Predictive Modelling and Helicity Dissipation Scaling Studies for Local Helicity Injection Non-Solenoidal ST Startup

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PEGASUS Toroidal Experiment

60th Annual Meeting of the APS
Division of Plasma Physics
Portland, OR

8 November 2018
Presentation TP11.00111

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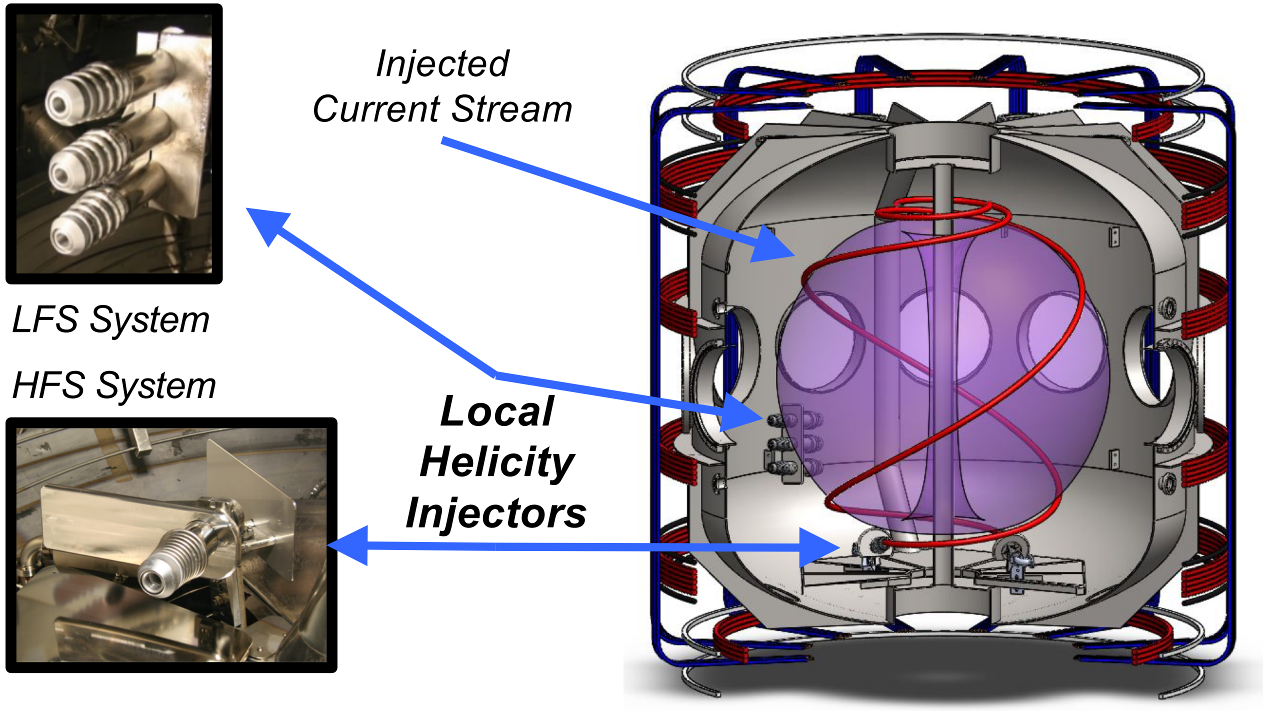
Predictive Modelling and Helicity Dissipation Scaling Studies for Local Helicity Injection Non-Solenoidal ST Startup

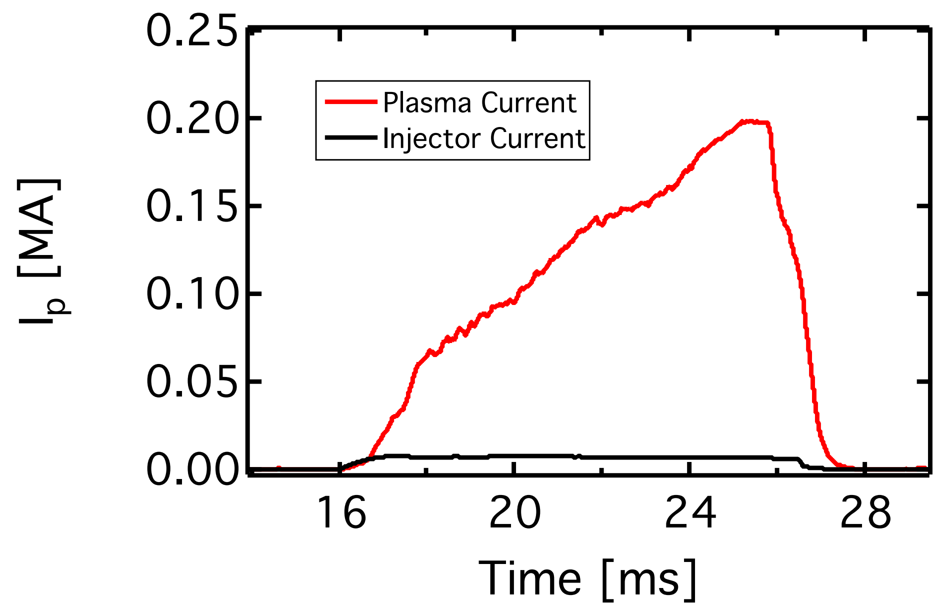
LHI Path to High I_p Startup	0-D Power Balance Model Insights	Validating URANIA Operational Scenario on PEGASUS	Dissipation in LFS LHI	Scaling LHI toward NSTX-U Startup
LHI is a Promising Non-Solenoidal Startup Technique	0-D Power Balance Model Incorporates Analytic Plasma Inductance (ψ_{Le}, ψ_{PF}) Formulae	Taylor Limit Increase Early in LFS Discharges: Access to Higher I_p	Inductive Reactance is the Dominant Contribution to Net Plasma Impedance	Model Applied to NSTX-U Geometry for Initial $I_p \sim$ 0.8 MA Scenario
Hierarchy of Physics Models Contribute to the Understanding of LHI Startup	LFS LHI Dominated by V_{IND}, V_{LHI} Drops as Plasma Grows	Experiment Tests Early Taylor Limit Scaling Through I_{TF} Scan	Similar T_e Profiles at Different I_{TF} Levels	URANIA Experiments will Test NSTX-U Startup Scenario
Path to High I_p Depends on Choice of LHI Injector Geometry	0-D Model Reproduces $I_p(t)$, Taylor Limited in Early Phase	Early Phase $I_p(t)$ Exhibits I_{TF} Scaling	Peaked T_e Profiles when Coupled to Injectors	Near Term PEGASUS Experiments to Establish URANIA Operation
LFS LHI is the Focus of Present PEGASUS Operations	Model Insights Provides Strategy Towards Scaling to Higher I_p	Early Phase I_p Scales with $\sqrt{I_{TF}}$ as Expected from Taylor Limit		LFS LHI Provides a Path Toward Scalable, non-inductive, high I_p Startup

LHI Path to High I_p Startup

LHI is a Promising Non-Solenoidal Startup Technique



Non-Solenoidal, High I_p ≤ 0.2 MA (I_{inj} ≤ 8 kA)



PEGASUS Parameters

A	1.15 – 1.3
R [m]	0.2 – 0.45
I_p [MA]	≤ 0.25
B_T [T]	< 0.15
Δt_{shot} [s]	≤ 0.025

- Edge current extracted from injectors
- Relaxation to tokamak-like state via helicity-conserving instabilities
- Used routinely for startup on PEGASUS

Hierarchy of Physics Models Contribute to the Understanding of LHI Startup

1. Taylor relaxation, helicity conservation
   - Steady-state maximum I_p limits

2. 0-D power-balance $I_p(t)$
   - V_{LHI} is effective LHI current drive
   - V_{IND} is net drive from PF, shape, I_p and L changes

3. 3D Resistive MHD (NIMROD)
   - Physics of LHI current drive mechanisms

J.L. Barr, et al. Nucl. Fusion Nuclear Fusion **58**, 076011 (2018)
D.J. Battaglia, et al. Nucl. Fusion **51** *073029 (2011)*
N.W. Eidietis, Ph.D. Thesis, UW-Madison (2007)
J. O'Bryan, C.R. Sovinec, Plasma Phys. Control. Fusion **56** *064005 (2014)*

Taylor Relaxation

$$\nabla \times B = \mu_0 J = \lambda B$$

$$\lambda_p \leq \lambda_{edge}$$

$$\Rightarrow \quad I_p \leq \sqrt{\frac{1}{B_{\theta+V,inj}/I_p} \frac{\Psi_T I_{inj}}{2\pi R_{inj} w_{inj}}}$$

Helicity Conservation

$$I_p R_p \leq V_{LHI} \approx \frac{A_{inj} B_{t,inj}}{\Psi_T} V_{inj}$$

Taylor Limit Constrained Power Balance

$$I_p[V_{LHI} + V_{IND} + V_{IR}] = 0\,; I_p \leq I_{TL}$$

Path to High I_p Depends on Choice of LHI Injector Geometry

LFS

- Pros:
  - More physical access → retractable helicity sources
  - Added poloidal field induction
  - Geometry allows for large A_{inj}
  - Less prone to PMI
  - Simpler null formation
- Cons:
  - Less V_{LHI} for same injector system (V_{inj}, A_{inj})
  - Passively unstable radial position

