Characterization of Low-Frequency MHD Activity in Local Helicity Injection

Carolyn E. Schaefer

M.W. Bongard, R.J. Fonck, J.A. Reusch, N.J. Richner

University of Wisconsin-Madison

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PEGASUS Toroidal Experiment

Layout

US Legal
8.5 x 14”

US Letter
8.5 x 11”

12:1 scale Panel size: 8’ x 4’

Characterization of Low-Frequency MHD Activity in Local Helicity Injection

Magnetic Measurements Needed to Study LHI Current Drive	Operational Regime with Reduced-MHD State	New 3D Hall Sensor Probe (MRS) to Study Field Structure	MRS Probe Used to Characterize Magnetic Structure
Local Helicity Injection Routinely Used for Non-Solenoidal Startup on Pegasus	Abrupt Transition to Reduced-MHD State is Observed	Insertable 3-D Hall Sensor Probe (MRS) to Measure Internal B(R,t) Built and Deployed on Pegasus	Probe Used to Characterize Magnetic Activity in Discharges Featuring MHD Transition
LHI Simulations Describe a Reconnection-Based Current Drive Mechanism	Adjustment of Experimental Parameters Governs Access to Low-MHD Regime	Calibrated Hall Sensors Tested with Vacuum Fields on Pegasus	Probe Array Shows Detailed Magnetic Structure in Edge Region
Observed Reduction of n=1 Motivates Further Exploration of Current Drive Mechanism(s)	Access to Low-MHD Regime is Restricted at Higher B_T , Contrary to Expectations from Simple Stability Theory	Fields Measured Perpendicular to Sensors are Mapped to Machine Coordinates	Measurements Show Combined I_p and I_{inj} Contributions at Edge
n=1 Activity Suggests Unstable Current Stream on Plasma Low Field Side	Several Possible Physical Mechanisms Responsible for Transition Behavior Under Consideration	MRS Frequency Response Allows for Investigation of $f < 50$ kHz Dynamics	Conclusions

Magnetic Measurements Needed to Study LHI Current Drive

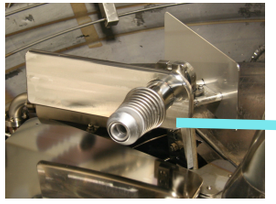
Local Helicity Injection Rountinely Used for Non-Solenoidal Startup on Pegasus

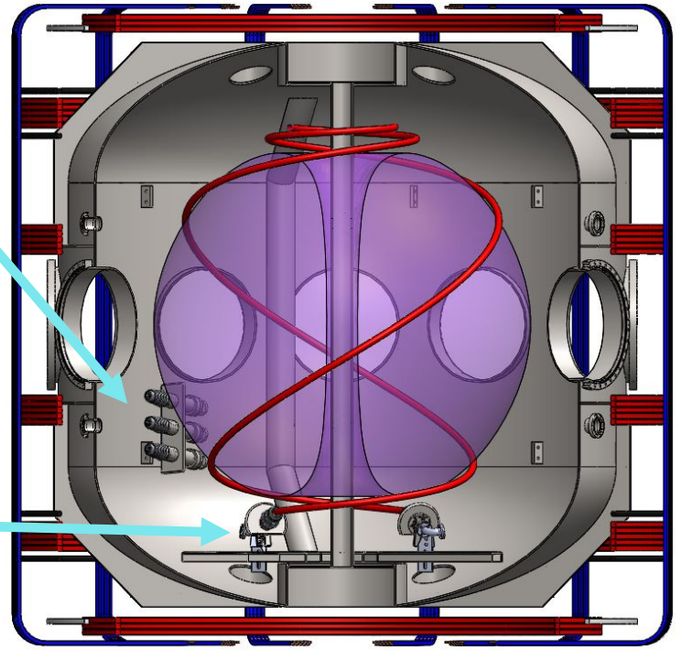
Low Field Side (LFS)



Local Helicity Injectors

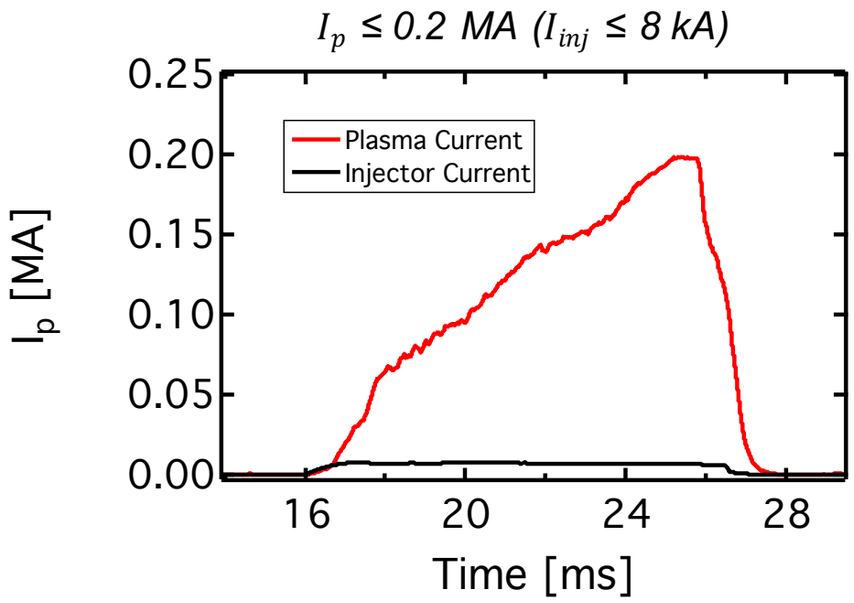
High Field Side (HFS)





Pegasus Parameters

A	$1.15 - 1.3$
R(m)	$0.2 - 0.45$
I_p (MA)	$\leq .23$
$B_{t,0}$ (T)	0.1-0.2
τ_{shot} (s)	≤ 0.025

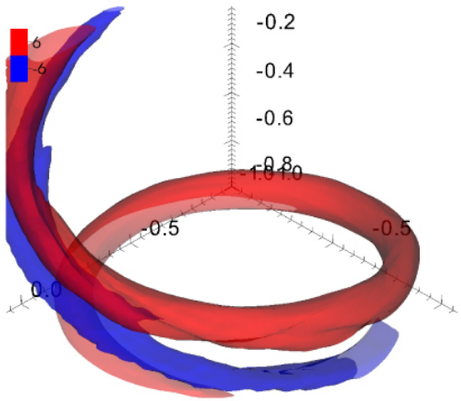


- Edge current extracted from local injectors
- Unstable current streams relax to tokamak-like state

