

# Expanding Non-Solenoidal Startup with Local Helicity Injection

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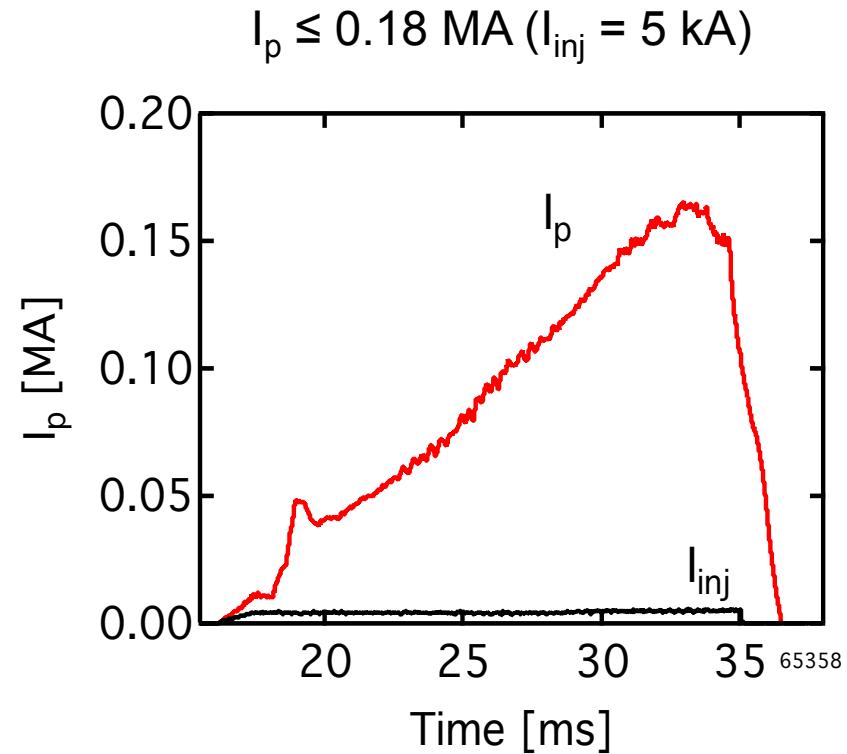
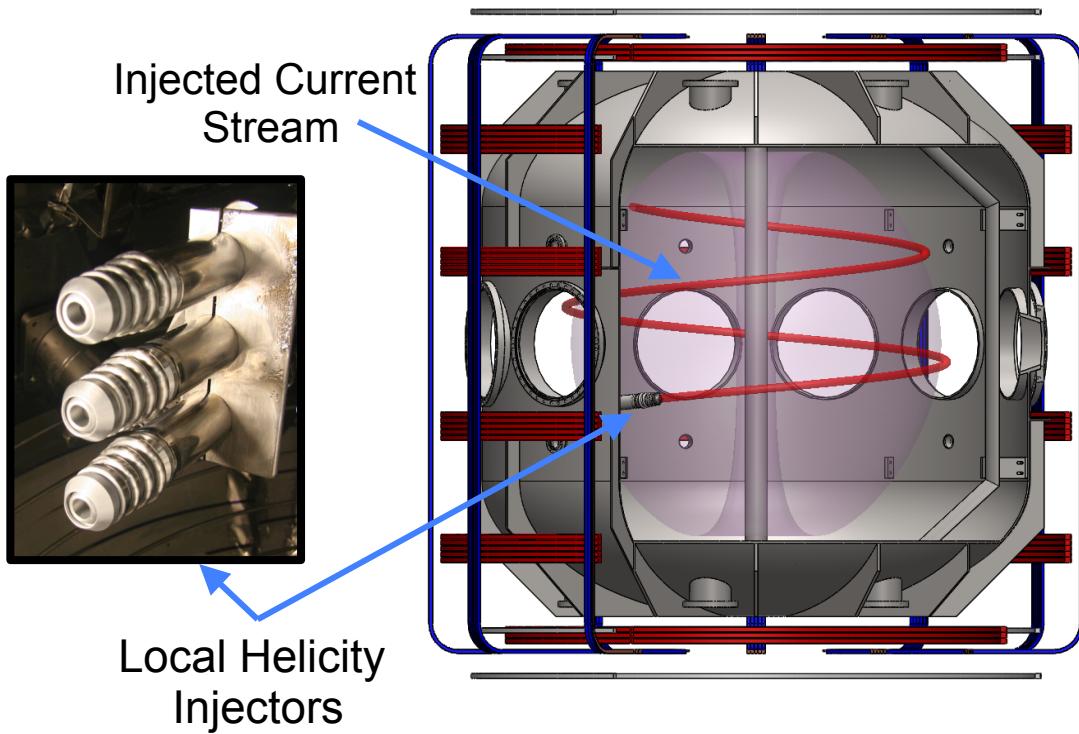
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PEGASUS  
Toroidal Experiment



