Low-*f* MHD and Reconnection Activity During Local Helicity Injection

J.L. Barr, M.W. Bongard, M. G. Burke, R.J. Fonck, J.A. Reusch, N.J. Richner

University of Wisconsin-Madison

58th APS DPP Annual Meeting

October 31st - November 4th 2016

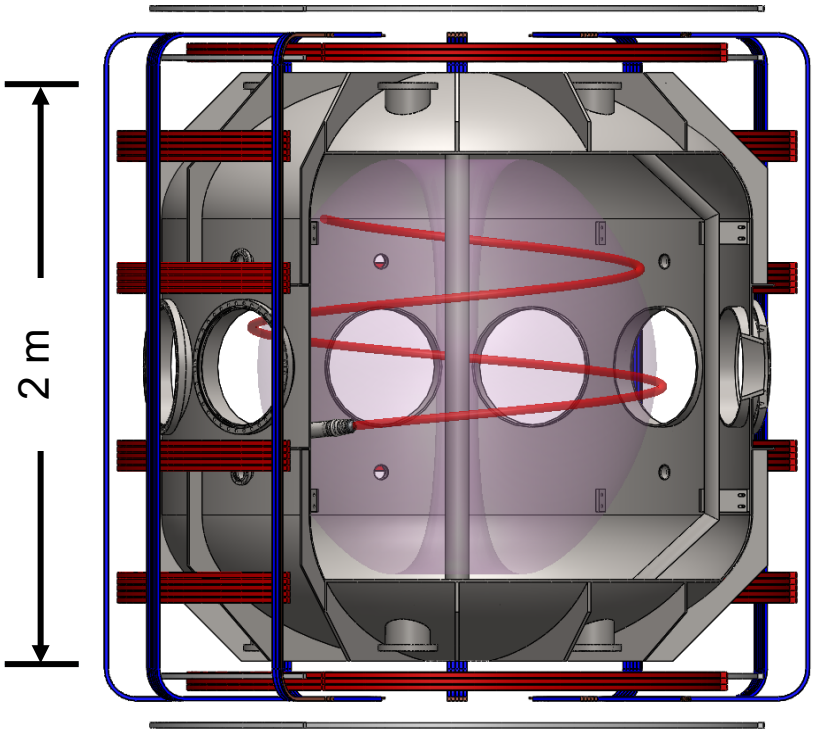
San Jose, CA

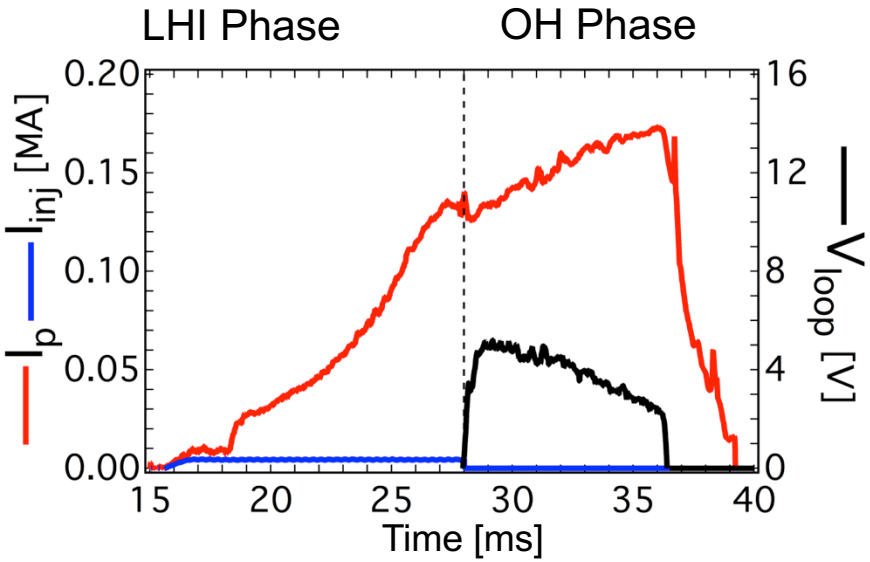
PEGASUS Toroidal Experiment

LHI MHD and Reconnection

- LHI exhibits large Alfvénic, n=1 MHD activity
  - Both continuous and bursting behavior
  - Structure consistent with kinking of injected current streams
- NIMROD simulations predict under-lying current drive mechanism of LHI
  - Current drive via periodic large-scale reconnection events
  - Many points of qualitative agreement with experiment
- Injector stream-to-stream reconnection drives anomalous ion heating in LHI
  - Both co-injected streams and adjacent windings of individual streams
  - Observed as soon as injection begins

LHI Provides Robust Non-Solenoidal Startup on the PEGASUS ST



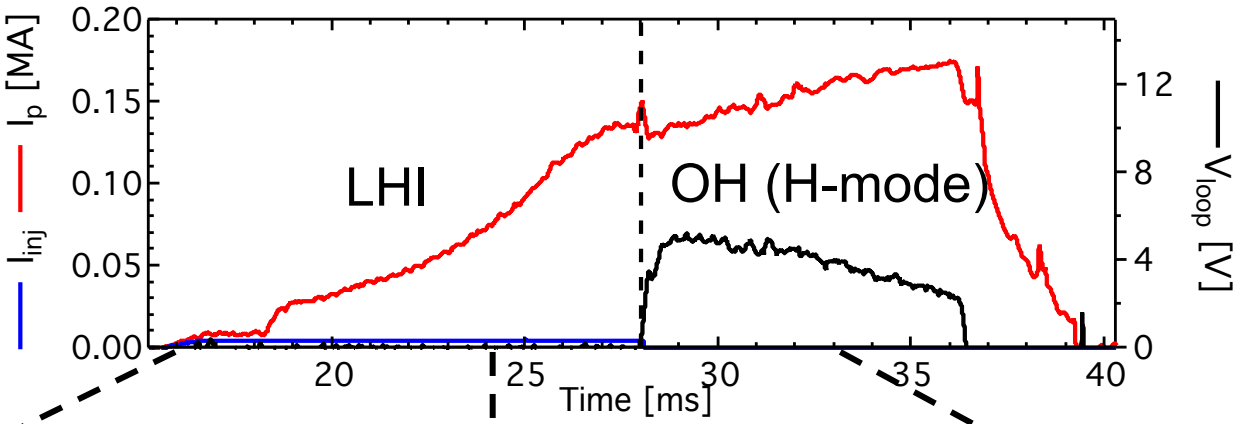


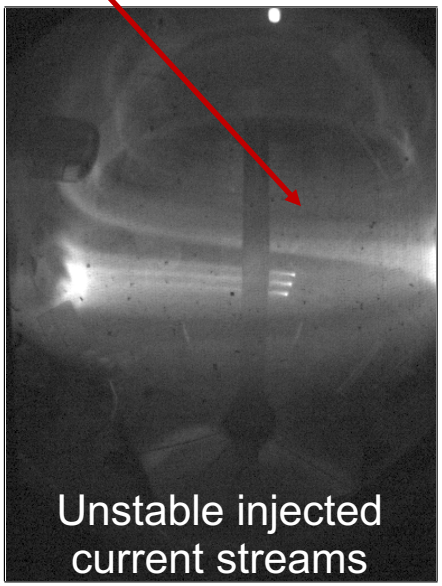
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .21
$B_{t,0}$ (T)	0.1-0.2
τ_{shot} (s)	≤ 0.025

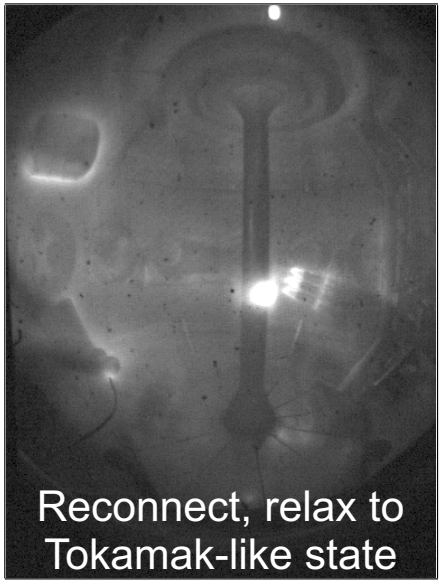
- Non-solenoidal ST Startup
  - Local Helicity Injection
- Tokamak Physics at $A \geq 1.15$
  - H-mode access, high β

