

Characterization of Magnetic Structure and Activity in Local Helicity Injection

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PEGASUS
Toroidal Experiment



Abstract

Characterization of Magnetic Structure and Activity in Local Helicity Injection

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Local Helicity Injection (LHI) is a non-solenoidal startup technique that initiates a tokamak-like discharge using electron current injectors at the plasma edge. Comparisons on the Pegasus ST of internal 3D $\mathbf{B}(R,t)$ Hall probe measurements with Thomson pressure profiles show the magnetic boundary is shifted up to 8 cm outward relative to the kinetic pressure edge. In Ohmic-driven discharges this disparity is not present. In comparison to Ohmic, LHI discharges show increased broadband and low-frequency $n = 1$ magnetic activity that is localized to the edge region where the injected current streams presumably exist and the kinetic pressure is near zero. The broadband activity exhibits power law behavior resembling Alfvénic turbulence, while high-frequency activity ($f \sim 2$ MHz) increases with total LHI drive. These observations, plus earlier reports of anomalous ion heating in the edge region, suggest a two-zone confinement structure during LHI consisting of an inner tokamak-like plasma and an outer force-free region of injected current. The outer region appears to be characterized by strong local magnetic and reconnection activity, poor thermal confinement, and presumably strongly stochastic field structures. These measurements are being applied to studies of the spontaneous reduction of low-frequency MHD activity and consequent improvement of LHI current drive.

Work supported by US DOE grants DE-FG02-96ER54375 and DE-SC0019008.

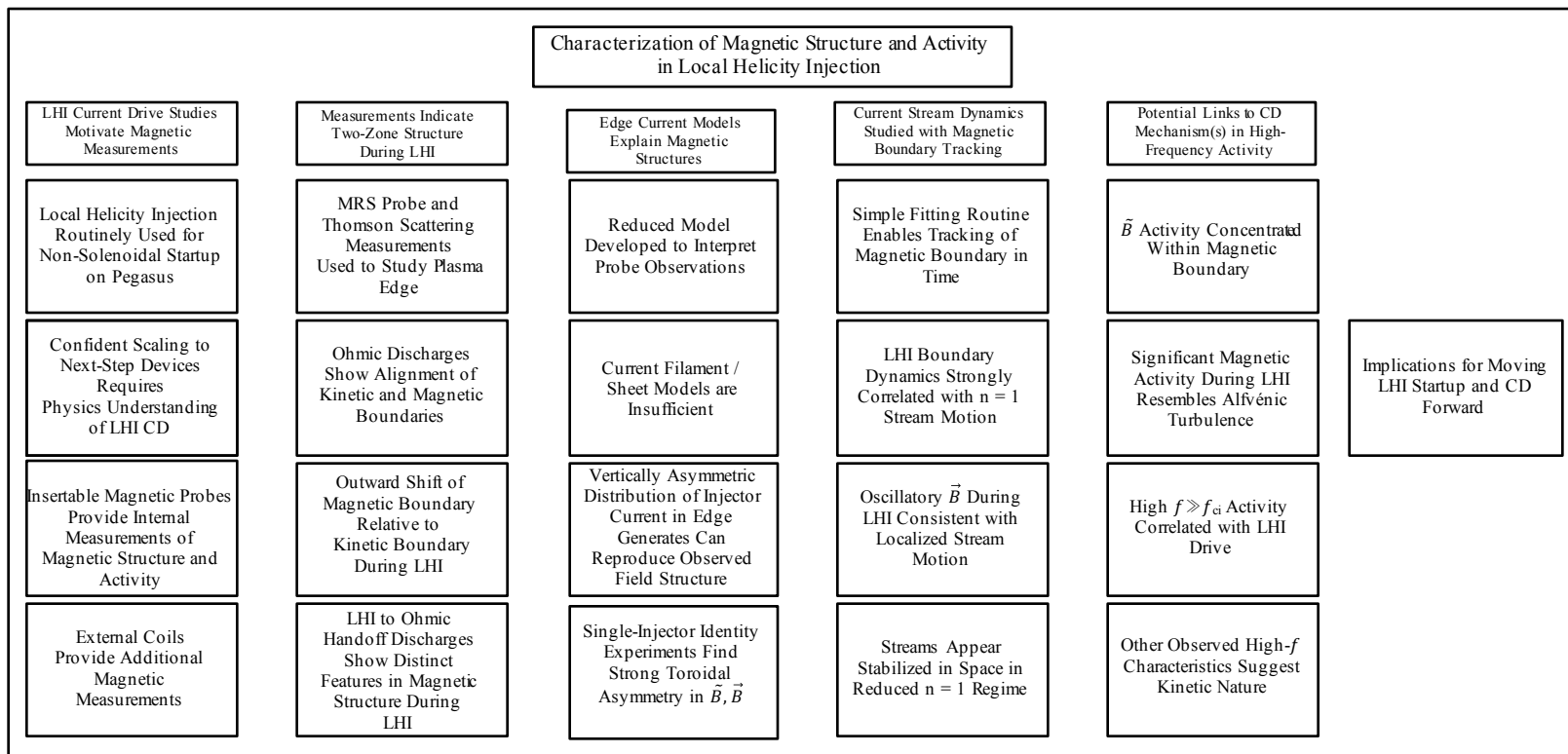


Layout Slide (Include for Posters)

12:1 scale Panel size: 8' x 4'

US Legal
8.5 x 14"

US Letter
8.5 x 11"

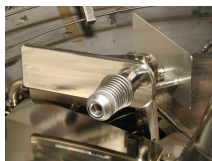




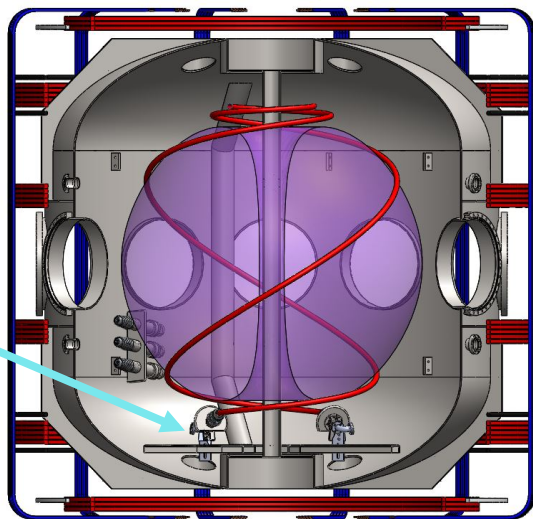
LHI Current Drive Studies Motivate Magnetic Measurements



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

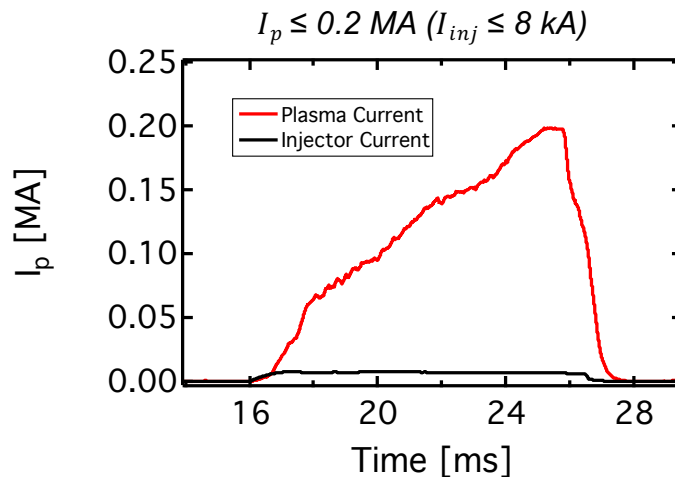


High Field
Side
(HFS)
Injectors



Pegasus Parameters

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

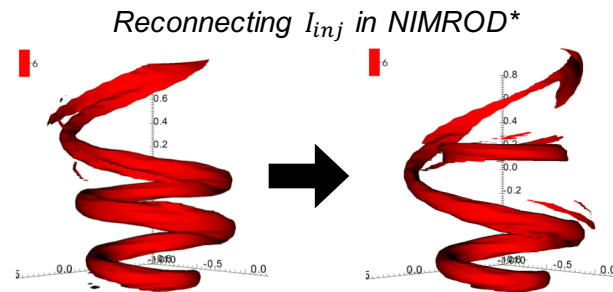


- Edge current extracted from compact injectors
- Unstable current streams relax to tokamak-like state

