Magnetic Structure and Activity During Local Helicity Injection

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University of
Wisconsin-Madison

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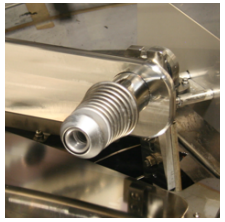


PEGASUS
Toroidal Experiment

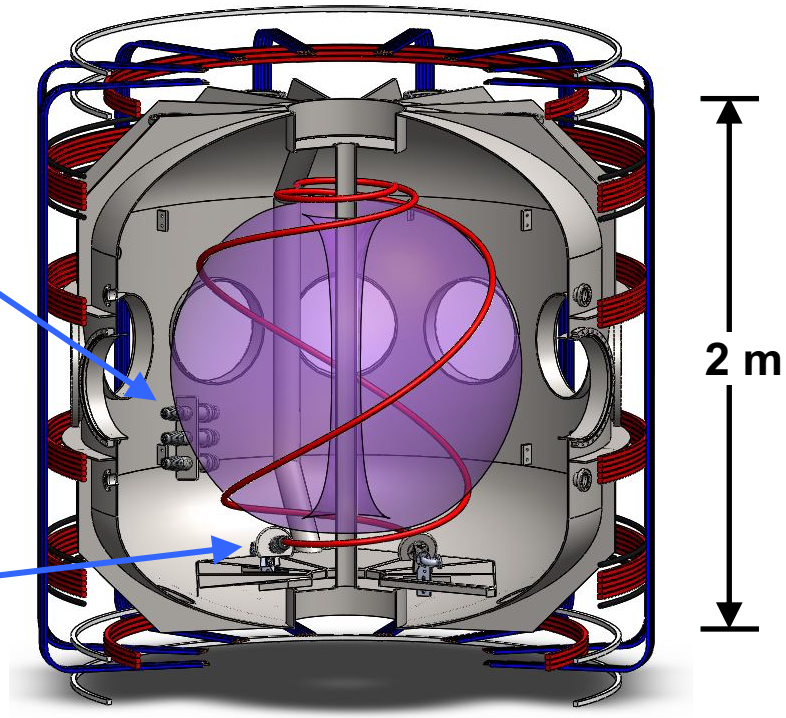
Local Helicity Injection (LHI) Routinely Used for Non-Solenoidal Startup on PEGASUS ST

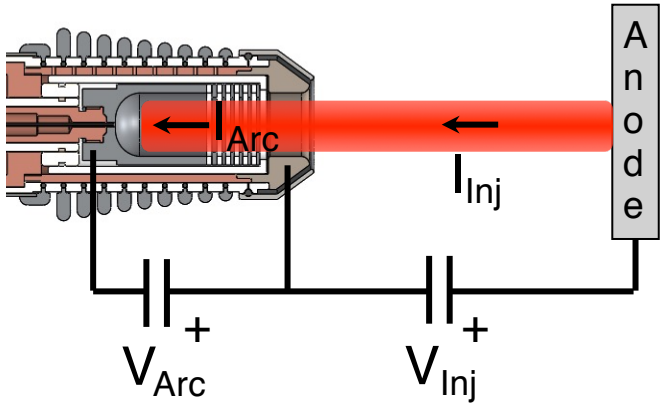
LFS Injectors



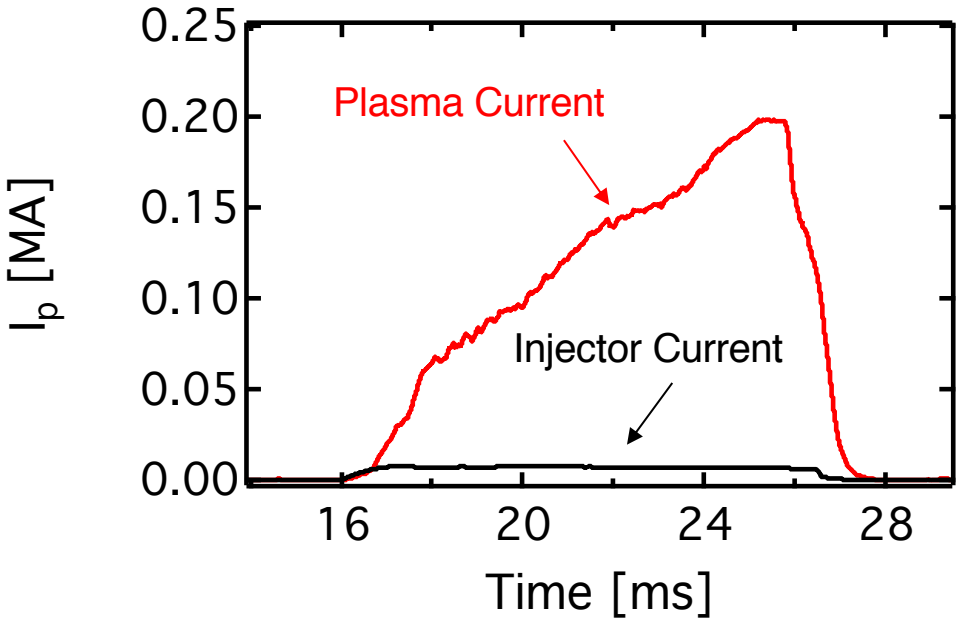


HFS Injectors





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

Confident Scaling to Next-Step Devices Req. Physics Understanding of LHI CD

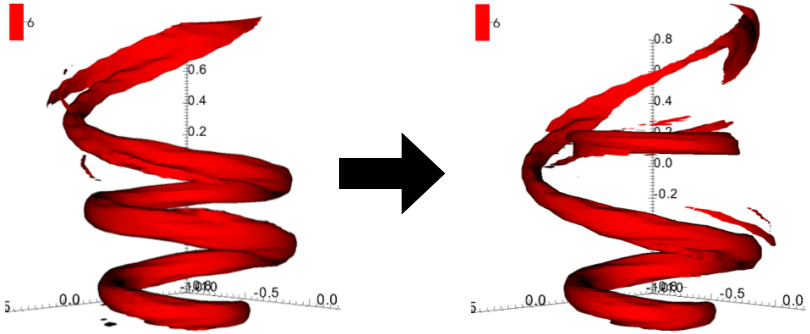
- LHI V_{eff} from helicity balance: $$V_{LHI} \lesssim \frac{A_{inj} B_{\phi,inj}}{\Psi_{tor}} V_{inj}$$