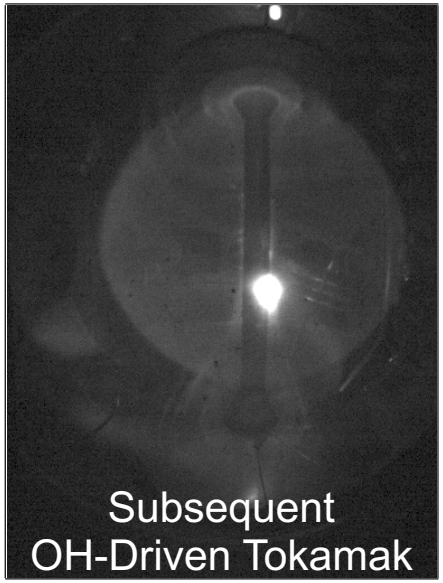
LHI Injects Current, Helicity to Form and Drive Tokamak-like Plasmas

Three-Injector Array



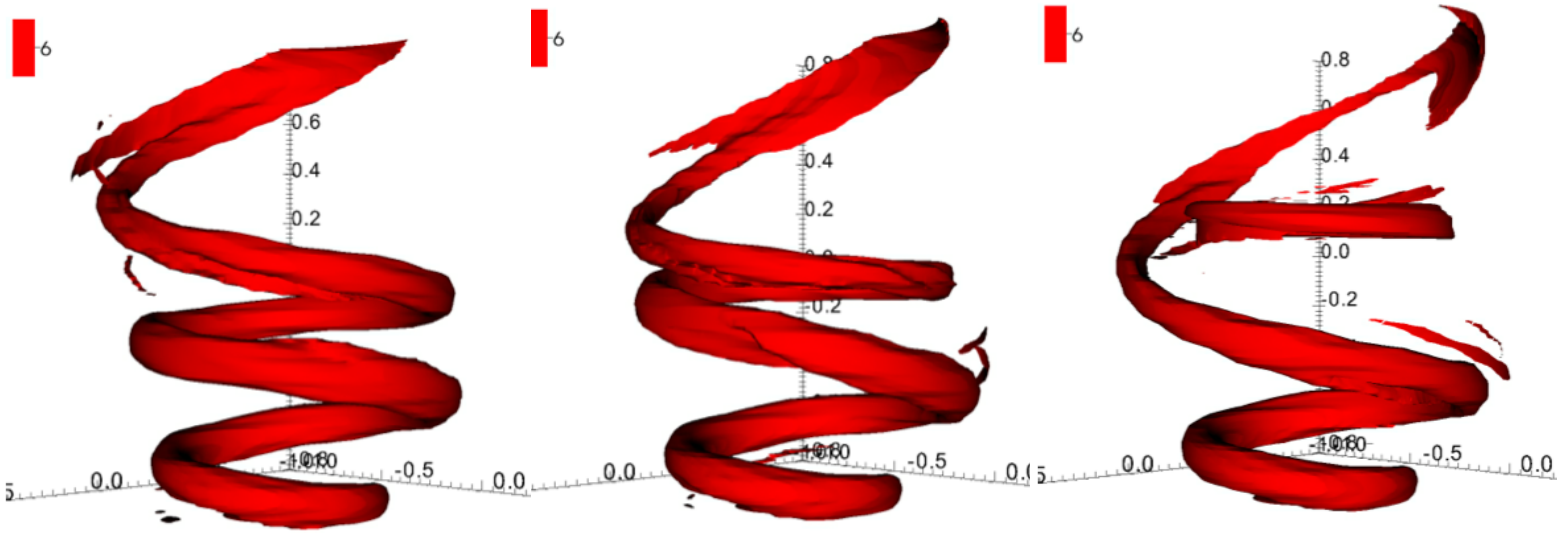






NIMROD Identifies Current Stream Reconnection as a Current Drive Source

- NIMROD: Single divertor injector, no inductive drive

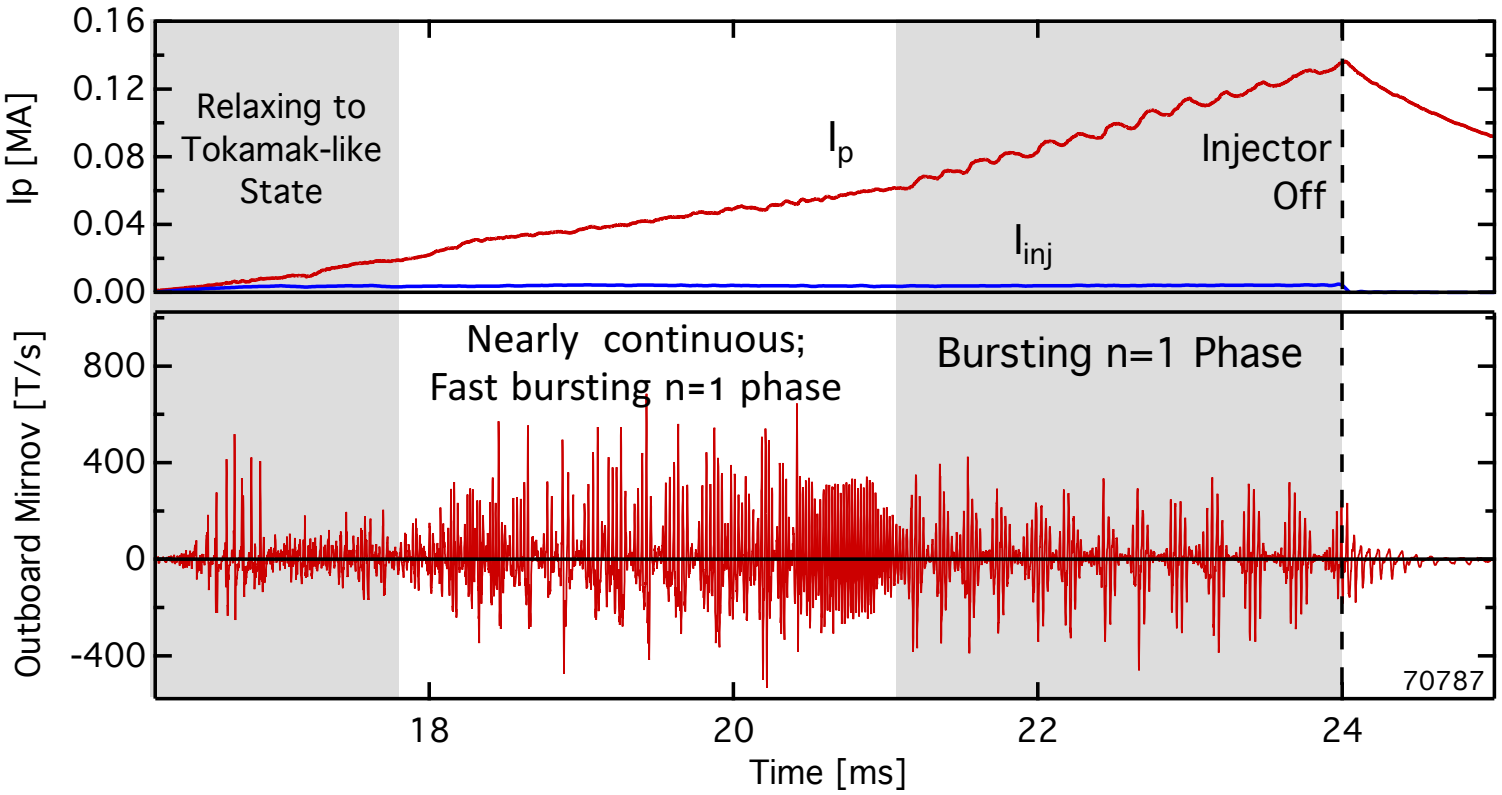


1. Streams follow field lines
2. Adjacent passes attract
3. Reconnection pinches off current rings

- Repeated events build current, poloidal flux
- After LHI off: flux-surfaces heal to Tokamak plasma

Low-*f*, n=1 Activity in LHI

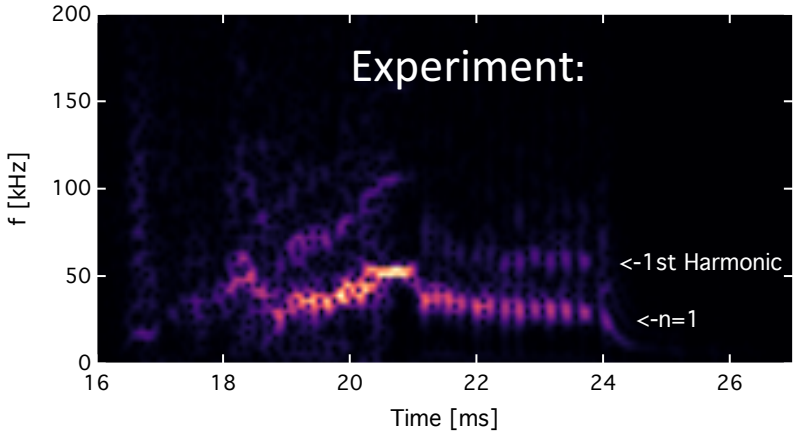
LFS LHI Plasmas Exhibit Large n=1 Magnetic Fluctuations



