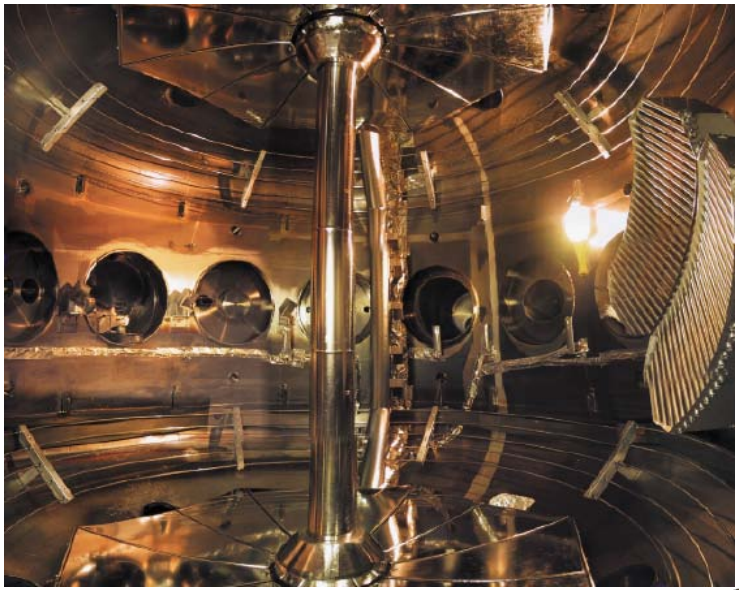
- Hall Probe diagnostic commissioned to constrain $J(\Psi)$
  - PEGASUS edge compatible with direct probe measurements

PEGASUS: A Mid-Size, Ultralow-A ST



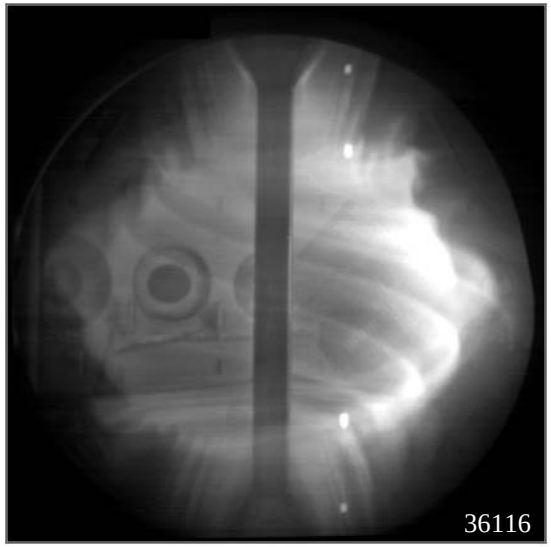
Experimental Parameters

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

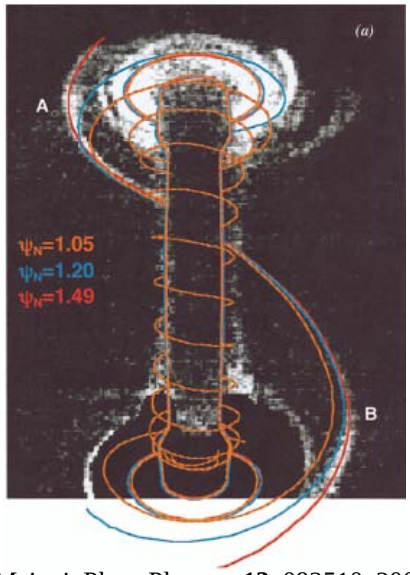


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ELM-like Structures Observed in PEGASUS

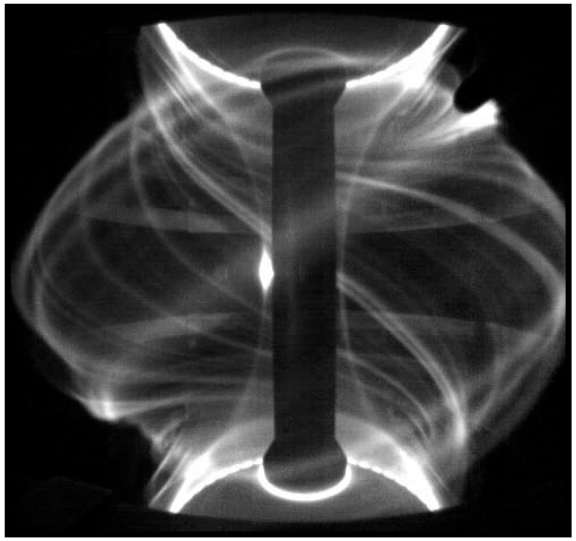


PEGASUS



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

NSTX



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

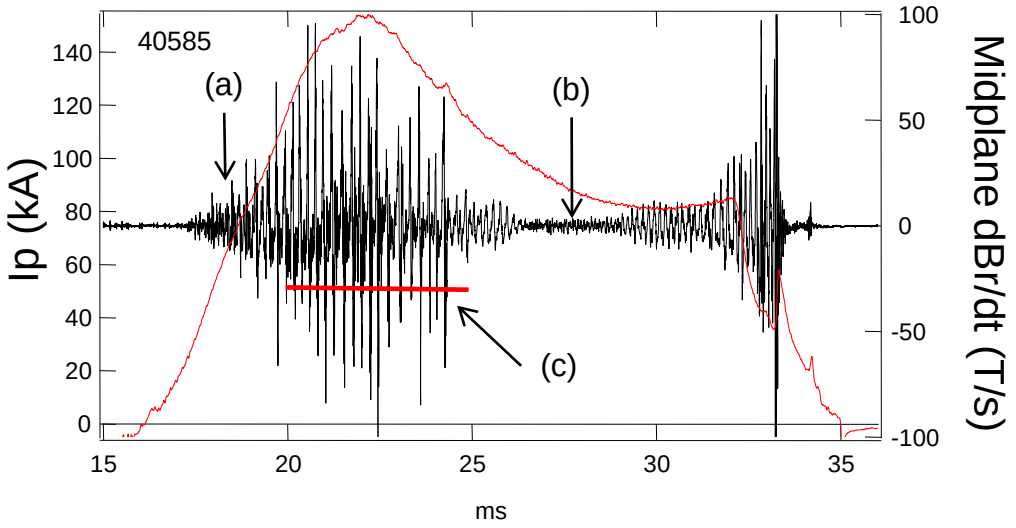
MAST

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

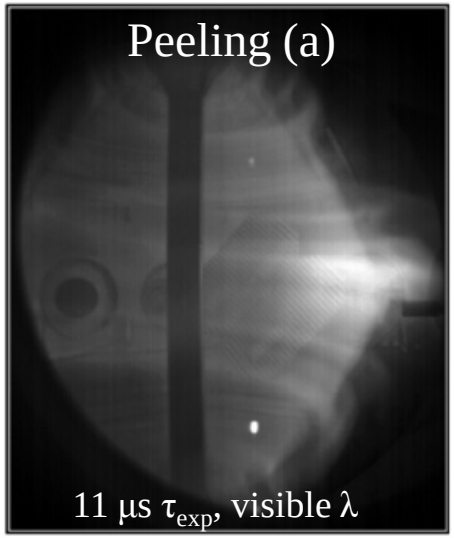
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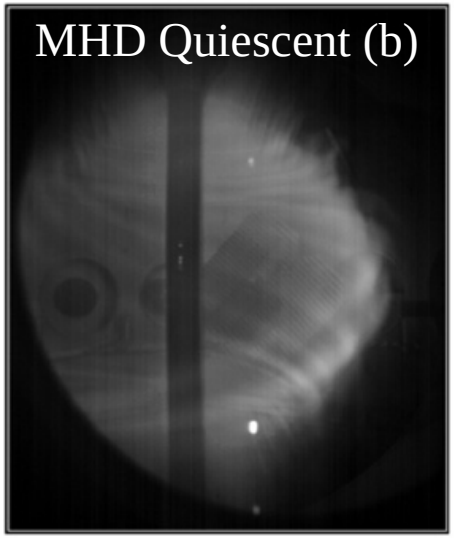
Two Distinct Filament Classes Observed

- Peeling (a)
  - EM signature: high m, low n
  - Coherent spatial structure
  - Filament rotation
  - Detachment, outboard radial propagation, acceleration



