Establishing Low-Field-Side to High-Field-Side Local Helicity Injection Startup Scenarios

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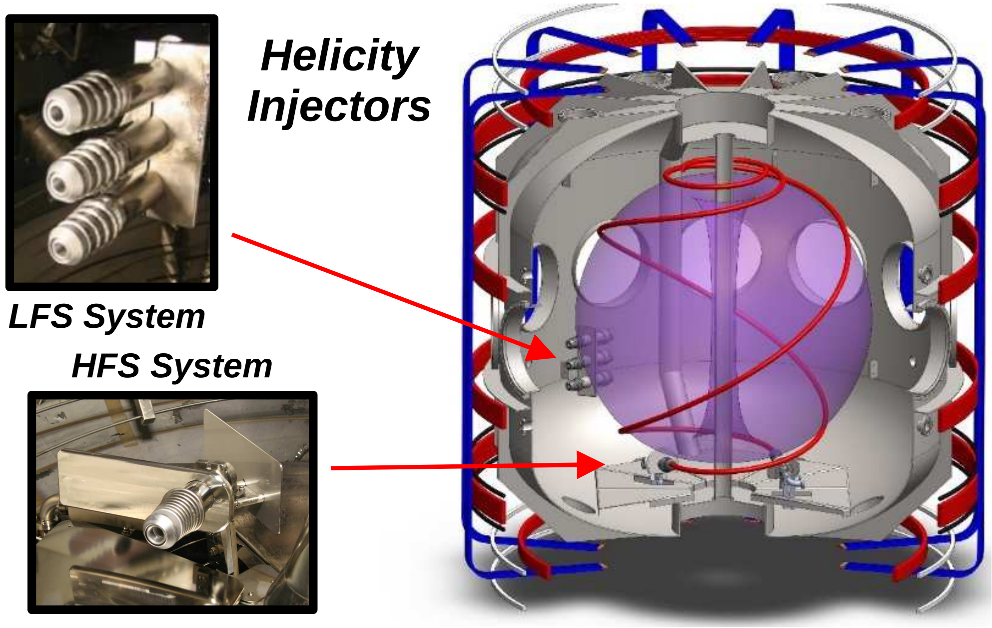
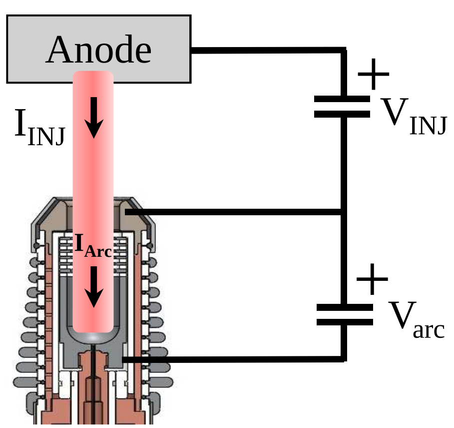
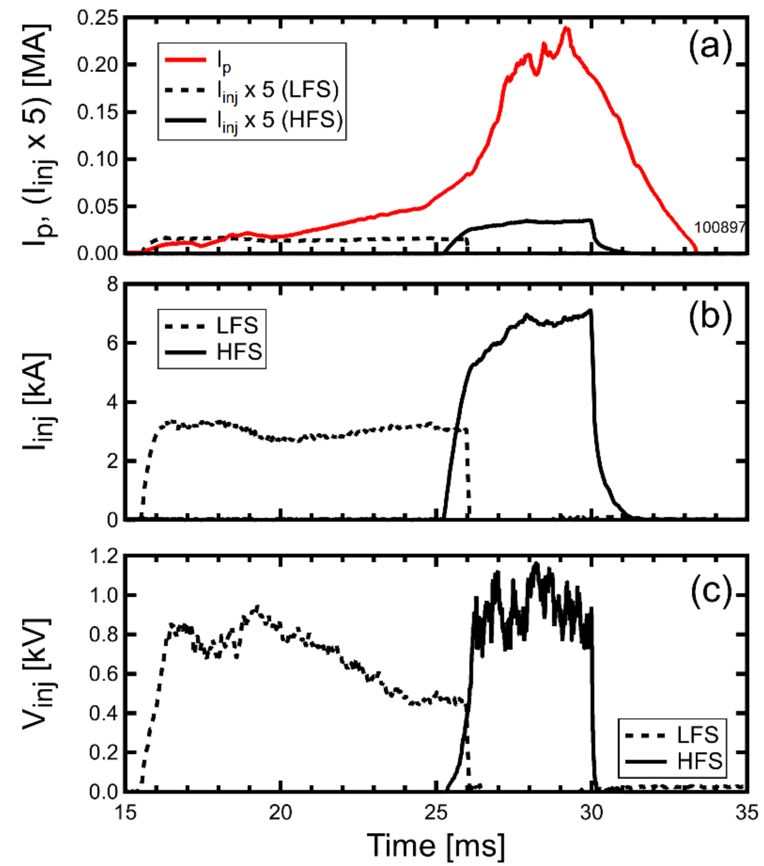
Non-Solenoidal Startup in the Pegasus ST	Challenges of Helicity Injection at Low R_{inj}	LFS to HFS Handoff at Full Toroidal Field	Characterization of Current Scaling in LHI	Paths to Improved Startup Using LHI
LHI Provides a Flexible and Robust Method of Non-Solenoidal Startup in the Pegasus ST	Relaxation of Current Streams Forms Tokamak-Like Plasma	LFS to HFS Injection Handoff Presents Many Benefits to HFS Operation	Plasma Current in LHI Dominated Discharges Shows Linear Scaling with LHI Drive	HFS Injection at Decreased Major Radius Impeded by Field Shaping Limitations
Global Helicity Balance and Taylor Relaxation Limits I_p	Relaxation at Low R_{inj} Constrained by Field Geometry	I_p > 0.2 MA Achieved Using HFS LHI Initialized by LFS LHI	Confinement Scaling Models Under Consideration	Larger Area Injectors for HFS LHI in Design Stage
Two Methods of LHI Currently Investigated in Pegasus	LHI Requires Close Proximity of Injectors to Plasma Edge	Thomson Scattering Profiles Show Strong Peaking of T_e and n_e in Handoff Discharges	Distinct MHD Regimes Observed in LHI	Advanced Injector Shapes to Provide Access to High Performance with LFS LHI
HFS LHI Has Been Focus of Recent Experiements	Increased PMI on Injector surfaces Observed in HFS LHI Discharges at Full B_T	Redistribution of Power in Magnetic Fluctuation Spectra Between LFS and HFS LHI	Transient MHD Transitions in Handoff Experiments Indicate Threshold Behavior	Conclusions and Future Work

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





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



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

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Global Helicity Balance and Taylor Relaxation Limits I_p

- Relaxation and current drive occur as a result of global helicity balance:

$$\frac{dK}{dt} = -2\int_V \eta \mathbf{J}\cdot \mathbf{B}\, d^3x - 2\frac{\partial \psi}{\partial t}\Psi - 2\int_A \Phi \mathbf{B}\cdot d\mathbf{s}$$

- I_p limit by balancing inductive and helicity drive with resistive dissipation:

$$I_p \le \frac{A_p}{2\pi R_0 \langle \eta \rangle}\left(\cancelto{0}{V_{IND}} + V_{LHI}\right); \quad V_{LHI} \equiv \frac{A_{inj} B_{inj}}{\Psi_T} V_{inj} \approx \frac{A_{inj}}{A_p}\frac{R_p}{R_{inj}} V_{inj}$$

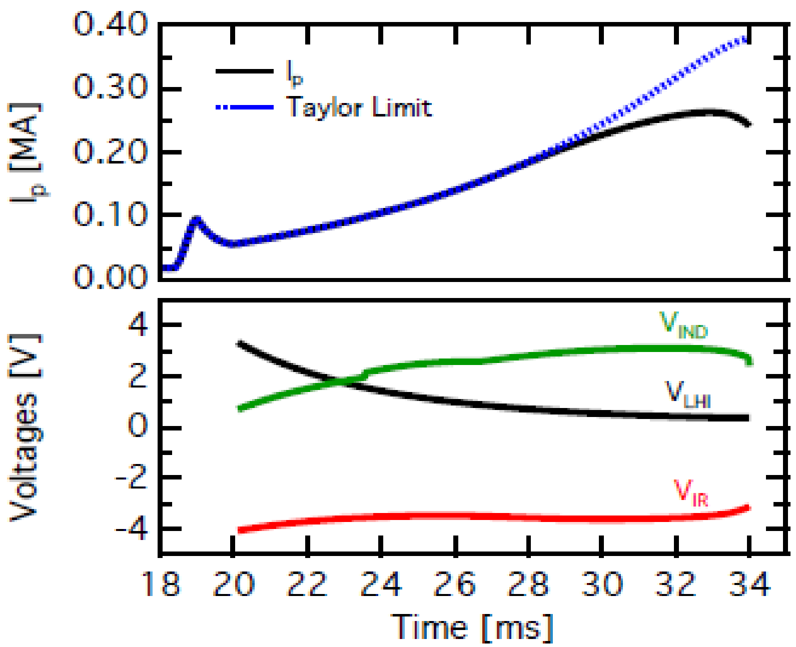
- Absolute I_p limit from Taylor relaxation:

$$\left\langle \frac{\mu_0 J_{||}}{B} \right\rangle \equiv \lambda_p \le \lambda_{edge}\,;\ I_p \le \sqrt{\frac{1}{B_{\theta+V,inj}/I_p}\frac{\Psi_T I_{inj}}{2\pi R_{inj} w_{inj}}} \sim \sqrt{\frac{I_{TF} I_{inj}}{w_{inj}}}$$