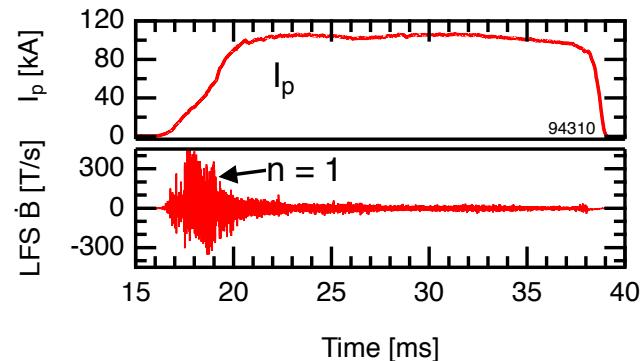


Confident Scaling to Next-Step Devices Requires Physics Understanding of LHI CD

- 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



Sustained I_p with $n = 1$ activity suppressed

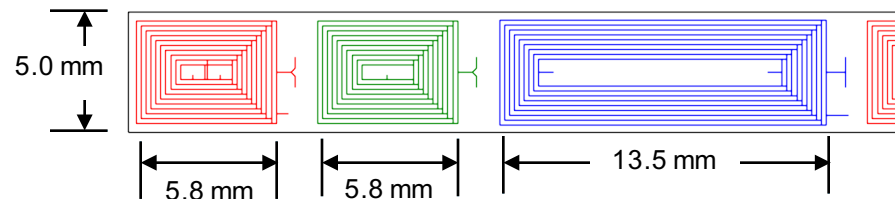




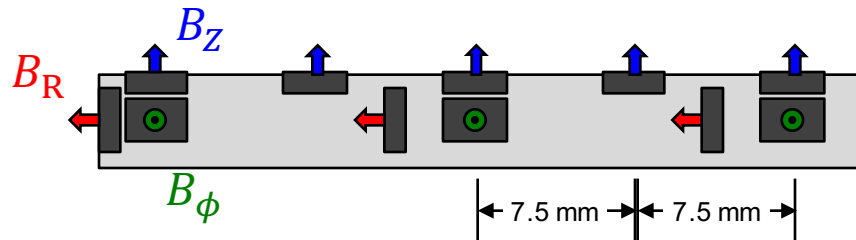
Insertable Magnetic Probes Provide Internal Measurements of Magnetic Structure and Activity

- MRA – $\dot{B}_Z(R)$ array
 - 15 channels, $\Delta R \sim 1$ cm
 - Calibrated transfer function to ~ 6 MHz
 - Active length of ~ 14 cm
- MRS – Hall sensor array
 - 3D $\vec{B}(R)$ at 8 channels: $\Delta R = 1.5$ cm
 - Additional 7 B_Z sensors: $\Delta R_{B_Z} = 0.75$ cm
 - Active length of ~ 11 cm

MRA Coil Layout



MRS Sensor Layout

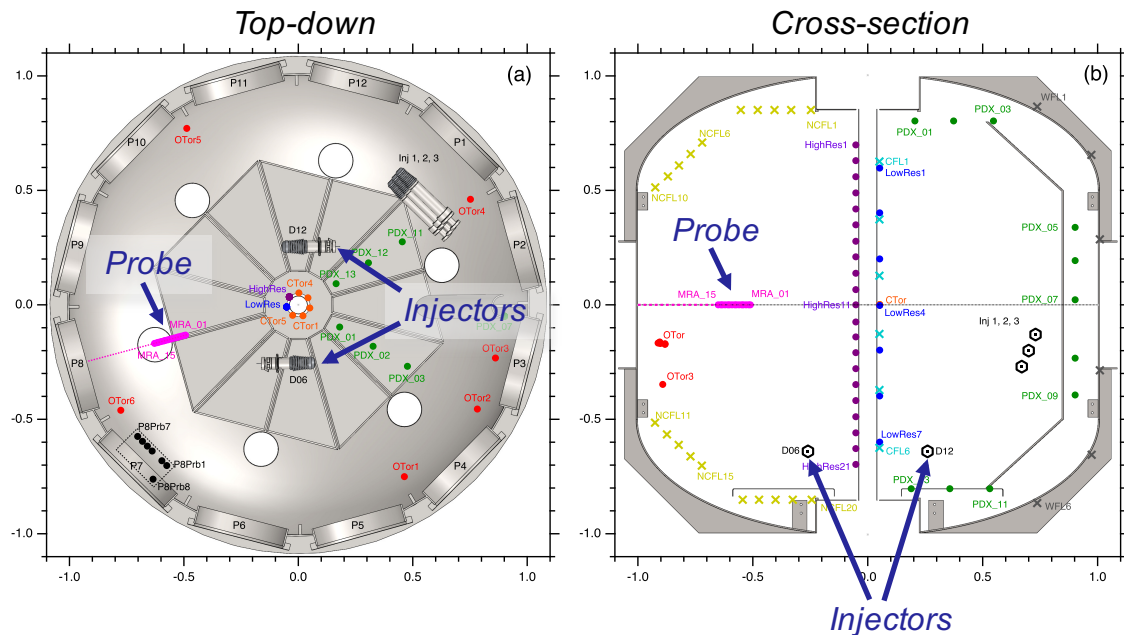




External Coils Provide Additional Magnetic Measurements

- Probe position adjustable along PEGASUS midplane
 - $Z \sim 0$ cm
 - $R = 50 - 100$ cm
- External magnetics provide additional outboard fluctuation measurements:
 - Toroidally and poloidally distributed Mirnov coils
 - Effective bandwidth of 400 kHz

PEGASUS Magnetic Diagnostic Layout



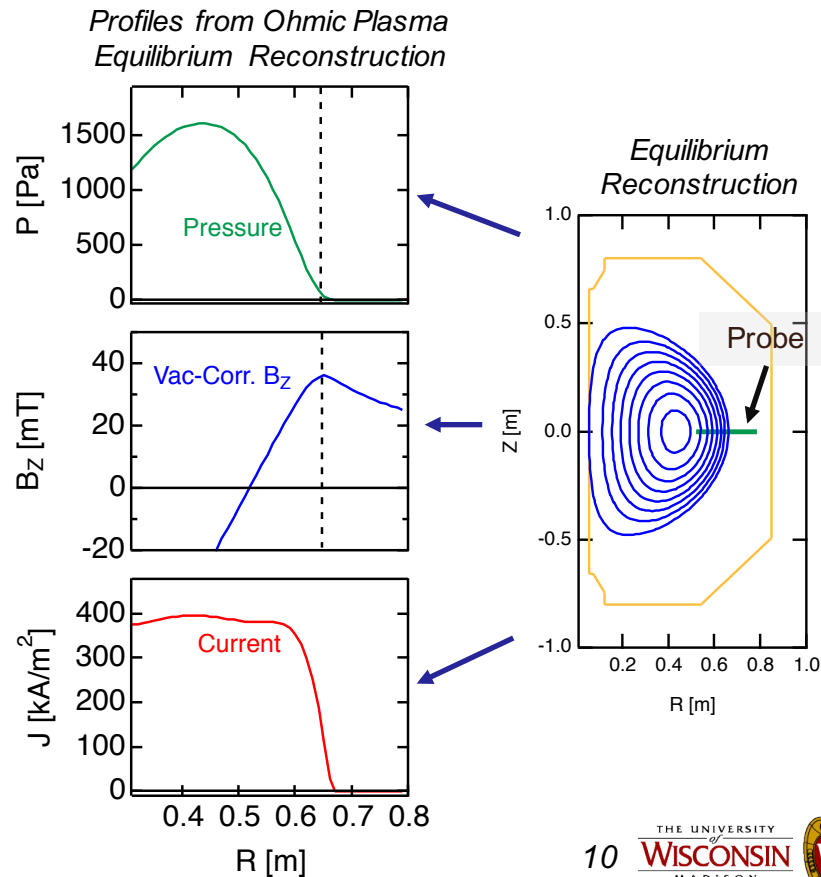


Measurements Indicate Two-Zone Structure During LHI



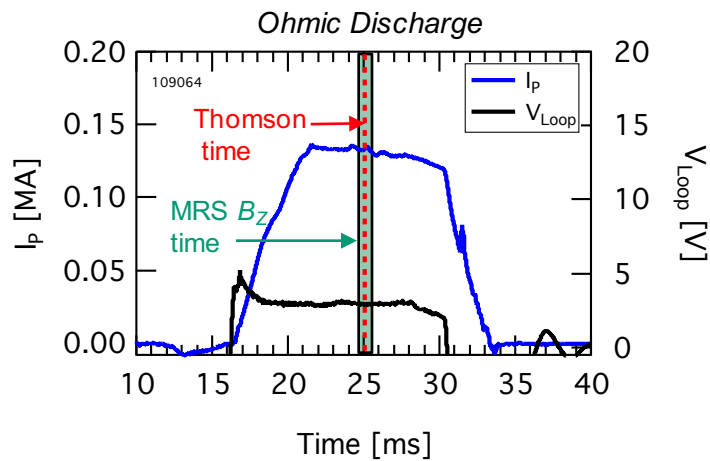
MRS Probe and Thomson Scattering Measurements Used to Study Plasma Edge

