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

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J.L. Barr, G.M. Bodner, M.W. Bongard, M.G. Burke, R.J. Fonck, E.T. Hinson, B.T. Lewicki, J.M. Perry, D.J. Schlossberg

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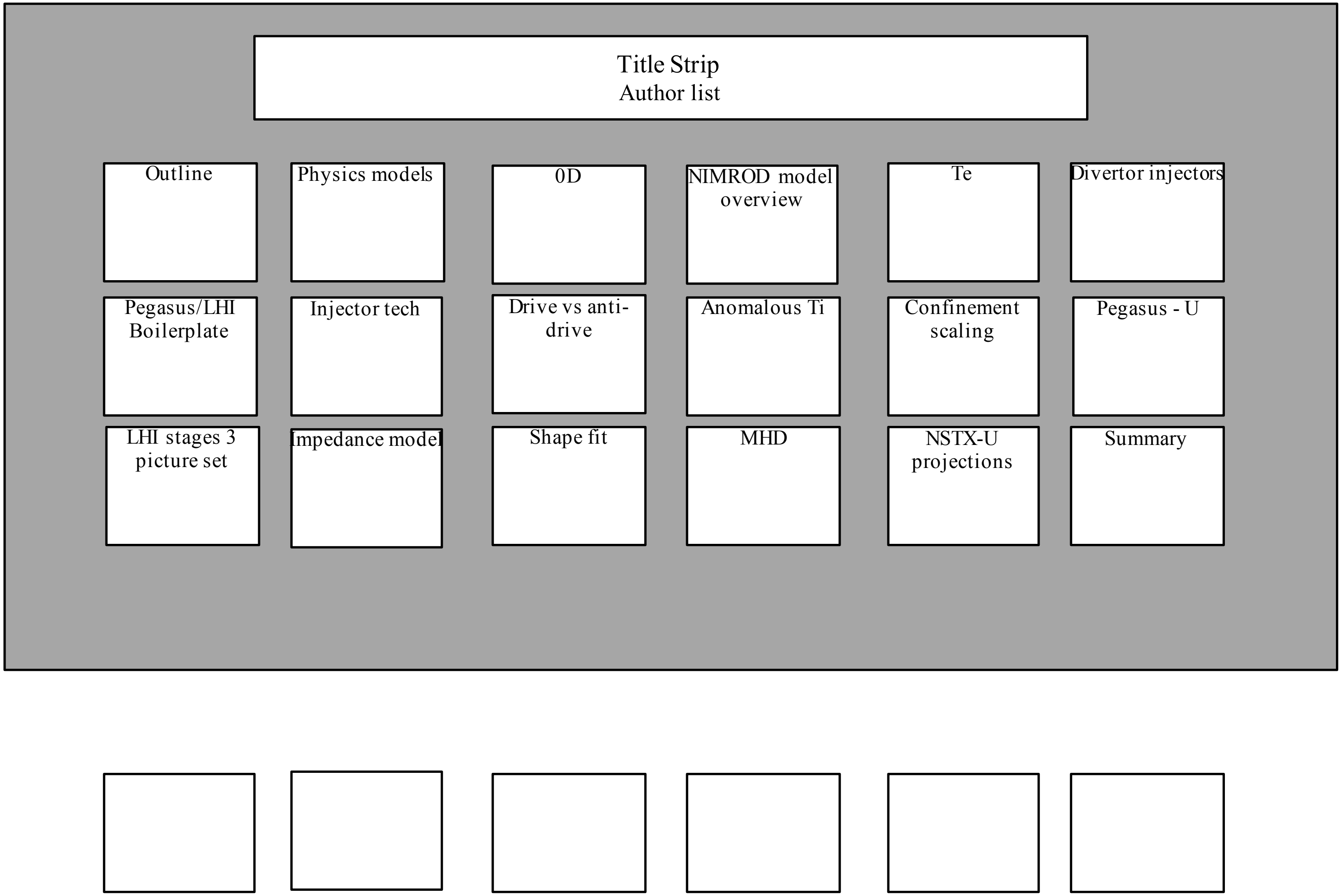
University of Wisconsin-Madison

PEGASUS Toroidal Experiment

Layout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Pegasus/LHI Boilerplate
Injector tech
Drive vs anti-drive
Anomalous Ti
Confinement scaling
Pegasus - U
LHI stages 3 picture set
Impedance model
Shape fit
MHD
NSTX-U projections
Summary

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

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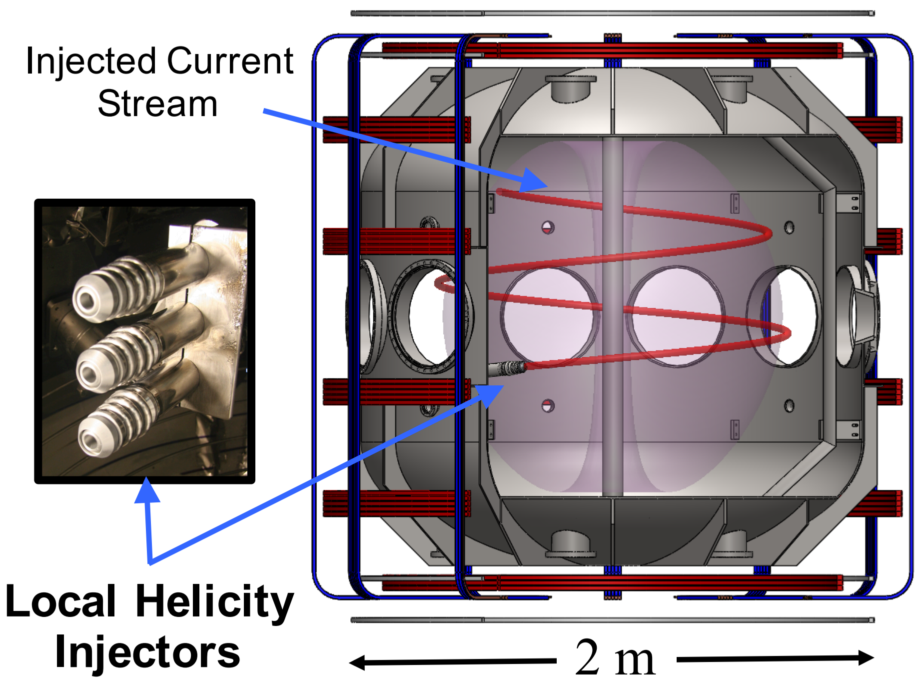
LHI is a Scalable Non-solenoidal Startup Technique

Current injected from local plasma source



Plasma Parameters

I_p	$\leq$ 0.18 MA
τ_{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
κ	1.4 – 3.7