Two Configurations of LHI Investigated in Pegasus

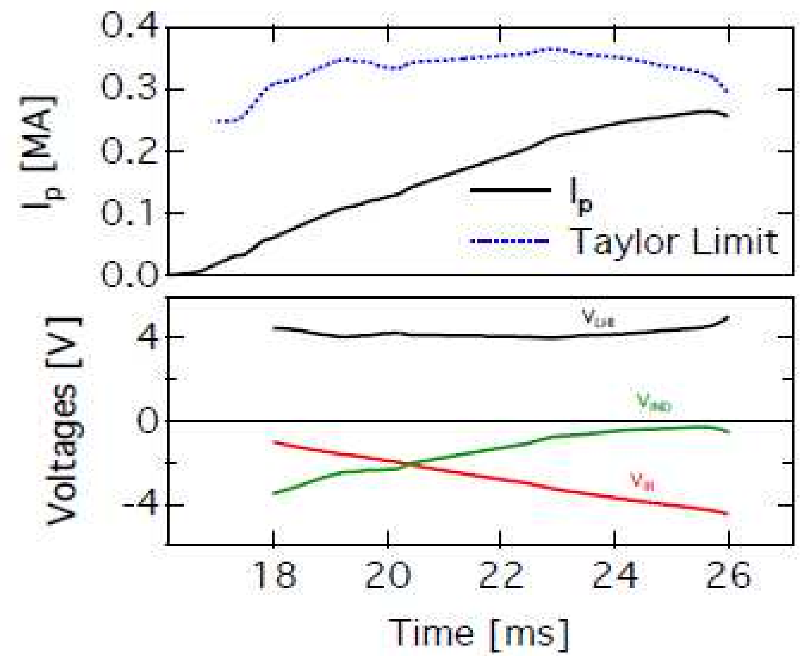
Low-Field Side (LFS) Injection

- 3-Injector set near outboard midplane
  - Poloidal field induction dominated; I_p mostly Taylor limited



High-Field Side (HFS) Injection

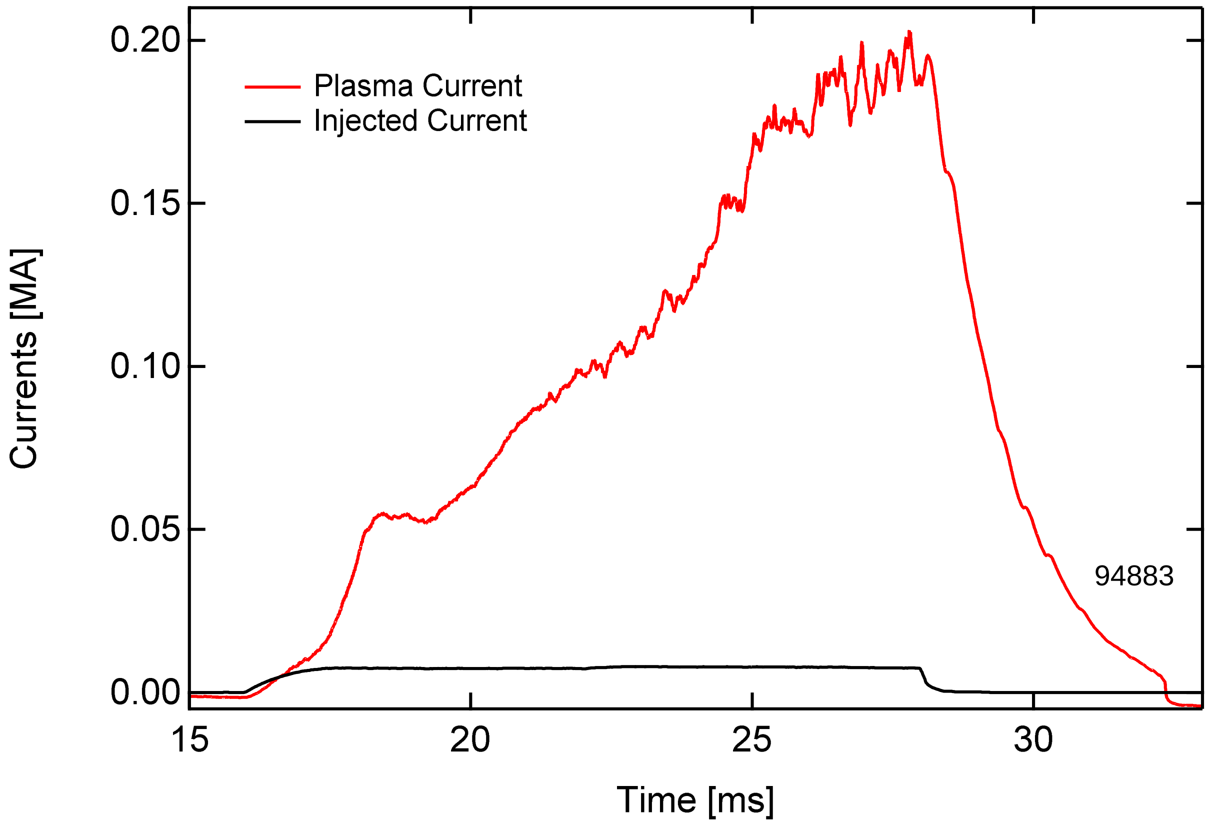
- 2-Injector set in lower divertor region
  - Helicity drive (V_{LHI}) dominated; I_p limited by helicity drive



- J.D. Weberski, TP11.00112

HFS LHI Has Been the Focus of Recent Experiments

- $I_p(t)$ dominated by helicity current drive with minimal inductive contributions
  - Close to regimes expected at larger scale (e.g. NSTX-U)
- $I_p \sim 0.2\ MA$ achieved with V_{LHI} as majority drive
  - Inductive drive ~ 0
  - Similar plasma performance to LFS LHI; stochastic losses do not dramatically impact performance
- Issues and questions for HFS LHI startup
  - Relaxation to tokamak more challenging
  - Higher PMI susceptibility at low R_{inj}
  - Tighter plasma shape requirements
  - Confinement and dissipation properties not well understood
  - Relation of MHD activity to current drive mechanisms

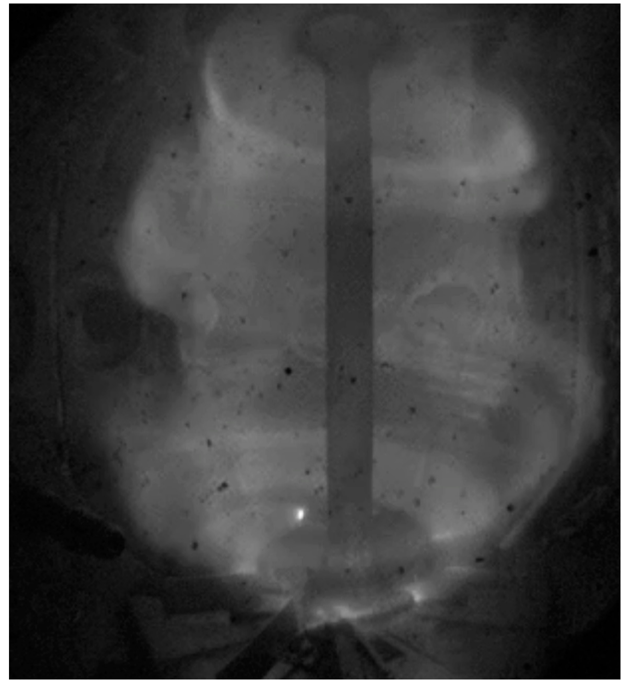


- Example highest achievable I_p via HFS-only LHI

Relaxation of Injected Current Streams Forms Tokamak-Like Plasma

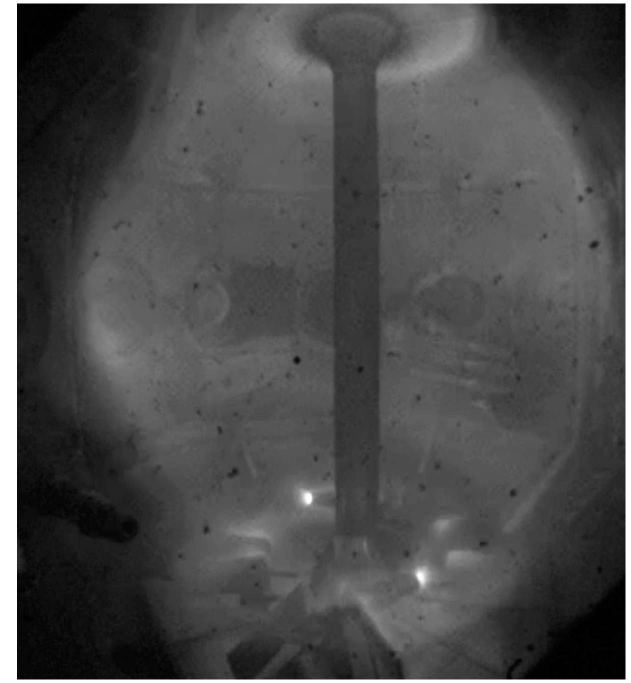
- Streams must maintain clearance of injector structures

