

Pegasus-III Experiment

Characterization of Injected Current Stream Structure and its Impact on Magnetic Topology in Local Helicity Injection on the Pegasus-III Experiment

C.E. Schaefer, M.W. Bongard, S.J. Diem, H.G. Frerichs, C. Pierren, J.A. Reusch, A.C. Sontag, J.M. Van Blarcum, J.D. Weberski

65th Annual Meeting of the APS Division of Plasma Physics
Denver, CO, Presentation BO08.00005
30 October 2023
Work Supported by US DOE Grant DE-SC0019008



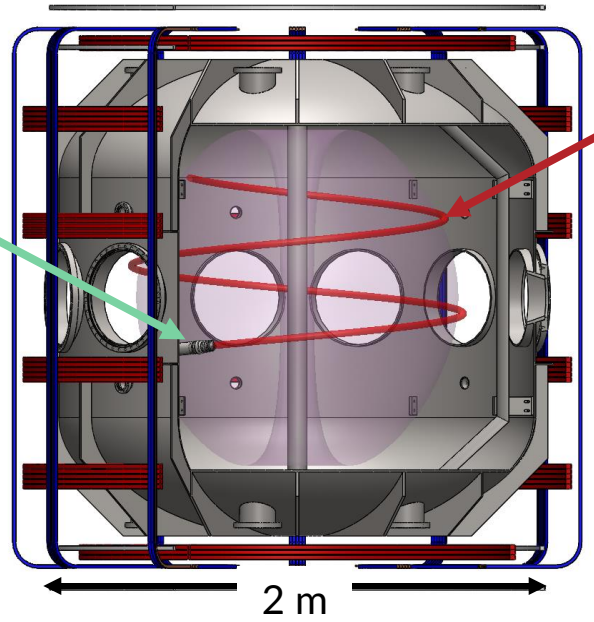
Department of Nuclear Engineering & Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Local Helicity Injection (LHI) Provides Nonsolenoidal Startup

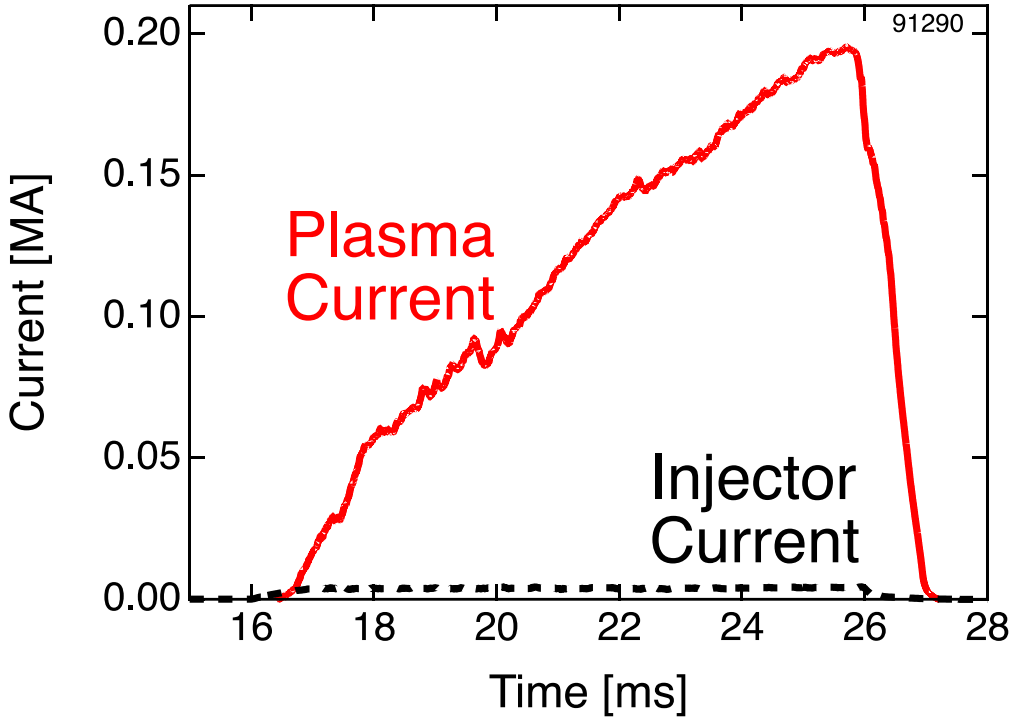
- Current extracted from small, modular injectors at plasma boundary[1]
- Relaxation to tokamak-like state via helicity-conserving instabilities