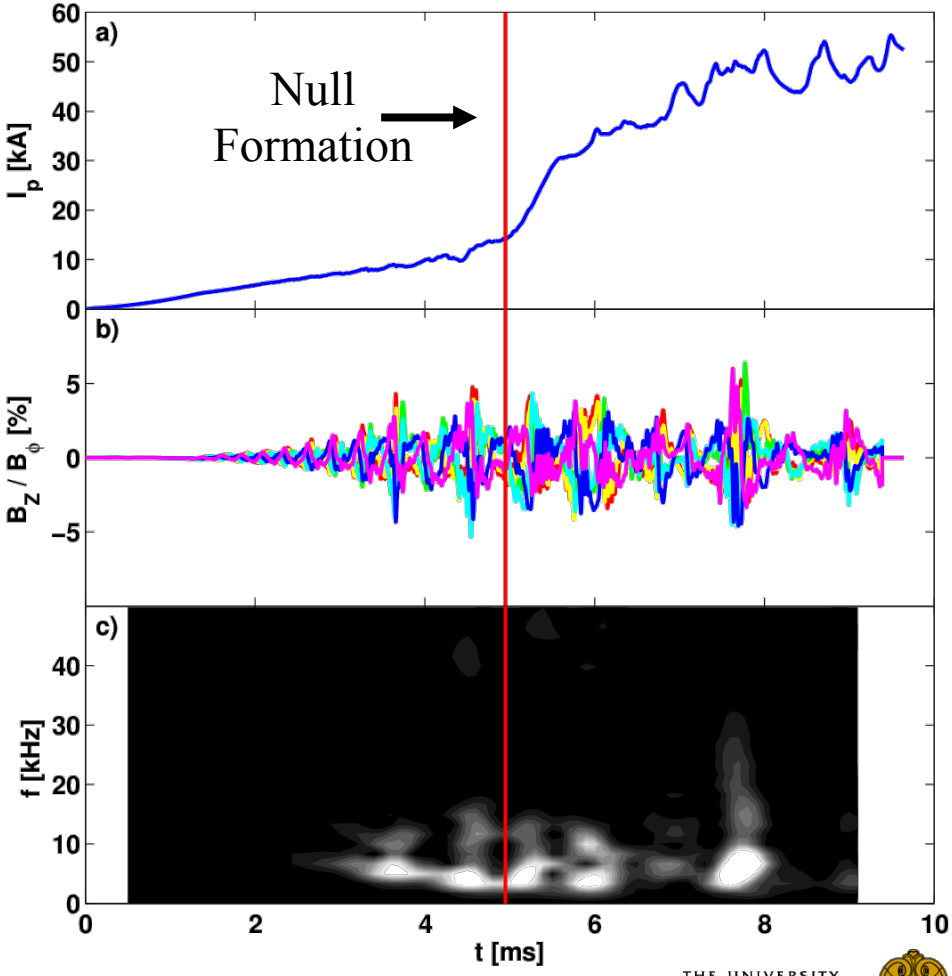
- Large n=1 activity ubiquitous in LFS LHI discharges
  - Often begins continuous, transitions to bursting behavior
  - 15 kHz ≤ f ≤ 70 kHz
  - $\delta b/B_t \sim 1–5\%$

NIMROD Predicts Current Stream Motion, Reconnection Source of Magnetic Activity

- NIMROD reconnection events:
  - Provide current drive
  - Source of Alfvénic MHD phenomena
- Qualitative agreement with experiment:
  - n=1 > n=2-10 combined
  - Similar frequencies: 5-20 kHz
  - Jumps in toroidal current

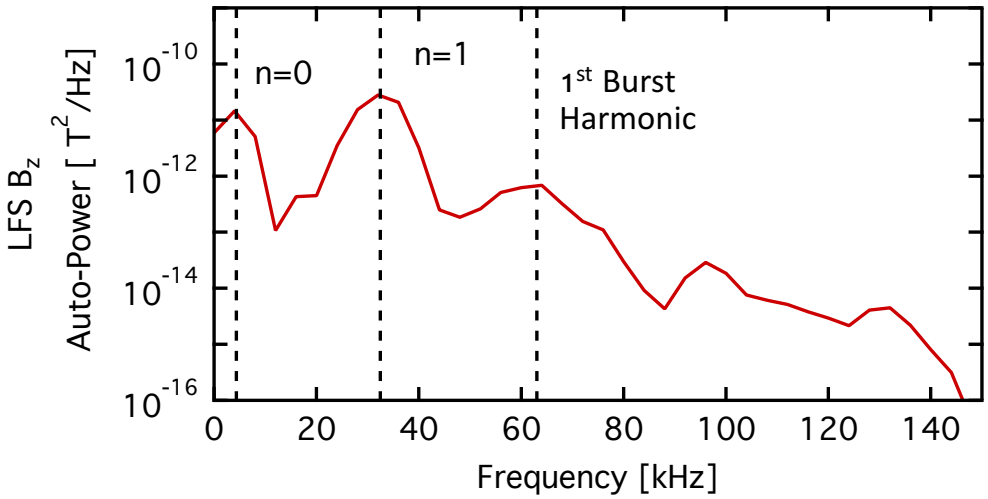


Simulation:

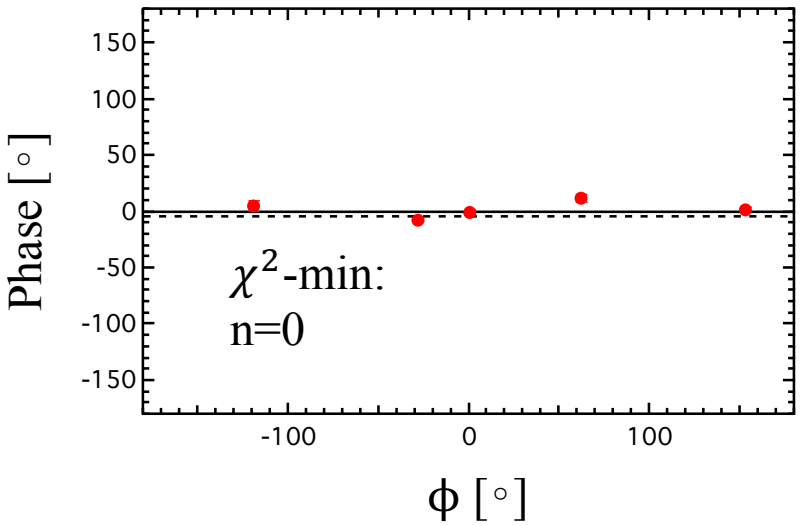


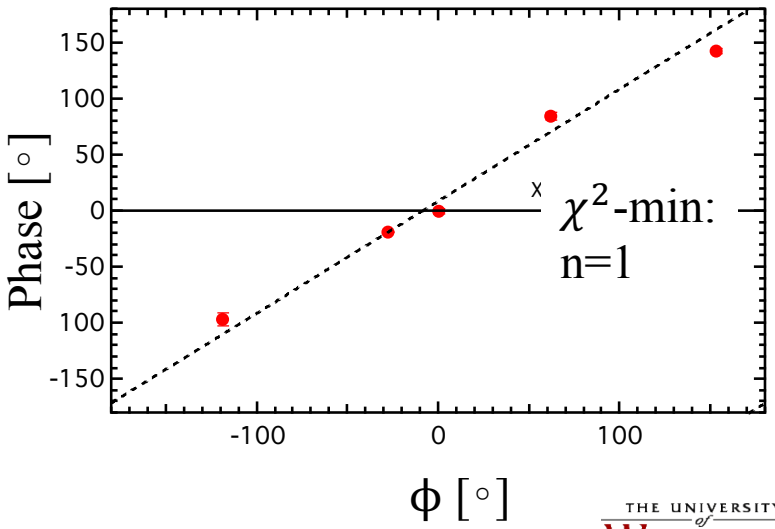
THE UNIVERSITY of WISCONSIN MADISON

Bursting n=1 Activity Coincides with Discrete n=0 Component



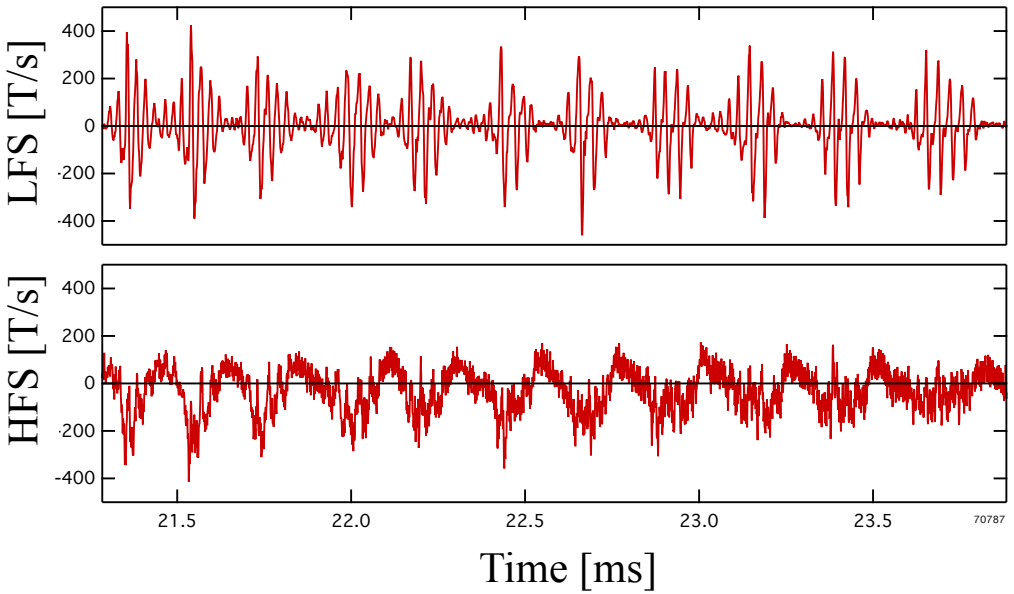
- Magnetic spectra includes:
  - n=1 during LHI
  - n=0 plasma motion, growth
- Bursting behavior:
  - Discrete n=0 inward motion

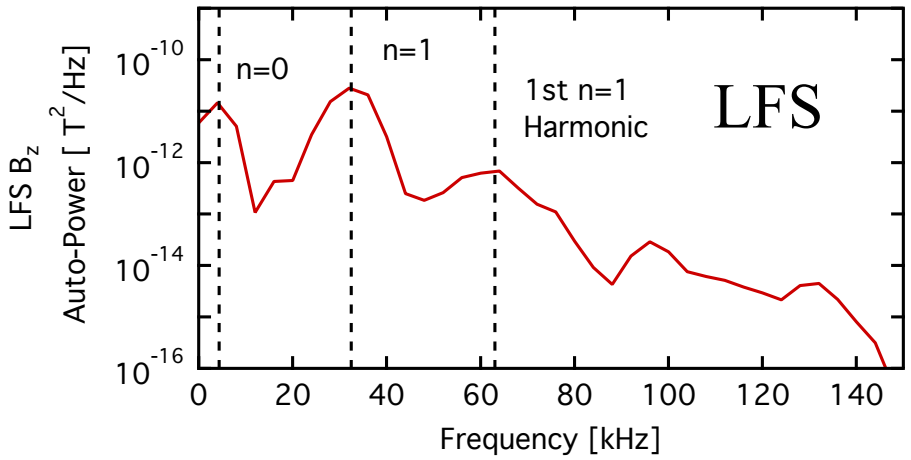


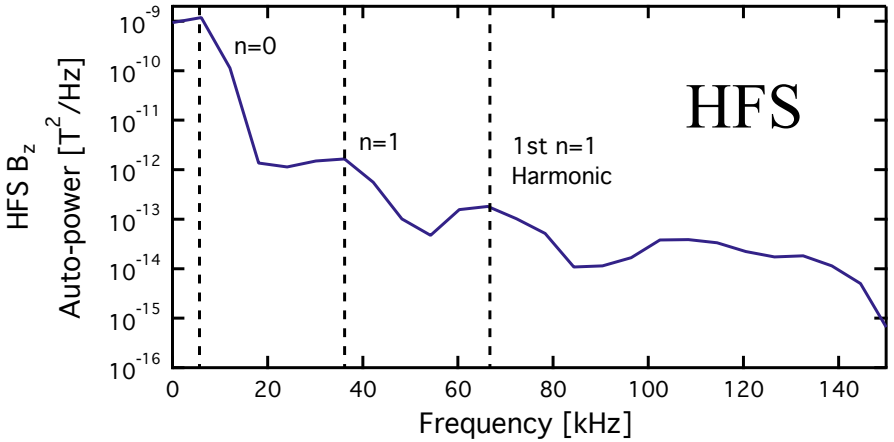


N=1 is Mode Spatially Localized to the LFS

- LFS magnetics:
  - Predominantly n=1 activity
- HFS magnetics:
  - Predominantly n=0 plasma motion, growth



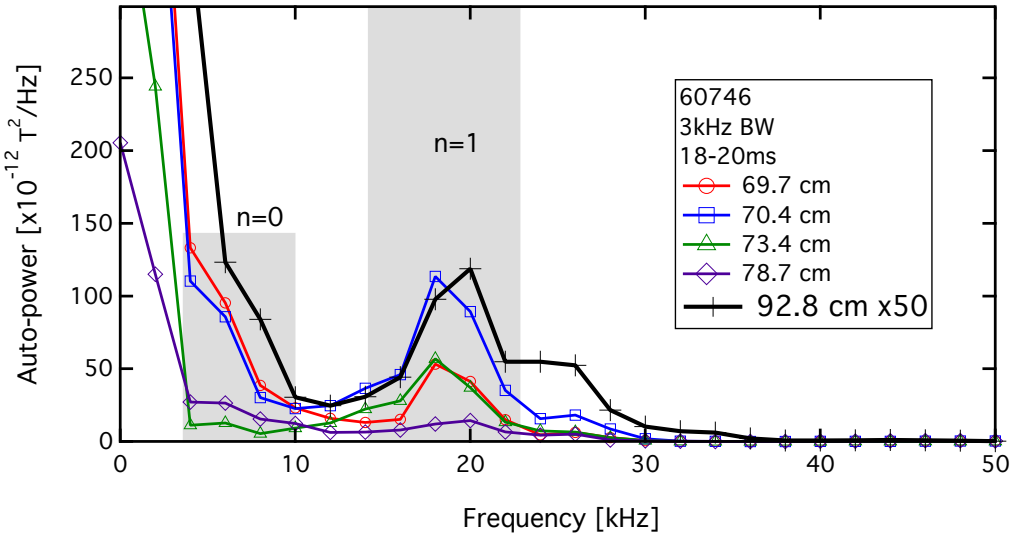




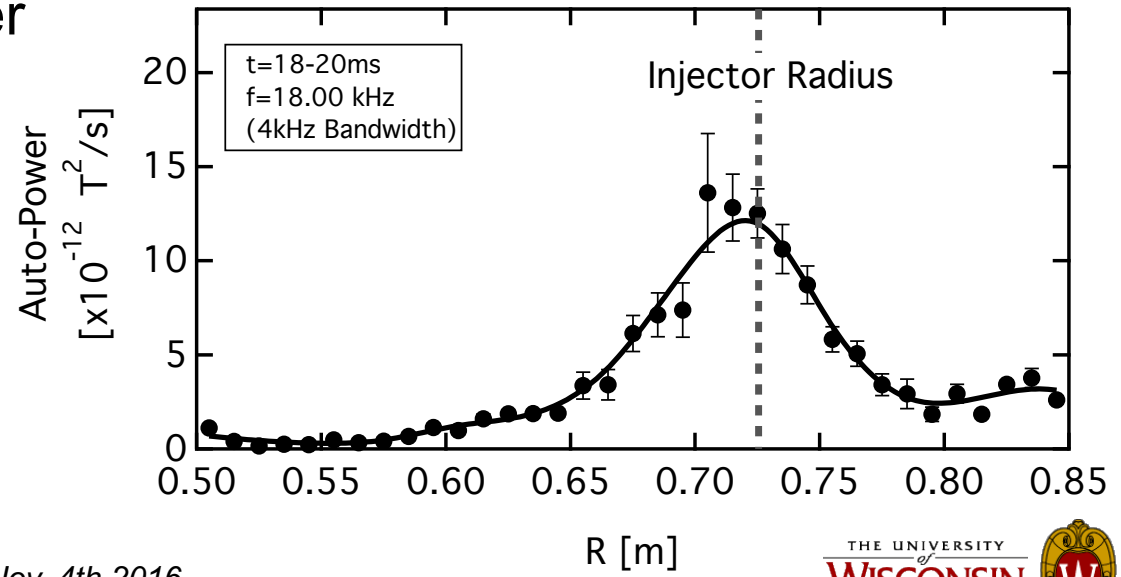
n=1 Source: Unstable Injected Current Streams

n=1 MHD Activity is Localized Near the Injector Radius

- Local B_z measurements:
  - Radial localization of n=1 activity
  - Measured with Hall Sensor array probe



- The n=1 mode auto-power peaked at injector radius
  - Repeated discharges
  - During bursting phase



