Advancing Local Helicity Injection for Non-Solenoidal Tokamak Startup

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PEGASUS Toroidal Experiment

Layout

12:1 scale

Panel size: A0 Portrait (0.841 m x 1.189 m)

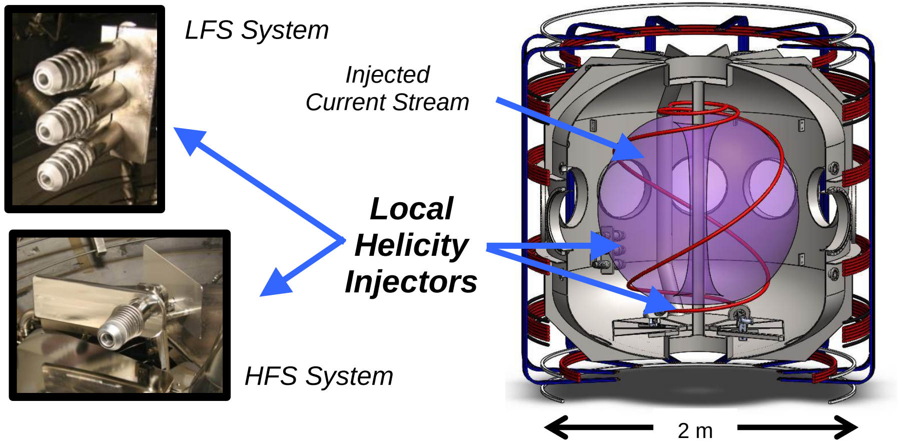
US Legal
8.5 x 14”

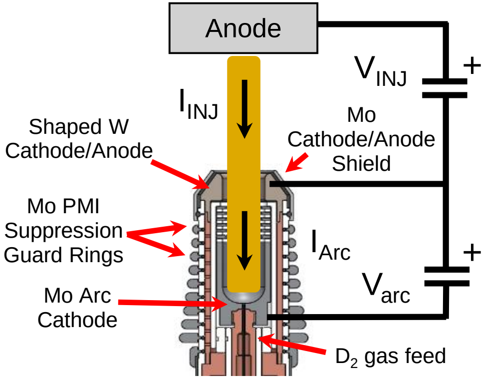
US Letter
8.5 x 11”

Recommended size per IAEA
110 cm x 85 cm (HxW)

Title Header (1/2 Height Legal)	
Research on the A ~ 1 Pegasus ST is Advancing the Physics and Technology Basis of Local Helicity Injection Non-Solenoidal Startup	Recent Experiments Suggest High Frequency Magnetic Activity and Reconnection Play a Role in LHI Current Drive
A Growing Understanding of Physics and Engineering Issues in LHI Informs its Application to Next-Step Machines	Operating Regime with Significant Reduction of Large-Scale MHD and Increased Ip Found During HFS Injection Experiments
Varying Injector Location Enables Study of LHI Physics and Engineering Tradeoffs	HFS LHI at Near-Unity A Provides access to β_t ~ 100% and Magnetic Configurations with Minimum |B| Wells
New Scenarios Developed to Transfer Between LFS → HFS Injector Systems and Combine Strengths of Each Geometry	URANIA Experiment: Converted PEGASUS Facility for US Non-Solenoidal Development Station

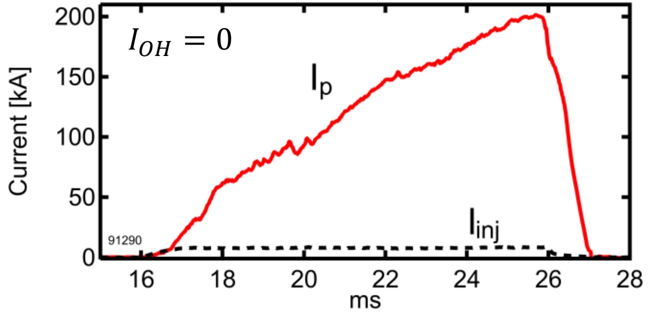
Research on the A ~ 1 PEGASUS ST is Advancing the Physics and Technology Basis of Local Helicity Injection Non-Solenoidal Startup





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 ($I_{inj} \leq 8$ kA)



- Solenoid-free startup desirable for ST, AT reactors
- LHI is promising method to accomplish this goal
  - Edge current extracted from injectors at boundary
  - Relaxation to tokamak-like state via helicity-conserving instabilities
  - Global current limits from Taylor relaxation, helicity balance
  - Hardware retractable prior to nuclear phase in reactor
- Routinely used for startup on PEGASUS

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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

