Investigating the Role of High Frequency Magnetic Activity in Local Helicity Injection Dynamics

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PEGASUS Toroidal Experiment

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Investigating the Role of High Frequency Magnetic Activity in Local Helicity Injection Dynamics

LHI is a Promising Technique for Non-Inductive Tokamak Startup	Three Main Magnetic Signatures are Observed During LHI			Summary
Local Helicity Injection Is Routinely Used for Non-Solenoidal Startup on PEGASUS	NIMROD Describes Current Drive Characterized by Bursts of Low Frequency, $n = 1$ Activity	Ubiquitous Spectral Feature at ~600 kHz Observed During LHI	Broadband Continuum Observed During LHI with Varying Power Laws	Summary of Magnetic Activity Observed During LHI
Understanding Magnetic Fluctuation Activity During LHI Is Critical for Scaling to Future Devices	$n = 1$ Mode Consistent with Line-Tied Kinking of Current Stream	Feature has been Isolated to Injector Arc and/or Current Streams	Different Frequency Bands Exhibit Different Propagation Behavior	Open Questions
Theory and Experiment Indicate Importance of Magnetic Fluctuation Activity during LHI	Operational Regime Found in High Field Side LHI with Sustained Current Drive in Absence of $n = 1$ Mode	Similar Fluctuations also Observed on Injector Voltage Measurements	Continuum has Coherence Lengths of L_R~1 cm, L_ϕ ~10 cm	Future Work
Insertable Magnetic Probes Deployed to Study Magnetic Activity	Indications of Shift to Short-Wavelength Activity in Reduced MHD State	Experimental Observations Suggest Feature is an Arc and/or Beam Instability	Investigating Reconnection & Turbulence as Source of Continuum Feature	

Abstract

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Local Helicity Injection (LHI) uses biased plasma arc sources at the plasma edge for non-solenoidal tokamak startup. Understanding the magnetic activity present in LHI and its scaling could prove crucial for applying this technique to future devices. Internal magnetic measurements on the Pegasus ST show three main features are present in LHI: a ~20–40 kHz peak from n = 1 line-tied kink motion of the injector current streams; an intermediate region near 0.6 MHz with higher fluctuation power; and broadband turbulence for f < 3 MHz A novel LHI regime is found at low $B_T \leq 0.075$ T where the n = 1 activity is suppressed, power at frequencies f > 0.1 MHz increases, and current drive efficiency is improved. This suggests that high-frequency activity could play a critical role in the current drive process. To investigate this, experiments to characterize and identify the observed activity are underway. Discharges with only the LHI current streams isolate the ~ 0.6 MHz feature to the injector arc and show sensitivities to injector voltage and/or current and magnetic field strength, suggestive of arc and/or kinetic instabilities. Experiments to determine the characteristic length and time scales of the broadband turbulence are underway.

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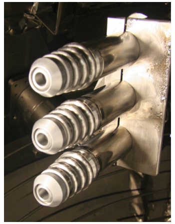
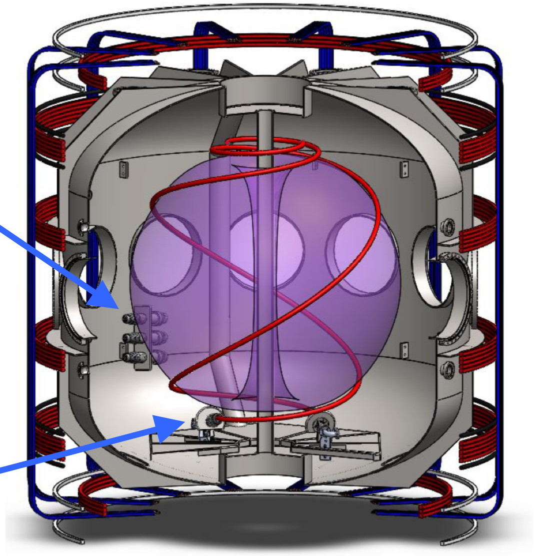
LHI is a Promising Technique for Non-Inductive Tokamak Startup

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

LFS Injectors



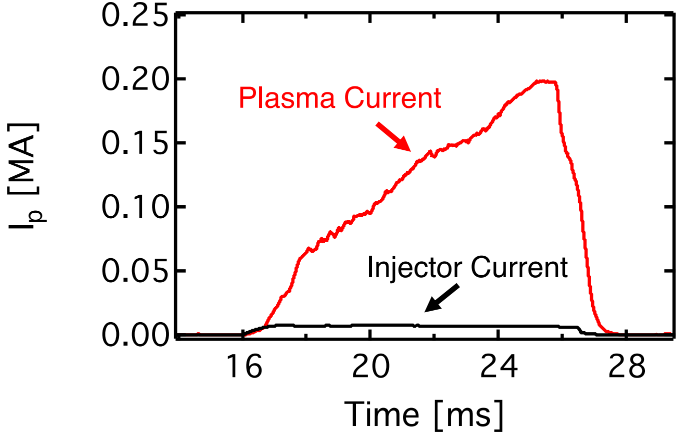


HFS Injectors

Pegasus Parameters

A	1.15 – 1.3
R [m]	0.2 – 0.45
I_p [MA]	$\leq$ 0.25
B_T [T]	$<$ 0.15
τ_{shot} [s]	$\leq$ 0.025

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



- Edge current extracted from injectors
- Relaxation to tokamak-like state via helicity-conserving instabilities

Understanding Magnetic Fluctuation Activity During LHI Is Critical for Scaling to Future Devices

- Studies of the magnetic activity present during LHI is motivated by:

