# Non-solenoidal Tokamak Startup and Near-Unity Toroidal Beta Using High-Field-Side Local Helicity Injection on the Pegasus ST


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G.M. Bodner, M.W. Bongard, M.G. Burke, R.J. Fonck, J.L. Pachicano, C. Pierren, N.J. Richner, C. Rodriguez Sanchez, D.J. Schlossberg, J.A. Reusch, and J.D. Weberski

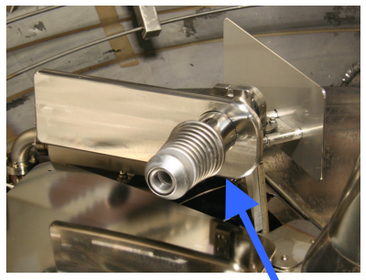
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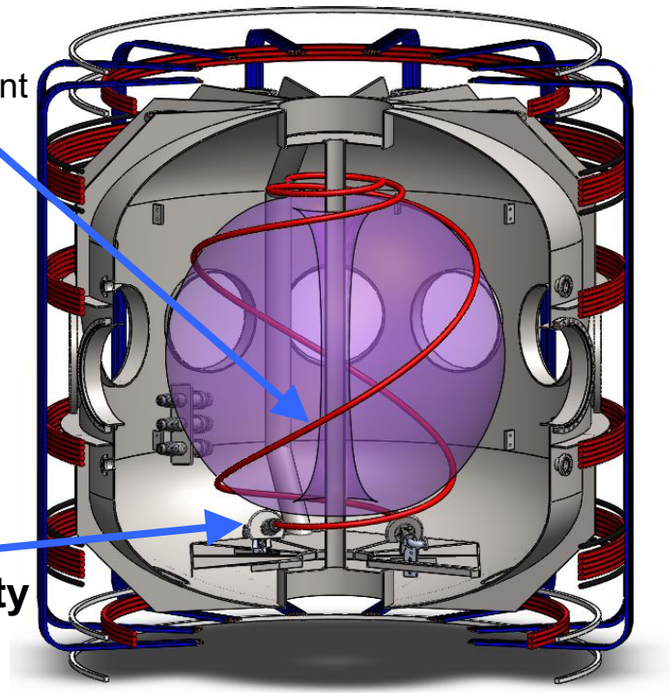

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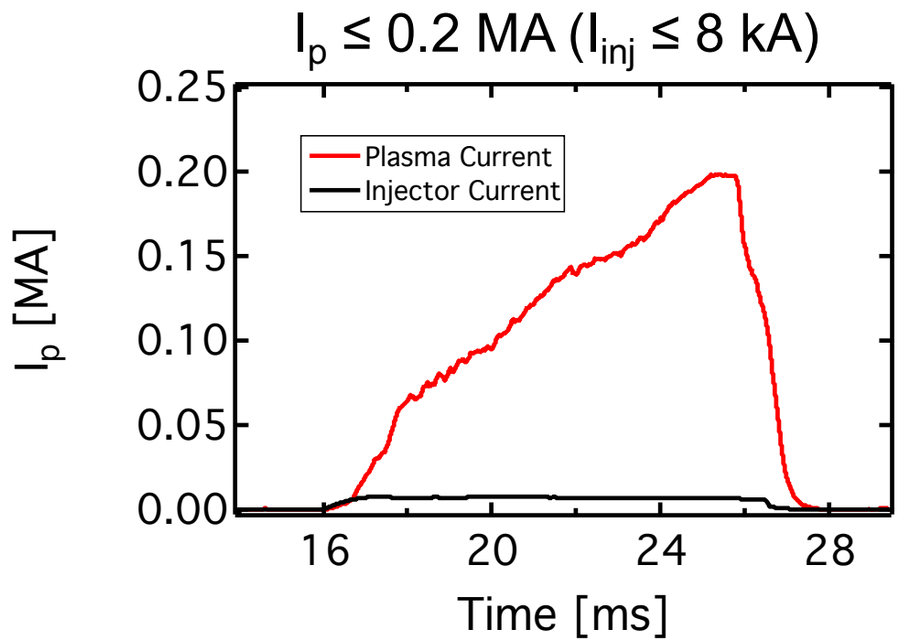
PEGASUS Toroidal Experiment

# Local Helicity Injection (LHI) is a Promising Non-Solenoidal Startup Technique






- Edge current extracted from injectors
- Relaxation to tokamak-like state via helicity-conserving instabilities
- Used routinely for startup on Pegasus



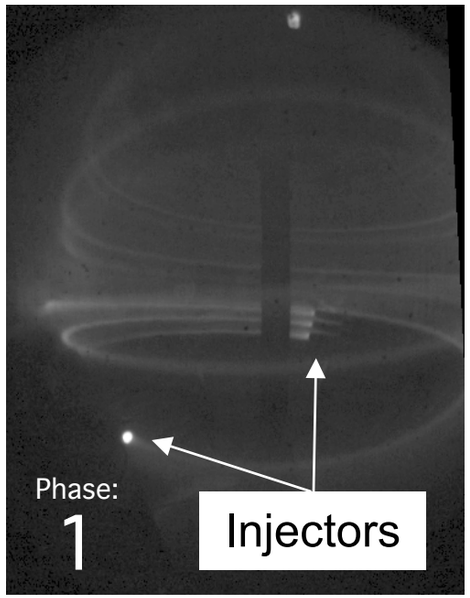

- Current drive quantified by:

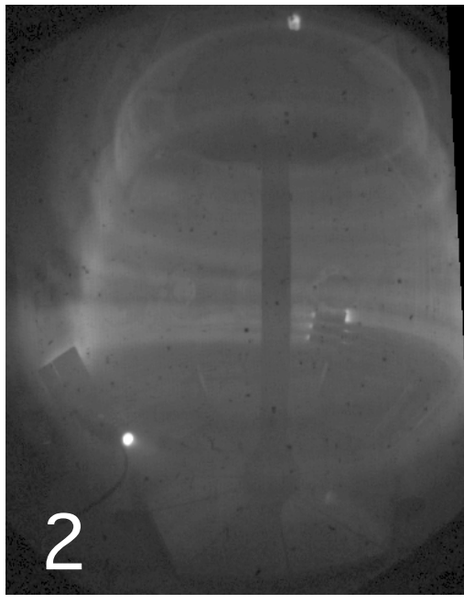
$$V_{LHI} \approx \frac{A_{inj} B_{\varphi,inj}}{\Psi} V_{inj}$$

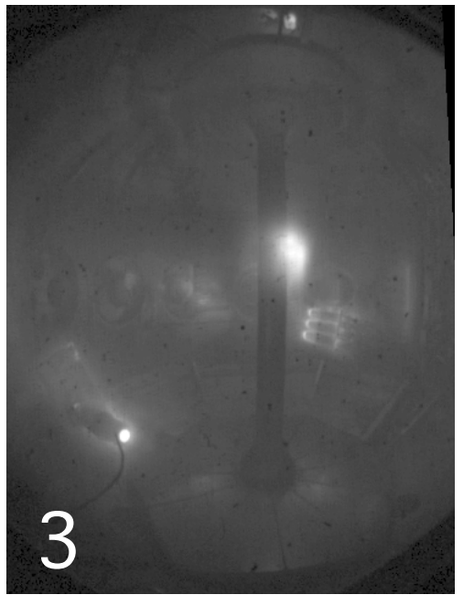
*J.M. Perry EPR 2017*

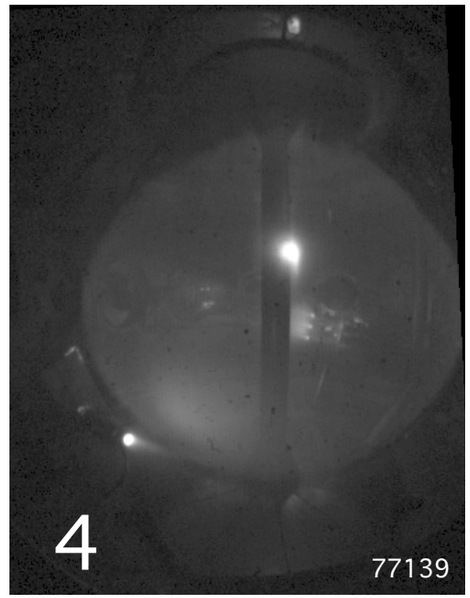
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# Local Plasma Sources Inject Current Streams that Reconnect, Form Tokamak-like Plasma



