Overview of Non-Solenoidal Startup Studies in the Pegasus ST

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University of Wisconsin-Madison

58th Annual Meeting of the APS Division of Plasma Physics

2 November 2016
San Jose, CA

PEGASUS Toroidal Experiment

Layout

8.5" x 11"

8' W x 4' H

		Title Banner				
Non-Solenoidal Startup via Local Helicity Injection	Technology and Diagnostic Development	Progress Toward Predictive Models of LHI		2016 Helicity Injection Campaign Highlights		
Local Helicity Injection (LHI) Provides Robust Non-Solenoidal Startup on the PEGASUS ST	Three HFS Injection Systems Implemented and Tested Since April 2016	Power Balance Model Provides Predictive Tool for $I_p(t)$	NIMROD Describes Current Helical Current Stream Reconnection as Drive Mechanism	LFS Local Helicity Injection Produces Core $T_e > 100$ eV	$I_p > 0.15$ MA Achieved Via HFS Injection To Date	
LHI Startup Scenarios Grow From Helical Current Streams to Quality, High I_p Plasmas	Multi-Year Technology Development has Produced Robust, High Performance Current Injectors	Analytic Formulation of Power Balance Model Elements Allow Partitioning of Energy Flow	Current Stream Interaction Manifests as Edge-Localized MHD Burst	T_e (R, t) Remains Peaked for LFS Injection Geometry and Minimal V_{IND}	HFS Helicity Injection Provides Non-Solenoidal Sustainment at High I_N	
High-Field-Side (Divertor) Injection Experiments Provide Confinement Tests & Higher I_p	Large-A_{inj} Injector Design Provides Enhanced Performance, Simplified Geometry	Equilibrium-Calibrated Inductance Model Improves Estimates of Non-Solenoidal V_{IND}	Reconnection-Driven Ion Heating Gives $T_i > T_e$ During LHI	Technical Challenges Arise for LHI Startup With HFS Injection Geometry	LHI Provides Access to High-β_T at A ~ 1 with Non-Solenoidal Sustainment and Anomalous Ion Heating	Reprints
Hierarchy of Physics Models Provide a Predictive Understanding for LHI Startup	Thomson Scattering Enhancements to Measure T_e and n_e Profiles During LHI	0-D Power Balance Model Used to Explore Projections for NSTX-U Startup	Different MHD Activity Observed Between LFS and HFS Injection Geometry	Poloidal Field Shaping Facilitates Relaxation at Full Toroidal Field ($B_{inj} = 0.23$ T)	Progress in Non-Solenoidal Startup on Pegasus	

Non-Solenoidal Startup via Local Helicity Injection

Technology and Diagnostic Development

Progress Toward Predictive Models of LHI

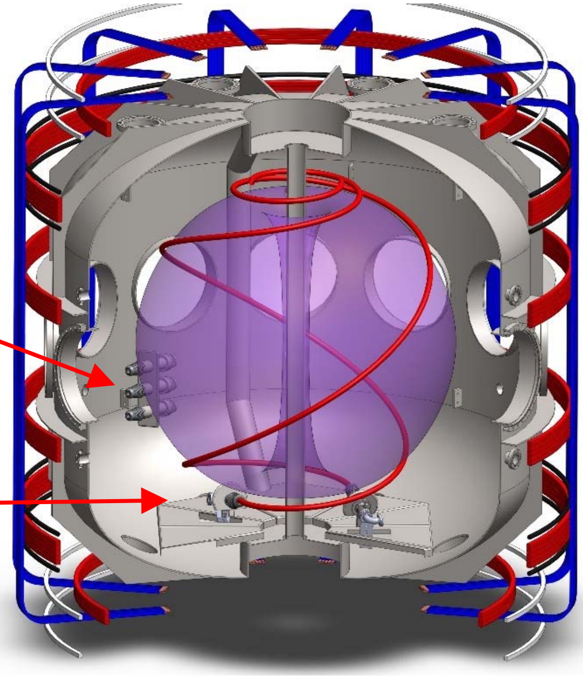
2016 Helicity Injection Campaign Highlights

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

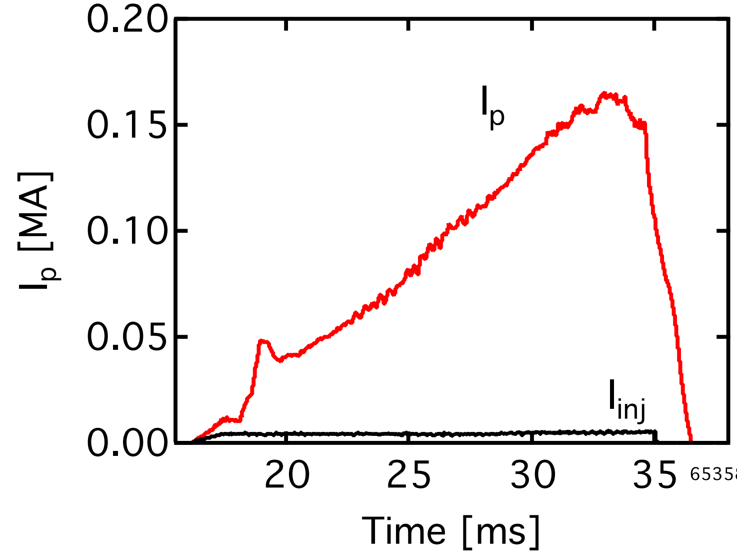
Helicity Injectors

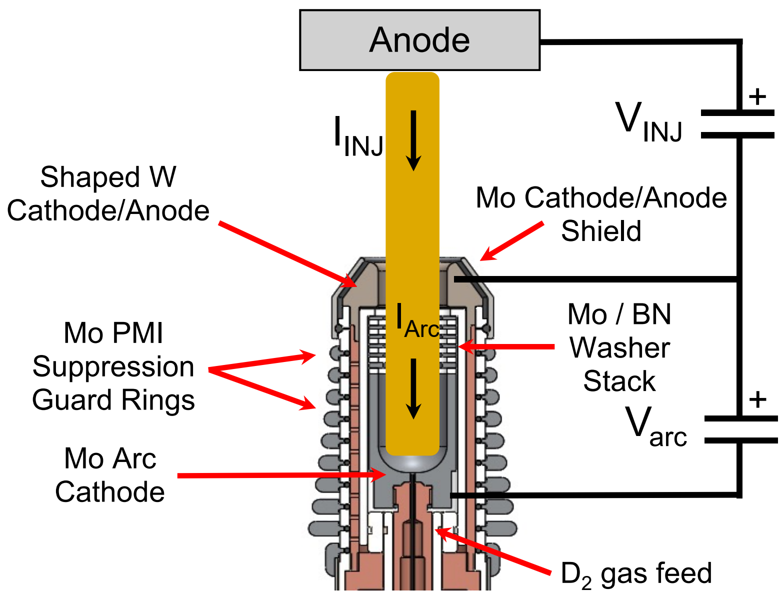
LFS System

HFS System



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





Plasma Parameters		Injector Parameters	
I_p	≤ 0.23 MA	$\sum I_{inj}$	≤ 14 kA
τ_{shot}	≤ 0.025 s	I_{inj}	≤ 4 kA
B_T	0.15 T	V_{inj}	≤ 2.5 kV
A	1.15–1.3	N_{inj}	≤ 4
R	0.2–0.45 m	A_{inj}	= 2-4 cm^2
a	≤ 0.4 m	I_{arc}	≤ 4 kA
κ	1.4–3.7	V_{arc}	≤ 0.5 kV

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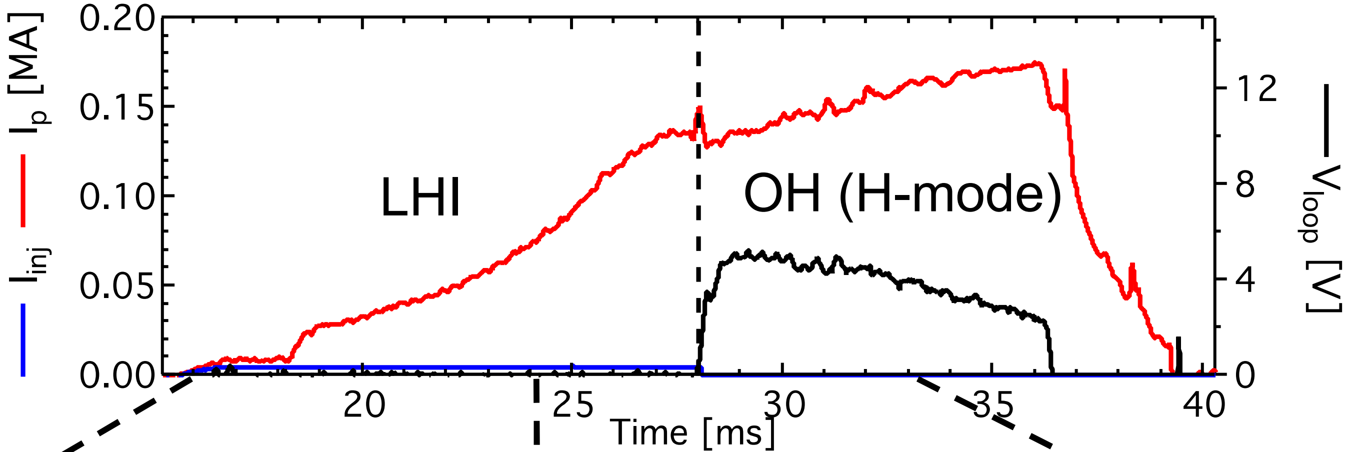
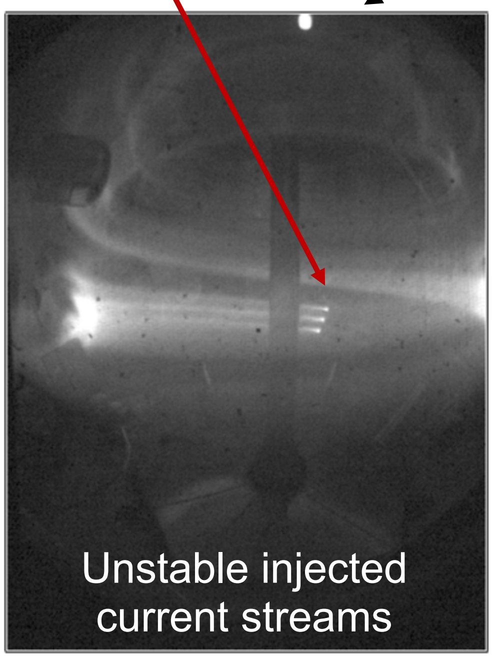
LHI Startup Scenarios Grow From Helical Current Streams to Quality, High I_p Plasmas

