Non-Solenoidal Startup on the Pegasus Spherical Tokamak

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N.J. Richner, C. Rodriguez Sanchez, D.J. Schlossberg, J.A. Reusch, J.D. Weberski

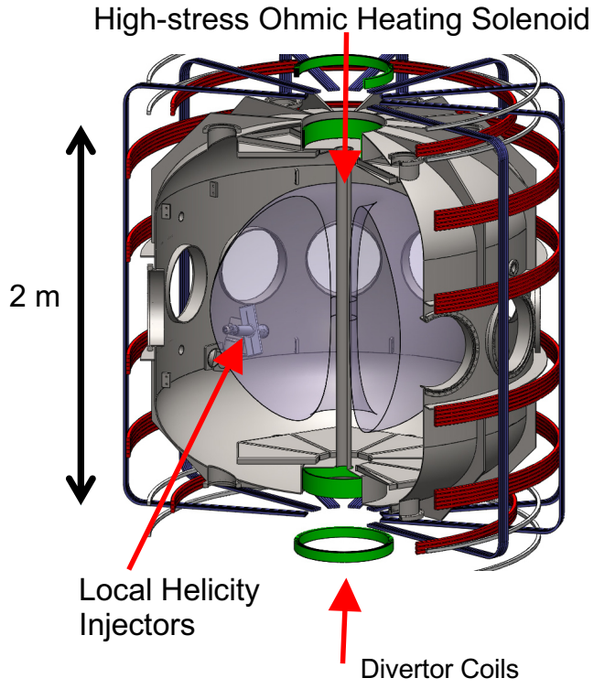
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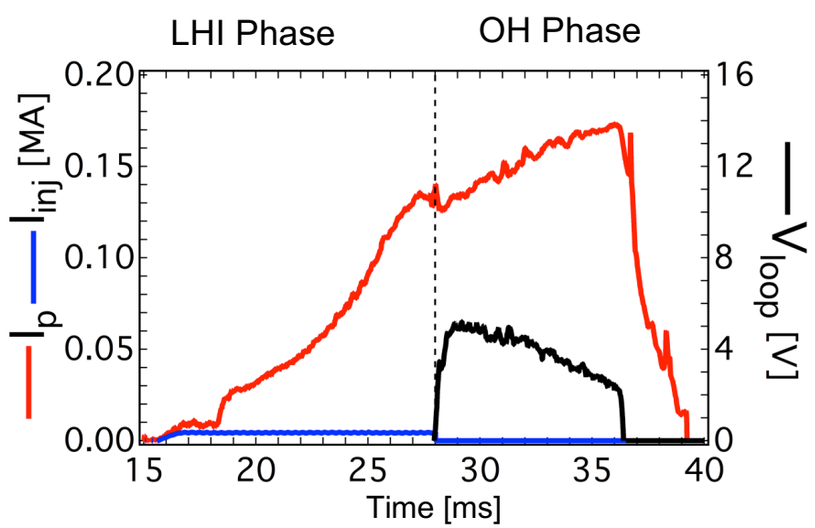
7 August 2017

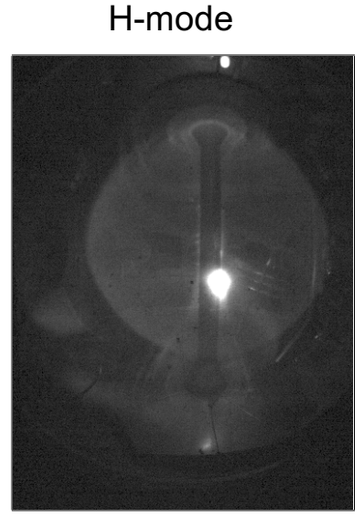
PEGASUS
Toroidal Experiment

Pegasus ST at A ~ 1 Facilitates AT Science Studies at Small Scale



A	1.15 – 1.3
R (m)	0.2 – 0.45
I_p (MA)	≤ 0.25
B_T (T)	< 0.2
$\Delta\tau_{shot}$ (s)	≤ 0.025





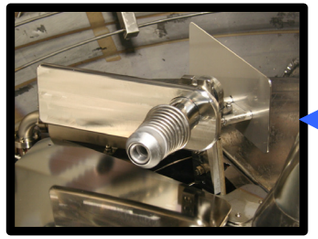
- Local Helicity Injection (LHI) for Non-Solenoidal ST Startup
  - Tokamak startup from injected current streams at plasma edge
- Access to high I_N > 10 and high β_t
  - Tokamak stability limits at A ~ 1
- H-mode Physics at Ultralow-*A*
  - H-mode and ELM characteristics (Recently concluded)

Local Helicity Injection is a Promising Non-Solenoidal Startup Technique



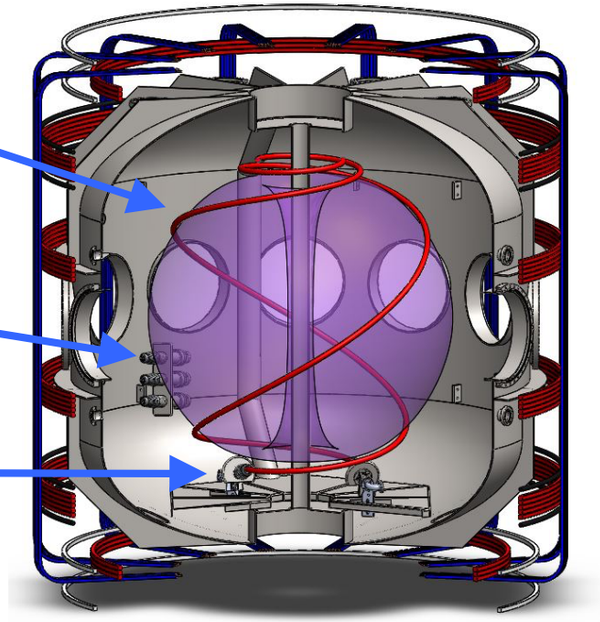
LFS System

HFS System

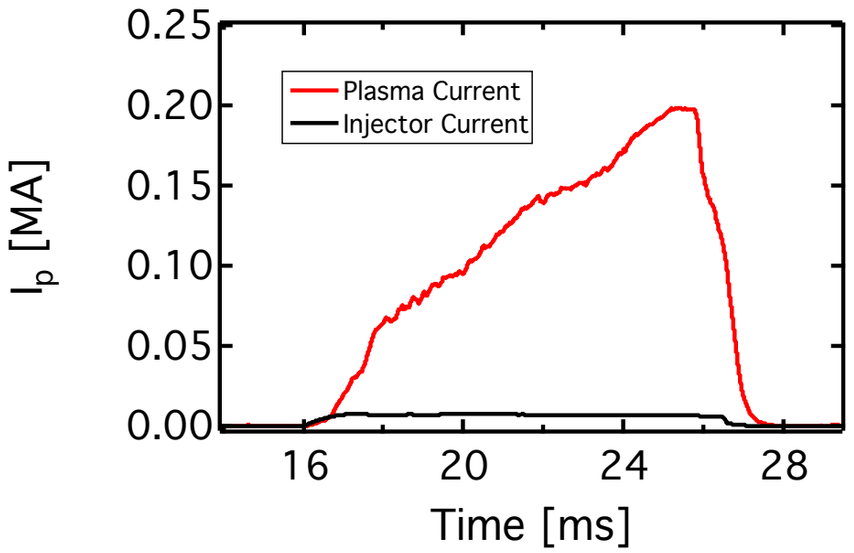


Injected Current Stream

Local Helicity Injectors



Non-Solenoidal, High $I_p \leq 0.2$ MA ($I_{inj} \leq 8$ kA)

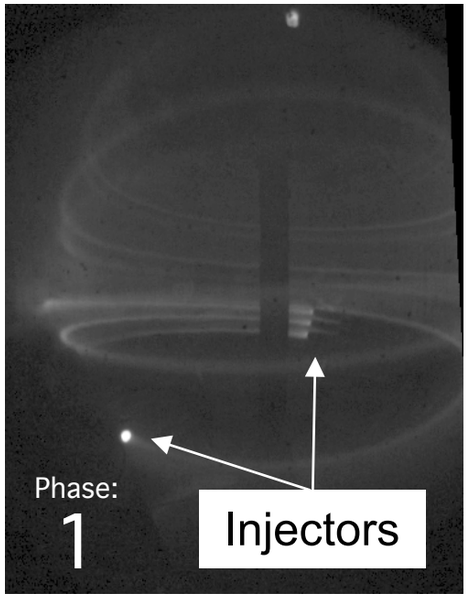


- Edge current extracted from injectors
- Relaxation to tokamak-like state via helicity-conserving instabilities
- Used routinely for startup on Pegasus

- Current drive quantified by

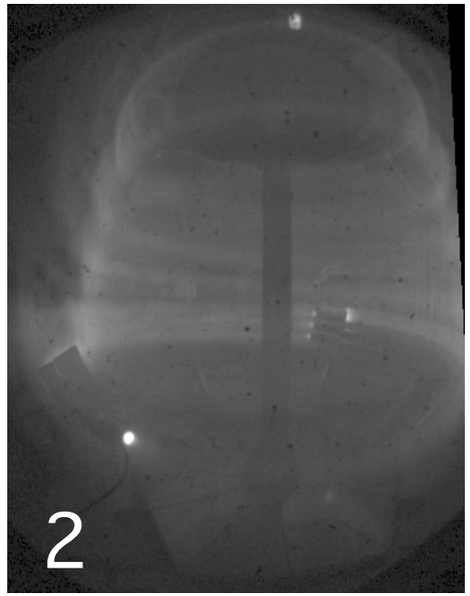
$$V_{LHI} \approx \frac{A_{inj} B_{\varphi,inj}}{\Psi} V_{inj}$$

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



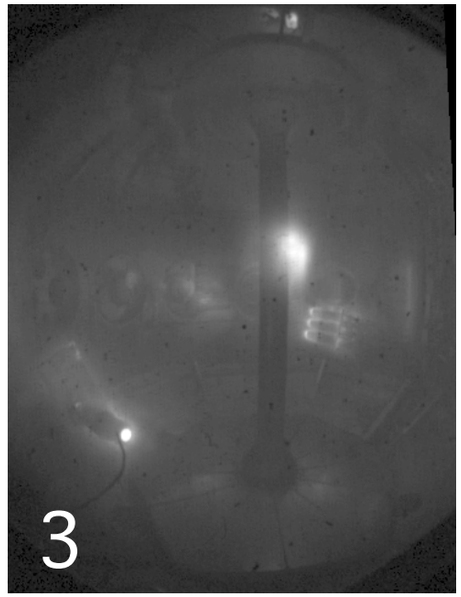
- Local source:

  Helical plasma streams



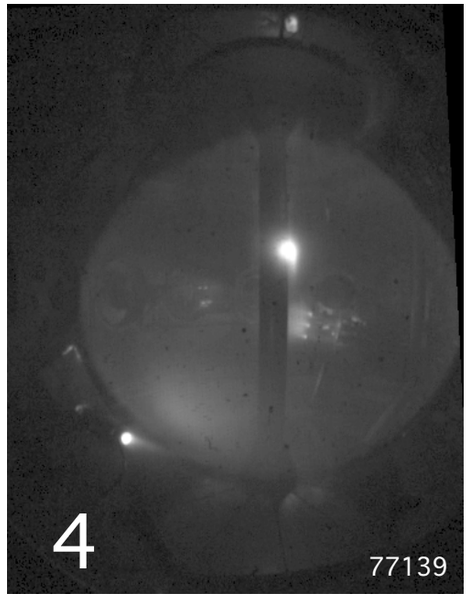
- Instability:

  Current driven along streams



- Reconnection:

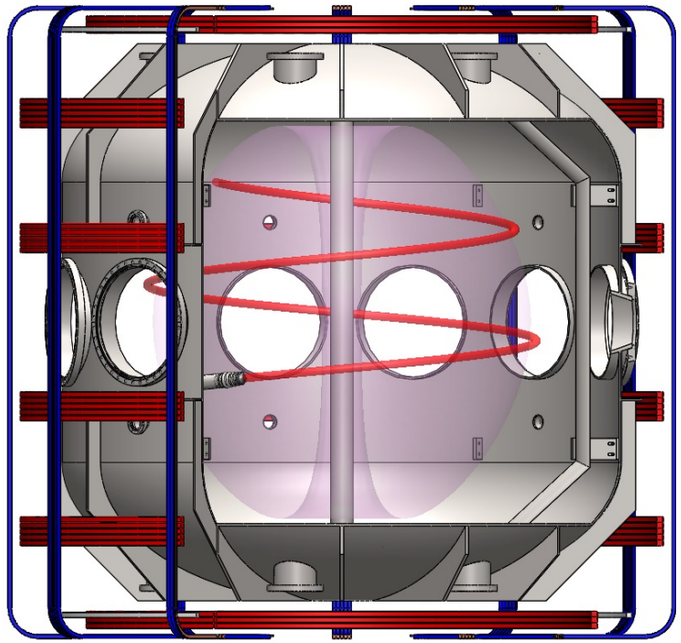
  Relaxation to tokamak-like state, current growth

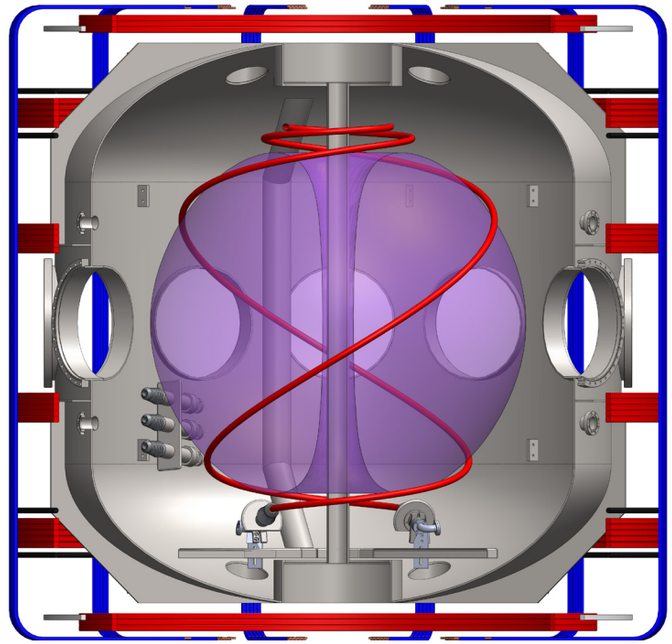


- Bias shutdown:

  High-I_p tokamak

Injector Location in LHI Emphasizes Different Physical Effects





Low-Field-Side (LFS) Injection:

- Injectors near outboard midplane

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

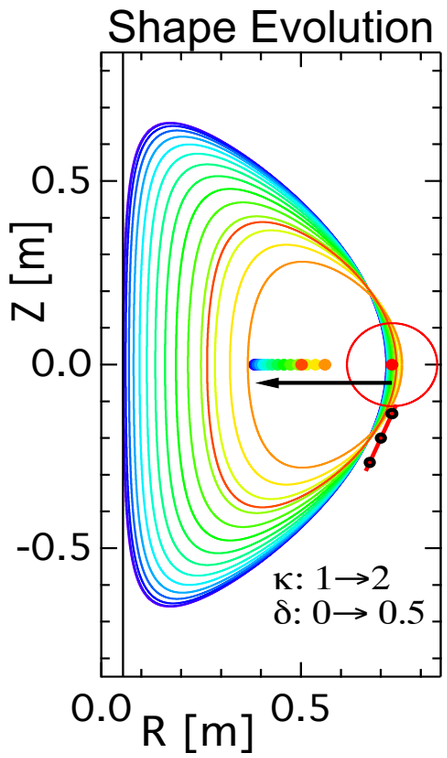
- Power balance relation:

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

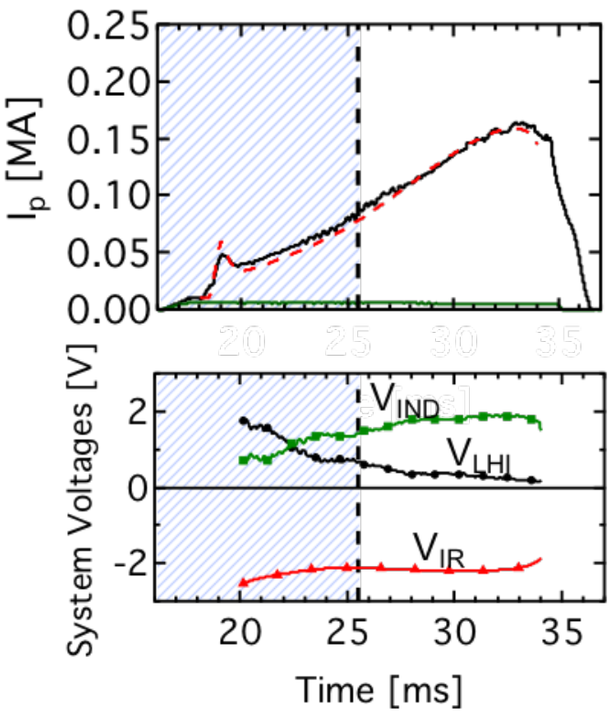
- Confinement behavior may be affected by dominant current drive type

- LFS injection maximizes inductive drive, V_{IND}

- Radial compression → large V_{IND}



- Net induction voltage dominates current drive



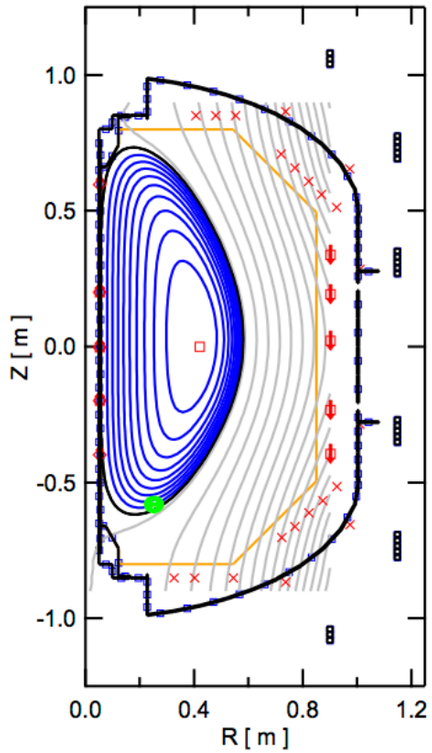
In Contrast, HFS Injection Dominated by Helicity Drive

- Low R_{inj} → high V_{LHI}

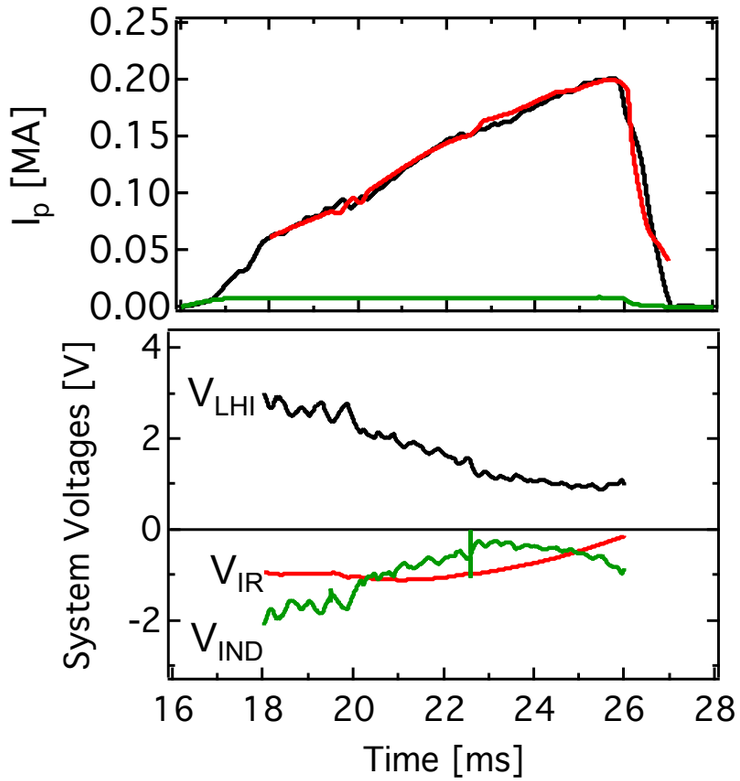
$$V_{LHI} = \frac{V_{inj} A_{inj} B_{inj}}{\Psi_{TF}} \sim \frac{1}{R_{inj}}$$