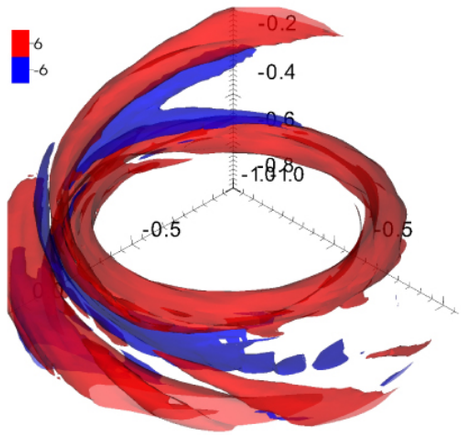
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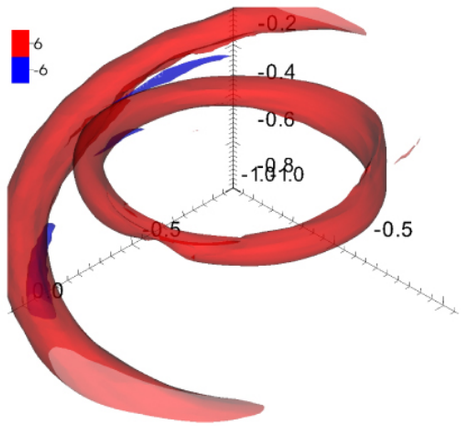
LHI Simulations Describe a Reconnection-Based Current Drive Mechanism



1. Stream follows helical path along field lines

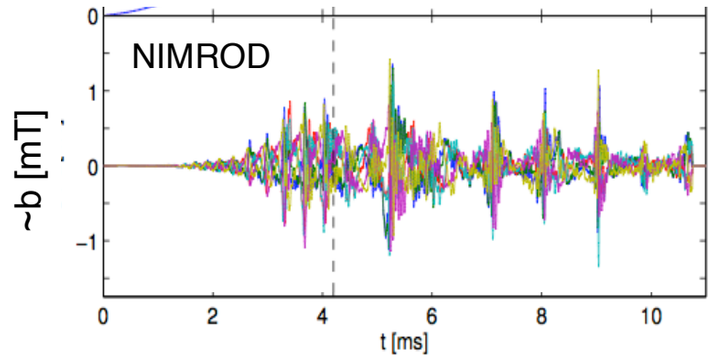


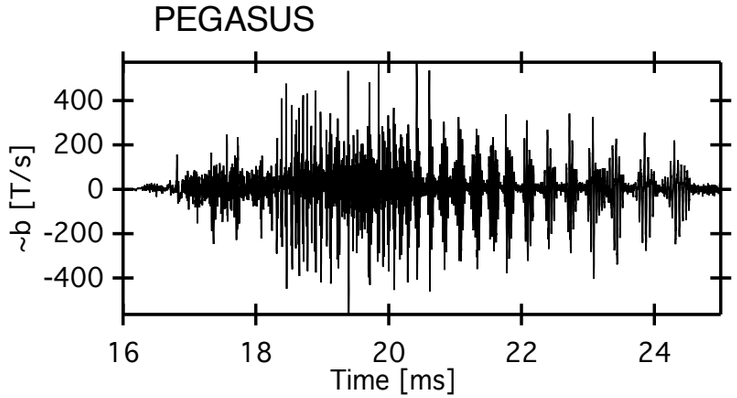
2. Attraction between adjacent passes deforms path



3. Reconnection pinches off current rings that diffuse radially inward

- Similar bursty $n = 1$ MHD behavior observed on Pegasus





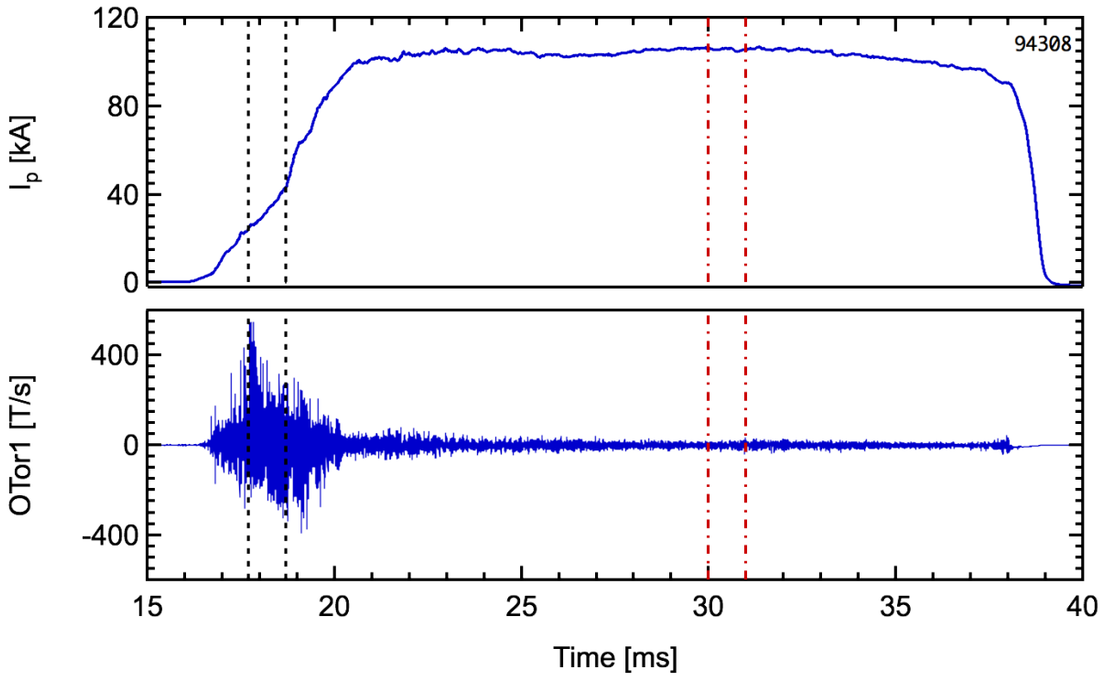
- NIMROD simulates mechanism for current growth during LHI
  - Multiple reconnection cycles build toroidal current and poloidal flux
  - Reconnection events are associated with bursts of $n = 1$ LFS activity

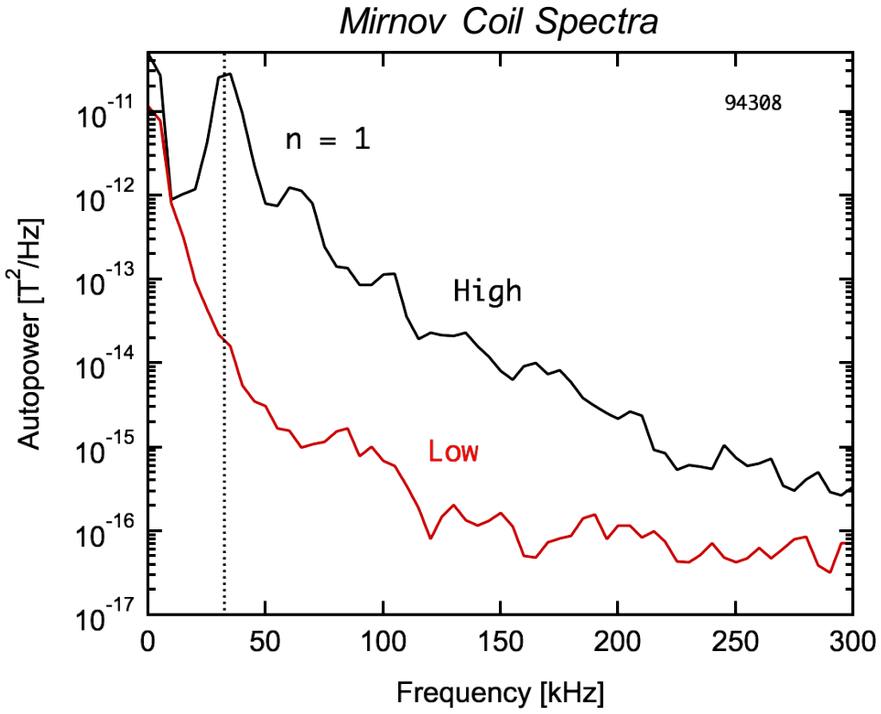
O'Bryan and Sovinec, Plasma Phys. Control. Fusion ***56*** *064005 (2014)*

