Overview of the PEGASUS Non-Solenoidal Startup Research Program

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

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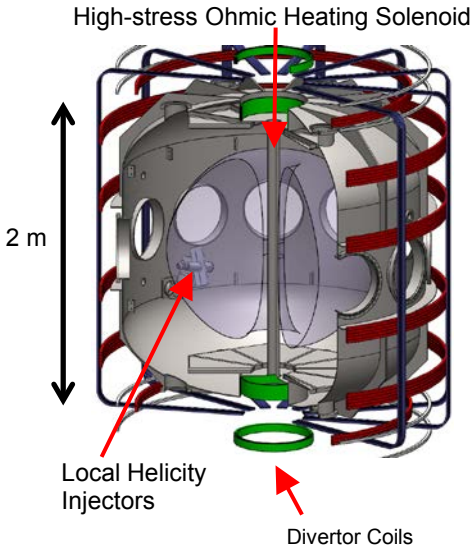
17th International ST Workshop
Seoul National University
Seoul, South Korea

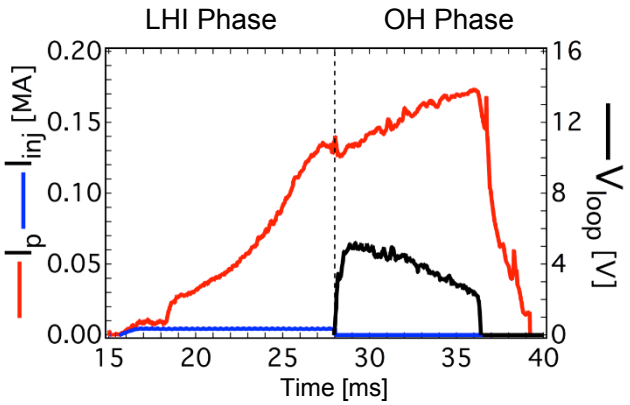
20 September 2017

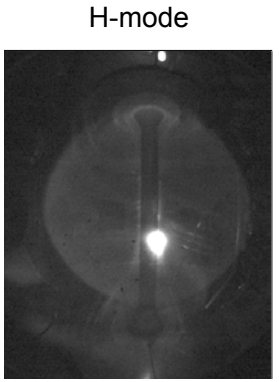


PEGASUS Toroidal Experiment

The $A \sim 1$ PEGASUS ST is Evolving To Become The US Center for Non-Solenoidal Startup







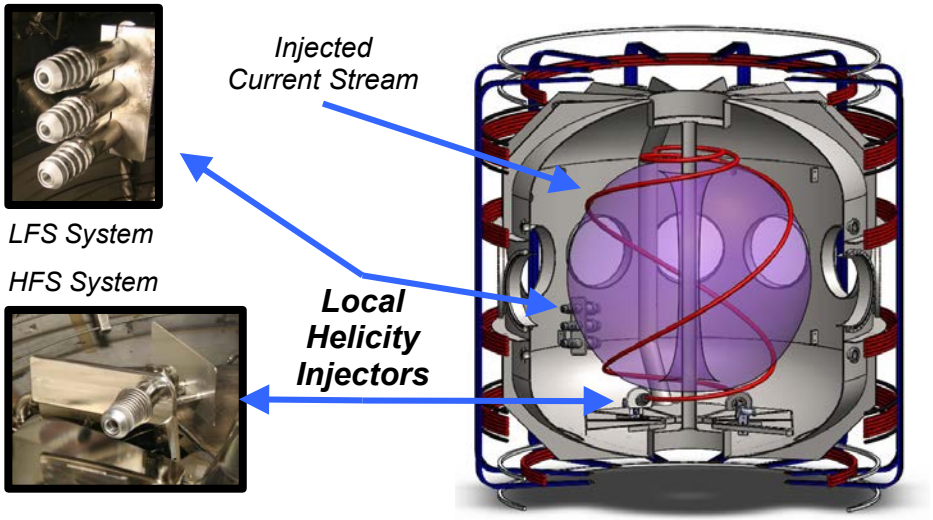
A	$1.15 - 1.3$
R [m]	$0.2 - 0.45$
I_p [MA]	≤ 0.25
B_T [T]	< 0.15
Δt_{shot} [s]	≤ 0.025

PEGASUS Program:

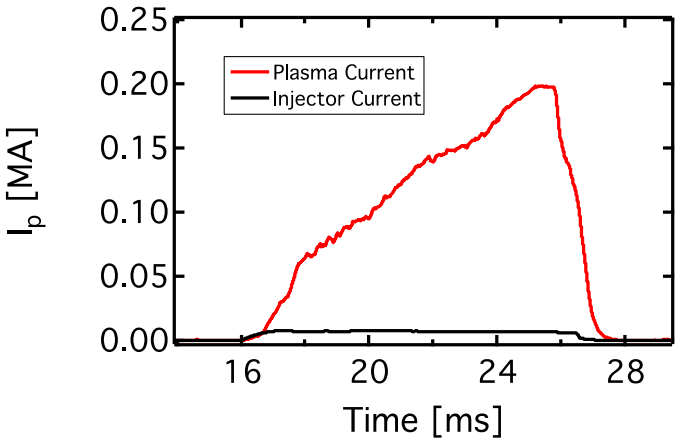
- Local Helicity Injection (LHI) for Non-Solenoidal ST Startup
- H-mode Physics at Ultralow-A *(recently concluded)**
- Access to high I_N > 10 and High β_t
- Proposed Facility Enhancements and New Program Directions

* *K.E. Thome, Phys. Rev. Lett.* ***116****, 175001 (2016)* *M.W. Bongard, IAEA FEC 2016 EX/P4-51*
R.J. Fonck, IAEA FEC 2016 OV/5-4 *K.E. Thome, Nucl. Fusion* ***57****, 022018 (2017)*

Local Helicity Injection is a Promising Non-Solenoidal Startup Technique



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

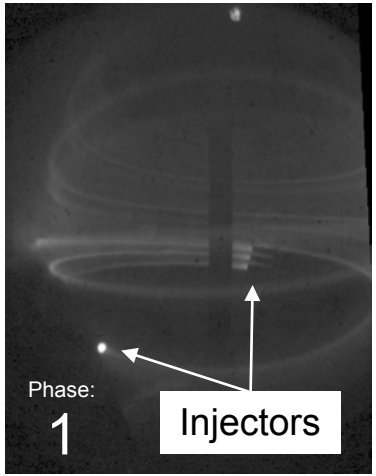


- Edge current extracted from injectors
- Relaxation to tokamak-like state via helicity-conserving instabilities
- Used routinely for startup on PEGASUS

- Current drive quantified by

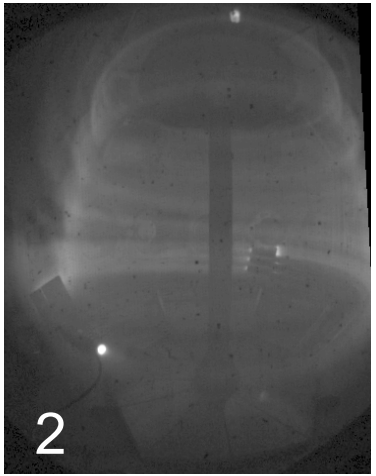
$$V_{LHI} \approx \frac{A_{inj} B_{T,inj}}{\Psi} V_{inj}$$

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



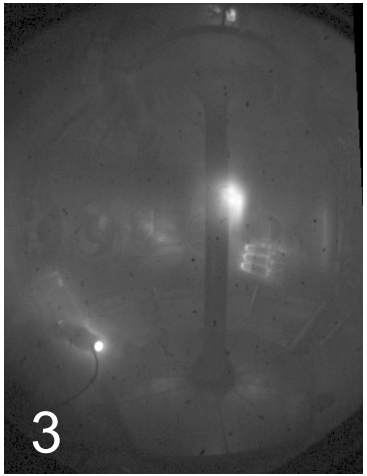
Local source:

Helical plasma streams



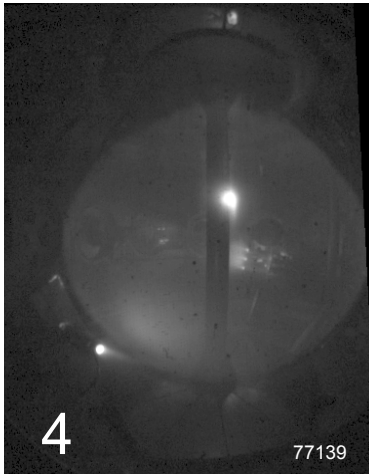
Instability:

Current driven along streams



Reconnection:

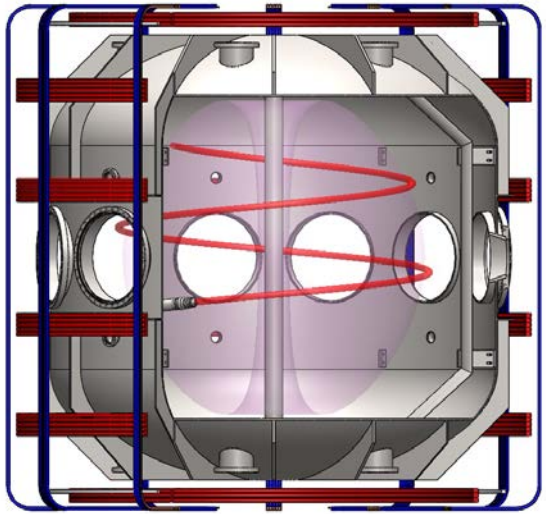
Relaxation to tokamak-like state, current growth

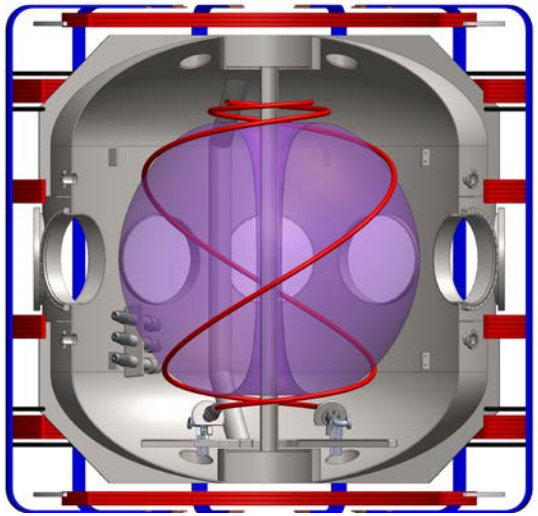


Bias shutdown:

High-I_p tokamak

Injector Location in LHI Emphasizes Different CD Mechanisms





Low-Field-Side (LFS) Injection:

- Injectors near outboard midplane

High-Field-Side (HFS) Injection:

- Injectors in lower divertor

LFS Injection Dominated by Inductive Current Drive

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

- Power balance relation:

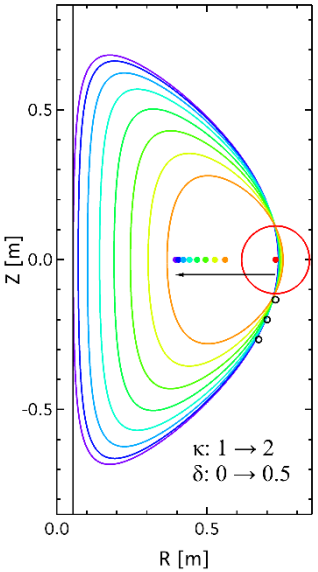
$$I_p[V_{LHI} + V_{IR} + V_{IND}] = 0$$

- Confinement behavior may be affected by dominant current drive type

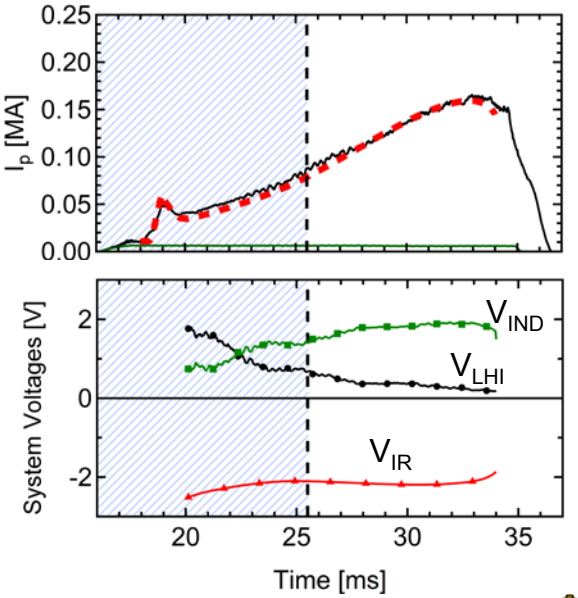
- LFS injection maximizes inductive drive, V_{IND}

- Radial compression → large V_{IND}

Shape Evolution



- Net induction voltage dominates current drive



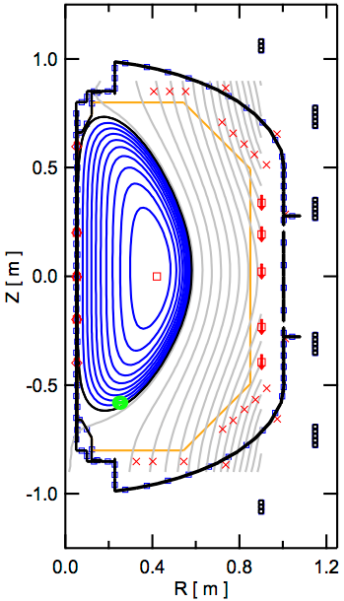
In Contrast, HFS Injection Dominated by Helicity Drive

- Low R_{inj} → high V_{LHI}

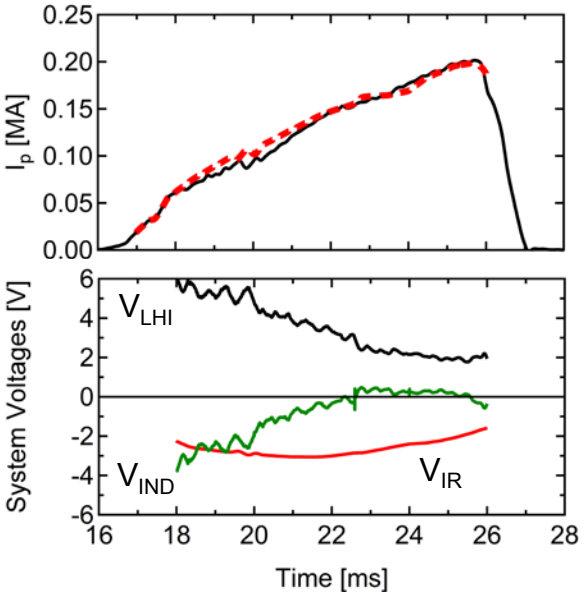
$$V_{LHI} = \frac{V_{inj} A_{inj} B_{inj}}{\Psi_{TF}} \sim \frac{1}{R_{inj}}$$