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

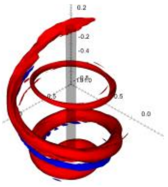
  - Helicity conservation

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

- 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

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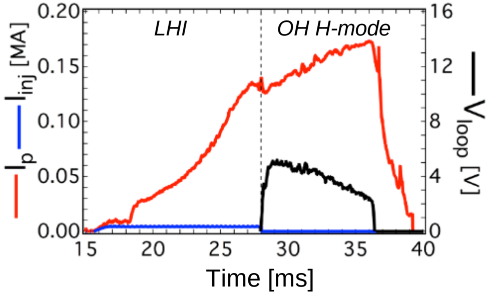
Coupled Physics/Engineering Needs

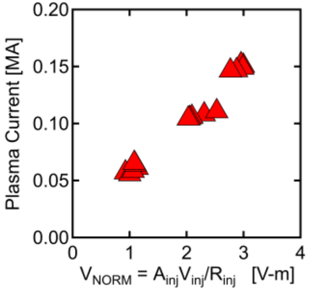
- Helicity injector source design
  - I_{inj}, w: set $I_{TL} \geq I_p$
  - $N_{inj} A_{inj} V_{inj}$: attain / sustain I_p
  - Armoring, limiters to minimize PMI
- Injector system geometry
  - Provide initial relaxation via near-PF null
  - Site conformal to desired plasma shape
  - Facility port access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



Outstanding Issues

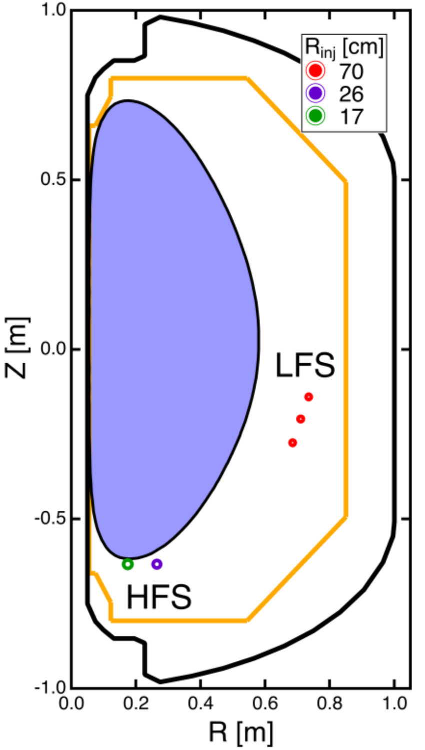
- Scaling to high I_p
  - Larger size
  - High B_T
  - Longer pulse
- Handoff to non-inductive CD
  - LHI → OH H-mode demonstrated
- Confinement, impurities, and dissipation during LHI
- LHI current drive mechanism

Low-B_T $I_p(V_{LHI})$ Scaling



Varying Injector Location Enables Study of LHI Physics and Engineering Tradeoffs

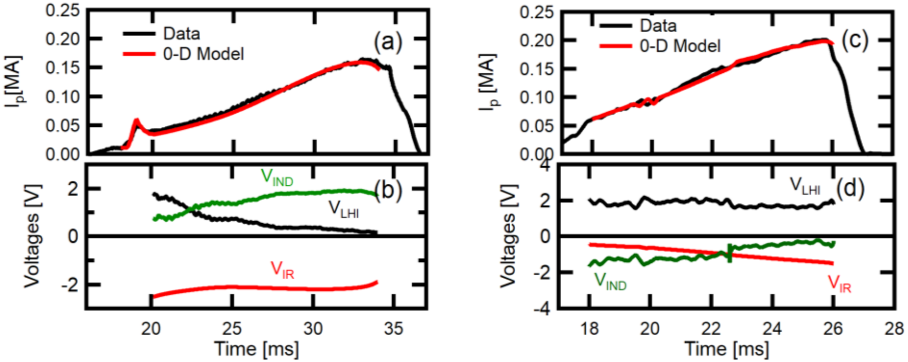
Location of LHI Systems, Static HFS Plasma Geometry



Injector System Comparisons

Quantity	LFS	HFS
N_{inj}	≤ 3	≤ 2
A_{inj}	2 cm²	4 cm²
R_{inj}	0.70 m	0.26 m
B_{inj}	≤ 0.08 T	≤ 0.22 T
V_{inj}	≤ 1.5 kV	≤ 1.5 kV
I_{inj}	6 kA	8 kA
P_{inj}	9 MW	12 MW
$\frac{V_{LHI}}{V_{LHI,LFS}}$	1	3.7

