Non-Solenoidal Startup via Helicity Injection in the PEGASUS ST

M.W. Bongard

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

University of Wisconsin-Madison

59th Annual Meeting of the APS
Division of Plasma Physics
Milwaukee, WI

26 October 2017



PEGASUS Toroidal Experiment

Layout

12:1 scale Panel size: 8’ x 4’

US Legal
8.5 x 14”

US Letter
8.5 x 11”

Non-Solenoidal Startup via Helicity Injection in the Pegasus ST

Local Helicity Injection (LHI) for Non-Solenoidal Tokamak Startup		2017 LHI Campaign Highlights: Confinement and Current Drive		Access to High IN > 10 and beta_t ~ 100%	Proposed Facility Enhancements and New Program Directions
Local Helicity Injection (LHI) is a Promising Non-Solenoidal Startup Technique	LFS Injection Dominated by Inductive Current Drive	Target Ip of 0.2 MA Without Solenoidal Induction Achieved	Reconnection-driven Ion Heating Gives Ti > Te During LHI	HFS LHI Provides High-beta_t, High I_n Operation at Extremely Low BT	Pegasus-E Proposed as US Non-Solenoidal Development Station
Local Plasma Sources Inject Current Streams that Reconnect to Form Tokamak-like Plasma	In Contrast, HFS Injection Dominated by Helicity Drive	Thomson Scattering Indicates Range of Te(R) Realized During LHI	HFS Injection: Reduction in Large-Scale MHD and Increased Ip Indicates More Complex Current Drive Mechanism	LHI at A~1 Expands the Operating Space for the ST to beta_t ~ 1	LHI Research Activities on Pegasus-E Will Test Scaling to High BT
Hierarchy of Physics Models Contribute Towards Predictive Understanding of LHI Startup	HFS Divertor Injector System Installed to Study HI-Dominant Regime	HFS LHI: Maximum Achieved Current Increases with V_LHI	Transition Coincident with Shift of MHD from Low to High Frequency	LHI Provides Access to Desirable ST Operating Space	High BT of Pegasus-E Facilitates RF/EBW and CHI Studies
Injector Location in LHI Emphasizes Different CD Mechanisms	Injector Alignment, Limiters, and Shield Plates Address Plasma-Material Interaction Challenges	NIMROD Simulations Indicate Helical Current Stream Reconnection as a Current Drive Mechanism	Long-pulse, Non-inductive HFS LHI Discharges Sustained Without Low-Frequency n=1 Activity	Unique Feature of High-beta_t Plasmas: Sustained min |B| Region	Broadening Studies of Non-Solenoidal Startup on Pegasus and Pegasus-E

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Local Helicity Injection (LHI) for Non-Solenoidal Tokamak Startup

2017 LHI Campaign Highlights: Confinement and Current Drive

Access to High I_N > 10 and $\beta_t \sim 100\%$



Proposed Facility Enhancements and New Program Directions

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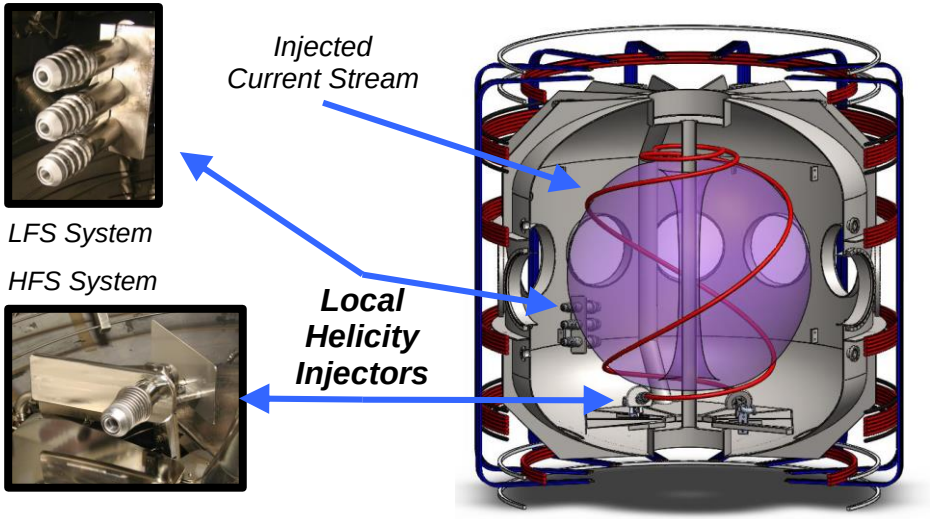
OAK RIDGE
National Laboratory

UNIVERSITY of WASHINGTON

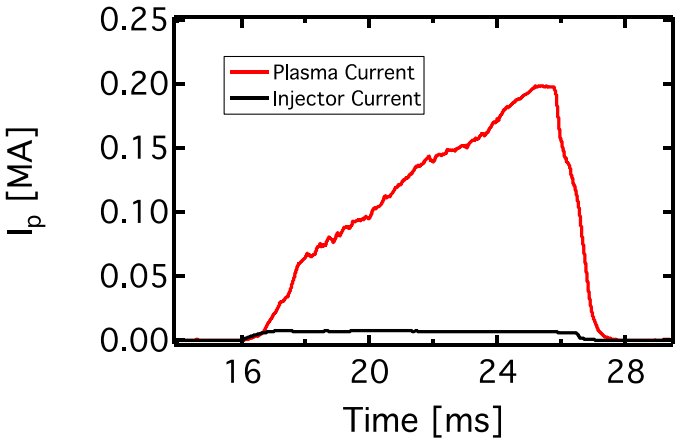
PPPL

NSTX-U

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

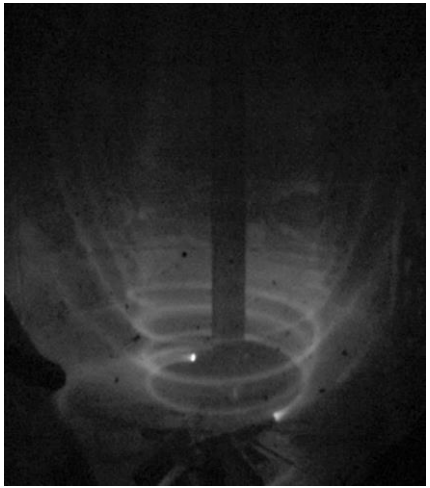
$$V_{LHI} \approx \frac{A_{inj} B_{T,inj}}{\Psi} V_{inj}$$