- MHD Quiescent L-mode (b)
  - No EM signature
  - Electrostatic turbulence: short-lived filaments observable when $\tau_{exp} \leq 20$ μs



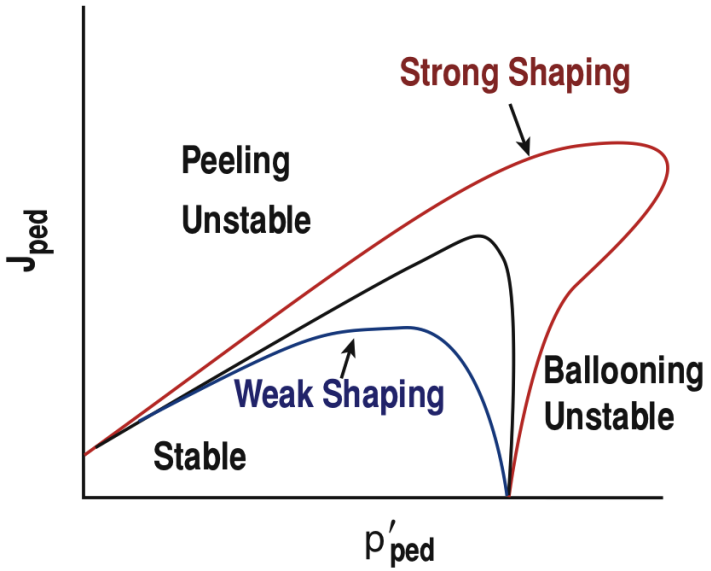


- Separated by n=1 internal tearing phase (c)

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Candidate Instability: The Peeling Mode

- Peeling-ballooning theory is a proposed mechanism for ELMs
  - Localized MHD edge instability
- Ballooning
  - p' drive from H-mode pedestal
- Peeling
  - Edge current, current gradient drive



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

- Qualitative guide: analytic peeling stability criterion*

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

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

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**

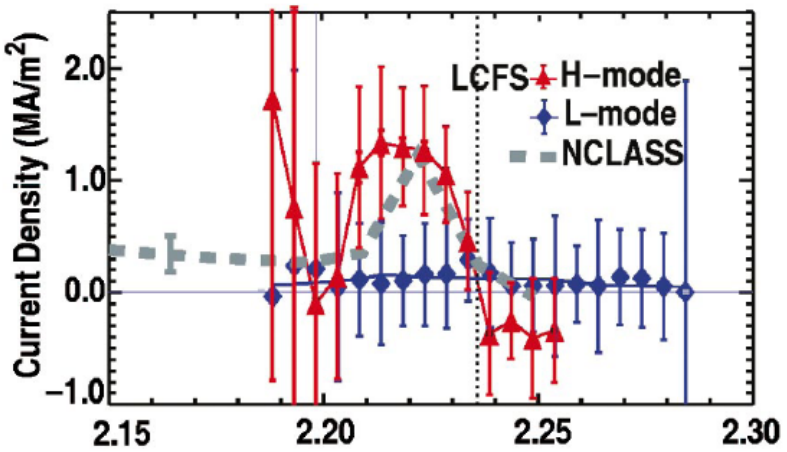
*: Thomas, Phys. Plasmas **12**, 056123 2005

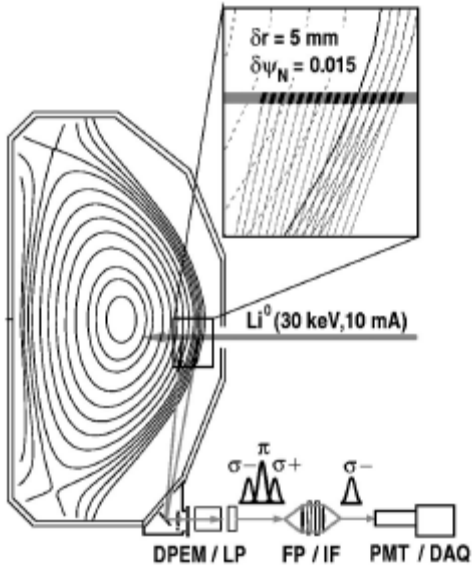
- PEGASUS operations at A → 1 lead to naturally high J_{edge}/B
  - Comparable to larger machines in H-mode
- However, *source* of peeling drive different
  - Large machines: H-mode p' → J_{BS}
  - PEGASUS: Large dI_p/dt (≤ 50 MA/s) → transient skin current

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Improved J_{edge} Measurements Desirable

- p(ψ) typically constrained via multichannel Thomson Scattering
  - PEGASUS system under design; initial implementation FY 2011
- Edge J(ψ) equally important to validate theory; rarely measured
  - Extremely challenging measurement on high-temperature ATs
  - Best results to date: DIII-D Li beam polarimetry
- Typical alternative: compute J
  - Calculates J_{BS} given experimental p(Ψ)
  - Questionable assumptions in edge





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

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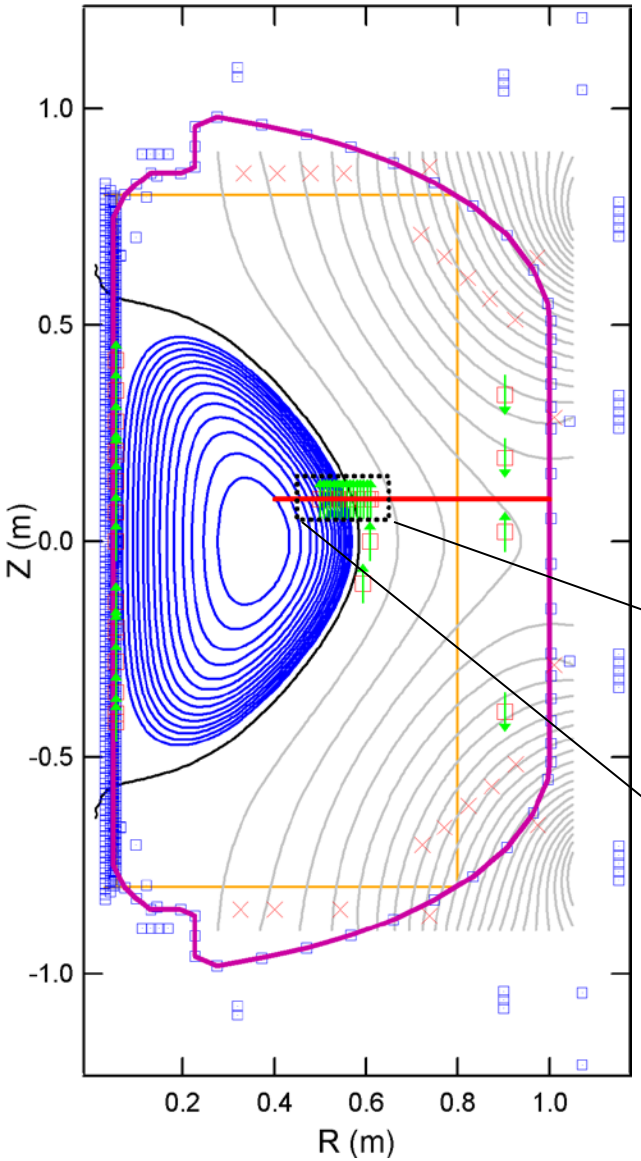
J Determined by **B**(R,t)

- Internal **B** constrains **J** through Ampere's law: $\frac{1}{\mu_0}\nabla \times \vec{B} = \vec{J}$
  - Requires spatially localized measurements
  - Edge stability theory validation demands time resolution ~ $\tau_{ELM} \leq 100$ μs

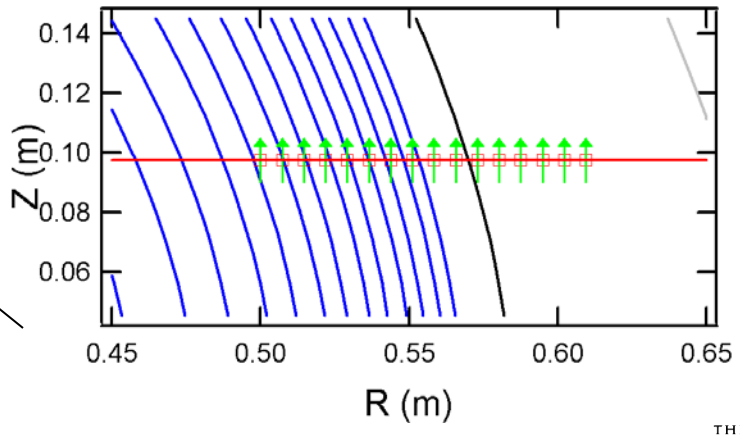
- J(ψ) obtained through equilibrium reconstruction

