Observations of Magnetic Turbulence During Local Helicity Injection on PEGASUS

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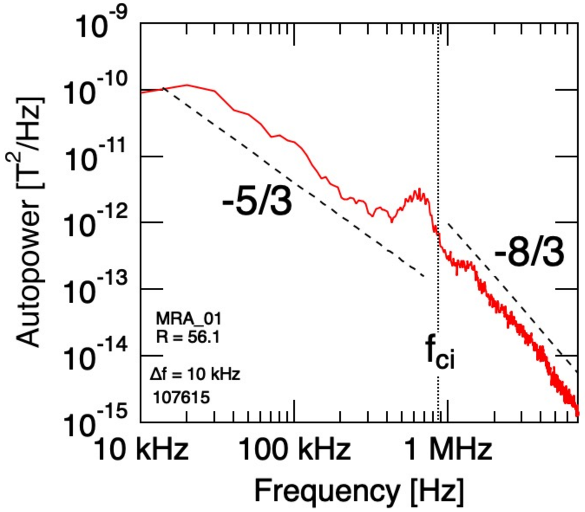
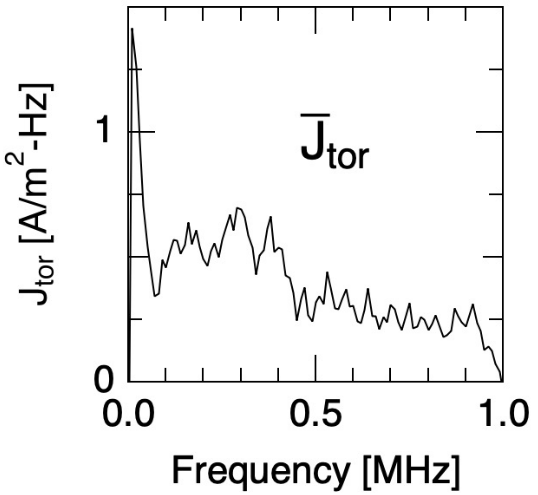
University of
Wisconsin-Madison

PEGASUS
Toroidal Experiment

Observations & Characteristics of Magnetic Activity Provide Working Model for LHI Current Drive

- Local helicity injection (LHI) used for nonsolenoidal current drive
  - Previously: total achieved current governed by global constraints
  - Focus now: understanding local, physical mechanisms that lead to current drive under those constraints
- Local current drive from beam-driven turbulence
  - Significant fluctuation activity driven by injector beams in plasma edge
  - Turbulent cascade consistent with Alfvénic turbulence driven by beam instabilities
  - Estimated fluctuation-driven J comparable to that of bulk plasma
- Provides working model for CD that can inform scaling of LHI

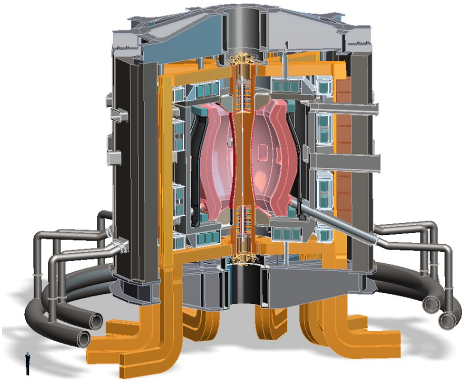




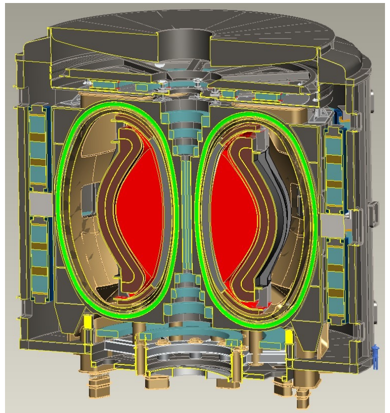
Non-Solenoidal Startup Is a Critical Need for the Spherical Tokamak, and May Benefit Advanced Tokamaks

- Nonsolenoidal startup & current drive is critical for the spherical tokamak
  - Need confirmed in repeated FESAC/community studies
  - Shielding / cost precludes OH in nuclear ST designs
- Benefits for tokamaks in general
  - Possible reduction in cost/complexity
  - Space for inboard shielding / blanket / RF
  - Lowers electromechanical stresses

ST-FNSF, FNSF / Pilot Plant Concepts
Shielding constrains OH viability



Solenoid-free
Cu
ST-FNSF

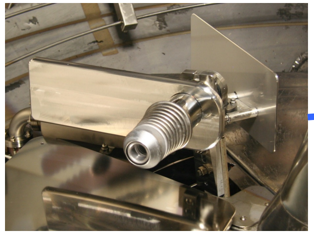


No / small OH
HTS
ST-FNSF / Pilot Plant

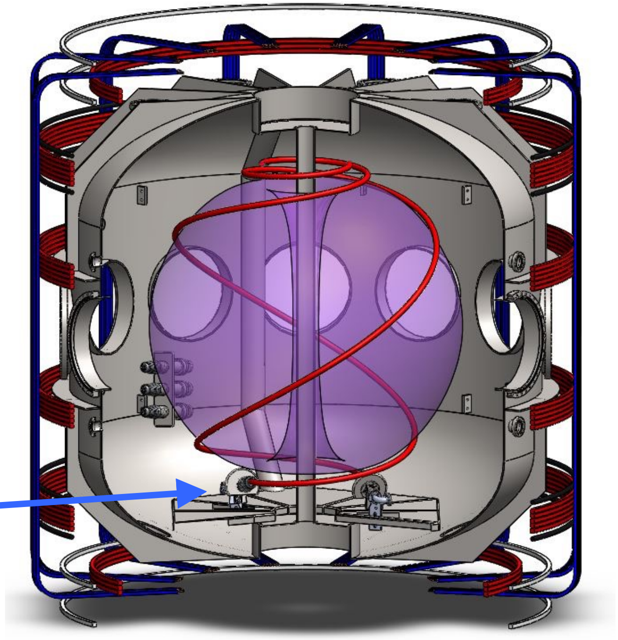
J.E. Menard et al., Nucl. Fusion ***56,*** *106023 (2016)*
J.E. Menard, Phil. Trans. R. Soc. A ***377****, 20170440 (2019)*

Local Helicity Injection Provides Non-Inductive Startup at Low *A*

Local Helicity Injectors



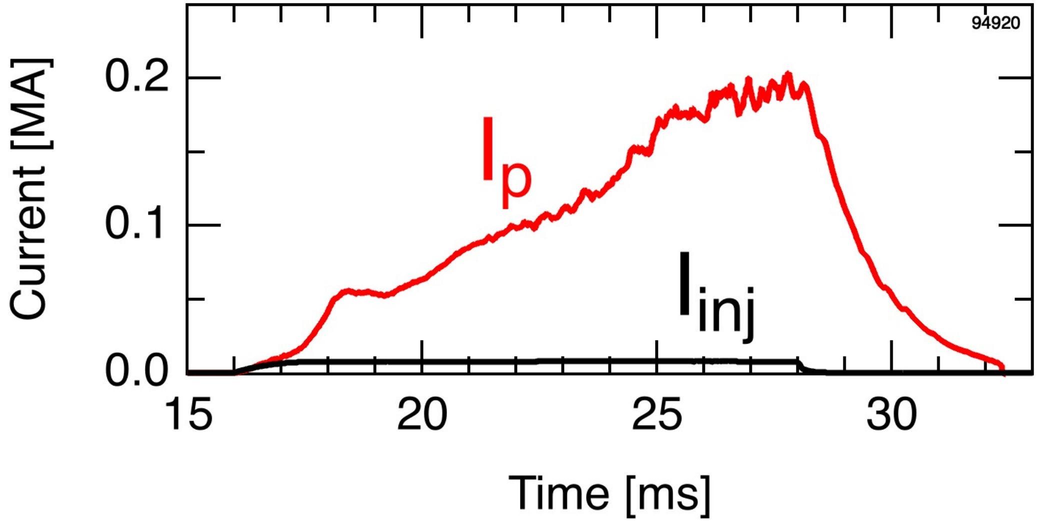
PEGASUS



PEGASUS Parameters

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

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



- Edge current extracted from small, modular injectors
- Relax to tokamak-like state via helicity-conserving instabilities
- Used routinely for startup and current drive on PEGASUS

