Radially Scanning Magnetic Probes to Study Local Helicity Injection Dynamics

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PEGASUS
Toroidal Experiment

Layout Slide (Include for Posters)

12:1 scale Panel size: 8' x 4'

US Legal
8.5 x 14"

US Letter
8.5 x 11"

Radially scanning magnetic probes to study Local Helicity Injection dynamics

Need to Understand LHI Current Drive Motivates Local Magnetic Measurements	Probes Deployed onto PEGASUS Toroidal Experiment	Magnetic Radial Array (MRA) Probe to Study High Frequency Magnetic Activity	Magnetic Radial Scanning (MRS) Probe to Study Field Structure and Evolution	Initial Probe Measurements Provide New Insights
Local Helicity Injection Routinely Used for Non-Solenoidal Startup on PEGASUS	Insertable Probe Assemblies Developed to Reuse Translatable Mechanical Assembly	15 Channel $\dot{B}$ Probe Built to Study High Frequency Activity	3D Hall Effect Probe Built to Study Field Structure and Current Dynamics	MRA Measurements Show Significant High Frequency Activity Present in LHI
NIMROD Describes a Reconnection-Based Current Drive Mechanism	Probes Complement External Magnetic Diagnostics	$\dot{B}$ Coils Implemented as Traces on Printed Circuit Board	Hall Effect Integrated Circuits Provide Linear Field Response	MRA Probes Spatial Structure of Magnetic Activity in LHI
Experimental Observations Suggest Additional Current Drive Mechanism(s) are Active in LHI	Probe Drive Assembly Allows for Precise Radial Positioning and Axial Alignment	Shielding Scheme Provides High Noise Immunity	3D Printed Frame Allows for Precise IC Alignment	MRS Measurements of PEGASUS Field-Only and LHI Plasma Discharges
PEGASUS Operating Space Enables Local Measurements with Insertable Probes	Local Digitization Used to Reduce Noise Pickup	$\dot{B}$ Sensors Absolutely Calibrated with Helmholtz Coil	Hall Sensors Calibrated Using 3-Axis Helmholtz Coil	New Magnetics Probes Provide Tools to Investigate Magnetic Activity Observed in LHI

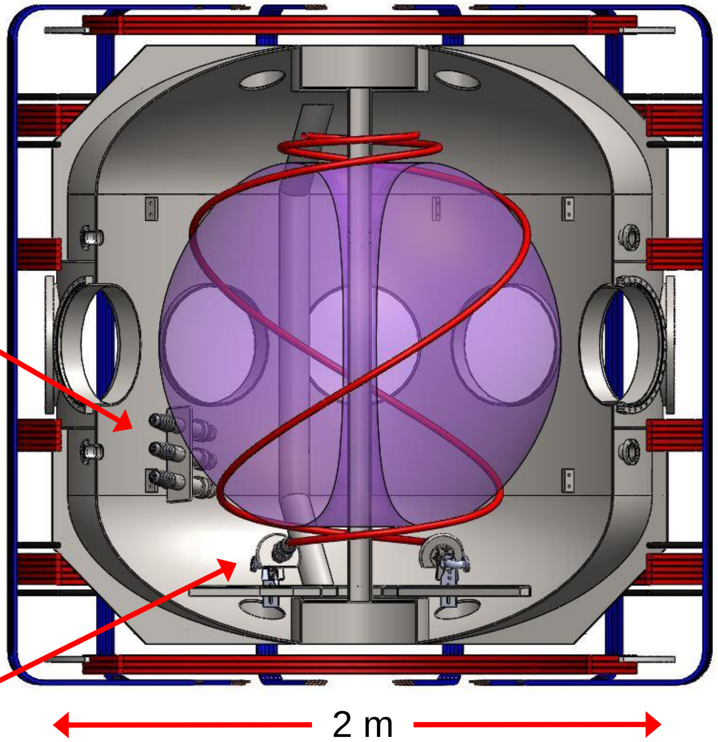
Need to Understand LHI Current Drive Motivates Local Magnetic Measurements

Local Helicity Injection Routinely Used for Non-Solenoidal Startup on PEGASUS

Low Field Side (LFS)

Local Helicity Injectors

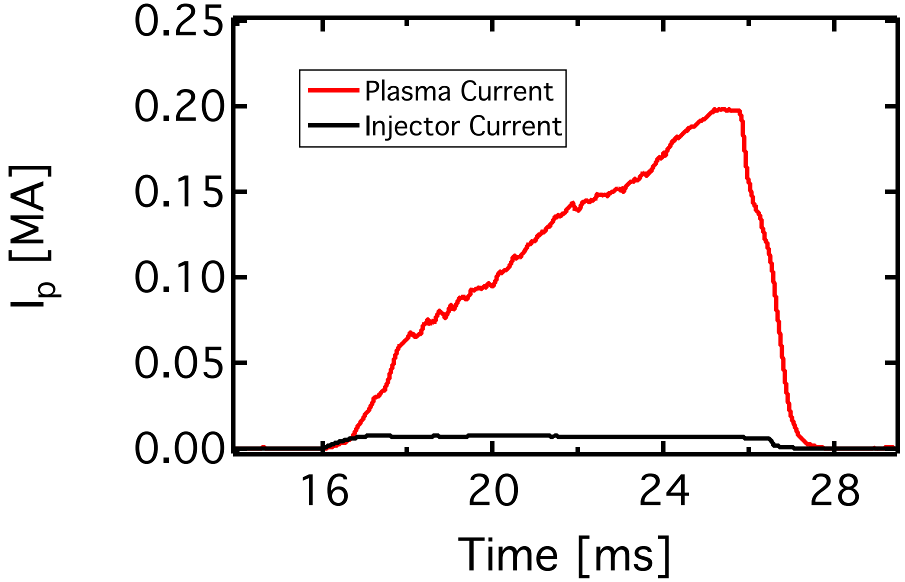
High Field Side (HFS)



Pegasus Parameters

A	1.15 – 1.3
R [m]	0.2 – 0.45
I_p [MA]	$\leq$ .25
B_T [T]	$\leq$ .15
τ_{shot} [s]	$\leq$ 0.025

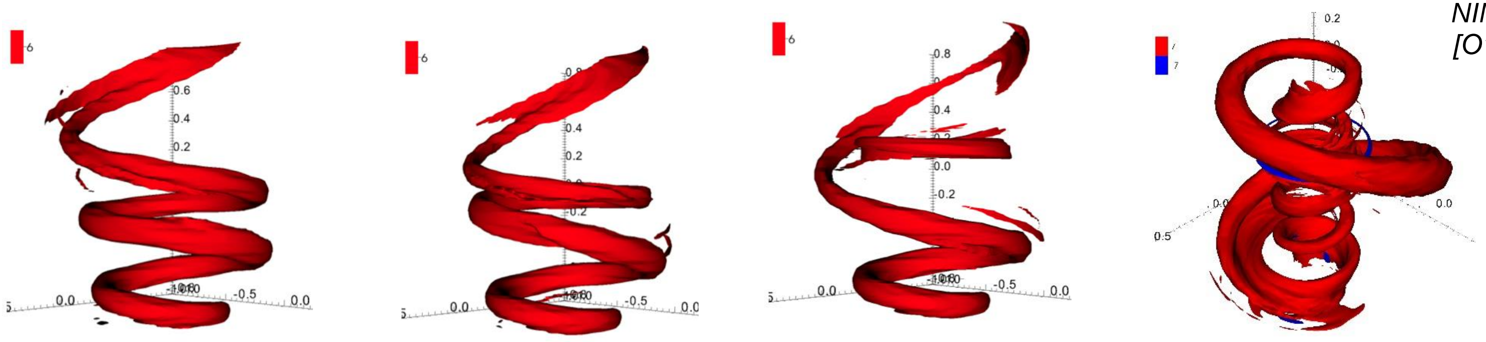
Non-Solenoidal, High I_p ≤ 0.2 MA (I_{inj} ≤ 8 kA)



- Current extracted from local injectors
- Unstable current streams relax to tokamak-like state

Reusch et al., Phys. Plasmas ***25****, 056101 (2018)*

NIMROD Describes a Reconnection-Based Current Drive Mechanism



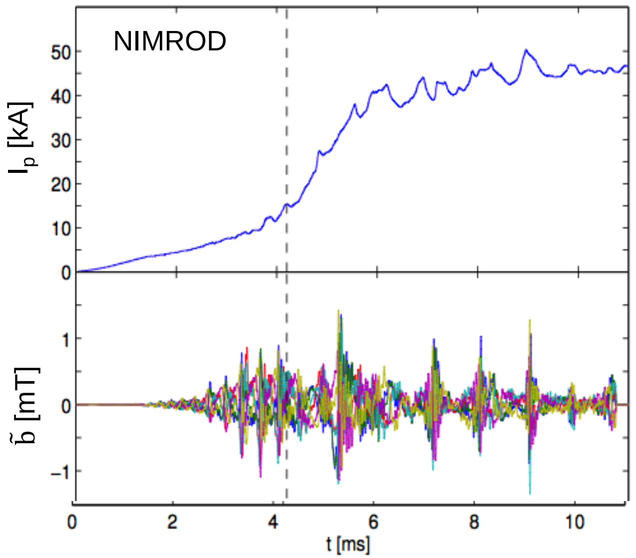
1. Streams follow field lines

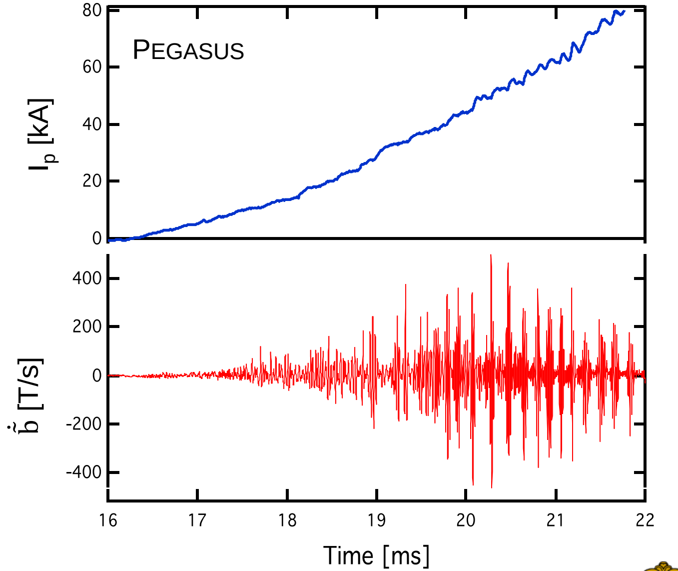
2. Adjacent passes attract

3. Reconnection pinches off current rings

Sustainment phase

NIMROD Simulation [O'Bryan PhD 2014]