Local Helicity Injectors



High Current Multiplication:
$I_p \leq 0.2$ MA with $I_{inj} \leq 8$ kA

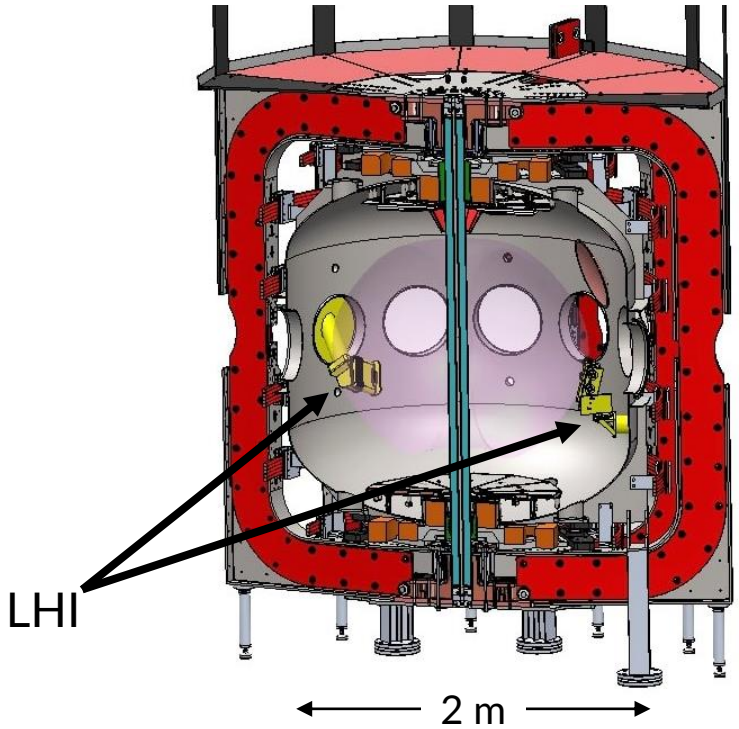


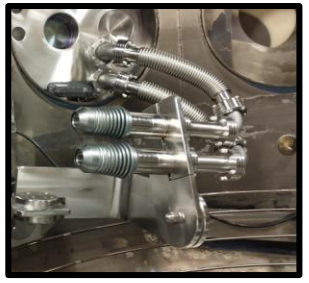
[1]Bongard et al., Nucl. Fusion **59** 076003 (2019)

Department of Nuclear Engineering & Engineering Physics
UNIVERSITY OF WISCONSIN-MADISON

LHI Studies Continue on New Pegasus-III Facility

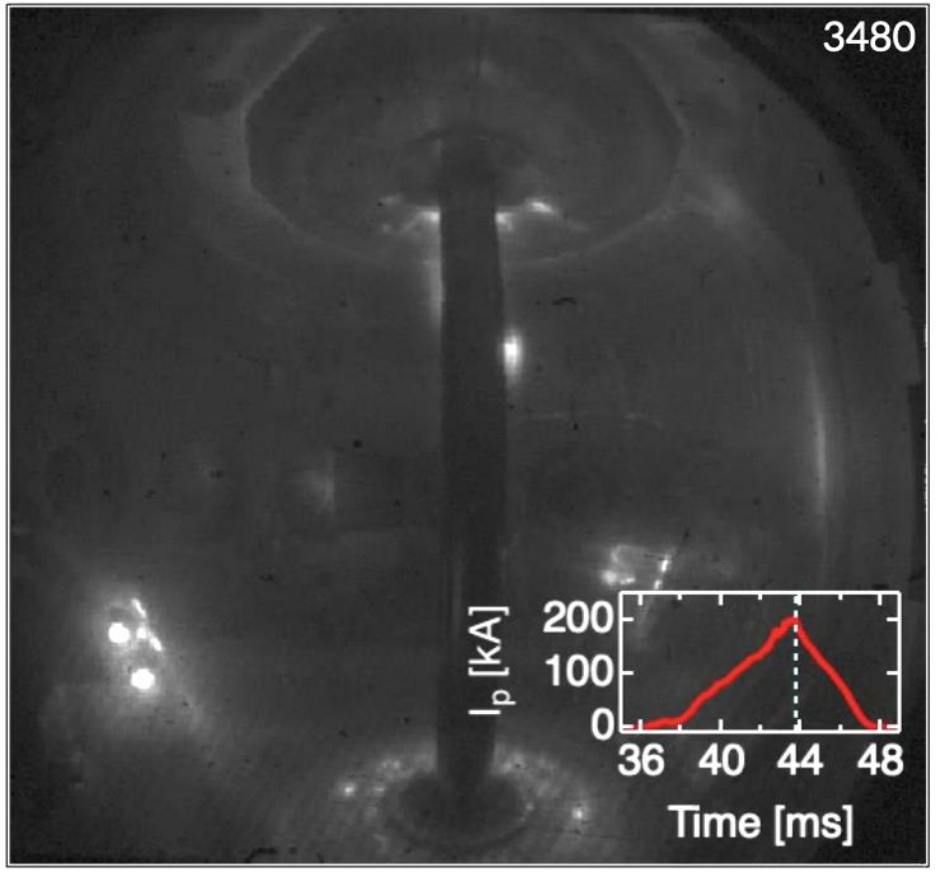
- Pegasus-III: a new facility for optimizing nonsolenoidal startup
- Current experiments are testing LHI at increased B_T (0.3T)[1]





LHI Array

LHI on Pegasus-III



[1]BO08.00007 – S. Diem

Department of Nuclear Engineering & Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Pegasus-III poster presentations: Friday AM (YP11.00029-41)

LHI Supplies Magnetic Helicity by Direct Current Injection

- Magnetic helicity K injected into the system[1]: $K = \int \boldsymbol{A} \cdot \boldsymbol{B} \; dV$
- Helicity balance: $\frac{dK}{dt} = -2\psi_T \frac{\partial \psi_p}{\partial t} - 2\oint_S \phi \boldsymbol{B} \cdot \hat{n} \, dS - 2\int_V \eta \, \boldsymbol{J} \cdot \boldsymbol{B} \; dV$