- Successful approaches to measuring J(R,t) employ B_p(R,t)
  - Beam-based methods: Localized, but poor- to moderate time resolution
    - Motional Stark Effect spectroscopy: core J
    - Li beam polarimetry: edge J
  - Faraday rotation polarimetry: good time response, but chordal
  - Direct probes: Localized, good time response, but incompatible with high T plasmas

Stability Analysis Requires Local Measurements

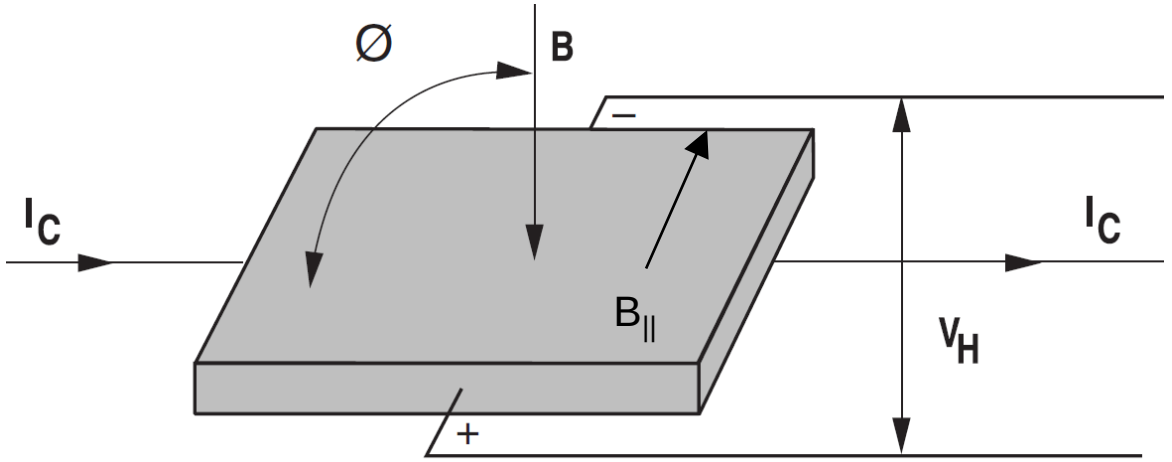


- Comparison of experimental equilibria with a stability analysis depends crucially on accuracy of reconstructions
  - E.g. Peeling-ballooning: edge $P(\psi)$, $J(\psi)$ profiles
- PEGASUS: Edge conditions allow for direct measurement of internal B_z
  - New diagnostic capability provides experimental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



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Solid-state Hall Sensors Sample **B** Directly



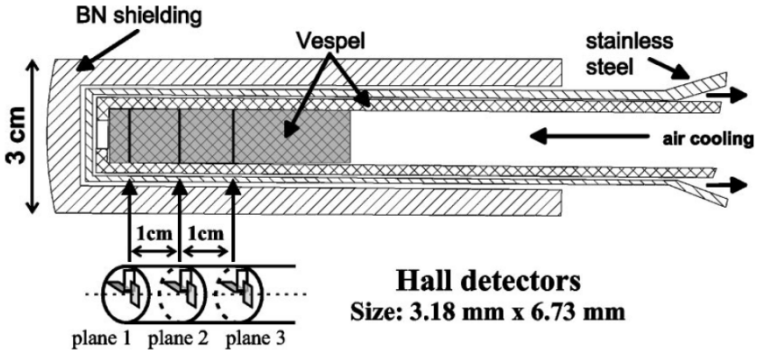
- High spatial resolution
- Good temporal response
  - ~10-30 kHz typical
- Simple operation
  - Requires modest control current I_c

- Generates $V_H = G_H I_c B \sin\varphi$
  - G_H combines all Hall physics effects; must be determined by calibration
  - DC contribution: $V_{DC}=1/2\ I_c\ R_{in}$
- G_H, R_{in} can weakly vary with device, operational parameters
  - Hall semiconductor, T_{sensor}, $B_{||}$

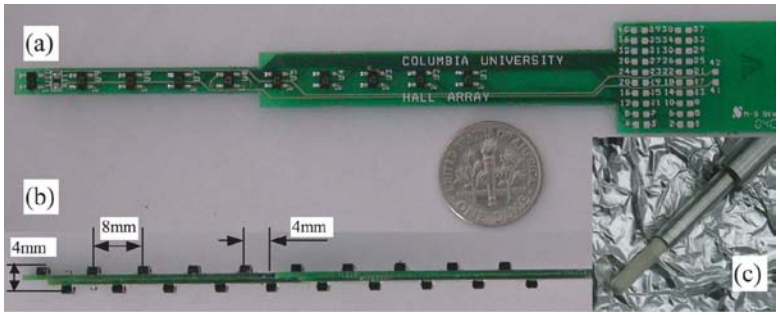
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Hall Arrays Provide Local B(t) in Tokamaks

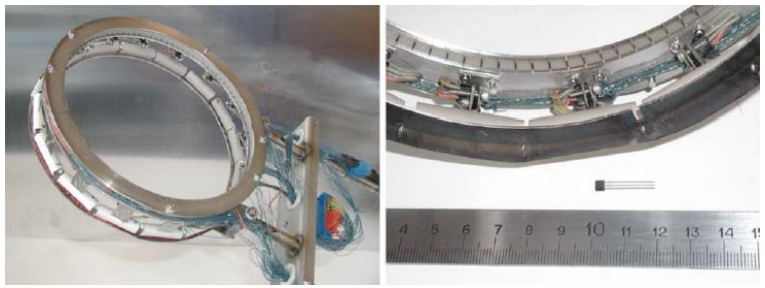
- TEXTOR*
  - External B_R, B_z fluctuations
- HBT-EP**
  - dB_z/dt, internal B_z
- CASTOR***
  - External $B_z \rightarrow$ plasma position
- PEGASUS
  - Internal $B_z \rightarrow J(\psi)$