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



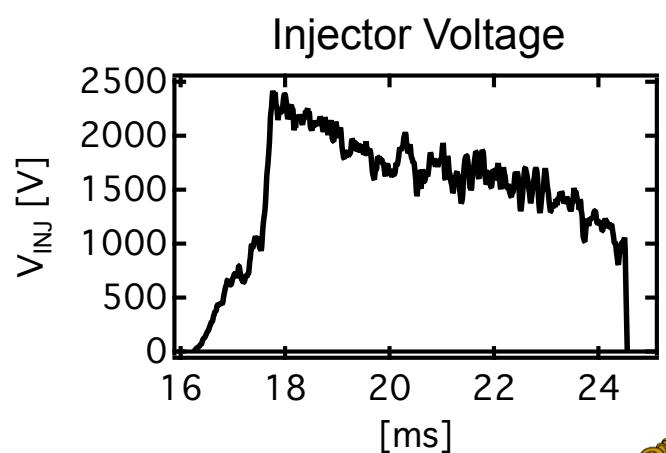
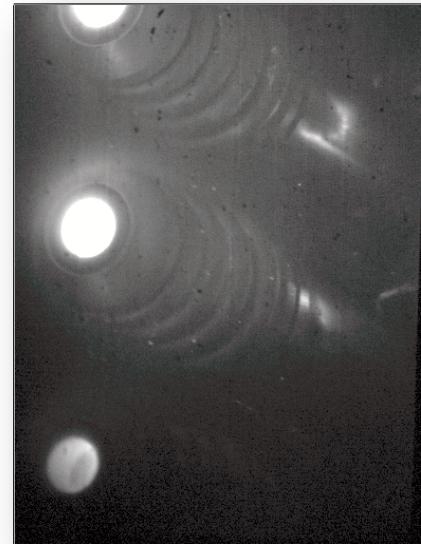
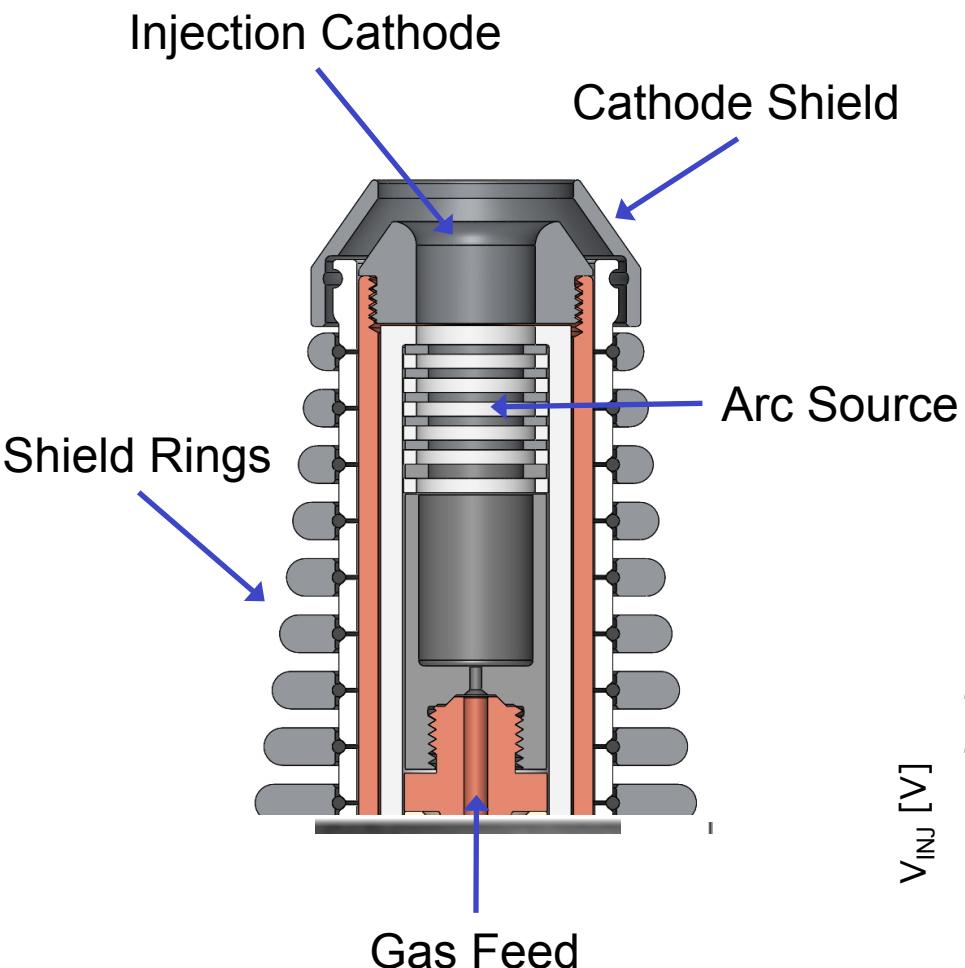
- Washer-stack arc sources inject edge current
- Unstable current streams form tokamak-like state via Taylor relaxation
- Compact, modular, and appears scalable to MA-class startup