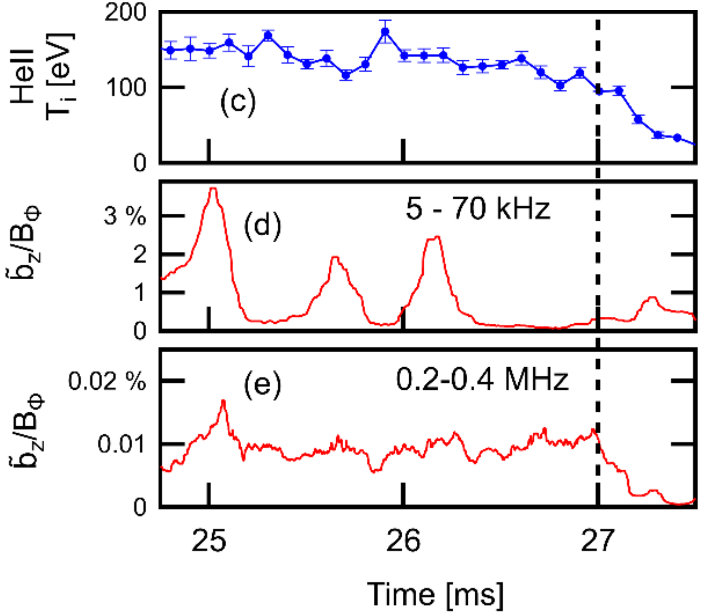
- Current drive
  - What physical mechanism(s) drive current in LHI dynamics?
  - How does the current drive relate to the observed magnetic fluctuations?
  - Can better understanding of the mechanism(s) be leveraged to improve the efficiency of LHI current drive?
  - How would the current drive scale to next-step devices?

- Stability
  - Are there any instabilities that could be potential show-stoppers for scaling LHI to high field and/or current?

Theory and Experiment Indicate Importance of Magnetic Fluctuation Activity during LHI

- NIMROD simulations suggests large scale reconnection events associated with low-frequency $n = 1$ activity as a current drive mechanism
- Reconnection-driven $T_i(t)$ correlated with continuous, high frequency activity (> 200 kHz)
- An operational regime has been found with sustained current drive and greatly reduced low frequency activity

Reconnection ion heating correlated with high-f MHD fluctuations

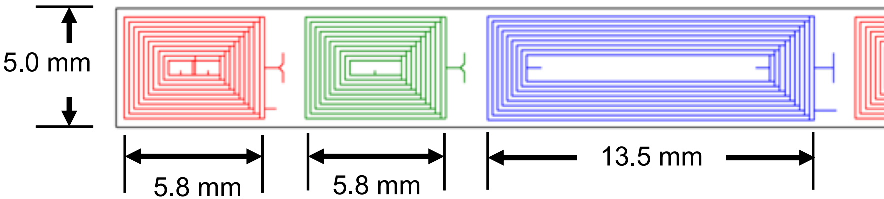


M.G. Burke et al., Nucl. Fusion **57** 076010 (2017)

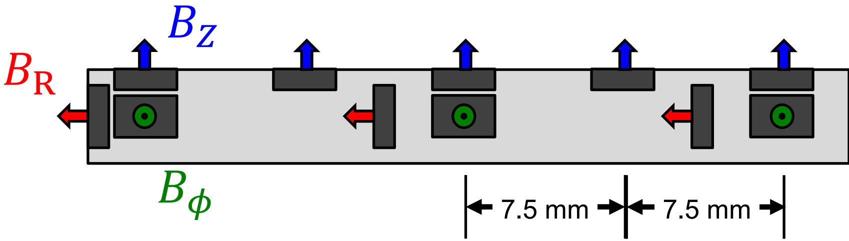
Insertable Magnetic Probes Deployed to Study Magnetic Activity

- MRA – $\dot{B}_Z(R)$ array
  - 15 channels, $\Delta R \sim 1$ cm
  - Calibrated transfer function to ~ 6 MHz
- MRS – Hall sensor array
  - 3D $\boldsymbol{B}(R)$ at 8 channels, $\Delta R = 1.5$ cm
  - 7 additional $B_Z(R)$ at intermediate R
- Position adjustable along PEGASUS midplane
  - $R = 54 - 100$ cm, $Z \sim 0$ cm
  - Common, remotely translatable mechanical assembly
  - Carbon armor

MRA Coil Layout



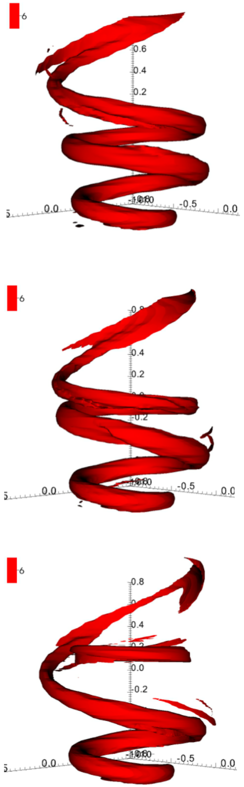
MRS Sensor Layout



N.J. Richner et al., Rev. Sci. Instr. **89** 10J103 (2018)

Three Main Magnetic Signatures are Observed During LHI

NIMROD Describes Current Drive Characterized by Bursts of Low Frequency, $n = 1$ Activity



