# Non-Solenoidal Tokamak Startup via Inboard Local Helicity Injection on the Pegasus ST

Justin M. Perry



University of Wisconsin-Madison

APS-DPP Meeting

11-2-2016



PEGASUS Toroidal Experiment

# Abstract


- Local Helicity Injection (LHI) is a non-solenoidal startup technique utilizing small injectors at the plasma edge to source current along helical magnetic field lines. Unstable injected current streams relax to a tokamak-like configuration with high toroidal current multiplication. Flexible placement of injectors permits trade-offs between helicity injection rate, poloidal field induction, and magnetic geometry requirements for initial relaxation. Experiments using a new set of large-area injectors in the lower divertor explore the efficacy of high-field-side (HFS) injection. The increased area (4 $cm^2$) current source is functional up to full Pegasus toroidal field ( T). However, relaxation to a tokamak state is increasingly frustrated for T with uniform vacuum vertical field. Paths to relaxation at increased field include: manipulation of vacuum poloidal field geometry; increased injector current; and plasma initiation with outboard injectors, subsequently transitioning to divertor injector drive. During initial tests of HFS injectors, achieved was limited to V by plasma-material interactions on the divertor plate, which were resolved by increasing injector elevation. In these experiments with helicity injection as the dominant current drive MA has been attained, with eV and $m^{-3}$. Extrapolation to full , longer pulse length, and kV suggest MA should be attainable in a plasma dominated by helicity drive .




THE UNIVERSITY of WISCONSIN MADISON

# Non-Solenoidal Tokamak Startup via Inboard Local Helicity Injection on the Pegasus ST

| LHI: Scalable Non-Solenoid Startup | Exploring LHI Physics With HFS Injection | Relaxation at Increased $B_{inj}$ | PMI Suppression | Preliminary Results | MHD Behavior with HFS Injection |
|---|---|---|---|---|---|
| Local Helicity Injection in the Pegasus ST | Research Goal: Investigate Physics of LHI-Dominant R | Understanding Requirements for Relaxation to a Tokamak-like Plasma Configuration | Challenge: Sustaining High $V_{inj}$ 1-2 cm from LCFS | Ip up to 0.15 MA achieved; Sustainment of $I_p$ > 0.1 MA | NIMROD Model Explains LHI Current Drive Mechanism |
| Stages of LHI Startup (3 pics of stages of LHI discharge) | Technical Challenges for LHI Startup with HFS Injection | Challenges to Relaxation at Increased $B_{inj}$ | Injector Alignment to Field Critical to PMI Mitigation | Te > 100 eV Measured during LHI Startup and Sustainment | MHD Activity: HFS Injection Shows Different Characteristics than LFS Injection |
| Helicity Conservation: Quantifying Current Drive from LHI | HFS Injection Implementation: Lower Divertor Injectors | Vacuum Poloidal Field Shaping Aids Relaxation with HFS Injection | Injector Proximity to Lower Divertor Plate Induces PMI | Power balance model shows different current drive components at HFS/LFS injection | Possible Differences in Current Drive Mechanism with HFS Injection |
| Flexible Injector Geometry: Different Physics with HFS and LFS Injection | Large-A Injector Design provides enhanced performance, simplified geometry | Vacuum Poloidal Field Shaping Affects Relaxation Physics | Repositioning and Injectors, Redesign of Local Limiters Mitigates PMI | Access to High $I_N$ | Summary |
| | | | | Access to High Beta | |



THE UNIVERSITY of WISCONSIN MADISON



# Local Helicity Injection



THE UNIVERSITY of WISCONSIN MADISON





# Injector Location Matters



THE UNIVERSITY of WISCONSIN MADISON



# Relaxation at Increased $B_{inj}$



THE UNIVERSITY of WISCONSIN MADISON



# PMI Suppression

# Preliminary Results



THE UNIVERSITY of WISCONSIN MADISON



# MHD Characteristics During HFS Injection

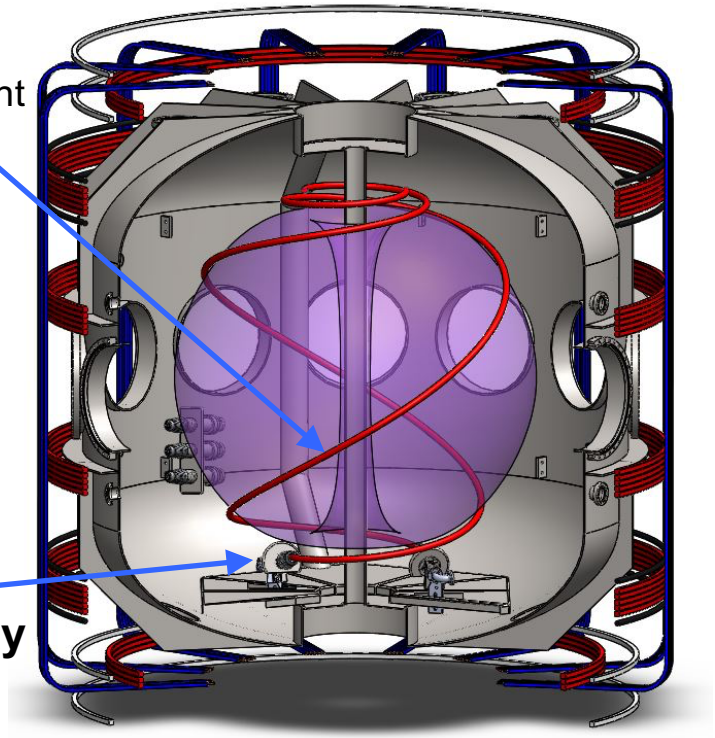


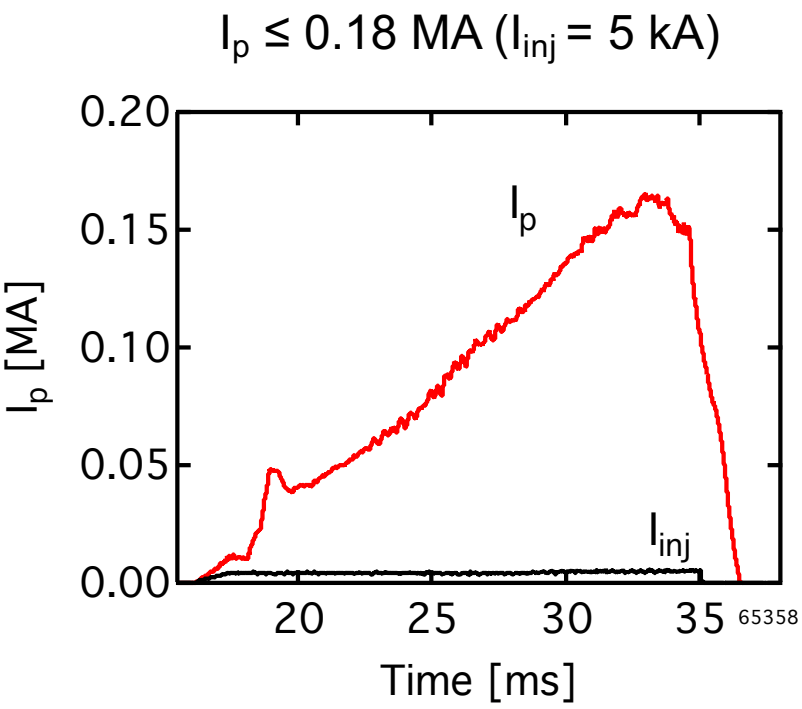




# Local Helicity Injection (LHI) is a Promising Non-Solenoidal Startup Technique






- Edge current extracted from injectors
- Unstable current streams form tokamak-like state via Taylor relaxation
- Used routinely for startup on Pegasus

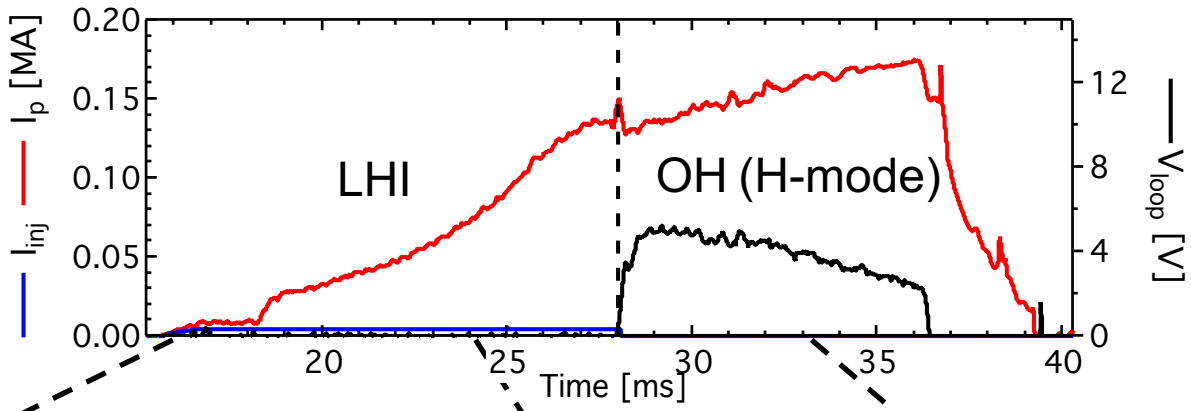


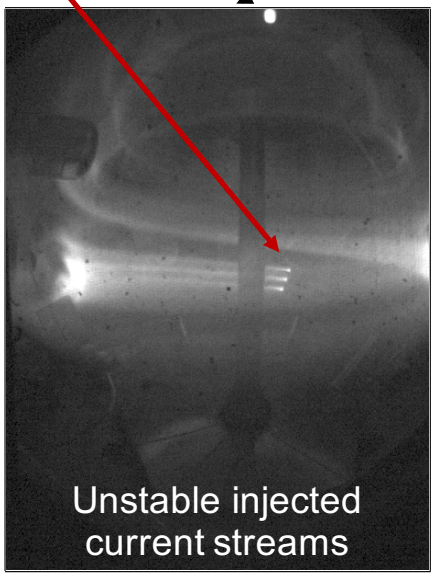
THE UNIVERSITY of WISCONSIN MADISON

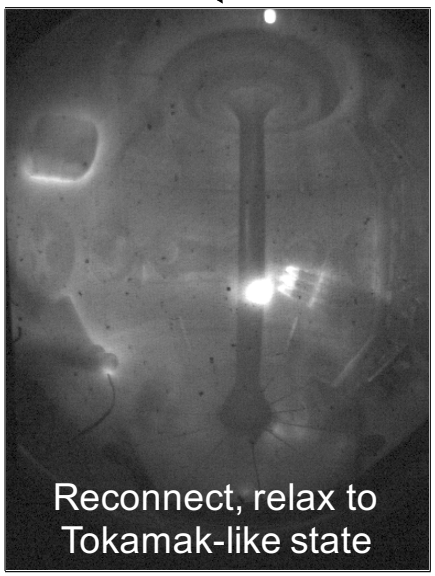
# Local Helicity Injection (LHI) Provides Robust ST Startup without OH Solenoid