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

- Static plasma shape → low V_{IND}



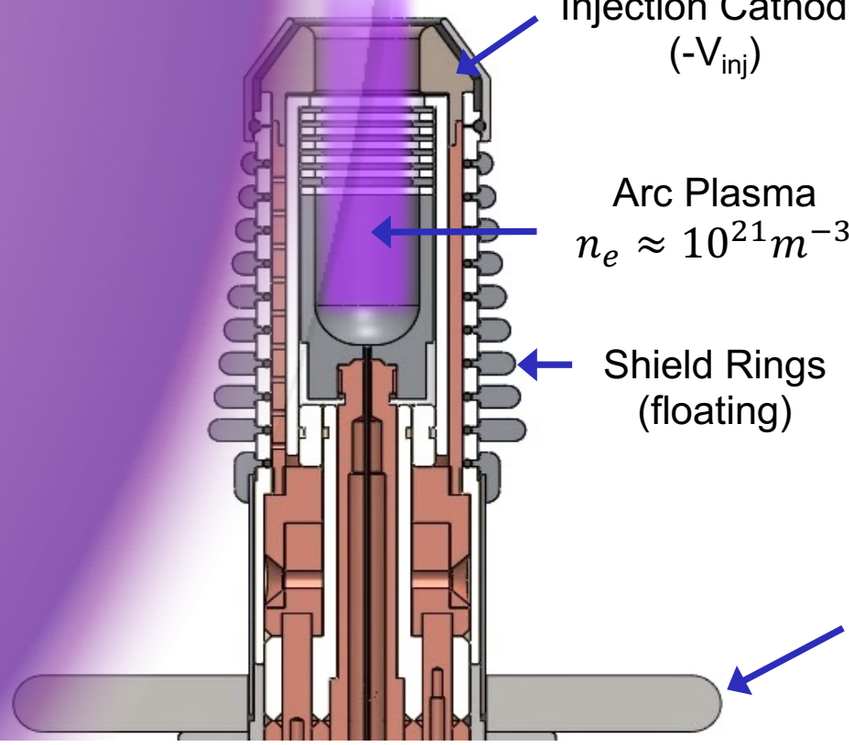
- HI dominates current drive



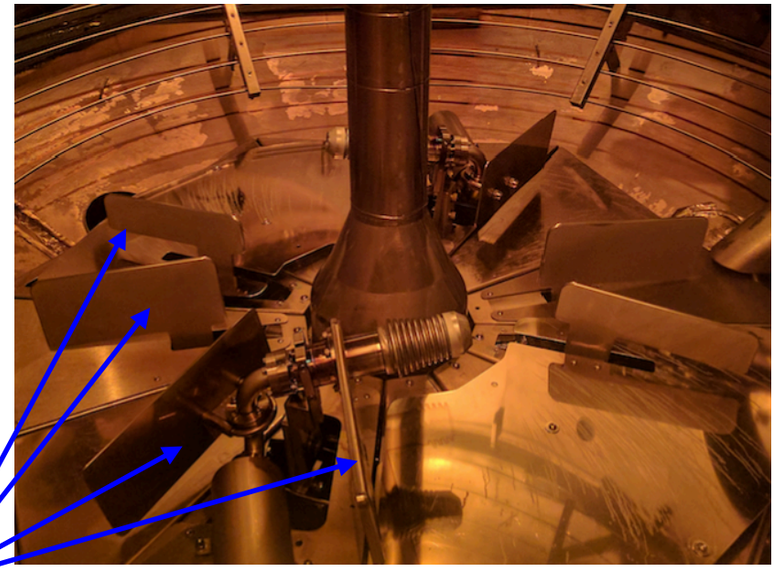
HFS Divertor Injectors Installed to Study HI-Dominant Regime

Tokamak Plasma Edge

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

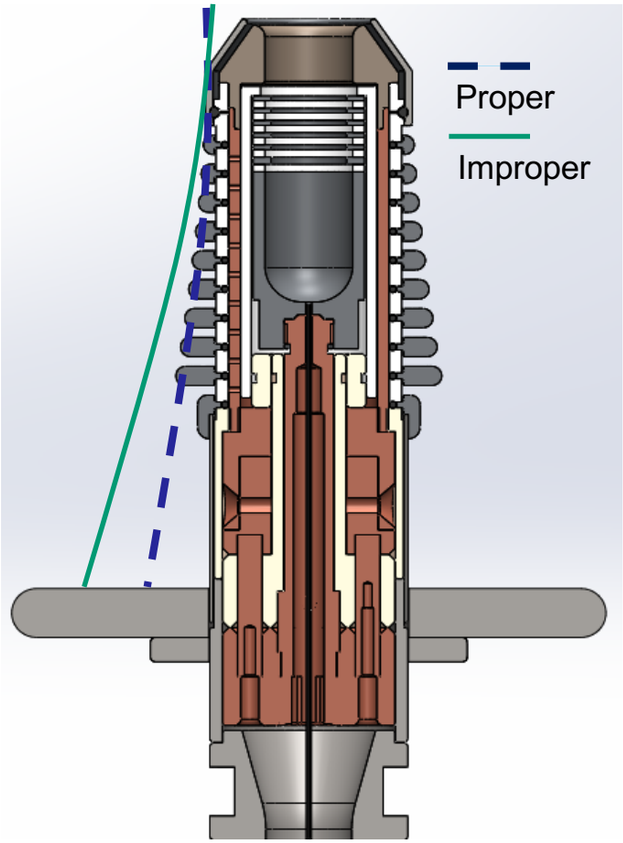


- 2 injectors in lower divertor
- 4x V_{LHI} over LFS Injection
- A_{inj} = 8 cm^2; $V_{inj} \leq$ 1.5 kV; $I_{inj} \leq$ 8 kA (8-12 MW total power)



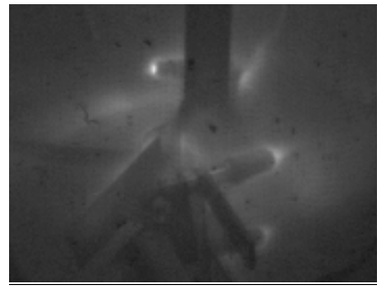
Injector Alignment, Local Limiters Critical to PMI Mitigation

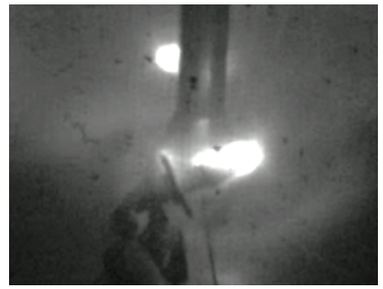
Injector Schematic and B Field Alignment

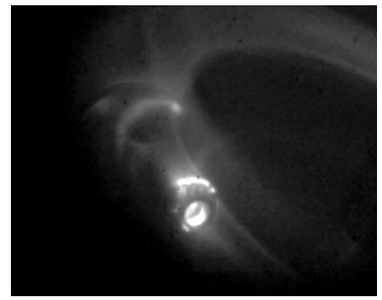


- Proper alignment:
  - Injector shadowed
  - High voltage standoff in tokamak SOL
- Improper limiter placement:
  - Injector immersed in plasma
  - Cathode spots on injector
- Improper alignment to local field:
  - Arc-back to limiter

Fast Visible Imaging







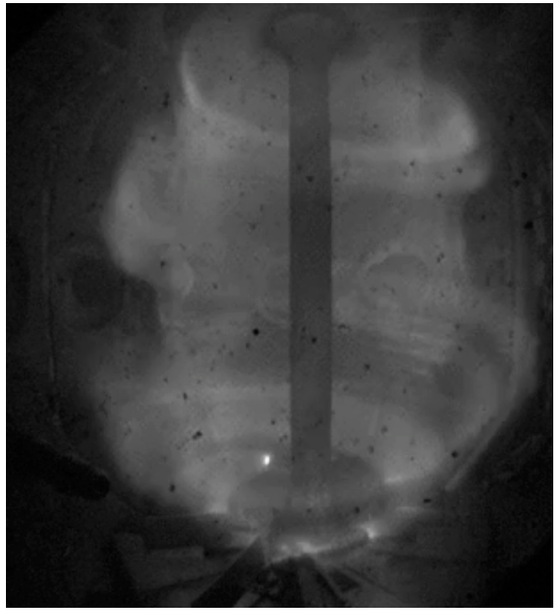
Initial Relaxation to Tokamak State Requires Strong Deformation of Vacuum Field

Injected current weakens vacuum B_z



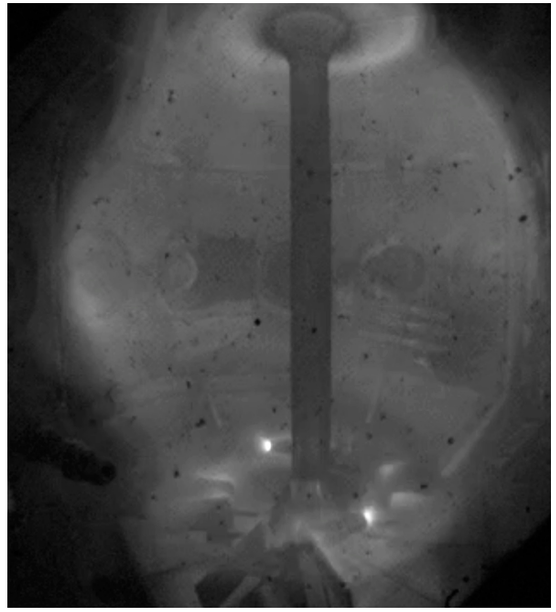
$I_p \sim N_{turns} \bullet I_{inj}$

Unstable current streams attract, reconnect



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

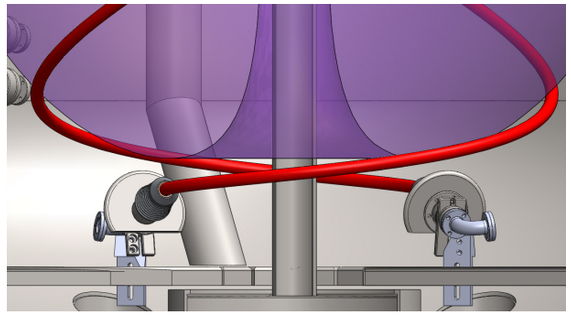
Tokamak-like plasma; rapid I_p growth



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

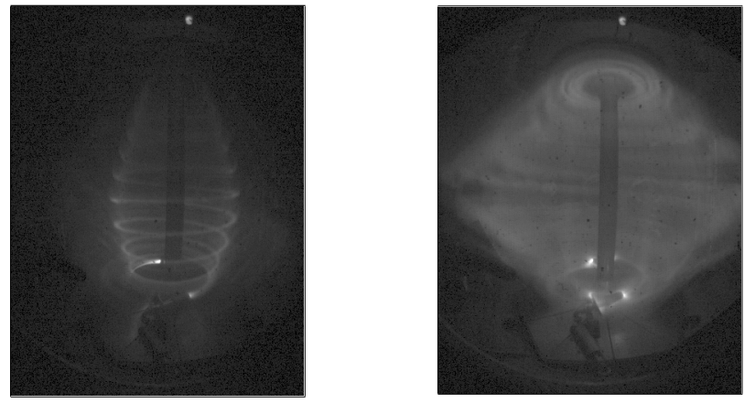
Relaxation Challenges with HFS Injection Addressed

