Investigating High Frequency Magnetic Activity During Local Helicity Injection on the PEGASUS Toroidal Experiment

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### Investigating High Frequency Magnetic Activity During LHI on PEGASUS

#### Transition to Reduced MHD State
- In Low MHD State, $n = 1$ Mode Absent
- A New Operational Regime with Reduced MHD

#### New Magnetics Probe
- MrA Probe Provides High Bandwidth, Low Noise Measurement
- MrA Development and Construction
- MrA Deployed on Pegasus

#### High Frequency Magnetic Content
- Significant High Frequency Activity Seen in LHI Plasmas
- High Frequency Power Increases in Low MHD Mode
- Spectral Peak at ~ 600 kHz
- High Frequency Peak Has Coherent Structure

#### Redistribution of Magnetic Power
- Transition Localizes Power to Plasma Interior
- Magnetic Power Shifts to Higher Frequencies

#### LHI Current Drive
- Local Helicity Injection Routinely Used for Non-Solenoidal Startup on Pegasus

#### NIMROD Describes a Reconnection-Based Current Drive Mechanism

#### Measurements on Pegasus consistent with NIMROD model for LFS LHI

#### $T_i$ Associated with High Frequency Content

#### A Range of Experimental Parameters Affect Access to Low MHD State

#### Physical Interpretation of MHD Reduction

### Summary and Conclusions
- Transition Localizes Power to Plasma Interior
- New Magnetics Probe
- High Bandwidth, Low Noise Measurement
- MrA Development and Construction
- MrA Deployed on Pegasus
- High Frequency Peak Has Coherent Structure

### Future Work
- Transition to Reduced MHD State
- Local Helicity Injection Routinely Used for Non-Solenoidal Startup on Pegasus
- NIMROD Describes a Reconnection-Based Current Drive Mechanism
- Measurements on Pegasus consistent with NIMROD model for LFS LHI
- $T_i$ Associated with High Frequency Content
- A Range of Experimental Parameters Affect Access to Low MHD State
- Physical Interpretation of MHD Reduction

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LHI Current Drive
State with Reduced MHD
New Insertable Magnetics Probe
High Frequency Magnetic Activity
Local Helicity Injection Routinely Used for Non-Solenoidal Startup on PEGASUS

- Current extracted from local injectors
- Unstable current streams relax to form tokamak-like state

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NIMROD Describes a Reconnection-Based Current Drive Mechanism

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

- Reconnection of current streams leads to $I_p$ growth
  - Discrete reconnection events pinch off current rings
  - Rings move inward, building up poloidal flux
  - Associated with $n = 1$ magnetic activity
  - NIMROD indicates this process happens throughout the discharge

• **NIMROD:**
  - Bursts of $n = 1$ outboard activity associated with ring formation

• **PEGASUS:**
  - Jumps in toroidal current associated with $n = 1$ events
  - Frequency range in qualitative agreement with NIMROD prediction
  - Internal magnetic measurements show power at injector radius
- Anisotropic ion heating in injector streams consistent with two-fluid reconnection
  - Channel $T_{i,\perp} > T_e$
  - $T_{i,\perp} \sim V_A^2$ of injected current streams

- $T_i(t)$ correlated with continuous, high frequency activity
  - Suggests considering short wavelength reconnection as another CD mechanism

Ion heating correlated with high-f MHD fluctuations, not discrete reconnection between helical streams
Unexpected MHD Reduction Can Occur During HFS LHI

- Low MHD mode characterized by:
  - Rise in plasma current
  - Fast, $> 10 \times$ reduction of $dB/dt$ on outboard Mirnovs

- Can have back-transitions and/or “bursty” behavior during low MHD state

- Note: “Low” MHD amplitude still $\gtrsim 10 \times$ larger in comparison to ohmic

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LHI Current Sustained in Low MHD State without $n = 1$ Activity

- $I_p$ Sustainment without $n = 1 \rightarrow$ additional current drive mechanism(s)
A Range of Experimental Parameters Affects Access to Low MHD State