TEXTOR Hall Probe*



HBT-EP Hall Probe Array**

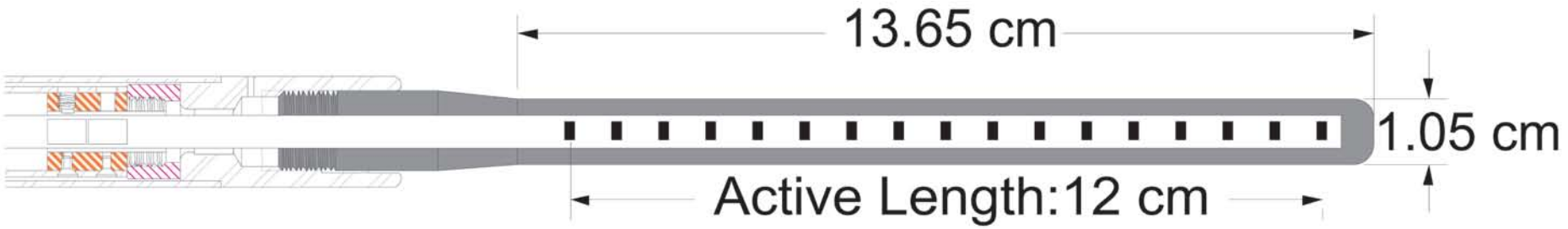


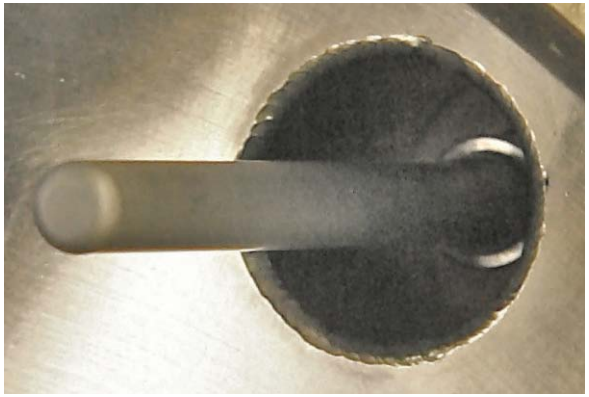
CASTOR Hall Array***

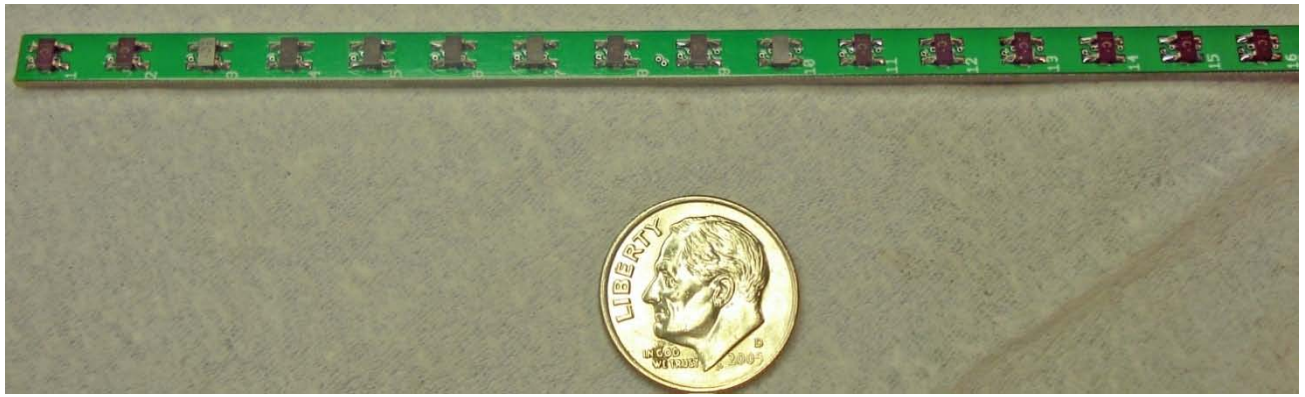
*: Ďuran, *et al.*, Rev. Sci. Instrum. **73**, 3482, 2002
: Liu, *et al.*, Rev. Sci. Instrum. **76, 093501, 2005
***: Ďuran, *et al.*, Rev. Sci. Instrum. **79**, 10F123, 2008

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PEGASUS Hall Probe Deployed



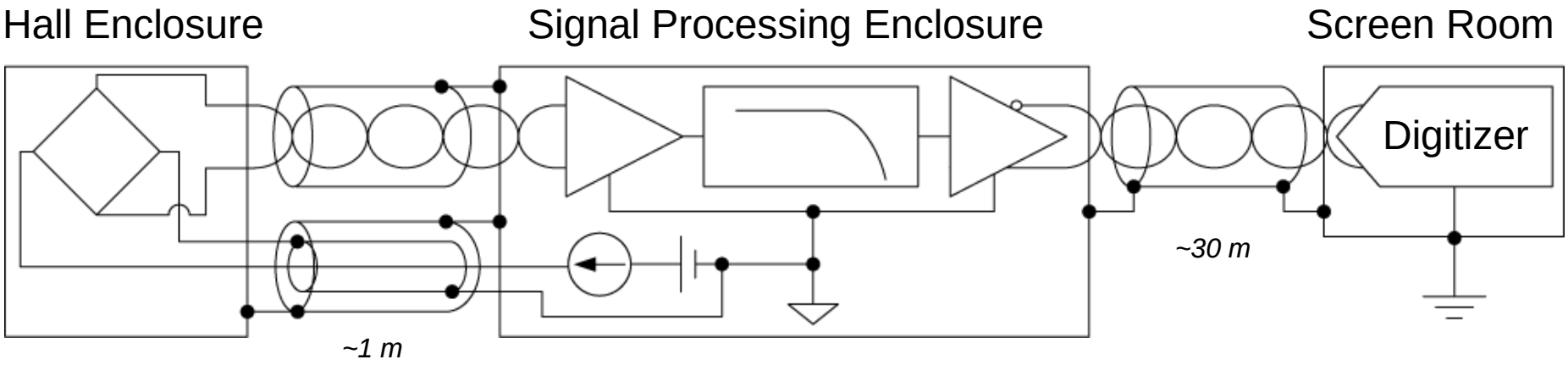




- Solid-state InSb Hall sensors
  - Sypris model SH-410
- 16 channels, 7.5 mm radial resolution
- C armor as low-Z PFC
- Slim profile minimizes plasma perturbation

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Integrated Electrical Shielding Required

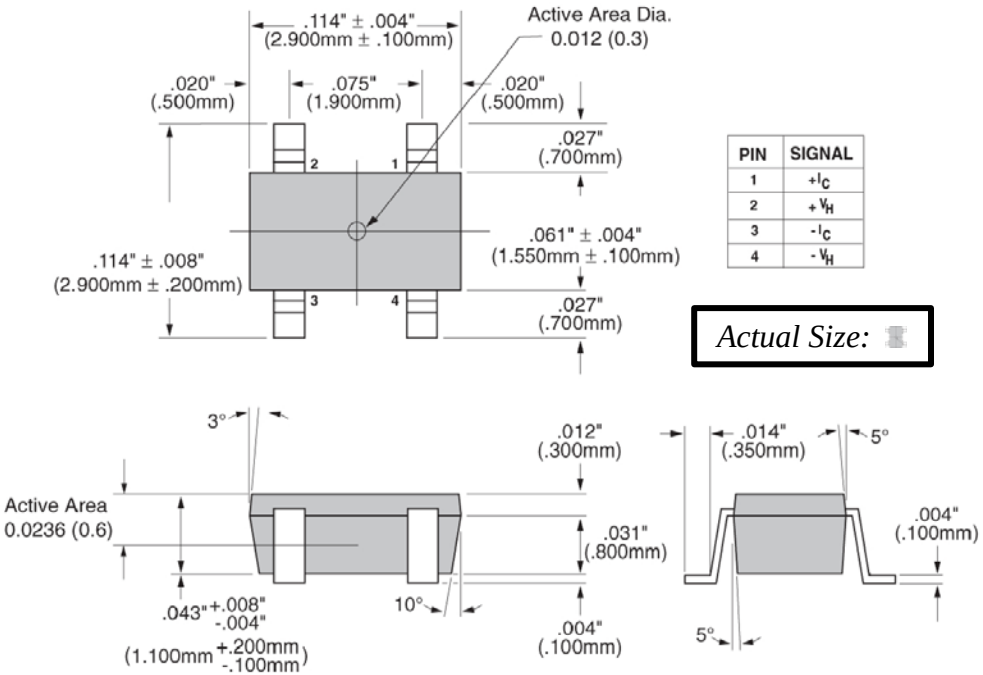


- Three electrostatically shielded segments
  - Necessary for EMI immunity
  - Interconnects via SCSI-68, triaxial cabling
- Four logical subsystems
  - Hall Probe Assembly
  - Signal Processing Module
  - I_c Source
  - Data Acquisition

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Sypris SH-410 Chosen as Hall Sensor

- Hall plate material: InSb
- High intrinsic sensitivity
  - 2.7 – 17.6 V/T, at 5 mA I_c
  - PEGASUS average: ~ 6 V_H/T
- Low Power Requirements
  - I_c ~ few mA
- Mass-produced technology
  - Surface-mount: small footprint
  - Low cost

