Advancing High Current Startup via Localized Helicity Injection in the Pegasus Toroidal Experiment

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on behalf of the Pegasus Team



University of Wisconsin-Madison

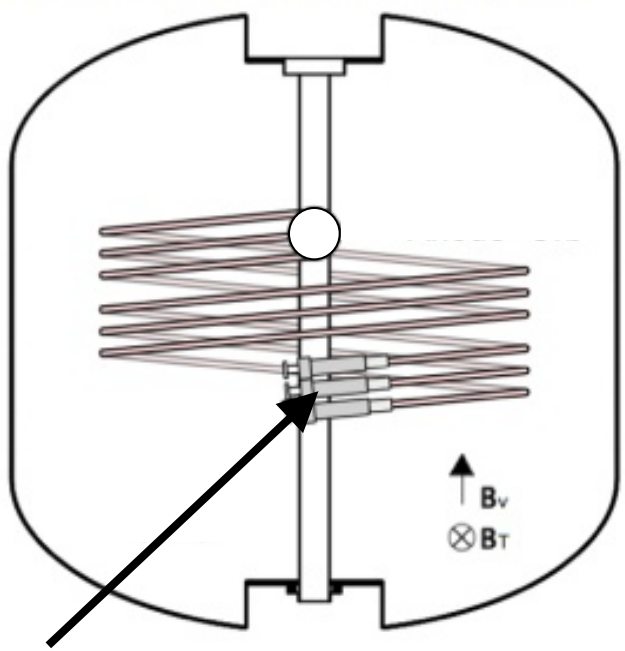
APS-DPP

Denver, CO
Nov. 11-15, 2013

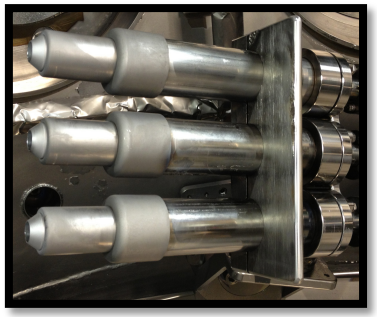


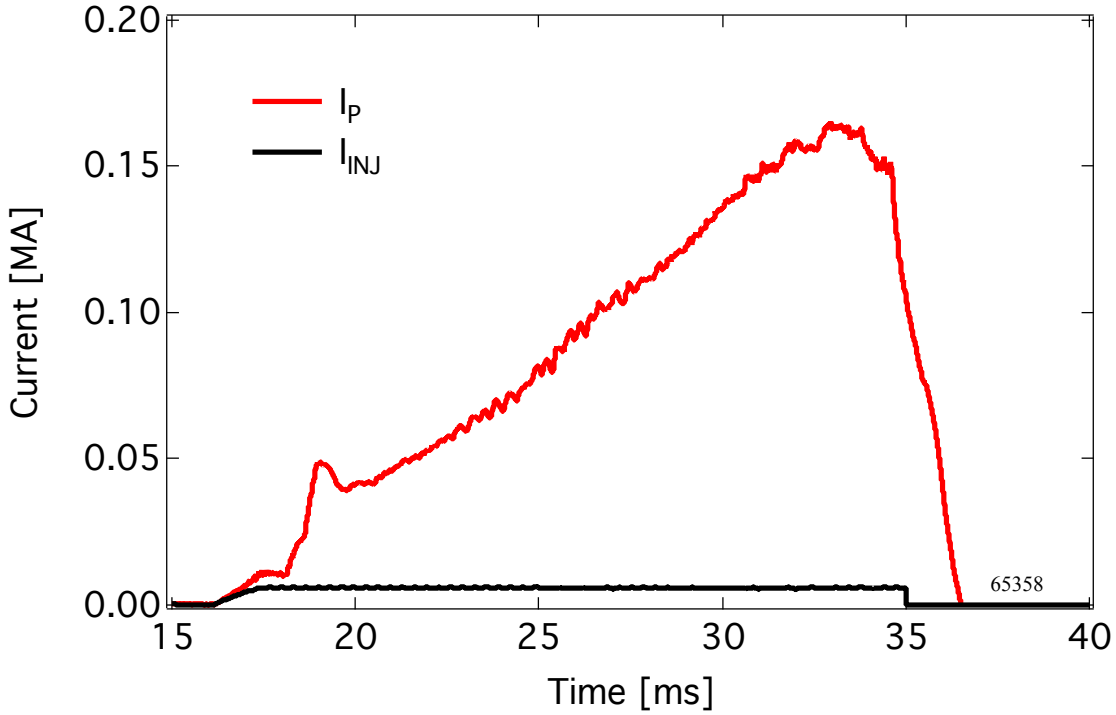
PEGASUS Toroidal Experiment

Pegasus is a Compact, Ultralow-A ST Developing Localized Helicity Injection Start-Up



