Local Helicity Injection Studies on the PEGASUS-III Experiment

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PEGASUS-III Experiment

Layout

12:1 scale Panel size: 8’ x 4’

US Legal
8.5 x 14”

US Letter
8.5 x 11”

Local Helicity Injection Studies on the PEGASUS-III Experiment

Pegasus-III and Solenoid-Free Startup	Local Helicity Injection	Recent Local Helicity Injection Campaign Highlights		LHI Systems for Pegasus-III	Experimental Plans
Non-Solenoidal Startup Is Critical for the Spherical Tokamak and May Benefit Advanced Tokamaks	Helicity Injection Drives Tokamak Plasmas	Multi-Year Campaign Concludes Injector Siting Driven by Practical, Rather than Physics Constraints	Broadband Magnetic Fluctuations Play Key Role in LHI Current Drive Mechanism	New LFS LHI Systems Built for First PEGASUS-III Experiments	Projecting LHI to Larger Facilities Requires Tests at Increasing B_T
Research on the A~1 PEGASUS ST Has Advanced the Physics and Technology Basis of Local Helicity Injection Non-Solenoidal Startup	Injectors are a Key Enabling Technology for LHI	Optimizing Taylor Limit can Improve LFS LHI Performance	Dynamo-Driven Current from Small-Scale, Beam-Driven Fluctuations Drives Bulk Current During LHI	New Multi-Level Buck Converters Implemented for Active V_{LHI} Control	Developing Non-Circular Injector for Future LHI Applications
Several Startup Approaches Developed and Tested Independently Worldwide	LHI is Subject to Access Conditions and Global I_p Limits	Understanding Scaling of Helicity Dissipation is Critical	Observations Suggest Sustained Injection Has Region of Magnetic Reconnection in Edge with Quiescent Core	Fully Digital Facility Timing, Control, and Protection	Initial EBW Heating Experiments Seek to Enhance LHI & CHI Current Drive
PEGASUS-III Will Provide a Dedicated US Platform for Solenoid-Free Startup Development [PEGASUS-III Upgrades Enable Comparative Study of Multiple Startup Methods]	A Growing Understanding of Physics and Engineering Issues in LHI Informs its Application to Next-Step Devices	Attainable T_e During LHI Also Set by Confinement Properties	LHI Plasmas Readily Couple to Subsequent Ohmic Drive	Cathode Spot Breakdown is Primary Technical Hurdle to High Voltage	Exciting Developments in Local Helicity Injection Physics and Technology

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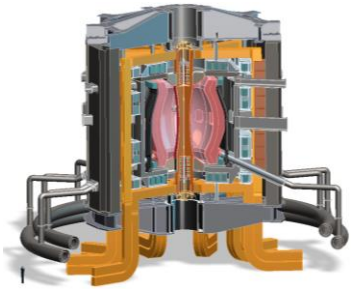
PEGASUS-III and Solenoid-Free Startup

Non-Solenoidal Startup Is Critical for the Spherical Tokamak and May Benefit Advanced Tokamaks

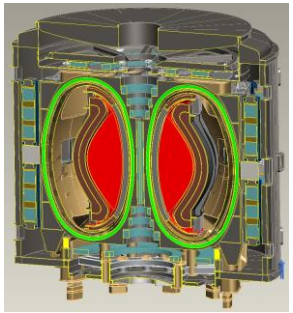
- Critical need for ST
  - Confirmed in repeated FESAC/community studies
  - Nuclear ST designs preclude OH due to shielding / cost
  - Any solenoid, if available, insufficient for full I_p ramp-up

- Benefits tokamaks in general
  - Possible reduction in cost/complexity of STs, ATs
  - More space for inboard shielding / blanket / RF
  - Lowers electromechanical stresses
  - Reduce/eliminate need for breakdown B_p null from PF system
  - May be required to fully support A optimization of next-step devices

ST-FNSF, FNSF / Pilot Plant Concepts
Shielding needs severely constrain OH viability



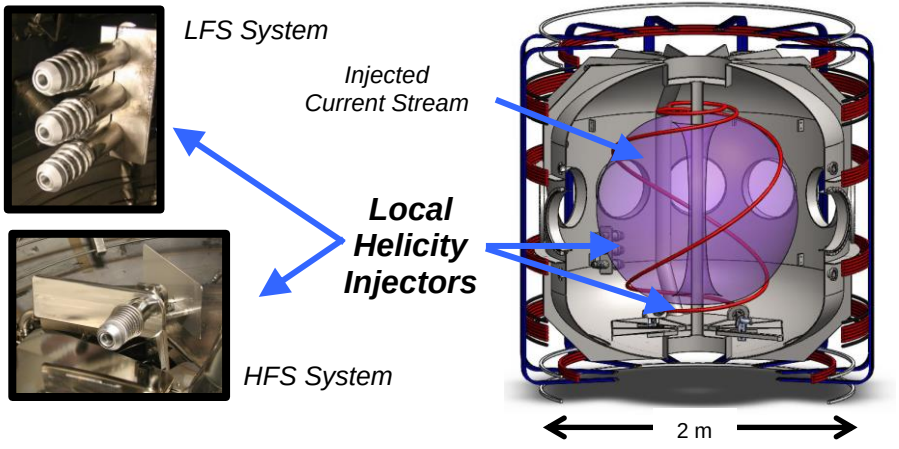
Solenoid-free
Cu
ST-FNSF

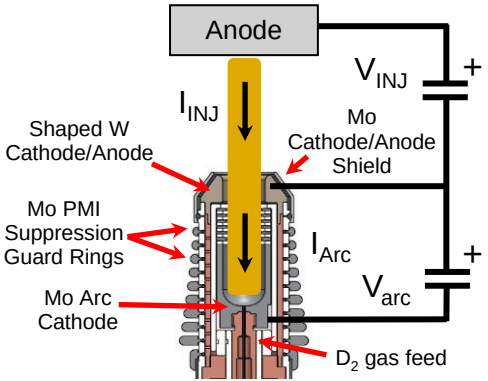


No / small OH
HTS
ST-FNSF / Pilot Plant

*J.E. Menard et al., Nucl. Fusion **56,** 106023 (2016)*
*J.E. Menard, Phil. Trans. R. Soc. A **377**, 20170440 (2019)*

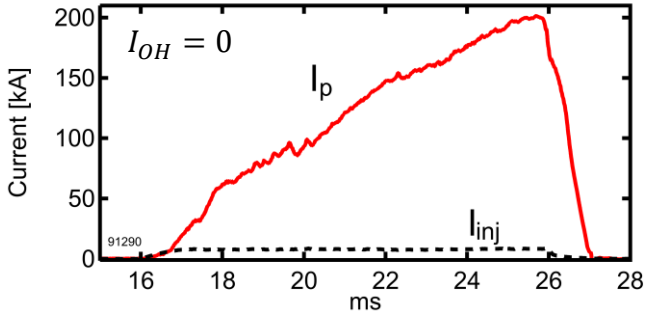
Research on the A ~ 1 PEGASUS ST Advanced the Physics and Technology Basis of Local Helicity Injection Non-Solenoidal Startup





PEGASUS Parameters		Injector Parameters	
I_p	≤ 0.23 MA	$\sum I_{inj}$	≤ 14 kA
Δt_{shot}	≤ 0.025 s	I_{inj}	≤ 4 kA
B_T	0.15 T	V_{inj}	≤ 2.5 kV
A	1.15–1.3	N_{inj}	≤ 4
R	0.2–0.45 m	A_{inj}	= 2-4 cm^2
a	≤ 0.4 m	I_{arc}	≤ 4 kA
κ	1.4–3.7	V_{arc}	≤ 0.5 kV

Non-Solenoidal I_p = 0.2 MA Plasma via LHI (I_{inj} ≤ 8 kA)



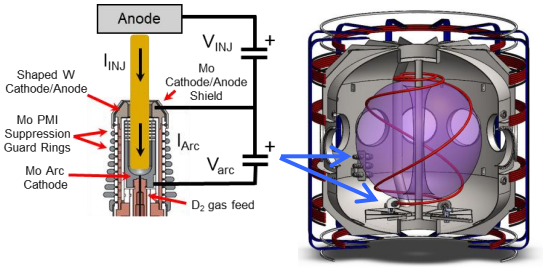
- LHI provides high-I_p, solenoid-free startup
  - Edge current extracted from injectors at boundary
  - Relaxation to tokamak-like state via helicity-conserving instabilities
  - > 0.2 MA I_p demonstrated
  - Hardware retractable prior to nuclear phase in reactor
- Routinely used for startup on PEGASUS ST