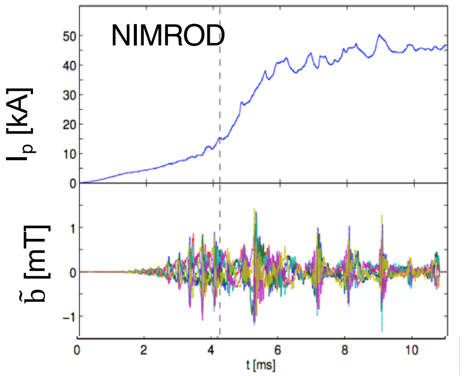
1. Streams follow field lines

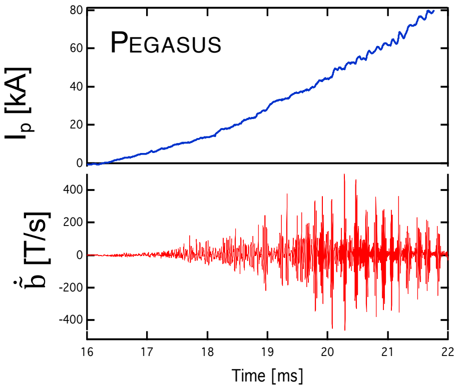
2. Adjacent passes attract

3. Reconnection pinches off current rings

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

Low Field Side LHI Shows Similar Behavior to NIMROD Predictions





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

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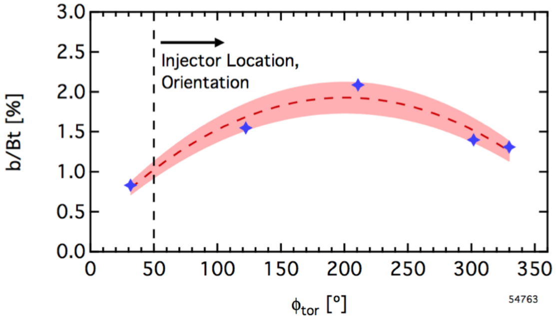
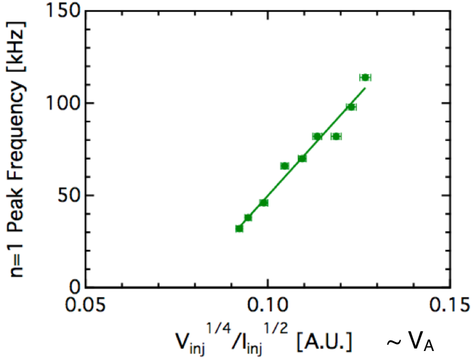
$n = 1$ Mode Consistent with Line-Tied Kinking of Current Stream

- Seen in frequency range of ~10 – 100 kHz
- $n = 1$ as characterized on LFS Mirnov arrays
- Line-tied kink structure
  - Toroidally asymmetric with node at injector ϕ
  - Alfvénic frequency scaling
  - Power concentrated at injector R

Fluctuation amplitude has node at injector ϕ



Frequency of n = 1 scales with V_A



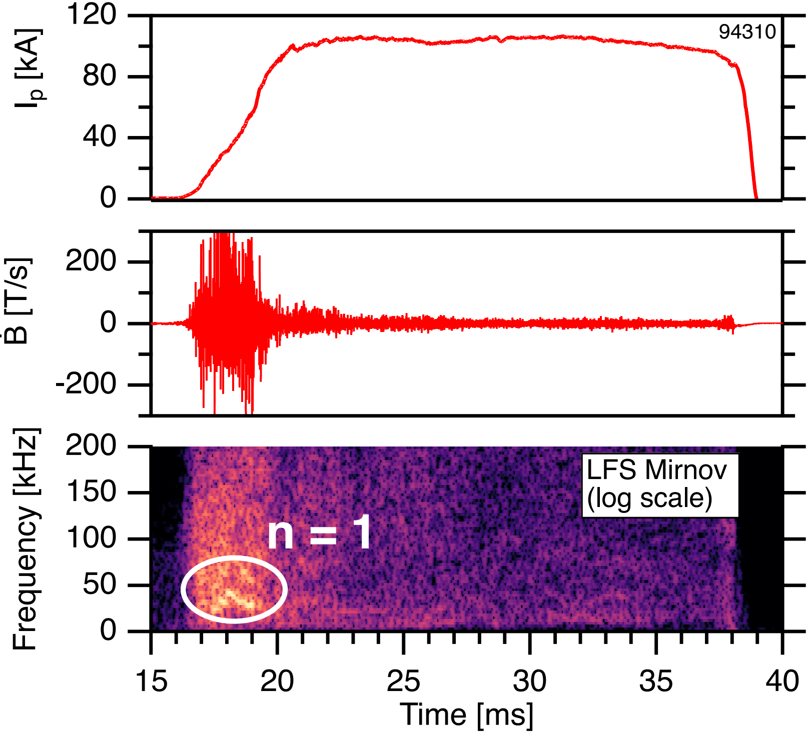
Barr, UW PhD Thesis (2016)

Operational Regime Found in High Field Side LHI with Sustained Current Drive in Absence of $n = 1$ Mode

- Reduced MHD regime characterized by:
  - Rapid reduction ($\gtrsim 10\times$) in magnetic activity as measured on LFS Mirnov arrays
  - Strong reduction / absence of $n = 1$ mode
  - Increased I_p and improved current drive efficiency
  - Have $\sim 2\times$ increase in plasma density
  - Mechanism for reduction unclear, under investigation [Schaefer TP11.00113]

- Sustained current drive in absence of $n = 1$ implies additional drive mechanism(s) are active in LHI

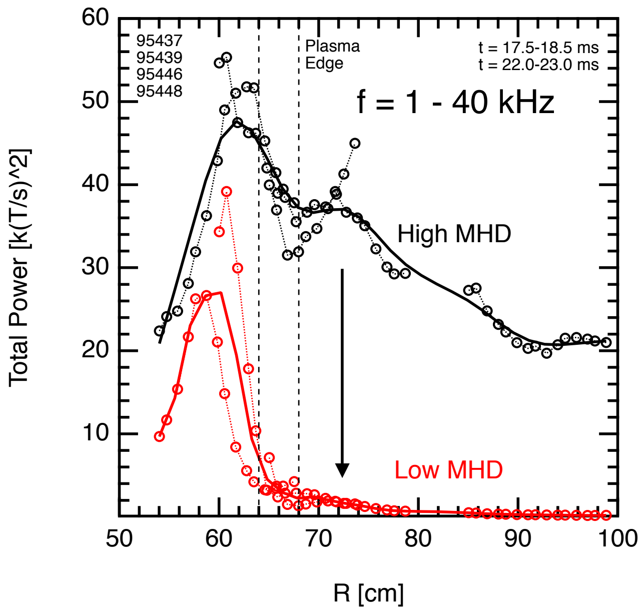
I_p Sustained for ~18 ms in Absence of $n = 1$ Mode



*Reusch et al., Phys. Plasmas **25**, 056101 (2018)*
*Perry et al., Nuc. Fusion **58**, 096002 (2018)*

