Investigating High Frequency Magnetic Activity During Local Helicity Injection on the PEGASUS Toroidal Experiment

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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”

Investigating High Frequency Magnetic Activity During LHI on PEGASUS

LHI Current Drive	Transition to Reduced MHD State	New Magnetics Probe	High Frequency Magnetic Content	Redistribution of Magnetic Power
Local Helicity Injection Routinely Used for Non-Solenoidal Startup on Pegasus	A New Operational Regime with Reduced MHD	A New Magnetic Diagnostic: the Magnetic Radial Array (MrA) Probe	Significant High Frequency Activity Seen in LHI Plasmas	Transition Localizes Power to Plasma Interior
NIMROD Describes a Reconnection-Based Current Drive Mechanism	In Low MHD State, $n = 1$ Mode Absent	MrA Probe Provides High Bandwidth, Low Noise Measurement	High Frequency Power Increases in Low MHD Mode	Magnetic Power Shifts to Higher Frequencies
Measurements on Pegasus consistent with NIMROD model for LFS LHI	A Range of Experimental Parameters Affect Access to Low MHD State	MrA Development and Construction	Spectral Peak at ~ 600 kHz	Summary and Conclusions
T_i Associated with High Frequency Content	Physical Interpretation of MHD Reduction	MrA Deployed on Pegasus	High Frequency Peak Has Coherent Structure	Future Work

LHI Current Drive

State with Reduced MHD

New Insertable Magnetics Probe

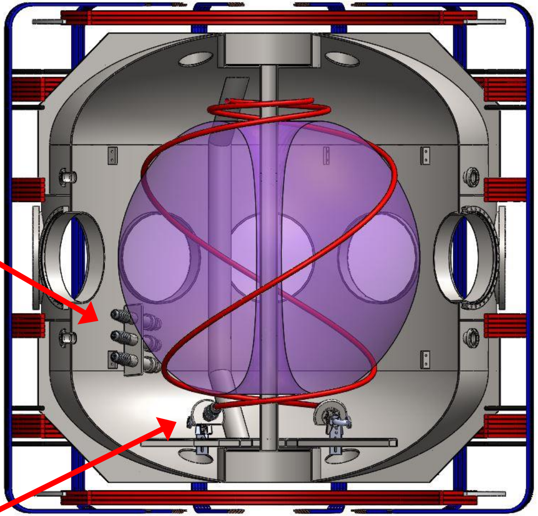
High Frequency Magnetic Activity

Redistribution of Magnetic Power

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

Low Field Side (LFS)

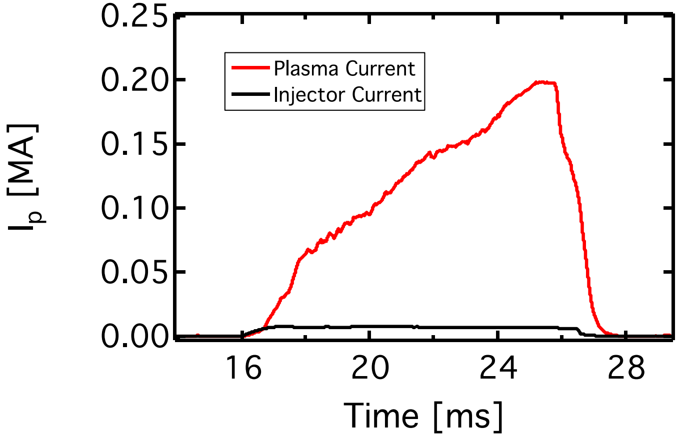
Local Helicity Injectors



High Field Side (HFS)

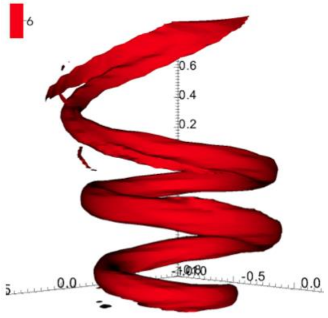
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .23
$B_{t,0}$ (T)	0.1-0.2
τ_{shot} (s)	≤ 0.025

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

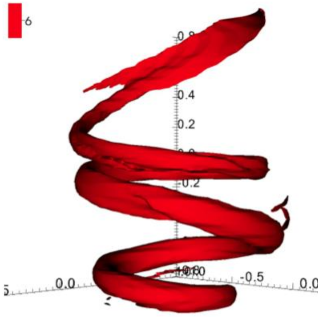


- Current extracted from local injectors
- Unstable current streams relax to form tokamak-like state

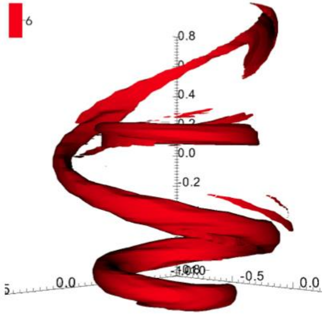
NIMROD Describes a Reconnection-Based Current Drive Mechanism