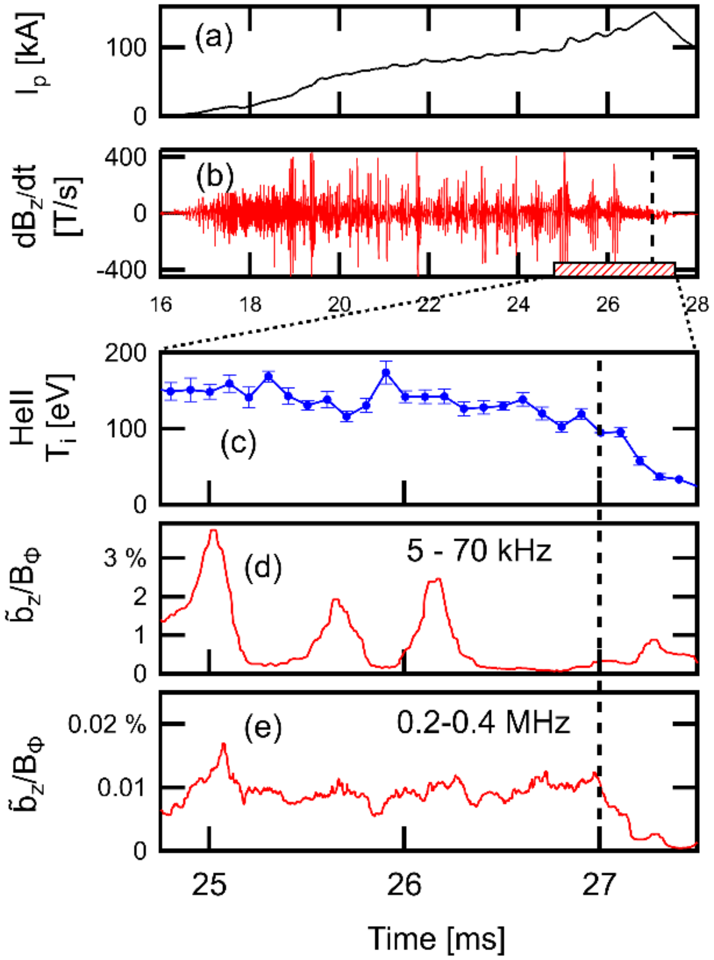
- NIMROD describes reconnection of current streams leading to I_p growth
  - Discrete reconnection events pinch off current rings, associated with $n = 1$ activity
  - Rings move inward, building up poloidal flux
  - This process happens throughout the discharge
- Evidence for this is observed on PEGASUS
  - Jumps in toroidal current associated with $n = 1$ events
  - Frequency range in qualitative agreement with NIMROD prediction
  - Internal magnetic measurements show power at injector radius

O'Bryan et al., Phys. Plasmas **19** *080701 (2012)*
O'Bryan and Sovinec, Plasma Phys. Control. Fusion **56** *064005 (2014)*

Experimental Observations Suggest Additional Current Drive Mechanism(s) are Active in LHI

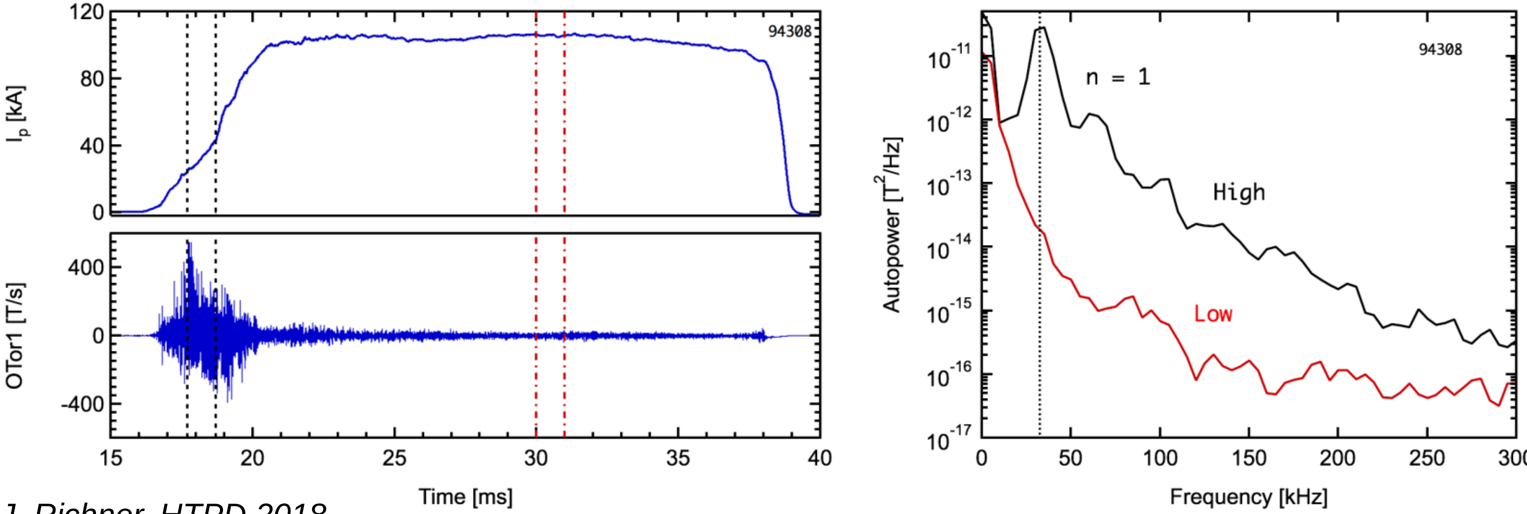
- Ion heating due to reconnection is better correlated with high frequency activity than $n = 1$ bursts
- Current drive persists in absence of low frequency, $n = 1$ mode
- Short-wavelength reconnection may provide another current drive mechanism

Ion heating correlated with high-f MHD fluctuations, not discrete reconnection between helical streams



M.G. Burke, et al. Nucl. Fusion **57** 076010 (2017)

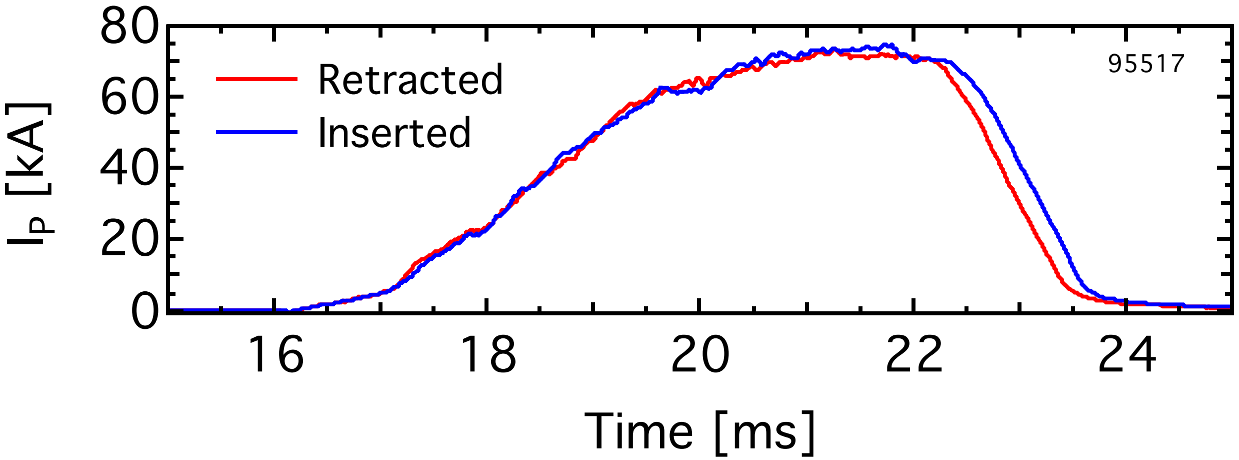
I_p sustainment in absence of low frequency, n = 1 activity

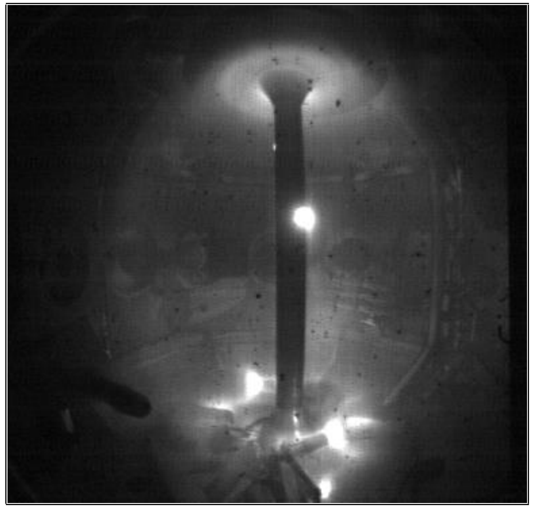


PEGASUS Operating Space Enables Local Measurements with Insertable Probes

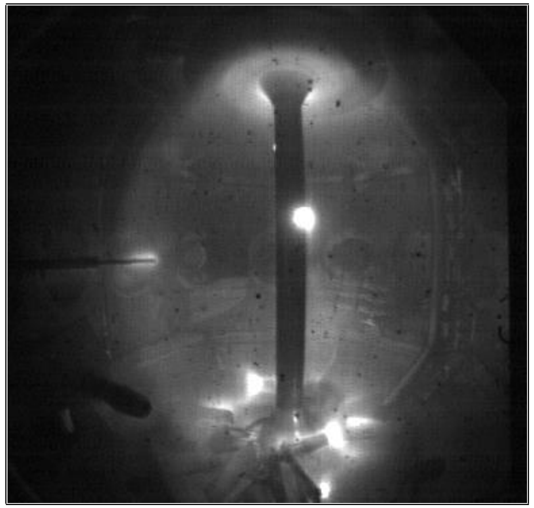
- With appropriate armoring and conditioning, LHI plasmas are amenable to probe measurements*
- Modest edge parameters in Pegasus:
  - $T_{e,edge} \sim 50$ eV
  - $n_{edge} \sim 5 \times 10^{18}$ m^{-3}
  - Shot duration ~ 10 ms
- Probes armored with low-Z, graphite
- Generally good reproducibility between plasmas with and without probe inserted
- Accessibility to probes motivates direct, local measurements of LHI plasmas