AC Helicity Injection

DC Helicity Injection

Helicity Dissipation

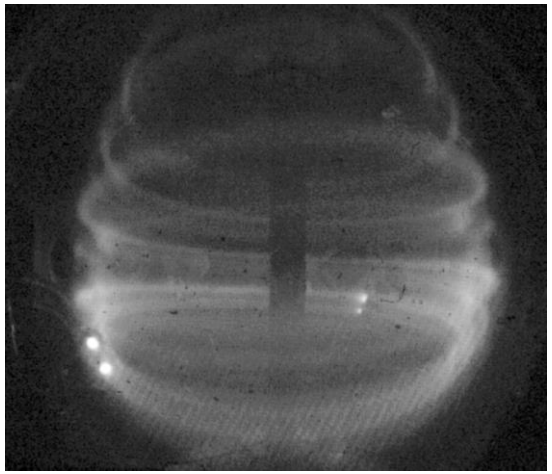
- Injecting current increases poloidal flux ψ_p linked with toroidal flux ψ_T from external coils
- Injection must be higher than dissipation for current drive

[1]Berger, Plasma Phys. Control. Fusion **41** B167 (1999)

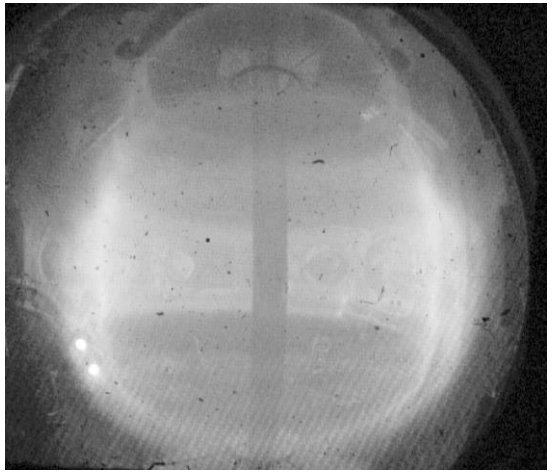
Department of Nuclear Engineering & Engineering Physics
UNIVERSITY OF WISCONSIN-MADISON

LHI Initiates a Tokamak-Like System

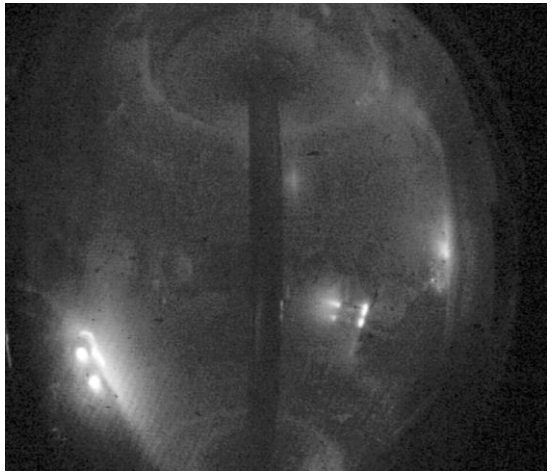
Fast Camera Images of LHI Stages



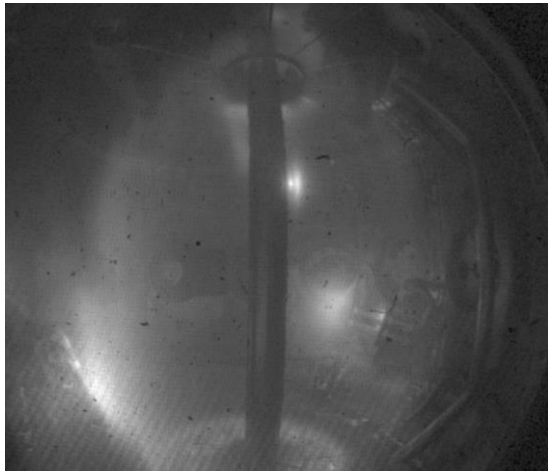
1. Injected current follows helical background field lines