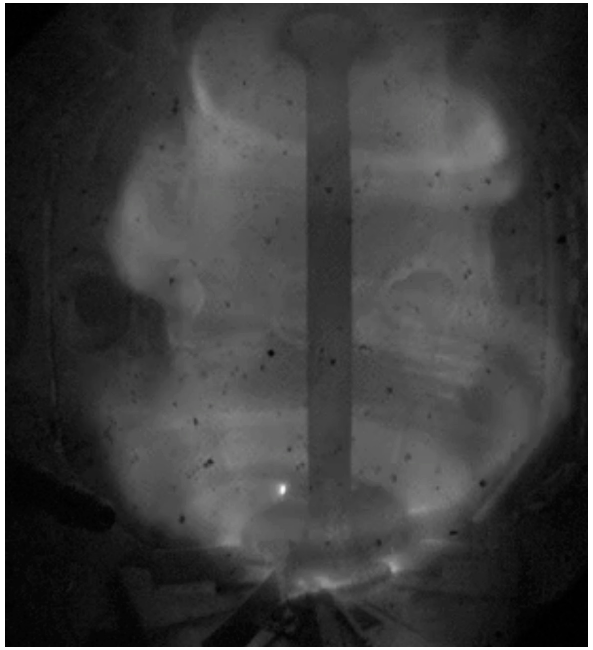
M.W. Bongard et al., Nucl. Fusion ***59****, 076003 (2019)*

LHI Startup Through Relaxation of Injected Current Streams

1. Injected current follows vacuum B_Z

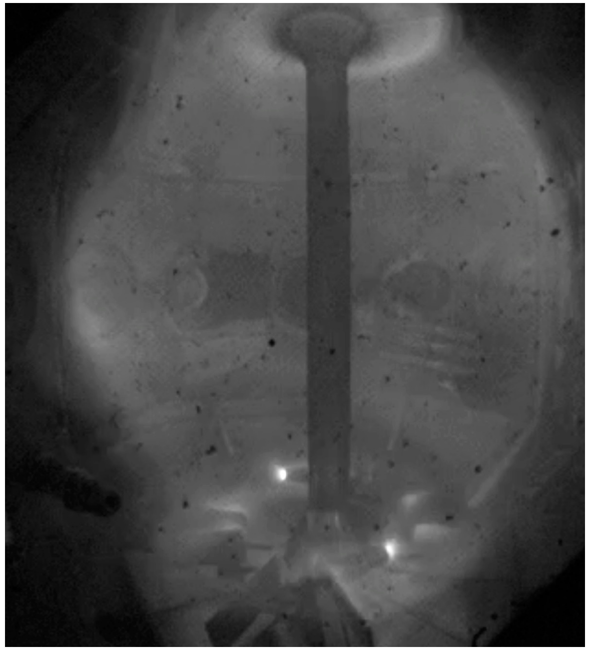
$$I_p \approx N_{turns} I_{inj}$$

2. Unstable current streams attract, reconnect



$$I_p \gtrsim N_{turns} I_{inj}$$

3. Tokamak-like plasma forms, rapid I_p growth



$$I_p \gg N_{turns} I_{inj}$$

Understanding HI Physics Crucial for Application to Future Devices

- Global limits to I_p for helicity injection are well-understood:

1) Helicity Conservation:

Effective LHI loop voltage

$$V_{LHI} = V_{inj} \frac{B_n A_{inj}}{\Psi_{tor}}$$

2) Taylor Limit:

I_p limited by edge $J_{\parallel}/B$ (related to I_{inj})

$$I_p \leq \frac{\Psi_{tor} I_{inj}}{2\pi R_{inj} B_{p,inj} w}$$

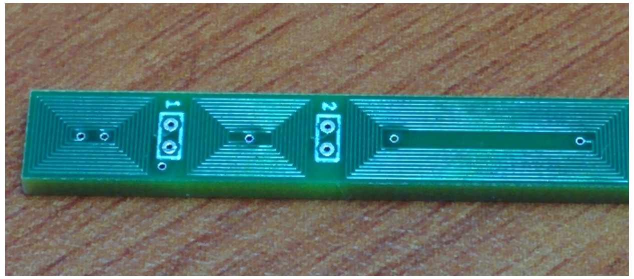
→ To extrapolate to fusion-scale, also need to understand the local current drive mechanism(s)

– Relaxation mediated by instabilities/turbulence → study $\tilde{b}$

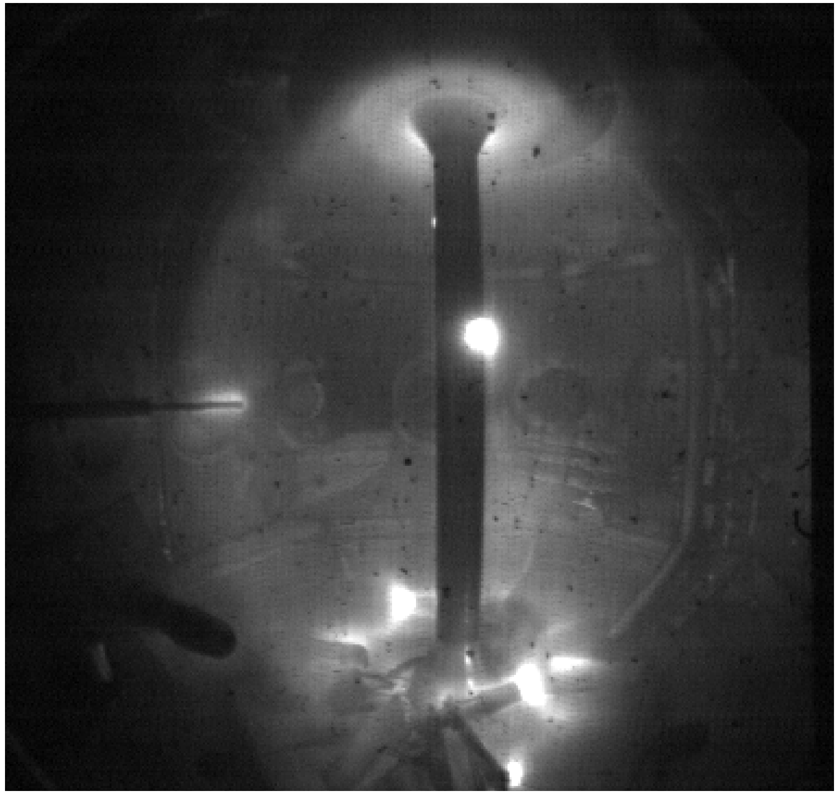
Insertable Probes Provide Direct, Local $\tilde{b}$ Measurements

- Modest edge n_e, T_e, B in PEGASUS permit use of insertable probes*

- Probes developed to study $\tilde{b}$ during LHI:**
  - High speed, 15 channel, 1-D ($\dot{B}_z$) array probe
  - High speed, 10 channel, 3-D $\dot{\mathbf{B}}$ array probe