Reproducible plasmas with probe inserted into plasma edge (R_{edge}~56 cm)





Probe retracted (98 cm)



Probe inserted (54 cm)

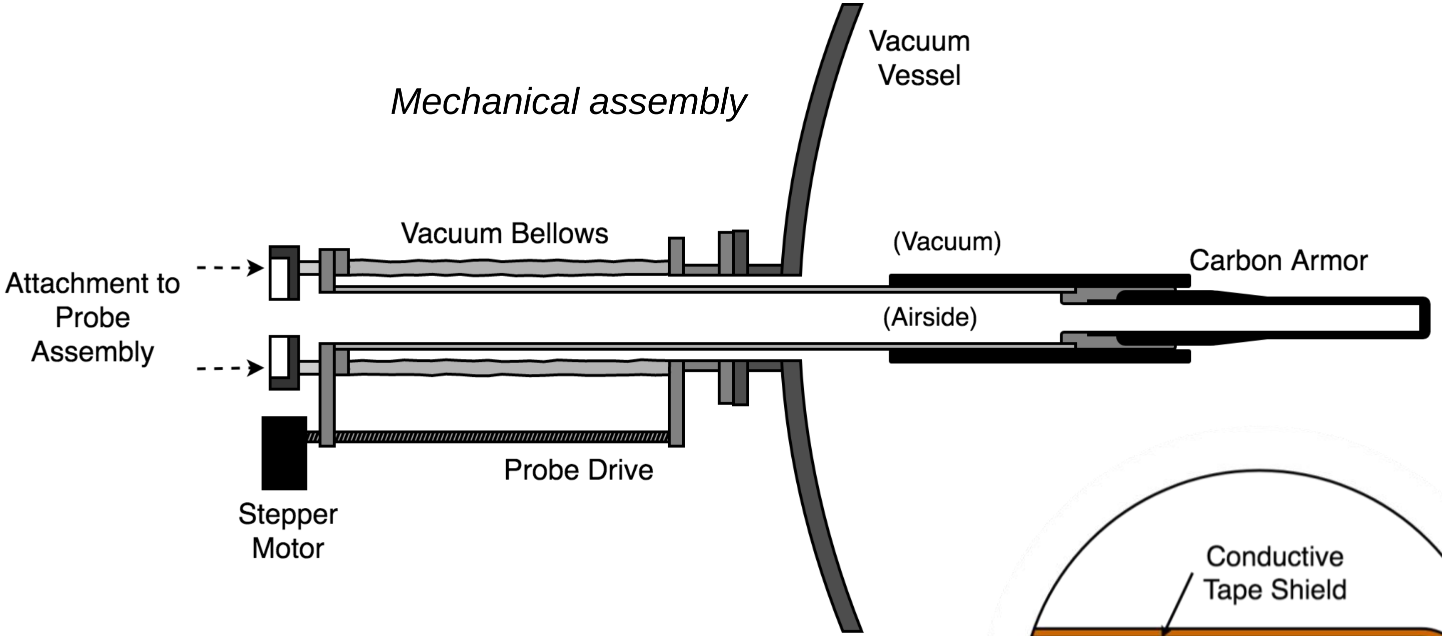
* *Thome et al.*, *Nuclear Fusion* **57**, 022018 (2017)

Probes Deployed onto
PEGASUS Toroidal Experiment

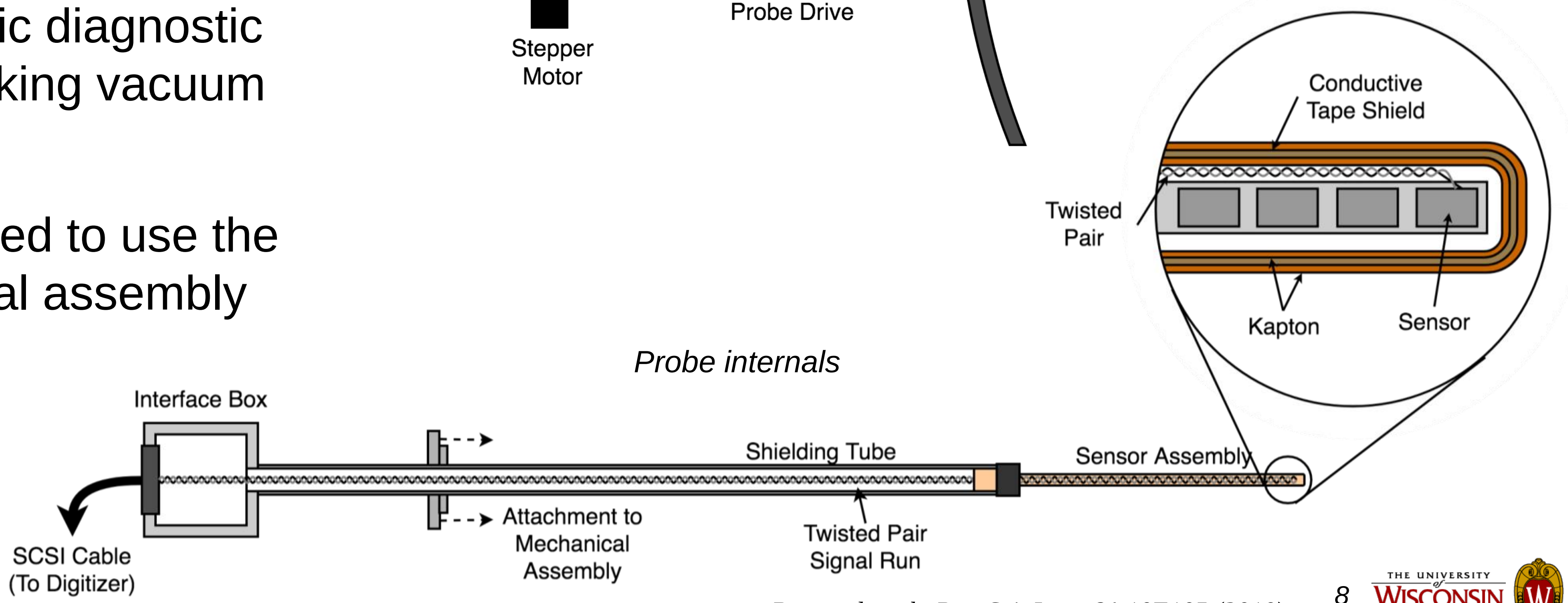
Insertable Probe Assemblies Developed to Reuse Translatable Mechanical Assembly

- Existing 1D Hall array probe separates mechanical assembly and air-side probe internals
- Probe internals can be swapped out to satisfy specific diagnostic needs without breaking vacuum
- New probes designed to use the common mechanical assembly

Mechanical assembly



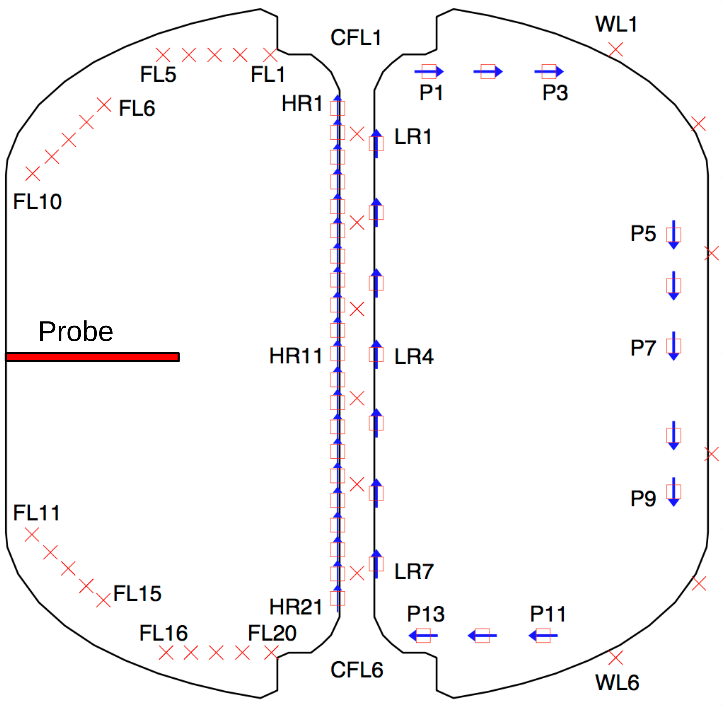
Probe internals



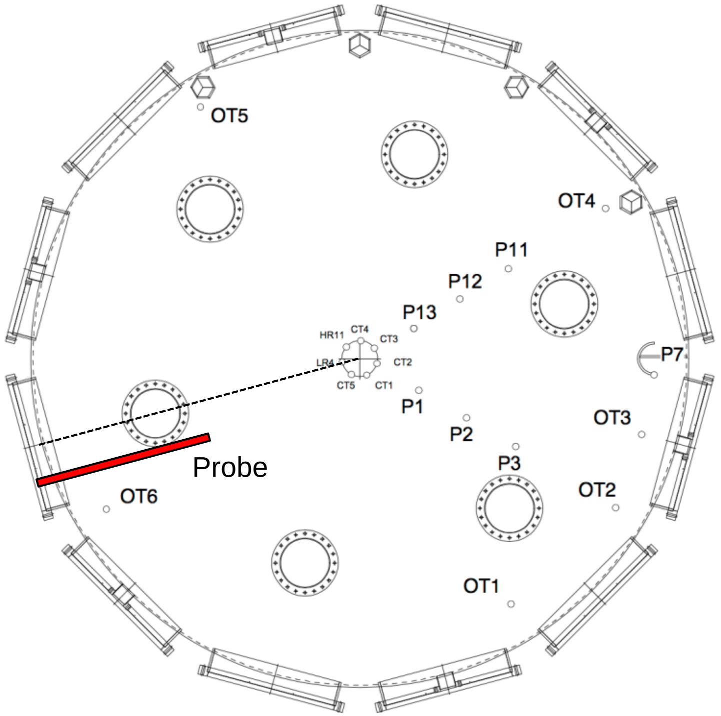
Bongard et al., Rev. Sci. Instr. **81** 10E105 (2010)

Probes Complement External Magnetic Diagnostics

PEGASUS Magnetic Diagnostic Layout



Cross-section



Top-down

- Probe insertion range:

  $R = 54 - 98$ cm

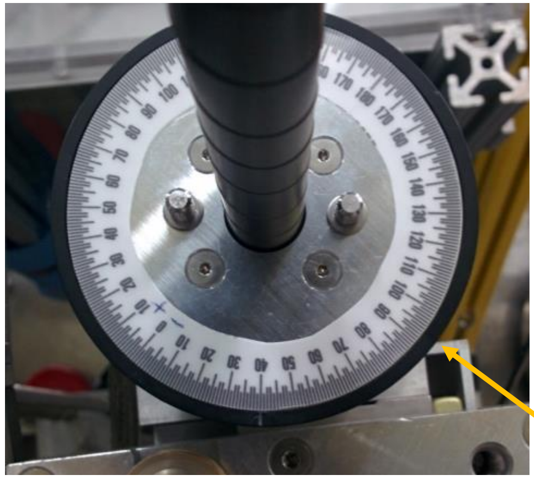
- Installed on machine midplane

  $Z = 0$ cm

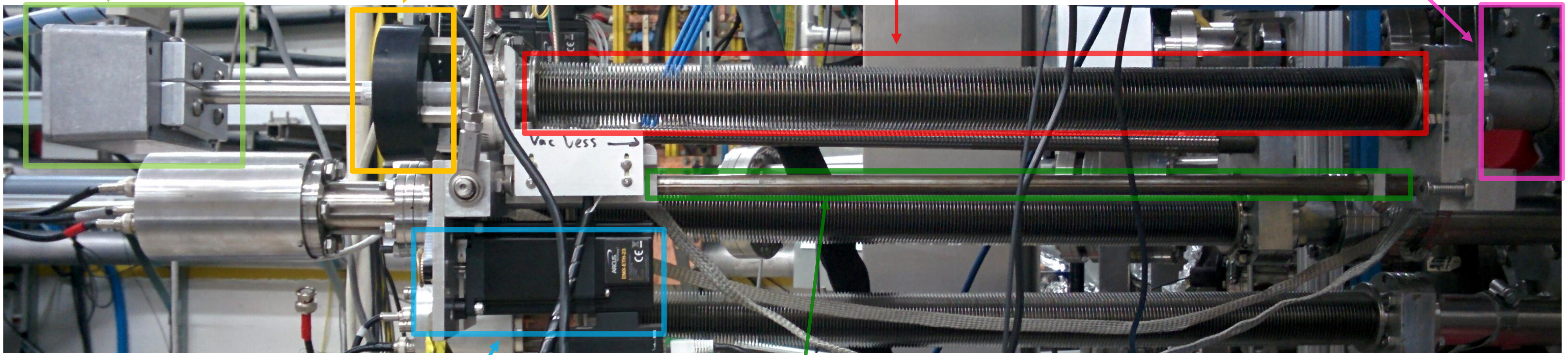
- Offset from radial line to centerstack

  $R_{tan} = 15.56$ cm

Probe Drive Assembly Allows for Precise Radial Positioning and Axial Alignment



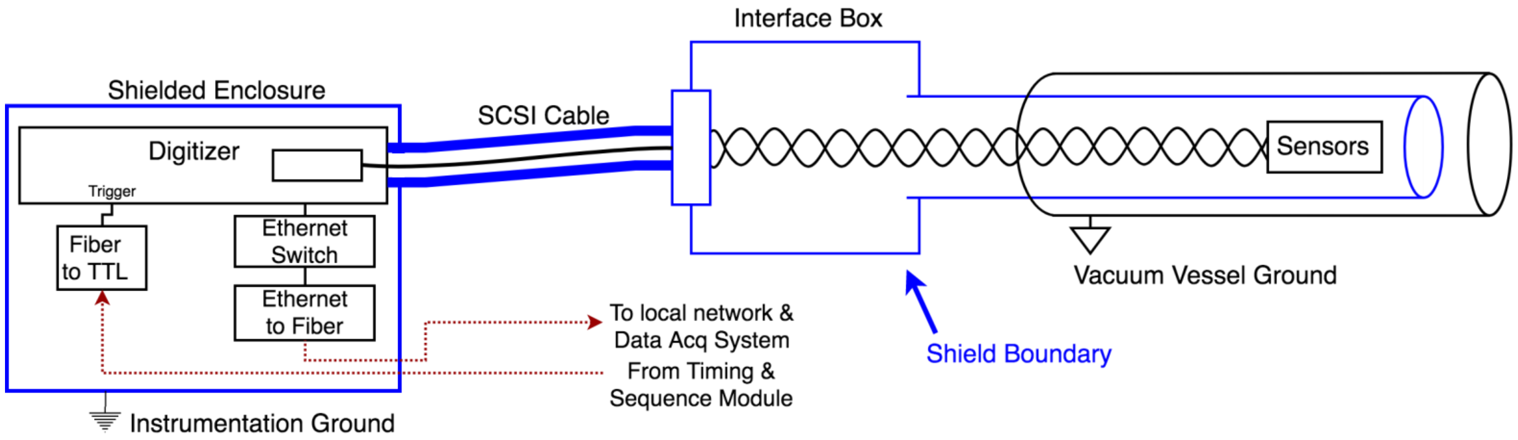
- Motorized probe drive allows for remote insertion / retraction
  - Insertion depth range: 54 – 98 cm
  - Submillimeter precision in radial position
- Rotatable mount allows for precise (0.5°) alignment to vertical field



Local Digitization Used to Reduce Noise Pickup

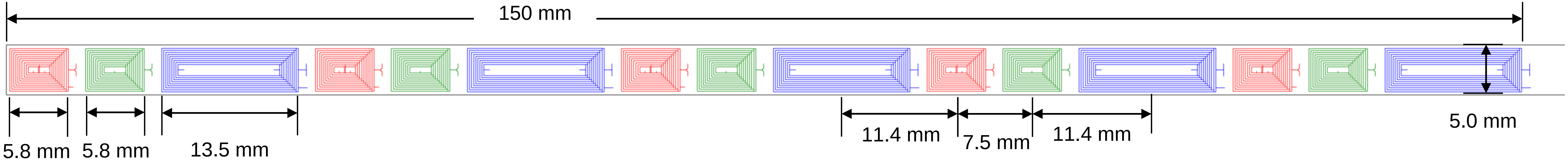
- Shielded enclosure houses digitizers used by probes
  - Located near machine, allowing short ($\lesssim$ 4 m) cable runs
  - Provides ground for electrostatic shielding of probe
- Signals digitized with fully differential, D-TACQ digitizers
  - MRA: ACQ132 – 2 MSPS, 16 eff. bit depth, built-in antialiasing
  - MRS: ACQ196 – 500 kSPS, 16 bit

Continuous electrostatic shield held at local digitizer ground



Magnetic Radial Array (MRA) Probe to Study High Frequency Magnetic Activity

15 Channel $\dot{B}$ Probe Built to Study High Frequency Activity



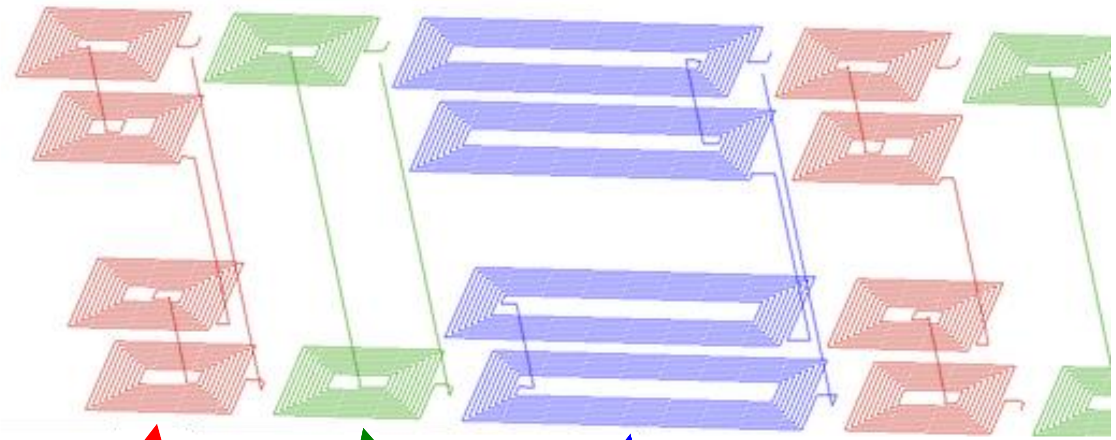
Magnetic Radial Array (MRA) Probe:

- 15 channel $\dot{B}_z(R,t)$
- $\dot{B}$ coils formed as traces in PCB
- Active length: 15 cm
  - Extend to and through plasma edge at maximum insertion
- Spatial resolution: ~ 1 cm
  - ρ_i ~1.1 cm
- Frequency response: $\gtrsim$ 1 MHz
  - f_{ci} ~ 760kHz, f_A ~ 0.05 - 5 MHz
- Sensitivity range: $\gtrsim$ 0.2 mV / (T/s)
- Absolute calibration with Helmholtz coil
- High noise immunity

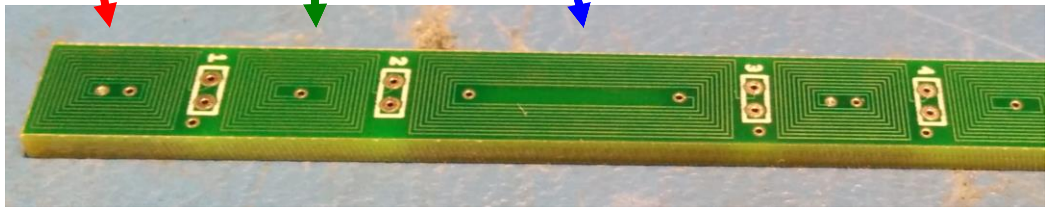
$\dot{B}$ Coils Implemented as Traces on Printed Circuit Board

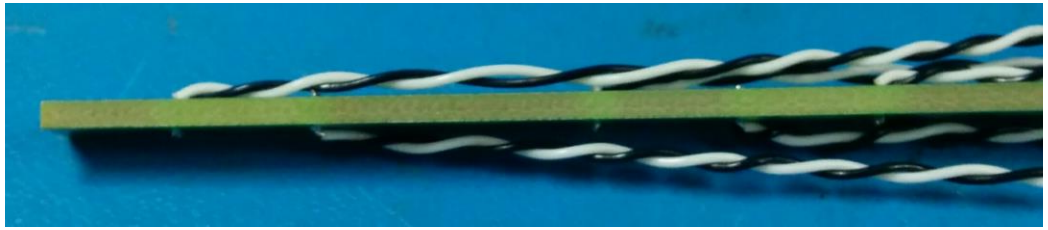
- Three coil geometries balance frequency response, signal sensitivity
- 32 AWG twisted pair leads minimize inductive noise pickup