1. Streams follow field lines

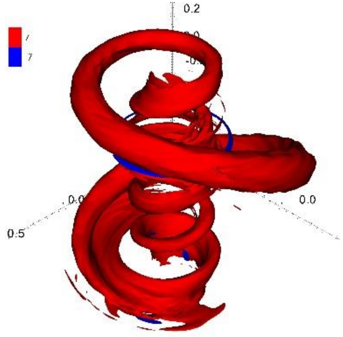


2. Adjacent passes attract



3. Reconnection pinches off current rings

Sustainment Phase

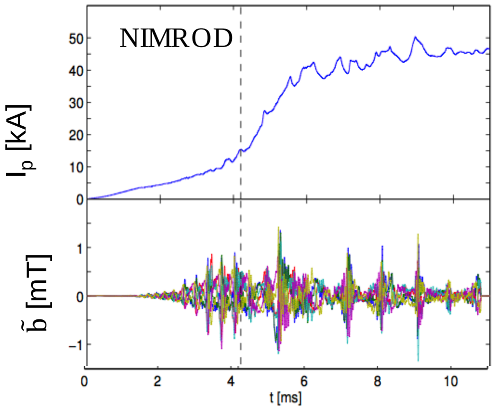


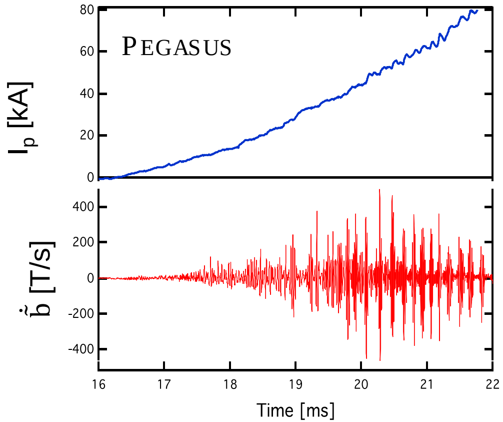
NIMROD Simulation [O'Bryan PhD 2014]

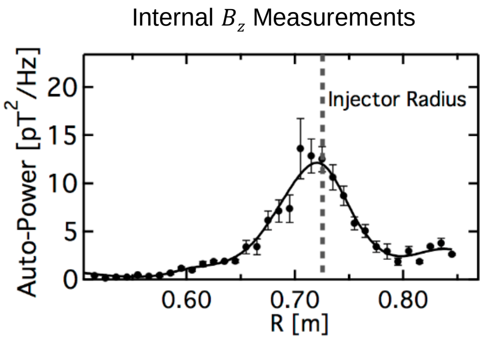
- Reconnection of current streams leads to I_p growth
  - Discrete reconnection events pinch off current rings
  - Rings move inward, building up poloidal flux
  - Associated with $n = 1$ magnetic activity
  - NIMROD indicates this process happens throughout the discharge

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

Measurements on PEGASUS Consistent with NIMROD model for LFS LHI



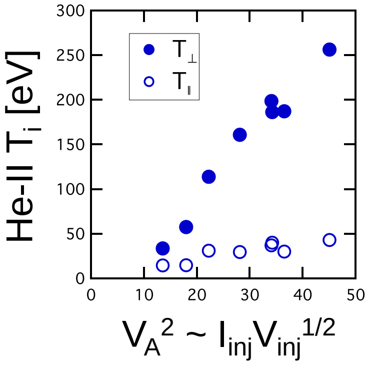




- NIMROD:
  - Bursts of $n = 1$ outboard activity associated with ring formation
- PEGASUS:
  - Jumps in toroidal current associated with $n = 1$ events
  - Frequency range in qualitative agreement with NIMROD prediction
  - Internal magnetic measurements show power at injector radius

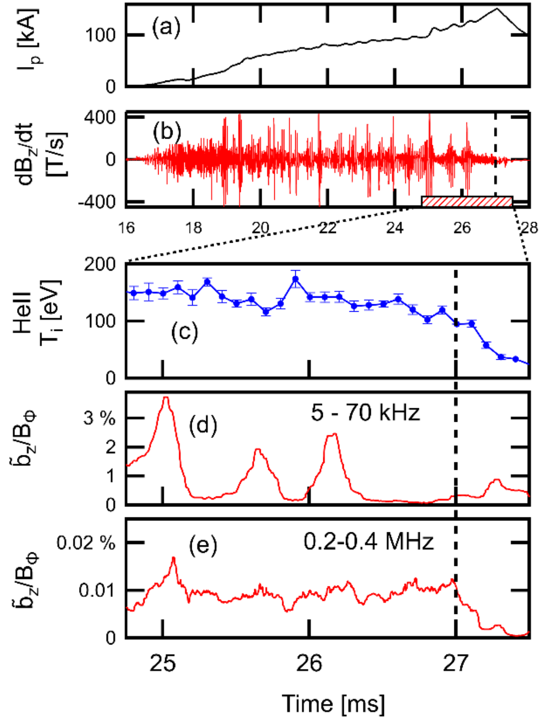
Reconnection Driven $T_i > T_e$ Associated with High Frequency Activity

- Anisoptropic ion heating in injector streams consistent with two-fluid reconnection
  - Channel $T_{i,\perp} > T_e$
  - $T_{i,\perp} \sim V_A^2$ of injected current streams



- $T_i(t)$ correlated with continuous, high frequency activity
  - Suggests considering short wavelength reconnection as another CD mechanism

