Non-Solenoidal Startup via Local Helicity Injection and Edge Stability Studies in the Pegasus Toroidal Experiment

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on behalf of the Pegasus Team

Workshop on Exploratory Topics in Plasma and Fusion Research

Fort Worth, TX
February 15, 2013
Exploiting Unique Aspects of the ST to Improve Fusion Energy Science

- Non-solenoidal startup: Increasing reactor attractiveness
  - Local Helicity Injection produces tokamak plasmas using edge current drive
    - Predictive understanding through helicity conservation, Taylor relaxation constraints
  - Reduces cost, complexity of device
  - Technique applicable to any tokamak, not just ST

- Edge physics: Detailed measurements of pedestal, ELM dynamics
  - Low-A naturally provides access to peeling instability underlying ELMs
    - Simplified diagnostic access → unique $J_{edge}(t)$ measurements
  - Extension to ITER-relevant peeling-ballooning physics via H-mode operation

- Testing boundaries of tokamak stability at ultimate geometric limit
  - High $\beta_T$, toroidal field utilization $I_p/I_{TF}$ as $A \rightarrow 1$

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## Pegasus is a Compact, Ultralow-A ST

### 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>≤ 0.23</td>
<td>≤ 0.30</td>
</tr>
<tr>
<td>$I_N$ (MA/m-T)</td>
<td>6 – 14</td>
<td>6 – 20</td>
</tr>
<tr>
<td>$RB_t$ (T-m)</td>
<td>≤ 0.06</td>
<td>≤ 0.1</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>1.4 – 3.7</td>
<td>1.4 – 3.7</td>
</tr>
<tr>
<td>$\tau_{\text{shot}}$ (s)</td>
<td>≤ 0.025</td>
<td>≤ 0.05</td>
</tr>
<tr>
<td>$\beta_t$ (%)</td>
<td>≤ 25</td>
<td>&gt; 40</td>
</tr>
</tbody>
</table>

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Local Helicity Injection Offers Scalable Non-Solenoidal Startup

- Current injected along helical vacuum field
  - Local, active current sources

- MHD relaxation, tokamak-like state
  - Constrained by helicity, Taylor relaxation limits

- Tokamak plasmas produced after injector shut off
  - Couples to alternative current drive sources

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Battaglia et al., Nucl. Fusion 51, 073029 (2011)
Helicity Input Provided by Edge-Localized Sources

- Flexible injector geometry
- Active arc ‘gun’ injectors provide initial current windup, relaxation
- Either active guns or separate electrodes can provide further growth, sustainment

![Diagram of Inboard and Outboard Injection](image)

Inboard Injection:
- $R_{inj} = 16 \text{ cm}, Z_{inj} = -75 \text{ cm}$

Outboard Injection:
- $R_{inj} = 70 \text{ cm}, Z_{inj} = -20 \text{ cm}$

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*: Eidietis et al., J. Fusion Energ. 26, 43 (2007)
**: Battaglia et al., Nucl. Fusion 51, 073029 (2011)
Helicity balance in a tokamak geometry:

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

- Helicity injection can be expressed as an effective loop voltage
- \(I_p\) limit depends on plasma confinement via resistivity \(\eta\)

Taylor relaxation of a force-free equilibrium:

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

Assumptions:

- Driven edge current mixes uniformly
- Edge fields average to tokamak-like structure

\(A_p, A_{\text{inj}}\) : Plasma, injector area
\(C_p\) : Plasma circumference
\(\Psi\) : Plasma toroidal flux
\(w\) : Edge current channel width
Achieving the Maximum $I_p$ at the Taylor Limit Requires Sufficient Helicity Injection Input Rate

$$V_{inj} = 1200 \, \text{V}$$

$$V_{eff} \approx \frac{A_{inj} B_{\phi,inj}}{\Psi} V_{inj}$$

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Battaglia et al., Nucl. Fusion 51, 073029 (2011)
Experimental Plasma Currents Follow Taylor Limit Scalings