Coil Geometry	Coil Size	PCB Layers	Sensitivity	Frequency Response
A	5.8 x 4.9 mm	4	3.52 cm^2	Medium
B	5.8 x 4.9 mm	2	1.80 cm^2	Fast
C	13.5 x 4.9 mm	4	9.55 cm^2	Slow



Type A Type B Type C

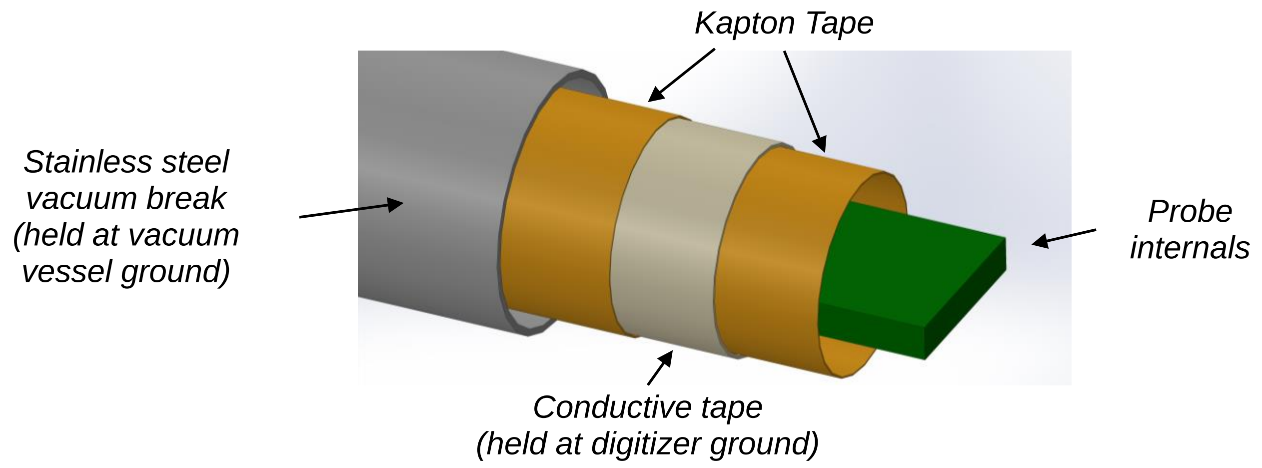




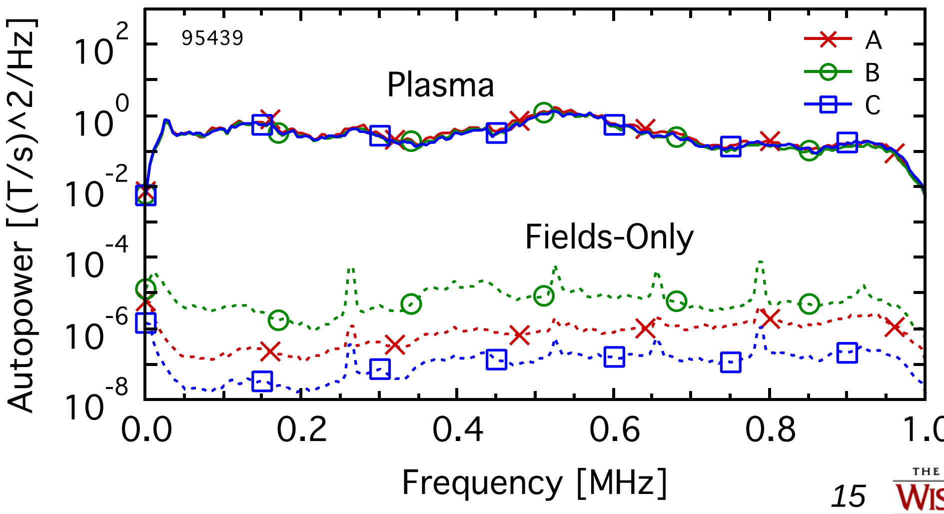
Shielding Scheme Provides High Noise Immunity

- Thin (4 mil) layer of conductive tape used for electrostatic shielding
- Thin-walled stainless steel tubing used as vacuum break and additional shielding
- Shield layers and probe terminals insulated with Kapton tape
- Skin-depth effects of full assembly corrected with Helmholtz coil measurements
- Used for both MRA and MRS probes

Cutaway drawing of electrostatic shield scheme



Signal-to-noise of MRA probe ~45 dB over frequency range of interest



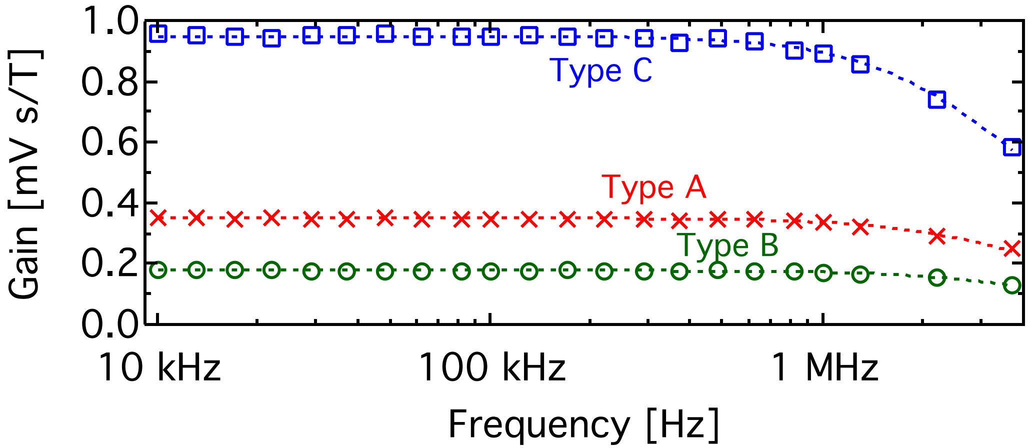
$\dot{B}$ Sensors Absolutely Calibrated with Helmholtz Coil

- Helmholtz coil measurements provide A_{eff} and frequency response calibration
  - 10 kHz – 4 MHz range
  - $\dot{B} = 0.5$ T/s – 200 T/s

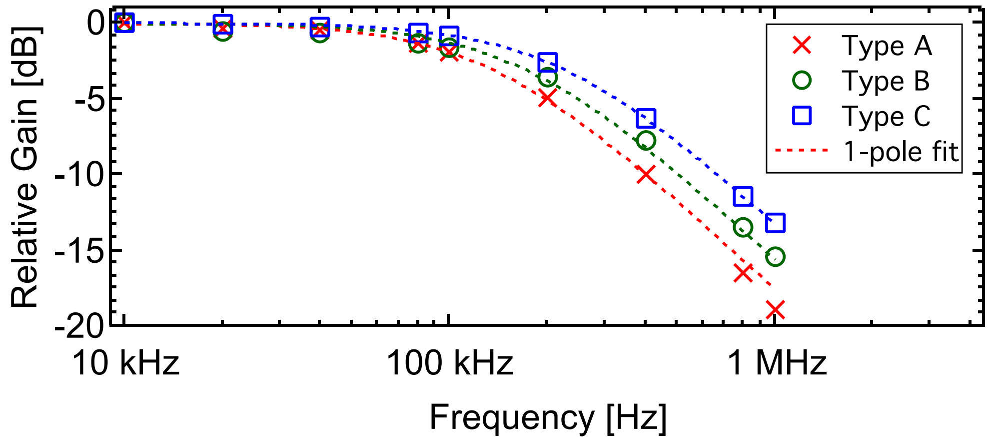
- Measured probe transfer function (including armor and shielding) used to correct MRA measurements
  - Measured gain consistent with assumed 1 pole roll-off from penetration depth effects
  - 1-pole transfer function fit to measured gain, and used to correct high frequency measurements

Coil Geometry	A_{eff}	Corner Frequency (coil)	Corner Frequency (coil + assembly)
A	3.52 cm^2	3.5 MHz	130 – 220 kHz
B	1.80 cm^2	4.0 MHz	170 – 210 kHz
C	9.55 cm^2	2.8 MHz	220 kHz

Flat coil response up to ~ 700 kHz with 200 Ω termination

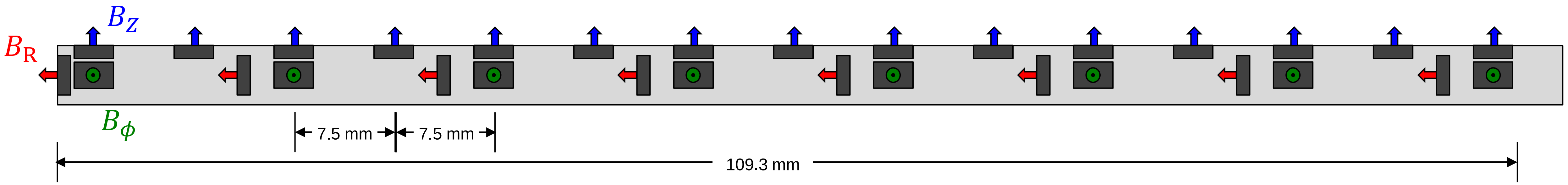


Measured transfer functions are used to correct $\dot{B}$ measurements



Magnetic Radial Scanning (MRS) Probe to Study Field Structure and Evolution

3D Hall Effect Probe Built to Study Field Structure and Current Dynamics



Magnetic Radial Scanning (MRS) Probe:

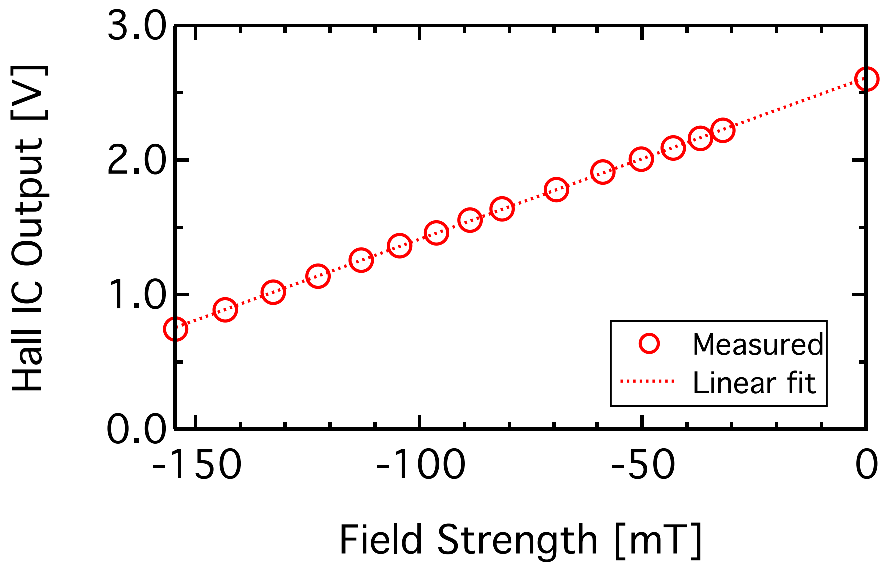
- 3D field measurements at 8 spatial points
  - 15 mm separation
  - Comparable to grid size of equilibrium reconstructions
- 7 additional B_z measurements
  - 7.5 mm vertical field resolution
  - Study helical current streams (strong J_ϕ component)
  - Investigate $|B|$ well effects
- Active length of ~ 11 cm

- Uses ratiometric Hall effect integrated circuits
  - Commercial product
  - High signal strength
  - Linear field response
  - Temperature independence ($\sim 0.04\%/°C$)
- No measured transverse field gain nonlinearity
- Flat frequency response to ~5 kHz
  - Adequate for equilibrium fields

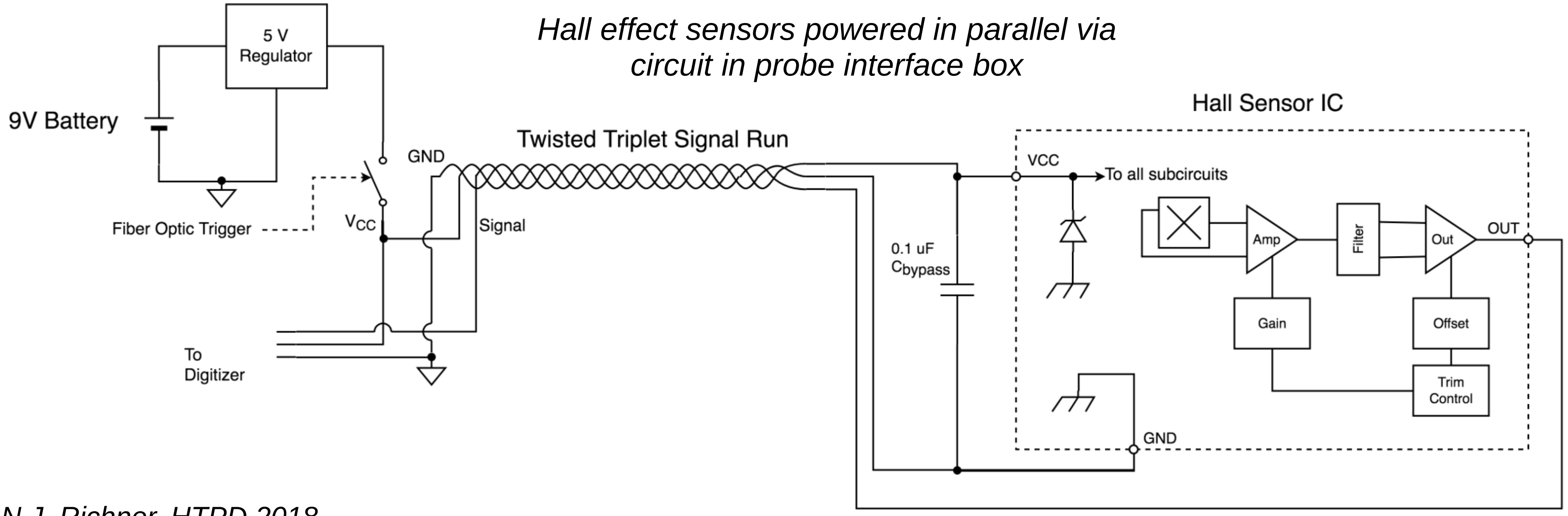
Hall Effect Integrated Circuits Provide Linear Field Response

- Using Allegro A1302 Hall effect sensor ICs
  - Amplifiers and compensators integrated into chip architecture
  - +5 V DC input
  - Linear voltage output proportional to applied field
  - Gain of ~13 V/T → full range of ± 177 mT
  - Temperature independent gain – 0.04%/°C
  - Compact, surface mount form factor

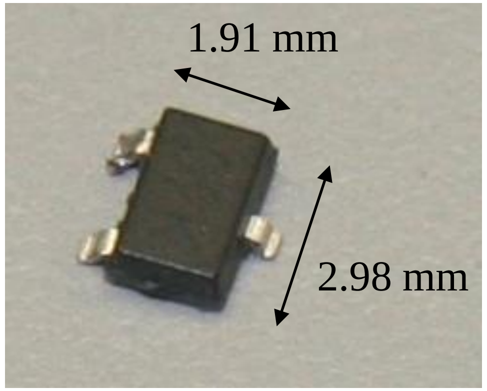
Linear sensor response to applied magnetic field



Hall effect sensors powered in parallel via circuit in probe interface box

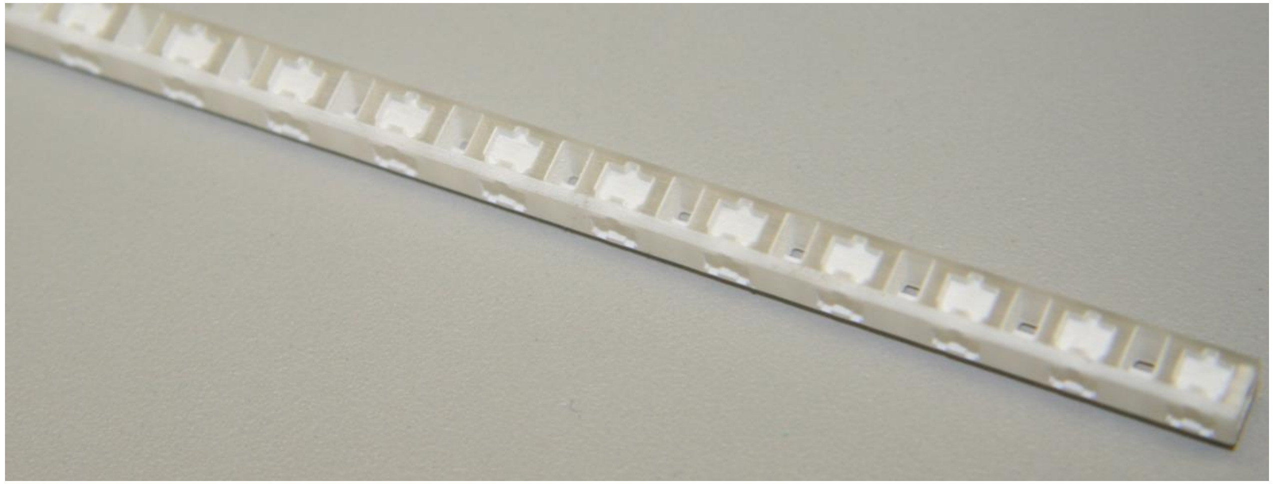


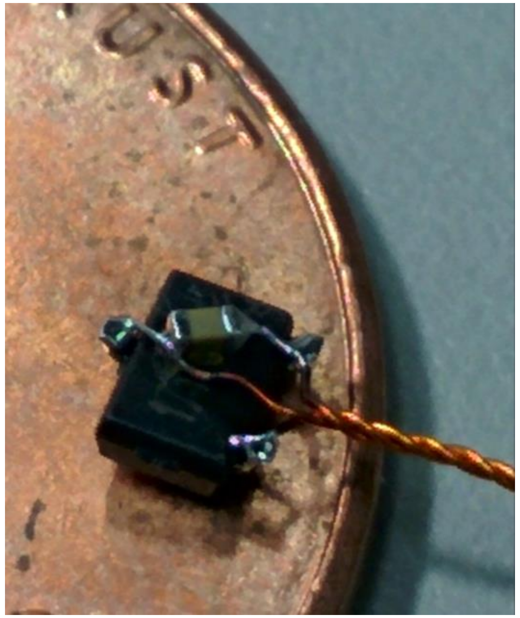
IC schematic, from A1301-2 datasheet

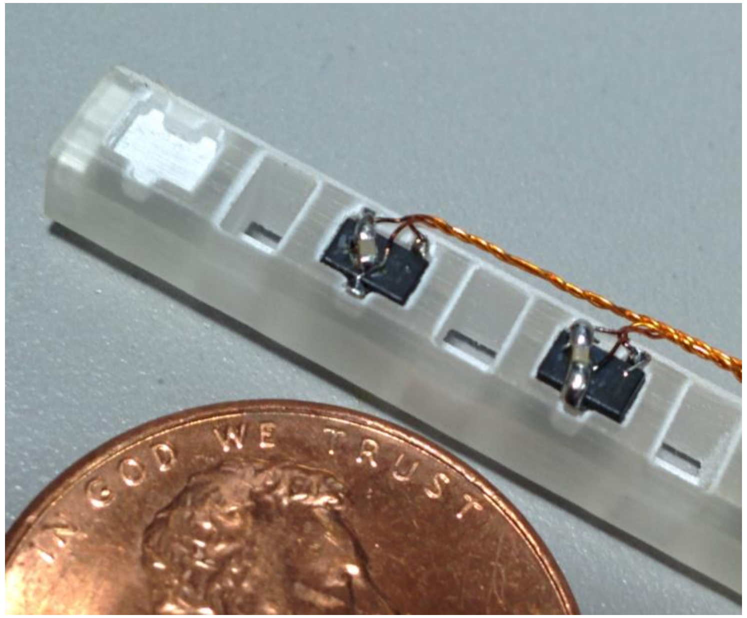


3D Printed Frame Allows for Precise IC Alignment

- Plastic sensor frame made with high resolution 3D printing
  - Accuracy ± 0.1 – 0.2 mm per 100 mm
  - Layer thickness 0.016 mm
- Sensor units glued into 3D printed frame
- Measured construction misalignment ~2°
- Bypass capacitor affixed to top of IC and soldered to IC and leads
  - 0.1uF 0402 (1005 metric) SMD capacitor
- 36 AWG polyamide coated twisted pair leads make electrical connections to ICs
- Active air cooling of probe internals to avoid damage to plastic frame







