Advancing Local Helicity Injection for Non-Solenoidal Tokamak Startup

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A Growing Understanding of Physics and Engineering Issues in LHI Informs its Application to Next-Step Machines

Varying Injector Location Enables Study of LHI Physics and Engineering Tradeoffs

New Scenarios Developed to Transfer Between LFS → HFS Injector Systems and Combine Strengths of Each Geometry

Research on the A ~ 1 Pegasus ST is Advancing the Physics and Technology Basis of Local Helicity Injection Non-Solenoidal Startup

Operating Regime with Significant Reduction of Large-Scale MHD and Increased Ip Found During HFS Injection Experiments

HFS LHI at Near-Unity A Provides access to $\beta_t \sim 100\%$ and Magnetic Configurations with Minimum $|B|$ Wells

Recent Experiments Suggest High Frequency Magnetic Activity and Reconnection Play a Role in LHI Current Drive

URANIA Experiment: Converted PEGASUS Facility for US Non-Solenoidal Development Station

Recommended size per IAEA 110 cm x 85 cm (HxW)
Solenoid-free startup desirable for ST, AT reactors

LHI is promising method to accomplish this goal
- Edge current extracted from injectors at boundary
- Relaxation to tokamak-like state via helicity-conserving instabilities
- Global current limits from Taylor relaxation, helicity balance
- Hardware retractable prior to nuclear phase in reactor

Routinely used for startup on PEGASUS

Non-Solenoidal $I_p = 0.2$ MA Plasma via LHI ($I_{inj} \leq 8$ kA)

PEGASUS Parameters
- $I_p \leq 0.23$ MA
- $\Delta t_{shot} \leq 0.025$ s
- $B_T = 0.15$ T
- $A = 1.15$–$1.3$
- $R = 0.2$–$0.45$ m
- $a \leq 0.4$ m
- $\kappa = 1.4$–$3.7$

Injector Parameters
- $\sum I_{inj} \leq 14$ kA
- $I_{inj} \leq 4$ kA
- $V_{inj} \leq 2.5$ kV
- $N_{inj} \leq 4$
- $A_{inj} = 2$–$4$ cm$^2$
- $I_{arc} \leq 4$ kA
- $V_{arc} \leq 0.5$ kV

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**LHI Physics Models**

- Global $I_p$ limits:
  - Taylor relaxation
  $$I_p \leq I_{TL} \sim \sqrt{I_{TF}I_{\text{inj}}/\omega}$$
  - Helicity conservation
  $$V_{LHI} \approx A_{\text{inj}} B_{T,\text{inj}} V_{\text{inj}} / \Psi$$

- Predictive power balance: $I_p(t)$
  $$I_p[V_{LHI} + V_{IR} + V_{IND}] = 0 ; I_p \leq I_{TL}$$

- 3D resistive MHD / NIMROD
  - Initial relaxation
  - Role of reconnection

**Coupled Physics/Engineering Needs**

- Helicity injector source design
  - $I_{\text{inj}}, \omega$: set $I_{TL} \geq I_p$
  - $N_{\text{inj}} A_{\text{inj}} V_{\text{inj}}$: attain / sustain $I_p$
  - Armoring, limiters to minimize PMI

- Injector system geometry
  - Provide initial relaxation via near-PF null
  - Site conformal to desired plasma shape
  - Facility port access compatibility

- Injector impedance and power systems
  - $Z_{\text{inj}} = Z_{\text{inj}}(n_{arc}, n_{\text{edge}}, ...)$

**Outstanding Issues**

- Scaling to high $I_p$
  - Larger size
  - High $B_T$
  - Longer pulse

- Handoff to non-inductive CD
  - LHI $\rightarrow$ OH H-mode demonstrated

- Confinement, impurities, and dissipation during LHI

- LHI current drive mechanism

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Varying Injector Location Enables Study of LHI Physics and Engineering Tradeoffs

- Extrema of feasible LHI geometries deployed in Pegasus

- Low-field-side (LFS) injection
  - Injectors on outboard midplane
  - High $R_{inj} \rightarrow$ low $V_{LHI}$
  - Dynamic shape $\rightarrow$ strong $V_{IND}$

- High-field-side (HFS) injection
  - Injectors in lower divertor
  - Low $R_{inj} \rightarrow$ strong $V_{LHI}$
  - Static shape $\rightarrow$ minimal $V_{IND}$