- Experiments in 2019 campaign characterized kinetic / magnetic boundary structure during LHI
- Thomson scattering measures kinetic boundary
 - $\approx 10\%$ maximum P_e level
- MRS probe measures magnetic boundary
 - Vacuum shot-corrected $\vec{B}_p \rightarrow$ plasma + stream field structure
 - Magnetic boundary from peak in $B_{Z,corr.}(R)$
- Equilibrium model: kinetic and magnetic boundaries should align for Ohmic plasmas
 - Edge current region hypothesized to yield radial displacement of magnetic boundary

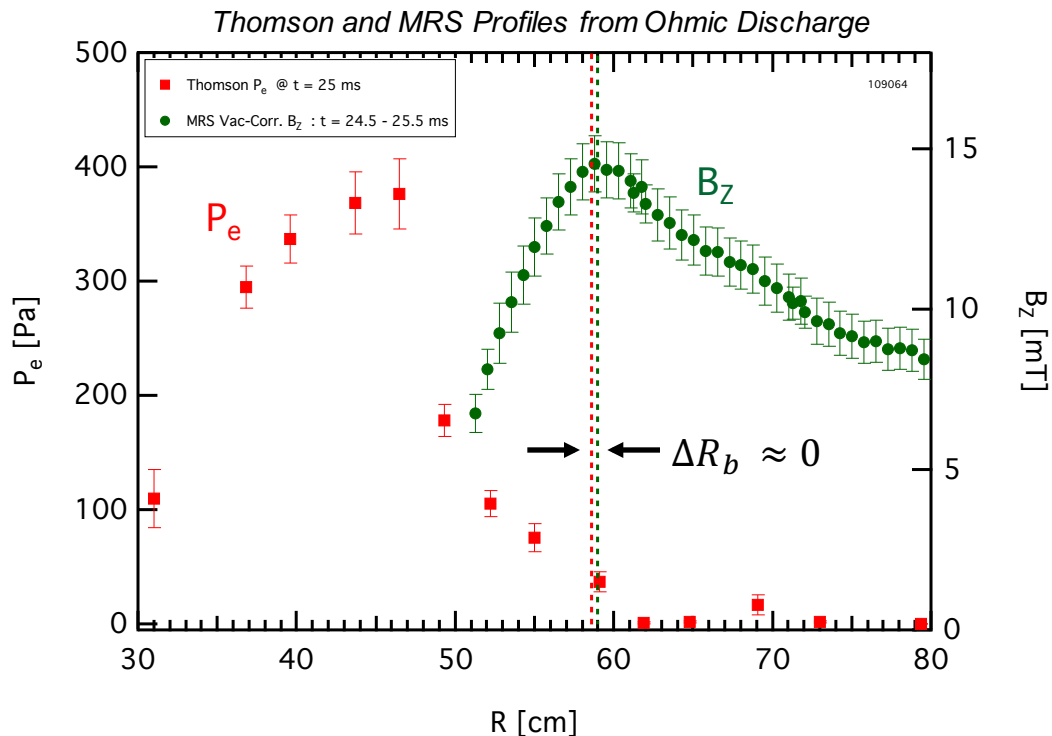




Ohmic Discharges Show Alignment of Kinetic and Magnetic Boundaries

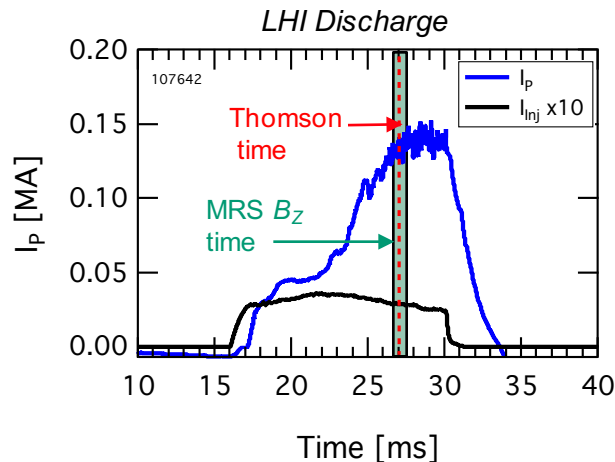


- Boundaries are aligned to within expected error

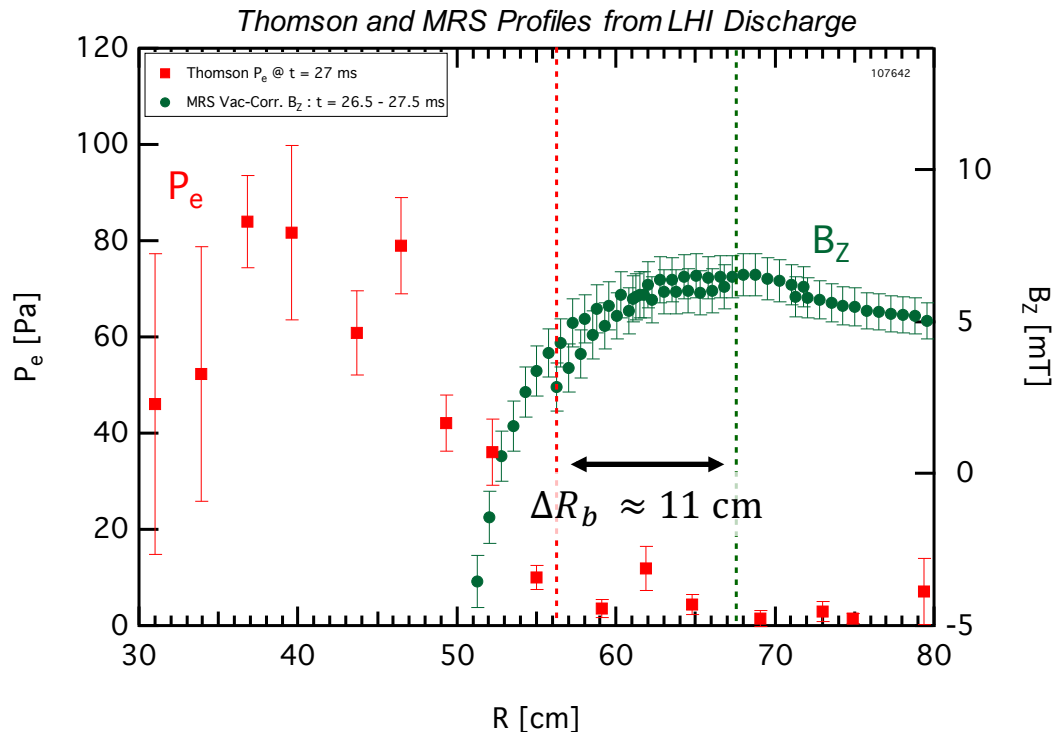




Outward Shift of Magnetic Boundary Relative to Kinetic Boundary During LHI

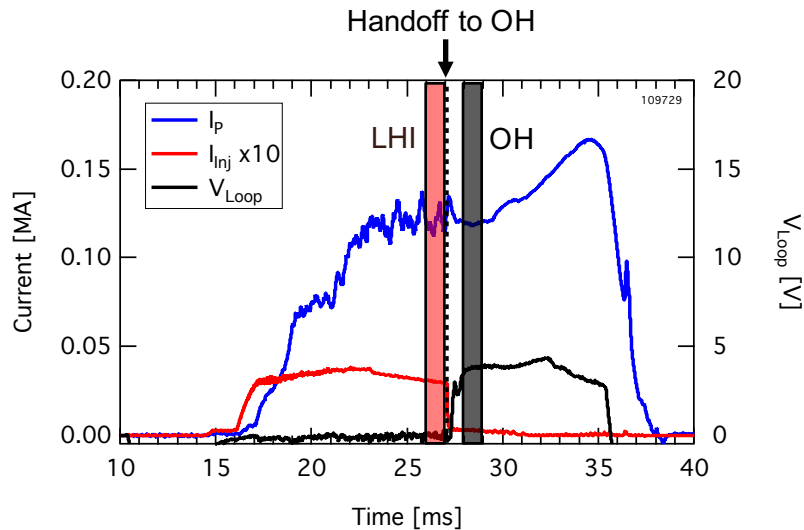


- Magnetic boundary shifted ~ 11 cm outward relative to kinetic boundary
- Suggests two-zone magnetic structure
 1. Inner confined plasma region
 2. Outer force-free current region