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Observed Reduction of n = 1 Motivates Further Exploration of Current Drive Mechanism(s)

- LHI current drive sustained in absence of *n* = 1 mode
- Implies additional current drive mechanism(s) are present



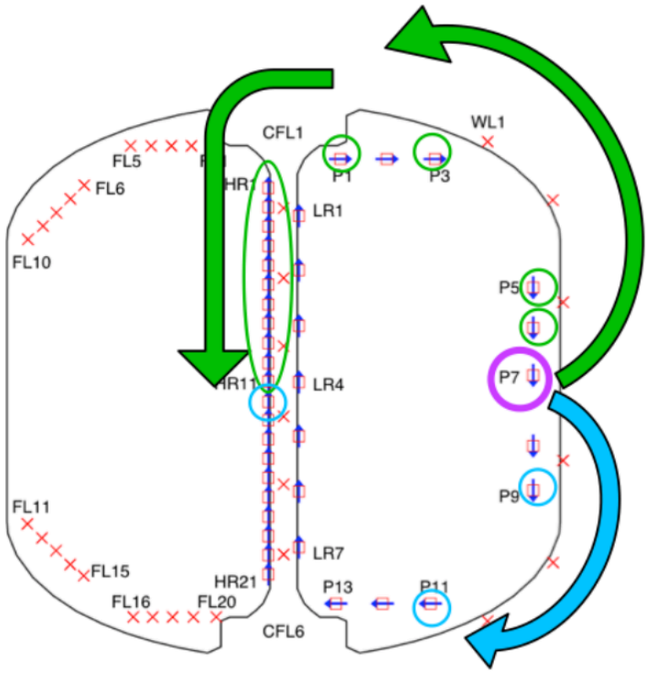


Perry et al., Nuclear Fusion ***58*** *096002 (2018)*

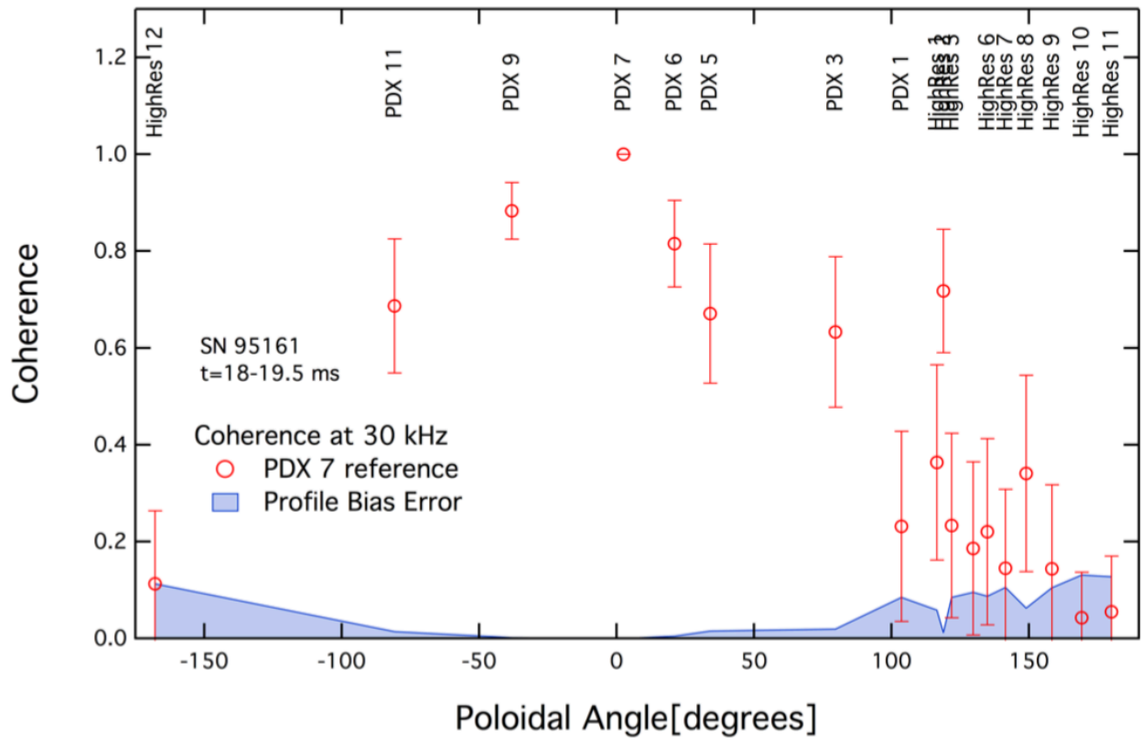
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n = 1 Activity Suggests Unstable Current Stream on Plasma Low Field Side

Tracing Poloidal Coherence from Mirnovs



Poloidal Coherence of n=1 Activity



- Coherence of *n* = 1 mode traced around machine magnetics
- Drop in coherence from LFS to HFS suggests unstable current streams on LFS

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Pachicano, UW MS Thesis (2018)

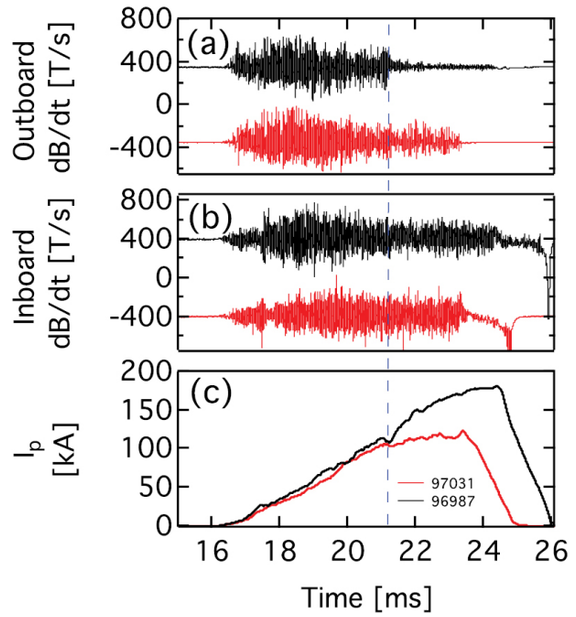
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Operational Regime with Reduced-MHD State

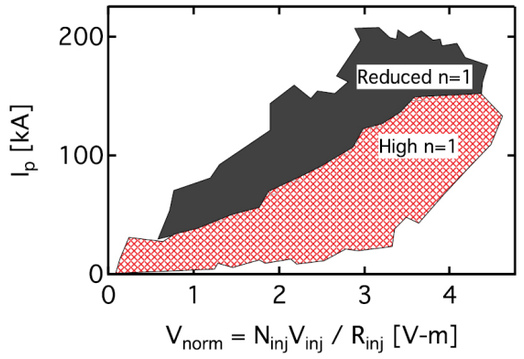
Abrupt Transition to Reduced-MHD State is Observed

