PEGASUS-III
Experiment

Characterization of Current Stream Structure in Local Helicity Injection on the PEGASUS ST

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Abstract

Characterization of Current Stream Structure in Local Helicity Injection on the Pegasus ST

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Local Helicity Injection (LHI) uses small, high-power electron current injectors at the plasma edge to provide non-solenoidal tokamak startup. LHI dynamics on PEGASUS are consistent with a discrete injected current stream structure that persists in the plasma edge region following relaxation. Scaling LHI to larger devices requires an understanding of how this current stream structure evolves in time and its potential effect on equilibrium properties. Strong ($\tilde{b}_Z/B_\phi$ ~ 10^{-2}), low-frequency (~20–50 kHz) n=1 activity is observed on the low field side (LFS) during LHI on PEGASUS and is well-characterized by a singly line-tied kink instability of the injected current streams. A simple model of an oscillating helical current stream just outside the plasma edge closely reproduces LFS dB_Z/dt and $\mathbf{B}(R,t)$ measurements. Accounting for the effects of this 3D current stream structure is important because prior work on other tokamaks has shown that even small, nonaxisymmetric perturbations (dB/B_0 ~ 10^{-4}) can greatly modify plasma performance. The helical current stream model can be used to inform future 3D equilibrium studies of LHI using codes like the Generalized Perturbed Equilibrium Code (GPEC).

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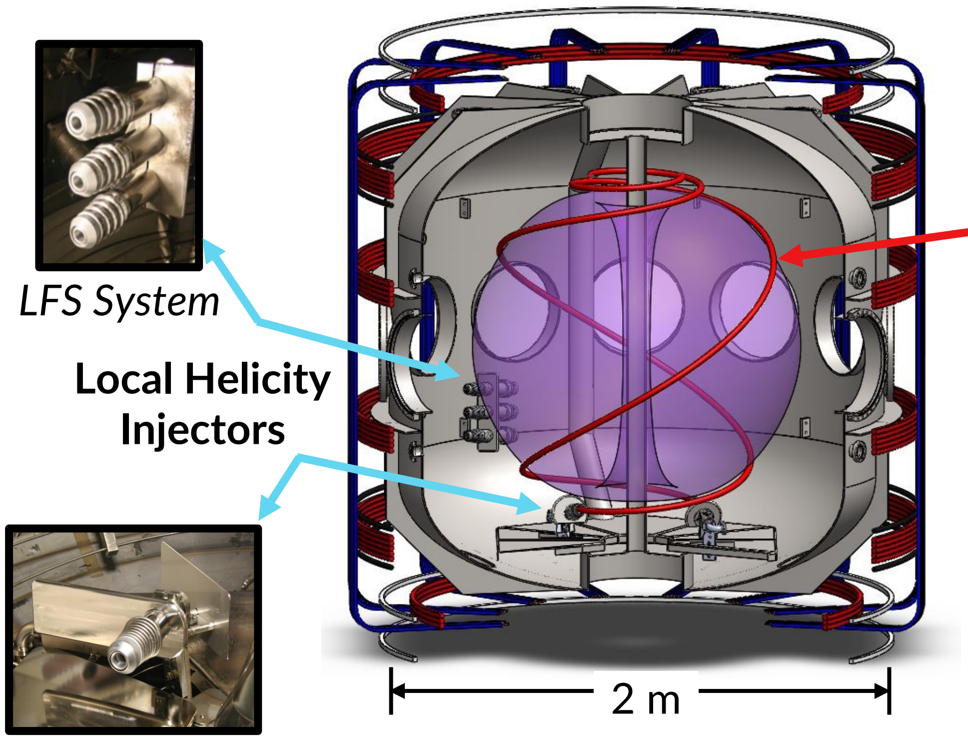
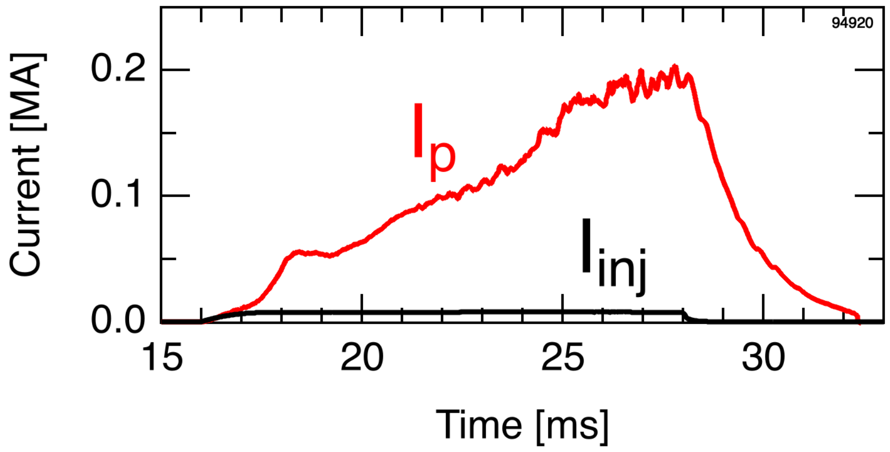
Characterizing LHI Current Stream Structure is Important for Understanding Transport and Scaling to Larger Devices

Experiments on the PEGASUS ST Used Local Helicity Injection for Non-Solenoidal Startup at Low *A*

PEGASUS



High Current Mulitplication: I_p ≤ 0.2 MA with I_{inj} ≤ 8 kA



- LHI used routinely for startup and current drive on PEGASUS
- Edge current extracted from small, modular injectors
- Unstable current streams relax to tokamak-like state via helicity-conserving instabilities

PEGASUS Parameters

A	1.15 – 1.3
R [m]	0.2 – 0.45
I_p [MA]	≤ 0.23
$B_{t,0}$ [T]	< 0.15
τ_{shot} [s]	≤ 0.025

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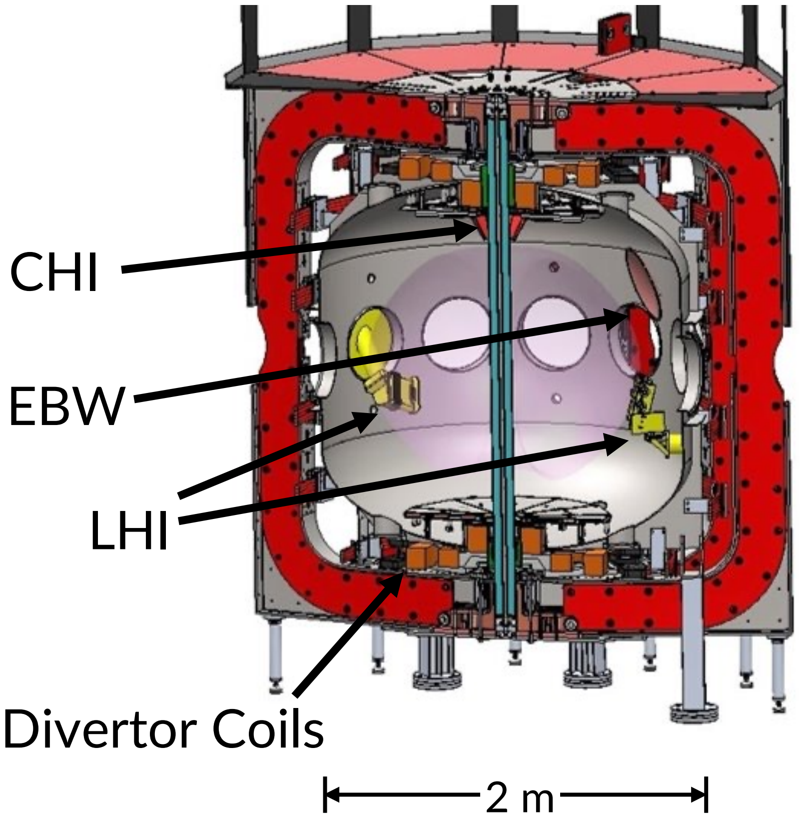
PEGASUS-III Experiment Enables Comparative Studies of Non-Solenoidal Startup Methods

Pegasus-III Mission: Solve solenoid free startup by investigating synergistic effects of non-solenoidal techniques using reactor relevant technology

Pegasus-III Features

- No solenoid: allows for 4× B_T increase
- Advanced local helicity injection (LHI): testing at increased B_T
- Coaxial helicity injection (CHI): transient and sustained
- RF assist, sustainment, and startup: heating and current drive via electron Bernstein wave (EBW) and electron cyclotron (EC)
- Expanded diagnostics
- Advanced control

PEGASUS-III



→ Coupling RF to LHI and scaling techniques to larger devices requires understanding LHI's impact on plasma edge