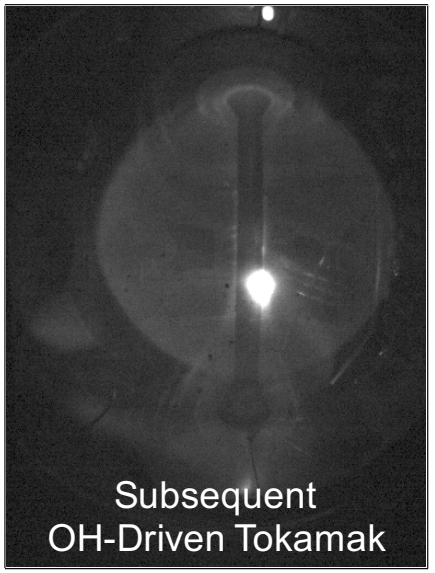
Three-Injector Array






*J.M. Perry, APS DPP 2016*

THE UNIVERSITY of WISCONSIN MADISON

# Helicity Injection Drives Toroidal Current

Total helicity $K$ in a tokamak geometry: $K = \int_V (\mathbf{A} + \mathbf{A}_{vac}) \cdot (\mathbf{B} - \mathbf{B}_{vac})\, d^3x$

$$\frac{dK}{dt} = -2\int_V \eta \boldsymbol{J}\cdot\boldsymbol{B}\, d^3x - 2\frac{d\psi}{dt}\Psi - 2\int_A \Phi\boldsymbol{B}\cdot d\boldsymbol{s} \quad \Rightarrow \quad I_p \le \frac{A_p}{2\pi R_0\langle\eta\rangle}(V_{ind} + V_{eff})$$

Resistive dissipation | Inductive drive | DC helicity injection

$$\dot{K}_{DC} = -2\int_A \Phi\mathbf{B}\cdot d\mathbf{s} = 2V_{inj}B_{\perp}A_{inj} \quad \Rightarrow \quad V_{eff} \approx \frac{A_{inj}B_{\phi,inj}}{\Psi}V_{inj}$$

Power balance relation incorporates all drive and anti-drive terms:

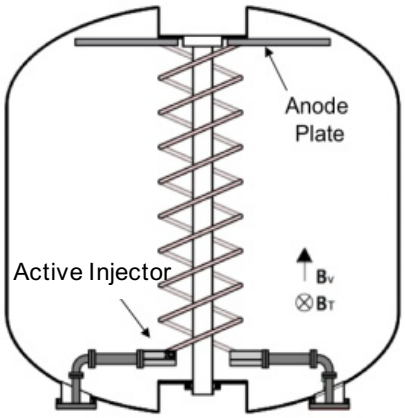
- LHI current drive ($V_{LHI}$)
- Net inductive drive ($V_{IND}$), includes:
  - Shape evolution
  - $I_p$ growth
  - PF induction
- Plasma resistance, anti-drive ($V_{IR}$)

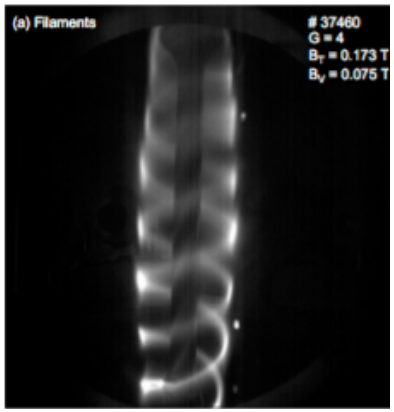
$$I_p\left[V_{LHI} + V_{IR} + V_{IND}\right] = 0$$



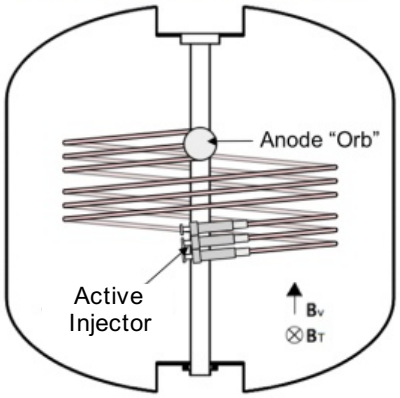
THE UNIVERSITY of WISCONSIN MADISON

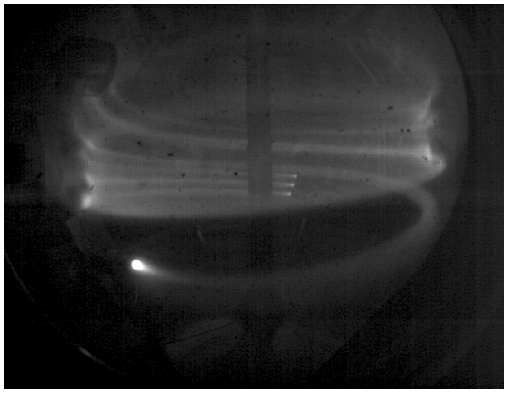
# Flexible Injector Geometry: Accessing Different Physics Through Varied Injector Location




$R_{inj}$ = 25cm, $Z_{inj}$ = -70 cm



$R_{inj}$ = 70 cm, $Z_{inj}$ = -20 cm

## High-Field-Side Injection:

- Injectors in lower divertor
- Increased $V_{eff}$ due to high field at injector
- More static plasma shape evolution

→ Reduced $V_{IND}$

## Low-Field-Side Injection:

- Injectors on outboard mid-plane
- Reduced $V_{eff}$ due to lower field at injector
- Highly dynamic plasma shape evolution

→ Increased $V_{IND}$



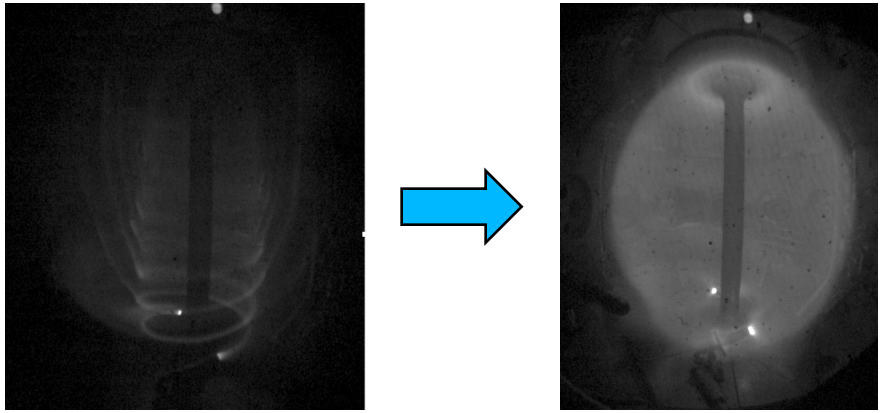
THE UNIVERSITY of WISCONSIN MADISON

# Investigating Physics of LHI Startup With $V_{LHI}$ as Dominant Current Drive

- Past experiments:
  - LHI startup to $I_p \geq 0.18$MA using LFS injection
  - $V_{IND} > V_{LHI}$ due to strong shape evolution, PF ramp
- Present research: $V_{LHI} \gg V_{IND}$ to isolate physics of LHI current drive
  - Confinement behavior with LHI drive dominant
  - Stronger predictive understanding of LHI system requirements
- Experimental requirements:
  - Increased $V_{LHI}$, sustained coupling to LHI current drive
  - Minimal shape evolution → minimal inductive effects
  - Demonstrate LHI efficacy at increased toroidal field

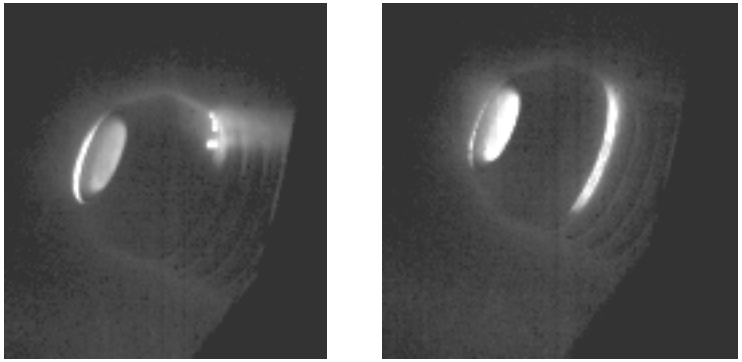
# Technical Challenges for LHI Startup with HFS Injection

- Initial relaxation to Tokamak state
  - More difficult for low $R_{inj}$, high $B_{inj}$
- 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)*

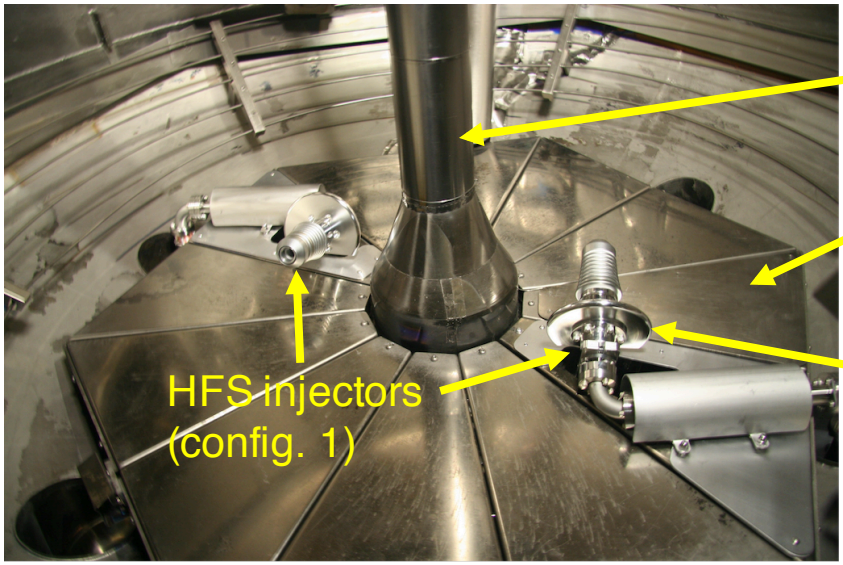




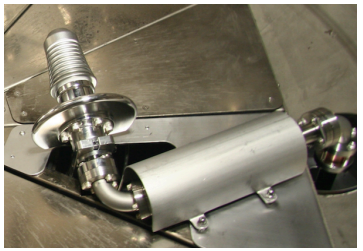
THE UNIVERSITY of WISCONSIN MADISON

# HFS Injection Implementation: Lower Divertor Injectors

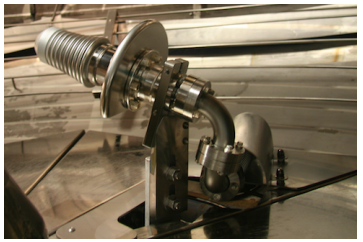
- Set of two injectors at toroidally opposite positions in divertor region
  - New injector design targeted toward HFS injection
- System design point:
  - 3-4 x increase in $V_{LHI}$ over past systems
  - $A_{inj} = 8$ cm$^2$ (total); $V_{inj} \geq 1.2$ kV; $I_{inj} \geq 8$ kA (total)
- Three injector geometries tested since April 2016
  - Variations in $R_{inj}$, $Z_{inj}$, local limiter geometry



