New Results from Non-solenoidal Startup via Local Helicity Injection on PEGASUS and Projections for NSTX-U

Joshua Reusch

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

And the PEGASUS team

University of Wisconsin-Madison

PEGASUS Toroidal Experiment

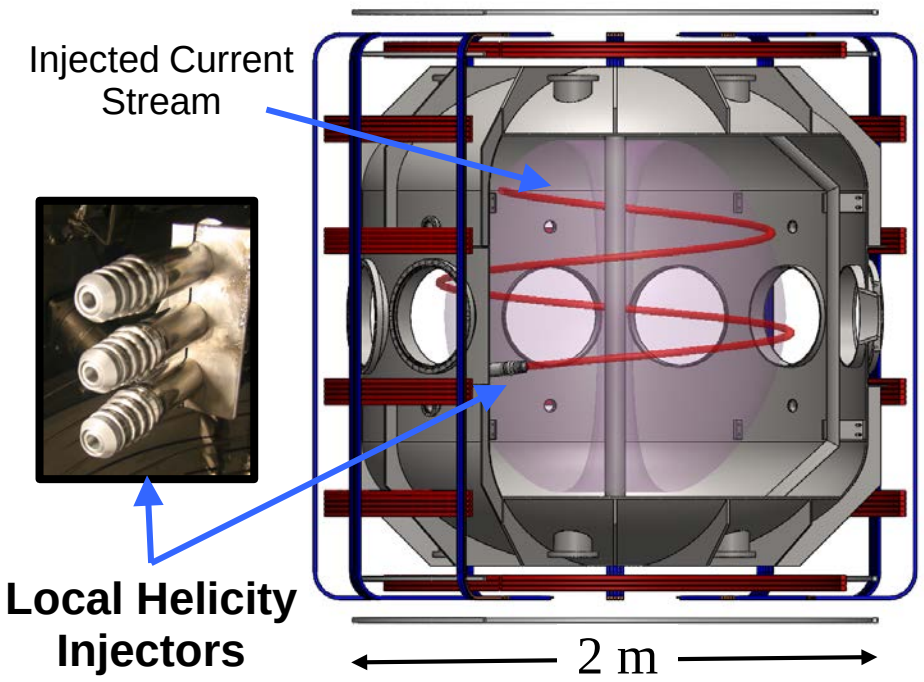
18th International Spherical Torus Workshop

Princeton, NJ

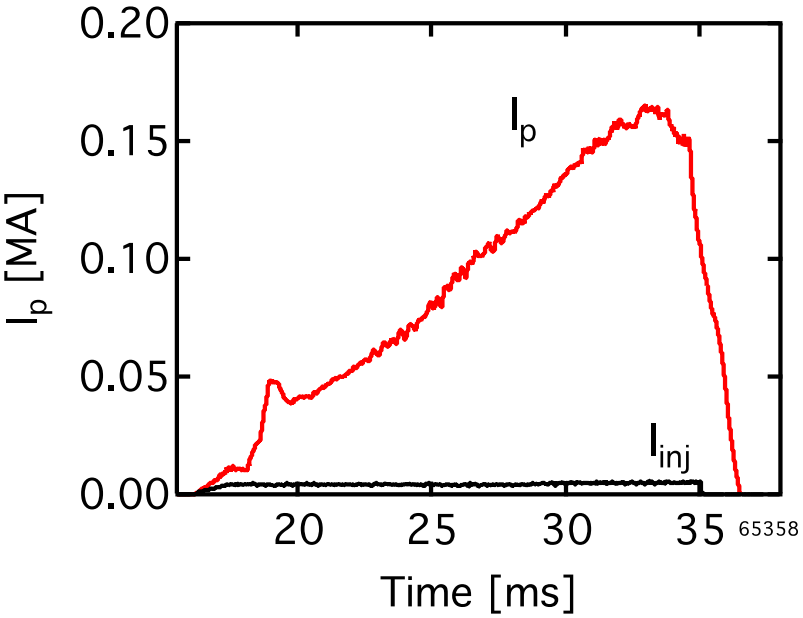
Nov. 6th, 2015

Local Helicity Injection (LHI) is a Scalable Non-solenoidal Startup Technique

Current injected from local plasma source



$I_p \leq 0.18$ MA (I_{inj} = 5 kA)