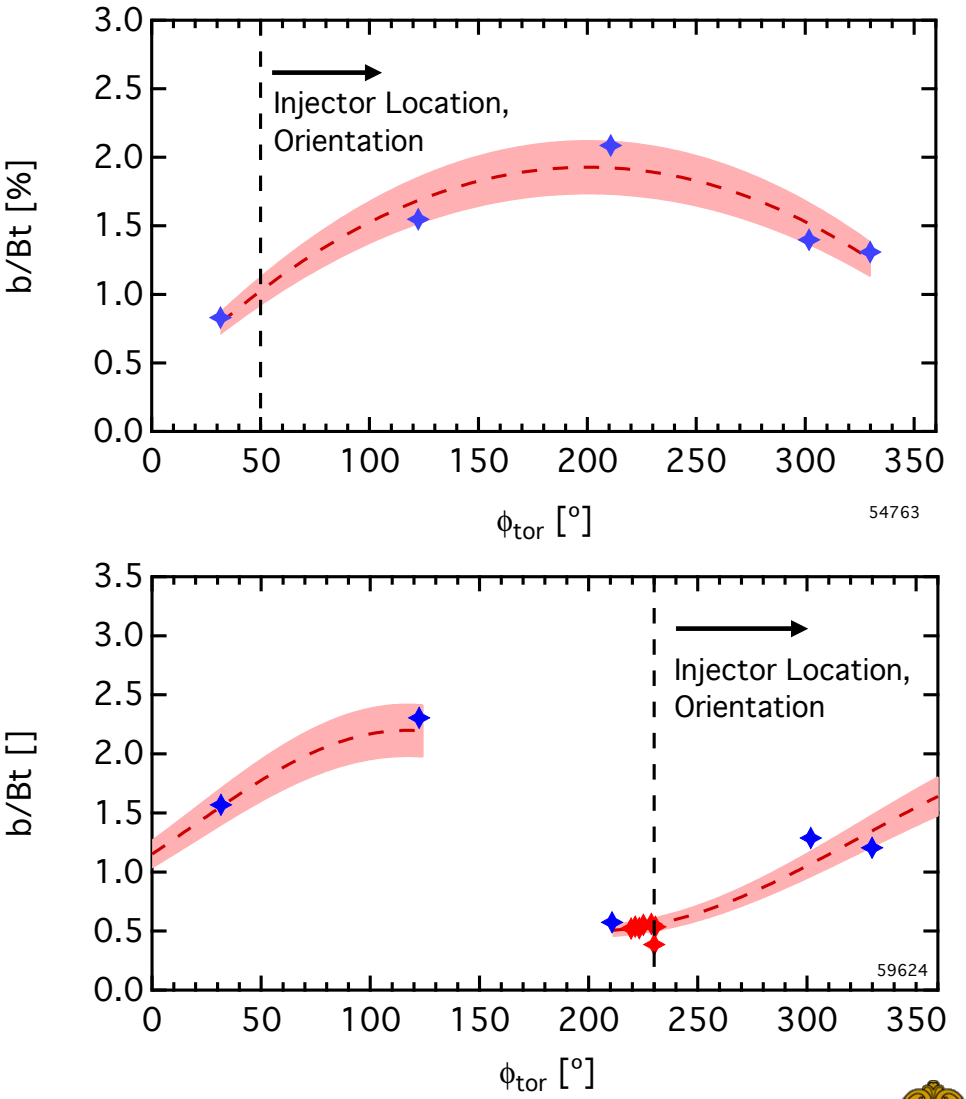
n=1 Amplitude is Toroidally Asymmetric

- The n=1 mode amplitude is toroidally asymmetric
  - Smallest near the injector face
- Toroidal asymmetry follows changes to injector location
- Line-tied kink-like structure
  - Node at injector radius
- Injected current streams are strongly kink unstable
  - I_{inj} = 2-3 kA, A_{inj} = 2 cm^2

See:

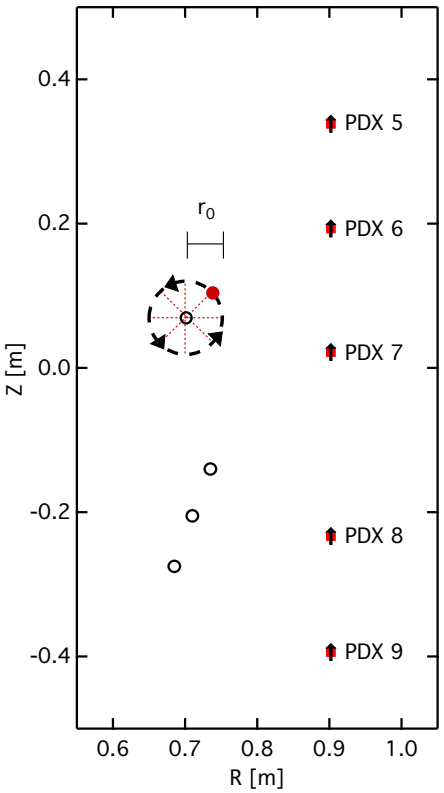
D. D. Ryutuv et al., Phys. Plasmas ***13****, 032105 (2006)*

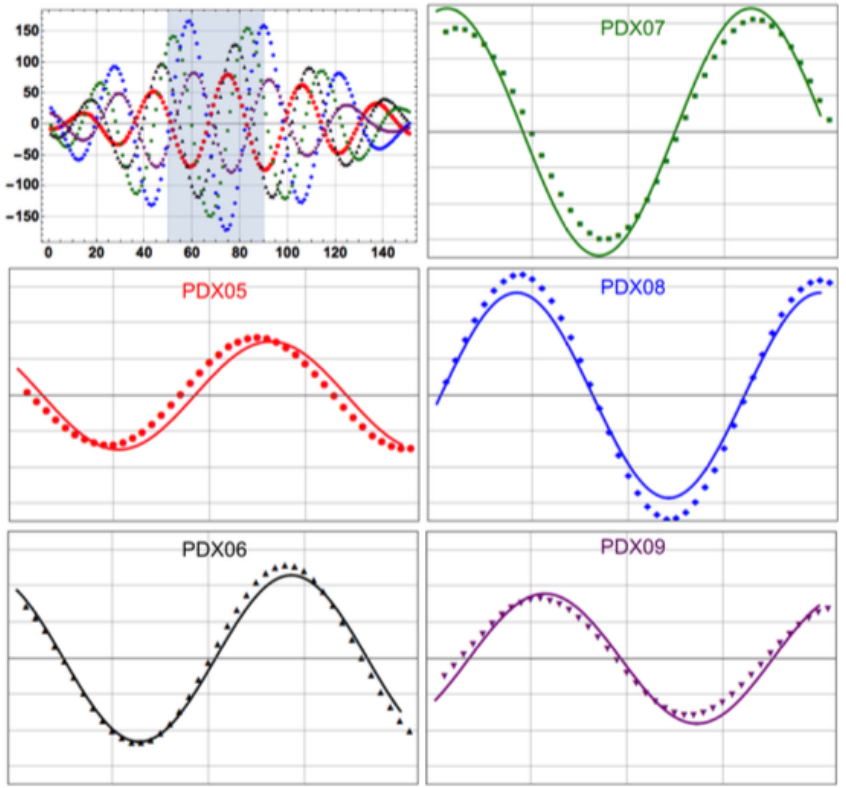
I. Furno et al., Phys. Rev. Lett. 97, 015002 (2006)



LFS Poloidal Magnetic Signals are Consistent with Oscillating Stream Source

- Reduced model of oscillating filament source with I_{inj}
  - Closely recreates measured LFS B_z phase, amplitude
  - Best fit location: R=59 cm, Z=13 cm





n=1 Activity in LHI is a Product of Injected Current Stream Motion

- Current stream oscillations = source of magnetic phenomena
  - Bursting behavior, spectra, amplitudes similar to simulation
  - Localization to LFS near injector radius