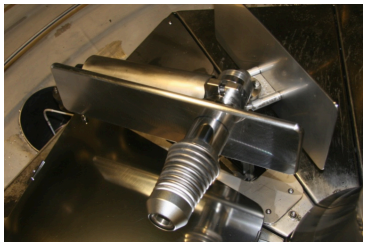

Config. 1



Config. 2

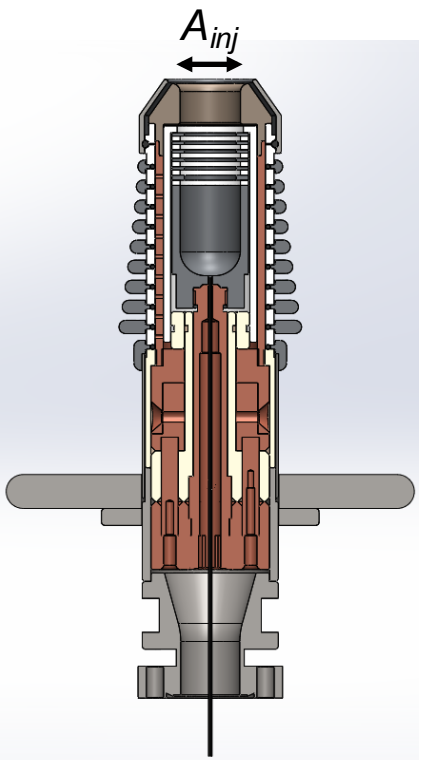


Config. 3

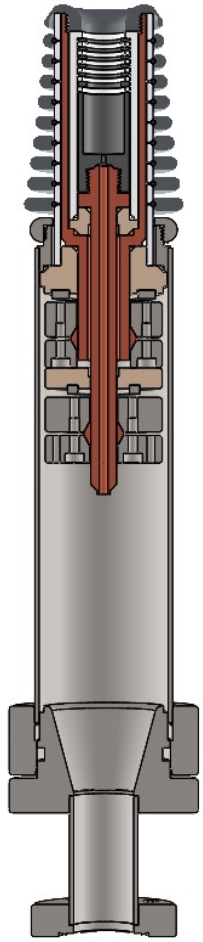


# Large-A Injector Design Provides Enhanced Performance, Simplified Geometry

- Multi-year technology development effort
- Formidable requirements:
  - $V_{inj} > 1\text{kV}$
  - High $J_{inj}$ ($\sim 1\text{kA/cm}^2$)
  - 1-2 cm from LCFS
- New large-area injectors:
  - Doubled $A_{inj}$ ($2\text{cm}^2 \rightarrow 4\text{cm}^2$)
  - Compact design to fit in divertor region
  - Modular assembly permits in-vessel maintenance, repositioning
  - Advanced materials for resilience in harsh environment



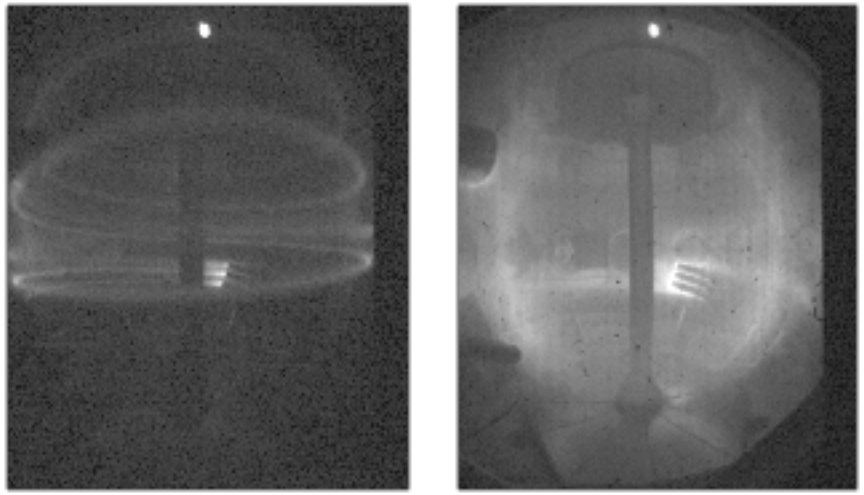

New: 4 $\text{cm}^2$



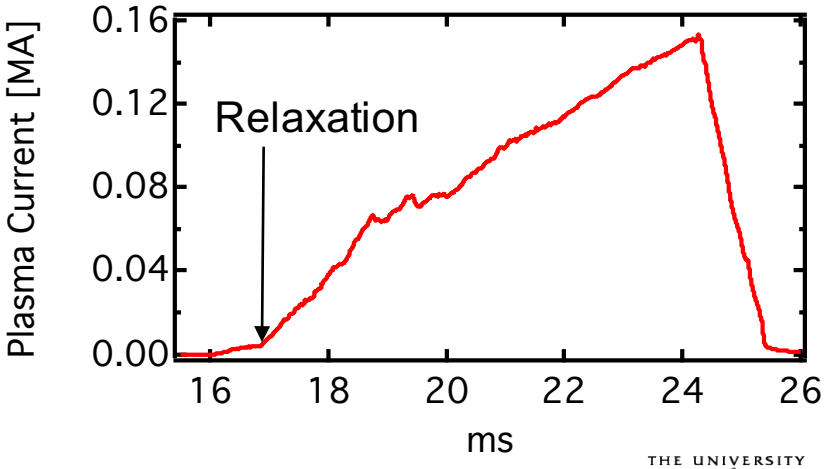
Old: 2 $\text{cm}^2$

# Understanding Requirements for Relaxation to a Tokamak-Like Configuration

- Unstable current streams follow helical path, deform vacuum field
- When $B_{z,inj} \approx -B_{z,vac}$ adjacent passes attract, reconnect
  - Closed toroidal current loops formed
  - Accumulation of poloidal flux
- Taylor relaxation toward lowest energy state
  - Tokamak-like plasma formed
  - Now $I_p >> I_{inj}$ possible



*Left: Current filaments follow vacuum field.*
*Right: null formation and relaxation to tokamak-like plasma.*
*Bottom: Plasma current rises during relaxation.*



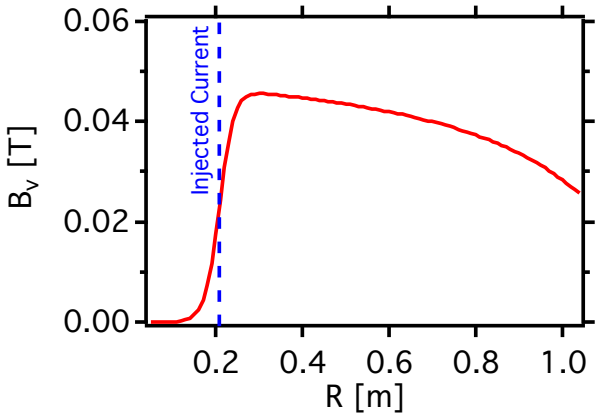


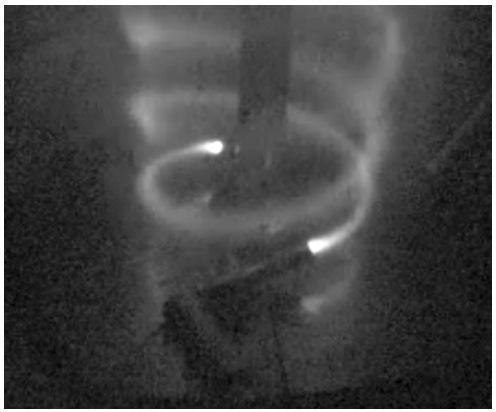

THE UNIVERSITY of WISCONSIN MADISON

# Challenges to Relaxation at Increased $B_{inj}$

- Relaxation condition:
  - Substantial weakening of vacuum $B_z$ by injected current streams
- Injector geometry sets minimum pitch ($B_z$ / $B_{tor}$)
  - Current streams must clear opposite injector: $2\pi R_{inj} \frac{B_z}{B_{tor}} > h_{inj}$
- HFS injection:
  - Higher $B_{tor}$, lower $R_{inj}$ than LFS injectors
    → more $B_z$ for clearance
  - Relaxation more difficult, unless $B_{tor}$ reduced or $I_{inj}$ increased
  - Operational goal: relaxation at full Pegasus $B_{tor}$

*Injected current must weaken vertical field locally for relaxation*



*Current streams must clear opposite injector*

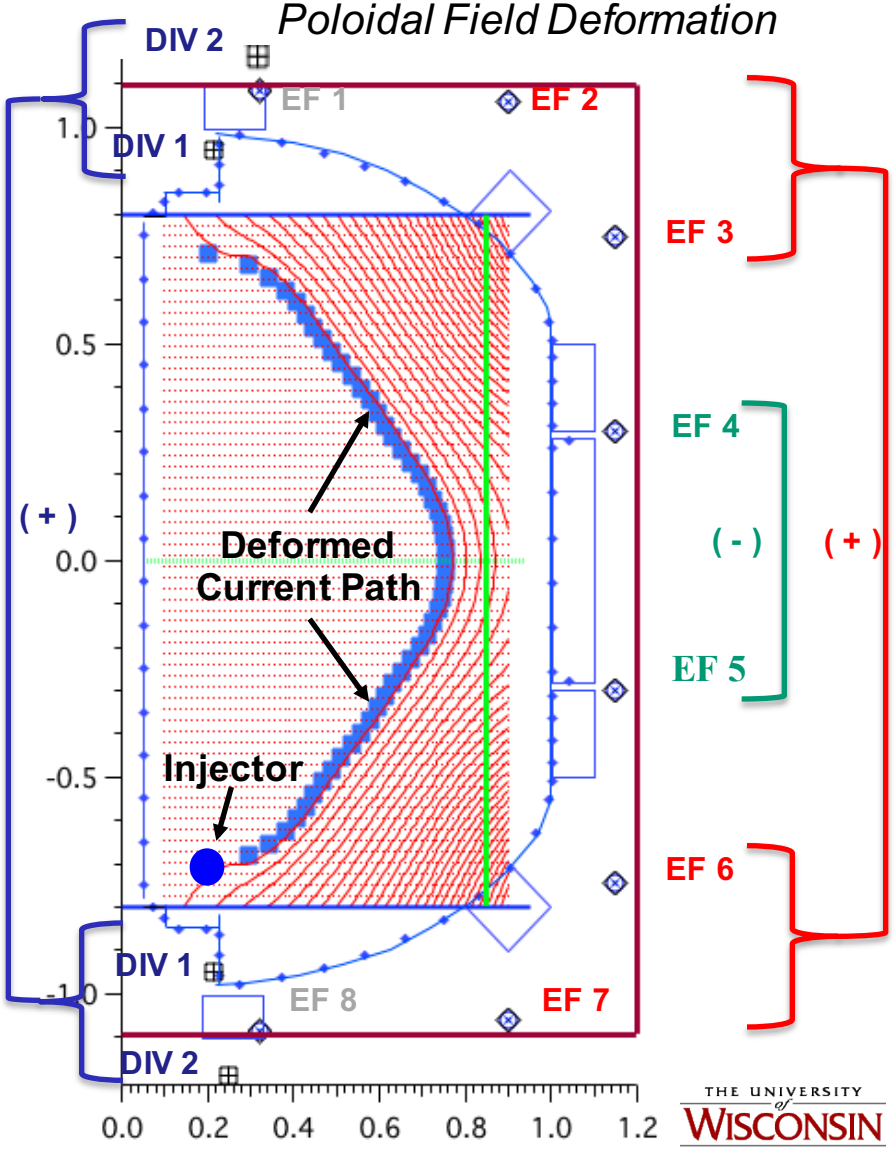


THE UNIVERSITY of WISCONSIN MADISON

# Strategy for Relaxation at Full Toroidal Field ($B_{inj}$ = 0.23 T)

- Highly shaped vacuum field:
  - Divertor coils positive (co-EF) to boost $B_z$ locally near injectors for clearance (**DIV 1, DIV 2**)
  - Mid-plane coils negative to assist null formation (**EF 45**)
  - Main equilibrium coils positive (**EF 23 + EF 67**)
  - Vacuum field weak at mid-plane, current streams able to overpower
- After relaxation, quickly ramp vertical field for force balance
- Limitation:
  - Deformed current path must not hit outer limiter