- Injector geometry sets minimum pitch (B_Z / B_T) for stream clearance

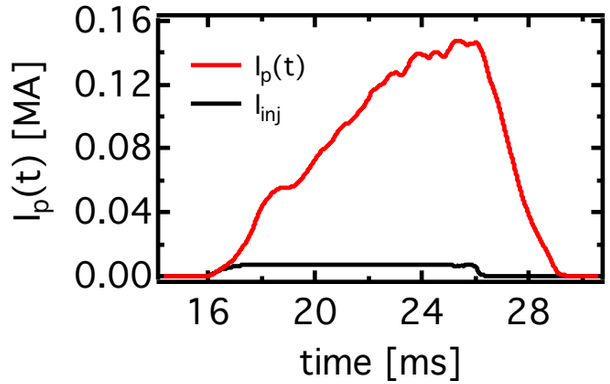


- HFS injection:
  - Lower R_{inj} → more B_Z for clearance
  - Relaxation impeded for fixed B_T , I_{inj}
- Solution: poloidal field shaping
  - B_z strong in divertor; weak at midplane
  - Increased I_{inj} required at increased B_T

Deformed B_{vac} Aids Relaxation



- Relaxation achieved at full Pegasus B_T

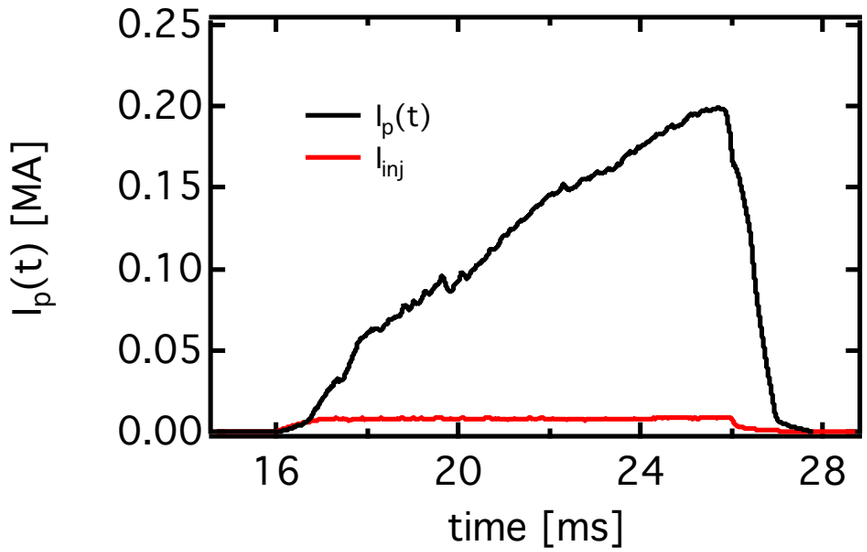


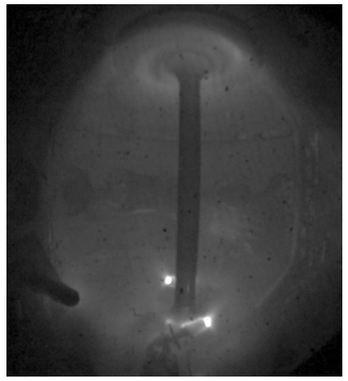
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HFS LHI Provides Access to High I_p Without Solenoidal Induction

- Non-solenoidal I_p = 0.2 MA ST startup achieved
  - Static plasma geometry
  - Current multiplication ~ 40 × I_{inj}
- V_{LHI} increased 4× over LFS injection
  - Access to high I_p with V_{LHI} dominant
  - High V_{LHI} aided by active cathode spot detection
- Facilitates studies of LHI confinement
  - Example: n_e / B_T / I_p scalings under present study

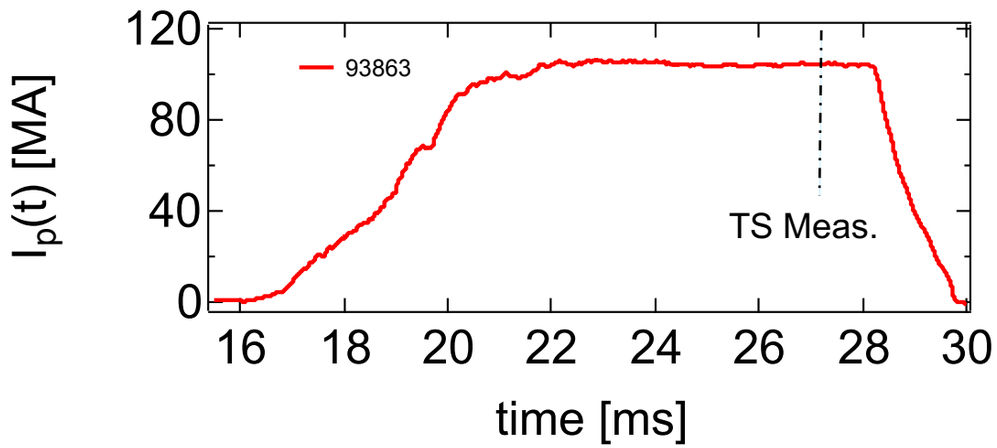
High I_p = 0.2 MA Driven Predominantly by V_{LHI}

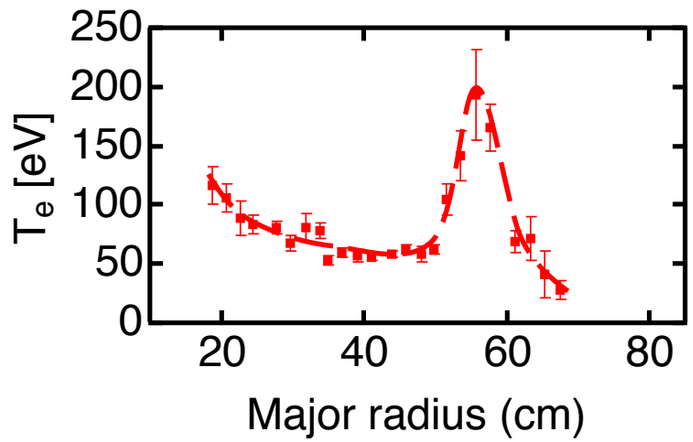




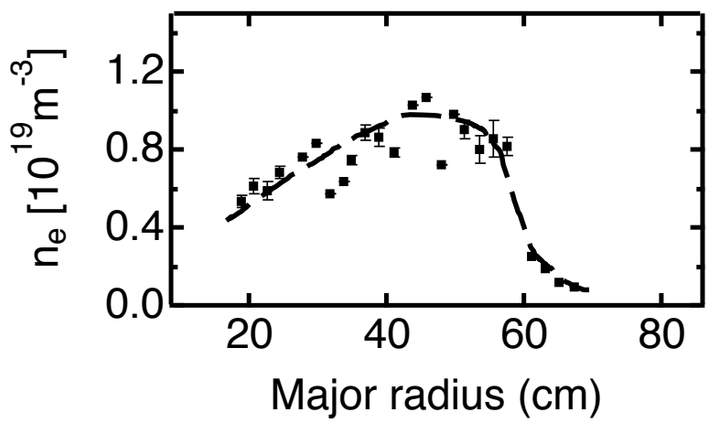
Thomson Scattering Often Shows Hollow T_e, Peaked n_e

- Static geometry, LHI-only discharges





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

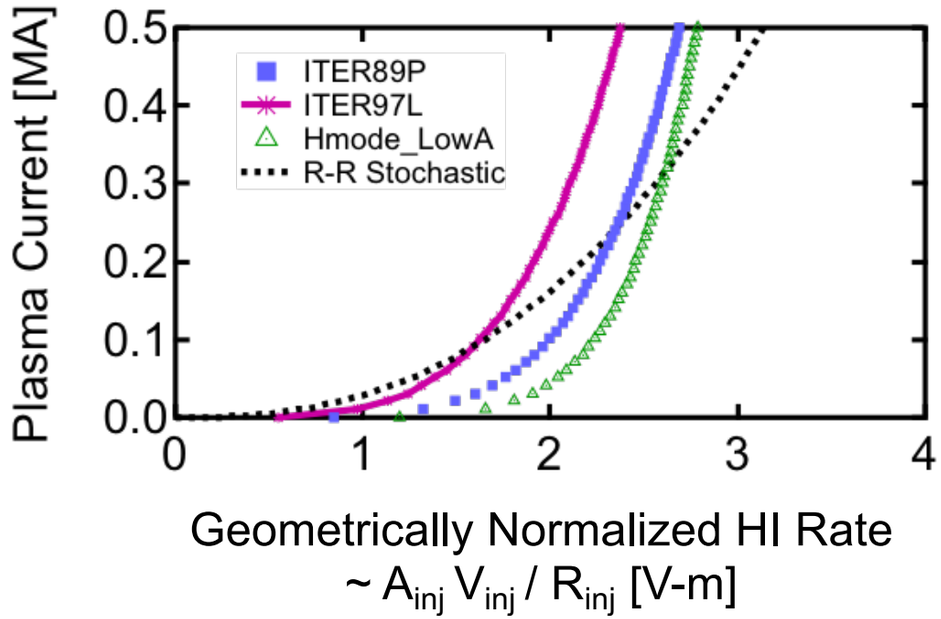


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Projecting Forward: Dissipation of Helicity is a Main Issue

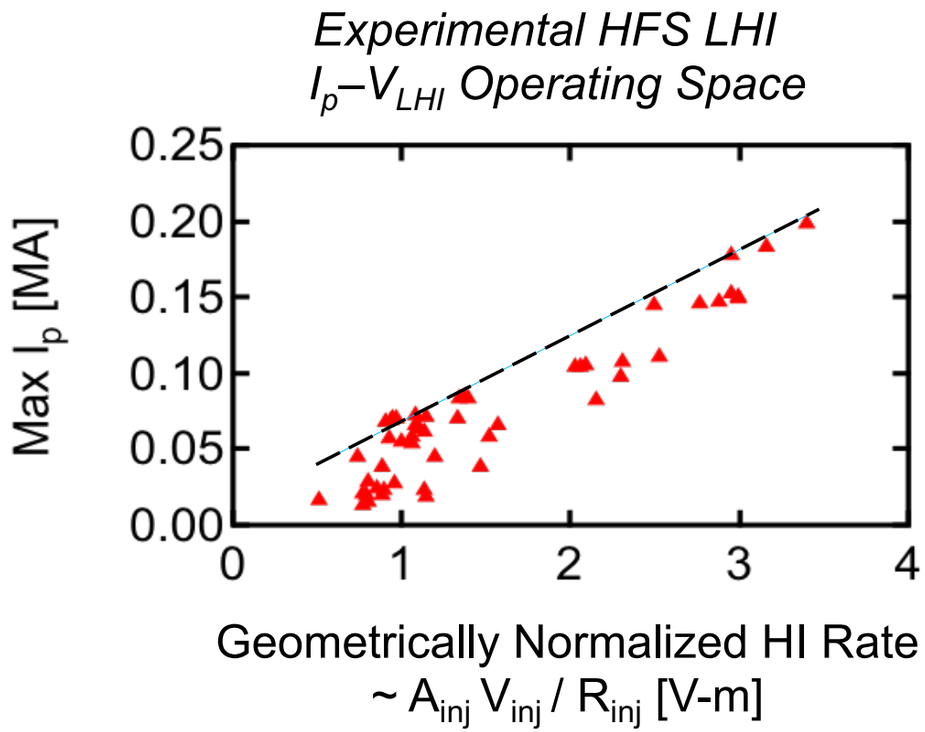
- Helicity input balanced by resistive dissipation
  - Plasma resistivity influenced by confinement properties
- Crude estimates of confinement inform operation space, assuming:
  - $P_{in} = V_{LHI} I_p$
  - $Z_{eff} = 1$
  - Fixed plasma geometry, B_T
- Understanding how I_p depends on HI rate is critical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

Confinement Scaling Estimates



To Date, Maximum 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 η
  - Classical vs. hyper-resistivity
  - Reconnection-driven electron heating
  - etc.