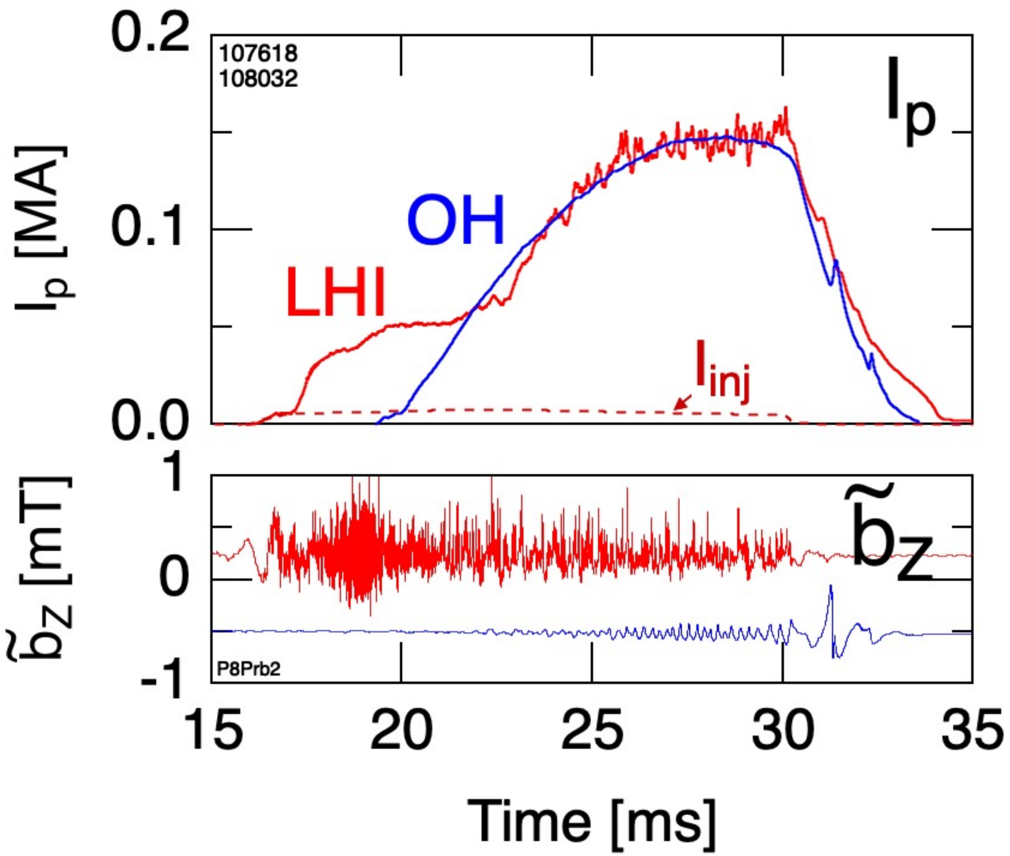
Probe Inserted into LHI Discharge



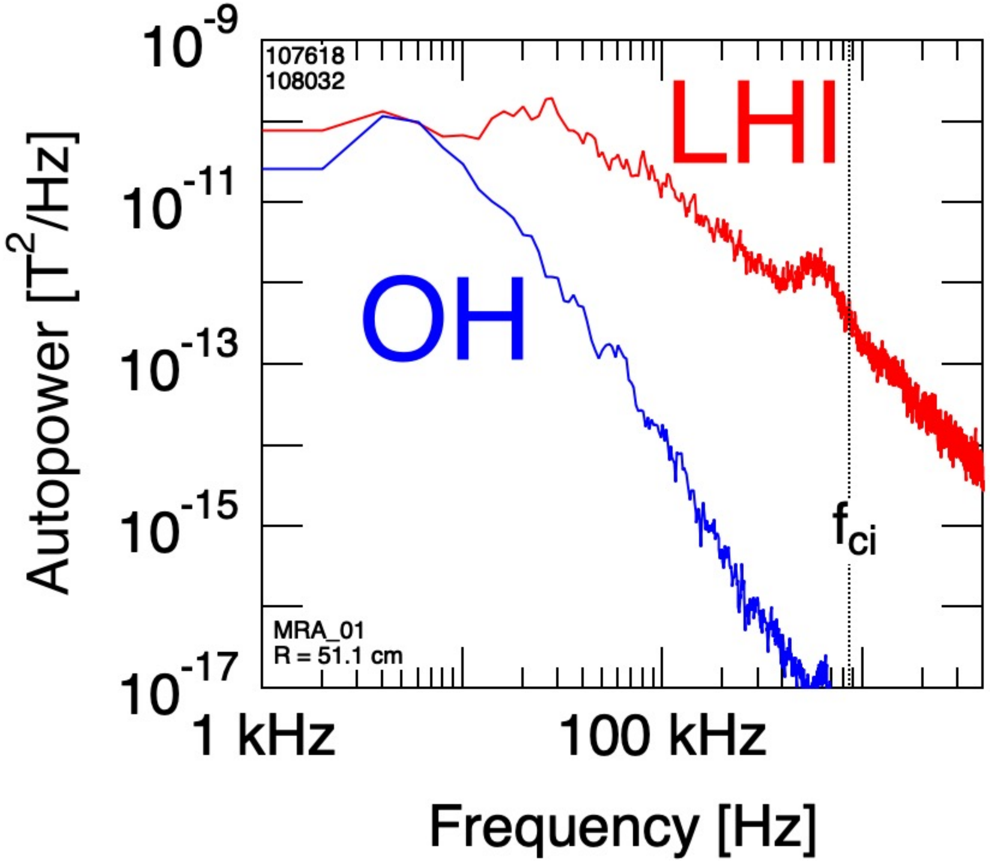
*K.E. Thome et al., PRL **116**, 175001 (2016)
N.J. Richner et al., Rev. Sci. Instr. **89 10J103 (2018)