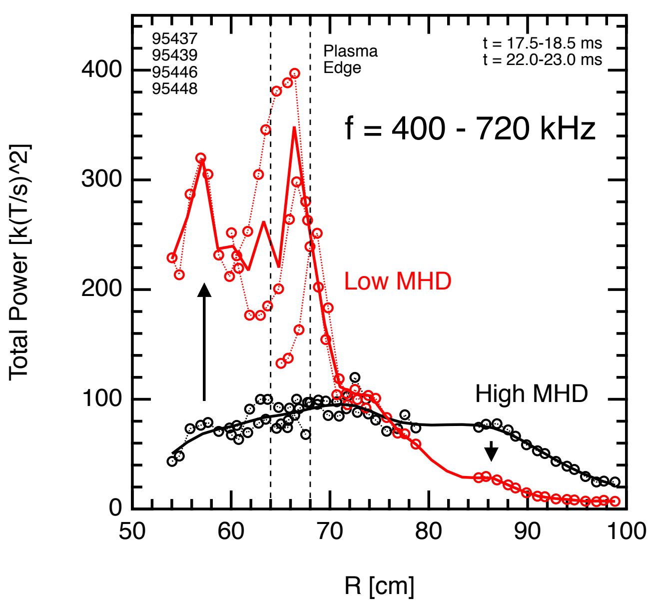
Indications of Shift to Short-Wavelength Activity in Reduced MHD State

Total power in 1 – 40 kHz window is decreased in low MHD state



- Low frequency activity persists with sharp gradient at plasma edge

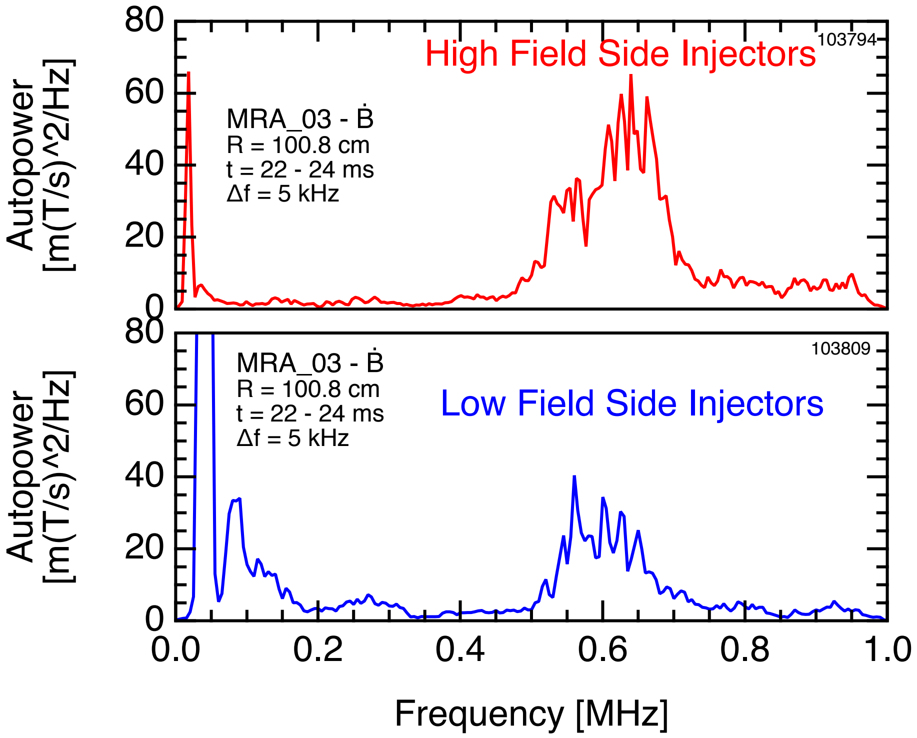
Total power in 400 – 720 kHz window increased at low R



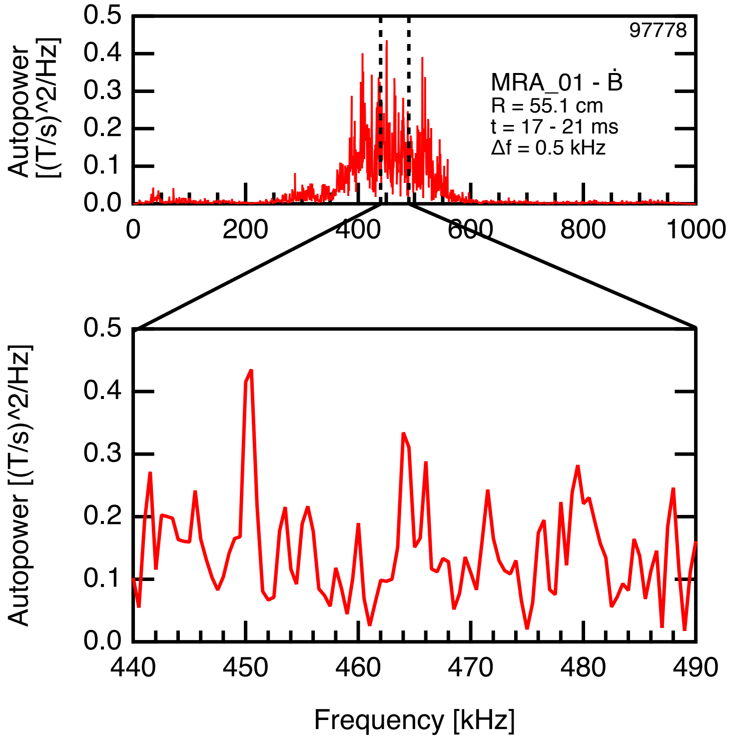
- Note: points at $R \lesssim 68$ cm indicate edge moving inward from probe perturbations