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



- Extrema of feasible LHI geometries deployed in Pegasus

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

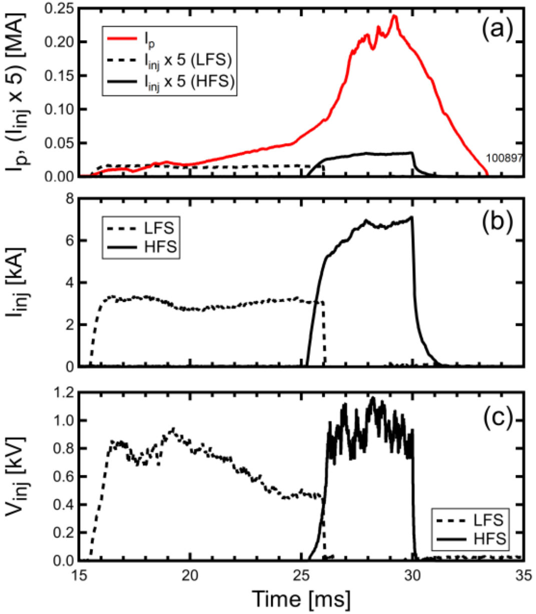
- High-field-side (HFS) injection
  - Injectors in lower divertor
  - Low R_{inj} → strong V_{LHI}
  - Static shape → minimal V_{IND}

- I_p ~ 0.2 MA attained in both geometries
  - Power supply and PMI limited

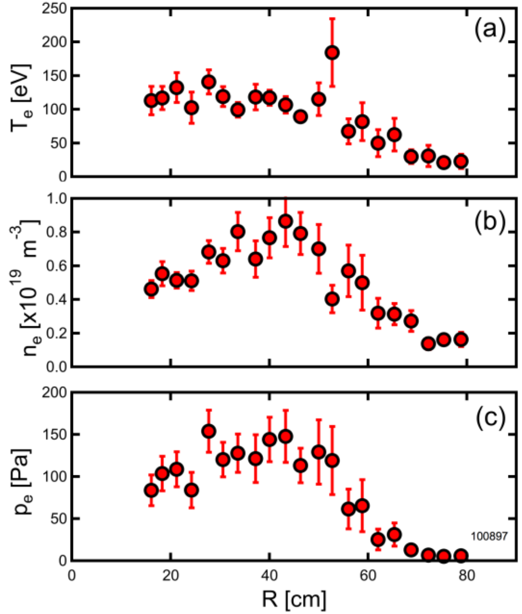
New Scenarios Developed to Transfer Between LFS → HFS Injector Systems and Combine Strengths of Each Geometry

- LFS → HFS handoff provides ready access to full-B_T operations with HFS injectors
  - LFS: Simpler relaxation access, lower PMI
  - HFS: Higher V_{LHI}
  - Seamless transfer between separate LHI systems
- Informs HFS high-B_T LHI system design
  - Relaxation, sustainment requirements may demand separate hardware features in higher-field machines
- Record LHI I_p = 0.225 MA attained
  - Peaked temperature, density pressure profiles
  - T_e > 100 eV, n_e ~ 1×10^{19} m^{-3}

I_p = 0.225 MA LFS → HFS LHI Startup
R_{inj} = 26 cm, B_T = 0.15 T



Thomson Scattering Profiles
R_{inj} = 26 cm, t = 28.5 ms



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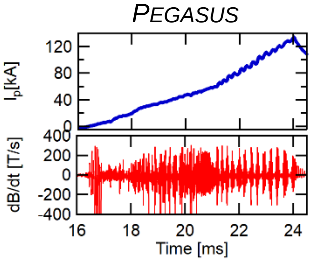
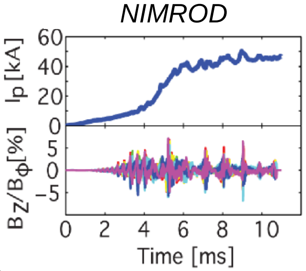
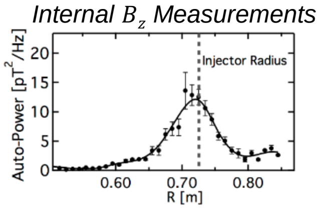
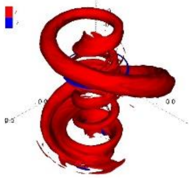
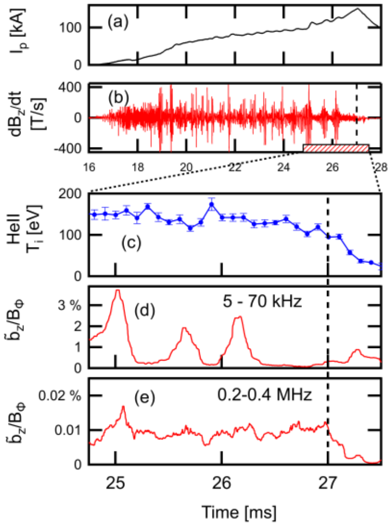
Recent Experiments Suggest High Frequency Magnetic Activity and Reconnection Play a Role in LHI Current Drive