Local Helicity Injectors





- Current injected along field lines
- Unstable current streams relax towards Taylor minimum energy (tokamak-like) state
- Consistent with helicity conservation

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Achievable I_p Constrained by Helicity Balance, Taylor Relaxation

- Taylor Relaxation:

$$I_p \leq \left[\frac{C_p}{2\pi R_{INJ}\mu_0} \frac{\Psi I_{INJ}}{w} \right]^{\frac{1}{2}}$$

with:

A_p, A_{inj}: Plasma, injector area

C_p: Plasma circumference

Ψ: Plasma toroidal flux

w: Edge current channel width

- Helicity Balance:

$$I_p \leq \frac{A_p}{2\pi R_0 \langle \eta \rangle} \left(V_{ind} + V_{eff} \right)$$

with:

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

- Experiments on Pegasus confirm $I_p^{max} \propto I_{inj}^{1/2}, I_{TF}^{1/2}, w^{-1/2}$

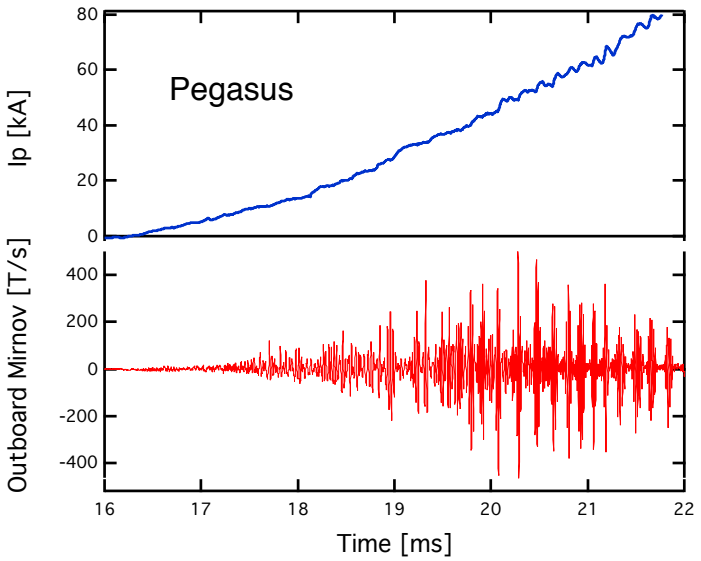
Battaglia *et al.*, Nucl. Fusion **51**, 073029 (2011)

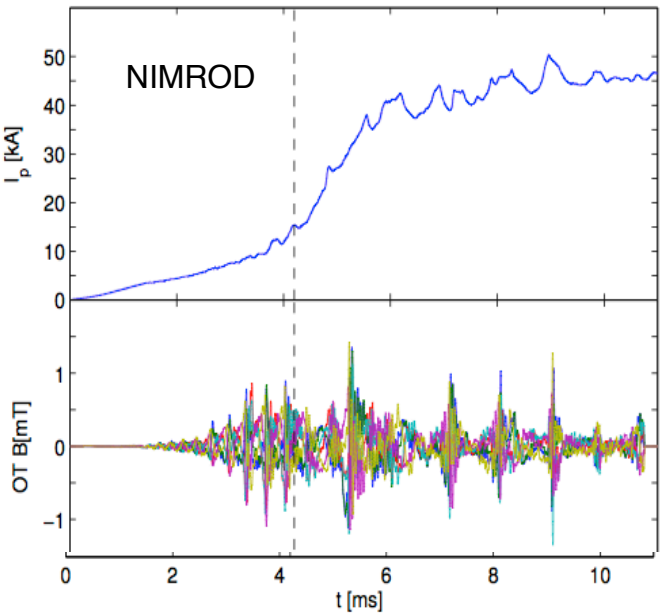
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Current Growth During LHI Correlated with Bursts of MHD Activity