• Taylor limit: \( I_{p,max} \propto \sqrt{I_{TF}I_{inj}} \)

• Limit appears absolute
  – Additional OH \( V_{loop} \) cannot raise \( I_p \) during LHI

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Battaglia et al., Nucl. Fusion 51, 073029 (2011)
Internal Measurements Show Null Formation, $J(R,t)$ Throughout LHI Discharge Evolution

- Initial relaxation to tokamak-like topology coincident with inboard null formation
  - Injected current filaments perturb vacuum $\mathbf{B}$
  - $B_z$ must be sufficiently low and/or $I_{inj}$ sufficiently high for null to form

- Hall probe* $B_z(R)$ provides $J_\phi(R)$ evolution
  - Predicted field null observed

Current Multiplication During LHI Accompanied by $n = 1$ Line-Tied Kink Activity

- Current multiplication, transport accompanied by MHD activity
- Two common spectral features
  - High-frequency 10–20 kHz $n = 1$
  - Low-frequency < 5 kHz $n = 0$
- $n = 1$ mode consistent with line tying
  - Activity localized near injector radius
  - Toroidal asymmetry in $\tilde{b}/B$
- $n = 0$ localized to plasma interior
  - Inward radial motion

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Magnetic Topology Rapidly Changes with Bursts of MHD Activity During Helicity Injection

- Each burst typically $\sim 0.1$ ms
- With each burst...
  - $\ell_i$ decreases $\rightarrow I_p$ increases
  - $R_0$ decreases $\rightarrow$ plasma expands
  - $B_{\phi,0}$ increases $\rightarrow q_0$ increases
  - Slight drop in $E_k$ and $E_m$
  - Little change in poloidal flux at plasma edge
  - Rapid decrease in the total trapped poloidal flux
- Temporally and spatially averaged $V_{\text{ind}} \sim 1.5$ V

Battaglia et al., Nucl. Fusion 51, 073029 (2011)

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Strong, Anisotropic Ion Heating Observed During Helicity Injection

- Strong ion heating correlated with $n = 1$ burst activity on multiple line species
- Ion $T_\perp > 2 T_\parallel$ is often observed
  - Similar phenomenon observed in MST** during magnetic reconnection

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Source Impedance Governed by Space Charge and Magnetic Current Limits

- Predictive impedance models required to design future startup systems
  - Taylor limit $\propto \sqrt{I_{inj}}$; Helicity input $\propto V_{inj}$
  - $Z_{inj}$ couples $I_{inj}, V_{inj} \rightarrow$ power requirements

- Two distinct regimes evident in active source I-V characteristics
  - Double-sheath space-charge limit
    - Low $I_{inj}, V_{inj}$
    - $I_{inj} \propto V^{3/2}$
  - Alfvén-Lawson magnetic current limit
    - High $I_{inj}, V_{inj}$
    - $I_{inj} \propto V^{1/2}$
    - Sheath expansion may also contribute

\[ I_{inj} \sim V^{1/2} \]
\[ V_{inj} \sim V^{3/2} \]
Local Helicity Input Requires Increasingly Capable Electron Current Injectors

- Active gun sources used for initial relaxation, sustainment
  - Arc plasma created in coaxial washer gun
  - Electron current extracted from arc

- Subsequent growth via electrode-based systems may offer scalable path forward
  - Goal: simultaneously optimize helicity injection, Taylor relaxation constraints
    - High $I_{\text{inj}}$ over extended area

- Need to develop large $A_{\text{inj}}$ uniform current injector
  - Minimize gas load

New ‘Showerhead’ Electrode Designed for Hollow-Cathode, High Area Helicity Injection

- Promising results from initial commissioning of new electrode
  - $I_p > 100$ kA with showerhead assist;
    $\leq 45$ kA without
  - Matched PF evolution, fueling

- Diffuse illumination of assembly, $I_p$ increase suggests high $A_{eff}$
Edge Stability Critical to Next-Step Fusion Devices

- Future fusion devices will operate in H-mode
  - Edge Localized Modes (ELMs) of concern