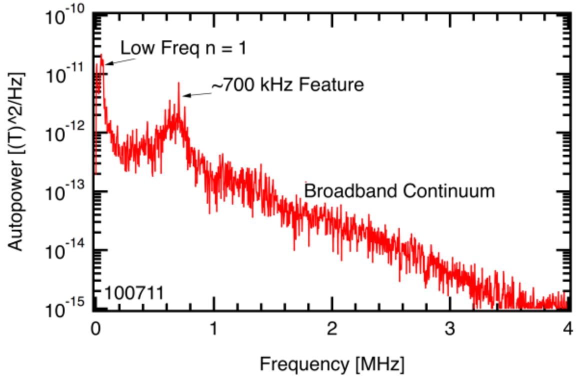












- NIMROD simulations of HFS LHI reproduce features observed in experiment
  - Relaxation to tokamak-like state
  - Bursty 10's kHz $n = 1$ activity on LFS Mirnovs
  - Identifies helical current stream reconnection as a current drive mechanism

- Anomalous, reconnection-driven ion heating present during LHI
  - Continuously sustains $T_i > T_e$
  - Consistent with two-fluid reconnection theory
  - T_i correlated with high frequency activity

- Internal magnetic measurements find significant high-frequency spectral content
  - ~700 kHz feature: arc source
  - Broadband continuum

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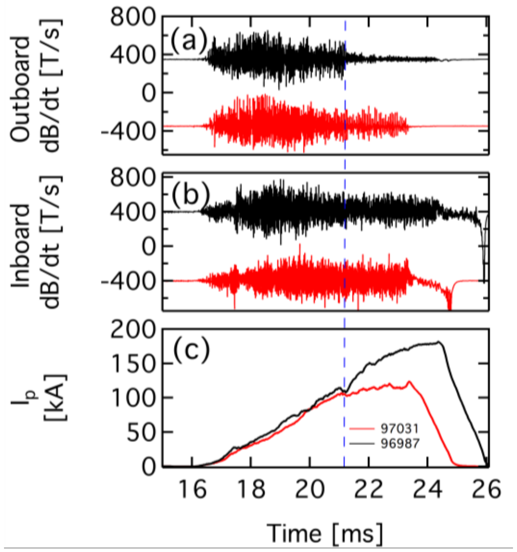
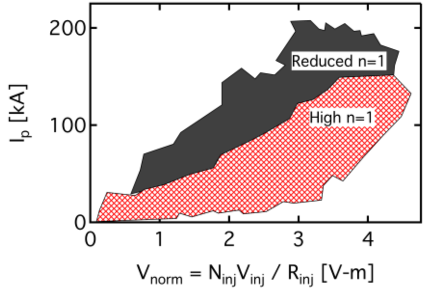
Operating Regime with Significant Reduction of Large-Scale MHD and Increased I_p Found During HFS Injection Experiments

- Abrupt MHD transition can lead to improved performance
  - Low-f $n = 1$ activity reduced by over 10× on LFS
  - Bifurcation in I_p evolution following transition
  - Up to 2× I_p at fixed V_{LHI}
  - Linear scaling of $I_p(V_{LHI})$ in this regime at low $B_T = 0.05$ T
- Sustained discharges without $n = 1$ activity possible
  - Implies $n = 1$ mode not responsible/required for LHI current drive
- Mechanism for transition unclear, under investigation
  - $n = 1$ reduction interpreted as stabilization of injector streams
  - Extremely sensitive to B_T, B_Z, I_p, fueling
  - Access scales with $I_p/I_{TF} \sim 1$: min-$|B|$ well?
  - If extensible to higher B_T, may afford simpler LHI system requirements

