Overview of Non-Solenoidal Startup Studies in the Pegasus ST

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Non-Solenoidal Startup via Local Helicity Injection

Local Helicity Injection (LHI) Provides Robust Non-Solenoidal Startup on the PEGASUS ST

LHI Startup Scenarios Grow From Helical Current Streams to Quality, High $I_p$ Plasmas

High-Field-Side (Divertor) Injection Experiments Provide Confinement Tests & Higher $I_p$

Hierarchy of Physics Models Provide a Predictive Understanding for LHI Startup

Technology and Diagnostic Development

Three HFS Injection Systems Implemented and Tested Since April 2016

Multi-Year Technology Development has Produced Robust, High Performance Current Injectors

Large-$A_e$ Injector Design Provides Enhanced Performance, Simplified Geometry

0-D Power Balance Model Used to Explore Projections for NSTX-U Startup

Thomson Scattering Enhancements to Measure $T_e$ and $n_e$ Profiles During LHI

0-D Power Balance Model Provides Predictive Tool for $I_p(t)$

Equilibrium-Calibrated Inductance Model Improves Estimates of Non-Solenoidal $V_{IND}$

Different MHD Activity Observed Between LFS and HFS Injection Geometry

Progress Toward Predictive Models of LHI

Power Balance Model Provides Predictive Tool for $I_p(t)$

Analytic Formulation of Power Balance Model Elements Allow Partitioning of Energy Flow

Equilibrium-Driven Ion Heating Gives $T_e > T_i$ During LHI

Reconnection-Driven Ion Heating as Drive Mechanism

Current Stream Interaction Manifests as Edge-Localized MHD Burst

Reconnection-Driven Ion Heating Gives $T_i > 100$ eV

Different MHD Activity Observed During LHI

2016 Helicity Injection Campaign Highlights

LFS Local Helicity Injection Produces Core $T_e > 100$ eV

$T_e (R, t)$ Remains Peaked for LFS Injection Geometry and Minimal $V_{IND}$

Technical Challenges Arise for LHI Startup With HFS Injection Geometry

LHI Provides Access to High-$\beta_t$ at $A \sim 1$ With Non-Solenoidal Sustainment and Anomalous Ion Heating

Poloidal Field Shaping Facilitates Relaxation at Full Toroidal Field ($B(t) = 0.23$ T)

Progress in Non-Solenoidal Startup on Pegasus

Reprints

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Progress Toward Predictive Models of LHI
2016 Helicity Injection Campaign Highlights
Local Helicity Injection (LHI) Provides Robust Non-Solenoidal Startup on the PEGASUS ST

Ip ≤ 0.18 MA via LHI (I_{inj} = 5 kA)

Plasma Parameters
- \( I_p \leq 0.23 \) MA
- \( \tau_{shot} \leq 0.025 \) s
- \( B_T \) = 0.15 T
- \( A \) = 1.15–1.3
- \( R \) = 0.2–0.45 m
- \( a \) ≤ 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
- \( N_{inj} \leq 4 \)
- \( A_{inj} = 2-4 \) cm²
- \( I_{arc} \leq 4 \) kA
- \( V_{arc} \leq 0.5 \) kV

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LHI Startup Scenarios Grow From Helical Current Streams to Quality, High $I_p$ Plasmas

Three-Injector Array

Unstable injected current streams

Null Formation

Relaxation

Reconnect, relax to Tokamak-like state

Injector Shutoff

Subsequent OH-Driven Tokamak

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High-Field-Side (Divertor) Injection Experiments Provide Confinement Tests & Higher $I_p$

- Initial HFS injector campaign in progress
  - Development to minimize PMI as $B_{TF}$ increases
- Configuration minimizes $V_{IND}$
- 3-4x increase in HI drive: $V_{eff} \sim A_{inj} V_{inj}/R_{inj}$
- Test reconnection mechanisms at higher $I_p$, $B_{TF}$
- Injectors at longer pulse, high-$B_{TF}$

NSTX-U Projected Performance:

- Ohmic L-mode
- Fixed $T_e = 150$ eV
- R-R Stochastic
- Fixed $T_e = 75$ eV

Normalized $V_{LHI}$: $A_{inj} V_{inj}/R_{inj}$ [V-m]

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Hierarchy of Physics Models Provide a Predictive Understanding for LHI Startup

1. Taylor relaxation, helicity conservation
   - Steady-state maximum $I_p$ limits
   \[
   I_p \leq I_{TL} \sim \sqrt{\frac{I_{TF} I_{inj}}{W}}
   \]

2. 0-D power-balance $I_p(t)$
   - $V_{LHI}$ for effective LHI current drive
   \[
   I_p \left[ V_{LHI} + V_{IR} + V_{IND} \right] = 0; \quad I_p \leq I_{TL}
   \]

3. 3D Resistive MHD (NIMROD)
   - Physics of LHI current drive mechanism
Three HFS Injection Systems Implemented and Tested Since April 2016

- Two injectors at toroidally opposite positions in lower divertor region

- Design point leverages high $A_{\text{inj}}$
  - $3-4\times$ increase in $V_{\text{LHI}}$ over prior systems
  - $A_{\text{inj}} = 8 \text{ cm}^2$ total
  - $V_{\text{inj}} \leq 1.2 \text{ kV}$
  - $I_{\text{inj}} \geq 8 \text{ kA}$ total

- Systems vary $R_{\text{inj}}, Z_{\text{inj}},$ local limiter geometry
  - Latest design incorporates floating, electropolished divertor shield plates
Multi-Year Technology Development has Produced Robust, High Performance Current Injectors

- Washer-stack arc source:
  - $J_{\text{inj}} \sim 1\text{kA/cm}^2$

- High-voltage in SOL: $V_{\text{inj}} > 1\text{kV}$
  - Frustum cathode
  - Floating cathode shield

- PMI control: 1-2 cm from LCFS
  - Cascaded shield rings
  - Local limiter
  - Mo, W PFCs

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Large-$$A_{\text{inj}}$$ Injector Design Provides Enhanced Performance, Simplified Geometry

- New injectors designed for HFS system
  - Doubled $$A_{\text{inj}}$$ (2 cm$$^2$$ → 4 cm$$^2$$)
  - Compact design for lower divertor region

- Modular internal assembly
  - Permits in-vessel maintenance/repositioning
  - Exterior PFC components rapidly adjusted about common arc chamber / fueling system
    - Changes to $$A_{\text{inj}}$$, shield structures
  - Integrated hypodermic gas feed alleviates field sensitivity from previous

- Refractory materials for resilience to harsh environment
  - W for high-$$V_{\text{inj}}$$ cathode/anode
  - Mo for external shield assemblies

New: 4 cm$$^2$$ Old: 2 cm$$^2$$
Thomson Scattering Enhancements to Measure $T_e$ and $n_e$ Profiles During LHI

- **Improved timing / synchronization**
  - Higher realized laser power
  - Lowered beam scrape-off losses

- **System automation**
  - Intra-shot beam alignment
  - Data acquisition

- **Stray light mitigation**
  - Baffling, electronic gating

- **Background signal reduction**
  - Wire grid polarizers
  - High speed shutters

Thomson Viewing Locations and $A \sim 1$ Plasma

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Power Balance Model Provides Predictive Tool for $I_p(t)$

\[ I_p \left[ V_{LHI} + V_{IR} + V_{IND} \right] = 0 \]

- $V_{LHI}$: effective drive
- $V_{IR}$: resistive dissipation
- $V_{IND}$: analytic, from shape(t)
- Taylor relaxation limit: $I_p \leq I_{TL}$

\[
\begin{align*}
I_p & \left[ V_{LHI} + V_{IR} + V_{IND} \right] = 0 \\
\end{align*}
\]

- Model reasonably recreates $I_p(t)$

\[
\begin{align*}
\text{Taylor} & \quad \text{LHI Drive Limited} \\
\end{align*}
\]

\[
\begin{align*}
\langle T_e \rangle &= 60 \text{eV} \\
\end{align*}
\]