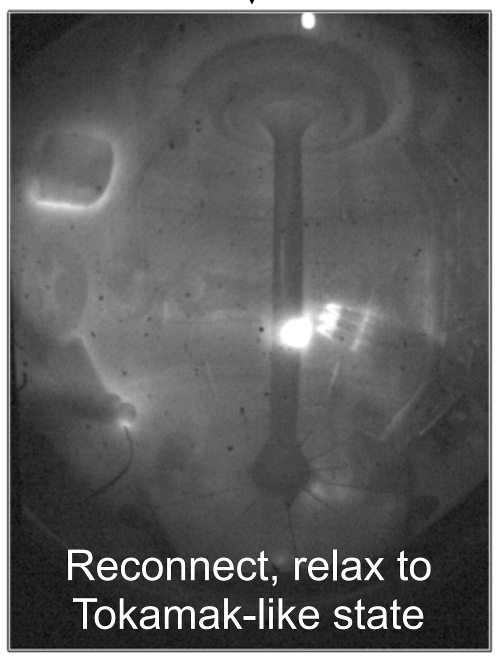
Three-Injector Array



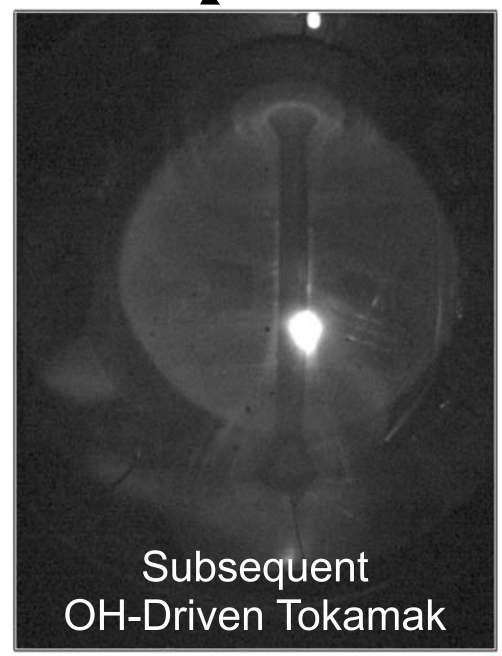


Null Formation

Relaxation



Injector Shutoff



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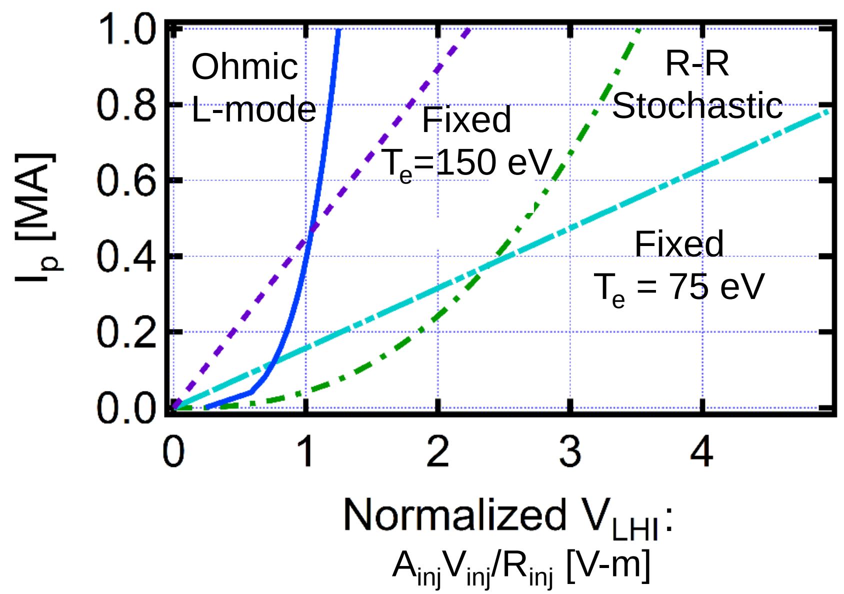
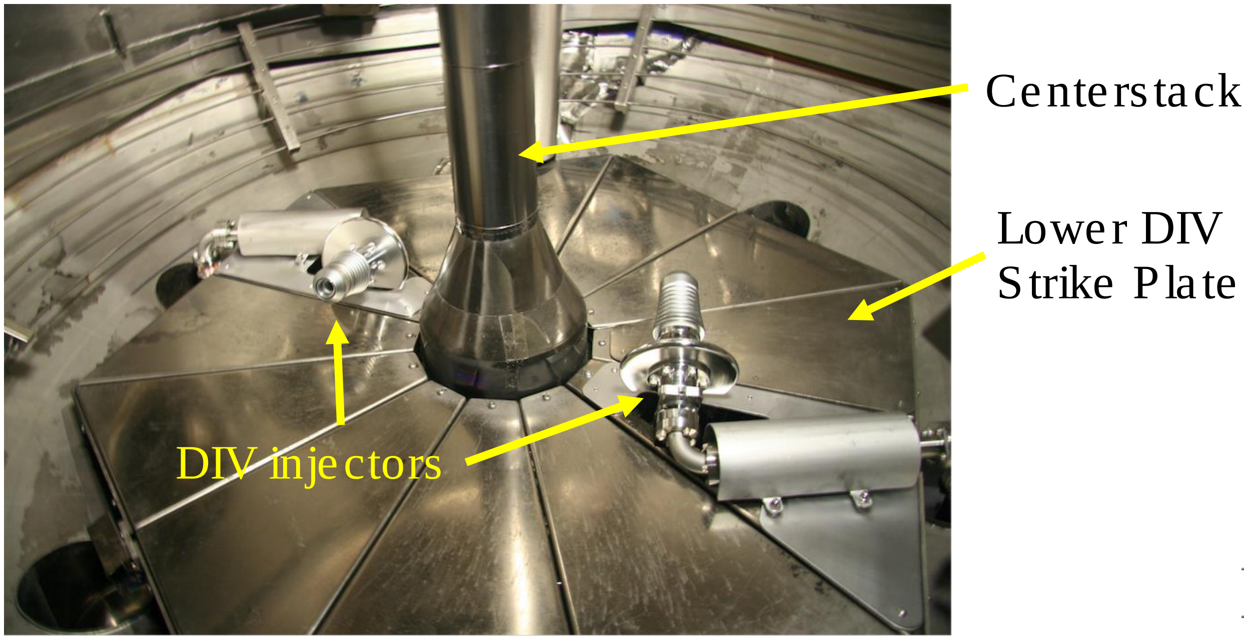
High-Field-Side (Divertor) Injection Experiments Provide Confinement Tests & Higher I_p

- 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





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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

Taylor Relaxation

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

Helicity Conservation

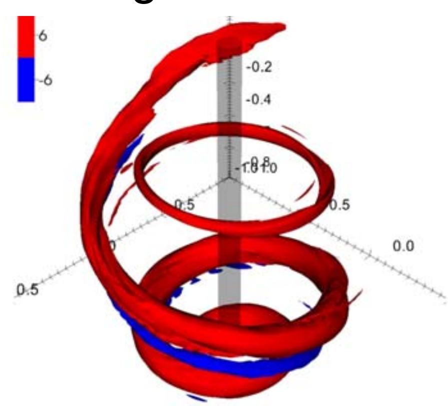
$$V_{LHI} \approx \frac{A_{inj} B_{\varphi,inj}}{\Psi} V_{inj}$$

2. 0-D power-balance $I_p(t)$
   – V_{LHI} for effective LHI current drive

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

3. 3D Resistive MHD (NIMROD)
   – Physics of LHI current drive mechanism

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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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_{inj}
  - 3–4× increase in V_{LHI} over prior systems
  - $A_{inj} = 8\ cm^2$ total
  - $V_{inj} \leq 1.2\ kV$
  - $I_{inj} \geq 8\ kA$ total

- Systems vary R_{inj}, Z_{inj}, local limiter geometry
  - Latest design incorporates floating, electropolished divertor shield plates

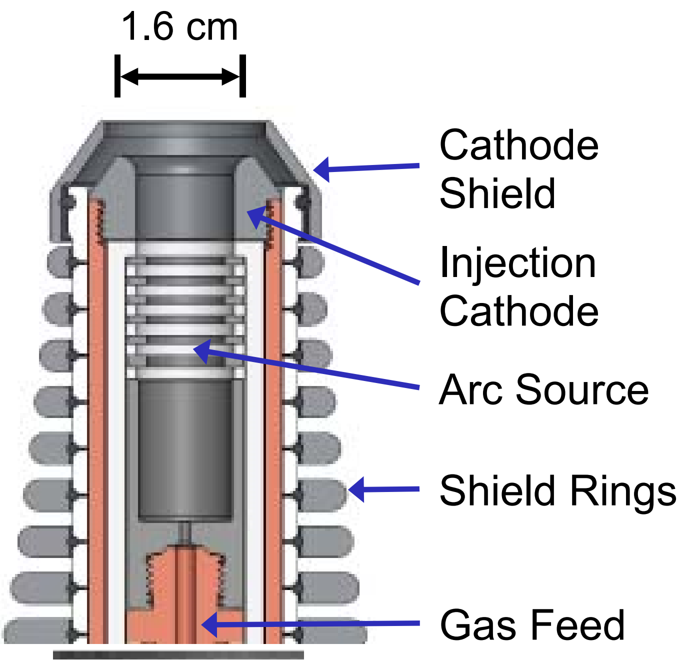
Configuration 1

Configuration 2

Configuration 3

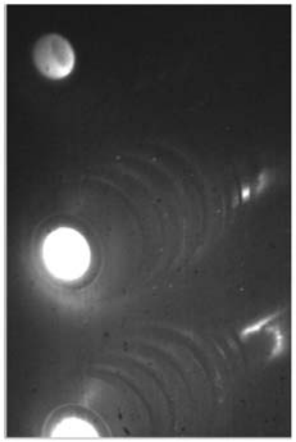
Multi-Year Technology Development has Produced Robust, High Performance Current Injectors

- Washer-stack arc source:
  - $J_{inj} \sim 1 kA/cm^2$
- High-voltage in SOL: V_{inj} > 1kV
  - Frustum cathode
  - Floating cathode shield
- PMI control: 1-2 cm from LCFS
  - Cascaded shield rings
  - Local limiter
  - Mo, W PFCs