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



- Injected current weakens B_z and enable reconnection
- Helicity conserving instabilities redistribute current

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



- Rapid I_p growth occurs

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

Conflicting Requirements for Relaxation at Low R_{inj}

- HFS injectors are toroidally staggered; each current stream must clear opposite injector

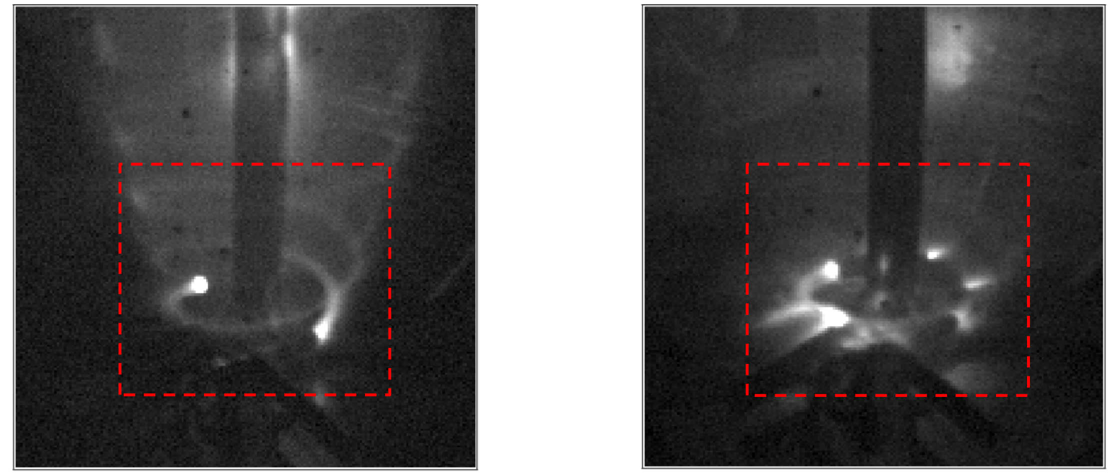
- Relaxation for HFS injection results from null formation in the vertical field at midplane:

$$\frac{\left|B_{z,vac} - B_{z,relax}\right|}{B_{z,vac}} \gtrsim 0.8$$

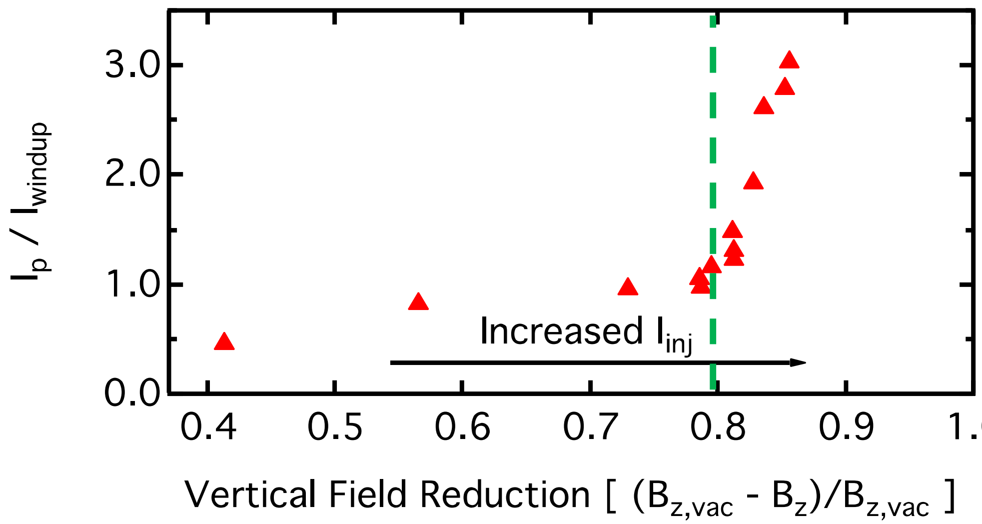
- As toroidal field increases, stronger vertical field is needed to maintain correct pitch

$$\frac{B_{z,inj}}{B_{T,inj}} > \frac{\Delta Z(\phi = 180°)}{\pi R_{inj}}$$

Sufficient Clearance | Insufficient Clearance

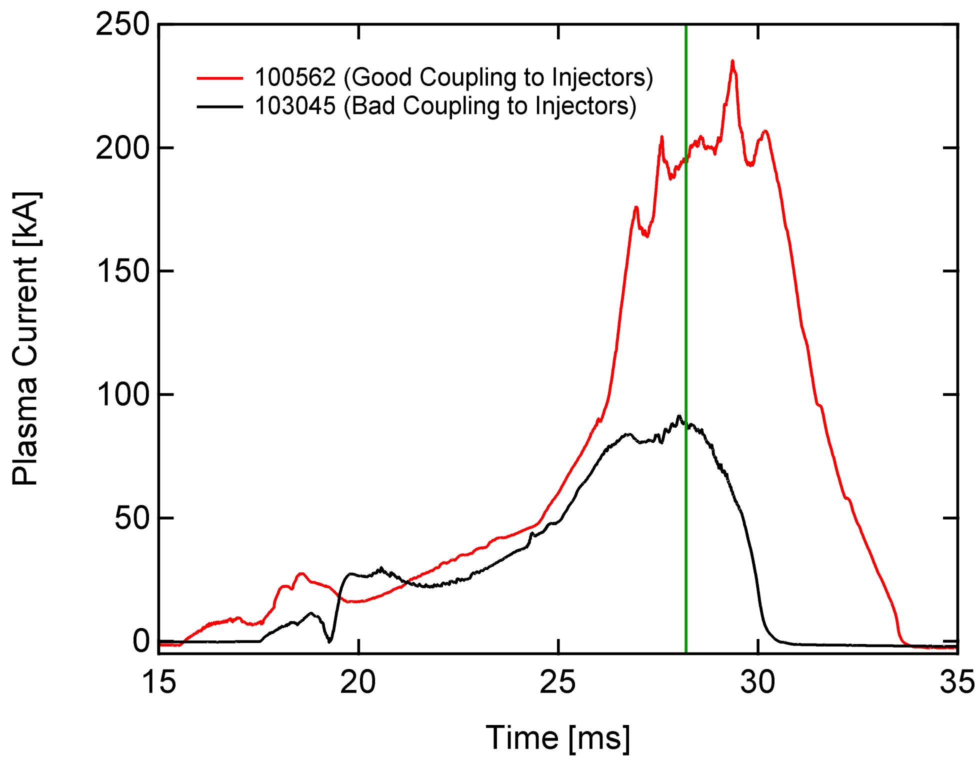


- Current multiplication increases greatly after critical B_z reduction



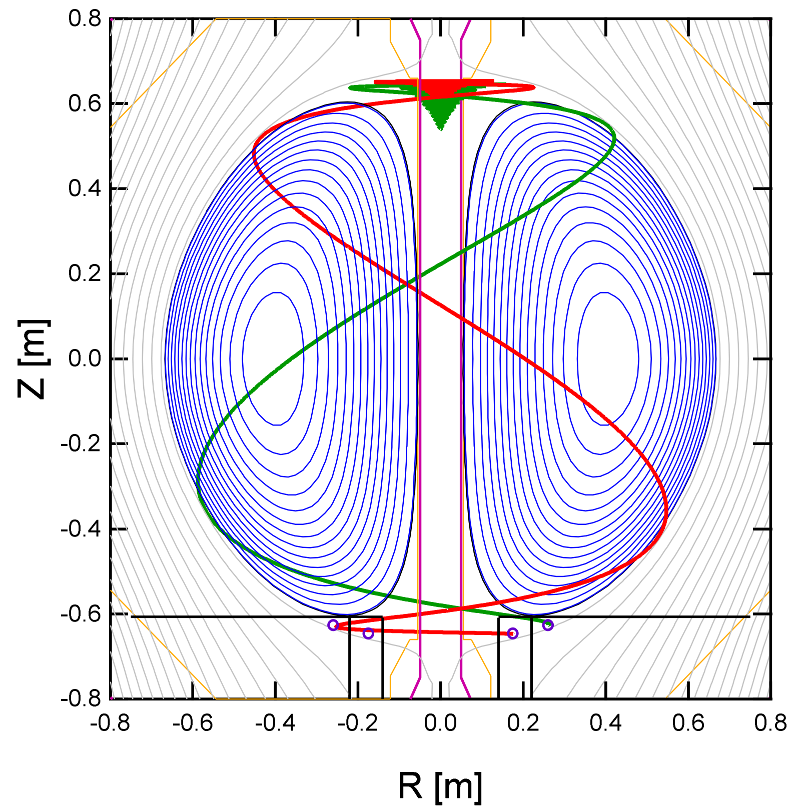
LHI Requires Close Proximity of Injectors to Plasma Edge

