# Towards a Predictive Capability for Local Helicity Injection Startup

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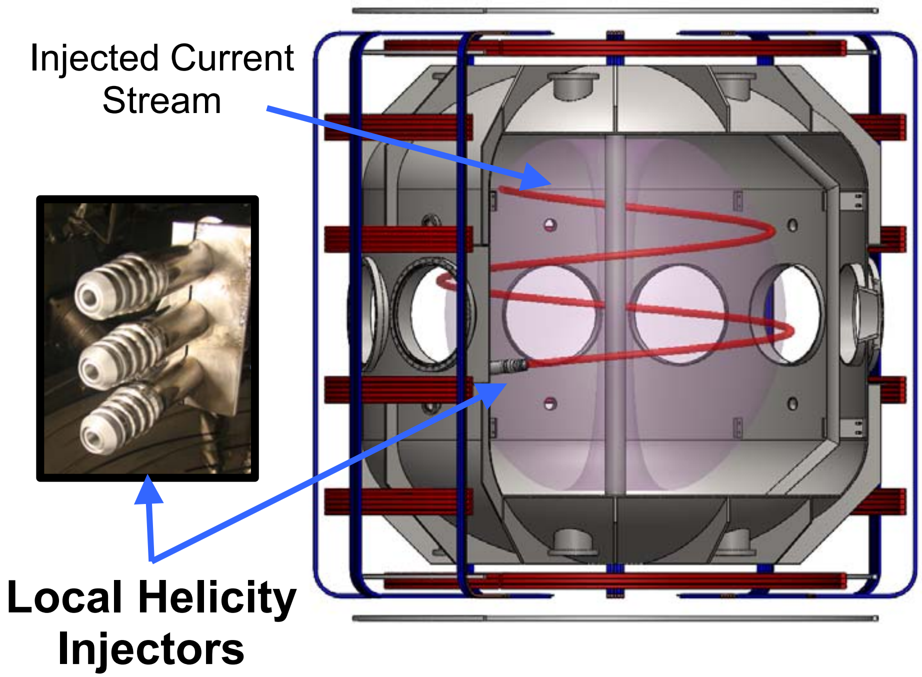
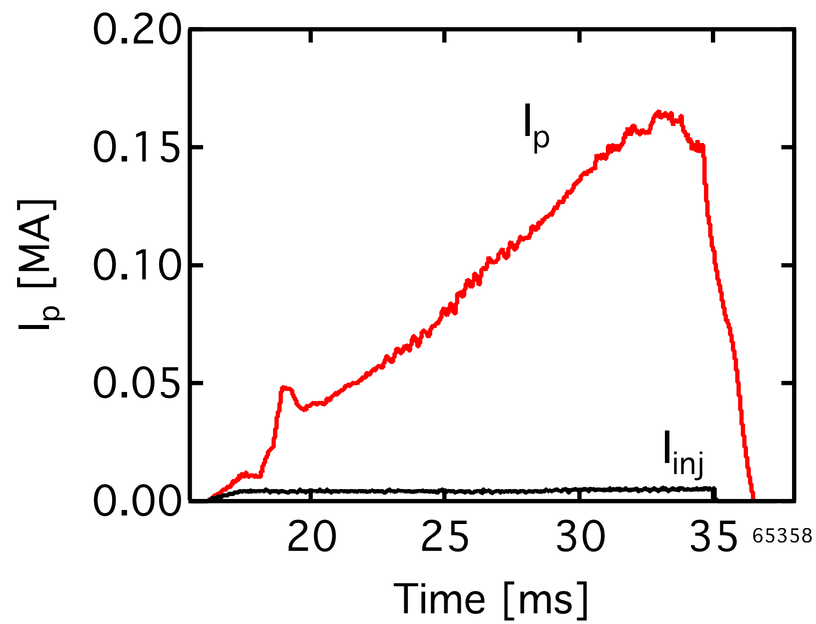
PEGASUS Toroidal Experiment

# Local Helicity Injection (LHI) is a Promising Non-Solenoidal Startup Technique

Current injected on outboard side




$I_p \leq 0.18$ MA ($I_{inj}$ = 5 kA)




- Unstable current streams form tokamak-like state via Taylor relaxation
- Appears scalable to MA-class startup

