Non-solenoidal Startup via Local Helicity Injection on PEGASUS: Progress and Plans

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57th Annual APS-DPP Meeting
Savannah, GA
Nov. 16th-20th, 2015
Significant Advances in Understanding of Local Helicity Injection (LHI) Startup Achieved

- LHI is a promising non-solenoidal startup technique

- Previous work identified global $I_p$ limits, drove multi-year technology development effort to optimize injectors

- 0-D power-balance model developed to interpret, predict dynamic LHI $I_p(t)$

- Full 3D resistive MHD simulations describe LHI drive mechanism
  - Key features of this model have now been identified in experiment

- Understanding transport, confinement scaling is key for extrapolation to NSTX-U and beyond

Work supported by US DOE Grants DE-FG02-96ER54375 and DE-SC0006928
LHI is a Scalable Non-solenoidal Startup Technique

- Significant $I_p$ (~180kA) attained with low injected current (~5kA)
- Compact, modular, and appears scalable to MA-class startup

Current injected from local plasma source

Injected Current Stream

Local Helicity Injectors

2 m

Plasma Parameters

- $I_p \leq 0.18$ MA
- $\tau_{\text{shot}} \leq 0.025$ 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

- $I_{\text{inj}} \leq 6.5$ kA
- $V_{\text{inj}} \leq 2.5$ kV

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Local Plasma Sources Inject Edge Current Streams that Relax, Form Tokamak-Like Plasma

- Local source: helical current stream
- MHD relaxation: tokamak-like state
- Result: Tokamak

J.A. Reusch, APS DPP 2015
Physics of LHI Encapsulated in a Hierarchy of Models

1. Maximum $I_p$ limits*

   $I_p \leq I_{TL} \sim \sqrt{\frac{I_{TF}I_{inj}}{W}}$

2. 0-D power-balance $I_p(t)$

   $I_p [V_{LHI} - V_{IR} + V_{IND}] = 0; \quad I_p \leq I_{TL}$

3. 3D Resistive MHD (NIMROD)**

   $V_{LHI} \approx \frac{A_{inj}B_{\psi,inj}}{\Psi} V_{inj}$

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Multi-year Technology Development has Produced Robust, High Performance Injectors

- **Injector requirements are formidable:**
  - $I_{\text{inj}} > 2kA$, $V_{\text{inj}} > 1kV$
  - High $J_{\text{inj}}$ ($\sim 1kA/cm^2$)
  - 1-2 cm from LCFS
  - No deleterious PMI

- **Robust high $V_{\text{inj}}$ achieved**
  - Cathode shaping and shielding mitigate cathode spots
  - Shield rings and local limiter (not shown) prevent arc-back
  - $\sim 3x$ increase in helicity input
  - See E.T. Hinson GP12.00117

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**Injector Voltage**

- $V_{\text{INJ}}$ [V]
- Time [ms]

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• Injector impedance model developed and tested in the last year*
  - Quasi-neutrality \(I_{\text{inj}} \sim n_{\text{edge}} V_{\text{inj}}^{0.5}\), expanding double layer \(I_{\text{inj}} \sim n_{\text{arc}} V_{\text{inj}}^{0.5}\)

![Graph showing the relationship between \(\frac{I_{\text{inj}}}{\sqrt{V_{\text{inj}}}}\) and \(n_{\text{edge}}\).]

**Impedance Model:**

\[
I_{\text{inj}} = \text{Min}[n_{\text{edge}}, \beta n_{\text{arc}}] e^{\sqrt{\frac{2eV_{\text{inj}}}{m_e}} A_{\text{inj}}}
\]

• Strong influence on injector design and operation \((V_{\text{LHI}} \sim V_{\text{inj}})\)
  - Sets power supply requirements; gives control actuator for \(V_{\text{LHI}}(t) \rightarrow I_p(t)\)
  - See E.T. Hinson GP12.00117

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0-D Power Balance Model Tracks the Dynamic LHI $I_p(t)$ Evolution*

- **Model elements:**
  - Inputs: $\langle \eta(t) \rangle$, $R_0(t)$, shape$(t)$, $V_{\text{inj}}(t)$, $\zeta_i(t)$
  - Confinement model under development for $\langle \eta(t) \rangle$

- **Model provides source and sink voltages**
  - Significant V-s from Shape$(t)$

- See J.L. Barr GP12.00116

\[
I_p \left[ V_{LHI} + V_{IR} + V_{IND} \right] = 0; \quad I_p \leq I_{TL}
\]
Surprisingly Strong Drive from Shape Evolution Dominates LHI $I_p(t)$

- Geometry change provides ~70% of total drive, dominates throughout

J.A. Reusch, APS DPP 2015
Fast Boundary Reconstruction Code Provides Shape(t) Analysis, Control

- Plasma treated as 4-6 filaments
  - Fit to external magnetics

- Validated against equilibrium reconstructions
  - Size: $R_0 \pm 1.5$ cm, $a \pm 1.5$ cm
  - Shape: $\kappa \pm 15\%$, $\delta \pm 25\%$

- Between-shot Shape(t) analysis
  - Allows shape control

- See J.L. Barr GP12.00116
NIMROD Describes Edge Reconnection Current Drive Mechanism*

1. Streams follow field lines
2. Adjacent passes attract, reconnect, pinch off current ring
3. $I_p$ builds; current filaments persist in NIMROD, not seen in PEGASUS

Anomalous Ion Heating Confirms Existence of Strong Reconnection Activity

- $T_i$ scales with expectations from reconnection experiments:
  - $T_i \sim B^2/\langle n_e \rangle \sim I_{inj} V_{inj}^{0.5}$