- Abrupt MHD transition can lead to improved plasma performance
  - Factor of 10 reduction of $n = 1$ activity on LFS
  - Up to 2x higher I_p realized at fixed V_{LHI}
  - Increased density, sharper edge on imaging
- Sustained discharges without $n = 1$ activity are possible
  - $n = 1$ not required for LHI current drive
  - Suggests other current drive mechanism(s) present
- Mechanism for transition is under investigation
  - $n = 1$ reduction interpreted as stabilization of current filaments on LFS, though it is unclear

New Reduced MHD Regime Improves Performance



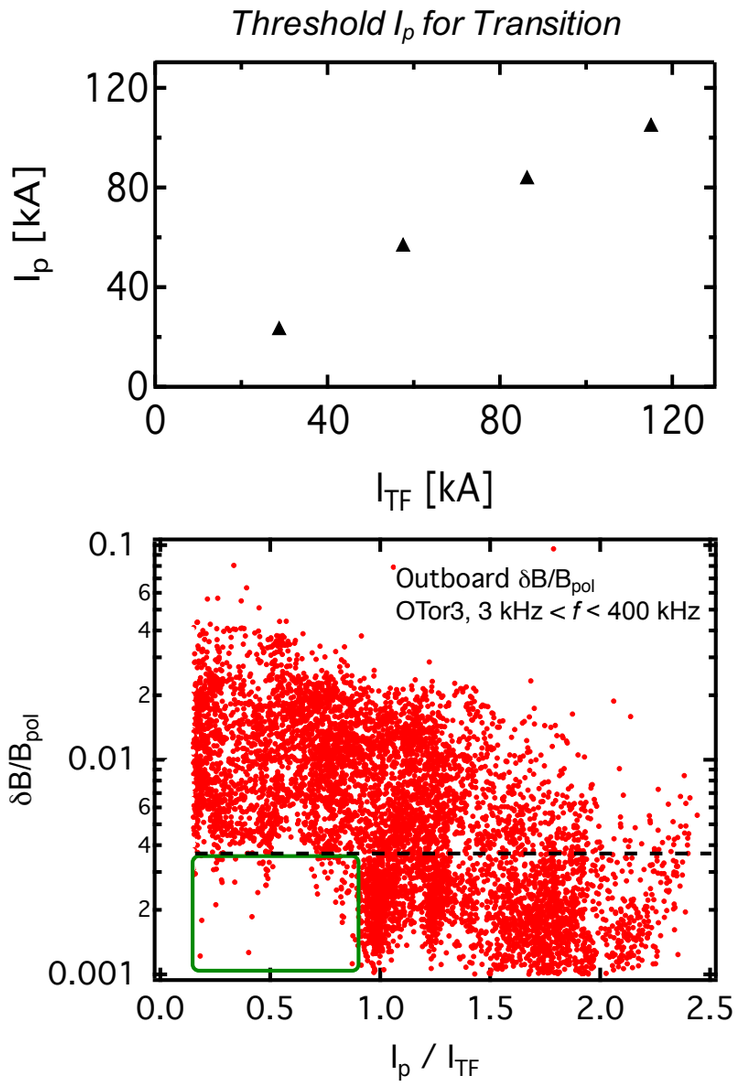
Operating Space for ~8,500 HFS LHI Discharges



*Perry et al., Nuclear Fusion **58** 096002 (2018)*

Adjustment of Experimental Parameters Governs Access to Low-MHD Regime

- Plasma current required to induce MHD transition increases proportionately to toroidal field
- For a given level of B_T, transition occurs above a threshold I_p
  - Primary correlation: $I_p / I_{TF} \gtrsim 1$
- Threshold I_p / I_{TF} lowered by certain factors:
  - Increased vertical flux in divertor regions
  - Increased edge neutral fueling
  - Reduced I_{inj}



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Perry, UW PhD Thesis (2018)

Access to Low-MHD Regime is Restricted at Higher B_T , Contrary to Expectations from Simple Stability Theory

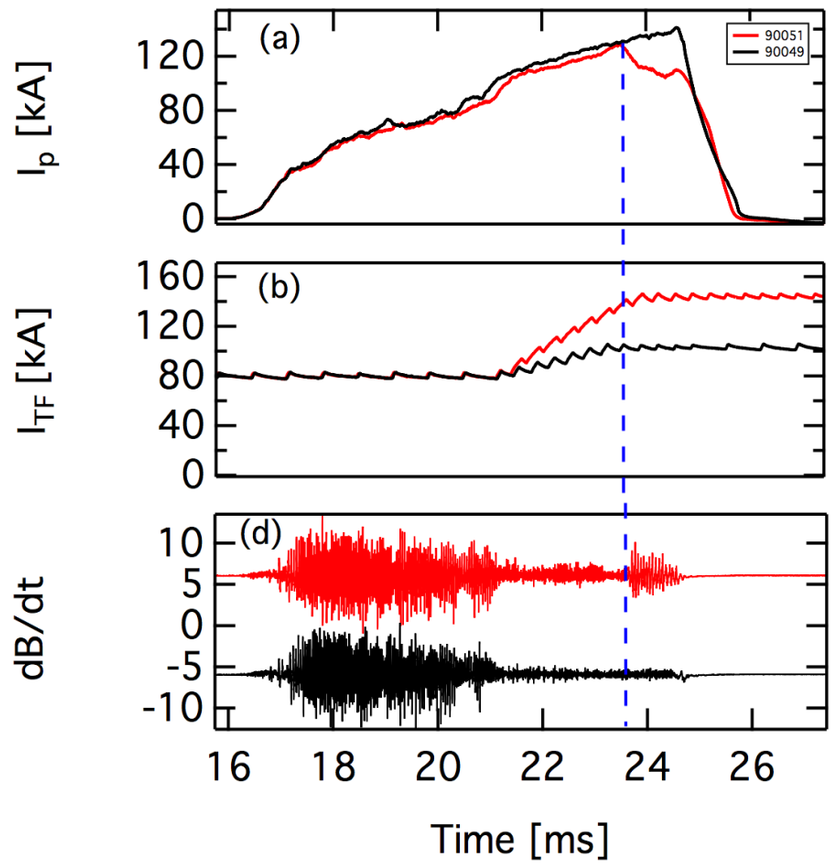
- Kruskal-Shafranov instability condition:

$$\frac{\mu_0 L \cdot I_{inj}}{\left(2\pi a_{inj}\right)^2 |B|} \gtrsim 1$$

- Injected current streams well above this limit for LHI geometry

- Empirical trend for MHD reduction inconsistent with stabilizing effect of |*B*| in theoretical limit
  - Low B_T (low I_{TF}, high I_P / I_{TF}) favorable for reduced MHD
  - Suggests additional stabilizing mechanisms present

Low I_{TF} favorable for reaching reduced-MHD regime



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Several Possible Physical Mechanisms Responsible for Transition Behavior Under Consideration