- Experiments show greatly reduced I_p when plasma edge is not near injectors



- Effects of good and bad coupling of the HFS injectors to the plasma. Green line: time point with equal V_{LHI}

- Coupling to plasma for HFS injection requires injectors outside of foot of plasma



- Field line trajectories from two injector locations

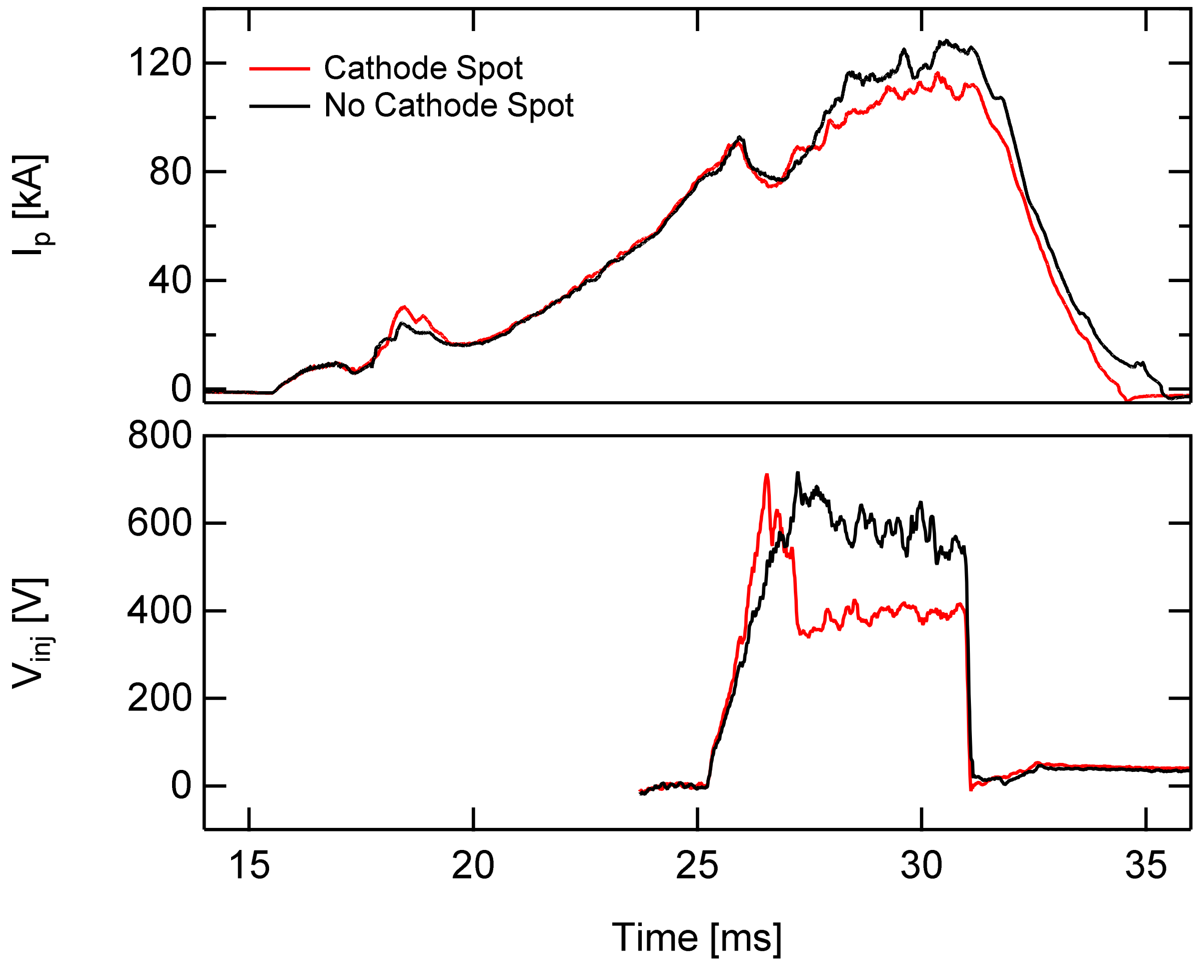
Increased PMI on Injector Surfaces Observed in HFS LHI at Full B_T

- Cathode spots occur at a critical electric field at the injector surface:
  - $E \sim \frac{V_{inj}}{\lambda_{De}} > E_{crit}$
  - Need to minimize n_e at bias surfaces

- High B_{TF} in divertor region leads to tight clearance of toroidal transits
  - Increases n_e near cathode due to presence of beam
  - Potential for surface heating, lowering E_{crit}

- High B_{guide} $(\sim B_{TF})$ may concentrate local n_e and lower E_{crit}

- Effects of a cathode spot on discharge evolution

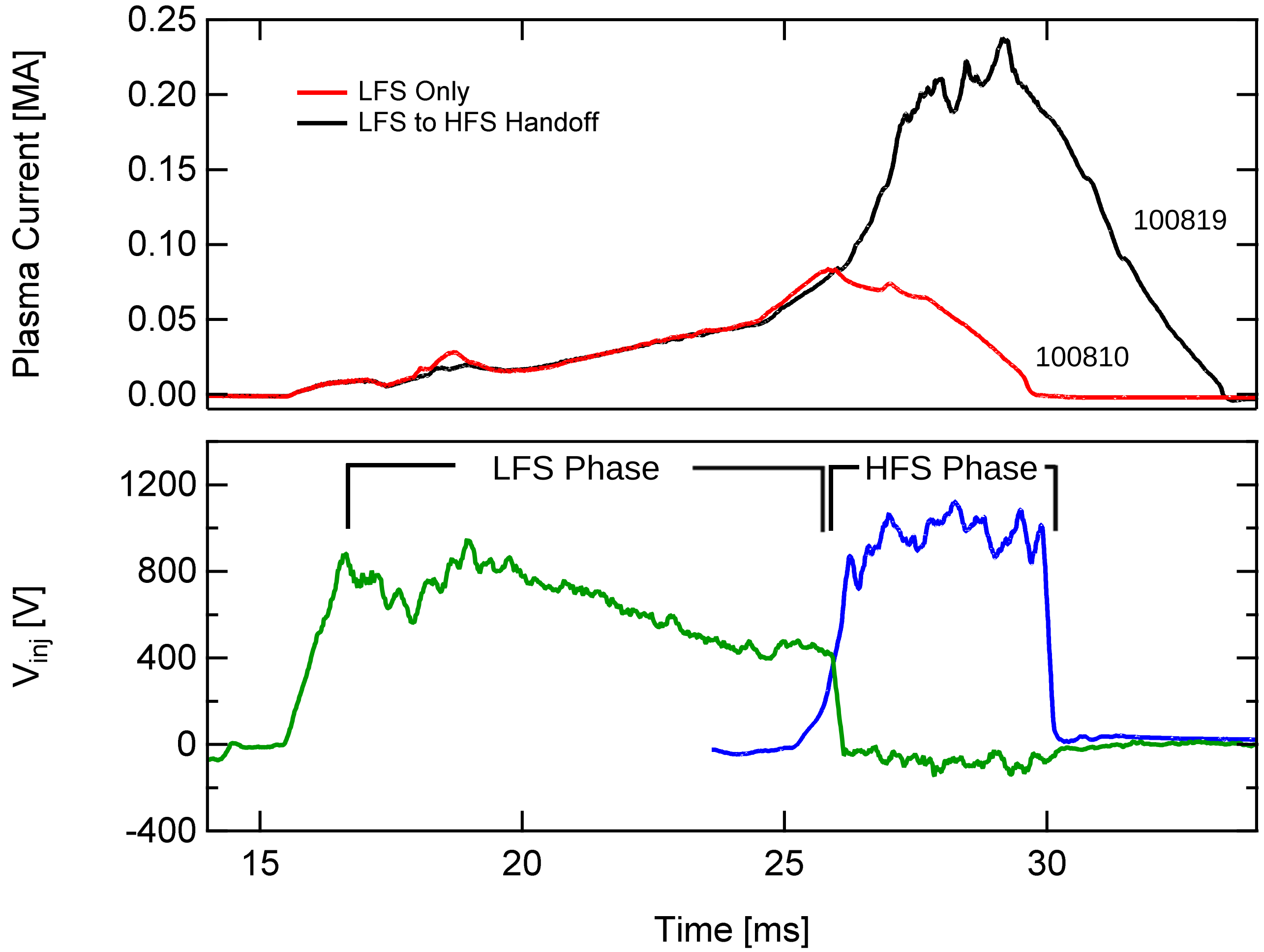


LFS to HFS Injection Handoff Presents Many Benefits to HFS Operation

- Removes relaxation requirement for HFS LHI
- Poloidal induction utilized for initial growth of I_p
- Reduced need for high I_{inj} and V_{inj} early in HFS phase leads to less PMI
- Coupling of helicity directly to a relaxed plasma allows for a higher vertical field
  - Additional stream clearance gained from increased field and from plasma shape
- Proof-of-concept for switching helicity injection sources mid-shot