*M.W. Bongard et al., Nucl. Fusion **59**, 076003 (2019)*

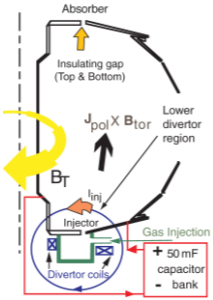
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Several Startup Approaches Developed and Tested Independently Worldwide

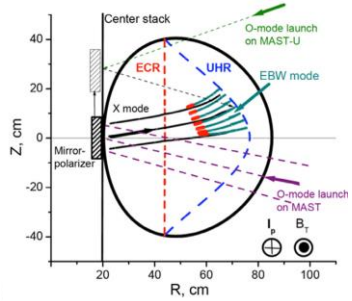
LHI



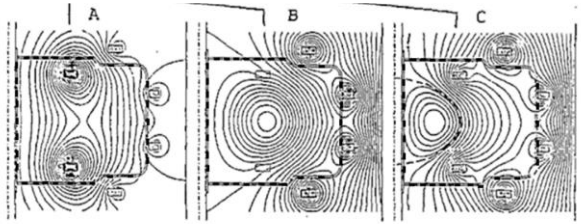
CHI



EBW RF



Merging / Compression



Helicity Injection

- Drives current on SOL open field lines
- Local Helicity Injection (LHI)
- Coaxial Helicity Injection (CHI)

Radiofrequency

- Ionize gas and ramp to desired plasma configuration
- EC, LH, EBW
- Potential synergies with HI startup

Reconnection

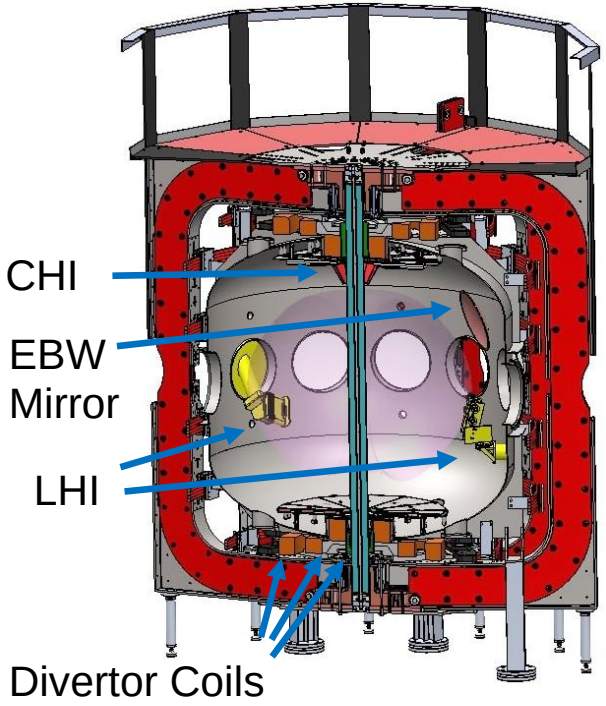
- Seed plasmas made by PF coils rapidly merged into center of VV
- Reconnects to make target plasma

*Bongard et al., Nucl. Fusion **59**, 076003 (2019)* *Raman and Shevchenko, Plasma Phys. Control. Fusion **56**, 103001 (2014)*
Bongard et al., APS-DPP-CPP Initiative (2019) *Gryaznevich and Sykes, Nucl. Fusion **57**, 072003 (2017)*

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PEGASUS-III Will Provide a Dedicated US Platform for Solenoid-Free Startup Development

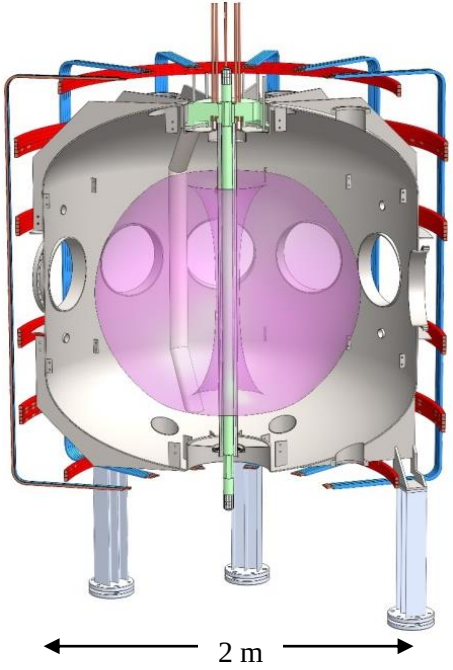
- Major upgrade to the PEGASUS ST facility in progress*
- Compare / contrast / combine concepts for solenoid-free startup in a dedicated facility
  - Local Helicity Injection
  - Coaxial Helicity Injection (Transient, Sustained)
  - RF assist and sustainment (EBW presently, ECH, ECCD in future)
  - Assess compatibility with NBI heating and current drive
- Goal: develop validated physics and technology basis for MA-class startup on NSTX-U and beyond



*Reusch et al., BP 11.00002, these proceedings
Garstka et al., Nucl. Fusion **46** S603 (2006)

PEGASUS-III Upgrade Enables Comparative Study of Multiple Startup Methods

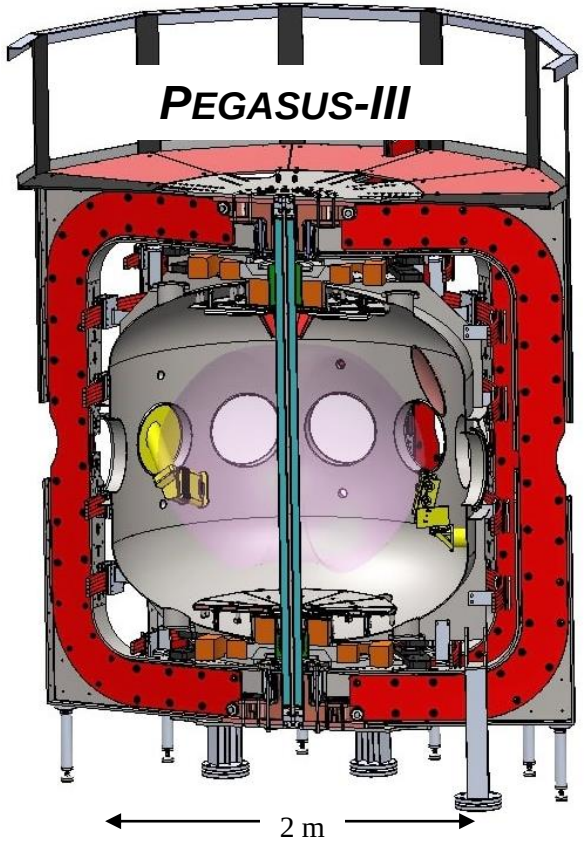
PEGASUS



- **Solenoid-free central column**
- Stronger, high-B_T assembly
- Active divertor coils
- CHI, RF, and next-gen LHI
- Expanded diagnostics

Parameter	PEGASUS	PEGASUS-III
I_{TF}	0.288 MA	1.15 MA
N_{TF}	12	24
ψ_{sol} (mWb)	40	0
R_{inner} [cm]	5.5	7.0
TF Conductor Area [cm^2]	13.2	72
$B_{T,max}$ [T] at R_0~0.4 m	0.15	0.58
B_T Flattop [ms]	25	50–100
A	1.15	1.18

PEGASUS-III



Reusch et al., BP 11.00002, these proceedings

Local Helicity Injection

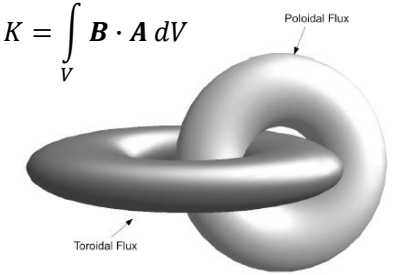
Helicity Injection Drives Tokamak Plasmas

- Current drive increases the amount of poloidal flux ψ_p linked with the toroidal flux created by external coils (magnetic helicity)

$$\frac{dK}{dt} = -2\frac{\partial \psi}{\partial t}\Psi - 2\int_S \Phi B \cdot dS - 2\int_V \eta \boldsymbol{J}\cdot\boldsymbol{B}dV$$

