Advancing Toward Reactor Relevant Startup via Localized Helicity Injection at the Pegasus Toroidal Experiment

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University of Wisconsin-Madison

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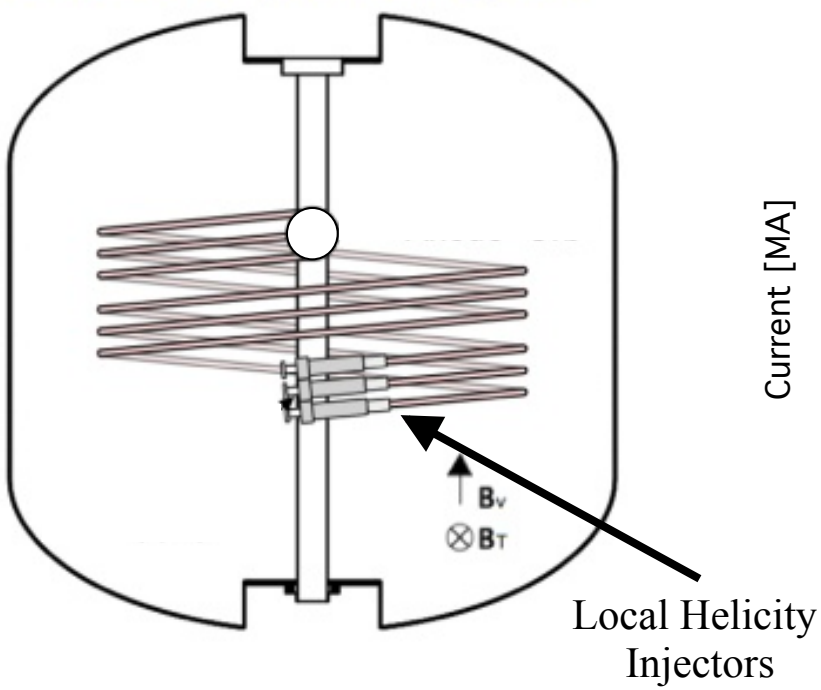


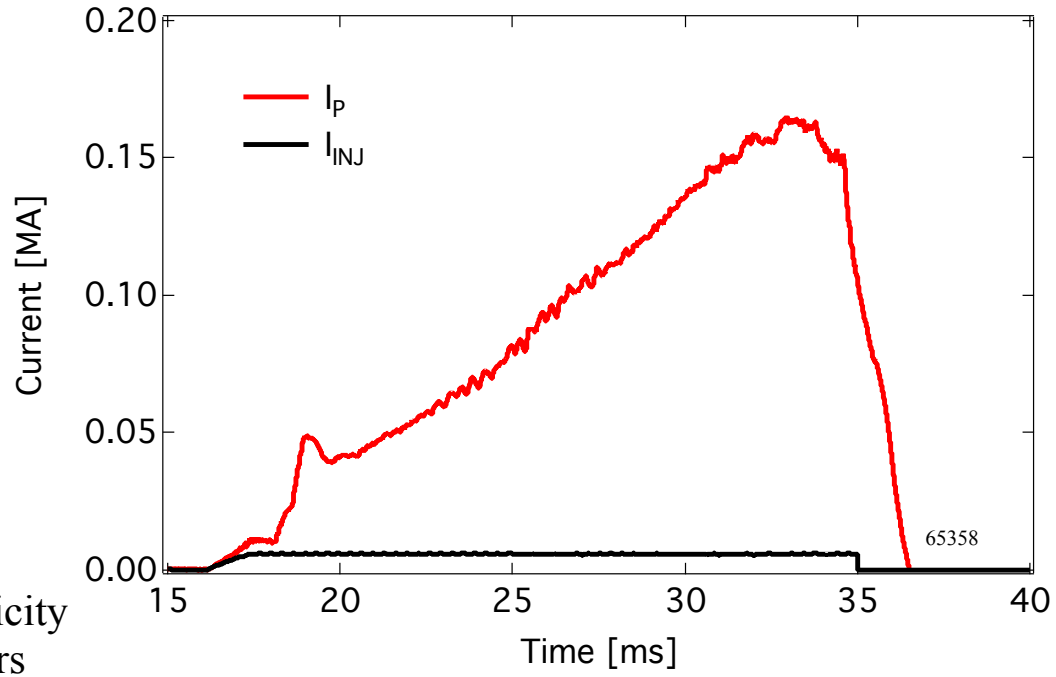
PEGASUS Toroidal Experiment

Localized Helicity Injection (LHI) is a Non-solenoidal Startup Technique

- Non-solenoidal startup is relevant to several ReNeW Thrusts
  - Thrust 16 – Develop the spherical torus
  - Thrust 18 – Achieve high performance with minimal field
  - Thrust 10 – Technology of plasma-surface interactions
- Startup without Ohmic solenoid induction is highly desirable
- LHI is a relatively simple startup technique
  - Appears scalable to MA-class startup