I_p > 0.2 MA Achieved Using HFS LHI Initialized by LFS LHI

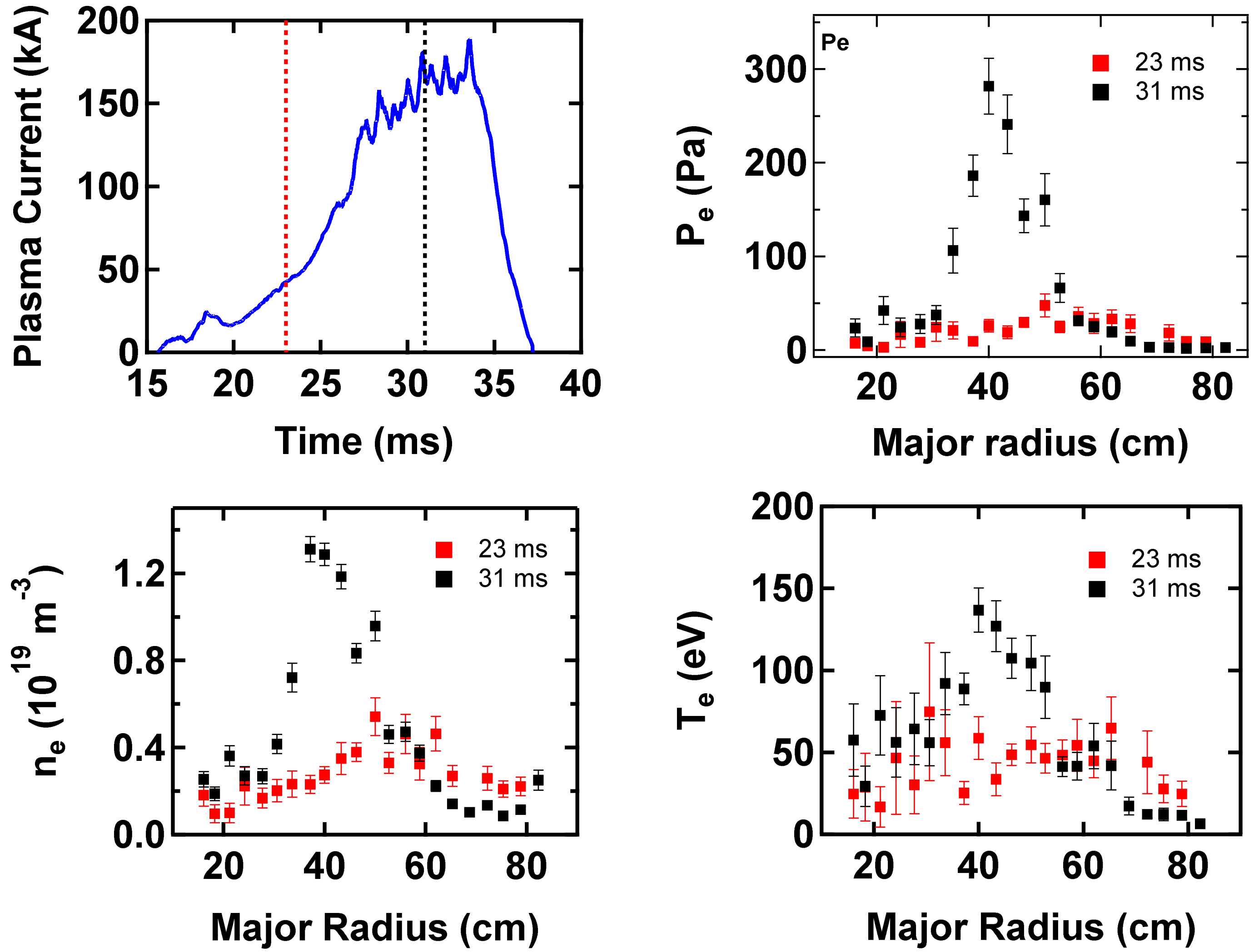
- 90 kA discharge established using LFS injection system
- LFS plasma decouples from injectors and moves inboard and elongation increases
- HFS injection system couples to this target plasma and drives current to $> 0.2\ MA$



Thomson Scattering Profiles Show Strong Peaking of T_e and n_e in Handoff Discharges

- Thomson scattering profiles transition from flat in LFS phase to peaked in HFS phase
  - LFS: T_e ~ 50 eV, n_e ~ 4 x 10^{18} m^{-3}
  - HFS: T_e ~ 125 eV, n_e ~ 1.2 x 10^{19} m^{-3}

- Peaked profiles during HFS phase suggest small stochastic losses
  - Pending scaling tests, V_{LHI}-dominated startup appears viable



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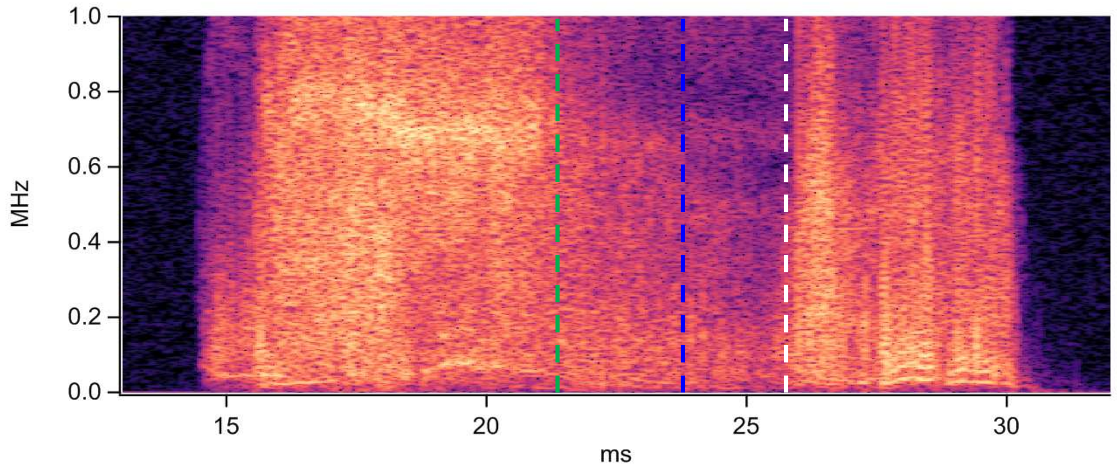
Redistribution of Power in Magnetic Fluctuation Spectra Between LFS and HFS LHI

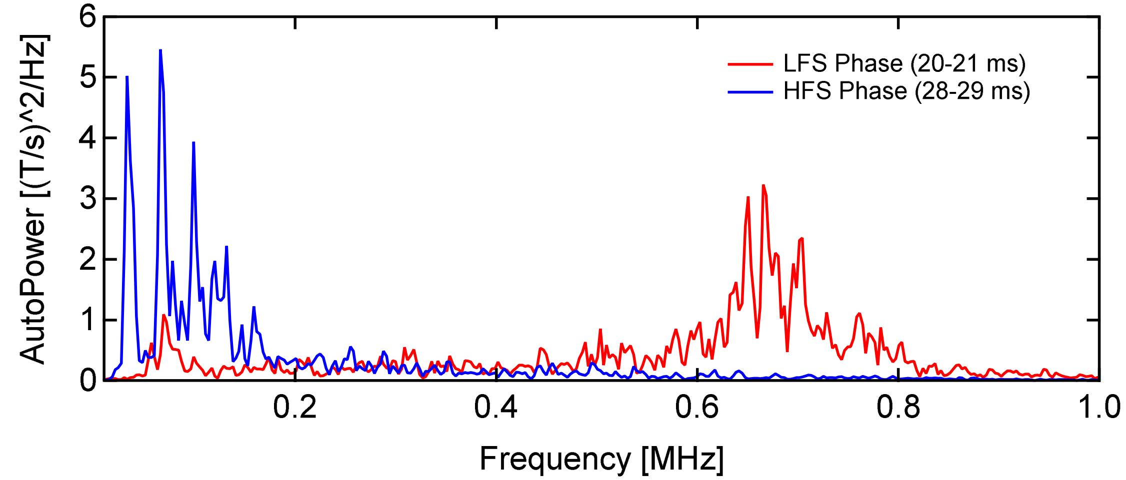
- Insertable Mirnov array probe used to measure magnetic fluctuations ($\delta\dot{B}_z$) in edge and SOL

- Edge magnetic spectral content changes abruptly around switch in LHI systems
  - HFS phase shows higher power at low frequencies, and overall less broadband

- Presence of HFS arc streams reduces amplitude of fluctuations in LFS plasma



- Sonogram of inner-most probe spatial channel throughout the duration of the discharge. Green: HFS gas start; Blue: HFS arc start; White: HFS bias start