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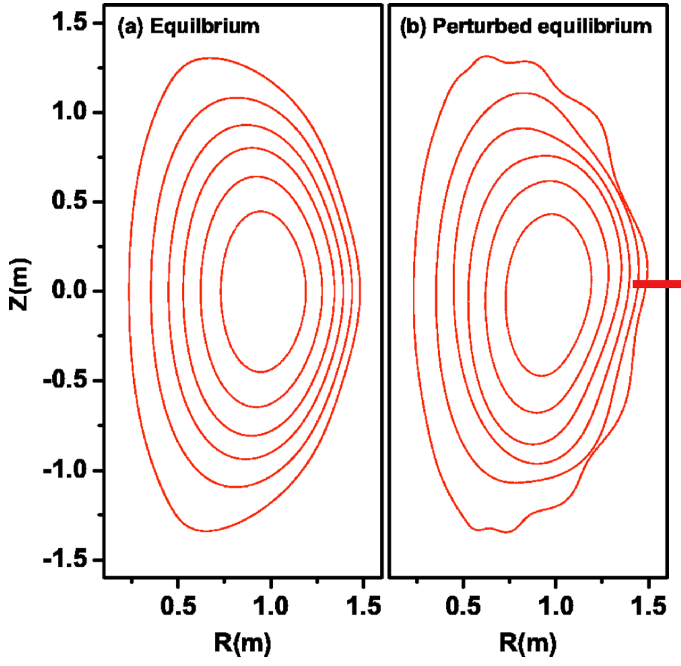
Large External Perturbations From LHI Streams Expected

- Small, nonaxisymmetric perturbations ($\frac{\delta B}{B_0}$ ~ 10^{-4}) shown to greatly modify plasma performance on other tokamaks

Perturbed equilibrium due to external perturbation on NSTX[1]



- External perturbation from LHI stream motion is strong: $\frac{\tilde{b}_Z}{B_\phi}$ ~ 10^{-2}
- Plasma response could have implications for core confinement and transport
  - Understanding is required for scaling to larger devices

Insertable probes provide unique diagnostic capability: direct, local measurements inside plasma edge region

[1]*Park et al., Phys. Of Plasmas* ***14*** *052110 (2007)*

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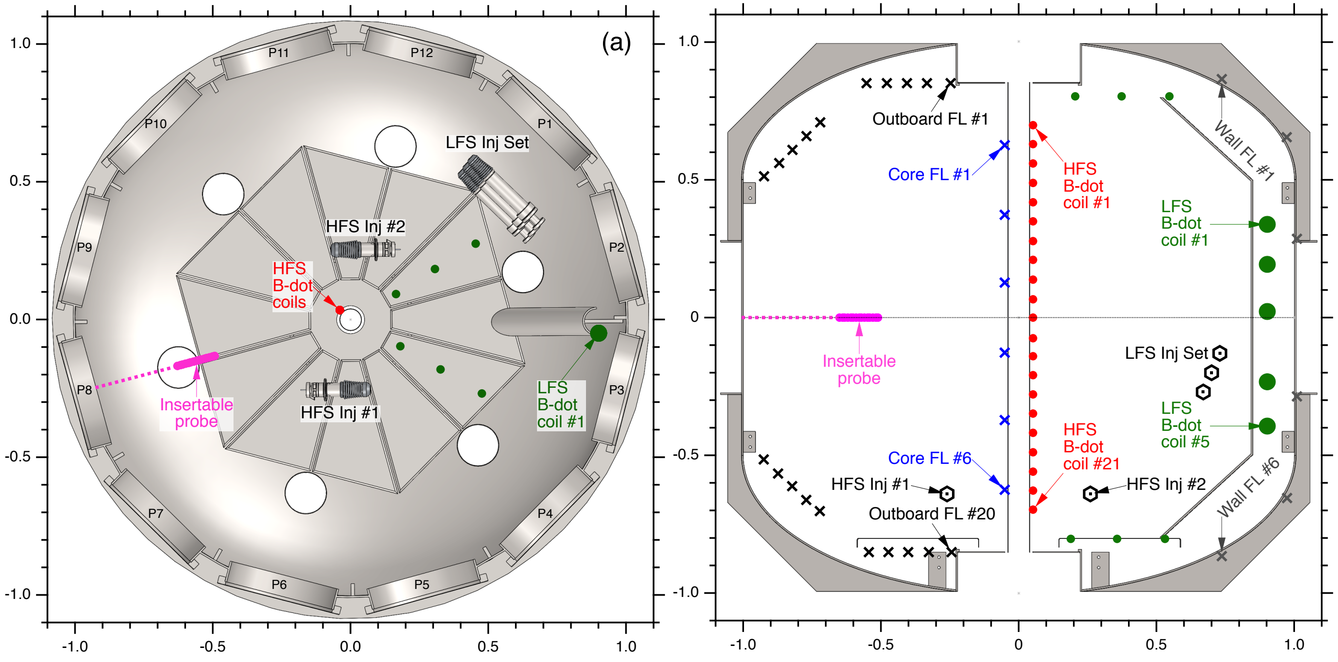
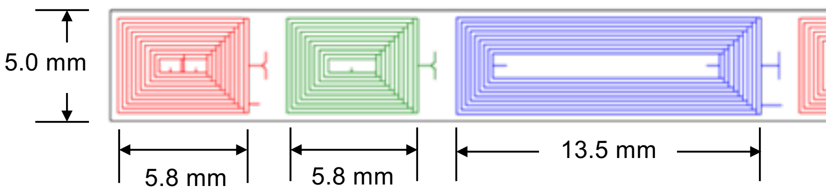
External Magnetics Supplement Internal Probe Measurements

PEGASUS Relevant Magnetic Diagnostic Layout

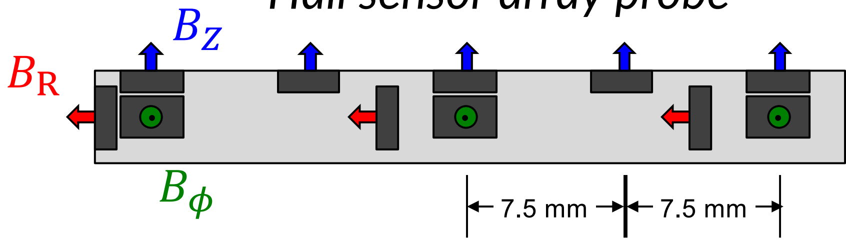
Top-down *Cross-section*



$\dot{B}_Z(R)$ array probe



Hall sensor array probe



- External magnetics provide additional outboard fluctuation measurements:
  - Toroidally and poloidally distributed Mirnov coils
  - Effective bandwidth of 400 kHz

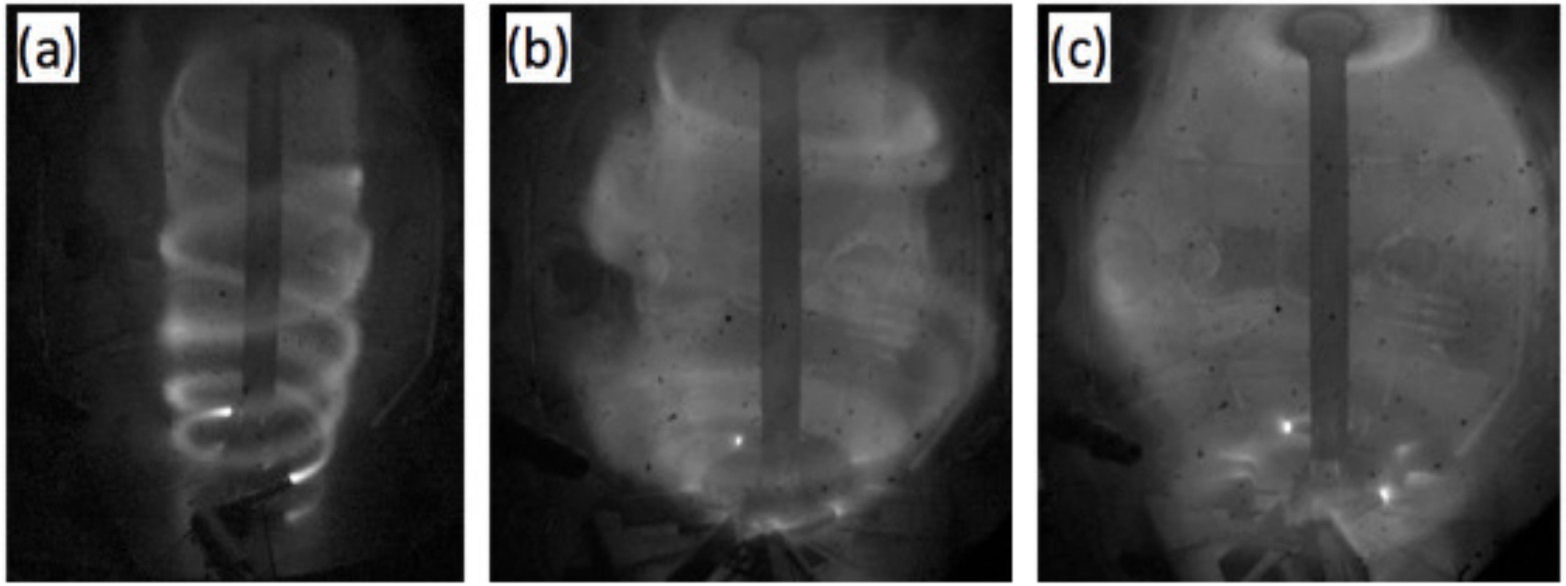
- Probe position adjustable along PEGASUS midplane
  - $Z \sim 0$ cm
  - $R = 50 – 100$ cm