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



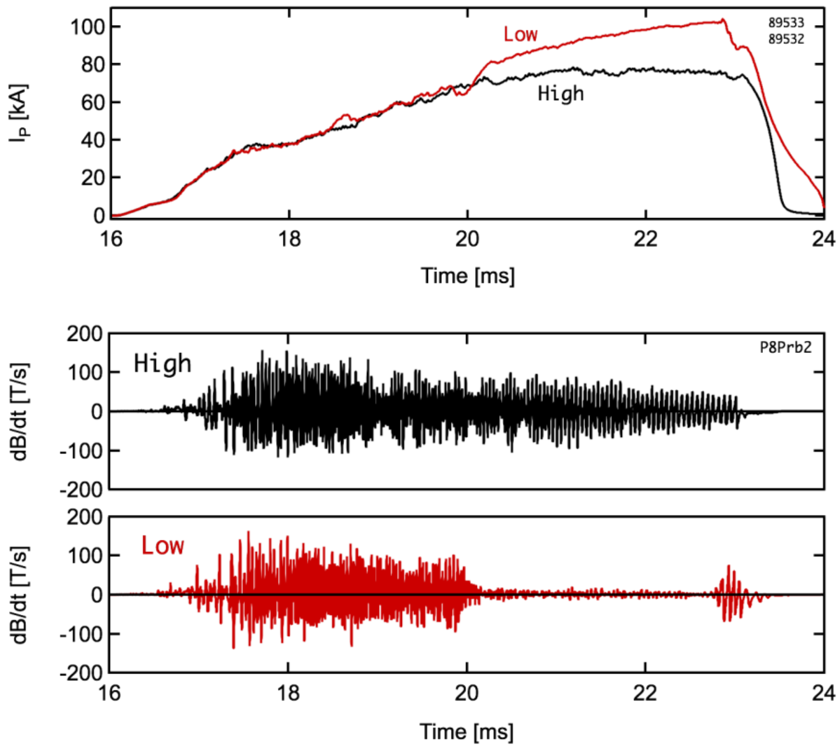
M.G. Burke, et al. Nucl. Fusion ***57*** *076010 (2017)*

Unexpected MHD Reduction Can Occur During HFS LHI

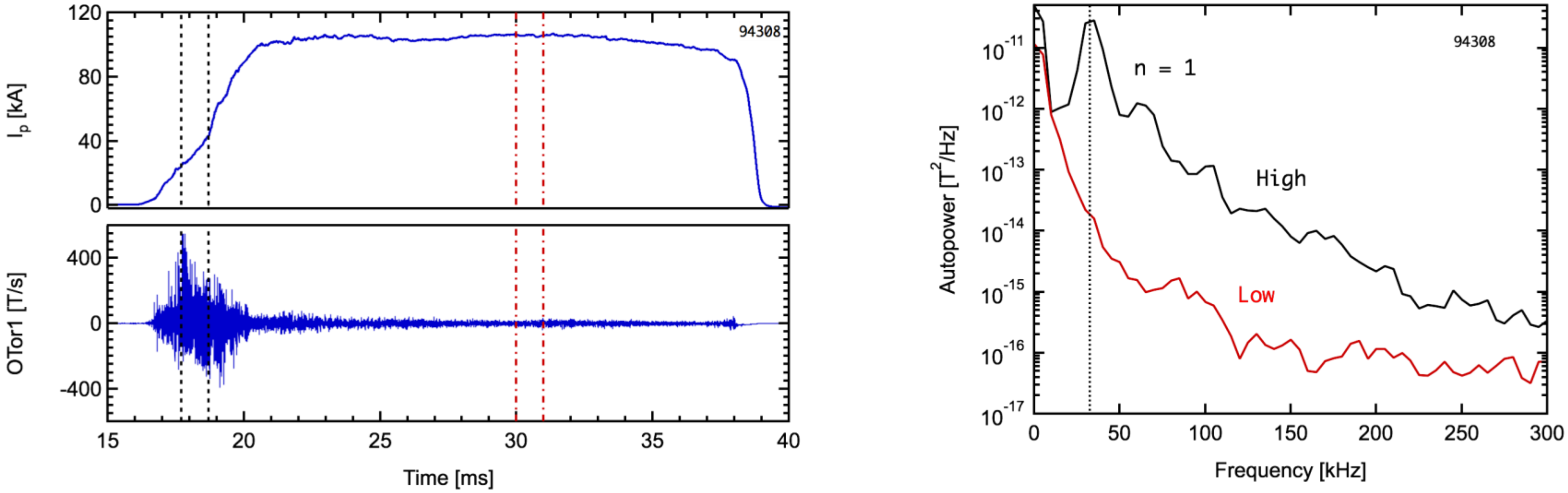
- Low MHD mode characterized by:
  - Rise in plasma current
  - Fast, $> 10\times$ reduction of dB/dt on outboard Mirnovs

- Can have back-transitions and/or "bursty" behavior during low MHD state

- Note: "Low" MHD amplitude still $\gtrsim 10\times$ larger in comparison to ohmic



LHI Current Sustained in Low MHD State without $n = 1$ Activity

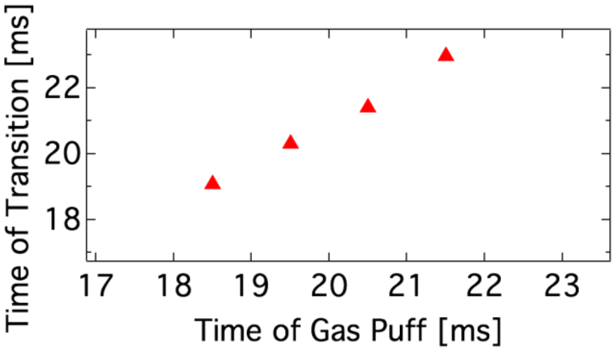


- I_p Sustainment without $n = 1$ → additional current drive mechanism(s)