- Reconnection of I_{inj} = potential CD (NIMROD*)
  - Associated with bursts of low-f $n = 1$ activity
  - Observed in experiment

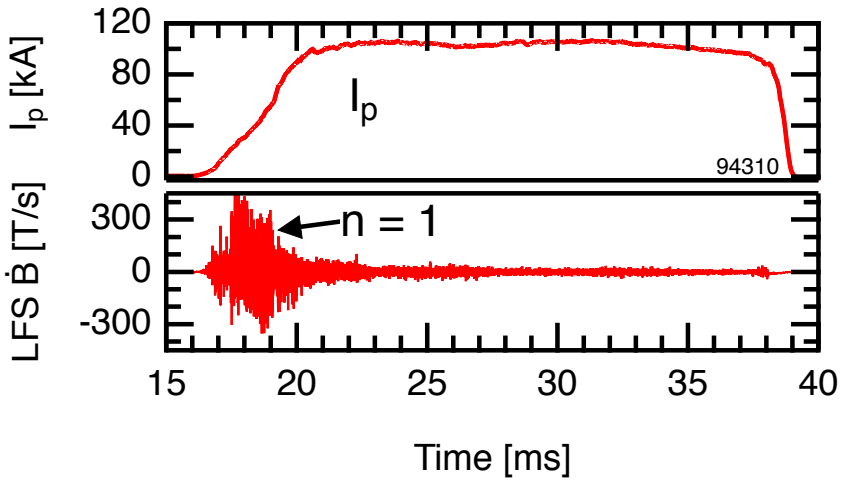
- Additional physics/CD mechanism(s) active
  - Regimes with sustained I_p and suppressed $n = 1$
  - Reconnection T_i correlated with high freq. activity**

→ Insertable probes used to investigate

*Reconnecting I_{inj} in NIMROD**



Sustained I_p with $n = 1$ activity suppressed



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

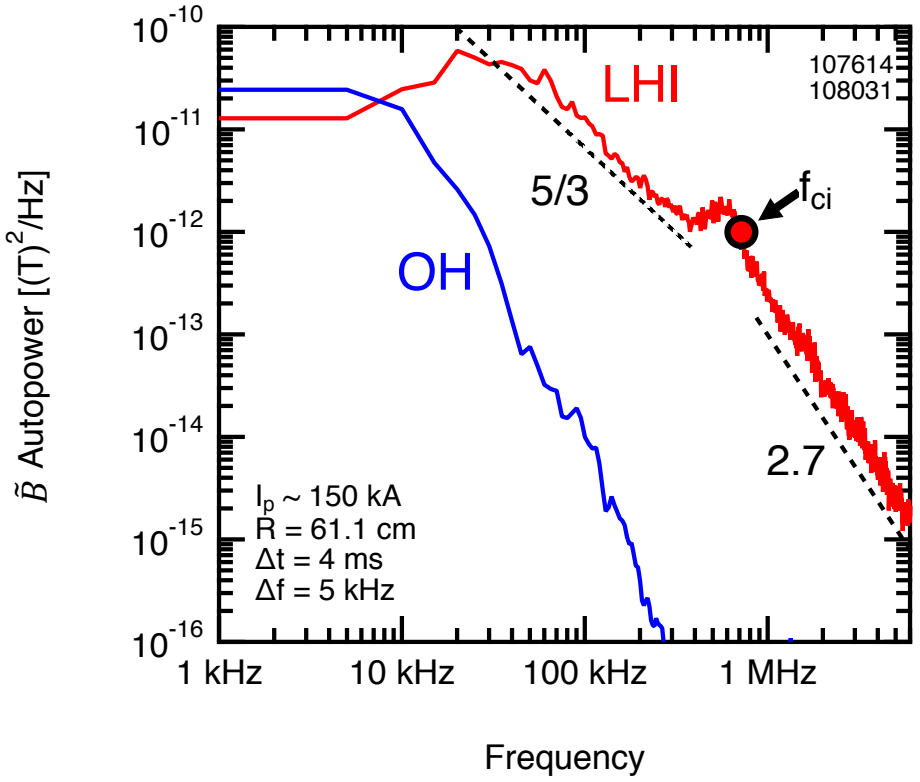
Burke et al., Nucl. Fusion **57 076010 (2017)