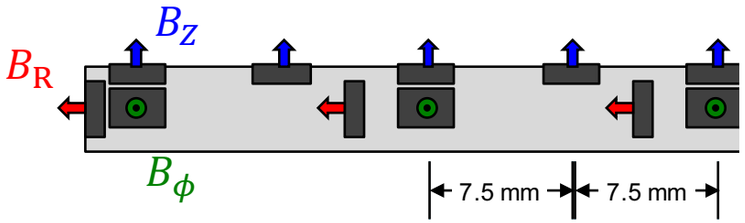
	Mechanism	Consistent	Inconsistent
Kruskal-Shafranov	Crossing stability threshold	I_{inj} dependence	Wrong I_{TF} dependence
Large Filament Separation	Inhibition of Island Coalescence	Correct I_p/I_{TF} dependence	No change with increased stream separation
Filaments Wrap Down Core	Magnetic anchor of filament on HFS	Explains change in I_{DIV} and paramagnetism	No clear I_p/I_{TF} dependence
Min |B| Region	Effect on energetics of kink stability?	Good correlation with conditions for transition	Mechanism unclear
Beam Breakup/Expansion	Larger beam no longer kink unstable	Potentially related to high freq. magnetic activity	No clear I_p/I_{TF} dependence

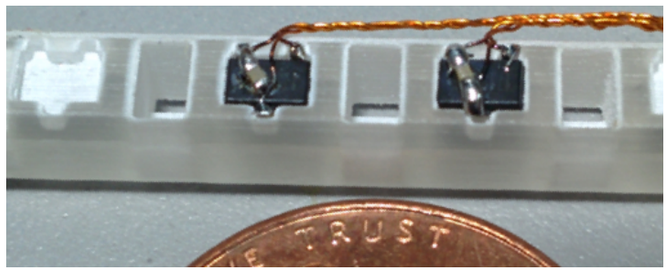
- Internal ***B****(R,t)* measurement useful for exploring some of these possible stabilizing mechanisms

New 3-D Hall Sensor Probe (MRS) to Study Field Structure

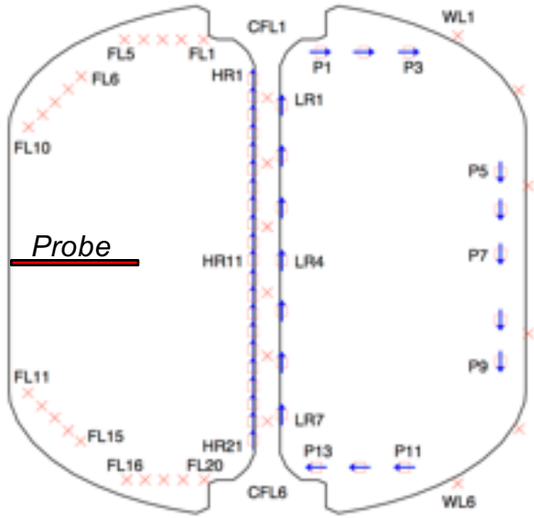
Insertable 3-D Hall Sensor Probe (MRS) to Measure Internal **B**(R,t) Built and Deployed on Pegasus

MRS probe schematic and nominal measurement directs for field-aligned probe

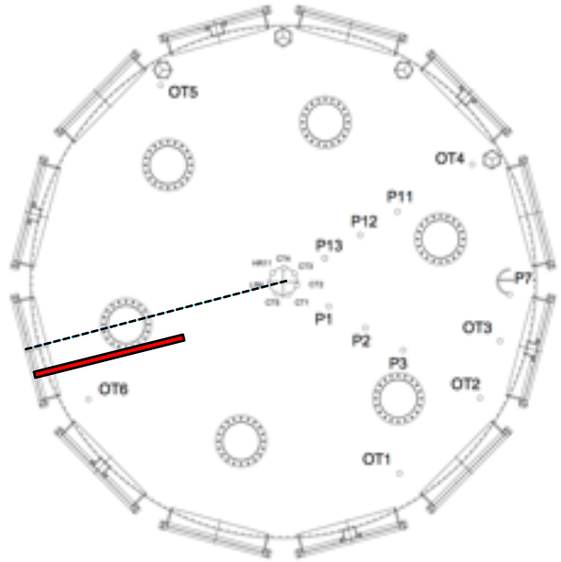




Cross-section



Top-down



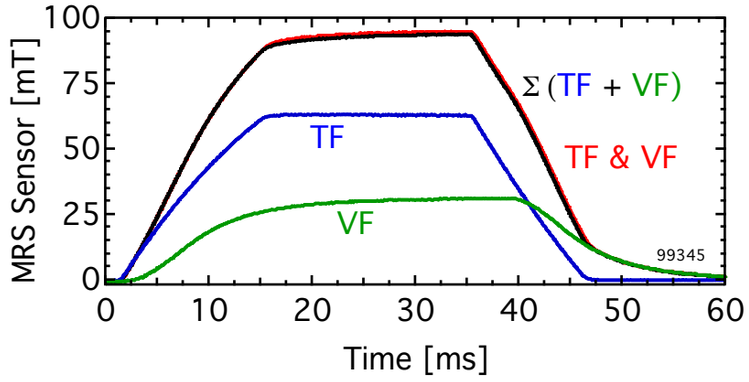
- Commercial, ratiometric Hall effect integrated circuits mounted in 3-D printed frame measure $B_\perp$ normal to sensor
  - No measured cross-field gain nonlinearity
  - Linear field response
  - Temperature independence ($\sim 0.04\%$ / °C)

- 3-D measurements at 8 spatial locations, ΔR = 15 mm
- Additional 7 B_Z sensors: ΔR_{B_Z} = 7.5 mm
- Active length of ~11 cm

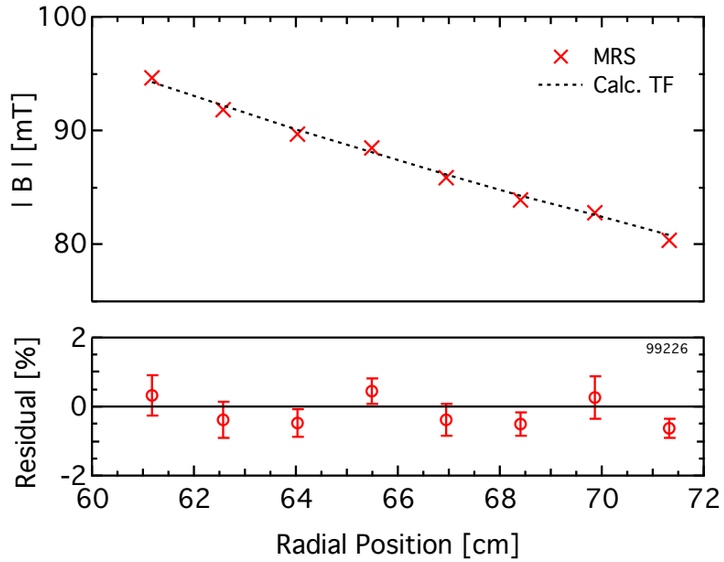
Calibrated Hall Sensors Tested with Vacuum Fields on Pegasus

- MRS probe absolutely calibrated with 3-axis Helmholtz coil
  - Each orthogonal field individually pulsed, sensor voltage measured
  - Individual field components used to generate calibration matrix with each sensor's gain in each direction
  - Cross-field pickup confirmed to be negligible
- Helmholtz calibration tested with vacuum fields on Pegasus
  - Measurements from combined TF and EF shot agree with linear sum of constituents to within 1% accuracy of I_{TF}
  - Perpendicular field nonlinearities negligible
- Calibration cross checked with Pegasus vacuum fields