Significant Broadband Magnetic Activity Present During LHI

Similar LHI and OH plasmas are compared

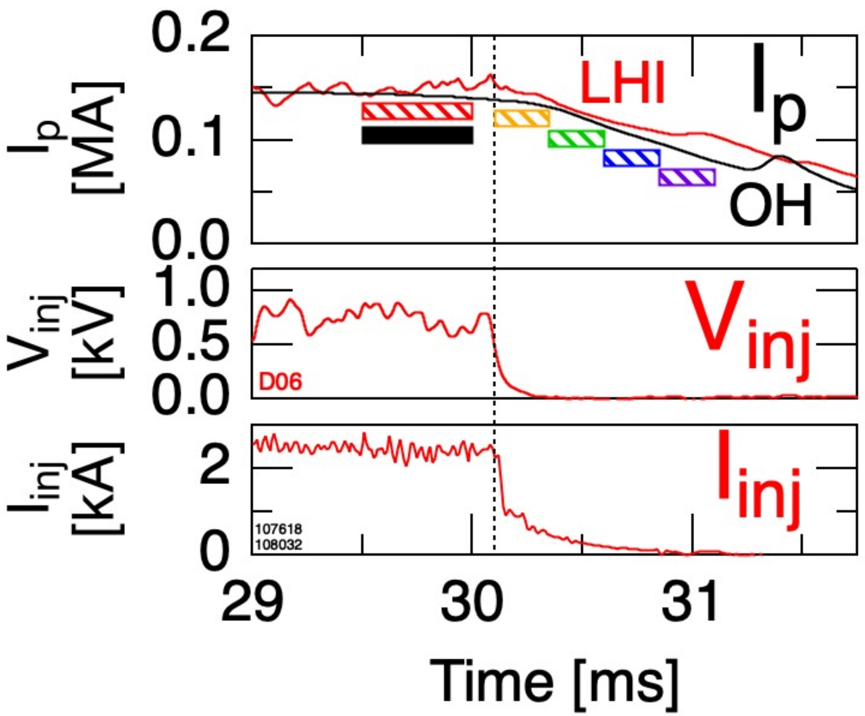


Edge magnetic activity in LHI ≫ that in Ohmic

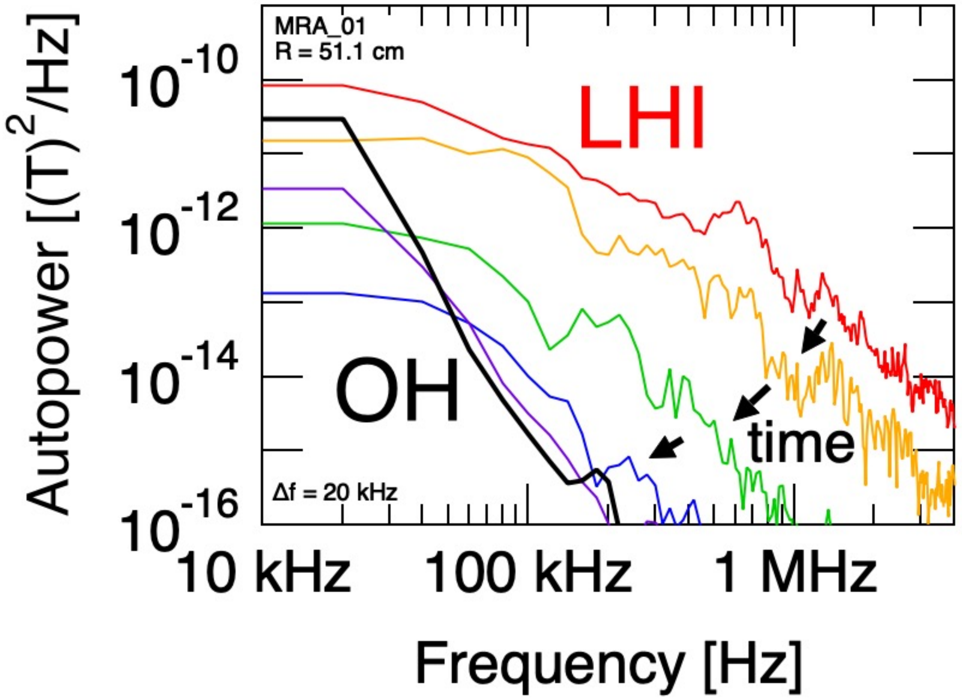


Decay of $\tilde{b}$ at Injector Shutoff → Activity due to LHI Drive

Time windows in decay phase



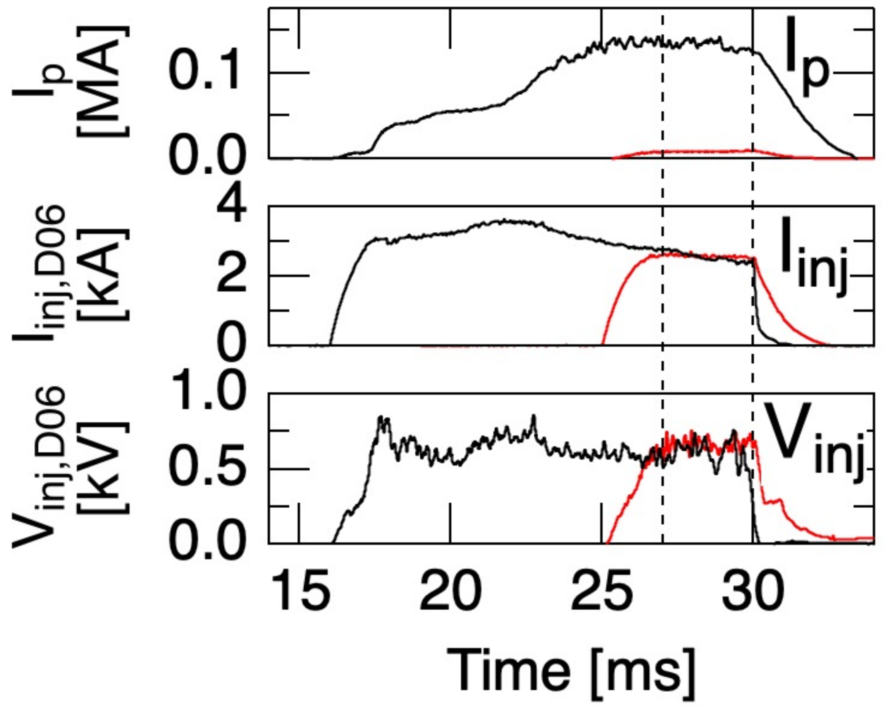
$\tilde{b}$ rapidly decays to OH level after shutoff



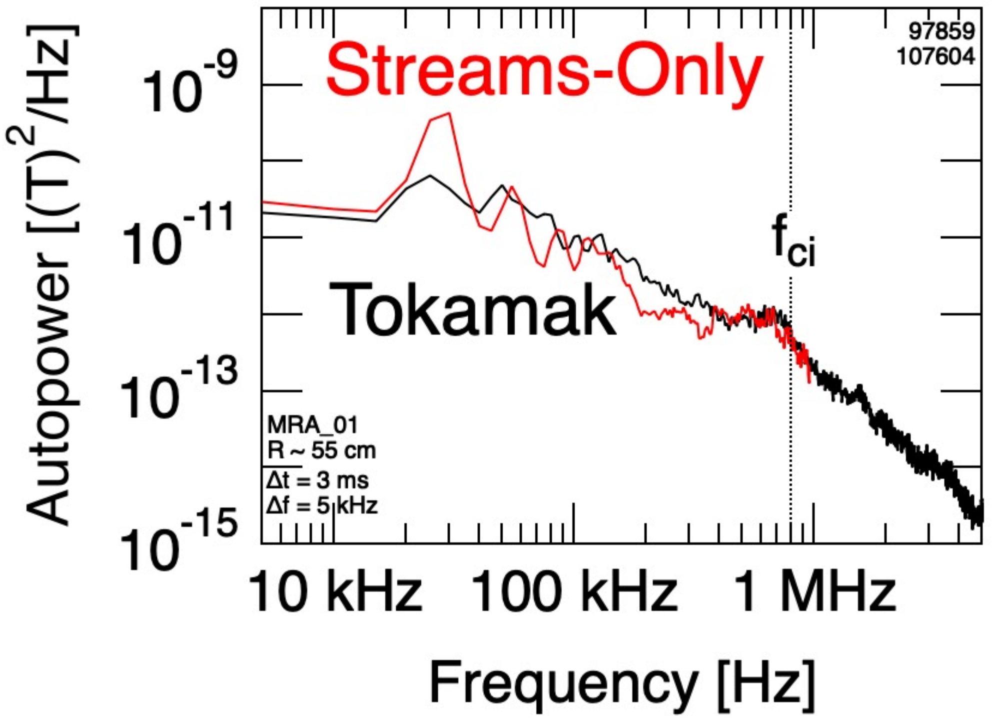
- Long I_p decay in LHI → formation of closed flux surfaces following shutoff.
- Time scale of relaxation from LHI spectra to Ohmic comparable to that seen in NIMROD simulations.

Turbulent $\tilde{b}$ Driven by Injected Electron Stream, Rather than Bulk Plasma

Compare stream-only and tokamak plasmas with similar I_{inj}, V_{inj}



Similar magnetic spectra are observed for stream-only and LHI tokamak plasma

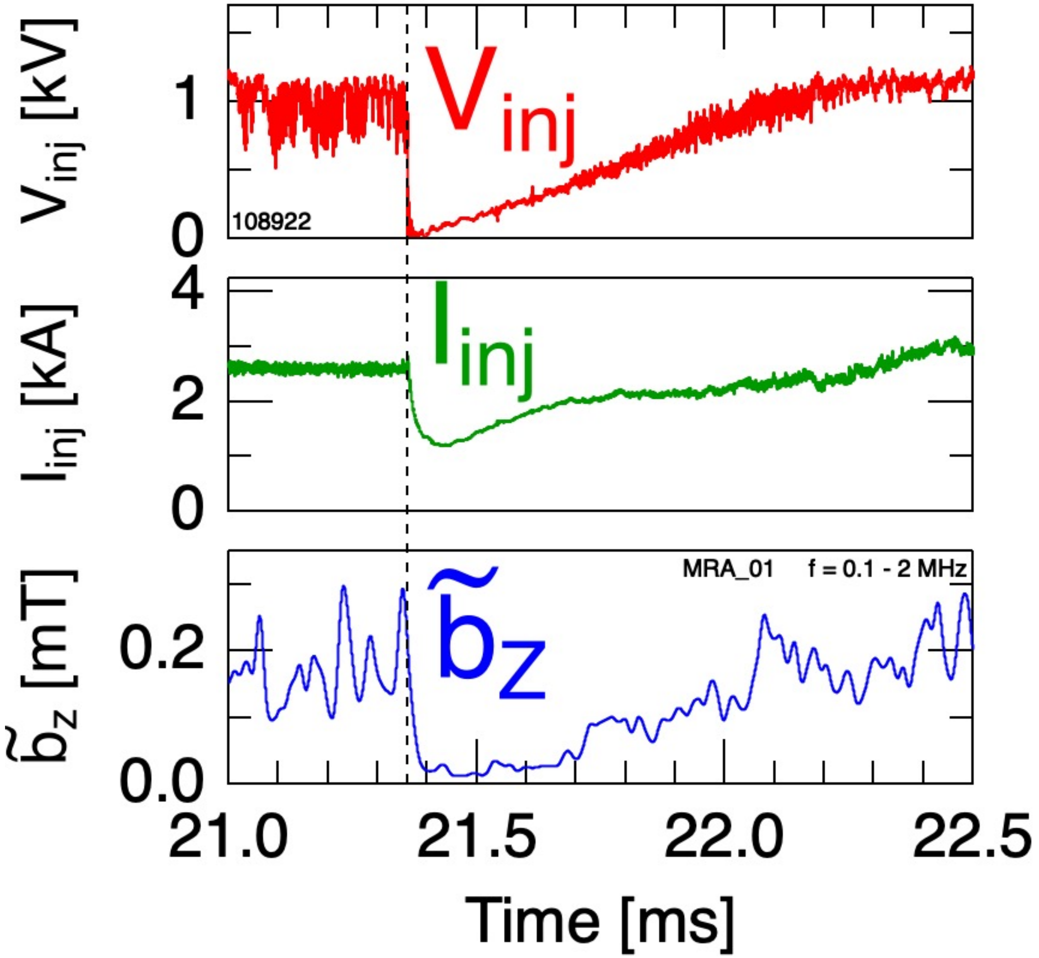


→ Relevant mechanisms driven by stream electron distribution, not background plasma