Ubiquitous Spectral Feature at ~600 kHz Observed During LHI

Feature observed in both LFS and HFS Injection

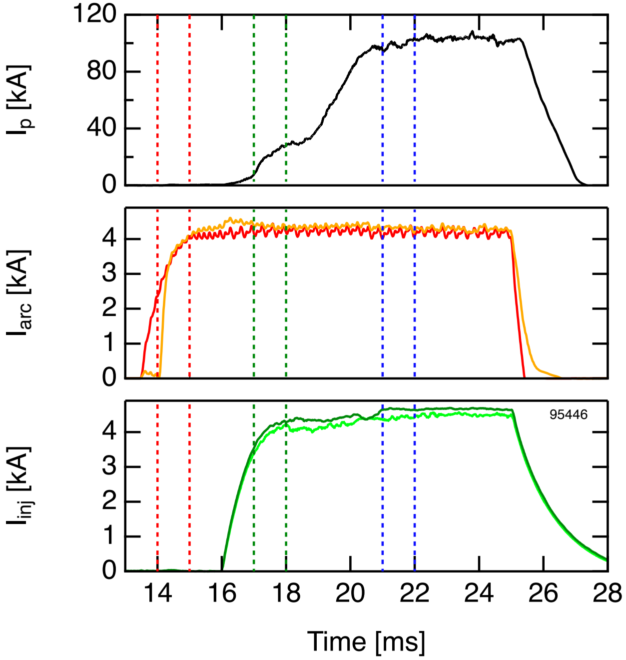


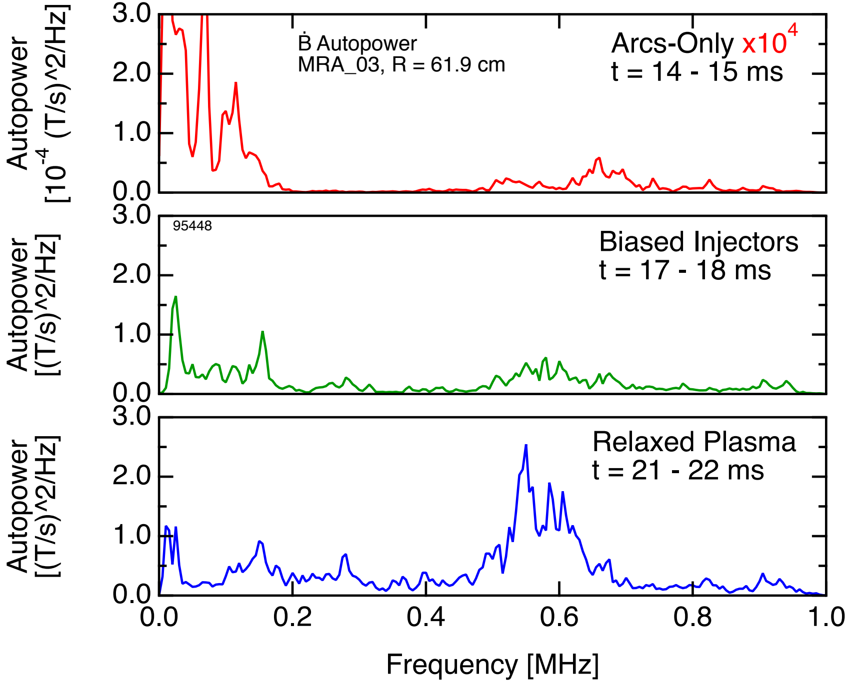
Feature comprised of many, discrete peaks, rather than single broad feature



Feature has been Isolated to Injector Arc and/or Current Streams

- Observed during arcs-only (no applied bias), at $\lesssim 1/100^{th}$ amplitude

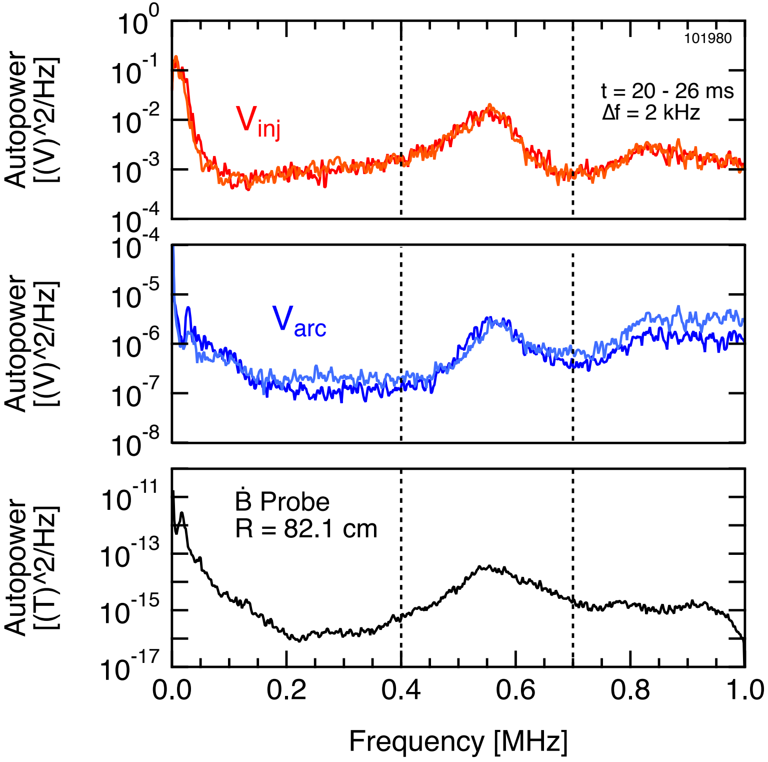




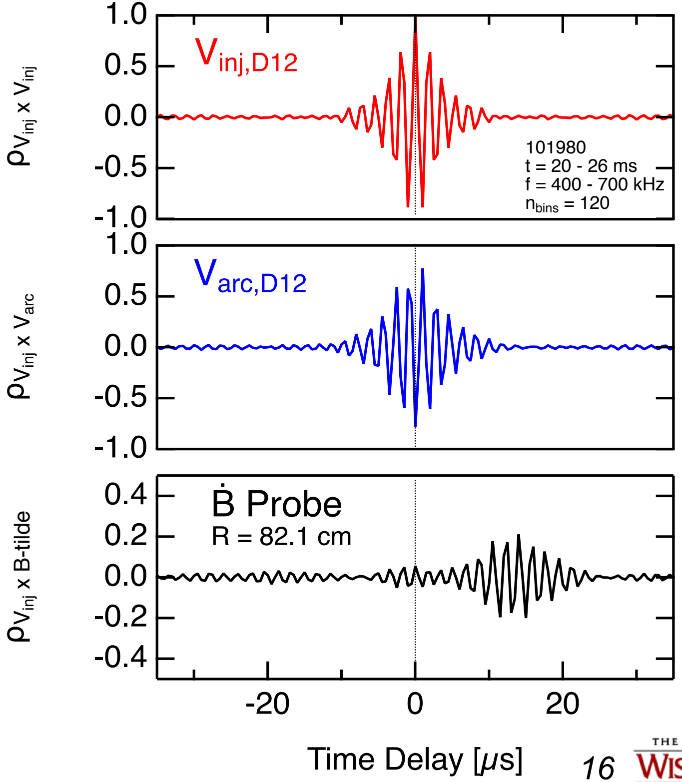
- Feature no longer present following injector shut-off