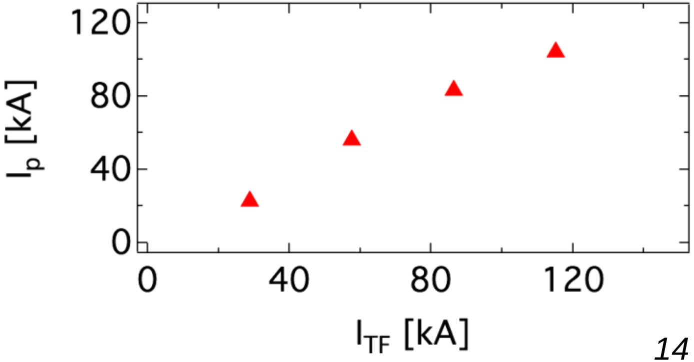
A Range of Experimental Parameters Affects Access to Low MHD State

- Access improved by:
  - Increased neutral fueling
  - Stronger vertical shaping
  - Higher I_p/B_t
  - Reduced current per injector

Neutral Fueling Changes Transition Time



Plasma Current at Time of Transition



Several Hypotheses for MHD Reduction under Consideration

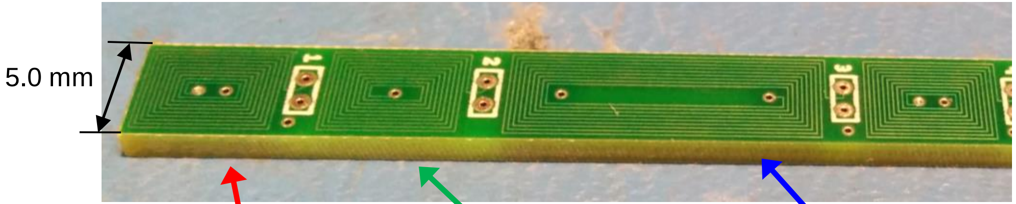
- Previous work: High MHD $n = 1$ mode consistent with line-tied kinking of current streams

- Absence of $n = 1$ in low MHD → stabilization of kink

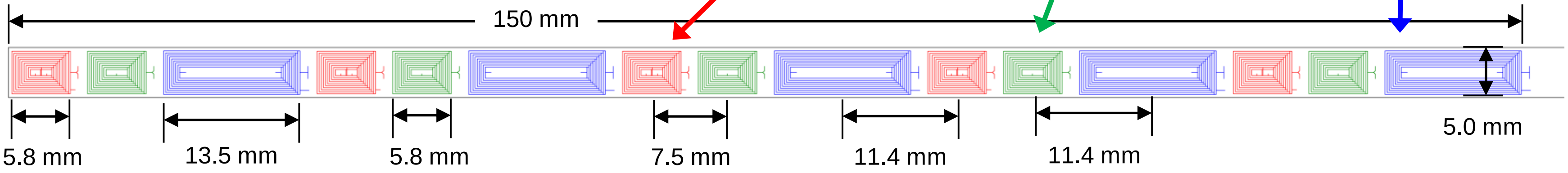
- Current hypotheses:
  - Change in boundary conditions in upper divertor region → doubly line tied kink
  - Magnetic anchor
  - Stabilization through coupling with highly conductive plasma edge
  - Expansion of the current channel via turbulent process

A New, High Frequency $\dot{B}$ Diagnostic: Magnetic Radial Array (MrA) Probe

- Insertable probe
- 15 channel $\dot{B}_z(R,t)$
- Coils formed by traces in PCB
- Different trace geometries balance A_{eff} and frequency response



Type A	Type B	Type C
$A_{eff} = 3.52\ \text{cm}^2$	$A_{eff} = 1.80\ \text{cm}^2$	$A_{eff} = 9.55\ \text{cm}^2$
4 layer	2 layer	4 layer



