Integrated Study of Solenoid Free Tokamak Startup on the PEGASUS and URANIA Experiments

J.A. Reusch

G.M. Bodner, M.W. Bongard, M.T. Borchardt, R.J. Fonck, J.A. Goetz, A.K. Keyhani, B.A. Kujak-Ford, B.T. Lewicki, M.D. Nornberg, A.C. Palmer, C. Pierren, A.T. Rhodes, N.J. Richner, C. Rodriguez Sanchez, C.E. Schaefer, J.D. Weberski, and G.R. Winz

University of Wisconsin-Madison

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PEGASUS Toroidal Experiment

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



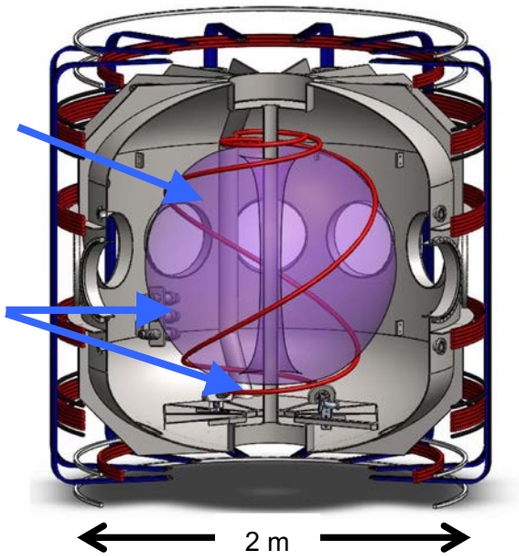
LFS System

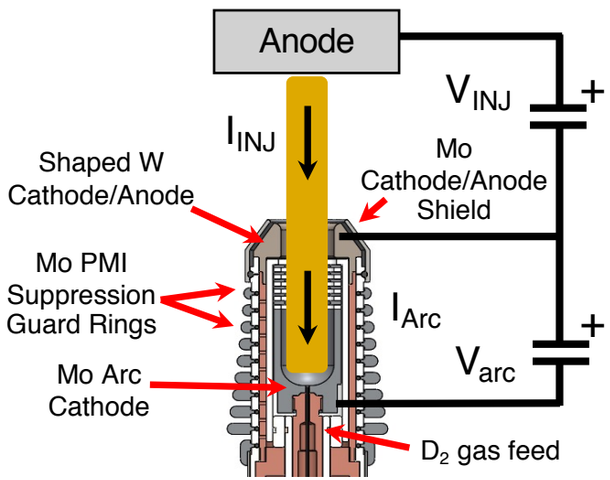
Injected Current Stream

Local Helicity Injectors



HFS System

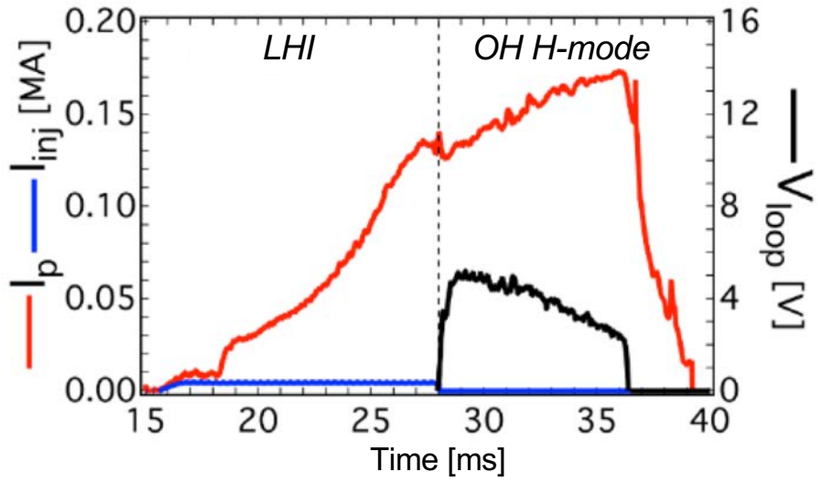




PEGASUS Parameters		Injector Parameters	
I_p	≤ 0.23 MA	$\sum I_{inj}$	≤ 8 kA
Δt_{shot}	≤ 0.025 s	I_{inj}	≤ 4 kA
B_T	0.15 T	V_{inj}	≤ 2.5 kV
A	1.15–1.3	N_{inj}	≤ 4
R	0.2–0.45 m	A_{inj}	$= 2\text{-}4$ cm^2
a	≤ 0.4 m	I_{arc}	≤ 4 kA
κ	1.4–3.7	V_{arc}	≤ 0.5 kV