- $V_{IND}$ dominates current drive with LFS mid-plane injection

\[
\begin{align*}
\end{align*}
\]

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Eidietis et al., J. Fusion Energ. 26, 43 (2007)
Battaglia et al., Nucl. Fusion 51, 073029 (2011)
Analytic Formulation of Power Balance Model

Elements Allow Partitioning of Energy Flow

\[ I_p \left[ V_{PF} + V_{geo} - V_{Wm} - V_{IR} + V_{LHI} \right] = 0 \]

- Recent Improvements
  - Revised \( L_p, B_z \) models*
  - Moving plasma boundary
  - Neoclassical resistivity

\[ V_{PF} = -\sum_{\text{coils}} \frac{d}{dt} \left[ \psi_{PF} \right] \approx -\frac{\partial}{\partial t} \left[ M_V \pi R_0^2 B_V \right] \]

\[ B_v = -\frac{\mu_0 I_p}{4\pi R_0} \left\{ \frac{1}{\mu_0} \frac{\partial L_e}{\partial R} + \frac{\ell_i}{2} + \beta_p - \frac{1}{2} \right\} \]

\[ M_V(\varepsilon, \kappa) = \frac{(1-\varepsilon)^2}{(1-\varepsilon)^2 c(\varepsilon) + d(\varepsilon)\sqrt{\kappa}} \]

\[ c(\varepsilon) = 1 + 0.98\varepsilon^2 + 0.49\varepsilon^4 + 1.47\varepsilon^6 \]

\[ d(\varepsilon) = 0.25\varepsilon(1 + 0.84\varepsilon - 1.44\varepsilon^2) \]

\[ V_{geo} = -\frac{d}{dt} \left[ L_e I_p \right] = -L_e \frac{dI_p}{dt} - I_p \frac{dL_e}{dt} \]

\[ a(\varepsilon) = \left( 1 + 1.81\sqrt{\varepsilon} + 2.05\varepsilon \right) \ln \left( \frac{8}{\varepsilon} \right) - \left( 2.0 + 9.25\sqrt{\varepsilon} + 1.21\varepsilon \right) \]

\[ b(\varepsilon) = 0.73\sqrt{\varepsilon} \left( 1 + 2\varepsilon^4 - 6\varepsilon^5 + 3.7\varepsilon^6 \right) \]

\[ L_e = \mu_0 R_0 \frac{a(\varepsilon)(1-\varepsilon)}{1-\varepsilon + \kappa b(\varepsilon)} \]

\[ \chi = \frac{C_p^2 L_i}{\mu_0 V_p} \]

\[ V_{LHI} = \frac{A_{inj} B_{\varphi,inj}}{\Psi} V_{inj} \]

\[ V_{IR} = I_p R_p = I_p \left( \frac{\langle \eta \rangle 2\pi R_0}{A_p} \right) \]

\[ V_{Wm} \approx -\frac{1}{I_p} \frac{d}{dt} \left( \frac{1}{2} L_i I_p^2 \right) \]

S. Ejima et al 1982 Nucl. Fusion 22 1313
J.A. Romero and JET-EFDA Contributors 2010 Nucl. Fusion 50 115002

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Equilibrium-Calibrated Inductance Model Improves Estimates of Non-Solenoidal $V_{\text{IND}}$

- Maintaining radial force balance provides $V_{\text{IND}}$
  - Originally calculated via H-N formulae

- Important to quantify contributions from shape, PF drive in LHI system design

- Model equilibrium database generated to test analytic formulae in realistic magnetic geometries
  - $N = 331$; $1.15 < A < 8$; $1 < \kappa < 3$
  - $0 < \beta_p < 1$; $0.2 < \ell_i < 0.75$

- Poor partitioning of $V_{\text{IND}}$ between shape, $V_{\text{PF}}$ components found
  - However, total flux estimates in better agreement

- Revised $V_{\text{IND}}$ model developed
  - Derived new coefficients in H-N formalism via fit to equilibrium database
  - Weak dependence on $\beta_p$, $\ell_i$ introduced
0-D Power Balance Model Used to Explore Projections for NSTX-U Startup