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

Initial Characterization of Injected Current Suggests Coherent Stream Structure

Fast Cameras Show Coherent Streams Prior to Relaxation

Phantom camera images of relaxation process during HFS LHI[1]



(a) Injected streams follow helical vacuum field lines

(b) Streams go unstable and reconnect

(c) Plasma relaxes to a tokamak-like state

- **Further analysis needed to characterize injected current structure in relaxed plasma**

[1]Perry et al., *Nucl. Fusion* **58** 096002 (2018)

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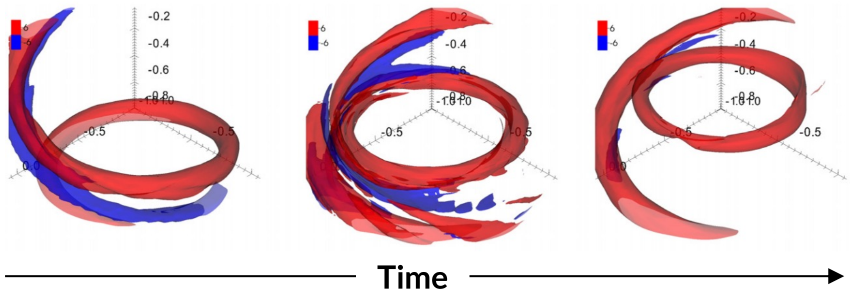
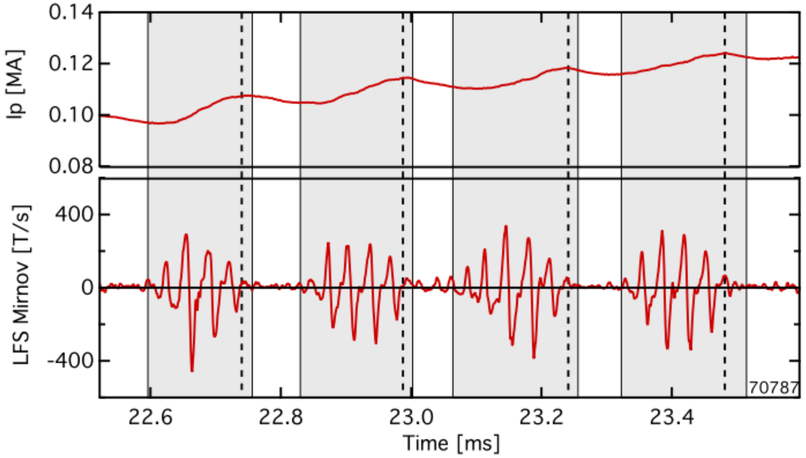
Macroscopic Reconnection Current Drive Mechanism Relies on Coherent Stream Structure

- NIMROD simulations show CD from macroscopic reconnection of adjacent stream passes
  - Adjacent passes attract, merge, and reconnect to form current rings
  - Rings diffuses inward, building poloidal flux
  - Model suggests coherent streams
- Mechanism consistent with experimental observations on PEGASUS
  - Experimental observation: bursts of *n*=1 activity correlated with increases in I_p
  - NIMROD shows similar bursts associated with CD
- Mechanism especially important in early phase of LHI

$\lambda = \mu_0 J_{||}/B$ surfaces from NIMROD simulations of stream reconnection event[1]



n=1 bursts correlated with I_p increases on Pegasus[2]



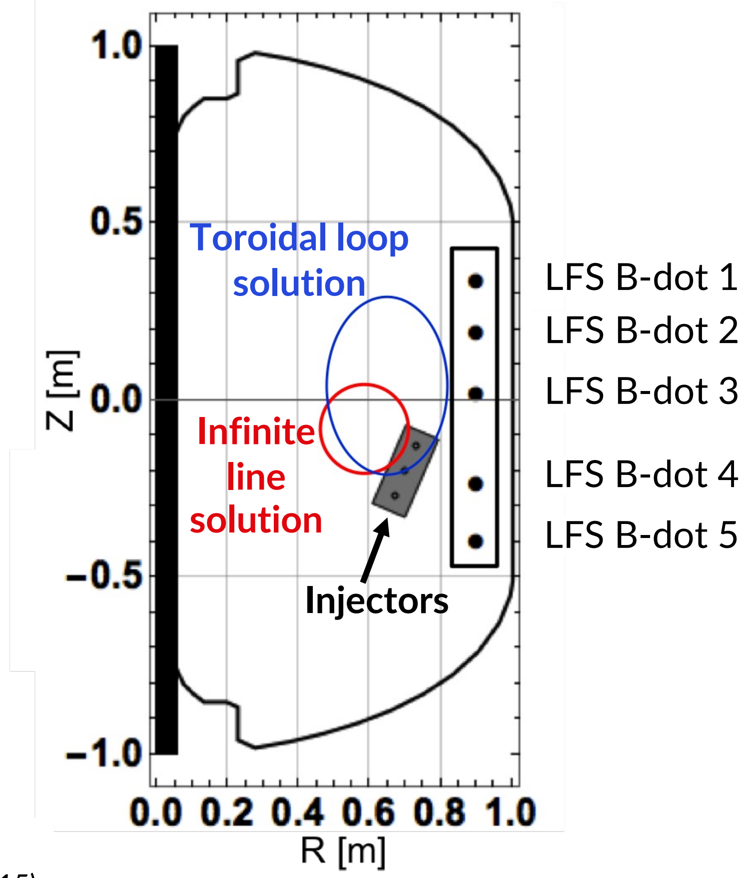
[1]O'Bryan and Sovinec, *Plasma Phys. Control. Fusion* **56** 064005 (2014)
[2]Barr, PhD Thesis, University of Wisconsin-Madison (2016)

Previous Work Shows Coherent Stream Oscillating in Edge Region During LFS LHI

- Bursts of *n*=1 activity on LFS magnetics well-characterized by a singly line-tied kink instability of injected current stream
  - Amplitude, phase of measured LFS $\dot{B}_Z$ should be consistent with oscillatory motion of a discrete stream
- Current stream modeled as an infinite line,[1,2] then as a toroidal loop[3,4] of current
- Fitting procedure used to determine (R, Z) of centroid position, oscillation size
- Simulated LFS $\dot{B}_Z$ data closely reproduced measured data

→ Source of *n*=1 activity is coherent injected current stream undergoing transverse oscillations in the edge region

(R,Z) location of oscillating stream from phase-amplitude analysis best fit solutions



[1]Hinson, PhD Thesis, University of Wisconsin-Madison (2015)
[2]Hinson et al., 57th APS-DPP Conference Proceedings, GP12.00117 (2015)
[3]Barr, PhD Thesis, University of Wisconsin-Madison (2016)
[4]Barr et al., 58th APS-DPP Conference Proceedings, NP10.00055 (2016)

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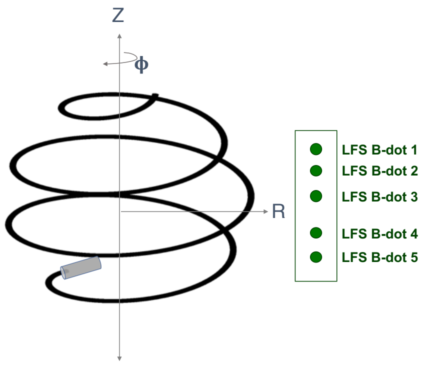
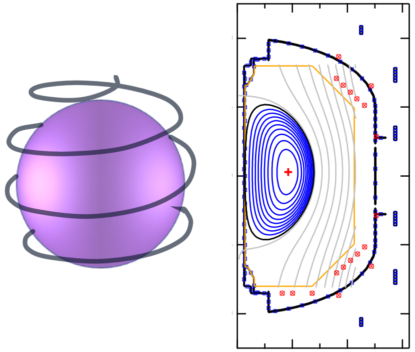
New Approach for LHI Current Stream Characterization