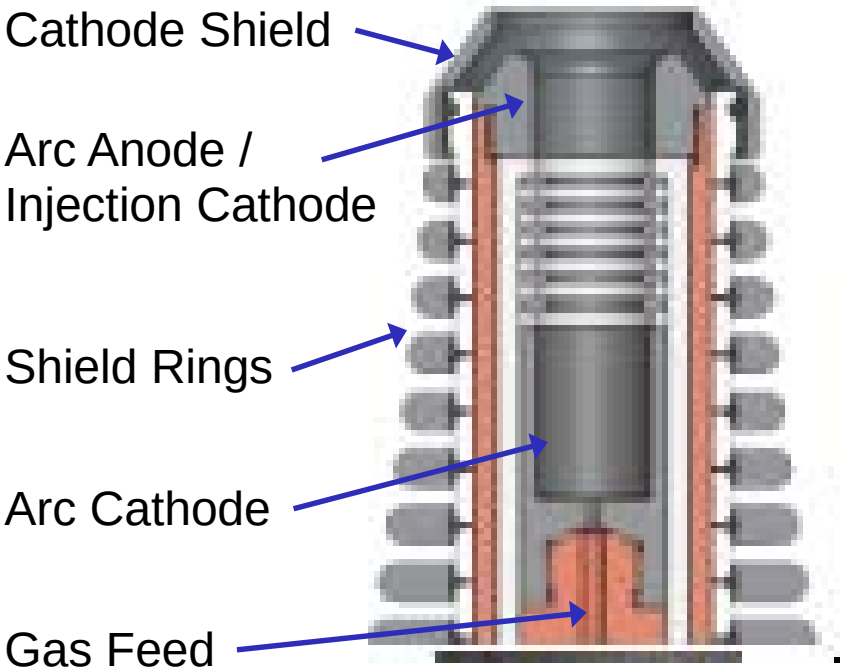


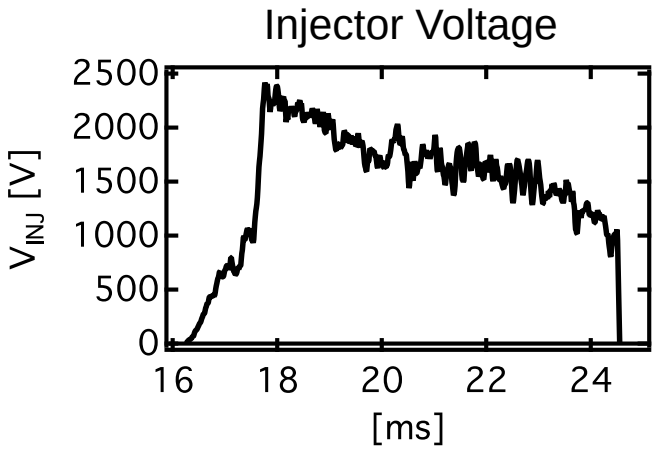
- Unstable current streams form tokamak-like state via Taylor relaxation
- Compact, modular, and appears scalable to MA-class startup

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

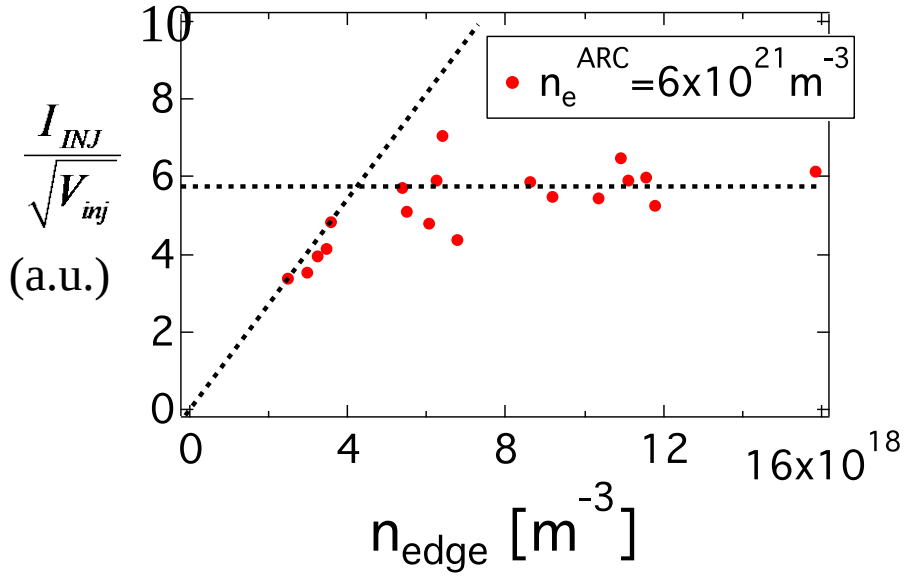
- Injector requirements are formidable:
  - $I_{inj} > 2kA$, $V_{inj} > 1kV$
  - High J_{inj} (~ $1kA/cm^2$)
  - 1-2 cm from LCFS
  - No deleterious PMI
- Robust high V_{inj} achieved
  - Cathode shaping and shielding mitigate cathode spots
  - Shield rings and local limiter (not shown) prevent arc-back
  - ~3x increase in helicity input





Injector Impedance Model Supports Extrapolation to Larger Scale

- Injector impedance model developed and tested*
  - 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
  - Model gives control actuator for $V_{LHI}(t) \rightarrow I_p(t)$

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

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Physics of LHI Encapsulated in a Hierarchy of Models

1. Maximum I_p limits*

Taylor Relaxation

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

Helicity Conservation

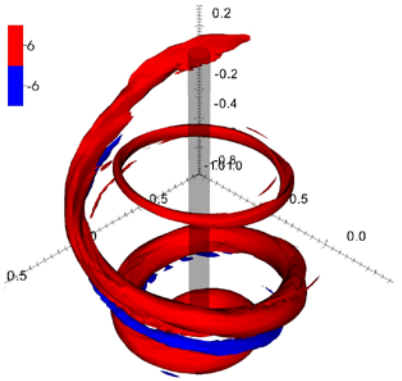
$$V_{LHI} \approx \frac{A_{inj} B_{\varphi,inj}}{\Psi} V_{inj}$$

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

- Lumped parameter model:
  - Inputs: $R_0(t)$, $I_p(0)$, η_0, $\kappa(t)$, $a(t)$, $\ell_i(t)$
  - Analytic low-A descriptions of L_p*, B_z**, $V_{eff}(t)$

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

$V_{IND} = V_{PF} + V_{geo}$

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

$$V_{IR} = I_p R_p = I_p \left(\frac{\langle \eta_{spitzer} \rangle 2\pi R_0}{A_p} \right)$$

$$V_{PF} = \sum_{coils} \frac{d}{dt}\left[\psi_{PF-Plas}\right] = \frac{\partial}{\partial t}\left[M_V \pi R_0^2 \, B_V\big|_{R_0} \right]$$

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

$$M_V(\varepsilon,\kappa) = \frac{(1-\varepsilon)^2}{(1-\varepsilon)^2 c(\varepsilon) + d(\varepsilon)\sqrt{\kappa}} \qquad c(\varepsilon) = 1 + 0.98\varepsilon^2 + 0.49\varepsilon^4 + 1.47\varepsilon^6$$

$$d(\varepsilon) = 0.25\varepsilon\left(1 + 0.84\varepsilon - 1.44\varepsilon^2\right)$$

$$V_{geo} = \frac{d}{dt}\left[L_p I_p\right] = \frac{d}{dt}\left[L_e I_p\right] + \frac{1}{I_p}\frac{d}{dt}\left(\frac{1}{2} L_i I_p^2\right)$$

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

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

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

*S.P. Hirshman and G.H. Nielson 1986 *Phys. Fluids* **29** 790

**O. Mitarai and Y. Takase 2003 *Fusion Sci. Technol.*

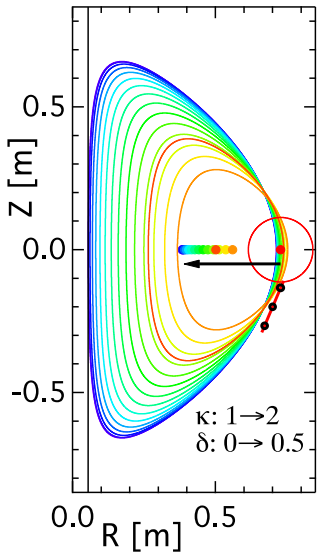
0-D Power Balance Model Tracks the Dynamic LHI $I_p(t)$ Evolution