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

- LHI current drive  $\sim V_{inj}$
- Formidable requirements:
  - $V_{inj} > 1\text{kV}$
  - High  $J_{inj}$  ( $\sim 1\text{kA/cm}^2$ )
  - 1-2 cm from LCFS
  - No deleterious PMI
- High  $V_{inj}$  achieved recently
  - $\sim 3\times$  increase in helicity input
- Model for injector impedance
  - E.T. Hinson – GP12.00117





# Global Power Balance Model: $I_p(t)$ Evolution

- LHI drive quantified by effective loop voltage:<sup>\*</sup>

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

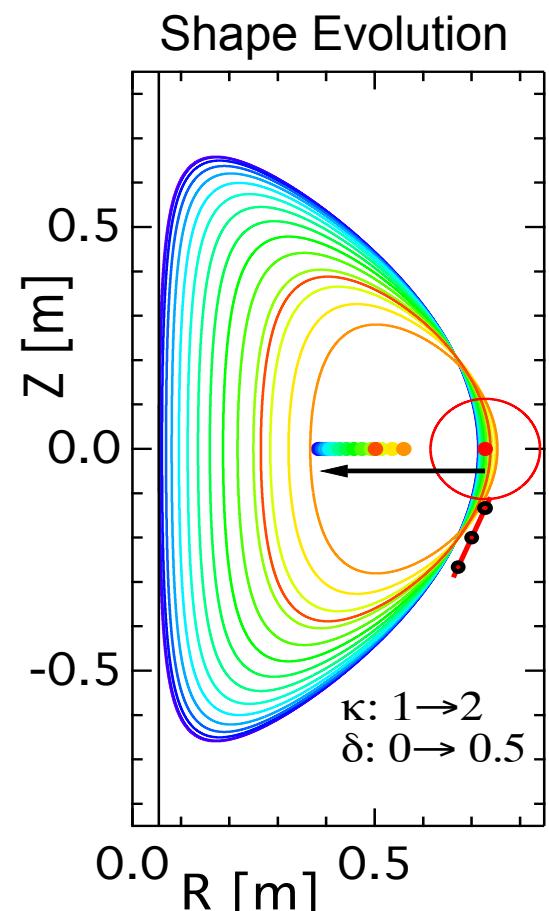
- Power balance relation:

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

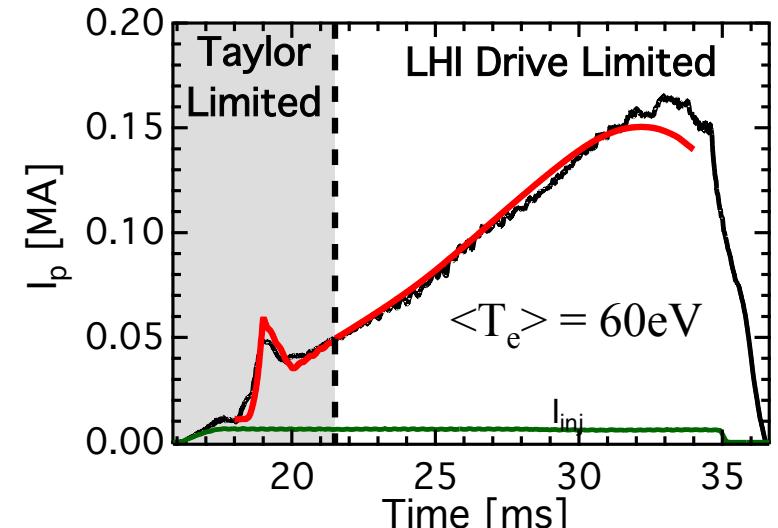
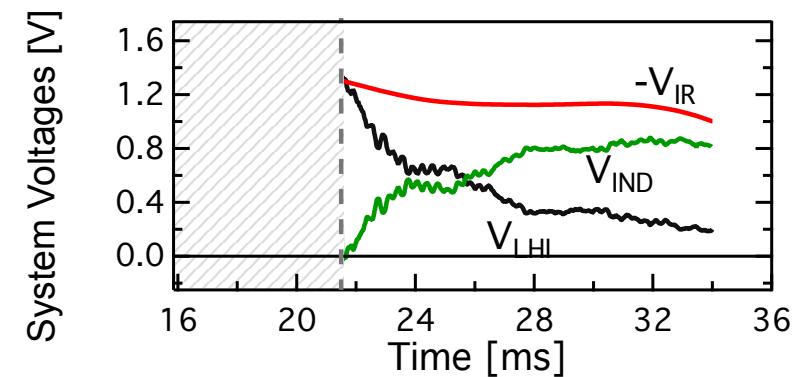
- Subject to Taylor relaxation current limit:<sup>\*\*</sup>

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

- Outboard injection → Strong radial compression



- Net induction voltage dominates current drive



<sup>\*</sup>: Eidietis *et al.*, J. Fusion Energ. **26**, 43 (2007)

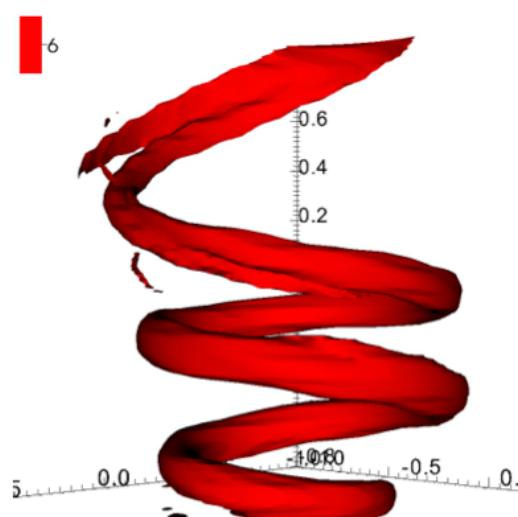
<sup>\*\*</sup>: Battaglia *et al.*, Nucl. Fusion **51**, 073029 (2011)





# Detailed Dynamical Model: NIMROD Predicts Current Stream Reconnection as Drive Mechanism

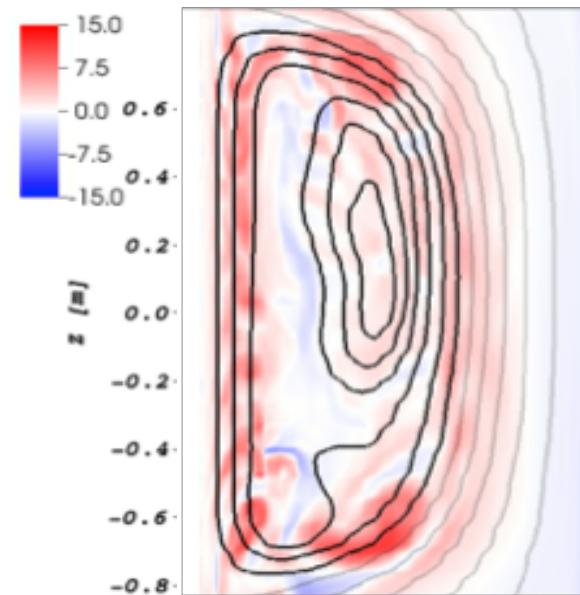
- Inboard injection, emphasizing LHI current drive over inductive drive