AC Helicity Injection | DC Helicity Injection | Helicity Dissipation

$$K = \int_V \boldsymbol{B}\cdot\boldsymbol{A}\, dV$$



- DC helicity injection can be represented by an effective loop voltage:

$$V_{LHI} = \frac{\oint_S \Phi\, \vec{B}\cdot d\hat{s}}{\Psi} = \frac{V_{inj}A_{inj}B_{inj}}{\Psi}$$

- Plasma current scales with injector **voltage**, **area**, and **location**

$$I_p = \frac{A_p V_{LHI}}{2\pi R_0 \langle\eta\rangle} \approx \frac{V_{inj}A_{inj}}{2\pi R_0\langle\eta\rangle}\left(\frac{B_{inj}}{B_0}\right)$$

Limits of DC HI geometry:
- LHI: Local, small-area sources
- CHI:* Large, coaxial electrodes

- Taylor relaxation limits I_p to lowest energy state that conserves K

$$\lambda \equiv \frac{\vec{J}\cdot\vec{B}}{B^2} \qquad \bar{\lambda}_{plasma} \le \bar{\lambda}_{edge} \rightarrow \boxed{I_p \le I_{inj}\frac{\phi_p}{\psi_{inj}}}$$

*Raman et al., BP 11.00005, these proceedings

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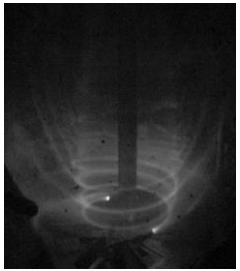
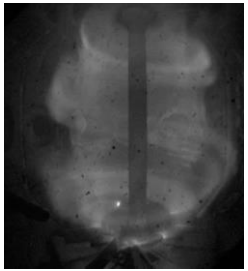
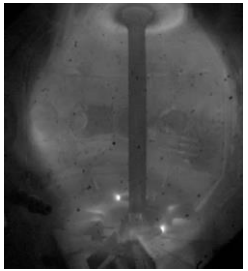
LHI is Subject to Access Conditions and Global I_p Limits

- Initial relaxation to tokamak-like state
  - Helical streams to (mostly) axisymmetric topology
  - Requires $B_{p,inj} \sim B_{z,vac}$
  - Injector stream pitch angle clearance $\propto B_z/B_T$

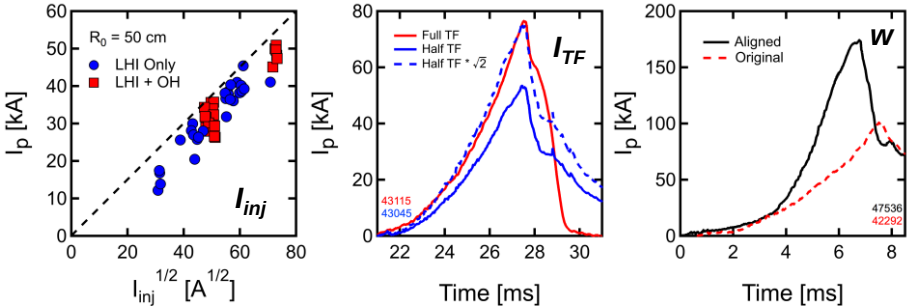
- Taylor relaxation limit
  - $\lambda_p \leq \lambda_{inj} \rightarrow$ $I_p \leq I_{TL} \sim \sqrt{I_{TF} I_{inj}/w}$

- Helicity balance limit

$$V_{LHI} \approx \frac{A_{inj} B_{T,inj}}{\Psi} V_{inj} \qquad I_p \leq V_{LHI}/R_p$$

Current Injection	***Relaxation***	***Driven Tokamak***
		
$I_p \sim N_{turns}\, I_{inj}$	$I_p \gtrsim N_{turns}\, I_{inj}$	$I_p \gg N_{turns}\, I_{inj}$

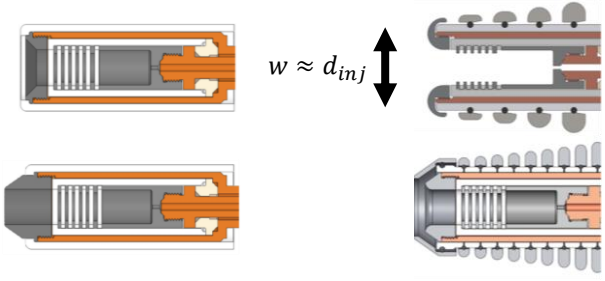
Taylor-Limited I_p Scalings



J.M. Perry et al., Nucl. Fusion **58** 096002 (2018) D.J. Battaglia et al., Nucl. Fusion **51** 073029 (2011)
M.W. Bongard, et al., Nucl. Fusion **59**, 076003 (2019)

Injectors Are A Key Enabling Technology for LHI

- Electron current sources are coupled physics/engineering problem
  - I_{inj} and w ($\approx d_{inj}$) set $I_{TL} \geq I_p$
  - $N_{inj}A_{inj}V_{inj}$ to attain/sustain I_p
  - Injector armoring, local limiters minimize plasma-material interaction
  - Conformal to desired plasma shape
- Upper bounds to V_{inj} from cathode spot onset
  - Cathode, shield ring features evolved to reduce likelihood
- Technology development effort: active arc sources preferred



Shaped Electrode Sources Evaluated

Passive



High I_{inj}

$A_{inj} << A_{elec}$

High Spot Rate

Active gas-fed



High I_{inj}

$A_{inj} \leq 10\% A_{elec}$

High Spot Rate

Active Sources Maximize V_{inj} and Minimize Cathode Spots



V_{inj} ~ 400 V

High Spot Rate



V_{inj} ~ 1000 V

Medium Spot Rate



V_{inj} ~ 1500 V

Low Spot Rate

*M.W. Bongard, et al., Nucl. Fusion **59**, 076003 (2019)*

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A Growing Understanding of Physics and Engineering Issues in LHI Informs its Application to Next-Step Machines

LHI Physics Models

- Global I_p limits:
  - Taylor relaxation

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

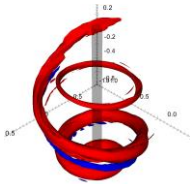
  - Helicity conservation

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

- Predictive power balance: $I_p(t)$

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

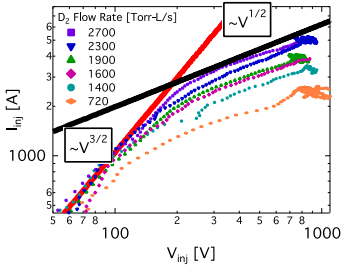
- 3D resistive MHD / NIMROD
  - Initial relaxation
  - Role of reconnection



Reconnecting LHI Current Stream

Coupled Physics/Engineering Needs

- Helicity injector source design
  - I_{inj}, w: set $I_{TL} \geq I_p$
  - $N_{inj} A_{inj} V_{inj}$: attain / sustain I_p
  - Armoring, limiters to minimize cathode spots
- Injector system geometry
  - Provide initial relaxation via near-PF null
  - Site conformal to desired plasma shape
  - Facility port access compatibility
- Injector impedance and power systems*
  - $Z_{inj} = Z_{inj}(n_{arc}, n_{edge}, \ldots)$

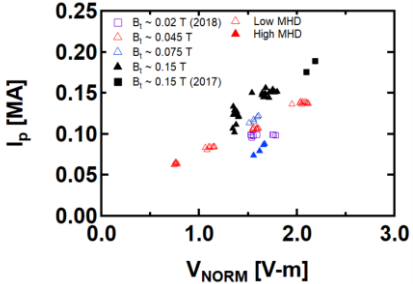


*E.T. Hinson et al., Phys. Plasmas **23** 052515 (2016)

Outstanding Issues

- Scaling to high I_p
  - Larger size
  - High B_T
  - Longer pulse
- Confinement, impurities, and dissipation during LHI
- LHI current drive mechanism
- Handoff to non-inductive CD
  - LHI → OH H-mode demonstrated

$I_p(V_{LHI}, B_T)$ HFS LHI Scaling



Recent Local Helicity Injection Campaign Highlights

Multi-Year Campaign Concludes Injector Siting Driven by Practical, Rather than Physics Constraints