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

- Static plasma shape → low V_{IND}



- HI dominates current drive

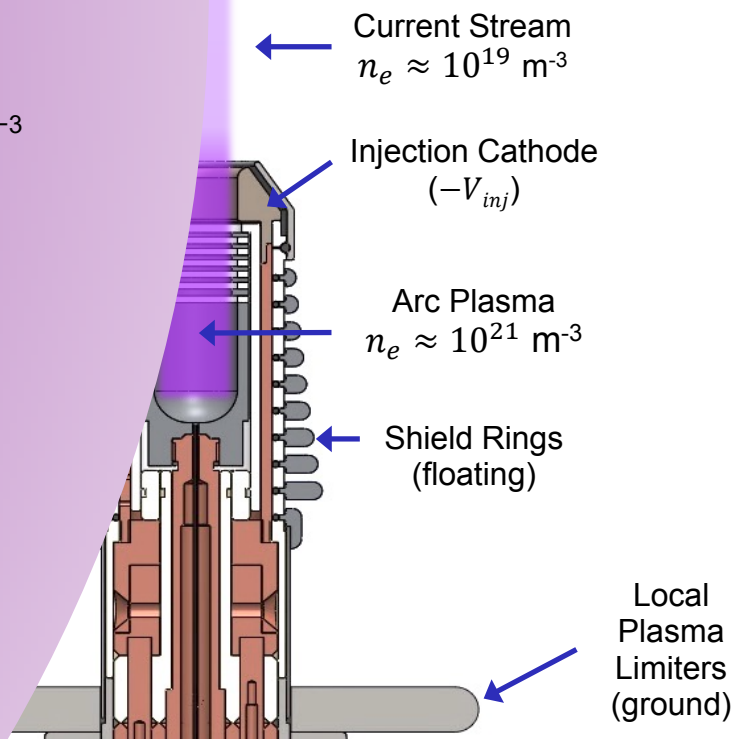


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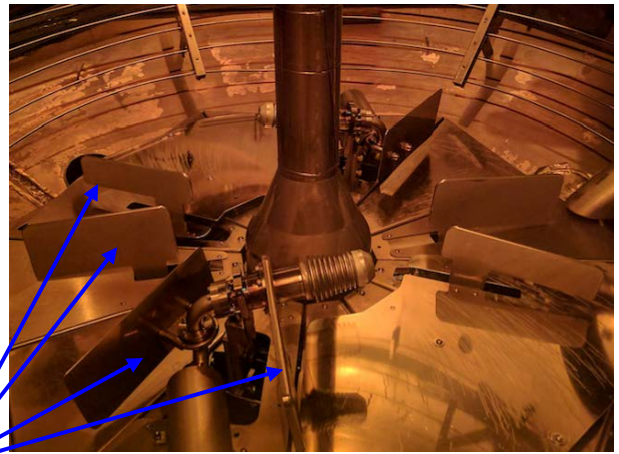
Since Last ST Workshop, HFS Divertor Injectors Installed to Study HI-Dominant Regime

Tokamak Plasma Edge

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

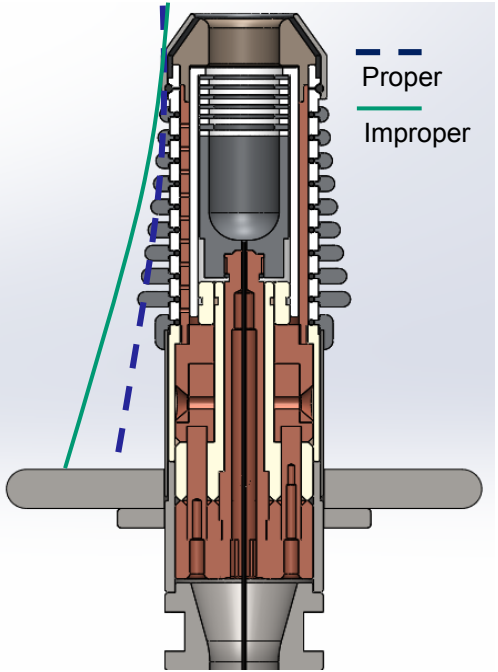


- 2 injectors in lower divertor
- 4× V_{LHI} over LFS injection
- A_{inj} = 8 cm^2; V_{inj} ≤ 1.5 kV; I_{inj} ≤ 8 kA (8–12 MW total power)



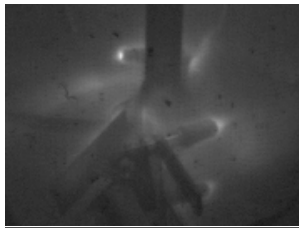
Injector Alignment, Local Limiters Critical to PMI Mitigation

Injector Schematic and Field Line Alignment

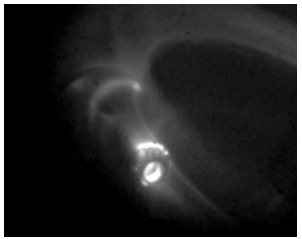


- Proper alignment:
  - Injector shadowed
  - High voltage standoff in tokamak SOL
- Improper limiter placement:
  - Injector immersed in plasma
  - Cathode spots on injector
- Improper alignment to local field:
  - Arc-back to limiter
- Local limiters, shield plates needed to minimize DIV plate interactions

Fast Visible Imaging

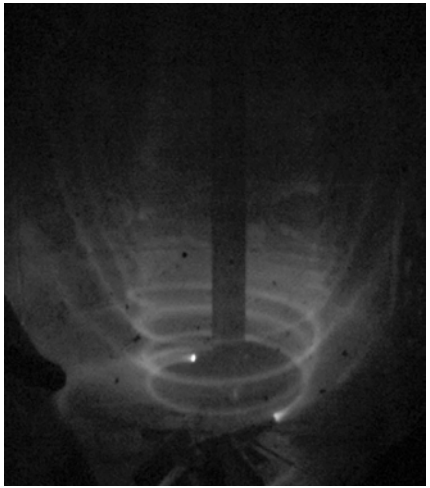






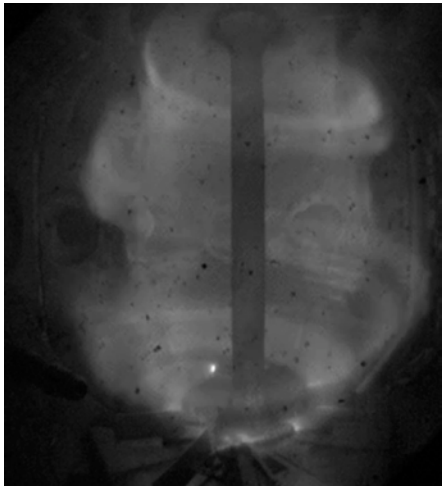
Relaxation Challenges with HFS Injection Addressed

Injected current weakens vacuum B_Z



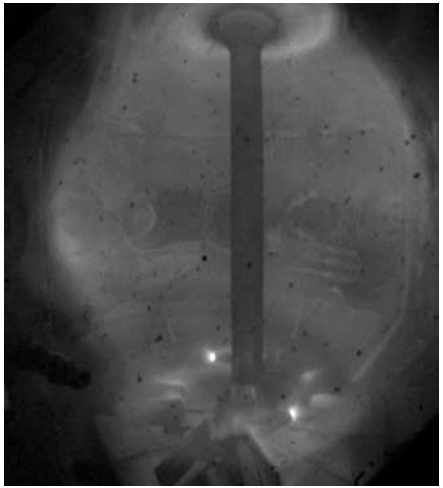
$I_p \sim N_{turns}\, I_{inj}$

Unstable current streams attract, reconnect



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

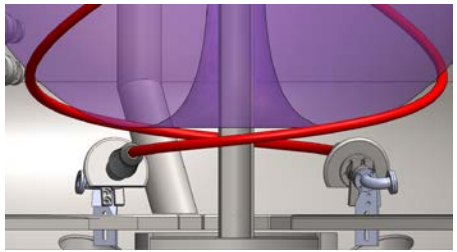
Tokamak-like plasma; rapid I_p growth



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

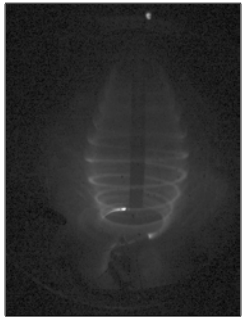
Initial Relaxation to Tokamak State Requires Strong Deformation of Vacuum Field