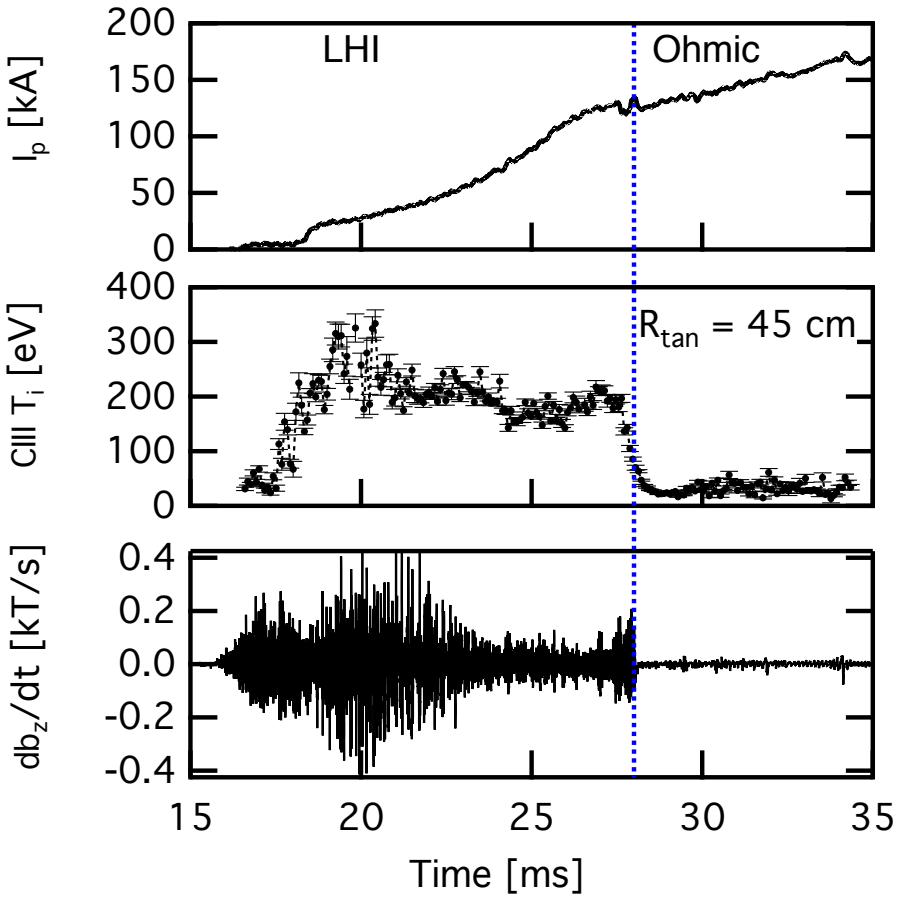
- Outstanding issues:
  - Relative fraction of n=1 activity from stream motion vs. Alfvén waves
  - Is the NIMROD predicted reconnection mechanism and induction sufficient to explain current buildup in experiment?

Anomalous Ion Heating

THE UNIVERSITY of WISCONSIN MADISON

During LHI Current Drive $T_i > T_e$

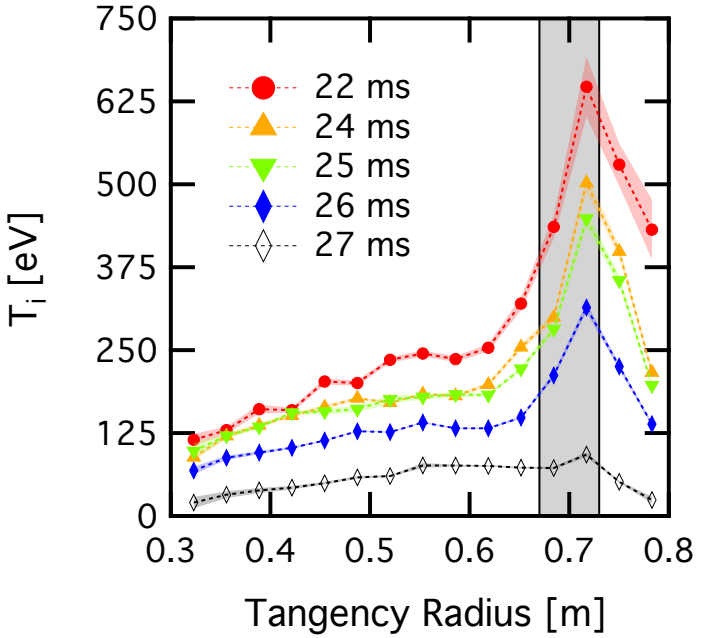
- $T_i \geq T_e \sim 100$ eV
- $T_{i,LHI} > 10x\ T_{i,OH}$
- $T_{i,LHI}$ as large as 650 eV
- Large amplitude MHD associated with magnetic reconnection
- $T_{i,\perp}$ increase agrees with reconnection theory



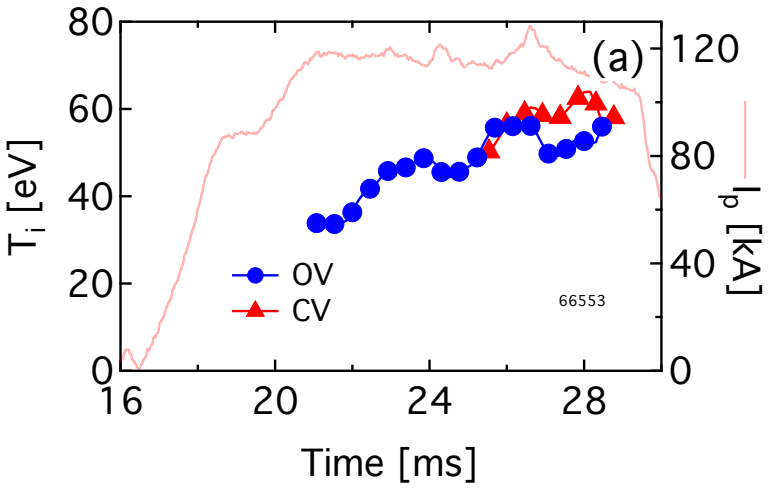
$T_i(R_{tan})$ Indicates Edge Localized Heating, Consistent with Filament Location

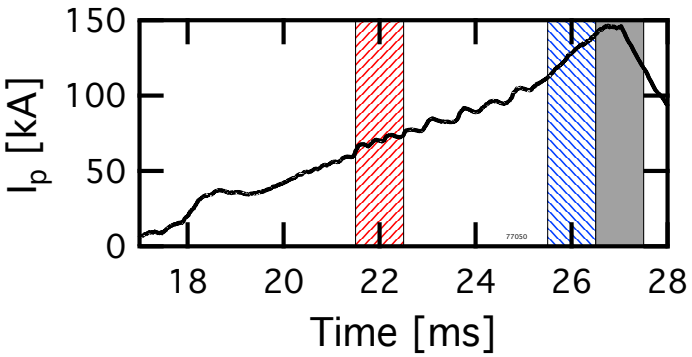
- OV T_i largest early in the discharge, but sustained over several confinement times
- Edge OV T_i peaking goes away after injector shutoff
- LHI Core $T_i > 100$ eV, substantially larger than core OV T_i in ohmic:

LHI $T_i(R_{tan})$:



Core Ohmic T_i:





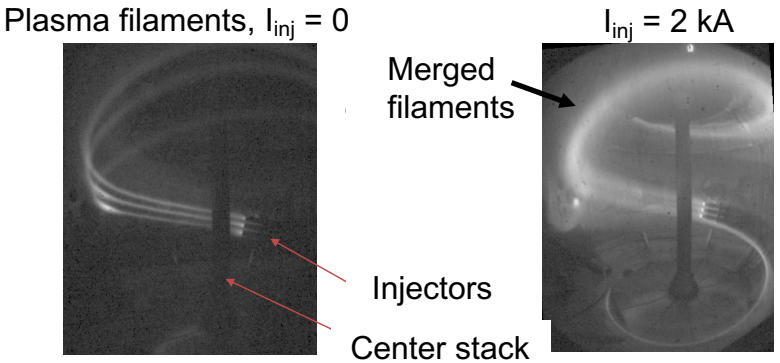
THE UNIVERSITY of WISCONSIN MADISON

Helium-II T_i Scales as Predicted by Magnetic Reconnection Theory

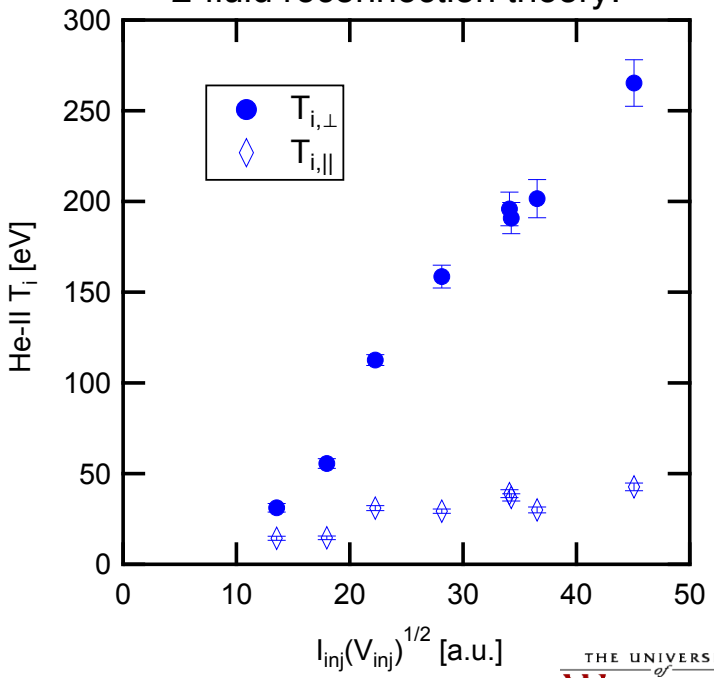
- High B_z experiments prevent helical winding reconnection
  - No large scale relaxation → no Tokamak
- Co-injected filament reconnection only:

$$n_b \propto \frac{I_{inj}}{\sqrt{V_{inj}}} \qquad \Delta\phi \approx \frac{B^2}{2e\mu_0 n_b} \propto I_{inj}\sqrt{V_{inj}}$$