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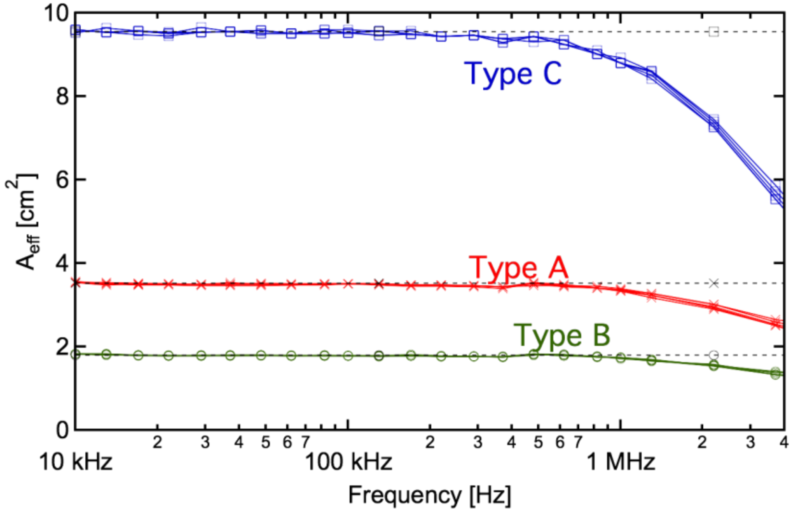
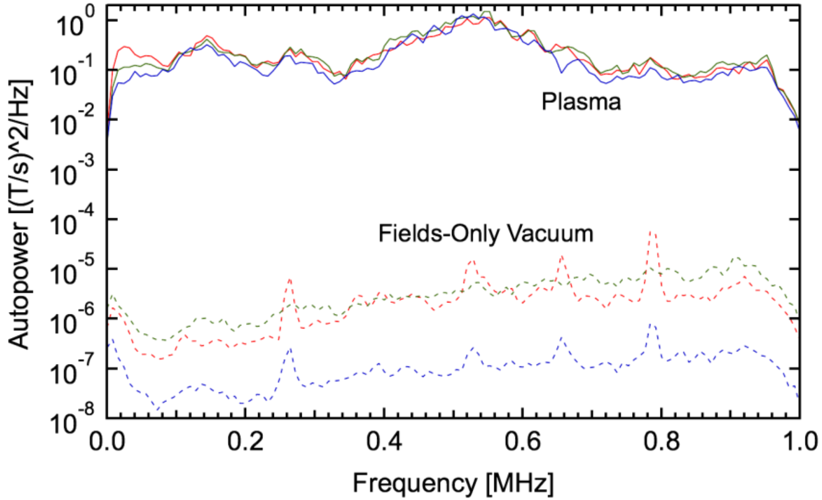
MrA Probe Provides High Bandwidth, Low Noise Measurement

A_{eff} Calibration



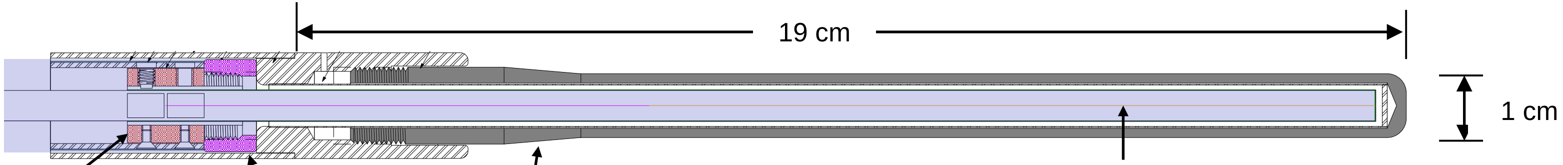
Signal to Noise Comparison in LHI Plasma



- Helmholtz coil measurements verify flat response to ~ 1 MHz

- High signal-to-noise
  - Shielded assembly
  - Short cable run
  - Fully differential digitization

MrA Utilizes Existing Armor and Drive Assembly of Hall Array Probe

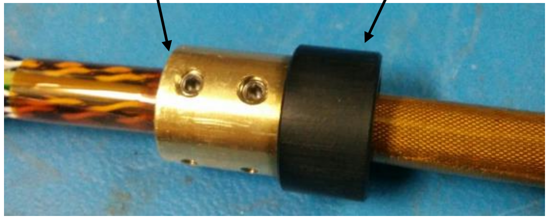


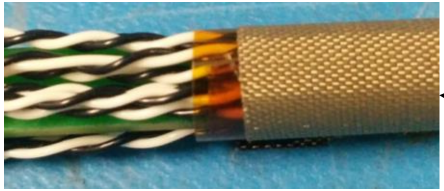
Shield Transition and PCB Mount

Delrin Bushing

Carbon Probe Armor

Probe Internals (airside)





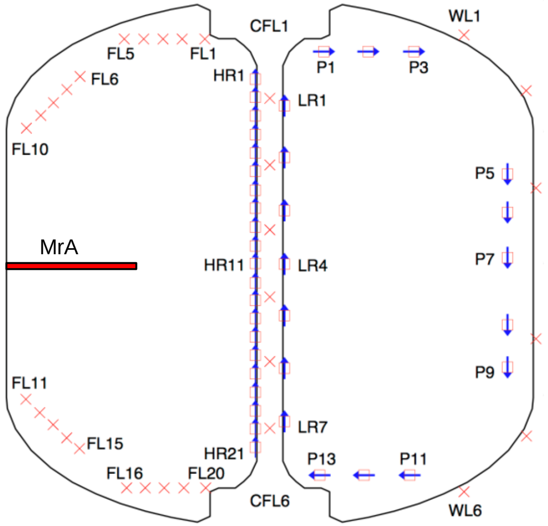
Thin (4 mil) Conductive Tape (electrostatic shield)

Twisted-pair flying leads to minimize pickup

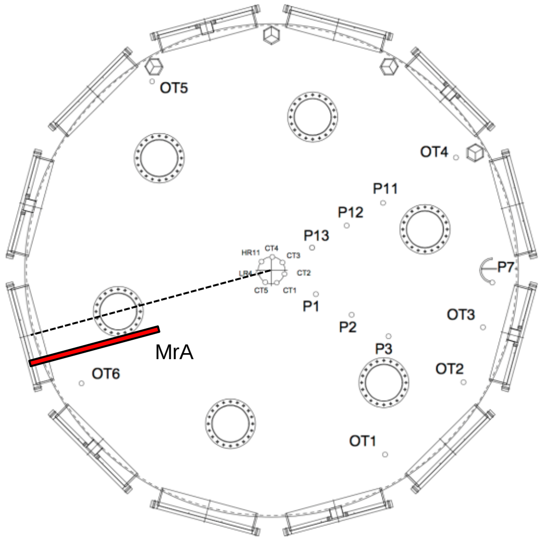
Bongard et al., Rev. Sci. Instr. ***81*** *10E105 (2010)*