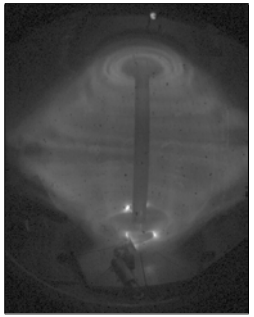
- Injector geometry sets minimum pitch (B_Z/B_T) for stream clearance



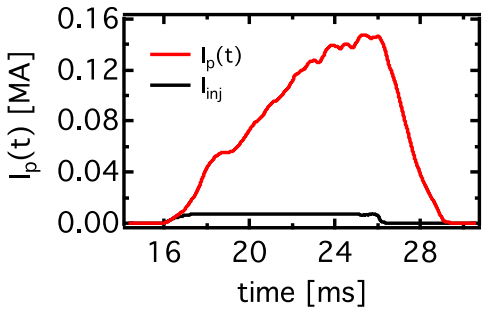
- HFS injection:
  - Lower $R_{inj} \rightarrow$ more B_Z for clearance
  - Relaxation impeded for fixed B_T, I_{inj}
- Solution: poloidal field shaping
  - B_Z strong in divertor; weak at midplane
  - Increased I_{inj} required at increased B_T

Deformed B_{vac} Aids Relaxation





- Relaxation achieved at full Pegasus B_T

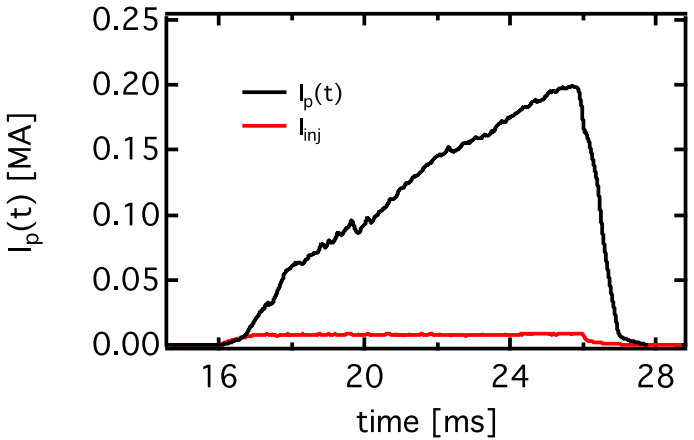


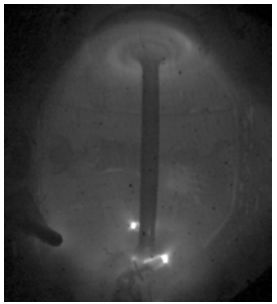
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Target I_p of 0.2 MA Without Solenoidal Induction Achieved

- Non-solenoidal I_p = 0.2 MA scenarios at full B_T
  - 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
  - First test of HFS injectors with modern technology
- Facilitates studies of LHI confinement
  - Example: n_e / B_T / I_p scalings under present study

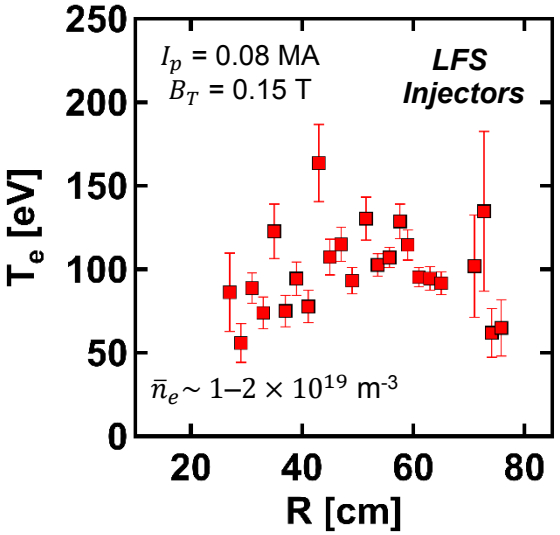
High I_p = 0.2 MA Driven Predominantly by V_{LHI}

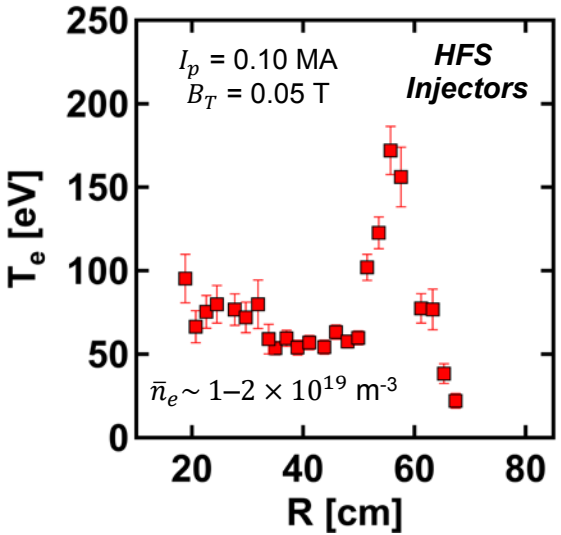


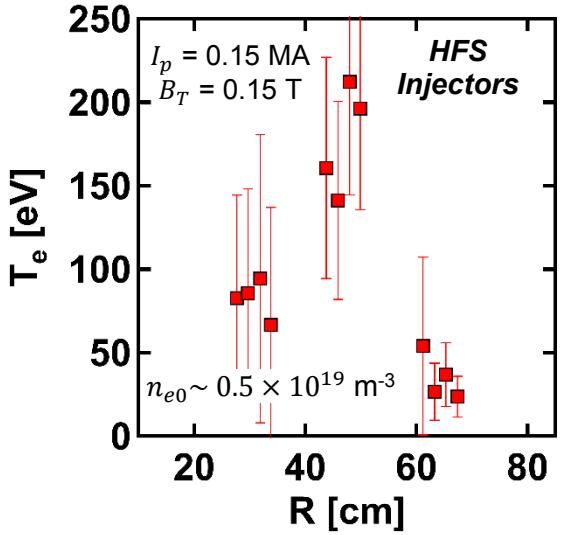


Thomson Scattering Indicates Range of $T_e(R)$ Realized During LHI

- $T_e(R)$ profiles vary with discharge evolution, n_e, shape, and B_T







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

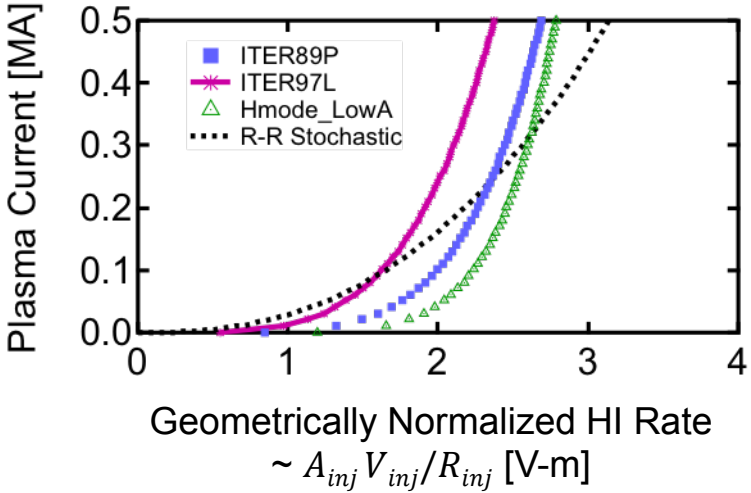
D.J. Schlossberg, Rev. Sci. Instrum. ***87****, 11E403 (2016); UW-Madison PhD Thesis (2016)*

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Projecting Forward: Dissipation of Helicity is a Main Issue