# A Hierarchy of Predictive Models Being Developed for LHI Startup

1. Maximum $I_p$ limits*

Taylor Relaxation

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

Helicity Conservation

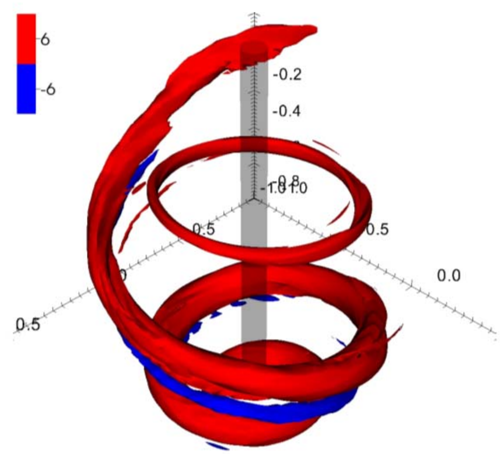
$$V_{LHI} \approx \frac{A_{inj} B_{\varphi,inj}}{\Psi} V_{inj}$$

1. 0-D power-balance $I_p(t)$

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

1. 3D Resistive MHD (NIMROD)**
   – See Sovinec, GP8.00047

Simulated current stream reconnection in NIMROD




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



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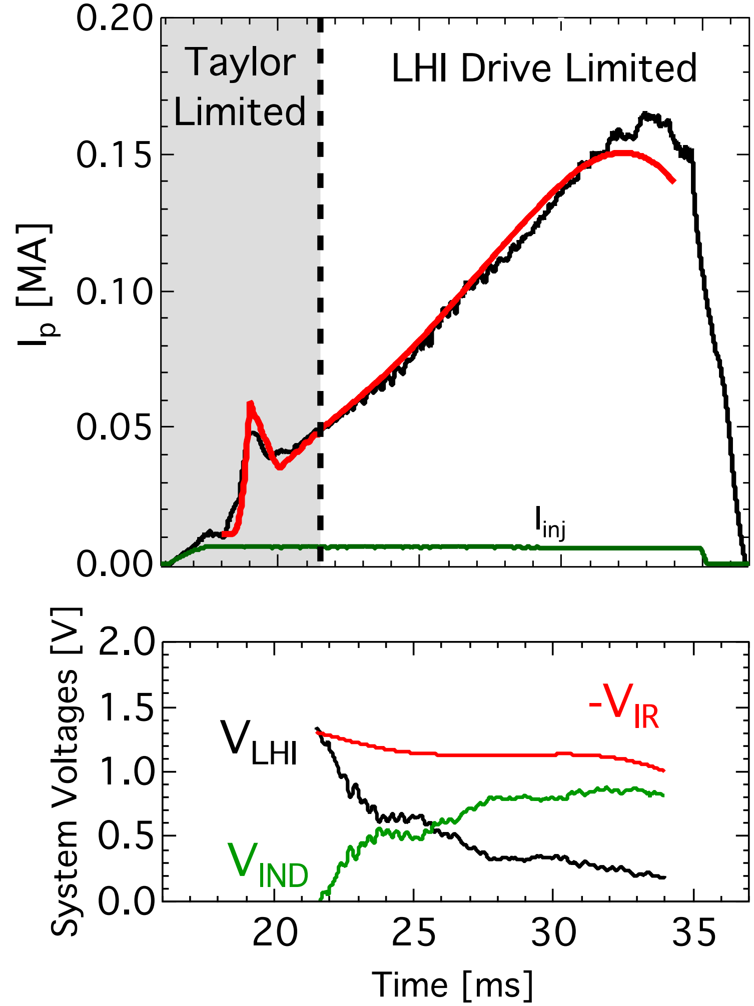
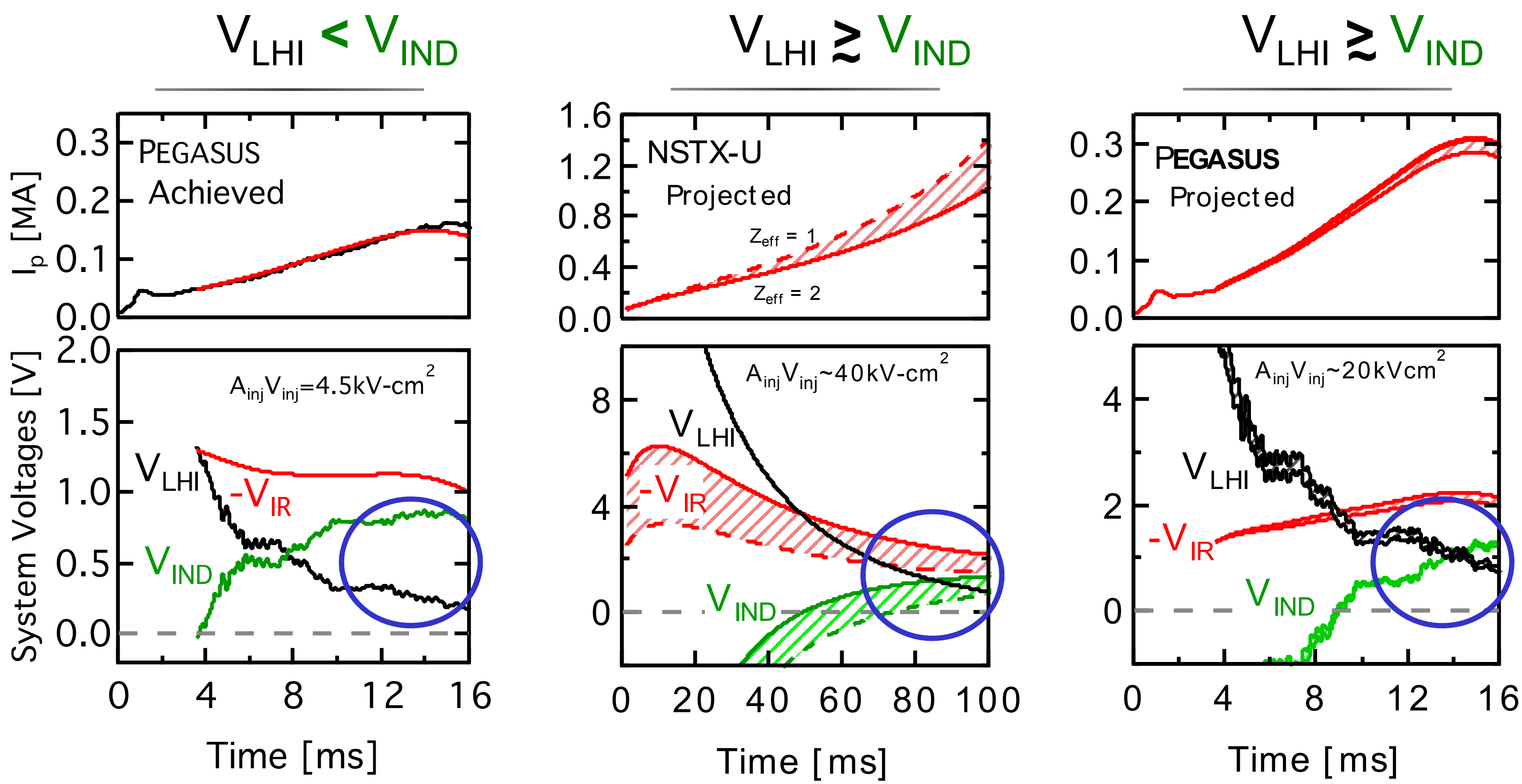
# 2. 0-D Power-Balance: Lumped-Parameter Model for Predictive $I_p(t)$