M.W. Bongard, APS-DPP 2017

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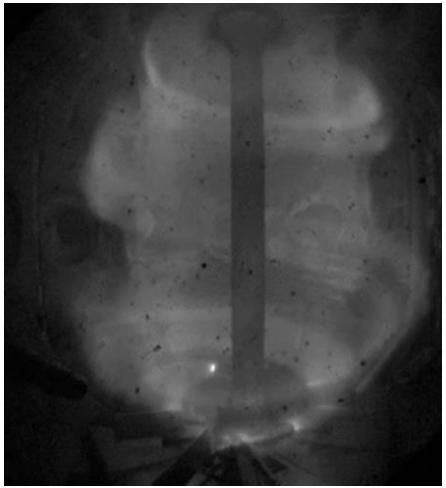
Local Plasma Sources Inject Current Streams that Reconnect to Form Tokamak-like Plasma

Injected current weakens vacuum B_Z



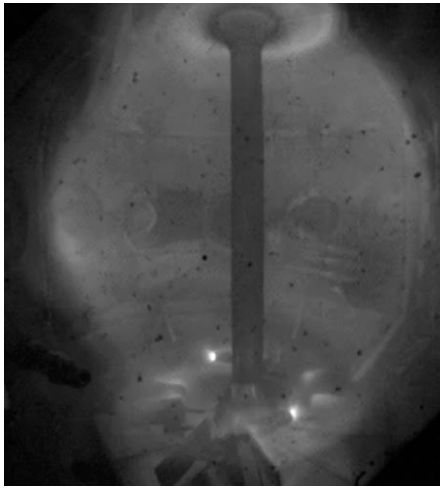
$I_p \sim N_{turns}\, I_{inj}$

Unstable current streams attract, reconnect



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

Tokamak-like plasma; rapid I_p growth



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

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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

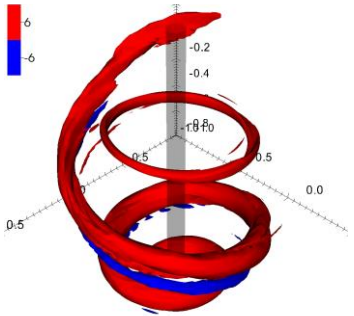
$$V_{LHI} \approx \frac{A_{inj} B_{T,inj}}{\Psi} V_{inj}$$

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

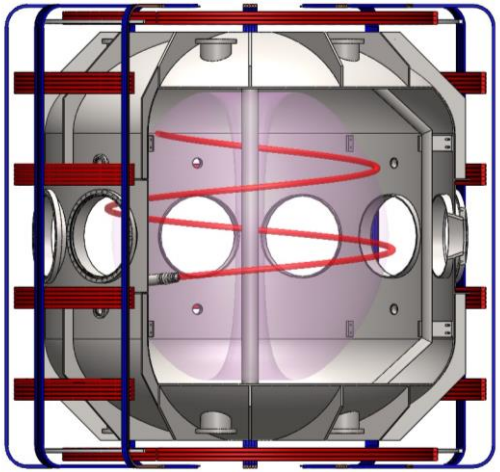
Reconnecting LHI Current Stream

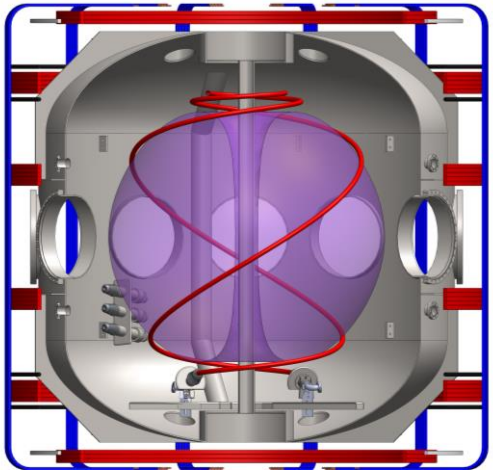


*D.J. Battaglia, et al. Nucl. Fusion **51** 073029 (2011)*
N.W. Eidietis, Ph.D. Thesis, UW-Madison (2007)
J. O'Bryan, Ph.D. Thesis, UW-Madison (2014)
*J. O'Bryan, C.R. Sovinec, Plasma Phys. Control. Fusion **56** 064005 (2014)*

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Injector Location in LHI Emphasizes Different CD Mechanisms





Low-Field-Side (LFS) Injection:

- Injectors near outboard midplane
- Emphasis: non-solenoidal induction

High-Field-Side (HFS) Injection:

- Injectors in lower divertor
- Emphasis: helicity drive

LFS Injection Dominated by Inductive Current Drive

- Power balance relation:

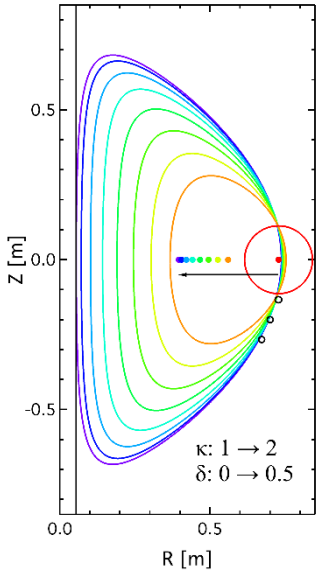
$$I_p[V_{LHI} + V_{IR} + V_{IND}] = 0$$

- Confinement behavior may be affected by dominant current drive type

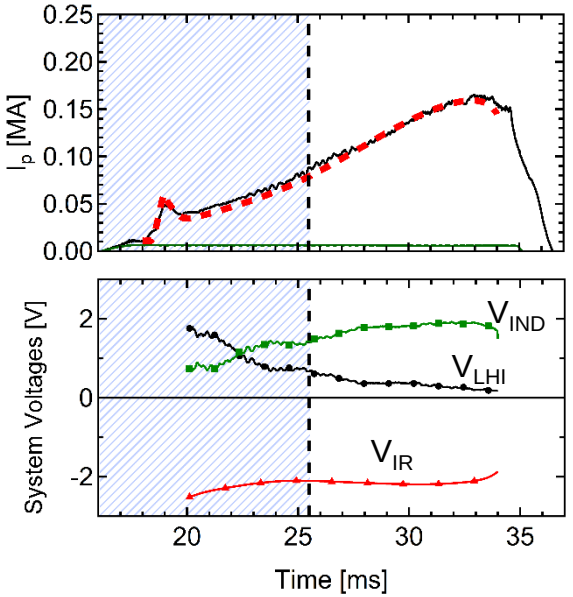
- LFS injection maximizes inductive drive, V_{IND}