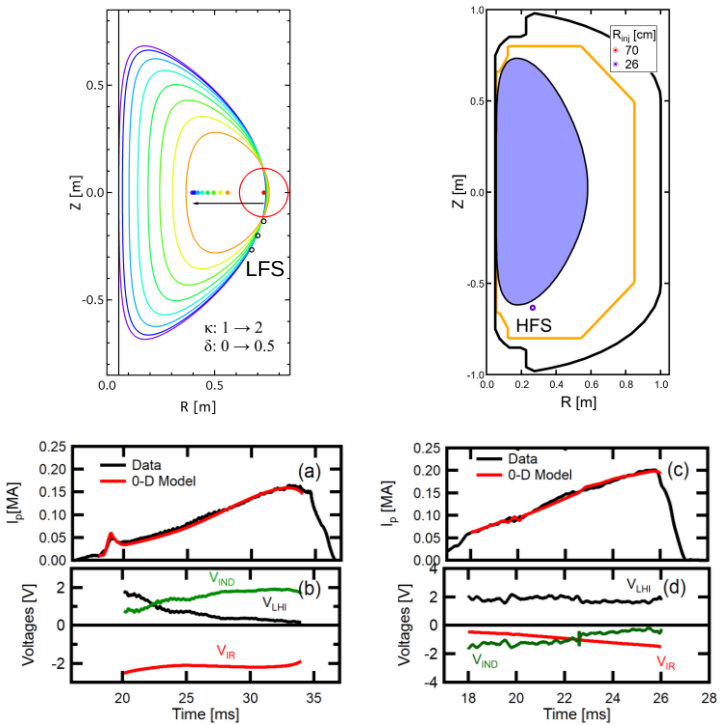
- Injector location affects dominant drive
  - Extrema of LHI geometries deployed in PEGASUS
  - Interpretive 0-D power balance modeling quantifies helicity balance drive terms, $I_{TL}(t)$

- Low-field-side Injection
  - Injectors on outboard midplane
  - High R_{inj} → low V_{LHI}
  - Dynamic shape → strong $V_{IND}(t)$

- High-field-side Injection
  - Injectors in lower divertor
  - Low R_{inj} → strong V_{LHI}
  - Static shape → minimal V_{IND}

- I_p ~ 0.2 MA attained in both geometries
  - Helicity balance critical physics; no significant confinement impact found
  - Capable of LFS → HFS handoff

LFS: Non-Solenoidal Induction ***HFS: Helicity Injection***



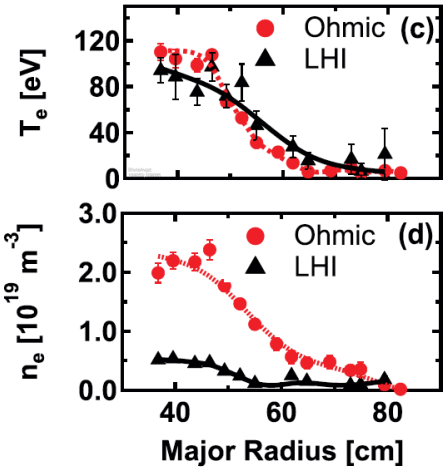
*J.L. Barr et al., Nucl. Fusion **58** 076011 (2018)*

*J.A. Reusch et al., Phys. Plasmas **25** 056101 (2018)*

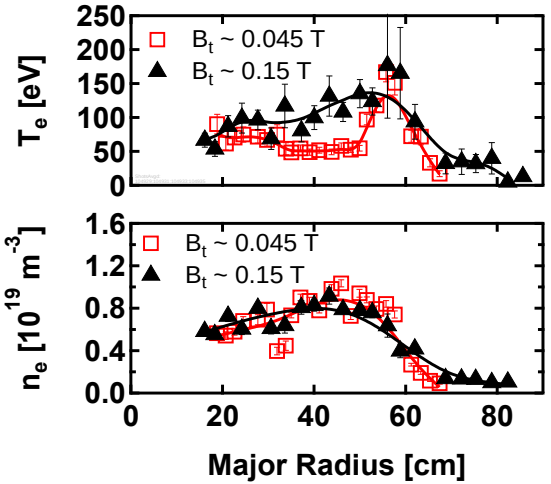
Understanding Scaling of Helicity Dissipation is Critical

- Dissipation in LHI $\propto Z_{eff} T_e^{-3/2}$ affects sizing of injector systems for desired target I_p, shape
  - Wide survey of LHI scenarios characterized with TS*

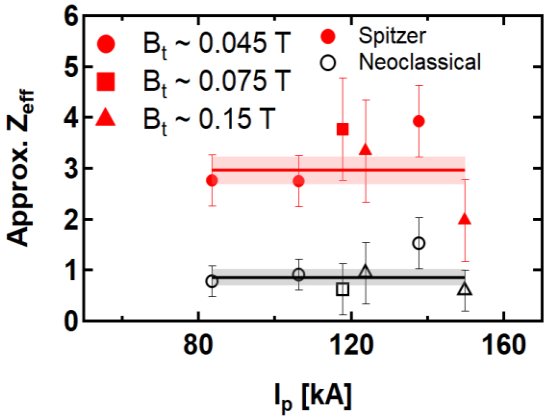
LHI-Driven Plasmas Comparable to Ohmic



LHI T_e Increases, Peaks as B_T Raised



Z_{eff} Scaling with I_p Determined From Volume-Averaged Resistivity*



- Peaked p_e profiles routinely observed
  - T_e > 100 eV, comparable to OH plasmas
- T_e structure, magnitude improves with B_T
- $Z_{eff} \sim 1$ inferred over wide range of B_T
  - Dominant radiator: low N charge states

*Bodner et al., Phys. Plasmas **28** 102504 (2021)

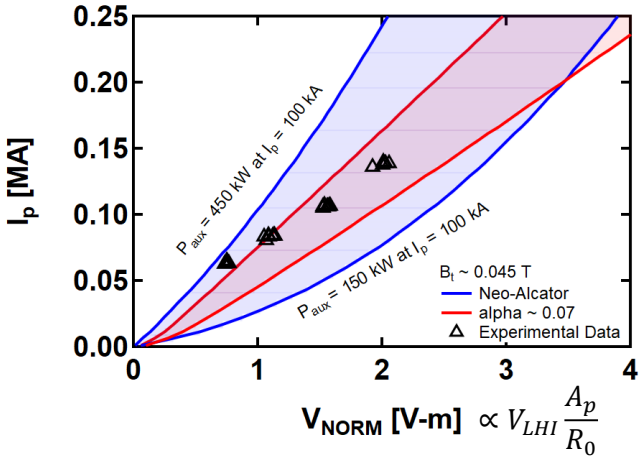
Attainable T_e During LHI Also Set by Confinement Properties

- No confinement model for LHI presently exists
  - Ohmic, collisional stochastic scalings considered
- Pure helicity-driven plasmas compared to scaling laws*
  - Cylindrical power balance code
  - Find I_p given empirical τ_E scalings, plasma geometry, and drive

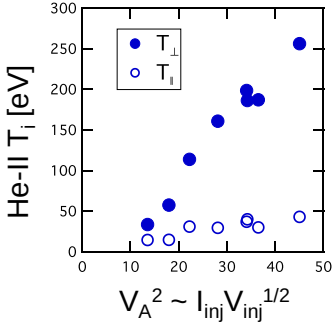
$$(V_{LHI} I_p + P_{aux})(1 - F_{RAD}) \sim \frac{W}{\tau_E}$$

  - Assume P_{aux} from ion, electron reconnection heating**
- LHI with modest P_{aux} consistent with linear Ohmic, collisional stochastic confinement scalings*
  - Other scalings and/or zero auxiliary heating clearly disagree
  - Steady-state $I_p(V_{NORM})$ values
- Favorable LOC comparison perhaps surprising finding
  - No *a priori* justification for Ohmic-like confinement given presence of open field lines, stochasticity during HI drive
  - Low-B_T effect? $B_T < 0.15$ T→ magnetic correlation length ~ ρ_S

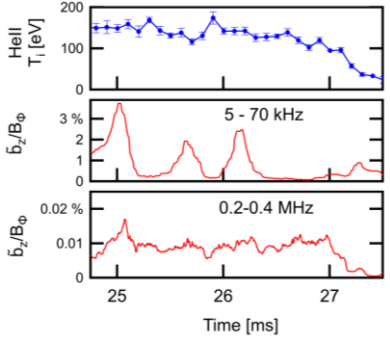
LHI I_p Scaling Assuming Linear Ohmic, Stochastic Confinement Regimes



Anisotropic Ion Heating from Reconnecting Current Streams



Ti Correlated with High-f $\tilde{b}$



*Bodner et al., Phys. Plasmas **28** 102504 (2021)
Burke et al., Nuclear Fusion **57 076010 (2017)