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Non-Solenoidal LHI Startup to OH H-mode



- 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
  - Over 0.2MA of plasma current demonstrated on PEGASUS
  - 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

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

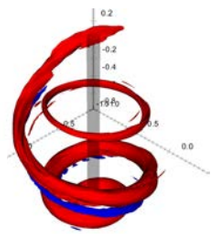
  - Helicity conservation

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

- 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



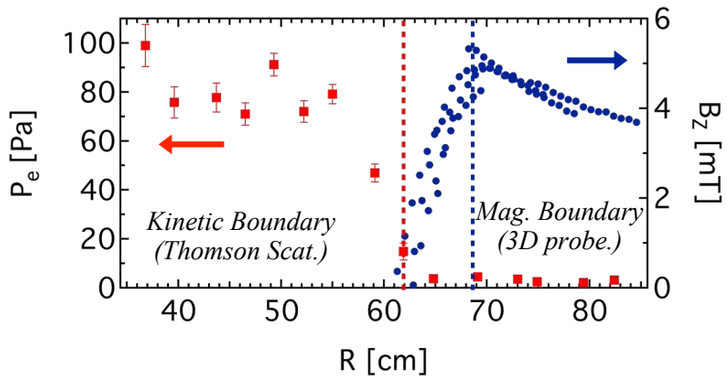
Reconnecting LHI Current Stream

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Outstanding Issues

- Confinement, impurities, and dissipation during LHI
  - "two-zone" structure observed
- LHI current drive mechanism(s)
- Scaling to high I_p
  - Larger size, higher B_T, longer pulse
- Handoff to non-inductive CD
  - LHI → OH H-mode demonstrated

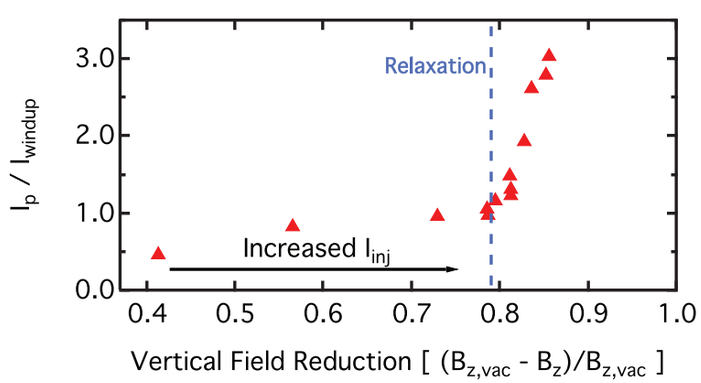
"Two Zone" confinement observed in LHI



Considerations for Next Step LHI

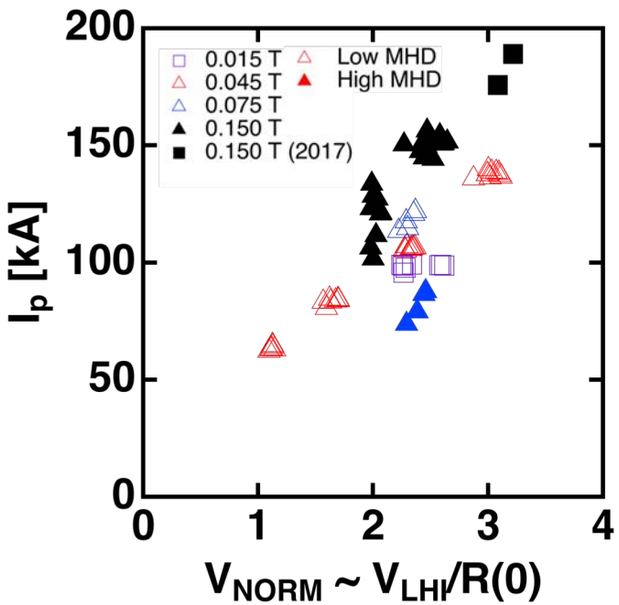
- Injector system geometry
  - Provide initial relaxation via near-PF null
  - CD efficiency / transport
  - Facility port access compatibility
- Helicity injector source design
  - I_{inj}, w: set $I_{TL} \geq I_p$
  - $N_{inj} A_{inj} V_{inj}$: attain / sustain I_p
  - Armoring, limiters to minimize PMI
- Injector impedance and power systems