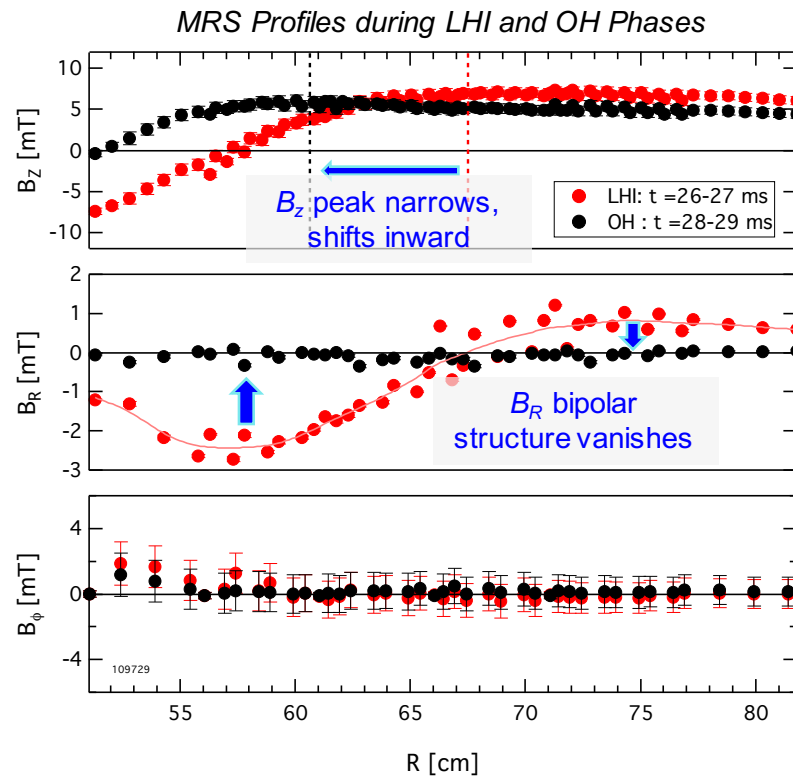




HFS LHI to Ohmic Handoff Discharges Show Distinct Features in Magnetic Structure During LHI



- Magnetic structure changes across LHI-OH transition
 - B_z peak narrows and shifts inward
 - Bipolar B_R structure vanishes
 - Structure changes on $\sim 100 \mu s$ timescale as I_{inj} falls off





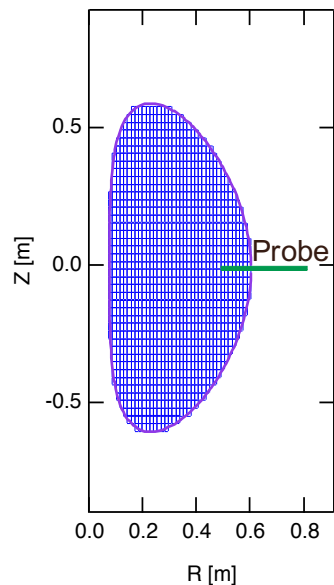
Edge Current Models Explain Magnetic Structures



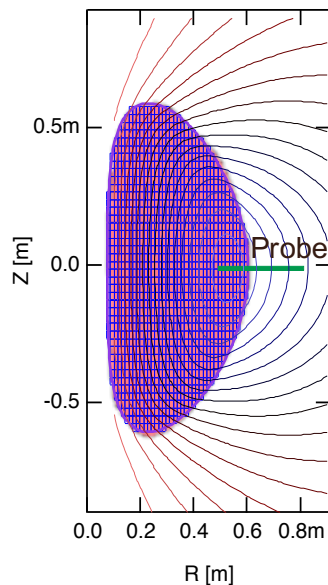
Reduced Model Developed to Interpret Probe Observations

- 2-D Axisymmetric current filaments as working element

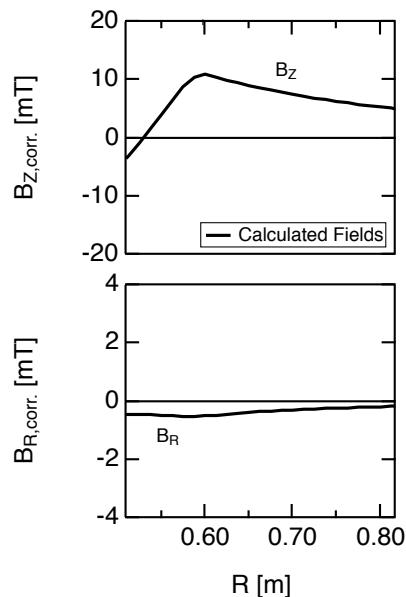
Extract $J(R, Z)$ grid from OH equilibrium



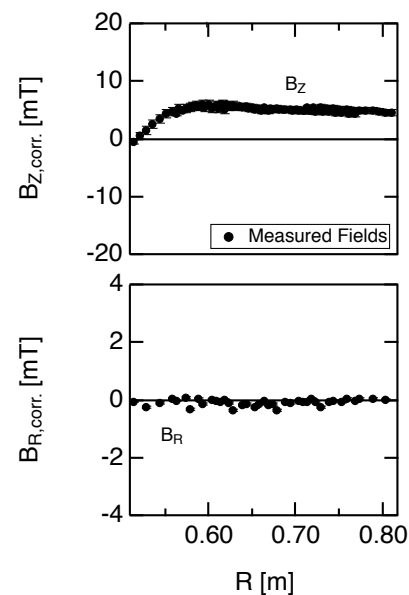
Calculate \vec{B} via axisymmetric Green response



Map B_Z, B_R to probe location



Compare to measured data



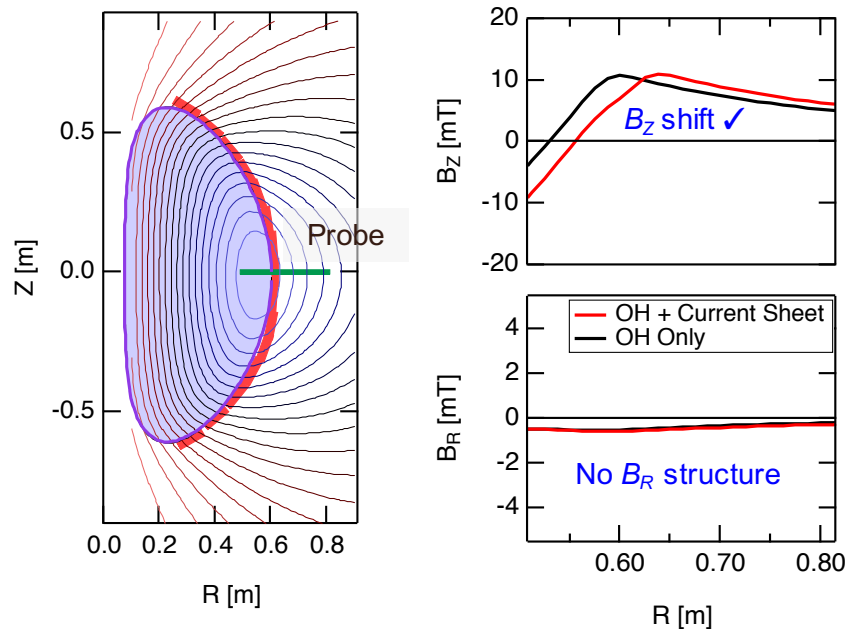


Current Filament / Sheet Models are Insufficient

- Assume: I_{inj} distributed along outer flux boundary

Current Model:
OH Plasma + Current Sheet

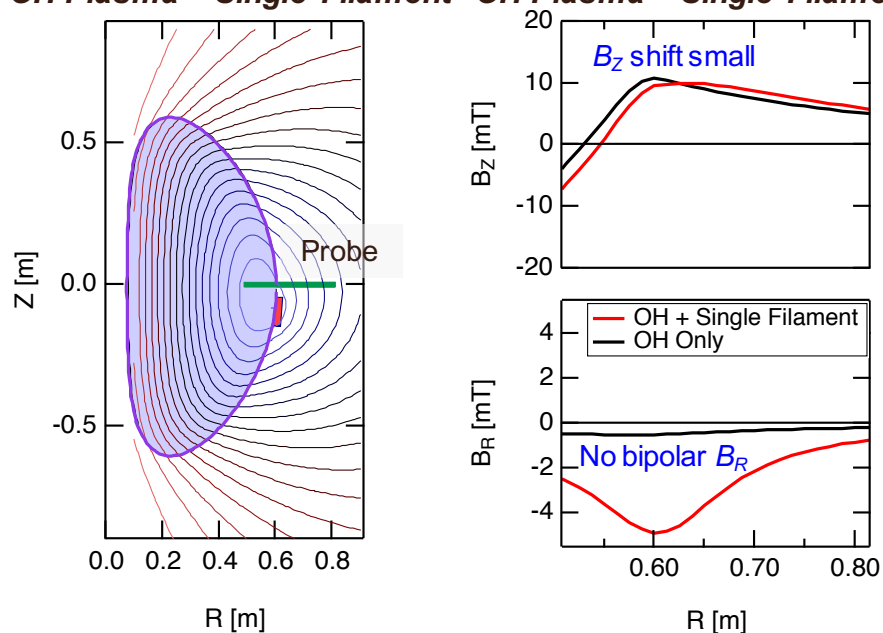
Field profiles calculated from
OH Plasma + Current Sheet