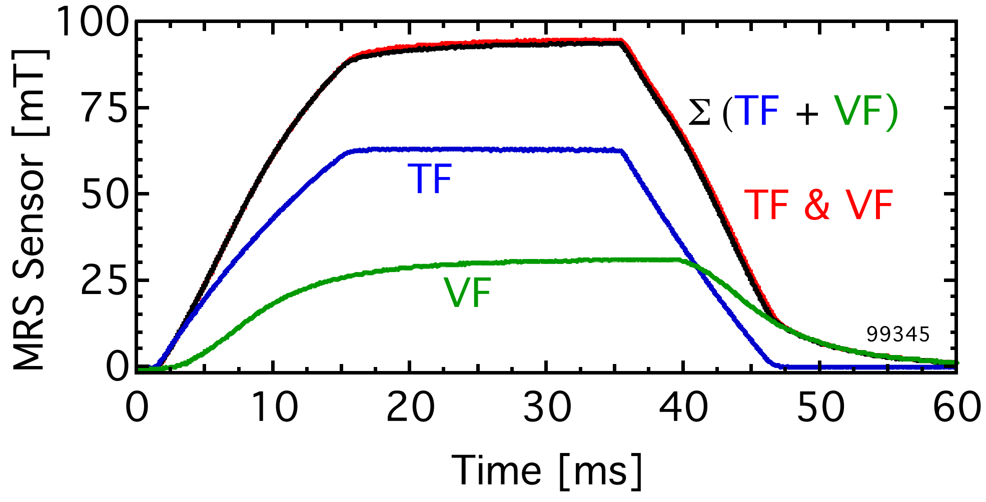
Hall Sensors Calibrated Using 3-Axis Helmholtz Coil

- 3-axis Helmholtz used to measure:
  - Absolute gain
  - Cross-field / misalignment pickup

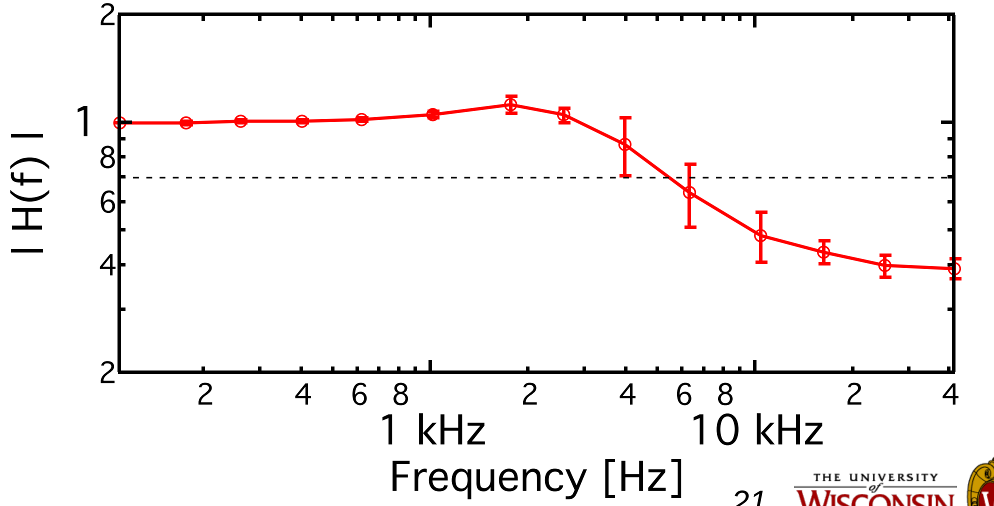
- Gain loss from cross-fields (seen previously to affect Hall sensors) not observed for Hall ICs used
  - Tested with 3-axis Helmholtz coil and vacuum fields on Pegasus
  - Orthogonal fields applied separately, then jointly
  - Signal from combined fields found to be same as sum of individuals, within uncertainty of measurement (~1%)

- Initial tests show sensor bandwidth ~ 5 kHz

No effect of cross-fields on sensor gain



Helmholtz coil tests show ~5 kHz bandwidth for a 3 chip set



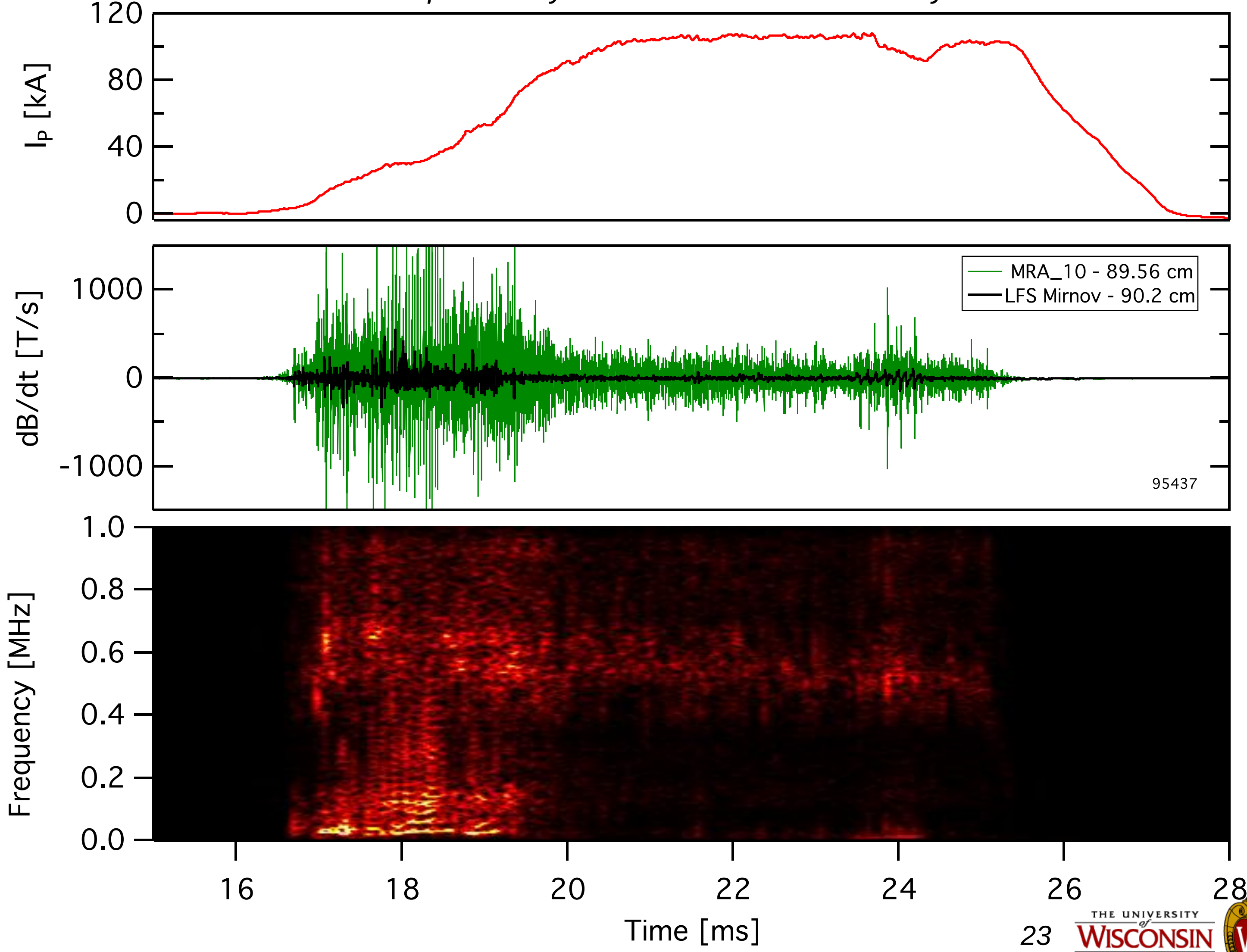
Initial Probe Measurements Provide New Insights

MRA Measurements Show Significant High Frequency Activity Present in LHI

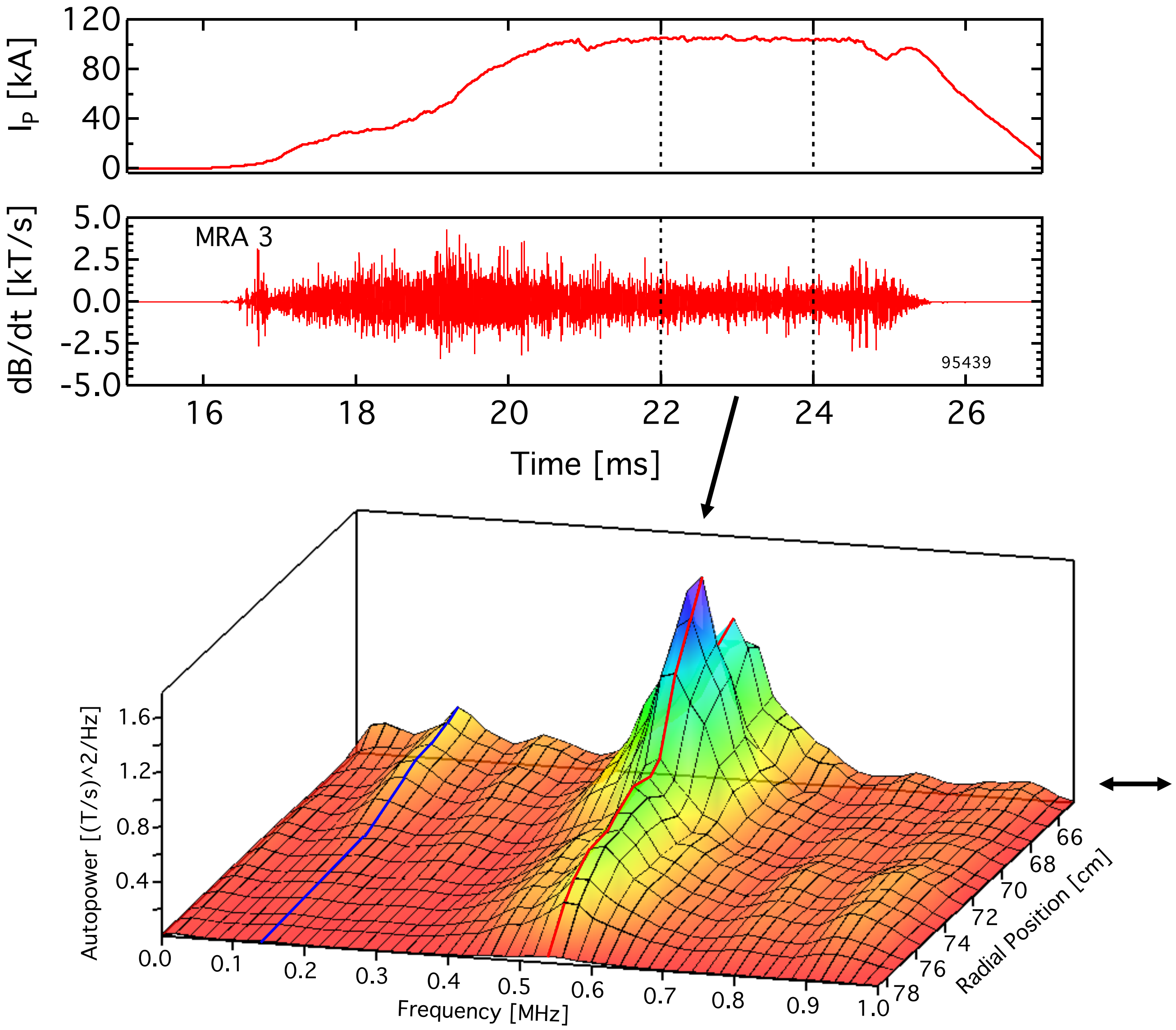
- Low frequency $n = 1$ peak
  - Associated with stream motion
  - Consistent with outboard Mirnovs