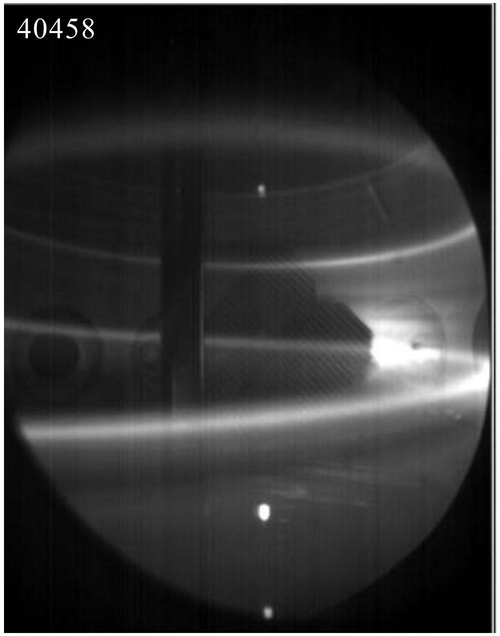
Injector Parameters

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

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

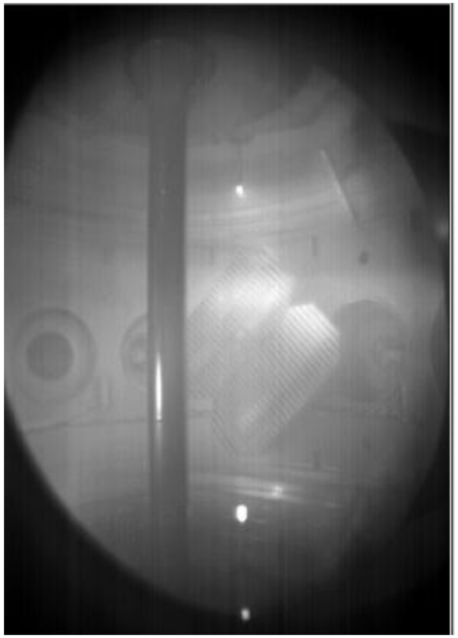
Local Plasma Sources Inject Edge Current Streams that Relax, Form Tokamak-Like Plasma

Initial Injection



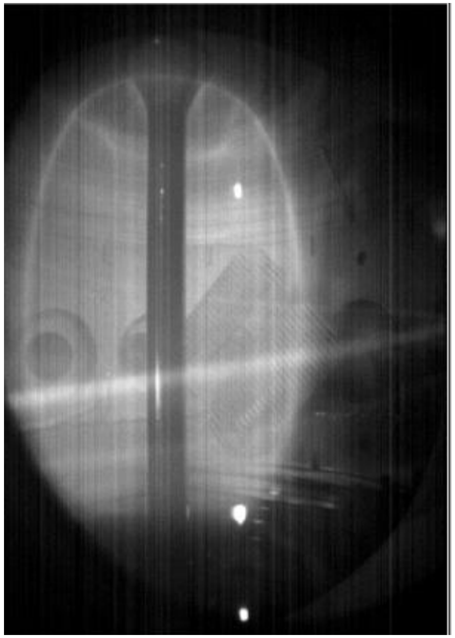
Relaxation

LHI Drive



Injector Shutoff

Post Drive



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

Physics of LHI Encapsulated in a Hierarchy of Models

1. Maximum I_p limits*

Taylor Relaxation

$$I_p \lesssim I_{TL} \sim \sqrt{\frac{I_{TF} I_{inj}}{w}}$$

Helicity Conservation

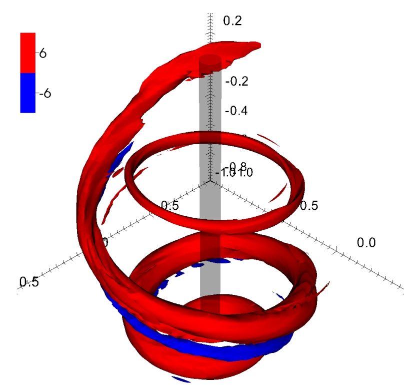
$$V_{LHI} \approx \frac{A_{inj} B_{\varphi,inj}}{\Psi} V_{inj}$$

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

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

3. 3D Resistive MHD (NIMROD)**

Reconnecting LHI Current Stream



*D.J. Battaglia, et al. Nucl. Fusion **51** (2011) 073029.
*N.W. Eidietis, Ph.D. Thesis, UW-Madison, 2007.
**J. O'Bryan, Ph.D. Thesis, UW-Madison, 2014.
J. O'Bryan, C.R. Sovinec, Plasma Phys. Control. Fusion **56 064005 (2014)

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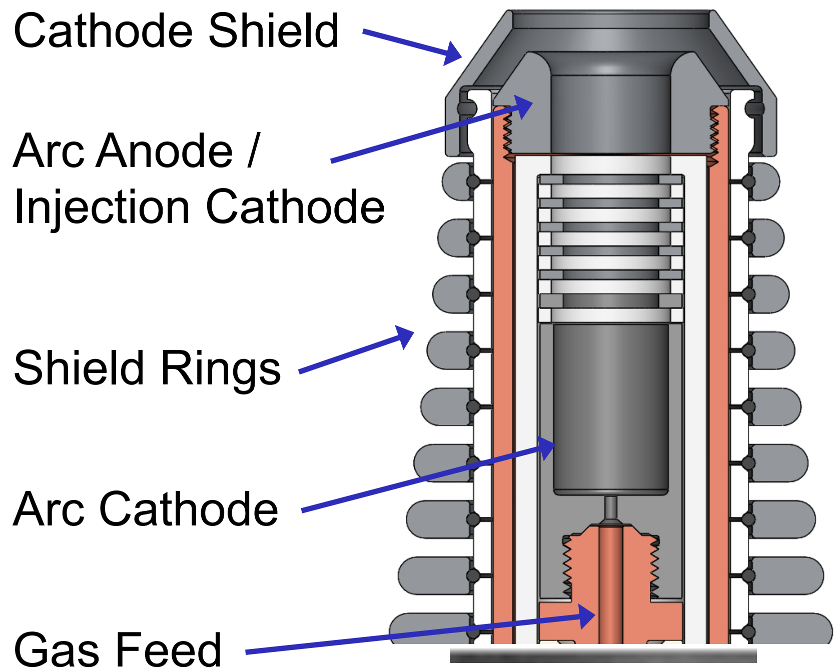
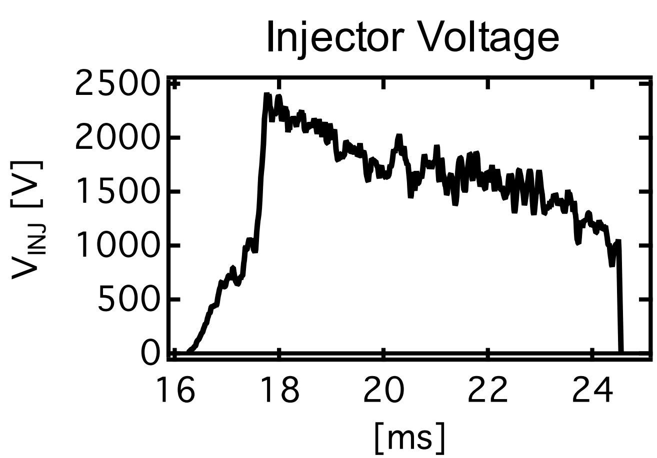
Multi-year Technology Development has Produced Robust, High Performance Injectors