Optimizing Taylor Limit Can Improve LFS LHI Performance

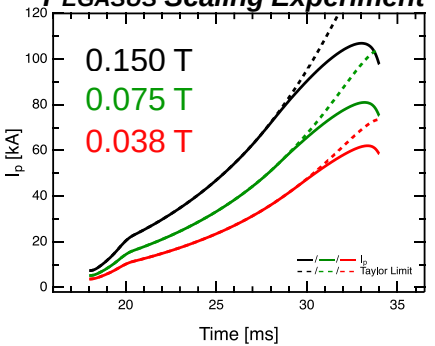
- Modeling insight:* optimizing early-phase Taylor limit in LFS LHI can maximize I_p
  - Small ΔI_{p0} via TL yields large $\Delta I_p(t)$
  - "Pre-charge" inductance of initial plasma
  - Raise W_M for subsequent geometric V_{IND} drive

- PEGASUS experiments manipulated I_{TL} via B_T
  - Shape evolution, I_{inj}, V_{inj} fixed
  - Higher I_{TL} better-utilizes high V_{LHI} at early time

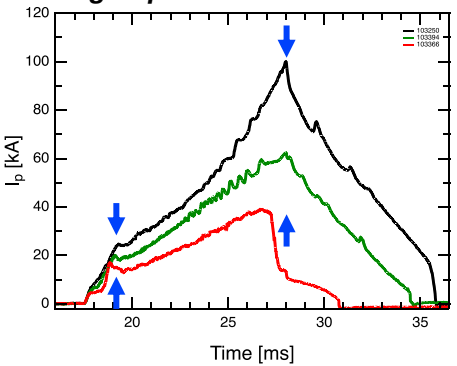
- Experiment-modeling agreement improves confidence in PEGASUS-III LHI projections

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

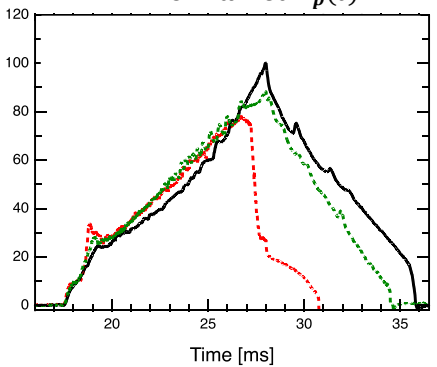
Model Projection for PEGASUS Scaling Experiment



Scaling Experiment Realizes Trend



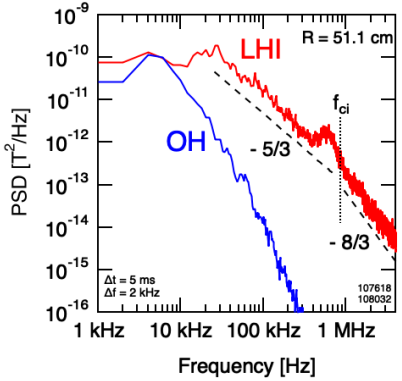
TL-Normalized $I_p(t)$



*J.L. Barr et al., Nucl. Fusion **58** 076011 (2018)

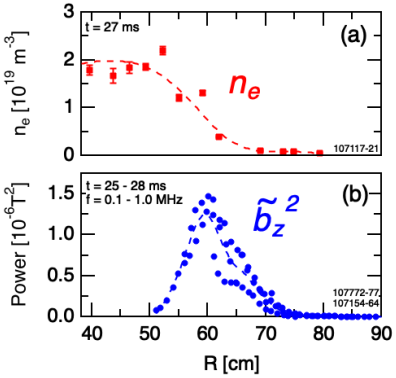
Broadband Magnetic Fluctuations Play Key Role in LHI Current Drive Mechanism

Broadband Alfvénic Turbulence Driven in LHI Current Streams



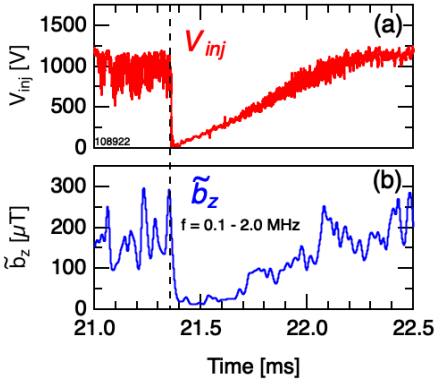
- Consistent with Alfvénic turbulence
  - -5/3 $f < f_{ci}$, -8/3 $f \gtrsim f_{ci}$
- $V_{inj} \rightarrow 0$: Rapid decay to OH spectrum
- Present in streams-only and driven tokamak states

Activity Localized in Confined Region on LFS, Far From Core



- High-resolution probe measures $\tilde{b}(R)$
  - Activity peaks near LFS edge inside ∇n_e, ∇T_e and declines to zero in core
  - Prior experiments find reconnection-driven T_i peaks in same region*
- Implies significant plasma volume may not be affected by activity
  - Favorable transport implications?

Strong Sensitivity to LHI V_{inj} Implies Kinetic Instability



- Super-Alfvénic beams drive $\tilde{b}$
  - At injector, $v_b \propto \sqrt{V_{inj}}$ via double layer acceleration***
  - $v_b \gg V_A$
- Injected streams also MHD unstable
  - K-S: $I_{inj} \gtrsim 100$ A $\ll I_{inj}$ for LHI
  - $n = 1$ line-tied kink activity**
  - Not correlated with LHI CD activity

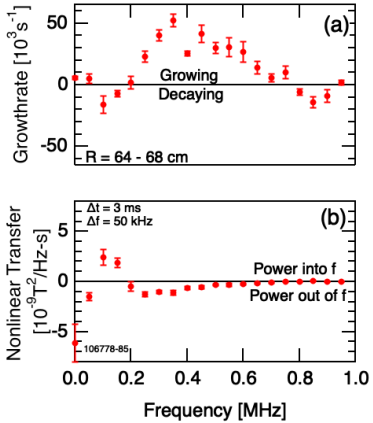
Richner et al., JI01.00004, these proceedings

*M.G. Burke et al., Nucl. Fusion **57** 076010 (2017)
J.A. Reusch et al., Phys. Plasmas **25 056101 (2018)
***E.T. Hinson et al., Phys. Plasmas **23** 052515 (2016)

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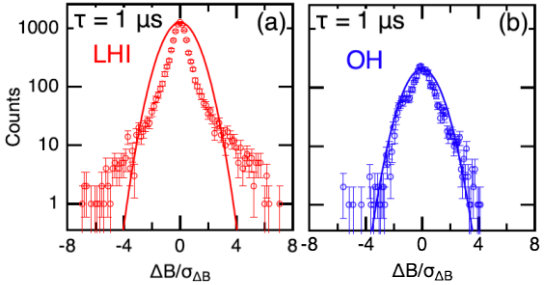
Dynamo-Driven Current from Small-Scale, Beam-Driven Fluctuations Drives Bulk Current During LHI

Nonlinear Transfer of Beam Modes to Other Spatial Scales



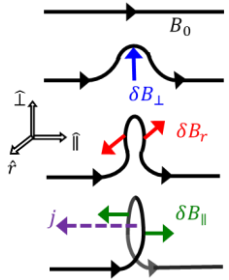
- High-order spectral analyses* find growth rate and nonlinear energy transfer of activity

Intermittency at Small Scales: Formation of Current Structures

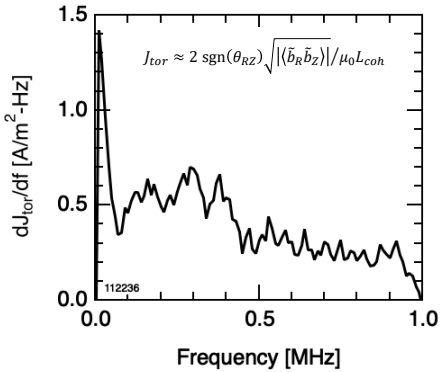


- Deviation of $\tilde{b}$ PDF from Gaussian during LHI indicates presence of small-scale filamentary structures
- α dynamo:** small J associated with $\tilde{b}$