Strong Sensitivity of $\tilde{b}$ to Electron Velocity Implies Beam Instability

- Strong correlation of $\tilde{b}$ with V_{inj} observed
- At injector: beam velocity $v_b \propto \sqrt{V_{inj}}$ via double layer acceleration*
- Dependency of $\tilde{b}$ on v_b implies beam instabilities
  - Additionally: $v_b \gg V_A, \quad v_b \gg v_{th,e}$

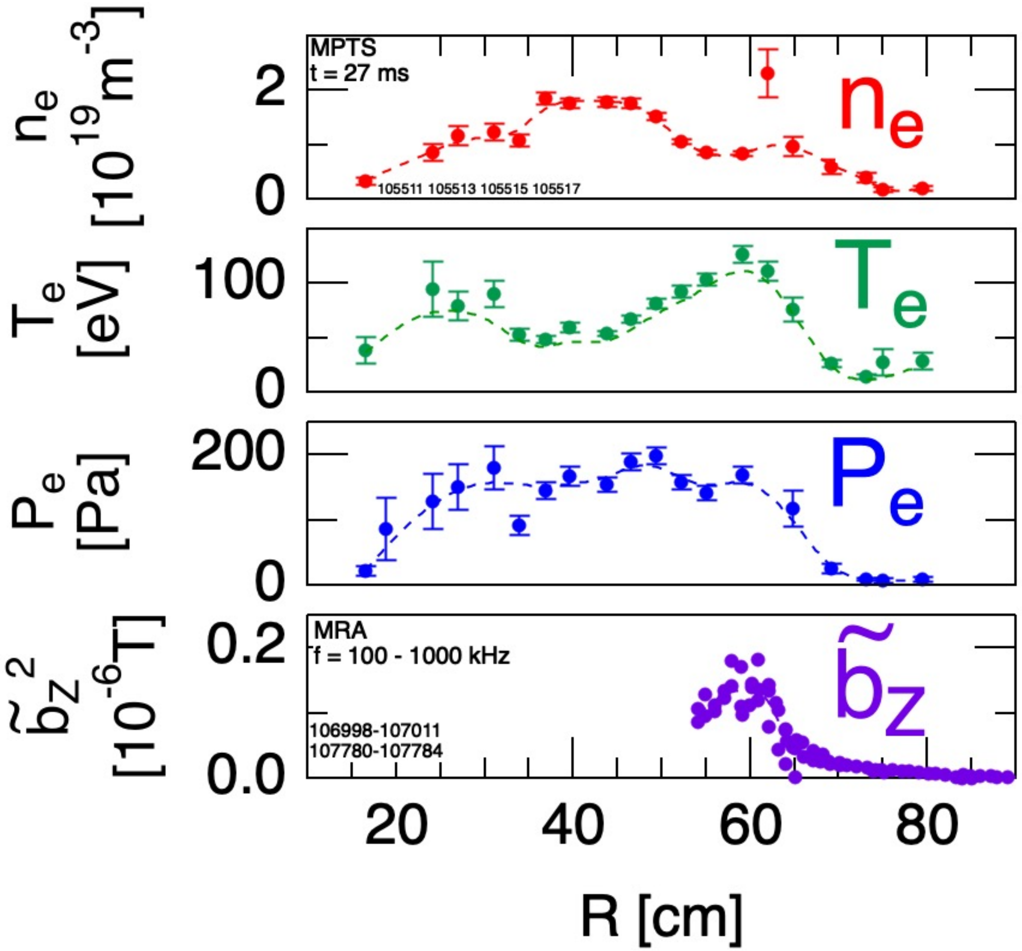
Injector voltage crowbarred mid-shot, gradually restored



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

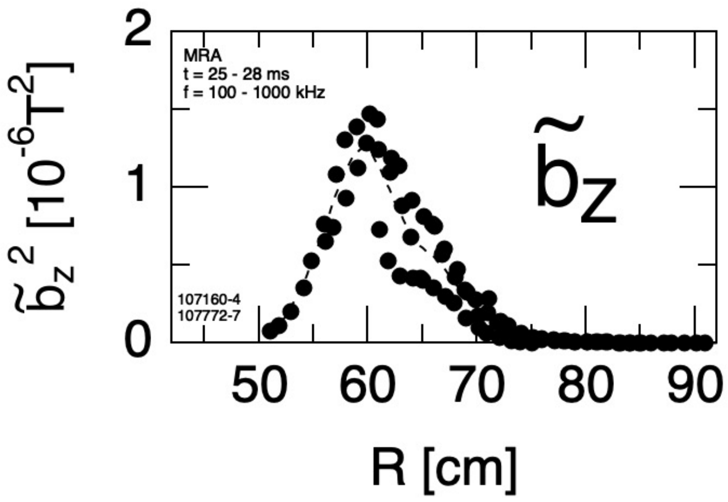
Magnetic Activity is Localized to Plasma Edge

Radial distribution of magnetic activity vs. kinetic profiles



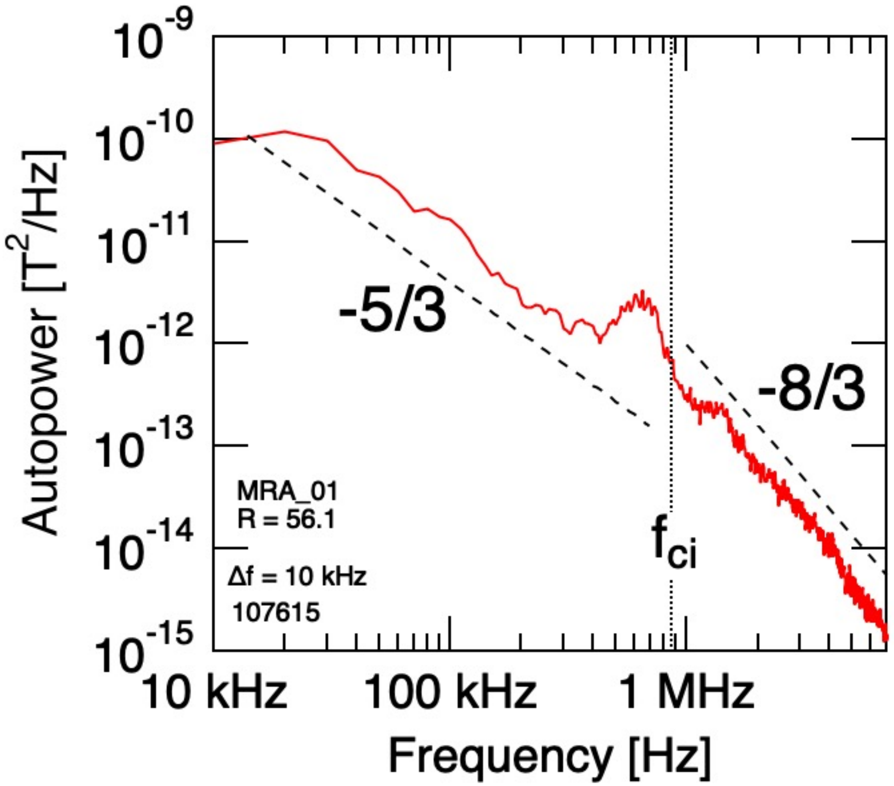
- $\tilde{b}$ peaked within plasma edge
  - Inboard of injector location projected to $Z = 0$
  - Similar R as injected current streams
  - $\tilde{b} \rightarrow 0$ toward R_0