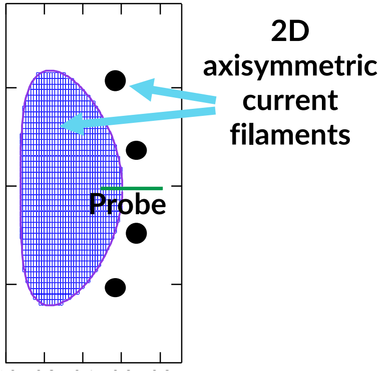
Helical current structure that best reproduces LFS Mirnov signals found using phase-amplitude fitting method



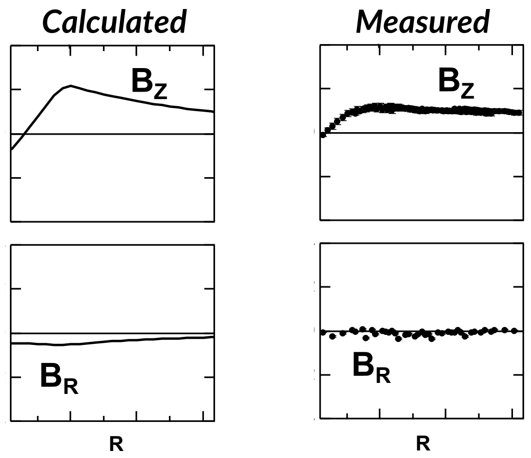
2D equilibrium reconstructed with inferred stream contribution subtracted



$J(R, Z)$ grid extracted from equilibrium, 2D projections of helical stream passes added



B_R, B_Z calculated via axisymmetric Green response, mapped to probe location and compared to measured data



Helical current stream structure used as input for 3D equilibrium studies of LHI

Helical current stream model verification

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Injected Current Modeled as an Oscillating Helical Current Stream

Model Expanded to Include 3D Helix Representation of Injected Current Stream

- Assume Gaussian wave packets for R_{stream}, Z_{stream} due to *n*=1 bursts:

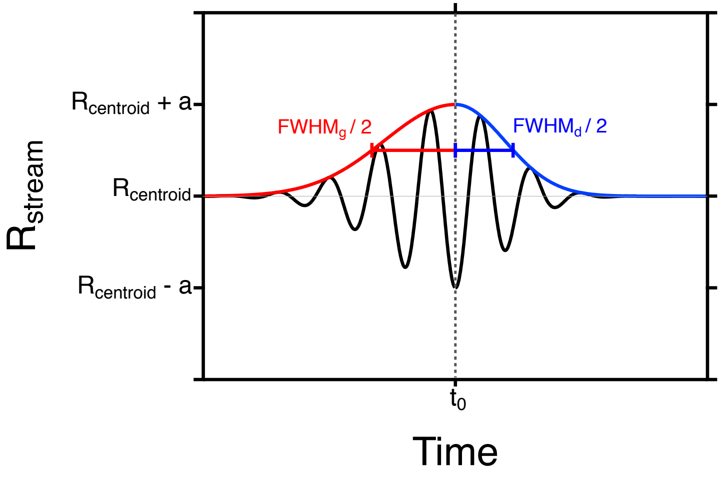
$$R_{stream} = R_{centroid} + a e^{\frac{-(t-t_0)^2}{\frac{FWHM^2}{4\ln(2)}}} \cos(2\pi f t + \varphi)$$

$$Z_{stream} = Z_{centroid} + b e^{\frac{-(t-t_0)^2}{\frac{FWHM^2}{4\ln(2)}}} \cos(2\pi f t + \varphi)$$

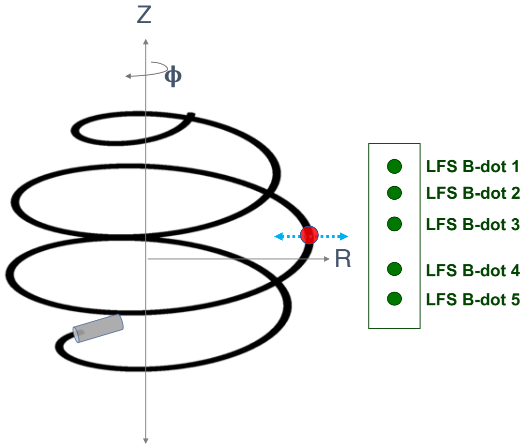
(red = fit parameter)

- 3D helix carrying I_{inj} generated from geometric parameters, where (R_{stream}, Z_{stream}) is radially outermost point
- Each point along helix can oscillate with time
- Simulated magnetic response is compared to *n*=1 burst in LFS $\dot{B}_Z$ data
- Best fit oscillating helix solution is determined

Gaussian wave packet representation of radial position for single point along helix



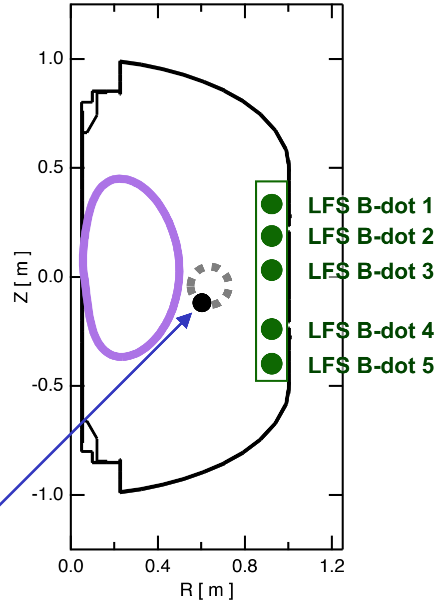
Oscillating helical current stream structure



Single-Injector HFS LHI Discharge Analyzed

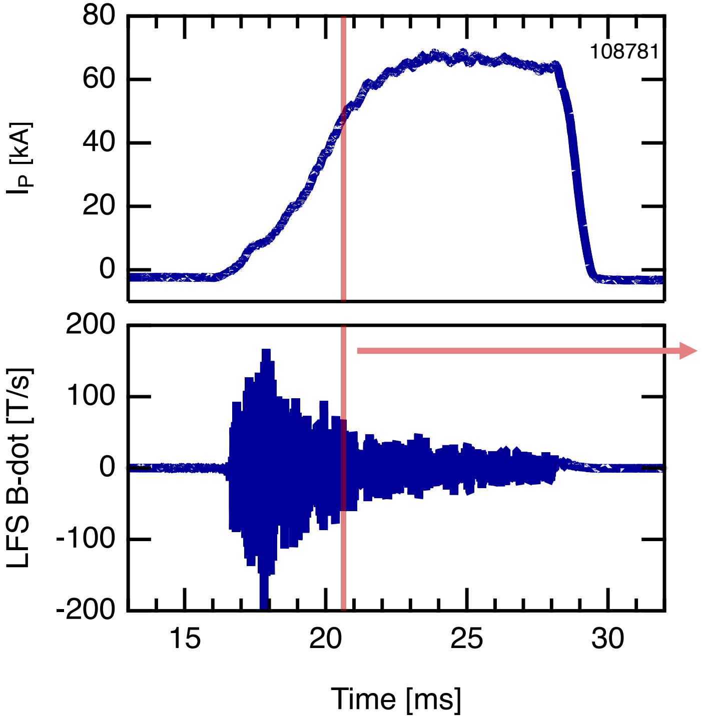
- Time window identified with *n*=1 burst resolvable as discrete event
- Poloidal variation of *n*=1 amplitude and phase observed in LFS $\dot{B}_Z$ data