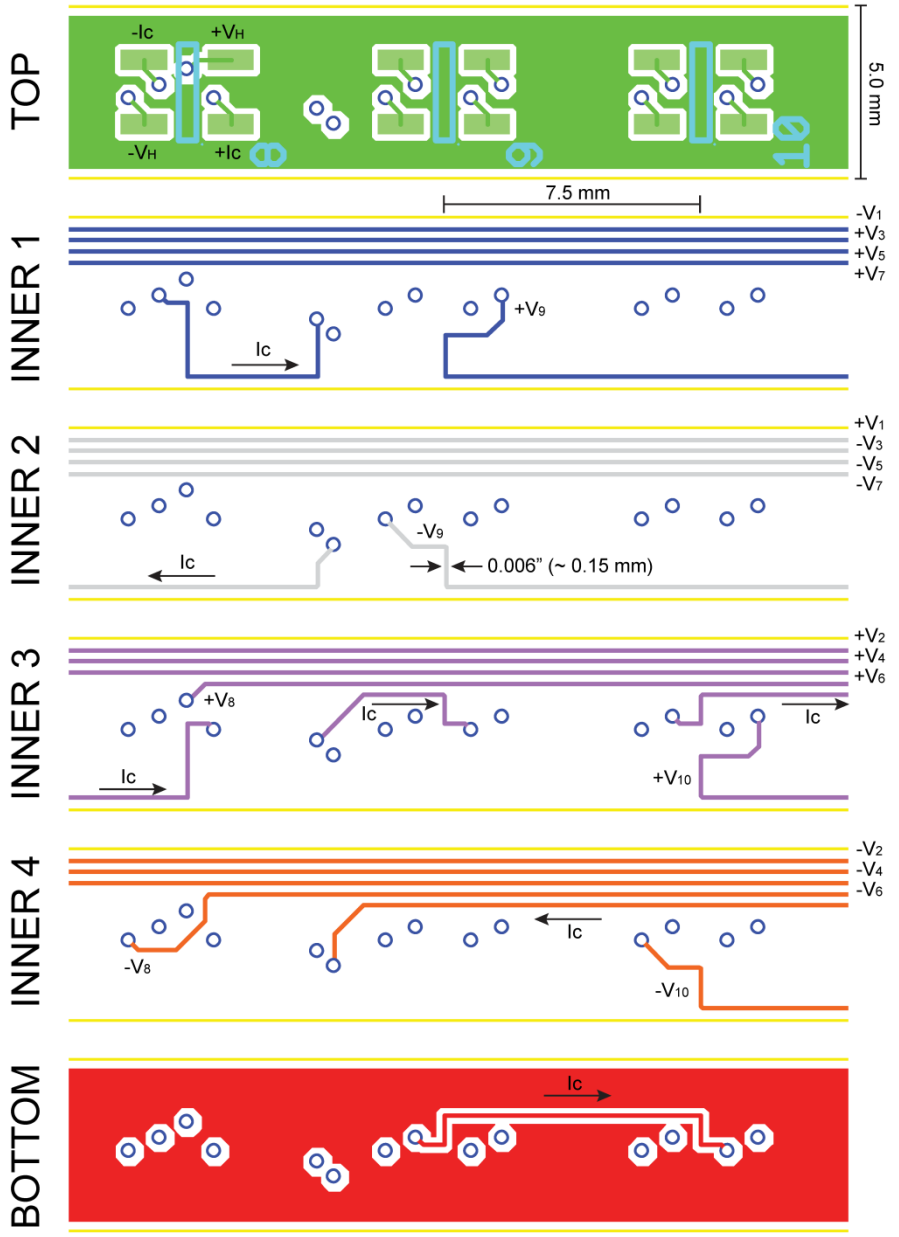


Sypris SH-410 Datasheet

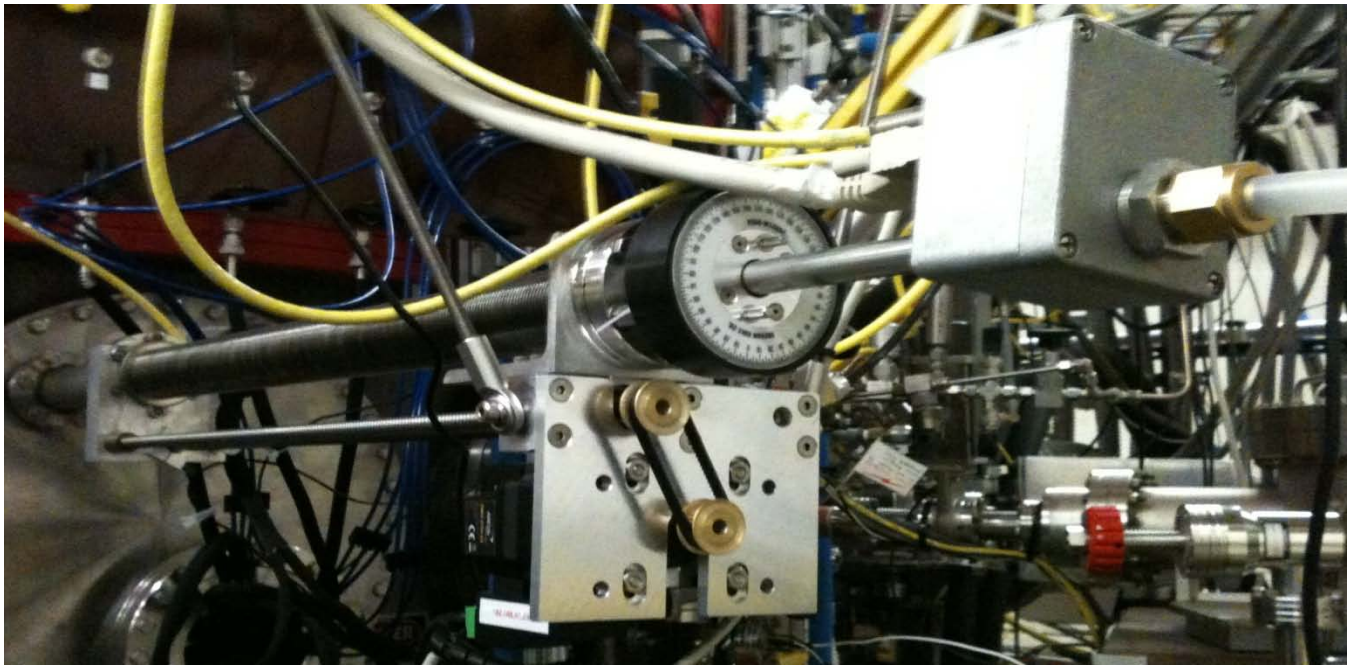
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Hall PCB Layout

- Narrow, long form factor
  - 0.5 cm x 30.0 cm
- 16 Hall Sensor Locations
  - 7.5 mm center-center spacing
- Series electrical topology
  - Ensures I_c is constant in all devices
- Six signal routing layers
- Overlapping trace design
  - Minimizes parasitic inductive pickup, compensates I_c

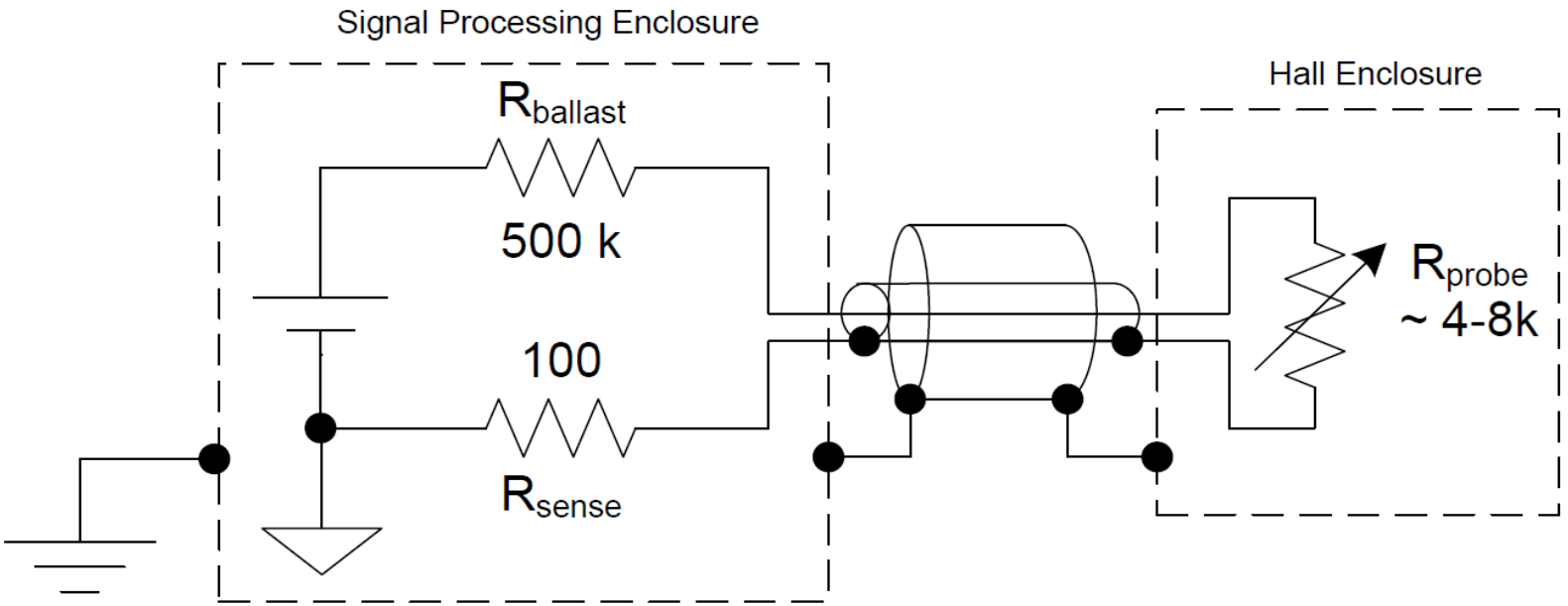


Modular Mechanical Design Implemented



- Shielded Hall Enclosure
  - Electrically isolated
  - Modularity: PCB easily replaced
  - Forced air probe cooling for temperature regulation
- Vacuum Mount and Linear Drive
  - Narrow snout: 9/32” OD, .005” thick
  - Graphite armor as low-Z PFC
  - Allows inner enclosure rotation for field alignment
  - Stepper motor drive