Relaxation occurs if LHI creates near-PF null

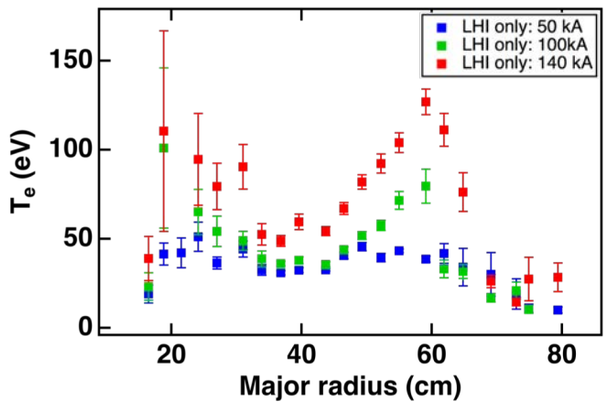


Helicity Balance Limited HFS LHI Discharges Exhibit Linear I_p, Positive B_T Scalings

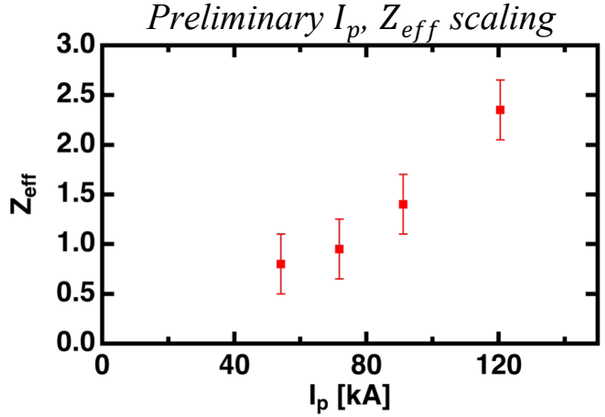
- With constant shape and n_e, I_p increases linearly with V_{LHI}
- CD efficiency increases modestly with B_T



- Observe variation in T_e with V_{LHI}
  - $B_T(0) = 0.045$T: T_e hollows as drive increases
  - Ψ mapping allows R_{plasma} calculation
  - Z_{eff} appears to increase with I_p

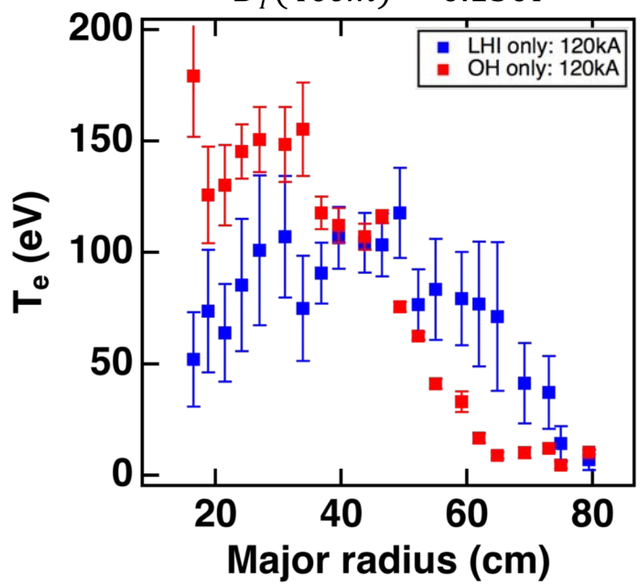


Preliminary I_p, Z_{eff} scaling



- At full B_T, T_e typically peaked
- Similar performance to OH L-mode at this field