LHI Relies on Magnetic Relaxation and Helicity Balance for Tokamak Startup



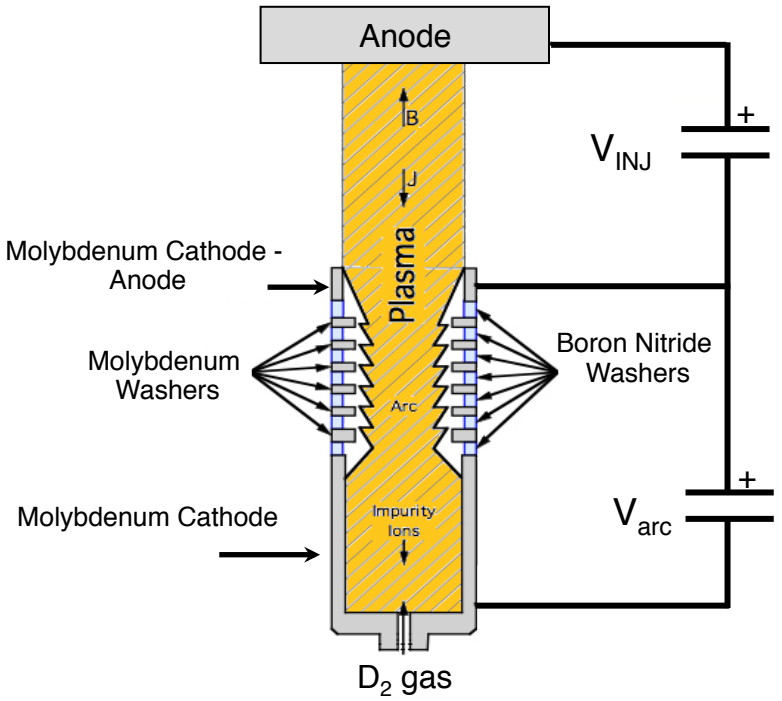


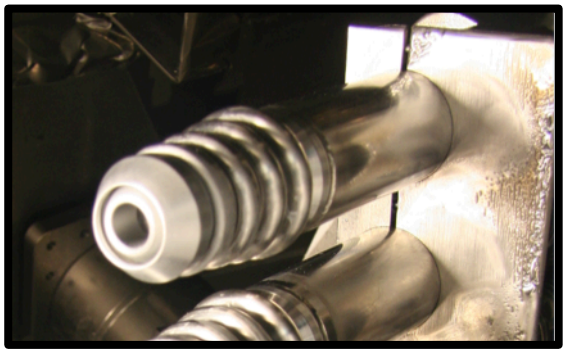
- Current injected along field lines
- Unstable current streams relax towards Taylor minimum energy (tokamak-like) state
- Achieved I_p consistent with helicity conservation

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LHI is Accomplished with Localized Current Sources in Plasma SOL

- Washer-gun plasma arc source serves as cathode for injector current
- Plasma cathode biased with respect to vacuum vessel
- I_{INJ} ~ 2 kA, V_{INJ} ~ 1 kV, A_{INJ} = 2 cm^2
- Located within 1-2 cm of LCFS





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Pursuing Development and Validation of Predictive Models for LHI Startup

Hierarchy of models under development

1. Global I_p limits
   - Helicity conservation
   - Taylor relaxation
2. Predictive $I_p(t)$ models
   - 0-D Energy conservation
     - Uses lumped parameter circuit model
   - "1.5-D" via TSC; employs confinement model
3. 3D Resistive MHD via NIMROD
   - First principles model

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1. Helicity Balance, Taylor Relaxation Determine Maximum I_p

- Taylor Relaxation:

$$I_p \le I_{TL} = \sqrt{\frac{C_p}{2\pi R_{INJ}\mu_0}\frac{\Psi I_{INJ}}{w}} \sim \sqrt{\frac{I_{TF} I_{INJ}}{w}}$$

with:

A_p, A_{inj}: Plasma, injector area

C_p: Plasma circumference

Ψ: Plasma toroidal flux

w: Edge current channel width

- Helicity Balance:

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

with:

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

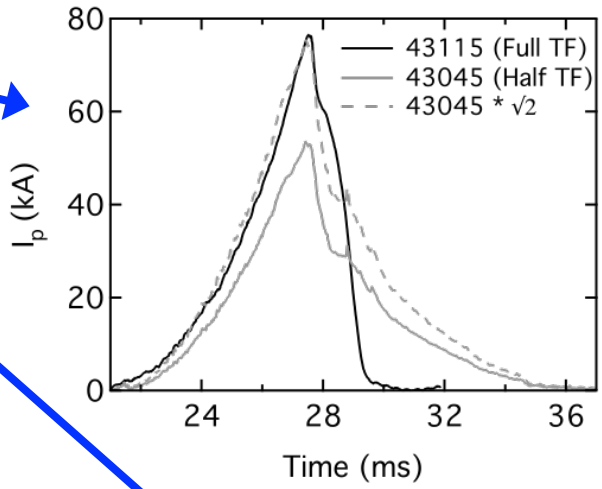
- I_p determined by lower of the two limits

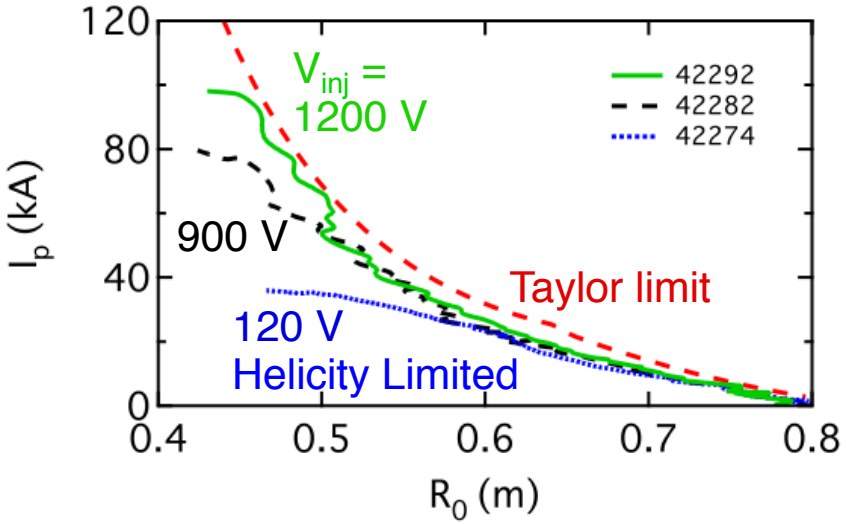
Battaglia *et al.*, Nucl. Fusion **51**, 073029 (2011)

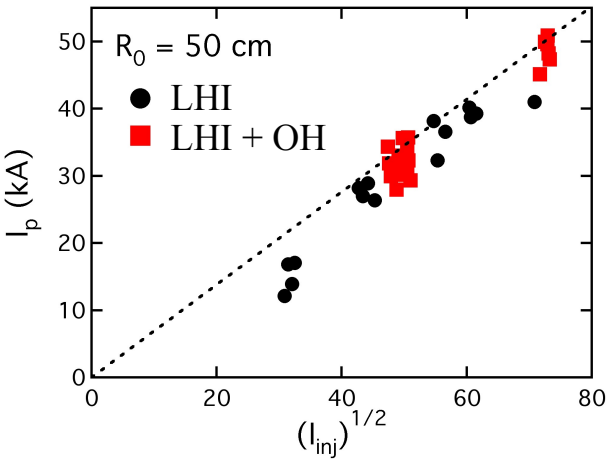
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1. Global Helicity Balance/Taylor Relaxation Limits Confirmed