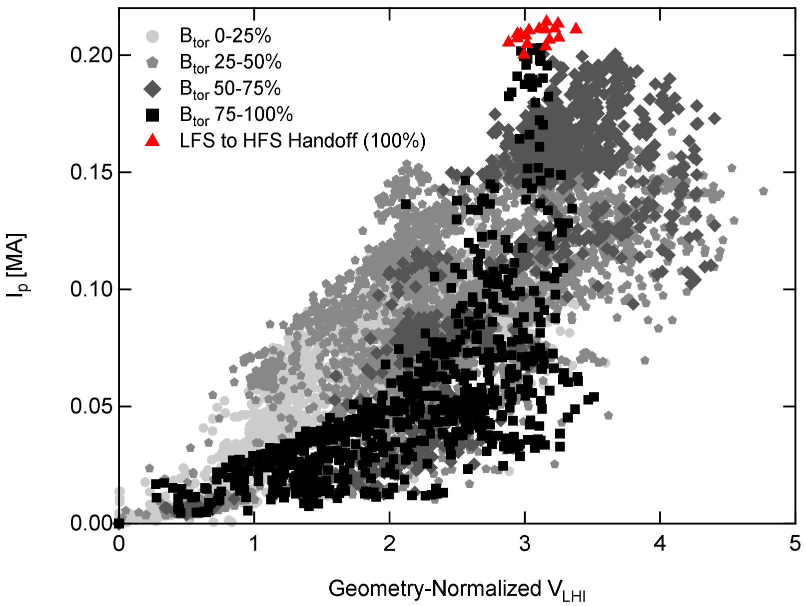
- Autopowers of probe ch.1 at representative time points of LFS and HFS phases

- N.J. Richner, TP11.00111

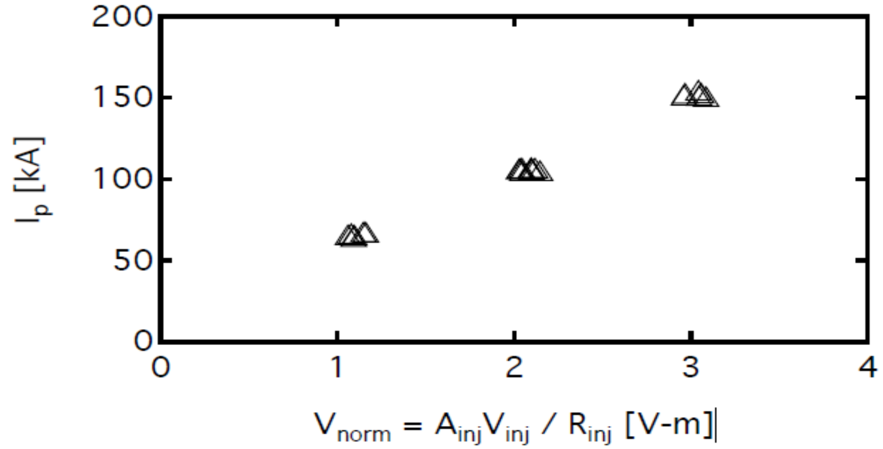
Plasma Current in LHI Dominated Discharges Shows Linear Scaling with LHI Drive

- Plotting I_p vs geometry-normalized V_{LHI} ($\equiv V_{norm} = \frac{A_{inj}V_{inj}}{R_{inj}}$) shows generally linear trend
- LFS to HFS handoff shots fit trend of full TF discharges
- HFS LHI experiments conducted with static geometry and I_p to isolate effects of V_{LHI}
  - $V_{IND} \sim 0$
- Linear scaling of I_p with V_{norm} observed
  - Validation needed for extended pulse duration at full B_{TF}

Handoff discharges fit trend of HFS-only data



Linear Scaling of I_p with V_{norm} for static geometry



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Confinement Scaling Models Under Consideration

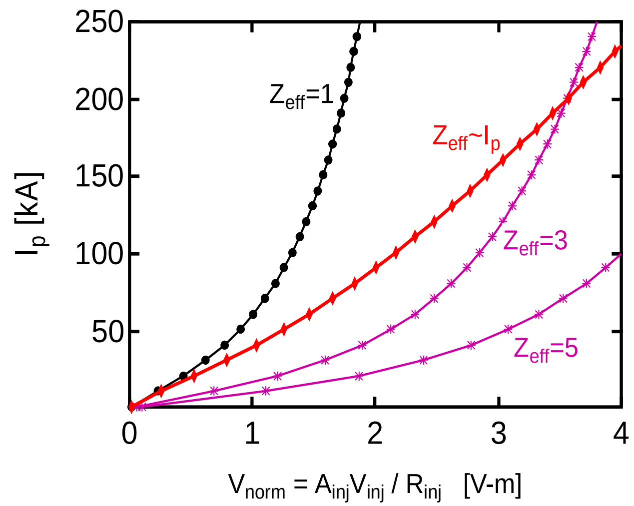
- Existing scaling laws may be useful to bracket LHI
  - Ohmic: stable flux surfaces throughout; most optimistic
  - Stochastic: broken flux surfaces throughout; pessimistic

- Linear scaling of I_p consistent with either extreme for specific hypotheses
  - ohmic confinement for $Z_{eff} \sim I_p$
  - stochastic confinement for $\frac{\delta b_r}{B} \sim V_{LHI}$

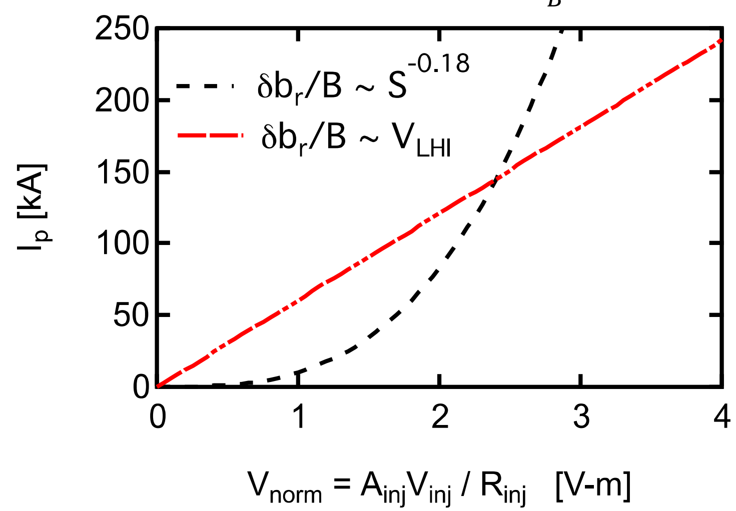
- 2-zone confinement model may be useful
  - Stochastic, poor confinement in edge with unstable current streams
  - Ohmic-like transport in more quiescent core plasma

- Initial data suggests poor edge, decent core
  - Flat $P_e(r)$ at edge with large $\dot{B}_z$
  - Peaked $P_e(r)$ in core region

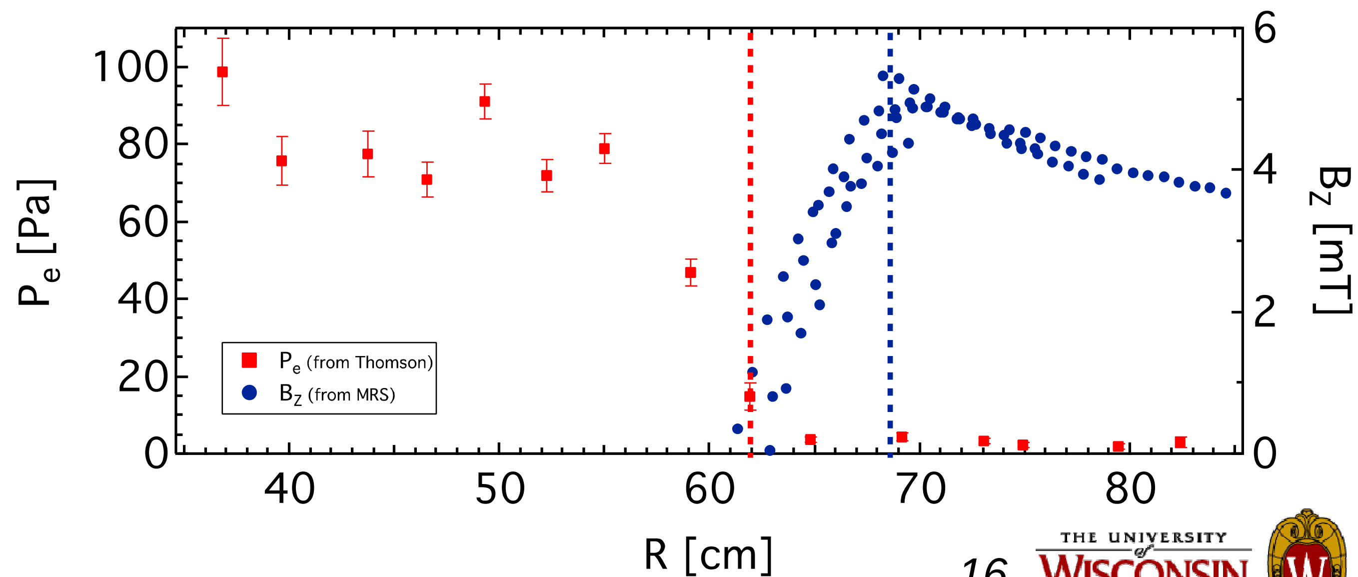
Ohmic Scaling for $Z_{eff} \sim I_p$



Stochastic Scaling for $\frac{\delta b_r}{B} \sim V_{LHI}$



Magnetic Edge (probe) vs Kinetic Edge (Thomson)