Different shot confirms $\tilde{b} \rightarrow 0$ *toward* R_0

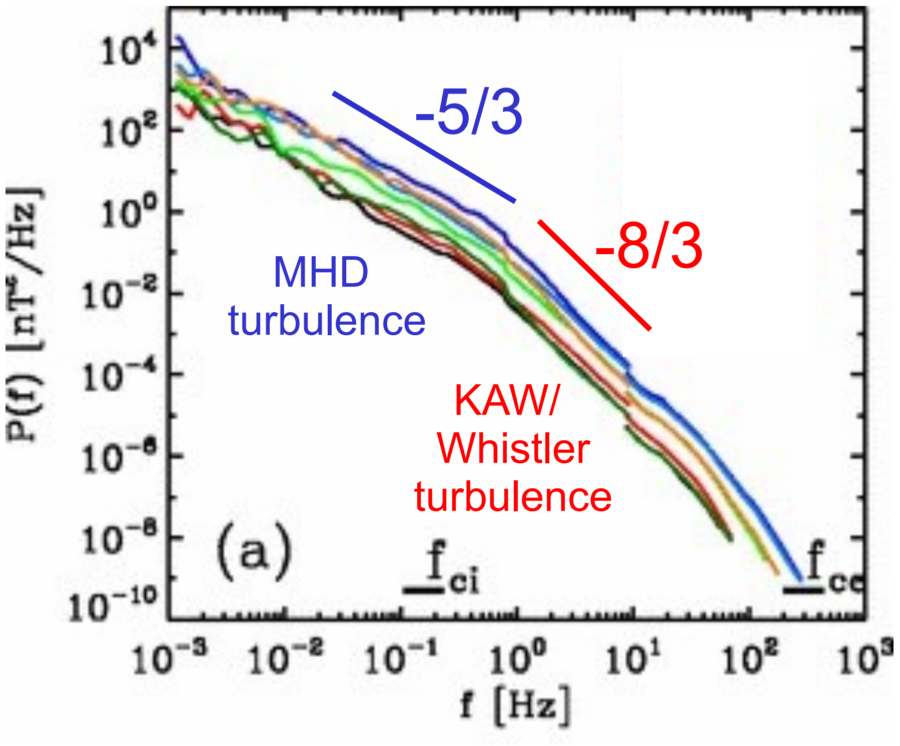


Form of Broadband $\tilde{b}$ Indicative of Alfvénic Turbulence

LHI Magnetic Power Spectra

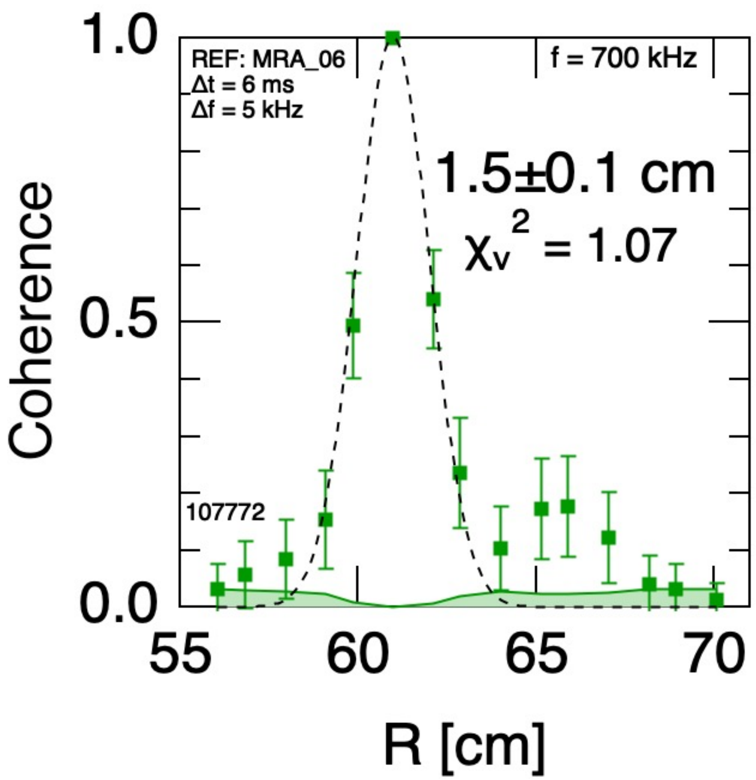


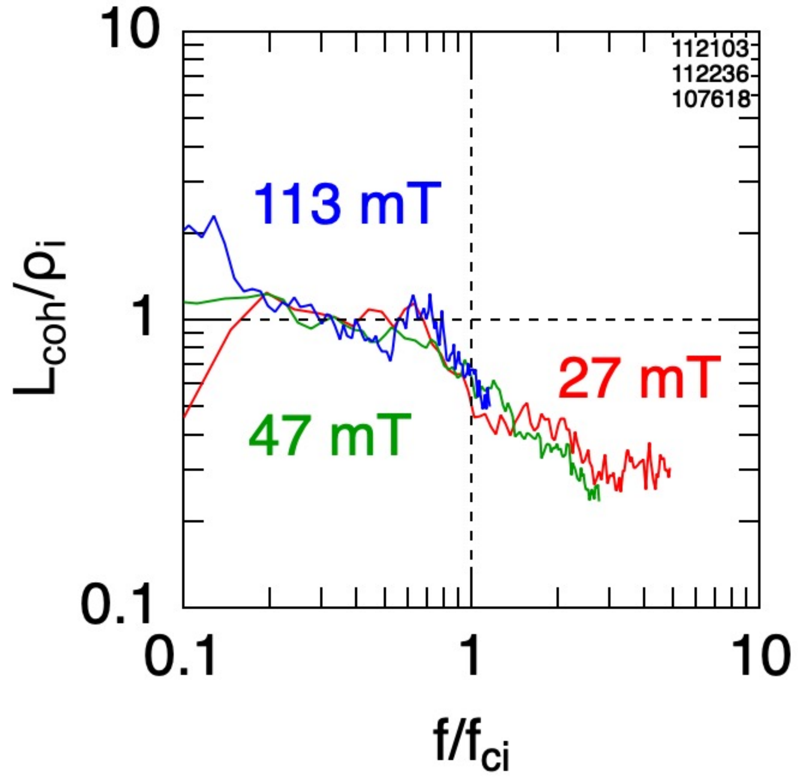
Solar Wind Magnetic Power Spectra



*Adapted from Alexandrvova, et.al., PRL, **103** 165003 (2009).*

Turbulent Scale Lengths Consistent with $k_\perp \rho_i \sim 1$





- Radial decay of coherence used to estimate turbulent scale length

- Normalized to f_{ci}, ρ_i
  → strong overlap of data

Accumulated Evidence Implies Energetic Electron Driven Alfvénic Activity

- Previous Slides: Observations consistent with beam-driven Alfvénic turbulence
  - Broadband $\tilde{b}$ associated with injectors, not bulk tokamak
  - Strong dependence of $\tilde{b}$ on beam velocity
  - Localization to edge region / injected stream location
  - Form of broadband activity ~ solar wind turbulence
  - Turbulent scale lengths $k_\perp \rho_i \sim 1$

→ Instability drive of turbulence has been identified

- **Next: look at properties/nature of saturated state that drives the dynamics of the plasma and how it relates to current drive**

Statistical Properties of LHI $\tilde{b}$ Indicate Small-scale Current Structures