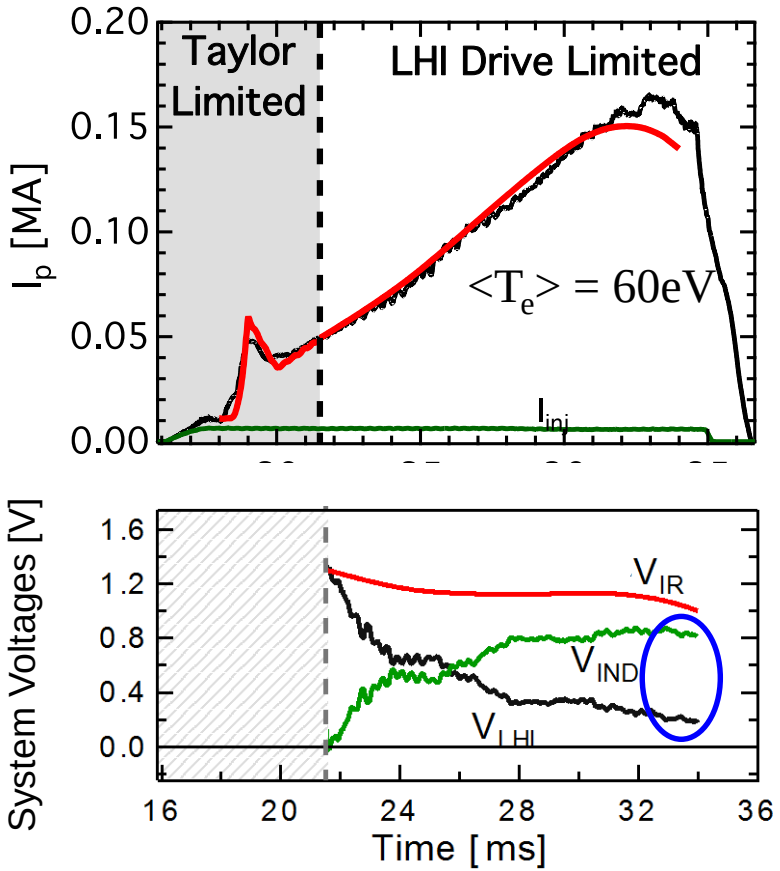
- Model elements:
  - Inputs: <η(t)>, $R_0(t)$, shape(t), $V_{inj}(t)$, $\ell_i(t)$
  - <η> calculated from Spitzer assuming characteristic $<T_e>$

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

- Model provides relative contribution from V_{LHI} and V_{IND}
  - Significant V-s from Shape(t)

Shape(t)



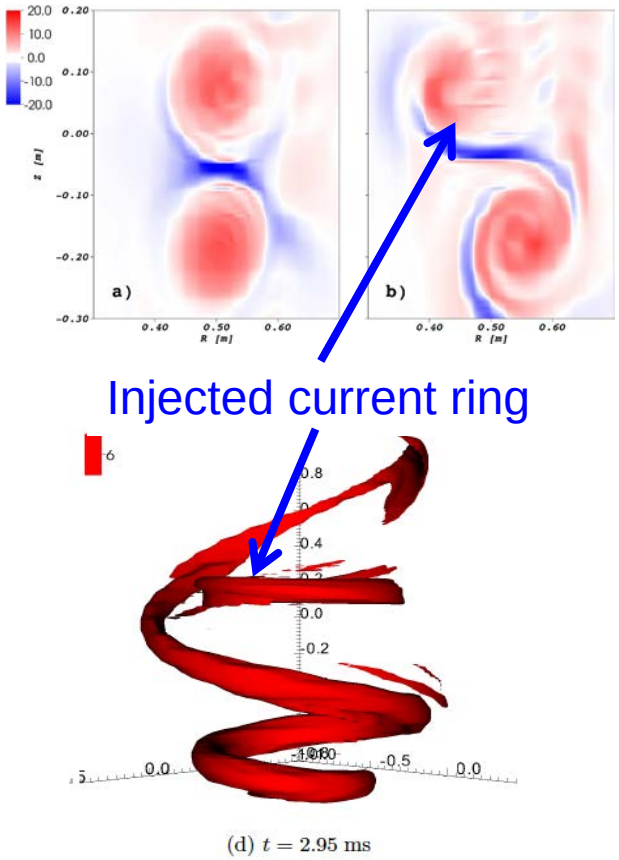


- All of this hinges on understanding of V_{IR} term

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NIMROD Describes Edge Reconnection Current Drive Mechanism

Current rings in NIMROD*



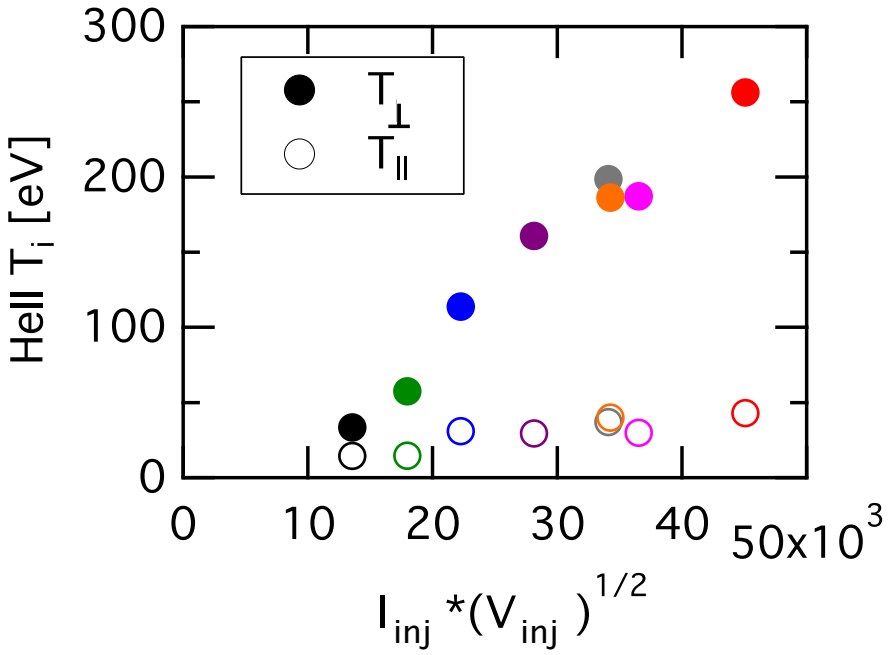
Observed current rings in PEGASUS (pre-tokamak plasma)