- Radial compression → large V_{IND}

Shape Evolution



- Net induction voltage dominates current drive



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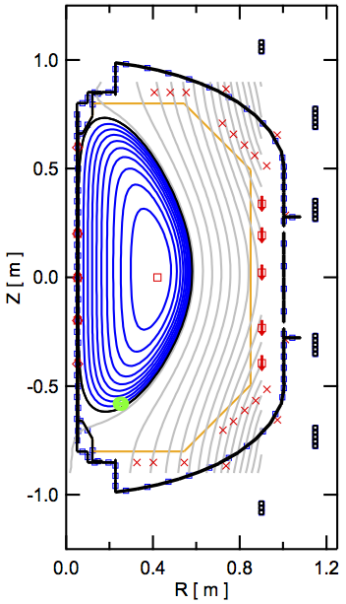
In Contrast, HFS Injection Dominated by Helicity Drive

- Low R_{inj} ➞ high V_{LHI}

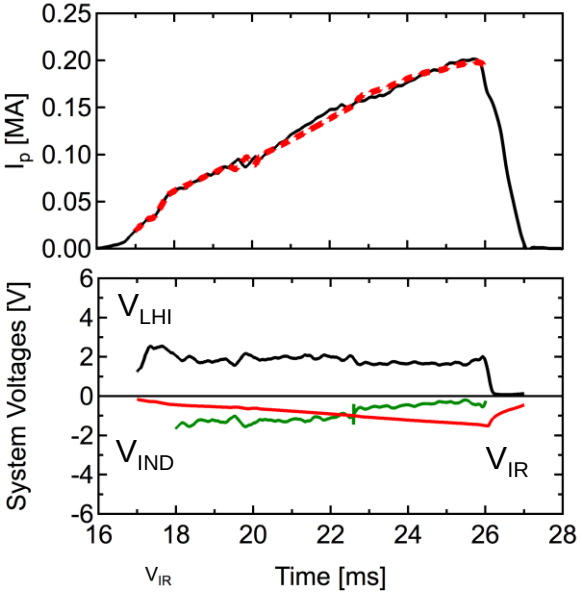
$$V_{LHI} = \frac{V_{inj} A_{inj} B_{inj}}{\Psi_{TF}} \sim \frac{1}{R_{inj}}$$

- 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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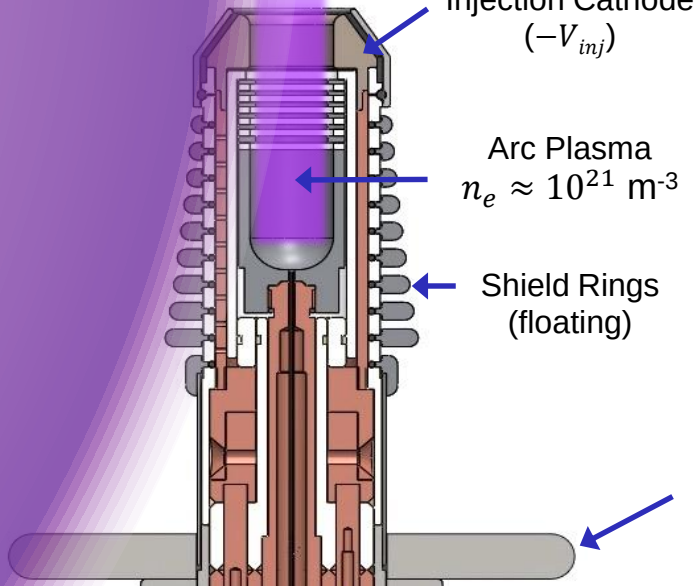
J.D. Weberski, UP11.00098

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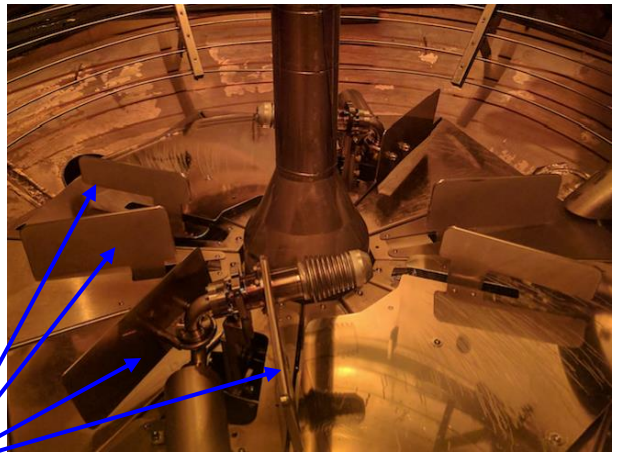
HFS Divertor Injector System Installed to Study HI-Dominant Regime

Tokamak Plasma Edge

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

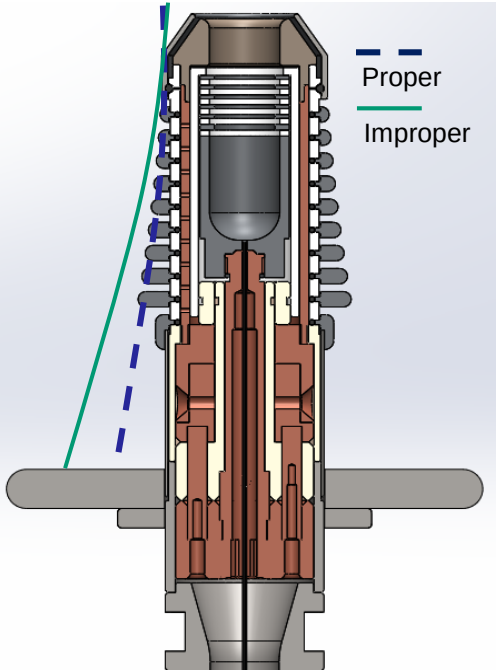


- 2 injectors in lower divertor
- 4× V_{LHI} over LFS injection
- A_{inj} = 8 cm^2; V_{inj} ≤ 1.5 kV; I_{inj} ≤ 8 kA (8–12 MW total power)



