Overview of the PEGASUS Non-Solenoidal Startup Research Program

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University of
Wisconsin-Madison

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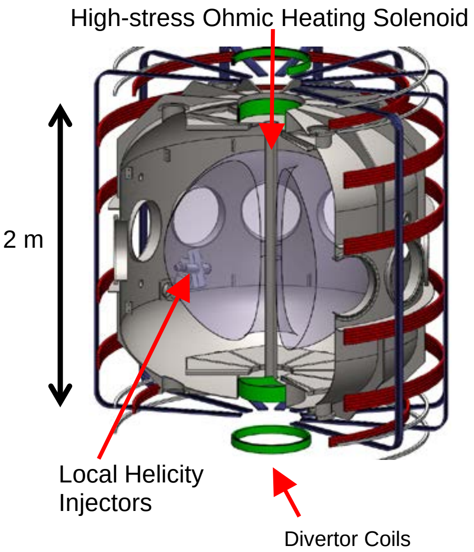
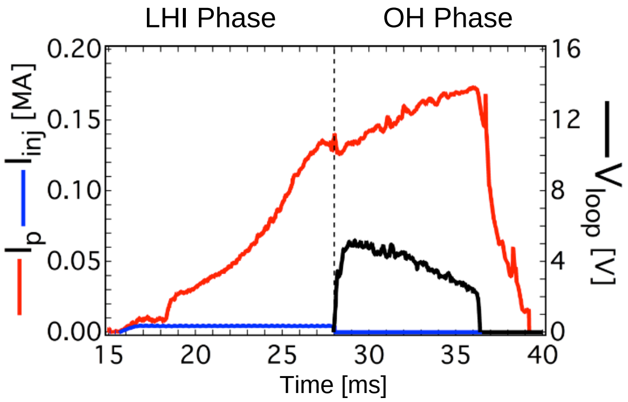
Seoul National University
Seoul, South Korea

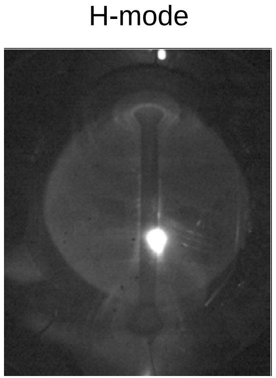
20 September 2017

PEGASUS
Toroidal Experiment

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







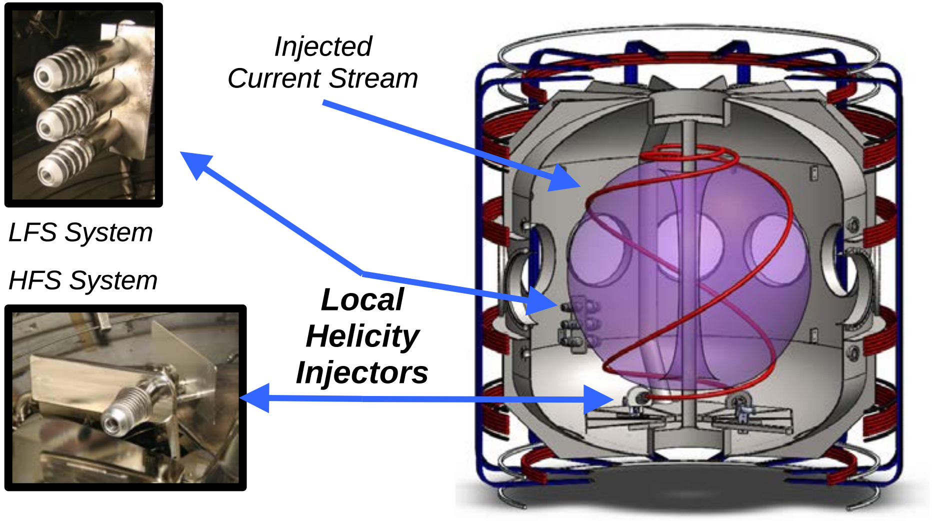
A	1.15 – 1.3
R [m]	0.2 – 0.45
I_p [MA]	$\leq$ 0.25
B_T [T]	< 0.15
Δt_{shot} [s]	$\leq$ 0.025

PEGASUS Program:

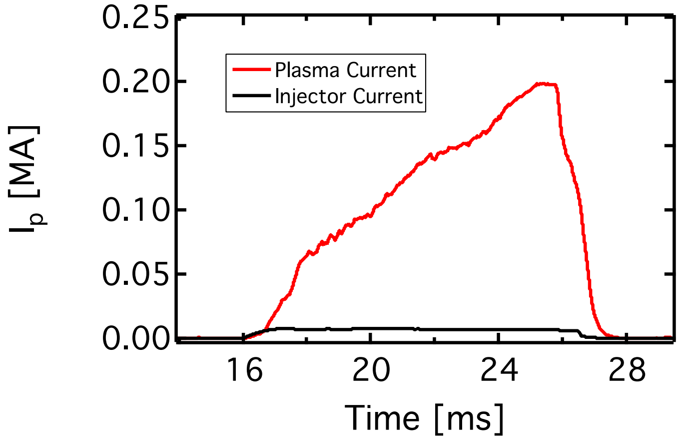
- Local Helicity Injection (LHI) for Non-Solenoidal ST Startup
- H-mode Physics at Ultralow-A *(recently concluded)**
- Access to high I_N > 10 and High β_t
- Proposed Facility Enhancements and New Program Directions

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

Local Helicity Injection is a Promising Non-Solenoidal Startup Technique



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

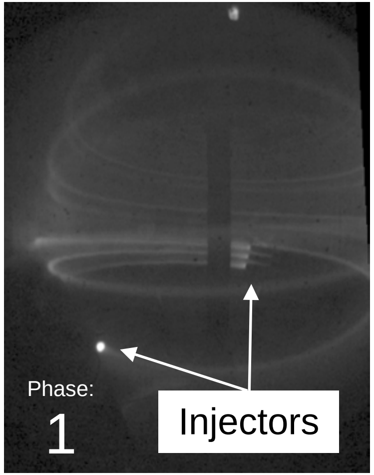


- Edge current extracted from injectors
- Relaxation to tokamak-like state via helicity-conserving instabilities
- Used routinely for startup on PEGASUS

- Current drive quantified by

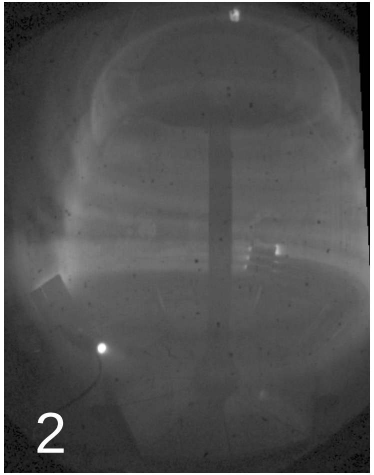
$$\boxed{V_{LHI} \approx \frac{A_{inj} B_{T,inj}}{\Psi} V_{inj}}$$

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



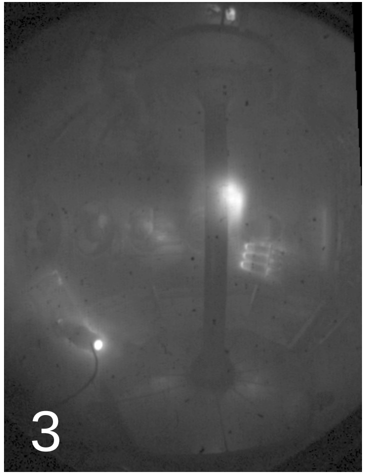
Local source:

Helical plasma streams



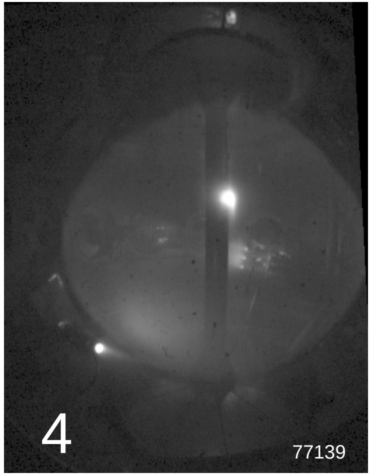
Instability:

Current driven along streams



Reconnection:

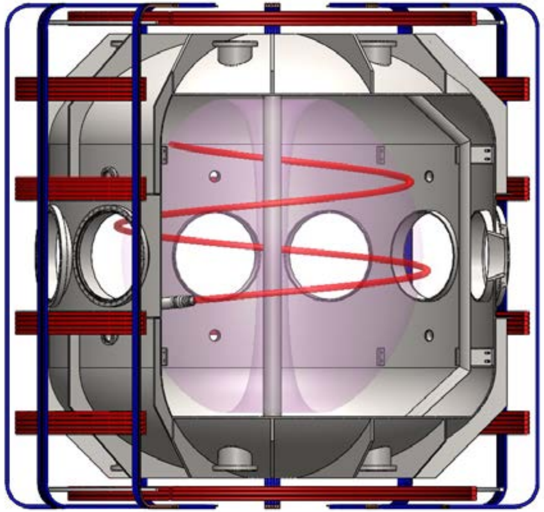
Relaxation to tokamak-like state, current growth