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

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

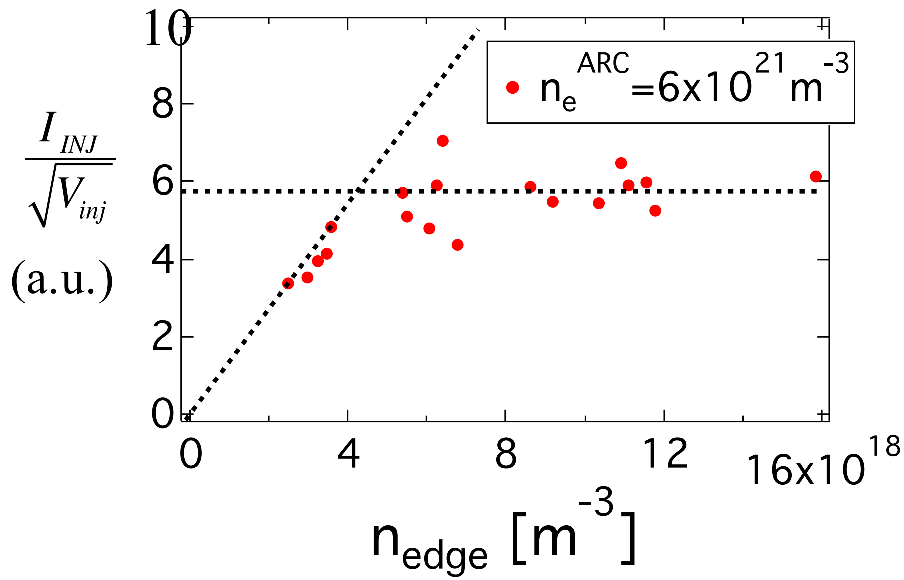




J.A. Reusch, APS DPP 2015

Optimization, Control of LHI Drive Enabled by Injector Impedance Model

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



Impedance Model:

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

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

* *E.T. Hinson, Ph.D. Thesis, UW-Madison, 2015.*

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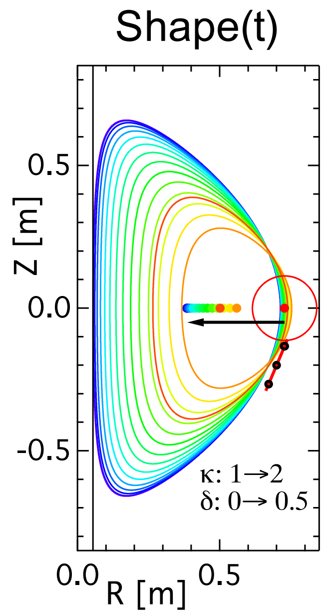
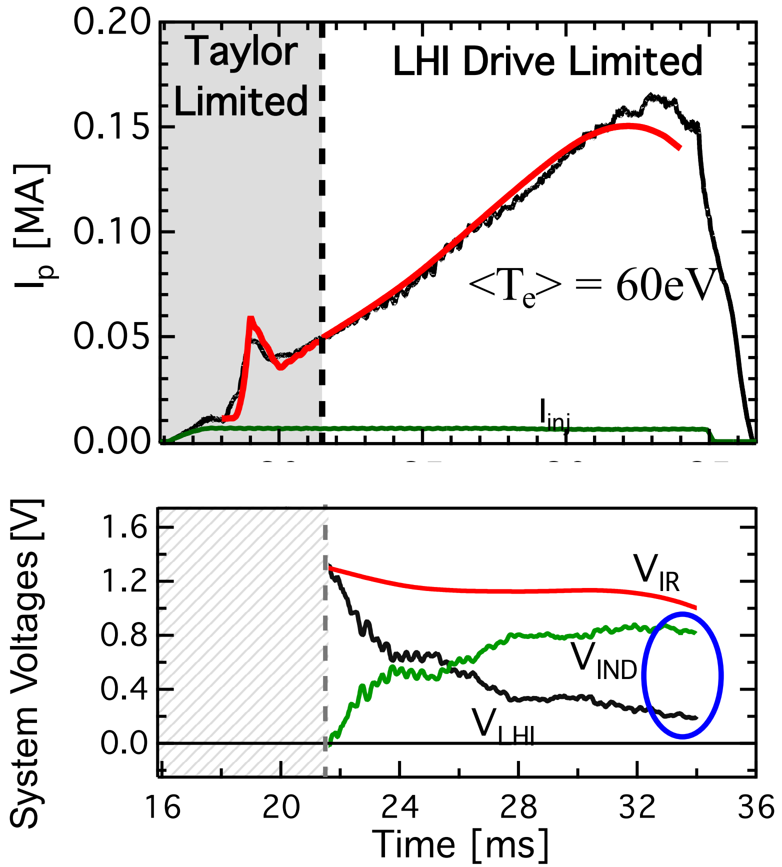
0-D Power Balance Model Tracks the Dynamic LHI $I_p(t)$ Evolution*