- Measured burst properties include
  - Two primary spectral components
    - n = 1 : 10–20 kHz @ R_{inj}, line-tied kink
    - n = 0 : < 5 kHz, plasma motion
  - Correlation with sharp I_p jumps

- NIMROD simulations produce bursty MHD
  - Bursts from transient reconnection events
  - Qualitative agreement with experiment



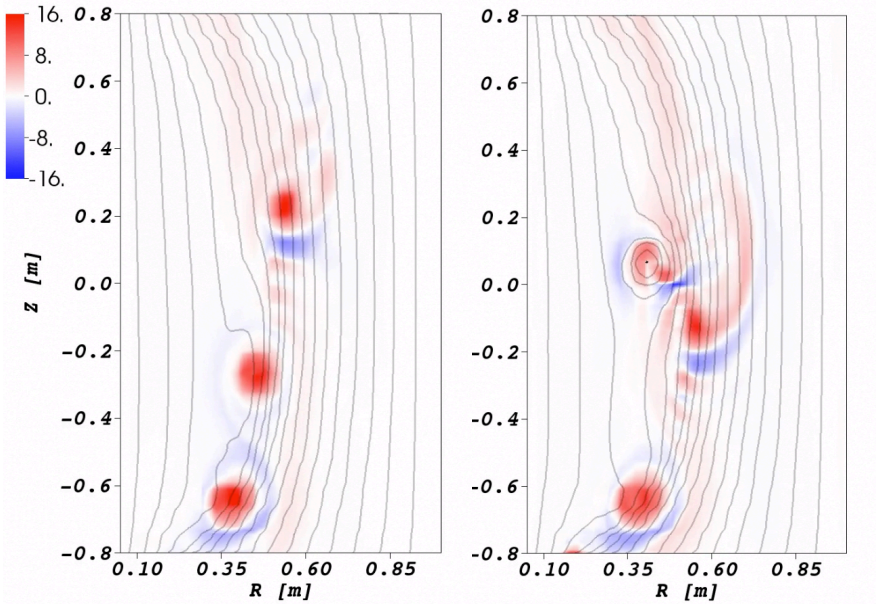


[O'Bryan Phys Plas.**19**, 2012]

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NIMROD Simulations Suggest Detailed Mechanism for LHI Current Drive

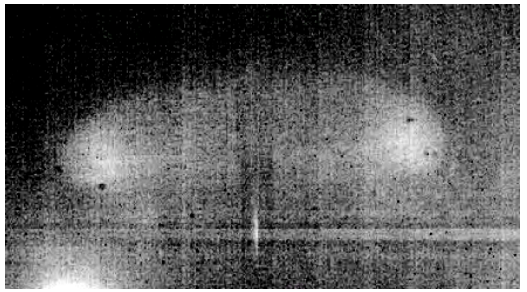
- Coherent current streams reconnect and inject axisymmetric current rings into core plasma
  - O'Bryan, this session



[O'Bryan Phys Plas.**19**, 2012]

Fast camera image of axisymmetric plasma ring, formed at an LHI-MHD burst

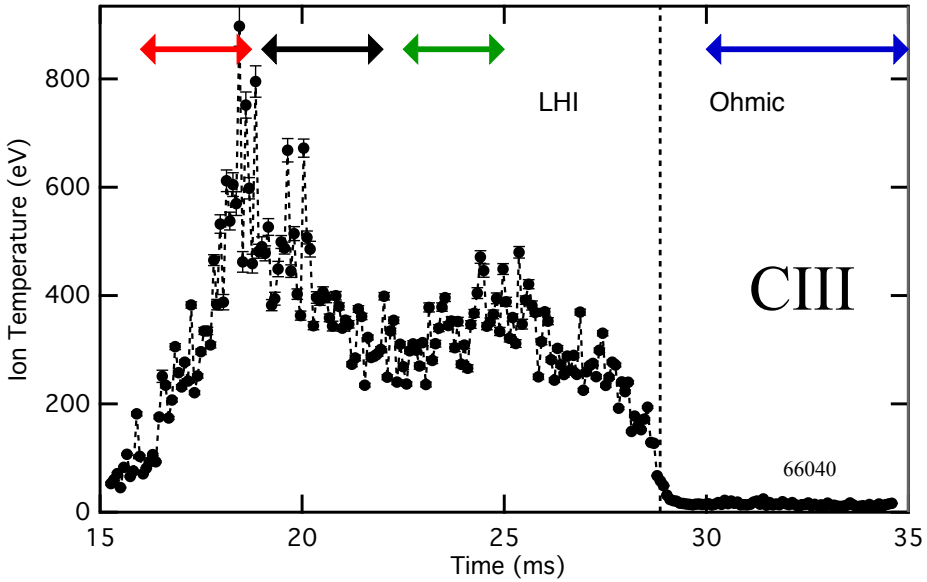
- Ringlets observed intermittently at early startup phase