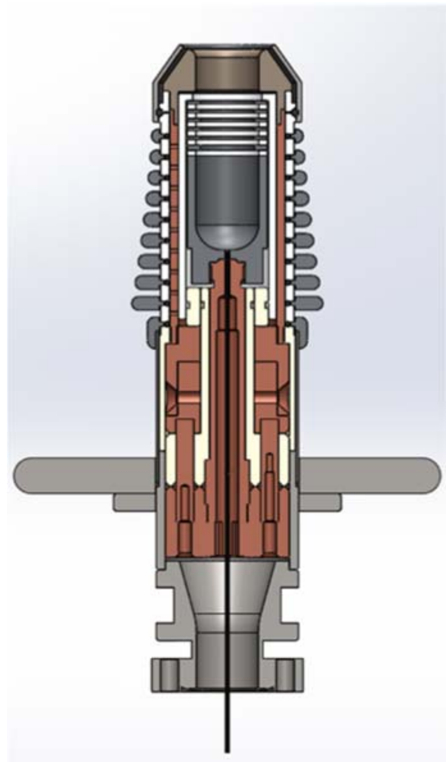
Three-Injector Array

Clean, High-V_{inj} Operation

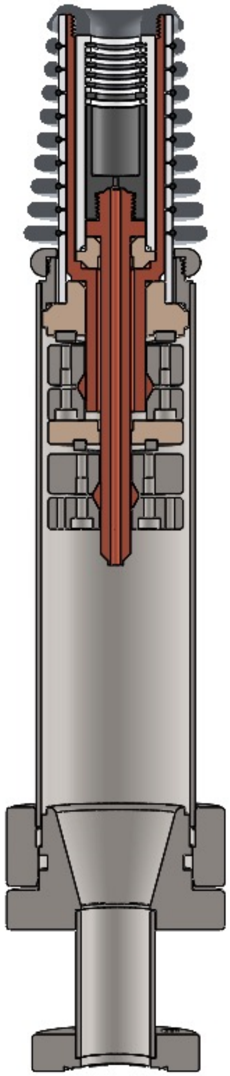


Large-A_{inj} Injector Design Provides Enhanced Performance, Simplified Geometry

- New injectors designed for HFS system
  - Doubled A_{inj} ($2\ cm^2 \rightarrow 4\ cm^2$)
  - 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_{inj}, shield structures
  - Integrated hypodermic gas feed alleviates field sensitivity from previous
- Refractory materials for resilience to harsh environment
  - W for high-V_{inj} cathode/anode
  - Mo for external shield assemblies



New: $4\ cm^2$

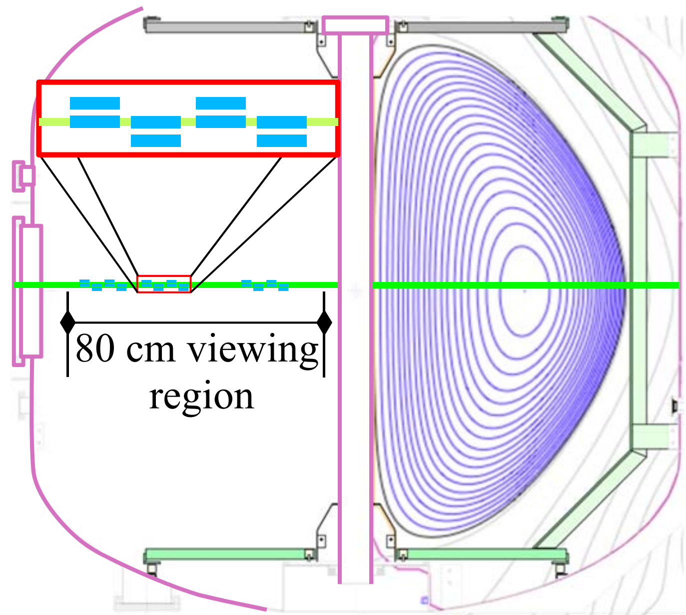


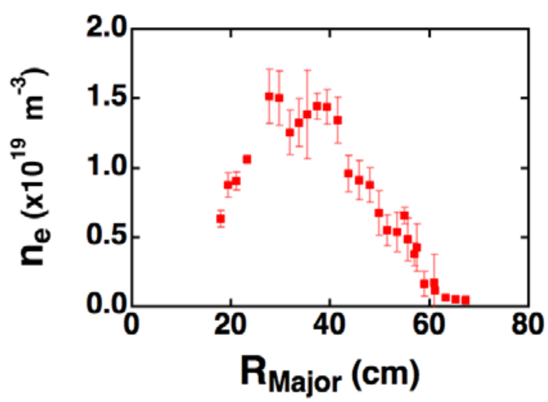
Old: $2\ cm^2$

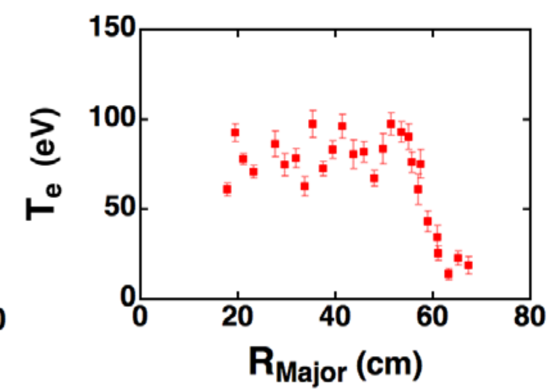
Thomson Scattering Enhancements to Measure T_e and n_e Profiles During LHI

- 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 ~ 1 Plasma





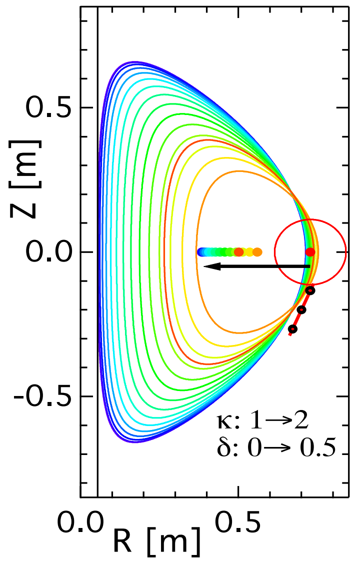


Power Balance Model Provides Predictive Tool for $I_p(t)$

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

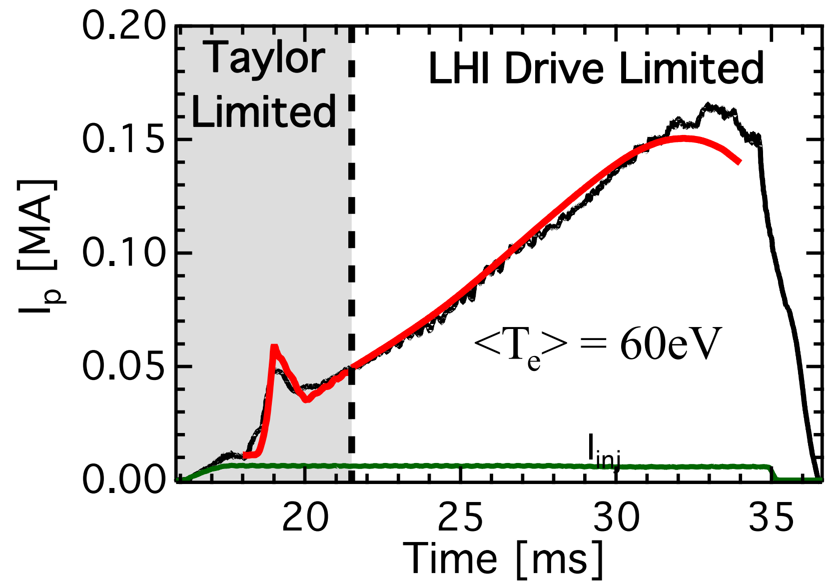
- V_{LHI}: effective drive
- V_{IR}: resistive dissipation
- V_{IND}: analytic, from shape(t)
- Taylor relaxation limit: $I_p \leq I_{TL}$

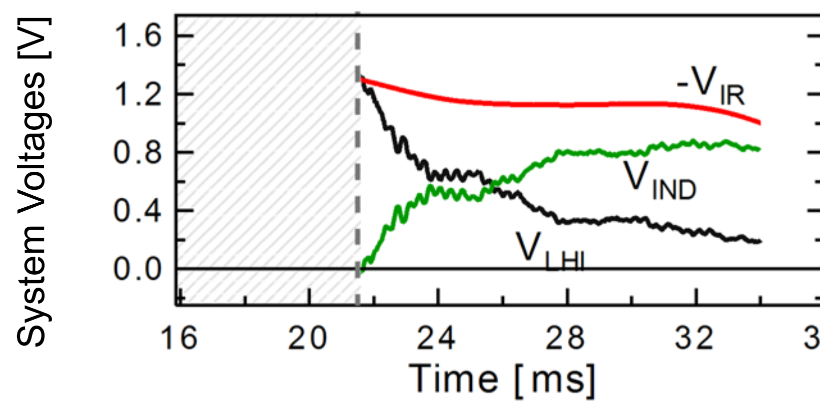
Shape Evolution



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

- Model reasonably recreates $I_p(t)$





Eidietis et al., J. Fusion Energ. ***26****, 43 (2007)*
S.P. Hirshman and G.H. Nielson 1986 Phys. Fluids ***29*** *790*
O. Mitarai and Y. Takase 2003 Fusion Sci. Technol.
Battaglia et al., Nucl. Fusion ***51****, 073029 (2011)*

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

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

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

- Recent Improvements
  - Revised L_p, B_Z models*
  - Moving plasma boundary
  - Neoclassical resistivity

Inductive Drive from Poloidal Fields

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

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

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

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

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

LHI Drive

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

Resistive Dissipation

$$V_{IR}=I_pR_p=I_p\left(\frac{\langle\eta\rangle 2\pi R_0}{A_p}\right)$$

Inductive Drive from Shape(t)

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

$$L_e=\mu_0R_0\frac{a(\varepsilon)(1-\varepsilon)}{1-\varepsilon+\kappa b(\varepsilon)}$$