α Dynamo: stretch, twist, & fold of B_0 drives current



Turbulence-Driven α Dynamo Drives Net I_p



- Polarity of $\tilde{b}(f)$ consistent with co-I_p $\tilde{J}(f)$ drive
- Integrated magnitude ~ reconstructed J (!)
  - $\int df\, J_{tor}(f) \approx \langle J_{tor} \rangle$
  - 600 kA/m^2 400 kA/m^2

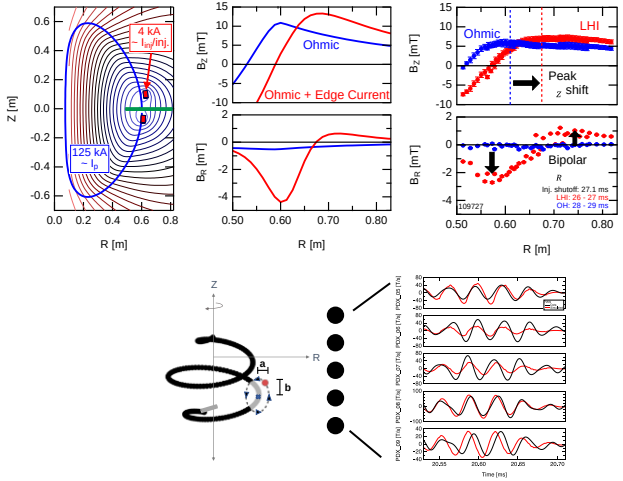
*Based on Kim et al., Phys. Plasmas **3** 3998 (1996)

**H.K. Moffatt, Magnetic field generation in electrically conducting fluids (1978)

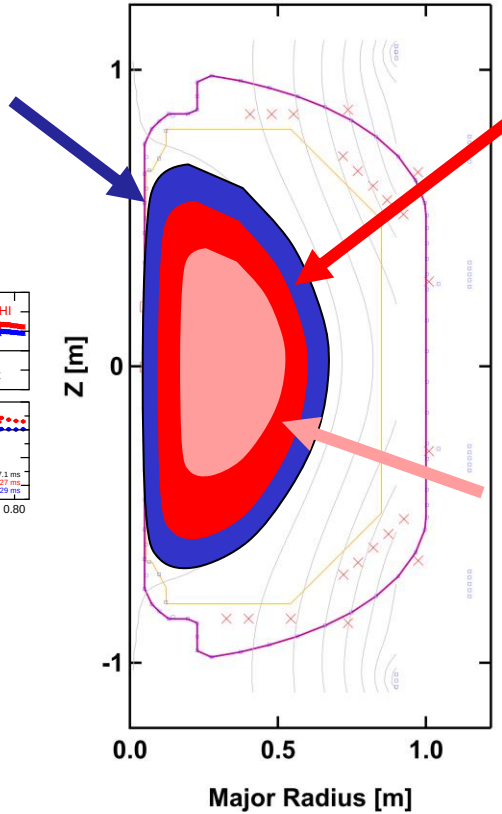
Observations Suggest Sustained Injection Has Region of Magnetic Reconnection in Edge with Quiescent Core

- **Injector Stream Region**
  - Force-free current streams in dynamic helical equilibrium
  - $n = 1$ kink motion of line-tied stream

Magnetic Measurements Confirm Presence of Injected Streams During LHI

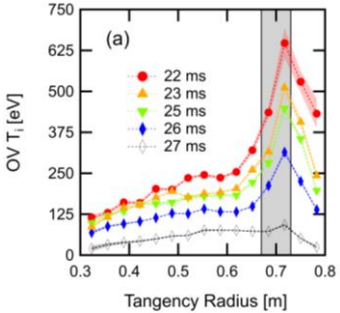


Multiple Zones of Physical Activity



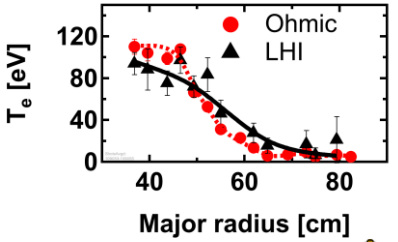
- **Current Drive and Reconnection Region**
  - Localization of Alfvénic turbulence and ion heating*

Edge-Localized, Reconnection-Driven T_i*



- **Confinement Region**
  - Tokamak-like toroidally-averaged closed flux surfaces

LHI Core $T_e(R)$ Similar to Ohmic**

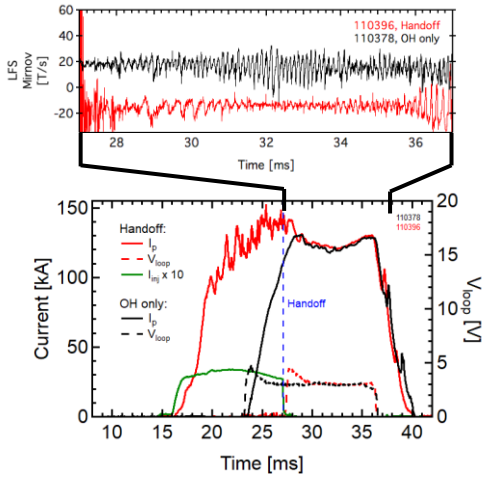


*Burke et al., Nuclear Fusion **57** 076010 (2017)
Bodner et al., Phys. Plasmas **28 102504 (2021)

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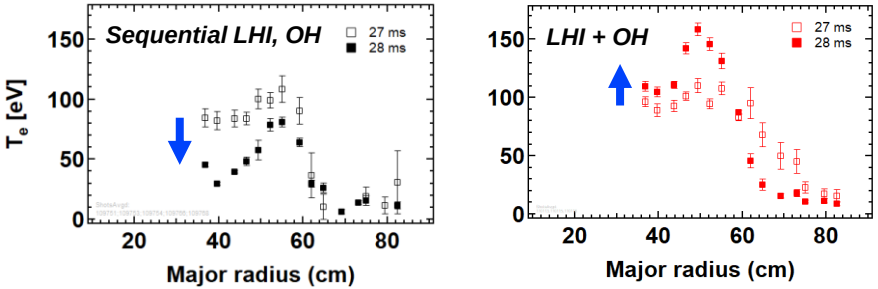
LHI Plasmas Readily Couple to Subsequent Ohmic Drive

LHI Produces Low ℓ_i Targets for Ohmic Sustainment



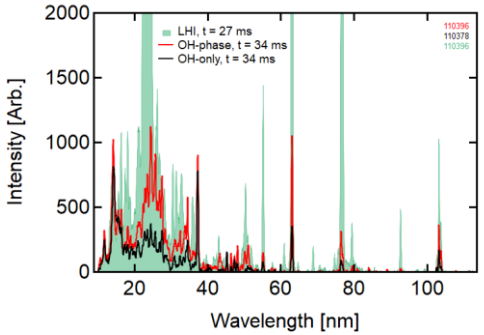
- Handoff to subsequent sustainment is success metric for any non-solenoidal startup technique
- LHI: Simple coupling to OH, access to H-mode

LHI + OH Drive: Higher T_{e0} After Handoff



- Favorable indicator for P_{aux} synergy studies?

Impurity Spectra Relax to OH Levels After Handoff

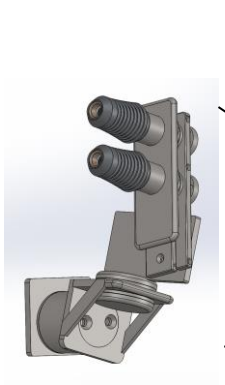


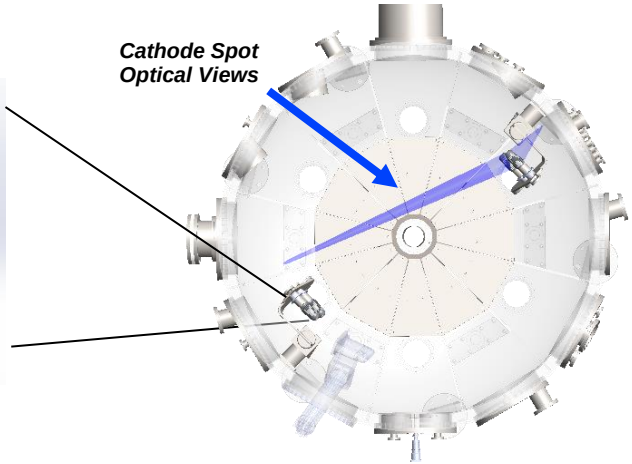
PEGASUS-III LHI Systems

New LFS LHI Systems Built for First PEGASUS-III Experiments

- Four-injector array built for initial operation
  - Two arrays of two 4 cm^2 injectors
  - Most powerful HI system fielded to date
- Non-circular injector assembly as next advance
  - Port-mounted active arc source
  - Optimize Taylor limit, HI rate
- New I_{inj} bias power supplies
  - Four multi-level buck converter supplies
  - Digital FPGA feedback control system
- Improved cathode spot detection and mitigation
  - Optical detection from plasma, wall-facing views