1. Streams follow field lines

2. Adjacent passes attract

3. Reconnection pinches off current rings



4. Accumulation of poloidal flux; current filaments persist



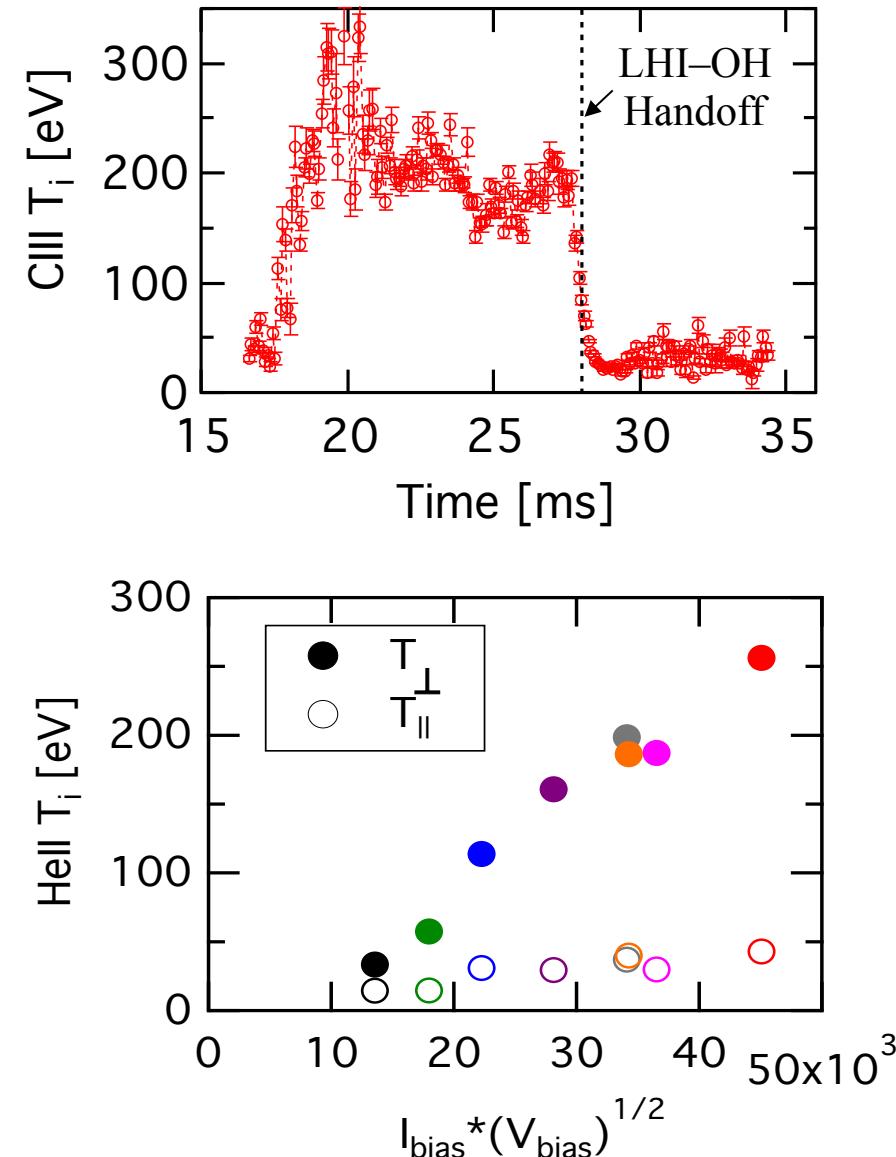


# Anomalous Ion Heating Supports Existence of Strong Reconnection Activity

- $T_i > T_e$  during LHI
  - $T_{i, \text{LHI}} \gg T_{i, \text{OH}}$
- $T_i$  scales with expectations from reconnection experiments:

$$T_{i,\perp} \sim \frac{B_{rec}^2}{n_e} \sim I_{inj} \sqrt{V_{inj}}$$

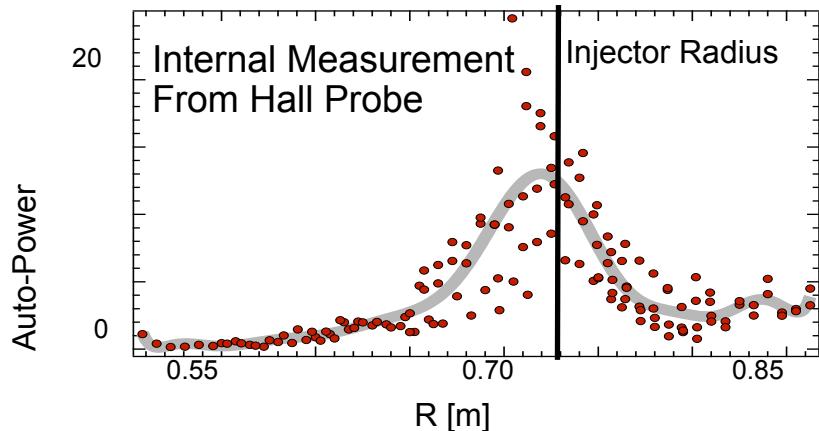
- Emerging evidence that ion heating is localized to edge
  - See M.G. Burke Poster:  
GP12.00122