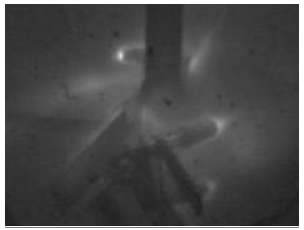
Injector Alignment, Limiters, and Shield Plates Address Plasma-Material Interaction Challenges

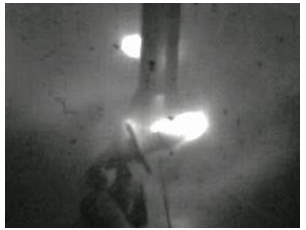
Injector Schematic and Field Line Alignment

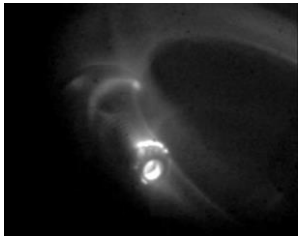


- Proper alignment:
  - Injector shadowed
  - High voltage standoff in tokamak SOL
- Improper limiter placement:
  - Injector immersed in plasma
  - Cathode spots on injector
- Improper alignment to local field:
  - Arc-back to limiter
- Local limiters, shield plates needed to minimize DIV plate interactions

Fast Visible Imaging





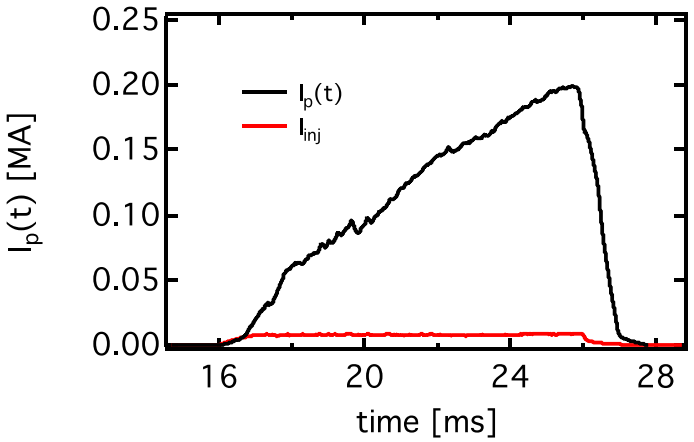


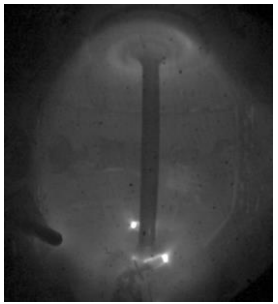
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Target I_p of 0.2 MA Without Solenoidal Induction Achieved

- 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}



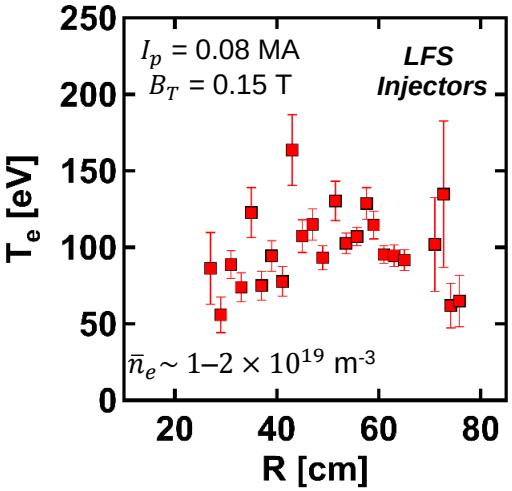


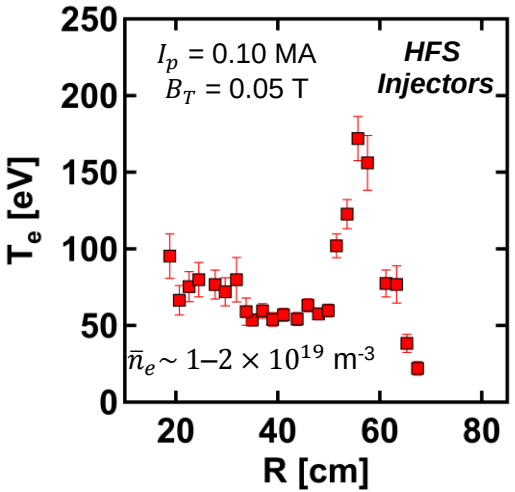
J.M. Perry, JO4.00003

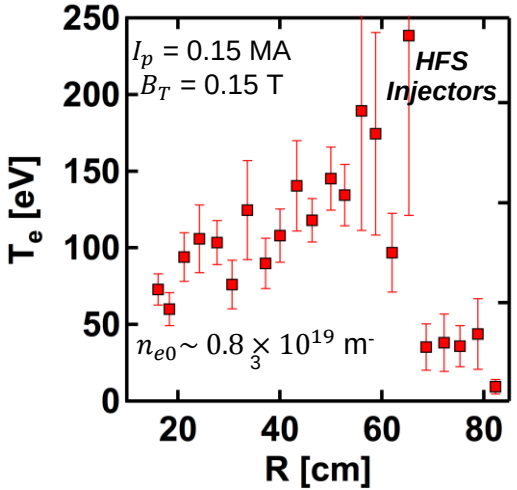
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Thomson Scattering Indicates Range of $T_e(R)$ Realized During LHI

