MHD During Relaxation and Growth of DC Helicity Injection Plasmas on PEGASUS

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PEGASUS DC HI MHD Outline

- PEGASUS’ DC helicity injection (HI) plasmas exhibit bursts of n=1 MHD while HI drive is applied
  - Additional n=0 oscillations have been identified and could be related to plasma formation or results of n=1 burst side-effects on the plasma

- The n=1 mode structure is peaked in the edge of the plasma near to the DC HI injector radii
  - Bursts exhibit toroidal asymmetries dependent on HI injector geometry suggestive of line-tying at the injector end

- Internal $B_z$ measurements confirm the formation of a null prior to relaxation to a tokamak-like state, and support aspects of the PEGASUS HI plasma evolution model

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PEGASUS is a compact ultralow-A ST

Equilibrium Field Coils
High-stress Ohmic heating solenoid

Vacuum Vessel

Toroidal Field Coils

Ohmic Trim Coils

Proposed Divertor Coils

Point-Source Helicity Injectors

Experimental Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Achieved</th>
<th>Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.15 – 1.3</td>
<td>1.12 – 1.3</td>
</tr>
<tr>
<td>R(m)</td>
<td>0.2 – 0.45</td>
<td>0.2 – 0.45</td>
</tr>
<tr>
<td>I_p (MA)</td>
<td>≤ 0.21</td>
<td>≤ 0.30</td>
</tr>
<tr>
<td>I_N (MA/m-T)</td>
<td>6 – 12</td>
<td>6 – 20</td>
</tr>
<tr>
<td>RB_t (T-m)</td>
<td>≤ 0.06</td>
<td>≤ 0.1</td>
</tr>
<tr>
<td>κ</td>
<td>1.4 – 3.7</td>
<td>1.4 – 3.7</td>
</tr>
<tr>
<td>τ_shot (s)</td>
<td>≤ 0.025</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>β_t (%)</td>
<td>≤ 25</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>P_{HHFW} (MW)</td>
<td>0.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Major research thrusts include:
- Non-inductive startup and sustainment
- Tokamak physics in small aspect ratio:
  - High-I_N, high-β stability limits
  - ELM-relevant edge MHD activity
Total helicity $K$ in a tokamak geometry:

$$K = \int_V \left( A + A_{vac} \right) \cdot \left( B - B_{vac} \right) \, d^3x$$

$$\frac{dK}{dt} = -2 \int_V \eta J \cdot B \, d^3x - 2 \frac{\partial \psi}{\partial t} \Psi - 2 \int_A \Phi B \cdot ds$$

- **Resistive Helicity Dissipation**
  - $E = \eta J \rightarrow$ much slower than energy dissipation ($\eta J^2$)
  - Turbulent relaxation processes dissipate energy and conserve helicity

- **AC Helicity Injection**
  - $\dot{K}_{AC} = -2 \frac{\partial \psi}{\partial t} \Psi = 2V_{loop} \Psi$
  - $\Psi$ is toroidal flux, $\psi$ is poloidal flux
    (e.g., current drive through solenoid induction)

- **DC Helicity Injection**
  - $\dot{K}_{DC} = -2 \int_A \Phi B \cdot ds = 2V_{inj} B_{\perp} A_{inj}$
  - $\Phi$ is electrostatic potential
Taylor Relaxation Criteria Sets the Maximum $I_p$ for a Given Magnetic Geometry

**Helicity balance in a tokamak geometry:**

\[
\frac{dK}{dt} = -2 \int_V \eta \mathbf{J} \cdot \mathbf{B} \, d^3x - 2 \frac{\partial \psi}{\partial t} \psi - 2 \int_A \Phi \mathbf{B} \cdot ds \quad \Rightarrow \quad I_p \leq \frac{A_p}{2\pi R_0 \langle \eta \rangle} \left( V_{ind} + V_{eff} \right)
\]