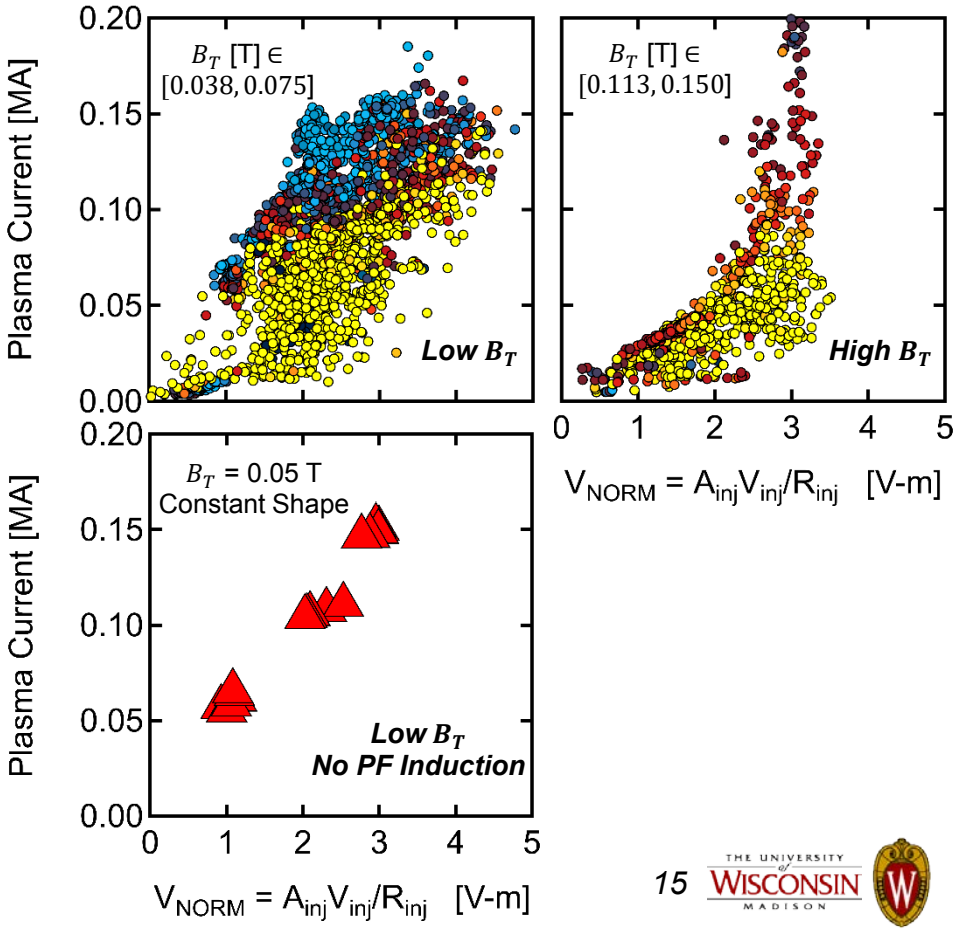
- Helicity input balanced by resistive dissipation
  - Simplistic global interpretation of helicity balance
  - Plasma resistivity influenced by confinement properties
- Crude estimates of confinement inform operation space, assuming:
  - $P_{in} = V_{LHI}\, I_p$
  - $Z_{eff} = 1$
  - Fixed plasma geometry,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

Confinement Scaling Estimates



To Date, Maximum Achieved Current Increases with V_{LHI}

- I_p generally increases with V_{eff}
  - Achieved I_p varies with B_T, MHD levels
  - Fixed geometry V_{eff} scans suggest linear scaling
- Predictive understanding requires more detailed knowledge
  - *e.g.* scaling with Z_{eff}, f_{GW}, B_T, plasma geometry, …
- Electron behavior is a point of emphasis for present work
  - Volume average η
  - Profile effects
    - T_e, Z_{eff}, $J(R)$, P_{rad}
  - Radiation losses



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

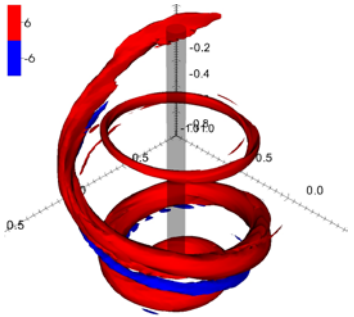
$$V_{LHI} \approx \frac{A_{inj} B_{T,inj}}{\Psi} V_{inj}$$

2. 0-D power-balance $I_p(t)$
   - V_{LHI} for effective LHI current drive

$$I_p [V_{LHI} + V_{IR} + V_{IND}] = 0 \; ; I_p \leq I_{TL}$$

3. 3D Resistive MHD (NIMROD)
   - Physics of LHI current drive mechanism

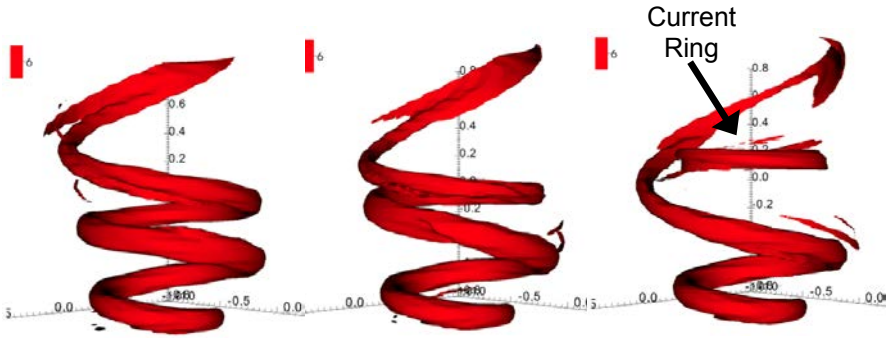
Reconnecting LHI Current Stream



*D.J. Battaglia, et al. Nucl. Fusion **51** 073029 (2011)*
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)*

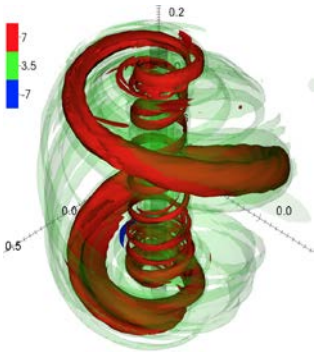
NIMROD Simulations Indicate Helical Current Stream Reconnection as a Current Drive Mechanism

NIMROD: Early Relaxation Phase in Divertor LHI Geometry

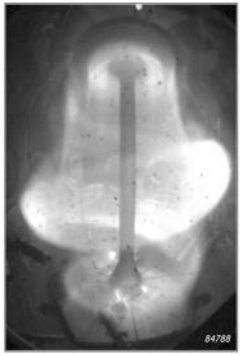


1. Streams follow field lines
2. Adjacent passes attract
3. Reconnection forms current rings

Early Formation Phase



NIMROD Simulation
[O'Bryan PhD 2014]



2016 PEGASUS
High-speed Imaging

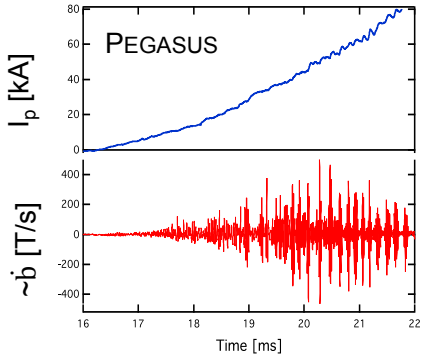
Fonck, IAEA FEC 2016 OV/5-4

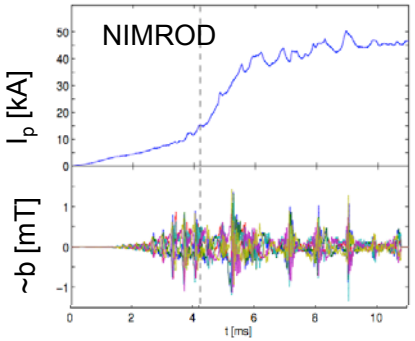
- Divertor LHI startup shows suggestive commonality between NIMROD simulations and experiment