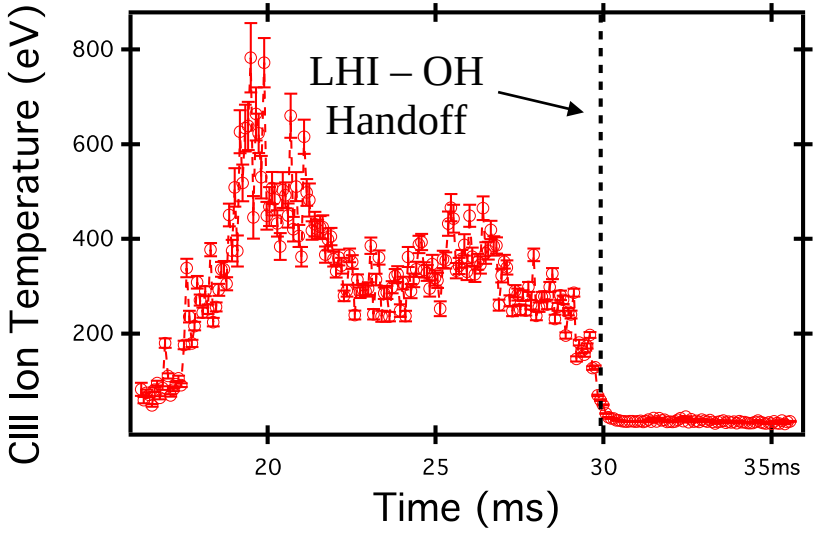
- At high I_p: streams persist in NIMROD; no visible streams in Pegasus
- Reconnection localized to edge, field most stochastic at edge

* *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*
  - $T_i \sim B^2/\langle n_e \rangle \sim I_{inj} V_{inj}^{0.5}$





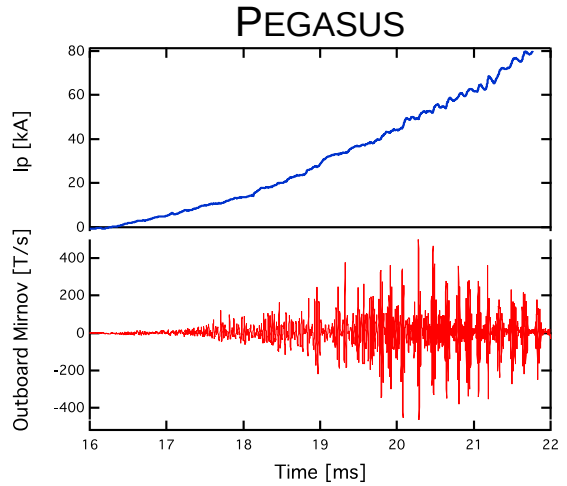
- Anomalous heating ($T_i > T_e$) persists through LHI phase

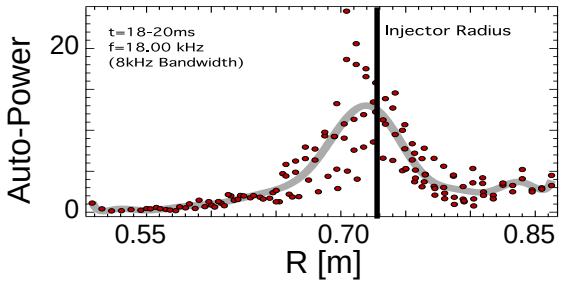
* *J. Yoo, et al., Phys. Rev. Lett., vol. 110, no. 21, p. 215007, May 2013*
Y. Ono, et al., Plasma Phys. Control. Fusion, vol. 54, no. 12, p. 124039, Dec. 2012.

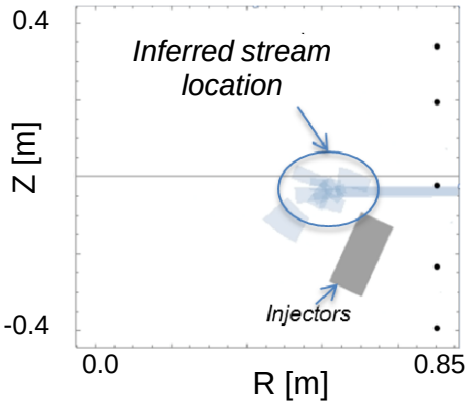
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Stream Interaction Manifests as Edge Localized MHD Burst

- MHD bursts accompany I_p growth
  - n=1 line tied kink structure
  - Localized in edge
- MHD analysis confirms existence of unstable current streams in edge*
  - Coherent streams persist at high I_p, consistent with NIMROD
  - Reconnection event at peak of MHD burst
- Suggests that majority of stochastic region localized to edge