THE UNIVERSITY of WISCONSIN MADISON

Significant Magnetic Activity During LHI Resembles Alfvénic Turbulence

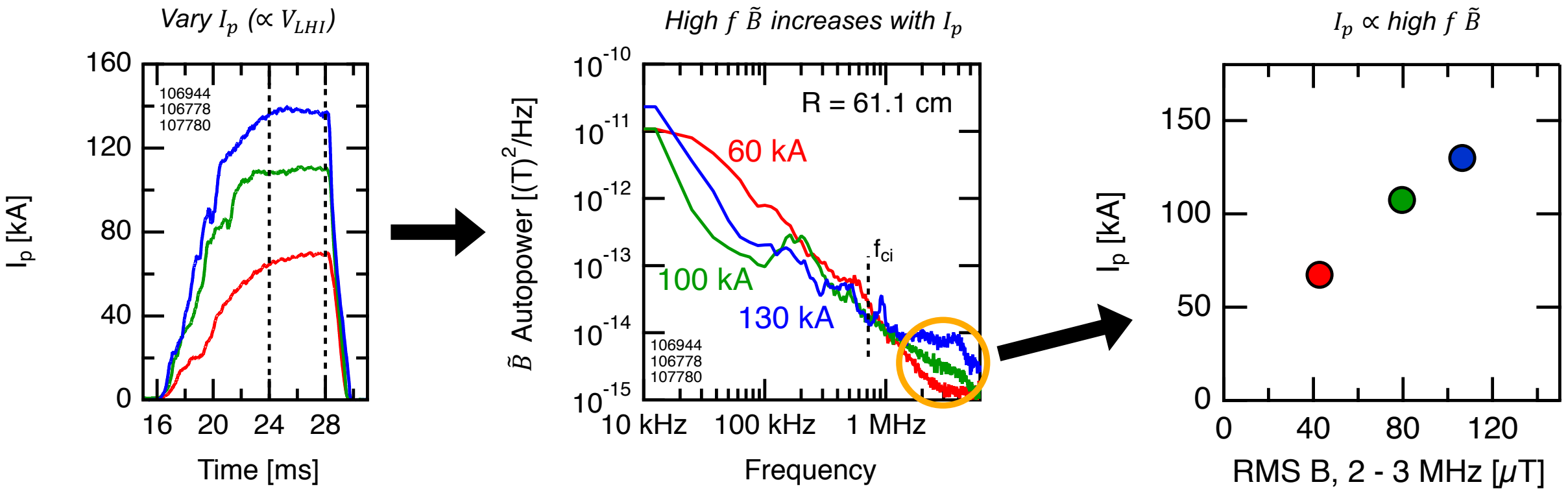
- Edge-localized high-f $\tilde{B}_{LHI} \gg \tilde{B}_{OH}$
- LHI spectral decay similar to Alfvénic turbulence:*
  - ~5/3 for $f < f_{ci}$ → MHD turbulence
  - ~2.7 for $f > f_{ci}$ → KAW and/or whistler turb.
- Such turbulence also associated w/ reconnection:
  - Localize turbulence → localize reconnection ?

Edge localized $\tilde{B}$ autopower spectrum



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

High $f \gg f_{ci}$ Activity Correlated with LHI Drive

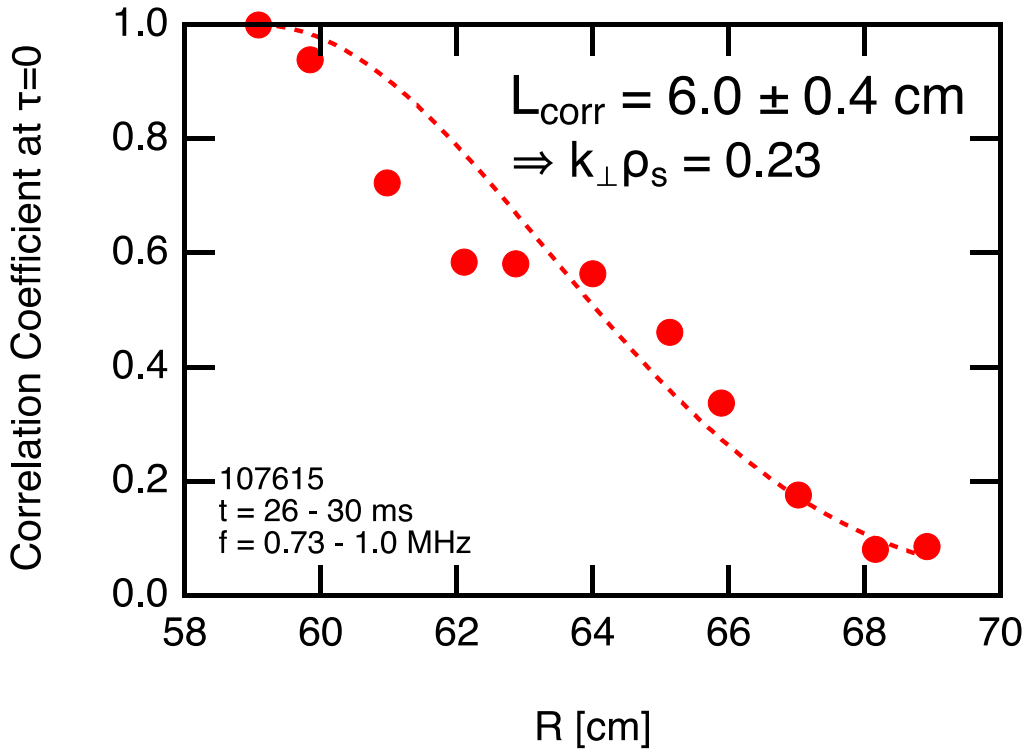


- Study helicity-sustained discharges w/ varying V_{LHI} → focus on LHI current drive

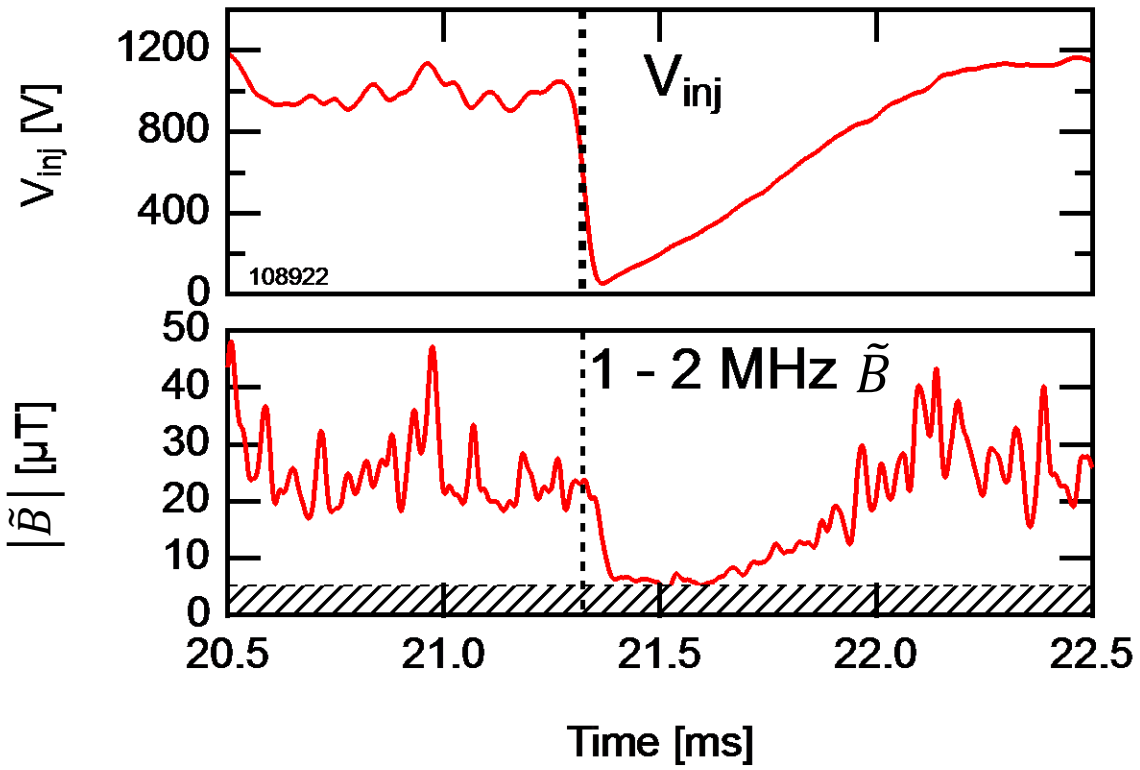
- Activity above ~ 1 MHz ($\gg f_{ci}$) increases with I_p, V_{LHI}