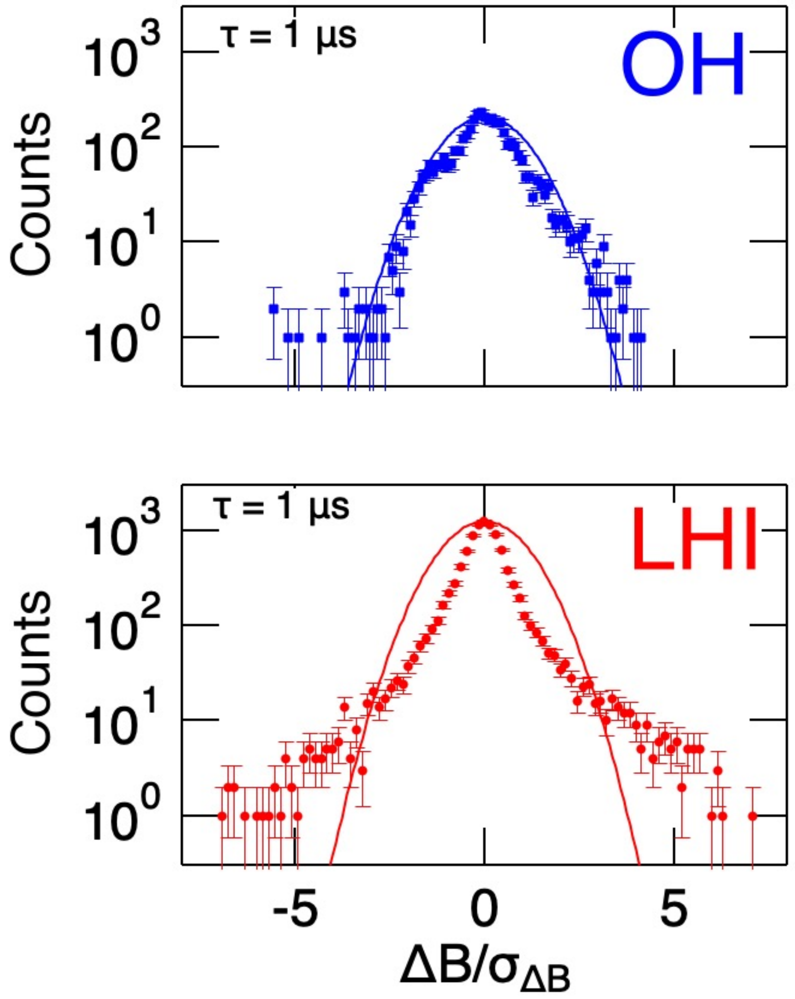
Statistical properties from PDF:

Random process:

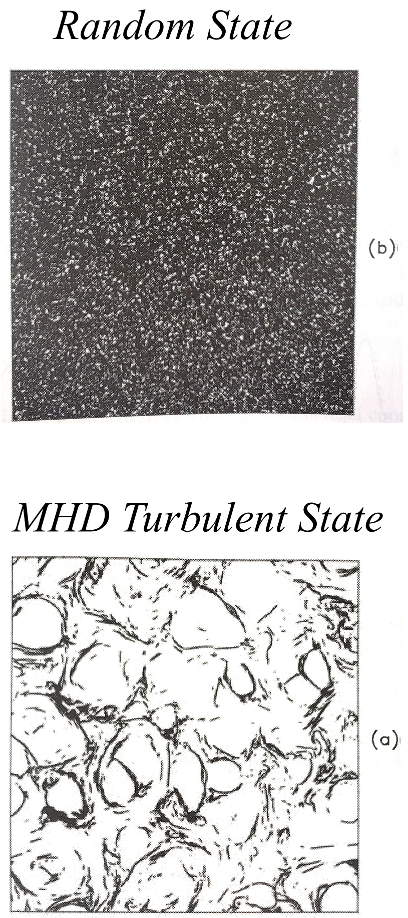
- Gaussian statistics

Intermittency:

- "Wings" at high ΔB



Intermittency in LHI $\tilde{b}$ → small-scale current structures



Adapted from fig. 7.2 of Biskamp, *Magnetohydrodynamic Turbulence (2003)*.

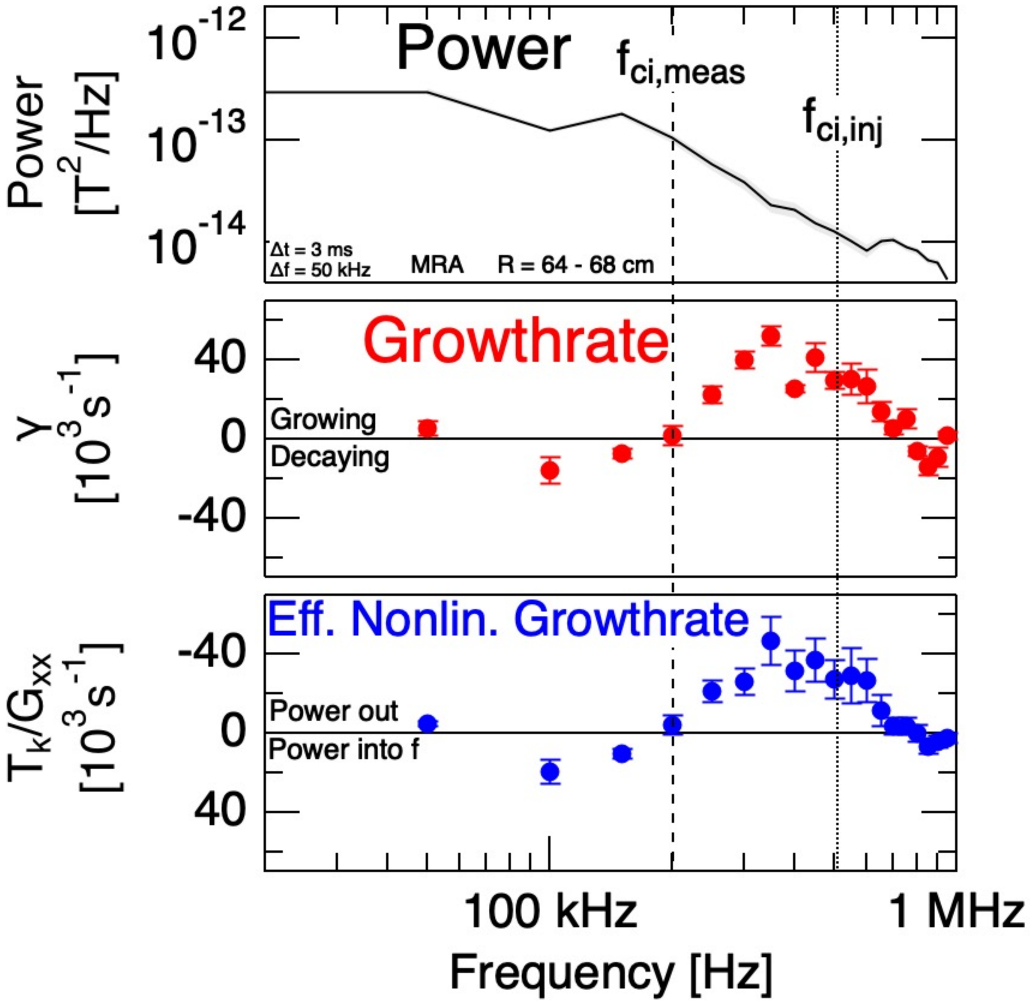
Magnetic Spectrum Shows Clear Region of Instability Growth

- Use higher-order PSD, adapted from technique used by Kim et.al.*

$$\underbrace{\frac{\partial P_k}{\partial t}}_{\text{Change in power at } k} = \underbrace{\gamma_k P_k}_{\text{Linear growth / damping rate}} + \sum_{k_1+k_2=k} \underbrace{T_k^{k_1 k_2}}_{\text{Nonlinear power transfer}}$$

- Spectral region identified, but physics regime depends on where modes are excited:
  - At source → modes in inertial range
    e.g., e^- beam Alfvén wave instability
  - At measurement location → kinetic modes
    e.g., e^- beam KAW instability

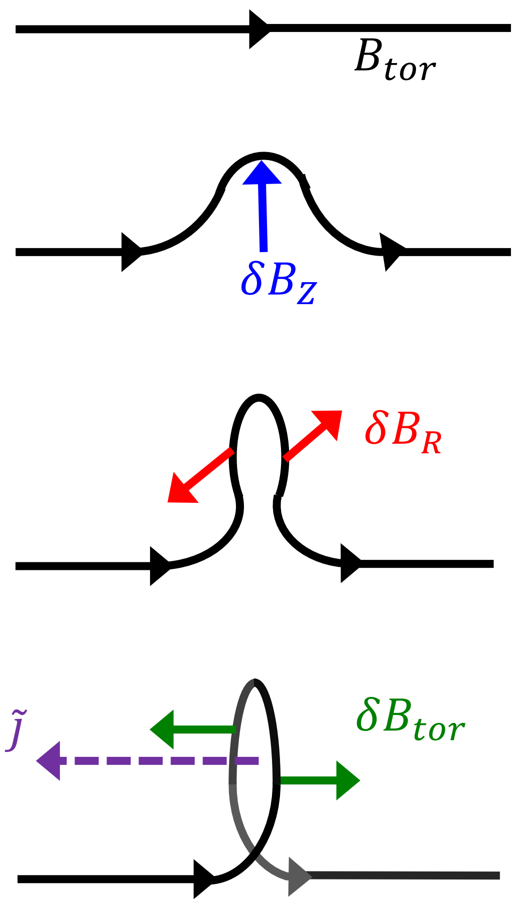
- Future studies needed to decouple these



*Kim et.al., Phys. of Plasmas, **3** 3998 (1996).