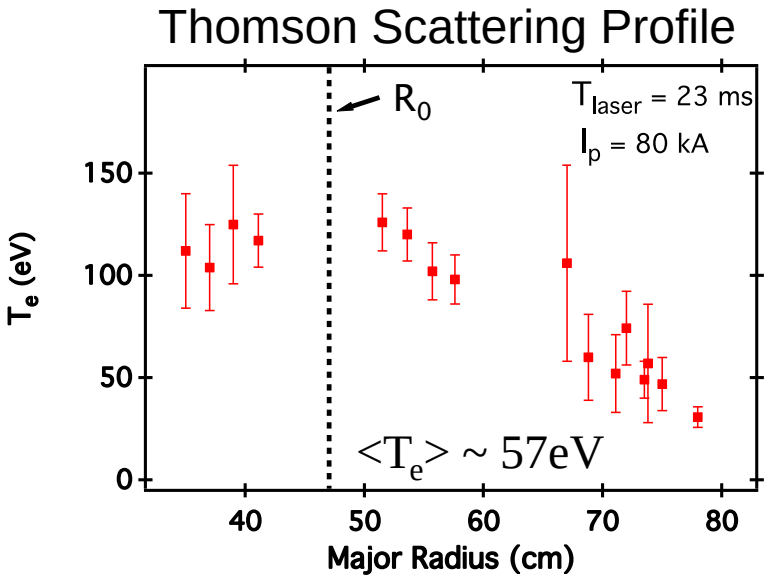




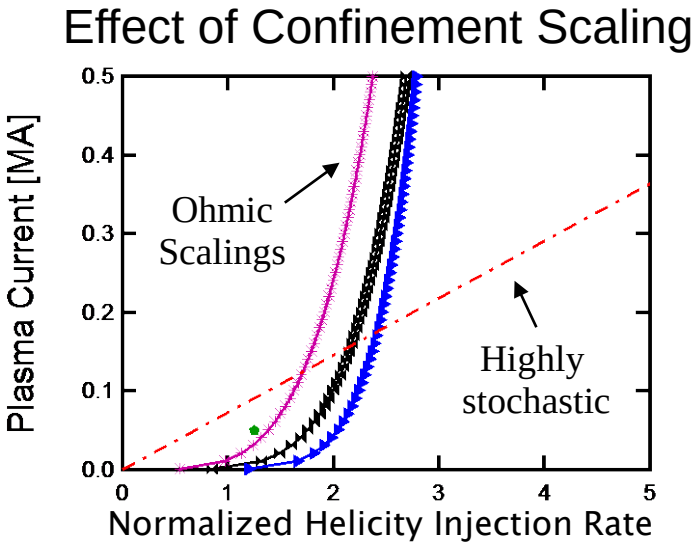
* *E.T. Hinson, Ph.D. Thesis, UW-Madison, 2015.*

Edge Localized Reconnection and Strong V_{IND} may Support Good Core Confinement, Scaling

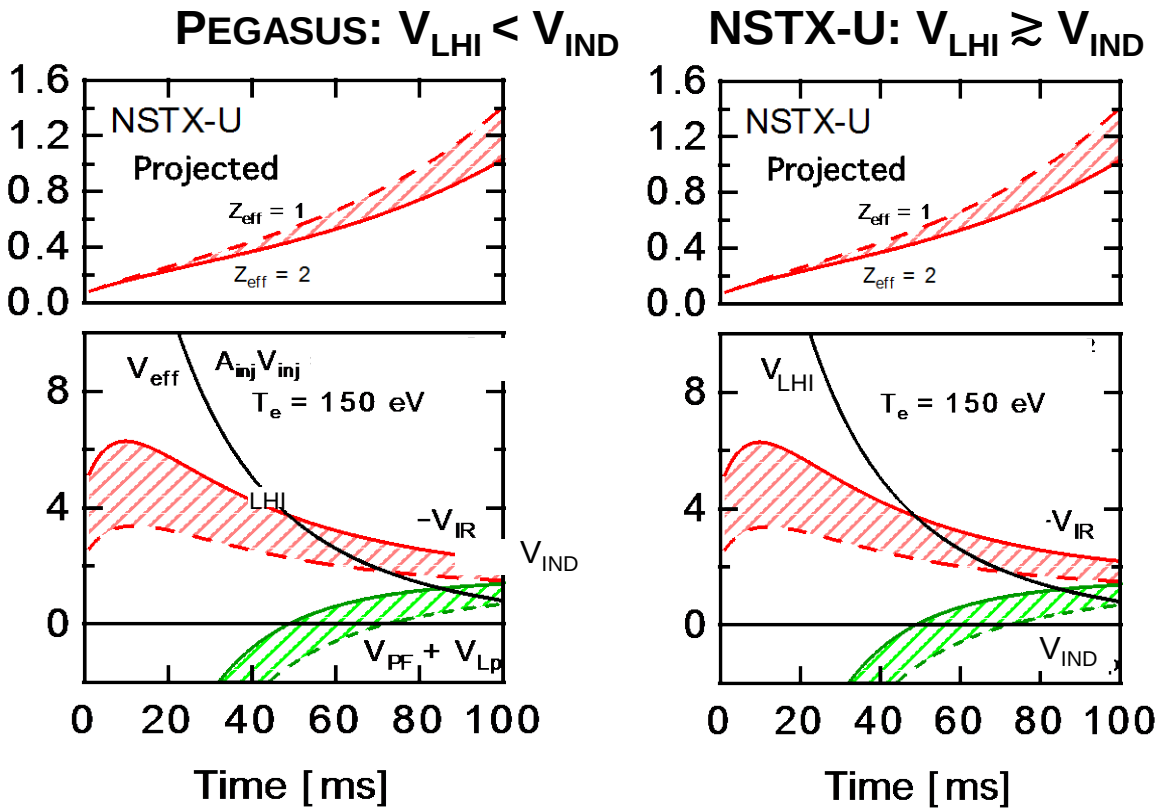
- First TS profile: peaked in core
  - Does not appear highly stochastic across profile
  - Comparable to Ohmic L-mode
  - Drive: V_{IND} (across plasma)
    V_{LHI} (edge)



- Projections to NSTX-U, beyond depend critically on confinement
  - Two zone (edge vs. core) confinement?



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



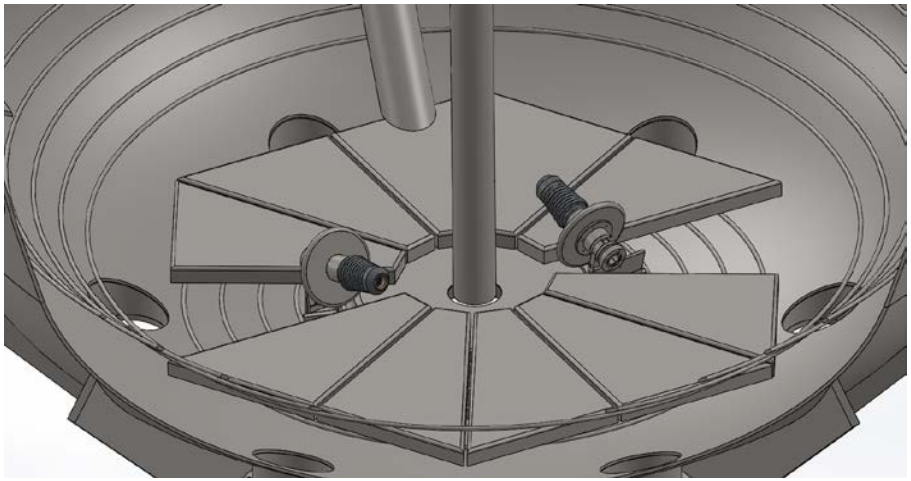
- Critical issue: unraveling effect of strong inductive drive
- Other important issues include: B_{TF}, I_p scalings; Long pulse performance