- Model elements:
  - Inputs: <η(t)>, $R_0(t)$, shape(t), $V_{inj}(t)$, $\ell_i(t)$
  - Confinement model under development for <η(t)>

$$I_p\left[V_{LHI}+V_{IR}+V_{IND}\right]=0;\ \ I_p \le I_{TL}$$

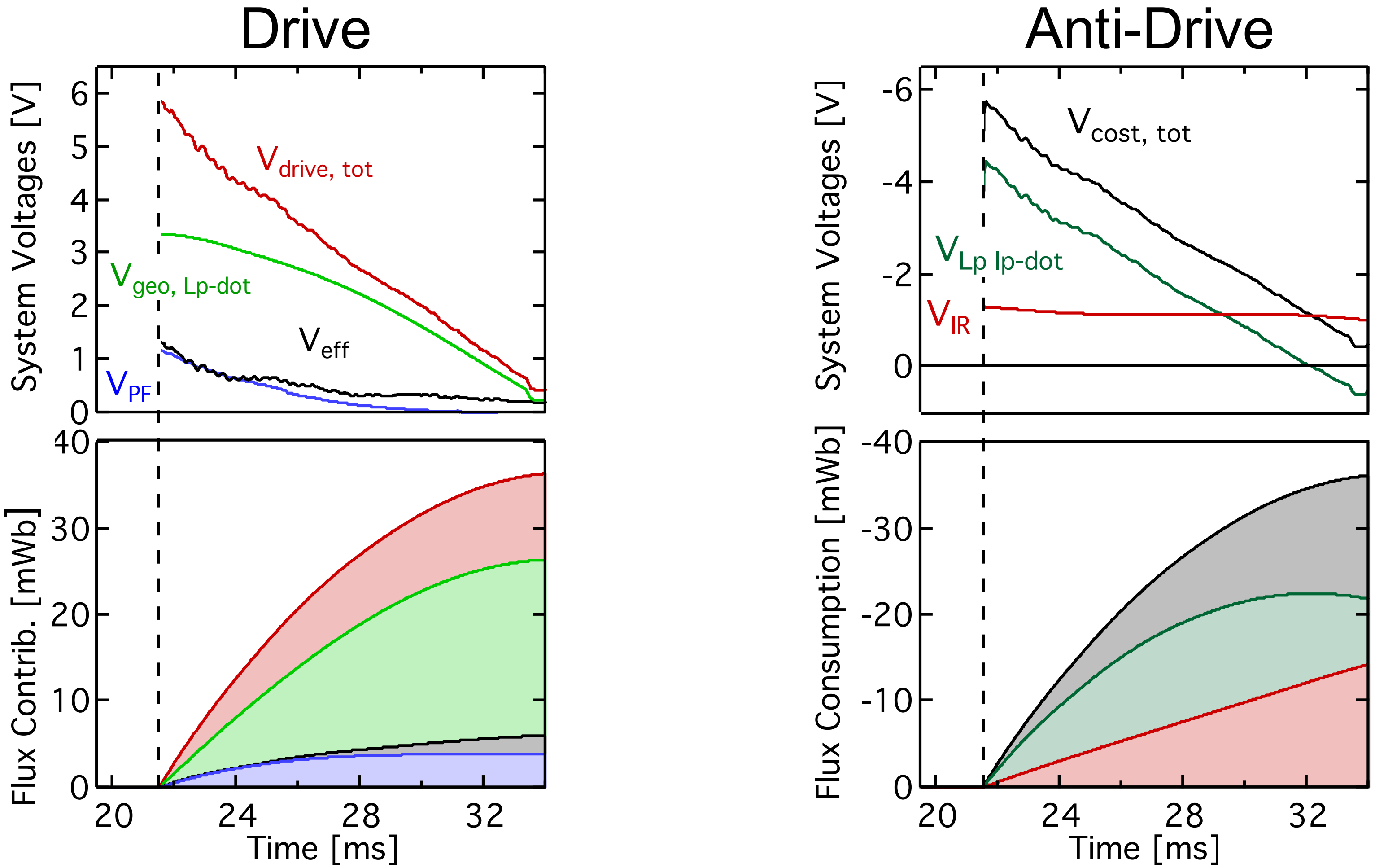




- Model provides source and sink voltages
  - Significant V-s from Shape(t)

- See J.L. Barr GP12.00116

Surprisingly Strong Drive from Shape Evolution Dominates LHI $I_p(t)$



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

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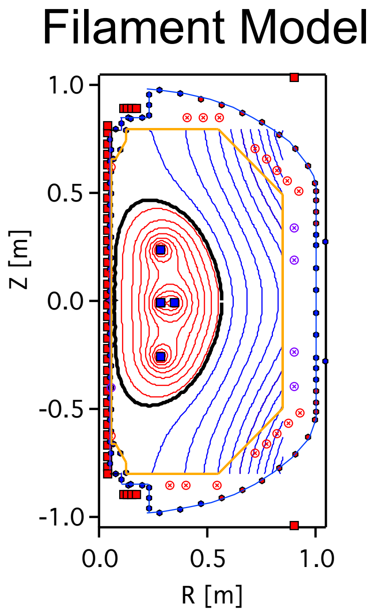
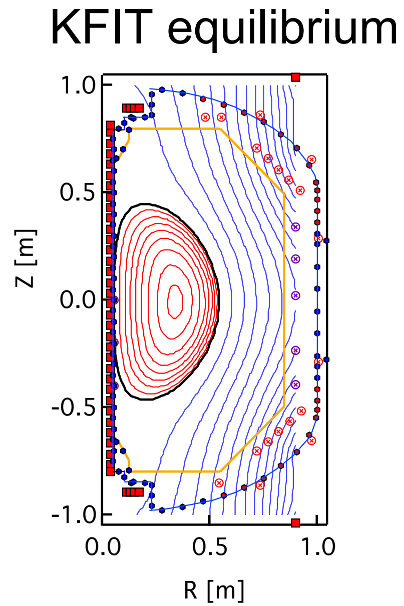
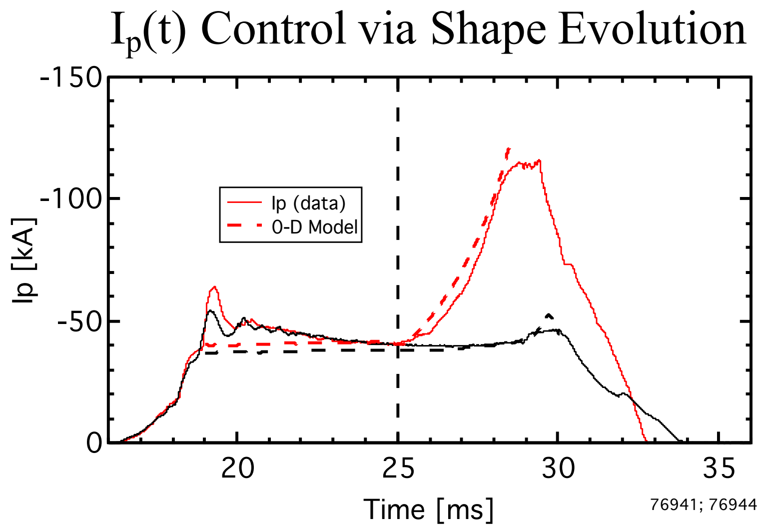
Fast Boundary Reconstruction Code Provides Shape(t) Analysis, Control