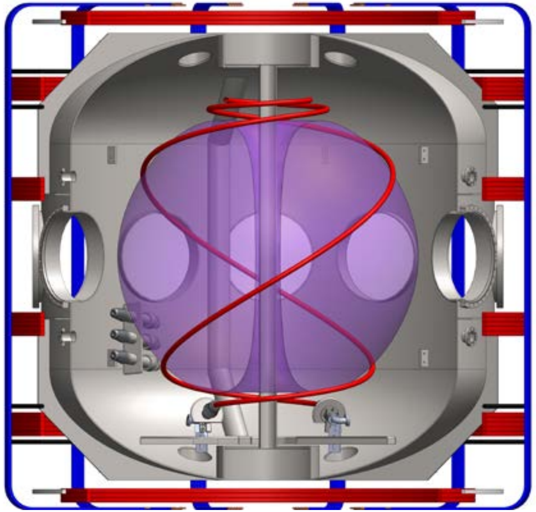


Bias shutdown:

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:

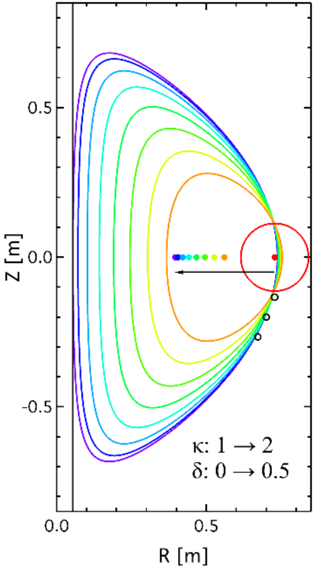
$$\boxed{I_p\left[V_{LHI} + V_{IR} + V_{IND}\right] = 0}$$

- Confinement behavior may be affected by dominant current drive type

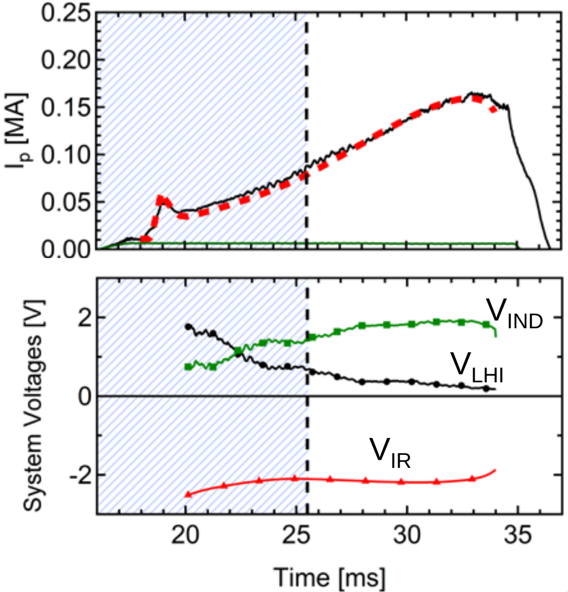
- LFS injection maximizes inductive drive, V_{IND}

- Radial compression ➞ large V_{IND}

Shape Evolution



- Net induction voltage dominates current drive



M.W. Bongard, ISTW 2017

J.L. Barr, UW-Madison PhD Thesis (2016)

In Contrast, HFS Injection Dominated by Helicity Drive

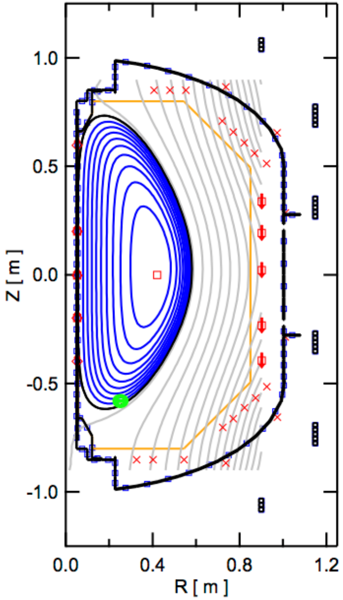
- Low R_{inj} ➞ high V_{LHI}

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

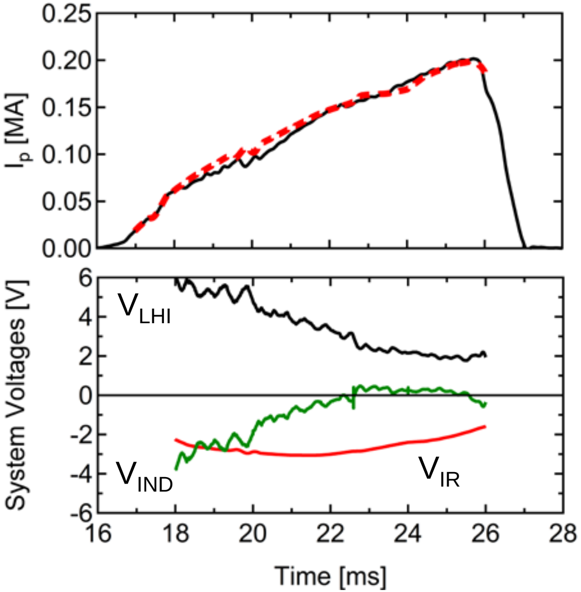
- HFS injection minimizes V_{IND}

- Fully HI-driven system may have different transport properties

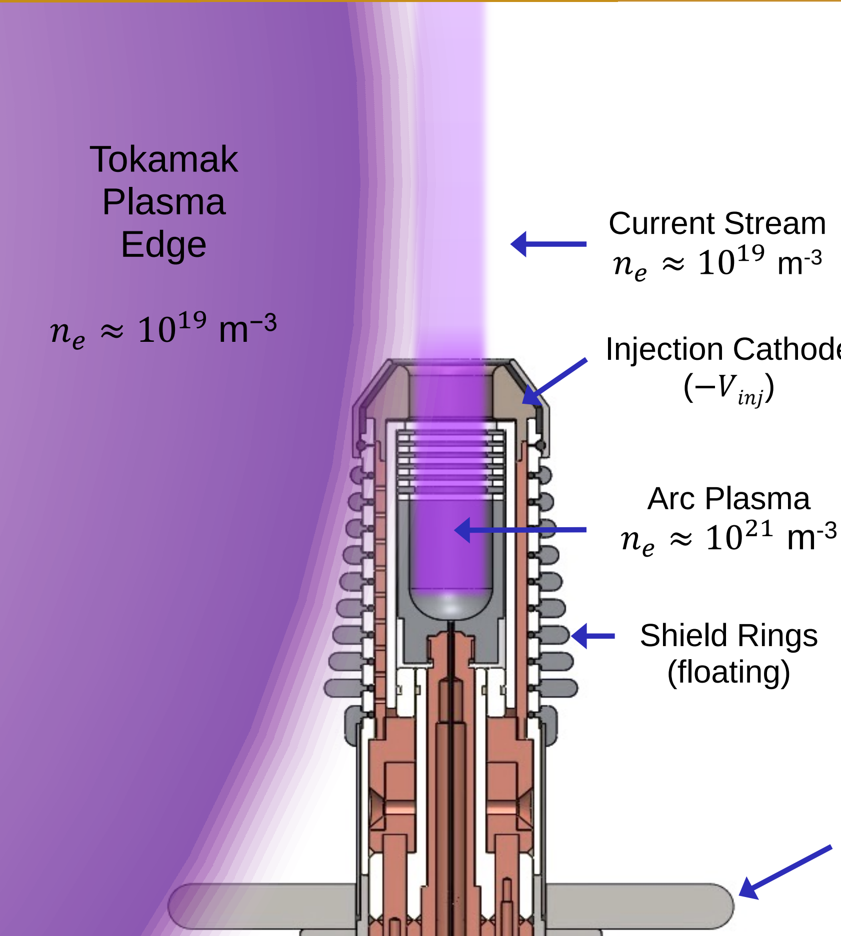
- Static plasma shape ➞ low V_{IND}



- HI dominates current drive



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



Tokamak Plasma Edge

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

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

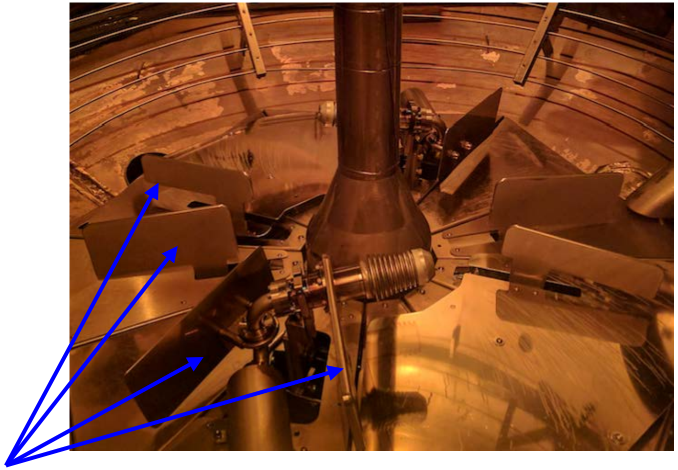
Injection Cathode
$(-V_{inj})$

Arc Plasma
$n_e \approx 10^{21}$ m^{-3}

Shield Rings
(floating)