Other Observed High-f Characteristics Suggest Kinetic Nature

- KAWs have $k_\perp \rho_s \sim 1$
  - Meas. $L_{corr,R} \sim 2\text{–}10$ cm → $k_\perp \rho_s \sim 0.1\text{–}0.7$
  - k_R^{-1} comparable to inj. diameter



- $\tilde{B}$ strong function of V_{inj}
  - LHI e⁻ beam: $v_{beam} \propto V_{inj}^{1/2}$
- e⁻ beam-driven KAWs:* $\gamma = \gamma(v_{beam})$



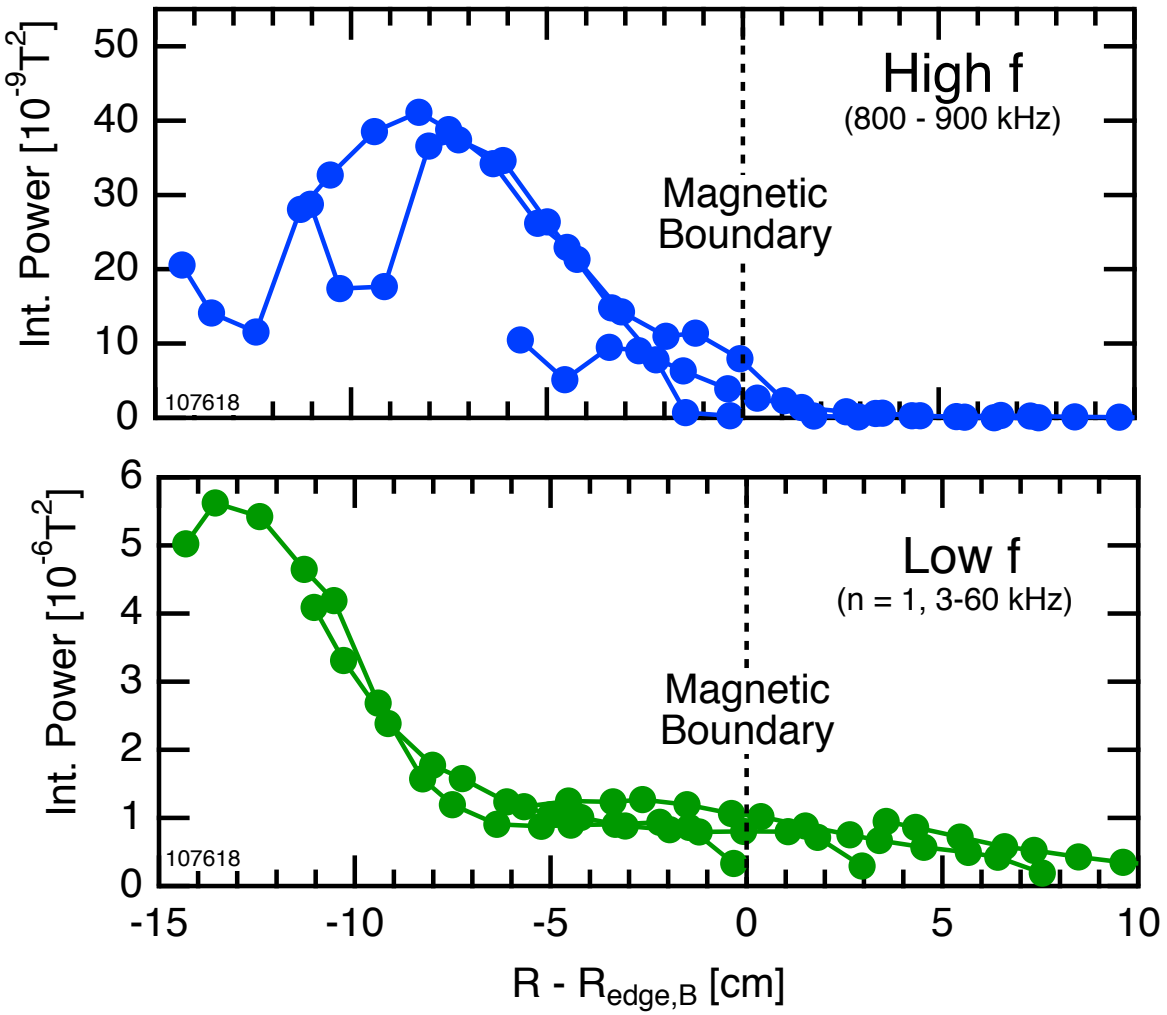
*Chen et al., ApJ **793** 13 (2014)

$\tilde{B}$ Activity Concentrated Within Magnetic Boundary

- Magnetic boundary from local $B_Z(R)$
- High f peaks interior to mag. boundary
- Low f ($n = 1$ mode) peaks further inward
- Significant turbulent magnetic activity

  → stochastic edge region ?