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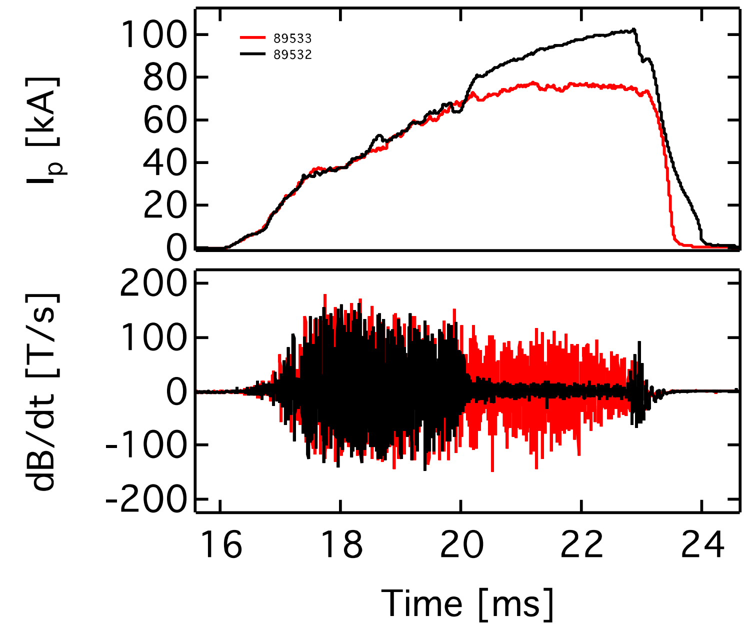
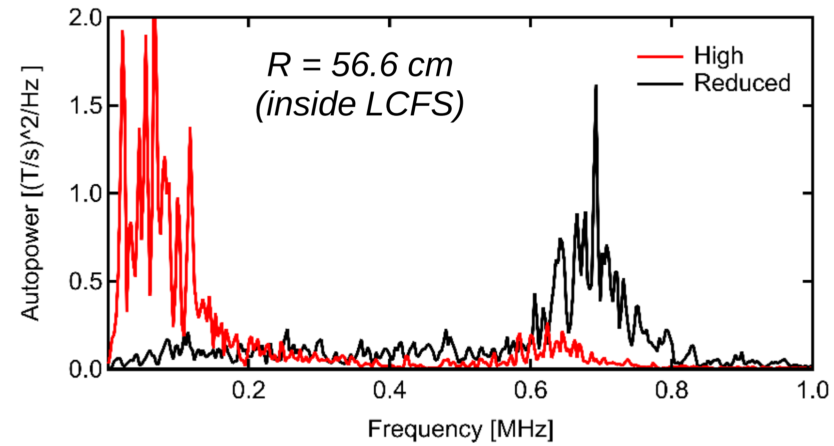
Distinct MHD Regimes Observed in HFS LHI

- “MHD Transition” characterized by abrupt reduction in amplitude of Mirnov signals
- Transition is accompanied by a jump in plasma current
- Reduction in Mirnov signal mainly due to $n = 1$ mode suppression





- Top: Plasma current and outboard Mirnov signals illustrating MHD transition (Red – with; Black – without)
- Bottom: Mirnov signal autopower showing n=1 reduction

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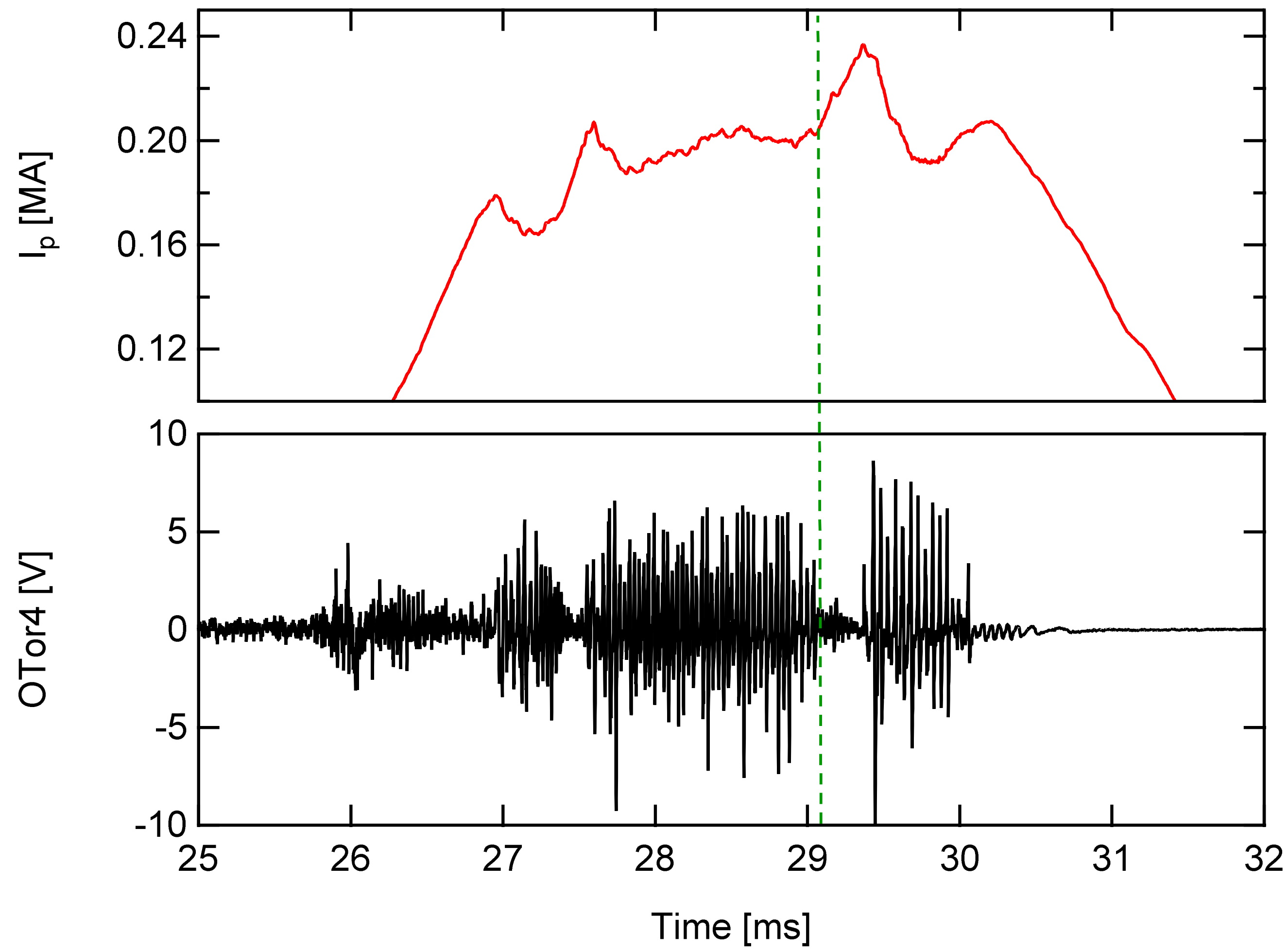
Transient MHD Transitions in Handoff Experiments Indicate Threshold Behavior

- Conditions for this transition have been empirically bounded by

$$\frac{I_p}{I_{TF}} \gtrsim 0.8$$

- Short MHD transition events observed in handoff discharges
  - Typical peak $\frac{I_p}{I_{TF}} \cong 0.7$; close to empirical threshold

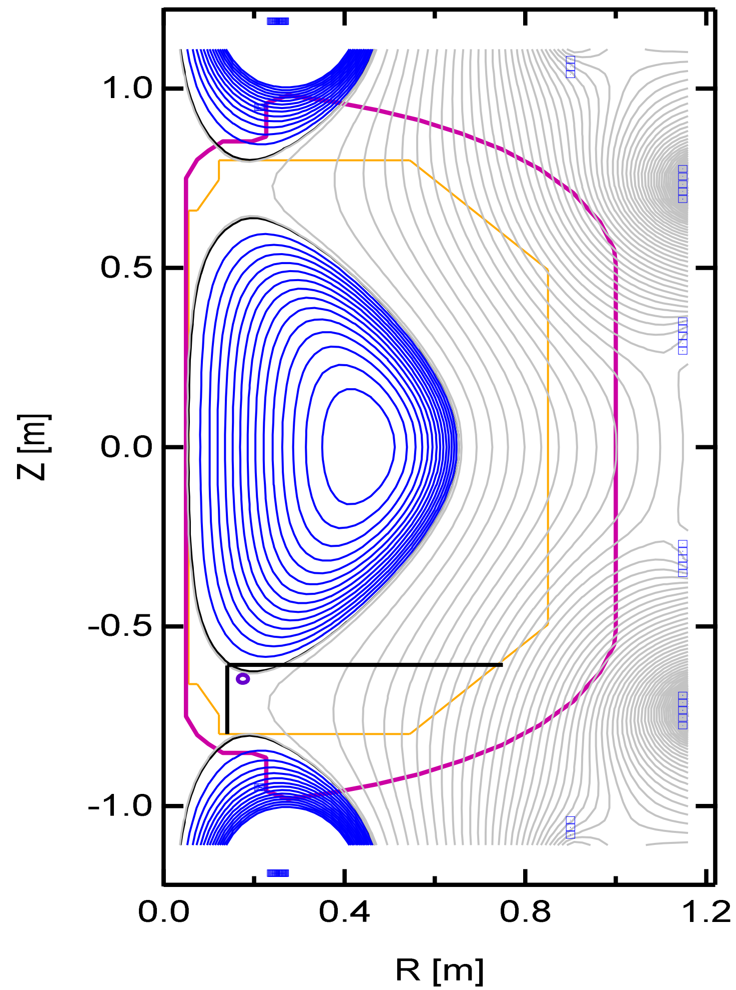
- Considering plasma conditions that may lead to line-tied kink stabilization