- At Taylor Limit: $I_p^{\max} \propto \sqrt{I_{INJ}}, \sqrt{I_{TF}}, w^{-1/2}$
- Limited to $I_p < I_{TL}$ if insufficient HI input rate







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

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2. When $I_p(t) <$ Taylor Limit 0-D Power Balance Model Predicts $I_p(t)$

- Lumped parameter model + helicity conservation:

$$I_p \left[V_{eff} + V_R + V_{PF} + V_{Lp} \right] = 0$$

  - V_{eff}: From helicity conservation
  - V_R: Resistive dissipation from assumed flat Spitzer $T_e(R,t) = 70eV$
  - V_{PF}: Poloidal induction voltage
  - V_{Lp}: Voltage due to plasma self-inductance

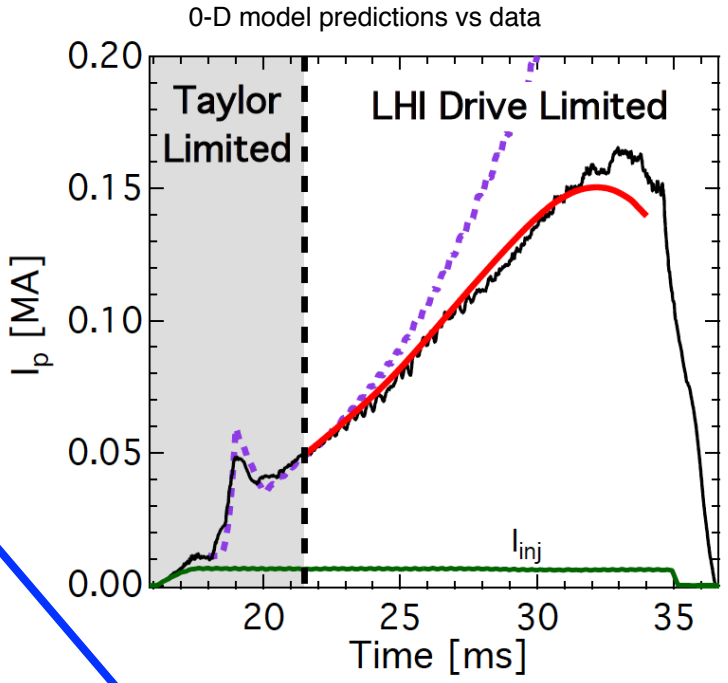
- Inputs: $R_0(t)$, $a(t)$, $Ip(t_0)$, $<\eta_0>$, $\kappa(t)$, $\ell_i\ (t)$
  - Analytic low-A descriptions of L_p, B_z, plasma shape

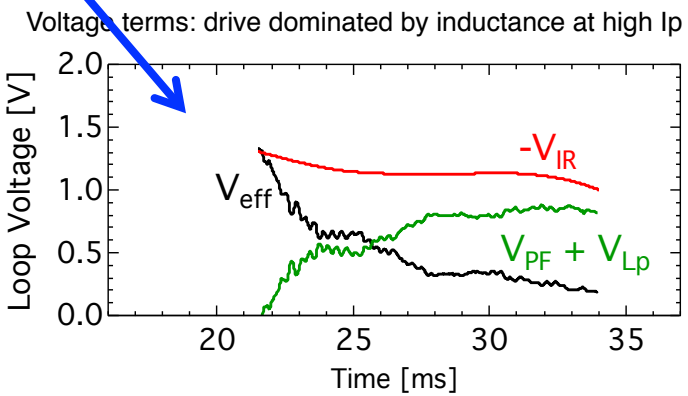
- Differential equation in $I_p(t)$ solved when $I_p(t) < I_{Taylor}(t)$

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2. Energy Balance Model Testing, Calibration Against Reconstructions and Data

- Initial tests give reasonable $I_p(t)$
  - At early times $I_p(t) = I_{Taylor}(t)$
  - Later times trajectory follows 0-D model
- Strong inductive component at high I_p
- Approach to model test/validation
  - Low A inductance formulas validation
  - Obtain η model with $T_e(R,t)$ measurements
  - Confirm early $I_p(t) = I_{Taylor}(t)$
  - Test helicity-dominated regime
  - Confirm V_{eff} model

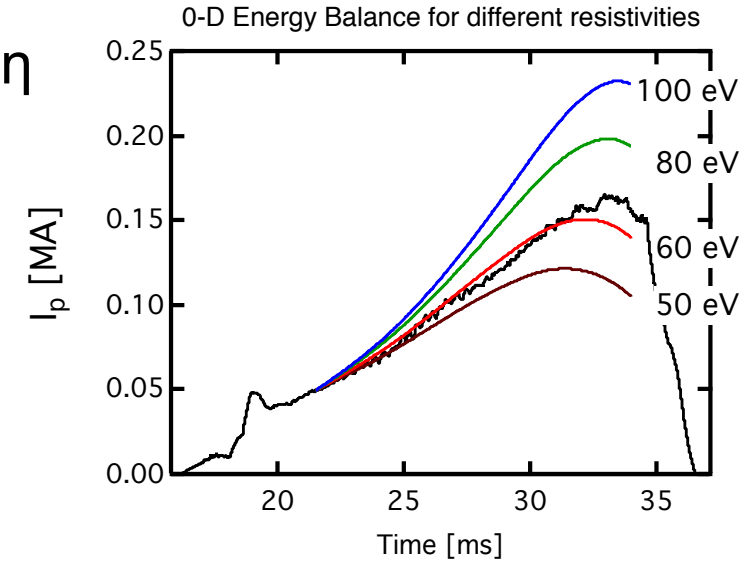




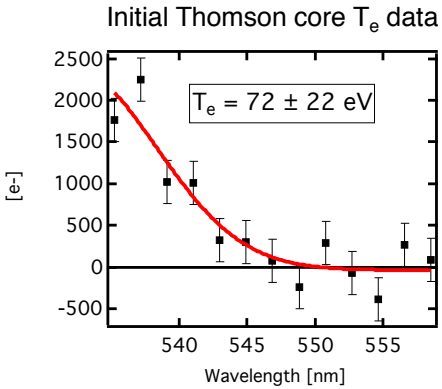
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2. Confinement and Resultant $T_e(R,t)$ Model Determines I_p Scaling with Device Size/V_{eff}