- 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







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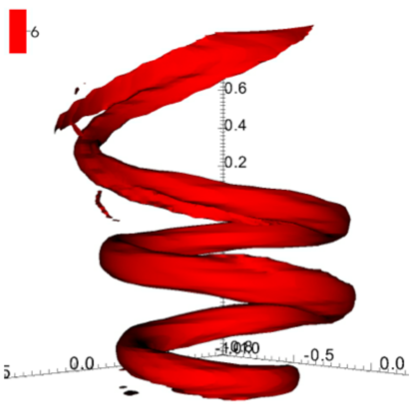
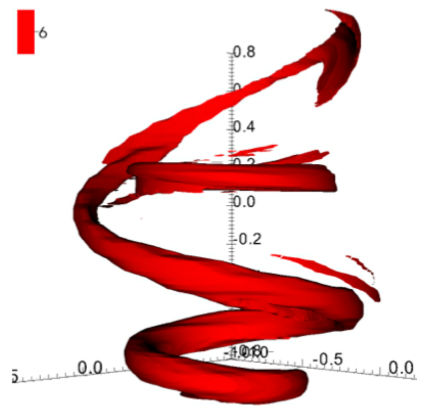
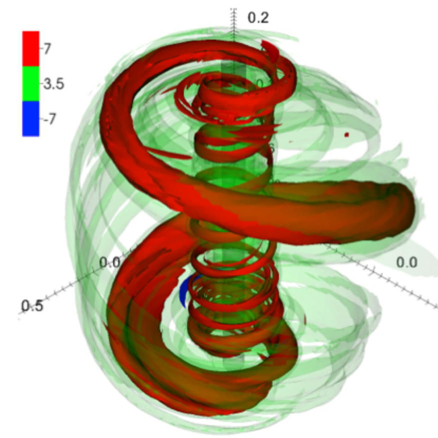
NIMROD Describes Edge Reconnection Current Drive Mechanism*



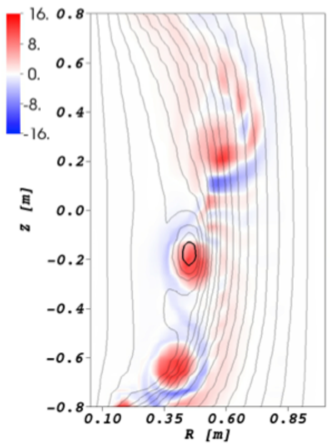


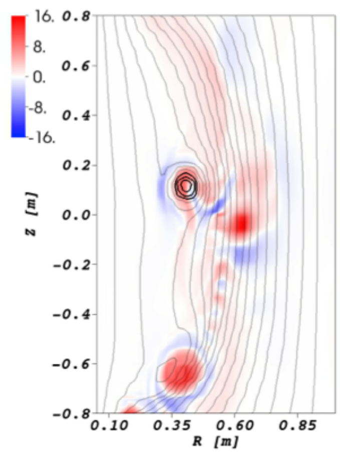


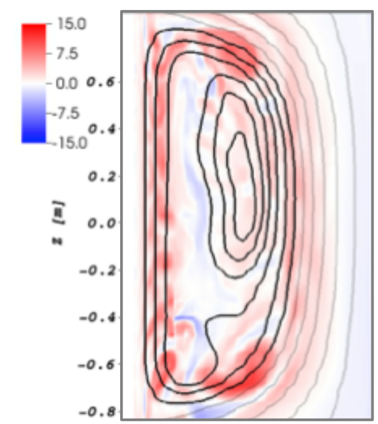
1. Streams follow field lines

2. Adjacent passes attract, reconnect, pinch off current ring

3. I_p builds; current filaments persist in NIMROD, not seen in PEGASUS



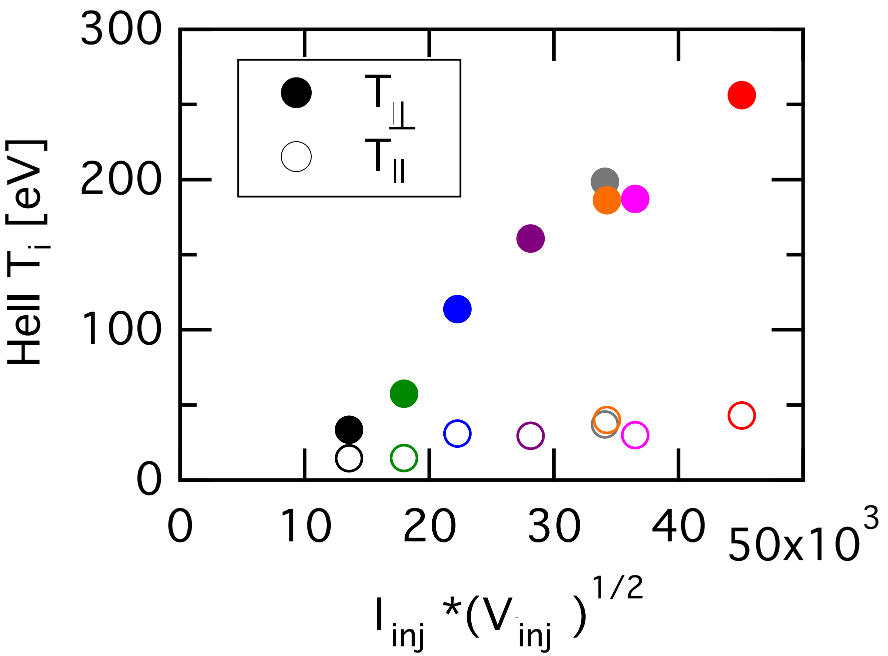


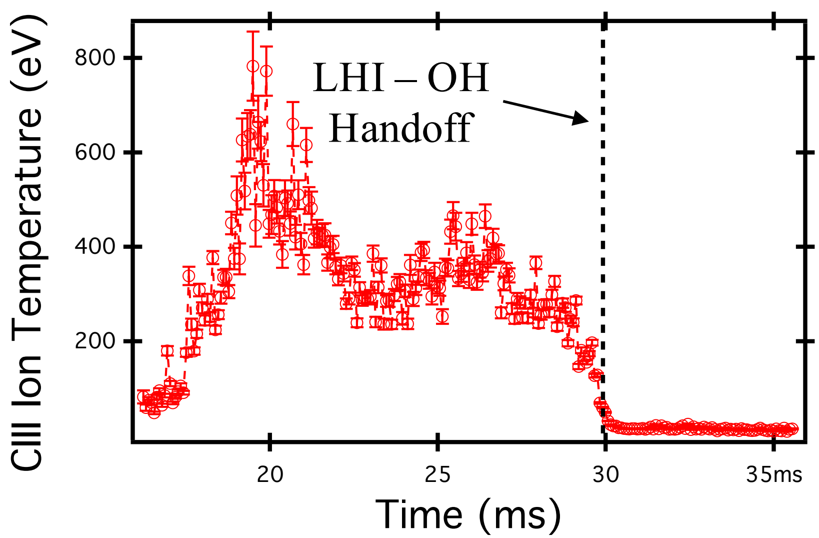


* *J. O'Bryan, et al., Physics of Plasmas,* ***19****, 080701 (2012)*
J. O'Bryan, C.R. Sovinec, Plasma Phys. Control. Fusion ***56*** *064005 (2014)*