MrA Deployed on PEGASUS

PEGASUS Magnetic Diagnostic Layout



Cross-section



Top-down

- Insertion range:

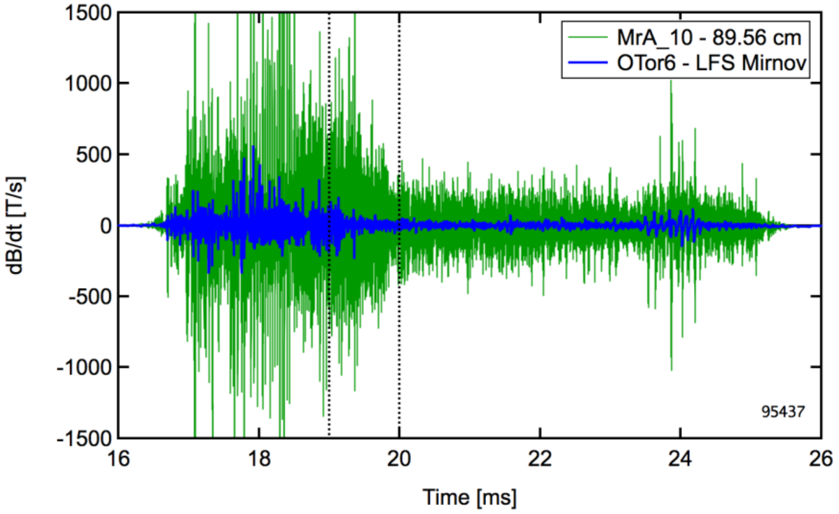
  $R = 54 - 90$ cm,

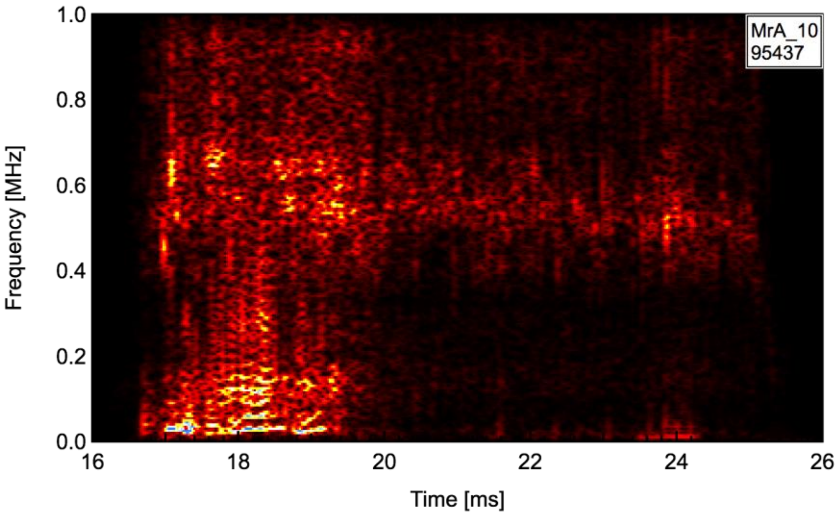
  $Z = 0$

- Signals digitized with D-tAcq ACQ132

- Rotatable mount for precise field alignment

MrA Shows Significant High Frequency Activity in LHI Plasmas





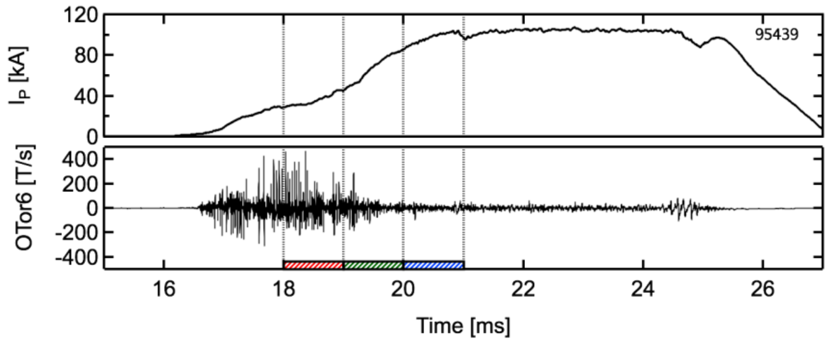
- Low frequency $n = 1$ peak
- Broad peak at ~ 600 kHz