HFS

- Pros:
  - Increased V_{LHI} for same injector system (V_{inj}, A_{inj})
  - Passively stable radial position
- Cons:
  - Reduced physical access
  - Space restriction in lower divertor region
  - More PMI prone
  - More difficult null formation

PRESENT APPROACH: LFS LHI provides more attractive path to high I_p startup

LFS LHI is the Focus of Present PEGASUS Operations

- PEGASUS Operations to develop URANIA scenarios
  - Validate LFS I_p scaling
    - Increase early phase Taylor Limit
    - Non-circular, high A_{inj} injector design testing
  - Electron confinement and impurity studies
- Moving to high I_p LHI development in URANIA Experiment
  - URANIA: upgraded PEGASUS for general non-inductive startup development
- Developing NSTX-U Startup in URANIA
  - High $B_{TF} \rightarrow I_p$, confinement scaling, and injector technology
  - Shape and V_{LHI} control
  - Expanded diagnostic capability
  - Advanced (large scale relevant) injector design

0-D Power Balance Model Insights

0-D Power Balance Model Incorporates Analytic Plasma Inductance (ψ_{L_e}, ψ_{PF}) Formulae

$$I_p\left[V_{PF} + V_{Le} - V_{W_m} - V_{IR} + V_{NICD}\right] = 0$$

($V_{PF} + V_{Le} - V_{W_m}$ = V_{IND})

- I_p(t) determined via numerically solving initial value problem
- Inputs: shape(t), $\langle\eta_p\rangle$, l_i(t), β_p(t)
- Analytic, finite-*A* descriptions calculate ψ_{L_e}, ψ_{PF} assuming radial force balance

Inductive Drive from Poloidal Fields

$$V_{PF} = -\frac{\partial}{\partial t}\psi_{PF} \approx -\frac{\partial}{\partial t}\left[I_p \; M_V \pi R_0^2 \left({B_V}/{I_p}\right)\right]$$

$$\frac{1}{\mu_0}\frac{B_V}{I_p} = -\frac{1}{4\pi R_0}\left\{\frac{1}{\mu_0}\frac{\partial L_e}{\partial R_0} + \left(\beta_p + \frac{l_i}{2}\right) - \frac{1}{2}\right\}$$

$$\frac{1}{\mu_0}M_V = \mathrm{R}_0\frac{(1-\epsilon)^2}{(1-\epsilon)^2 f_c + f_d\sqrt{\kappa}}$$

Plasma Magnetic Energy Change

$$V_{W_m} = \frac{1}{I_p}\frac{\partial}{\partial t}\left[\tfrac{1}{2}L_i I_p^2\right] - V_{RTT} \qquad L_i = \mu_0 l_i \frac{V_P}{{\ell_P}^2}$$

$$V_{RTT} = \frac{I_p}{2\mu_0}\oiint_{S_P}\left(\frac{B_p}{I_p}\right)^2 \overrightarrow{v_b}(\theta)\cdot\hat{n}\,dS$$

$\left({B_p}/{I_p}\right)$ from Miller local equilibrium model

Shape, B_t, q_{edge} dependencies

Inductive Drive from Shape Evolution

$$V_{L_e} = -\frac{\partial}{\partial t}\left[L_e I_p\right]$$

$$\frac{1}{\mu_0}L_e = R_0\frac{f_a(1-\epsilon)}{(1-\epsilon)+\kappa f_b}$$

f_a = fitting function

Resistive Dissipation

$$V_{IR} = I_p R_p = I_p\left(\frac{\langle\eta_p\rangle 2\pi R_0}{A_p}\right)$$

LHI Drive

$$V_{LHI} = \frac{A_{inj}B_{\phi,inj}}{\Psi_T}V_{inj}$$

J.L. Barr et al., Nucl. Fusion Nuclear Fusion **58**, 076011 (2018)

LFS LHI Dominated by V_{IND}, V_{LHI} Drops as Plasma Grows

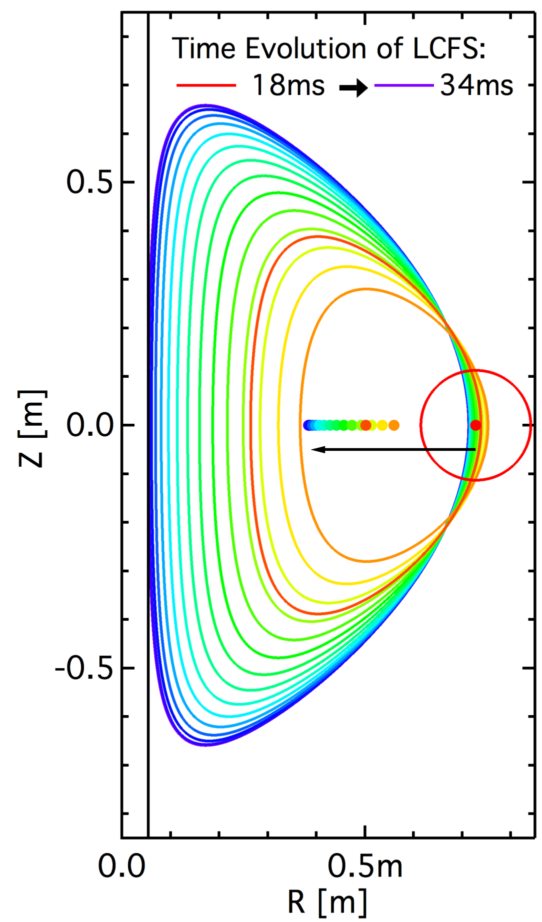
Taylor Limited Phase

- Small, outboard limited plasma
  - Low Taylor Limit
  - Ample Drive

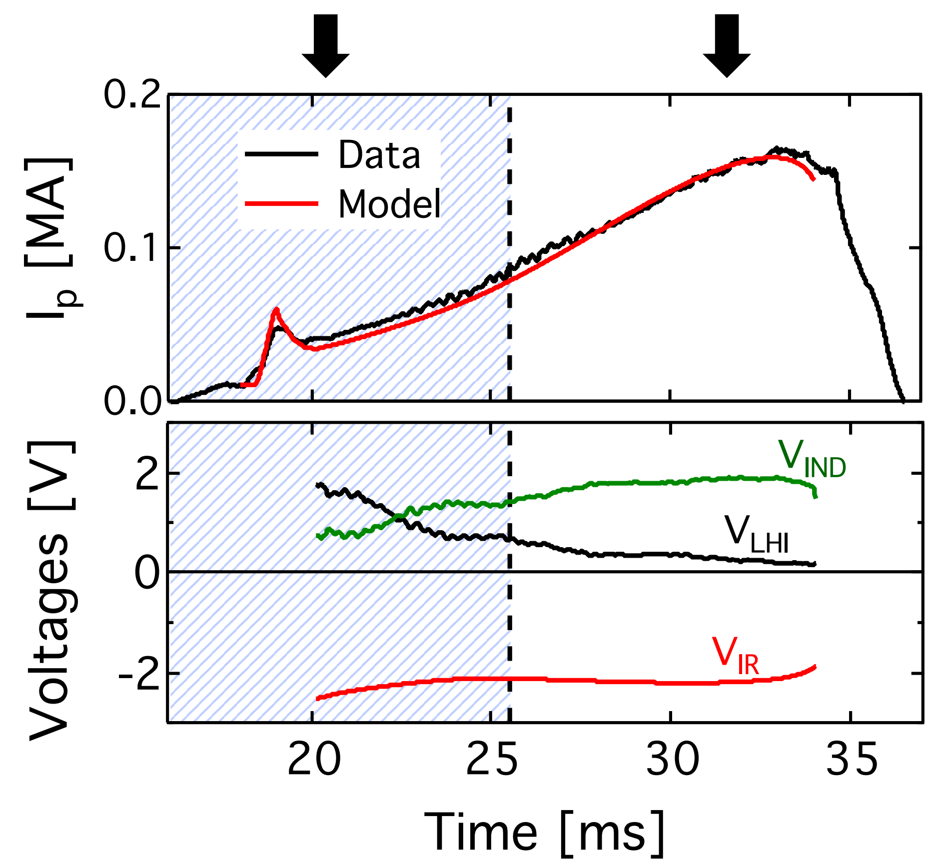
Drive Limited Phase

- Plasma expands inward
  - Taylor Limit increases
  - V_{LHI} decreases
  - V_{IND} dominates