Current stream motion produces magnetic response on LFS $\dot{B}_Z$ 1-5 array

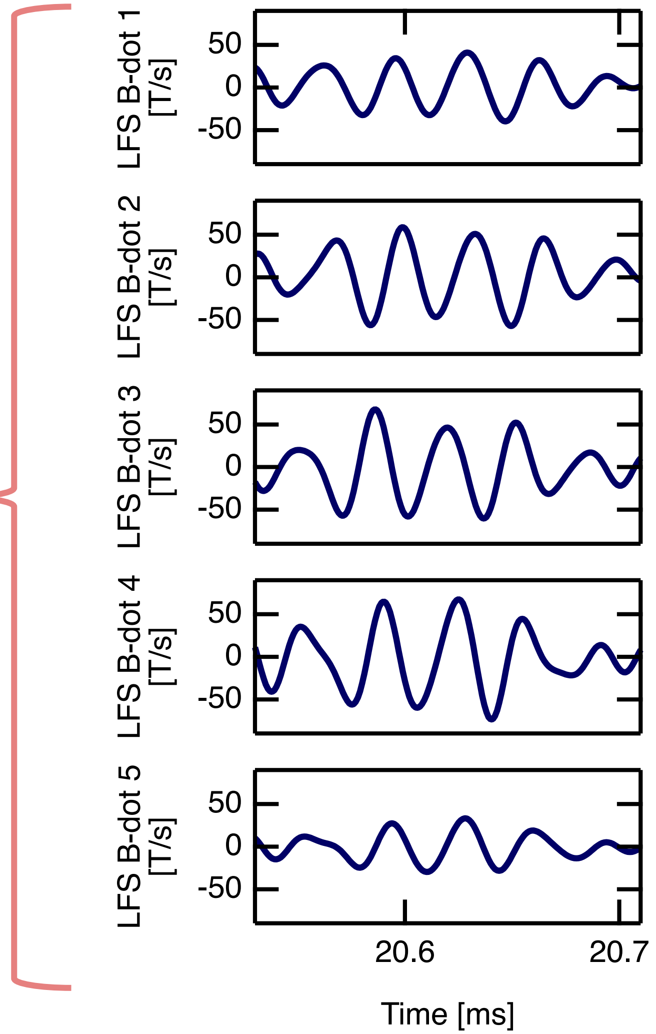


Oscillating current stream produces *n*=1 burst

Single-injector HFS LHI discharge has discernable $n = 1$ burst events earlier in time



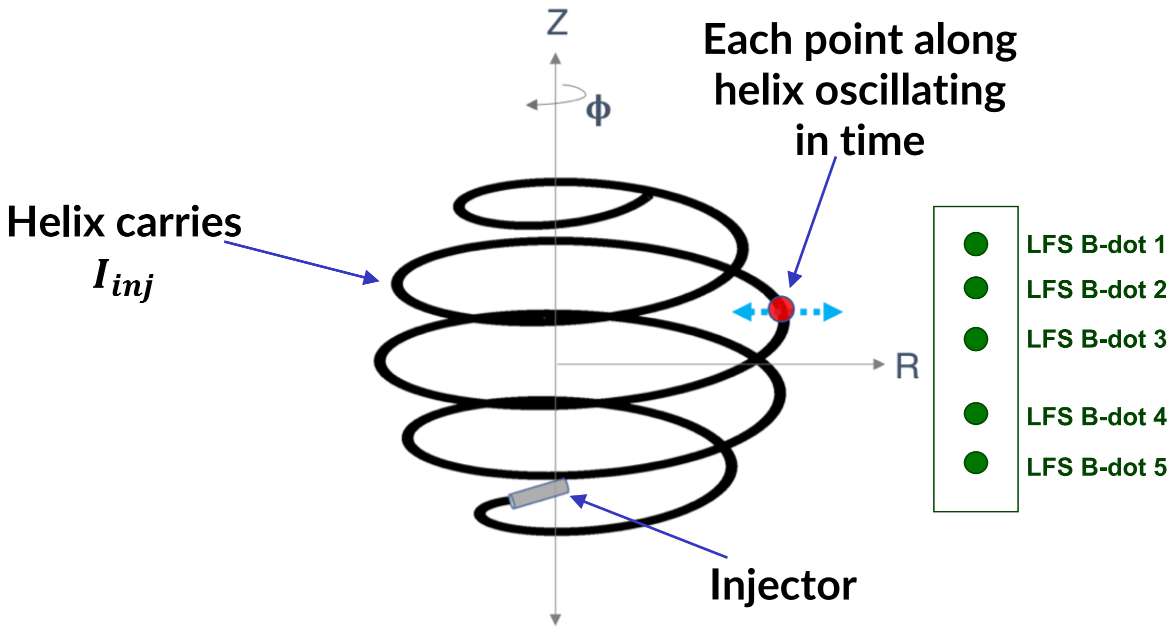
$n = 1$ burst observed on LFS $\dot{B}_Z$ signals within time window



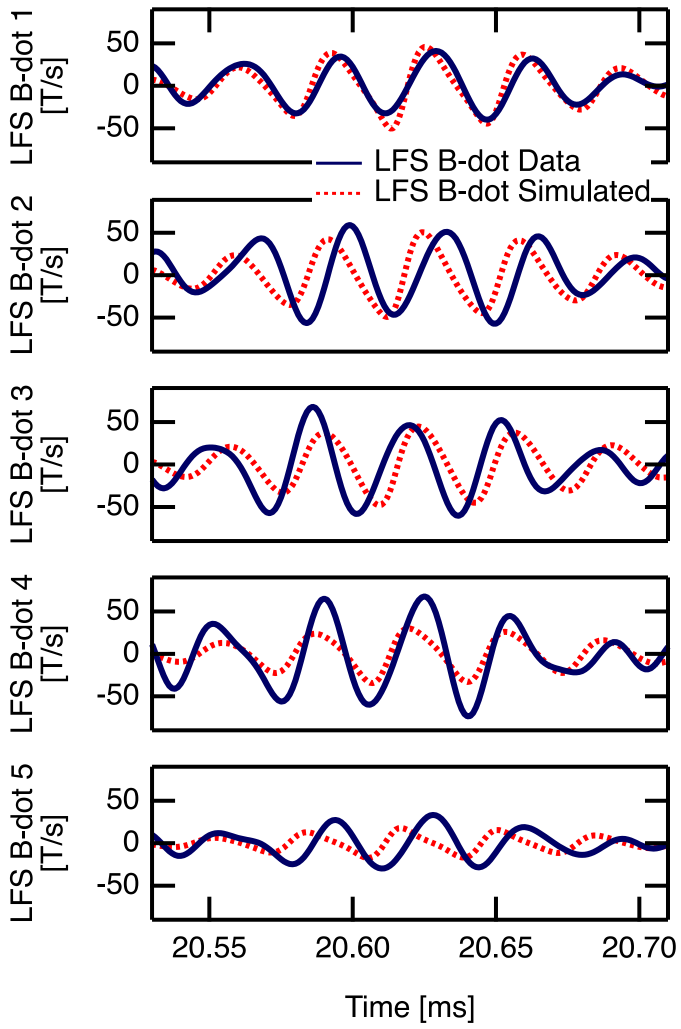
Current Stream Model Reproduces LFS $\dot{B}_Z$ Measurements

- Fitting method determines helical current structure with magnetic response that most closely fits LFS $\dot{B}_Z$ data

Best fit solution of helical stream model: helix at a single time point



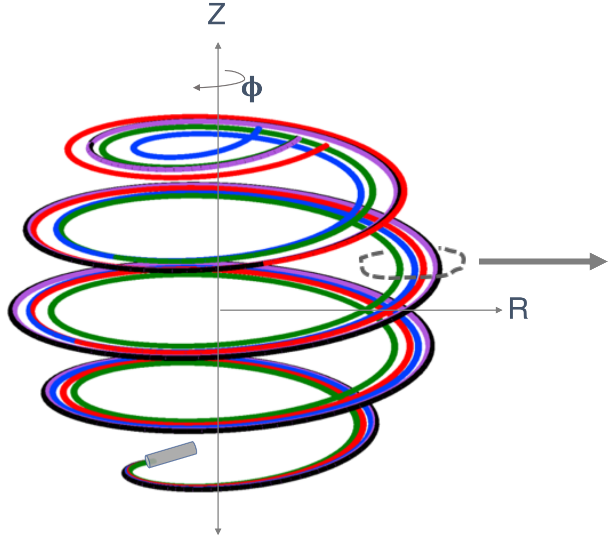
Simulated magnetic response from best fit helix compared with LFS $\dot{B}_Z$ data