2. Current streams go unstable, reconnect



3. Plasma relaxes to a "tokamak-like" state



4. Tokamak plasma after injector shutoff: stream perturbation goes away

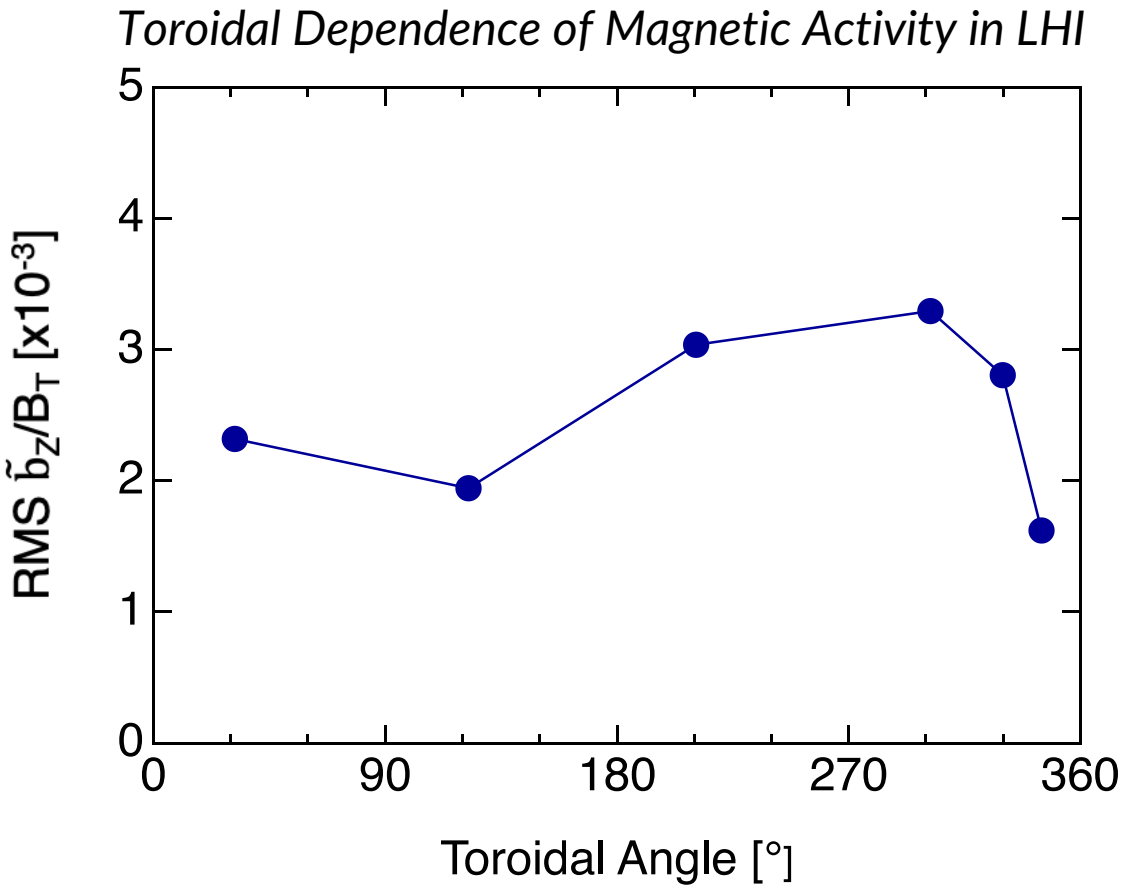
I_{inj} = 3-4 kA per injector,
4 injectors total on Pegasus-III

Majority of magnetic energy is in axisymmetric mode

Department of Nuclear Engineering & Engineering Physics
UNIVERSITY OF WISCONSIN-MADISON

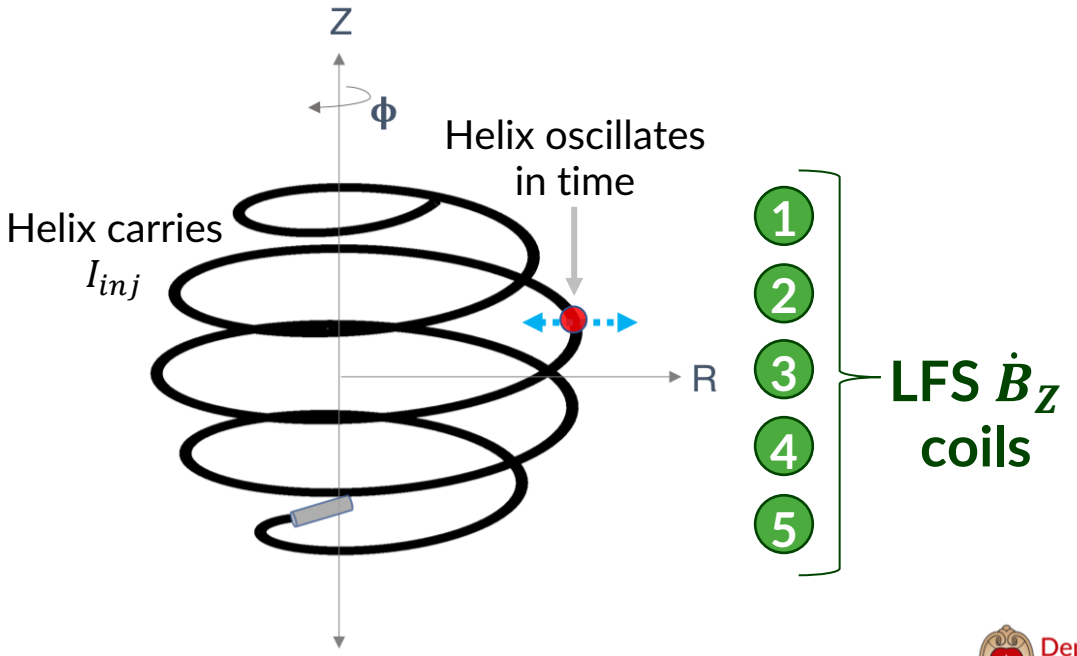
LHI Current Streams Create Large 3D Magnetic Perturbation

