Magnetic Activity During LHI Startup and Sustainment on PEGASUS

Nathan J. Richner

G.M. Bodner, M.W. Bongard, S.J. Diem, R.J. Fonck,

M.D. Nornberg, C.E. Schaefer, J.D. Weberski

University of Wisconsin-Madison

62nd Annual Meeting of the APS
Division of Plasma Physics
Virtual Meeting

9–13 November 2020
Presentation ZP06.00003

PEGASUS
Toroidal Experiment

Abstract

Magnetic Activity During LHI Startup and Sustainment on PEGASUS

N.J. Richner, G.M. Bodner, M.W. Bongard, S.J. Diem, R.J. Fonck, M.D. Nornberg, C.E. Schaefer, J.D. Weberski

Department of Engineering Physics, University of Wisconsin-Madison, Madison, WI 53706

Local helicity injection (LHI) is a non-solenoidal tokamak startup technique using biased plasma sources for DC helicity injection. This process relies upon magnetic reconnection and relaxation mechanism(s) that convert the helicity from injected current streams into bulk plasma current through helicity-conserving instabilities. To inform this process, high-bandwidth local magnetic measurements have been obtained in a broad survey of LHI operational (I_{inj}, V_{inj}, B_t, injector geometry) and physics regimes (e.g. stream-only, actively driven, decaying, etc.). Significant broadband high-frequency activity is present in LHI discharges compared to Ohmic plasmas. $\tilde{B}$ features power-law behavior with spectral indices of ~5/3 for $f<f_{ci}$ and ~8/3 for $f > f_{ci}$. Similar signatures are attributed to MHD and KAW/whistler wave turbulence, respectively, in astrophysical contexts, and is predicted to have an inverse cascade of magnetic helicity. Such turbulence has also been observed in reconnection systems. High frequency activity $f>f_{ci}$ is correlated with LHI drive voltage V_{inj} and/or injected beam velocity $v_b \propto V_{inj}^{1/2}$, further suggesting a kinetic role. Activity at f~2 MHz (2–4 f_{ci}) is found to scale linearly with applied LHI drive. Its potential role in the current drive process is under investigation.

Work supported by US DOE grants DE-SC0019008 and DE-SC0020402.

Outline

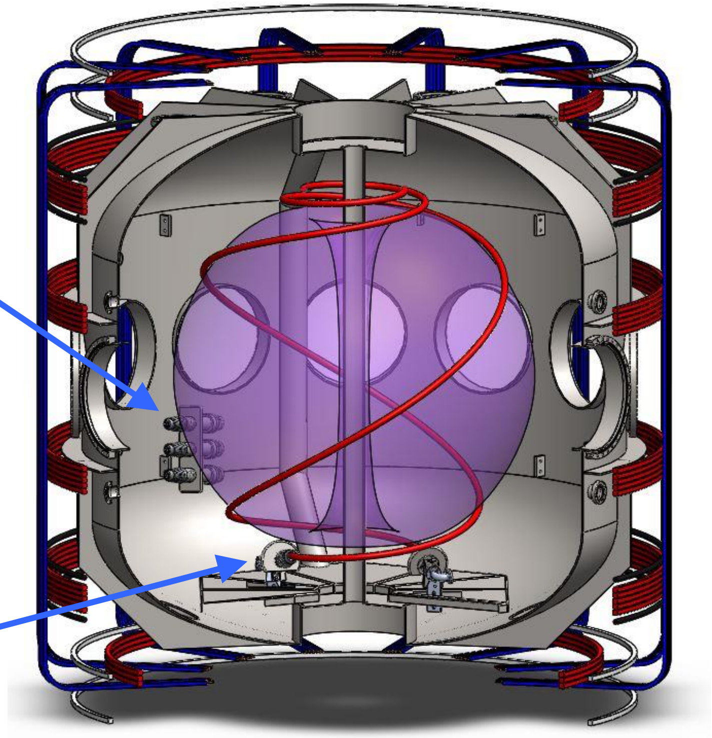
- Local Helicity Injection and Motivation for Investigating $\tilde{B}$ During LHI
- Significant Magnetic Activity is Observed During LHI
- Observed Activity Suggestive of Magnetic Turbulence
- Assessing Role of Magnetic Activity in LHI Current Drive
- Summary & Conclusions

Outline

- Local Helicity Injection and Motivation for Investigating $\tilde{B}$ During LHI
- Significant Magnetic Activity is Observed During LHI
- Observed Activity Suggestive of Magnetic Turbulence
- Assessing Role of Magnetic Activity in LHI Current Drive
- Summary & Conclusions

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

LFS Injectors

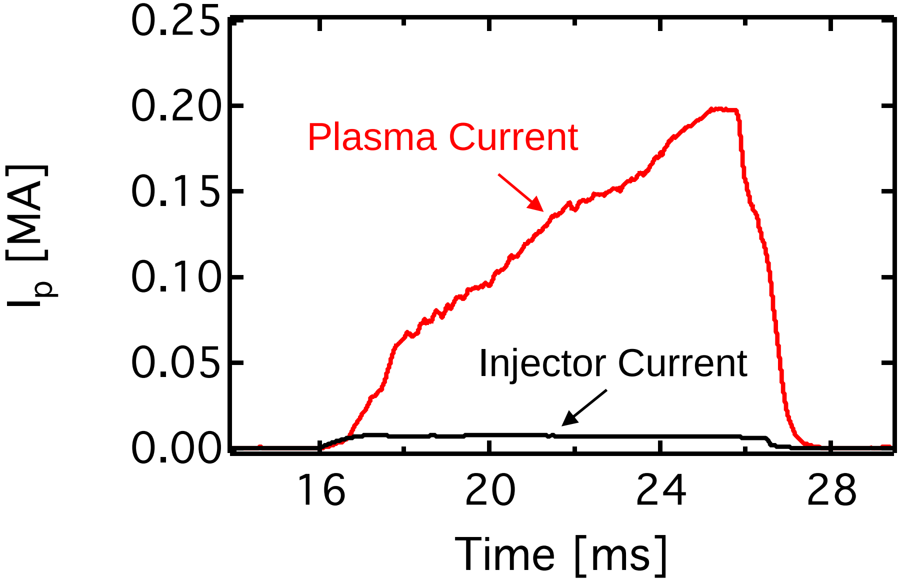


HFS Injectors

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

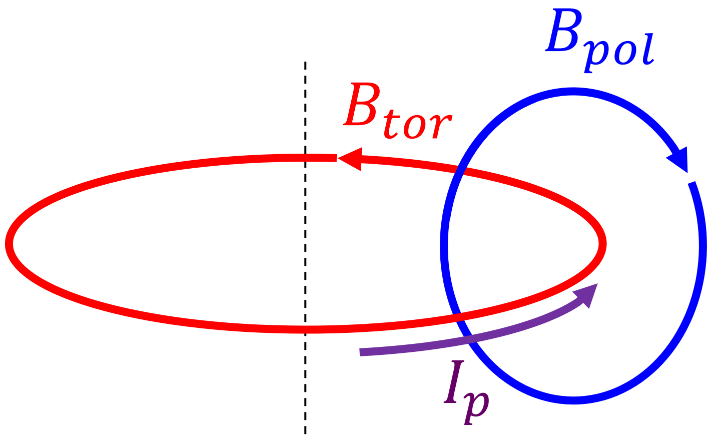
Magnetic Relaxation and Reconnection Crucial to LHI Current Drive

- LHI relies on conservation of magnetic helicity K

$$K = \int \mathbf{A} \cdot \mathbf{B} \, d^3x \quad \propto \quad I_p \Psi_{tor}$$

  - Increasing K of system → increasing plasma current I_p
  - Sufficient helicity injection drives and/or sustains I_p

Toroidal system: K represents linkage of toroidal and poloidal fluxes



D.J. Battaglia, UW PhD Thesis (2009)

- Magnetic relaxation drives system to minimum energy state constrained by same total K
  - Taylor/Relaxed state: $\nabla \times \mathbf{B} = \lambda \, \mathbf{B}$ for constant λ
  - Redistributes currents/helicity from injected scale to global scale

- Magnetic reconnection is a necessary part of DC helicity injection
  - DC helicity is injected through boundary along open field lines
  - Reconnection is necessary to convert the open field line configuration into tokamak-like topology

*T.H. Jensen & M.S. Chu, Phys. Fluids **27** 12 (1984)*
*J.B. Taylor, Rev. Mod. Phys. **58** 3 (1986)*

Understanding Magnetic Activity Present During LHI Could Inform Relaxation & CD Processes