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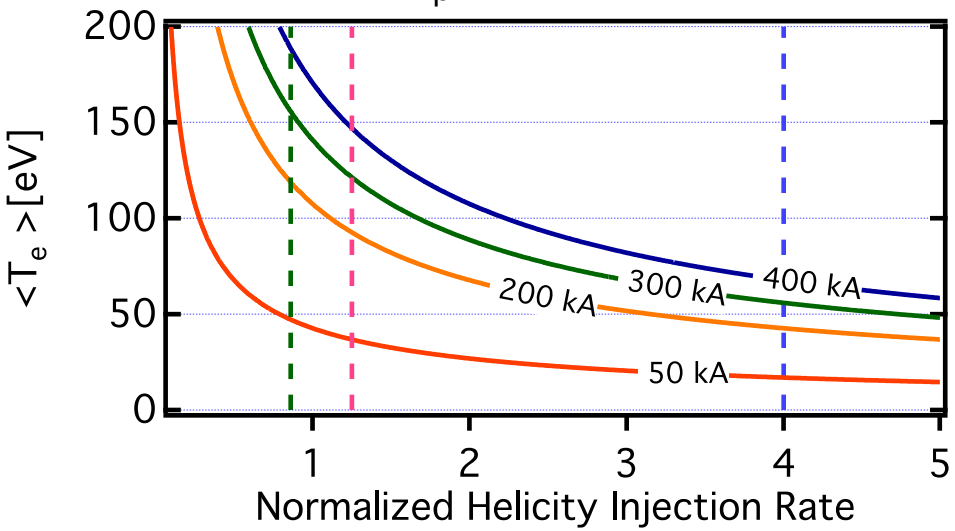
Divertor Injection: Vary Injector Geometry to Separate Inductive and Helicity Drive Effects

- 3-4x increased helicity input
- Minimal inductive drive: ~ fixed geometry
  - Separates effects: edge reconnection Vs. inductive drive
  - Confinement measurements in transport equilibrium
- Lower R → increased B_{TF} test
- Allows higher I_p startup

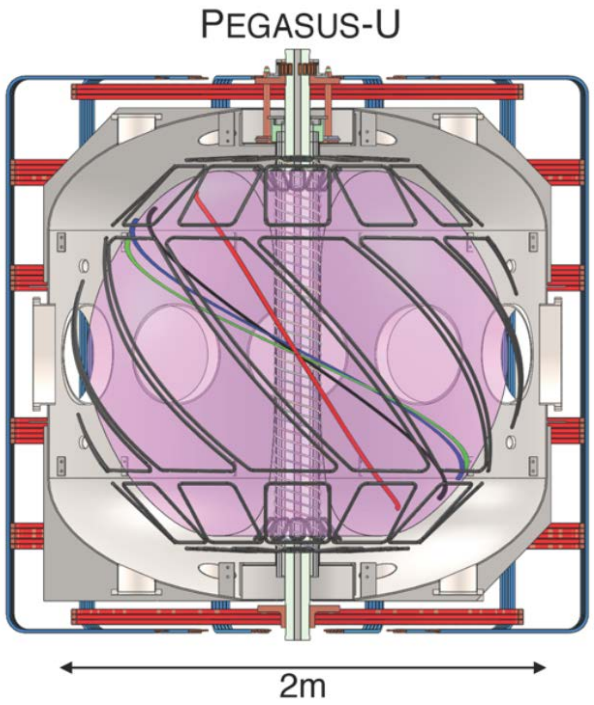
Divertor Injector CAD



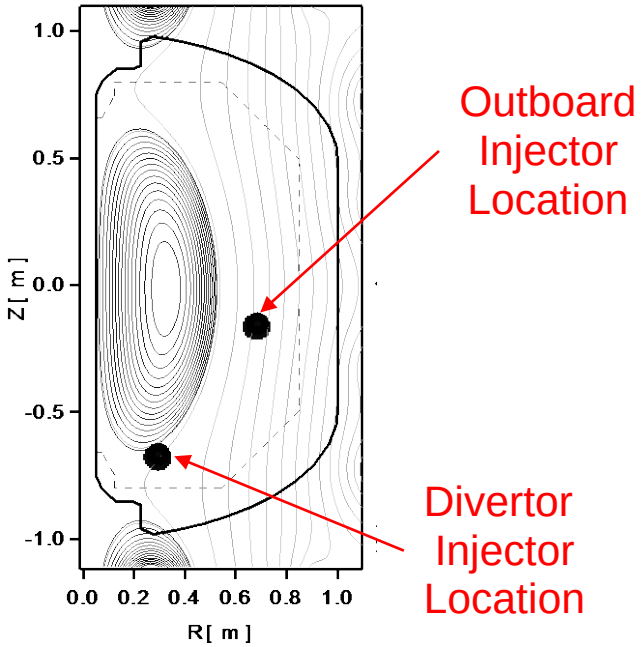
Projected I_p with Divertor Injection



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} ~ 0.8T: 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