- Injected current streams in LHI create large 3D perturbation: $\frac{\tilde{b}_Z}{B_T} \sim 10^{-3} - 10^{-2}$
- 3D perturbations as small as $\frac{\delta B}{B_0} \sim 10^{-4}$ shown to drive transport and modify confinement on other tokamaks
- Expected to deform magnetic surfaces and induce stochastic edge region

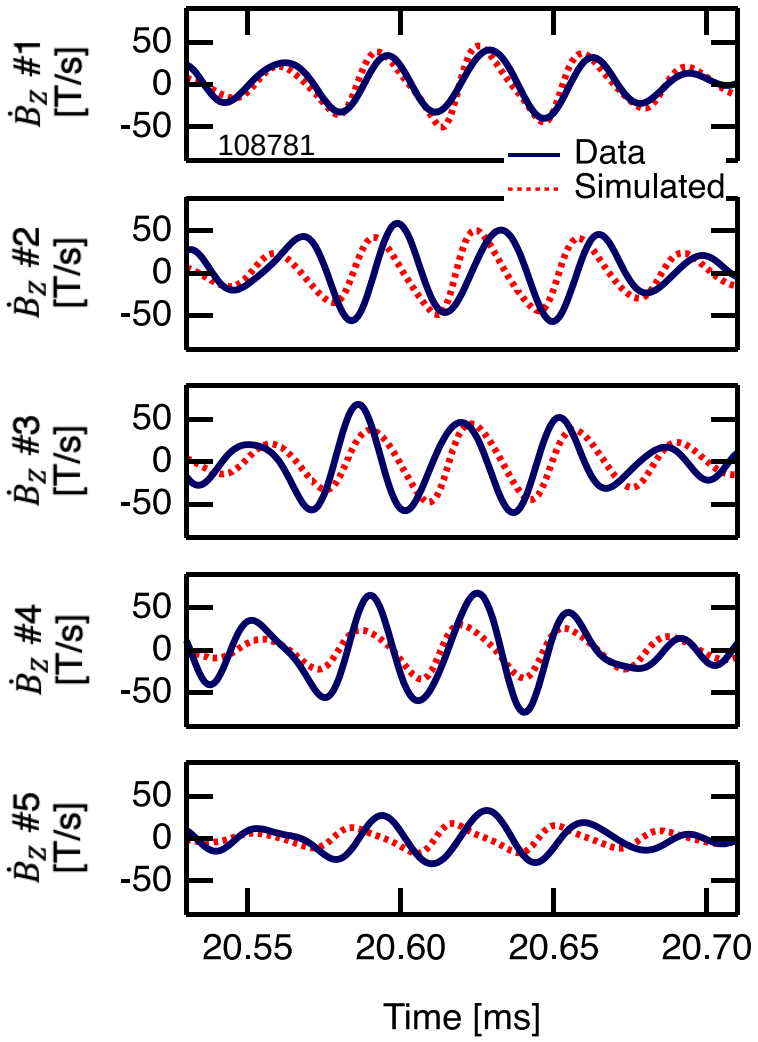


Helical Stream Model Reproduces $\dot{B}$ Measurements

- Singly line-tied kink of injected streams manifests as a bursty n=1 mode on Pegasus[1]
  - f~20—50 kHz
  - Poloidal variation of n=1 bursts observed in LFS $\dot{B}_Z$ data
- Fitting method determines helical current structure that best reproduces data



LFS $\dot{B}_Z$ Data Compared with Simulated $\dot{B}_Z$ from Best-Fit Helix



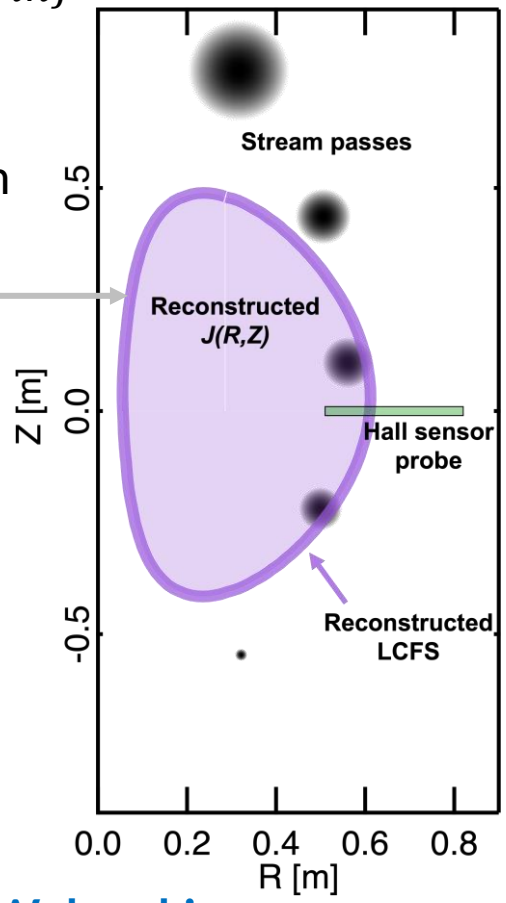
[1]Reusch et al., Phys. Plasmas **25** 056101 (2018)

Department of Nuclear Engineering & Engineering Physics
UNIVERSITY OF WISCONSIN-MADISON