- $T_e(R)$ 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

G.M. Bodner, UP11.00087

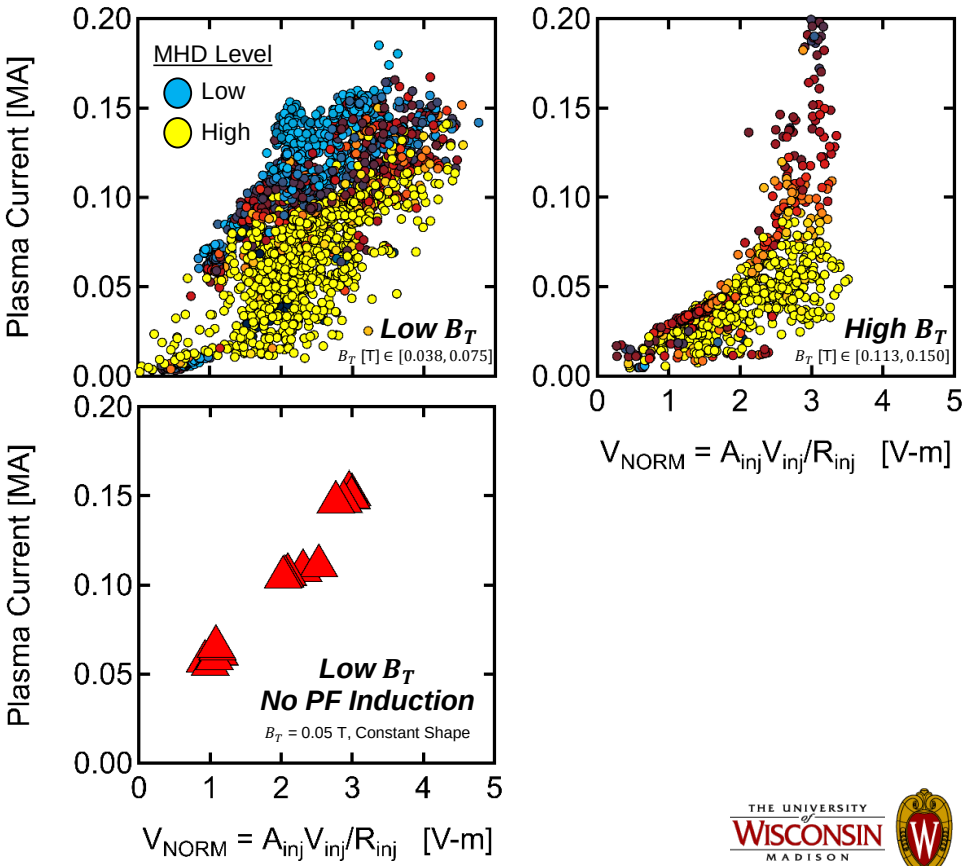
D.J. Schlossberg, Rev. Sci. Instrum. ***87****, 11E403 (2016)*
D.J. Schlossberg, UW-Madison PhD Thesis (2016)

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HFS LHI: Maximum Achieved Current Increases with V_{LHI}

- Understanding how I_p depends on HI rate is critical to predictive capability
- I_p generally increases with V_{LHI}
  - Achieved I_p varies with B_T, MHD levels
  - Fixed geometry V_{LHI} scans suggest linear scaling
- Predictive understanding requires more detailed knowledge
  - *e.g.*, effects of Z_{eff}, f_{GW}, B_T, plasma geometry, …

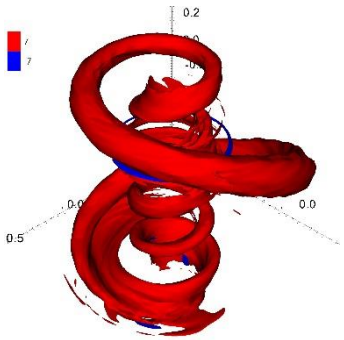
Experimental HFS LHI I_p–V_{NORM} Operating Spaces:

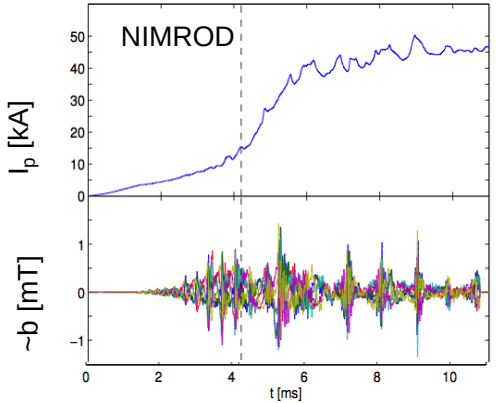


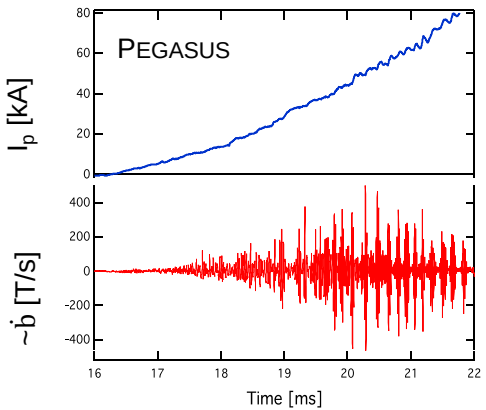
M.W. Bongard, APS-DPP 2017

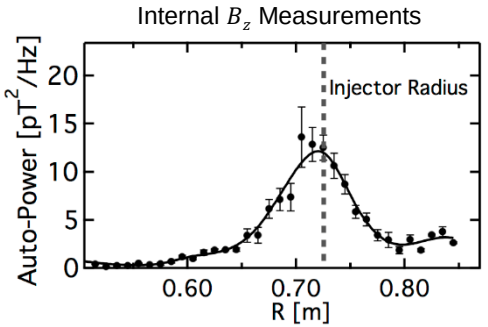
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NIMROD Simulations Indicate Helical Current Stream Reconnection as a Current Drive Mechanism







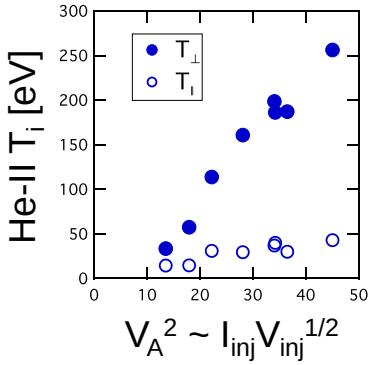


- HFS Simulation: Current stream reconnection produces MHD bursts
- LFS injection: MHD bursts and ion heating support presence of outboard stream reconnection
  - Low frequency: 20–80 kHz, $n = 1$
  - Consistent with line-tied kink instability
- Internal B measurements localize coherent streams in LFS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