- Model depends critically on estimate of η
  - V_{eff}, V_{geo}, V_{PF} drive vs V_R dissipation
  - Need $T_e(R,t)$ model to estimate $I_p V_R$ term



- Initial tests invoke simple flat T_e profile
  - Assuming dominance of stochastic transport
  - $\langle T_e \rangle \sim 70$eV estimated from V-UV spectroscopy



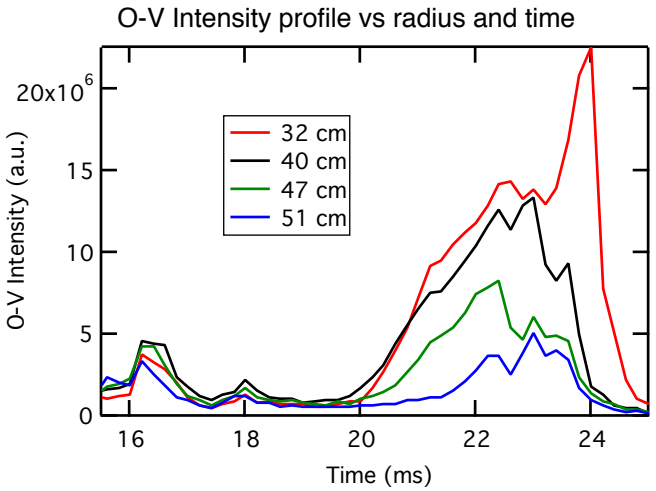
- Thomson scattering measurements imminent
  - $T_e(R,t)$ to provide accurate η model
  - Will inform confinement model

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2. Impurity Spectroscopy Hints at Hotter Core T_e, Inconsistent with Stochastic Confinement

- O-V core intensity >> edge intensity
- Possible dual confinement regime?

Warm Core	Cool Edge
OH-like confinement	Stochastic confinement
Inductive drive	Reconnection
Low MHD	Large MHD



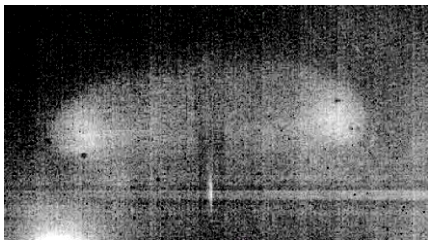
- Ohmic-like core ⇒ favorable scaling at higher B_{TF}, a, R_0
- Will resolve with Thomson scattering
  - Confinement model needed for TSC

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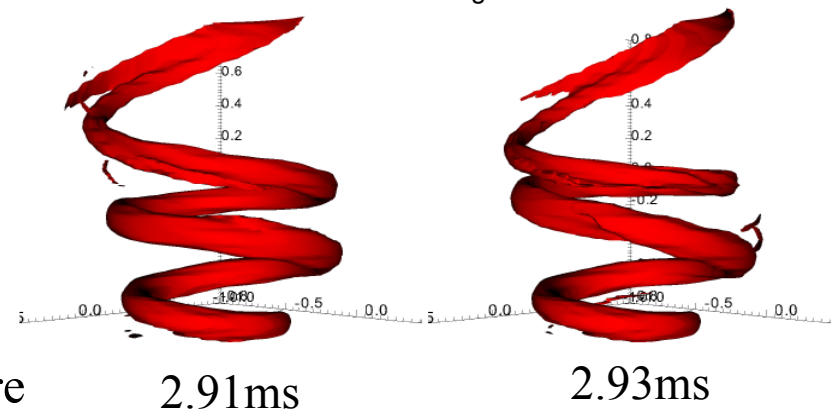
3. NIMROD Simulations Show Current Growth Resulting from Reconnection in Edge

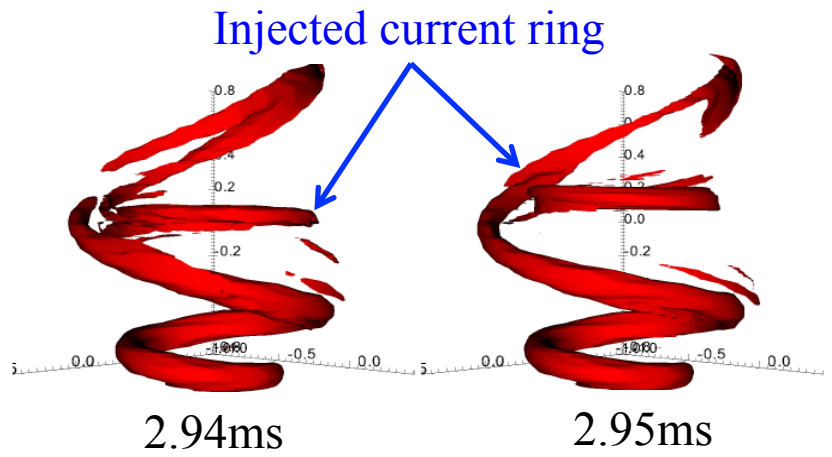
- Resistive MHD simulation of divertor injection
- Current growth via intermittent reconnection
  - Coherent current streams in edge
  - Filaments reconnect to inject rings into core
  - Poloidal flux buildup and Ip multiplication
- Intermittent plasma ringlets observed