Typical LFS Geometry Evolution



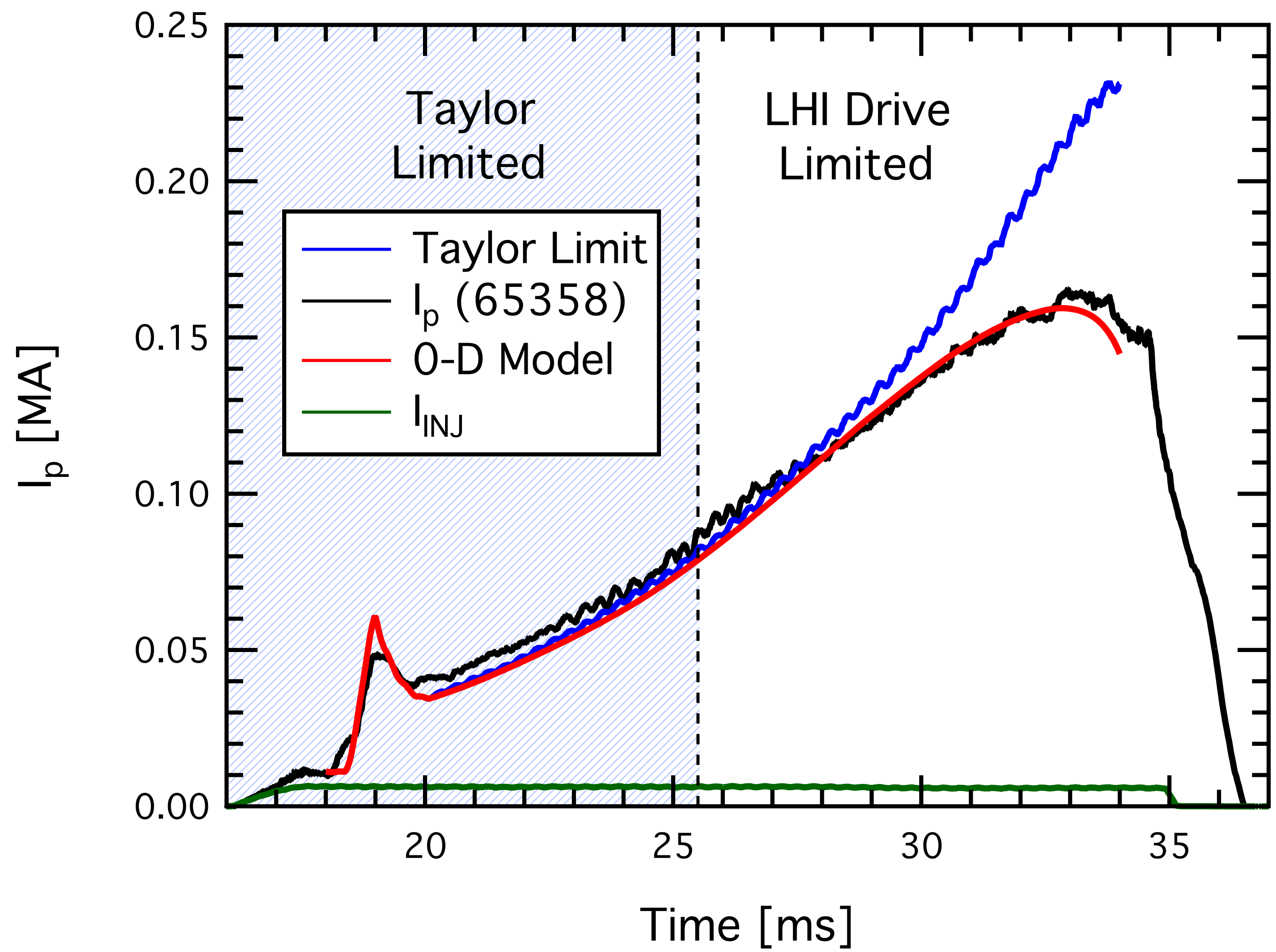
Taylor Limited Phase **LHI Drive Limited Phase**



0-D Model Reproduces $I_p(t)$, Taylor Limited in Early Phase

- Model reproduces experiment
  - Assumed constant $\langle \eta_p \rangle$
  - Constrained shape evolution
  - Experimental injector parameters

- Two-phase $I_p(t)$ evolution
  - Early: Taylor Limited
  - Late: Drive Limited



Model Inisghts Provides Strategy Towards Scaling to Higher I_p

- Increase net poloidal flux in early phase to provide more V-sec during shape evolution

- Increase Taylor limit in the early phase of the discharge

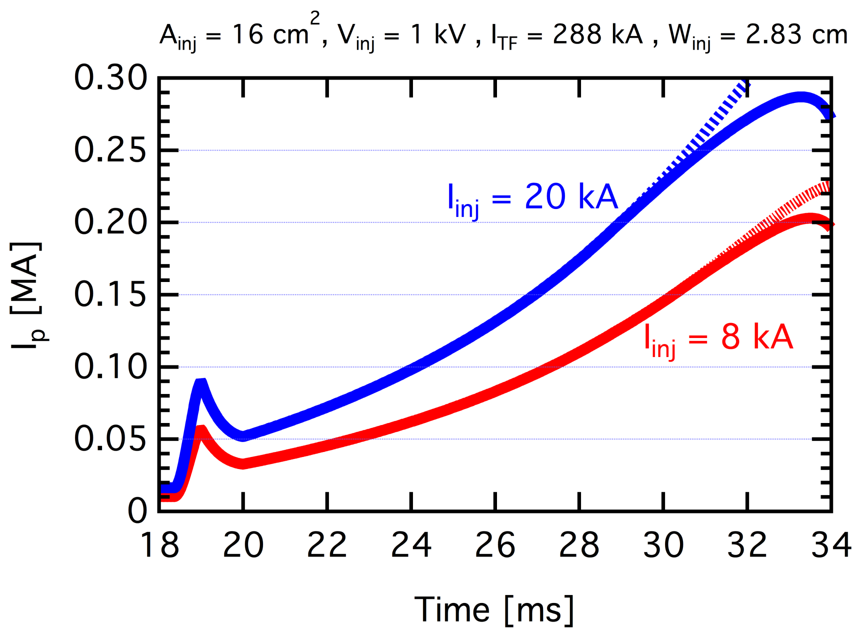
- Provide sufficient V_{LHI} to drive system up to early phase Taylor limit

Validating URANIA Operational Scenario on PEGASUS

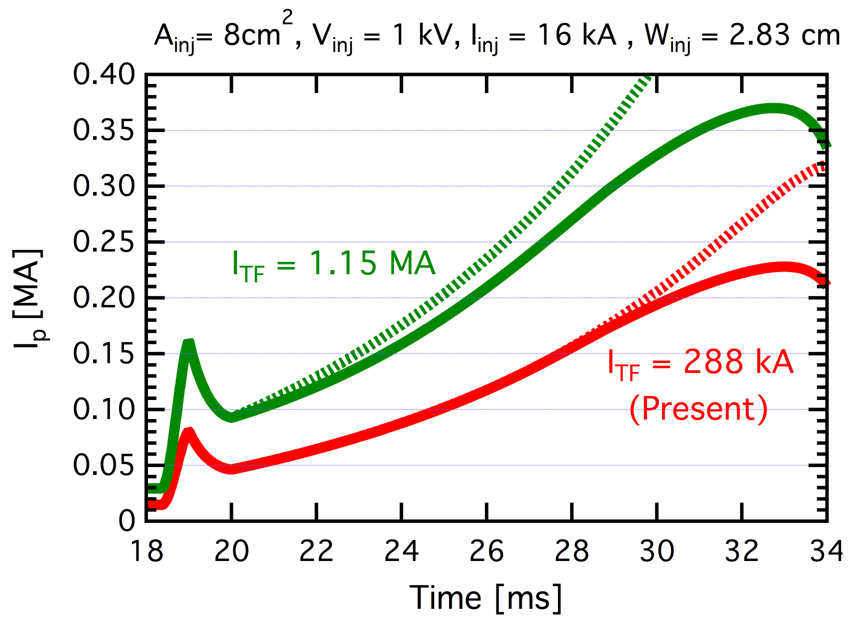
Taylor Limit Increase Early in LFS Discharges: Access to Higher I_p

- LFS discharges experience an extended Taylor-limited I_p phase
- Increase Taylor limit through injector design or facility modifications $I_{TL} \sim \sqrt{\frac{I_{TF} I_{INJ}}{W_{INJ}}}$