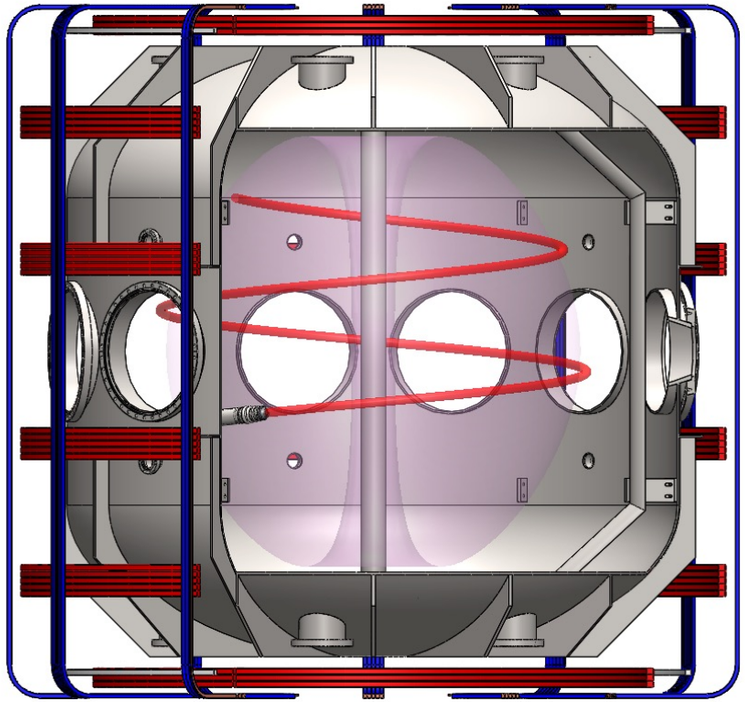




- Local source: Helical plasma streams
- Instability: Current driven along streams
- Reconnection: relaxation to tokamak-like state, current growth
- Result at bias shutdown: Tokamak



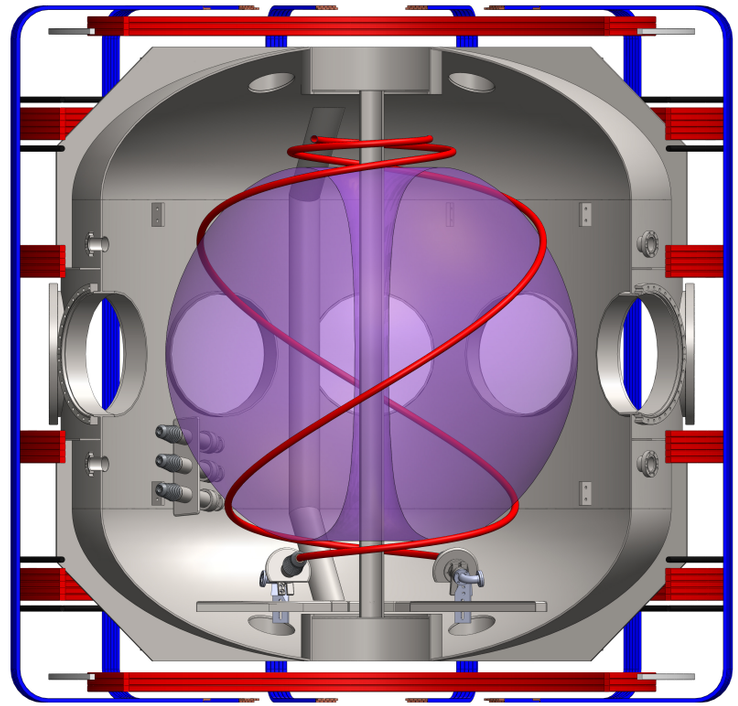
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# Flexible Injector Geometry: Accessing Different Physics Through Varied Injector Location



## Low-Field-Side (LFS) Injection:

- Injectors on outboard mid-plane



## High-Field-Side (HFS) Injection:

- Injectors in lower divertor

# Low-Field-Side Injection Dominated by Inductive Current Drive

- Injector location: tradeoff between HI driven and inductively driven current

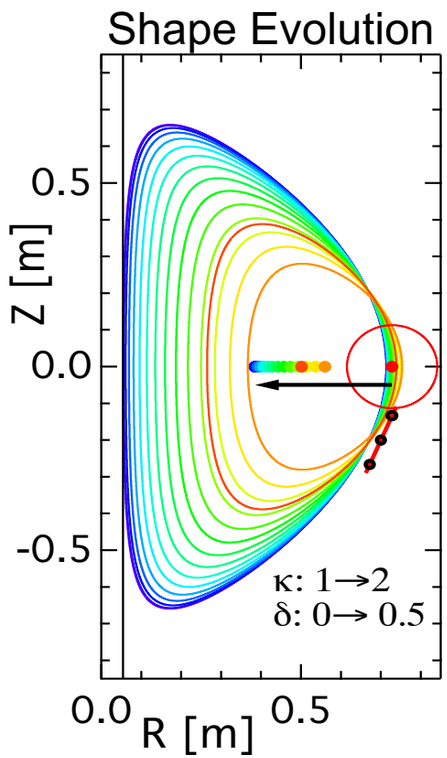
- Power balance relation:

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

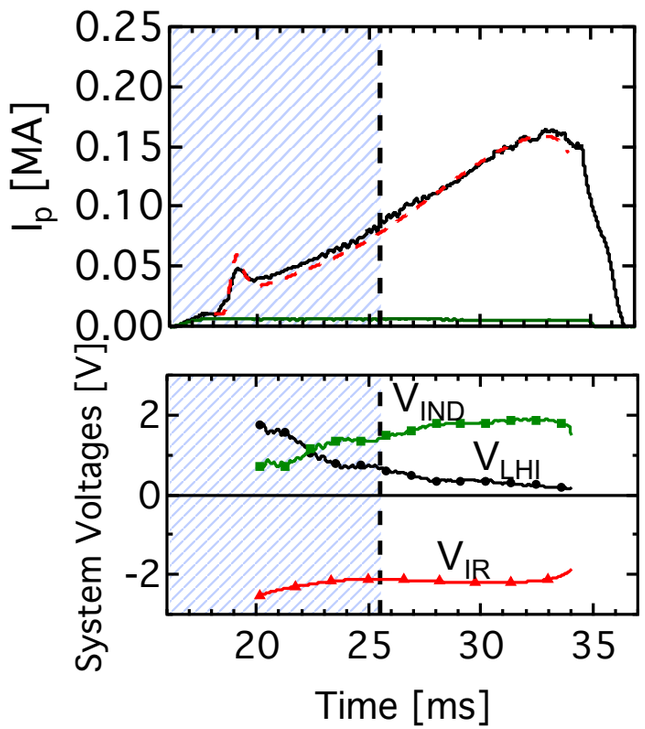
- Confinement behavior may be affected by dominant current drive type

- LFS injection maximizes inductive drive, $V_{IND}$

- Radial compression → large $V_{IND}$




- Net induction voltage dominates current drive






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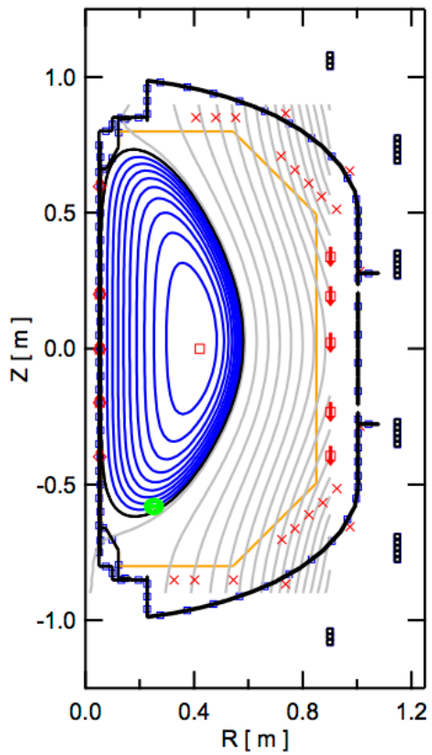
# In Contrast, HFS Injection Dominated by Helicity Drive