Fast camera image of ringlet



Calculated current rings in NIMROD*



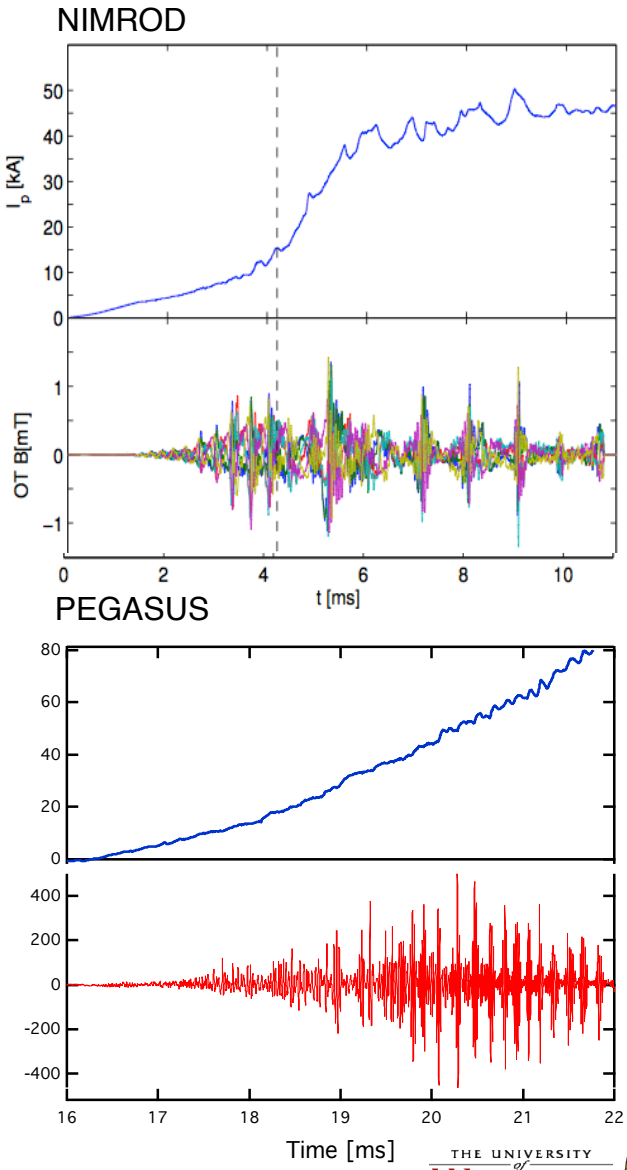


*J. O'Bryan, PhD. Thesis, UW Madison 2014

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3. NIMROD Calculations reproduce bursty MHD seen in experiment

- MHD bursts from reconnection seen on synthetic diagnostics
- Qualitative similarity with experiment
  - V_{INJ} spikes consistent with inductive response to detaching ring
  - Timed with sharp $\Delta I_p \sim I_{INJ}$ jumps

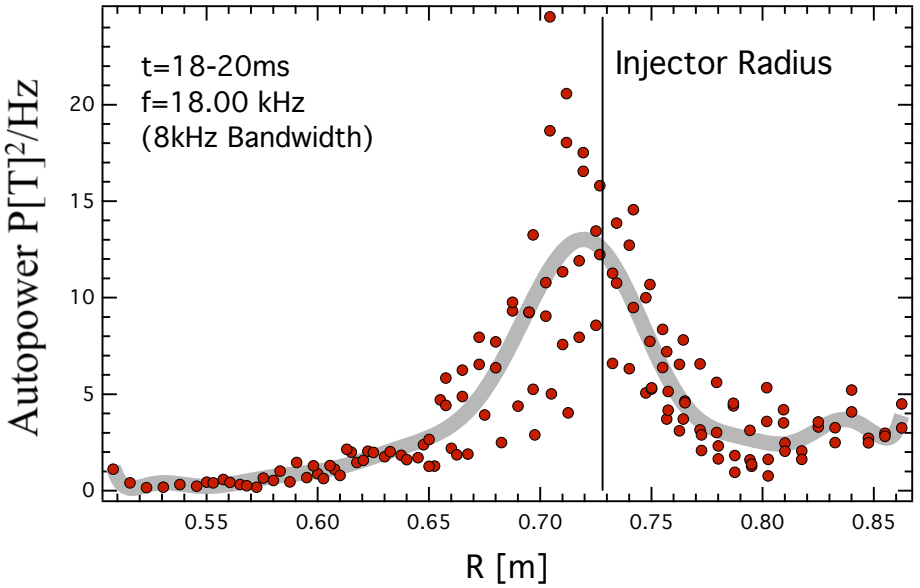


*[O'Bryan Phys Plas.**19**, 2012]*

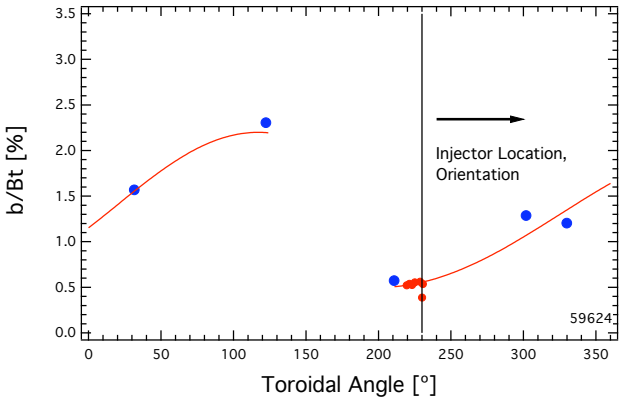
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3. Edge-Localization of MHD Consistent with NIMROD Reconnection Model

- High frequency: n=1
  - 10-40kHz
  - Peaked near injector radius
  - Toroidally asymmetric
    - Line tied kink-like
    - Consistent with streams



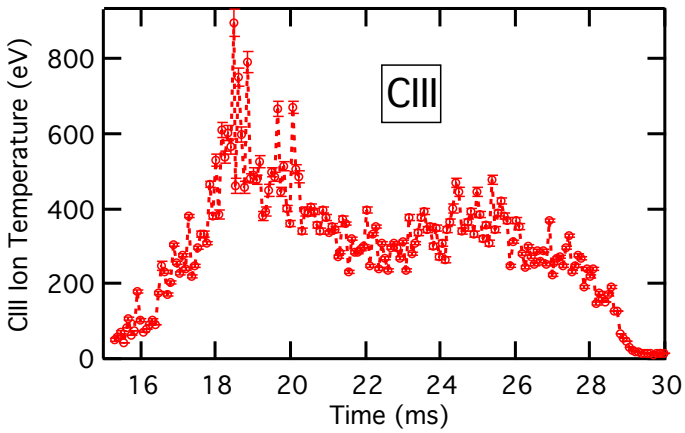
- Low frequency: n=0
  - <5kHz
  - Exists throughout plasma interior
  - Consistent with plasma motion