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Strong Reconnection-Induced Impurity Ion Heating Observed during LHI in Pegasus

- NIMROD shows magnetic reconnection during LHI
  - Ion heating widely observed in reconnection experiments
- Consistent with ion cyclotron heating mechanism
  - LHI MHD spectra show significant power in IC resonance region

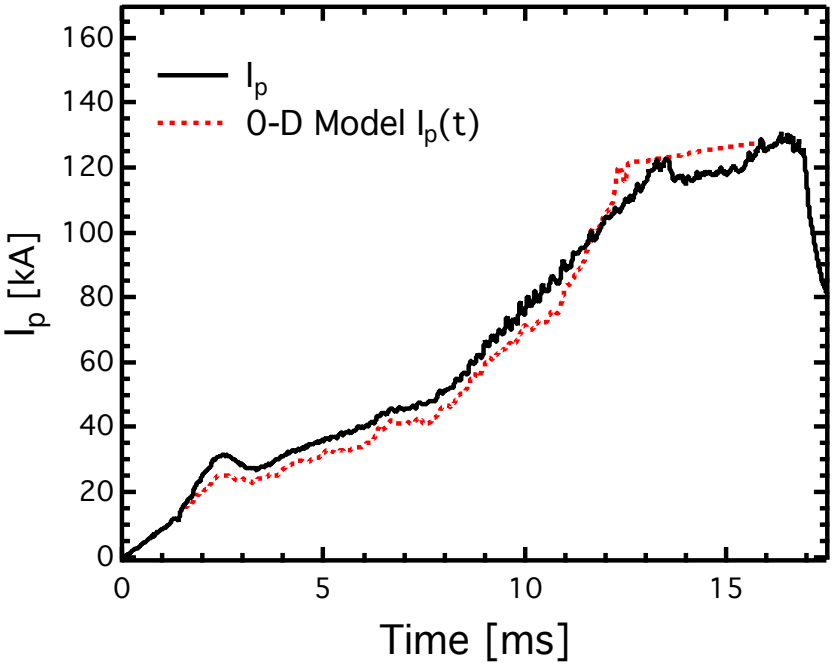


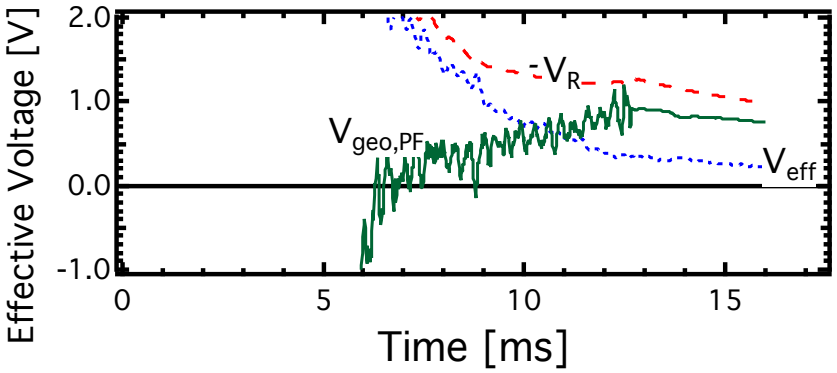
M. G. Burke, Thurs. AM Poster Session, TP8.00020

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Energy/Helicity Model Reproduces $I_p(t)$ in LHI Discharges