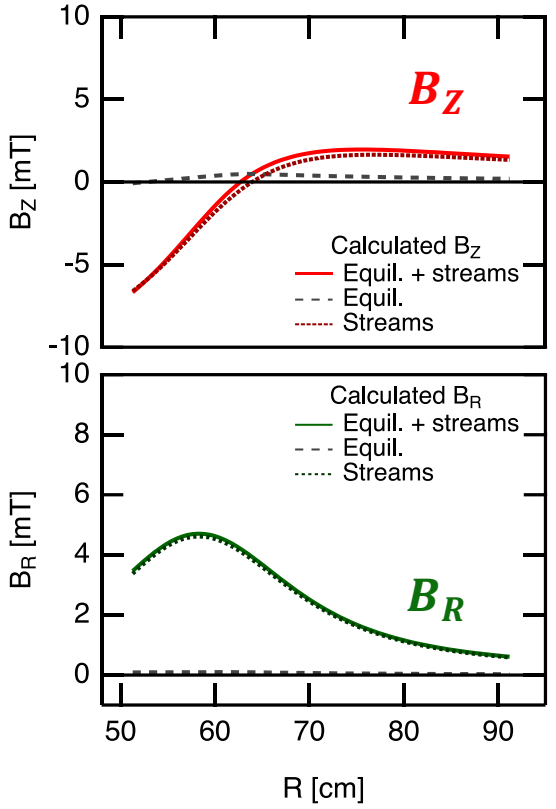
2D Filament Model Reproduces Observed Time-Averaged Field Structure

2D current distribution: $J(R,Z)$ from equil. reconstruction + I_{inj} at helix pass locations

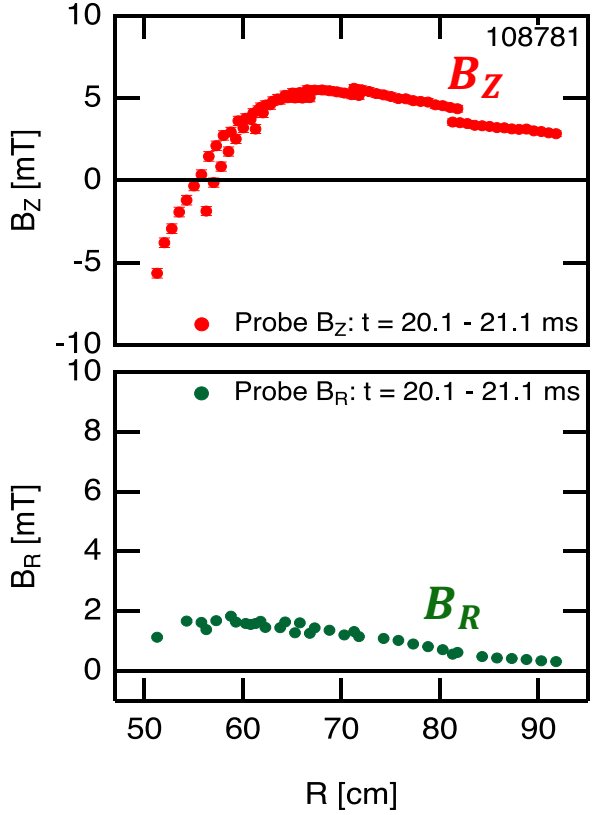
Stream contribution removed during equilibrium reconstruction[1]