- Low $R_{inj}$ → high $V_{LHI}$

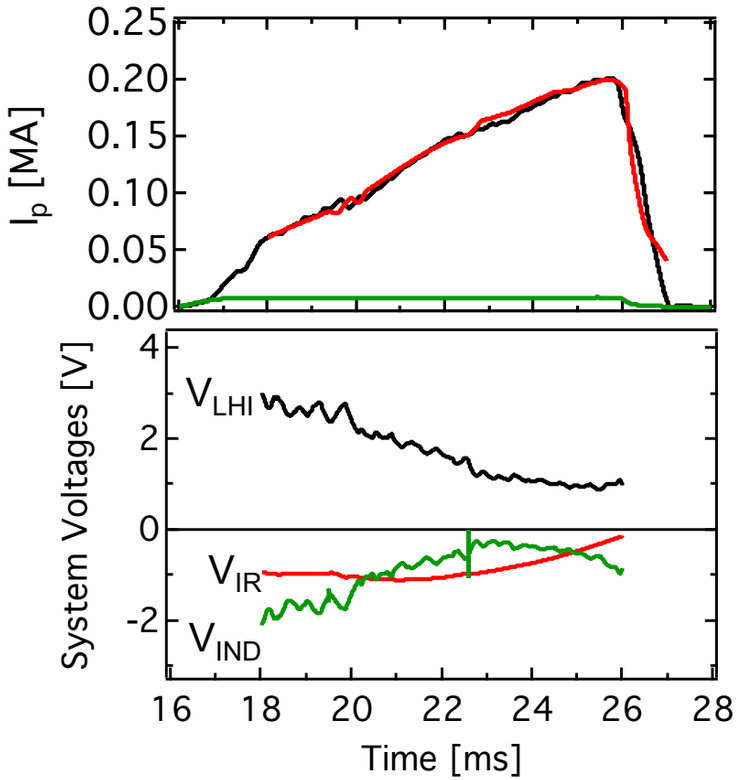
$$V_{LHI} = \frac{V_{inj} A_{inj} B_{inj}}{\Psi_{TF}} \sim \frac{1}{R_{inj}}$$

- HFS injection minimizes $V_{ind}$
- Fully HI-driven system may have different transport properties

- Static plasma shape → low $V_{IND}$




- HI dominates current drive



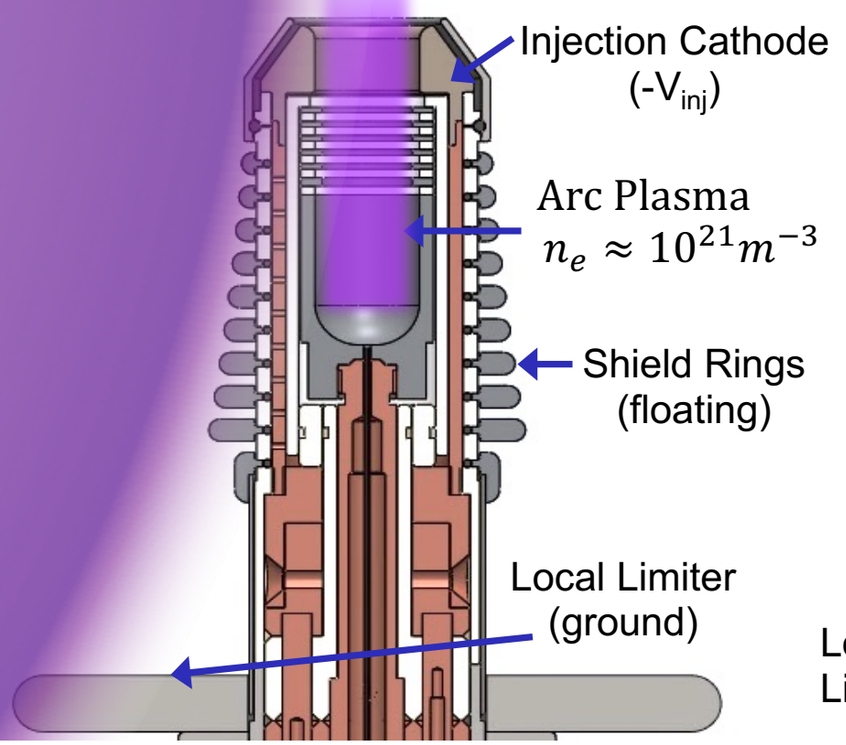



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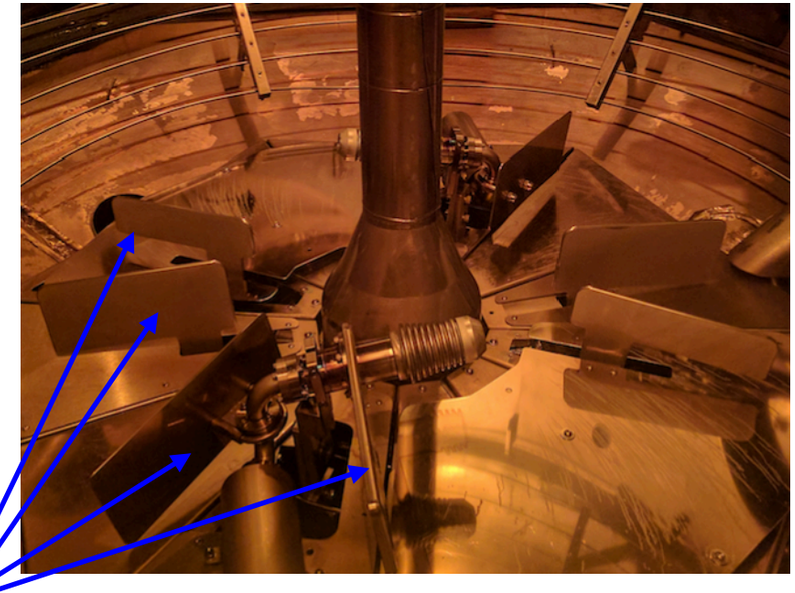
# HFS Divertor Injectors Installed to Study HI-Dominant Regime

Tokamak Plasma Edge

$n_e \approx 10^{19} m^{-3}$




- 2 injectors in lower divertor
- 4x $V_{LHI}$ over LFS Injection
- $A_{inj}$ = 8 cm$^2$; $V_{inj}$ ≤ 1.5 kV; $I_{inj}$ ≤ 8 kA (8-12 MW total power)

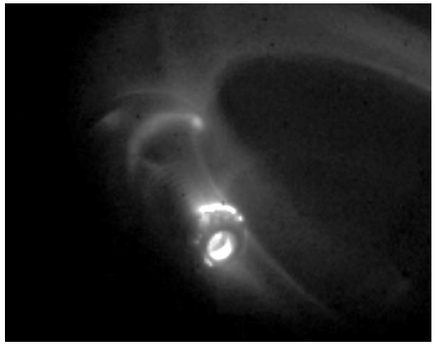


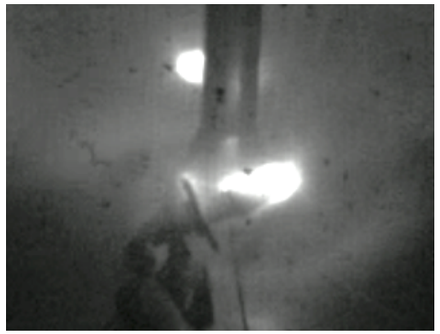
Local Plasma Limiters

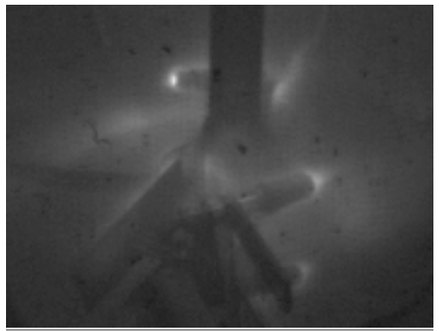
*J.M. Perry EPR 2017*

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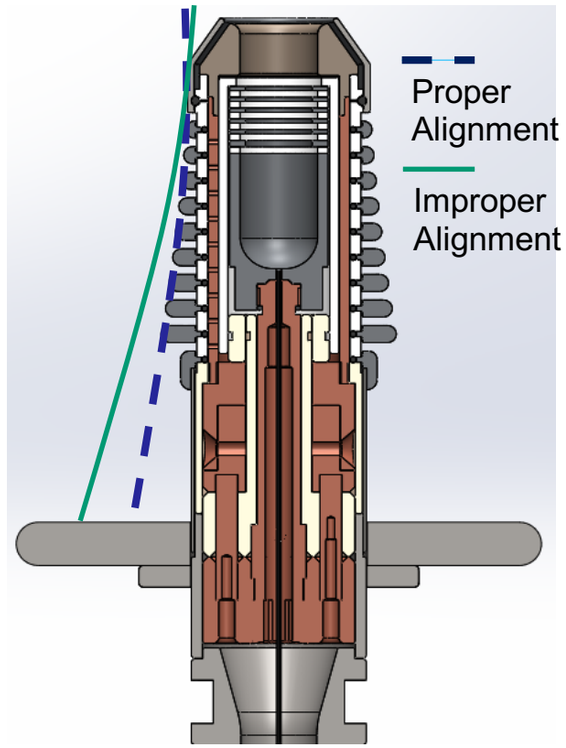
# Injector Alignment, Local Limiters Critical to PMI Mitigation