- Helicity injection can be expressed as an effective loop voltage
- $I_p$ limit depends on the scaling of plasma confinement via the $\eta$ term

**Taylor relaxation of a force-free equilibrium:**

\[
\nabla \times \mathbf{B} = \mu_0 \mathbf{J} = \lambda \mathbf{B} \quad \Rightarrow \quad \mu_0 I_p \leq \frac{\mu_0 I_{inj}}{\Psi_T} \leq \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}} \quad \Rightarrow \quad I_p \leq \left[ \frac{C_p \Psi_T I_{inj}}{2\pi R_{inj} \mu_0 w} \right]^{1/2}
\]

Assumptions:
- Driven edge current mixes uniformly in SOL
- Fields average to tokamak-like structure

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A_p Plasma area
C_p Plasma circumference
$\Psi_T$ Plasma toroidal flux
$w$ Edge current channel width
HI is an Alternative to OH Induction and is Accompanied by Strong MHD

- HI offers an alternative to OH induction for plasma startup
  - HI on PEGASUS has produced plasmas with $I_p \leq 0.17$ MA consistent with Taylor relaxation
- HI on PEGASUS is accompanied by strong MHD activity
- To understand and implement more effective HI current drive, we are motivated to better understand:
  - Relaxation dynamics and the requirements for relaxation
  - The role of the observed magnetic activity in current drive
PEGSASUS External Magnetics

• PEGASUS has an extensive magnetic diagnostics set including:
  – Arrays of toroidal (11) and poloidal (43) Mirnov Coils
  – Insertable toroidal Mirnov Coil probe array
  – Insertable radial Hall sensor probe array
Solid-state InSb Hall Effect sensors
- Sypris model SH-410
- Weak variance with $T_{\text{sensor}}$ and $B_{||}$ are correctable with calibration
- 16 channels, 7.5 mm radial resolution

Slim C armor as low-Z PFC
- Minimizes plasma perturbation
- 25 kHz bandwidth
- Innermost sensor $R > 50.8\text{cm}$
- Used to diagnose both PEGASUS OH and HI plasmas

Local $J_\varphi(R)$ Can Be Estimated From Hall Sensor Array $B_z$ Measurements

- Petty, *et al.*\textsuperscript{*} showed that $J_\varphi$ for a plasma with elliptical cross-section can be calculated from on-midplane $B_z$ measurements:

$$
\mu_0 J_\varphi = - \left( \frac{B_z}{\kappa^2 (R - R_0)} + \frac{\partial B_z}{\partial R} \right)
$$

\textsuperscript{*}Petty, C. C., *et al.*, Nuclear Fusion, 42, 1124, 2002

- Assumes a Grad-Shafranov equilibrium
  - Note that this is an estimate, and during helicity injection this is not assured

- Assuming typical P\textsc{E}G\textsc{A}S\textsc{U}S shaping parameters ($\kappa=1.75$, $R_0=0.4$), $J_\varphi$ over the Hall sensor array can be estimated
  - Note that $R_0$ and $\kappa$ are changing with time
Mode Structure
PEGASUS Plasmas Exhibit Two Fluctuating $B_{pol}$ Components

- The slowest varying $B_{pol}$ fields are applied $B_z$ and bulk plasma $B_{pol}$

- Poloidal field measurements show 2 fluctuating components:
  - Bursty activity:
    - 20-80 kHz
    - $\delta b/B_t \sim 0.2 - 3\%$
  - Lower frequency activity, coincide with bursts
    - 2-10 kHz
    - $\delta b/B_t \sim 0.1 - 1\%$

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Previous study by D. Battaglia* has shown:

- **Bursts correspond with:**
  - Jumps in $I_p$
  - Abrupt inward motion of $R_0$
  - Drop in $l_i$

- **Typical frequencies:** $20kHz < f < 80kHz$

- **Typically $n=1$**

*Figures and analysis from D. Battaglia thesis:  
Continuous type MHD is also observed in HI PEGASUS discharges
- Likely a series of many bursts, or similar phenomenon