Constant Current Source Provides I_c

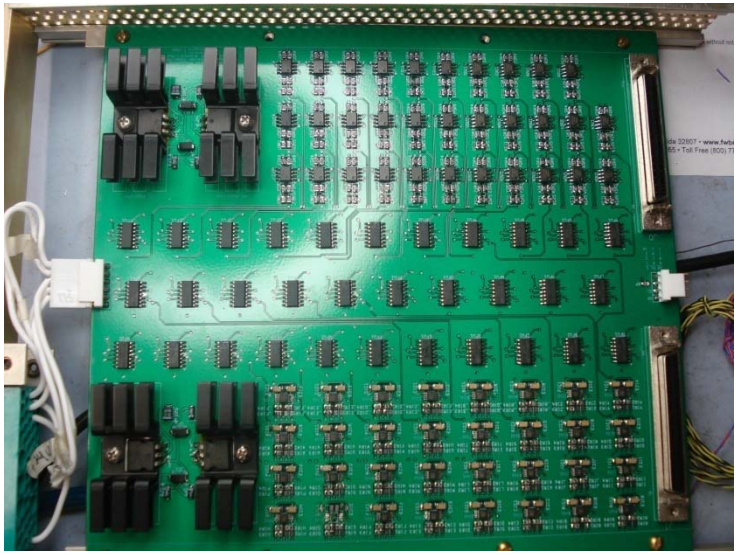


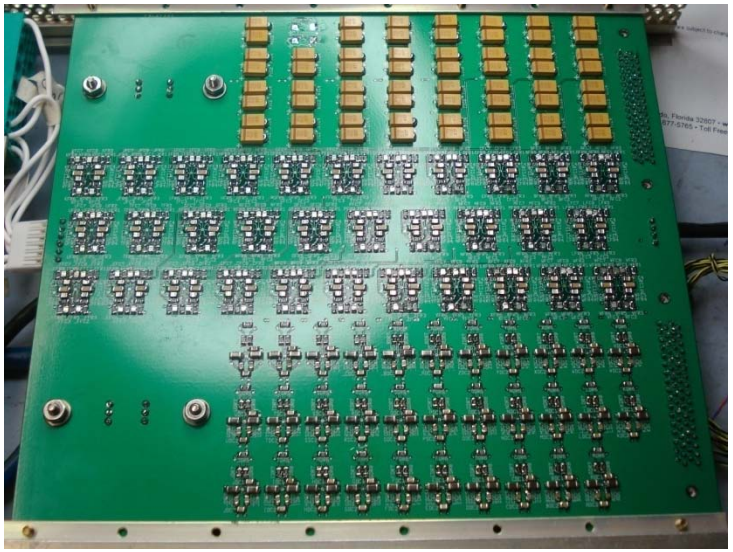
- Hall sensors' resistance R_{in} weakly varies with temperature, $B_{||}$
  - Constant-I_c source counteracts these effects
- Initial implementation: "brute force"
  - HVPS + ballast resistor
  - Approximates stiff source as $R_{ballast} >> R_{probe}$

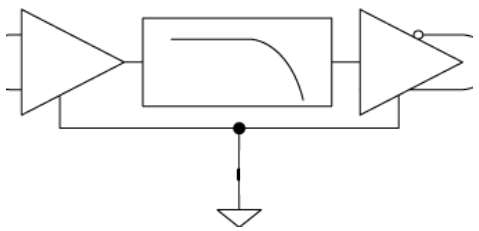
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Local Preamplifier Obtains V_H

- Custom NIM Implementation
  - Six-layer PCB, 32-channel module
- Precision instrumentation amplifier
  - AD8250: Digitally-programmable gain
- Sallen-Key Butterworth Antialiasing
- Differential Line Driver
  - National LMH6550: Active EMI rejection





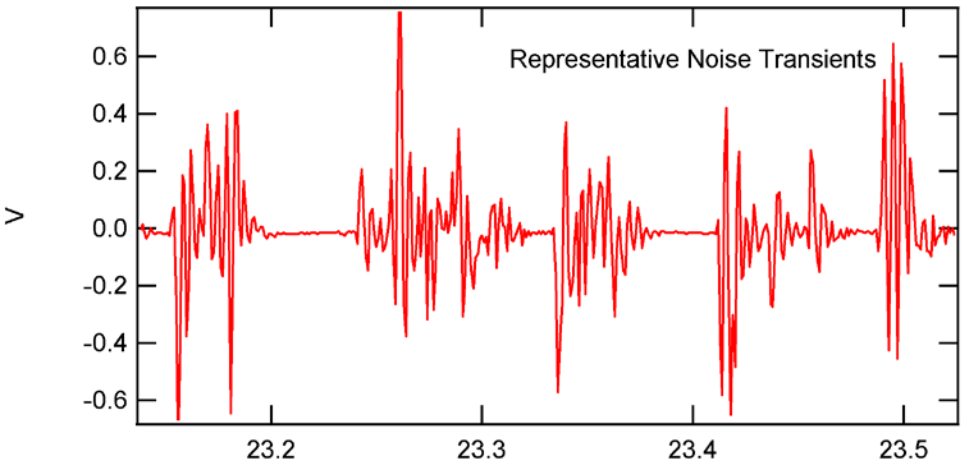


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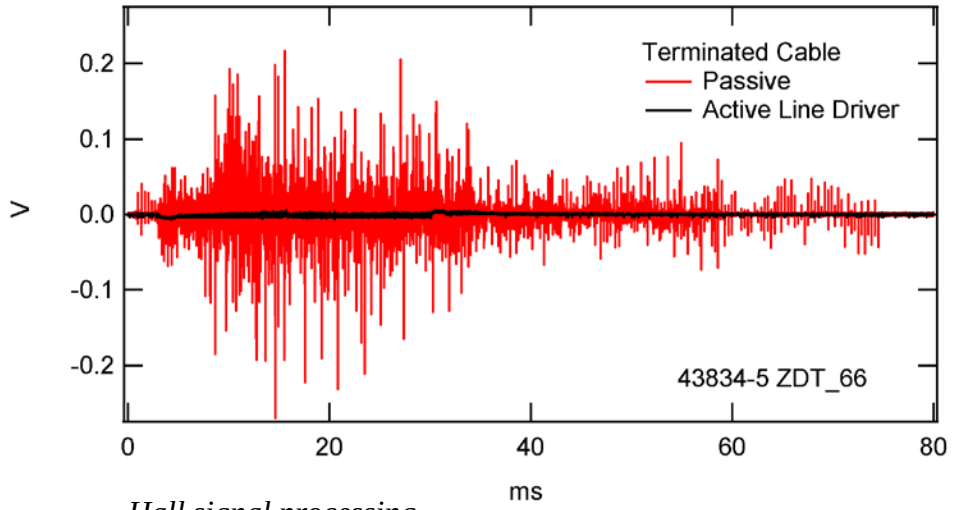
Electrostatic Noise Effectively Suppressed

- PEGASUS 100 MVA switching power systems generate transient noise bursts
  - $dV_{CM}/dt \sim 2$ kV/μs @ 5 kHz
  - Capacitively coupled

- Successful suppression techniques developed
  - High-quality electrostatic shields
  - Triaxial shielding for cabling
  - Fully differential analog signal processing
  - Differential line drivers
  - Local DC-DC conversion for electronic power supplies



Noise pulses in unshielded digitizer.