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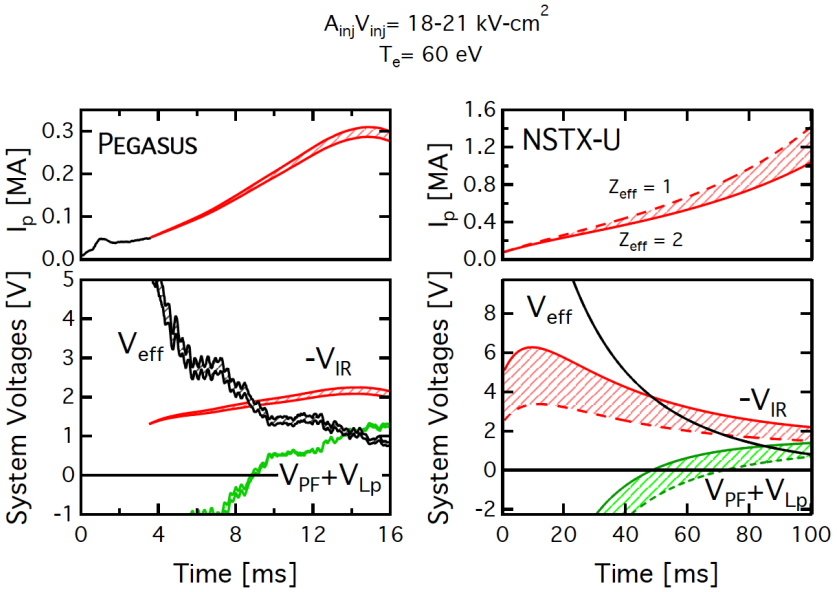
3. NIMROD Model Testing Requires Research on Multiple Fronts

- Consistency with magnetic probe data
- Search for evidence of coherent current streams in edge region
  - Compare magnetics signal with modeling of dynamic current streams
  - Considering soft X-ray imaging diagnostic deployment
- Implementation of 2nd generation divertor injectors in planning stage
- Ion dynamics
  - Reconnection (ion) heating
- Continued development of NIMROD model



0-D Modeling Predicts LHI System Requirements for MA startup in NSTX-U

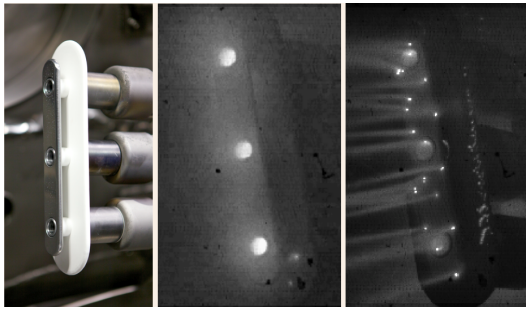
- Requirements for NSTX-U and beyond predicted by 0-D model
  - Required HI rate $V_{inj}A_{inj}B_{TF}$
  - Power systems required
- MA startup on NSTX looks feasible
  - Requires $V_{eff} > V_{geo} + V_{PF}$
  - Occurs at $I_p \sim 0.2$-0.3 MA in Pegasus
  - HI-dominated transport important
- Requires measurements at increased V_{inj}, $B_{TF,inj}$, Δt_{pulse},



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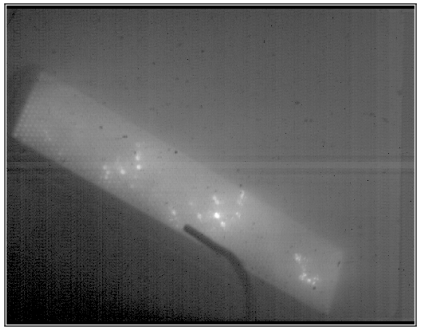
Tests of Various Injector Concepts Favor Smaller A_{INJ}, High V_{INJ}

- Tests of large-area passive electrodes show reduced effective A_{INJ}
  - Integrated metallic electrode surface
    - Cathode spot emission

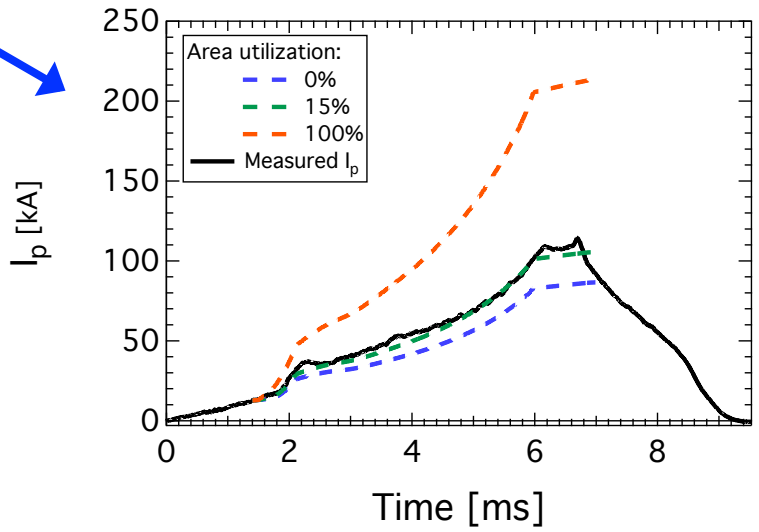


Above: integrated electrode injector assembly

  - Large area gas-effused Mo Plate
    - Hollow cathode emission
    - Non-uniform J_{INJ}, effective $A_{INJ} = 0.15\ A_{GEOMETRIC}$