- $T_{HeII,\perp} \propto \Delta\phi \propto I_{inj}\sqrt{V_{inj}}$
- $T_\perp \gg T_\parallel$
- T_i increases with changes in I_{inj} and V_{inj}
- $T_\perp$ increases with B_{guide}



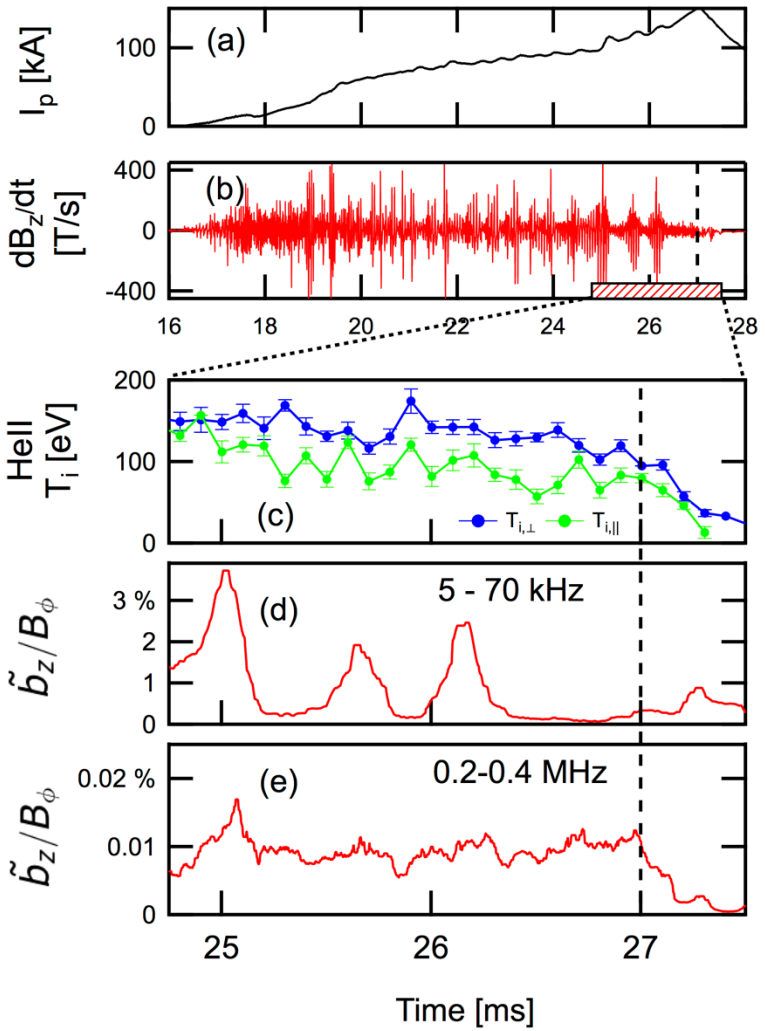
Ion heating consistent with 2-fluid reconnection theory:



THE UNIVERSITY of WISCONSIN MADISON

T_i Not Obviously Correlated with n=1 Mode, Correlated with High Frequency Turbulence

- Discharges developed with isolated bursts of n = 1 activity, $T_{i,\perp}$ and $T_{i,\parallel}$ measured over burst
- Neither temperature deviates significantly from the average during the burst
- T_i and fluctuation levels above 200 kHz appear correlated
- Continuous ion heating from reconnection between collinear current streams
  - No effect on current drive efficiency
  - Significant ion heating (~ few 0.1 MW)

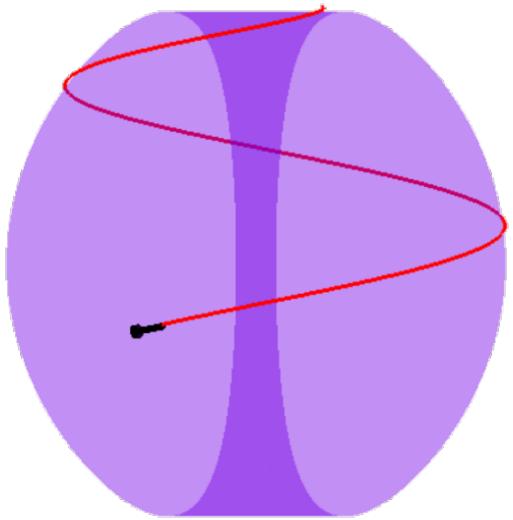


Coinciding Burst Phenomena, Frequency Scaling

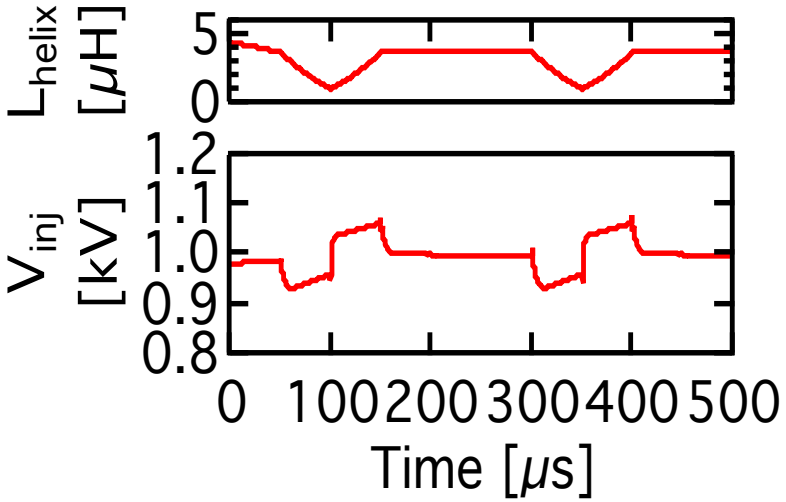
THE UNIVERSITY of WISCONSIN MADISON

Injector Impedance Transients Expected with NIMROD Predicted Reconnection Events

- NIMROD simulation predicts helical stream reconnection
  - Ejection of a helical turn
  - Effect on injector impedance likely



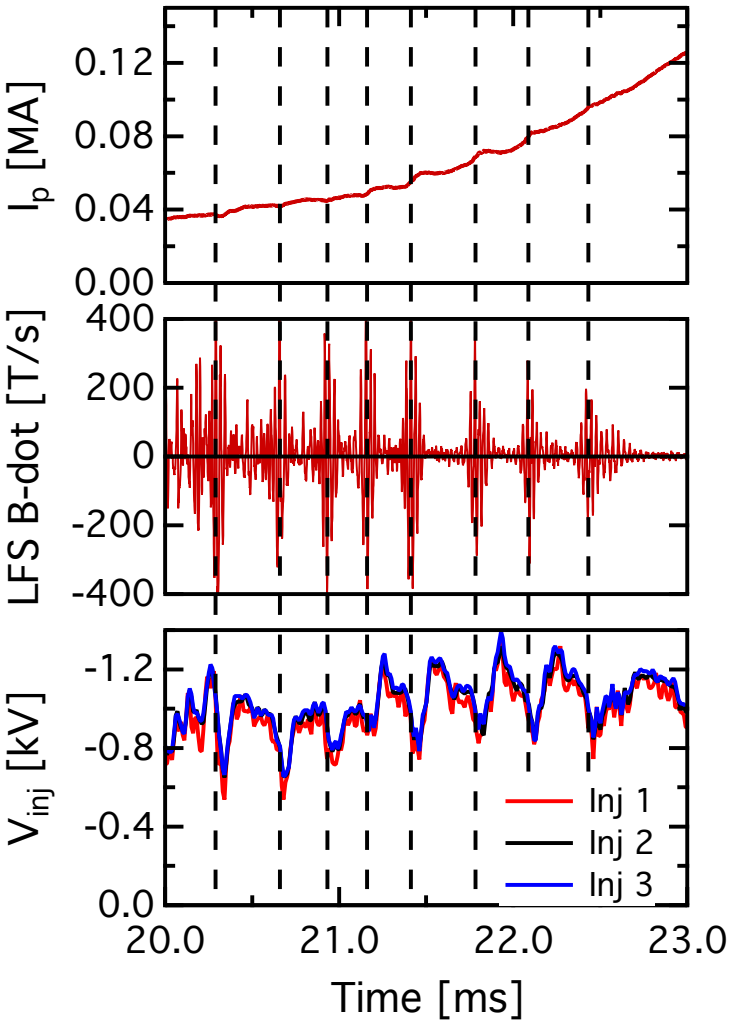
- Reduced model of impedance effect:
  - Inductance: sparse helical inductor
    H.W. Grover, Inductance Calculations
  - Transient drop of 1 turn
  - Drop, rebuild in typical burst time: $\Delta t \sim 100 \mu s$