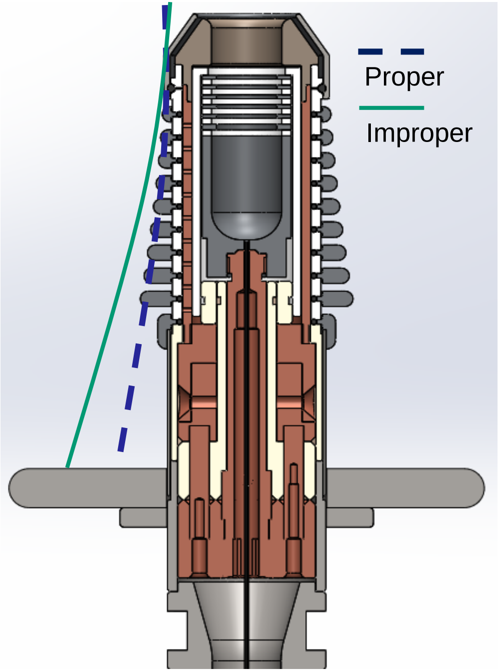
Local Plasma Limiters (ground)

- 2 injectors in lower divertor
- 4× 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 Field Line Alignment

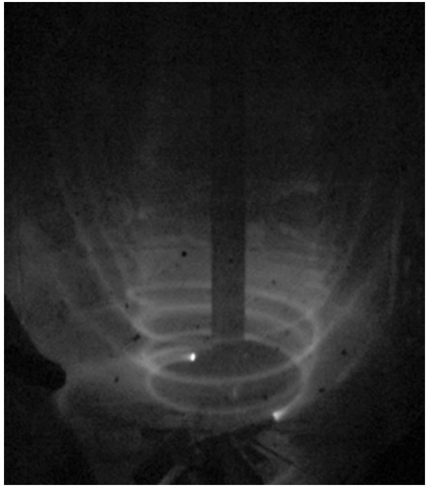


- Proper alignment:
  - Injector shadowed
  - High voltage standoff in tokamak SOL
- Improper limiter placement:
  - Injector immersed in plasma
  - Cathode spots on injector
- Improper alignment to local field:
  - Arc-back to limiter
- Local limiters, shield plates needed to minimize DIV plate interactions

Fast Visible Imaging

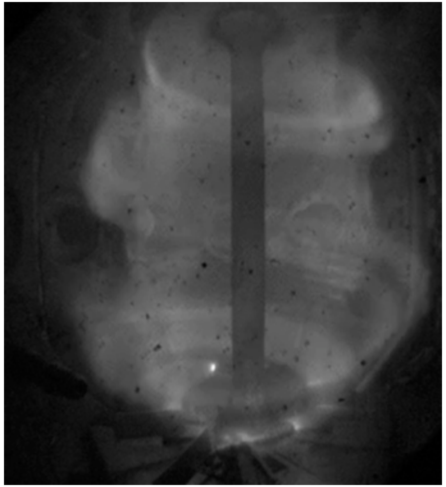
Relaxation Challenges with HFS Injection Addressed

Injected current weakens vacuum B_Z



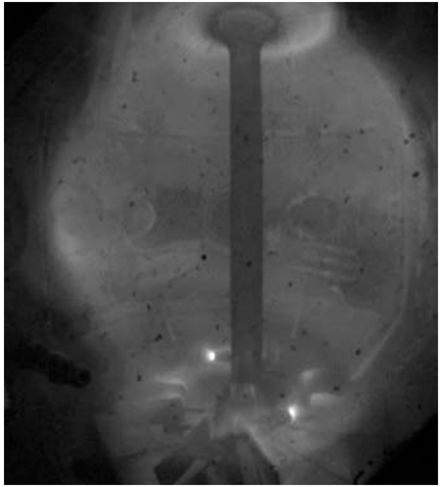
$I_p \sim N_{turns} I_{inj}$

Unstable current streams attract, reconnect



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

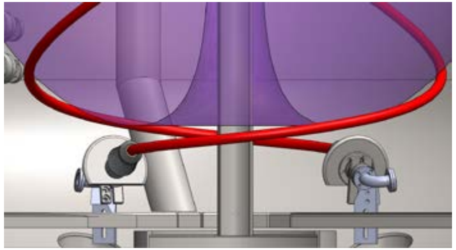
Tokamak-like plasma; rapid I_p growth



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

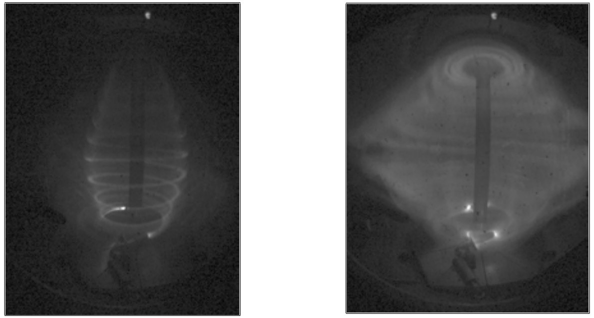
Initial Relaxation to Tokamak State Requires Strong Deformation of Vacuum Field

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

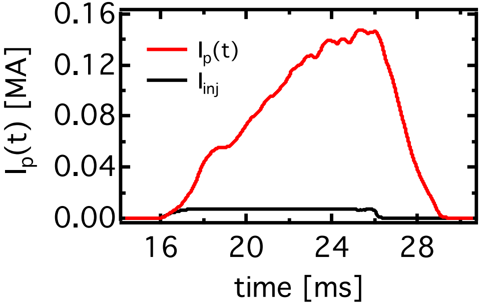


- HFS injection:
  - Lower $R_{inj} \rightarrow$ more B_Z for clearance
  - Relaxation impeded for fixed B_T, I_{inj}
- Solution: poloidal field shaping
  - B_Z strong in divertor; weak at midplane
  - Increased I_{inj} required at increased B_T

Deformed B_{vac} Aids Relaxation



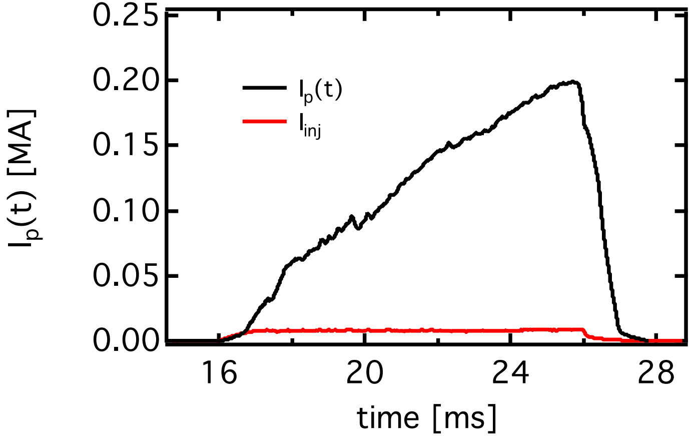
- Relaxation achieved at full Pegasus B_T

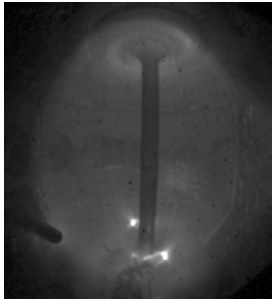


Target I_p of 0.2 MA Without Solenoidal Induction Achieved

- 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}





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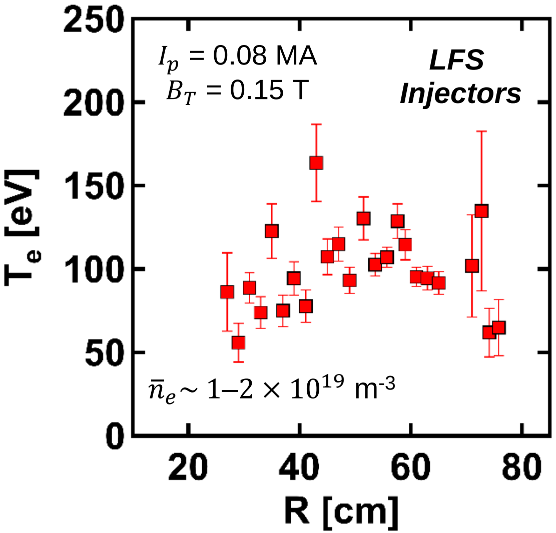
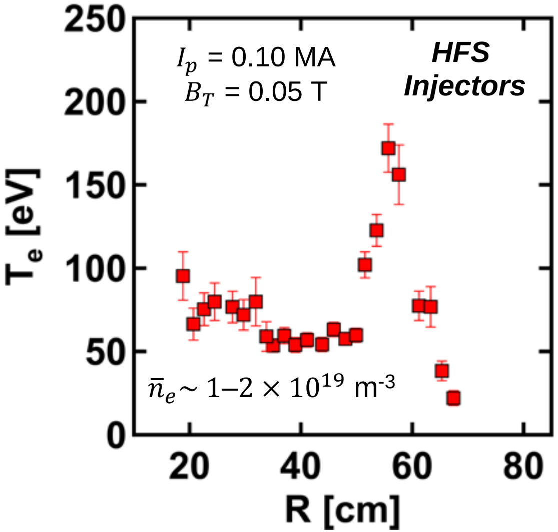
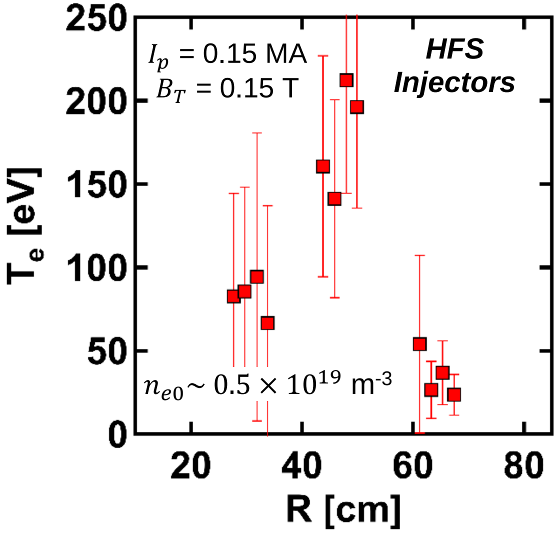
Thomson Scattering Indicates Range of $T_e(R)$ Realized During LHI