PEGASUS-III LHI Injector Systems and Cathode Spot Mitigation Views





LHI Injector Assembly



LHI Injector Socket



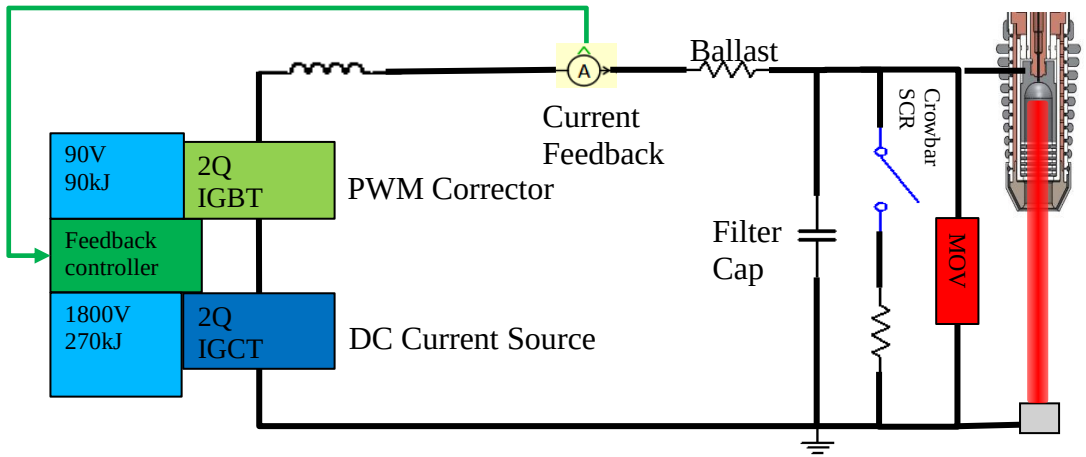
Prototype Non-Circular Injector



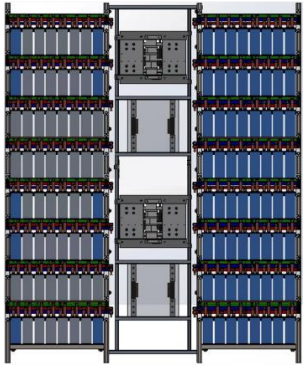
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New Multi-Level Buck Converters Implemented for Active V_{LHI} Control

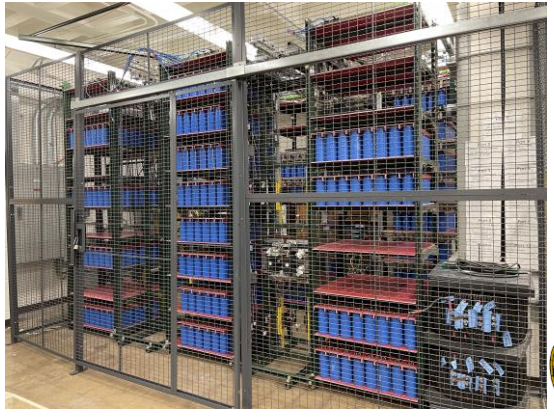
MLBC Concept – One Converter per LHI Source



Integrated Stored Energy, IGBT, and IGCT Bridges



Constructed Power Supplies

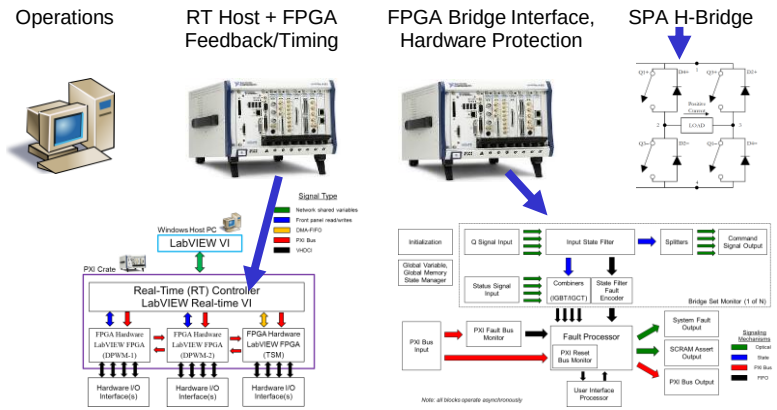


- MLBC supply to drive 4 kA at 1 kV with sub-ms V_{out} control
  - 1800 V from IGCT system $\pm$ 900 V(t) on fast timescales from corrector
- 16 MVA planned for initial experiments

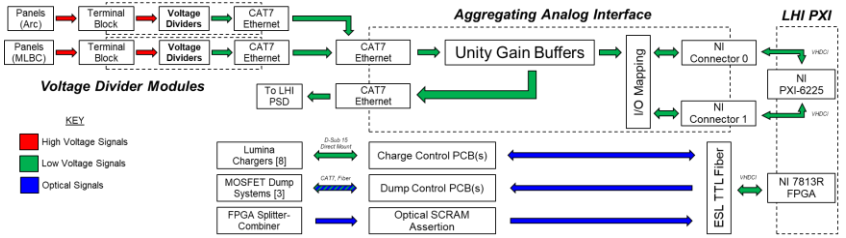
Fully Digital Facility Timing, Control, and Protection

- Digital Feedback Controllers
  - 16 coil set controllers, 15 kHz PID loop rate
  - 1Q, 2Q, 4Q bridge set topologies
  - IGBT, IGCT power silicon communications
  - Over-current fault protection
- Switching power amplifier protection
  - Continuous hardware fault protection on < 10 μs timescales
- Timing, Clocks, and Triggering
  - FPGA-generated timing and optical trigger distribution
  - GPS-synchronized absolute time triggering
  - Provides IEEE 1588 grandmaster for lab systems
- Stored energy charge / dump control and monitoring
  - Multiple switchyards, distributed architecture
  - Process variable archival to SQL database

New PEGASUS-III Control Systems



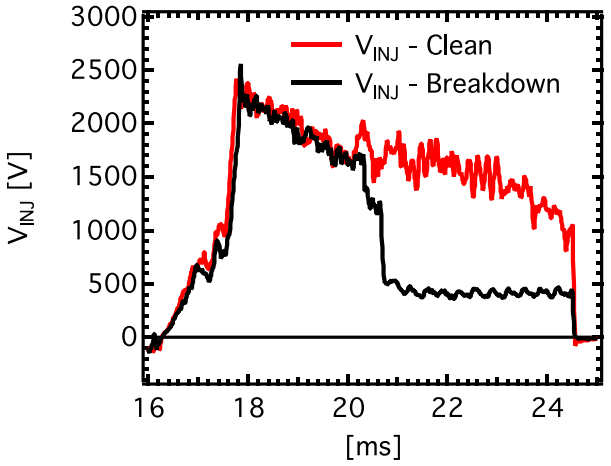
LHI Charge / Dump Control and Monitoring Elements

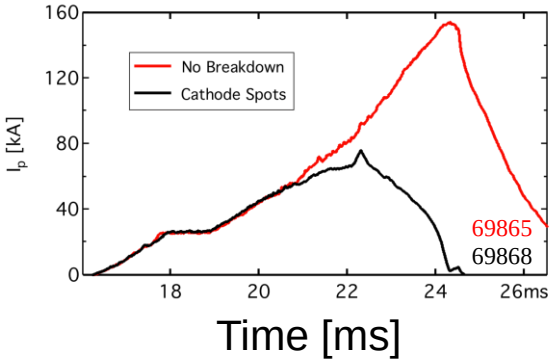


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Cathode Spot Breakdown is Primary Technical Hurdle to High Reliability

- Cathode spots occur at a critical surface E_{inj}
  - $E_{inj} \sim \frac{V_{inj}}{\lambda_{De}} > E_{crit}$
  - Need to minimize n_e, V_{inj} at bias surfaces
- Cathode spots abruptly decrease A_{inj} and V_{LHI}
  - Damages injector surfaces, requires reconditioning
  - Sources high-Z impurities from material
- MA-class LHI must mitigate cathode spots
  - Minimize onset probability
  - Technical measures to detect, protect injectors
  - Long-pulse: brief (μs) V_{inj} interruption circuitry
- PEGASUS-III strategy: multi-view optical detection and tests of mitigation concepts
  - Proof-of-principle tests extinguished/restarted V_{inj} < 1 ms