- Helicity dissipation ($V_{IR}$) dependent on $T_e$, realized electron confinement

- Importance of $V_{LHI}$, $V_{IND}$ depends on injector geometry, plasma growth scenario
  - Final plasma depends strongly on full time evolution

- Injector geometry emphasizes different drive terms
  - LFS injection: $V_{LHI}$ early, $V_{IND}$ late
  - HFS: injection mainly $V_{LHI}$

- Need to explore plasma evolution with different dominant drive terms
  - Informs predictive model
  - Future: High $I_p$ tests in both geometries

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NIMROD Describes Helical Current Stream Reconnection as Drive Mechanism

- Divertor injection → minimal inductive drive

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

Divertor LHI Startup Shows suggestive commonality between experiment and NIMROD modeling

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- Magnetics localize coherent streams in edge
  - Infers NIMROD streams in edge

- Reconnection-drive edge ion heating

- Any stochastic reconnection region may be localized to edge
Reconnection-Driven Ion Heating Gives $T_i > T_e$ During LHI

- Impurity $T_i(0) \sim 100 - 500 \text{ eV} > T_e$ routinely observed during LHI

- Continuous ion heating from reconnection between collinear current streams
  - No effect on current drive efficiency
  - Significant ion heating (~ few 0.1 MW)

Ion heating correlated with high frequency MHD fluctuations, not with discrete reconnection between helical streams

Ion heating consistent with 2-fluid reconnection theory

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Different MHD Activity Observed Between LFS and HFS Injection Geometry

- **LFS (outboard) injection:**
  - MHD initially continuous, large amplitude, $n = 1$
  - Transitions to intermittent bursts later in the discharge
  - Burst spacing increase with $I_p$
  - Similar to NIMROD simulation

- **HFS (inboard) injection:**
  - Continuous, large-amplitude $n = 1$ activity early on
  - Abrupt cut-off in large amplitude activity
  - Reduced $n = 1$ magnitude for remainder of discharge

- **Differences suggest multiple current drive mechanisms present**

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LFS Local Helicity Injection Produces Core $T_e > 100$ eV

- Plasma shape grows inward from LFS injectors
  - Shape evolution generates $V_{\text{IND}}$
  - $V_{\text{IND}} > V_{\text{LHI}}$ during high-$I_p$ phase

- Peaked $T_e(R)$ during drive phase (connected)
  - Not strongly stochastic
  - After disconnect radial compression drives skin current

- Core $n_e > 10^{19}$ m$^{-3}$, $T_e \geq 100$ eV provides target for subsequent CD

\[ \text{M.W. Bongard, APS-DPP 2016} \]
• Plasmas with same LFS LHI system and static geometry evolution
  - Lower performance due to shape constraint
    • High $R_0$, reduced $A_{\text{plasma}}$
  - $V_{\text{IND}} \sim 0 < V_{\text{LHI}}$; $T_e(0) \sim 80$ eV

• $T_e(R)$ peaked while driven by outboard LHI

Contrast-enhanced high-speed image and fast boundary reconstructions
Technical Challenges Arise for LHI Startup With HFS Injection Geometry

- **Initial relaxation to tokamak state**
  - More difficult for low $R_{\text{inj}}$, high $B_{\text{inj}}$
  - Magnetic geometry constrained by injector clearance requirements

- **Current source behavior at increased $B_{\text{inj}}$**

- **Plasma-material interactions**
  - PMI on injector surfaces
    - inhibits $V_{\text{inj}}$
    - can damage injectors
  - PMI on machine surfaces
    - Impedes reproducibility
    - More severe for HFS injection

Above: LHI plasma before and after relaxation

Below: example of PMI on injector (left), eventually leading to insulator failure (right)

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• Milestone for HFS LHI system achieved