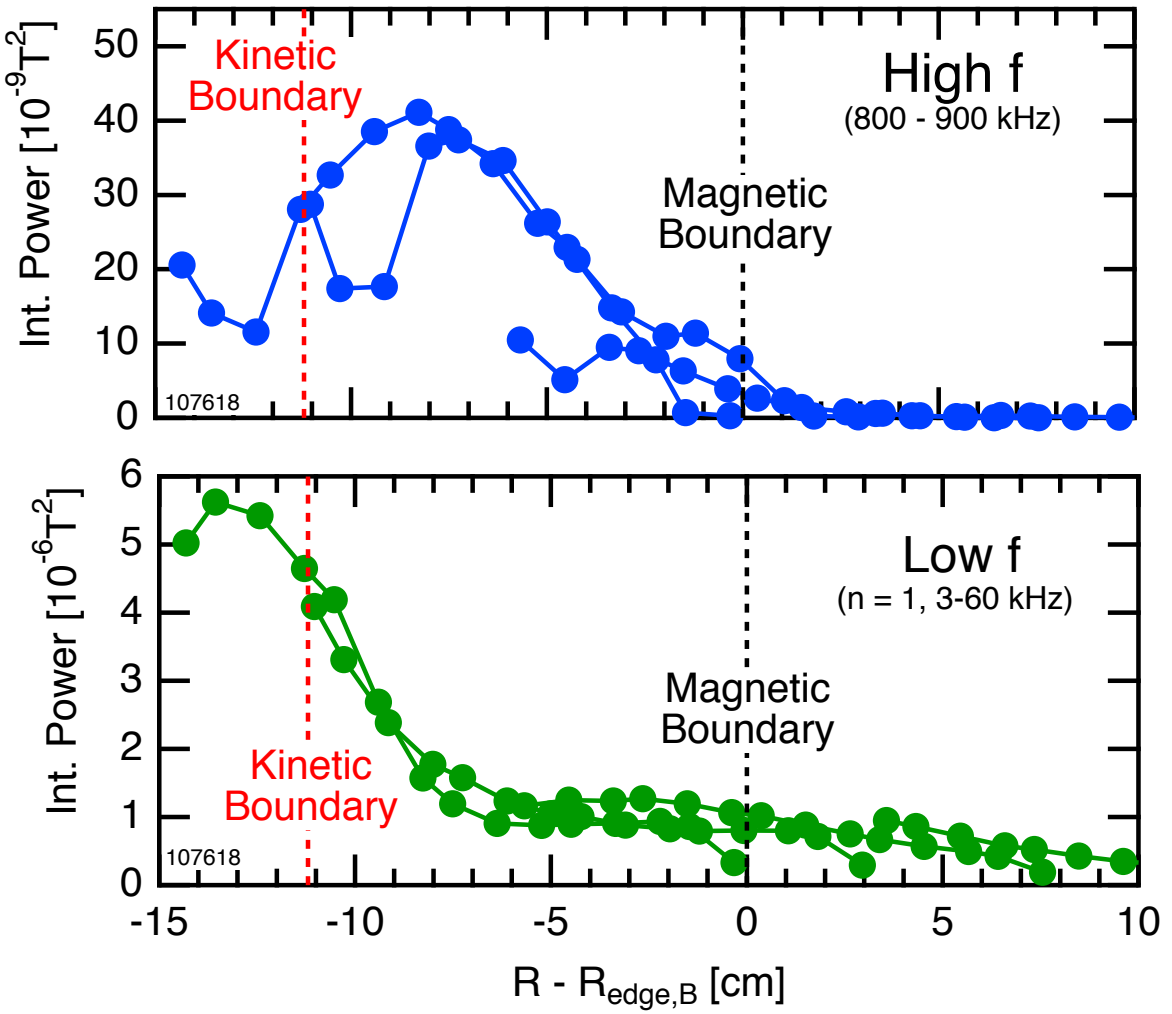
Radial localization of $\tilde{B}$ power