- Magnetic relaxation is a dynamic process

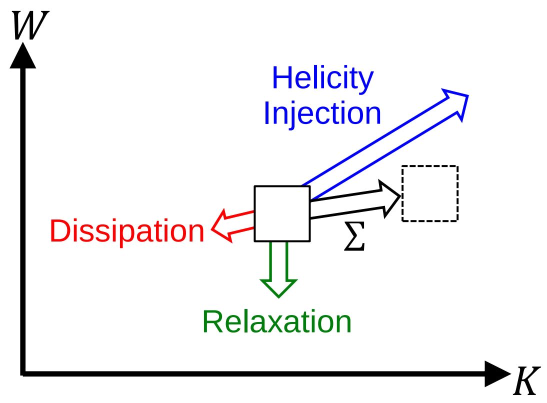
  → Need mechanism(s) to mediate it, e.g., **instabilities/turbulence**

- Components needed for relaxation inform activity of interest:
  1. Preferential **conservation of magnetic helicity** over magnetic energy
  2. Relaxation toward constant λ implies **redistribution of fields & currents**
  3. Change in topological properties implies **magnetic reconnection**

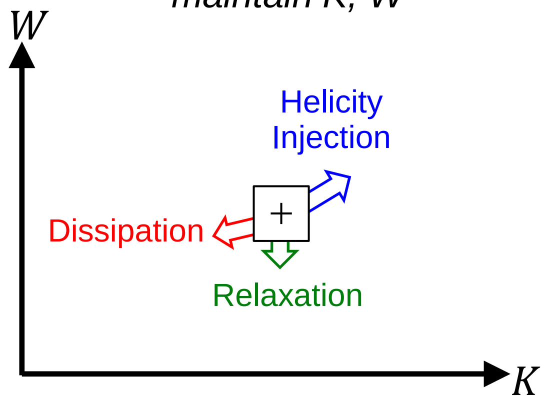
- Magnetic fluctuations integral to CD from dynamo EMFs
  – e.g., MHD dynamo $\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{B}} \rangle$, Hall dynamo $\langle \tilde{\mathbf{J}} \times \tilde{\mathbf{B}} \rangle / n_e e$

- Variety of spatial scales at which relevant activity could occur
  – e.g. system-scale MHD modes, multi-scale turbulence, small-scale microinstabilities

Current Drive: Sufficiently high helicity injection pushes system to higher K, W



Steady-state: helicity injection & relaxation balance dissipation to maintain K, W



Insertable Magnetic Probes Deployed to Study $\tilde{B}$

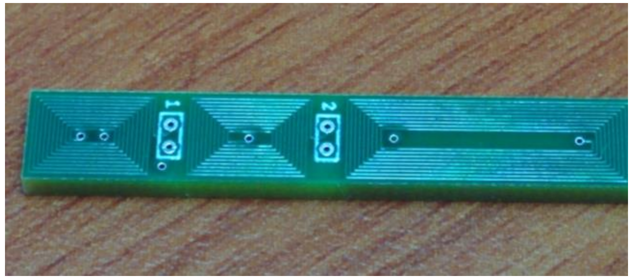
- PEGASUS operational regime allows for use of insertable probes
  - Short shot durations, low T
  - Graphite-armored assembly
  - Insertable: $R_{tip} = 50 - 90$ cm, centered on midplane $Z = 0$
  - Interchangeable probe internals

- MRA: $\dot{B}_Z(R)$ array probe
  - 15 spatial points, $\Delta R \sim 1$ cm
  - Characterized frequency response to ~ 6 MHz

- MRS: 3D $\dot{\mathbf{B}}(R)$ probe
  - 10 spatial points, $\Delta R = 1$ cm
  - Characterized frequency response to ~ 6 MHz

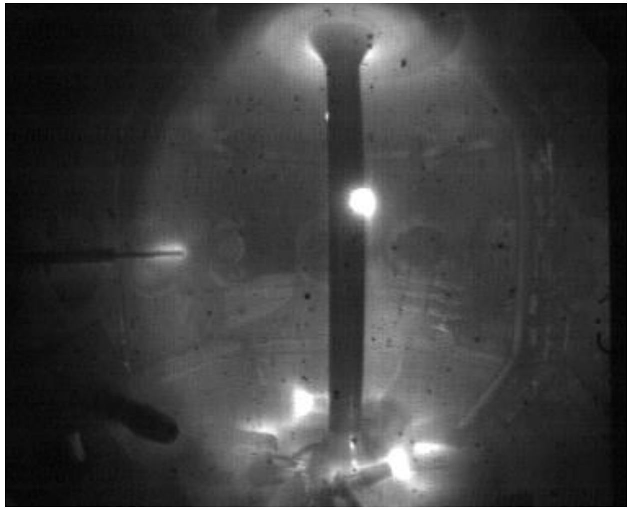
- MRT: 3D Hall probe
  - $\mathbf{B}(R)$ at 8 points, $\Delta R = 1.5$ cm
  - 7 additional $B_Z(R)$, effective $\Delta R = 0.75$ cm
  - $\lesssim 0.1$ ms time resolution

MRA $\dot{B}$ sensors formed using spiral traces on printed circuit board



5 mm

Probe inserted into an LHI-driven discharge



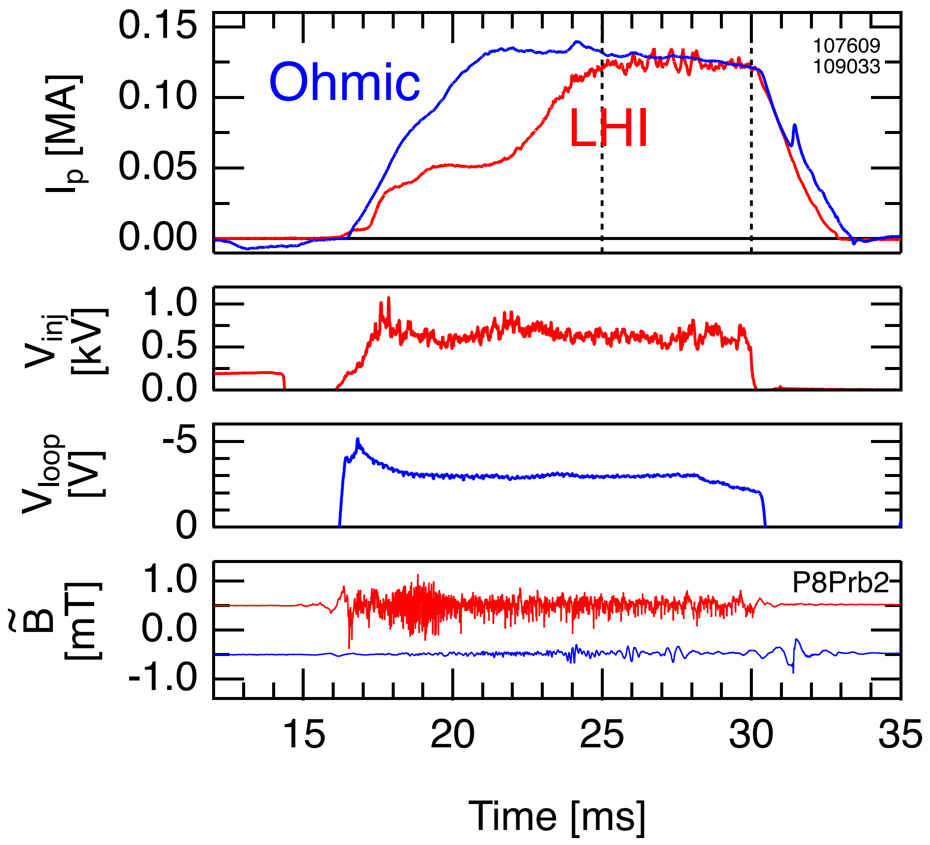
N.J. Richner et al., Rev. Sci. Instr. ***89*** *10J103 (2018)*