Similar Fluctuations also Observed on Injector Voltage Measurements

Feature at ~560 kHz on V_{inj}, V_{arc}, and $\tilde{B}$



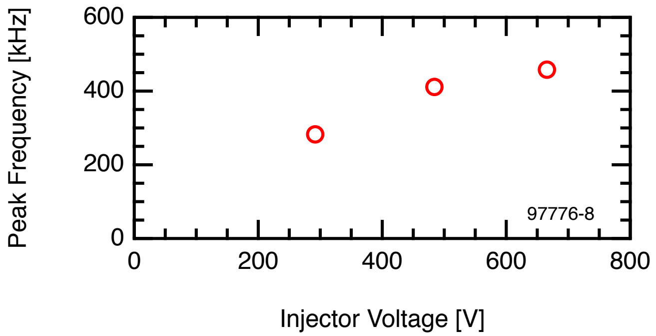
Cross-correlation analysis shows injector signature appears on probe with 14 μs delay (~ $L_{||}/V_A$)



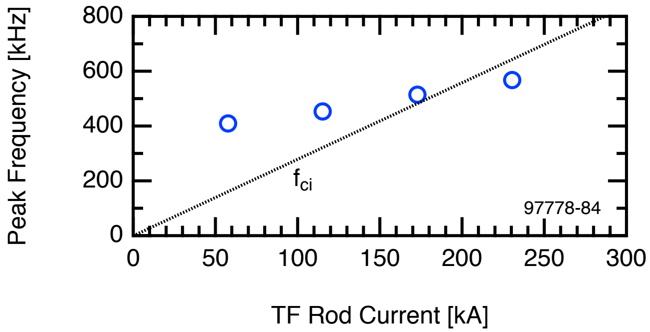
Experimental Observations Suggest Feature is an Arc and/or Beam Instability

- Isolated to injector arc and/or stream
- Frequency scales with V_{inj} and/or I_{inj}, and B
- Possibilities under consideration:
  - Arc Instability
    - Instability in arc that is propagated along current stream with the application of injector bias
    - $\tilde{n}_{arc}$ → Impedance → $\tilde{I}_{beam}$ → $\tilde{B}$
    - $\boldsymbol{E}\times\boldsymbol{B}$ instability? Parasitic instability?
  - Beam Instability
    - Could expect scaling with V_{inj}: $v_{beam} \sim \sqrt{\frac{2V_{inj}}{m_e}}$
    - Two-stream instability? Filamentation instability?