- Model elements:
  - Inputs: $R_0(t)$, shape(t), $V_{LHI}(t)$, $\eta(t)$, $\ell_i(t)$
  - Low-*A* inductance, force-balance
- Reasonable agreement between calculated $I_p(t)$ and measurement
- High-$I_p$: current drive dominated by PF induction, geometry evolution

0-D model predictions vs data



# Physics Test for MA Startup on NSTX-U Requires Increased Helicity Injection Drive

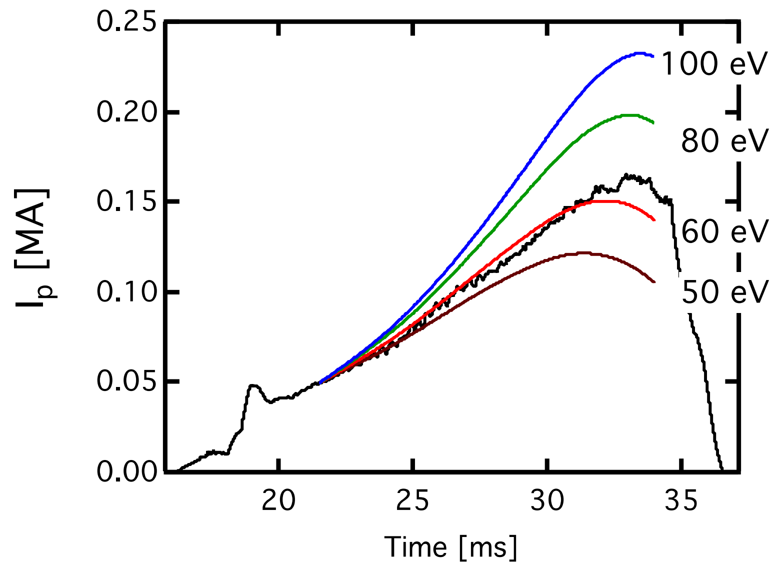



- Confinement when $V_{LHI} \gtrsim V_{IND}$ is a critical issue
  - At $I_p \sim 0.2$–$0.3$ MA in PEGASUS

*J.L. Barr, APS DPP 2014*

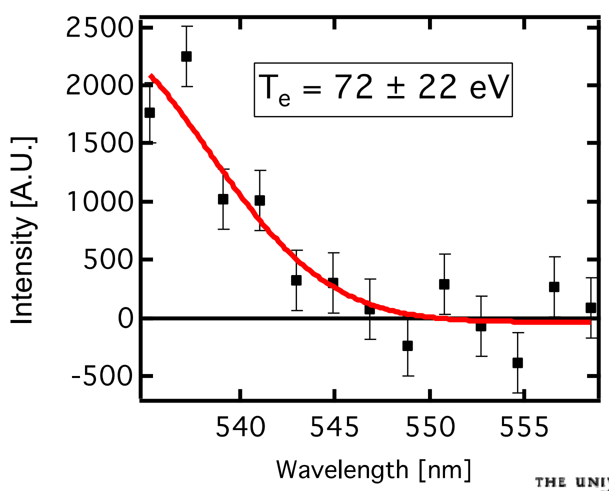
# Knowledge of Confinement an Important Question for Predictability

- $I_p(t)$ model depends critically on η
  - Initial Thomson scattering: $T_e(0)$~70 eV




- Dual confinement regimes?

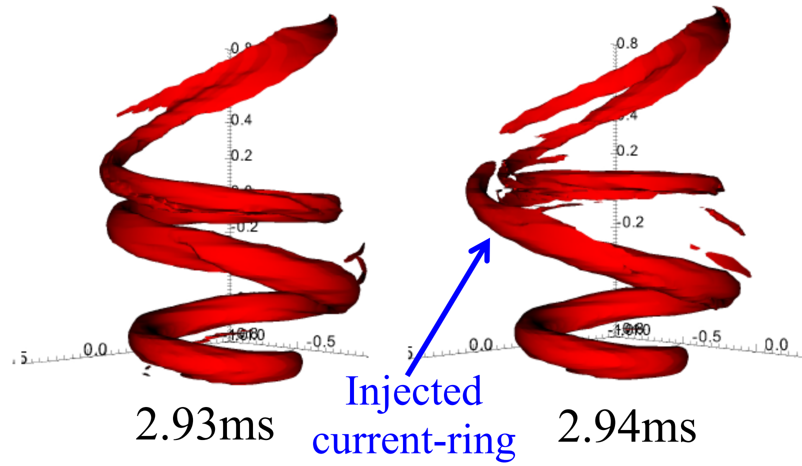
| Warm Core | Cool Edge |
|---|---|
| OH-like | Stochastic |
| Inductive drive | Reconnection |
| Low $\tilde{B}/B$ | Large $\tilde{B}/B$ |