Hierarchy of Physics Models Contribute Towards Predictive Understanding of 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

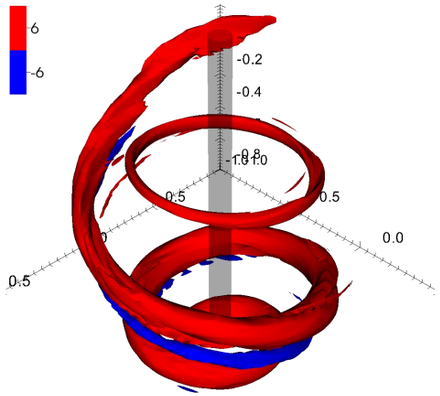
$$V_{LHI} \approx \frac{A_{inj} B_{\varphi,inj}}{\Psi} V_{inj}$$

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

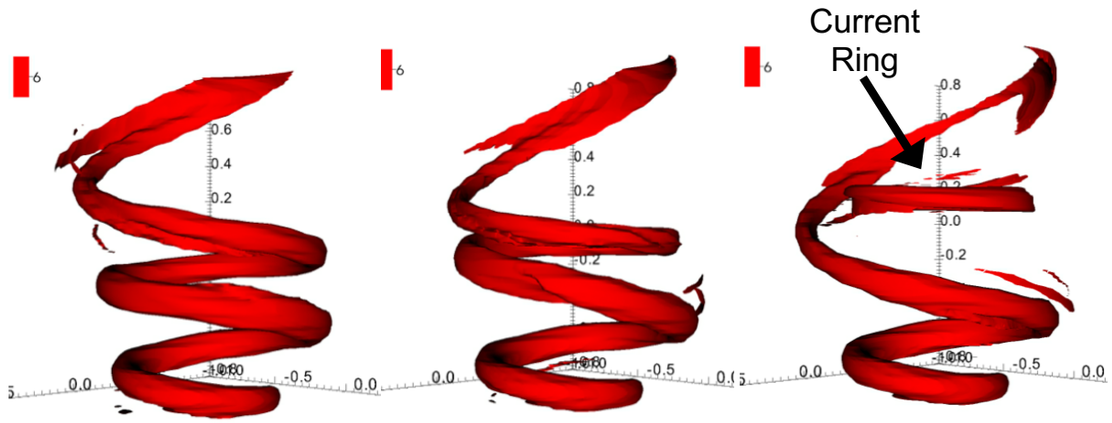
Reconnecting LHI Current Stream



*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)*

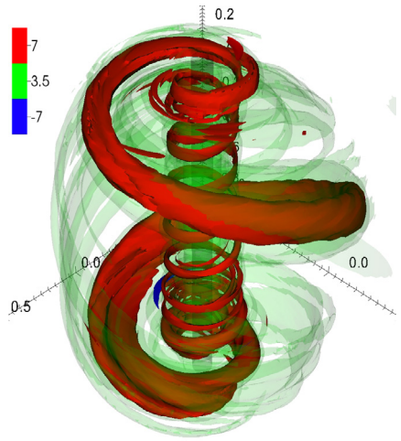
NIMROD Simulations Indicate Helical Current Stream Reconnection as a Current Drive Mechanism

NIMROD: Early Relaxation Phase in Divertor LHI Geometry

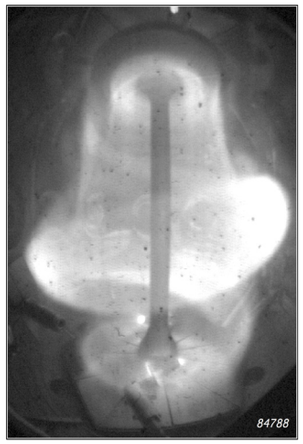


1. Streams follow field lines
2. Adjacent passes attract
3. Reconnection forms current rings

Late Formation Phase



NIMROD Simulation [O'Bryan PhD 2014]



2016 PEGASUS High-speed Imaging

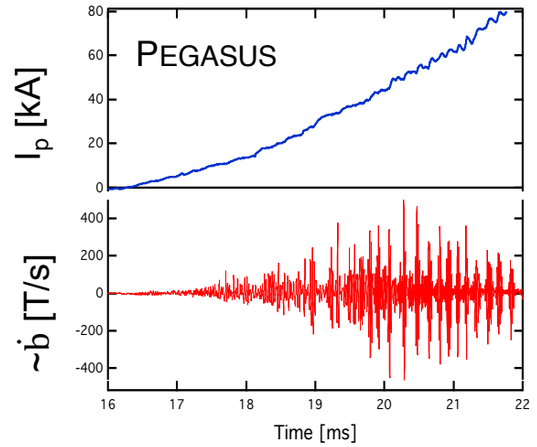
Fonck, IAEA FEC 2016 OV/5-4

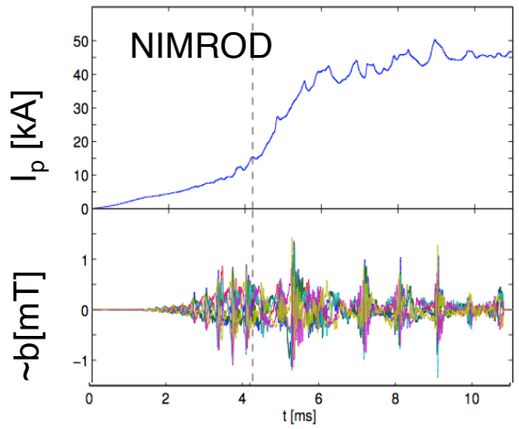
- Divertor LHI startup shows suggestive commonality between NIMROD simulations and experiment

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

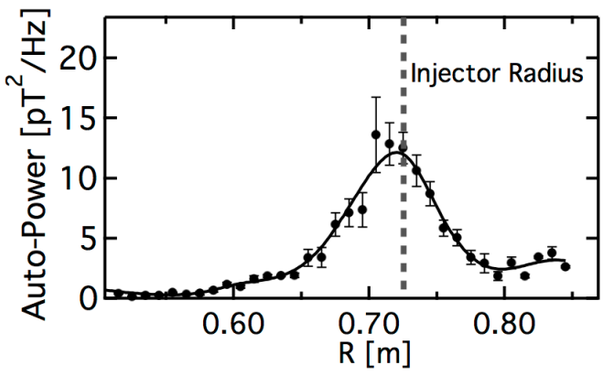
Current Stream Interaction Manifests as Edge-Localized MHD Burst

- LFS injection: MHD bursts support outboard stream reconnection as a drive
  - Low frequency: 20–80 kHz, n = 1
  - Consistent with line-tied kink instability
- Internal magnetic measurements localize coherent streams in LFS edge
- Reconnection-driven edge ion heating
- Suggests any stochastic reconnection region may be localized to edge

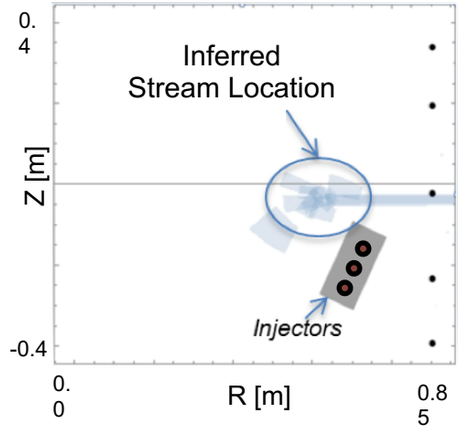




Internal B_z Measurements

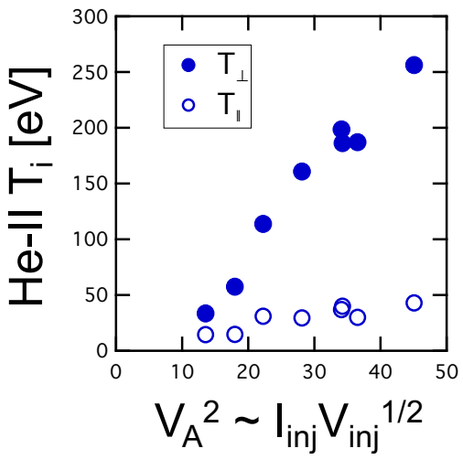


External B_z Phase Correlation



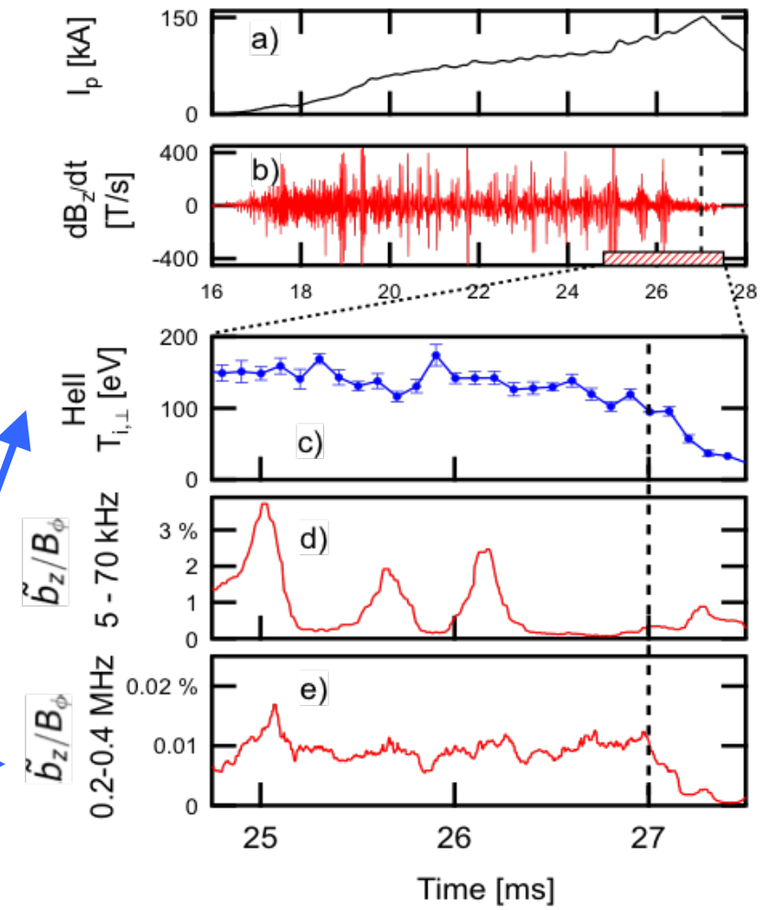
Reconnection-driven Ion Heating Gives $T_i > T_e$ During LHI