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

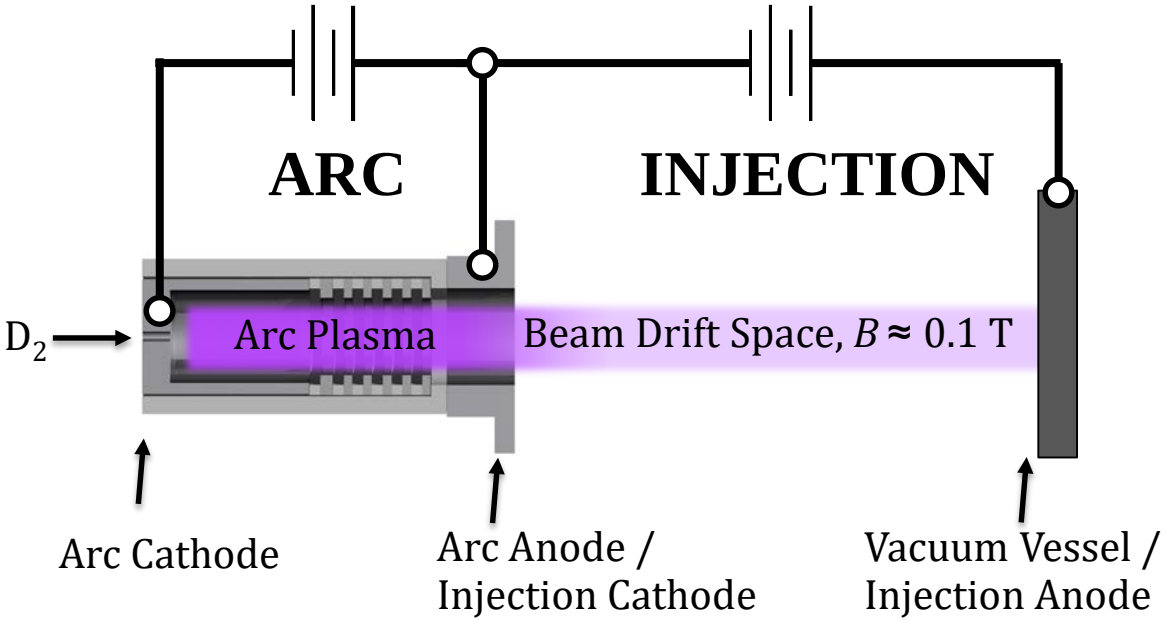
- Improved injectors: robust operation at > 1kV
  - Injector impedance model gives actuator for V_{LHI}, PS design point
- 0-D power balance model provides prediction of $I_p(t)$
  - Input power primarily from V_{IND} in present tests
  - Confinement scaling is critical unknown
- Surprisingly good core confinement indicated by TS
  - Peaked core T_e ~ 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 NSTX-U and beyond

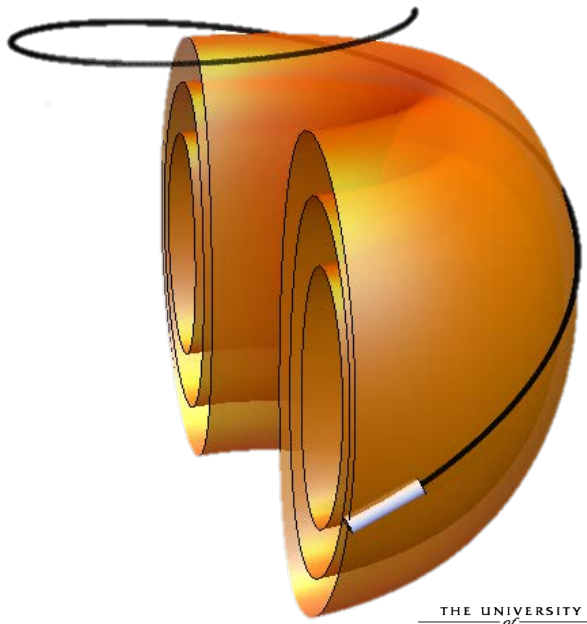
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Backup

LHI on Pegasus utilizes small active arc current sources located in the SOL

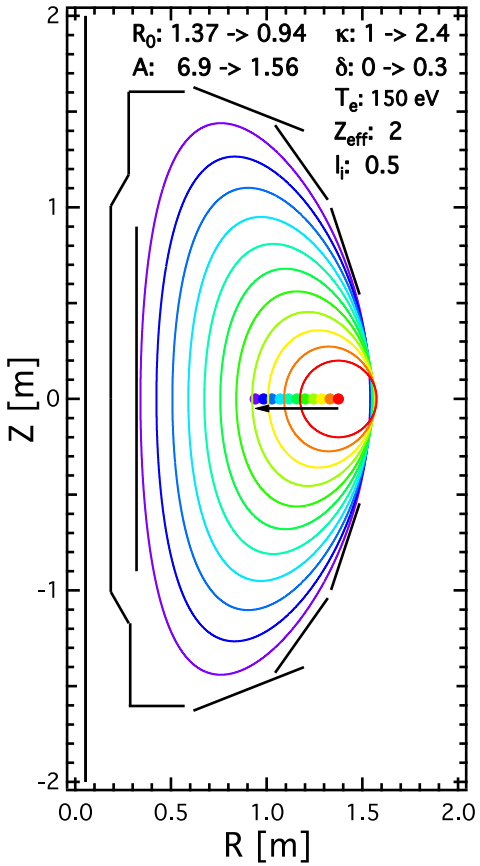
- Injectors are washer gun style plasma arc sources
- 2-stage circuit: arc and injection circuits “daisy chained”
- Uses current stiff source, voltage set by plasma physics