Centroid frequency vs V_{inj} at I_{TF} = 115 kA

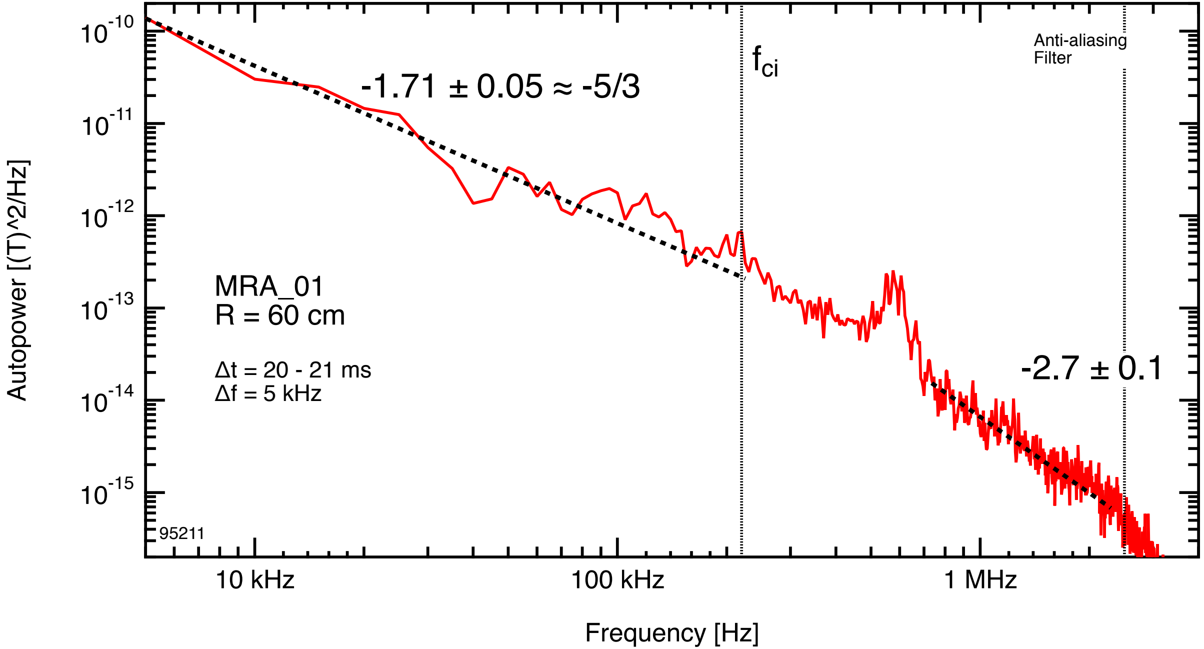


Frequency increases weakly with B at fixed V_{inj}, I_{inj}



Broadband Continuum Observed During LHI with Varying Power Laws

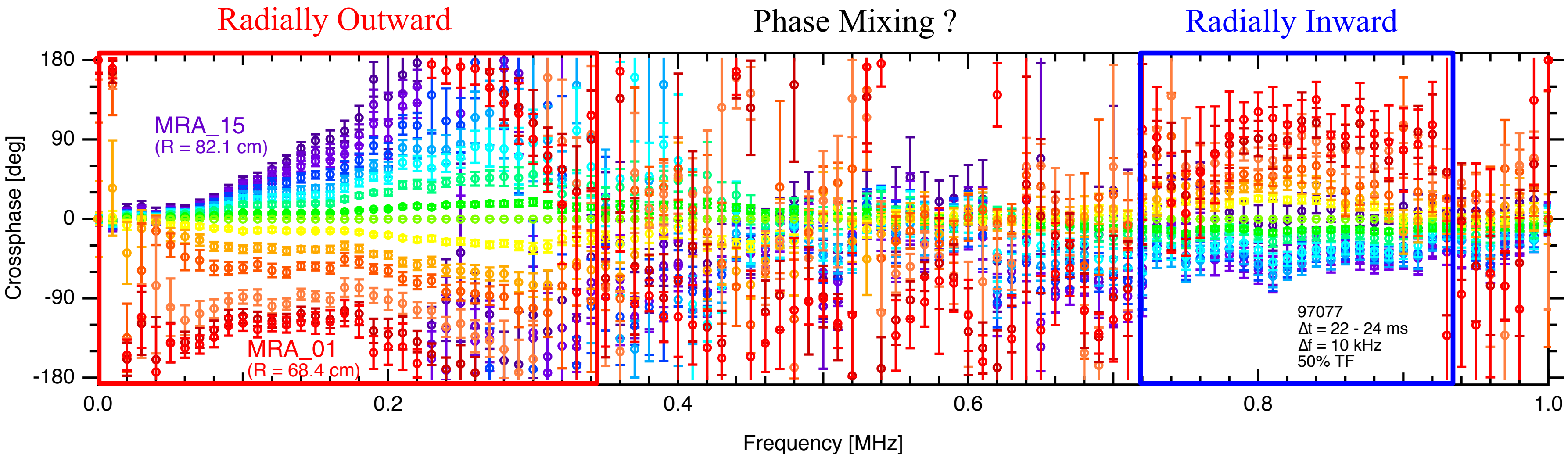
- Broadband power observed to noise floor of insertable magnetics probe



- Appears to follow different power laws for different frequency regimes

Different Frequency Bands Exhibit Different Propagation Behavior

- Cross-phase calculated between middle channel with respect to others in radial Ḃ array
  - Low frequencies: phase lag for sensors at higher R → $v_{ph,R}$ radially outward
  - High frequencies: phase lead for sensors at higher R → $v_{ph,R}$ radially inward



- Initial analysis suggests dependencies on B, spatial location, and reduced vs high MHD state

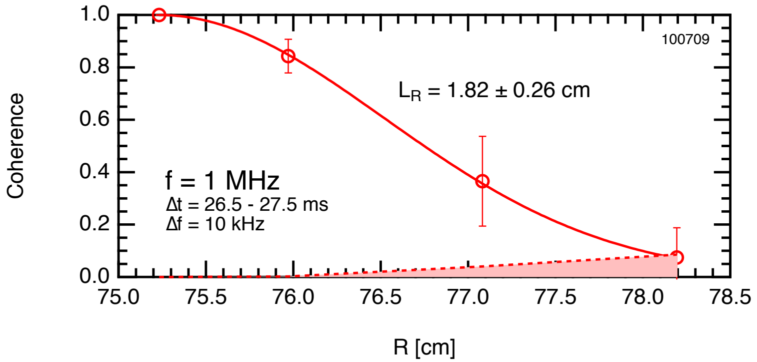
Continuum has Coherence Lengths of L_R~1 cm, L_ϕ ~10 cm

- Radial coherence lengths of ~ 0.5 - 2 cm
- Toroidal coherence lengths of ~ 10 - 30 cm, using near-edge Mirnov array
- For comparison:

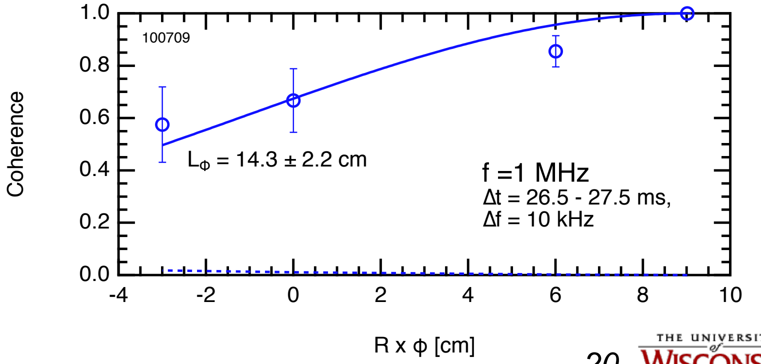
$\rho_i \sim 0.7$ cm $\qquad \frac{\omega_{pi}}{c} \sim 25$ cm $\qquad \frac{\omega_{pe}}{c} \sim 0.4$ cm

- Flexibility of DTACQ ACQ132 digitizer enables faster digitization at reduced channel count:
  - 16 ch at 2 MSPS → 4 ch at 8 MSPS, per probe
  - For radial array probe, $L \sim 3$ cm
  - For toroidal array probe, $L \sim 12$ cm
- Fit with Gaussian profile