HFS Injection at Decreased Major Radius Impeded by Shaping Limitations

- Scaling of V_{LHI} indicates increased drive as injectors move inboard
  - $V_{LHI} \sim \frac{A_{inj} V_{inj}}{R_{inj}}$

- Experiments at $R_{inj} = 17.5\ cm$ encountered geometry obstacles
  - Location of lowest-z point of plasma must be inboard and below injector position
  - Field shaping coils in Pegasus limit $R_{inj,min} \sim 21\ cm$



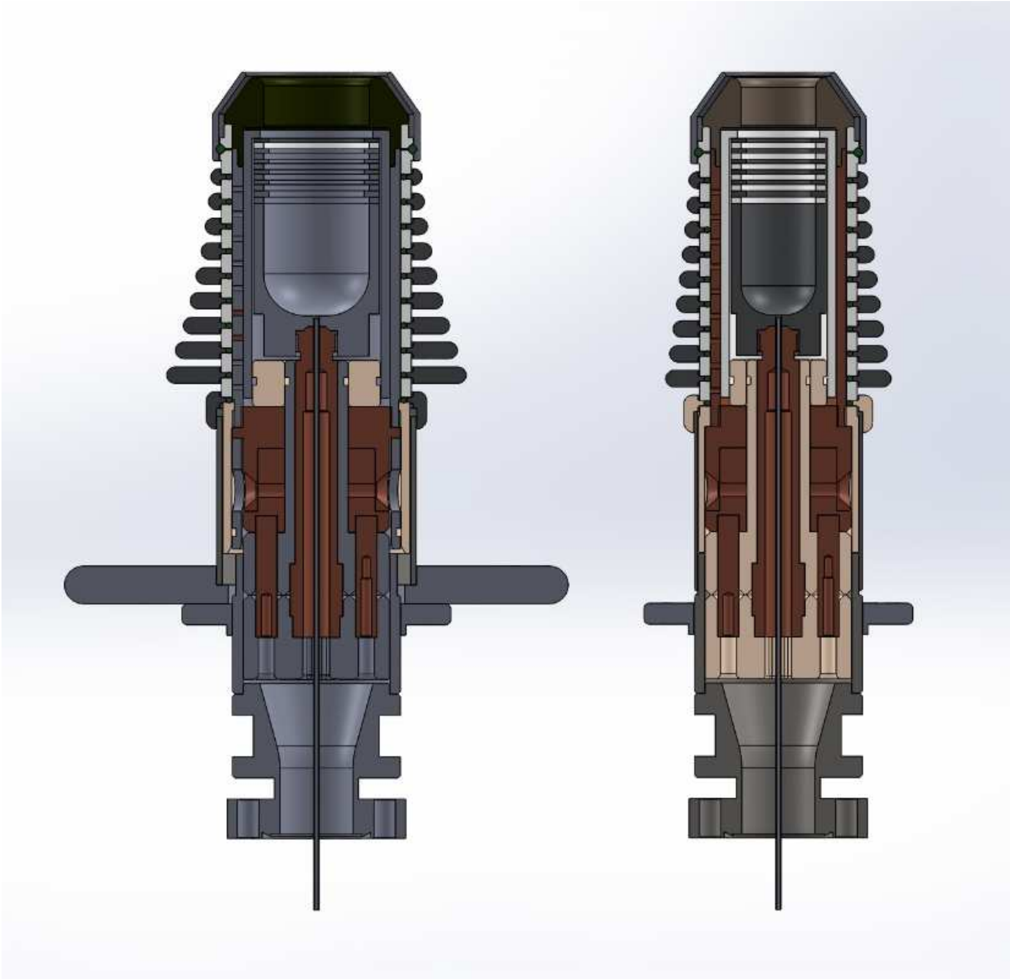
- Predictive equilibrium of strongest available shaping with Pegasus coils.

Larger Area Injectors for HFS LHI in Design Phase

- Due to limitations on R_{inj} and V_{inj}, increasing A_{inj} presents most promising near term path to higher performance

- Two 6-8 cm^2 aperture injectors currently being designed based on 4 cm^2 designs

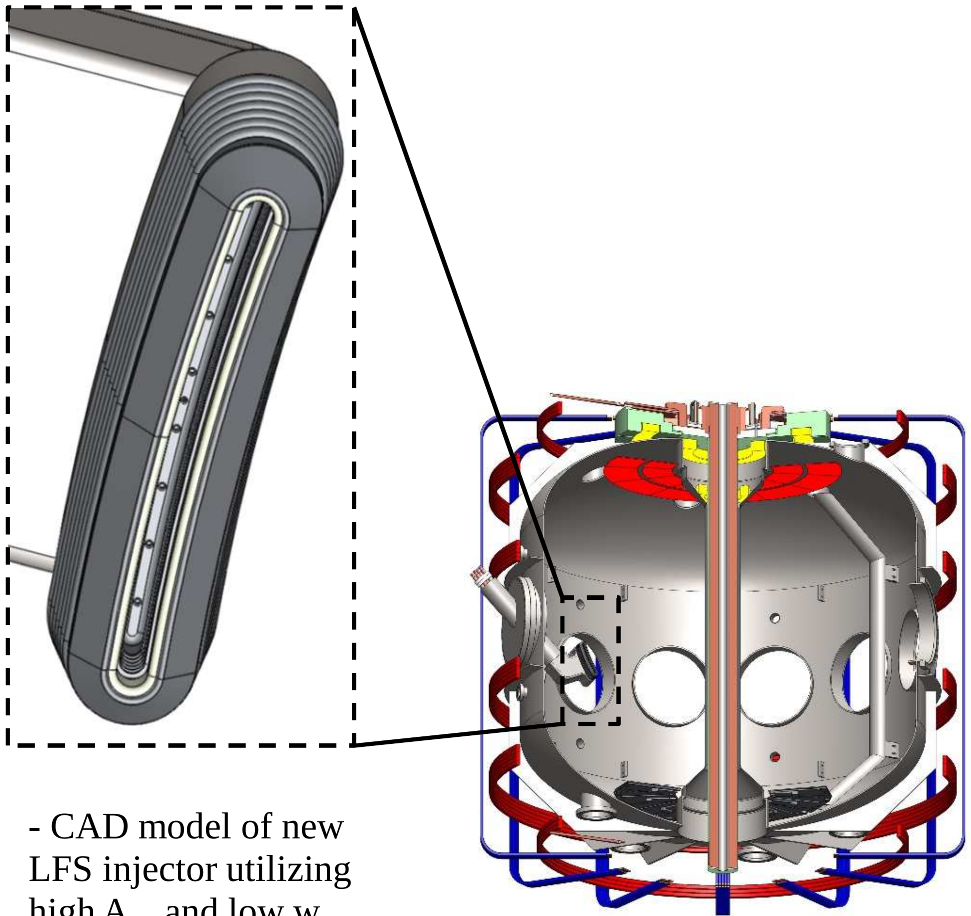
- Limits on increasing A_{inj} further:
  - Arc plasma eventually becomes hollow
  - Less effective coupling to plasma



- Left: 8 cm^2 gun design vs Right: 4 cm^2 existing gun design

Advanced Injector Shapes to Provide Access to High Performance with LFS LHI

- Design of a high A_{inj}, low w_{inj} injector is underway for LFS LHI
  - Increased I_{inj} capability while maintaining low w_{inj} to increase Taylor limit
  - Large A_{inj} allows for low V_{inj} operation
- Injector shape conforms to flux surfaces to improve coupling
- Active gas feedback control to balance I_{inj} and V_{inj}
- Anode fueling to improve arc stability
- Programmable $V_{inj}(t)$ for plasma evolution control



- CAD model of new LFS injector utilizing high A_{inj} and low w_{inj}

Conclusions and Future Work

- Handoff between the two helicity injection systems in Pegasus has achieved reliable, high performance operation at $I_p > 0.2\ MA$
  - Conceptual validation of transferring current drive between multiple helicity injection systems
- Transient MHD transition at full B_{TF} suggests threshold behavior
  - Understanding and controlling transition may enhance current drive efficiency
- Confinement scaling models offer several options to describe I_p vs V_{LHI}
  - Data hints at different core/edge behavior
- Further optimization of injector geometry to improve performance of LHI
  - Larger area injectors to increase V_{LHI}
  - Advanced injector shapes to increase Taylor limit and improve power coupling to the plasma

Non-Solenoidal Startup in the Pegasus ST

Challenges of Helicity Injection at Low R_{inj}

LFS to HFS Handoff at Full Toroidal Field

Characterization of Current Scaling in LHI

Paths to Improved Startup Using LHI

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