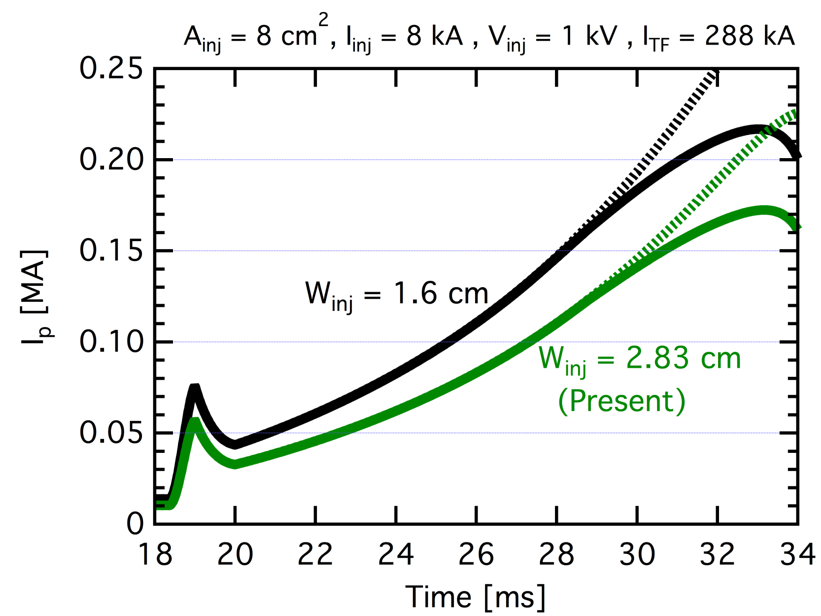
Increase I_{inj}



Increase I_{TF}



Decrease W_{inj}



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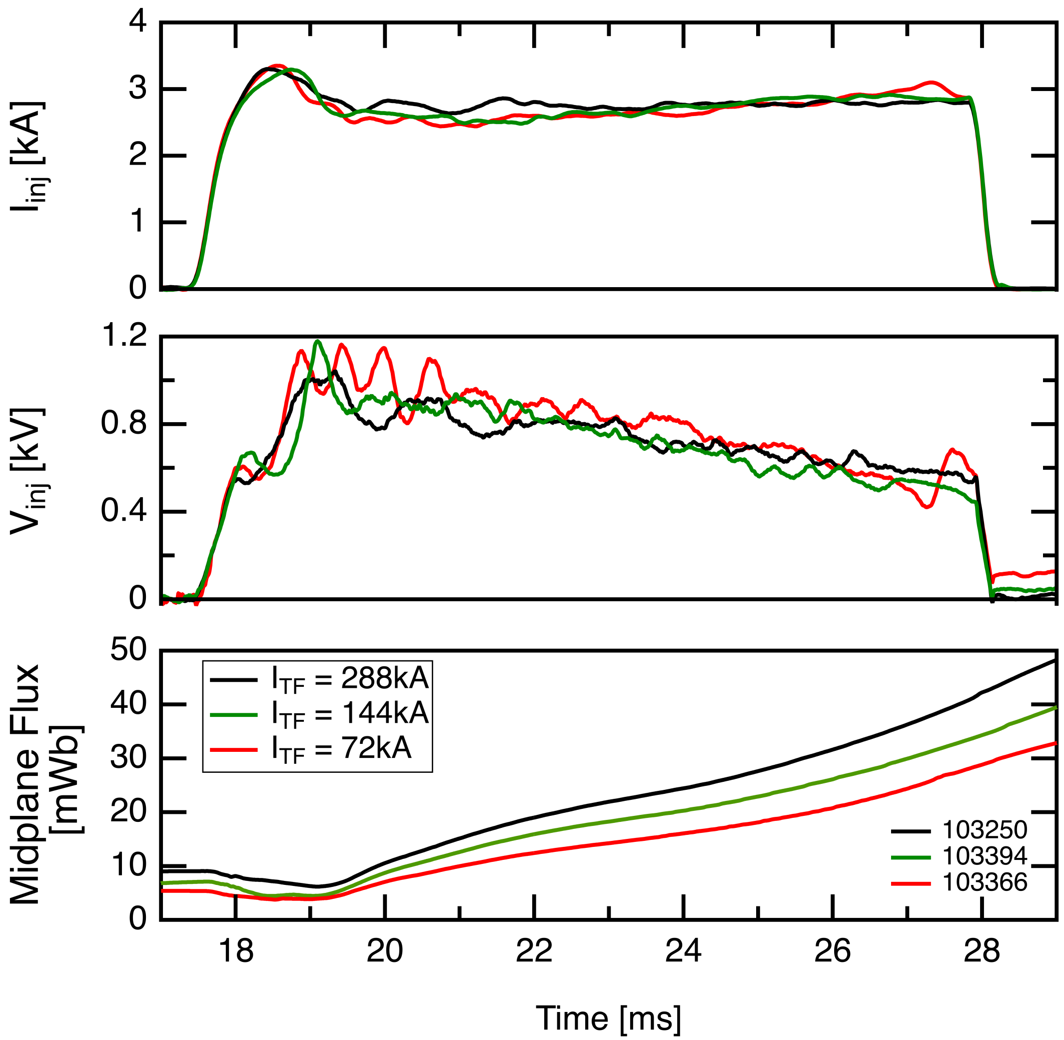
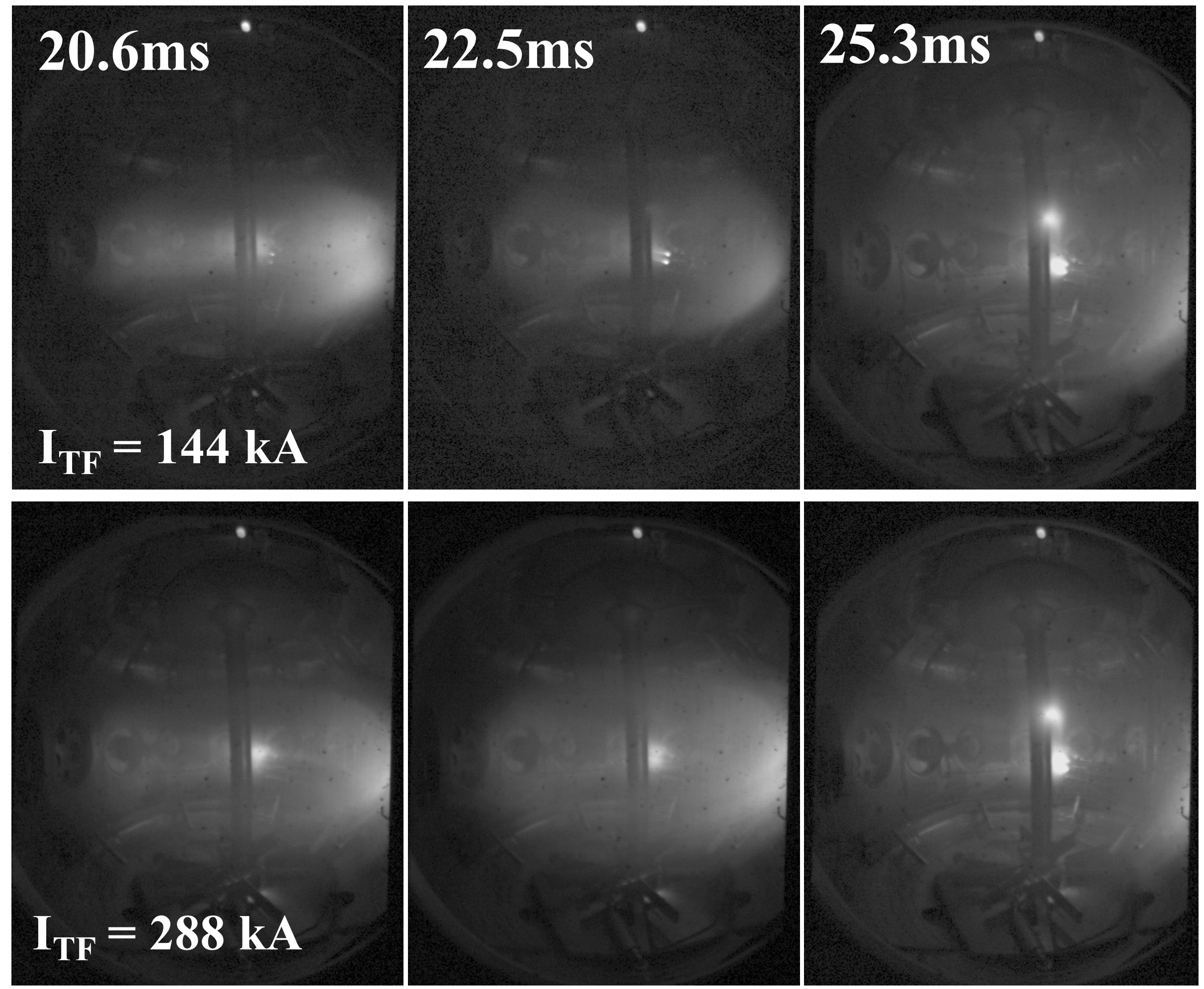
Experiment Tests Early Taylor Limit Scaling Through I_{TF} Scan