No effect of cross-fields on sensor gain



Calibrated measurements consistent with Pegasus fields



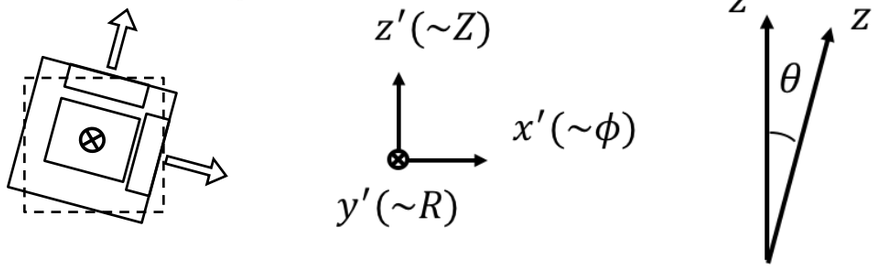
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*Richner et al., RSI **89** 10J103 (2018)*

Fields Measured Perpendicular to Sensors are Mapped to Machine Coordinates

Axial Misalignment Correction

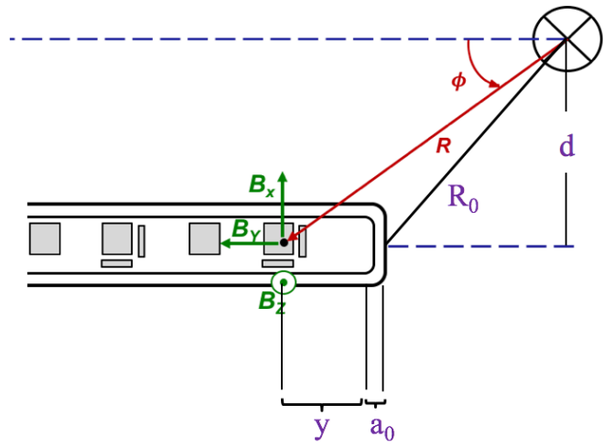
- Find angle for rotation transform that minimizes $|B_z'|$ in TF-only shot and $|B_x'|$ in EF-only shot:



- Transform to rotated frame:

$$\begin{bmatrix} B_x' \\ B_y' \\ B_z' \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix}$$

Mapping to Machine Coordinates

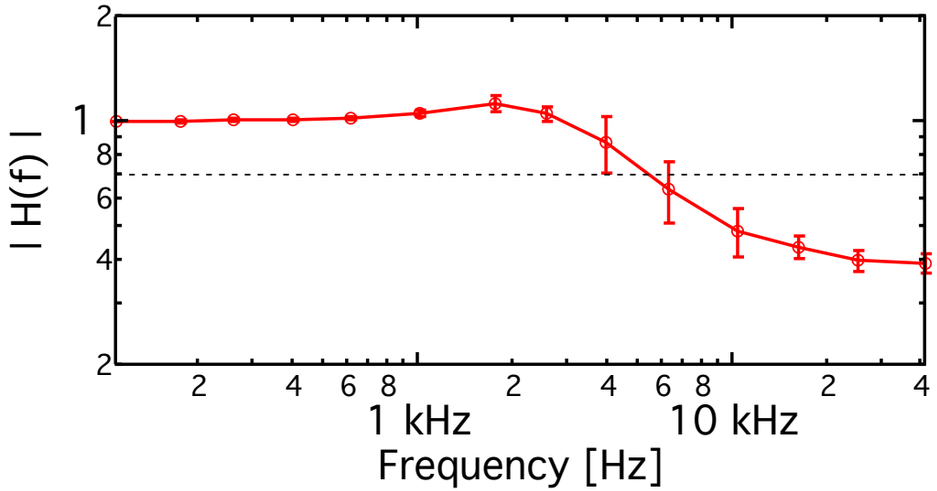


- Machine coordinates R and ϕ depend on known constants and y
- Transform to R, Z, ϕ:

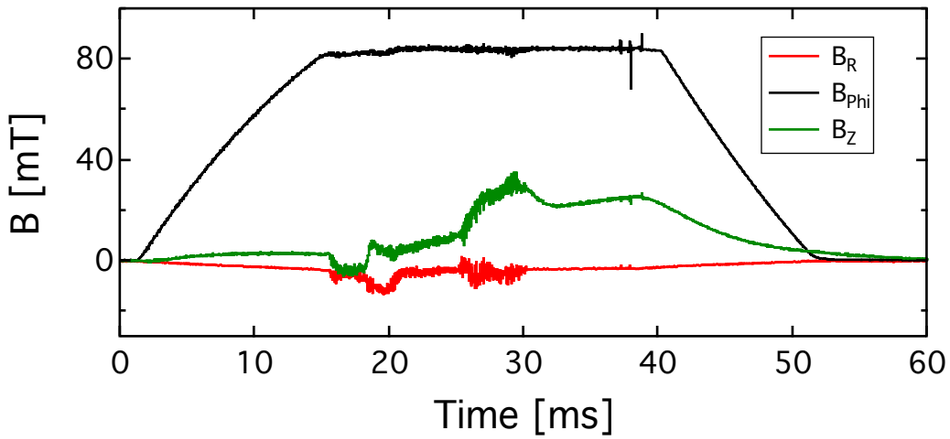
$$\begin{bmatrix} B_R \\ B_\phi \\ B_z \end{bmatrix} = \begin{bmatrix} -\sin\phi & \cos\phi & 0 \\ -\cos\phi & -\sin\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} B_x' \\ B_y' \\ B_z' \end{bmatrix}$$

MRS Frequency Response Allows for Investigation of f < 50 kHz Dynamics

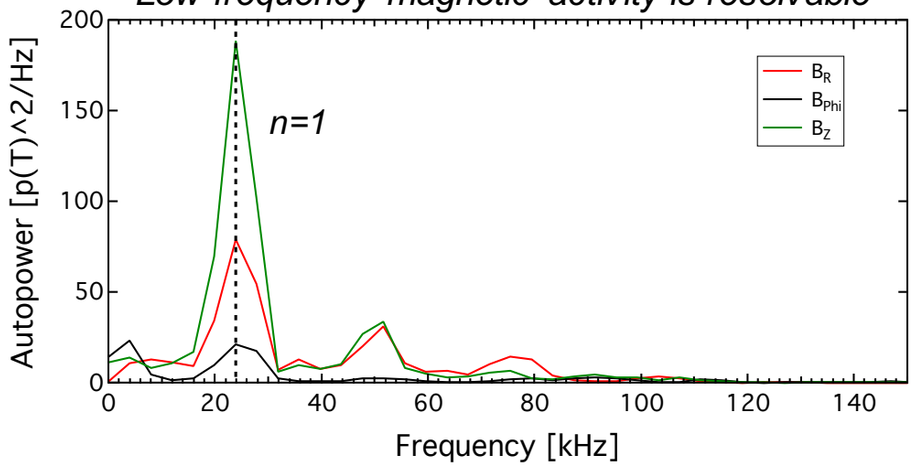
- Helmholtz coil test shows flat frequency response to ~5 kHz
- Frequency response allows for low-frequency features to be resolved
  - $n = 1$ mode associated with injected current streams is observable
  - Supports equilibrium field structure studies