*2-D Multi-Filament Model of Poloidal Field Deformation*

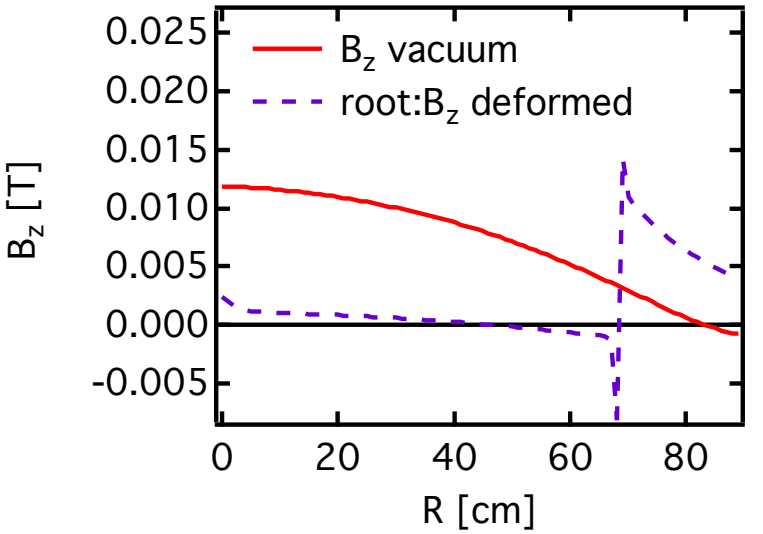


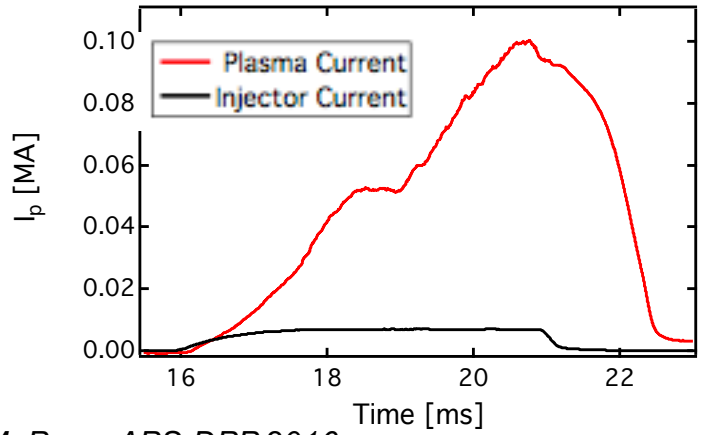



THE UNIVERSITY of WISCONSIN MADISON

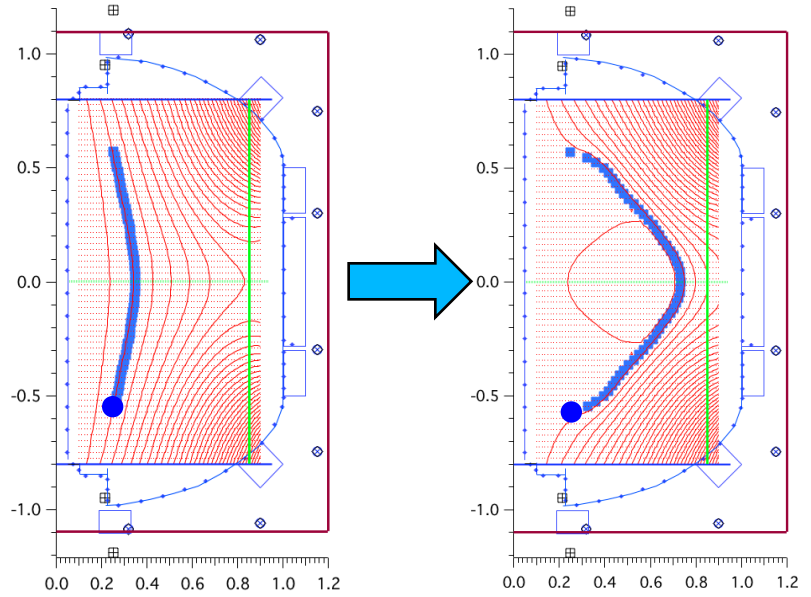
# Successful Relaxation at Full Toroidal Field ($B_{inj}$ = 0.23 T)

- Successfully employed for relaxation at full field:

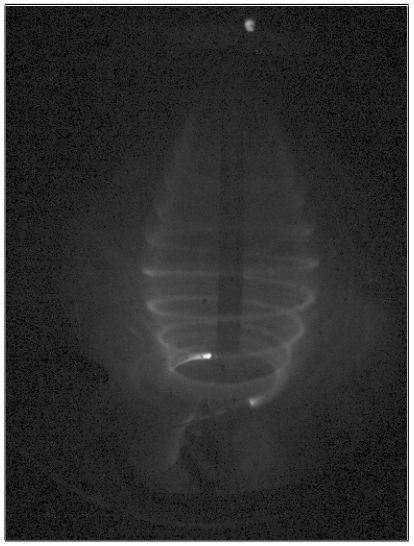



*J.M. Perry, APS DPP 2016*




*Vacuum Field* *Deformed Field*

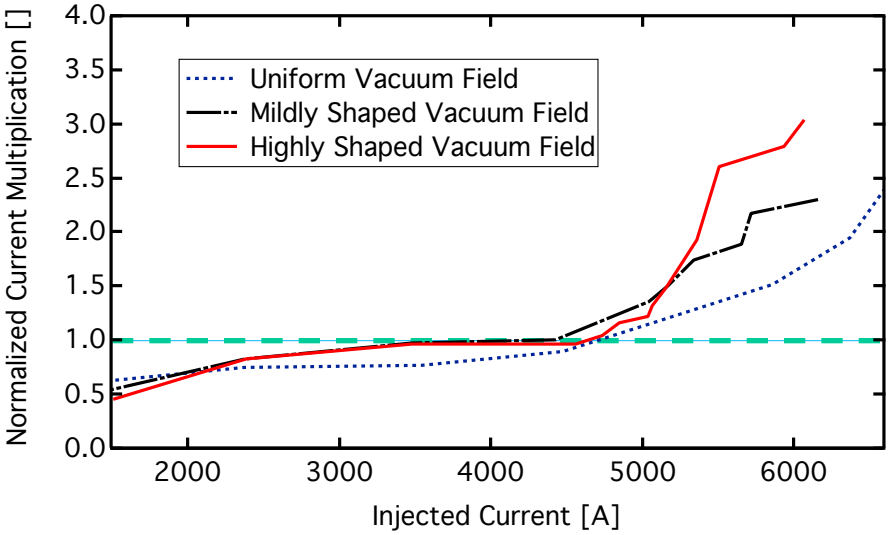


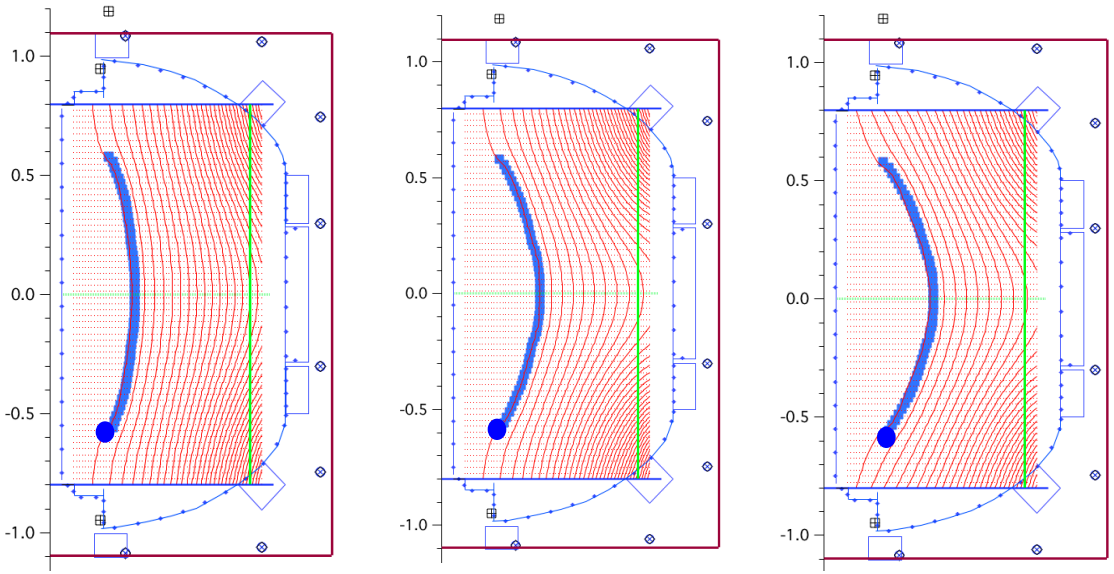


# Vacuum Poloidal Field Shaping Affects Relaxation Physics

- Current multiplication increases rapidly with $I_{inj}$ once relaxation is achieved
  - Pre-relaxation: $I_p \approx I_{inj} \times N_{turns}$
  - Post-relaxation:

    $I_p \approx I_{inj} \times M; M \gg N_{turns}$
- With shaped vacuum fields:
  - $M$ increases more rapidly with $I_{inj}$