- $T_e(R)$ 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

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

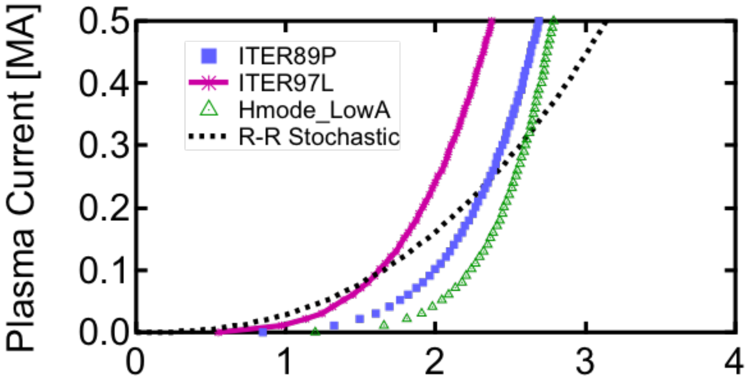
Projecting Forward: Dissipation of Helicity is a Main Issue

- 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

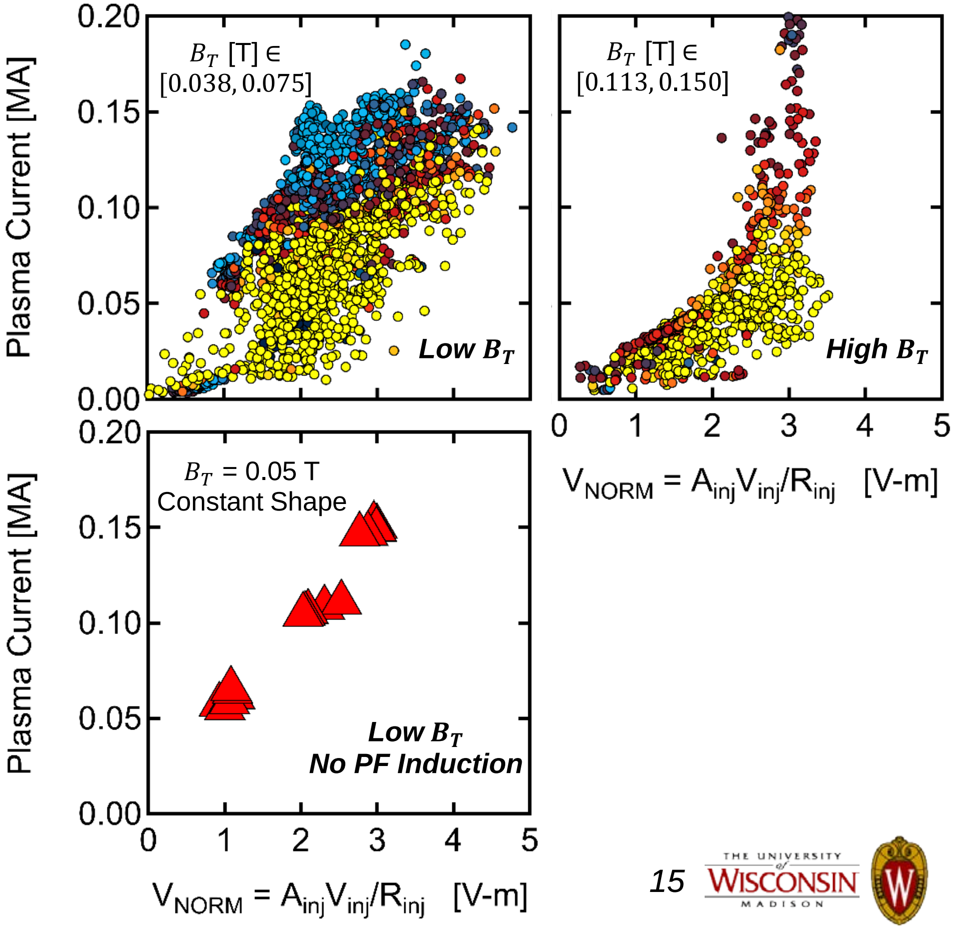
Confinement Scaling Estimates



Geometrically Normalized HI Rate
~ $A_{inj}\, V_{inj}/R_{inj}$ [V-m]

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

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

Helicity Conservation

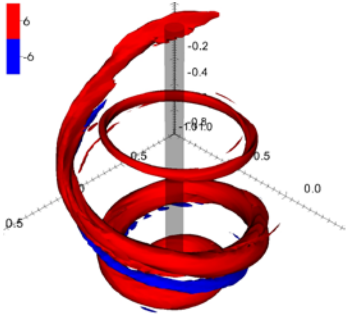
$$\boxed{V_{LHI} \approx \frac{A_{inj} B_{T,inj}}{\Psi} V_{inj}}$$

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

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

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

Reconnecting LHI Current Stream

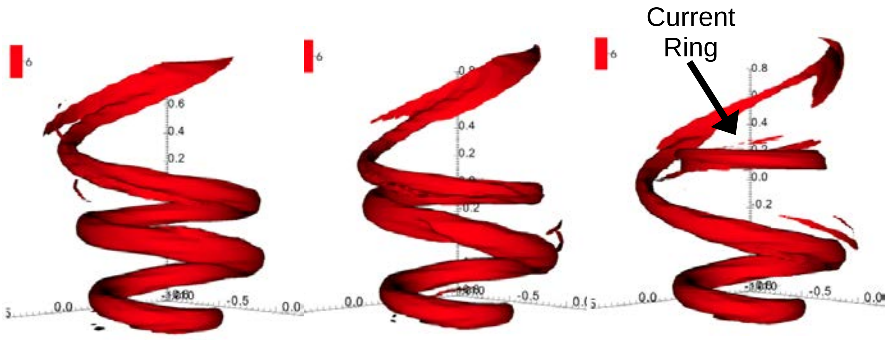


*D.J. Battaglia, et al. Nucl. Fusion **51** 073029 (2011)*
N.W. Eidietis, Ph.D. Thesis, UW-Madison (2007)
J. O'Bryan, Ph.D. Thesis, UW-Madison (2014)
*J. O'Bryan, C.R. Sovinec, Plasma Phys. Control. Fusion **56** 064005 (2014)*

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

NIMROD: Early Relaxation Phase in Divertor LHI Geometry

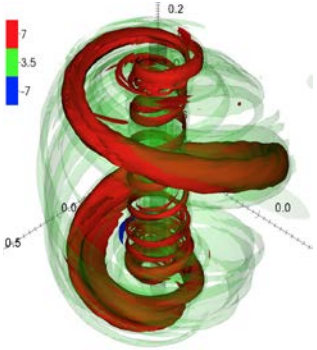
Early Formation Phase



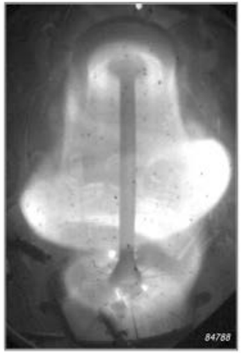
1. Streams follow field lines

2. Adjacent passages attract

3. Reconnection forms current rings



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

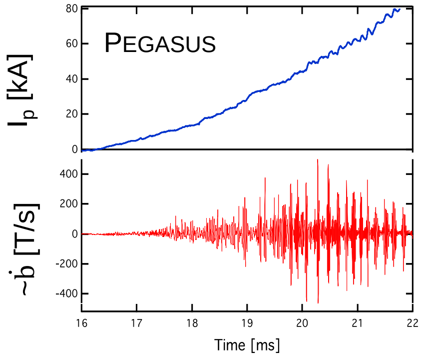
O'Bryan et al., Phys. Plasmas **19** *080701 (2012)*
O'Bryan and Sovinec, Plasma Phys. Control. Fusion **56** *064005 (2014)*

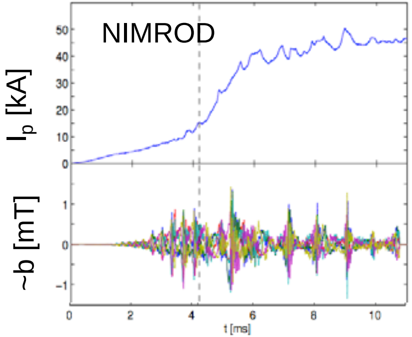
Current Stream Interaction Manifests as Edge-Localized MHD Burst