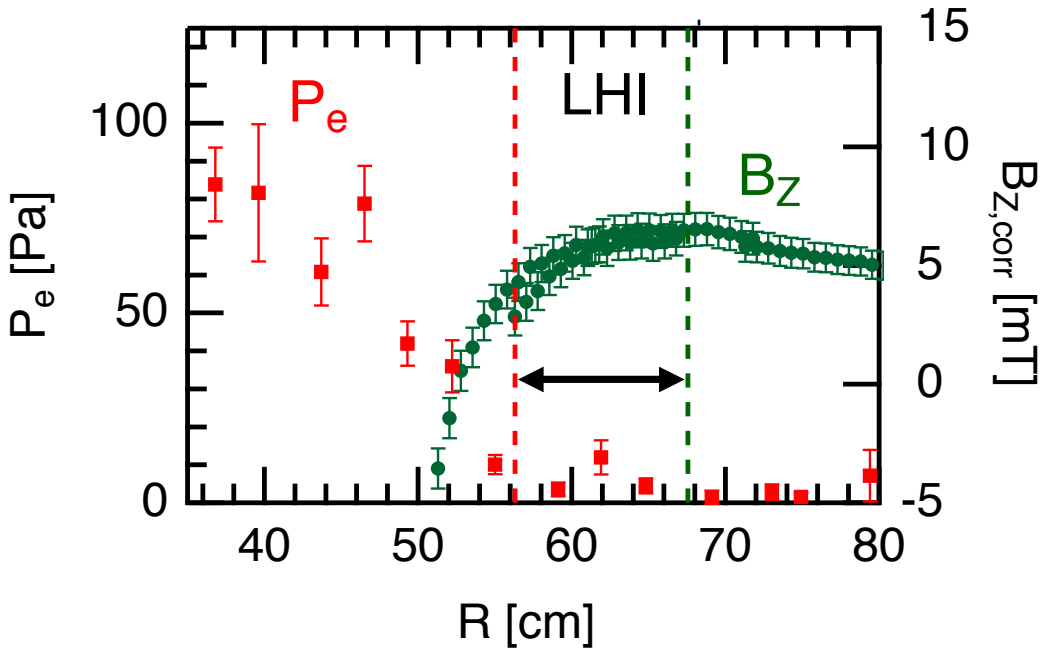
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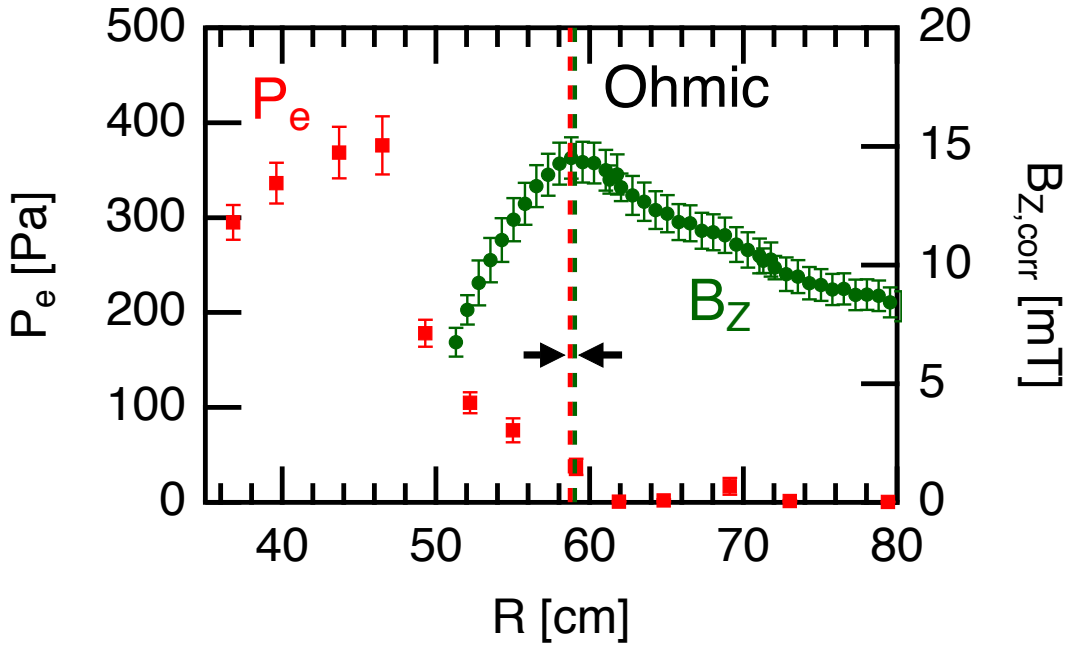
- Magnetic boundary from local $B_Z(R)$
- High f peaked interior to mag. boundary
- Low f ($n = 1$ mode) peaked further inward
- Significant turbulent magnetic activity
  - → stochastic edge region ?
  - – Kinetic boundary from $P_e(R)$

Radial localization of $\tilde{B}$ power



Magnetic and Kinetic Boundaries Separate During LHI



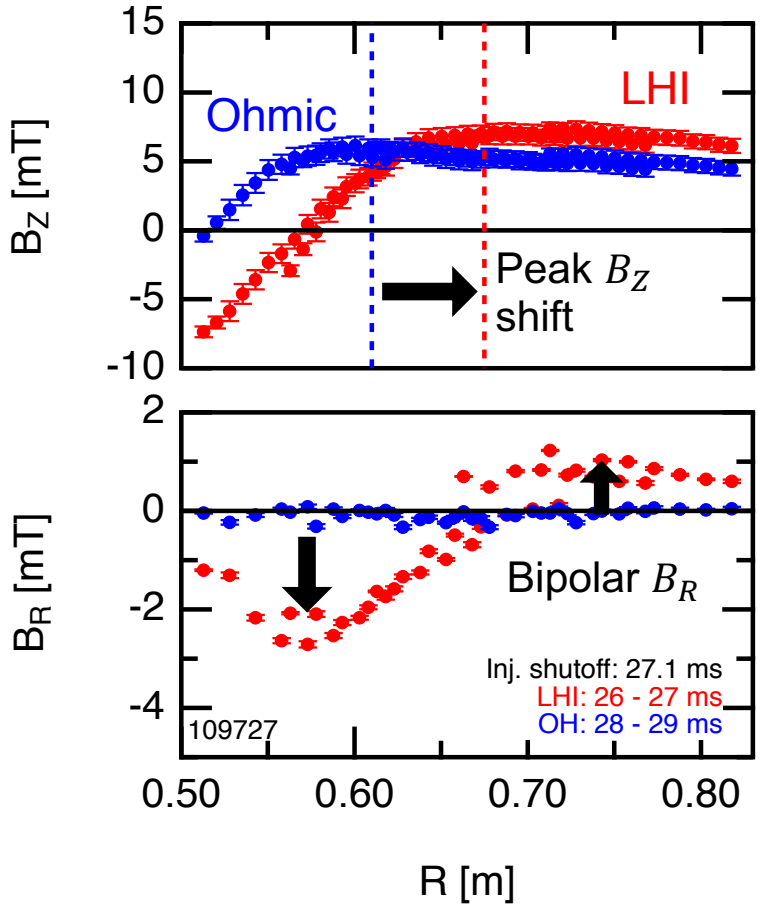


- LHI: $\boldsymbol{R_{mag}} \approx \boldsymbol{R_{kin}} + 10$ cm
- OH: $\boldsymbol{R_{mag}} \approx \boldsymbol{R_{kin}}$