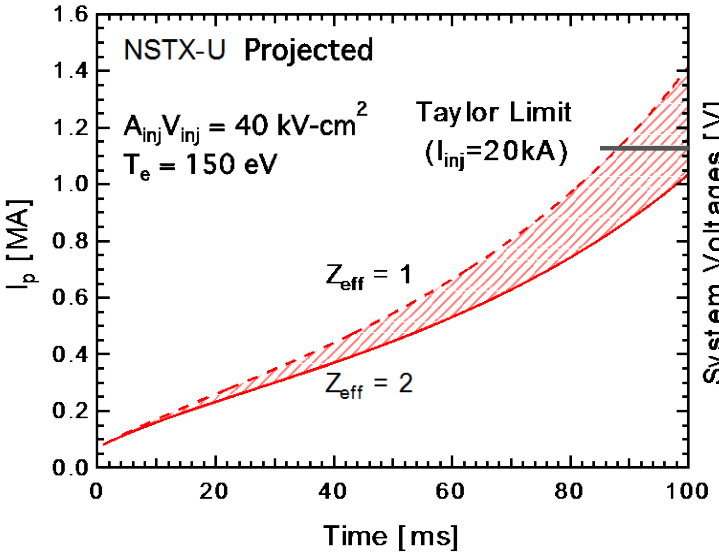


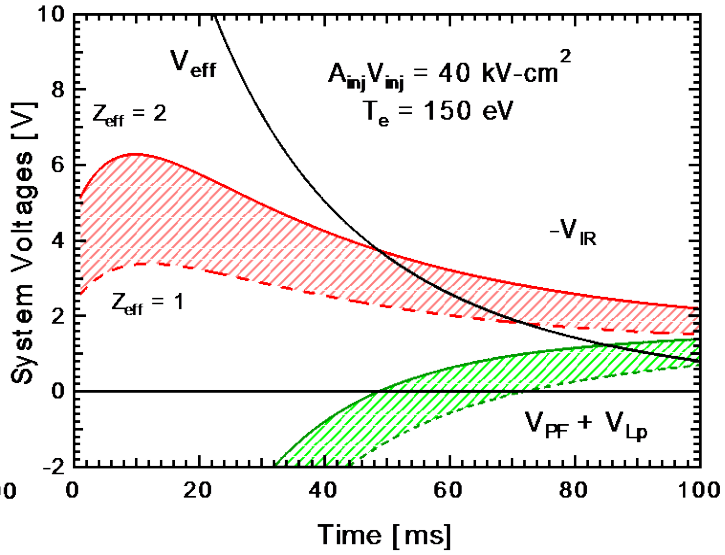


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Model Applied to NSTX-U Geometry for Initial I_p~1 MA Start-up Scenario Prediction







- Significant LHI drive required to achieve I_p ~ 1 MA
  - Predicted A_{inj} V_{inj} requirement estimates: ~ 40 cm^2-kV

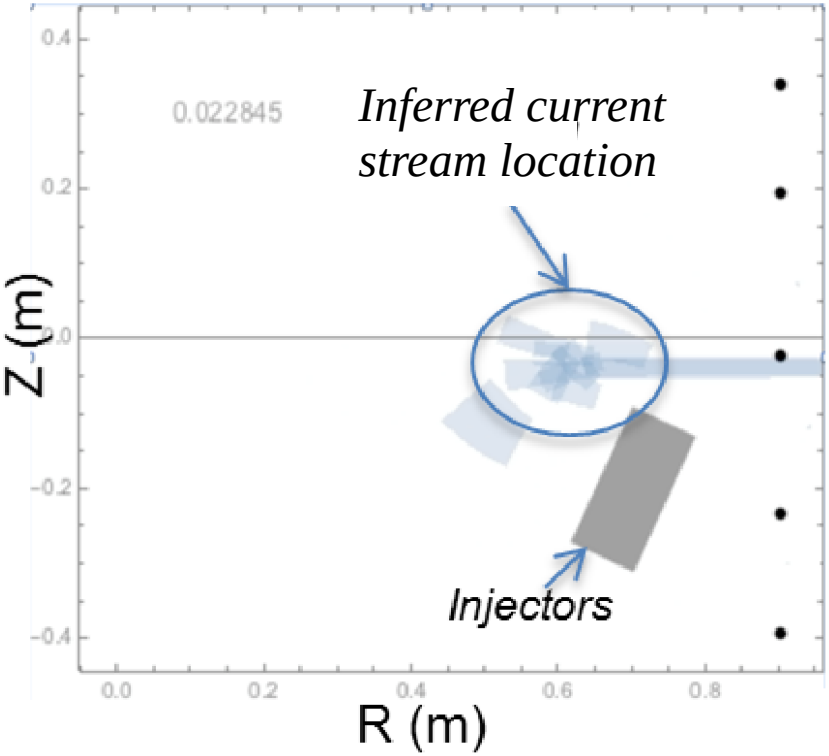
*C. Neumeyer *et all* (2009) *23rd IEEE/NPSS Symposium on Fusion Engineering*

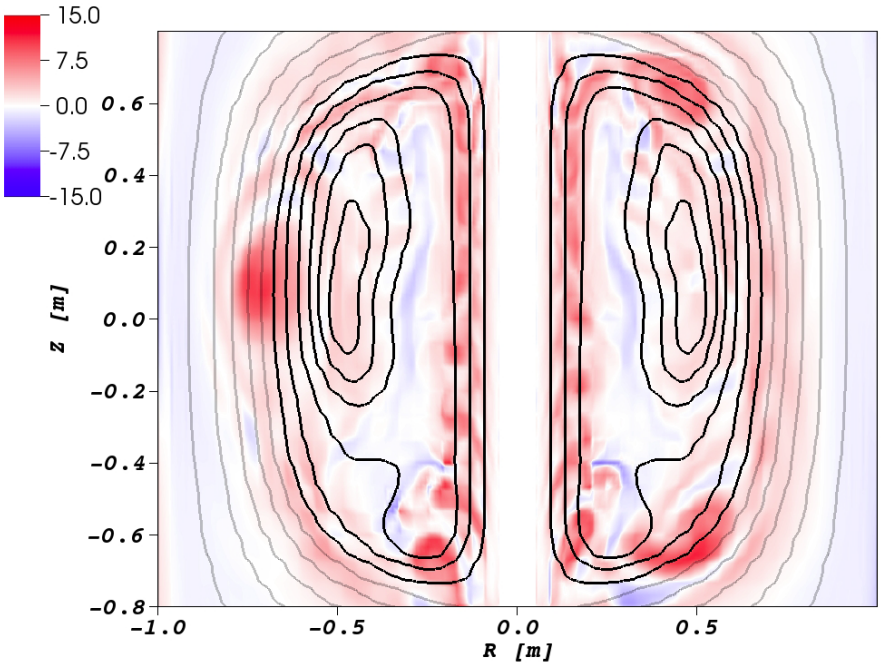
**C. Neumeyer (2001) "NSTX Internal Hardware Dimensions"
http://nstx.pppl.gov/nstx/Engineering/NSTX_Eng_Site/Technical/Machine/NSTX_Engr_Machine_Dims_cm.html

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Indirect evidence of localized current filaments throughout the LHI drive phase also observed.

- NIMROD predicts streams remain coherent in the edge at high I_p
- Bulk plasma current sustained by continued reconnection events





- Correlation analysis of edge Mirnov array show source is localized in space

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