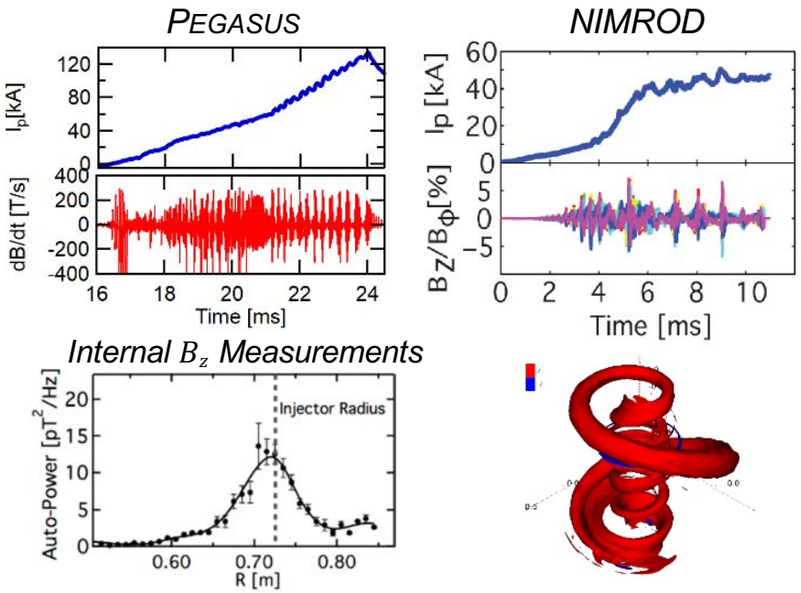
LHI – OH comparison
$B_T(40cm) = 0.150T$

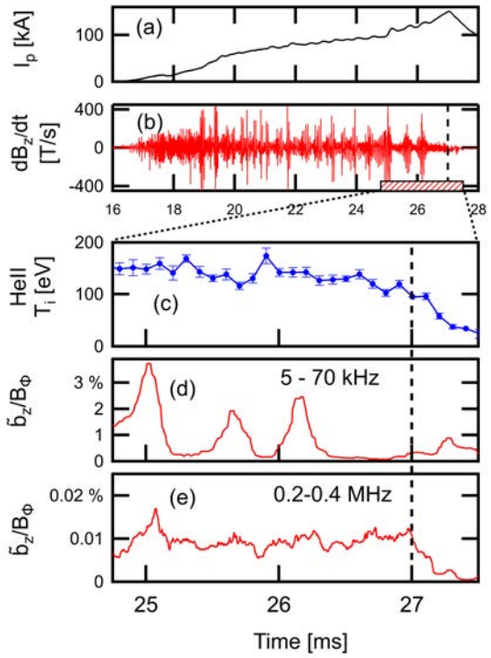


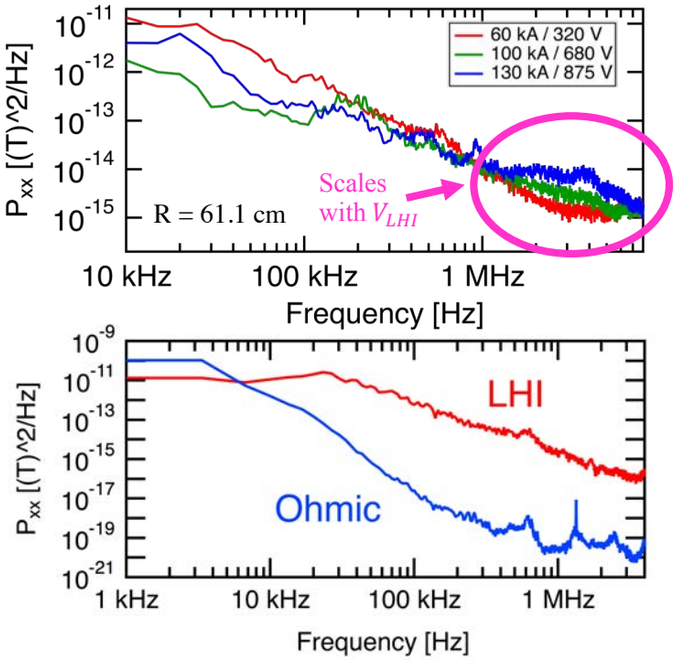
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Recent Experiments Suggest High Frequency Magnetic Fluctuations Fundamental to Underlying LHI Current Drive