- Assume: I_{inj} from single pass of helix dominates \vec{B}

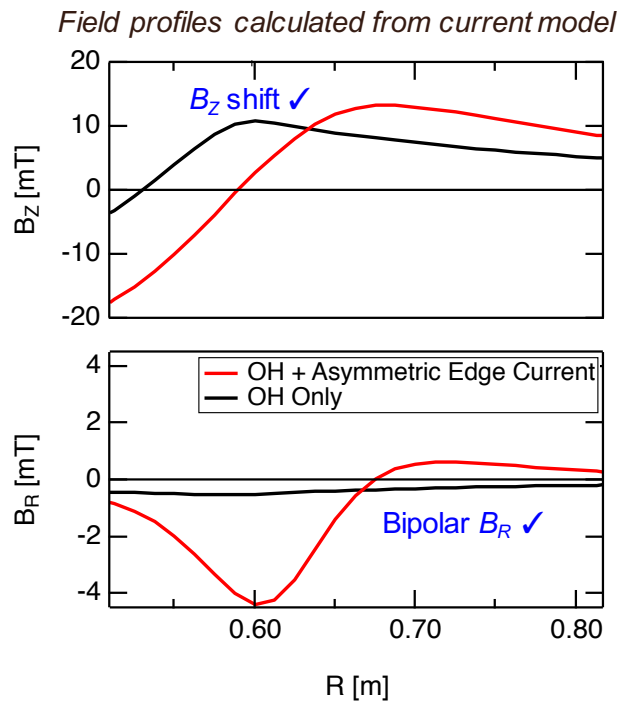
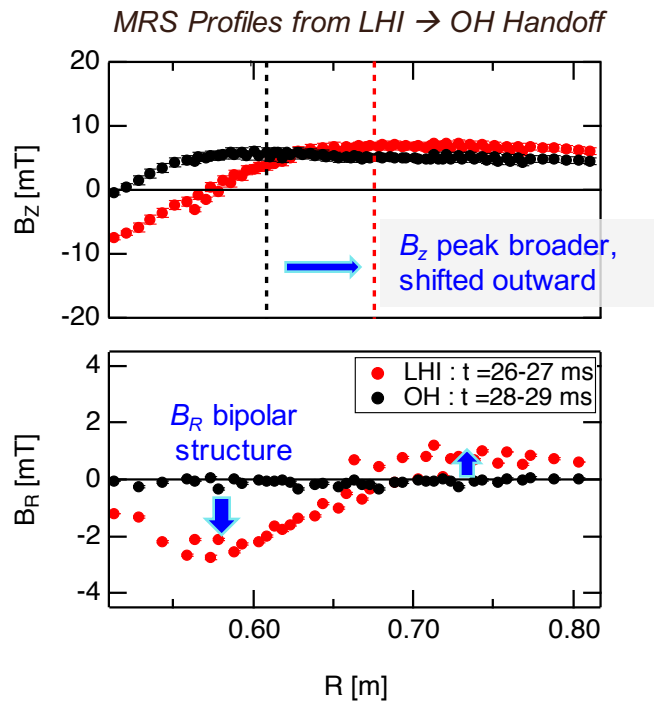
Current Model:
OH Plasma + Single Filament

Field profiles calculated from
OH Plasma + Single Filament

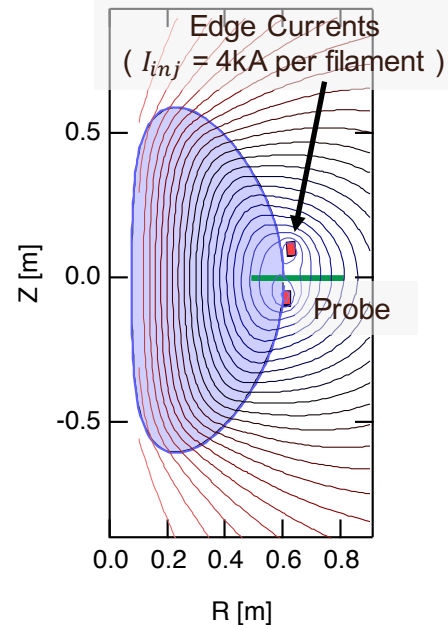




Vertically Asymmetric Distribution of Injector Current in Edge Can Reproduce Observed Field Structure



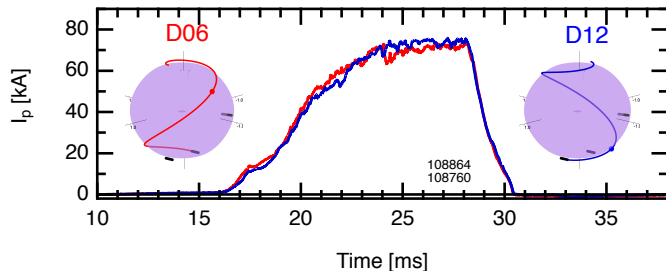
Current Model: **OH Plasma + Asymmetric Edge Current**



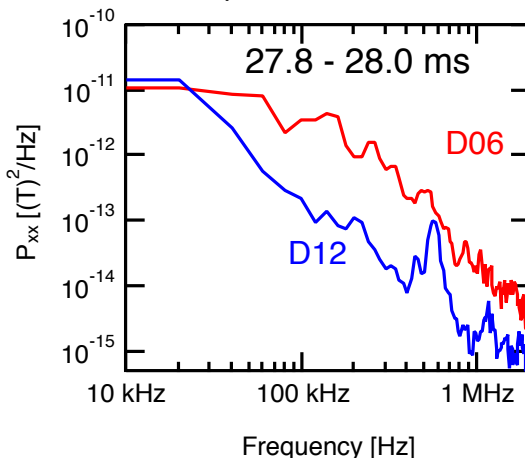


Single-Injector Identity Experiments Find Strong Toroidal Asymmetry in \tilde{B} , \vec{B}

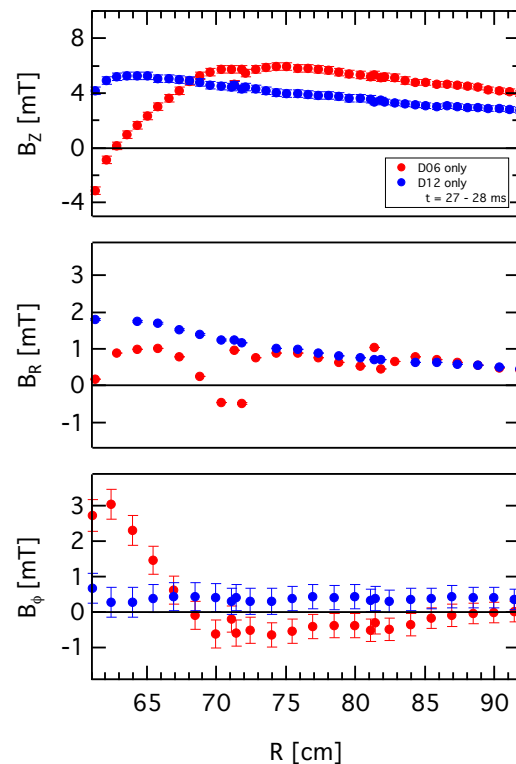
Single Injector Discharge Comparison:
Identical I_P & programming,
different injector location



Power Spectra from MRA Probe



Field Profiles from MRS Probe



- Two similar discharges developed: each driven by single injector, with a 180° toroidal separation between injectors
- Significant differences in measured high frequency fluctuation power and average magnetic structure observed
- Asymmetries imply localization of current streams
 - Motivates future 3-D treatment