- Improper alignment to local field:
  - Arc-back to limiter
- Improper limiter placement:
  - Injector immersed in plasma
  - Cathode spots on injector
- Proper alignment:
  - Injector shadowed
  - Improved high voltage standoff






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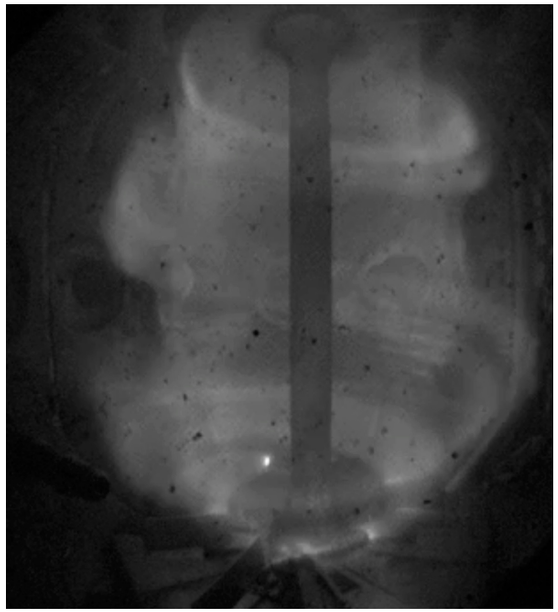
# Initial Relaxation to Tokamak State Requires Strong Deformation of Vacuum Field

Injected current weakens vacuum $B_z$



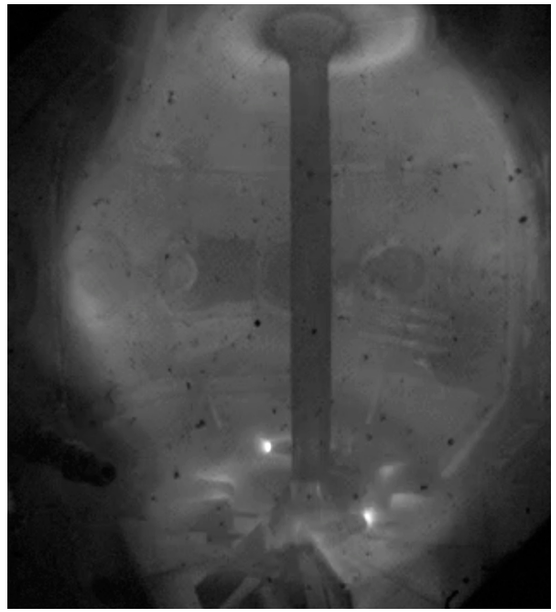
$I_p \sim N_{turns} \bullet I_{inj}$

Unstable current streams attract and reconnect



$I_p \gtrsim N_{turns} \bullet I_{inj}$

Tokamak-like plasma; rapid $I_p$ growth



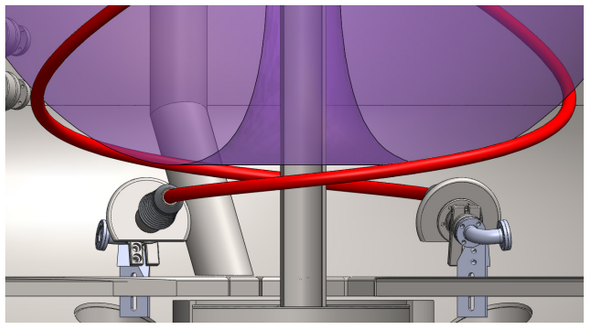
$I_p \gg N_{turns} \bullet I_{inj}$



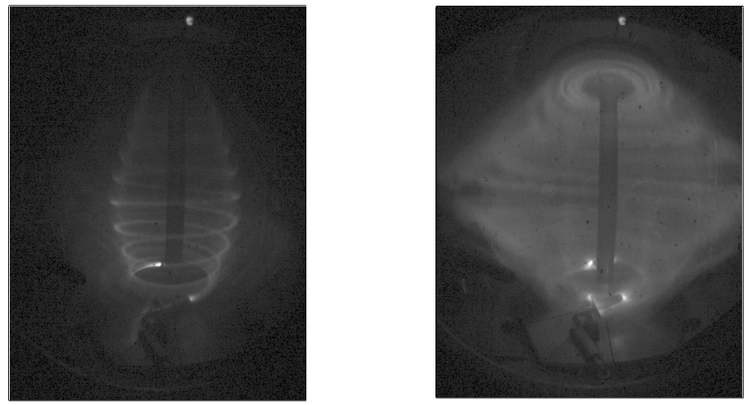
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# Relaxation Challenges with HFS Injection Addressed

- Injector geometry sets minimum pitch ($B_z$ / $B_{tor}$) for stream clearance

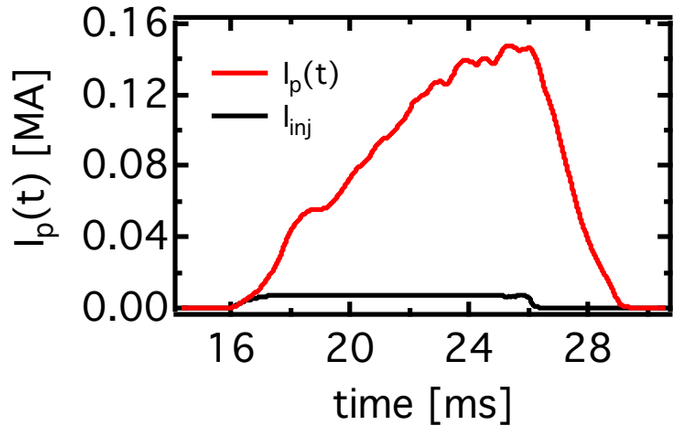


*Deformed $B_{vac}$ aids relaxation*



- HFS injection:
  - Lower $R_{inj}$ → more $B_z$ for clearance
  - Relaxation impeded for fixed $B_t$, $I_{inj}$
- Solution: poloidal field shaping
  - $B_z$ strong in divertor; weak at midplane
  - Increased $I_{inj}$ required at increased $B_t$