- Injector parameters matched



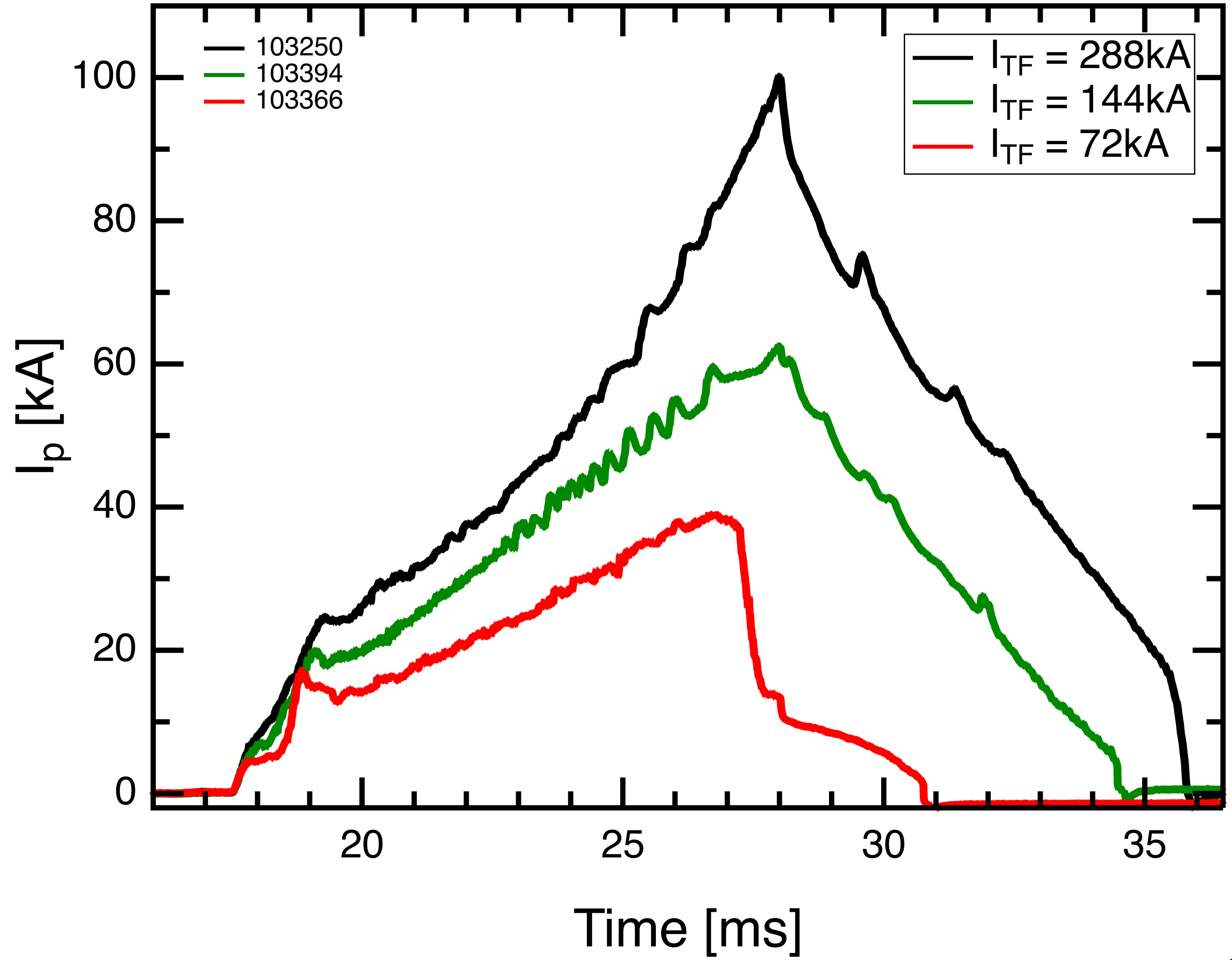
- Comparable Shape Evolution



Early Phase $I_p(t)$ Exhibits I_{TF} Scaling

- Higher performance achieved as I_{TF} increased

- Behavior similar to model expectations
  - Modify early phase I_p via I_{TF}
  - Higher performance at end of discharge



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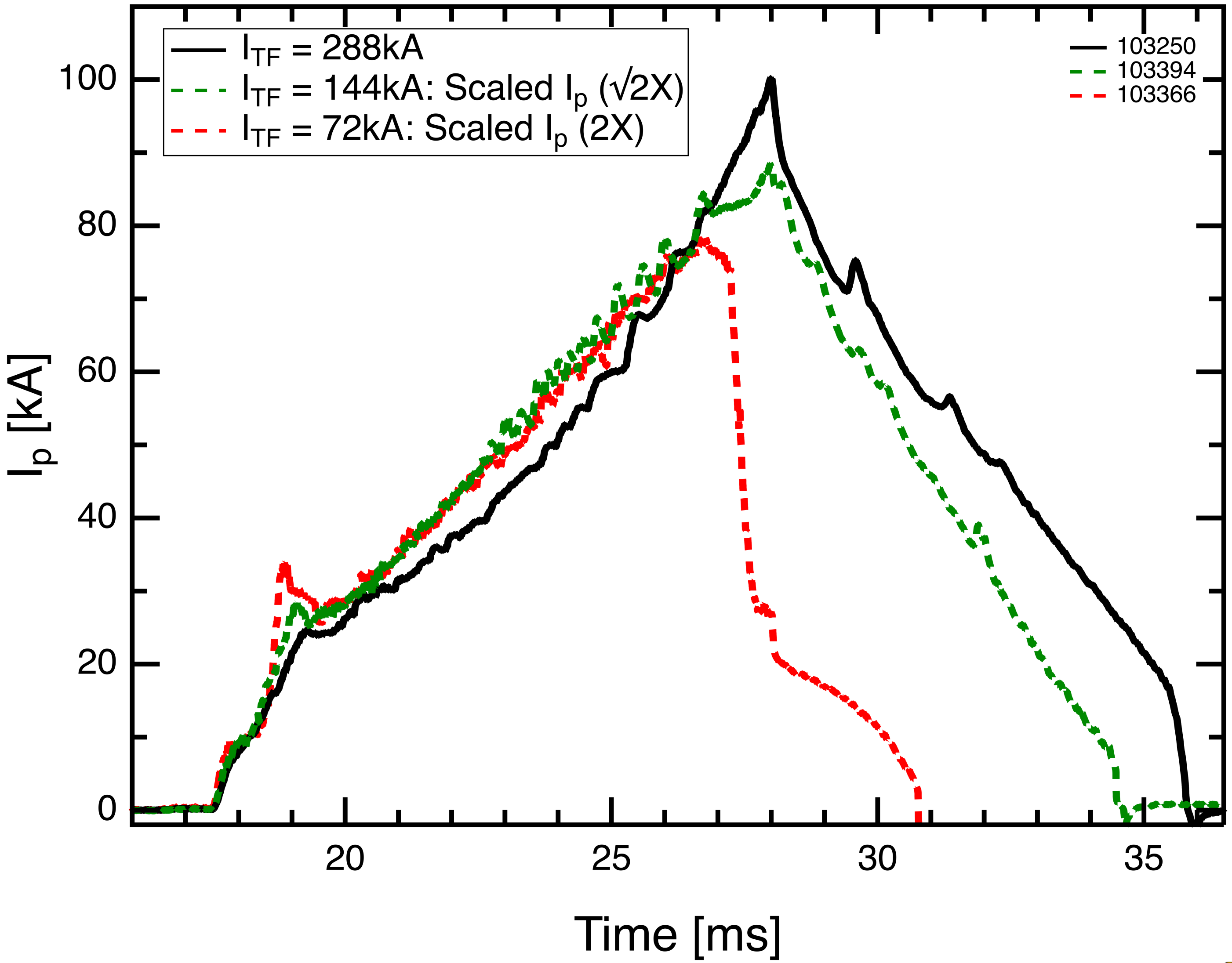
Early Phase I_p Scales with $\sqrt{I_{TF}}$ as Expected from Taylor Limit

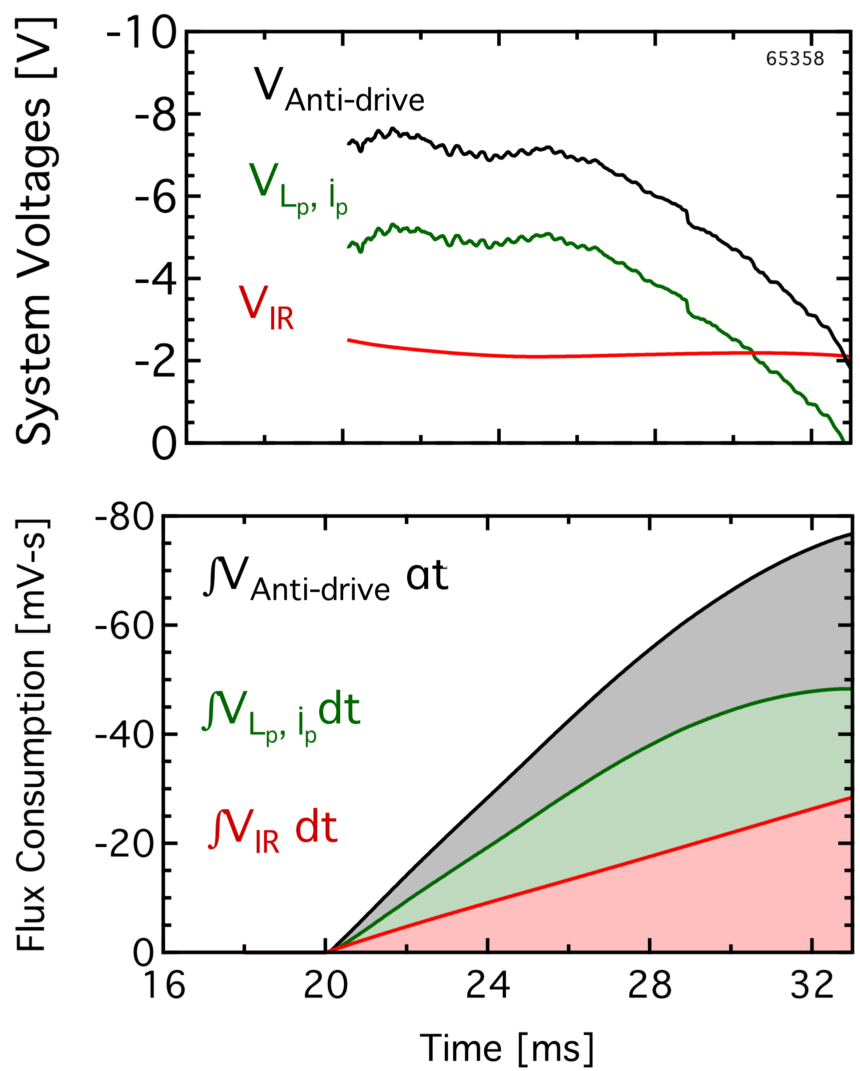
- Consistent with comparable plasma shape evolution
  - $I_{TL} \sim \sqrt{A_p}$