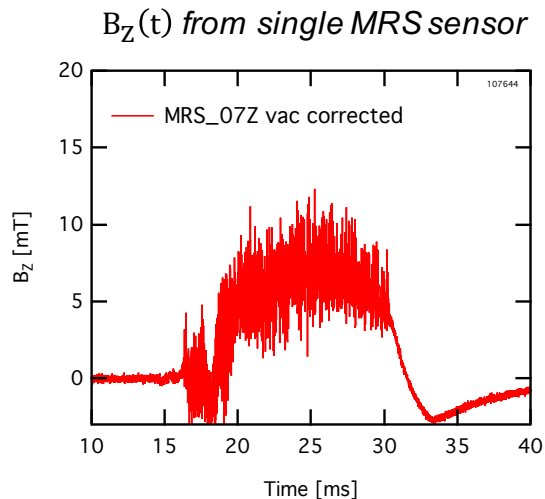




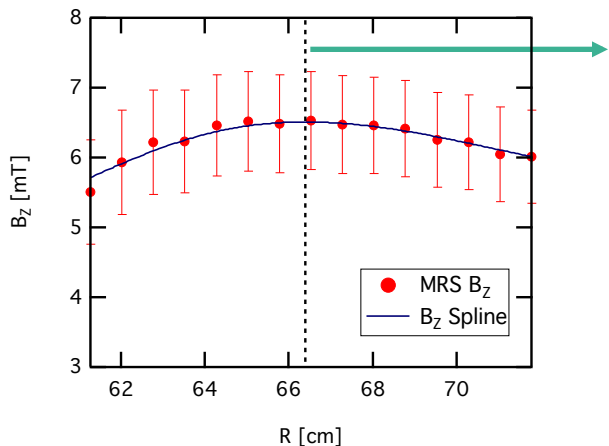
Current Stream Dynamics Studied with Magnetic Boundary Tracking



Simple Fitting Routine Enables Tracking of Magnetic Boundary in Time

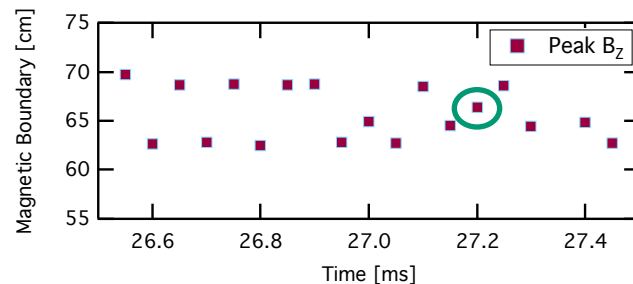


Magnetic boundary determined
from peak in spline fit to
 $B_Z(R)$ profile at $t = 27.2$ ms

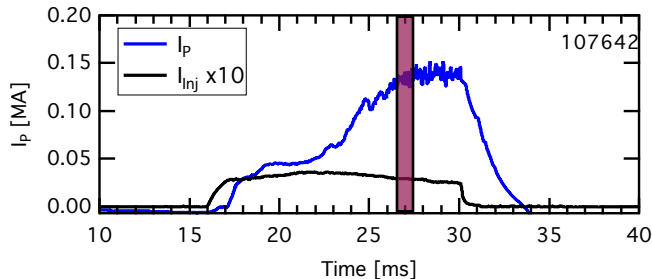


* σ_{B_Z} includes absolute gain error

Tracking magnetic boundary
at times within window

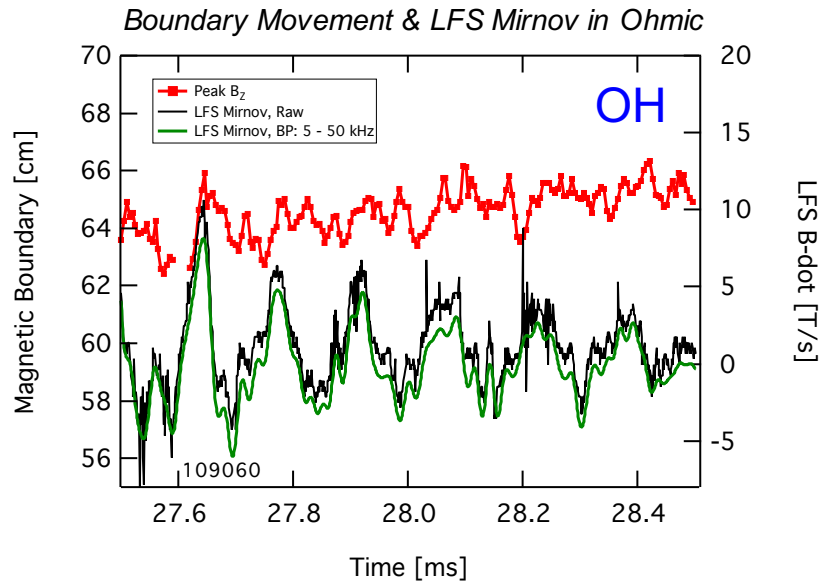


Boundary tracking time window

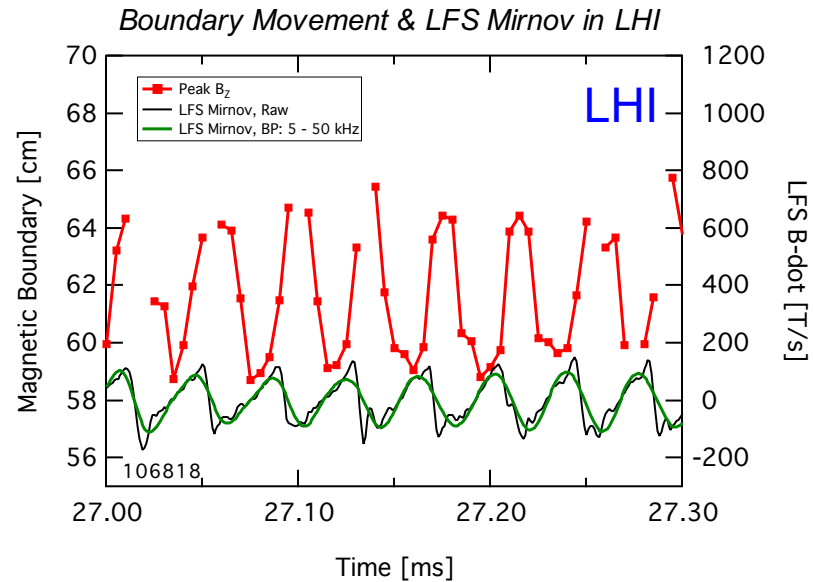




LHI Boundary Dynamics Strongly Correlated with $n = 1$ Stream Motion



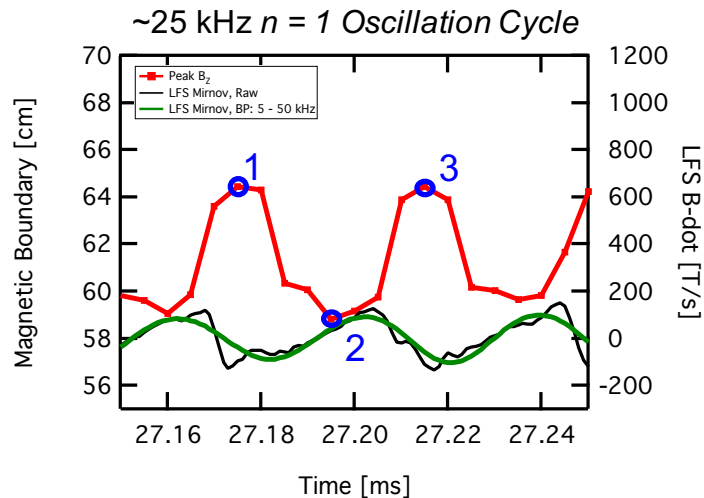
- Low boundary variation: $\Delta R_{b,mag} \lesssim \pm 1$ cm
- Correlation with $n = 1$ tearing mode (≈ 8 kHz)



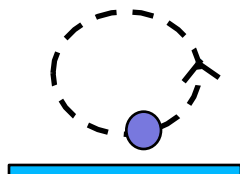
- High boundary variation: $\Delta R_{b,mag} \approx \pm 2.5$ cm
- Strong correlation with $n = 1$ line-tied kink activity in streams (≈ 25 kHz)