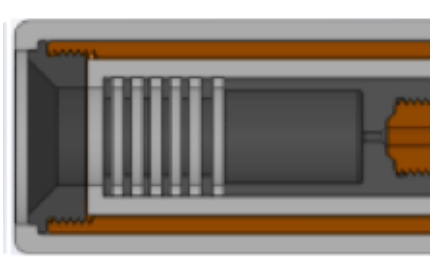
- Conclusion: Arc-based injector system most effective path to maximize HI rate

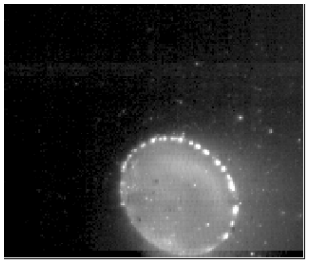


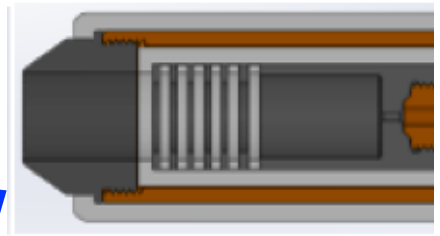
Controlling Plasma-Material Interaction is Enabling High V_{INJ} Operation

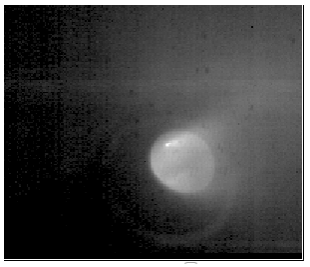
- Injector requirements include
  - Large A_{inj}, J_{inj}
  - $V_{inj} > 1$ kV
  - $\Delta t_{pulse} \sim$ 10-100 ms
  - Minimize PMI

  …all adjacent to tokamak LCFS



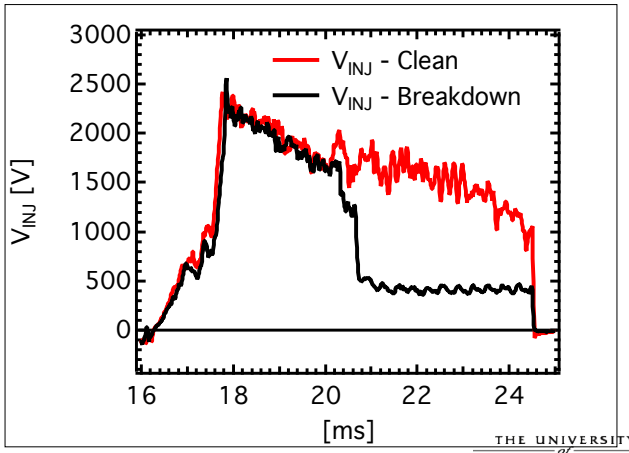






- Advanced injector design enables high V_{inj}
  - Cathode shaping to mitigate cathode spots
  - Shielding of cathode, insulators to prevent injector breakdown
  - 3x improvement in V_{inj}, Δt_{pulse}

Voltage of quiescently operating injectors (red) and voltage after breakdown of overdriven injectors (black)

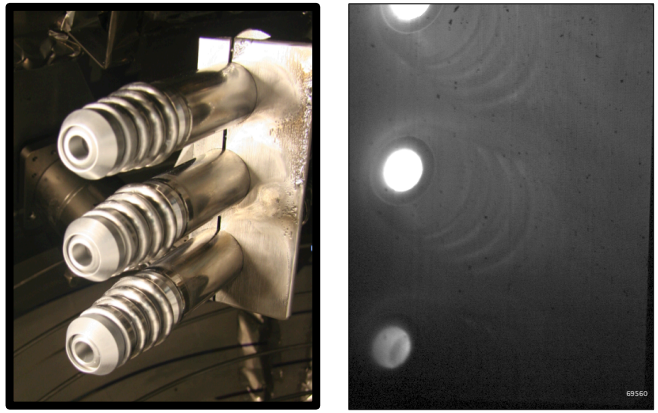


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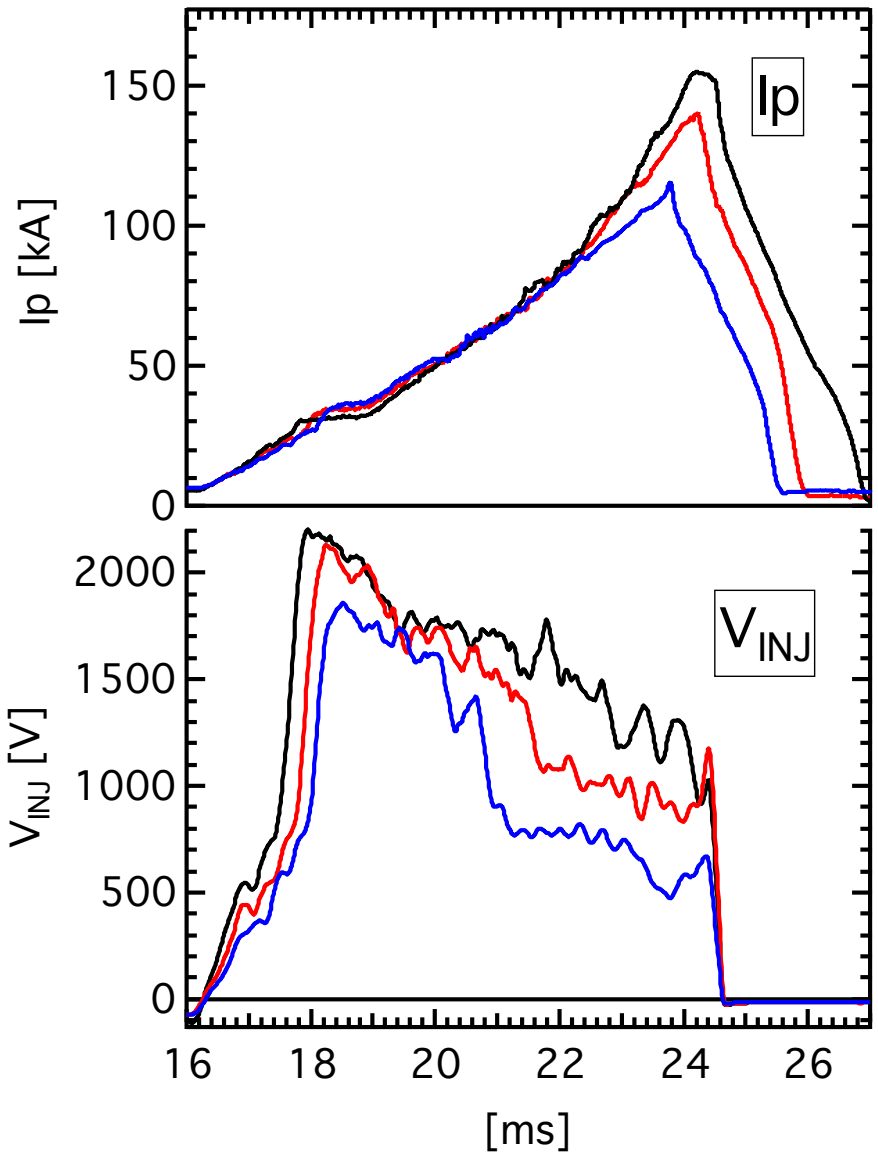
Hints of Higher Ip Emerging as the HI Rate Approaches the Induction Drive Levels