- 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

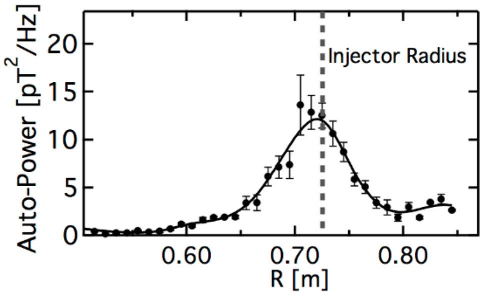
- Internal magnetic measurements localize coherent streams in LFS edge

- Suggests any stochastic reconnection region may be localized to edge

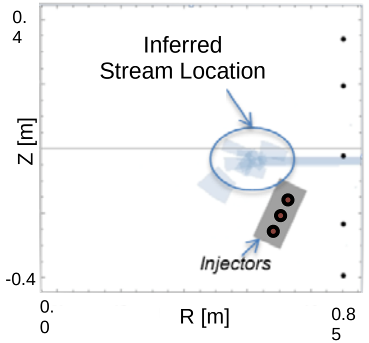




Internal B_z Measurements



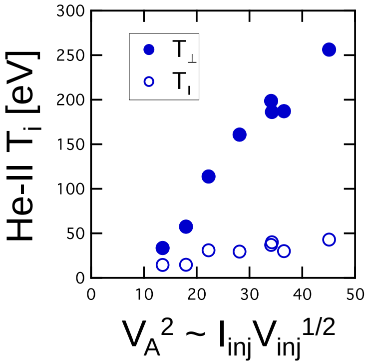
External B_z Phase Correlation



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)

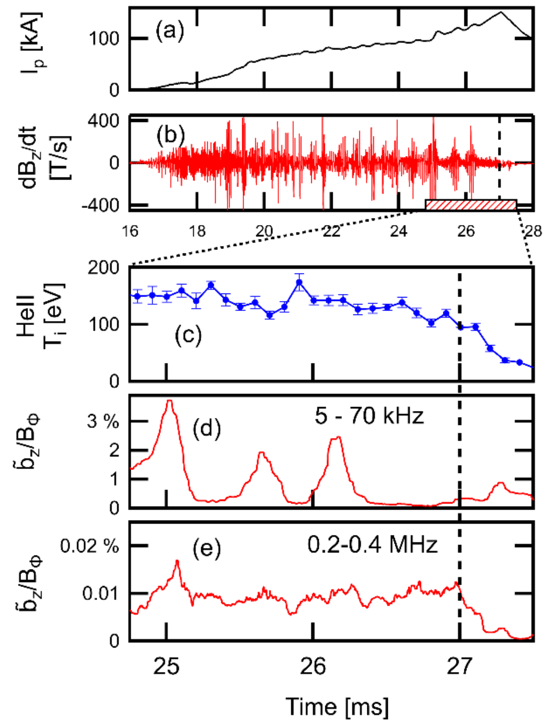
Reconnection-driven Ion Heating Gives $T_i > T_e$ During LHI

- 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

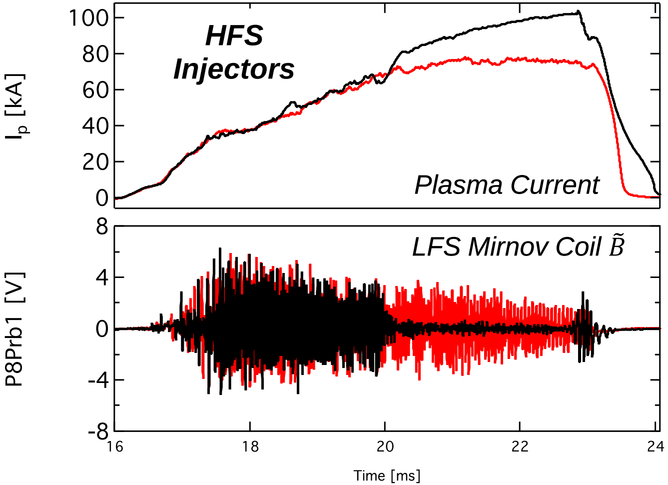
Ion heating correlated with high-f MHD fluctuations, not discrete reconnection between helical streams



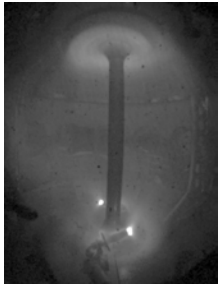
M.G. Burke, et al. Nucl. Fusion **57** *076010 (2017)*

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

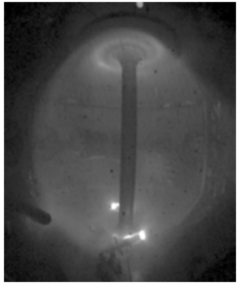
- HFS injection: initially similar to LFS
  - Large scale $n = 1$ at 20–80 kHz
  - Consistent with line-tied kink
- Abrupt MHD transition can occur:
  - Low-f $n = 1$ activity reduced by over 10×
  - Extremely sensitive to B_T, B_Z, I_p, fueling
- Bifurcation in I_p evolution following transition
  - 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



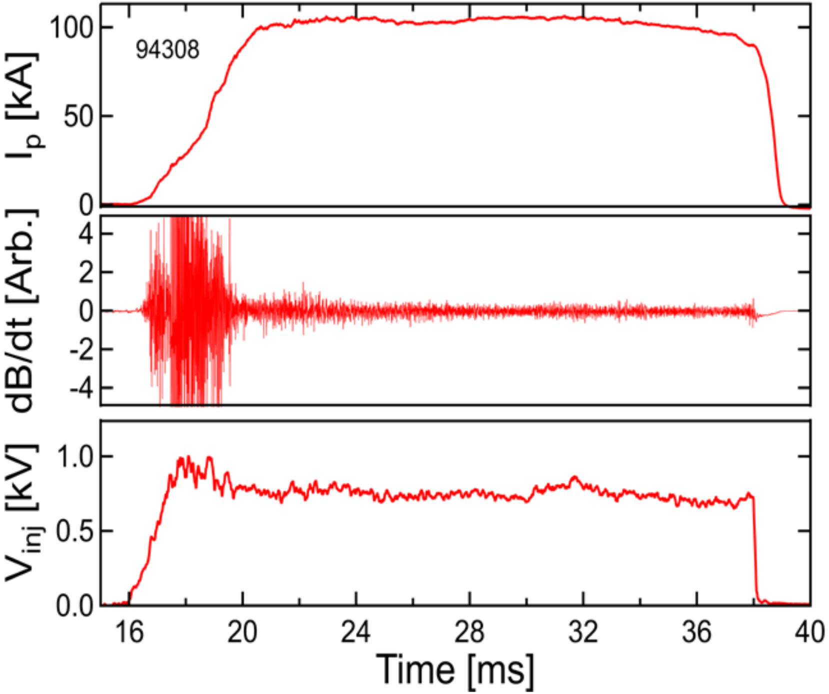
Reduced MHD



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

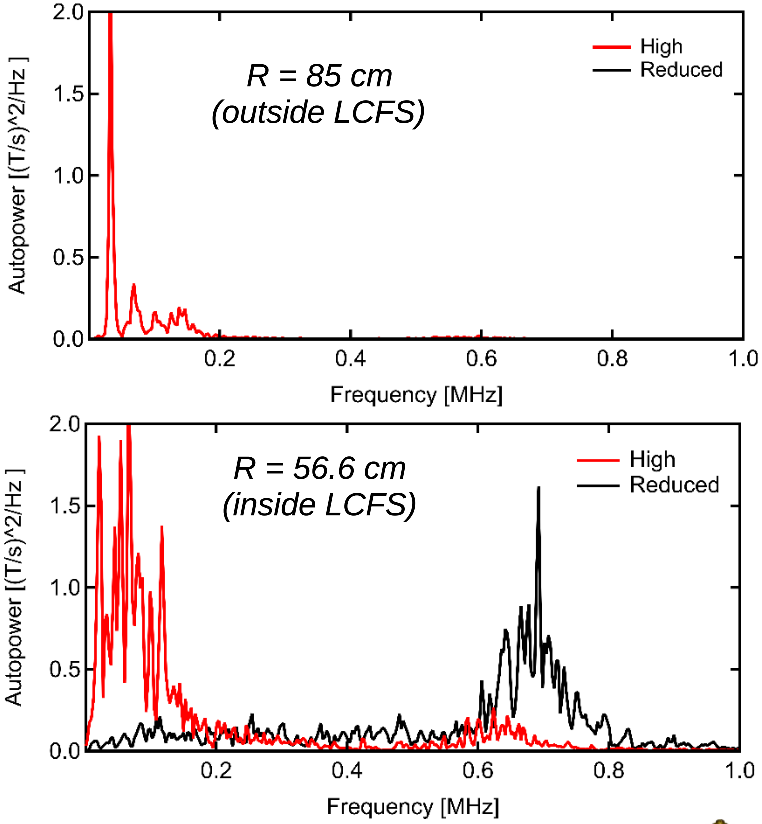
- Current sustained in reduced MHD regime
  - $n = 1$ activity suppressed during I_p flattop
  - Pulse length limited by power supplies