- Peak at ~ 600 kHz
  - Observed throughout discharge
  - Short wavelength activity?
  - For comparison:
    - f_{ci} ~ 530 kHz
    - f_A ~ 280 kHz
  - Present even in absence of tokamak plasma
    - Stream instability?

MRA probe shows significant high frequency content in LHI, not previously seen with LFS Mirnov arrays

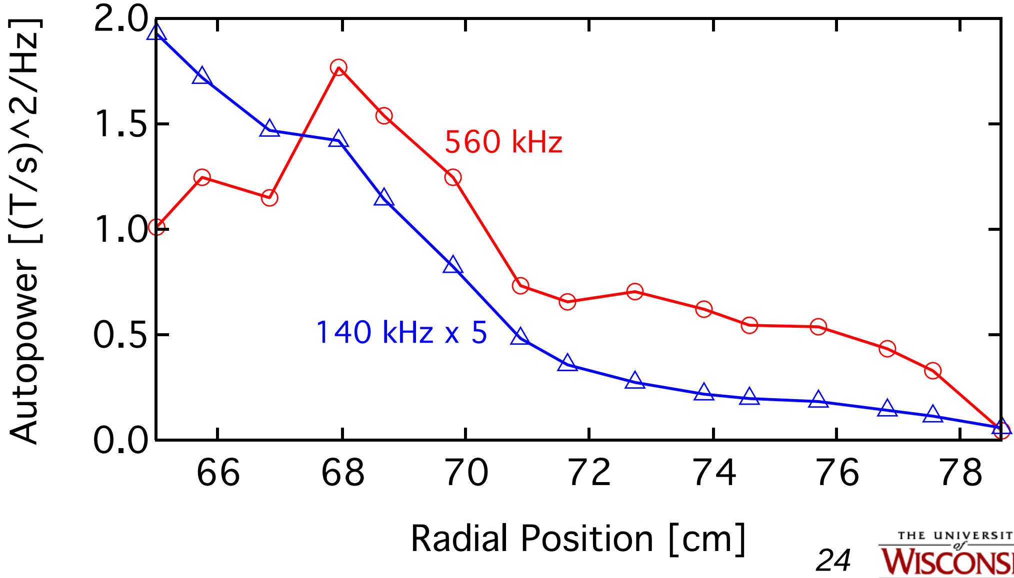


MRA Probes Spatial Structure of Magnetic Activity in LHI



- High-frequency activity at ~ 600 kHz peaks at $R \sim 68$ cm, just outside plasma edge ($R_{edge} \sim 62$ cm)
- Low-frequency activity increases as move further into plasma

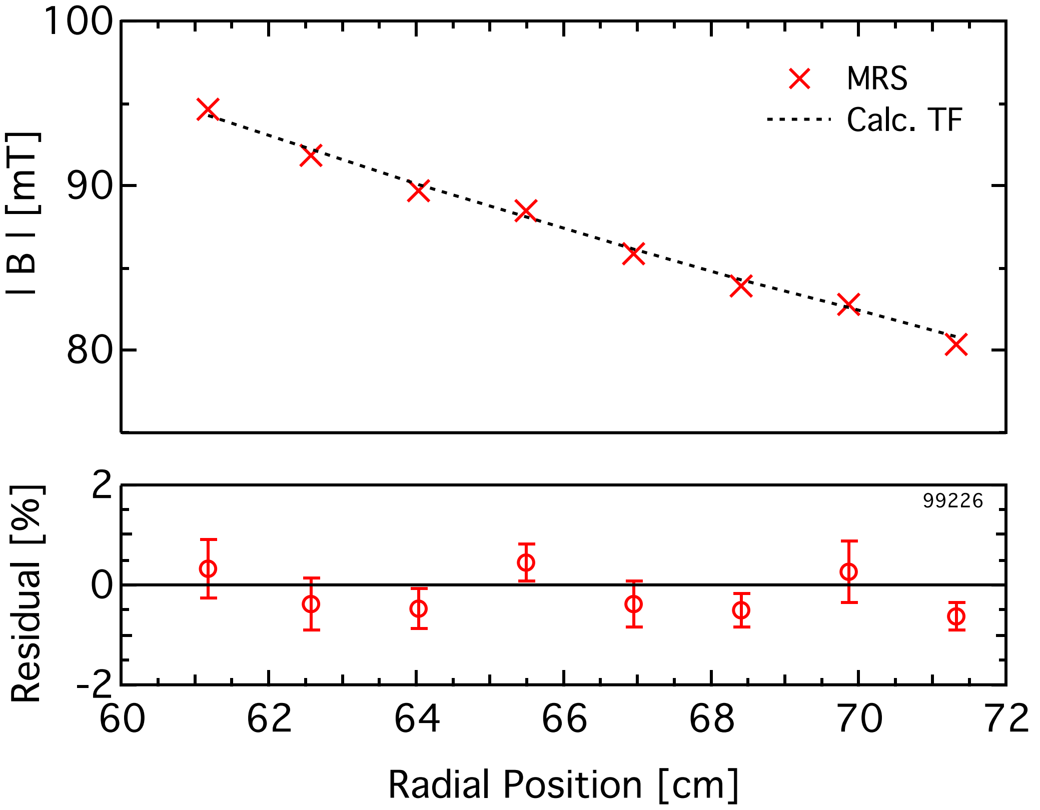
Low and high frequency activity show different spatial structure



MRS Measurements of PEGASUS Field-Only and LHI Plasma Discharges

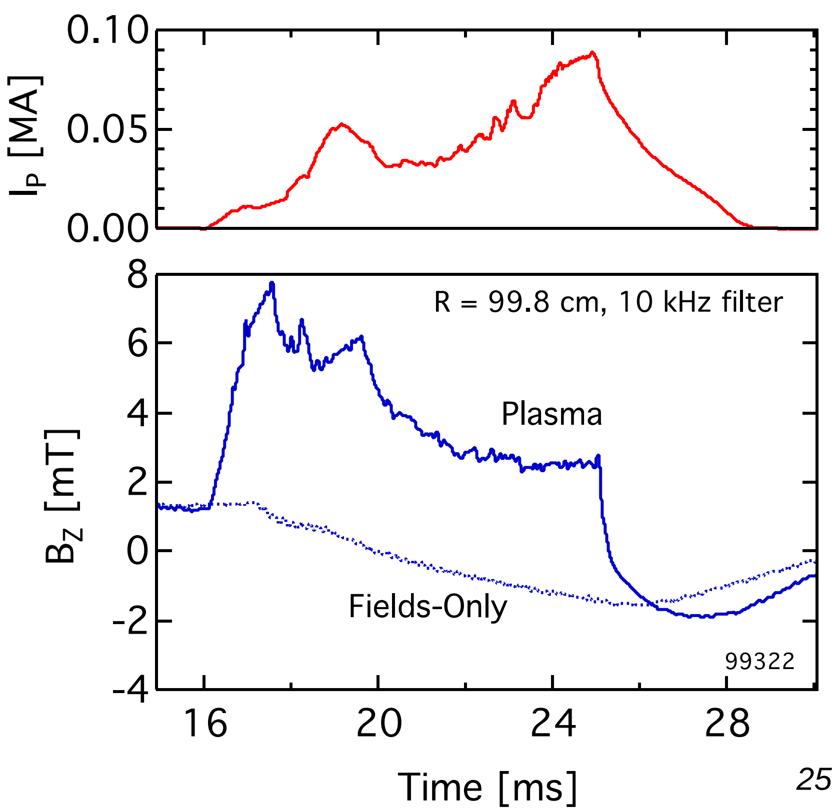
- MRS calibration cross checked with Pegasus vacuum fields

Calibrated MRS measurements consistent with Pegasus fields



- Initial data taken near vessel wall during LHI
  - $R_{Ch01} \sim 99$ cm
  - Strong wall coupling

MRS measurements in presence of LHI plasma



New Magnetics Probes Provide Tools to Investigate Magnetic Activity Observed in LHI

- Magnetic Radial Array (MRA) Probe
  - High-frequency ($\gtrsim$ 1 MHz) $\dot{B}_Z$ array using traces in printed circuit board
  - 15 radially separated measurements over 15 cm
  - Strong signal-to-noise over frequency band of interest
  - Developed to study short-wavelength, high frequency magnetic activity
- Magnetic Radial Scanning (MRS) Probe
  - Low frequency (~5 kHz) Hall effect probe using commercial Hall effect integrated circuits
  - 8 radially separated 3D measurements over 11 cm, and additional B_Z between each 3D measurement
  - Developed to study LHI current dynamics, |B| effects, and provide internal equilibrium constraints
- Probes use mechanical assembly and armor from existing Hall probe
- Local digitization and careful grounding and shielding used to reduce noise pickup
- Absolute probe calibration with Helmholtz coils