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

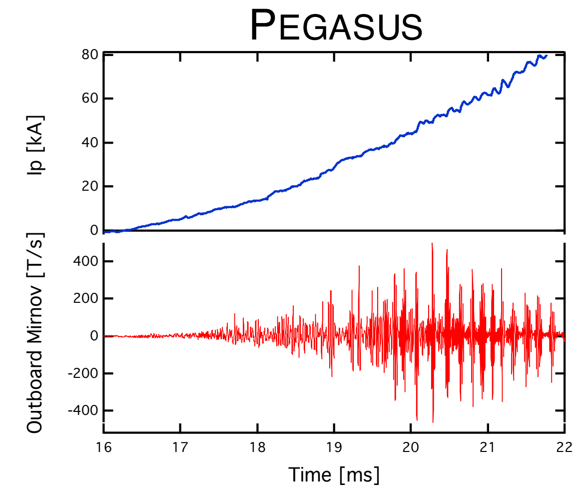
* *J. Yoo, et al., Phys. Rev. Lett., vol. 110, no. 21, p. 215007, May 2013*
Y. Ono, et al., Plasma Phys. Control. Fusion, vol. 54, no. 12, p. 124039, Dec. 2012.

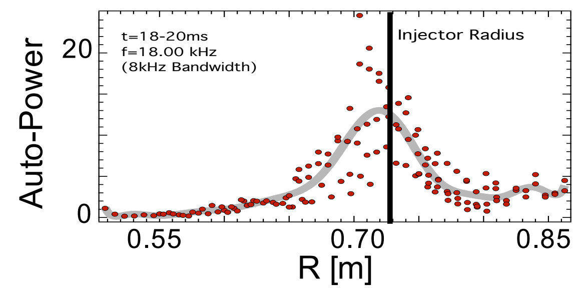
MHD Analysis Shows Existence of Unstable Current Streams in Edge

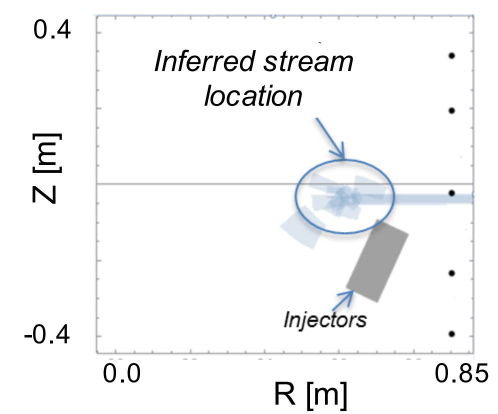
- MHD bursts accompany I_p growth
  - n=1 line tied kink structure
  - Localized in edge

- 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

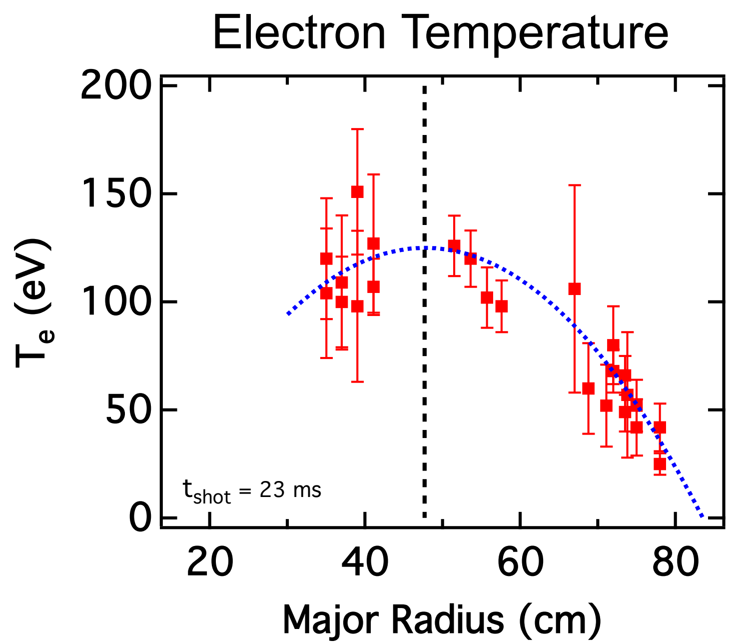


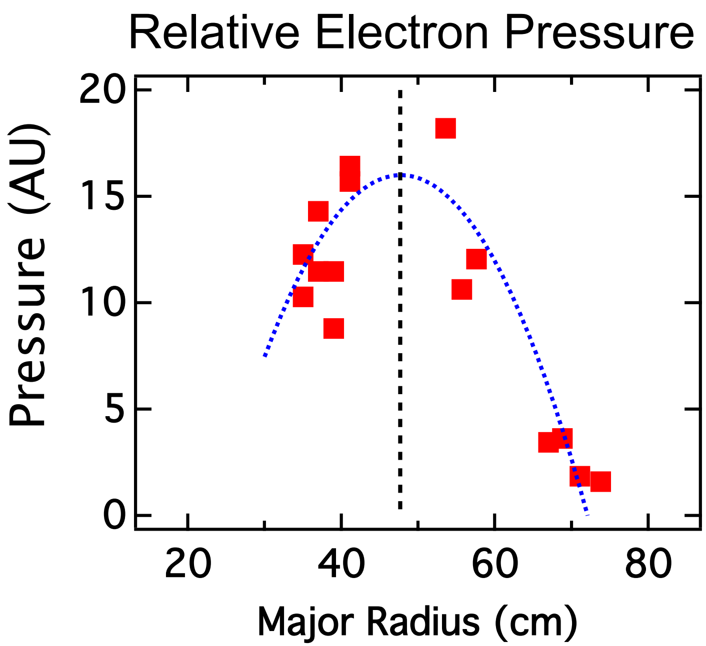




* *E.T. Hinson, Ph.D. Thesis, UW-Madison, 2015.*
E.T. Hinson GP12.00117

Edge Localized Reconnection, Strong V_{IND} Support Good Core Confinement in PEGASUS