- URANIA scenario utilizes this scaling to achieve higher I_p performance



Dissipation in LFS LHI

Inductive Reactance is the Dominant Contribution to Net Plasma Impedance



$$V_{Anti-drive} = V_{IR} + V_{L_p,\dot{I_p}}$$

- **Resistive dissipation**
  - V_{IR}: ~1–2 V
  - ~40% of V-s
  - Assumed $\langle T_e \rangle = 70\ eV$
  - Assumed $Z_{eff} M_{neo} = 2.85$

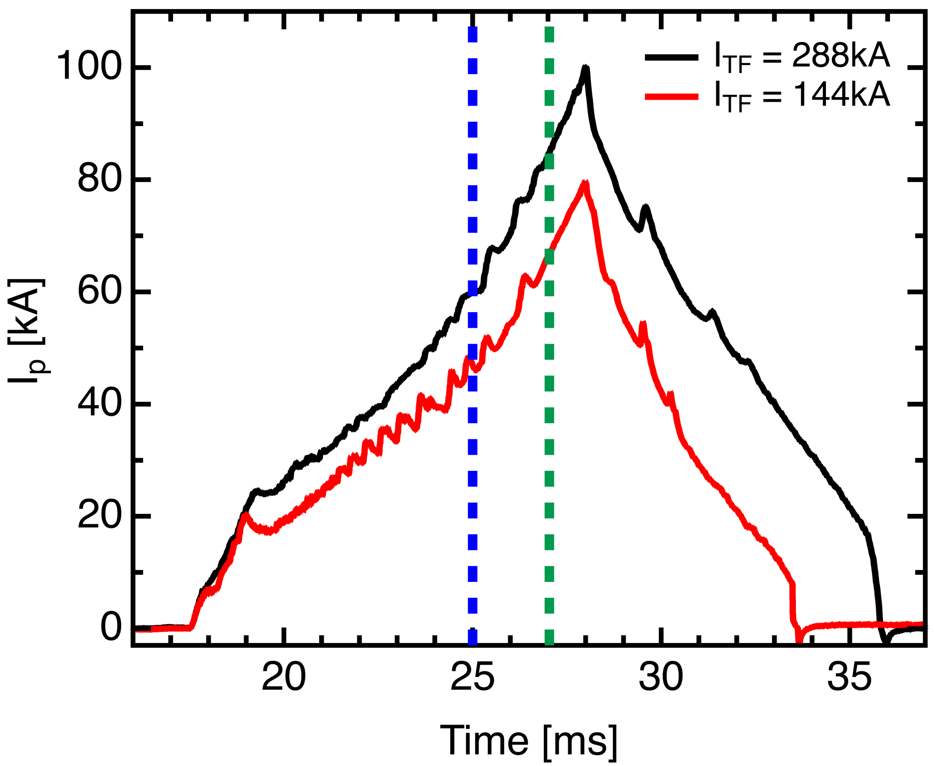
$$V_{IR} = I_p \left(\frac{\langle \eta_p \rangle 2\pi R_0}{A_p} \right)$$

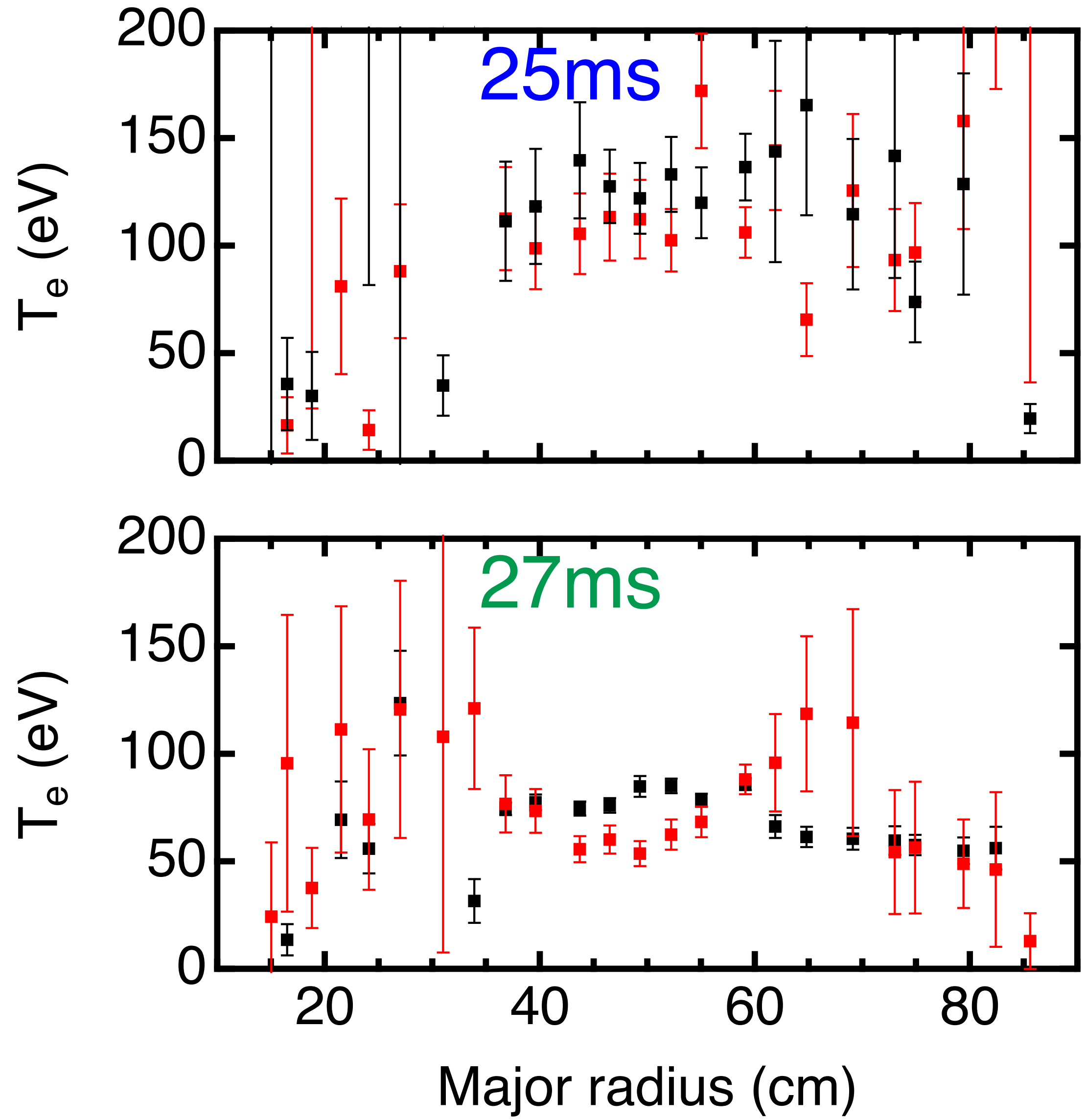
- **Inductive reactance**
  - $V_{L_p,\dot{I_p}}$: ~ 4–6 V
  - ~60% of V-s

$$V_{L_p,\dot{I_p}} = -L_e \frac{dI_p}{dt}$$

Similar T_e Profiles at Different I_{TF} Levels

- Similar $\langle T_e \rangle$ → similar $\langle \eta_{spitzer} \rangle$
  - Assumed constant Z_{eff}