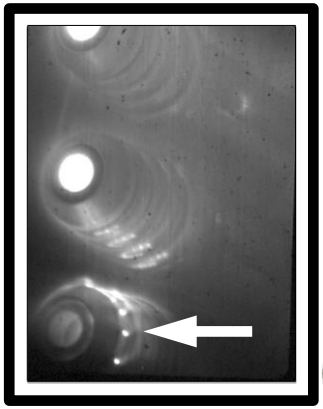




Clean



Cathode Spot Breakdown

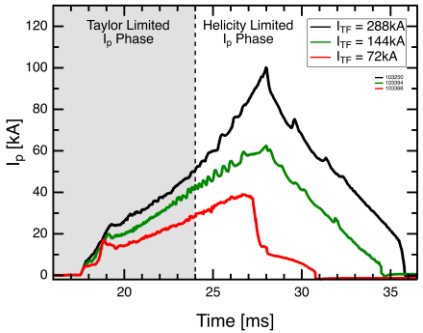


Experimental Plans

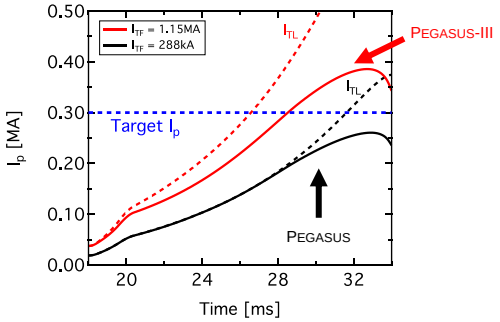
Projecting LHI to Larger Facilities Requires Tests at Increasing B_T

Realize Increased I_p Expected with Higher B_T

PEGASUS B_T Scaling Experiment



PEGASUS-III Projection

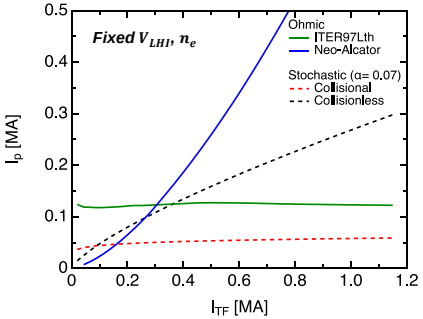


- Upgraded B_T impacts many LHI research objectives
  - Demonstrate $I_p/I_{p,max} = 1$ via solenoid-free startup
  - Eliminate degeneracies in confinement projections
  - Expand accessible I_{inj} Alfvenic Mach number range
  - Facilitate RF resonance access for auxiliary heating, CD
- Overlap accessible B_T with NSTX-U operational space

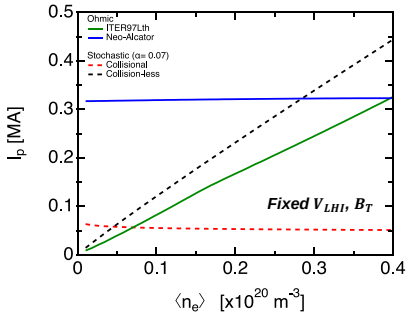
Test Projections of Core Confinement Models

Confinement Scaling	I_p Trend with Increasing V_{LHI}	Increasing B_T	Increasing n_e
Linear Ohmic (Neo-Alcator)	↑	↑	–
Saturated Ohmic (ITER97L)	↓	–	↑
Collisional Stochastic*	↑	–	–
Collisionless Stochastic	↓	↑	↑

I_p Scaling with B_T



I_p Scaling with n_e



*Bodner et al., Phys. Plasmas **28** 102504 (2021)

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Advancing LHI Technology with Non-Circular Injectors

- Non-circular injectors may optimize LHI siting
  - High I_{inj}, low w_{inj} → raise Taylor limit
  - Large A_{inj} → high V_{LHI} at low V_{inj} (improve reliability)

Taylor limit

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

Helicity limit

$$I_p \leq V_{LHI} / R_p \sim A_{inj} V_{inj}$$

- Prototype injector successfully fabricated
  - Arc channel: 1 cm × 16.2 cm
  - A_{inj} = 16 cm^2
  - Arc channel to LCFS: 1.8 cm
  - Non-refractory elements simplify fabrication

- PEGASUS-III: complete with refractory components
  - V_{inj} ~ 500 V, I_{inj} < 16 kA

Advanced Non-Circular Injector in PEGASUS-III



Integrated Prototype Fabricated

Single Port-Mount Structure

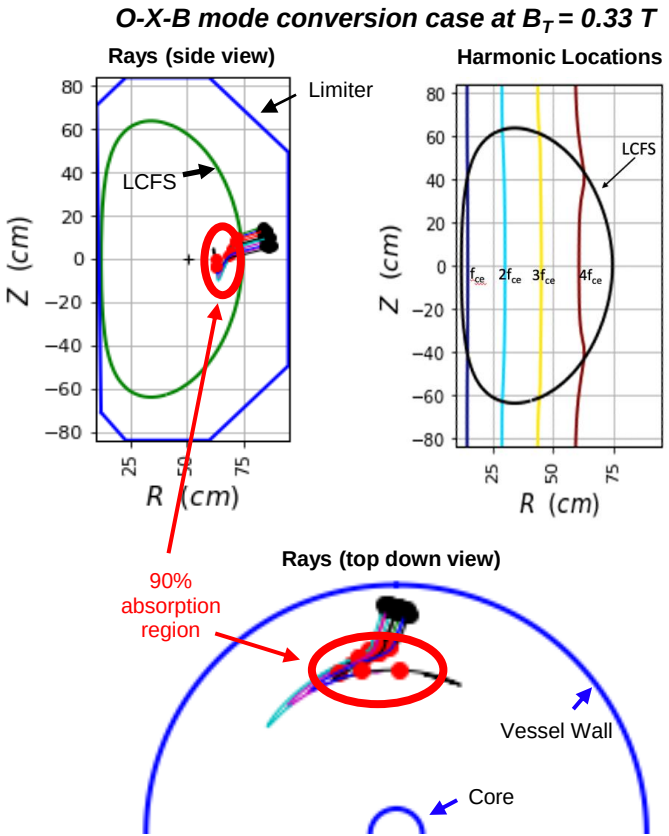


Conforms to Edge Flux Surface Geometry



Initial EBW Heating Experiments Seek to Enhance LHI & CHI Current Drive

- Initial experiments: heat LHI/CHI afterglow
  - Heating post CD shutoff extends decay, tailors profiles
- Test EBW drive concurrent with LHI
  - Increasing T_e can increase current drive efficiency
  - Explore tailoring the current profile
- Experimental target of injecting 100+ kW
  - Source frequency of 28 GHz launched into decaying LHI-produced plasma ($B_T = 0.33$ T)
  - Near midplane launch
    - $n_{\parallel} = -0.55$ to -0.45
  - Varying B_T can be used to change absorption location



Exciting Developments in Local Helicity Injection Physics and Technology

Progress in LHI Physics Understanding

- LHI current drive mechanism connects micro-scale turbulence to macroscopic I_p levels*
  - Dynamo EMFs from coherent $\tilde{b}$ Alfvenic turbulence
  - Driven by beam instabilities in injector stream
- Helicity dissipation, impurities, and confinement
  - T_e during LHI can equal Ohmic levels
  - LHI T_e increases with B_T
  - $Z_{eff} \sim 1$ inferred from resistivity analysis
- Scaling to next-step devices
  - Taylor limit experiments confirm PEGASUS-III strategy
  - Compatibility with Ohmic drive and H-mode access

Near-Term Experimental Thrusts for PEGASUS-III

- Assess impact of higher B_T on attainable I_p, T_e, n_e
  - Confinement scaling
  - Current source physics and technology
  - Characterization of impurity content
- Establish operational scenarios with new injectors
  - Highest power circular injector array fielded to date
  - B_T: 0.15 → 0.6 T, dynamic shape evolution
  - RF target scenario development
- Test reactor-scaling physics and technology
  - Need for super-Alfvenic electron beam sources
  - Test advanced non-circular injectors
  - RF and NBI compatibility and synergies

*Richner et al., JI01.00004, these proceedings

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