Outline

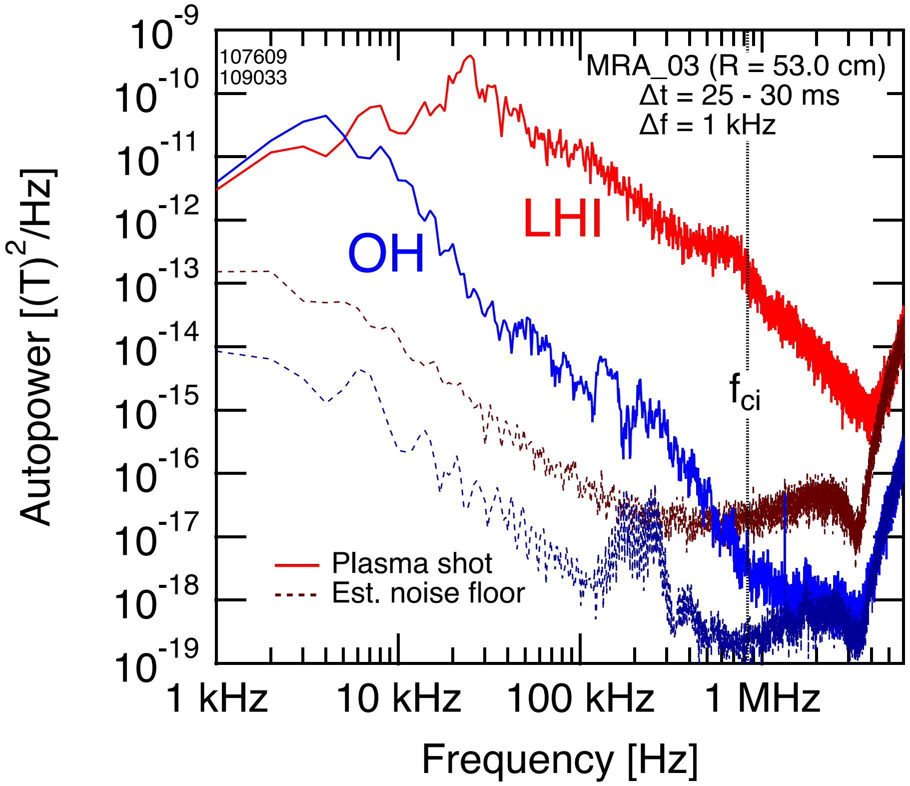
- Local Helicity Injection and Motivation for Investigating $\tilde{B}$ During LHI
- Significant Magnetic Activity is Observed During LHI
- Observed Activity Suggestive of Magnetic Turbulence
- Assessing Role of Magnetic Activity in LHI Current Drive
- Summary & Conclusions

Significantly More Magnetic Activity is Observed During LHI Relative to Ohmic Drive

Waveforms from comparable $I_p \sim 0.12\ MA$ LHI, Ohmic shots



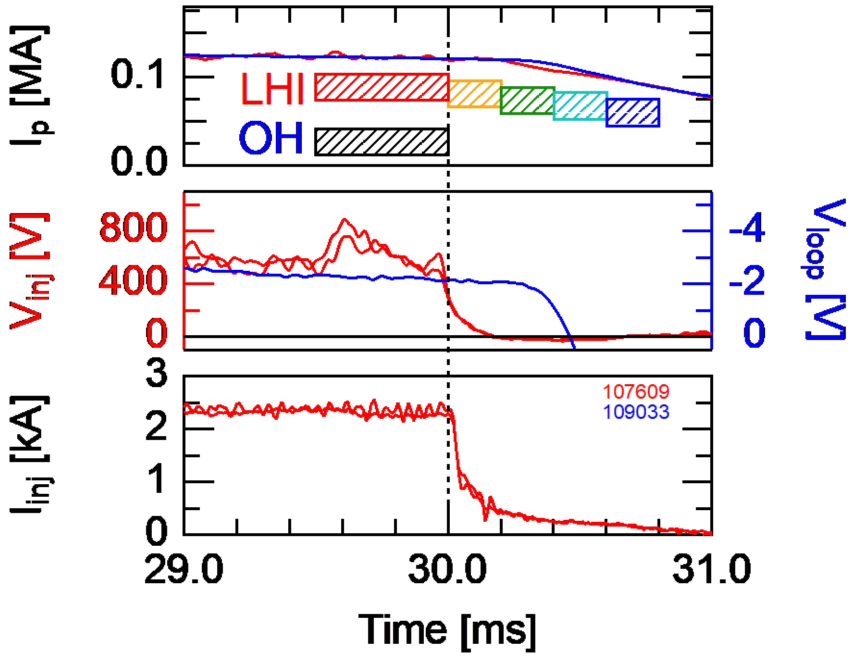
Internal $\tilde{B}$ autopower spectra



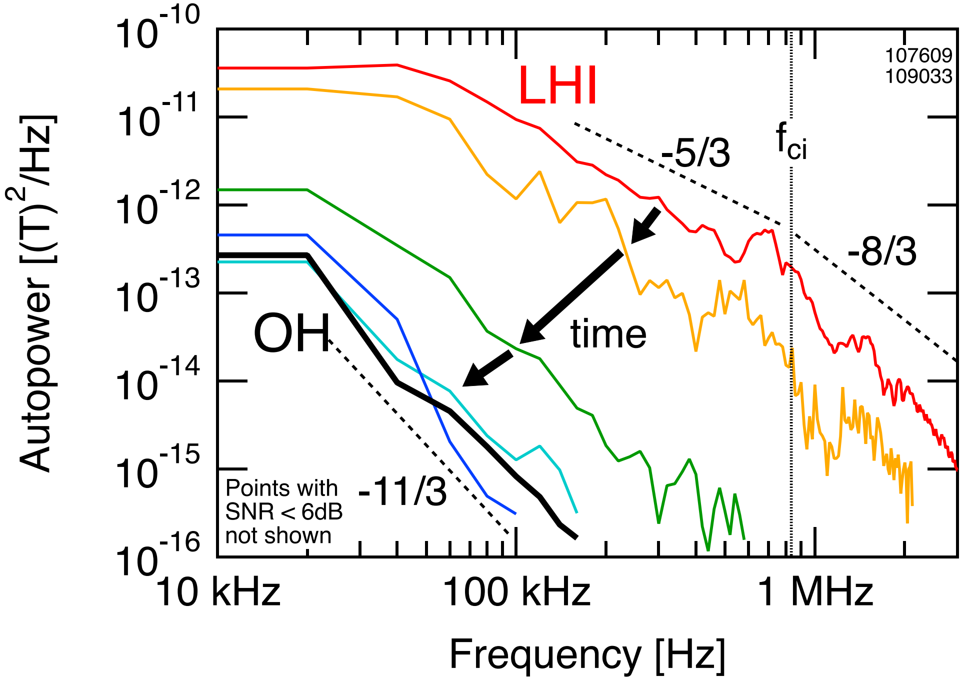
- $\tilde{B}$ spectrum for LHI greater amplitude than Ohmic, particularly at high frequency

At Shutoff of Injectors, Spectrum Rapidly Decays to Ohmic-Like State

LHI decay compared against OH using short time windows



$\tilde{B}_Z$ autopower for LHI decay rapidly approaches that of Ohmic



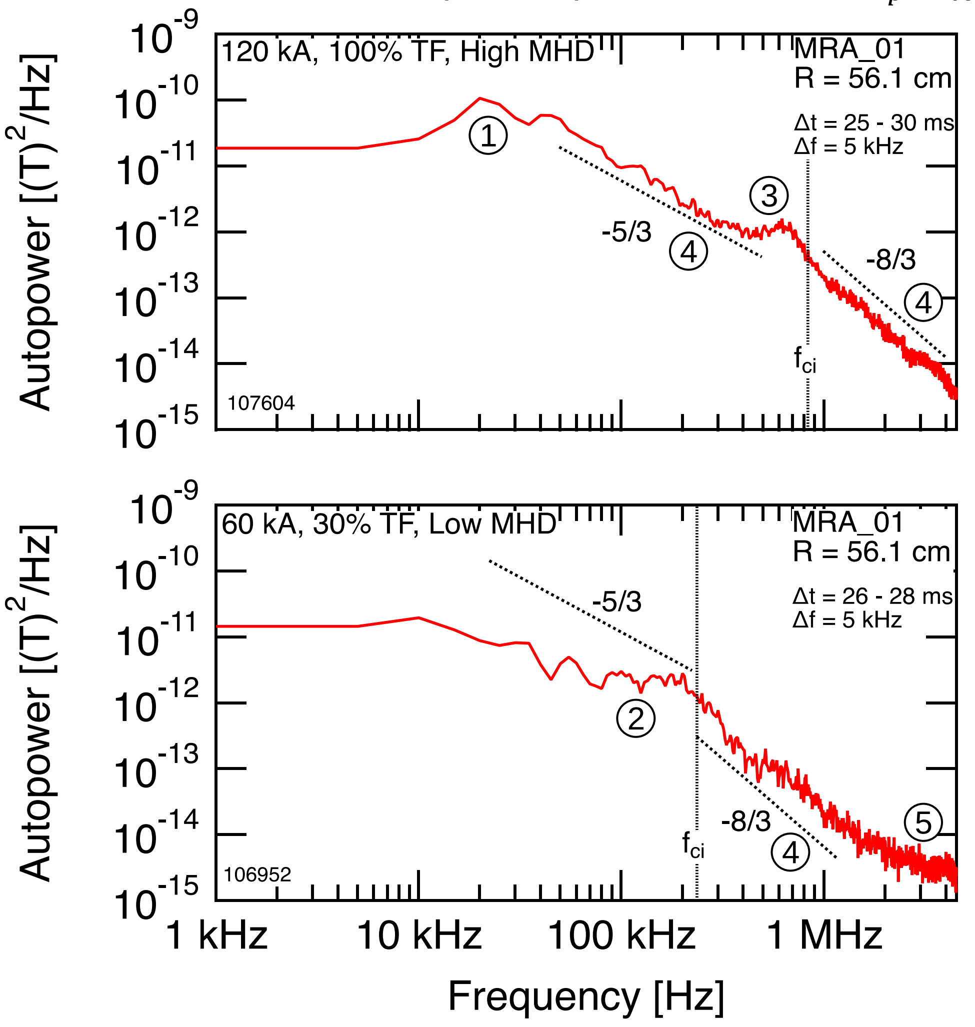
- LHI decay $\tilde{B}$ spectrum approaches that of Ohmic spectrum in ≈ 0.5 ms
  - For comparison: $\tau_A \sim \frac{a}{V_A} \sim 0.86\ \mu s$ $\tau_{R,Spitzer} \sim \frac{\mu_0 a^2}{\eta_{Spitzer}} \sim 21$ ms $\tau_{R,neo} \sim \frac{\mu_0 a^2}{\eta_{neo}} \sim 15$ ms $\tau_{tearing} \sim \tau_R^{3/5} \tau_A^{2/5} \sim 0.30$ ms
- NIMROD simulations: flux surfaces rapidly heal after injector shutoff*
  - Observed rapid decrease of $\tilde{B}$ fluctuations consistent with this