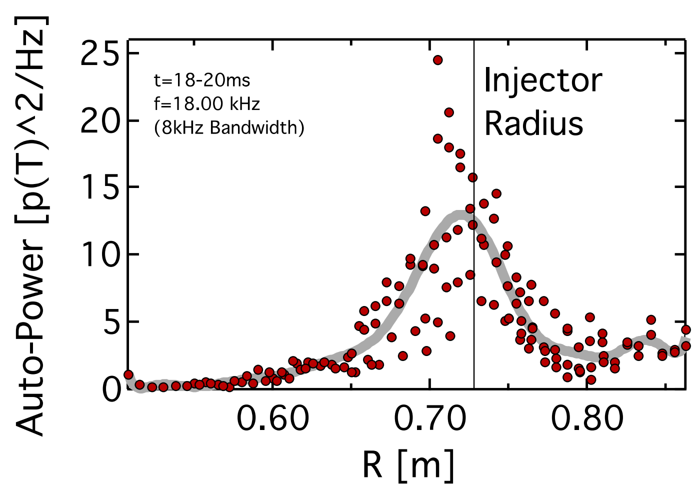


# 3. NIMROD Simulations Show $I_p$ Growth Resulting from Reconnection in Edge

- Resistive MHD modeling (NIMROD)
- Divertor injection
  - Coherent current streams reconnect
  - Inject current rings
- Qualitative agreement to experiment:
  - Injector-localized MHD
  - Intermittent MHD bursts
  - $\Delta I_p \sim I_{inj}$ jumps
  - Reconnection driven anomalous ion heating observed (M.G. Burke, PP8.00095)

Calculated current rings in NIMROD**



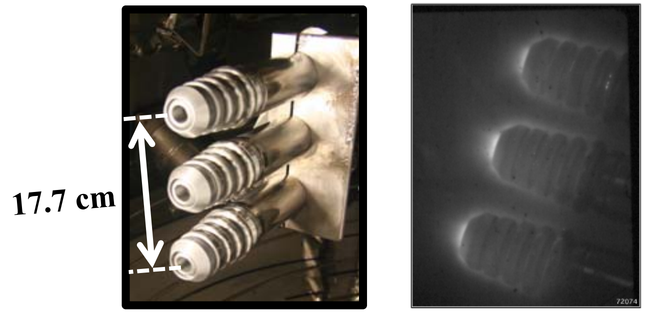

**J. O'Bryan, PhD. Thesis, UW Madison 2014

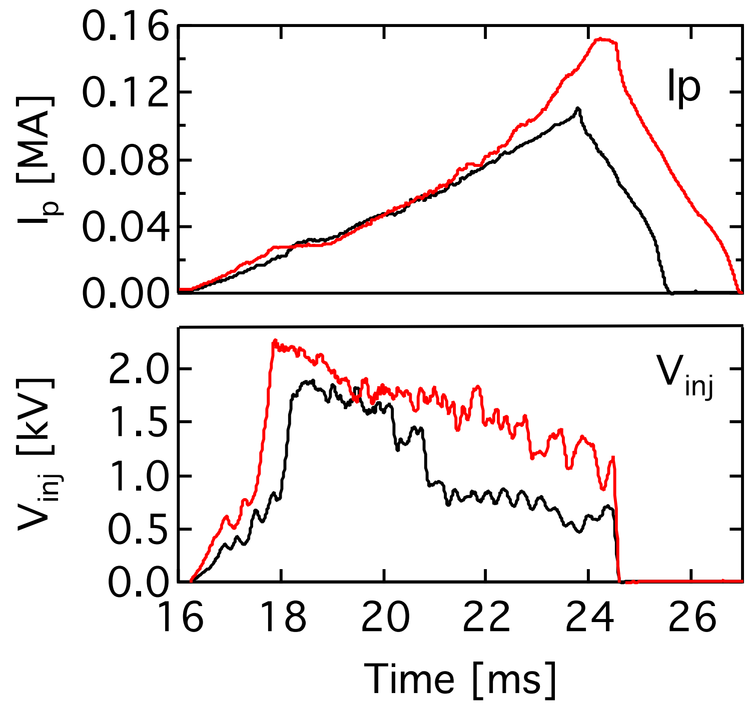
# Understanding Injector Physics Enables High $V_{inj}$ Operation

- High-power, low-PMI while immersed in scrape-off plasma
  - Cathode shaping mitigates cathode spots
  - Shield rings, local limiter prevent arc-back
- $I_p$ increases with $V_{inj}$
- $J_{inj}$, $V_{inj}$ depend on tokamak scrape-off density
  - Space-charge neutralization of streams

$$J_{INJ} = n_{edge} e \sqrt{\frac{2e}{m_e}} \sqrt{V_{INJ}}$$

*Advanced injectors with quiescent operation*




*J.L. Barr, APS DPP 2014*

# Technology & Science Challenges for NSTX-U & Beyond

- Long-pulse startup (0.1 s)
  - Injector heat load
  - Edge density control
  - Plasma control
- High $B_{TF}$
  - Confinement scaling
  - Effective injector size
  - Initial tokamak formation
  - Reconnection with high guide field
- Plasma size scaling
- Close fitting wall
  - Potentially complicates relaxation