- Peeling-balloonning theory believed to underlie most damaging Type-I ELM
  - Pressure, current density gradients in edge drive ideal MHD instabilities
  - Detailed $J_{\text{edge}}$ measurements needed

\[ \propto \frac{qRJ_{||}}{B} \]

***: Snyder, Phys. Plasmas 12, 056115 (2005); Hegna, Phys. Plasmas 3, 584 (1996)
• Spherical tokamaks naturally provide strong peeling drive
  – Toroidal field utilization $I_p/I_{TF} \sim J/|B|

• **PEGASUS** accesses peeling modes
  – Strong $J/|B| \sim 1$ MA/m$^2$-T at $A \leq 1.3$
  – Comparable to DIII-D in H-mode

• Machine parameters permit internal edge measurements
  – Short pulse lengths (< 50 ms)
  – Modest $T_e < 200$ eV
Pegasus Peeling Mode Features Match Empirical and Theoretical Expectations

- Short lifetimes with high poloidal coherence
- Detachment, radial propagation of filaments
- High-m, low-n structure
- Mode amplitude increases with theoretical drive J/B

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**J** edge Dynamics Measured on ELM Timescales

- Peeling mode filament forms from initial “current-hole” J\textsubscript{edge} perturbation*
  - Validates formation mechanism hypothesized by EM blob transport theory**

- Filaments carry current I\textsubscript{f} \sim 100-220 A
  - I\textsubscript{f} < 0.2 % of I\textsubscript{p}, similar to MAST ELMs

- Radial motion qualitatively consistent with transient magnetostatic repulsion
  - Measured v\textsubscript{R} consistent with available analytic models***

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H-mode Access: More Detailed ELM Tests and Possible Post-HI Current Drive Enhancement

- Ohmic H-mode achieved with new central column (high-field-side) fueling system
  - Standard L-mode with strong low-field-side external fueling

- Standard H-mode signals seen
  - Reduced D_α emission
  - Quiescent edge between ELM events
  - Type I and III ELMs suggested
  - Improved confinement inferred

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Thome et al. APS-DPP 2012
Redd et al., IAEA FEC 2012
Toroidal Flow Reverses at L–H Transition

- Toroidal rotation measured via $T_i$ spectrometry* in L, Ohmic H-mode discharges
  - No external momentum input

- L-mode flows are in the counter-current direction

- H-mode shots reverse rotation at L → H transition
  - Effect seen on MAST** and NSTX during HFS fueling


• Internal B measurements from Hall array* yield local $J_\phi(R,t)$**

• Current gradient scale length significantly reduced in H-mode
  – $L \rightarrow H: 6 \rightarrow 2 \text{ cm}$

**: C.C. Petty et al., Nucl. Fusion 42, 1124 (2002)
J_{\text{edge}}  ELM Dynamics Observed

- J(R,t) profiles measured throughout single Type III ELM
  - n = 1 EM precursor
  - ~10% I_p loss, negligible $\Delta\Phi$

- Current-hole perturbation accompanies pedestal crash
  - Similar to peeling modes in Pegasus

- Rapid recovery of H-mode pedestal

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• Significant progress with non-solenoidal startup of ST
  – Increasing understanding of HI physics to project towards MA-class startup
    • Helicity balance, relaxation current limits determine ultimate $I_p$
    • Complex MHD drives $J(R,t)$ and reconnection-driven ion heating
    • Sheath and magnetic current limits govern injector impedance
  – Developing advanced edge current sources for increased helicity injection

• Leveraging low-A regime to test edge stability theory
  – Peeling mode characteristics consistent with theory
    • Onset, spatial structure, MHD virulence consistent with ideal MHD
    • Nonlinear dynamics: filament creation / propagation from $J_{\text{edge}}$ current-hole
  – ITER-relevant ELM stability tests of peeling-ballooning modes

• LHI $J(R,t)$ control and H-mode access support high-$\beta$ studies of tokamak limits
  – Deploying enhanced divertor coils for separatrix operation