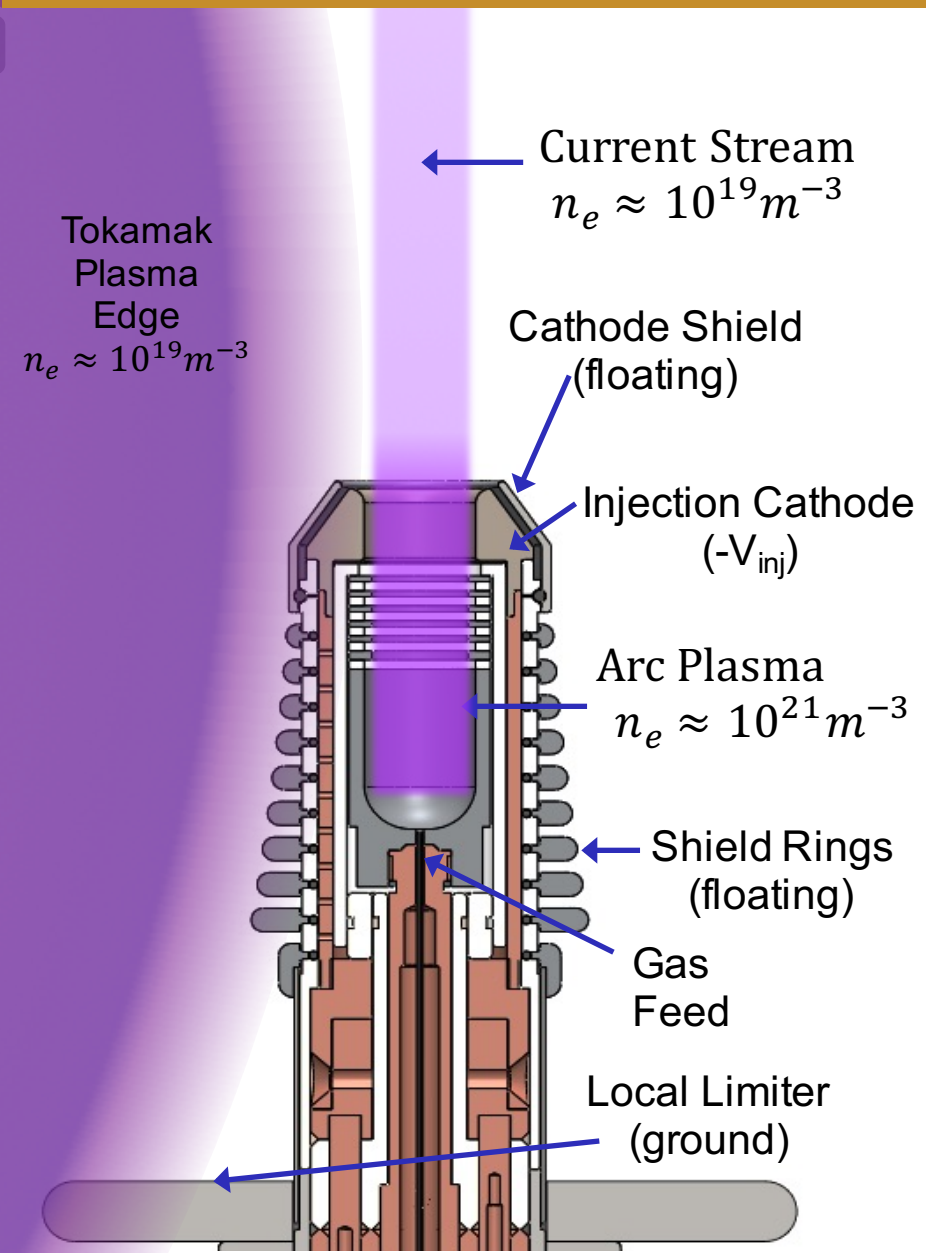




*Increased shaping of vacuum field* →

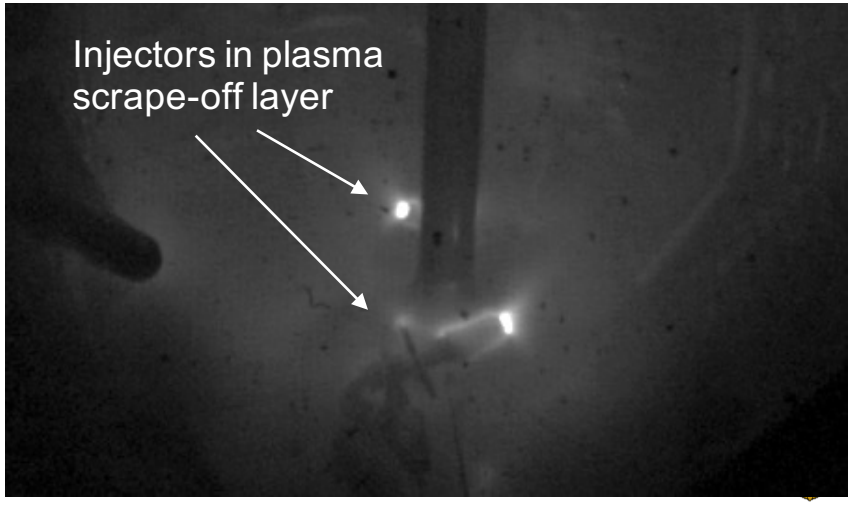
*J.M. Perry, APS DPP 2016*

THE UNIVERSITY of WISCONSIN MADISON

# Challenge: Sustaining $V_{inj}$ > 1kV within 1-2 cm of LCFS

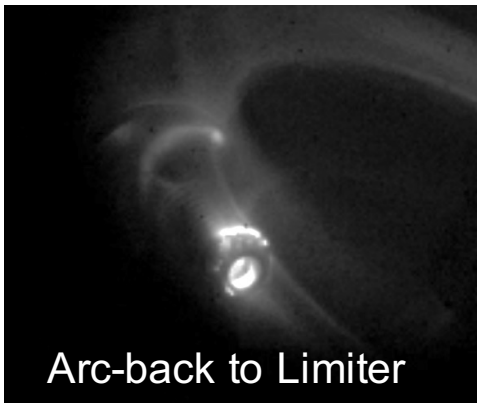


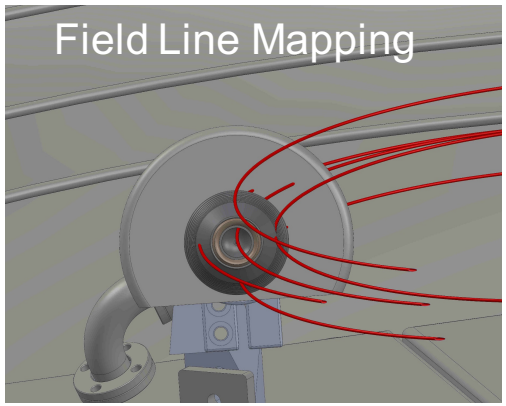

- Injectors biased by $V_{inj}$ ≥ 1 kV
- Must be 1-2 cm from plasma edge for current drive coupling
- Injector design minimizes PMI
  - Local limiter reduces plasma impact
  - Shield rings prevent arcing to limiter
  - Cathode shield reduces local $n_e$

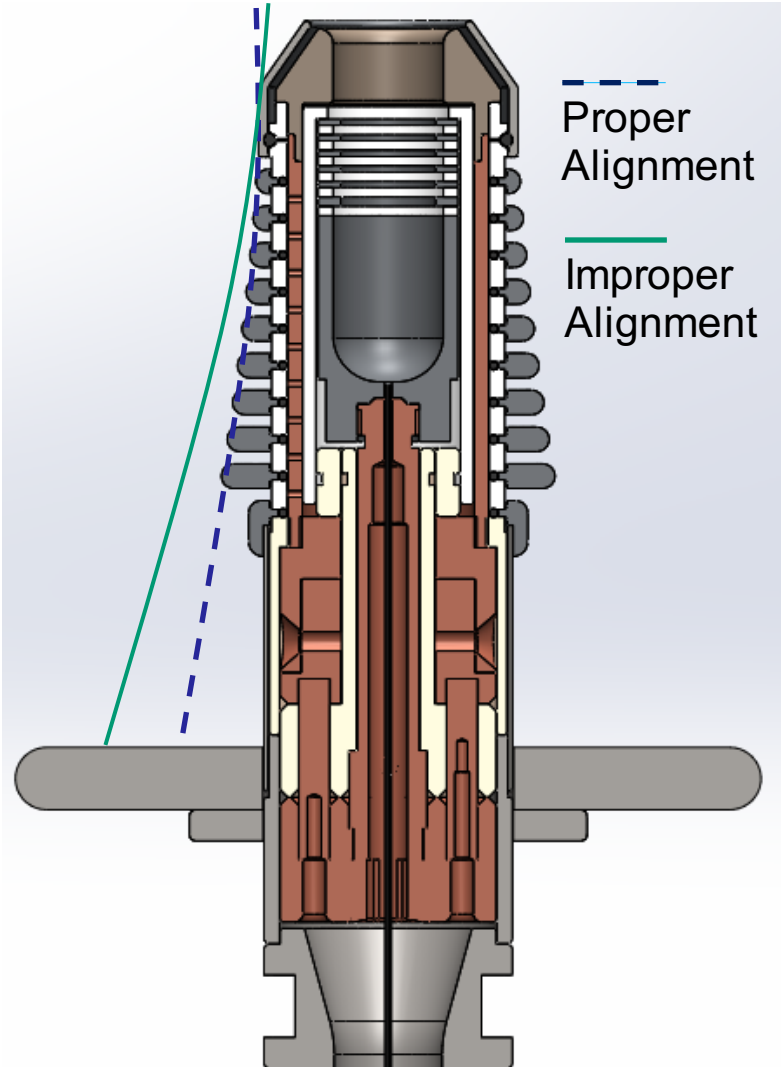


# Injector Alignment to Local Magnetic Field Critical to PMI Mitigation

- Floating shield rings block path for arcing back to grounded limiter
- Improper injector alignment permits magnetic line of sight for arcing to limiter
- Curvature of field lines depends on $B_{tor}$ / $B_{pol}$ → varies with $I_p$
  - Shield structures must function for range of conditions



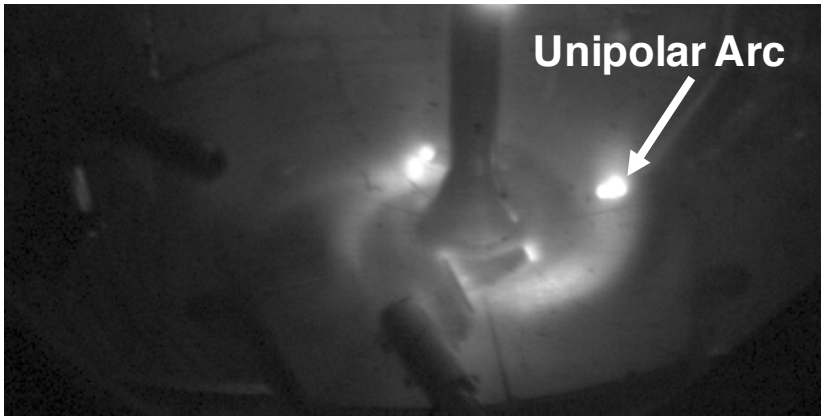



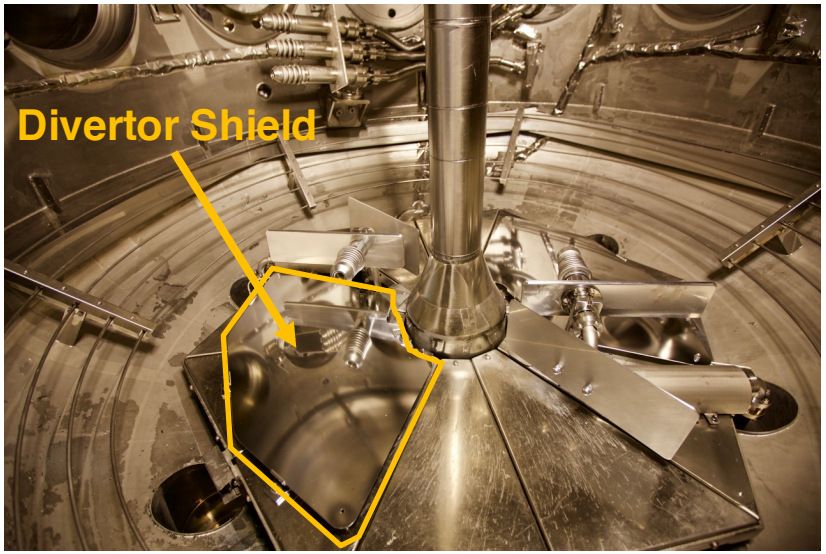

*J.M. Perry, APS DPP 2016*

THE UNIVERSITY of WISCONSIN MADISON

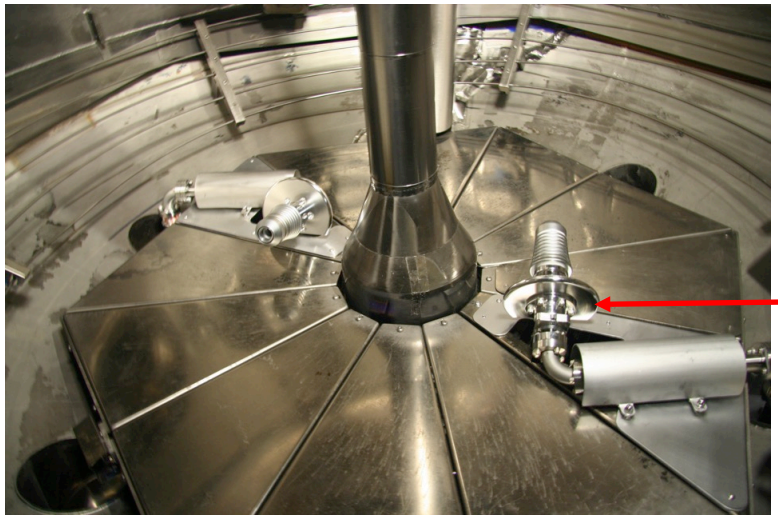
# Injector Proximity to Lower Divertor Plate Induces PMI