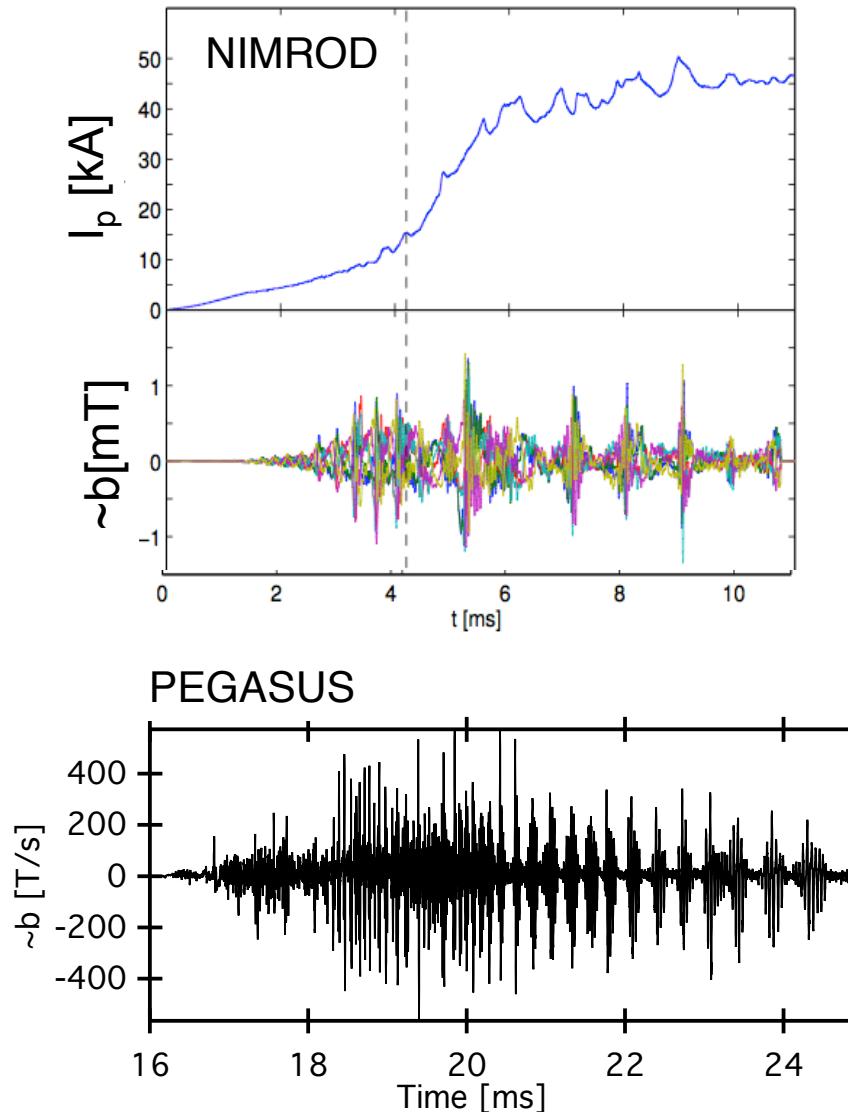


# Stream Interaction Manifests as Edge Localized MHD Burst

- MHD bursts accompany  $I_p$  growth
  - Localized in edge\*
  - $n=1$  line-tied kink structure
- Coherent streams persist in edge, matching NIMROD predictions