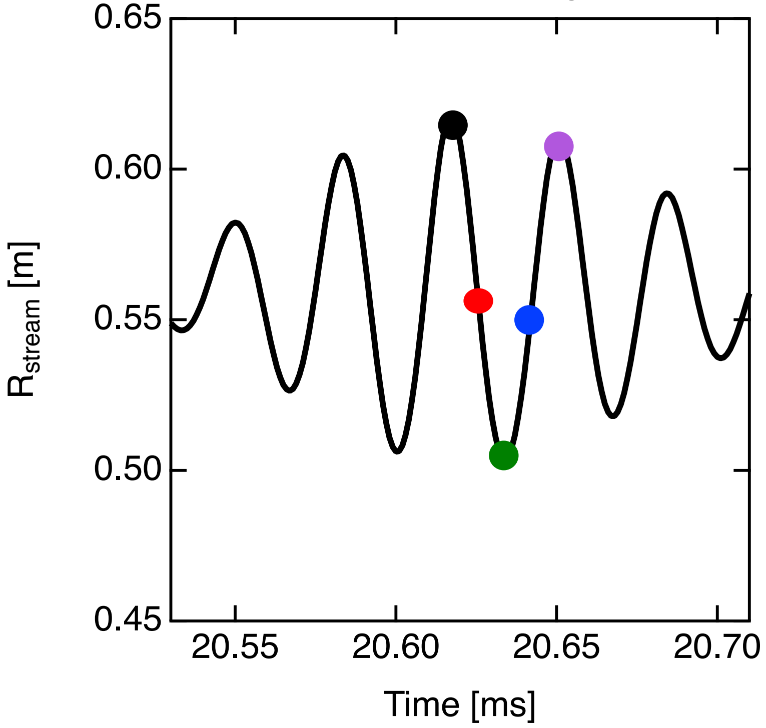
Oscillatory Motion of Helical Current Stream

- Each point along helix translates in time
- Oscillation amplitude grows then decays, corresponding to *n*=1 burst
- Oscillation size increases with distance from injector along helix

Oscillatory motion of best fit helix: colors represent helices at different time points



Radial stream position of radially outermost point along helix



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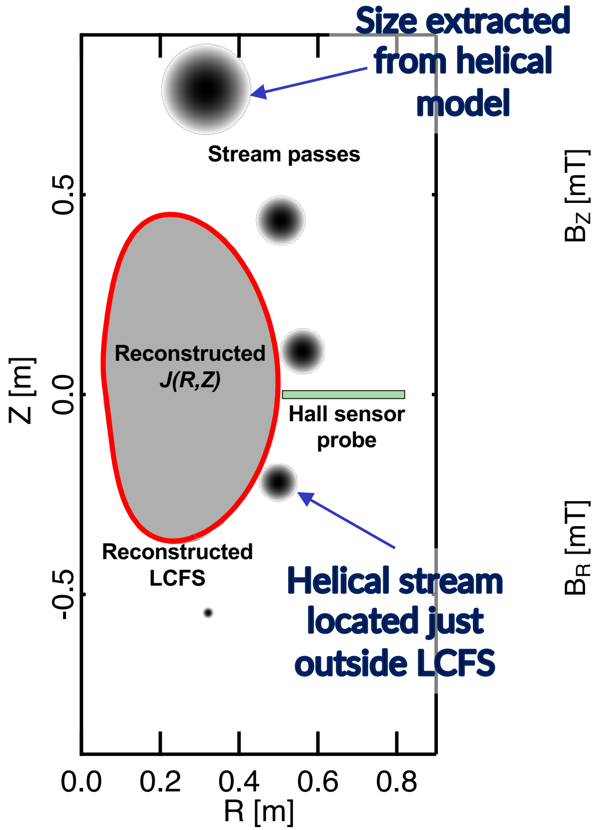
2D Filament Model Reproduces Observed Field Structure

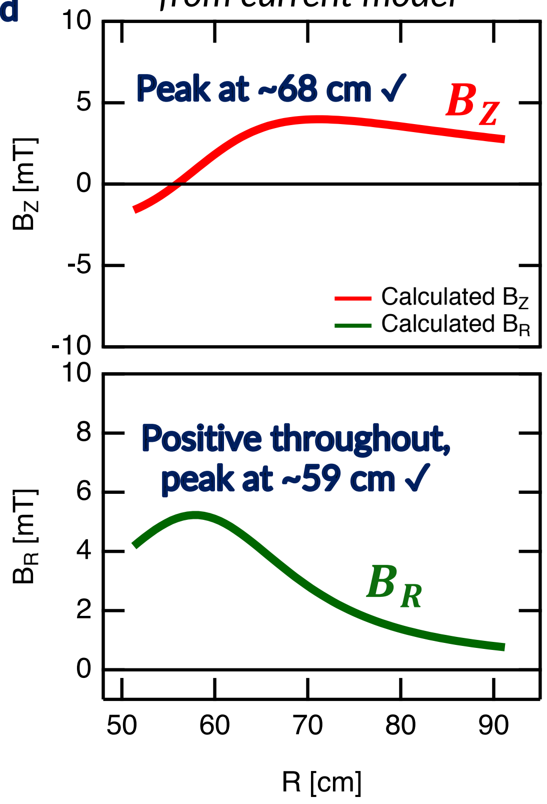
Method

- Equilibrium reconstructed at time of helical stream analysis
- $J(R, Z)$ extracted from equilibrium
- I_{inj} added at location of each helix pass
- B_Z, B_R calculated via axisymmetric Green response, mapped to probe location
- Calculated profiles compared to measured data

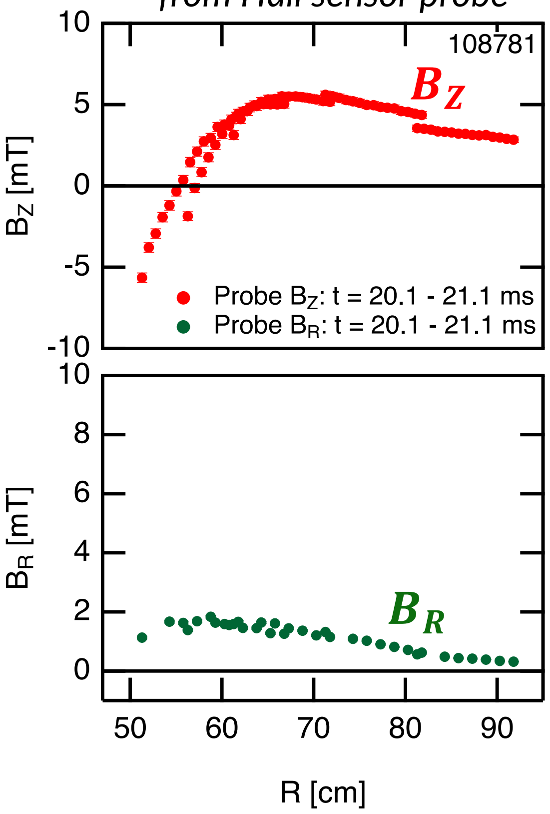
Current distribution in poloidal plane of Hall sensor probe



Calculated field profiles from current model



Measured field profiles from Hall sensor probe



→ Helical stream model qualitatively reproduces measured field

Investigating Time Dynamics of Current Stream Structure

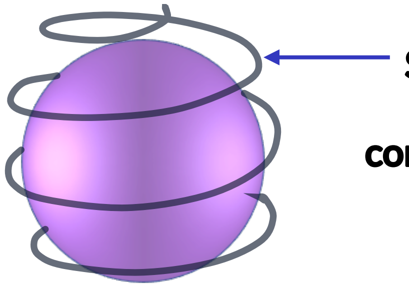
Equilibrium Reconstructed Later in Time for Single-Injector LHI Discharge, Stream Contribution Subtracted

Method

- Reconstruct equilibrium including LHI stream contribution
- Correct for LHI stream windup:

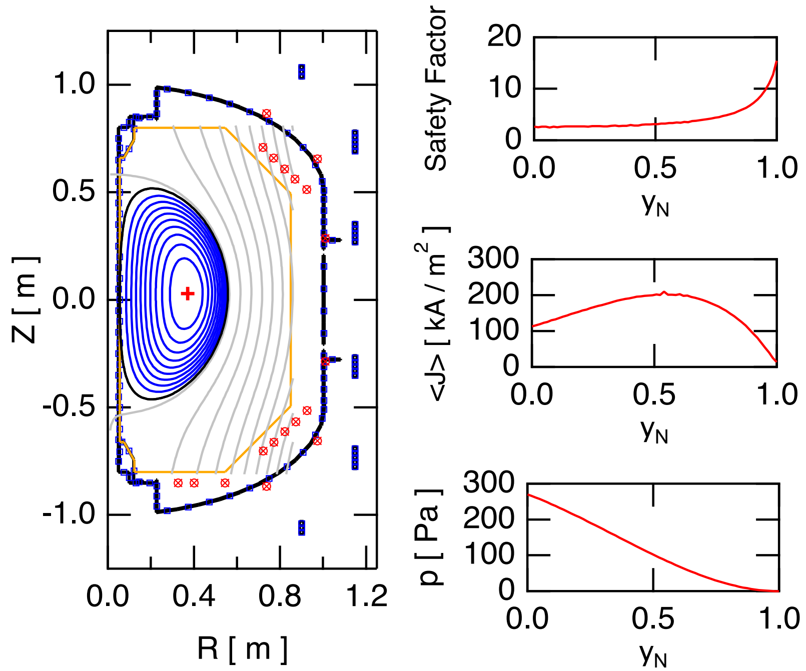
$$I_{p,corrected} = I_{p,total} - \left(I_{inj}\right) \cdot \left(\text{\# stream passes through eq. solution plane}\right)$$