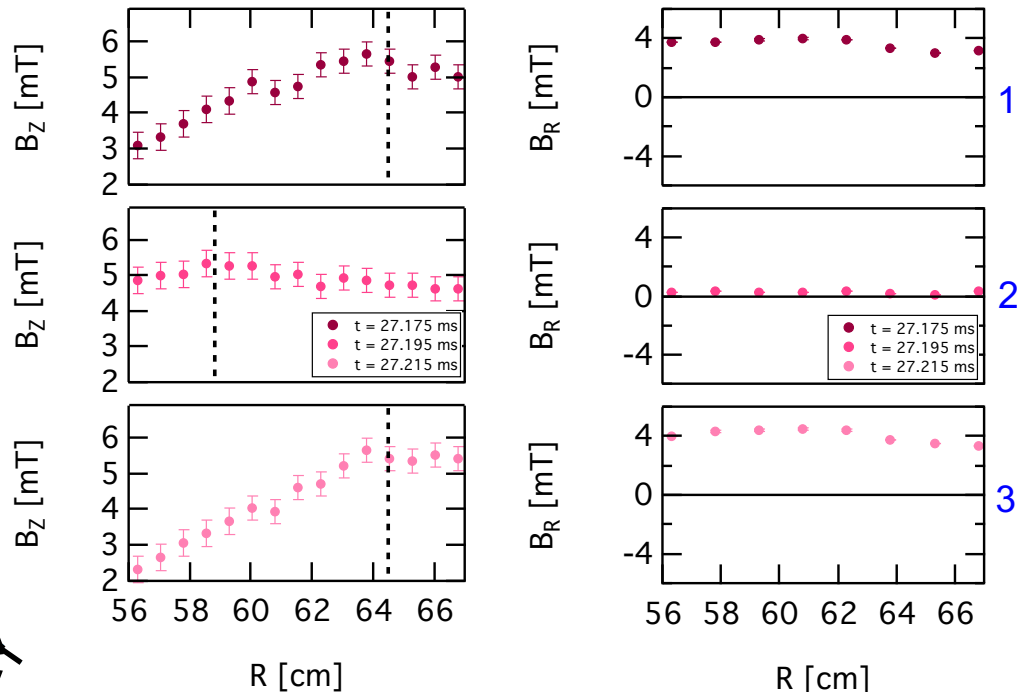
Oscillatory \vec{B} During LHI Consistent with Localized Stream Motion



- $B_z(R, t)$: in-out radial motion
- DC offset of $B_R(R, t)$ oscillates about zero
- Consistent with stream above probe sensor



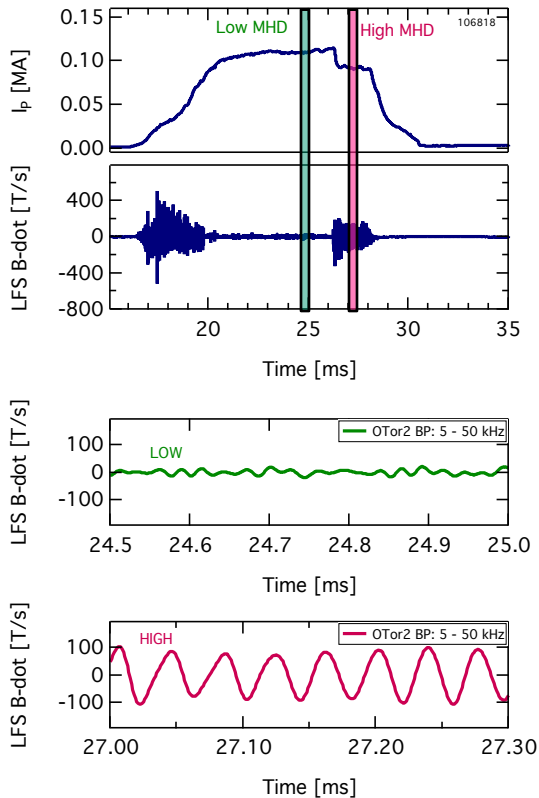
MRS B_z and B_R Profiles at Highlighted Times



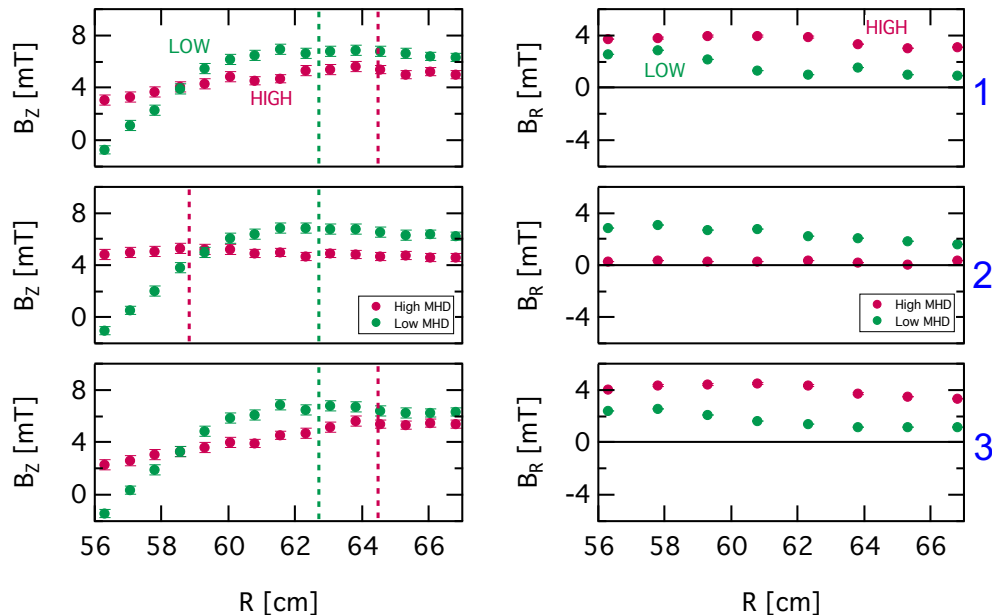


Streams Appear Stabilized in Space in Reduced $n = 1$ Regime

Discharge has phases with low & high $n = 1$ activity



Comparison of MRS B_Z and B_R Profiles Over Oscillation Cycle in Low and High MHD



- High-MHD phase has oscillatory motion
- Reduced $n = 1$ phase has relatively stable stream position