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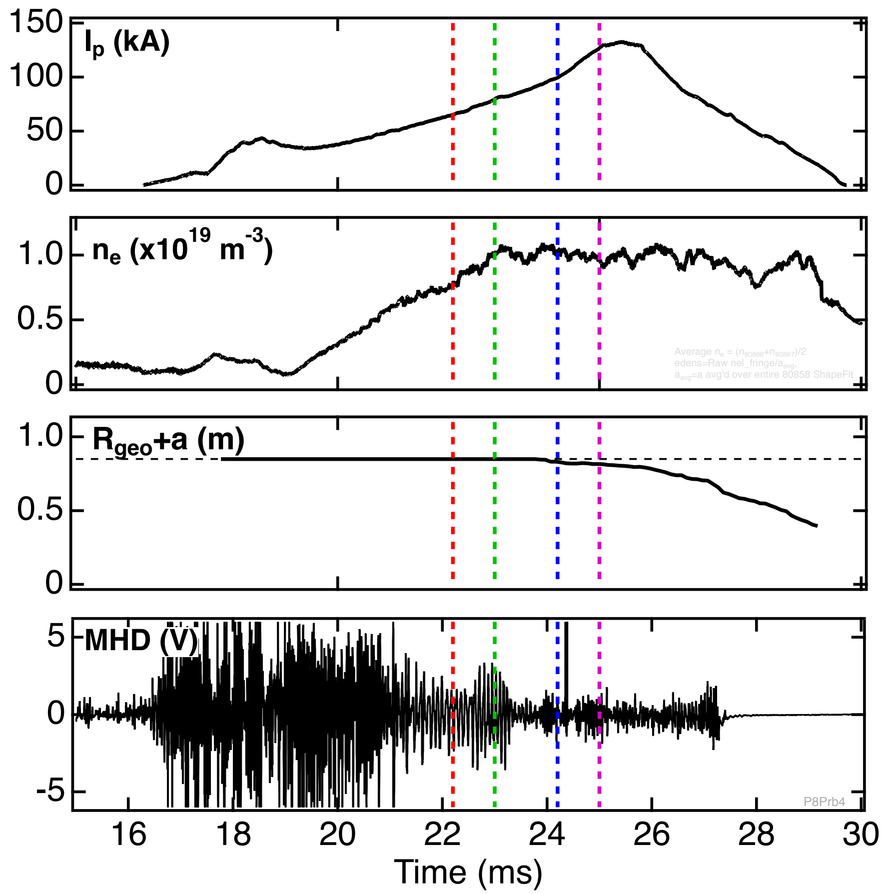
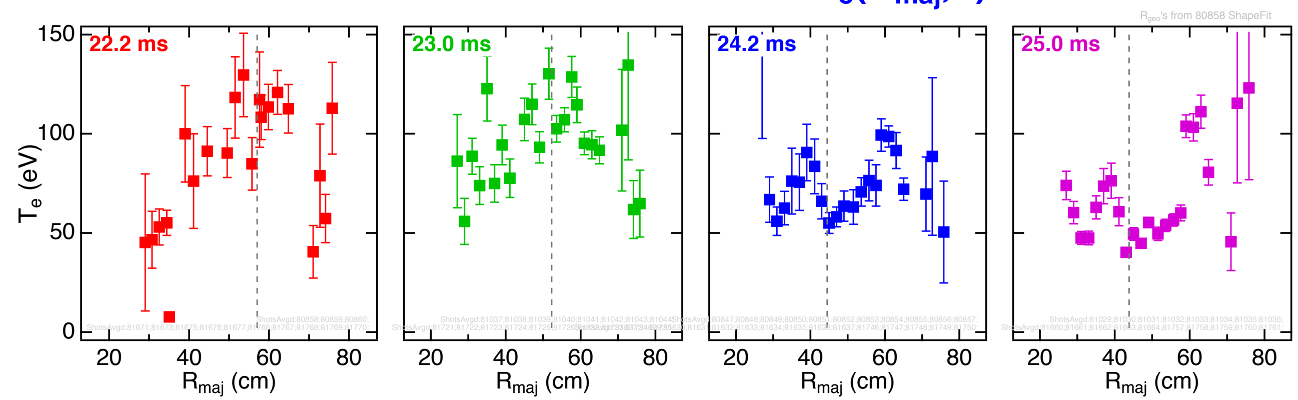
Peaked T_e Profiles when Coupled to Injectors

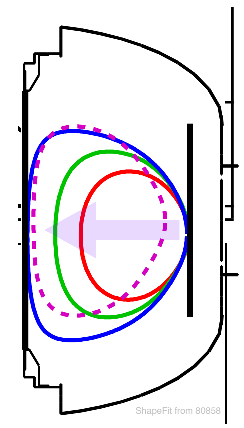
Majority Inductive Drive in Later Half of Discharge

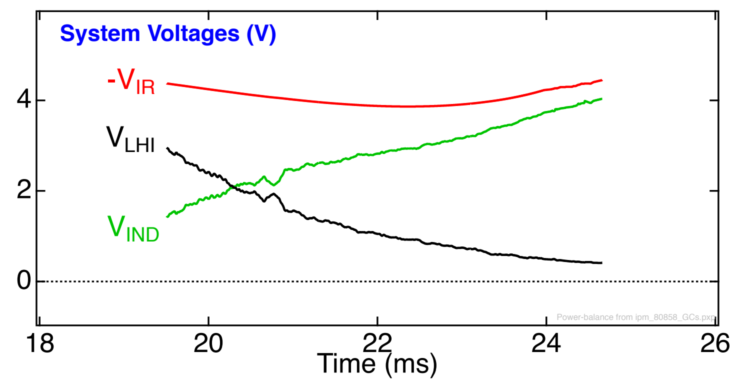


I_{TF} ~ 288 kA

Inductive-Drive Dominant $T_e(R_{maj}, t)$







- Model $\langle \eta_p \rangle$ consistent with measured $\langle T_e \rangle$ and typical $M_{neo} \approx 2$ and $Z_{eff} \approx 3$ for PEGASUS
  - Z_{eff} and helicity dissipation are under active investigation

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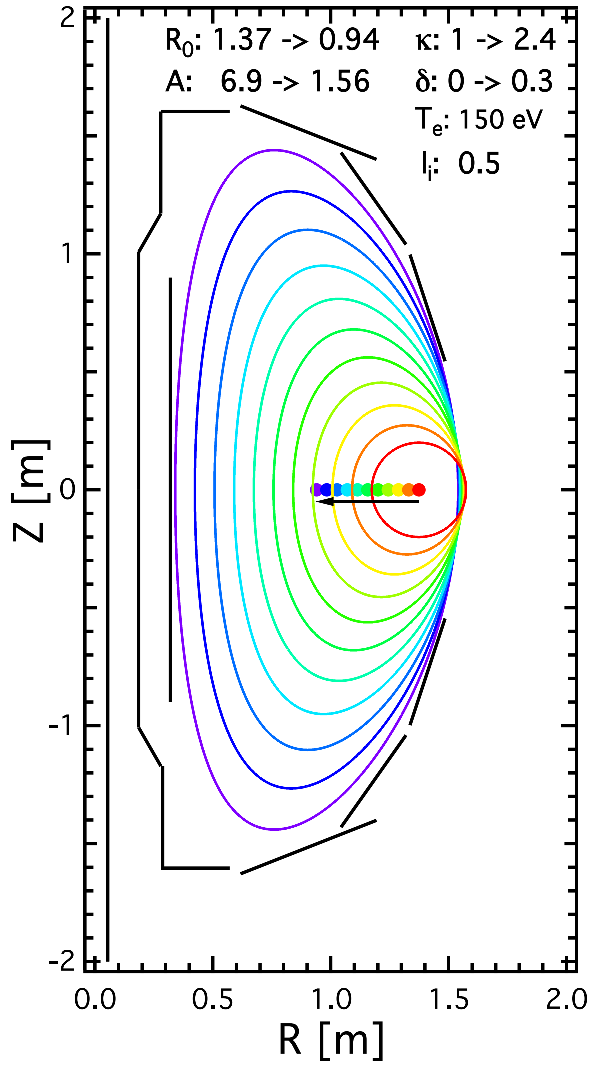
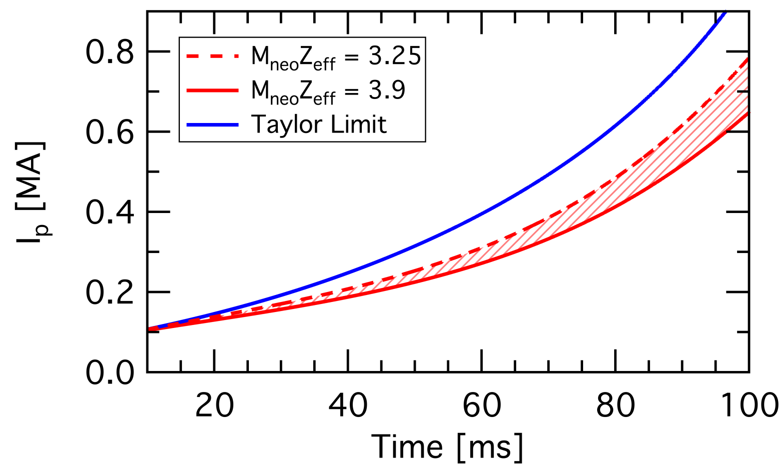
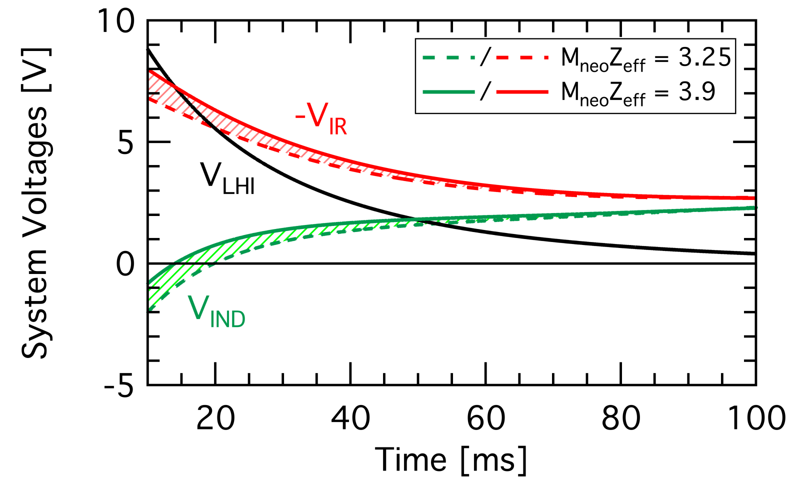
Scaling LHI toward NSTX-U Startup