Coherence vs R using Radial Ḃ Array Probe



Coherence vs Arc Length using Near-Edge Toroidal Ḃ Array

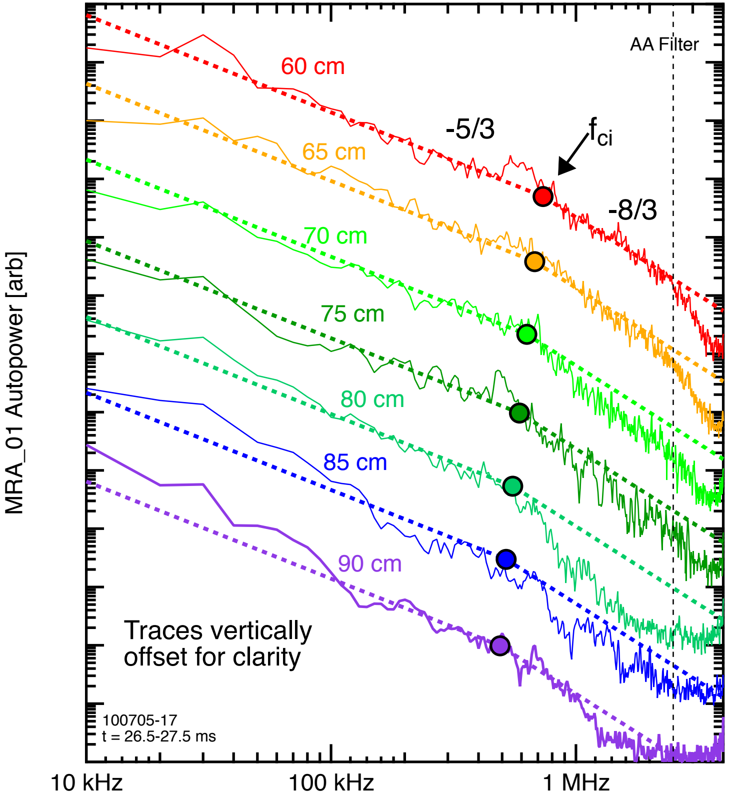


Investigating Reconnection & Turbulence as Source of Continuum Feature

- Measurements of reconnection turbulence in astrophysics show power law behavior:
  - $b^2 \propto f^{-5/3}$ for $f < f_{ci}$
  - $b^2 \propto f^{-8/3}$ or $b^2 \propto f^{-7/3}$ for $f > f_{ci}$
  - Additional break(s) at higher frequencies with steeper slope(s) have also been observed

- Observed spectra during LHI appear to follow similar power laws, with frequency break at $f \approx f_{ci}$
  - -5/3 → MHD turbulence ?
  - -8/3 → KAW turbulence ?

- Preliminary analysis also suggests dependencies on field strength and spatial position



*C.C. Chaston et al., PRL **100**, 175003 (2008)*
*J.P. Eastwood et al., PRL **102**, 035001 (2009)*

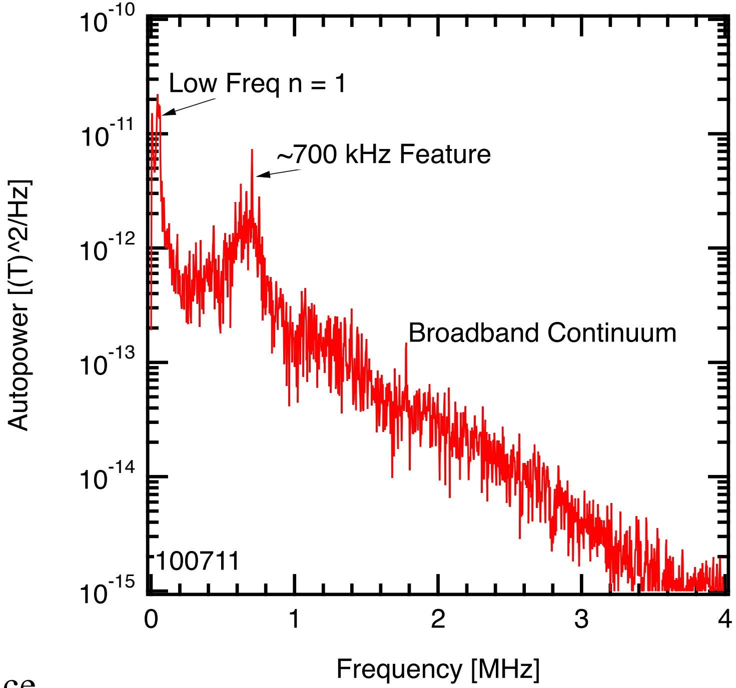
Summary

Summary of Magnetic Activity Observed During LHI

1. Peak at ~10 – 100 kHz
   - $n = 1$ characteristic
   - Consistent with line-tied kinking of injected current
   - $\gtrsim 10\times$ decrease in amplitude in reduced MHD state

2. Spectral feature at ~ 600 kHz
   - Associated with injector arcs and/or injected streams
   - Consists of many discrete peaks
   - Frequency scales with injector power and field

3. Broadband, turbulent-like continuum
   - Power laws similar to those observed in reconnection turbulence
   - Different propagation behavior for different frequency bands



Open Questions

- What is the cause of the MHD transition and can it be leveraged?
  - Most high performance HFS LHI shots are in reduced MHD state
  - Understanding the physical mechanism could enable utilizing this feature at higher B_{TF}, I_p

- What role, if any, does the 600 kHz feature play in LHI?
  - Evidence consistent with an instability in the plasma arc and/or a beam instability in the current stream

- Is the broadband continuum integral to LHI current drive and/or a byproduct of it?
  - Is the continuum/turbulent power responsible for current drive?
  - Investigating short wavelength reconnection and turbulent/dynamo current drive as potential mechanisms
  - How does the continuum in LHI compare to Ohmic-driven plasmas?

Future Work

- Experiments to test if 600 kHz feature is critical to current drive in LHI
  - Can the 600 kHz feature be stabilized? (anode fueling?)
  - If so, can current still be driven in absence of this feature?

- Determine how the magnetic activity scales as the LHI drive is increased

- Long term: test other known current drive mechanisms, ie. $\langle \tilde{v} \times \tilde{B} \rangle$, $\langle \tilde{j} \times \tilde{B} \rangle$
  - Development of Mach probe and/or CHERS system ($\tilde{v}$)
  - Development of a Rogowski coil probe ($\tilde{j}$)

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