- Relaxation achieved at full Pegasus $B_t$

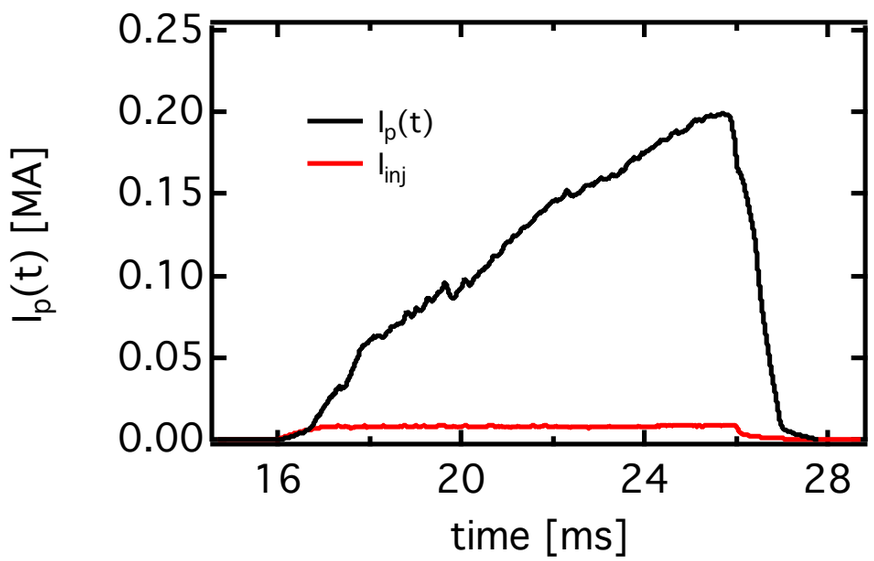




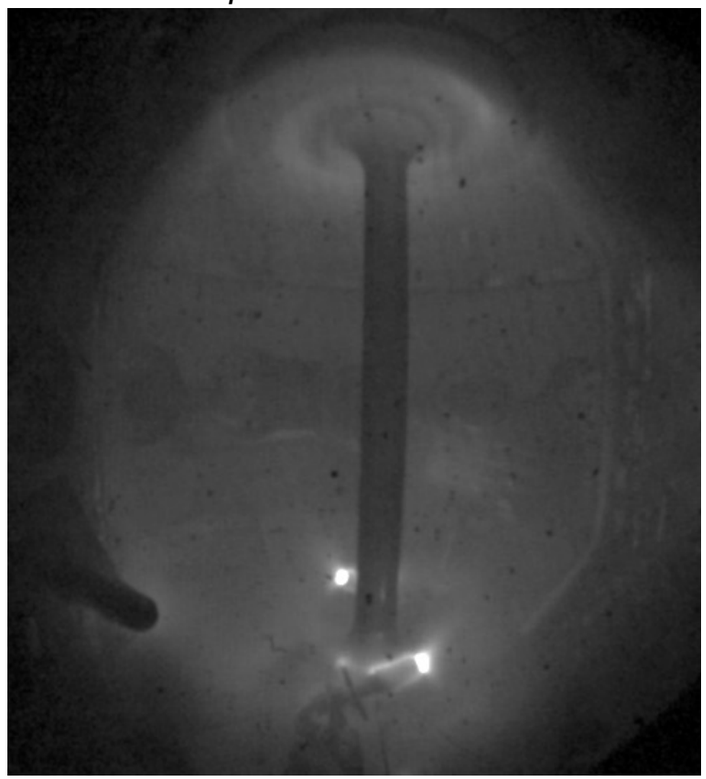

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# High $I_p$ Attained at Static Geometry with HFS Injection

- 0.2 MA startup achieved
  - Current multiplication 40 x $I_{inj}$
- $V_{LHI}$ increased 4x over LFS injection
  - Access to high $I_p$ with $V_{LHI}$ dominant




*High $I_p$, $V_{LHI}$ Dominant*

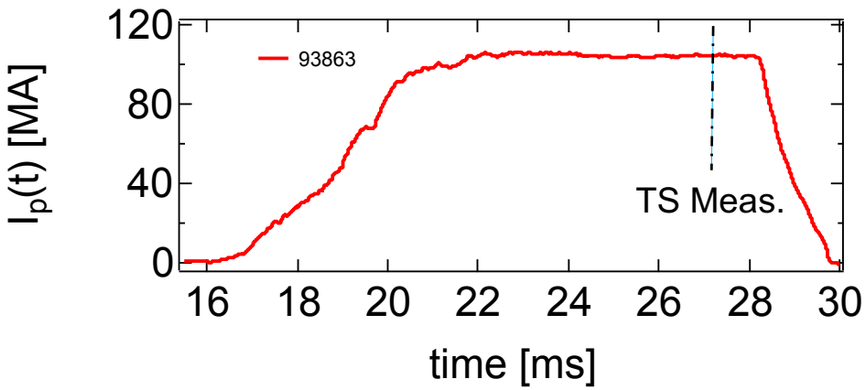


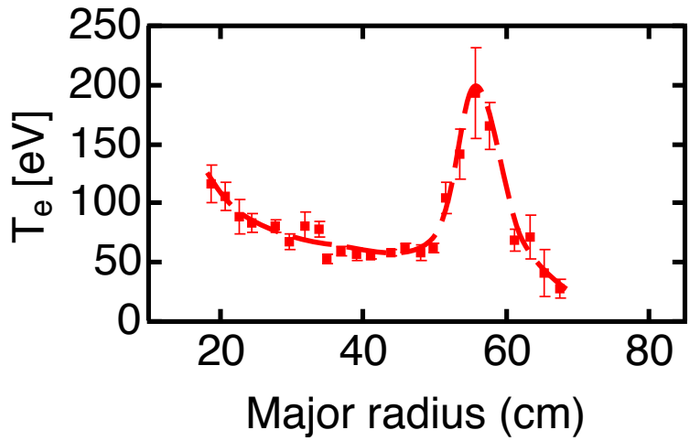


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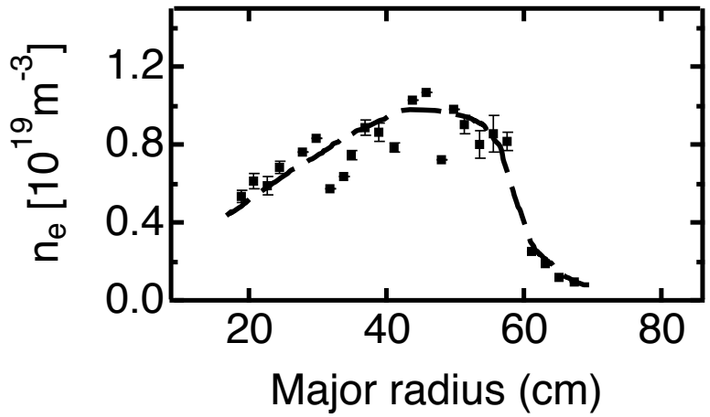
# Thomson Scattering Often Shows Hollow $T_e$, Peaked $n_e$

- Static geometry, LHI-only discharges




- Issues under study:
  - Core vs. edge transport
  - $Z_{eff}$, $P_{rad}$
  - Pulse length
  - $B_t$, $n_e$ effects

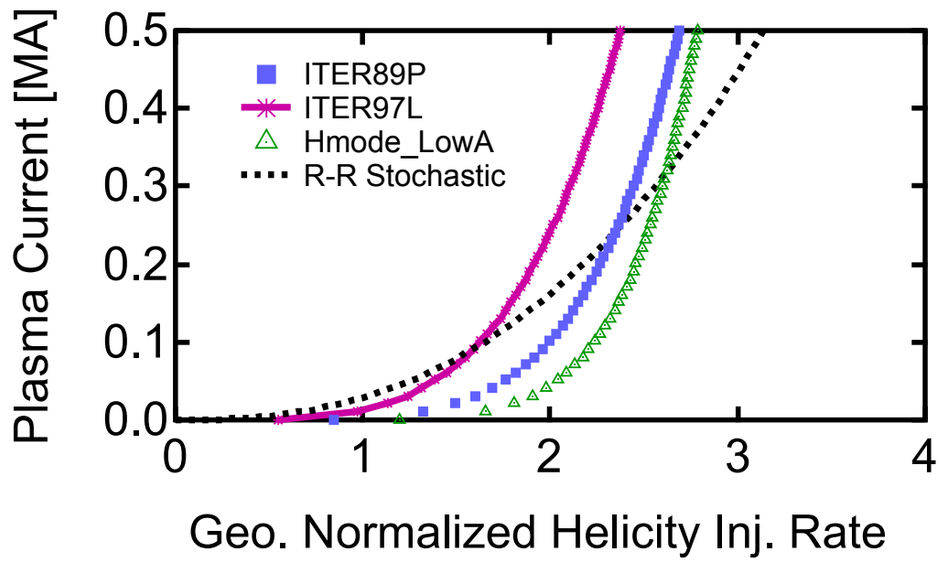





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# Projecting Forward: Dissipation of Helicity is a Main Issue

- Helicity input balanced by resistive dissipation
  - Plasma resistivity influenced by confinement properties
- Crude estimates of confinement inform operation space, assuming:
  - $P_{in} = V_{LHI} \bullet I_p$
  - $Z_{eff} = 1$
  - Fixed plasma geometry, $B_t$
- Understanding how $I_p$ depends on HI rate is critical to predictive capability