- 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

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- 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
  - Suggests $n = 1$ not critical

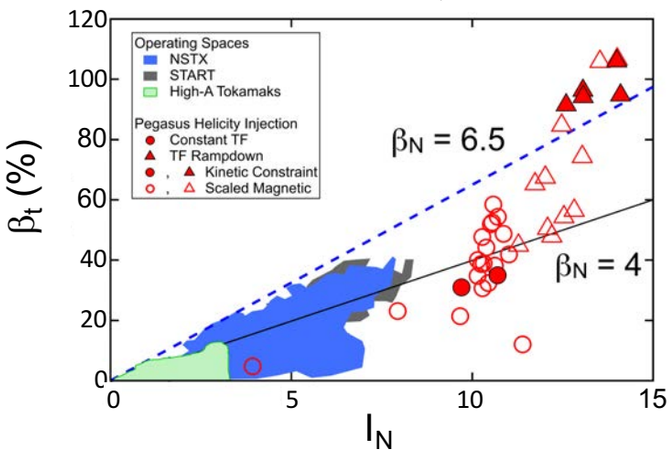
- Internal magnetic measurements find high-frequency spectral content scales with I_p and/or V_{LHI}
  - High frequency shows strongest correlation with I_p
  - Significantly lower fluctuation power seen in OH plasmas

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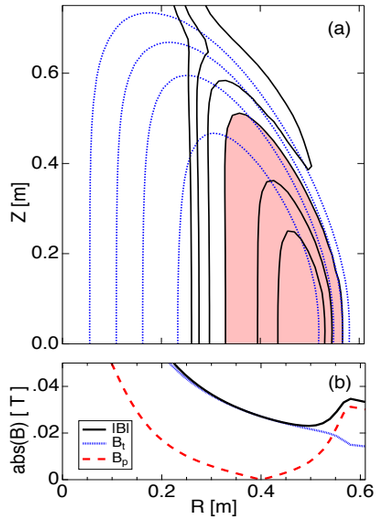
LHI at Near-Unity A Enables Access to Extreme ST Operating Space

- Access to highly-shaped, $\beta_t \sim 100\%$ plasmas*
  - Low $I_{TF} \sim 0.6\, I_p$
  - $A \sim 1$: high κ, low ℓ_i, high I_N, 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
  - High degree of omnigeneity of magnetic surfaces
  - 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 $\beta_p < 1$)

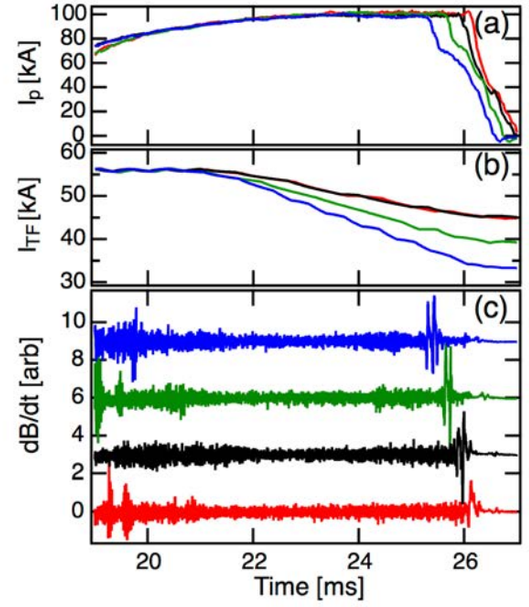
Troyon Stability Diagram for Tokamaks, STs