- Reconstruct equilibrium with $I_{p,corrected}$



Subtract LHI stream contribution to I_p

Windup-corrected equilibrium reconstruction for single-injector LHI discharge: t = 25 ms

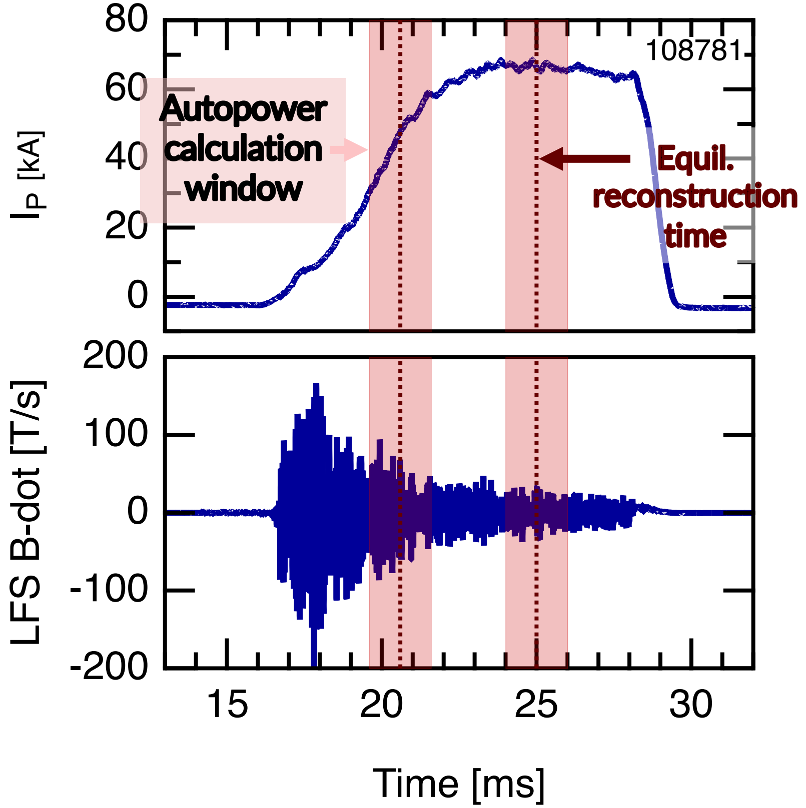


Equilibrium Parameters
Shot 108781, 25.00 ms

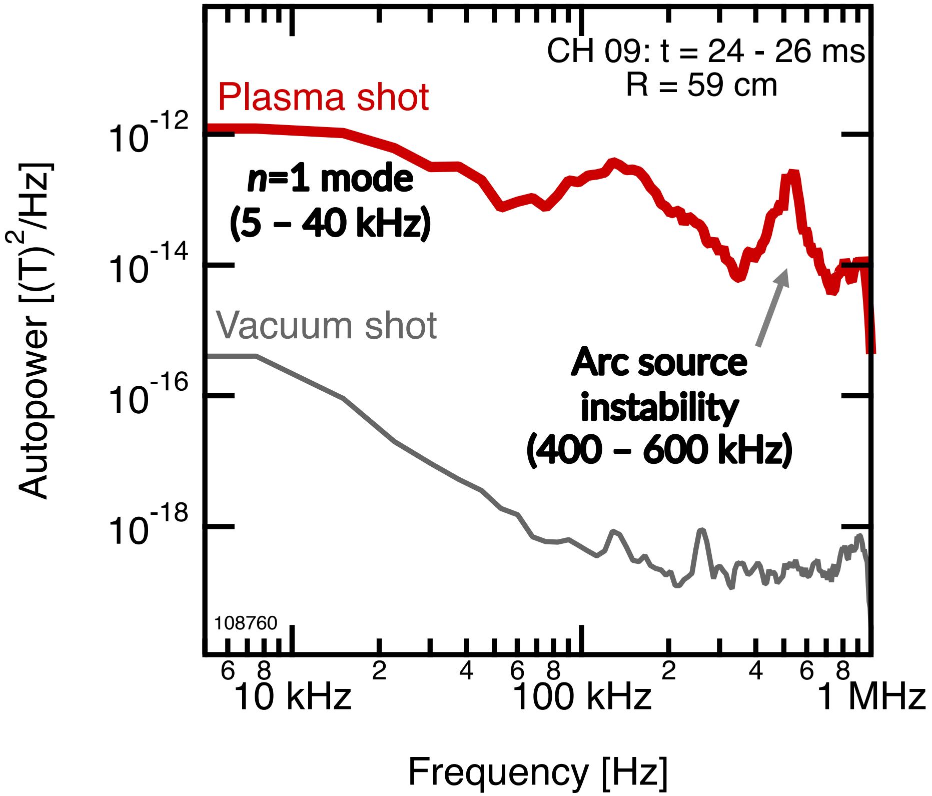
I_p	63.3 kA	R_0	0.306 m
β_t	0.094	a	0.251 m
l_i	0.43	A	1.22
β_p	0.30	κ	2.0
W	255 J	δ	0.39
B_{T0}	0.0434 T	q_{95}	9.66

Insertable $\dot{B}_Z(R)$ Probe Used to Study Time-Evolving Localization of Injected Current During HFS LHI

Single-injector HFS LHI discharge with time windows used for mode localization analysis



Representative LHI autopower spectrum from $\dot{B}_Z(R)$ probe with stream-relevant spectral features identified



- Spectral features associated with LHI streams isolated
  - ***n*=1 mode**: line-tied kinking motion of streams → associated with CD from macroscopic reconnection
  - **Arc source instability**[1]: arc source fluctuations swept along stream → centroid f increases with $|B|, V_{inj}, I_{inj}, v_{beam}$

C.E. Schaefer, APS-DPP 2022

[1] *Richner, PhD Thesis, University of Wisconsin-Madison (2021)*

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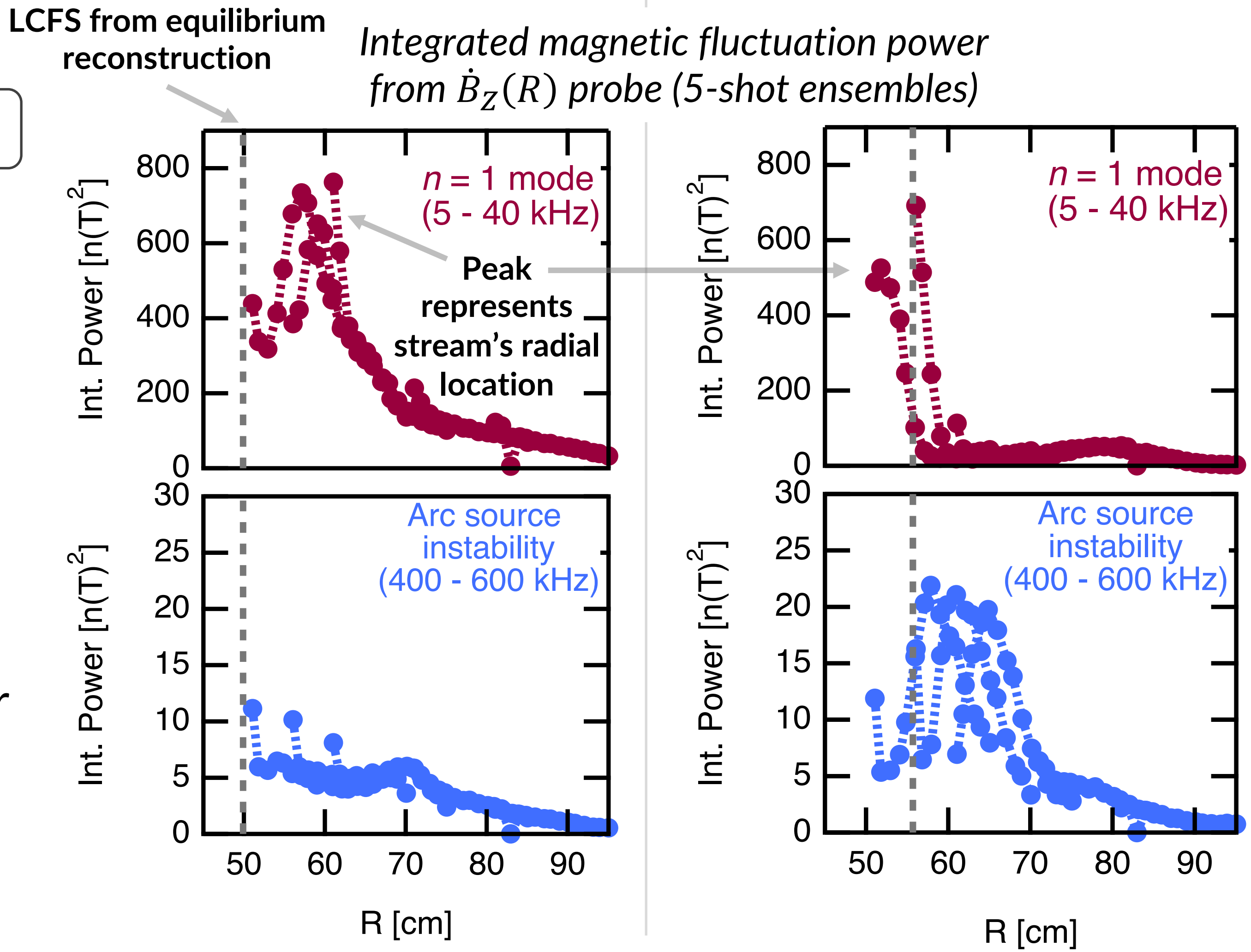
Spatial Localization of Stream Features Changes as HFS LHI Discharge Evolves