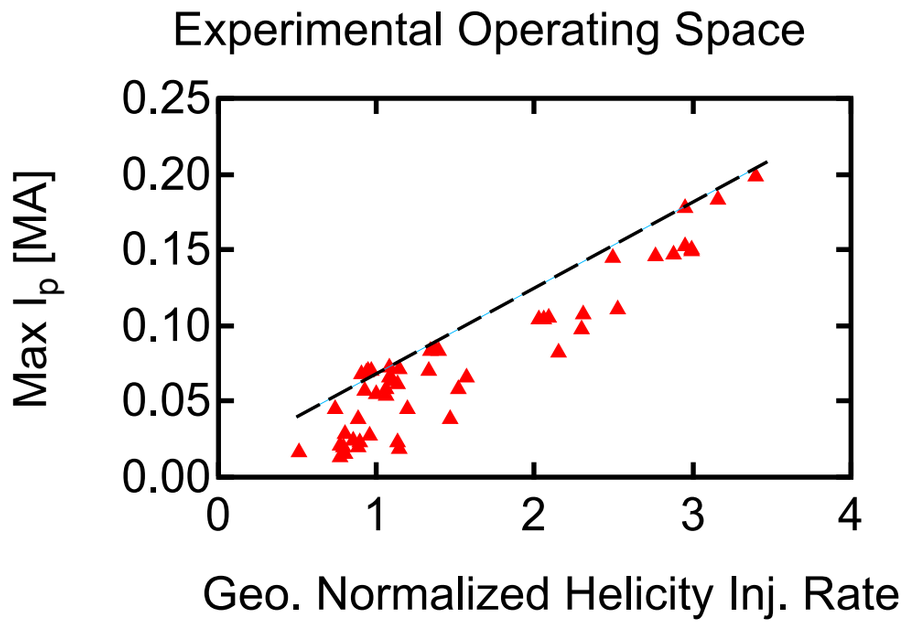





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# To Date, Max achieved Current Linear in $V_{LHI}$

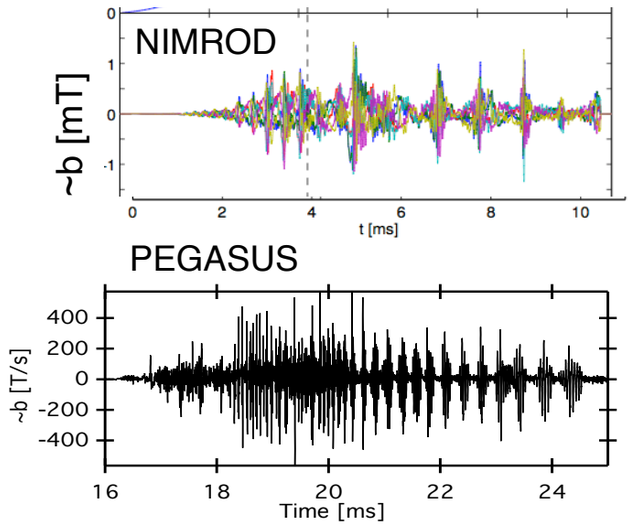
- Peak experimental $I_p \sim V_{eff}$
- $Z_{eff}$, $f_{GW}$, $B_T$, plasma geometry must be accounted for
- Electron dynamics and confinement are a major emphasis of coming work
  - Effects of current profile
  - Volume average $\eta$
  - Classical vs. hyper-resistivity
  - Reconnection-driven electron heating
  - etc

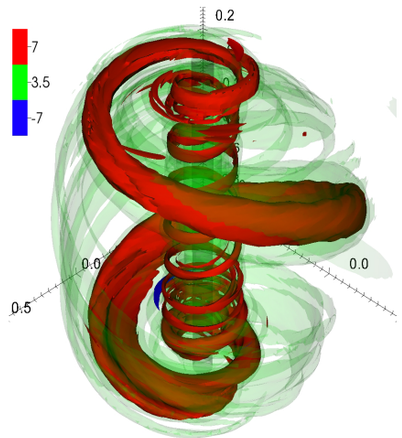




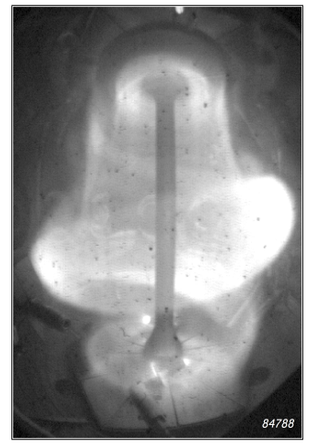

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# NIMROD Simulations Indicate Helical Current Stream Reconnection as a Current Drive Mechanism



*NIMROD Simulation*
*[O'Bryan PhD 2014]*




*2016 PEGASUS*
*High-speed Imaging*

- LFS injection: 20-80 kHz MHD bursts support outboard stream reconnection as a drive
- Bursts localized to injected current streams
- Consistent with line-tied kink instability

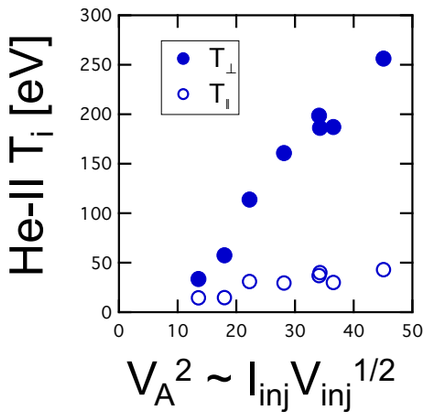
- HFS startup shows commonality between NIMROD simulations and experiment



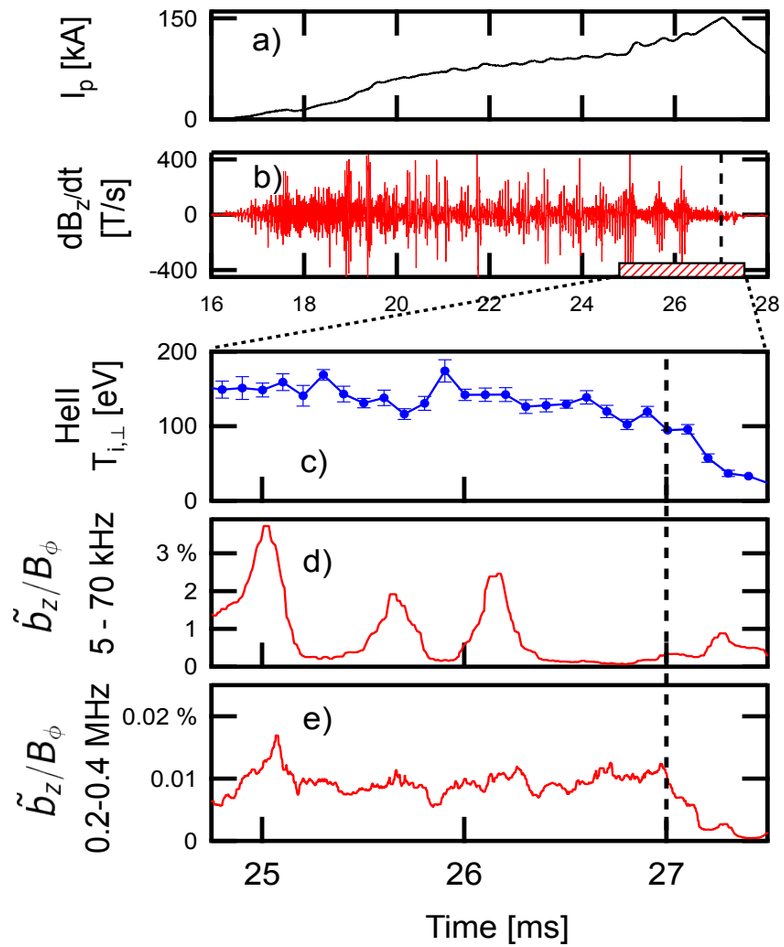
*J. O'Bryan, C.R. Sovinec, Plasma Phys. Control. Fusion* ***56*** *064005 (2014)*

# Anomalous Ion Heating Indicates High Frequency Activity Linked to Reconnection

- Anisoptropic ion heating consistent with two-fluid reconnection model
  - Channel $T_{i,\perp} > T_e$
  - $T_{i,\perp} \sim V_A^2$ of injected current streams




- Correlated with high $f$ activity
  - Suggests considering short wavelength reconnection as additional CD