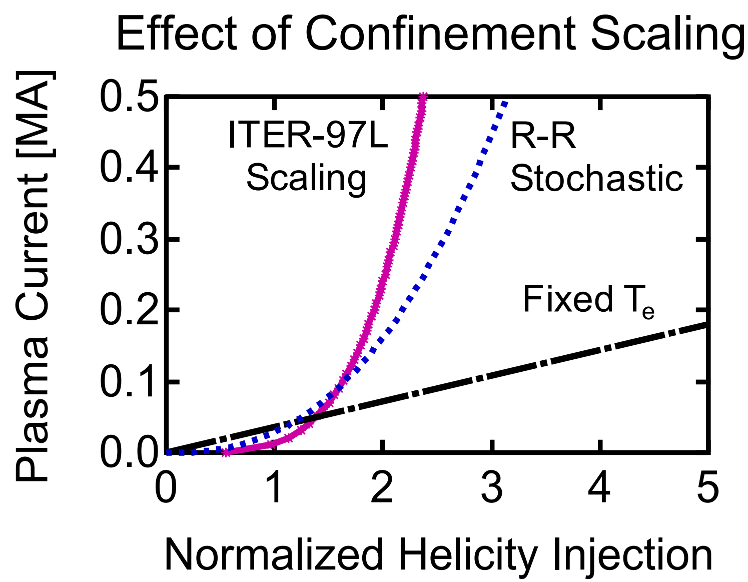


- Peaked T_e and P_e indicate good core confinement
  - Does not appear highly stochastic across profile
  - $T_e(0)$ comparable to Ohmic L-mode at 80kA
- May indicate two zone confinement
  - Drive: V_{IND} (across plasma), V_{LHI} (edge)

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 ⟹ larger good confinement zone?
  - w_{stoch} likely scales with w_{stream}
  - Larger high T_e volume ⟹ lower injector requirements
- Implications of R-R vs. Ohmic scaling under investigation*



R-R Stochastic I_p Scaling Relation

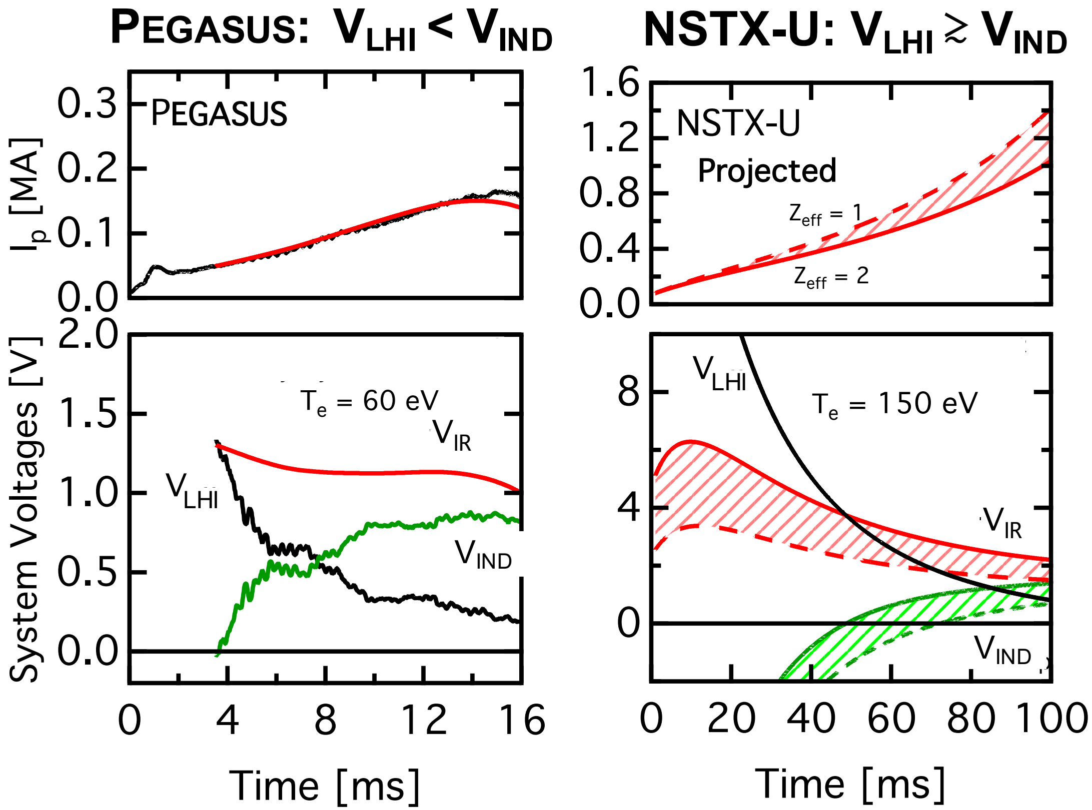
$$\chi_{collisional} = \nu_{\parallel}{}^2\tau_c\left(\frac{\delta B_r}{B_{tor}}\right)^2 \sim \frac{T_e{}^{5/2}}{n_e}(S^{-\alpha})^2$$

$$P_{in} = I_p V_{LHI} \qquad \frac{W}{P_{in}} \sim \tau_E \sim \frac{a^2}{\chi_{collisional}}$$

$$I_p \sim (V_{LHI})^{\frac{10/3-2\alpha}{4/3-2\alpha}}(B_0)^{\frac{2\alpha}{4/3-2\alpha}} \Longrightarrow I_p \sim (V_{LHI})^{\frac{5}{2}}$$

* *A.B. Rechester and M.N. Rosenbluth, PRL* ***40*** *(1) 1978*
C.R. Sovinec and S.C. Prager, Phys. Plasmas ***3*** *(3) 1996*
Stoneking, et al., Phys. Plasmas ***5*** *(4) 1998*