*J.B. O'Bryan & C.R. Sovinec, Plasma Phys. Control. Fusion **56** 064005 (2018)

Distinct Features of LHI Magnetic Spectrum Have Been Identified

- Several features robustly observed during LHI:
  1. Peak at ~10–50 kHz
     - $n = 1$, consistent with line-tied kink of I_{inj}
  2. Activity in ~100 kHz range
  3. Broad "Peak" at ~ 700 kHz
     - Observed in arc- and stream-only discharges
     - Centroid frequency scales with V_{inj}, $|B|$
  4. Broadband, turbulent-like continuum
     - Power-law decay with frequency, spectral break at f_{ci}
  5. High frequency activity $f > f_{ci}$
     - Found to be correlated with LHI drive
- For certain operational regimes, low frequency mode (1) becomes stabilized / greatly reduces amplitude
  – Referred to here as "Low MHD" state*

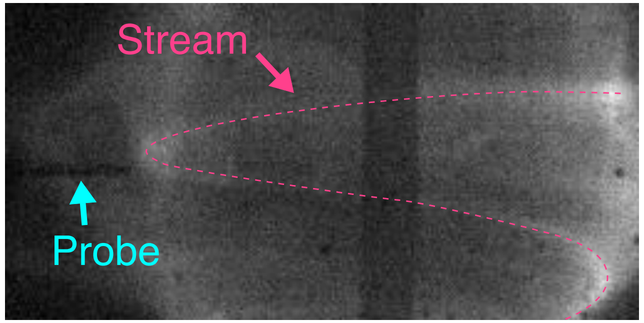
LHI internal $\tilde{B}$ autopower spectra at different I_p, B_{tor}



*J.M. Perry et al., *Nuc. Fus.* **58**, 096002 (2018)
M.W. Bongard et al., *Nuc. Fus.* **59**, 076003 (2019)

Stream-Only Discharges Show Similar Spectral Features

Fast camera image from stream-only discharge

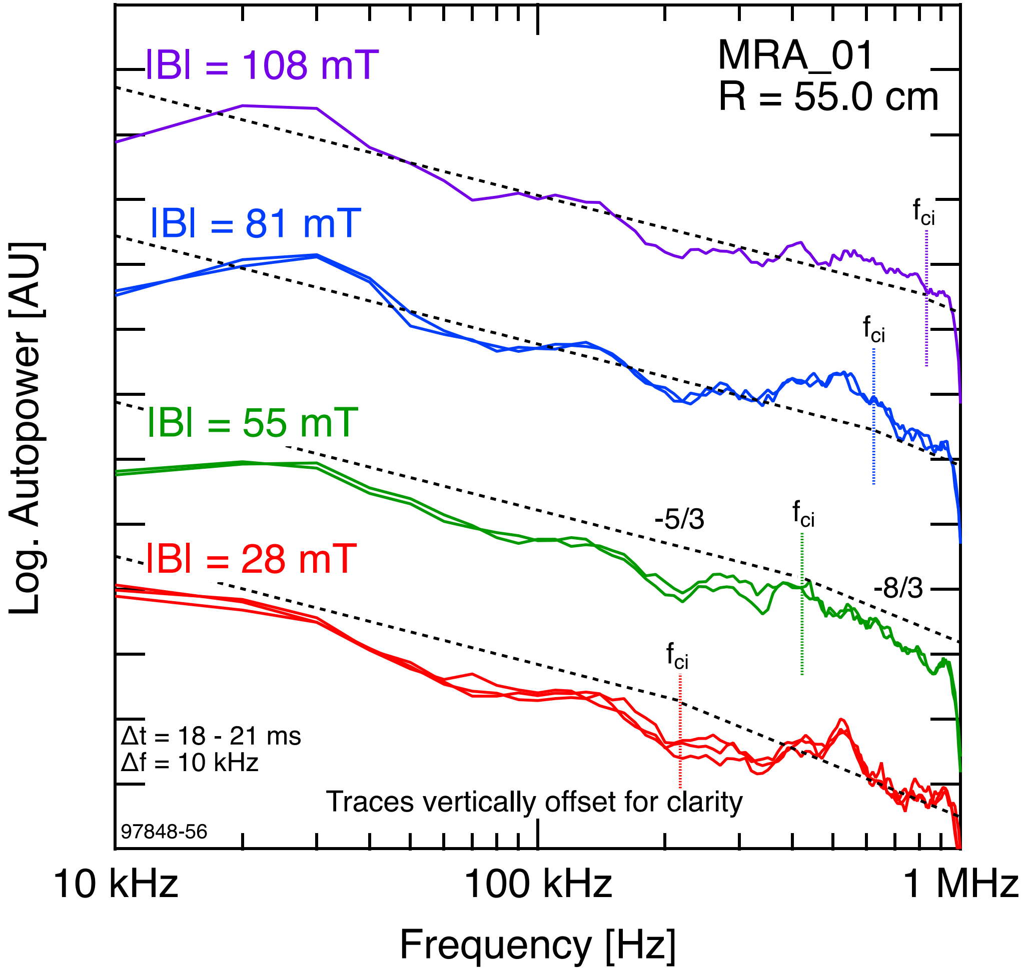


- Discharges developed where tokamak-like state is prevented from forming & injected stream passes near magnetic probe

- $\tilde{B}$ spectra show similar features to that of relaxed tokamak-like LHI discharges

→ **Suggests injected current streams as source of magnetic fluctuations**

$\tilde{B}$ autopower for multi-shot $|B|$ scan with stream-only discharges



Outline

- Local Helicity Injection and Motivation for Investigating $\tilde{B}$ During LHI
- Significant Magnetic Activity is Observed During LHI
- Observed Activity Suggestive of Magnetic Turbulence
- Assessing Role of Magnetic Activity in LHI Current Drive
- Summary & Conclusions

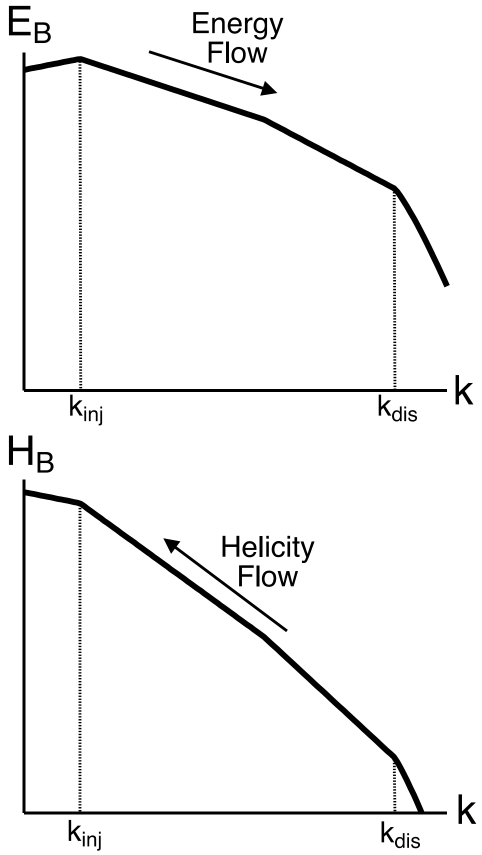
Magnetic Turbulence Could be Integral to Relaxation, Reconnection, and Current Drive