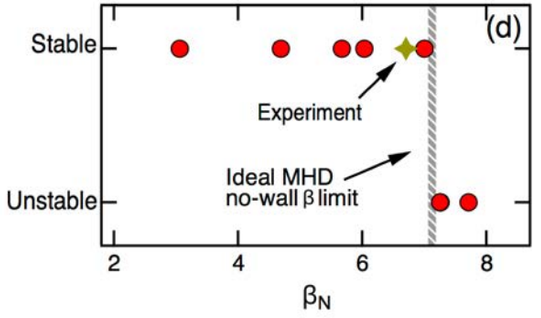


Min $|B|$ Well in $\beta_t \sim 100\%$ Plasma



Disrupts at the No-wall β Limit





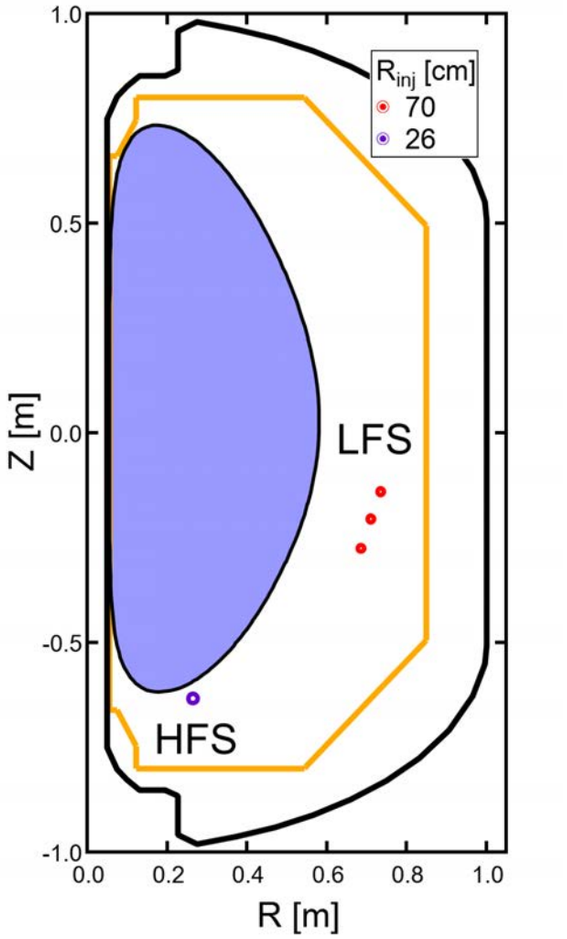
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*Schlossberg, D.J., *et al.*, PRL, 2017
Reusch, J.A., *et al.*, Phys. Plasmas, 2018

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Assessing Physics and Engineering Tradeoffs of Injector System Location

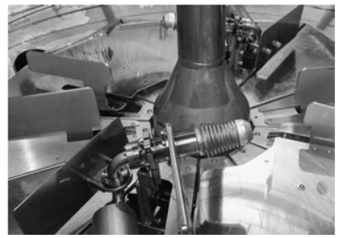
Location of LHI Systems, Static HFS Plasma Geometrv



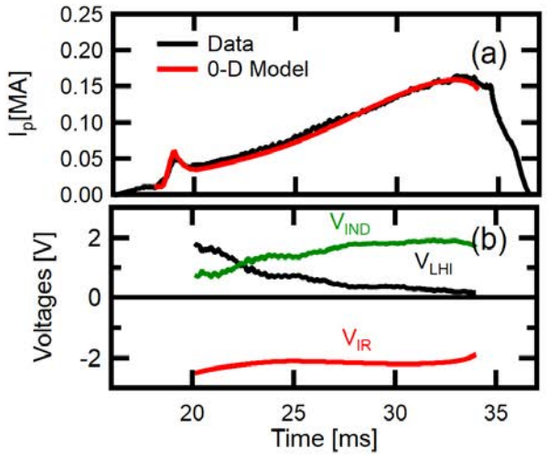
Injector System Comparisons

Quantity	LFS	HFS
N_{inj}	≤ 3	≤ 2
A_{inj}	2 cm^2	4 cm^2
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