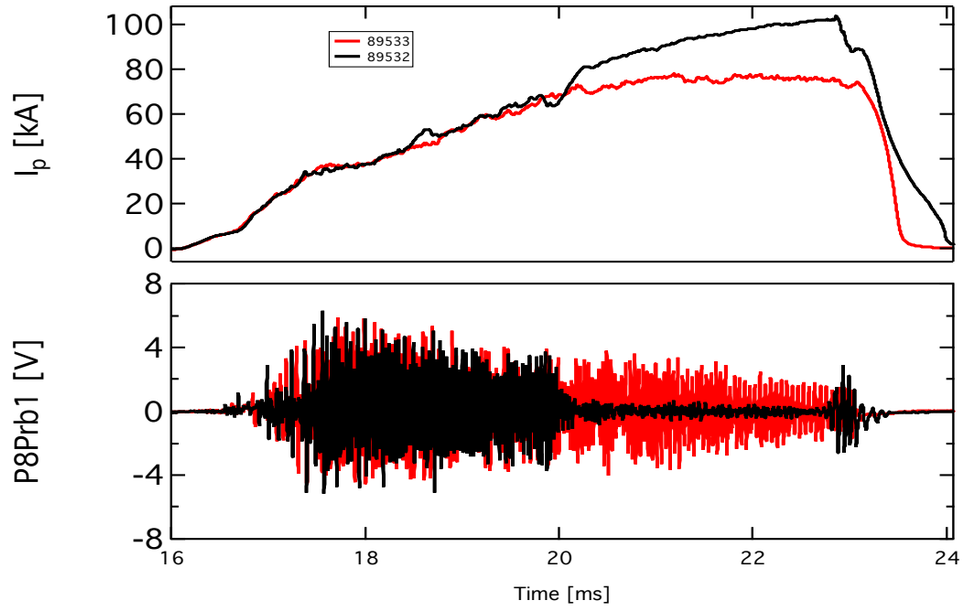


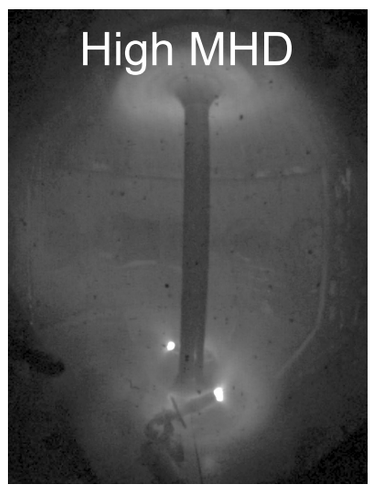

*M. G. Burke, et al. Nucl. Fusion 57, 076010 (2017).*

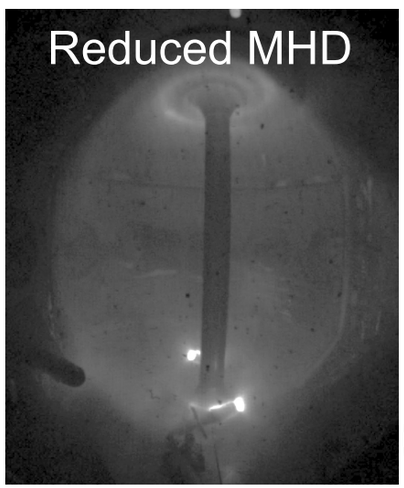
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# HFS Injection Exhibits More Complex MHD Behavior

- Initially similar to LFS injection
  - Large scale n=1 at 20-80 kHz
  - Consistent with line-tied kink
- Abrupt MHD transition can occur:
  - Low-*f* n=1 activity reduced by over 10x
  - Extremely sensitive to $B_t$, $B_z$, $I_p$, fueling
- Bifurcation in $I_p$ evolution:
  - Current growth continues after transition
  - $n_e$ rises, edge sharpens visibly
- Understanding and controlling this MHD activity may be central to increasing $I_p$



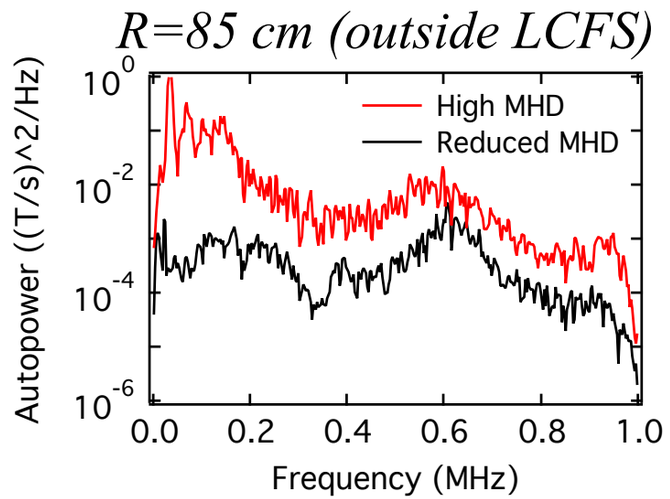



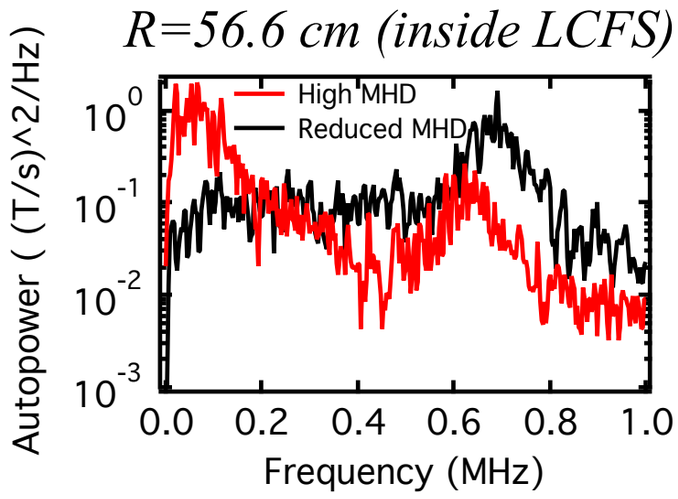




*J.M. Perry EPR 2017*

# Understanding MHD Transition Motivates Experiments, New Diagnostics

- Reduction in low *f* activity: stabilization of kinked injector streams
  - Mechanism of stabilization under investigation
- High *f* activity persists (~600 kHz)
  - Points to additional current drive mechanism
  - Link to short $\lambda$ turbulence?
  - Reconnection on inboard side (NIMROD)?
- New high *f* insertable probes:
  - High-*f* activity increased in plasma interior after transition



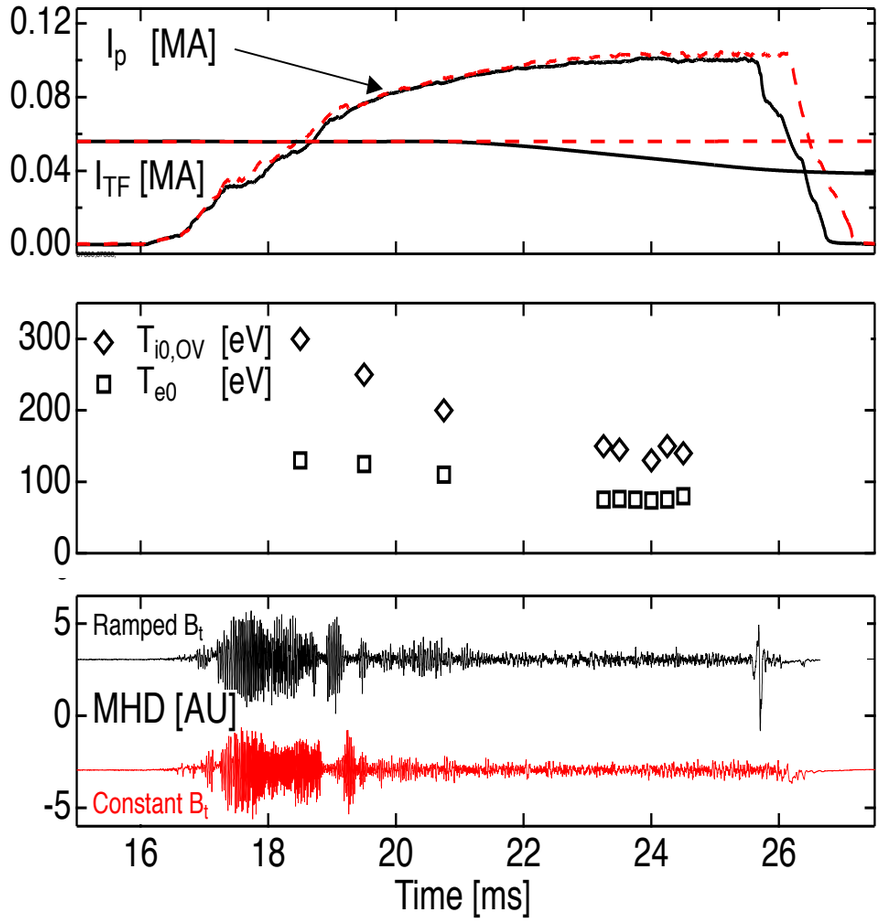






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# HFS Injection Facilitates High-Performance Operation at Extremely Low $B_t$