- $I_p \sim 0.2$ MA attained in both geometries
  - Power supply and PMI limited

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**Injector System Comparisons**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>LFS</th>
<th>HFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{inj}$</td>
<td>$\leq 3$</td>
<td>$\leq 2$</td>
</tr>
<tr>
<td>$A_{inj}$</td>
<td>$2 \text{ cm}^2$</td>
<td>$4 \text{ cm}^2$</td>
</tr>
<tr>
<td>$R_{inj}$</td>
<td>$0.70 \text{ m}$</td>
<td>$0.26 \text{ m}$</td>
</tr>
<tr>
<td>$B_{inj}$</td>
<td>$\leq 0.08 \text{ T}$</td>
<td>$\leq 0.22 \text{ T}$</td>
</tr>
<tr>
<td>$V_{inj}$</td>
<td>$\leq 1.5 \text{ kV}$</td>
<td>$\leq 1.5 \text{ kV}$</td>
</tr>
<tr>
<td>$I_{inj}$</td>
<td>$6 \text{ kA}$</td>
<td>$8 \text{ kA}$</td>
</tr>
<tr>
<td>$P_{inj}$</td>
<td>$9 \text{ MW}$</td>
<td>$12 \text{ MW}$</td>
</tr>
<tr>
<td>$\frac{V_{LHI}}{V_{LHI,LFS}}$</td>
<td>$1$</td>
<td>$3.7$</td>
</tr>
</tbody>
</table>

**LFS: Non-solenoidal Induction**

**HFS: Helicity Injection**
New Scenarios Developed to Transfer Between LFS $\rightarrow$ HFS Injector Systems and Combine Strengths of Each Geometry

- LFS $\rightarrow$ HFS handoff provides ready access to full-$B_T$ operations with HFS injectors
  - LFS: Simpler relaxation access, lower PMI
  - HFS: Higher $V_{LHI}$
  - Seamless transfer between separate LHI systems

- Informs HFS high-$B_T$ LHI system design
  - Relaxation, sustainment requirements may demand separate hardware features in higher-field machines

- Record LHI $I_p = 0.225$ MA attained
  - Peaked temperature, density pressure profiles
  - $T_e > 100$ eV, $n_e \sim 1 \times 10^{19}$ m$^{-3}$
Recent Experiments Suggest High Frequency Magnetic Activity and Reconnection Play a Role in LHI Current Drive

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- NIMROD simulations of HFS LHI reproduce features observed in experiment
  - Relaxation to tokamak-like state
  - Bursty 10’s kHz $n = 1$ activity on LFS Mirnovs
  - Identifies helical current stream reconnection as a current drive mechanism

- Anomalous, reconnection-driven ion heating present during LHI
  - Continuously sustains $T_i > T_e$
  - Consistent with two-fluid reconnection theory
  - $T_i$ correlated with high frequency activity

- Internal magnetic measurements find significant high-frequency spectral content
  - ~700 kHz feature: arc source
  - Broadband continuum
Operating Regime with Significant Reduction of Large-Scale MHD and Increased $I_p$ Found During HFS Injection Experiments

- Abrupt MHD transition can lead to improved performance
  - Low-$f$ $n = 1$ activity reduced by over $10\times$ on LFS
  - Bifurcation in $I_p$ evolution following transition
  - Up to $2\times I_p$ at fixed $V_{LHI}$
  - Linear scaling of $I_p(V_{LHI})$ in this regime at low $B_T = 0.05$ T

- Sustained discharges without $n = 1$ activity possible
  - Implies $n = 1$ mode not responsible/required for LHI current drive

- Mechanism for transition unclear, under investigation
  - $n = 1$ reduction interpreted as stabilization of injector streams
  - Extremely sensitive to $B_T$, $B_Z$, $I_p$, fueling
  - Access scales with $I_p/I_{TF} \sim 1$: min-$|B|$ well?
  - If extensible to higher $B_T$, may afford simpler LHI system requirements

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HFS LHI at Near-Unity A Provides Access to $\beta_t \sim 100\%$ and Magnetic Configurations with Minimum $|B|$ Wells

- Access to highly-shaped, high $\beta_t$ plasmas
  - Low $I_{TF} \sim 0.6 I_p$
  - $A \sim 1$: high $\kappa$, low $\ell_i$, and high $\beta_{N,max}$
  - Reconnection-driven $T_i > T_e$
  - Disrupting at ideal no-wall stability limit

- High-$\beta_t$ equilibria contain large min-$|B|$ region
  - Up to 47% of plasma volume
  - Potentially favorable for stabilization of drift modes, reduction of stochastic transport

- Minimum $|B|$ regime arises from 3 major influences
  - $B_p \sim B_T$ at $A \sim 1$
  - Hollow $J(R)$
  - Pressure-driven diamagnetism (although $\beta_p < 1$)

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**URANIA Experiment: Converted PEGASUS Facility for US Non-Solenoidal Development Station**

- **Mission:** compare / contrast / combine reactor-relevant startup techniques at $I_p \sim 0.3$ MA
  - LHI, CHI, RF/EBW Heating & CD
  - Goal: guidance for ~1 MA startup on NSTX-U, beyond

- **Upgrades from PEGASUS to URANIA:**
  - New centerstack assembly: No solenoid magnet
  - Increase $B_T$ 4×: 0.15 → 0.6 T
  - Longer pulse: 25 → 100 ms
  - Improved shape control with new PF, divertor coils
  - Diagnostic neutral beam: kinetic and impurity diagnostics
  - EBW RF Heating & CD (w/ ORNL)
  - Transient, Sustained CHI (w/ Univ. Washington, PPPL)

- **Engineering design underway**
  - Centerstack upgrade scheduled for late 2019

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