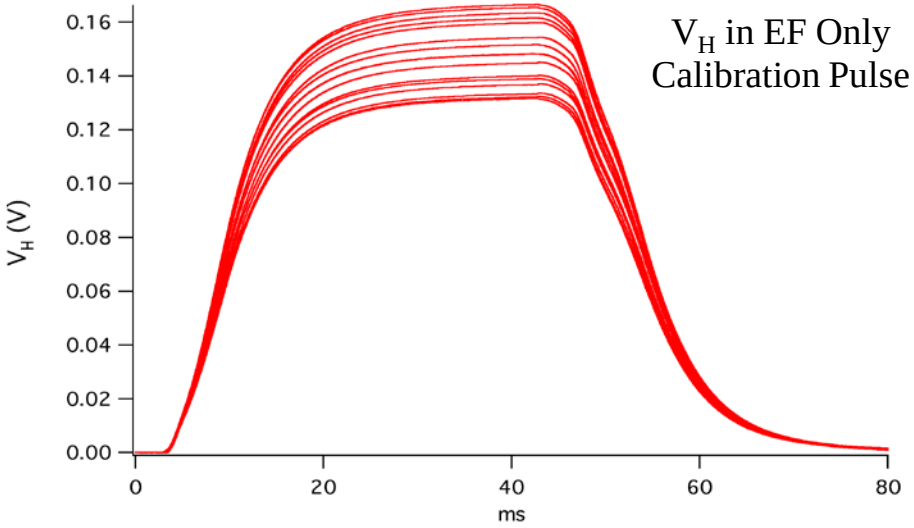


Hall signal processing electronics actively suppress pickup in 30m cable run.

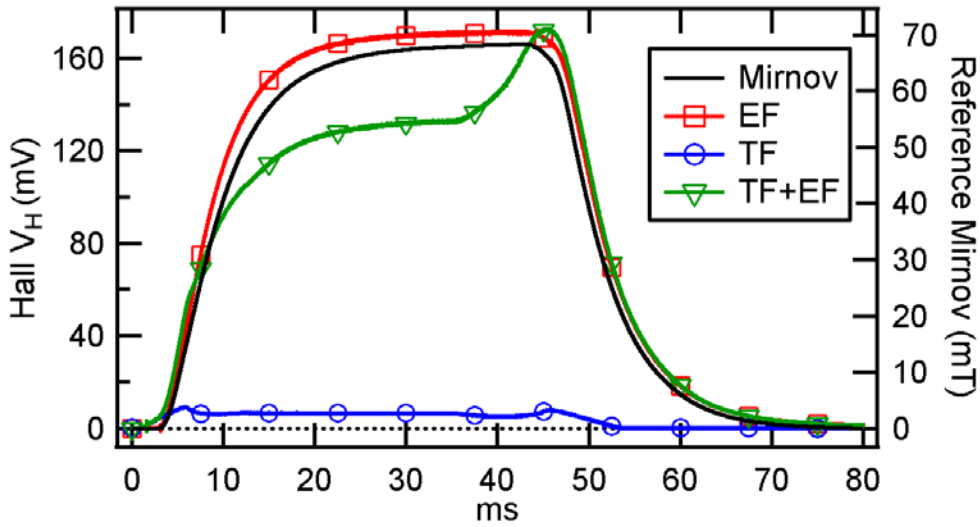
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In-situ Calibration Compensates Weak Nonlinearites

- Hall G_H varies with physical, operational parameters
  - Linear in temperature, weakly nonlinear in $B_{\|}$
  - Nevertheless, effects are repeatable and well-characterized



- Two-shot calibration technique accounts for these effects
  - TF only: Obtains V_H due to probe misalignment
  - TF + long-pulse EF: V_H due to B_z
  - G_H from comparison to absolutely-calibrated Mirnov coils

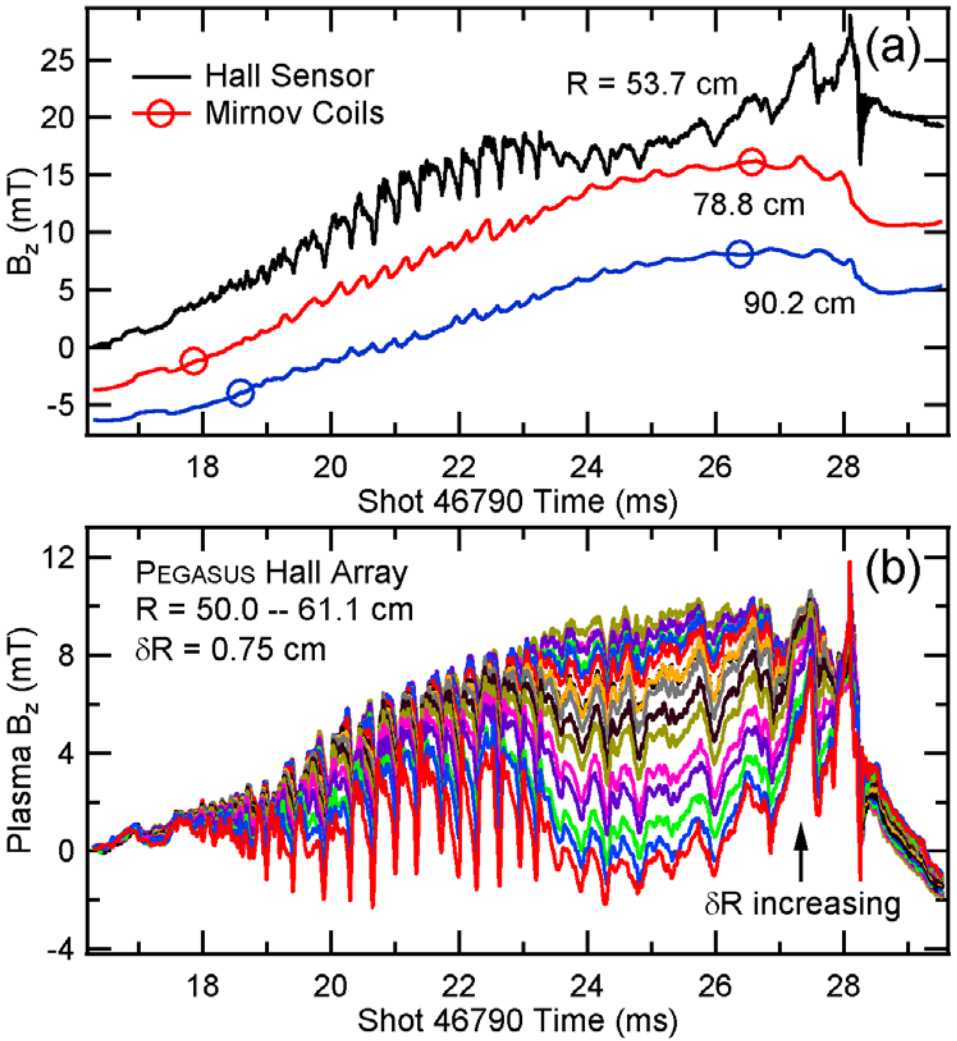


Nonlinear gain reduction in G_H due to presence of B_φ exceeds misalignment voltage; similar effects seen on HBT-EP.