Injector technology evolving to meet physics challenges

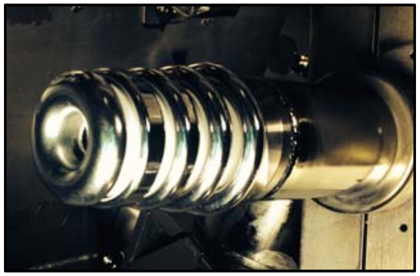
**Concave cathode**

↓

**Frustum cathode, local limiter**

↓

**High heat-flux cathode, shield rings**



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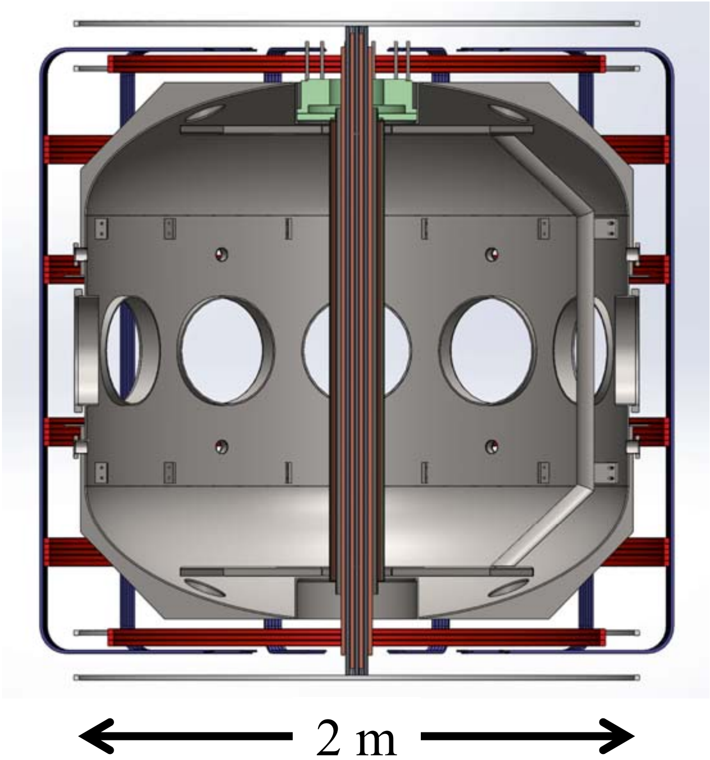
# PEGASUS-U to Address Physics, Technology for Scalable LHI Startup

- Long pulse startup (0.1 s)
- New central column ($A$ ~ 1.2)
  - Increased $B_{TF}$ (5x)
  - New OH solenoid, PPPL (6x V-s)
- Enhanced divertor coils
- Upgraded High-$V_{LHI}$ Injectors
  - Remotely insertable
- Core diagnostics:
  - Multipoint TS
  - CHERS via DNB
- Supporting the 5 year plan for NSTX-U

PEGASUS-U



# Moving Towards Predictable, MA-Class, Non-Solenoidal Startup

- A hierarchy of models is being developed for LHI startup:
  - Max $I_p$: helicity conservation, Taylor relaxation
  - $I_p(t)$: 0-D power-balance (future: TSC)
  - Detailed dynamics: resistive MHD (NIMROD)

- Outstanding issues:
  - Scaling to high toroidal field, longer-pulse, large size
  - Confinement, stability in LHI drive dominant regime
  - Edge density, $J_{inj}$ control strategies
  - Advanced injector development

- PEGASUS-U will address critical LHI physics issues for NSTX-U

*K.E. Thome talk: next this session, GO3*
*PEGASUS group posters: session PP8*

# Predictive Understanding of Plasma Impedance Required for Projecting to Higher $I_p$

- Determines feasible $V_{INJ}$, $A_{INJ}$, $I_{INJ}$ and demands on power system

- Governed by plasma physics of arc source and tokamak edge
  - Low $I_{INJ}$: Double layer $J_{INJ} \sim V_{INJ}^{3/2}$
  - High $I_{INJ}$: Space charge neutralization of e-beam by edge plasma

$$J_{INJ} = n_{edge} e \sqrt{\frac{2e}{m_e}} \sqrt{V_{INJ}}$$

- $n_{edge}$ dependence to be validated
  - Assuming $n_{edge} \sim$ fill pressure

*Ramp-up I-V characteristics for Pegasus injectors agrees with 2-parameter model across wide range of fill pressures*