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

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

Plasma Magnetic Energy Change

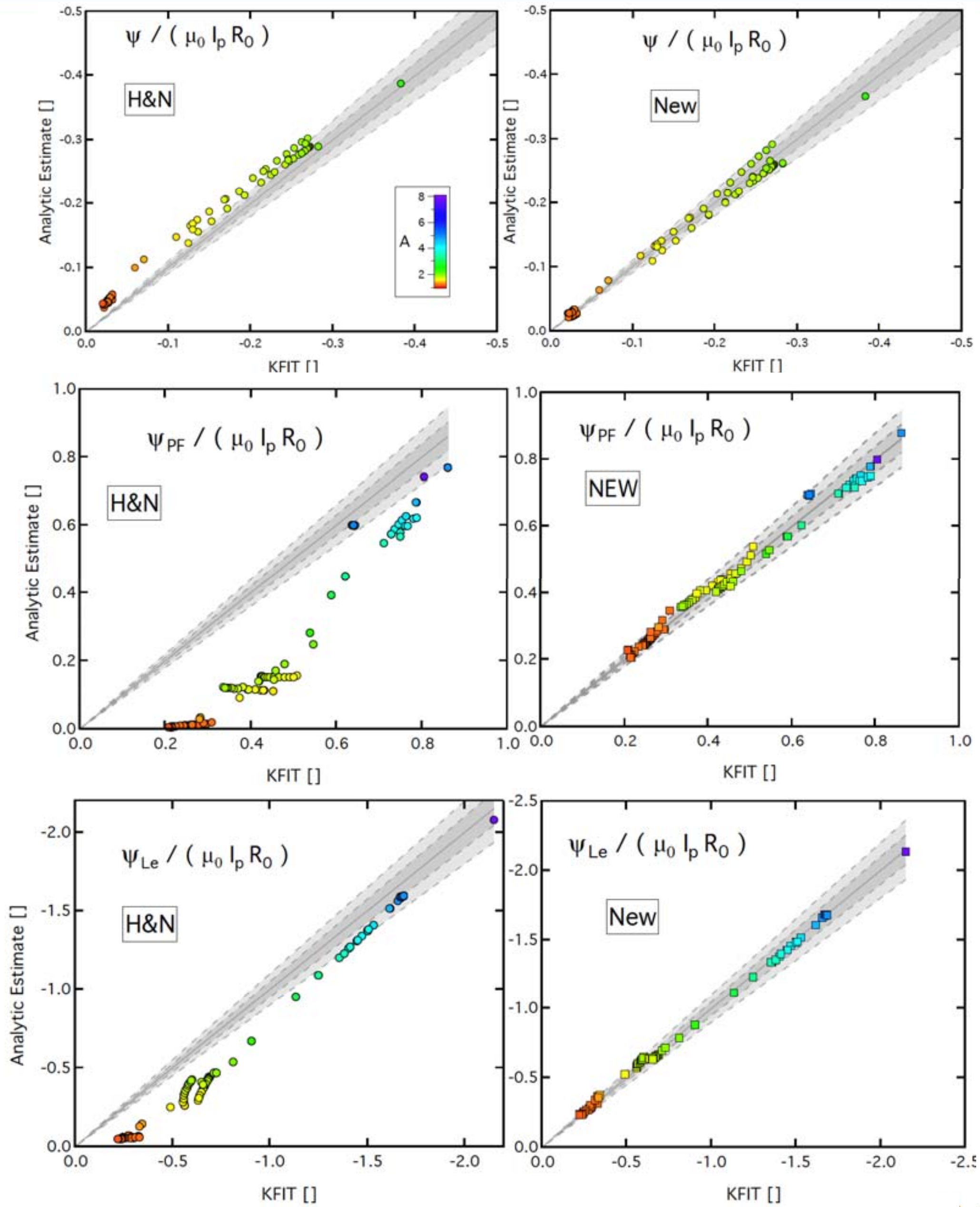
$$V_{W_m}\approx-\frac{1}{I_p}\frac{d}{dt}\left(\frac{1}{2}L_iI_p^2\right)$$

$$\ell_i=\frac{C_p^2}{\mu_0V_p}L_i$$

* S.P. Hirshman and G.H. Nielson 1986 *Phys. Fluids* **29** 790
O. Mitarai and Y. Takase 2003 *Fusion Sci. Technol.*
S. Ejima et al 1982 *Nucl. Fusion* **22** 1313
J.A. Romero and JET-EFDA Contributors 2010 *Nucl. Fusion* **50** 115002

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

- Maintaining radial force balance provides V_{IND}
  - Originally calculated via H-N formulae
- Important to quantify contributions from shape, PF drive in LHI system design
- Model equilibium 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_{IND} between shape, V_{PF} components found
  - However, total flux estimates in better agreement
- Revised V_{IND} model developed
  - Derived new coefficients in H-N formalism via fit to equilibrium database
  - Weak dependence on β_p, ℓ_i introduced



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

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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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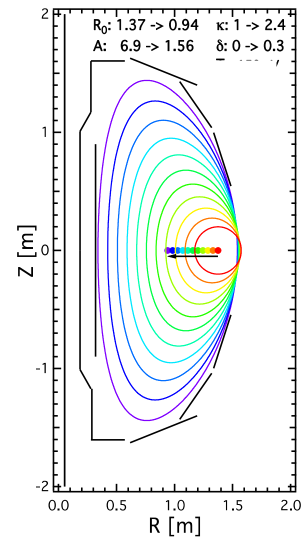
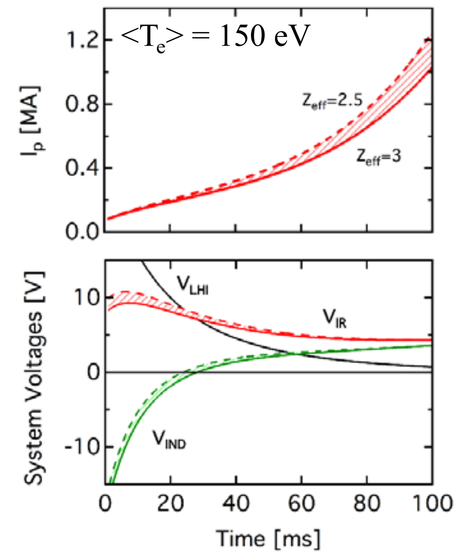
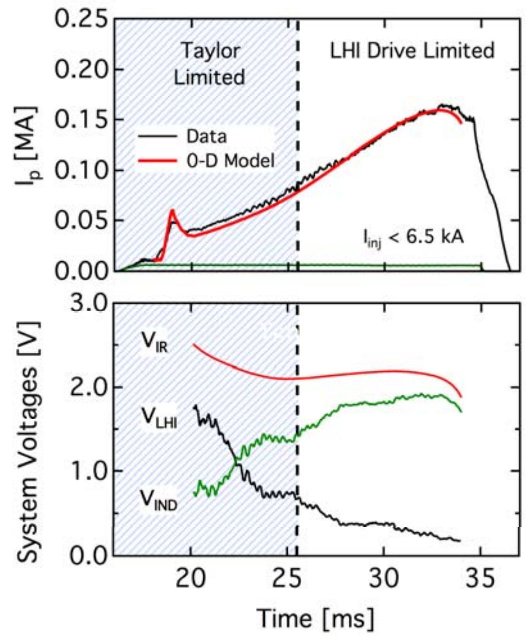
Shape evolution for LFS LHI on NSTX-U



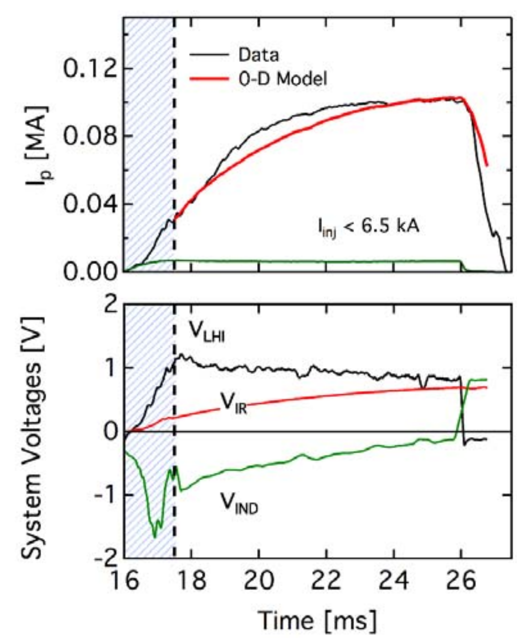
NSTX-U: Projected



LFS PEGASUS

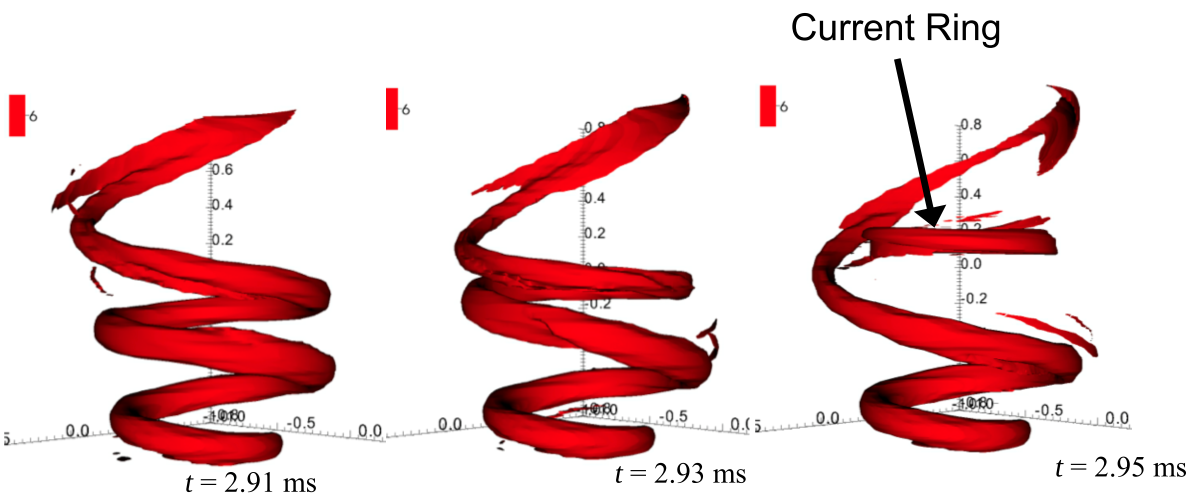


HFS PEGASUS



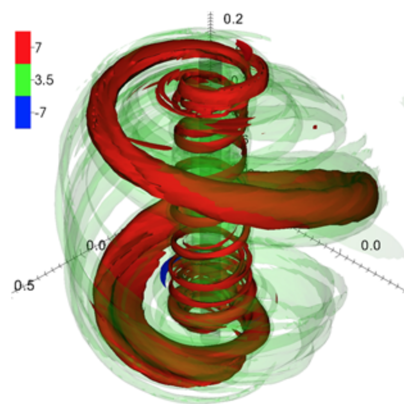
NIMROD Describes Helical Current Stream Reconnection as Drive Mechanism