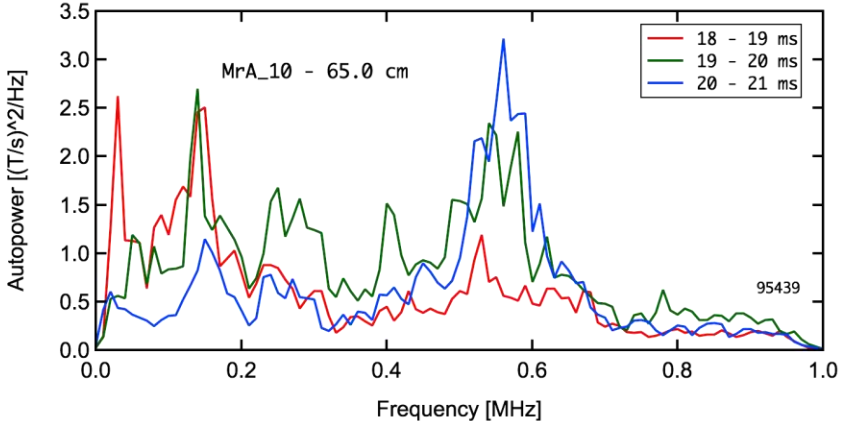
High Frequency Activity Increases After Transition to Low MHD

- In high MHD:
  - Low frequency, $n = 1$ peak
  - Peak at 150 kHz
  - Small, broad peak at ~ 570 kHz

- In low MHD:
  - Low frequency peak strongly reduced
  - 150 kHz peak decreases in magnitude
  - Peak at 570 kHz substantially increases

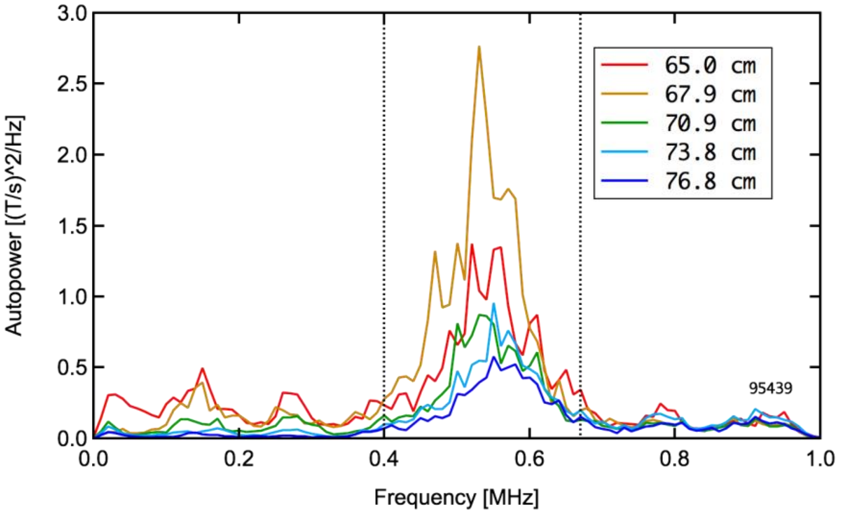
- Magnitude of this effect increases as move into plasma edge



