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

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San Jose, CA
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

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>1.15 – 1.3</td>
</tr>
<tr>
<td>$R(m)$</td>
<td>0.2 – 0.45</td>
</tr>
<tr>
<td>$I_p$ (MA)</td>
<td>$\leq 0.21$</td>
</tr>
<tr>
<td>$B_{t,0}$ (T)</td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>$\tau_{\text{shot}}$ (s)</td>
<td>$\leq 0.025$</td>
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</tbody>
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LHI Injects Current, Helicity to Form and Drive Tokamak-like Plasmas

Unstable injected current streams
Reconnect, relax to Tokamak-like state
Subsequent OH-Driven Tokamak

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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

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Low-\( f, \ n=1 \) Activity in LHI
Large n=1 Magnetic Fluctuations

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

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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

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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

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N=1 is Mode Spatially Localized to the LFS

- **LFS magnetics:**
  - Predominantly n=1 activity

- **HFS magnetics:**
  - Predominantly n=0 plasma motion, growth

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**LFS**

- Frequency [kHz]
  - n=0
  - n=1
  - 1st n=1 Harmonic

**HFS**

- Frequency [kHz]
  - n=0
  - n=1
  - 1st n=1 Harmonic

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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
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

- $I_{\text{inj}} = 2-3$ kA, $A_{\text{inj}} = 2$ cm$^2$

See:


LFS Poloidal Magnetic Signals are Consistent with Oscillating Stream Source

- Reduced model of oscillating filament source with $I_{\text{inj}}$
  - 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
During LHI Current Drive $T_i > T_e$

- $T_i \geq T_e \sim 100$ eV
- $T_{i,LHI} > 10 \times T_{i,OH}$
- $T_{i,LHI}$ 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

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

![Graph showing Core Ohmic $T_i$ vs time and $I_p$ vs time](image)

![Graph showing $T_i(R_{tan})$ vs tangency radius](image)
Helium-II $T_i$ Scales as Predicted by Magnetic Reconnection Theory

- High $B_z$ experiments prevent helical winding reconnection
  - No large scale relaxation $\Rightarrow$ no Tokamak
- Co-injected filament reconnection only:
  \[ n_b \propto \frac{I_{inj}}{\sqrt{V_{inj}}} \quad \Delta \phi \approx \frac{B^2}{2e\mu_0 n_b} \propto I_{inj}\sqrt{V_{inj}} \]
- $T_{\text{HeII},\perp} \propto \Delta \phi \propto I_{inj}\sqrt{V_{inj}}$
- $T_{\perp} \gg T_{||}$
- $T_i$ increases with changes in $I_{inj}$ and $V_{inj}$
- $T_{\perp}$ increases with $B_{guide}$

![Plasma filaments, $I_{inj} = 0$](image1)
![Merged filaments](image2)

![Ion heating consistent with 2-fluid reconnection theory](image3)
$T_i$ 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)

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Coinciding Burst Phenomena, Frequency Scaling
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
    \[ H.W. \text{ Grover, Inductance Calculations} \]
  - Transient drop of 1 turn
  - Drop, rebuild in typical burst time:  \[ \Delta t \approx 100 \mu s \]

- \[ \frac{dL_{\text{helix}}}{dt} \rightarrow \delta V_{\text{inj}} \approx 100 \text{ V} \]
Experimental $V_{\text{inj}}$ Transients Consistent with Stream-to-Stream Reconnection

- Bursts time with $V_{\text{inj}}$ transients:
  - Coincide with $n=1$ bursts
  - $I_p$ transients as well

- $\delta V_{\text{inj}} \sim 100\text{-}200\text{V}$

- Measured $V_{\text{inj}}$ transients consistent with reconnection:
  - Loss of helical stream winding

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n=1 Frequency is Alfvénic

- Injector impedance an indicator of e-beam density:
  \[ n_b \sim I_{inj}/V_{inj}^{1/2} \rightarrow f_A \sim v_A \sim \frac{1}{\sqrt{n_b}} \sim V_{inj}^{1/4}/I_{inj}^{1/2} \]

- 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
  - $V_{\text{inj}}$ 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?