- Unipolar arcs on lower divertor
  - Can lead to bursts of ejecta that trigger PMI on injectors
  - More prevalent in increased $B_{tor}$
- Improvement: increased separation between injector and divertor plate
  - $\Delta Z$: 9 cm → 23 cm
  - PMI partially mitigated
- Electrically floating shield plates installed above divertor
  - Highly polished surface
  - Preliminary results: reduced incidence/severity of PMI

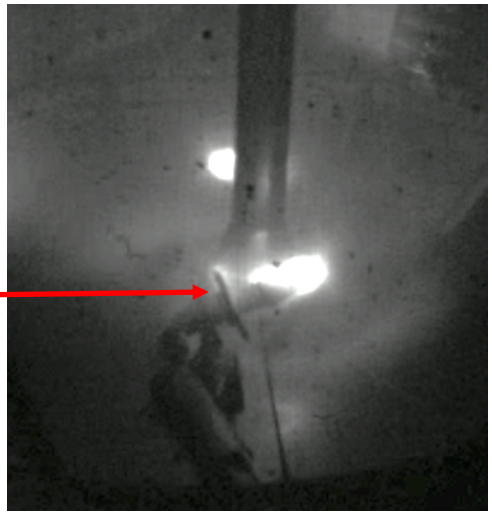


# Redesigned Local Limiters Shield Injector More Effectively

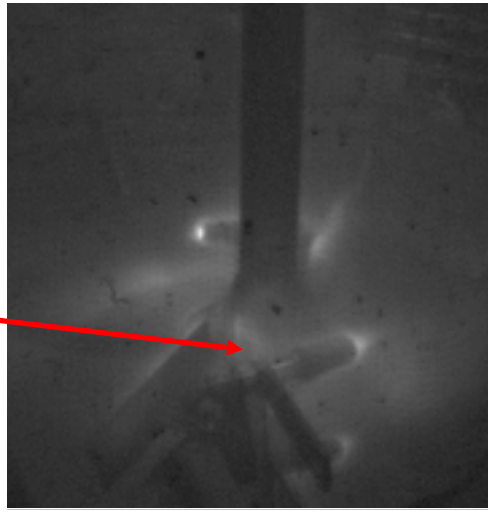


Original limiter:
injector immersed in
plasma edge





New limiter:
injector protected
from plasma impact

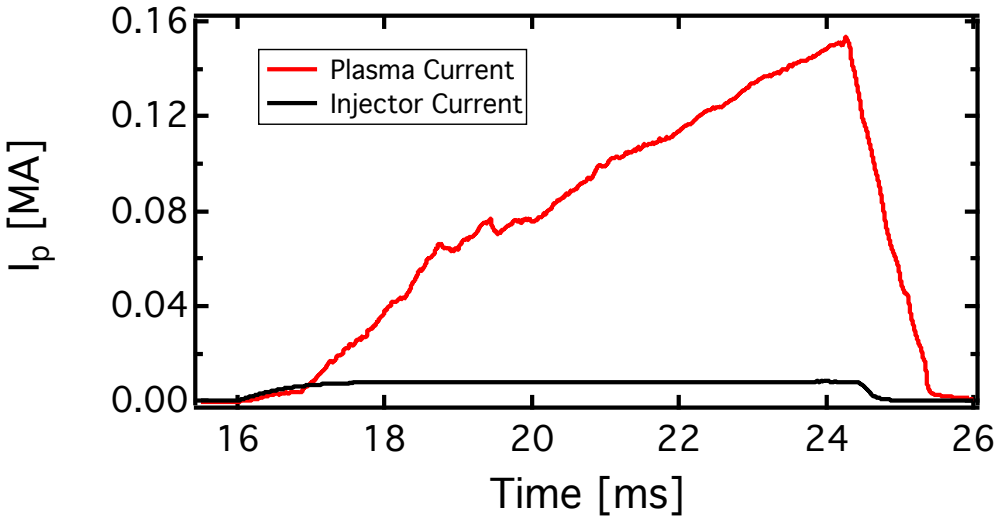


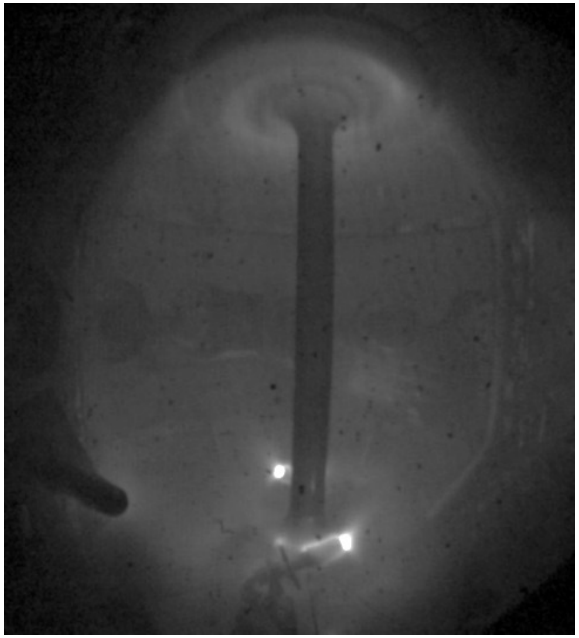


THE UNIVERSITY of WISCONSIN MADISON

# To Date, $I_p$ > 0.15 MA Achieved With HFS Injection

- $V_{LHI}$ increased 2x over previous experiments
- Most operations at low field:
  - $B_{inj}$=0.046-0.092 T (20-40% of max)
  - Reduced PMI, easier relaxation
- Demonstration of relaxed discharges at full field
  - $B_{inj}$=0.23 T, $I_{TF}$ = *0.288* MA
  - $I_p \approx 0.1\ MA$
- Progress on PMI mitigation
  - Modified limiter/injector position
  - Entangled with geometry requirements for coupling to plasma
- Ongoing research campaign



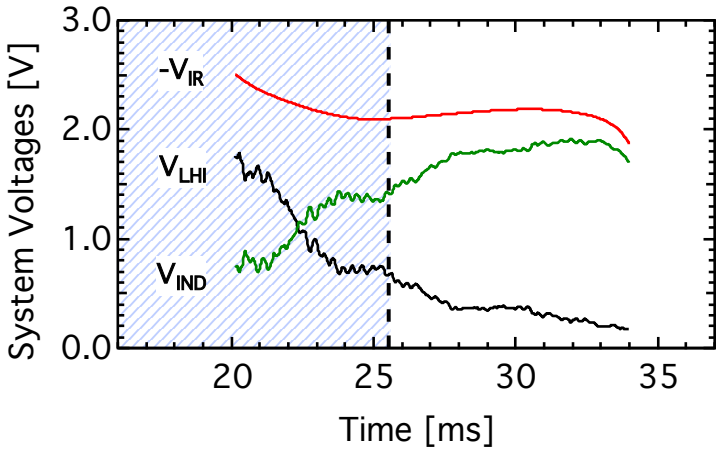



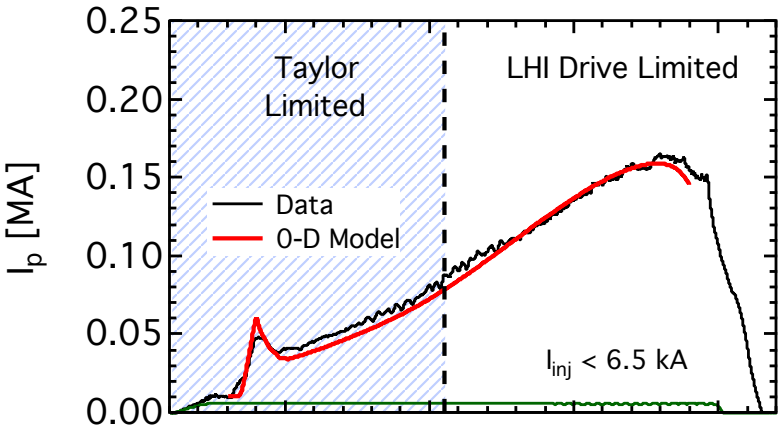


THE UNIVERSITY of WISCONSIN MADISON

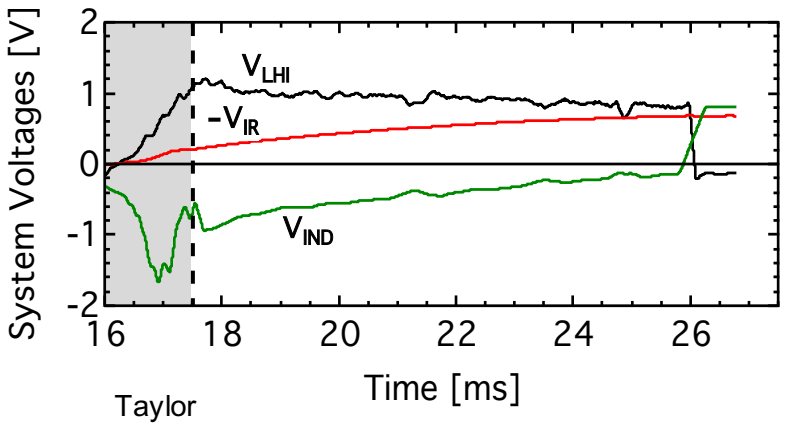
# 0-D Power Balance Model Illuminates Different Current Drive Components for HFS/LFS Injection

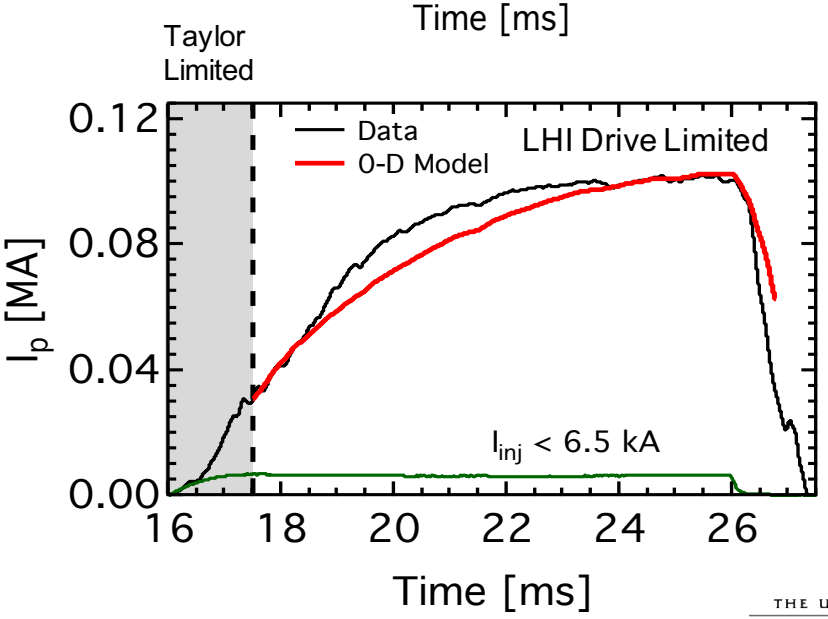
**LFS Injection**: net induction voltage dominates current drive