- I_p = 0.1 MA non-inductive scenario
  - Constant shape
  - Zero measured PF induction



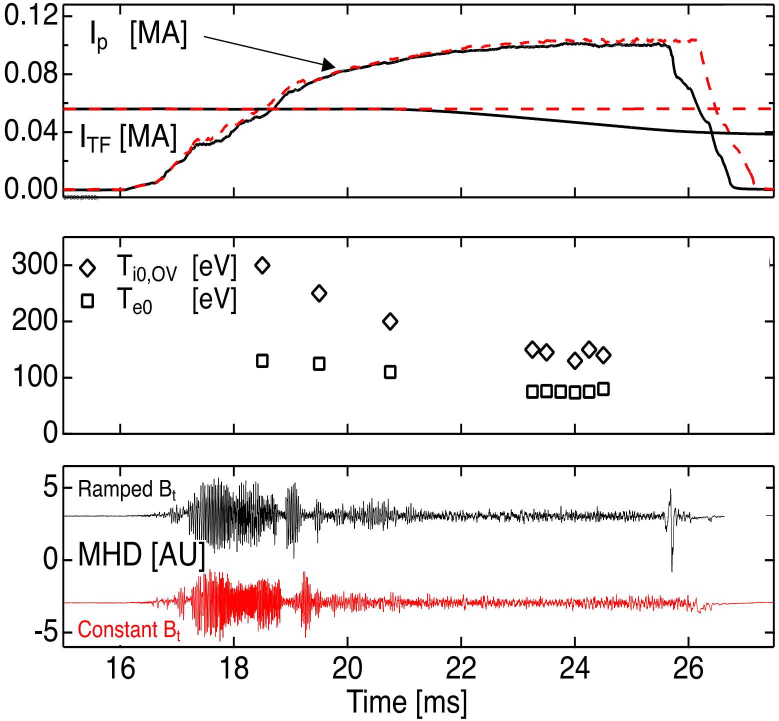
Transition Coincident with Shift of MHD From Low to High Frequency

- 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

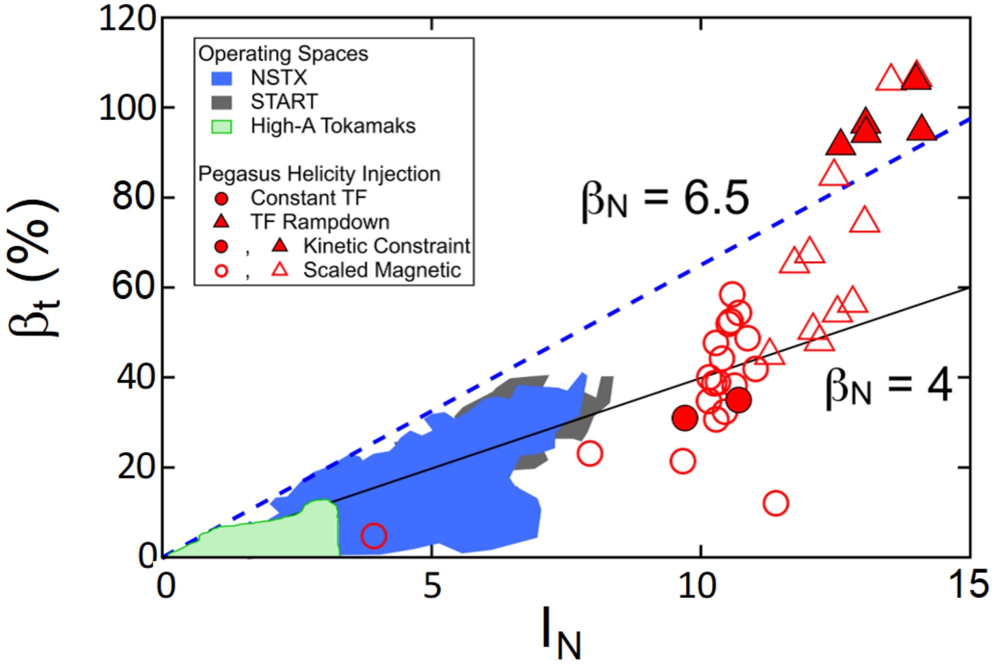


D.J. Schlossberg et al., PRL **119** 035001 (2017)

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)*

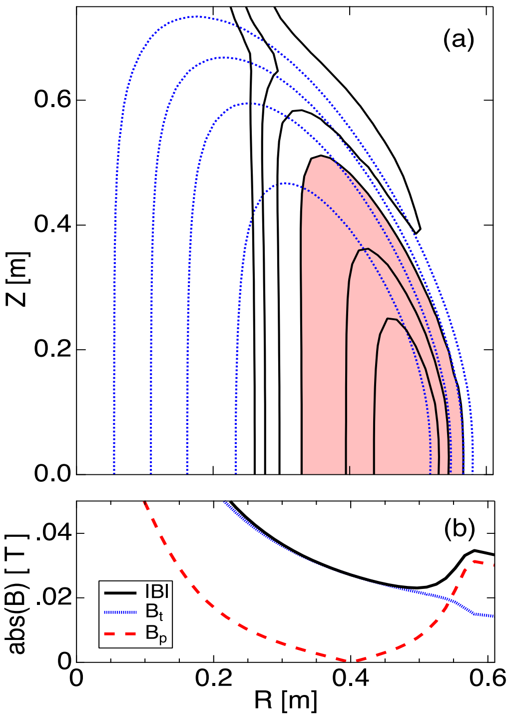
Unique Feature of High-β_t LHI Plasmas: Sustained min $|B|$ Region

- 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

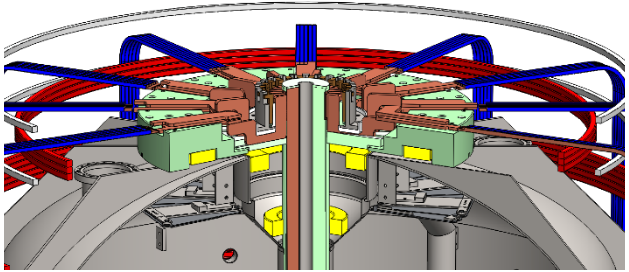
High-β_t equilibrium flux surfaces (blue), $|B|$ (black), and min-$|B|$ region (red)

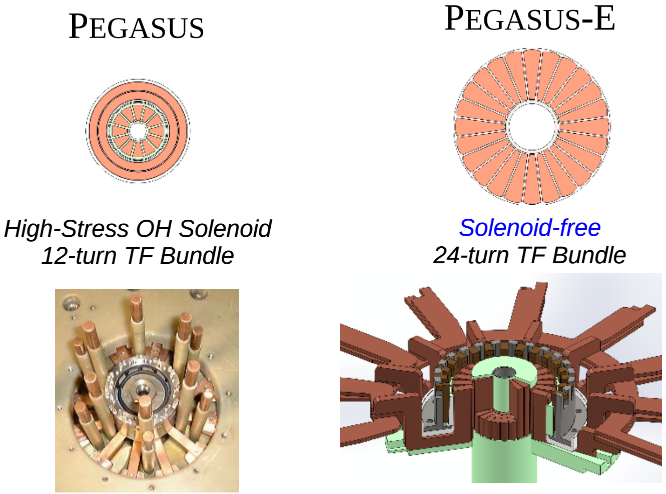


D.J. Schlossberg et al., *Phys. Rev. Lett.* **119** 035001 (2017)

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





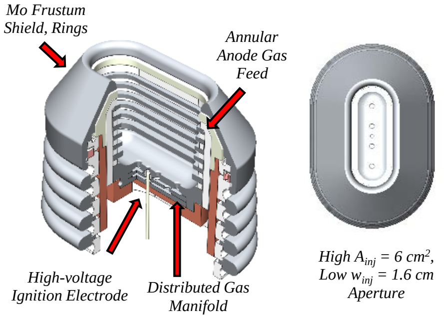
LHI Research Activities on PEGASUS-E Will Test Scaling to High B_T

- 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]	± 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 $R_0 \sim 0.4$ 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

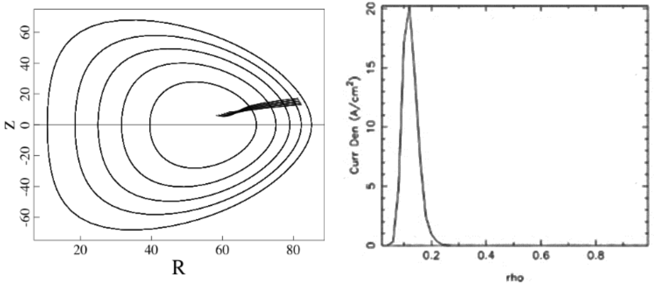


Refurbished PBX-M DNB

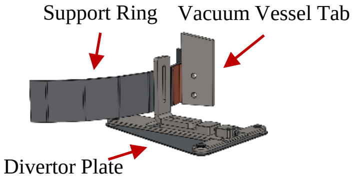
High-B_T of PEGASUS-E Facilitates RF/EBW and CHI Studies