Calibrated fields from one sensor triplet



Low-frequency magnetic activity is resolvable

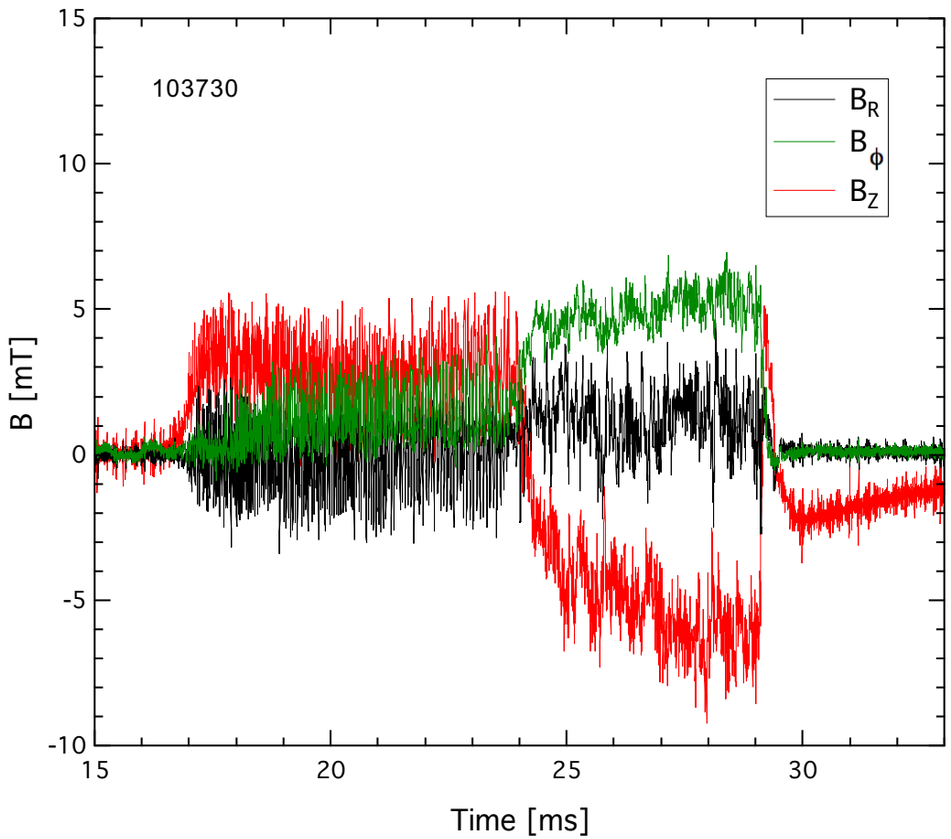


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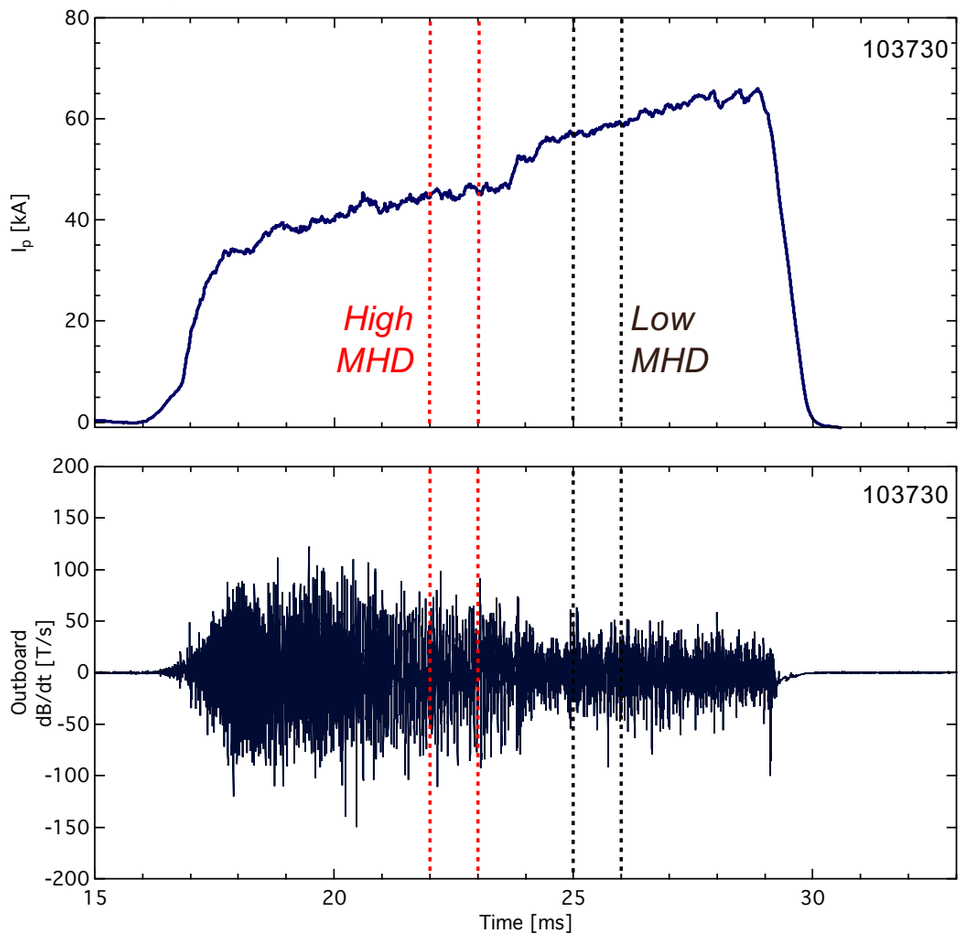
MRS Probe Used to Characterize Magnetic Structure

Probe Used to Characterize Magnetic Activity in Discharges Featuring MHD Transition

Vacuum-corrected, calibrated fields from one MRS sensor triplet (R_{MRS} = 59 cm)