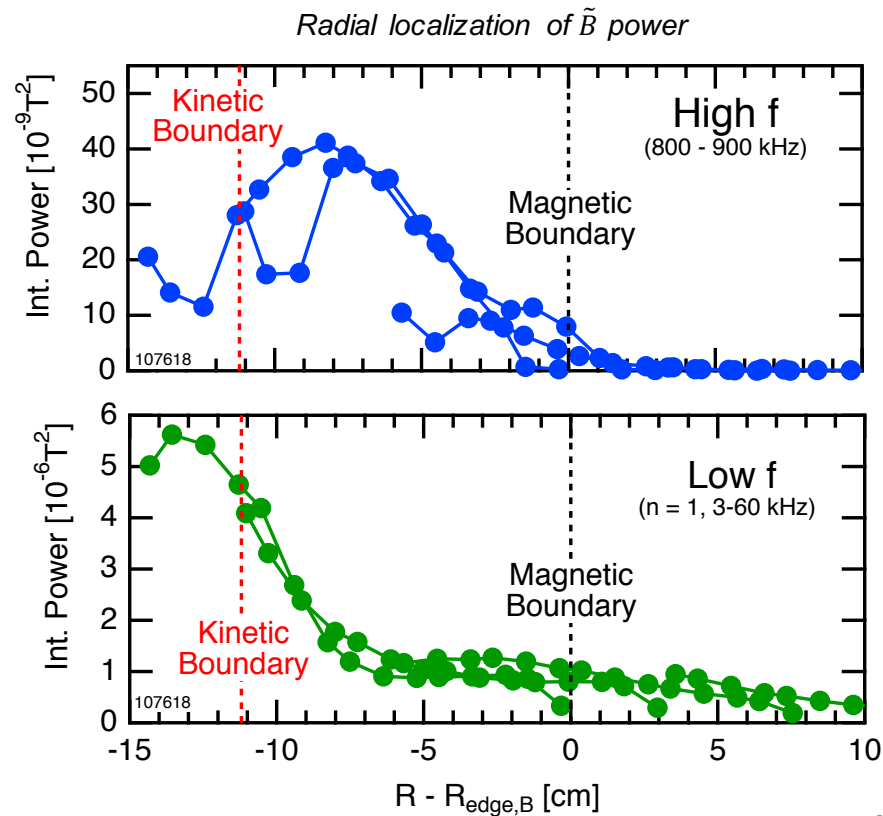


Potential Links to CD Mechanism(s) in High-Frequency Activity



\tilde{B} Activity Concentrated Within Magnetic Boundary

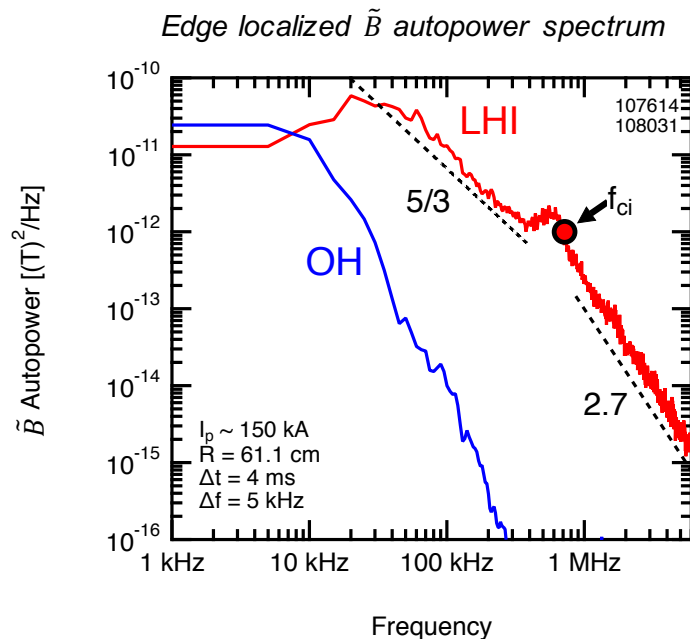
- High f peaked between kinetic and magnetic boundaries
- Low f ($n = 1$ mode) peaked inward of kinetic boundary
- Significant turbulent magnetic activity consistent with stochastic edge region





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: *
 - $\sim 5/3$ for $f < f_{ci}$ \rightarrow MHD turbulence
 - ~ 2.7 for $f > f_{ci}$ \rightarrow KAW and/or whistler turb.
- Such turbulence also associated w/ reconnection:
 - Localize turbulence \rightarrow localize reconnection ?

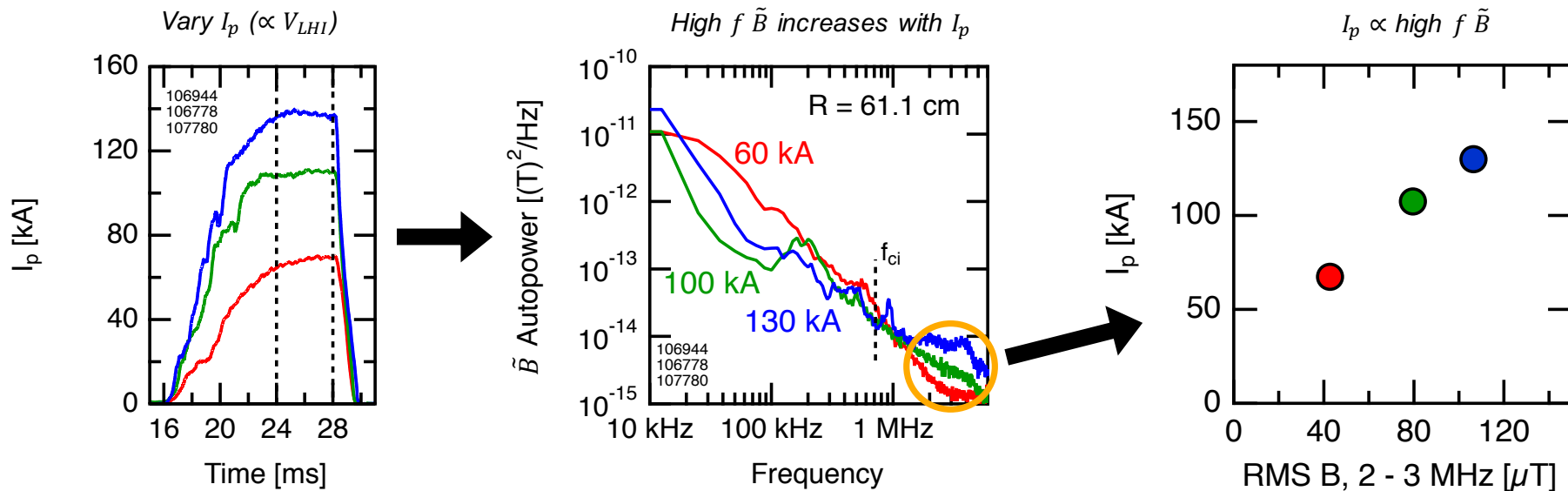


*C.C. Chaston et al., PRL **100**, 175003 (2008)

J.P. Eastwood et al., PRL **102**, 035001 (2009)



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

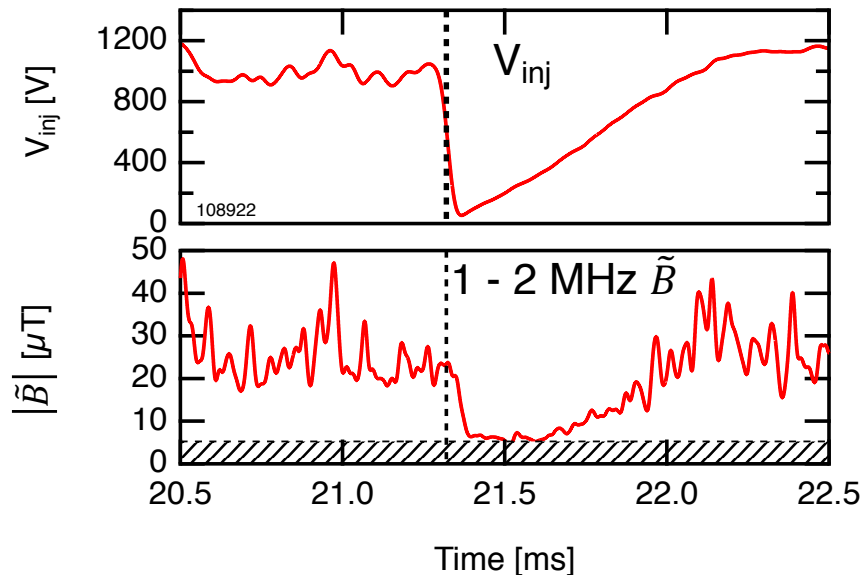


- Study helicity-sustained discharges w/ varying $V_{LHI} \rightarrow$ focus on LHI current drive
- Activity above ~ 1 MHz ($\gg f_{ci}$) increases with I_p , V_{LHI}

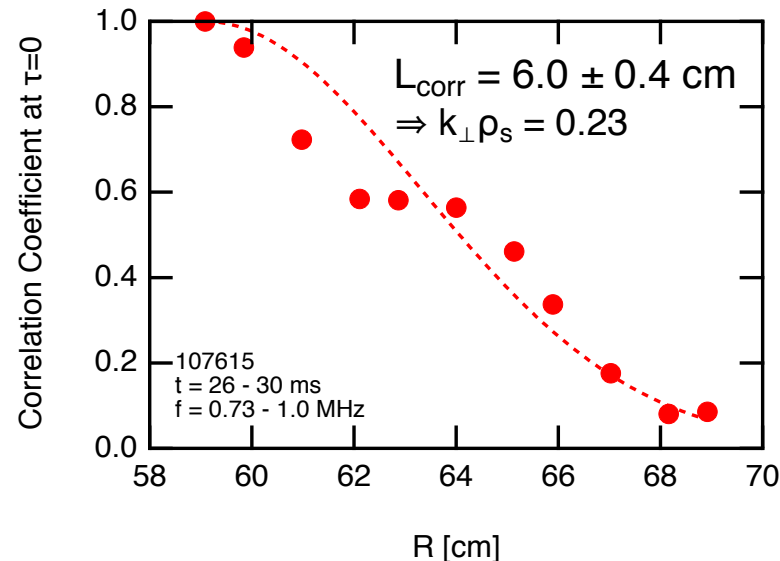


Other Observed High- f Characteristics Suggest Kinetic Nature

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



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



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





Implications for Moving LHI Startup and CD Forward

- Measurements indicate two-zone structure during LHI
 - Inner confined plasma region
 - Outer force-free current region
- Reduced current model reproduces LHI edge magnetic structures with discrete current streams
- Observed LHI $\vec{B}(R, t)$ dynamics also consistent with discrete injector streams
 - Oscillatory $\vec{B}(R, t)$ consistent with localized $n = 1$ line-tied stream motion
 - Streams stabilized in space during reduced $n = 1$ regime
- High frequency magnetic activity in LHI edge may suggest mechanisms for underlying current drive
 - Located in force-free region, $\tilde{B} \propto V_{LHI}, I_P$
 - Potential effects under investigation: Alfvénic turbulence, reconnection activity, KAW





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