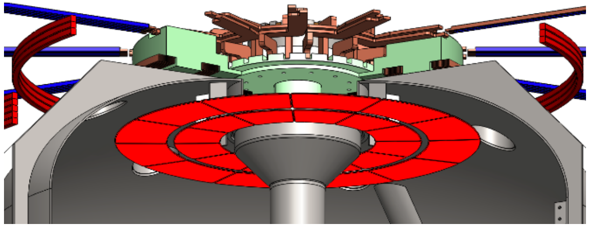
- EBW heating and CD; synergy with HI startup
  - T_e increase for compatibility with non-inductive sustainment (e.g. NBCD)
  - Potential for direct RF startup
  - Initial concept: ~ 400 kW EBW RF, 9 GHz (TBD)
  - ORNL collaboration
- Deploy “simple” CHI systems
  - Flexible, segmented floating anode 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

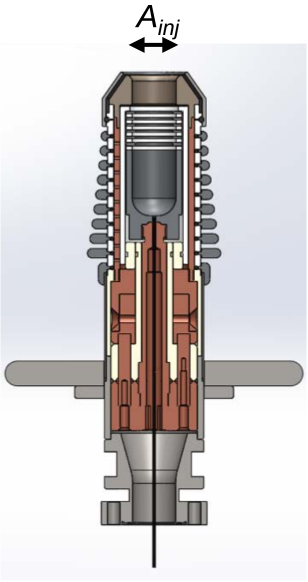
- LHI and $A \sim 1$ enable access to high-I_N, high-β_t regime
  - Stability tests at extreme toroidicity

- 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

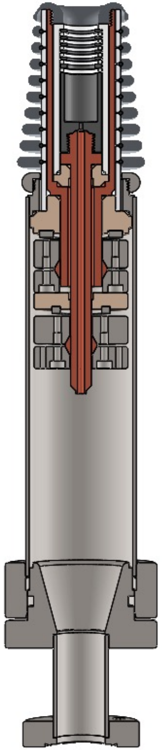
BACKUPS

Large-A Injector Design Provides Enhanced Performance, Simplified Geometry

- New large-area injectors:
  - Doubled A_{inj}: 2 $\mathrm{cm}^2 \rightarrow 4\ \mathrm{cm}^2$
  - 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

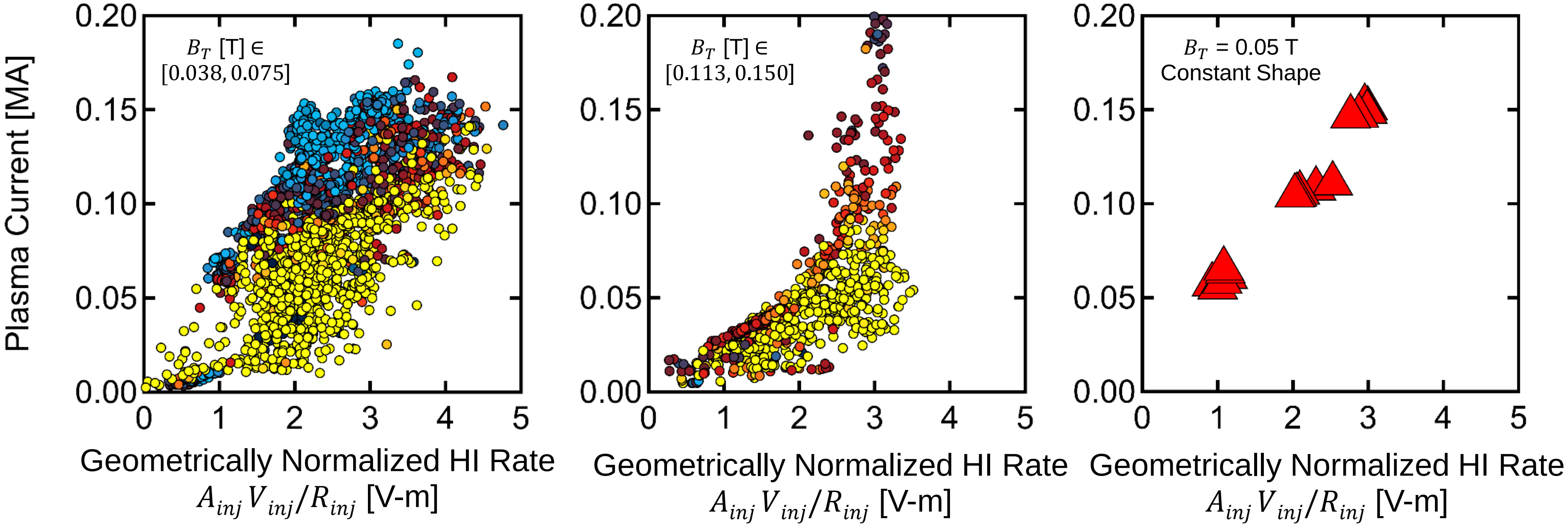


New: 4 cm^2



Old: 2 cm^2

Experimental HFS LHI I_p–V_{LHI} Operating Spaces

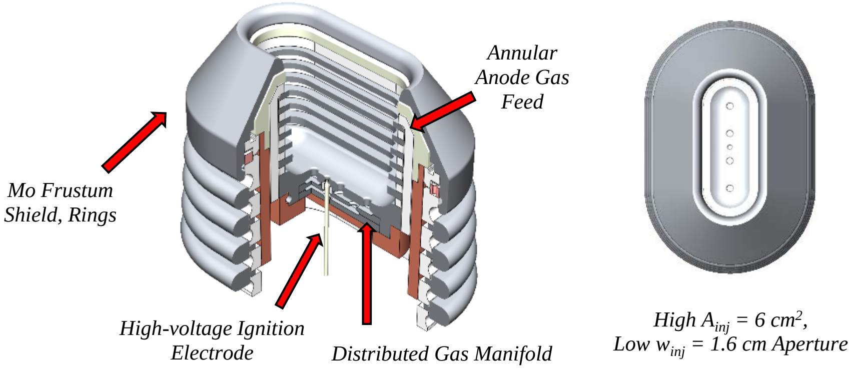


Presently Funded Near-Term LHI Research Activities

- **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

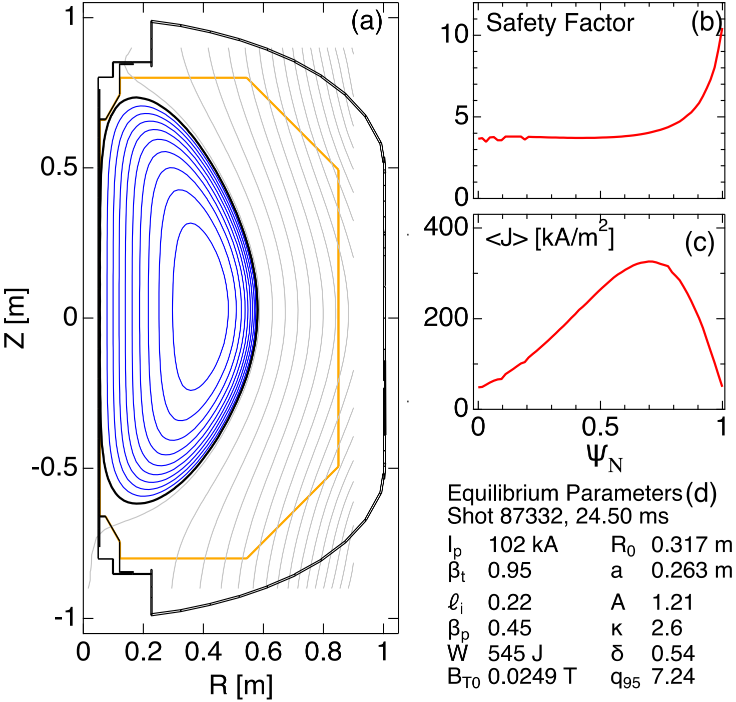
Non-Circular, High-A_{inj} Helicity Injector Renderings



Partial-kinetic Equilibrium Reconstructions of High-β_t Plasmas

- Edge location and core pressure constrained by TS profiles

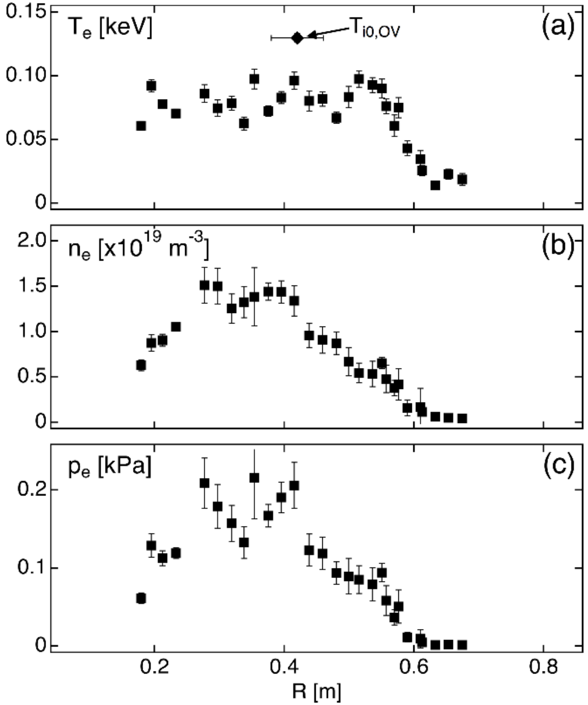
B_T Rampdown Equilibrium



Equilibrium Parameters (d)
Shot 87332, 24.50 ms

I_p	102 kA	R_0	0.317 m
β_t	0.95	a	0.263 m
ℓ_i	0.22	A	1.21
β_p	0.45	κ	2.6
W	545 J	δ	0.54
B_{T0}	0.0249 T	q_{95}	7.24