- Divertor injection → minimal inductive drive

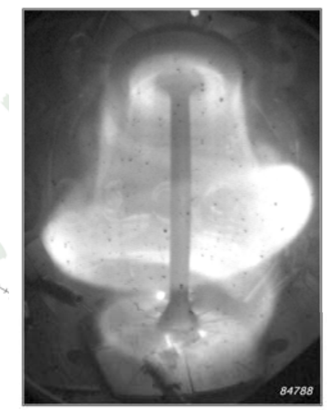


1. Streams follow field lines
2. Adjacent passes attract
3. Reconnection pinches off current rings

Divertor LHI Startup Shows suggestive commonality between experiment and NIMROD modeling



NIMROD Simulation [O'Bryan PhD 2014]

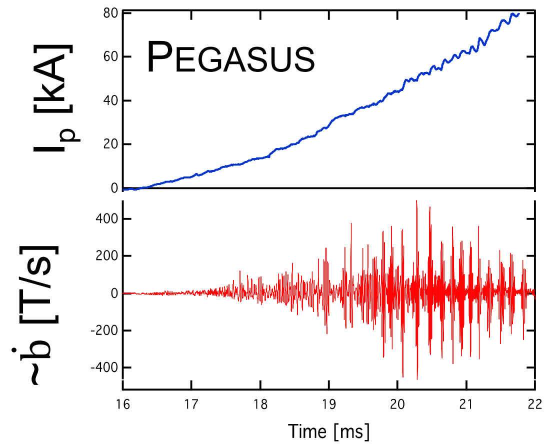


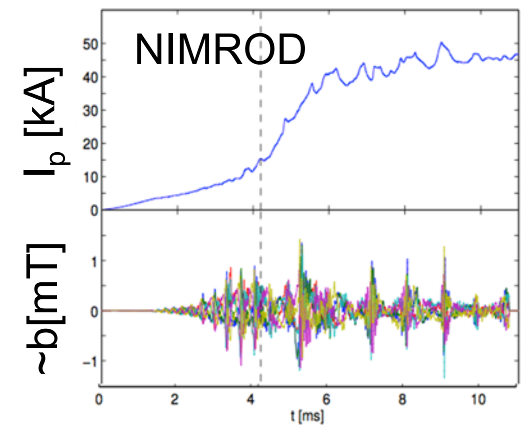
May 2016 PEGASUS High-speed Imaging

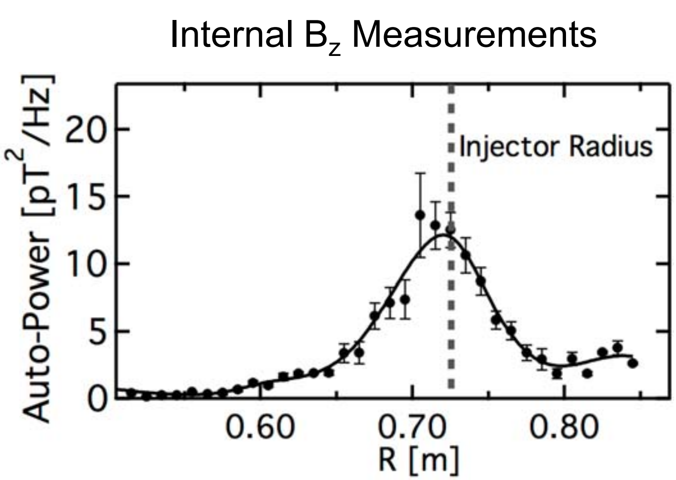
*J. O'Bryan, et al., Physics of Plasmas, **19**, 080701 (2012)*
*J. O'Bryan, C.R. Sovinec, Plasma Phys. Control. Fusion **56** 064005 (2014)*

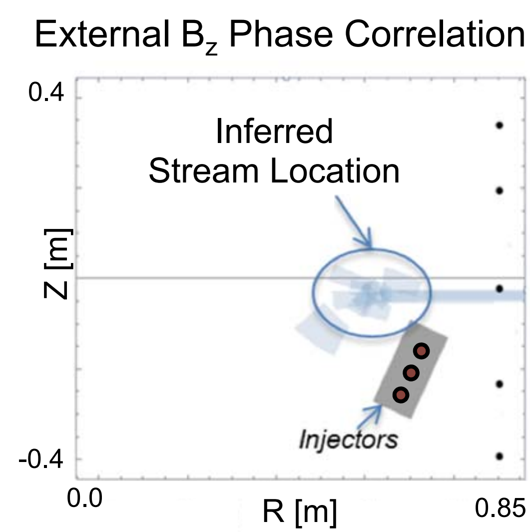
Current Stream Interaction Manifests as Edge-Localized MHD Burst

- 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





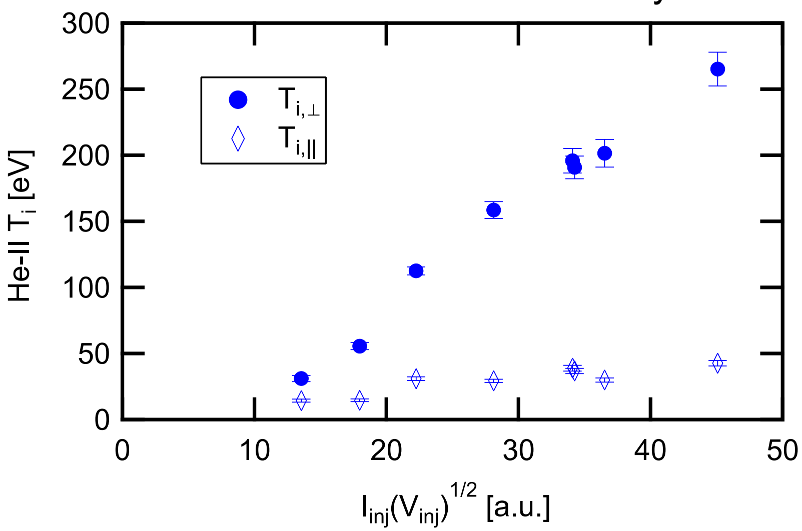




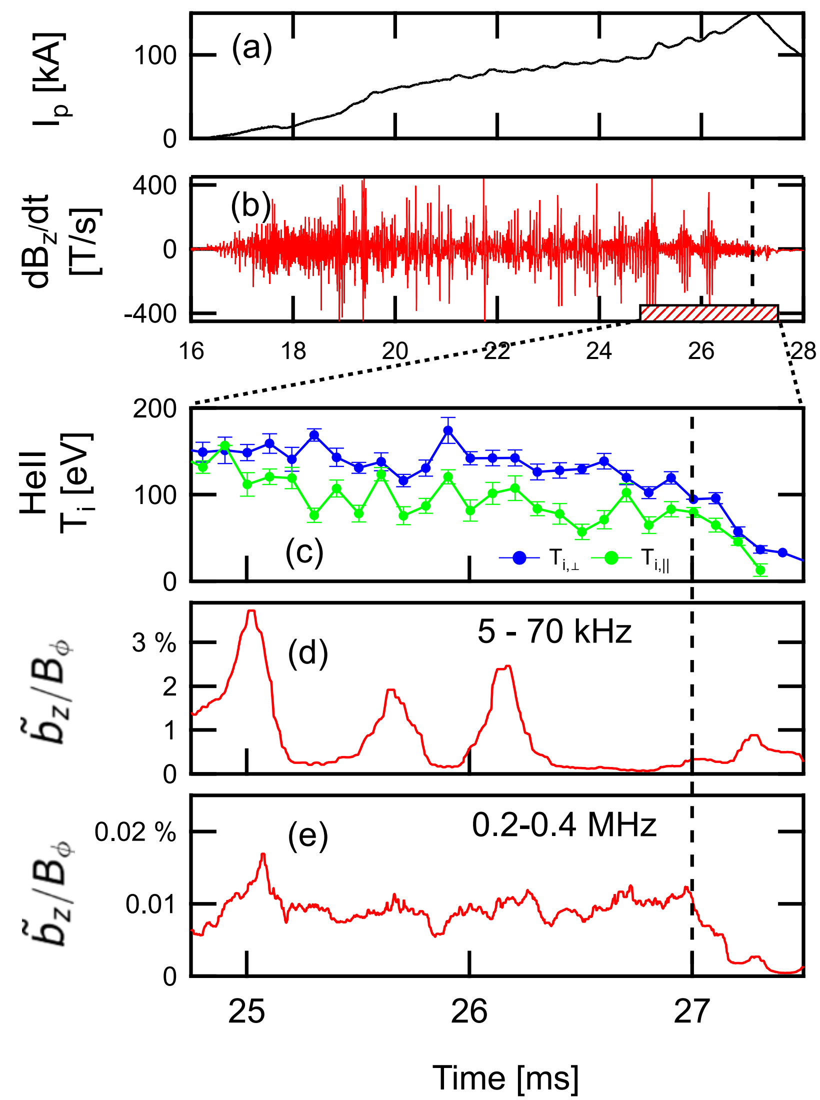
Reconnection-Driven Ion Heating Gives $T_i > T_e$ During LHI

- Impurity $T_i(0)$ ~ 100 – 500 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 consistent with 2-fluid reconnection theory