Modeled B_Z, B_R from current distribution



Measured profiles are qualitatively similar to modeled

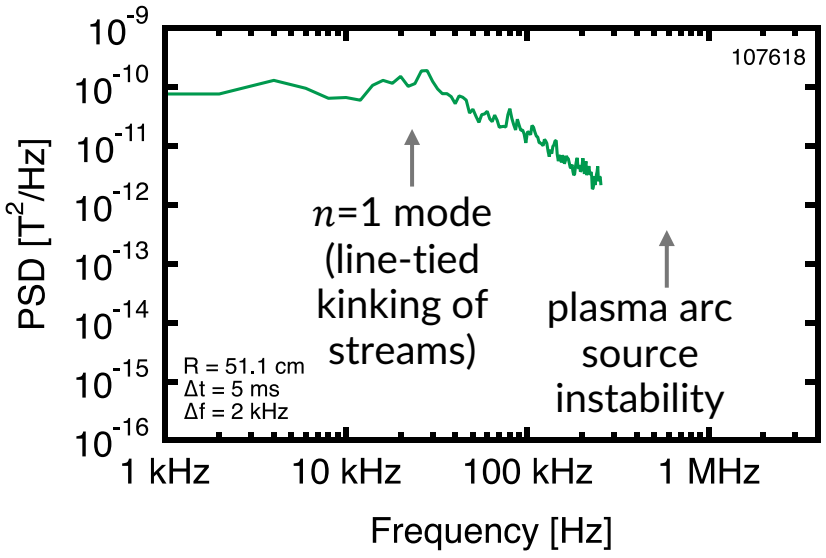


[1]YP11.00039 – J. Weberski

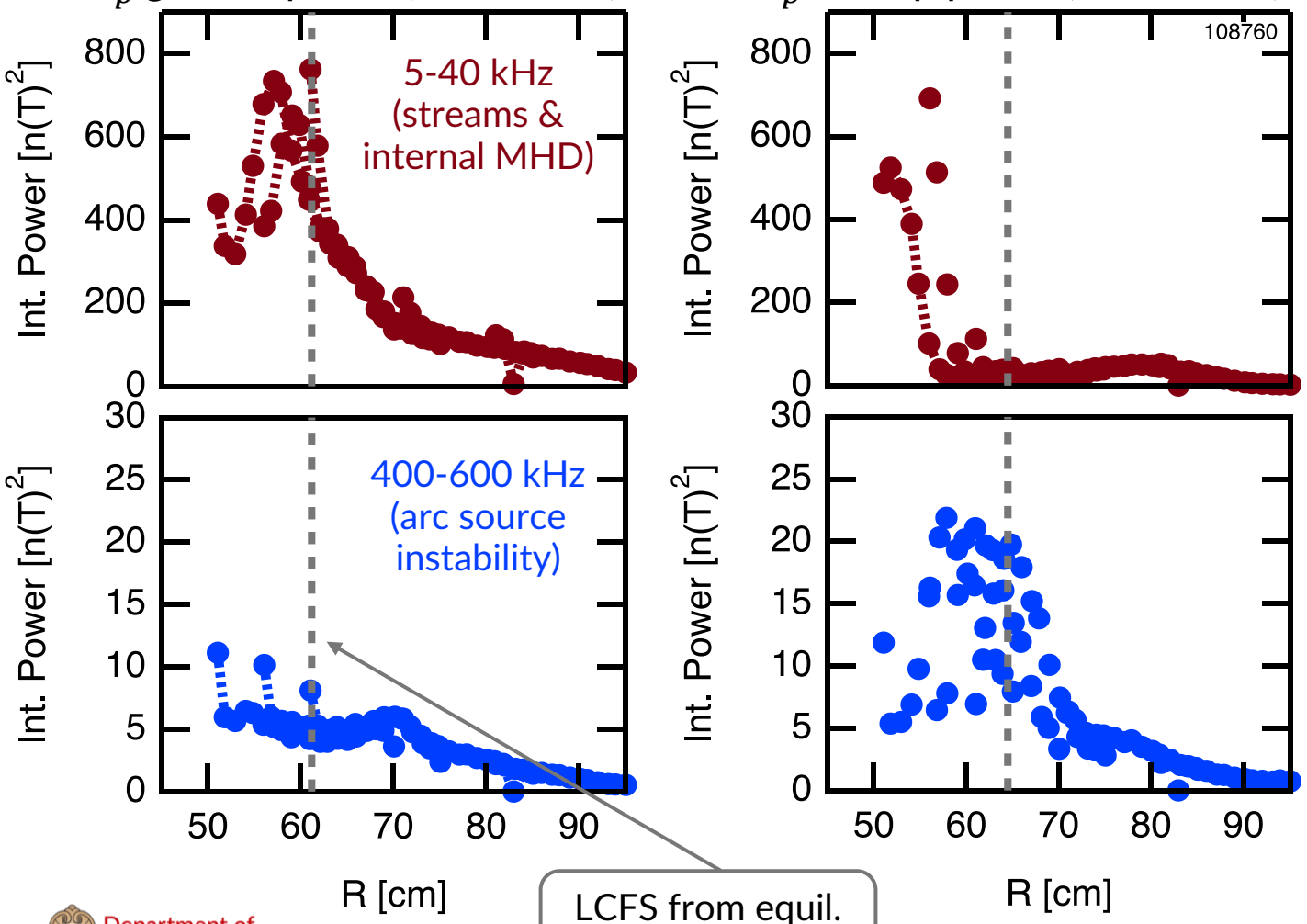
Department of Nuclear Engineering & Engineering Physics
UNIVERSITY OF WISCONSIN-MADISON

Time-Evolving Spatial Localization of Current Stream Magnetic Signatures

- Stream signatures identified in LHI magnetic spectrum[1]
- Earlier in time: 10s of kHz power peaks at LCFS
- Later in time: 100s of kHz power peaks at LCFS



Integrated Magnetic Fluctuation Power from $\dot{B}_Z(R)$ Probe

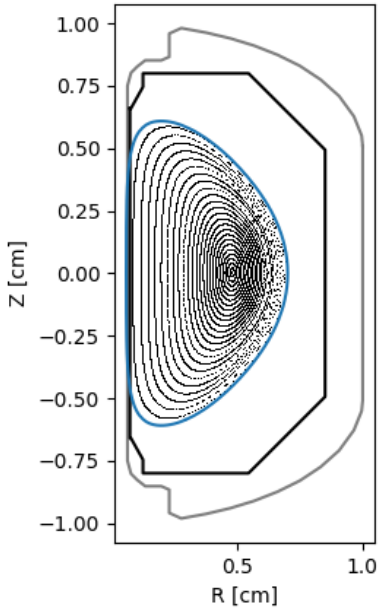


[1]Richner et al., Phys. Rev. Lett. **128** 105001 (2022)

Perturbation Modeling Suggests Injected Current Stream Impacts Magnetic Topology

- Data consistent with 3D stream surrounding tokamak-like core
- FLARE: field line analysis and reconstruction environment
- Tool estimates impact of edge-localized stream on tokamak magnetic topology