- Low-A: stability at high $I_N$
- HFS LHI: unique operation space
  - Low $I_{TF} \sim 0.6\ I_p$
  - $I_N = 5A\frac{I_p}{I_{TF}} > 10$ accessible
  - Natural high $\kappa$, low $\ell_i$
- Reconnection-driven $T_i > T_e$
- Ramped $B_t$ discharges terminate disruptively at ideal no-wall stability limit
  - Consistent with DCON analysis

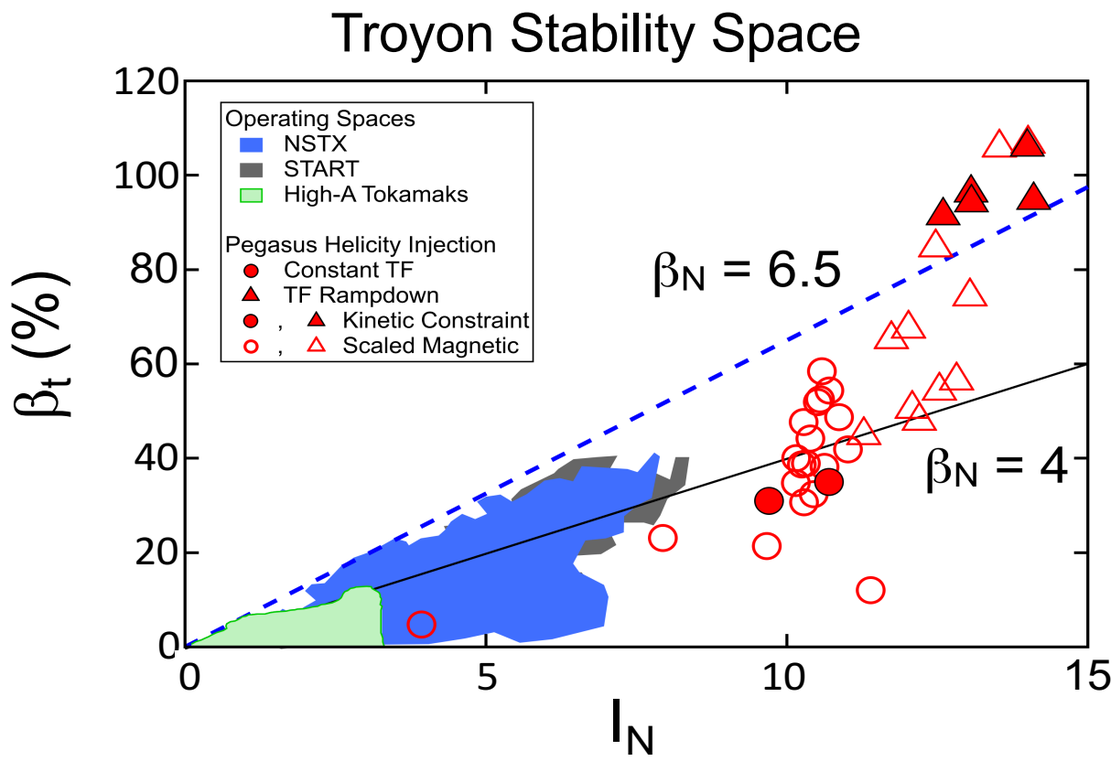



*D.J. Schlossberg, PRL. **119** 035001 (2017)*

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# LHI at A~1 Expands the Operating Space for the ST to $\beta_t \sim 1$

- Access to $\beta_t \sim 1$ readily achieved
  - facilitated by A~1, LHI
- A~1:
  - Naturally high $\kappa$
  - High $I_N$ stability limit
- LHI:
  - Strong auxiliary heating
  - Low $\ell_i$
- Low $\ell_i$ at low-A: high $\beta_{N,max}$[1]





1. J. E. Menard, et al. Phys. Plasmas 11, 639 (2004).

2. D.J. Schlossberg, PRL. **119** 035001 (2017)





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# LHI Provides Access to Desirable ST Operating Space

- High $\beta_t$, high $I_N$, low $\ell_i$, high $\kappa$, non-solenoidally sustained plasmas are a goal of the ST program[1]
  - Target operating space of NSTX-U at high performance
  - Pegasus reaches much of this space, albeit at modest performance

| ST Target | NSTX, NSTX-U | Pegasus |
|---|---|---|
| High $\kappa$ | Low A | A = 1.15 → $\kappa \approx 2.5$ |
| Low $\ell_i$ | Bootstrap, Off-axis NBI, EBW | LHI edge CD → $\ell_i \approx 0.2$ |
| High $I_N$ | High $I_p$, low A, wall stabilization | Low $B_t$, A~1, no-wall limit |
| High $\beta_t$, $\beta_N$ | NBI, RF Heating | Recon. Ion Heating |
| Non-solenoidal sustainment | Bootstrap, NBI, RF | LHI |
| Collisionality | Very low | Modest |

- Allows near-term access and stability studies

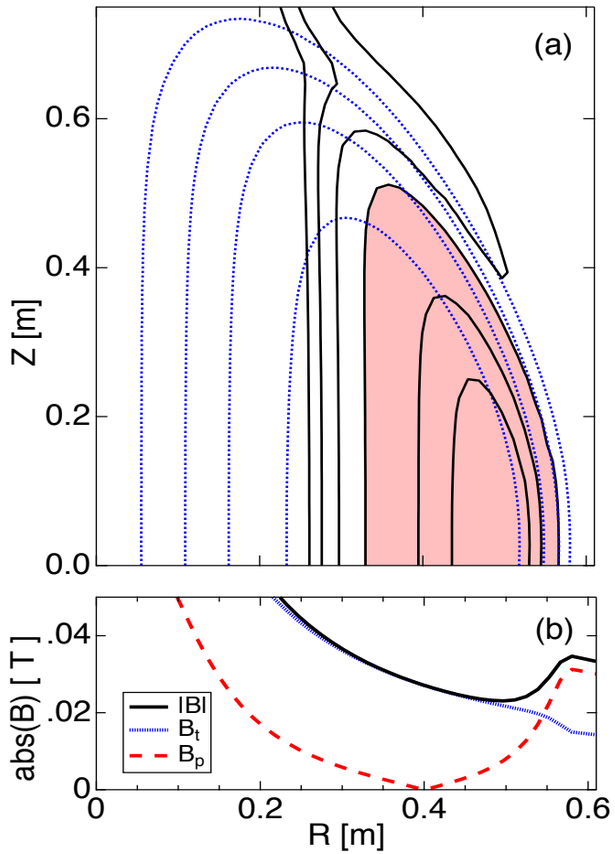


*J. E. Menard et al., Nucl. Fusion 56, 106023 (2016).*

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# Unique Feature of High- $\beta_t$ LHI Plasmas: Sustained min |B| Region

- High-$\beta_t$ equilibrium contains min |B| region
  - Spans up to 47% of plasma volume
  - Well deepens and broadens as $\beta_t$ increases
- Region persists for several energy confinement times
- Potentially favorable for stabilization of drift modes, reduction of stochastic transport
  - Presently under investigation




*J.M. Perry EPR 2017*

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# Divertor LHI Enables Access to High-$I_p$, High Performance Plasmas

- High-field-side LHI: increased current drive from HI, reduced $V_{IND}$
- PMI at HFS injection largely mitigated by injector geometry, local plasma limiters
- Attainable $I_p$ scales with helicity injection rate
- New reduced-MHD regime discovered
- Focus increasing on electron dynamics and $I_p$ scaling
- $\beta_T \approx 100\%$ attained at low field due to unique properties of LHI plasmas at A~1



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