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



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

Analytic Formulation of Power Balance Model Elements Allow Partitioning of Energy Flow

$$I_p\left[\underbrace{V_{PF}+V_{geo}-V_{W_m}}_{V_{IND}}-V_{IR}+V_{LHI}\right]=0$$

- Recent Improvements
  - Revised L_p, B_Z models*
  - Moving plasma boundary
  - Neoclassical resistivity

Inductive Drive from Poloidal Fields

$$V_{PF}=-\sum_{coils}\frac{d}{dt}\left[\psi_{PF}\right]\approx-\frac{\partial}{\partial t}\left[M_V\,\pi R_0^2\,B_V\big|_{R_0}\right]$$

$$B_V=-\frac{\mu_0 I_p}{4\pi R_0}\left\{\frac{1}{\mu_0}\frac{\partial L_e}{\partial R}+\frac{\ell_i}{2}+\beta_p-\frac{1}{2}\right\}$$

$$M_V(\varepsilon,\kappa)=\frac{(1-\varepsilon)^2}{(1-\varepsilon)^2c(\varepsilon)+d(\varepsilon)\sqrt{\kappa}}$$

$$c(\varepsilon)=1+0.98\varepsilon^2+0.49\varepsilon^4+1.47\varepsilon^6$$

$$d(\varepsilon)=0.25\varepsilon\left(1+0.84\varepsilon-1.44\varepsilon^2\right)$$

LHI Drive

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

Resistive Dissipation

$$V_{IR}=I_pR_p=I_p\left(\frac{\langle\eta\rangle 2\pi R_0}{A_p}\right)$$

Inductive Drive from Shape(t)

$$V_{geo}=-\frac{d}{dt}\left[L_eI_p\right]=-L_e\frac{dI_p}{dt}-I_p\frac{dL_e}{dt}$$

$$L_e=\mu_0R_0\frac{a(\varepsilon)(1-\varepsilon)}{1-\varepsilon+\kappa b(\varepsilon)}$$

$$a(\varepsilon)=\left(1+1.81\sqrt{\varepsilon}+2.05\varepsilon\right)\ln\left(\frac{8}{\varepsilon}\right)-\left(2.0+9.25\sqrt{\varepsilon}+1.21\varepsilon\right)$$

$$b(\varepsilon)=0.73\sqrt{\varepsilon}\left(1+2\varepsilon^4-6\varepsilon^5+3.7\varepsilon^6\right)$$

Plasma Magnetic Energy Change

$$V_{W_m}\approx-\frac{1}{I_p}\frac{d}{dt}\left(\frac{1}{2}L_iI_p^2\right)$$

$$\ell_i=\frac{C_p^2}{\mu_0V_p}L_i$$

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* *S.P. Hirshman and G.H. Nielson 1986 Phys. Fluids* ***29*** *790*

O. Mitarai and Y. Takase 2003 *Fusion Sci. Technol.*

S. Ejima et al 1982 Nucl. Fusion ***22*** *1313*

J.A. Romero and JET-EFDA Contributors 2010 Nucl. Fusion ***50*** *115002*

Equilibrium-Calibrated Inductance Model Improves Estimates of Non-Solenoidal V_{IND}

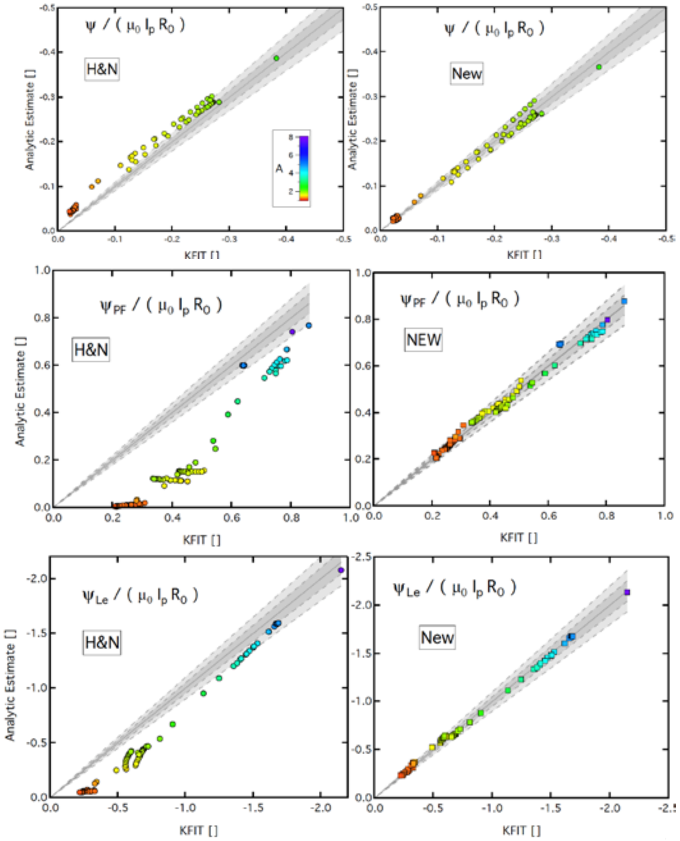
- Maintaining radial force balance provides V_{IND}
    - Originally calculated via H-N formulae

- Important to quantify contributions from shape, PF drive in LHI system design

- Model equilibrium database generated to test analytic formulae in realistic magnetic geometries
    - $N = 331$; $1.15 < A < 8$; $1 < \kappa < 3$
    - $0 < \beta_p < 1$; $0.2 < \ell_i < 0.75$

- Poor partitioning of V_{IND} between shape, V_{PF} components found
    - However, total flux estimates in better agreement

- Revised V_{IND} model developed
    - Derived new coefficients in H-N formalism via fit to equilibrium database
    - Weak dependence on β_p, ℓ_i introduced



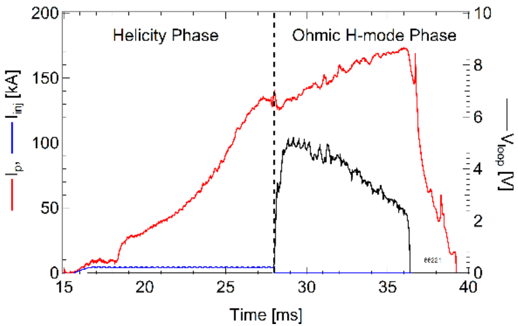
S.P. Hirshman and G.H. Nielson 1986 *Phys. Fluids* **29** 790

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

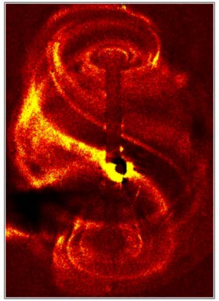
- Key results of campaign:
  - Confirmed L-H power threshold discrepancy as A → 1
  - First access to, characterization of ELMs at A < 1.3
  - High spatiotemporal measurements across pedestal
  - First measurements of nonlinear $J(R)$ dynamics during single ELMs
  - 3D field application from LHI injectors may alter ELM stability

LFS LHI → OH H-mode Handoff



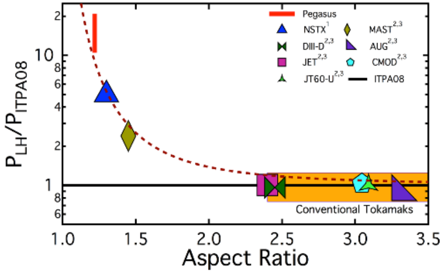
Bongard, IAEA FEC 2016 EX/P4-51

Large ELM in Pegasus



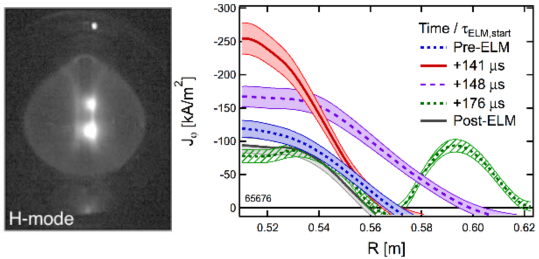
FES Transients Workshop Report Cover
Bongard, IAEA FEC 2016 EX/P4-51

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



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

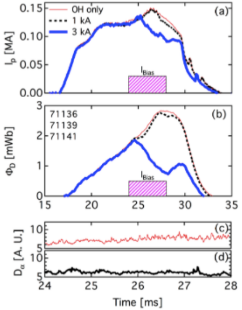
Unique H-mode Edge Pedestal Diagnostic Access



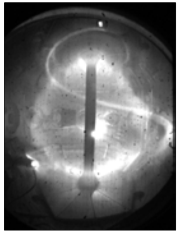
Diverted H-mode plasma *Measured ELM J(R, t) Dynamics*

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

ELM Modification by 3D Edge Current Injection From Helicity Injectors



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



Bongard, IAEA FEC 2016 EX/P4-51

M.W. Bongard, ISTW 2017