- Access improved by:
  - Increased neutral fueling
  - Stronger vertical shaping
  - Higher $I_p/B_t$
  - Reduced current per injector

Neutral Fueling Changes Transition Time

Plasma Current at Time of Transition
Several Hypotheses for MHD Reduction under Consideration

• Previous work: High MHD $n = 1$ mode consistent with line-tied kinking of current streams

• Absence of $n = 1$ in low MHD $\rightarrow$ stabilization of kink

• Current hypotheses:
  – Change in boundary conditions in upper divertor region $\rightarrow$ doubly line tied kink
  – Magnetic anchor
  – Stabilization through coupling with highly conductive plasma edge
  – Expansion of the current channel via turbulent process
A New, High Frequency $\dot{B}$ Diagnostic: Magnetic Radial Array (MrA) Probe

- Insertable probe
- 15 channel $\dot{B}_z(R, t)$
- Coils formed by traces in PCB
- Different trace geometries balance $A_{eff}$ and frequency response

Type A
- $A_{eff} = 3.52 \text{ cm}^2$
- 4 layer

Type B
- $A_{eff} = 1.80 \text{ cm}^2$
- 2 layer

Type C
- $A_{eff} = 9.55 \text{ cm}^2$
- 4 layer

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• Helmholtz coil measurements verify flat response to ~ 1 MHz

• High signal-to-noise
  – Shielded assembly
  – Short cable run
  – Fully differential digitization
MrA Utilizes Existing Armor and Drive Assembly of Hall Array Probe

Shield Transition and PCB Mount
Delrin Bushing
Carbon Probe Armor
Probe Internals (airside)

Thin (4 mil) Conductive Tape (electrostatic shield)
Twisted-pair flying leads to minimize pickup

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• Insertion range:
  \[ R = 54 - 90 \text{ cm}, \]
  \[ Z = 0 \]

• Signals digitized with D-tAcq ACQ132

• Rotatable mount for precise field alignment
MrA Shows Significant High Frequency Activity in LHI Plasmas

- Low frequency $n = 1$ peak
- Broad peak at ~ 600 kHz
High Frequency Activity Increases After Transition to Low MHD

- **In high MHD:**
  - Low frequency, \( n = 1 \) peak
  - Peak at 150 kHz
  - Small, broad peak at \( \sim 570 \text{ kHz} \)

- **In low MHD:**
  - Low frequency peak strongly reduced
  - 150 kHz peak decreases in magnitude
  - Peak at 570 kHz substantially increases

- Magnitude of this effect increases as move into plasma edge
570 kHz Peak Localized to Plasma Edge in Low MHD Phase

- Amplitude of high frequency peak has strong spatial dependence

- Summing power about the 570 kHz Peak:
  - Power largest near plasma edge
  - Sharply falls off as move outside plasma boundary ➔ short wavelength?
• Cross-power
  – Broad peak in high MHD phase
  – Increase in low MHD phase

• Cross-phase
  – Flat in high MHD phase
  – Possible structure in low MHD phase

• Coherence
  – > 0.5 over several probe channels, in both low and high MHD phases
Transition Localizes Power to Plasma Interior

- **Low Frequency:** 0 – 60 kHz
  - High MHD: Broad radial extent, peaks interior to plasma edge
  - Low MHD: Concentrated to a ~ 10 cm range, falls off rapidly beyond this

- **High frequency:** 460 – 720 kHz
  - High MHD: Nearly flat profile
  - Low MHD: Reduction beyond plasma edge, but large increase inside

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Summary and Conclusions

- In some LHI discharges, prominent $n = 1$ mode observed, consistent with NIMROD model of filament merging and reconnection

- Recent LHI experiments demonstrate mode of operation with current growth/sustainment in absence of $n = 1$ activity
  - Suggests additional physics / current drive mechanism(s) at play

- New magnetics probe, MrA, developed to investigate high frequency content

- Significant high frequency activity is present in LHI
  - Power is more localized during low MHD phase $\rightarrow$ shift to small wavelength?
  - Peak at 570 kHz observed that increases in amplitude during low MHD phase