- Lumped parameter model + helicity conservation
  - $I_p\left[V_{eff} + V_{PF} - V_{geo} - V_R\right] = 0$
  - Inputs: $R_0(t)$, $I_p(0)$, η_0, $\kappa(t)$, $\delta(t)$, $a(t)$, $\ell_i(t)$
  - Analytic low-A descriptions of ℓ_e, B_z, $V_{eff}(t)$
- Initial tests give reasonable $I_p(t)$
  - Code validation and detailed experimental tests required
  - Validation via reconstructions ongoing
- Most drive during LHI appears to be from geometric/poloidal induction

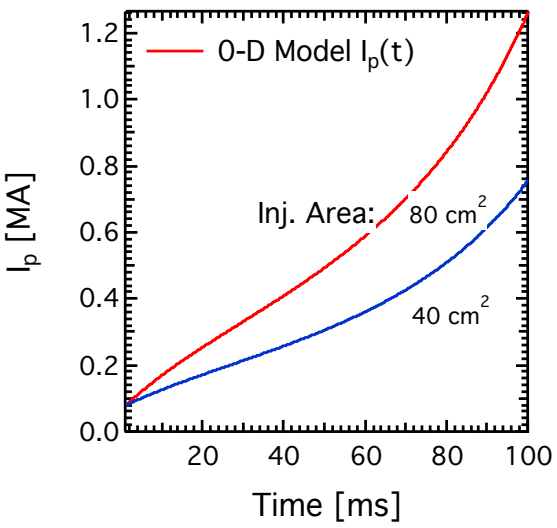


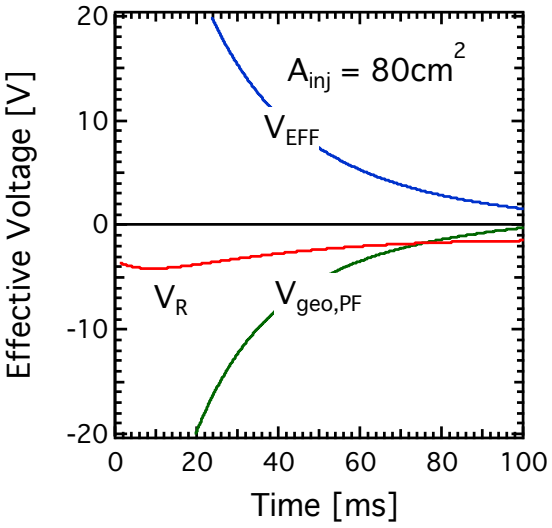


MA-Class Startup in Large Experiments Requires Helicity Drive to Dominate

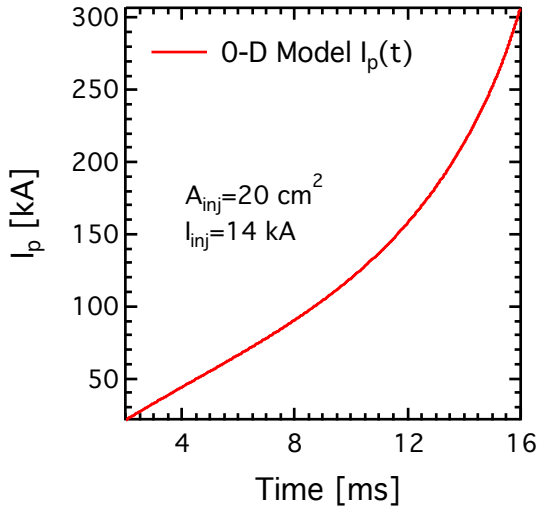
- Need $V_{eff} > V_{geo/PF}$
  - NSTX-U/FNSF-relevant regime (~1 MA)
  - In Pegasus, occurs at 300 kA
- NSTX-U ~1 MA regime at 2-4x Pegasus injectors
  - $A_{inj} \propto V_{inj}^{-1}$
  - Final design dependent on further injector development
- Physics test requires increased V_{inj}, A_{inj} measurements on Pegasus

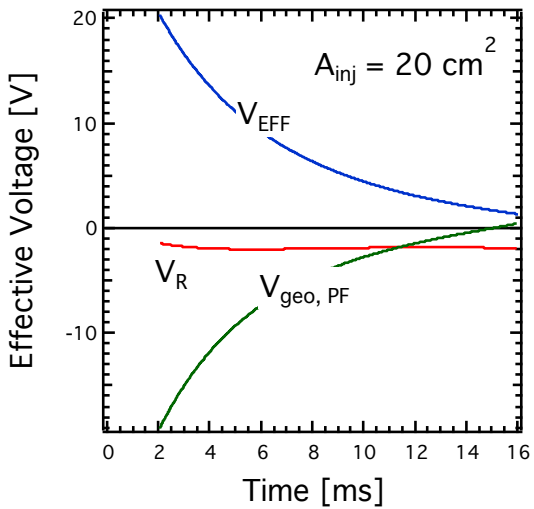
NSTX-U:





Pegasus:

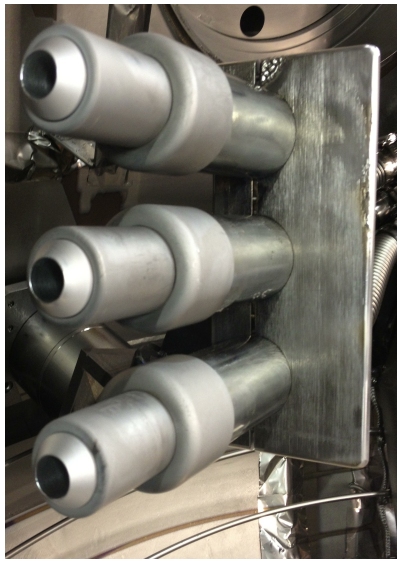




Applying High Current/Voltage in Edge Region is Formidable Challenge

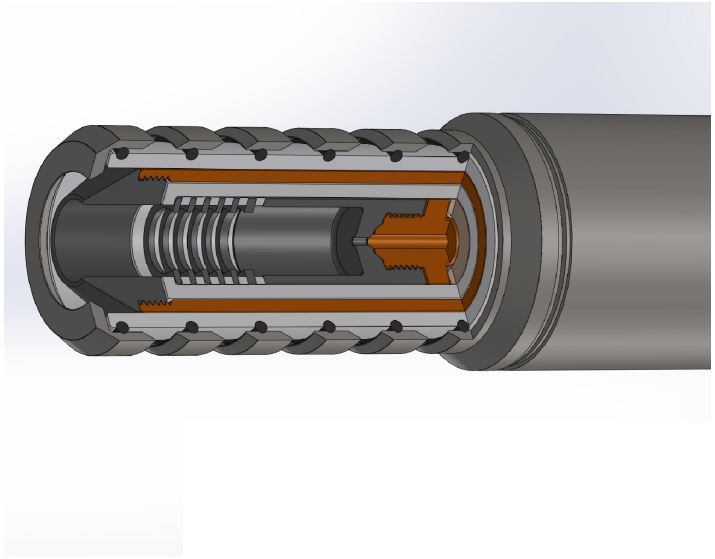
- Injector requirements include
  - Large A_{inj}, J_{inj}
  - $V_{inj} > 1$ kV
  - Multi-MW power input
  - $\Delta t_{pulse} \sim$ 10-100 ms
  - Minimize PMI

  …all adjacent to tokamak LCFS



Frustum-shaped cathode injectors mitigate PMI

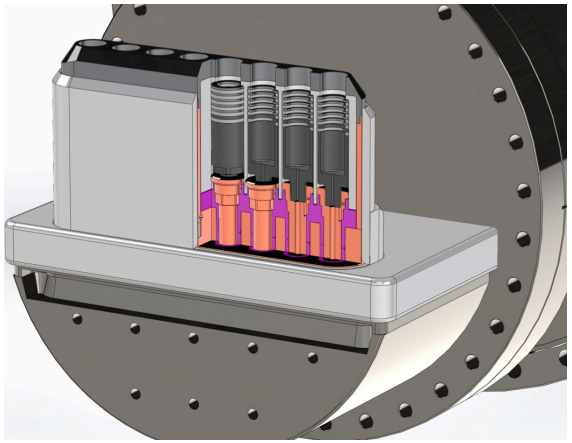
- Explored injectors/power system designs*
  - ~3x improvement in V_{inj}, Δt_{pulse}