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)

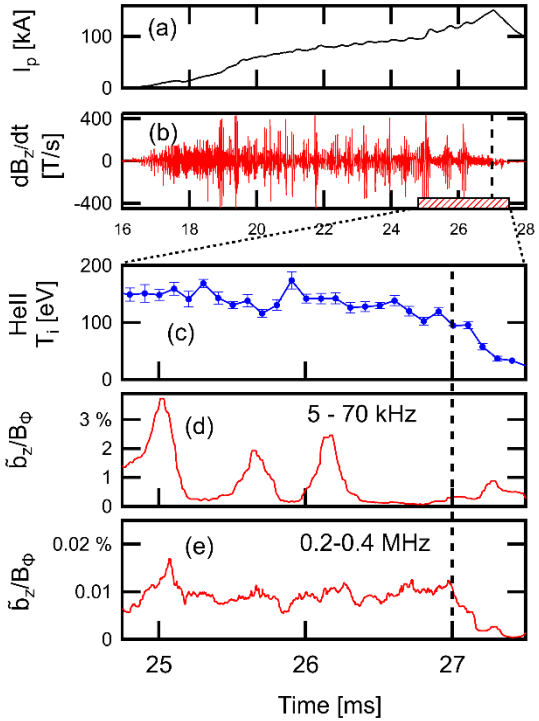
Reconnection-driven Ion Heating Gives $T_i > T_e$ During LHI

- 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

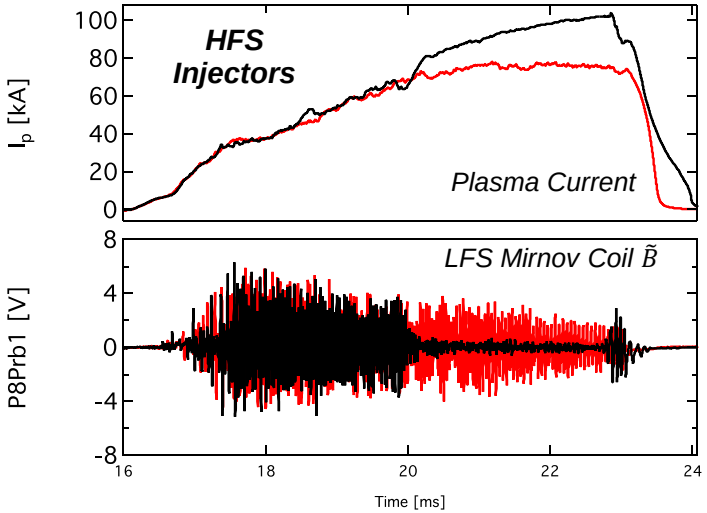
Ion heating correlated with high-f MHD fluctuations, not discrete reconnection between helical streams



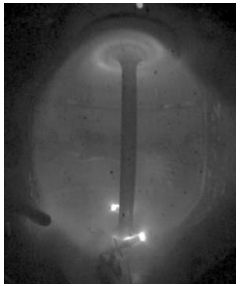
*M.G. Burke, et al. Nucl. Fusion **57** 076010 (2017)*

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
- 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



Fast Imaging During Reduced MHD

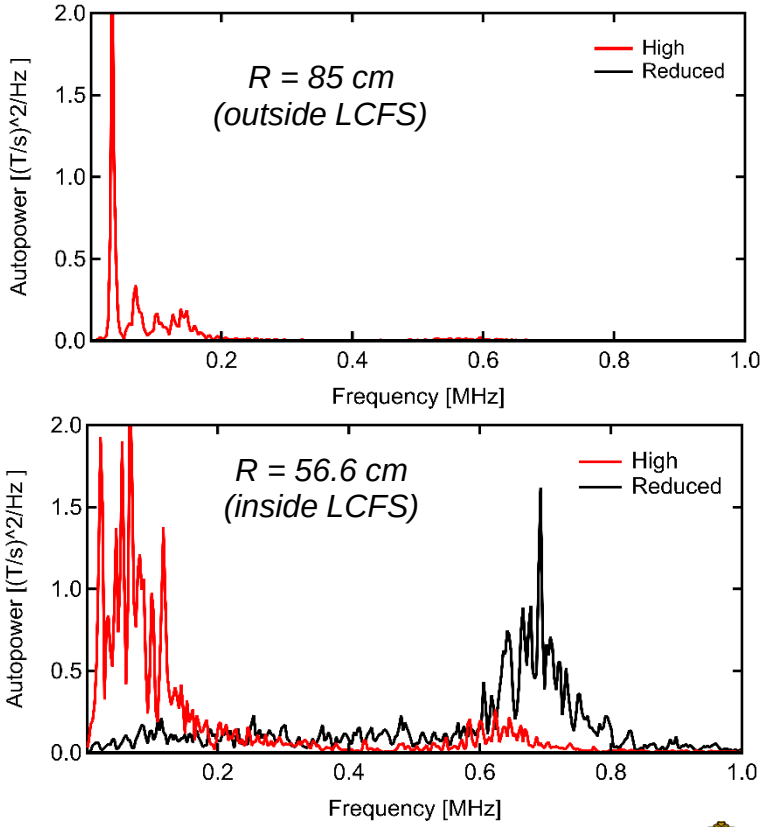


N.J. Richner, UP11.00088
J.L. Pachicano, UP11.00092

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Transition Coincident with Shift of MHD From Low to High Frequency