- Magnetic turbulence is a candidate mechanism for relaxation
  - Preferential decay of magnetic energy over magnetic helicity
    - $\dot{W} \sim \quad \eta \sum k^2 B_k^2$
    - $\dot{K} \sim -2\,\eta \sum k \;\; B_k^2$
  - Inverse cascade of magnetic helicity
    - e.g., small flux tubes merging into larger structures

- Magnetic turbulence and reconnection often observed together
  - Turbulence can develop from activity generated by reconnection
  - Reconnection can play role in dynamics of magnetic turbulence, particularly at small scales
  - Turbulence can enhance effective resistivity, increasing reconnection rate

- Correlated fluctuations can drive/redistribute current via dynamo EMFs
  - e.g., MHD dynamo $\langle \tilde{v} \times \tilde{b} \rangle$, Hall dynamo $\langle \tilde{j} \times \tilde{b} \rangle / e n_e$ explicitly require magnetic fluctuations

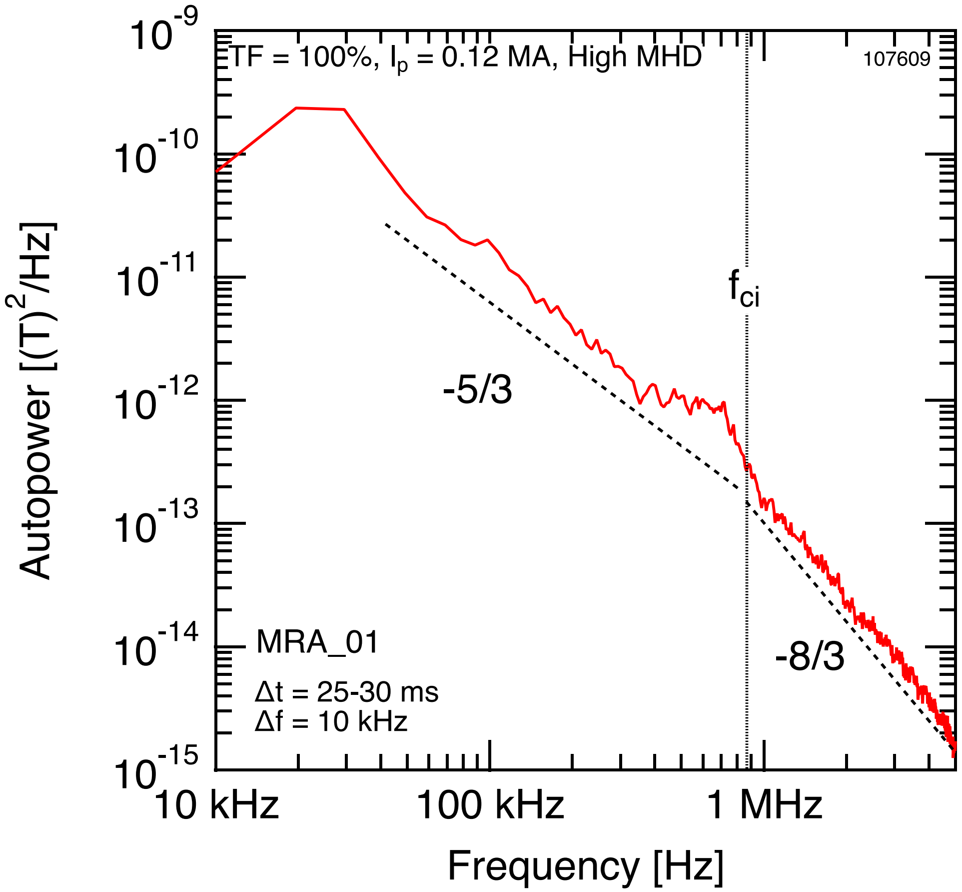
Schematic showing spectra and cascade of energy and helicity in magnetic turbulence



J.B. Taylor, Phys. Plasm. 7:5, 1623-1629 (2000)
D. Biskamp, Magnetohydrodynamic Turbulence (2003)
A. Pouquet et al., Earth and Space Sci. ***6****, 3 351-369 (2019)*

Spectral Indices of Broadband Activity Suggestive of MHD, Alfvénic Turbulence

Relatively consistent power law behavior is observed for internal $\tilde{B}$ autopower



- Broadband activity with power law behavior robustly observed during LHI
  - Spectral decay indices are relatively consistent over variety of operational conditions (e.g., I_p, B_{tor}, injector params.)
  - Spectral break tracks with local f_{ci}

- Spectral decay indices similar to those of magnetic turbulence in astrophysical systems with reconnection:*
  - $E_B(k) \sim k^{-5/3}$ → MHD turbulence
  - $E_B(k) \sim k^{-8/3}$ → KAW turbulence

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

Broadband Activity Located Near Plasma Edge

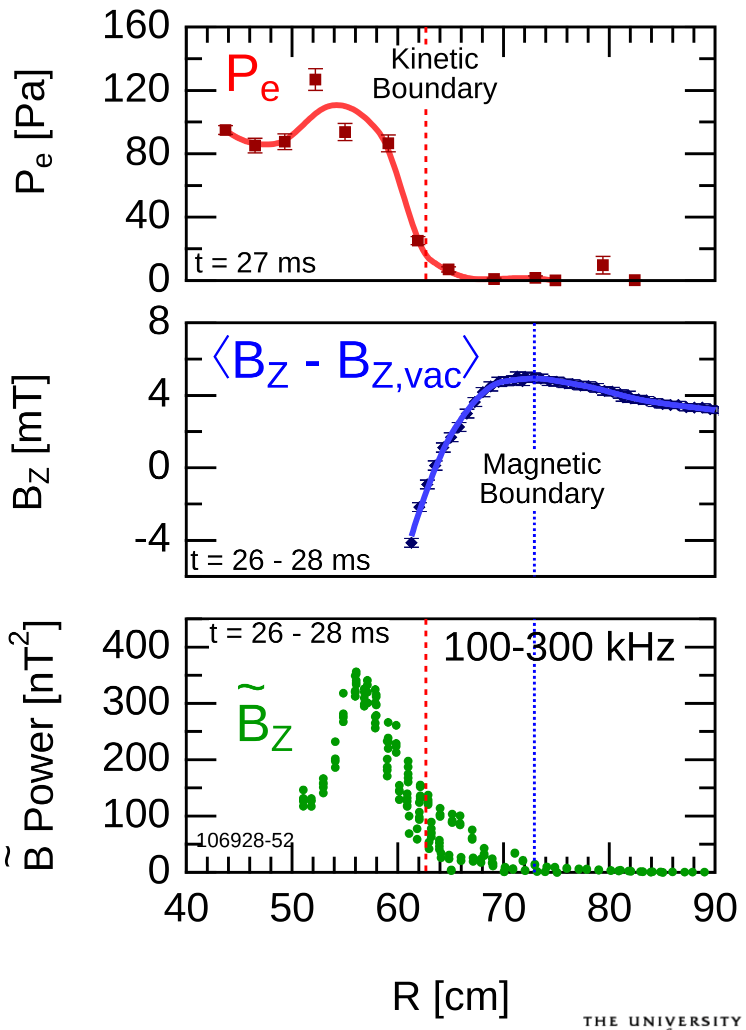
- Comparing spatial distribution of $\tilde{B}$ against kinetic & magnetic profiles of LHI tokamak-like plasma

- "Kinetic boundary"
  - Spatial location where $\nabla^2 P_e$ is maximized
    → Edge of pressure gradient & confined plasma

- "Magnetic boundary"
  - Compares plasma & field-only vacuum shots to determine contribution to $B_Z(R)$ from tokamak-like plasma + injected streams
  - Defined as peak in time-averaged $B_{Z,plasma} = B_{Z,tot} - B_{Z,vac}$
    → Edge of current region
      → $R > R_{edge}$: B_Z falls off with $\approx 1/R$ decay
      → $R < R_{edge}$: $B_Z \propto I_{enclosed}(R)$