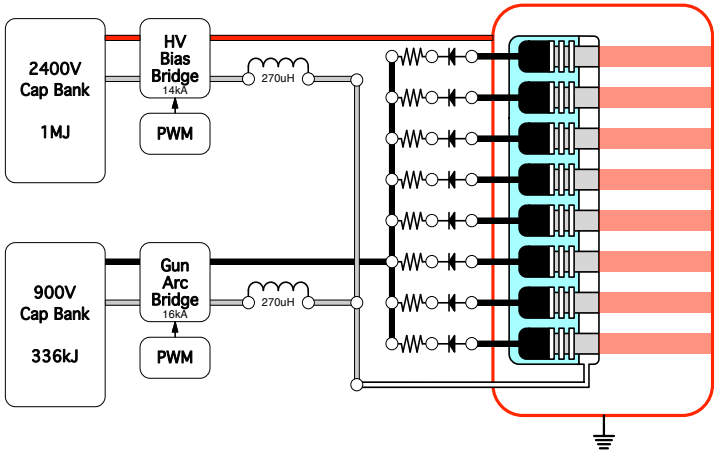
- Answer: integrated arc injector array
  - Present focus on increasing V_{inj}

Integrated Arc Injector Array will Facilitate High V_{eff} Test in Pegasus

- Integrated 8-injector array in fabrication
  - 16 cm^2 array with internal uniform gas distribution
  - Will test helicity-dominated regime needed for NSTX-U / FNSF



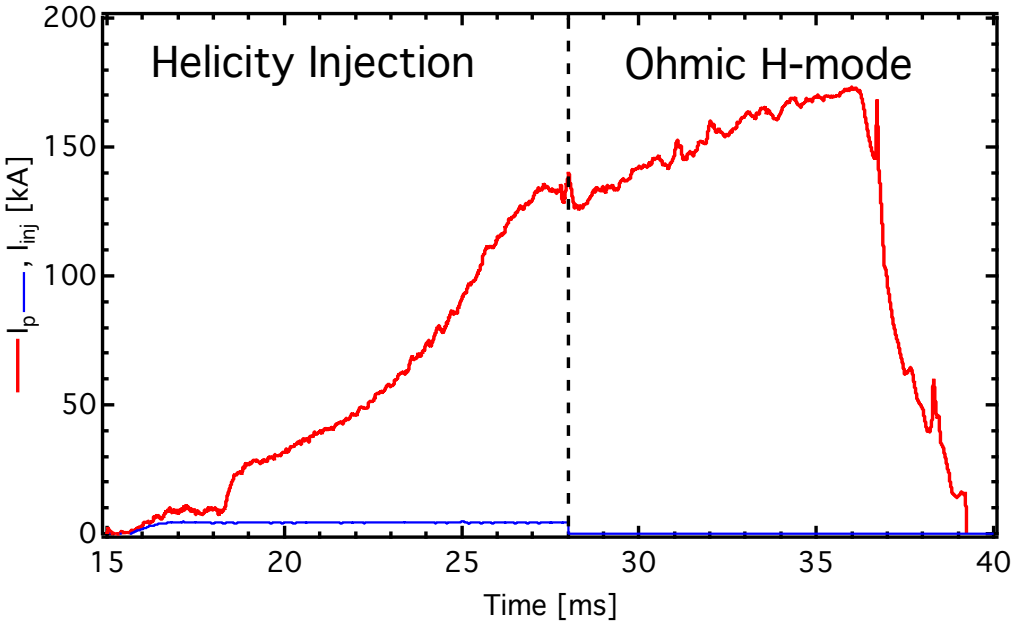
- Monolithic power systems



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LHI Extends Available V-s for Pegasus Discharges

- Increased V-s supports physics campaigns
  - Confinement/edge stability studies
  - H-mode studies
  - High β_T studies



- While still under development, LHI is routine operations tool

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Significant Progress Towards MA-Class Helicity Injection Startup

- Helicity balance/Taylor relaxation place limits on max I_p
- Predictive modeling of HI discharge physics progressing
  - NIMROD simulations elucidate current injection physics
  - Lumped parameter model provides predictive $I_p(t)$
- Tests of types and geometries of electron current injectors
  - Most attractive option is a multi-injector plasma arc array
- Next steps: Increase PMI suppression/voltage standoff, test large-area integrated injector array
  - Allows access to NSTX-U relevant regime ($V_{eff} > V_{inductive}$)

Posters: Thursday Morning Poster Session, TP8.00017-24

Talk available at: http://pegasus.ep.wisc.edu/Technical_Reports/APS_DPP.htm#APS13

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