Typical frequencies: 10kHz < f < 50kHz

Typically n=1
n=1 Mode Amplitude is Toroidally Asymmetric

- The n=1 mode amplitude is toroidally asymmetric
  - Smallest near the injector face (cathode)

- n=1 toroidal asymmetry follows changes to injector toroidal location

- This structure is suggestive of a line-tied kink mode with one end moving*
  - Line-tying at the injector face with the other end free or moving

*See:
n=1 MHD Activity is Localized Near the Injector Radius

- Local $B_z$ measurements show radial localization of bursty n=1 mode

- The n=1 mode is localized near the injector radius
Pegasus Lower Frequency Magnetic Activity is n=0

- Slower 2-10 kHz magnetic fluctuations are n=0, and strongest in the plasma interior

- Possible or likely causes:
  - Expected inward expansion (strongest in early relaxation phase)
  - Known radial plasma motion, current profile changes caused by n=1 bursts

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Previous work* has shown that sufficient current supplied from the helicity injectors is expected to perturb the local magnetic field to create a field null, which is required for relaxation to a tokamak-like state.

\[ I_\phi = 0 \text{ A} \]
\[ I_\phi = 4 \text{ kA} \]

2-D force free current model

*D. J. Battaglia, et al., Nucl. Fusion, 51, 073029, 2011
Representative Discharge Probed to Study Relaxation

• Relaxation occurs soon after null formation in initial low-$B_z$ period

• Internal $B_z$ measurements confirm predicted poloidal field null formation
Internal $B_z(R)$ Measurements Allow for Calculation of Current Profile Evolution

- $J_\phi(R)$ calculation shows current build in plasma interior:
  - Initially, current is concentrated in the edge region (red)
  - Current simultaneously builds in the plasma core while dropping in the edge (red to blue to green)
  - Finally, $J_\phi(R)$ becomes peaks in the plasma core after detaching from the injectors (yellow)
Current streams combine into diffusive current layer

Field null is formed and current builds in plasma interior

Tokamak-like state is formed, detaches from injectors

*D-alpha camera imaging with fish-eye lens. See K. E. Thome poster, *Improved density control in the Pegasus Toroidal Experiment using internal fueling*, for information on this diagnostic.
• Continuous n=1 modes are commonly observed in HI-driven toroidal plasmas (STs and Spheromaks)
  – The observed n=1 structure is thought to be a kink mode
  See:

• Relevant MHD simulations for PEGASUS are underway:
  – See poster:
Future Work

• Upgrade radial $B_z$ probe diagnostic for faster frequency response to measure and relate $J_\phi$ to local MHD fluctuations
  – Movable or multiple diagnostics could provide further detail of n=1 mode structure
  – Details of n=1 mode relation to current drive is still under investigation

• Comparison to numerical simulations

• Considering local MHD and Hall dynamo measurements
  – Faster, localized PEGASUS $T_i$ spectrometer measurements could resolve $v$-fluctuations for MHD Dynamo measurements
  – Local, fast $J_\phi$ fluctuation measurements for Hall Dynamo measurements
Conclusions

- **PEGASUS’ DC helicity injection plasmas exhibit bursts of n=1 magnetic perturbations while HI drive is applied**
  - Mode structure is toroidally asymmetric – suggestive of line-tying on-or-near the injector
  - The n=1 mode is also radially localized near to the injector

- **n=0 magnetic fluctuations are also observed during helicity drive on PEGASUS**
  - The n=0 fluctuations are largest in the plasma interior, and likely related to plasma inward expansion and/or motion associated with n=1 burst activity

- **Internal B_z measurements confirm poloidal null formation prior to relaxation, and corresponding J_φ calculations show buildup of current density into the plasma interior during HI**
  - Calculations show tokamak-like, peaked profile after detachment