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



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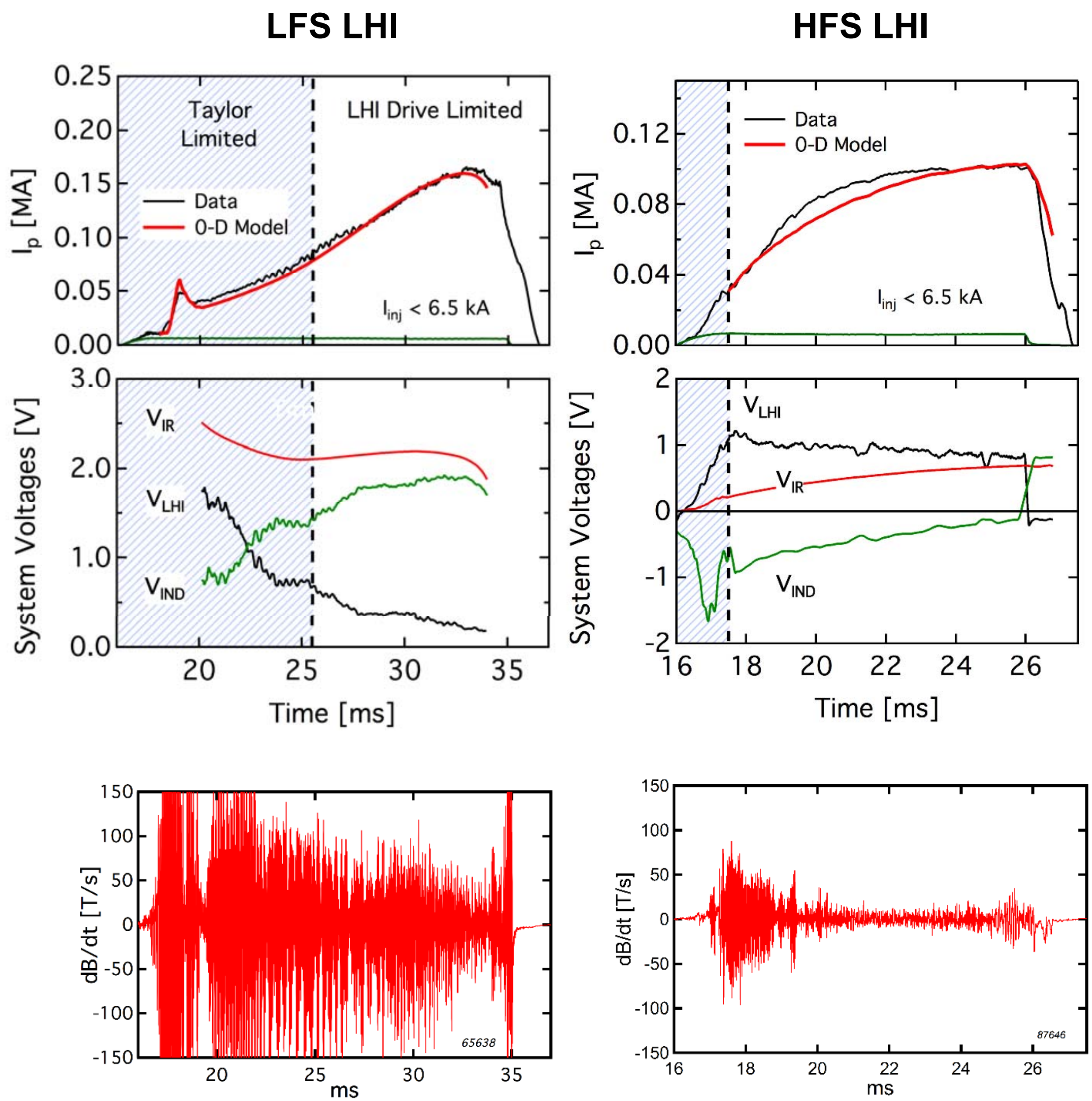
Different MHD Activity Observed Between LFS and HFS Injection Geometry

- 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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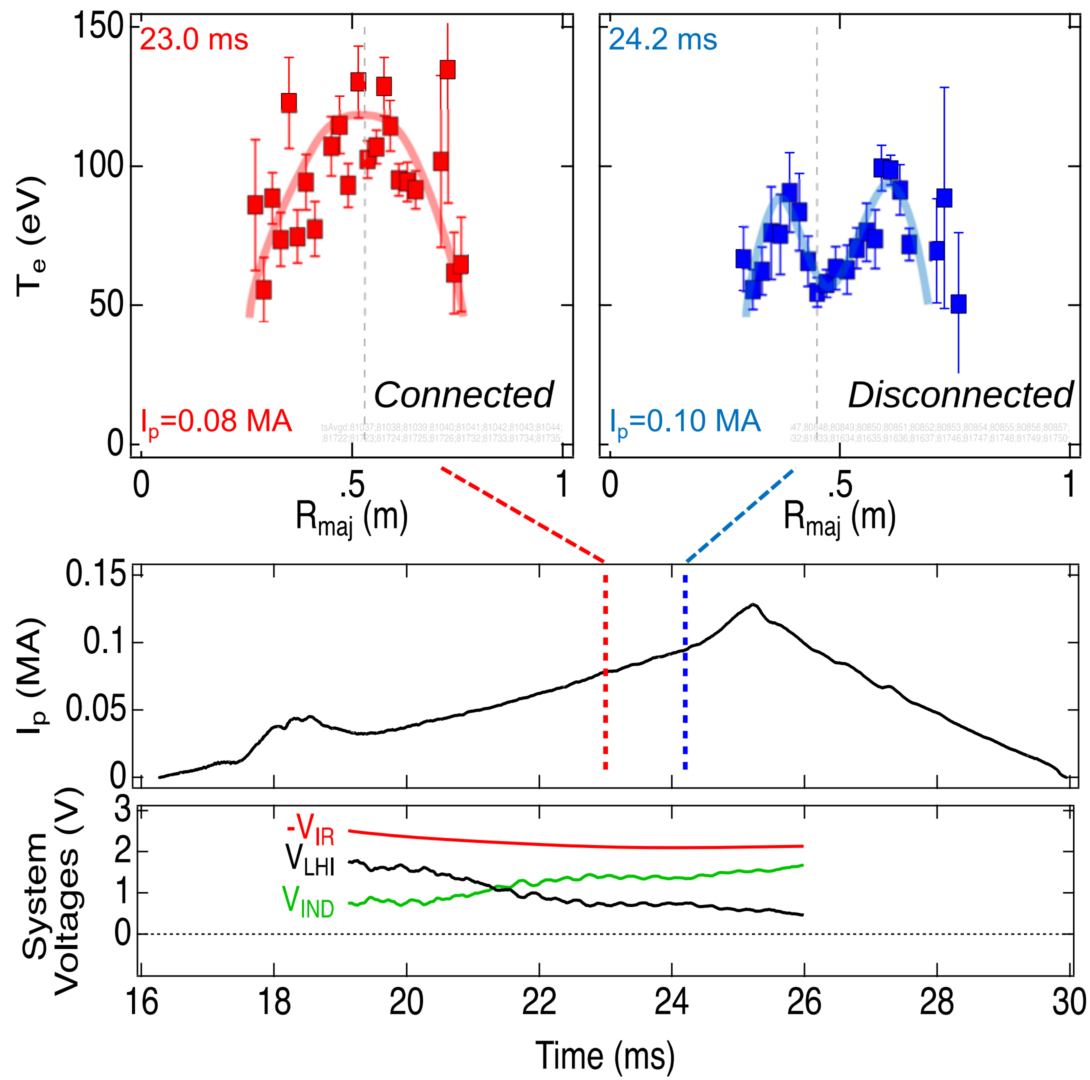
LFS Local Helicity Injection Produces Core T_e > 100 eV

- Plasma shape grows inward from LFS injectors
  - Shape evolution generates V_{IND}
  - $V_{IND} > V_{LHI}$ 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

Peaked $T_e(R)$ while Connected to Injectors



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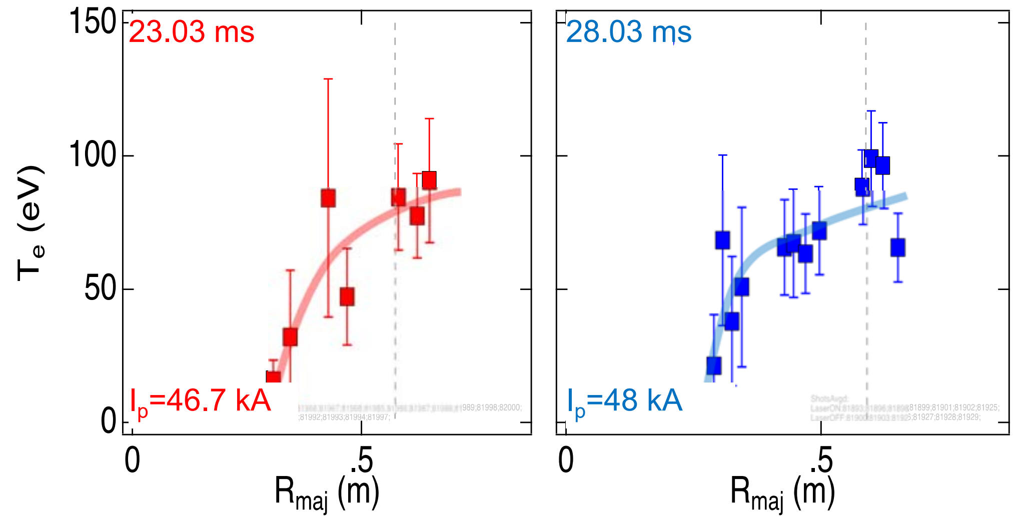
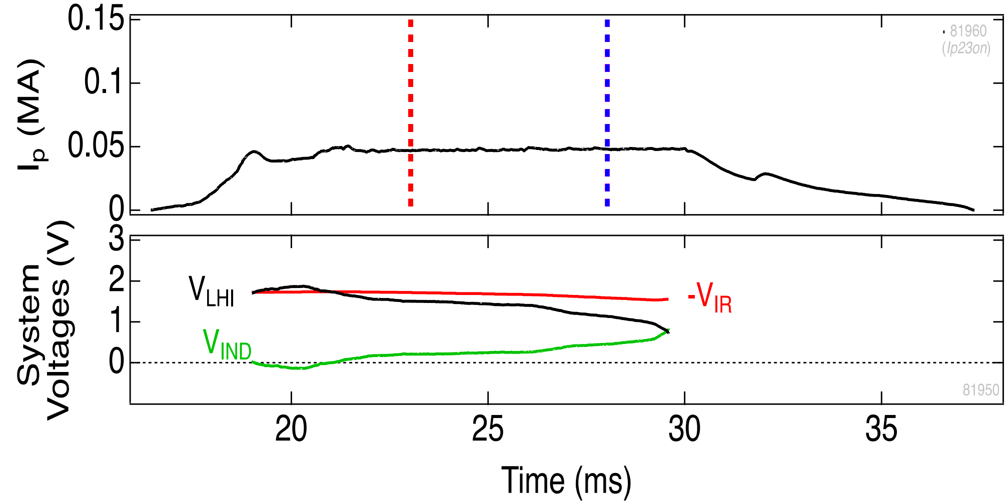
T_e (R, t) Remains Peaked for LFS Injection Geometry and Minimal V_{IND}

- Plasmas with same LFS LHI system and static geometry evolution
  - Lower performance due to shape constraint
    - High R_0, reduced A_{plasma}
  - $V_{IND} \sim 0 < V_{LHI}$; $T_e(0) \sim 80$ eV