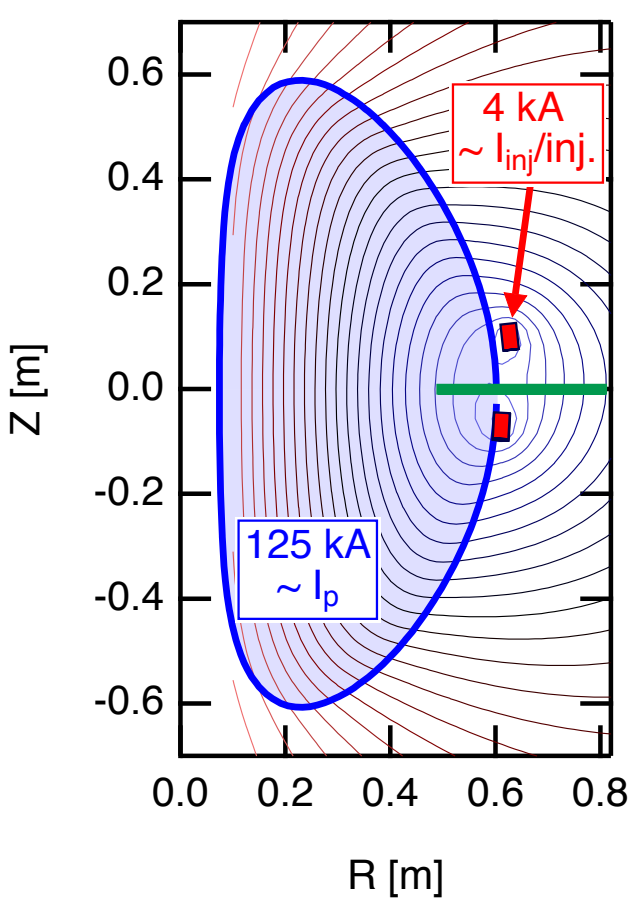
- Implies two-zone structure in LHI:
  1) Inner confined plasma
  2) Adjacent force-free current region

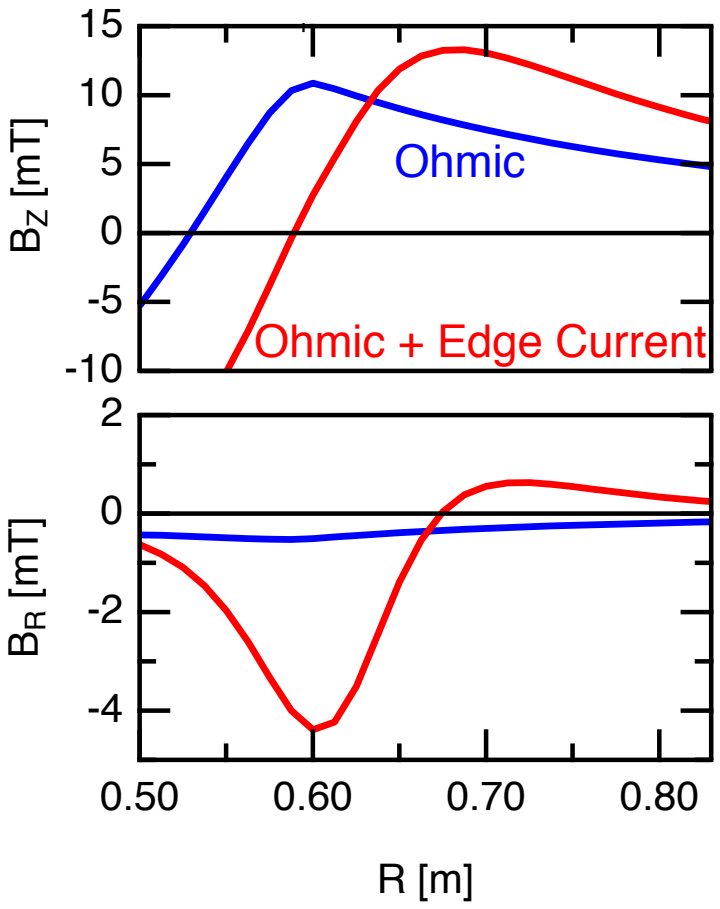
Average **B** Structure in LHI Appears Consistent with Localized *J*

Measurements
from LHI → OH Handoff



2D axisym. model qual. replicates observed structure

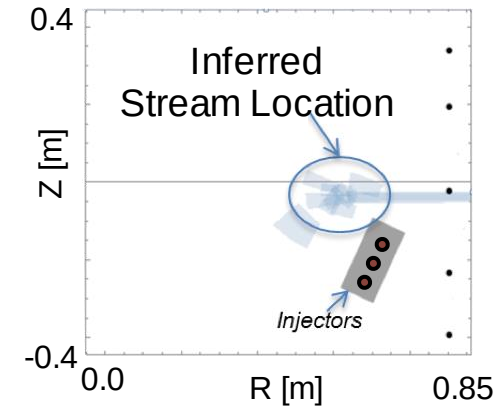




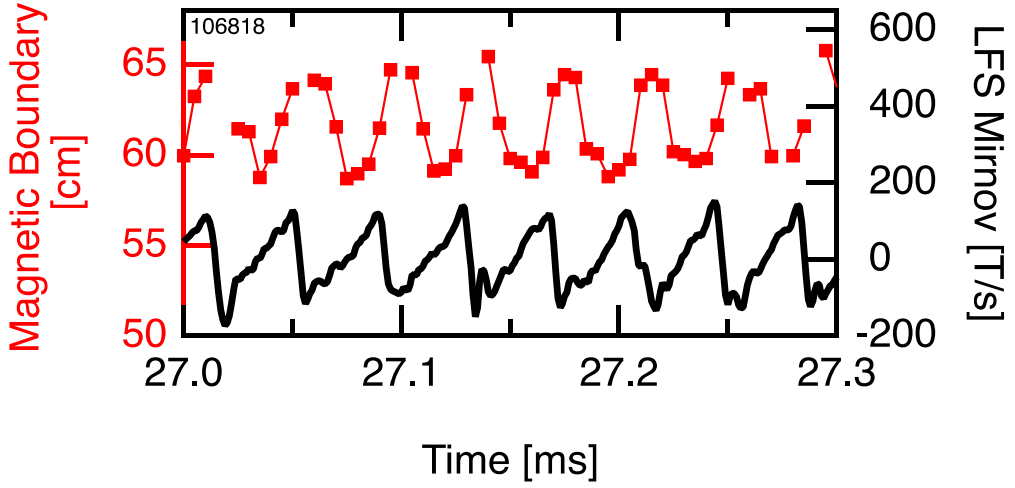
Time Dynamic $\mathbf{B}$ Also Consistent with Localized Edge J

- LHI I_{inj} is kink unstable
  - Line-tied, $n = 1$, $f \sim 10 - 50$ kHz
- Prev. phase correlation analysis:*
  → Localized elliptical motions
- Meas. magnetic boundary correl. with $n = 1$