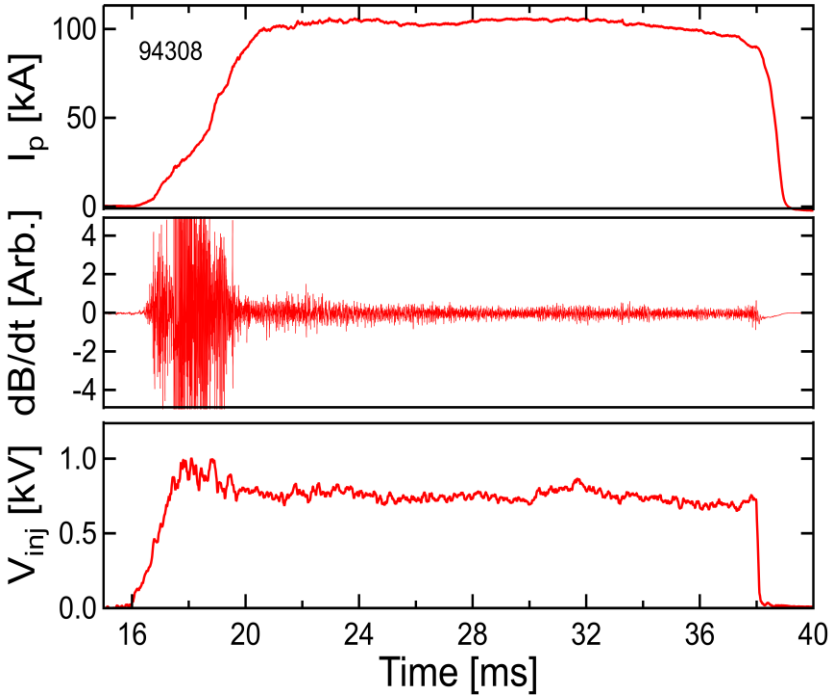
- Reduction in low-frequency activity presently interpreted as stabilization of kinked injector streams
  - Mechanism of stabilization under investigation
- New high-frequency insertable probes deployed
  - First results indicate high-frequency content near plasma edge
  - High-frequency content unobservable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



N.J. Richner, UP11.00088
J.L. Pachicano, UP11.00092

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

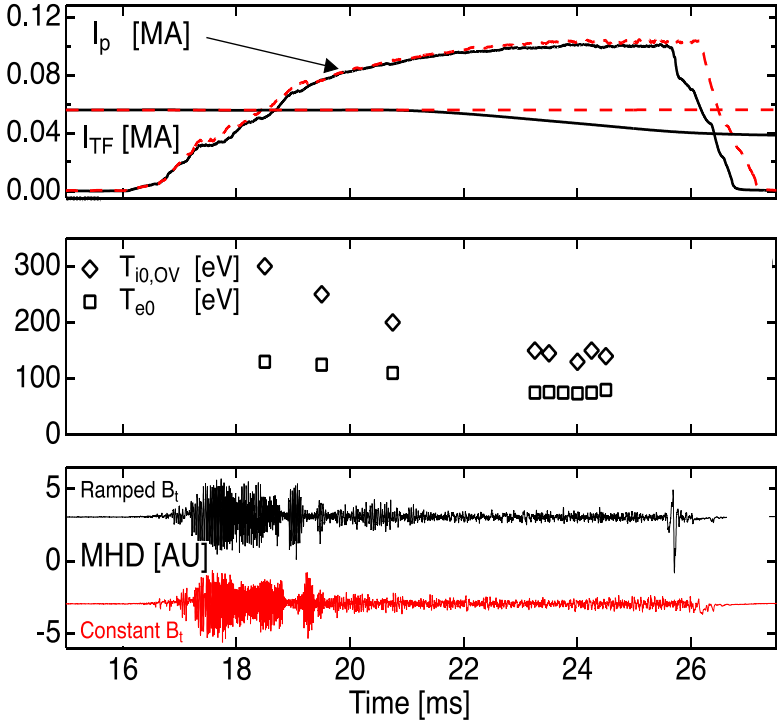
- Current sustained in reduced MHD regime
  - $n = 1$ activity suppressed during I_p flattop
  - Pulse length limited by power supplies
- I_p = 0.1 MA non-inductive scenario
  - Constant shape
  - Zero measured PF induction



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HFS LHI Provides High-β_t, High-I_N 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



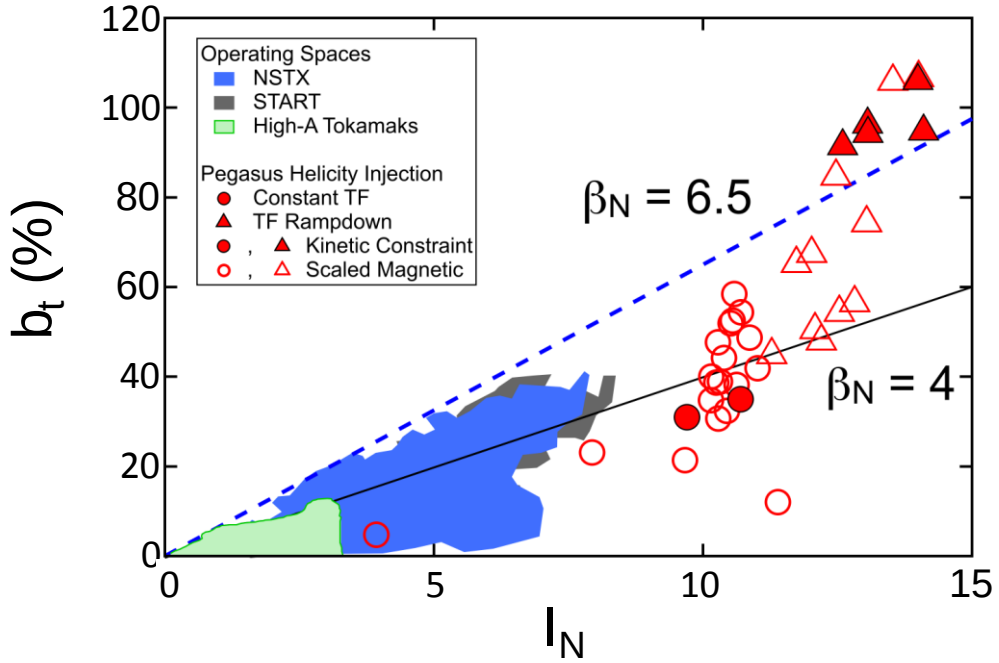
*D.J. Schlossberg et al., PRL **119** 035001 (2017)*

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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