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



- $T_i(t)$ correlated with continuous, high frequency activity
  - Suggests considering short wavelength reconnection as additional CD

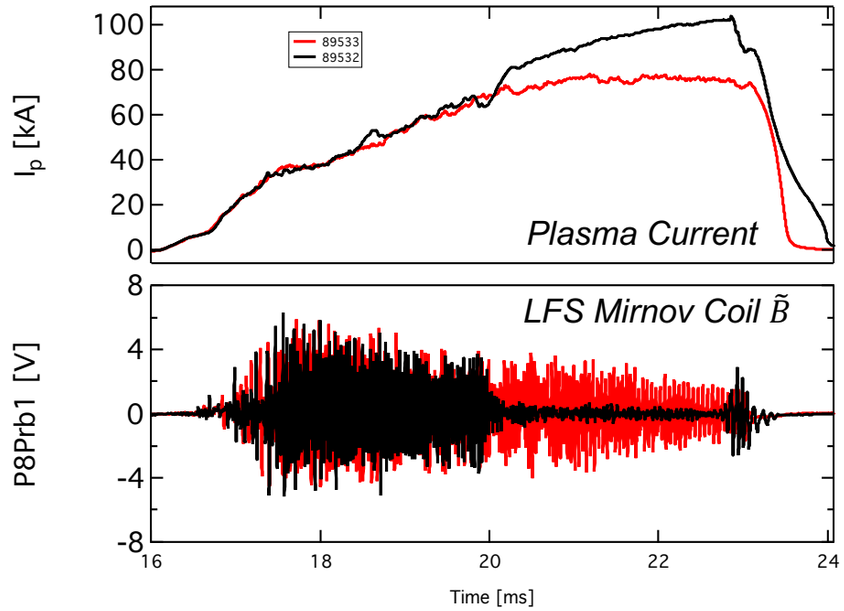
Ion heating correlated with high-f MHD fluctuations, not discrete reconnection between helical streams



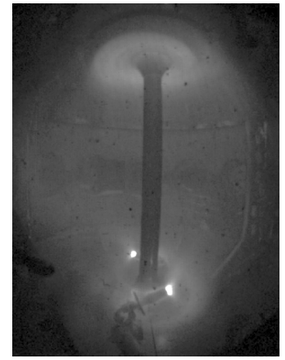
M.G. Burke, et al. Nucl. Fusion **57**, 076010 (2017)

HFS Injection Found to Exhibit More Complex MHD Behavior

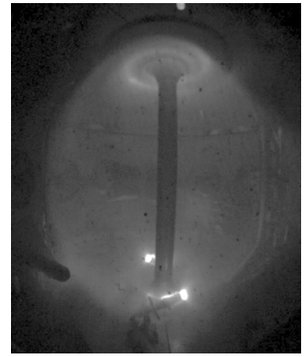
- Initially similar to LFS injection
  - Large scale n=1 at 20–80 kHz
  - Consistent with line-tied kink
- Abrupt MHD transition can occur:
  - Low-f $n = 1$ activity reduced by over 10×
  - Extremely sensitive to B_T, B_Z, I_p, fueling
- Bifurcation in I_p evolution following transition
  - Current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



High MHD

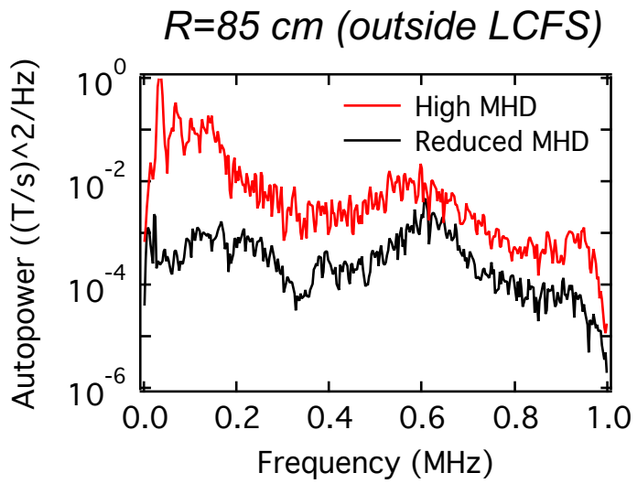


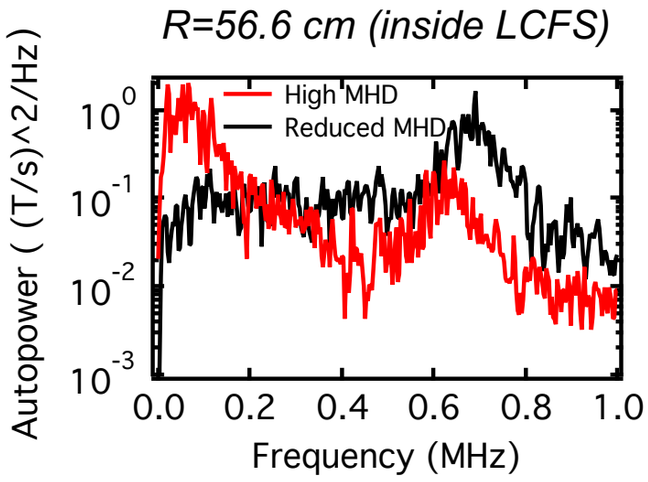
Reduced MHD



Understanding MHD Transition Motivates New Experiments and Diagnostic Capabilities

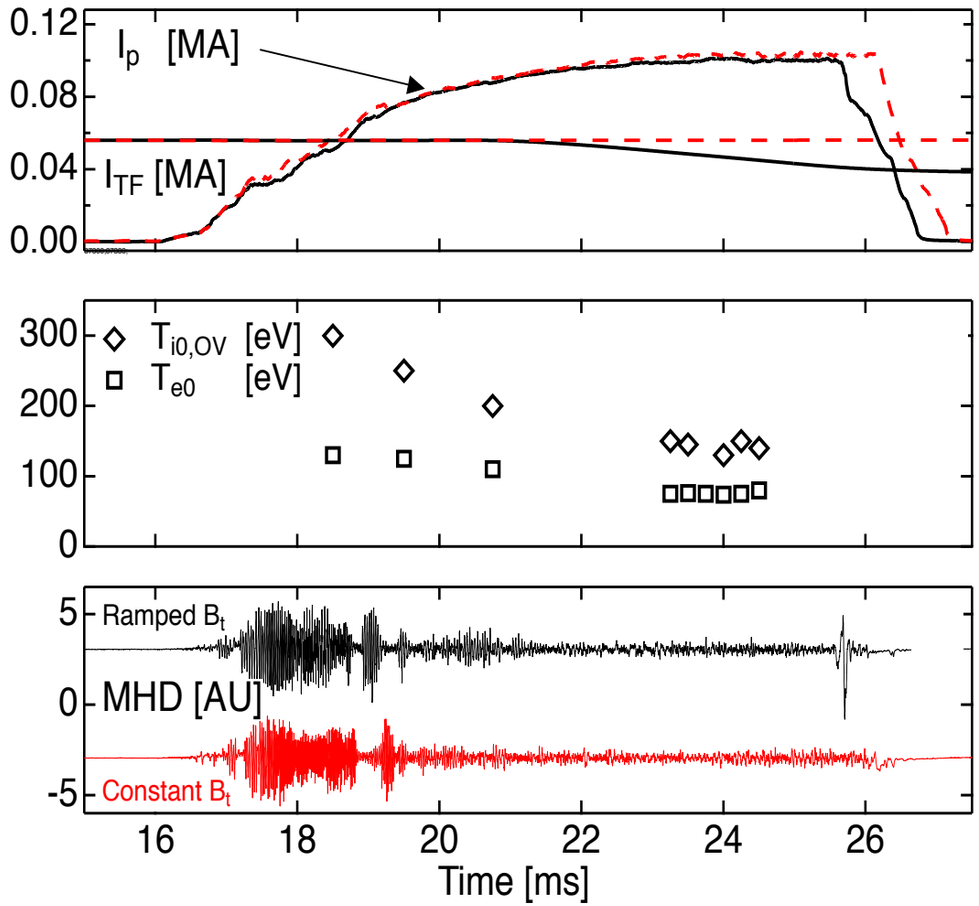
- Reduction in low-frequency activity presently interpreted as stabilization of kinked injector streams
  - Mechanism of stabilization under investigation
- High-frequency activity persists (~600 kHz)
  - Points to additional current drive mechanism
  - Link to short λ turbulence?
  - Reconnection on inboard, high-field side (NIMROD)?
- New high-frequency insertable probes deployed
  - First results indicate high-frequency activity increases in plasma edge region after transition





HFS LHI Provides High-Performance Operation at Extremely Low B_T

- Near-unity 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 κ, low ℓ_i
- Reconnection-driven $T_i > T_e$
- Ramped B_T discharges terminate disruptively at ideal no-wall stability limit
  - Consistent with DCON analysis