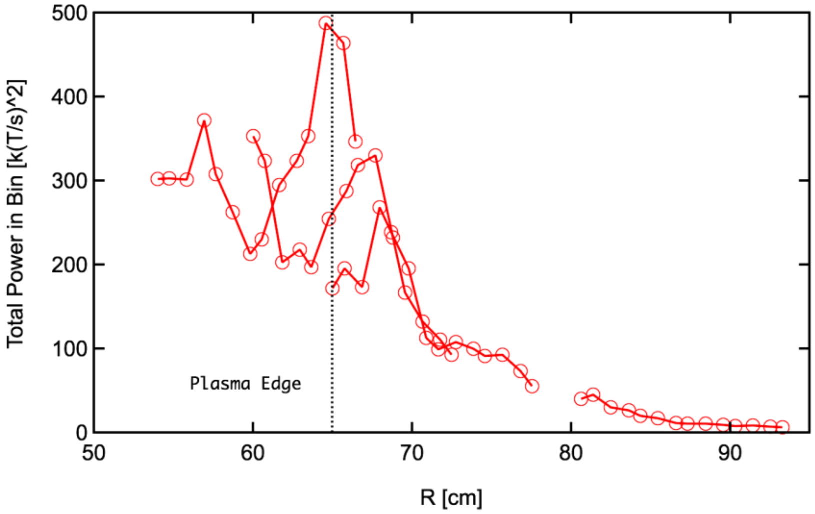


570 kHz Peak Localized to Plasma Edge in Low MHD Phase

Autopower Spectra in Low MHD Phase



Total Autopower from 400 - 670 kHz



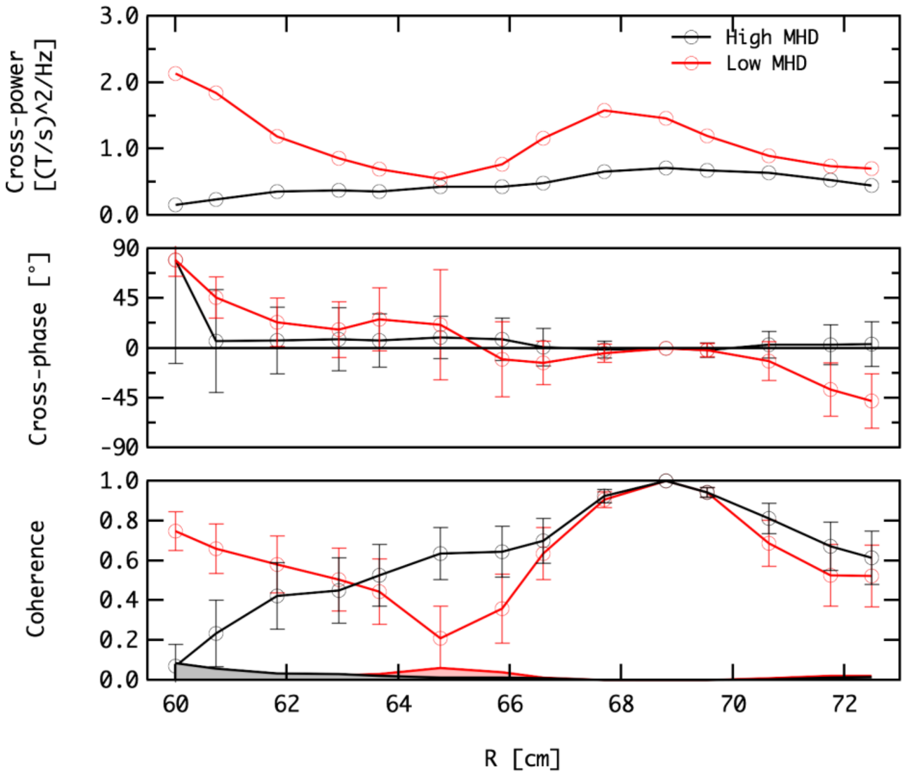
- Amplitude of high frequency peak has strong spatial dependence

- Summing power about the 570 kHz Peak:
  - Power largest near plasma edge
  - Sharply falls off as move outside plasma boundary → short wavelength?

Preliminary Analysis Suggests 570 kHz Peak has Coherent Structure

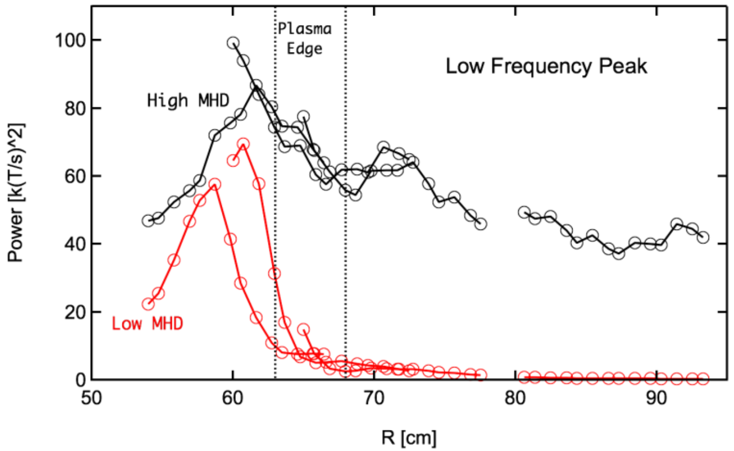
- Cross-power
  - Broad peak in high MHD phase
  - Increase in low MHD phase
- Cross-phase
  - Flat in high MHD phase
  - Possible structure in low MHD phase
- Coherence
  - > 0.5 over several probe channels, in both low and high MHD phases

Cross-Power,-Phase, and Coherence at 570kHz vs R

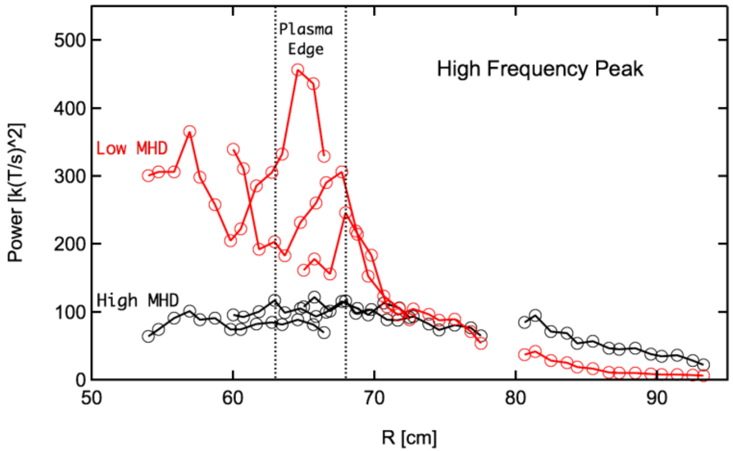


Transition Localizes Power to Plasma Interior

Total Autopower from 0 - 60 kHz



Total Autopower from 460 - 720 kHz



- Low Frequency: 0 – 60 kHz
  - High MHD: Broad radial extent, peaks interior to plasma edge
  - Low MHD: Concentrated to a ~ 10 cm range, falls off rapidly beyond this
- High frequency: 460 – 720 kHz
  - High MHD: Nearly flat profile
  - Low MHD: Reduction beyond plasma edge, but large increase inside

Summary and Conclusions

- In some LHI discharges, prominent $n = 1$ mode observed, consistent with NIMROD model of filament merging and reconnection
- Recent LHI experiments demonstrate mode of operation with current growth/sustainment in absence of $n = 1$ activity
  - Suggests additional physics / current drive mechanism(s) at play
- New magnetics probe, MrA, developed to investigate high frequency content
- Significant high frequency activity is present in LHI
  - Power is more localized during low MHD phase → shift to small wavelength?
  - Peak at 570 kHz observed that increases in amplitude during low MHD phase