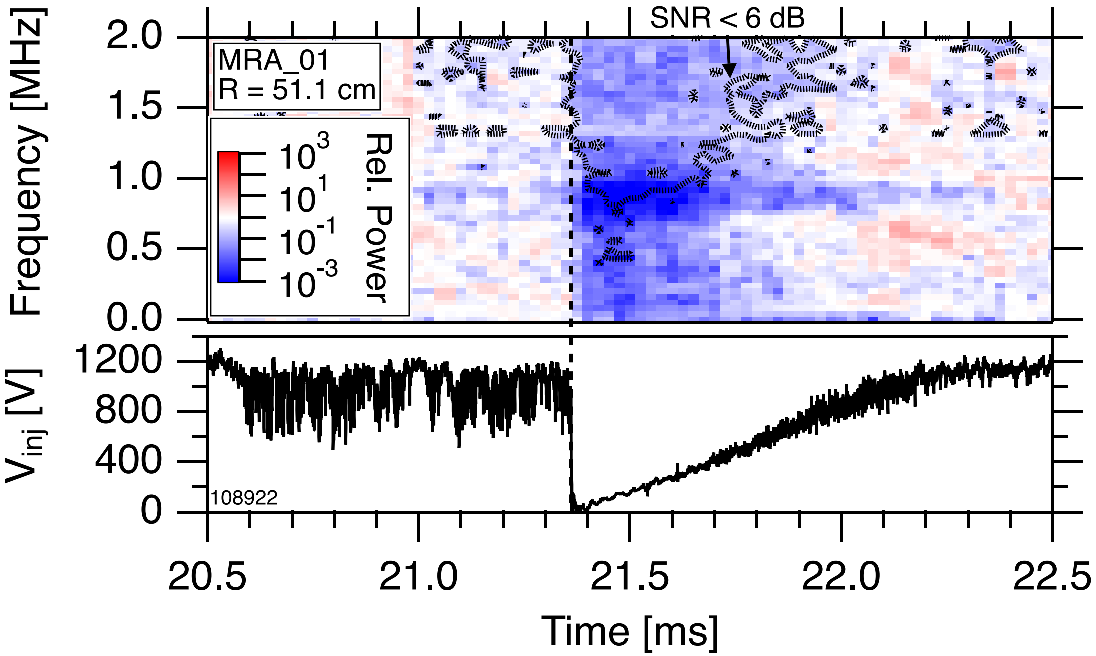
- $\tilde{B}$ activity increases within magnetic boundary, but peaks **within** pressure gradient

Radial distribution of $\tilde{B}$ relative to kinetic and mean magnetic field profiles



Experiments with Rapid Shutoff of V_{inj} Suggest Potential v_{beam} Dependency

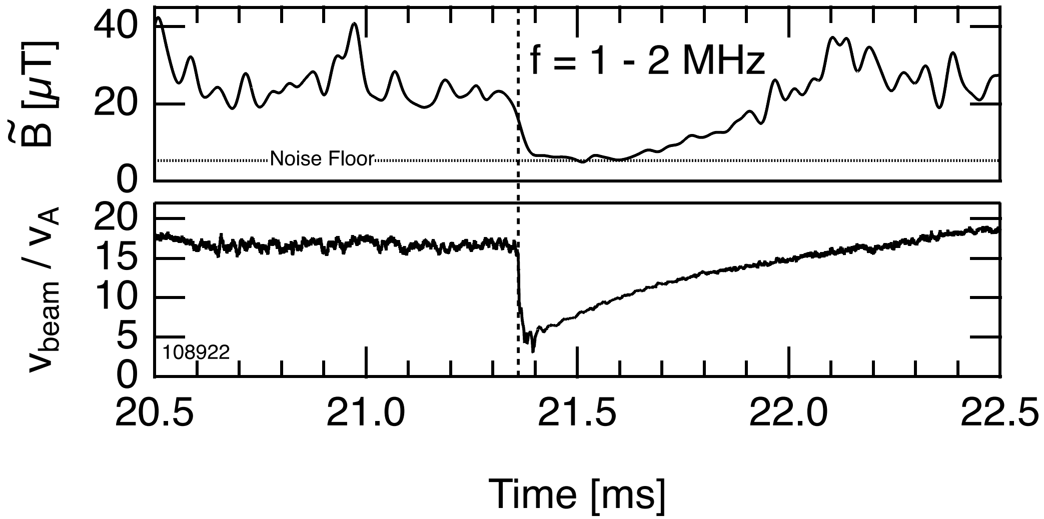
At injector shutoff, fluctuation power greatly reduced across all f



- V_{inj} rapidly shut off, gradually ramped back up
- Autopower of probe $\tilde{b}$ using short, moving time window, normalized to mean before shutoff (20.0–20.5 ms)

→ $\tilde{B}$ rapidly reduces following V_{inj} shutoff

$\tilde{b}$ returns as beam Alfvénic Mach number increases



- Previous work:* double layer at injector aperture → $v_{beam} \approx \sqrt{2eV_{inj}/m_e}$
- $\tilde{b}$ reestablishes as V_{inj} increases → dependency v_{beam} and/or Alfvénic Mach #

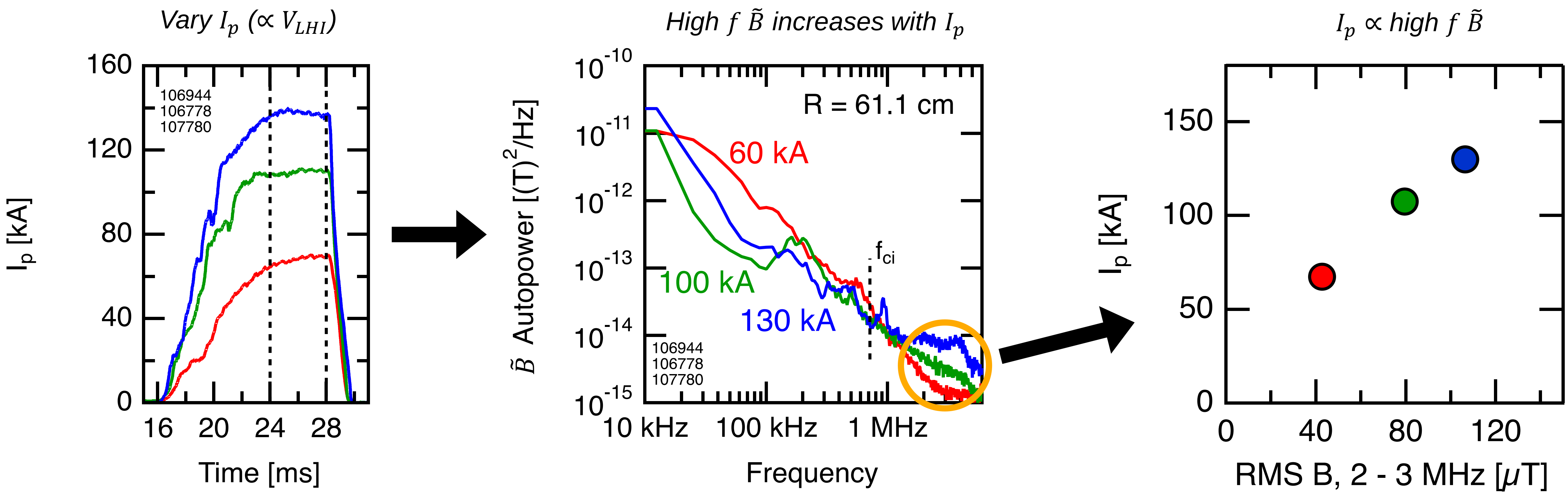
→ Kinetic/beam instabilities driving broadband magnetic activity ?

*E.T. Hinson et al., Phys. Plasmas **23** 052515 (2016)