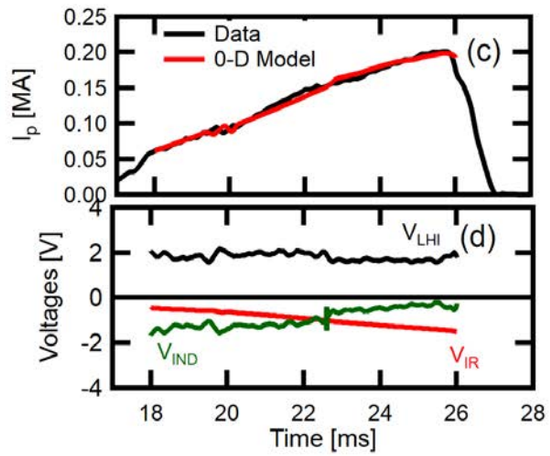




LFS: Non-solenoidal Induction



HFS: Helicity Injection



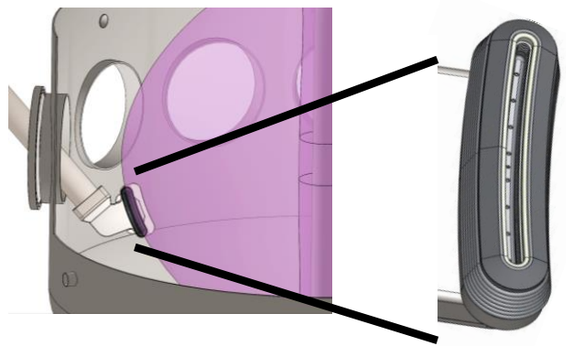
- Extrema of feasible LHI geometries deployed in Pegasus
- Low-field-side (LFS) injection
  - Injectors near outboard midplane
  - Relaxation readily achieved
  - High R_{inj} → low V_{LHI}
  - Dynamic shape → strong V_{IND}
- High-field-side (HFS) injection
  - Injectors in lower divertor
  - Relaxation challenging
  - Low R_{inj} → strong V_{LHI}
  - Static shape → minimal V_{IND}
- I_p ~ 0.2 MA, similar T_e and n_e attained in both geometries
- Conclusion: Choice of injector location driven by practical rather than physics considerations

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Next Step LHI: Physics/Engineering Requirements Make LFS Injection More Attractive, Reactor Relevant Solution

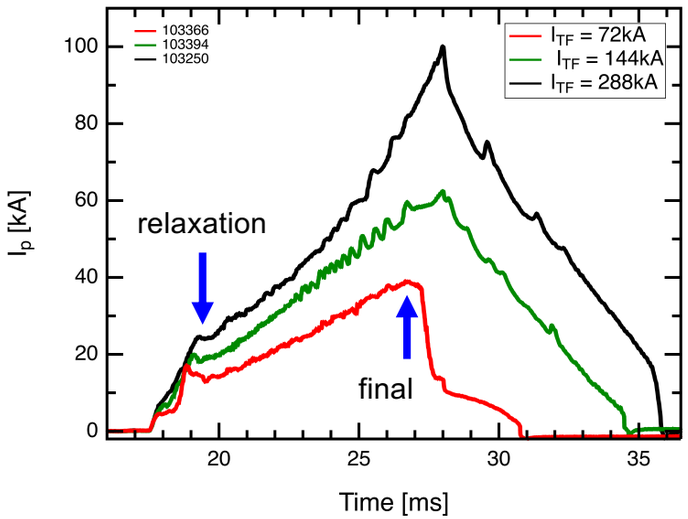
- Outboard midplane access allows fully retractable system
- Power-balance modeling: LFS LHI has extended Taylor-limited I_p phase
  - Suggests strong I_p gains possible by increasing I_{TL} early in time
- B_T scan experiments on PEGASUS support this
  - Increase of < 20 kA at relaxation results in > 60 kA final
- URANIA will have 4x increase in B_T to raise I_{TL}

Next Step LFS LHI System

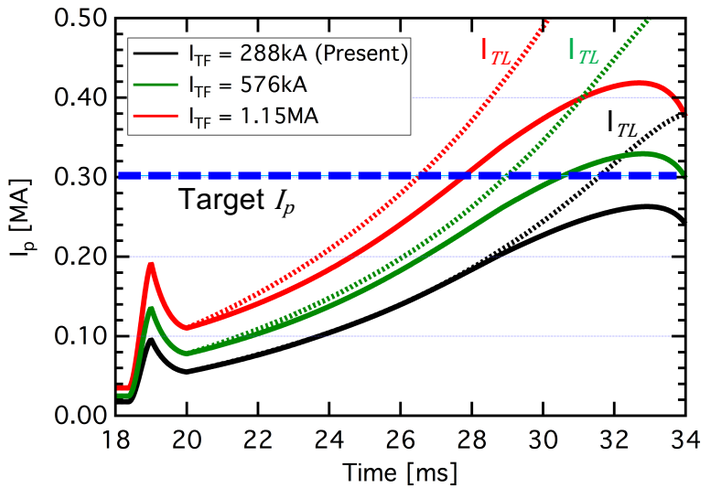


High $A_{inj} = 16\text{cm}^2$
High $I_{inj} = 16\text{kA}$
Low $w = 1\text{cm}$
Low $V_{inj} < 1\text{kV}$