**HFS Injection**: LHI drive dominates; net induction is negative



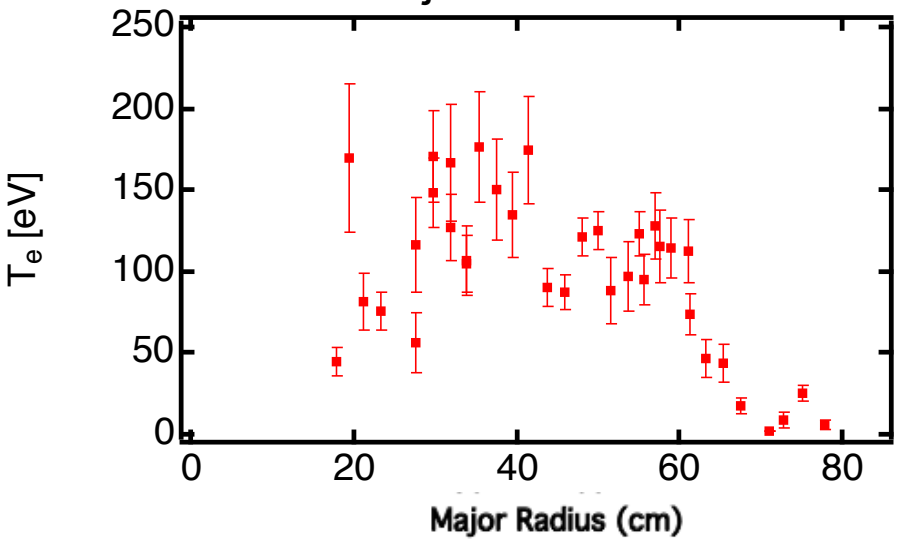

*J.M. Perry, APS DPP 2016*

THE UNIVERSITY of WISCONSIN MADISON

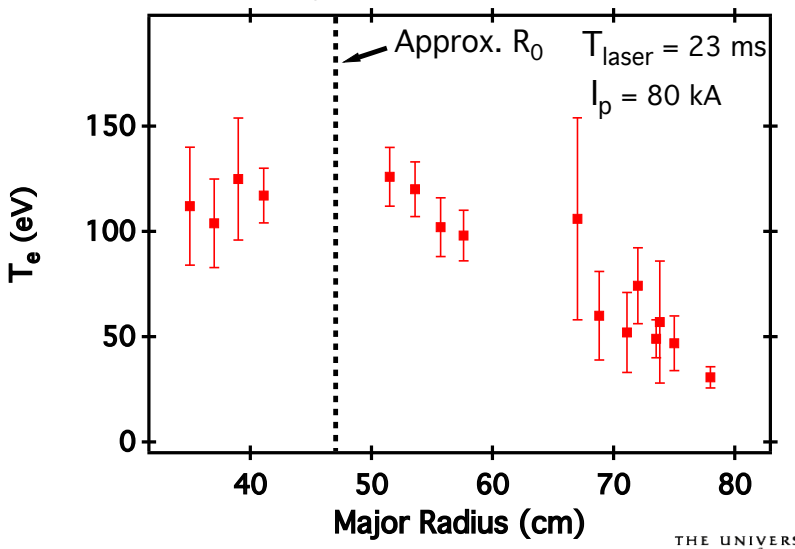
# LHI-Dominant Regime: Similar $T_e$, $n_e$ to LFS Injection

- Thomson Scattering profiles:
  - sustained $T_e > 100$ eV
  - $< n_e > \approx 1 \times 10^{19}\ m^{-3}$
- Plasma sustained by LHI current drive, no inductive drive
  - $T_e$, $n_e$ similar to inductive-dominant discharges (LFS injection)
  - Also comparable to Ohmic discharges in Pegasus

HFS Injection




LFS Injection



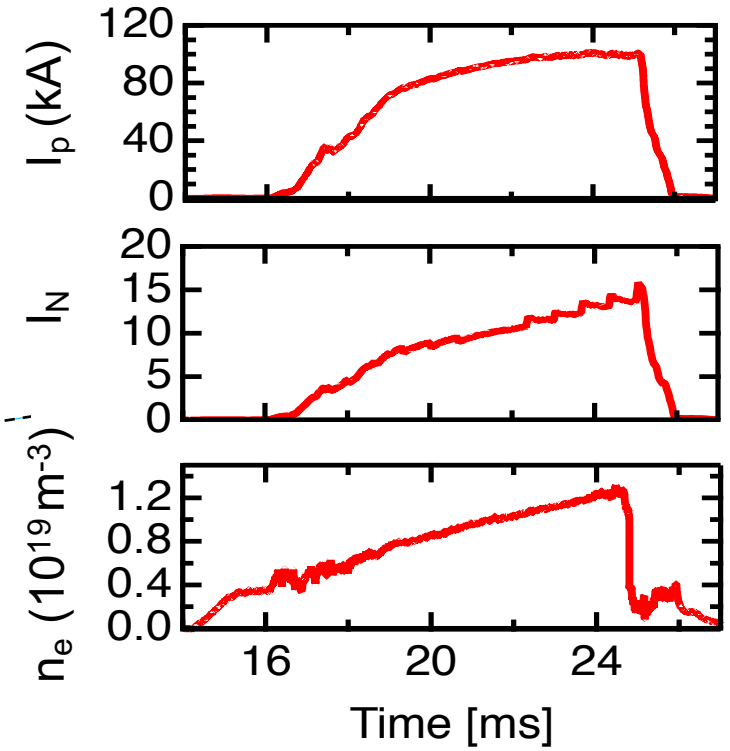

*J.M. Perry, APS DPP 2016*

THE UNIVERSITY of WISCONSIN MADISON

# HFS Injection Provides Non-Solenoidal Sustainment at High $I_N$

- Low $I_{TF}$ ~ 0.6 $I_p$
- $I_N = 5A\frac{I_P}{I_{TF}} > 10$
  - Constant or ramped-down $B_{TF}$
- HFS injector geometry -> naturally high elongation
- Ready access to High $\beta_T$
  - Aided by anomalous ion heating ($T_i > T_e$)

*Access to $I_N > 14$, $n_e$ ~ 1e19 $m^{-3}$ with HFS Injection, $B_{TF}$ Ramp-down*



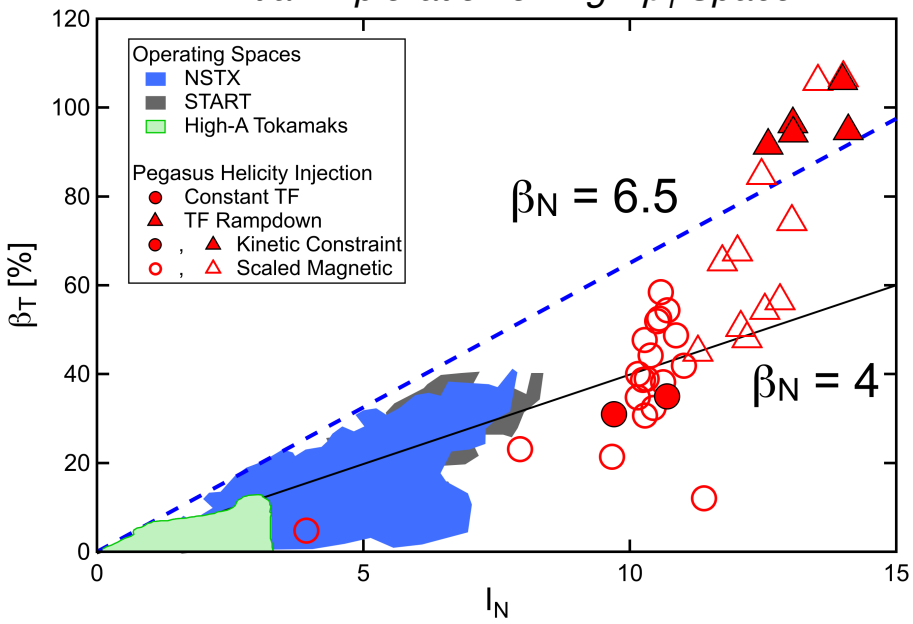


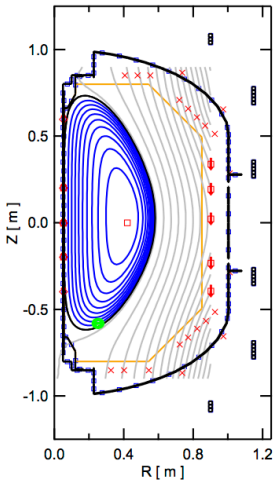

THE UNIVERSITY of WISCONSIN MADISON

# LHI Provides Access to High-$\beta_T$ at A ~ 1 with Non-Solenoidal Sustainment and Anomalous Ion Heating

- Equilibrium reconstructions indicate high $\beta_T$ (~<P>/$B_{T0}^2$)
- High $\beta_T$ plasmas often terminated by disruption
  - n = 1, low-m precursors
- Expands $I_N$, $\beta_T$ space for stability studies at extreme toroidicity
  - Campaign underway to document, extend to higher $I_p$
  - Improved LHI injector hardware to increase $I_p$, $B_{TF}$ access

*Initial Exploration of High-$\beta_T$ Space*



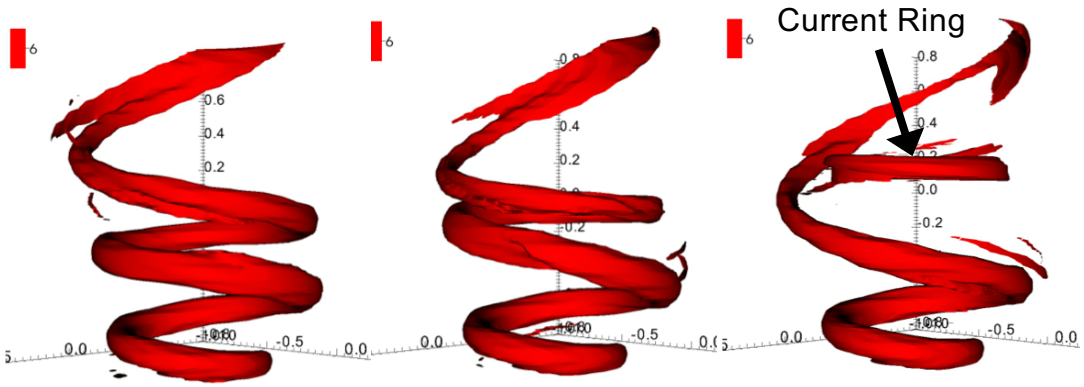

Equilibrium Parameters
Shot 87332, 24.50 ms, Undo 72

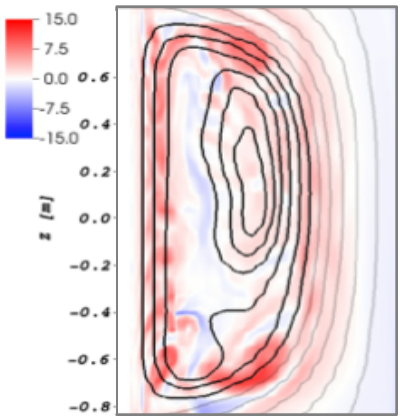
| | | | |
|---|---|---|---|
| $I_p$ | 102 kA | $R_0$ | 0.317 m |
| $\beta_t$ | 0.95 | a | 0.263 m |
| $\ell_i$ | 0.22 | A | 1.21 |
| $\beta_p$ | 0.45 | $\kappa$ | 2.6 |
| W | 545 J | $\delta$ | 0.54 |
| $B_{T0}$ | 0.0249 T | $q_{95}$ | 7.24 |