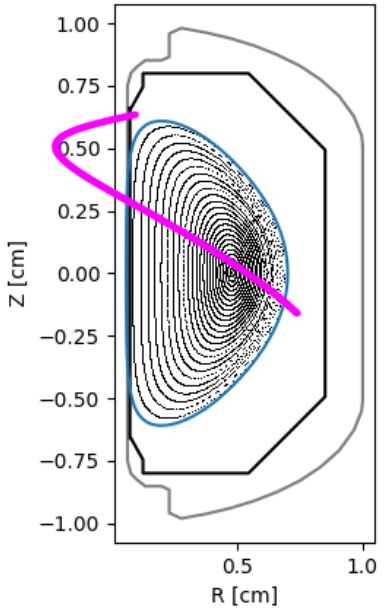
Modeled Equilibrium



Perturbation Modeling Suggests Injected Current Stream Impacts Magnetic Topology

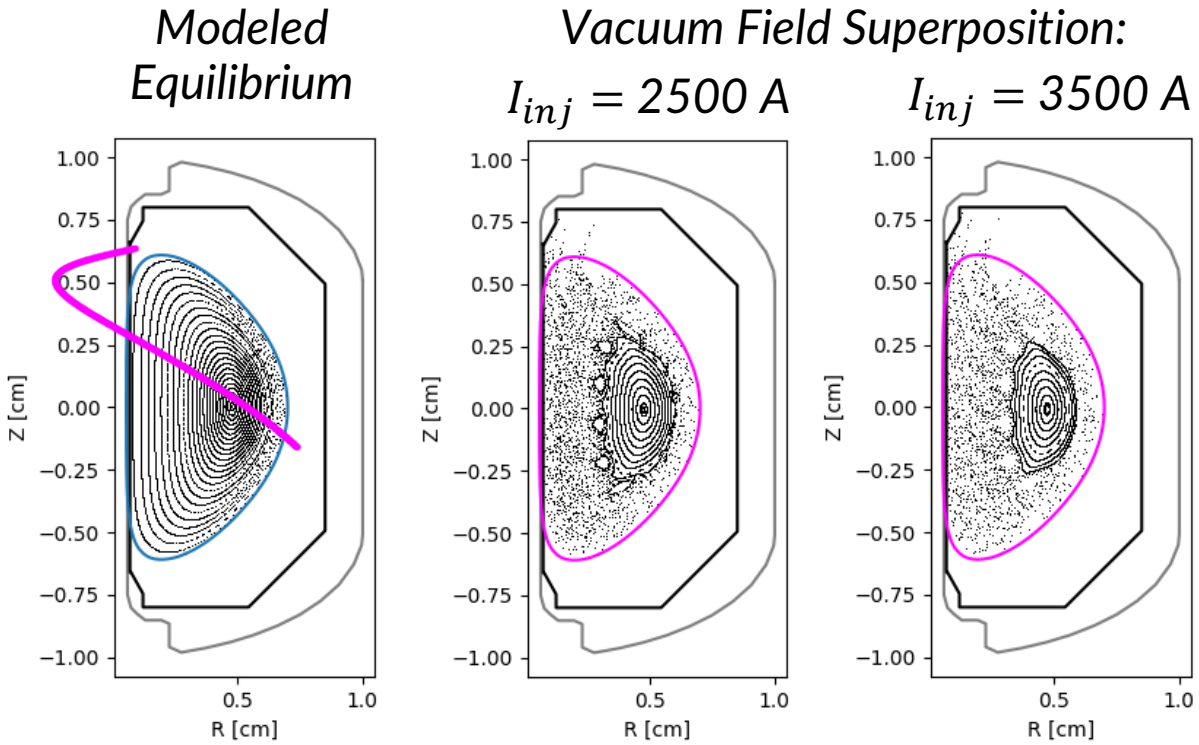
- Data consistent with 3D stream surrounding tokamak-like core
- FLARE: field line analysis and reconstruction environment
- Tool estimates impact of edge-localized stream on tokamak magnetic topology
- Vacuum approximation used for perturbation field

Modeled Equilibrium + *Injected Current Stream*



Perturbation Modeling Suggests Injected Current Stream Impacts Magnetic Topology

- Data consistent with 3D stream surrounding tokamak-like core
- FLARE: field line analysis and reconstruction environment
- Tool estimates impact of edge-localized stream on tokamak magnetic topology
- Vacuum approximation used for perturbation field
- Streams ergodize magnetic structure, potentially induce island structures



Implications for realized transport & confinement, scalability of LHI

not included yet

$$\boldsymbol{B}_{total} = \boldsymbol{B}_{equil} + \boldsymbol{B}_{pert,vacuum} + \boldsymbol{B}_{response}$$

Department of Nuclear Engineering & Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Growing Evidence for Persistent 3D Current Stream Structure that Impacts Magnetic Topology During LHI

- Injected current streams create strong 3D perturbation
- Model of an oscillating, 3D, current-carrying flux tube surrounding axisymmetric plasma reproduces LFS $\dot{B}_Z$ and $\boldsymbol{B}(R)$ meaurements
- Stream-related magnetic signatures persist in plasma edge region
- Preliminary field line tracing analysis shows injected current streams induce stochastic edge layer and magnetic islands → implications for scaling LHI
- Further stream structure characterization is underway for LHI on Pegasus-III