- Higher injector voltage operation shows increased I_p at as V_{eff} increases
  - Enabled by new high V_{INJ} injector

"Pagoda"-style injectors with quiescent operation



Injector voltages and associated I_p



Predictive Understanding of Plasma Impedance Required for Projecting to Higher I_p

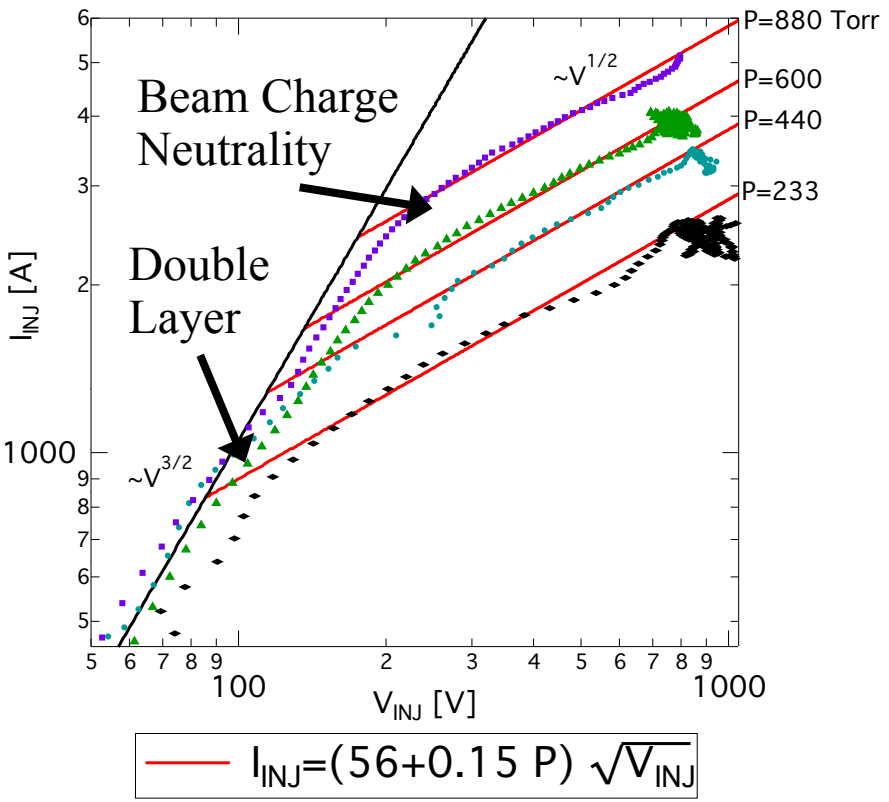
- Determines feasible V_{INJ}, A_{INJ}, I_{INJ} and demands on power system

- 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

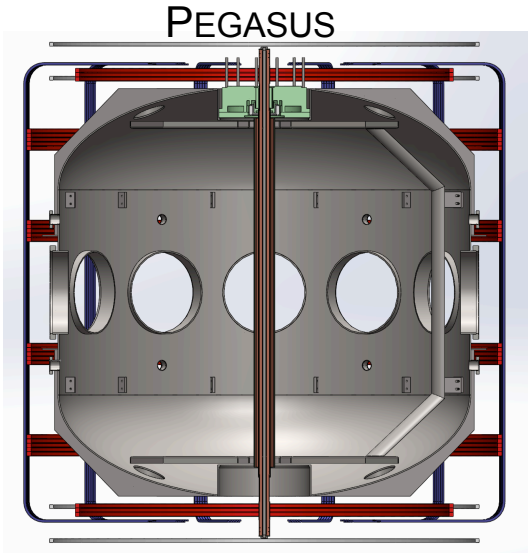
Ramp-up I-V characteristics for Pegasus injectors agrees with 2-parameter model across wide range of fill pressures



Critical Issues for LHI Predictive Understanding Addressed by Pegasus-U

- Physics Issues
  - Confinement and transport
  - Plasma control/evolution at long pulse
  - Injector Physics
    - Scaling with B_{TF}
    - Heat loads
  - Compatibility with divertor (and passive plates?)

- Proposed facility upgrades to address those issues
  - Higher B_{TF} (5x increase)
  - Longer pulse (100ms)
  - LHI startup with divertor and passive plates
  - Diagnostics: multipoint TS; CHERS via DNB



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Towards MA-Class Non-Solenoidal Startup

- Pegasus is developing the understanding of localized helicity injection, a non-solenoidal startup technique for NSTX-U and beyond

- A hierarchy of models to understand and scale LHI is being developed
  - Helicity balance/Taylor relaxation place limits on max I_p
  - 0-D modeling to predict $I_p(t)$
  - Future TSC modeling will incorporate transport model
  - NIMROD illuminates detailed physics

- Better understanding of injector physics enables improved injection rate

- Proposed upgrades to facility are focused on testing LHI at increased HI rate, long pulse and high toroidal field

Talk available at: http://pegasus.ep.wisc.edu/Technical_Reports/