Outline

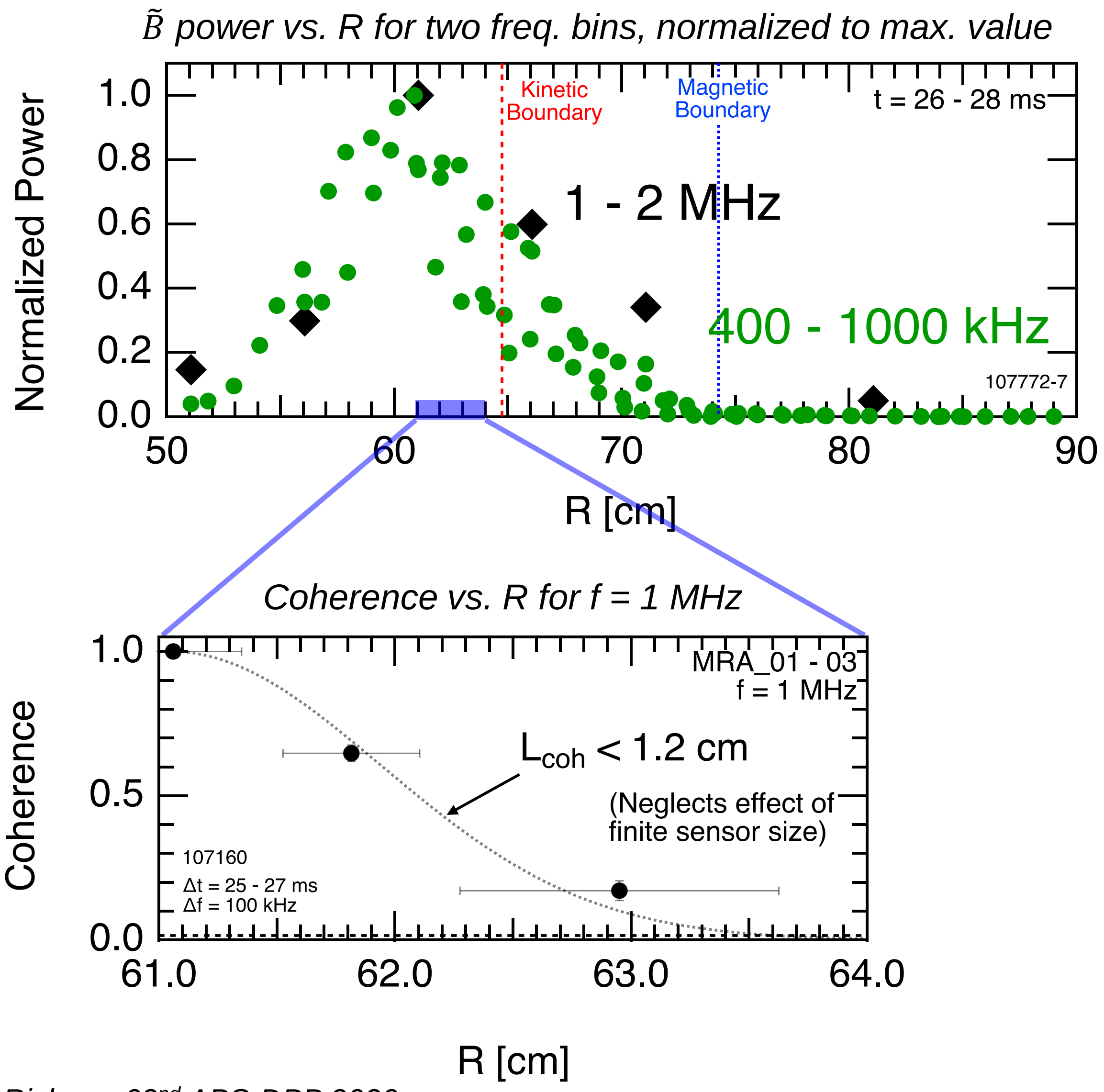
- Local Helicity Injection and Motivation for Investigating $\tilde{B}$ During LHI
- Significant Magnetic Activity is Observed During LHI
- Observed Activity Suggestive of Magnetic Turbulence
- Assessing Role of Magnetic Activity in LHI Current Drive
- Summary & Conclusions

High Frequency $f > f_{ci}$ Activity is Correlated with I_p, LHI Drive



- Similar helicity-sustained discharges developed with varying LHI drive
- $\tilde{B}$ amplitude for $f \gg f_{ci}$ increases with I_p, V_{LHI}

High Frequency Activity Concentrated in Similar Spatial Region as Broadband Fluctuations

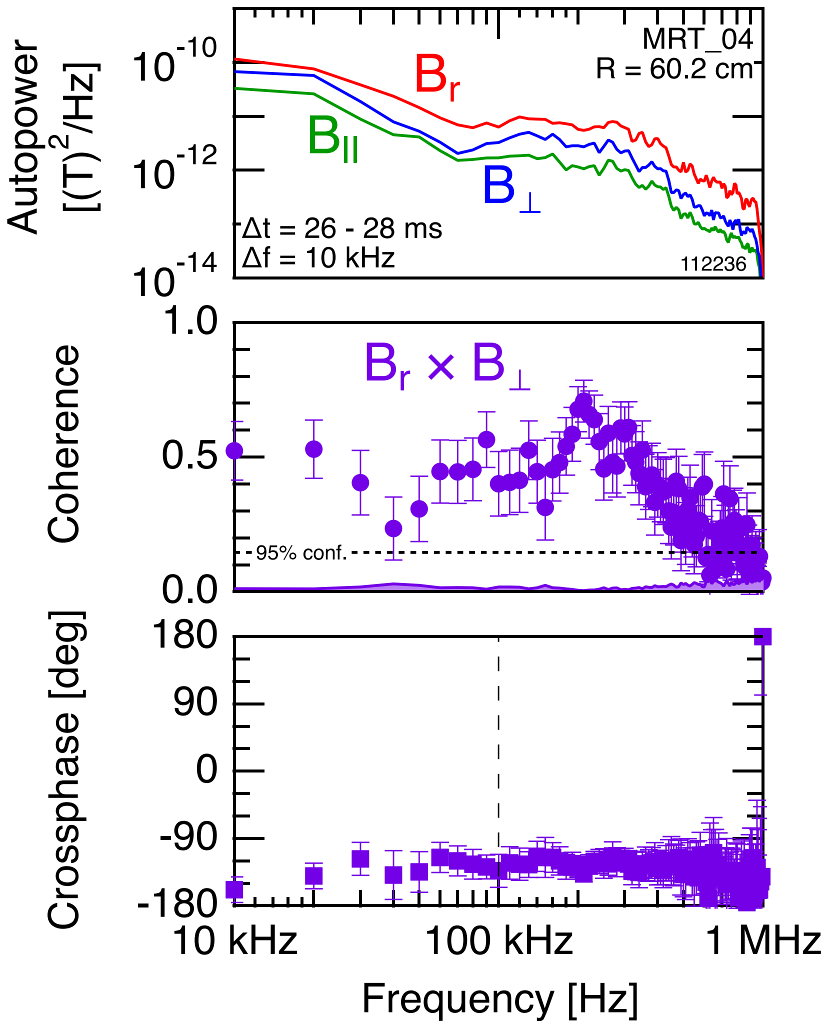


- Similar spatial distribution as broadband fluctuations
  - Similar physical source / related to injected current stream?
  - Localized **interior** to edge of confined region

- Radial coherence length much shorter than spatial distribution
  - Measured radial L_{coh} imply characteristic turbulent scale lengths are much shorter than the spatial distribution of the activity
  - Could suggest relatively low fluctuation-induced transport, in qualitative agreement with observed confinement during LHI

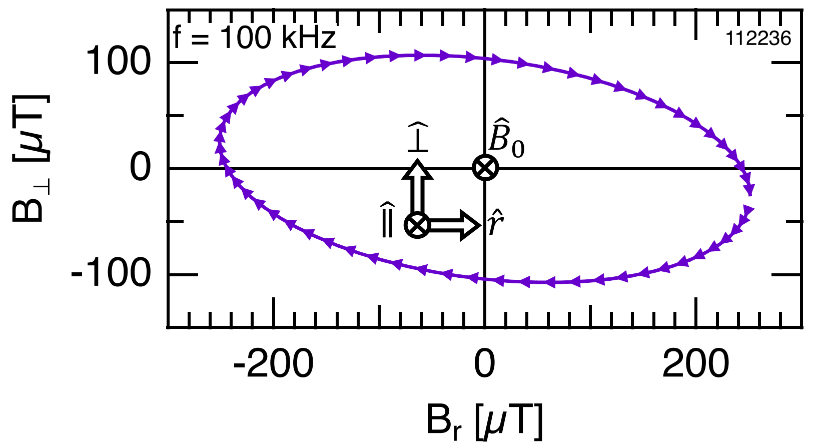
Correlation Between $\tilde{B}_R$, $\tilde{B}_Z$ Indicates Net Circular Polarization

Autopower for components of $\tilde{\mathbf{B}}$, and coherence & crossphase between two field-normal directions



- Correlations between different components $\tilde{\mathbf{B}}$ important to helicity transport & dynamo EMFs
  - Circularly polarized activity can carry/transport* "helicity density" $h = \mathbf{a} \cdot \mathbf{b}$
  - Phasing important in dynamo EMFs, informs drive / anti-drive
  - Care about components normal to $\mathbf{B_0}$ → $\tilde{B}_r$, $\tilde{B}_\perp$
- Significant correlation found between components of $\tilde{\mathbf{B}}$
  - Right-handed circular/elliptical polarization wrt. $\mathbf{B_0}$
  - Observed over wide frequency range