- Suggests reconnection region may be localized to edge



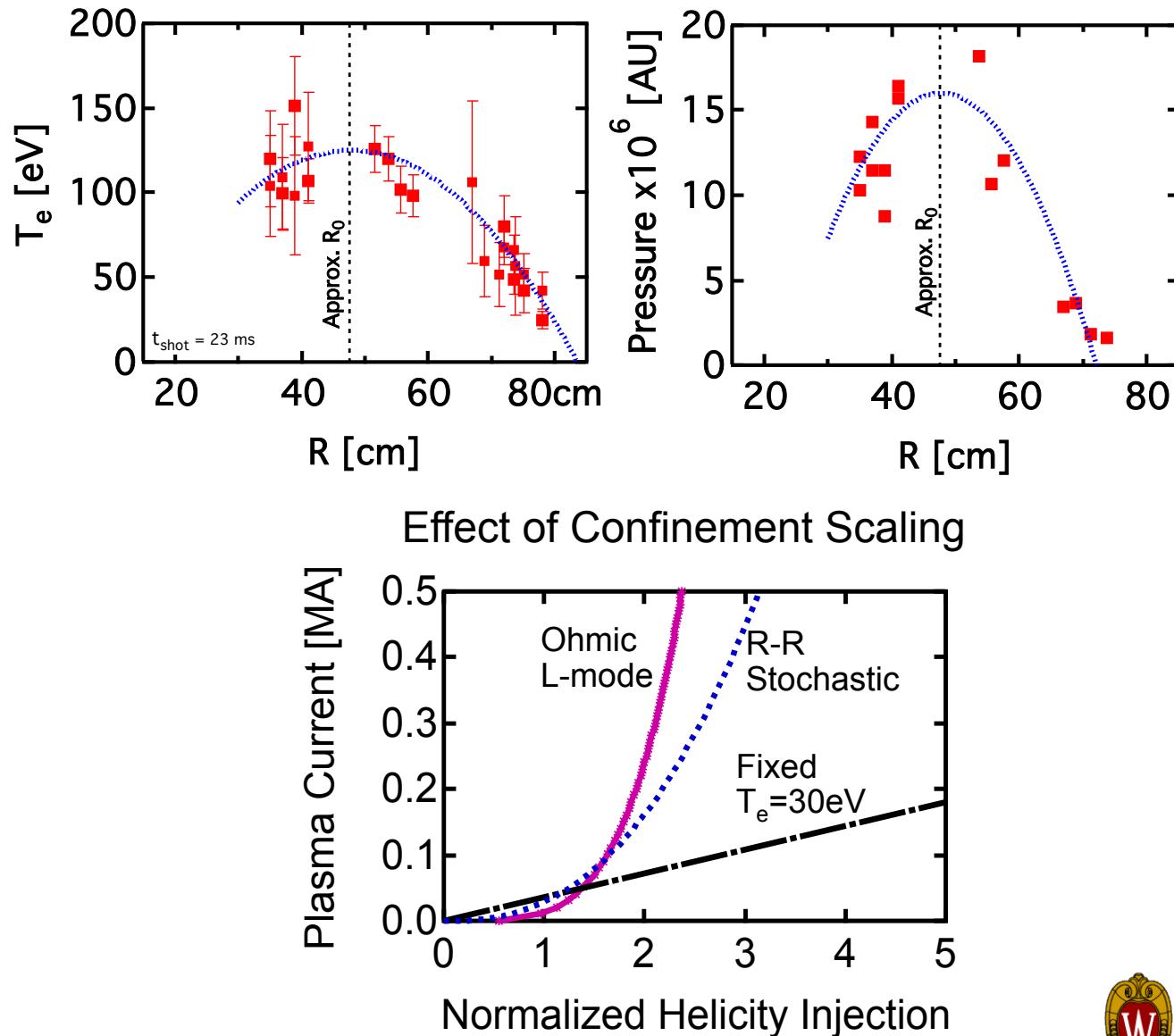
\* E.T. Hinson, Ph.D. Thesis, UW-Madison, 2015.