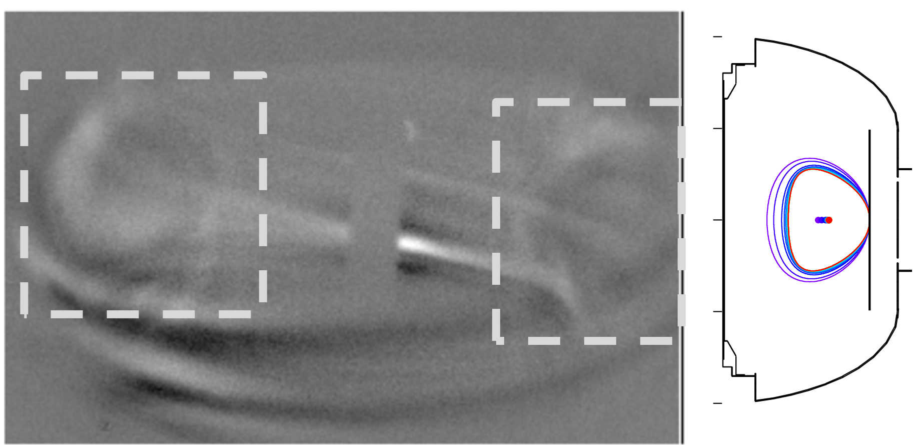
- T_e(R) peaked while driven by outboard LHI

T_e(R) > 85 eV with majority LFS LHI-drive





Contrast-enhanced high-speed image and fast boundary reconstructions



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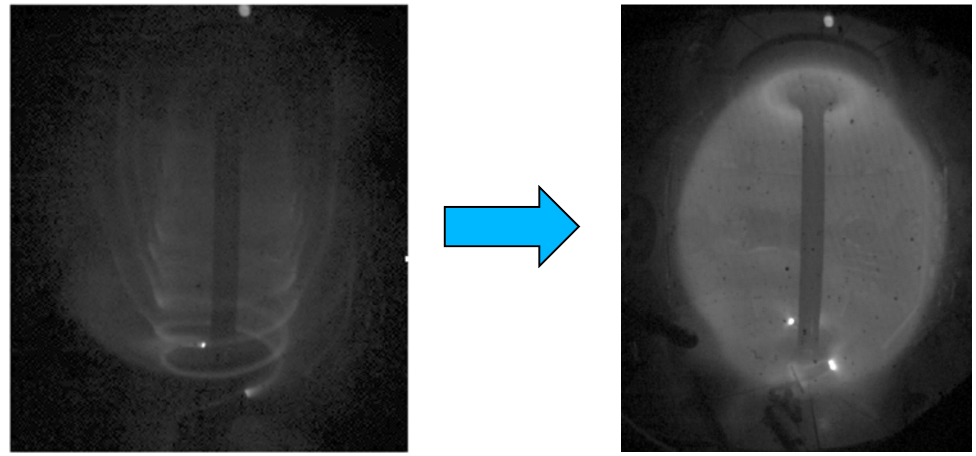
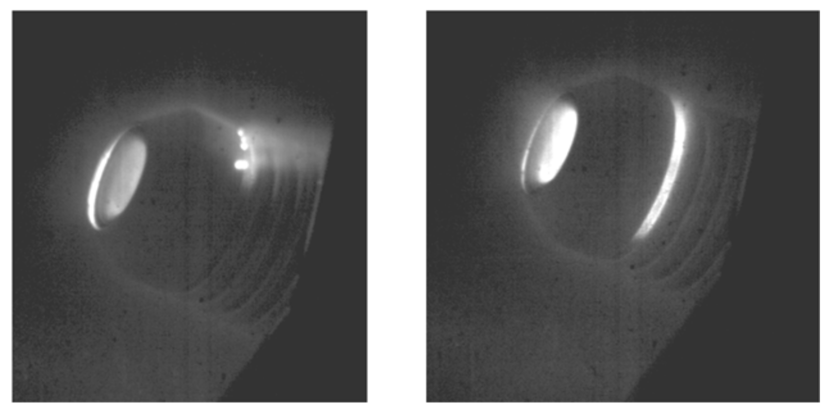
Technical Challenges Arise for LHI Startup With HFS Injection Geometry

- Initial relaxation to tokamak state
  - More difficult for low R_{inj}, high B_{inj}
  - Magnetic geometry constrained by injector clearance requirements
- Current source behavior at increased B_{inj}
- Plasma-material interactions
  - PMI on injector surfaces
    - inhibits V_{inj}
    - can damage injectors
  - PMI on machine surfaces
    - Impedes reproducibility
    - More severe for HFS injection



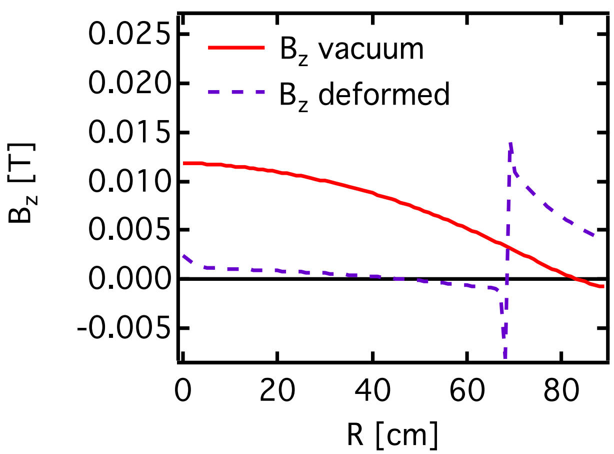
Above: LHI plasma before and after relaxation

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

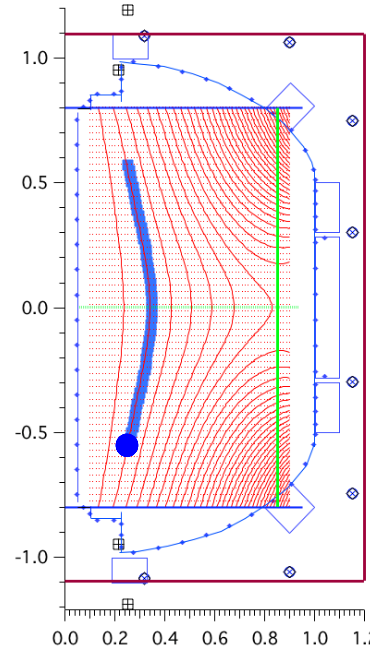


Poloidal Field Shaping Facilitates Relaxation at Full Toroidal Field (B_{inj} = 0.23 T)

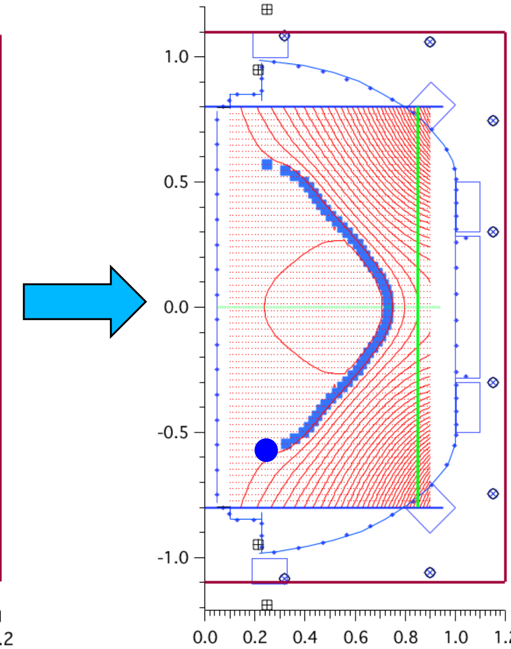
- Milestone for HFS LHI system achieved
- Technical challenge with HFS injectors:
  - Lower R_{inj} → higher B_{TF} with respect to LFS system
    - → more B_z for injector clearance (~ B_z/B_{TF})
  - B_{TF} increased ~ 10× over previous experiments
    - → Relaxation at constant I_{inj} more difficult
- Poloidal field shaping key to full-field relaxation
  - Reduces midplane |B| and maintains injector clearance
  - Limited by I_{inj}-deformed streams contacting vessel