t = 20.6 ms

- *n*=1 fluctuation power strongest just outside edge
  - Consistent with helical current stream model
- Relatively low fluctuation power from arc source instability



t = 25 ms

- *n*=1 fluctuation power strongest just inside plasma edge
  - Suggests streams become entrained into confined, tokamak-like region
- Fluctuation power from arc source instability peaked outside plasma edge, despite stream movement inward

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Time-Evolving Current Stream Structure During LFS LHI will be Explored on PEGASUS-III

HFS LHI

- Focus of recent studies on PEGASUS
- Discharges have static shape
- Utilizes direct LHI drive
- Current stream characterization
  - Streams remain coherent following relaxation ✓
  - Helical stream model reproduces magnetic measurements ✓
  - Entrainment of streams into tokamak-like region observed later in time ✓

LFS LHI

- Focus of planned studies on PEGASUS-III
- Discharges have dynamic shape
- Utilizes LHI and non-solenoidal inductive drive
- Current stream characterization
  - Streams remain coherent following relaxation[1-4] ✓
  - 3D structure characterization
  - Degree of stream entrainment throughout discharge

Will be explored on PEGASUS-III

[1] *Hinson, PhD Thesis, University of Wisconsin-Madison (2015)*
[2] *Hinson et al., 57th APS-DPP Conference Proceedings, GP12.00117 (2015)*
[3] *Barr, PhD Thesis, University of Wisconsin-Madison (2016)*
[4] *Barr et al., 58th APS-DPP Conference Proceedings, NP10.00055 (2016)*

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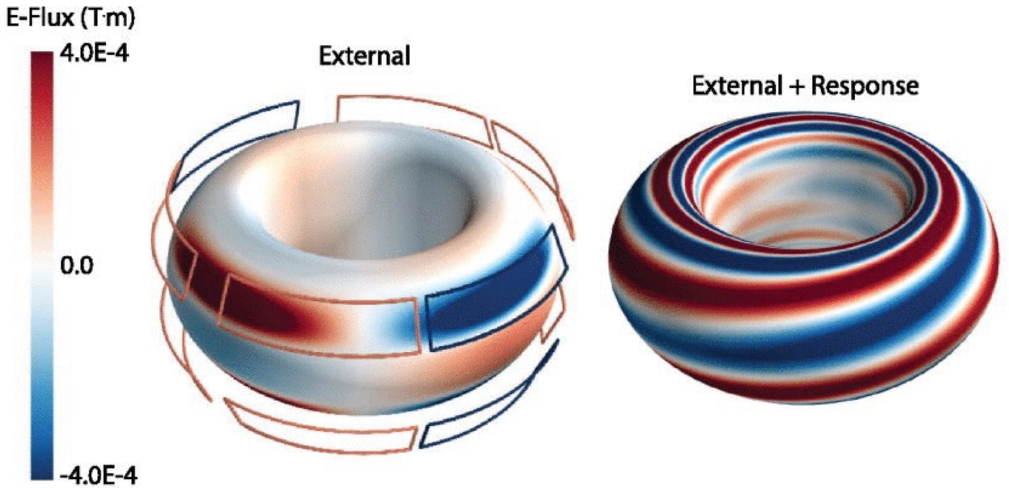
Effects of LHI Current Stream on Plasma Equilibrium Properties

Calculating Perturbed Equilibrium with GPEC

- The Generalized Perturbed Equilibrium Code (GPEC) is a 3D physics tool that calculates linear, perturbed nonaxisymmetric tokamak equilibria
- Physics applications of GPEC
  - 3D field coil optimization
  - Predicting resonant coupling for edge-localized modes (ELMs), error field correction (EFC), and neoclassical toroidal viscous (NTV) torque
  - 3D measurement validation
- Matrix formalism approach allows for multi-modal plasma response calculation
- Runs within OMFIT framework[1,2]

Ideal Perturbed Equilibrium Code (IPEC) used to calculate plasma response to applied external perturbation[3]*



External flux applied on IPEC control surface

Perturbed equilibrium external flux

**IPEC is the purely ideal MHD precursor to GPEC*
[1] *Meneghini et al., Nucl. Fusion* ***55****, 083008 (2015)*
[2] *Meneghini and Lao, Plasma Fusion Res.* ***8****, 2403009 (2013)*
[3] *Adapted from Logan et al., Phys. of Plasmas* ***23****, 056110 (2016)*

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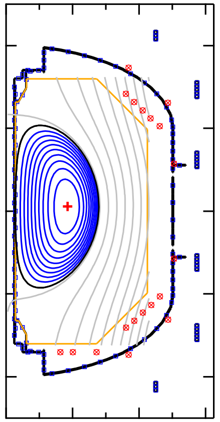
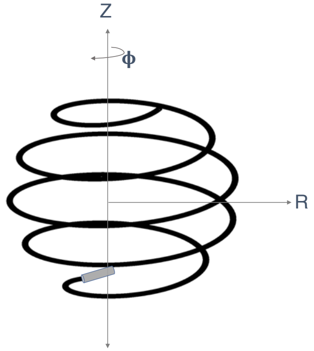
LHI Helical Current Stream Structure Used as Input to GPEC

Inputs

- 2D equilibrium reconstruction, stream windup correction applied



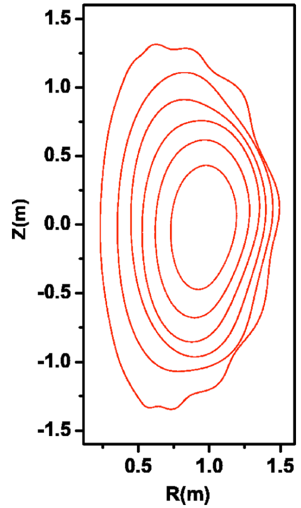
- Applied 3D field calculated from helical current stream



GPEC

Outputs

- Perturbed 3D equilibrium



NSTX example[1]

- Amplitude & phase of perturbed magnetic field δB

Can use insertable probes and coil arrays on PEGASUS-III to experimentally verify δB

[1]*Park et al., Phys. Of Plasmas* ***14*** *052110 (2007)*

Summary & Implications for Future Studies

- Coupling RF to LHI and scaling non-solenoidal startup techniques to larger devices requires understanding how LHI impacts plasma edge
- Strong $\left(\frac{\tilde{b}_Z}{B_\phi} \sim 10^{-2}\right)$, low-frequency (~20-50 kHz) *n*=1 activity is observed on the LFS during LHI
  - Well-characterized by line-tied kink instability of injected current streams
  - Coherent stream oscillating in the edge region reproduces *n*=1 bursts observed on LFS magnetics
  - Spatial localization of *n*=1 fluctuation power suggests stream entrainment during HFS LHI
- Simple model of an oscillating, discrete helical current stream just outside the plasma edge following relaxation reproduces LFS magnetic measurements during HFS LHI
  - Similar analysis will characterize stream structure during LFS LHI on PEGASUS-III
- Helical current stream model used to inform external perturbation in future 3D equilibrium studies
  - Magnetic measurements on PEGASUS-III will experimentally verify GPEC calculations of δB

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