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

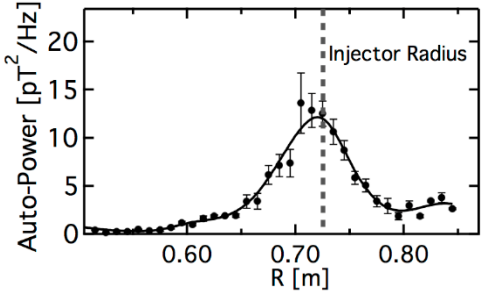
Current Stream Interaction Manifests as Edge-Localized MHD Burst

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

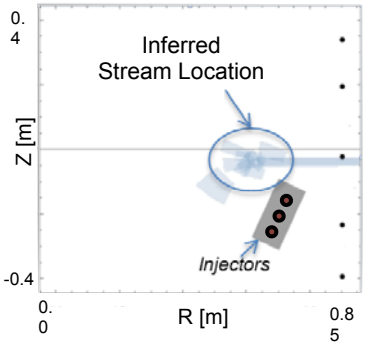




Internal B_z Measurements



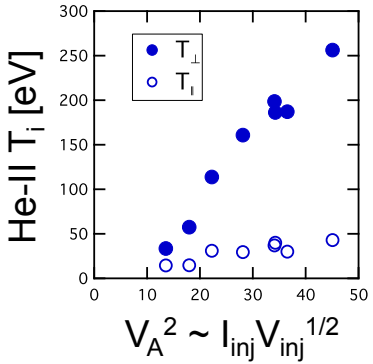
External B_z Phase Correlation



J.L. Barr, UW-Madison PhD Thesis (2016)
J.B. O'Bryan, UW-Madison PhD Thesis (2014)
E.T. Hinson, UW-Madison PhD Thesis (2015)

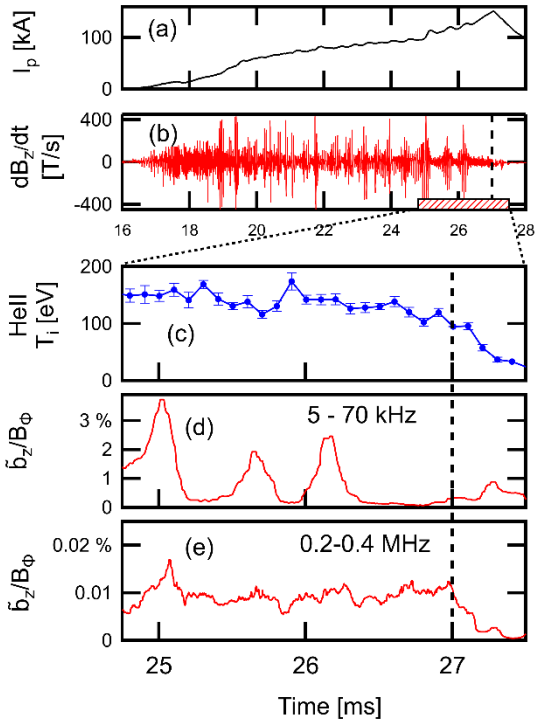
Reconnection-driven Ion Heating Gives $T_i > T_e$ During LHI

- 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



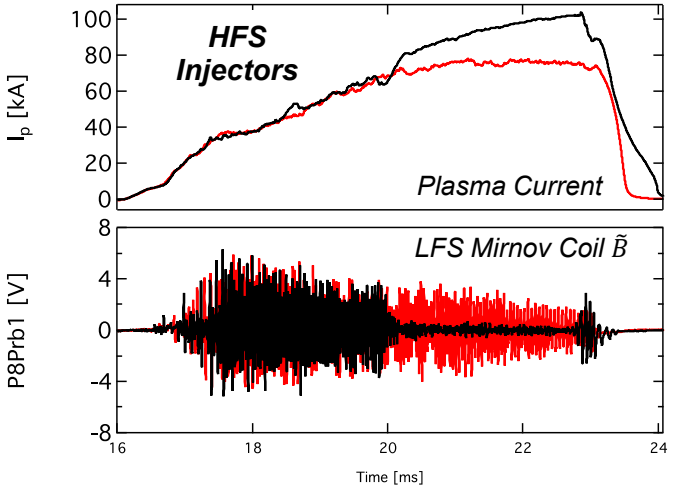
- $T_i(t)$ correlated with continuous, high frequency activity
  - Suggests considering short wavelength reconnection as another CD mechanism

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

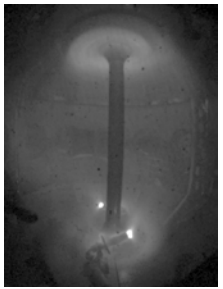


HFS Injection: Reduction in Large-Scale MHD and Increased I_p Indicates More Complex Current Drive Mechanism

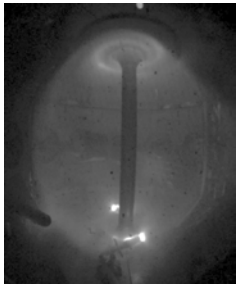
- HFS injection: initially similar to LFS
  - Large scale $n = 1$ at 20–80 kHz
  - Consistent with line-tied kink
- Abrupt MHD transition can occur:
  - Low-f $n = 1$ activity reduced by over 10×
  - Extremely sensitive to B_T, B_Z, I_p, fueling
- Bifurcation in I_p evolution following transition
  - Current growth continues after transition
  - n_e rises, edge sharpens visibly
  - Preliminary indications of E_R shear at edge via probes
- MHD evolution indicates strong CD mechanism independent of MHD bursts