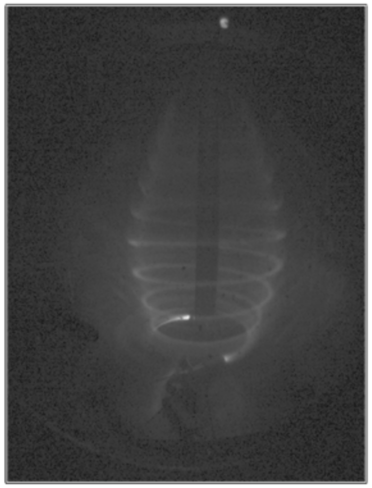


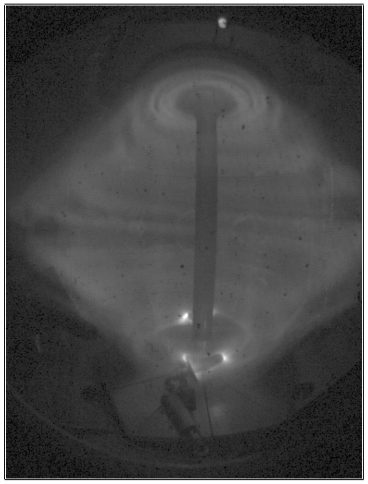
Vacuum Field



Deformed Field

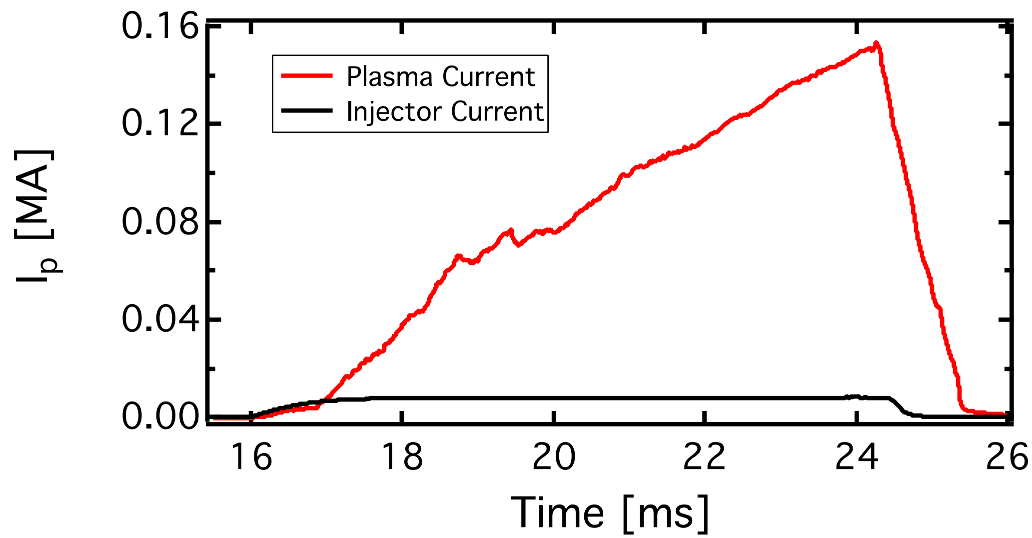


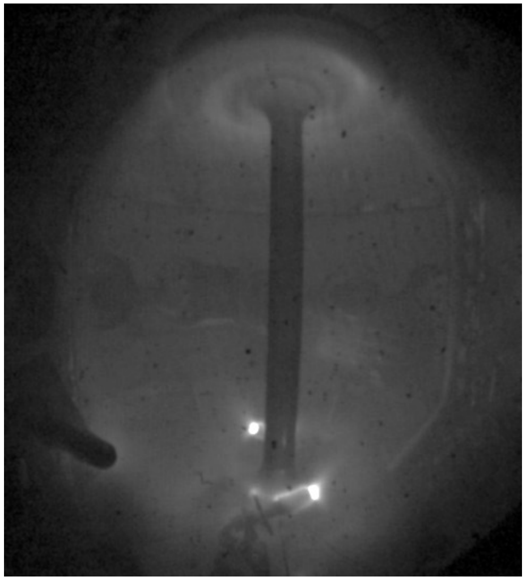




I_p > 0.15 MA Achieved Via HFS Injection To Date

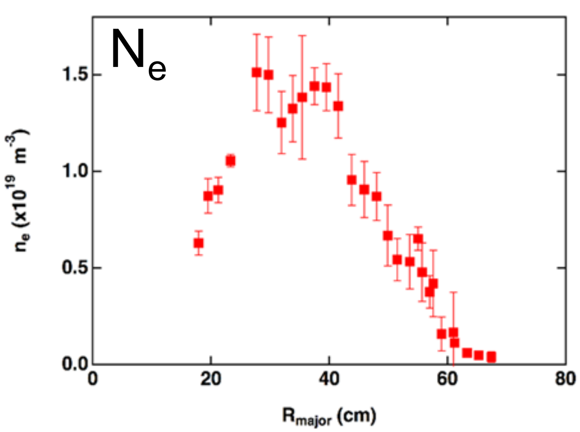
- V_{LHI} ~ 1 kV increased 2× over previous HFS LHI experiments
- Most operations at low field:
  - B_{inj} = 0.046-0.092 T
    - (20-40% of Pegasus maximum)
  - Reduced PMI, easier relaxation
- Full B_{TF} scenarios developed
  - B_{inj} = 0.23 T, I_{TF} = 0.288 MA
  - $I_p \approx 0.1$ MA
  - PMI more prevalent at high B_{TF}
- Injector geometry variants addressing observed PMI
  - Improvements found in each iteration

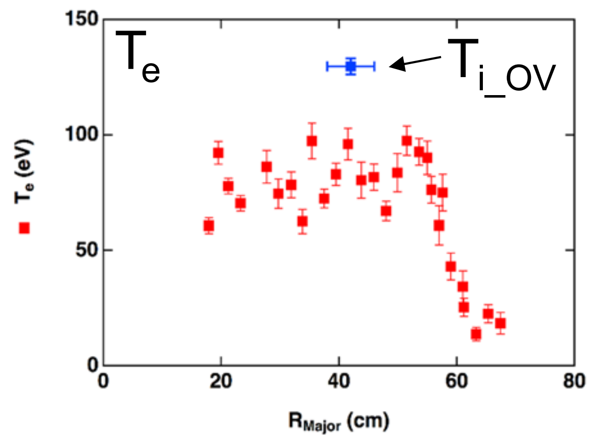




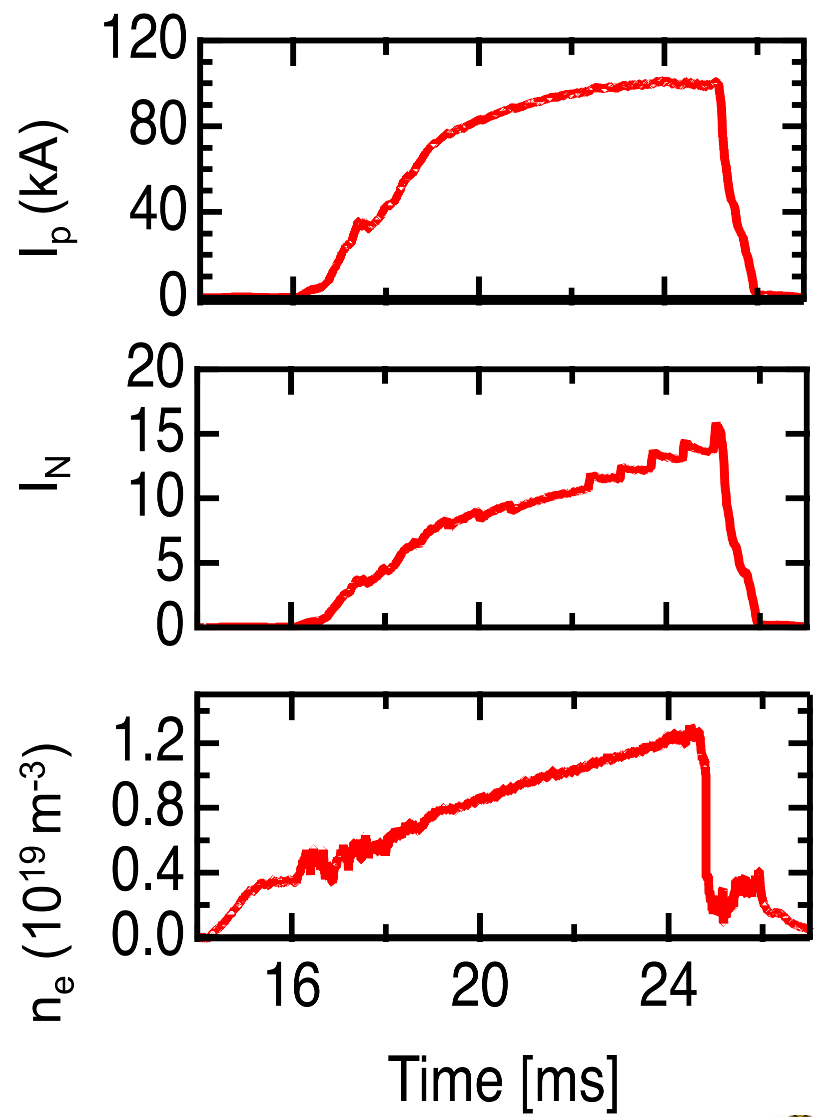
HFS Helicity Injection Provides Non-Solenoidal Sustainment at High I_N

- 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 β_T
  - Aided by anomalous ion heating





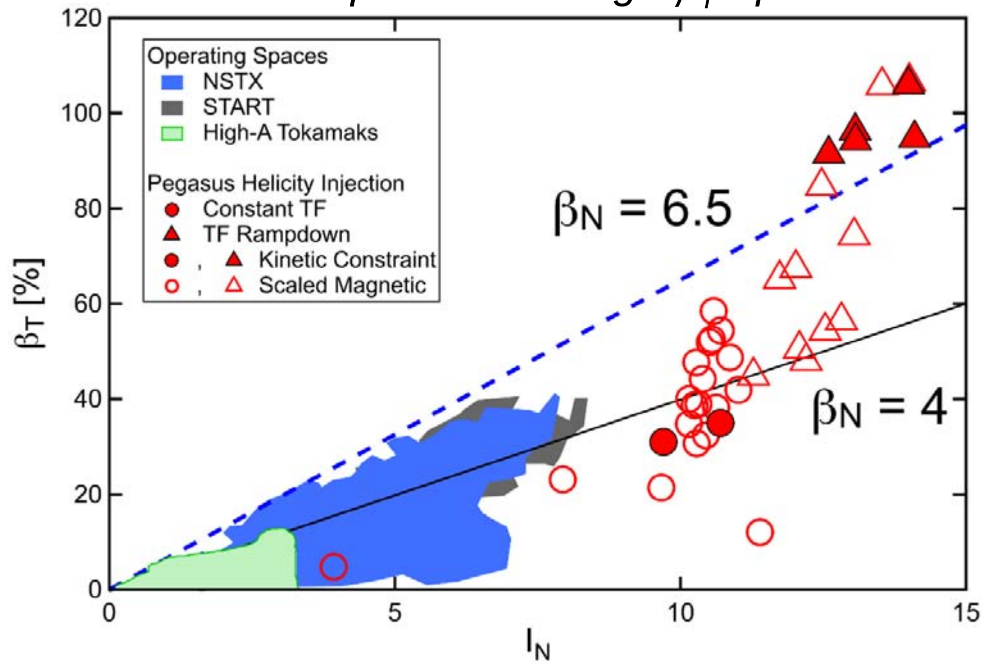
Access to $I_N > 14$, $n_e \sim 1x19\ m^{-3}$ with HFS Injection, B_{TF} Rampdown



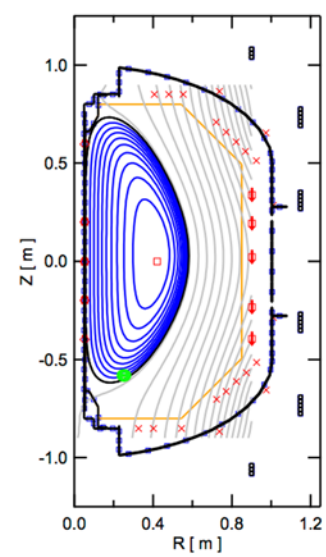
LHI Provides Access to High-β_T at A ~ 1 with Non-Solenoidal Sustainment and Anomalous Ion Heating

- Equilibrium reconstructions with kinetic constraints used to determine $\beta_T \equiv 2\mu_0 \langle p \rangle / B_{T0}^2$
  - 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

Initial Exploration of High-β_T Space



- High β_T plasmas often terminated by disruption
  - n = 1, low-m precursors



Equilibrium Parameters
Shot 87332, 24.50 ms, Undo 72

I_p	102 kA	R_0	0.317 m
β_t	0.95	a	0.263 m
ℓ_i	0.22	A	1.21
β_p	0.45	κ	2.6
W	545 J	δ	0.54
B_{T0}	0.0249 T	q_{95}	7.24

- Expands accessible high I_N, β_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_{TF} access

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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 β_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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