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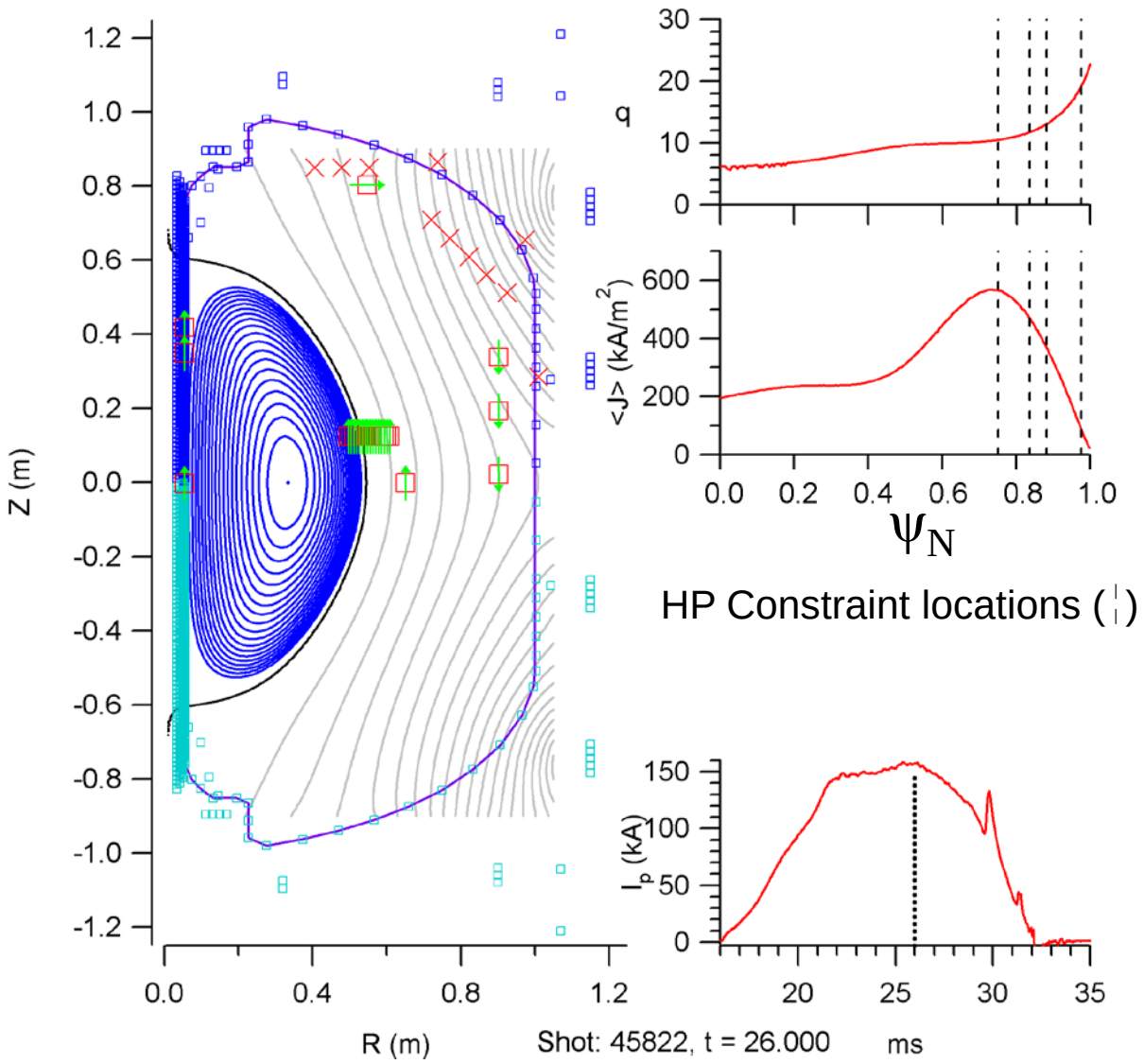
Initial Tests Yield Precision B_z Measurements

- Internal probing yields no measurable plasma perturbation, according to:
  - I_p evolution / sustaining V_{loop}
  - Achieved shape (ℓ_i evolution)
  - SPRED impurity spectroscopy
- Compares favorably with external Mirnov coils
  - n=1 MHD well-resolved
- Full array yields spatially resolved $B_z(R,t)$
  - Allows inference of $J(R,t)$, $J(\Psi)$



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Initial Reconstructions Constrain J(ψ)



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

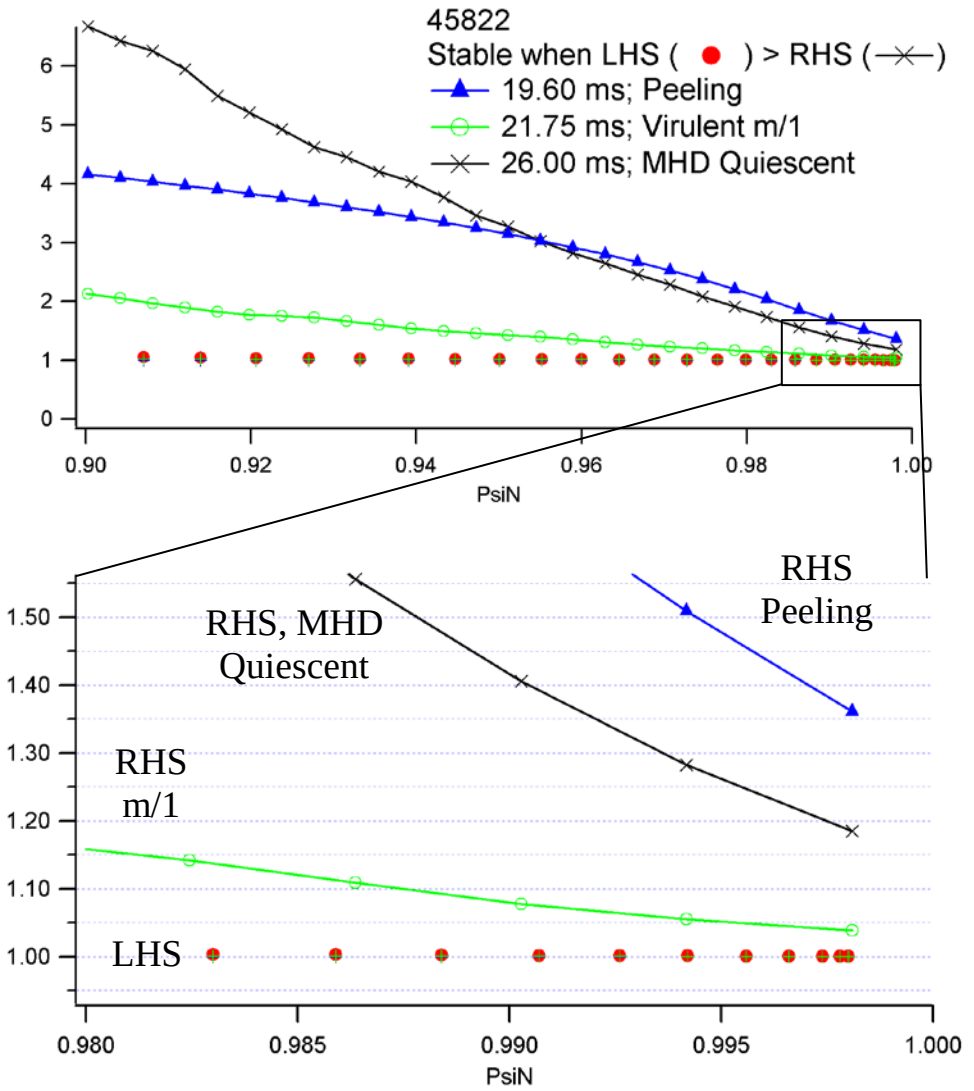
*Sontag, A., Nucl. Fusion **48,** 095006 , 2008

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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Observed Edge Instability Consistent with Qualitative 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, in agreement with theoretical expectation
- Motivates additional, detailed comparisons with peeling-ballooning theory
  - Stability analysis via DCON, ELITE



Unstable if RHS > LHS

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Current and Future Work

- Equilibrium and stability studies with accurate j(ψ)
  - Enhancements to KFIT to accommodate diagnostic capabilities
  - Significant code development activity underway

- Direct analysis techniques*
  - Infer J(R,t) directly from $B_z(R,t)$

- Improvements to Hall Probe System
  - Near-term:
    - Improve signal conditioning, data acquisition to increase S/N
  - Longer-term:
    - 2nd generation PCB: improved spatial resolution, stronger J(ψ) constraint

*: Petty, *et al.*, Nucl. Fusion **42**, 1124, 2002

Summary

- Localized filamentary edge instabilities in PEGASUS consistent with peeling drive
  - Triggered during conditions of naturally high $\langle J_{edge}/B \rangle$
  - Initial equilibrium analysis: strongest peeling drive present when observed
  - Improvements to equilibrium parameterization and coupling to DCON, ELITE to provide more rigorous comparison with peeling-ballooning theory
- New Hall probe diagnostic deployed to directly constrain J(ψ)
  - Precision, internal $B_z(R,t)$ obtained without plasma perturbation
  - Electrostatic shielding scheme, signal processing suppress switching noise
  - Modular design allows simplified upgrades

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Reprints of this and other PEGASUS presentations are available at

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