Gaps in Understanding Must be Addressed for Extrapolation to NSTX-U and Beyond

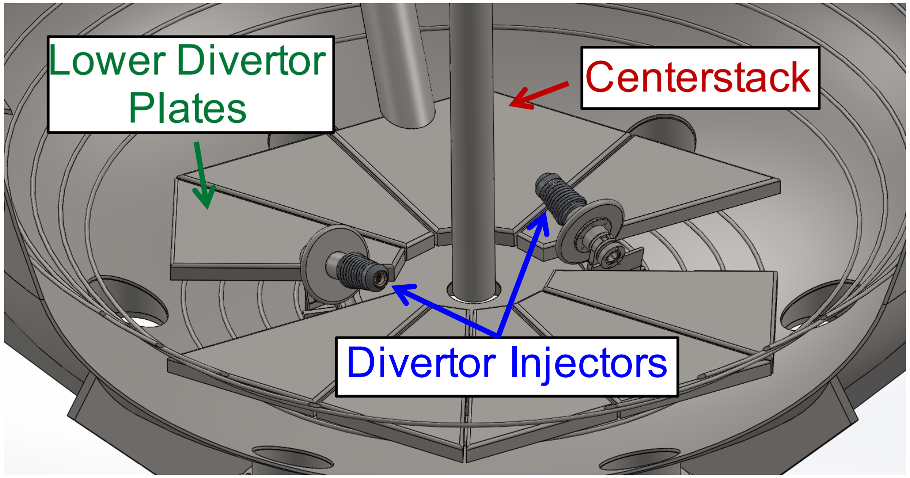


- Critical issue: unraveling effect of strong inductive drive
- Other important issues include: B_{TF}, I_p scalings; Long pulse performance

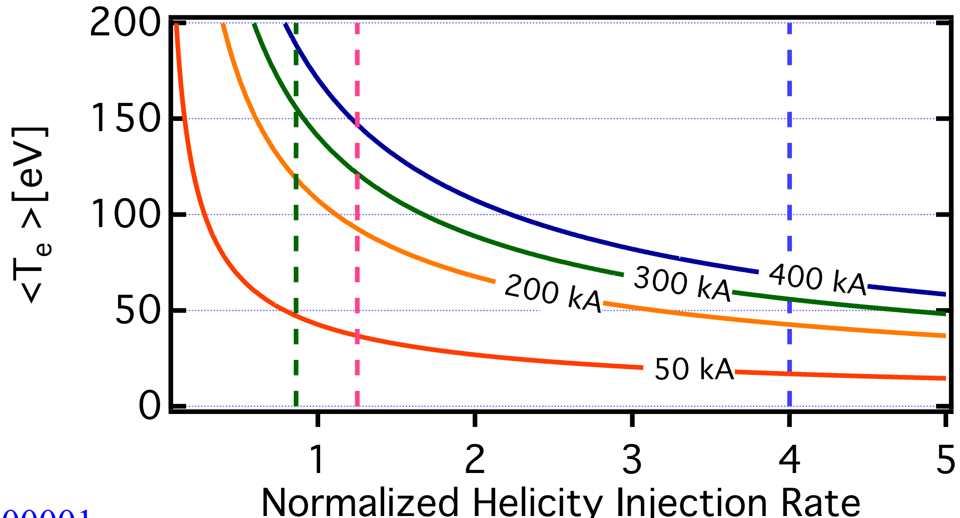
Divertor Injection Addresses Critical Confinement Scaling Issue for Extrapolation to NSTX-U

- 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 → increased B_{TF} test
- Allows higher I_p startup

Divertor Injector CAD

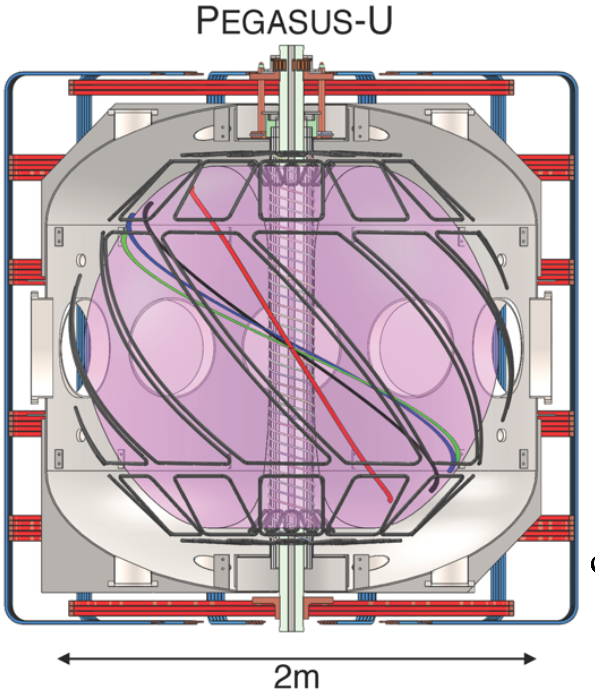


Projected I_p with Divertor Injection

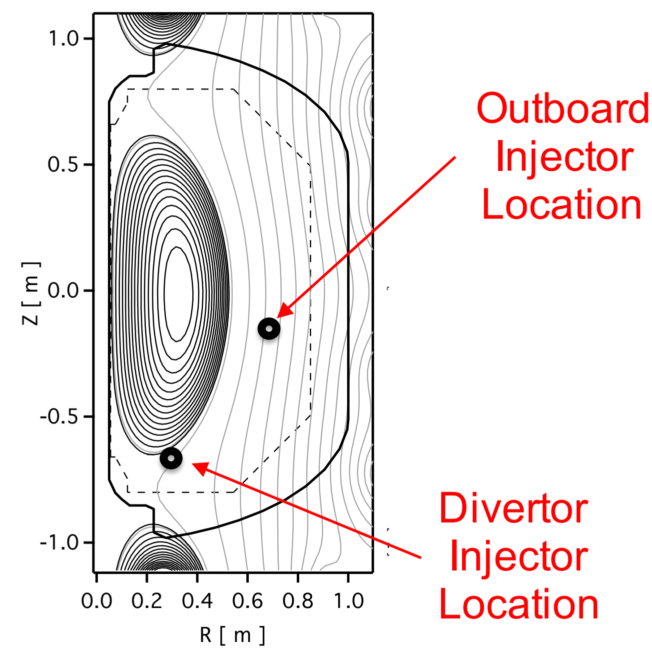


See J.M. Perry PO6.00001

Critical Issues for LHI Predictive Understanding Addressed by Pegasus-Upgrade



Projected LHI Equilibrium



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

Progress in Experiment and Modeling: Moving Towards MA-class Non-solenoidal Startup

- 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

For more PEGASUS presentations see:

Posters (this session)

- GP12.00113: Reusch, *Non-solenoidal Startup via Local Helicity Injection on Pegasus: Progress and Plans*
- GP12.00114: Fonck, *The Pegasus-Upgrade Experiment*
- GP12.00115: Thome, *Effect of Aspect Ratio on H-mode and ELM Characteristics*
- 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*
- GP12.00120: Kriete, *H-mode Edge Turbulence and Pedestal Measurements in Pegasus Plasmas using Langmuir Probes*
- 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