# Edge Localized Reconnection and Strong $V_{IND}$ May Support Good Core Confinement, Favorable Scaling

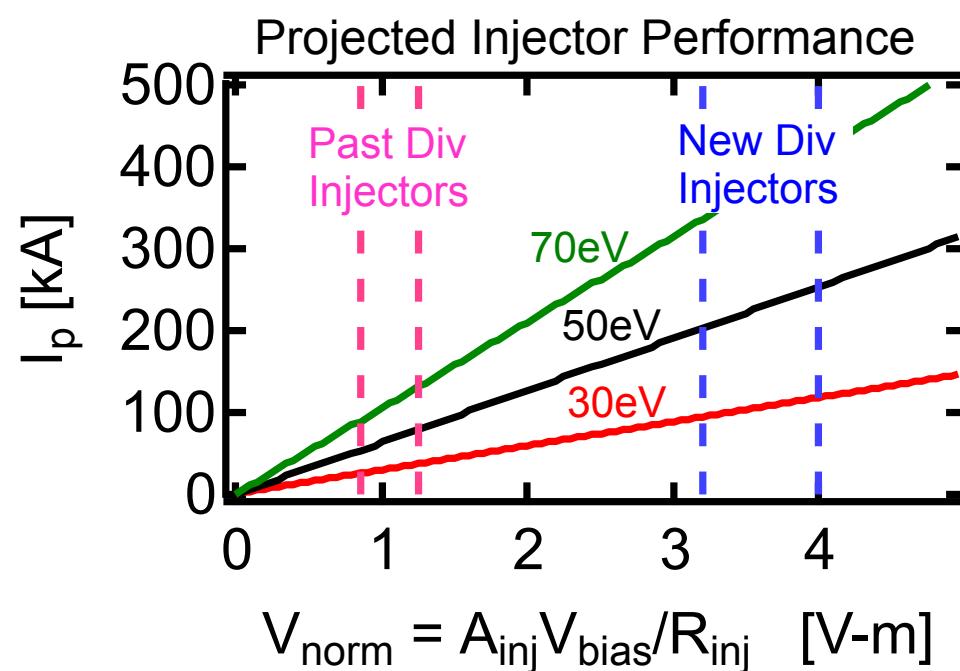
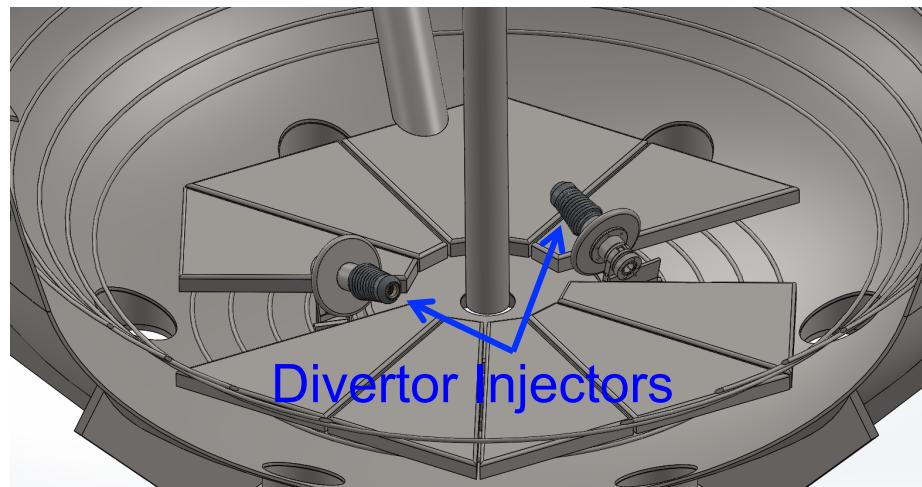
- Thomson scattering shows strong central peaking
  - $T_e$  and pressure profiles
  - Central  $T_e$  comparable to Ohmic L-mode
- Contrasts with expectations of highly stochastic field across profile
  - May reflect different drives operating:
    - $V_{IND}$  (across plasma)
    - $V_{LHI}$  (edge)
- If good confinement persists, scaling to NSTX-U very favorable
  - Need to understand influence of helicity injection vs. inductive drive





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

- Fixed plasma geometry → minimal inductive drive
  - Separates effects: edge reconnection Vs. inductive drive
- HFS → 3-4x increased helicity input
  - Access to higher  $I_p$  startup
  - Increased  $B_{TF}$  test
  - NSTX-U relevant physics
- New injectors fabricated, ready for install
  - Large aperture, high voltage design
  - Initial tests before Jan 1.





# Building the Physics and Technology Basis for Scalable LHI

- **Increased Performance**
  - Injector technology development allows reliable operation at high  $V_{\text{inj}}$
  - Suppression of PMI
- **Increased Understanding**
  - Experimental evidence supports NIMROD current drive mechanism
  - Outboard injection: reconnection localized to edge, strong inductive drive
  - Thomson Scattering: Ohmic-like core confinement
    - Favorable scaling to high current startup?
- **Next Steps: studies of confinement and scalability**
  - Divertor injectors → increased helicity injection, reduced inductive effects
  - NSTX-U relevant physics regime