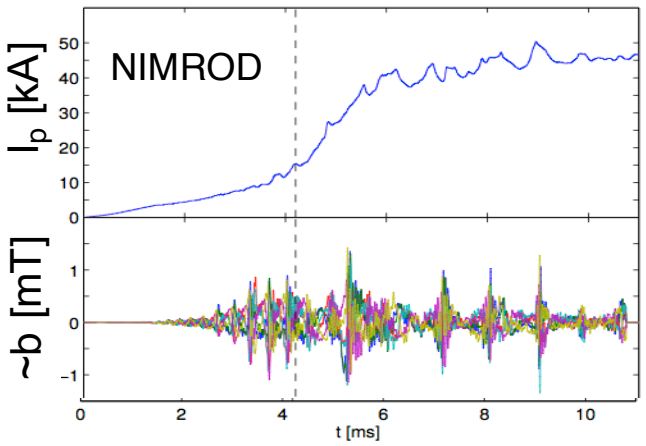
THE UNIVERSITY of WISCONSIN MADISON

# NIMROD Simulations Describe Current Helical Current Stream Reconnection as Drive Mechanism

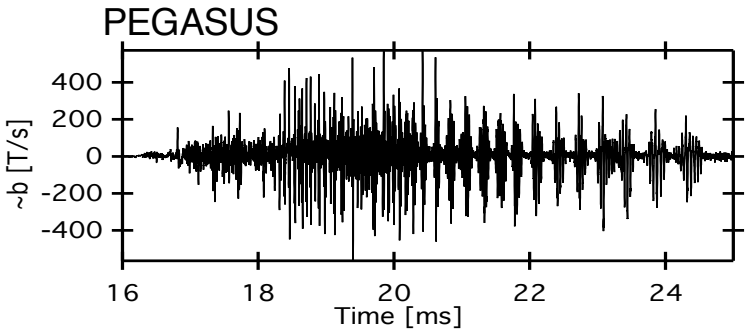



1. Streams follow field lines
2. Adjacent passes attract
3. Reconnection pinches off current rings
4. Accumulation of poloidal flux; current filaments persist




- Reconnection events produce MHD bursts; seen in both simulation and experiment

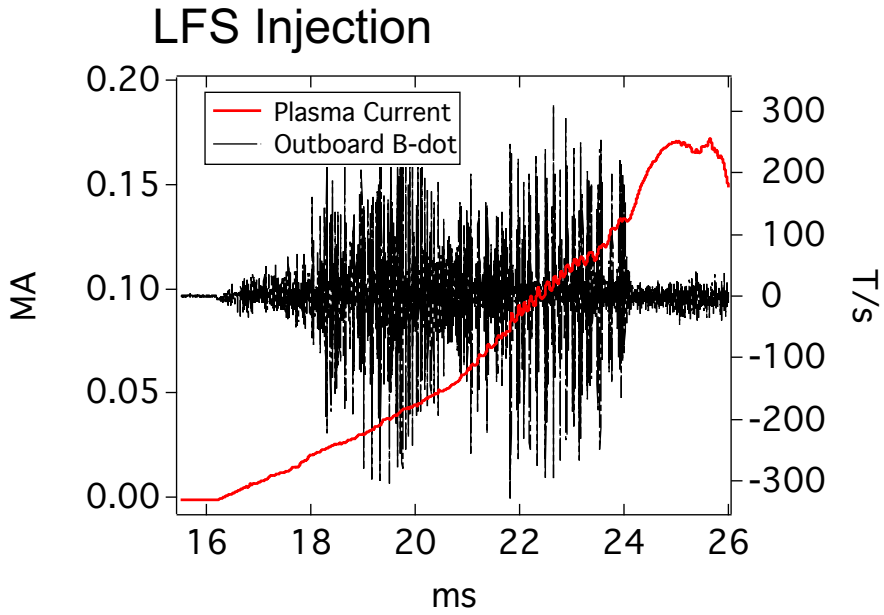


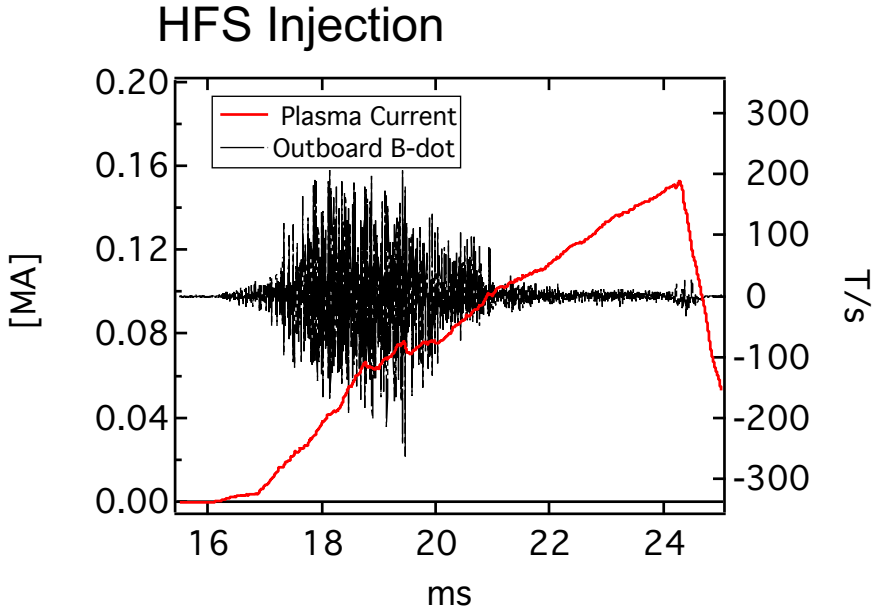



*J. O'Bryan, et al., Physics of Plasmas,* ***19****, 080701 (2012)*
*J. O'Bryan, C.R. Sovinec, Plasma Phys. Control. Fusion* ***56*** *064005 (2014)*

THE UNIVERSITY of WISCONSIN MADISON

# MHD Activity During HFS Injection Shows Different Behavior from LFS Injection



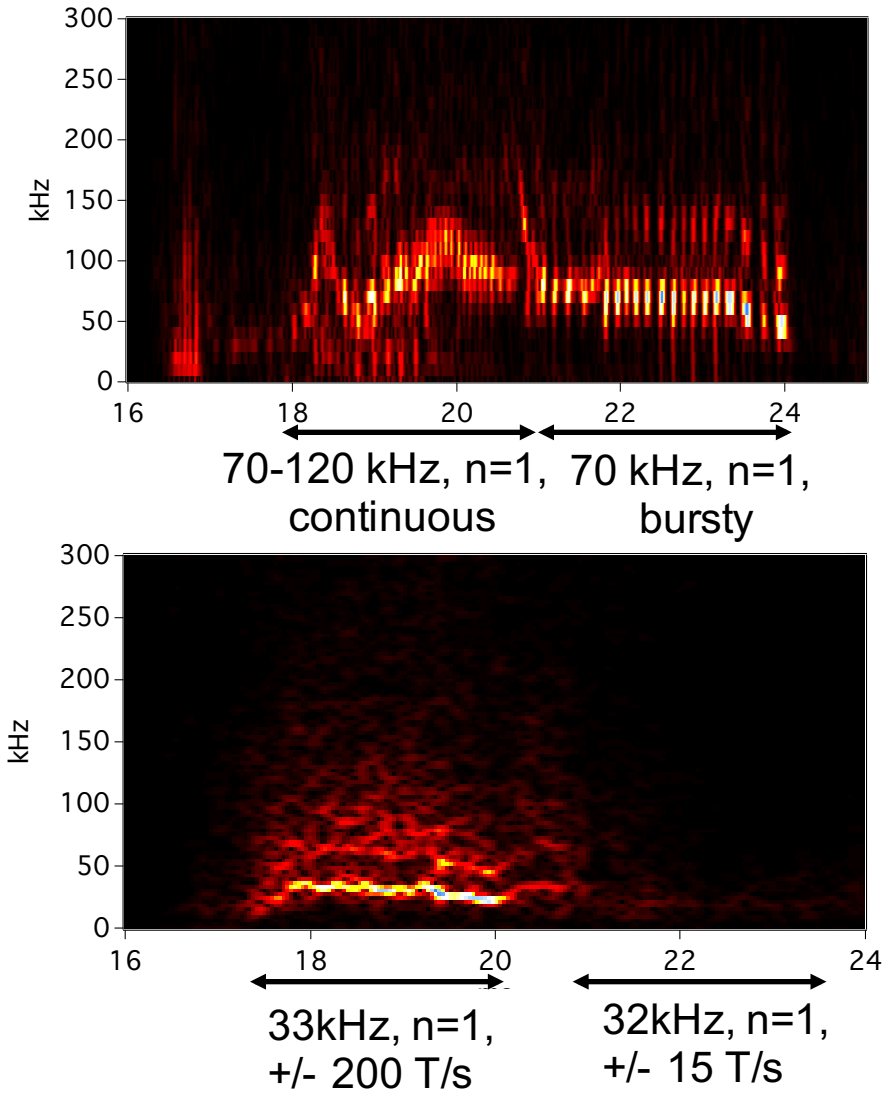

- LFS (outboard) injection:
  - MHD initially continuous, large amplitude, N=1
  - Transitions to intermittent bursts later in the discharge
  - Burst spacing increase with $I_p$
  - Similar to NIMROD simulation

- HFS (inboard) injection:
  - Continuous, large-amplitude N=1 activity early on
  - Abrupt cut-off in large amplitude activity
  - Reduced amplitude N=1 for remainder of discharge

THE UNIVERSITY of WISCONSIN MADISON

# Differences Suggest Multiple Current Drive Mechanism at Play

- LFS (outboard) Injectors:
  - MHD indicative of stream merger and reconnection drive mechanism through entire discharge
- HFS (outboard) Injectors:
  - MHD indicative of stream merger and reconnection drive mechanism initially
  - As $B_{pol}$ increases, stream separation increases; at some critical level, signs of magnetic coalescence instability cease
  - $I_p$ growth continues, pointing to additional reconnection-based drive mechanism






THE UNIVERSITY of WISCONSIN MADISON

# Summary

- High-Field-Side injection provides access to startup with LHI as the dominant current drive :
  - Increased $V_{LHI}$ due to higher field at low $R_{inj}$
  - Quasi-static plasma geometry, minimizing inductive drive terms
- HFS injection implemented in Pegasus lower divertor
  - System design point: 3-4 x increase in LHI current drive
  - Technical hurdles:
    - Relaxation at increased $B_{inj}$
    - PMI Suppression
    - Injector geometry for sustained coupling to plasma
- Preliminary results show feasibility of HFS injection
  - $I_p > 0.15$ MA achieved with LHI as dominant current drive
  - Relaxed plasmas at full Pegasus TF ($B_{inj} = 0.23$ T)
  - New MHD behavior suggests additional physics, multiple current drive mechanisms



THE UNIVERSITY of WISCONSIN MADISON