High MHD



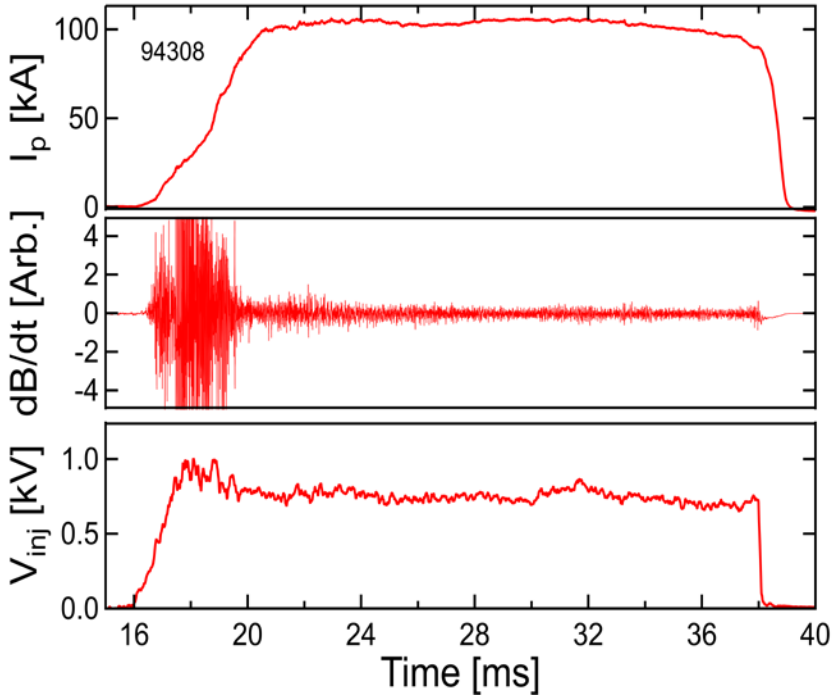
Reduced MHD



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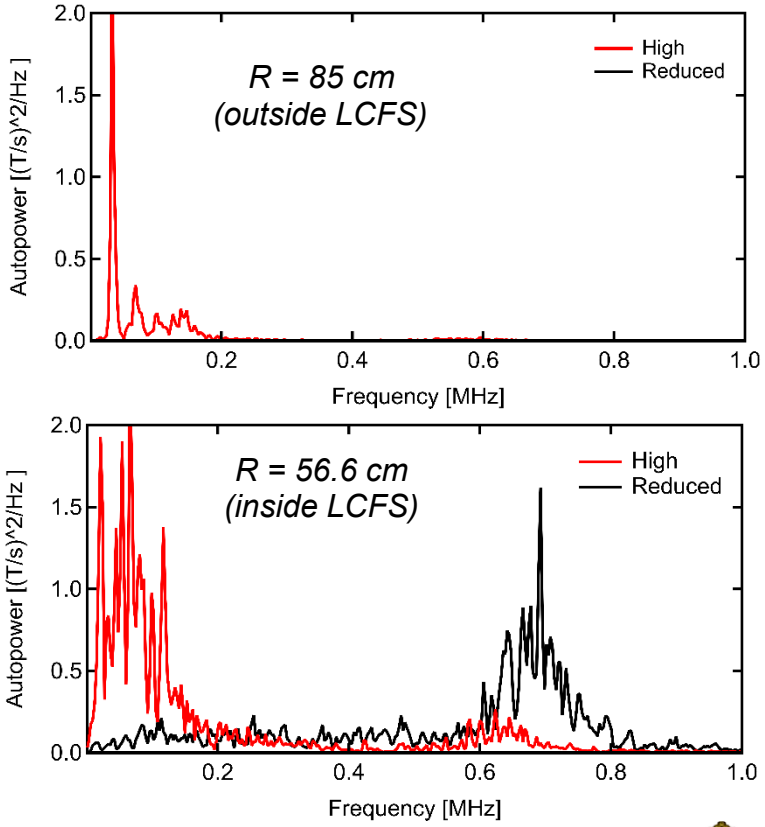
Long-pulse, Non-inductive HFS LHI Discharges Sustained Without Low-Frequency $n = 1$ Activity

- Current sustained in reduced MHD regime
  - $n = 1$ activity suppressed during I_p flattop
  - Pulse length limited by power supplies
- I_p = 0.1 MA non-inductive scenario
  - Constant shape
  - Zero measured PF induction



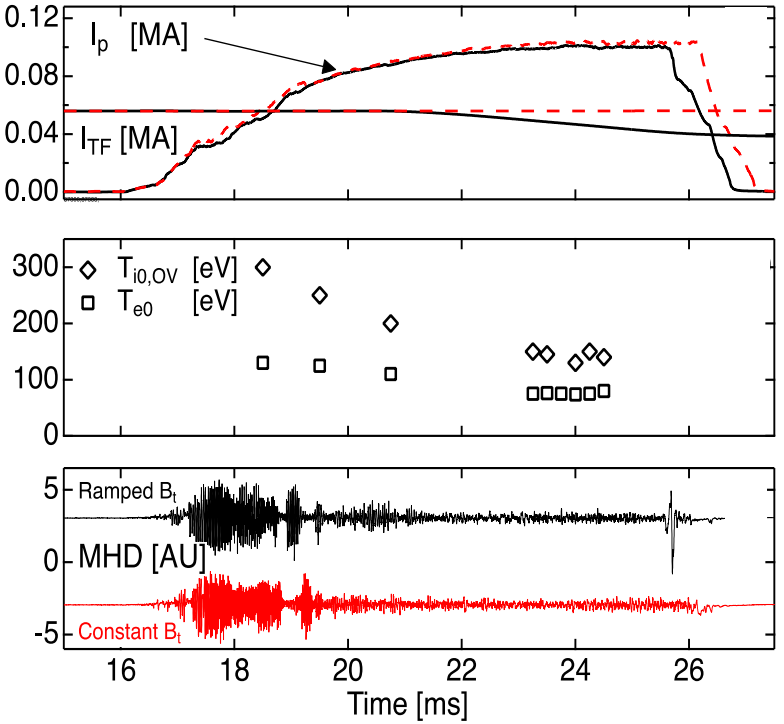
Transition Coincident with Shift of MHD From Low to High Frequency

- Reduction in low-frequency activity presently interpreted as stabilization of kinked injector streams
  - Mechanism of stabilization under investigation
- New high-frequency insertable probes deployed
  - First results indicate high-frequency content near plasma edge
  - High-frequency content unobservable on outboard sensors
- Correlated with additional CD mechanism
  - Link to short λ turbulence?
  - Reconnection on inboard, high-field side (NIMROD)?



HFS LHI Provides High-Performance Operation at Extremely Low B_T

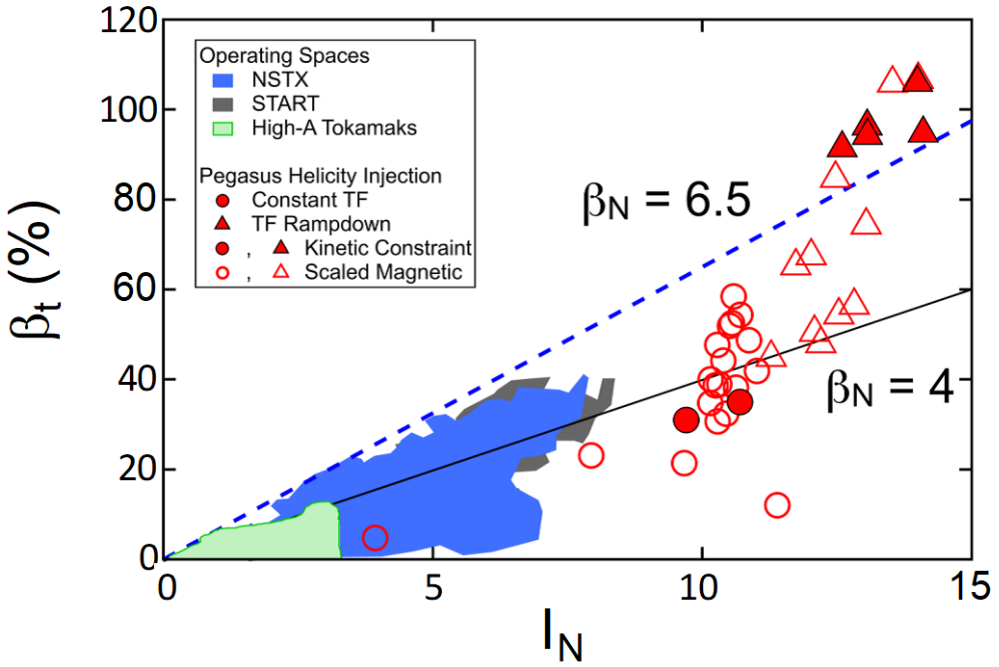
- Access to highly-shaped, high β_t plasmas
- HFS LHI: unique operation space
  - Low $I_{TF} \sim 0.6\, I_p$
  - $I_N = 5A\frac{I_p}{I_{TF}} > 10$ accessible
  - Naturally high κ, low ℓ_i
- Reconnection-driven $T_i > T_e$
- Ramped B_T discharges terminate disruptively at ideal no-wall stability limit
  - Consistent with DCON analysis



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

- World record $\beta_t \sim 1$ achieved
  - Facilitated by $A \sim 1$ and LHI
- $A \sim 1$:
  - 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



R.J. Fonck, IAEA FEC 2016 OV/5-4
D.J. Schlossberg et al., Phys. Rev. Lett. ***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 through different mechanisms

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, $A \sim 1$, 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

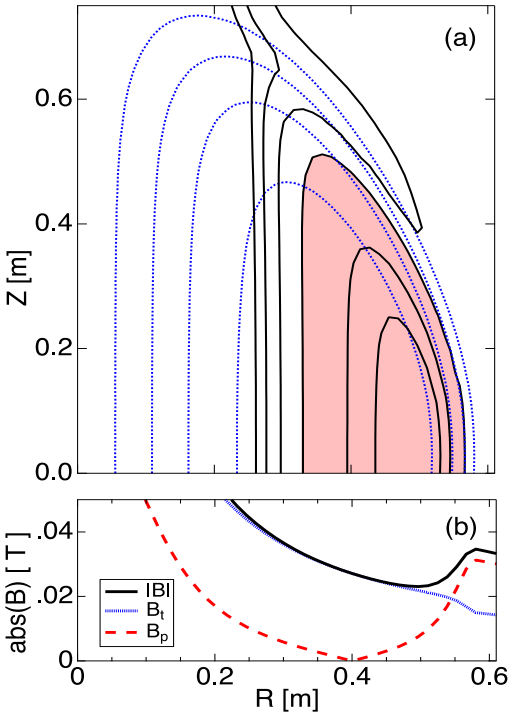
J.E. Menard et al., Nucl. Fusion ***56*** *106023 (2016)*