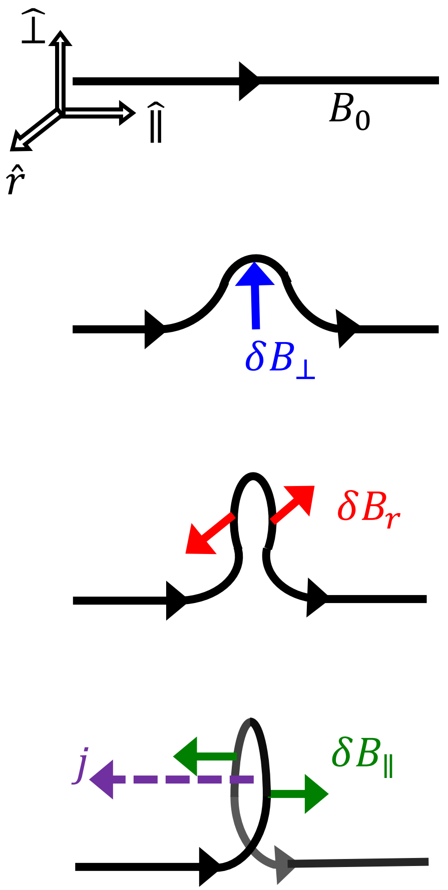
Phasing indicates RH elliptical polarization



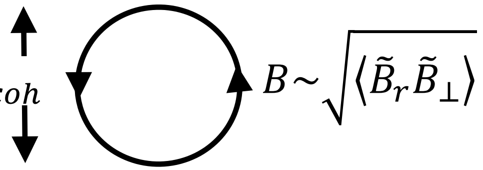
*V.S. Chan et al., Phys. Fluids B **2** 1441 (1990)

Polarization of Activity Suggestive of Dynamo Current Drive

α Dynamo: stretch, twist, & fold of B_0 drives current*

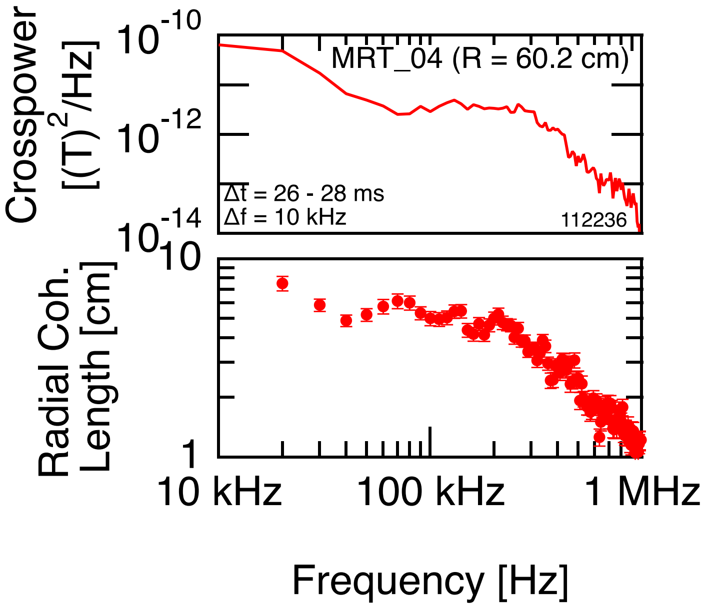


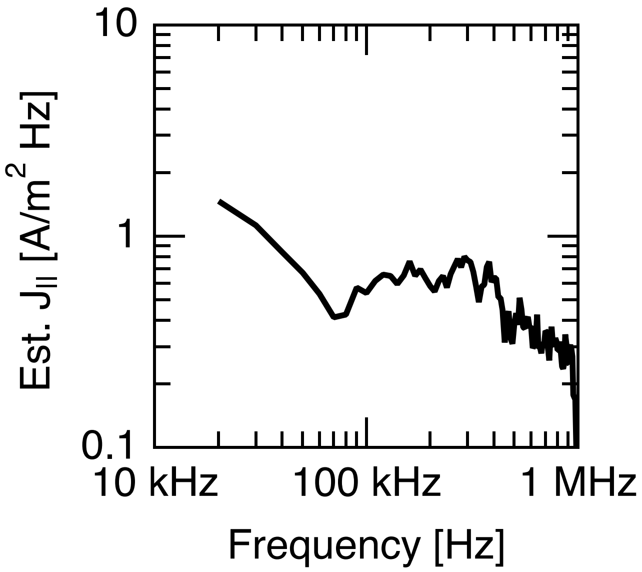
- α dynamo: EMF from twisting & folding of magnetic field into loops
- Crude est. of $J_\parallel$ from correlated field fluctuations using simplistic model:



$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} \quad \rightarrow \quad J_\parallel \sim \frac{2\sqrt{\langle \tilde{B}_R \tilde{B}_Z \rangle}}{\mu_0 L_{coh}}$$

Coherent power and radial coherence lengths used to compute frequency-dependent estimate of $J_\parallel$





Integrating over all freq.:

$$J_\parallel \sim 460\ \mathrm{kA/m^2}$$

For comparison:

$$\langle J_{tor} \rangle \sim 250\ \mathrm{kA/m^2}$$

$$J_{tor,max} \sim 600\ \mathrm{kA/m^2}$$

*H.K. Moffatt, Magnetic field generation in electrically conducting fluids (1978)

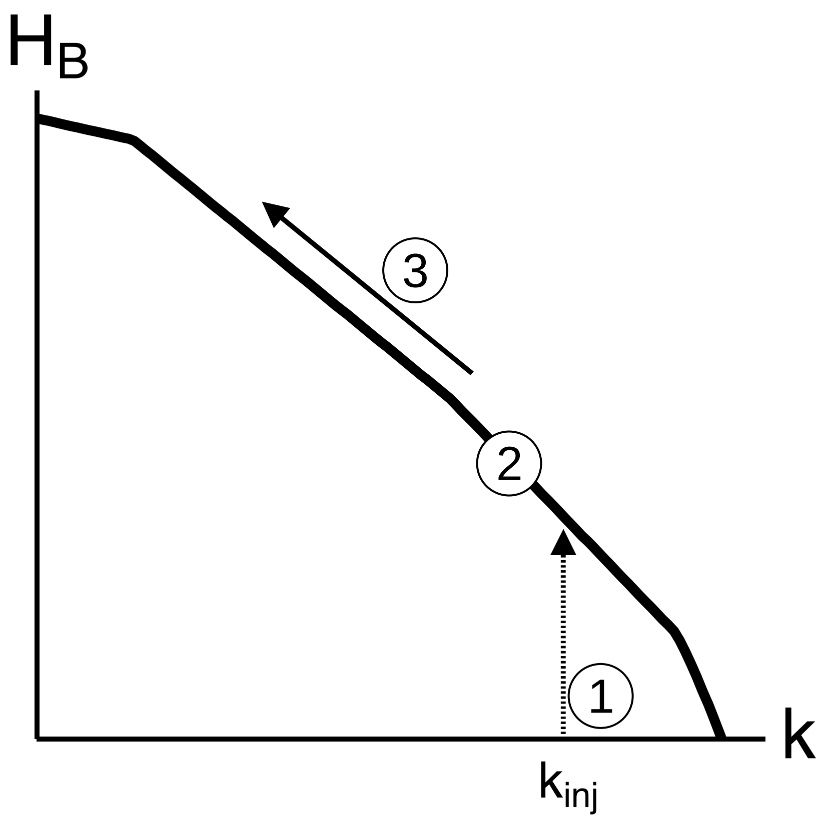
Outline

- Local Helicity Injection and Motivation for Investigating $\tilde{B}$ During LHI
- Significant Magnetic Activity is Observed During LHI
- Observed Activity Suggestive of Magnetic Turbulence
- Assessing Role of Magnetic Activity in LHI Current Drive
- Summary & Conclusions

Characterization of Magnetic Activity Present During LHI Informs Dynamics, Relaxation, and Current Drive

- Significant magnetic activity is present during LHI
- Broadband fluctuations are suggestive of MHD/Alfvénic turbulence
- High frequency activity $f > f_{ci}$ is correlated with current drive
- Correlation & phasing between components of $\tilde{\mathbf{B}}$ over broad frequency range suggestive of dynamo CD

Suggests Working Model for Current Drive During LHI



1. Beam/kinetic instabilities in injected current streams, drive small-scale fluctuations
2. Nonlinear coupling between generated activity drives broadband magnetic turbulence
3. Turbulence transfers helicity via inverse cascade
4. Broadband fluctuations in the cascade generate current via dynamo effect
5. In steady-state, dynamo EMFs in turbulent cascade balance resistive dissipation of large-scale I_p

Reprints

Reprints of this and other PEGASUS presentations are available online at

https://pegasus.ep.wisc.edu/technical-reports/conference-presentations/