PEGASUS Scaling Experiment: Varying Initial I_{TL} Raises Final I_p



0-D $I_p(t)$ Power-Balance Projections with New Injector System



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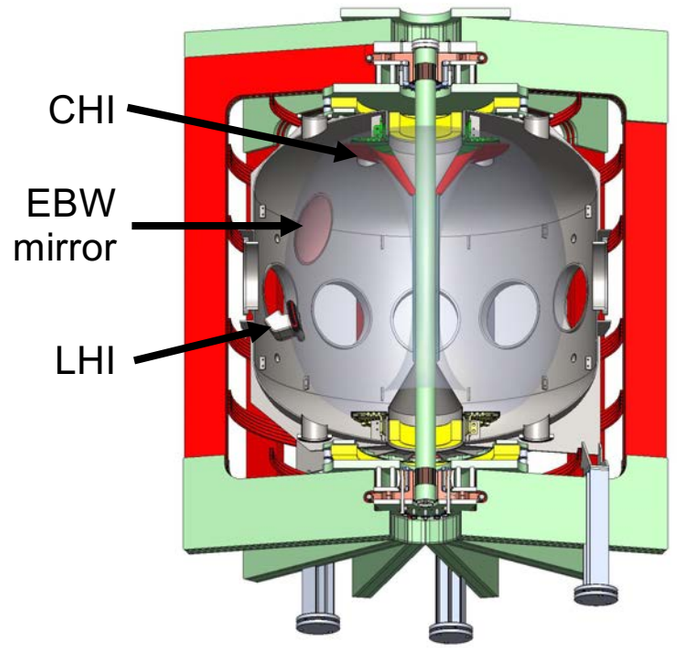
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URANIA Experiment: Converting PEGASUS Facility to US Non-Solenoidal Development Station

- 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 in progress
  - Centerstack upgrade scheduled for late 2019

$B_T \leq 0.6$ T; Multi-coil Divertor

No OH Solenoid!



Collaborative Enterprise

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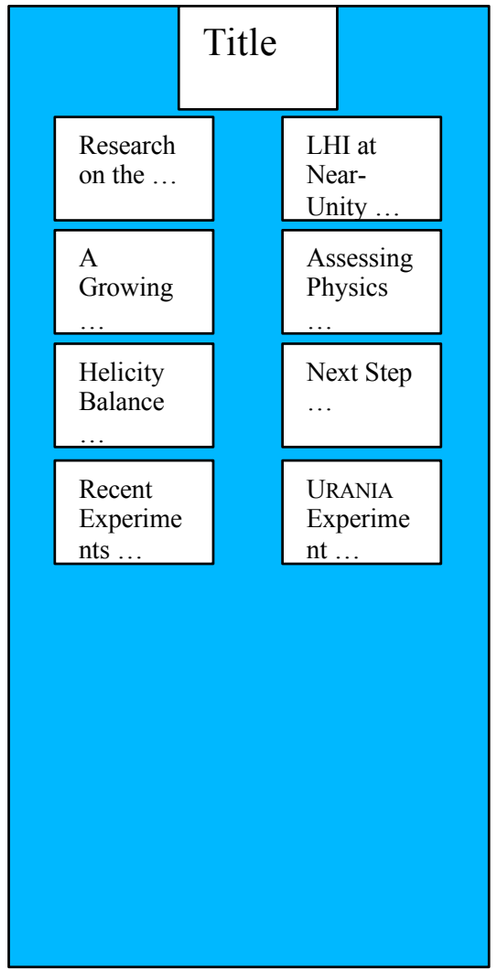
UNIVERSITY of WASHINGTON

OAK RIDGE National Laboratory

PPPL

URANIA Experiment

Layout



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