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

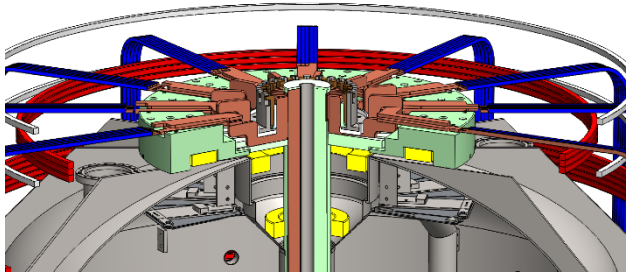
- High-β_t equilibrium contains large minimum $|B|$ region
  - Up to 47% of plasma volume
  - Well deepens and broadens as β_t increases
  - Persists for several energy confinement times
- Minimum $|B|$ regime arises from 3 major influences
  - $B_p \sim B_T$ at $A \sim 1$
  - Hollow $J(R)$
  - Pressure-driven diamagnetism (although $\beta_p < 1$)
- 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)

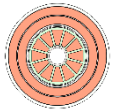


PEGASUS-E: US Non-Solenoidal Development Station

- Compare / contrast / combine reactor-relevant startup techniques
  - LHI, CHI, RF/EBW Heating & CD
  - Goal: guidance for ~1 MA startup on NSTX-U, beyond
- PEGASUS-E (Enhanced)
  - No solenoid magnet
  - Increase B_T 4×: 0.15 → 0.6 T
  - Longer pulse
  - Active shape control
  - Kinetic and impurity diagnostics
  - RF Heating & CD (w/ ORNL)
  - Transient, Sustained CHI (w/ Univ. Washington, PPPL)
- Proposals submitted to US DOE
  - Decisions expected late 2017



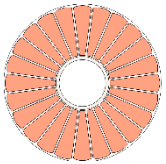
PEGASUS



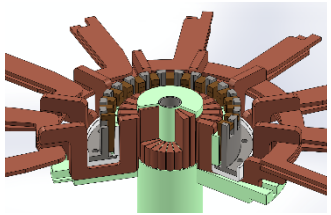
High-Stress OH Solenoid
12-turn TF Bundle



PEGASUS-E



Solenoid-free
24-turn TF Bundle



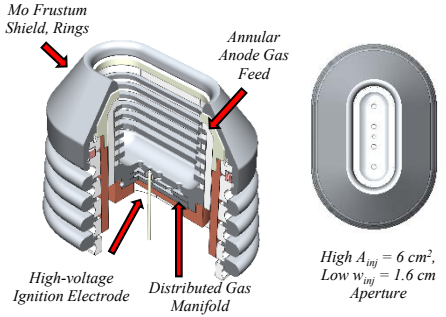
LHI Research Activities on PEGASUS-E Will Test Scaling to High B_T

- Physics Issues
  - Taylor limit I_p scaling
  - Efficiency / confinement scaling
  - Relaxation accessibility
  - MHD behavior & CD mechanisms
  - PMI and impurities
  - Advanced injector technology
    - Increased HI drive with high Taylor limit

- Facility Enhancements
  - 24-turn TF rod; power system
  - Programmable $V_{eff}(t)$ control
  - PF coils and power systems
    - X-point, shape control
  - DNB spectroscopy
    - $\tilde{B}(R,t), J(R,t), T_i(R,t), n_e(R,t), n_Z(R,t)$
  - Impurity diagnostics
    - SPRED, VB, bolometry

Parameter	PEGASUS	PEGASUS-E
R_{sol} [cm]	4.9	N/A
I_{sol} [kA]	$\pm$ 24	0
ψ_{sol} (mWb)	40	0
N_{TF}	12	24
$N_{TF} \times I_{TF}$	0.288 MA	1.15 MA
$B_{T,max}$ [T] at R_0~0.4 m	0.15	0.60
A	1.15	1.22
B_T Flattop [ms]	50	100
TF Conductor Area [cm^2]	13.2	151
I_p Target [MA]	0.2	0.3

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



Refurbished PBX-M DNB



M.W. Bongard, ISTW 2017

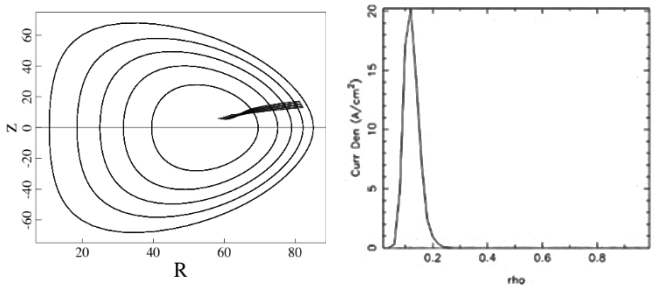
High-B_T of PEGASUS-E Facilitates RF/EBW and CHI Studies

- EBW heating and CD; synergy with HI startup
  - T_e increase for compatibility with non-inductive sustainment (e.g. NBCD)
  - Potential for direct RF startup
  - Initial concept: ~ 400 kW EBW RF, 9 GHz (TBD)
  - ORNL collaboration

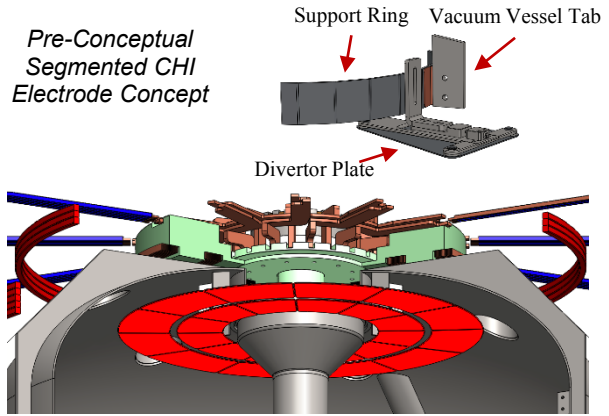
- Deploy "simple" CHI systems
  - Flexible, segmented floating anode and cathode structures
  - Transient and/or Sustained CHI
  - Univ. Washington, PPPL collaboration

- LHI – CHI – RF Experiments
  - Generate significant closed-flux I_p with CHI
  - Compare T_e, n_e, Z_{eff}, $J(R)$, usable I_p
  - Coupling to consequent CD mechanism

GENRAY, CQL3D Modeling Indicates Core Absorption for EBW Heating, CD



Pre-Conceptual Segmented CHI Electrode Concept



Broadening Studies of Non-Solenoidal Startup on PEGASUS and PEGASUS-E

- Local Helicity Injection provides non-solenoidal startup and sustainment
  - Flexible injection geometry balances V_{LHI} and V_{IND} drive, engineering constraints
  - Appears scalable to large scale; open questions on confinement, reconnection dynamics and B_T scaling
- New high-field-side injector systems exploring strong V_{LHI} limit
  - Relaxation to tokamak demonstrated with HFS system
  - I_p up to 0.2 MA with $I_{inj} \leq 8$ kA
  - New reduced-MHD regime discovered
  - $I_{p,max}$ scales with helicity injection rate
  - Focus increasing on electron dynamics and I_p scaling
- LHI and $A \sim 1$ enable access to high-I_N, high-β_t regime
  - Stability tests at extreme toroidicity
- PEGASUS-E: Proposed US non-solenoidal R&D facility
  - LHI, RF, CHI startup at $B_T > 0.5$ T
  - Projection to NSTX-U and beyond