• Technical challenge with HFS injectors:
  – Lower $R_{\text{inj}} \rightarrow$ higher $B_{\text{TF}}$ with respect to LFS system
    • $\rightarrow$ more $B_z$ for injector clearance ($\sim B_z/B_{\text{TF}}$)
  – $B_{\text{TF}}$ increased $\sim 10 \times$ over previous experiments
    • $\rightarrow$ Relaxation at constant $I_{\text{inj}}$ more difficult

• Poloidal field shaping key to full-field relaxation
  – Reduces midplane $|B|$ and maintains injector clearance
  – Limited by $I_{\text{inj}}$-deformed streams contacting vessel

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$I_p > 0.15 \text{ MA Achieved Via HFS Injection To Date}$

- $V_{LHI} \sim 1\text{ kV}$ increased 2× over previous HFS LHI experiments

- Most operations at low field:
  - $B_{\text{inj}} = 0.046-0.092\text{ T}$
    - (20-40% of Pegasus maximum)
  - Reduced PMI, easier relaxation

- Full $B_{\text{TF}}$ scenarios developed
  - $B_{\text{inj}} = 0.23\text{ T, } I_{\text{TF}} = 0.288\text{ MA}$
  - $I_p \approx 0.1\text{ MA}$
  - PMI more prevalent at high $B_{\text{TF}}$

- Injector geometry variants addressing observed PMI
  - Improvements found in each iteration
HFS Helicity Injection Provides Non-Solenoidal Sustainment at High $I_N$

- Constant geometry: minimal $V_{IND}$
- Low $I_{TF} \sim 0.6 I_p$
- $I_N > 10$ accessible
  - Constant or ramped-down $B_{TF}$
- Potential for high $\beta_T$
  - Aided by anomalous ion heating

![Graphs showing Ne, Te, T_{i_ov}, I_p, I_N, n_e vs. Time][1]

Access to $I_N > 14$, $n_e \sim 1 \times 10^{19} \text{ m}^{-3}$ with HFS Injection, $B_{TF}$ Rampdown

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LHI Provides Access to High-$\beta_T$ at $A \sim 1$ with Non-Solenoidal Sustainment and Anomalous Ion Heating

- Equilibrium reconstructions with kinetic constraints used to determine $\beta_T \equiv 2\mu_0 \langle p \rangle / B_T^2$
  - Matches external magnetics, $p_{tot}(0)$, and edge in $T_e(R)$
  - Includes anomalous $T_i(0)$
  - Some caveats for these initial results
    - Assumes closed flux surfaces inboard of injectors
    - Role of SOL edge current
    - Magnetics-only reconstructions scaled via comparison to those with kinetic constraints
    - Need full kinetic profiles in future

- High $\beta_T$ plasmas often terminated by disruption
  - $n = 1$, low-m precursors

- Expands accessible high $I_N$, $\beta_T$ space for tokamak stability studies at extreme toroidicity
  - Campaign underway to document, extend to higher $I_p$
  - Improving LHI injector hardware to increase $I_p$, $B_T$ access

*Initial Exploration of High-$\beta_T$ Space*

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Progress in Non-Solenoidal Startup on Pegasus

- **LHI provides high $I_p$, non-solenoidal tokamak startup**
  - Flexible injection geometry balances $V_{LHI}$ and $V_{IND}$ drive, engineering constraints
  - Improved power balance model suggests technique is scalable to larger devices
  - Questions remain on confinement and reconnection dynamics
    - Thomson scattering: Peaked $T_e$, $n_e$ suggest favorable realized confinement

- **New high-field-side injector systems exploring strong $V_{LHI}$ limit**
  - Injector operation and relaxation to tokamak demonstrated at full TF ($B_{inj} \sim 0.25$ T)
  - Completely $V_{LHI}$ driven startup and sustainment realized
  - Non-solenoidal $I_p(t)$ via LHI enables access to stability tests at extreme toroidicity
    - Sustained operation at high $I_N$, high $\beta_T$

- **Present campaign:**
  - Optimize HFS injector implementation to mitigate PMI at high $B_{TF}$
  - Develop high $I_p$ scenarios to test scalings in LFS, HFS geometries
  - Design CHI system for comparison studies (with PPPL, U. Wash)
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