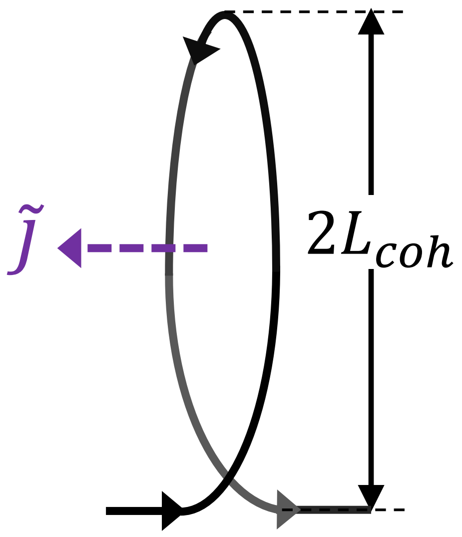
Coherent Fluctuations Drive Current via Dynamo EMFs

α Dynamo: stretch, twist, & fold of $\mathbf{B}$ *→ current*



Correlated Fluctuations Modeled as Ampèrian Loops

$$\mu_0 \tilde{\mathbf{J}} = \nabla \times \tilde{\mathbf{B}}$$



Net coherent power

$$\bar{J}_{tor}(f) \approx 2\,\mathrm{sgn}(\theta_{RZ}) \frac{\sqrt{\langle \tilde{b}_Z \tilde{b}_R \rangle}}{\mu_0 L_{coh,R}}$$

Co- vs. counter- drive

Broadband Dynamo EMFs can Account for LHI Current Drive

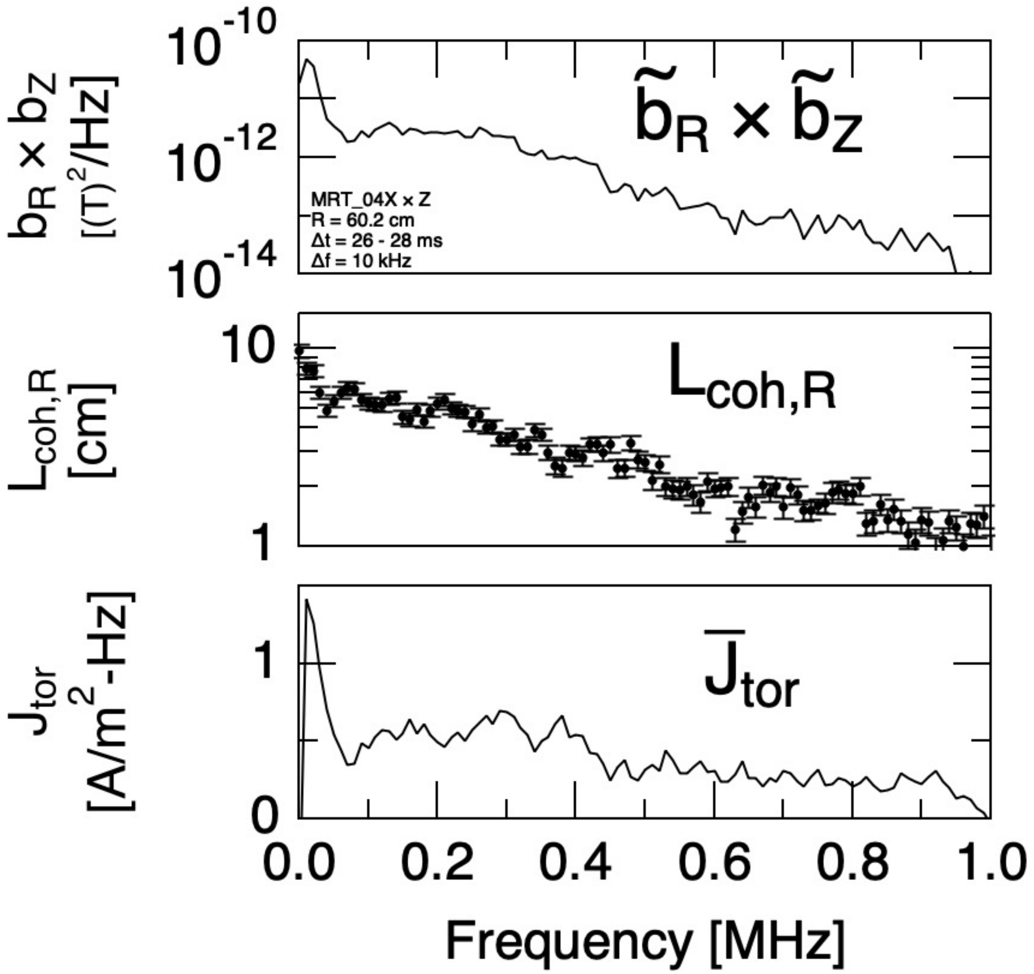
- Calculate $\bar{J}_{tor}(f)$ from probe data
  - $\bar{J}_{tor} \approx 2\,\mathrm{sgn}(\theta_{RZ})\sqrt{|\langle \tilde{b}_R \tilde{b}_Z \rangle| / (\mu_0 L_{coh})}$
- Integrating over all frequencies:

$\rightarrow$ $\bar{J}_{tor} \approx$ 400 kA/m²

- Comparable to equilibrium tokamak:

$\langle J_{tor} \rangle \approx$ 250 kA/m²

$J_{tor,max} \approx$ 600 kA/m²



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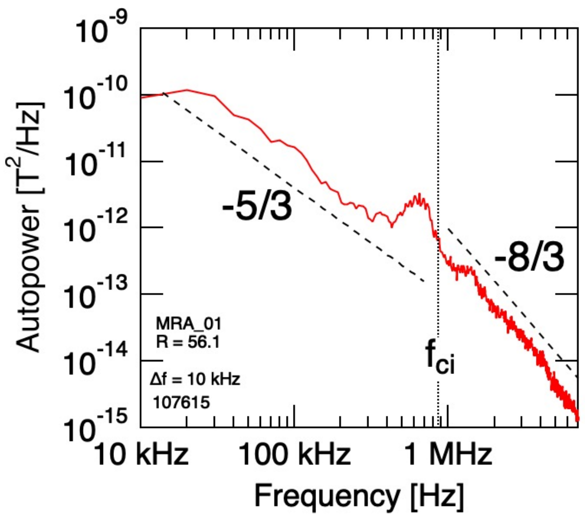

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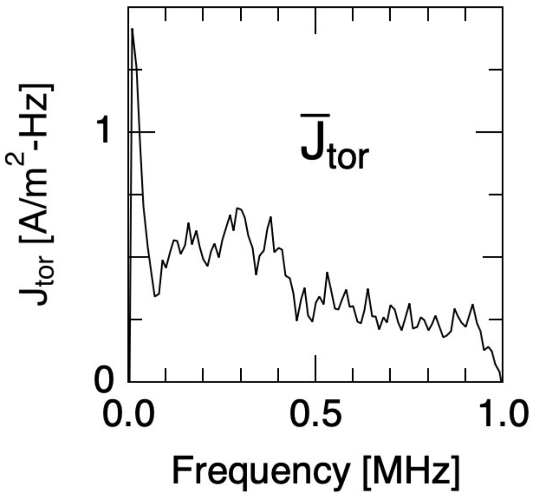

- Provides working model for CD that can inform scaling of LHI

PEGASUS-III Provides a Platform for Advancing This Understanding

- LFS injection
  → Reduce ambiguity of relevant f_{ci}

- Higher B, higher n, lower V_{inj}
  → Much wider range of beam Mach numbers

- Injector size, geometry variation
  → Scale lengths vs. physical size of beam

See also:
→ Contributed talk in **UO08** session (Thurs. PM)
→ Posters in **BP11** session (Mon. AM)
also online: pegasus.ep.wisc.edu

PEGASUS-III features:

- No solenoid
- 4x toroidal field
- Advanced control
- Expanded diagnostics