- $dL_{helix}/dt \rightarrow \delta V_{inj} \sim 100$ V

Experimental V_{inj} Transients Consistent with Stream-to-Stream Reconnection

- Bursts time with V_{inj} transients:
  - Coincide with n=1 bursts
  - I_p transients as well
- $\delta V_{inj} \sim$100-200V
- Measured V_{inj} transients consistent with reconnection:
  - Loss of helical stream winding



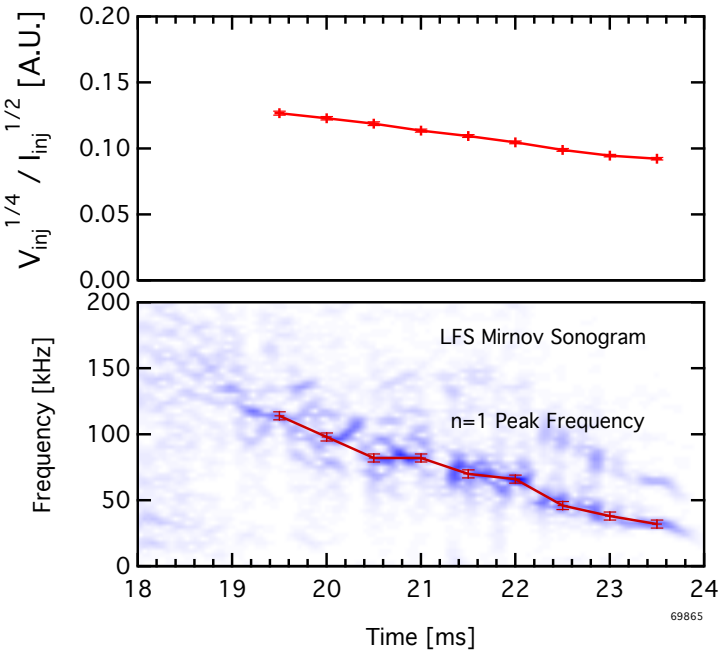
n=1 Frequency is Alfvénic

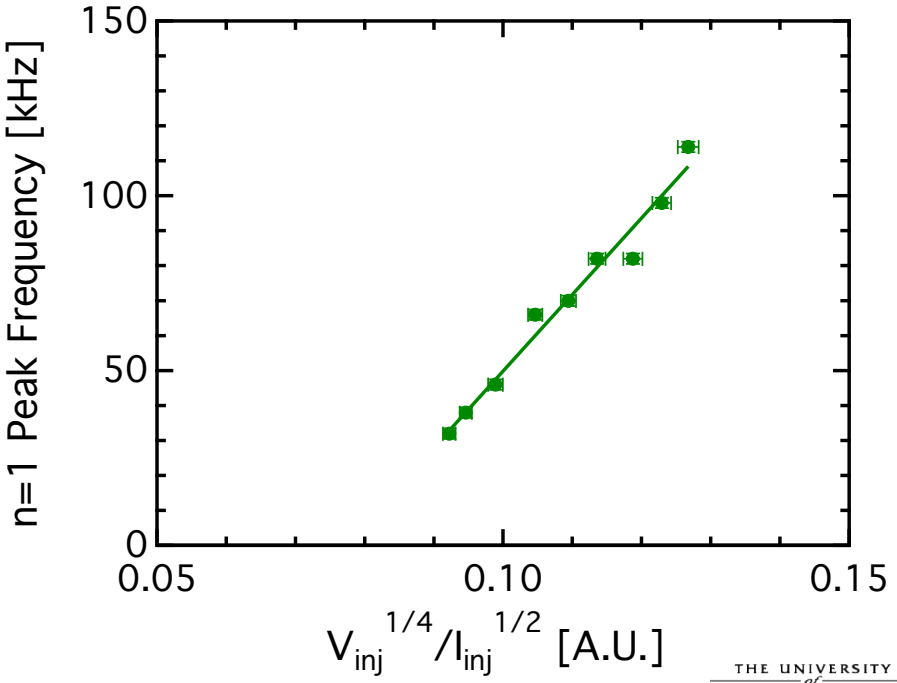
- Injector impedance an indicator of e-beam density:

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

$$n_b \sim I_{inj}/V_{inj}^{1/2} \quad \rightarrow \quad f_A \sim v_A \sim \frac{1}{\sqrt{n_b}} \sim V_{inj}^{1/4}/I_{inj}^{1/2}$$

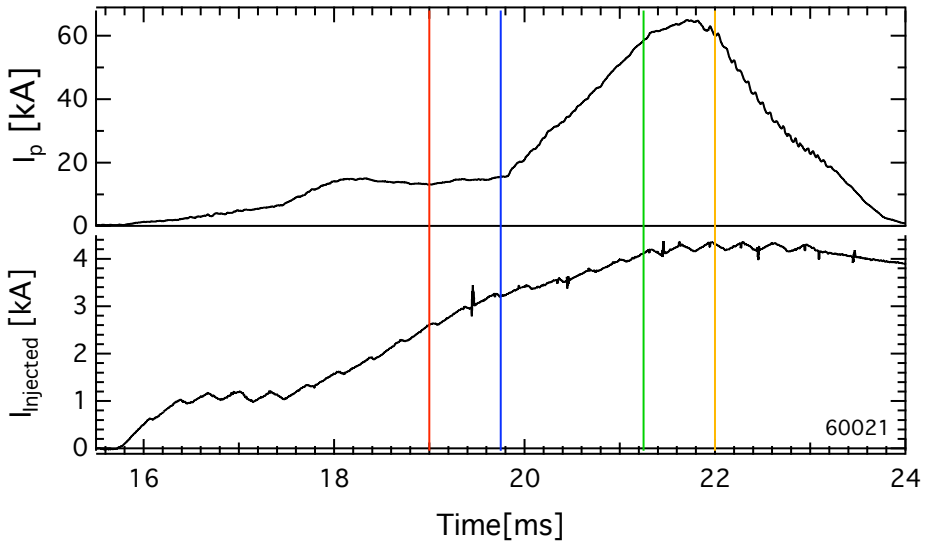
- n=1 frequency scales like Alfvén frequency
  - NIMROD: Alfvén waves along injected current streams



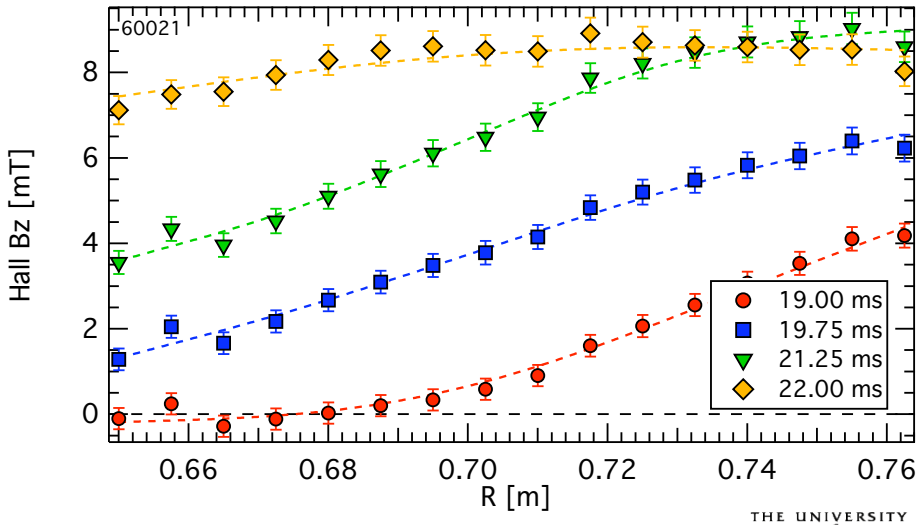


Approximate Null Formation Prior to Large Scale Relaxation Confirmed

- Relaxation occurs soon after null formation in initial low-B_z period
  - Observed in experiment and simulation



- Internal B_z measurements confirm predicted poloidal field null formation



n=1 Burst Activity is Consistent with Injected Helical Stream Dynamics

- LFS LHI plasmas exhibit large, Alfvénic bursts of n=1 activity
  - Radially localized near injectors
  - Poloidal structure consistent with unstable current stream in the edge
  - Toroidally asymmetric amplitude indicates toroidally line-tied to injectors
  - V_{inj} transients are consistent with NIMROD predicted detached current ring
- Anomalous ion heating is evidence of reconnection activity
  - Localized to the injection region
- Open question: how much current drive this mechanism leads to?