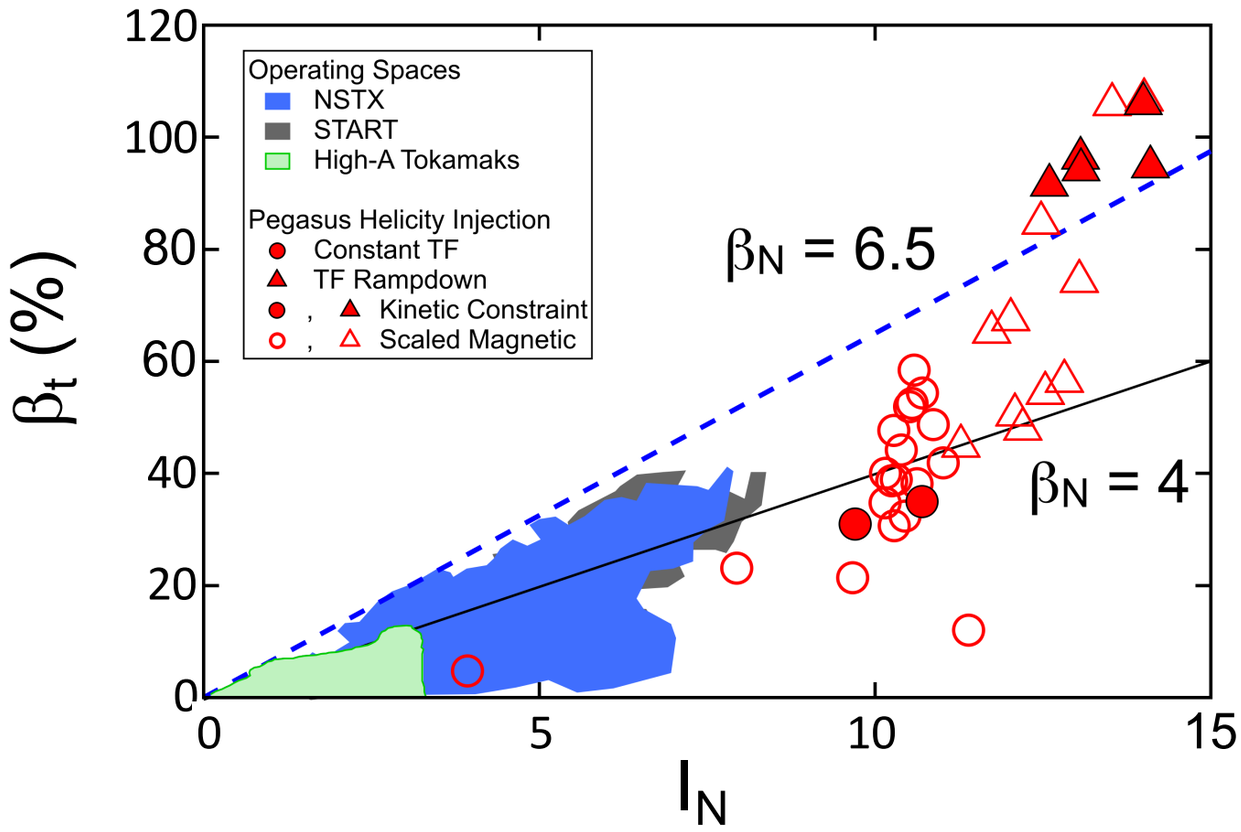


*D.J. Schlossberg et al., PRL **119** 035001 (2017)*

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 κ
  - High I_N stability limit
- LHI:
  - Strong ion auxiliary heating
  - Edge current drive → low ℓ_i
- Low ℓ_i at low-A: high $\beta_{N,max}$

Troyon Stability Diagram for Tokamaks, STs



*D.J. Schlossberg et al., PRL **119** 035001 (2017)*
*J.E. Menard et al., Phys. Plasmas **11**, 639 (2004)*

LHI Provides Access to Desirable ST Operating Space

- Non-solenoidal sustained plasmas with high-β_t, low ℓ_i, high κ, high I_N, are ST research goal
  - 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 κ	Low A	A = 1.15 $\rightarrow$ $\kappa \approx 2.5$
Low ℓ_i	Bootstrap, Off-axis NBI, RF	LHI edge CD $\rightarrow$ $\ell_i \approx 0.2$
High I_N	High I_p, low A, wall stabilization	Low B_t, A ~ 1, no-wall limit
High β_t, β_N	NBI, RF Heating	Reconnection Ion Heating
Non-solenoidal sustainment	Bootstrap, NBI, RF	LHI
Collisionality	Very low	Modest

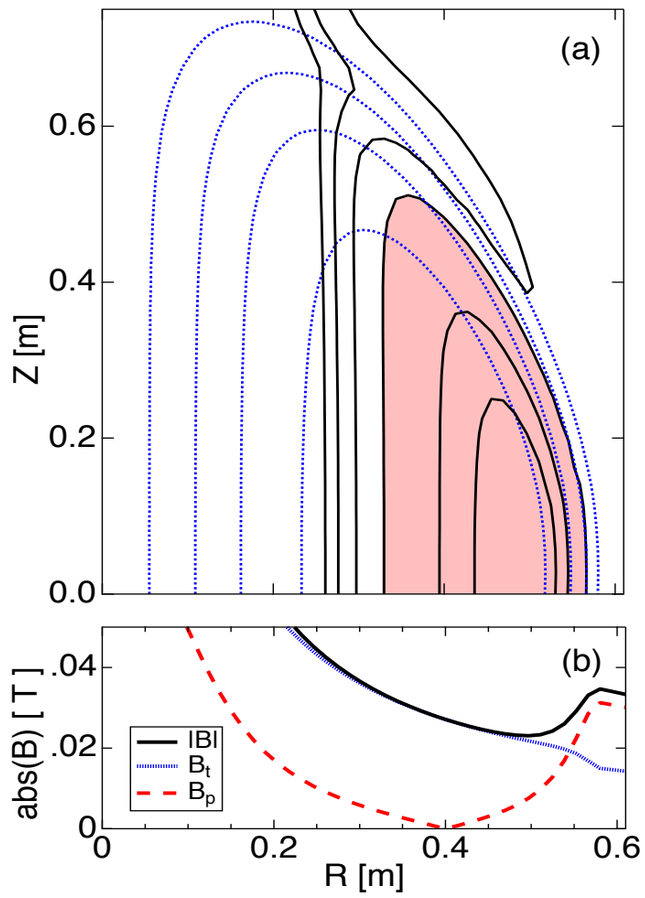
- LHI facilitates near-term access and stability studies

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

Unique Feature of High-β_t LHI Plasmas: Sustained min |B| Region

- High-β_t equilibrium contains large minimum |B| region
  - Up to 47% of plasma volume
  - Well deepens and broadens as β_t increases
- Region persists for several energy confinement times
- Potentially favorable for stabilization of drift modes, reduction of stochastic transport
  - Presently under investigation

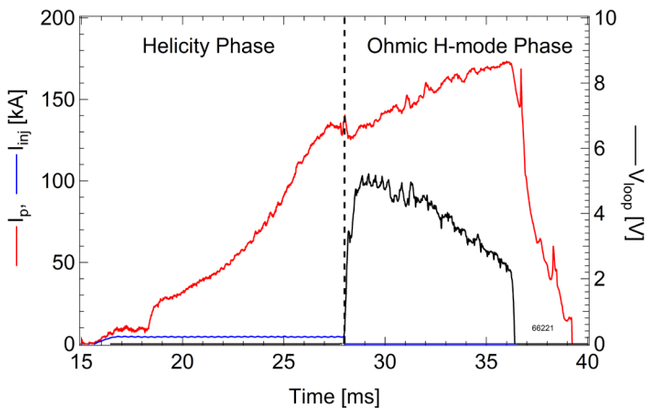
High-β_t equilibrium flux surfaces (blue), |B| (black), and min-|B| region (red)



LHI Capabilities Aided Recently-Concluded H-mode Physics Thrust

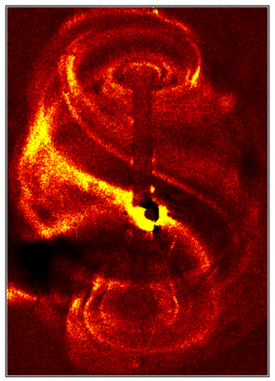
- Low B_T at A ~ 1 → Low P_{LH} and Access to Ohmic H-mode
  - LHI plasmas coupled to OH: highest-performance H-mode discharges
- Key results of campaign:
  - Confirmed L-H power threshold discrepancy as A → 1
  - First access to, characterization of ELMs at A < 1.3
  - High spatiotemporal measurements across pedestal
  - First measurements of nonlinear $J(R)$ dynamics during single ELMs
  - 3D field application from LHI injectors may alter ELM stability

LFS LHI → OH H-mode Handoff



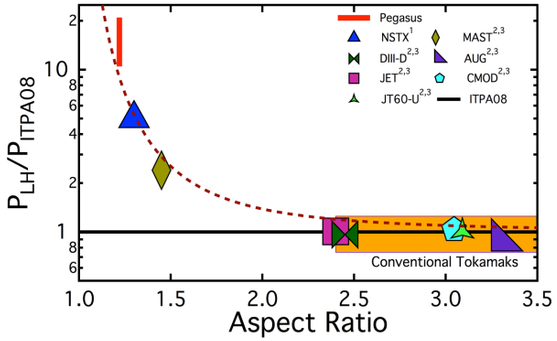
Bongard, IAEA FEC 2016 EX/P4-51

Large ELM in PEGASUS



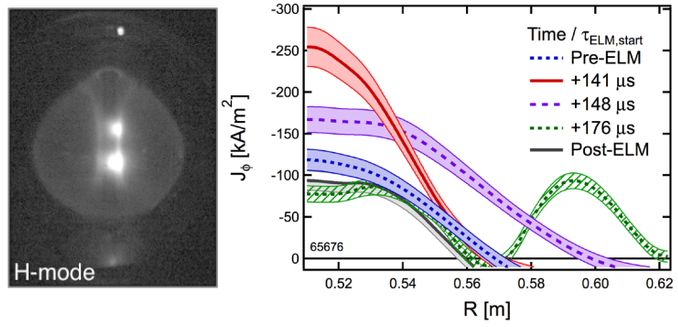
FES Transients Workshop Report Cover
Bongard, IAEA FEC 2016 EX/P4-51

Multi-Machine P_{LH} / P_{ITPA08} Comparison



*Thome, PRL **116**, 175001 (2016)*

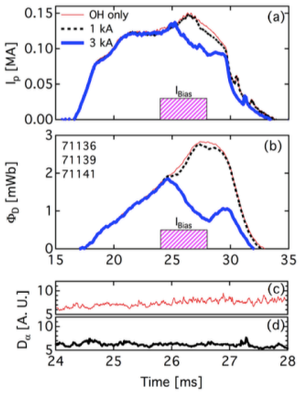
Unique H-mode Edge Pedestal Diagnostic Access