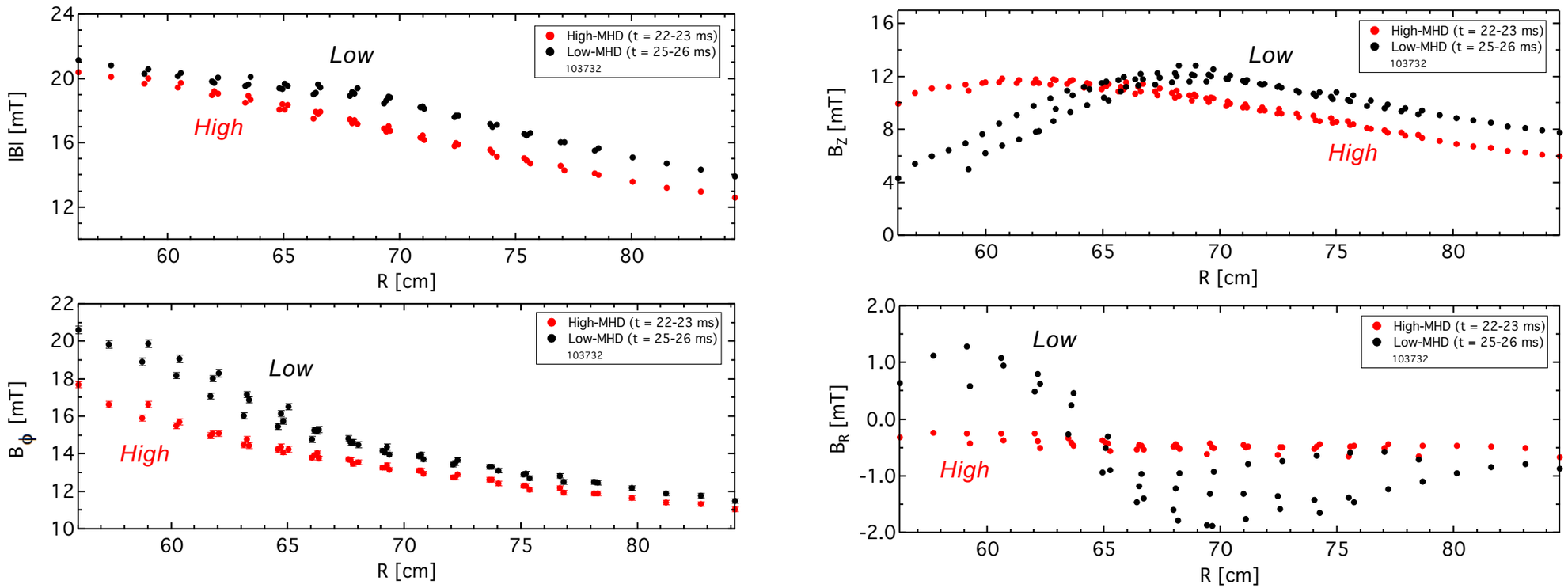
I_p and LFS Mirnov MHD for representative shot



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Probe Array Shows Detailed Magnetic Structure in Edge Region

B(*R,t*) Comparisons Between High-MHD and Low-MHD Phases

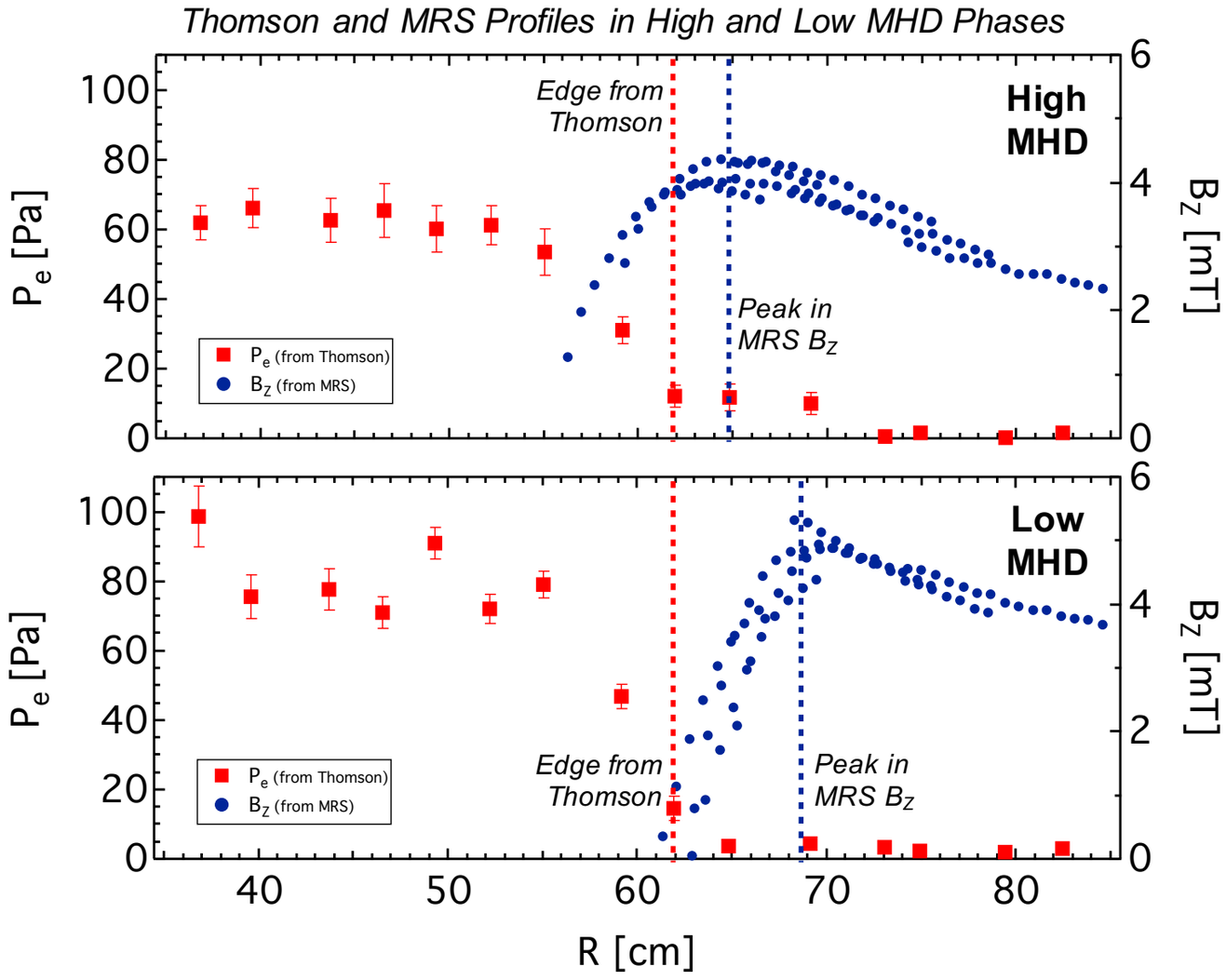


- B_ϕ changes consistent with diamagnetic loop
- Total $|B|$ similar, but change in $\Delta|B|$ at inner radii
- B_R shows complex structure in low-MHD phase

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Measurements Show Combined I_p and I_{inj} Contributions at Edge

- Peak and zero crossing of $B_Z(R)$ suggest tokamak current surrounded by injected current sheet
- Edge from Thomson profile differs from peak inflection point from MRS
- Near-zero pressure in inferred stream region
- Suggestive of strongly stochastic transport in edge



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Conclusions

- Sustainment of LHI current drive in absence of $n = 1$ activity during low-MHD operating regime suggests other current-drive mechanism(s) present
- Internal $\boldsymbol{B}(R,t)$ measurement useful for exploring certain stabilizing mechanism(s) responsible for MHD transition that are under consideration
- New 3D Hall Sensor Probe (MRS) built and deployed on Pegasus to study equilibrium magnetic field structure and current stream dynamics
- MRS used to analyze field structure during discharges featuring MHD transition
  - Notable change in $\Delta|B|$ at inner radii observed between high and low MHD phases
  - Complex B_R structure observed during low-MHD phase
- $B_Z(R)$ profile shows combined I_p and I_{inj} contributions at plasma edge
  - Field structure suggests system comprised of tokamak current surrounded by injected current sheet
  - Comparison to Thomson pressure profiles suggests presence of strongly stochastic transport in edge region

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