- Anomalous heating ($T_i > T_e$) persists through LHI phase

- See M.G. Burke GP12.00122

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MHD Analysis Shows Existence of Unstable Current Streams in Edge

- MHD bursts accompany $I_p$ growth
  - $n=1$ line tied kink structure
  - Localized in edge

- Correlation analysis of bursts consistent with interacting streams*
  - Coherent streams persist at high $I_p$, consistent with NIMROD
  - Reconnection event at peak of MHD burst

- Confinement degradation from stochasticity may be localized to edge

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  E.T. Hinson GP12.00117
Edge Localized Reconnection, Strong $V_{\text{IND}}$ Support Good Core Confinement in PEGASUS

Electron Temperature

Relative Electron Pressure

- **Peaked** $T_e$ and $P_e$ indicate good core confinement
  - Does not appear highly stochastic across profile
  - $T_e(0)$ comparable to Ohmic L-mode at 80kA

- **May indicate two zone confinement**
  - Drive: $V_{\text{IND}}$ (across plasma), $V_{\text{LHI}}$ (edge)

See: D.J. Schlossberg GP12.00118
G.M. Bodner GP12.00119
Two Zone Confinement in LHI May Scale Favorably to NSTX-U and Beyond

- $I_p$ increases significantly with $T_e$
  - Confinement critical for projections to larger devices

- Larger machine $\Rightarrow$ larger good confinement zone?
  - $w_{\text{stoch}}$ likely scales with $w_{\text{stream}}$
  - Larger high $T_e$ volume $\Rightarrow$ lower injector requirements

- Implications of R-R vs. Ohmic scaling under investigation*

\[ \chi_{\text{collisional}} = v_{\|}^2 \tau_c \left( \frac{\delta B_r}{B_{\text{tor}}} \right)^2 \sim \frac{T_e^{5/2}}{n_e} (S^{-\alpha})^2 \]

\[ P_{\text{in}} = I_p V_{LHI} \quad \frac{W}{P_{\text{in}}} \sim \tau_E \sim \frac{a^2}{\chi_{\text{collisional}}} \]

\[ I_p \sim \left( V_{LHI} \right)^{\frac{10}{3} - 2\alpha} \left( B_0 \right)^{\frac{2\alpha}{4/3 - 2\alpha}} \Rightarrow I_p \sim \left( V_{LHI} \right)^{\frac{5}{2}} \]

* A.B. Rechester and M.N. Rosenbluth, PRL 40 (1) 1978
C.R. Sovinec and S.C. Prager, Phys. Plasmas 3 (3) 1996
Gaps in Understanding Must be Addressed for Extrapolation to NSTX-U and Beyond

- Critical issue: unraveling effect of strong inductive drive
- Other important issues include: $B_{TF}$, $I_p$ scalings; Long pulse performance

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Divertor Injection Addresses Critical Confinement Scaling Issue for Extrapolation to NSTX-U

- Varied injector geometry separates inductive and helicity drive effects
- 3-4x increase in $V_{LHI}$
- Minimal $V_{IND}$: ~ fixed geometry
  - Confinement measurements in transport equilibrium
- Lower $R \Rightarrow$ increased $B_{TF}$ test
- Allows higher $I_p$ startup

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See J.M. Perry PO6.00001
Critical Issues for LHI Predictive Understanding Addressed by Pegasus-Upgrade

- Increased $B_{TF}$, $t_{pulse}$ extends scalings to NSTX-U relevant levels
  - Injector $B_{TF} \sim 0.8T$: reconnection current drive; poloidal null formation; injector physics
  - Pulse length $\sim 100$ ms: variable inductive drive; injector integrity
  - Diagnostics: CHERS via DNB; multi-point probe arrays, SXR camera
  - See R.J. Fonck GP12.00114

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• Improved injectors: robust operation at > 1kV
  – Injector impedance model gives actuator for $V_{LHI}$, PS design point

• 0-D power balance model provides prediction of $I_p(t)$
  – Input power primarily from $V_{IND}$ in present tests
  – Confinement scaling is critical unknown

• NIMROD provides detailed physics picture
  – New results support stream reconnection based current drive mechanism

• Surprisingly good core confinement indicated by TS
  – Peaked core $T_e \sim 120$ eV comparable to Ohmic L-mode
  – Coupled with NIMROD picture, may indicate 2-zone confinement

• Divertor injectors and Pegasus-U to address critical scaling issues

J.A. Reusch, APS DPP 2015
For more PEGASUS presentations see:

Posters (this session)

- GP12.00114: Fonck, *The Pegasus-Upgrade Experiment*
- GP12.00116: Barr, *Power Balance Modeling and Validation for ST Startup Using Local Helicity Injection*
- GP12.00117: Hinson, *Physics of Plasma Cathode Current Injection During LHI*
- GP12.00118: Schlossberg, *New Electron Temperature Measurements During Local Helicity Injection and H-mode Plasmas at the Pegasus Toroidal Experiment*
- GP12.00119: Bodner, *Spatial Expansion and Automation of the Pegasus Thomson Scattering Diagnostic System*
- GP12.00121: Bakken, *Progress Toward a New Technique for Measuring Local Electric Field Fluctuations in High Temperature Plasmas*
- GP12.00122: Burke, *Ion Heating During Local Helicity Injection Plasma Startup in the Pegasus ST*

Talks (Wednesday, Nov. 18th, 2:00 PM–5:00 PM, Room: 201/202)

- PO6.00001: Perry, *Expanding Non-solenoidal Startup with Local Helicity Injection to Increased Toroidal Field and Helicity Injection Rate*
- PO6.00006: Bongard, *H-mode and Edge Physics on the Pegasus ST: Progress and Future Directions*

For reprints go to https://pegasus.ep.wisc.edu/Technical_Reports/TechReports.htm