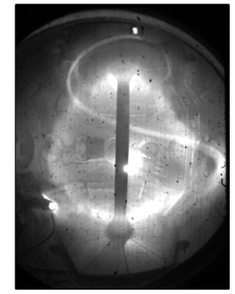


Diverted H-mode plasma *Measured ELM J(R, t) Dynamics*

Bongard, IAEA FEC 2016 EX/P4-51
Fonck, IAEA FEC 2016 OV/5-4

ELM Modification by 3D Edge Current Injection From Helicity Injectors





Bongard, IAEA FEC 2016 EX/P4-51

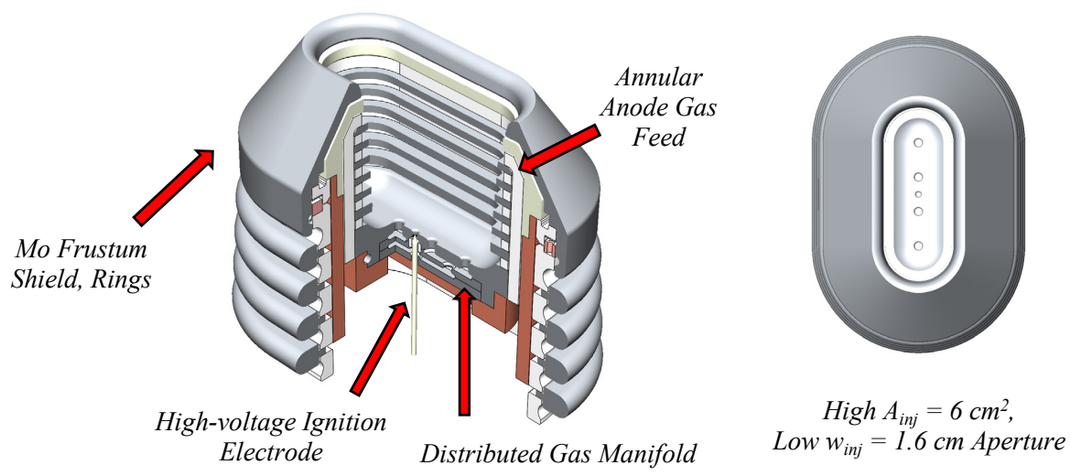
*Thome, NF **57**, 022018 (2017)*

Presently Funded Near-Term LHI Research Activities

- **Science Topics**
  - Scaling to higher I_p through increased V_{eff}
    - Increased V_{eff} via R_{inj}, A_{inj}, injector shape
    - Increase I_{inj} & Taylor limit to improve inductive $I_p(t)$
    - Programmable V_{eff} (~V_{loop}) for $I_p(t)$ control
  - Confinement during LHI
  - Tests of NIMROD, power-balance models
    - Local $\tilde{B}$ measurements and MHD reduction
    - Search for short wavelength reconnection
  - Document, evaluate min $|B|$ configuration
- **Technology Development**
  - High-A_{inj}, non-circular LHI injectors
  - 32 MVA V_{inj} power system

- **Implications:**
  - Understanding LHI mechanisms, scalings
  - Z_{eff} assessment & PMI control
  - Assessment of injector locations

Non-Circular, High-A_{inj} Helicity Injector Renderings



Progress in Non-Solenoidal Tokamak Startup on Pegasus

- Local Helicity Injection provides non-solenoidal startup and sustainment
  - Flexible injection geometry balances V_{LHI} and V_{IND} drive, engineering constraints
  - Taylor Relaxation, Helicity conservation, and resistive MHD modeling
  - Appears scalable to large scale; open questions on confinement and reconnection dynamics

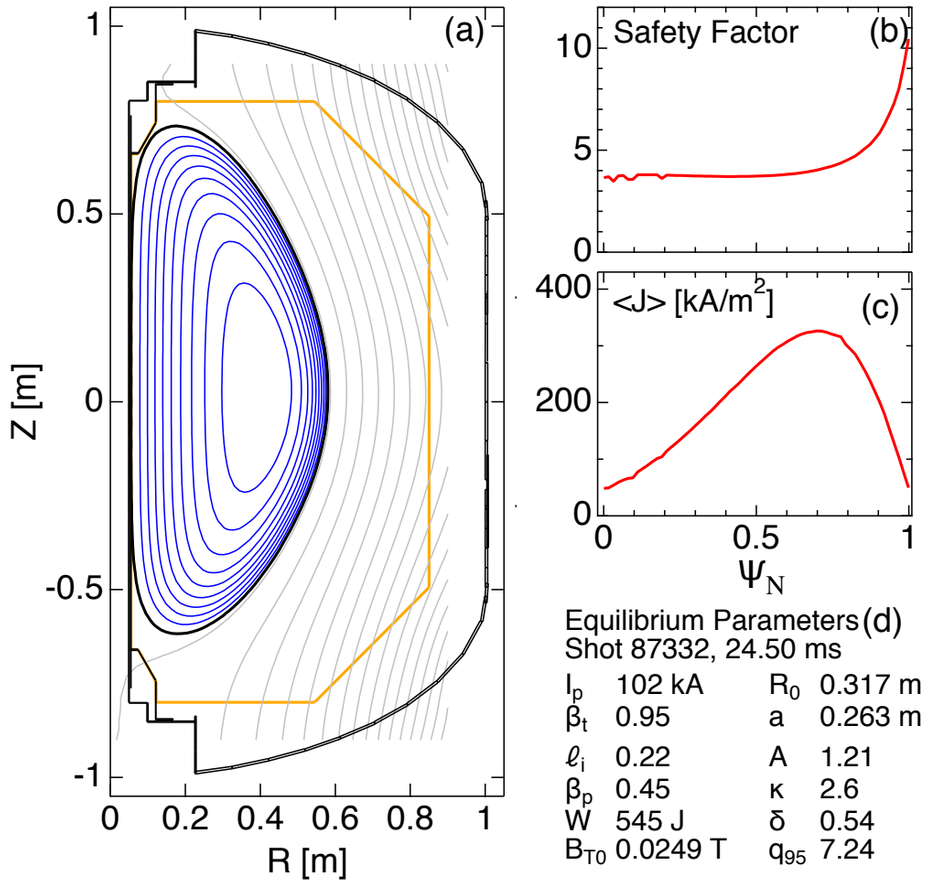
- New high-field-side injector systems exploring strong V_{LHI} limit
  - Injector operation and relaxation to tokamak demonstrated at full TF ($B_{inj} \sim 0.25$ T)
  - I_p up to 0.2 MA with $I_{inj} \leq 8$ kA
  - Completely V_{LHI} driven startup and sustainment realized
  - PMI at HFS injection largely mitigated by injector geometry, local plasma limiters
  - New reduced-MHD regime discovered
  - Attainable I_p scales with helicity injection rate
  - Focus increasing on electron dynamics and I_p scaling

- Non-solenoidal $I_p(t)$ via LHI enables access to stability tests at extreme toroidicity
  - Sustained operation at high I_N, world-record β_T

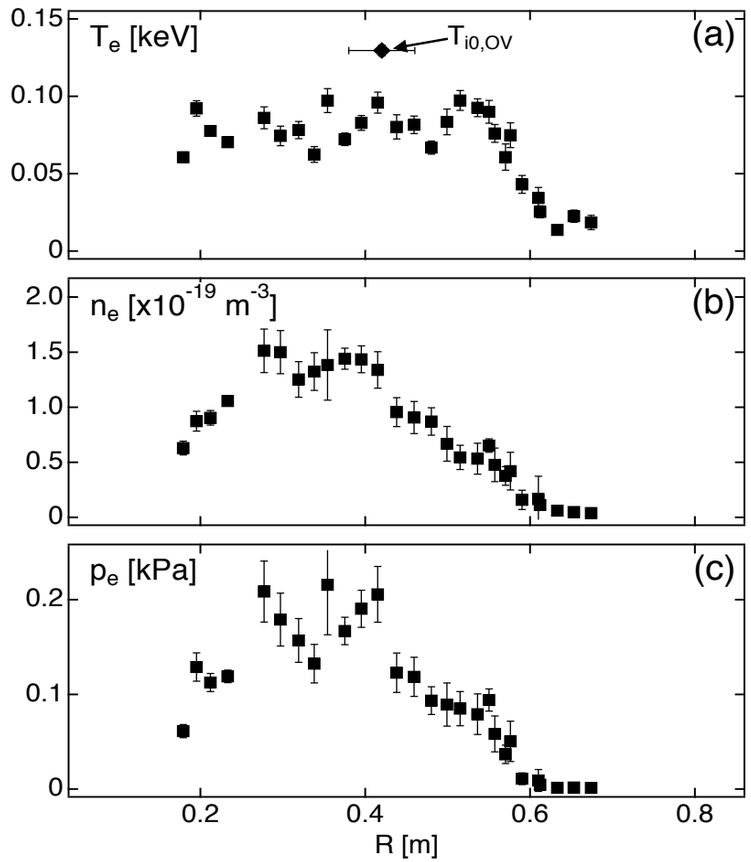
Partial-kinetic Equilibrium Reconstructions of High-β_t Plasmas

- Edge location and core pressure constrained by TS profiles

B_t Rampdown Equilibrium



Kinetic Profiles [TS], Core $T_{i,OV}$



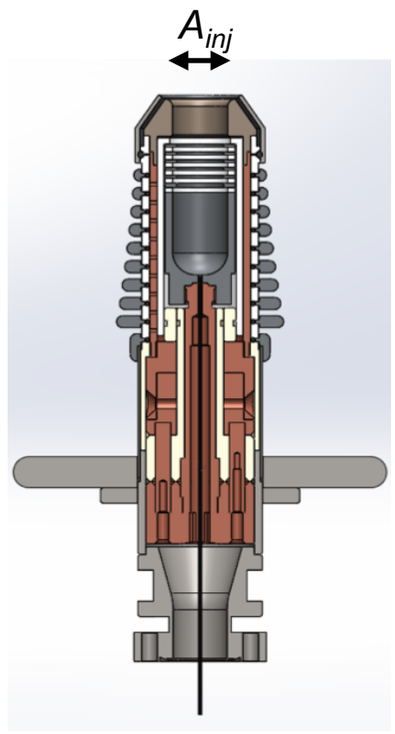
M.W. Bongard, PSI-Center Meeting 2017

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

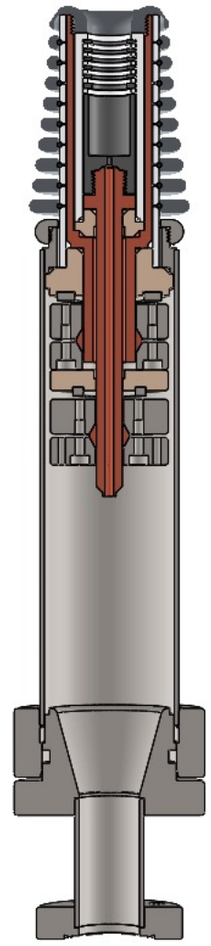
THE UNIVERSITY of WISCONSIN MADISON

Large-A Injector Design Provides Enhanced Performance, Simplified Geometry

- New large-area injectors:
  - Doubled A_{inj}: 2 cm^2 → 4 cm^2
  - Increased I_{inj}: 2 kA → 4 kA
  - Compact design to fit in divertor region
  - Modular assembly permits in-vessel maintenance; rapid design iterations
- Resilient design for increased reliability
  - Tungsten electrode
  - Greater active cooling
  - Better protection of insulators



New: 4 cm^2



Old: 2 cm^2