M.W. Bongard, APS-DPP 2017

J.A. Reusch, TI3.00004

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)*

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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

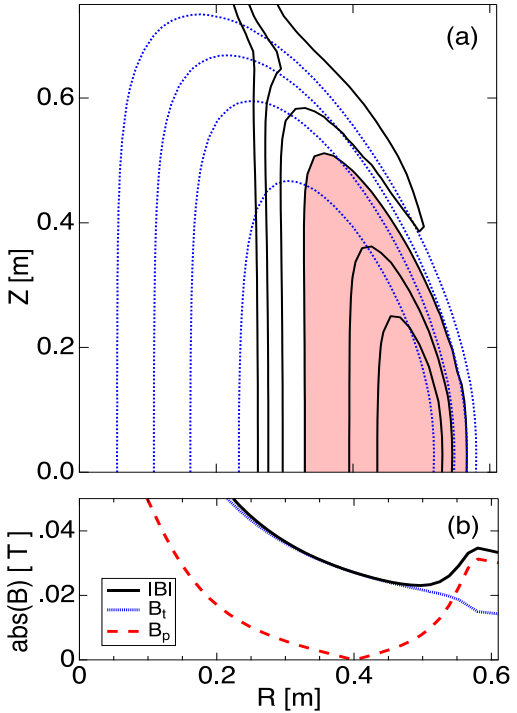
- LHI facilitates near-term access and stability studies

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

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

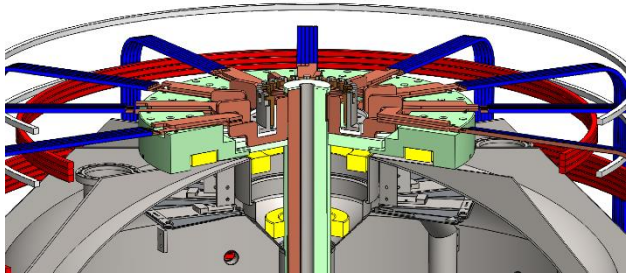
- High-β_t equilibrium contains large minimum $|B|$ region
  - Up to 47% of plasma volume
  - Well deepens and broadens as β_t increases
  - Persists for several energy confinement times
- Minimum $|B|$ regime arises from 3 major influences
  - $B_p \sim B_T$ at $A \sim 1$
  - Hollow $J(R)$
  - Pressure-driven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

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

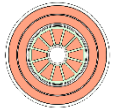


PEGASUS-E Proposed as US Non-Solenoidal Development Station

- 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



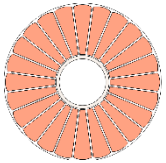
PEGASUS



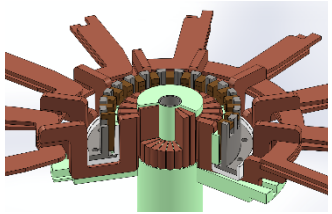
High-Stress OH Solenoid
12-turn TF Bundle



PEGASUS-E



Solenoid-free
24-turn TF Bundle



M.W. Bongard, APS-DPP 2017

R.J. Fonck, JO4.00003
C. Pierren, UP11.00086

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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

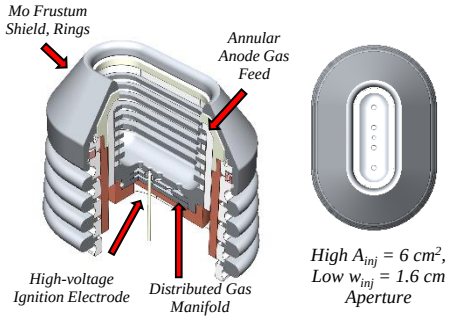
- Facility Enhancements
  - 24-turn TF rod; power system
  - Programmable $V_{eff}(t)$ control
  - PF coils and power systems
    - X-point, shape control
  - DNB spectroscopy
    - $\tilde{B}(R,t), J(R,t), T_i(R,t), n_e(R,t), n_Z(R,t)$
  - Impurity diagnostics
    - SPRED, VB, bolometry

M.W. Bongard, APS-DPP 2017

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

C. Pierren, UP11.00086

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



Refurbished PBX-M DNB



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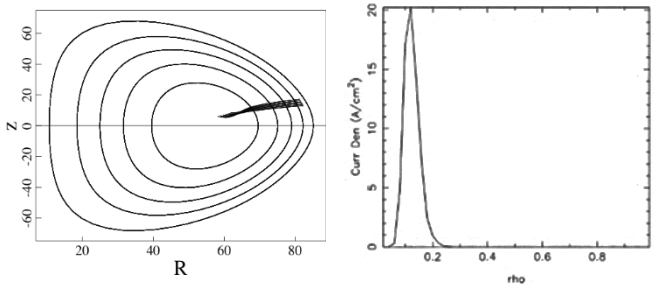
High-B_T of PEGASUS-E Facilitates RF/EBW and CHI Studies

- 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

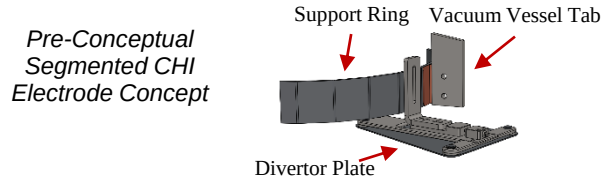
- Deploy “simple” CHI systems
  - Flexible, segmented floating anode and cathode structures
  - Transient and/or Sustained CHI
  - Univ. Washington, PPPL collaboration

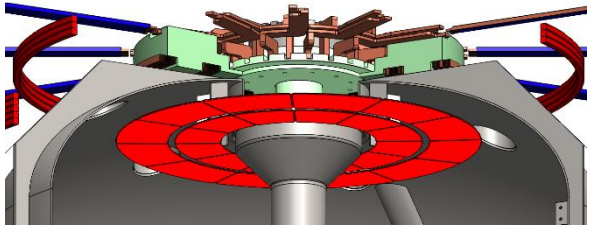
- LHI – CHI – RF Experiments
  - Generate significant closed-flux I_p with CHI
  - Compare T_e, n_e, Z_{eff}, $J(R)$, usable I_p
  - Coupling to consequent CD mechanism

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

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