New Reduced MHD Regime Improves Plasma Performance



Operating Space for ~8,500 HFS LHI Discharges



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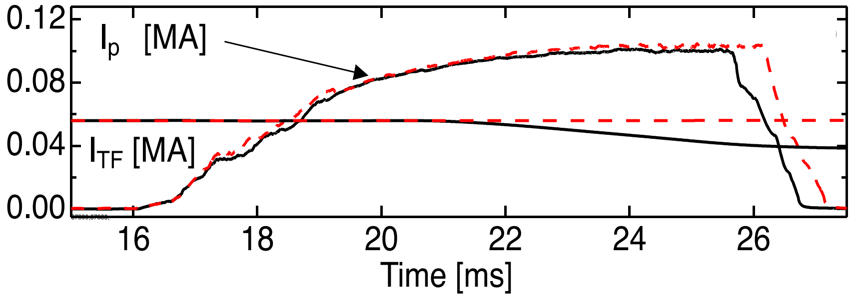
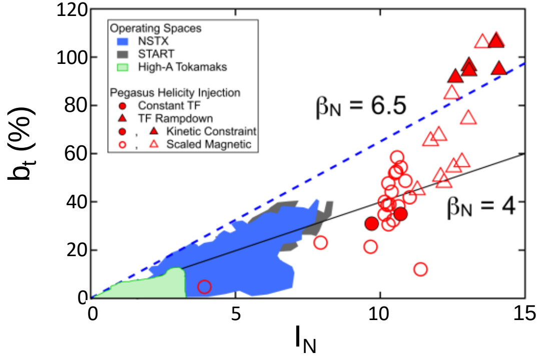
HFS LHI at Near-Unity A Provides Access to $\beta_t \sim 100\%$ and Magnetic Configurations with Minimum $|B|$ Wells

- Access to highly-shaped, high β_t plasmas
  - Low $I_{TF} \sim 0.6\ I_p$
  - $A \sim 1$: high κ, low ℓ_i, and high $\beta_{N,max}$
  - Reconnection-driven $T_i > T_e$
  - Disrupting at ideal no-wall stability limit
- High-β_t equilibria contain large min-$|B|$ region
  - Up to 47% of plasma volume
  - Potentially favorable for stabilization of drift modes, reduction of stochastic transport
- Minimum $|B|$ regime arises from 3 major influences
  - $B_p \sim B_T$ at $A \sim 1$
  - Hollow $J(R)$
  - Pressure-driven diamagnetism (although $\beta_p < 1$)

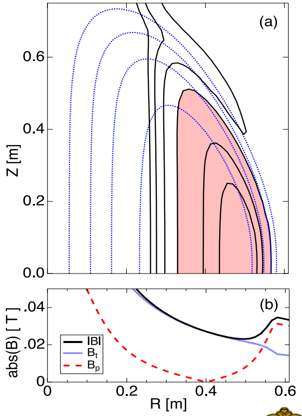
High $I_N = 5AI_p/I_{TF} > 10$ accessible at $A \sim 1.2$ in PEGASUS



Troyon Stability Diagram for Tokamaks, STs



Min $|B|$ Well in $\beta_t \sim 100\%$ Plasma



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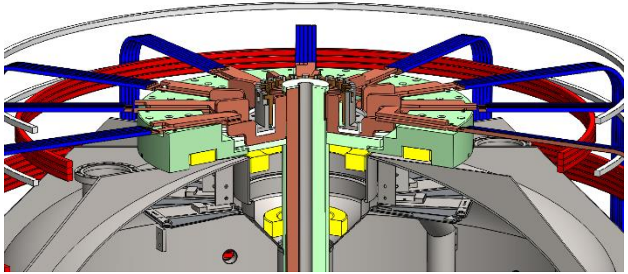
URANIA Experiment: Converted PEGASUS Facility for US Non-Solenoidal Development Station

- Mission: compare / contrast / combine reactor-relevant startup techniques at $I_p \sim 0.3$ MA
  - LHI, CHI, RF/EBW Heating & CD
  - Goal: guidance for ~1 MA startup on NSTX-U, beyond
- Upgrades from PEGASUS to URANIA:
  - New centerstack assembly: No solenoid magnet
  - Increase B_T 4×: 0.15 → 0.6 T
  - Longer pulse: 25 → 100 ms
  - Improved shape control with new PF, divertor coils
  - Diagnostic neutral beam: kinetic and impurity diagnostics
  - EBW RF Heating & CD (w/ ORNL)
  - Transient, Sustained CHI (w/ Univ. Washington, PPPL)
- Engineering design underway
  - Centerstack upgrade scheduled for late 2019

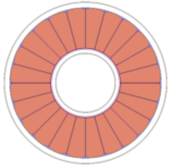
URANIA Concept Drawing



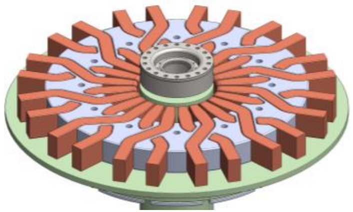
PEGASUS

High-Stress OH Solenoid
12-turn TF Bundle

URANIA



Solenoid-free
24-turn TF Bundle



URANIA Experiment

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