External B_z Phase Correlation



Magnetic boundary in-phase with $n = 1$



C.E. Schaefer Poster GP10:123 (Tues. AM)

*E.T. Hinson, UW-Madison PhD Thesis (2015)
J.A. Reusch et al., PoP **25** 056101 (2018)

Implications for Moving LHI Startup & Current Drive Forward

- High-f magnetic activity correlated with LHI current drive
  - Measured properties suggestive of Alfvénic turbulence, reconnection activity, & KAWs
  - Precise role in LHI CD, detailed mechanism, & scaling to higher B_{TF}, I_p still under investigation

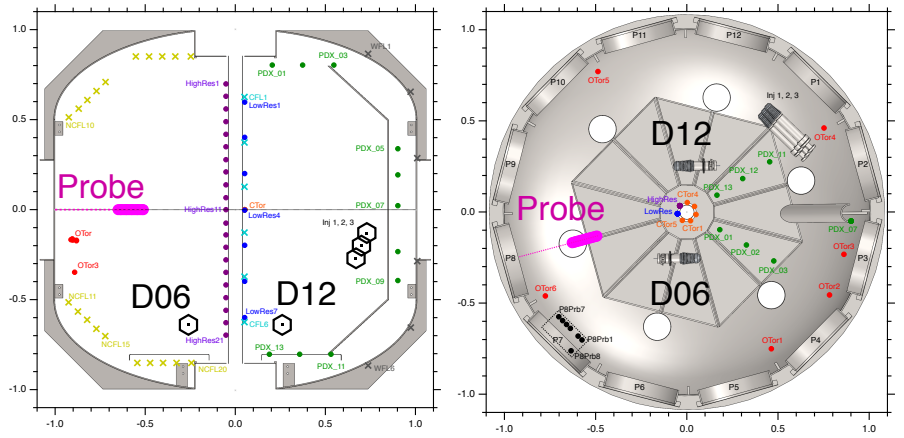
- Measured kinetic and magnetic structures suggest 2-zone model
  - Confined tokamak-like plasma + force-free current region
  - Implications for confinement & current drive efficiency
    - Helicity dissipation → η → T_e
    - Scaling of $\langle T_e \rangle$, $\langle n \rangle$ and achievable I_p depends on core transport models: OH? Stochastic ?

- PEGASUS-III addresses B_{TF}, I_p scaling

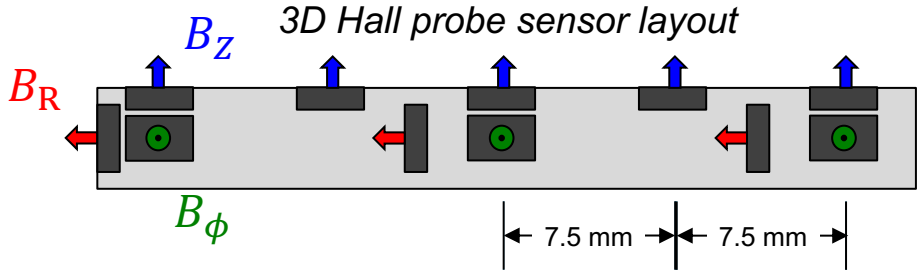
More information: PEGASUS posters in GP10 session (Tuesday morning)

Insertable magnetic probes allow direct investigation of magnetic structure and activity during LHI

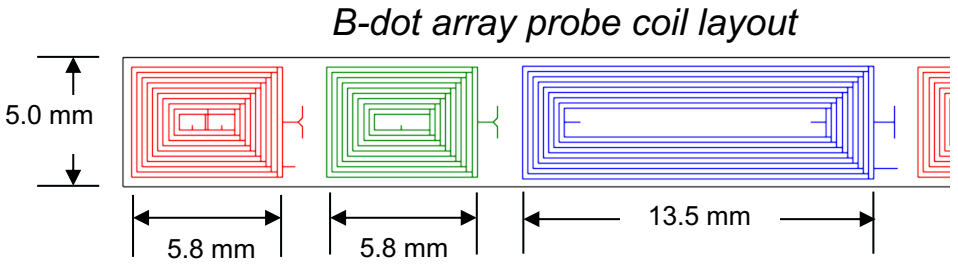
- PEGASUS operational regime allows for use of insertable probes
  - Short shot durations, low T
  - Graphite-armored assembly
  - Insertable: $R_{tip} = 50 - 90$ cm, centered on midplane $Z = 0$



- 3D Hall probe: → $\mathbf{B}(R)$ at 8 points, $\Delta R = 1.5$ cm
  → 7 addtl. $B_Z(R)$, eff. $\Delta R = 0.75$ cm
  → Flat freq. response to ~ 5 kHz



- $\dot{B}$ array probe: → $\widetilde{B_Z}$ at 15 points, $\Delta R \sim 1$ cm
  → Characterized frequency response to ~ 6 MHz



- Vacuum field subtraction to isolate plasma contribution

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

Abstract

Magnetic structure and activity during local helicity injection

Local helicity injection (LHI) is a nonsolenoidal startup technique that uses biased plasma sources to inject DC magnetic helicity and drive current. For confident scaling to future devices, better understanding of the properties of LHI-generated plasmas and the mechanism(s) through which current is driven could prove crucial. Comparisons of Thomson scattering and radially scanning magnetic probe measurements find the magnetic boundary is shifted up to 8 cm outward relative to the kinetic edge during LHI. This suggests a two-region structure is present: an edge force-free region dominated by the current stream(s); and an inner confined region with a tokamak-like plasma. LHI-driven plasmas have greater magnetic activity than comparable Ohmic discharges, with the activity asymmetrically distributed and localized to the injector stream region. Following shutoff of the injectors, this power rapidly (≈ 0.5 ms) decays and symmetrizes, and the remaining activity resembles that of an Ohmic-driven discharge. Broadband activity during LHI has power law behavior resembling that of Alfvénic turbulence which is expected to cascade helicity to large scales and has been observed in other reconnecting systems. The role of this activity in helicity transport and current drive, along with high frequency activity $f \approx 2$ MHz ($\approx$2–4 f_{ci}) that increases with LHI drive, is being investigated.