Model Applied to NSTX-U Geometry for Initial I_p ~ 0.8 MA Scenario



*C. Neumeyer *et all* (2009) *23rd IEEE/NPSS Symposium on Fusion Engineering*



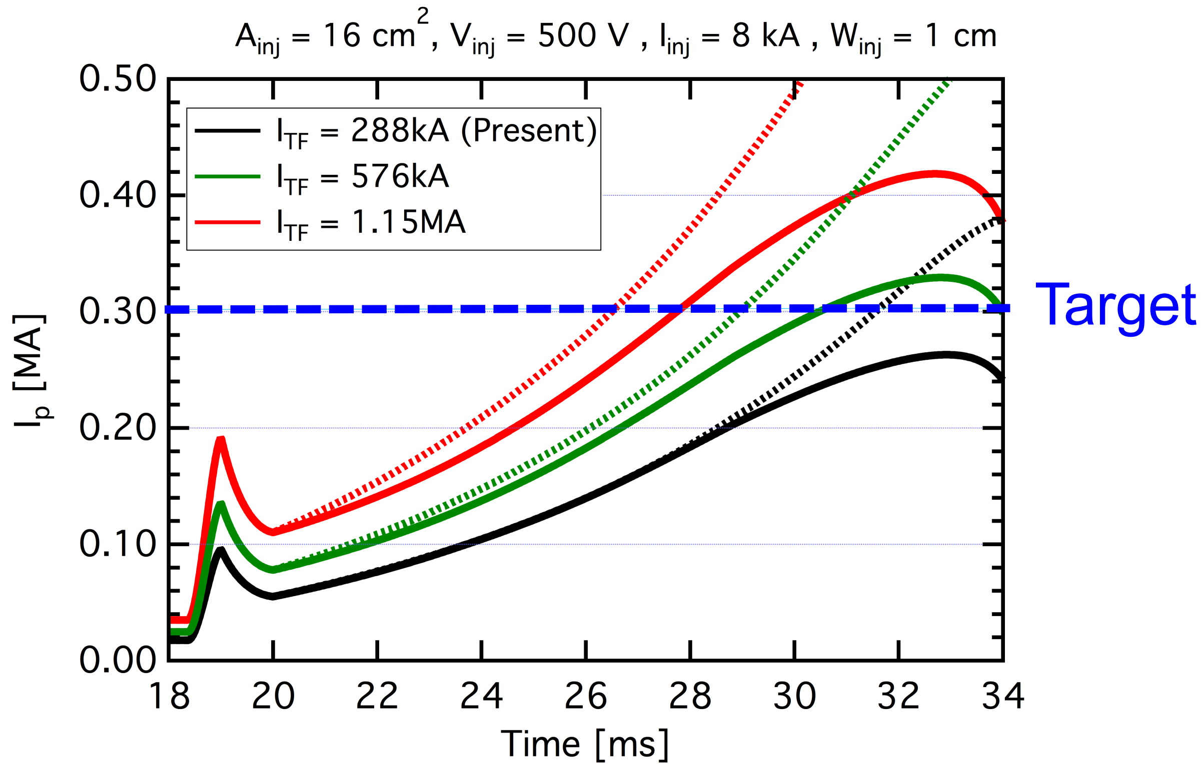


- I_p ~ 0.8 MA achievable with reasonable LHI system
  - $B_{TF,0}$ @ full size (100ms) = 1 T
  - $\langle T_e \rangle \sim 150$ eV assumed; $M_{neo} = 1.3$; $Z_{eff} = 2.5$-3
  - $A_{inj}V_{inj} = 20$ kVcm^2; $I_{inj} = 20$ kA
- Important physics and technology questions remain for projection:
  - Confinement and current drive efficiency scaling to large size, high B_{TF}
  - Low V_{inj} at high V_{LHI} for PMI control

URANIA Experiments will Test NSTX-U Startup Scenario

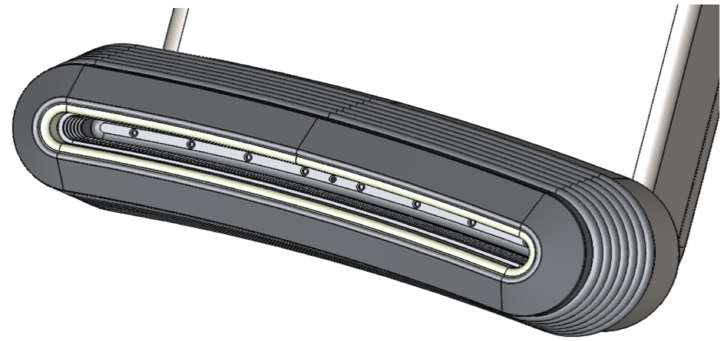
- Physics Tests
  - Scaling to $I_p \sim 0.3$ MA
  - Increase $B_{TF} \sim 0.6$T
  - Validate high I_p through early Taylor Limit increase
  - Demonstrate high V_{LHI} at low V_{inj}
- Technology Tests
  - Low V_{INJ} ➞ Avoid PMI
  - "Slit" injector design on LFS
  - Removable single port injector access
  - $V_{inj}(t)$ control
  - Active injector gas control
  - Long pulse operation

Model projection for next gen. LHI system



Non-circular, High-A_{inj} Helicity Injector Rendering

High A_{inj} = 16 cm^2
Low W_{inj} = 1 cm aperture



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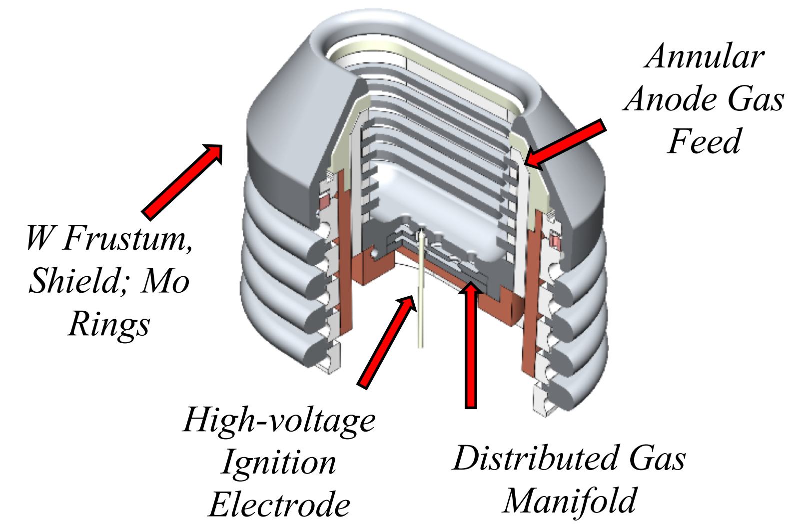
Near Term PEGASUS Experiments to Establish URANIA Operation

- Push injector current density limit
  - $J_{inj} > 1\ kA * cm^{-2}$
  - Control neutral particle density → maintain V_{inj}
- Test non-circular, high A_{inj} LFS system
- Thomson scattering documentation of typical LFS LHI scenario
  - Investigate electron confinement behavior
- Ohmic operations
  - Taylor limit scaling
  - LHI → ohmic handoff

Non-Circular, High-A_{inj} Helicity Injector Renderings



High A_{inj} = 6 cm^2, Low w_{inj} = 1.6 cm Aperture

LFS LHI Provides a Path Toward Scalable, Non-Inductive, High I_p Startup

- Path to high I_p depends on increasing Taylor limit early in discharge
- I_{TF} scans demonstrate higher I_p with increased early Taylor limit
  - Controlled shape evolution, injector parameters, and resistive dissipation
- URANIA Experiments will test NSTX-U Startup Scenario
  - Scaling LHI to higher I_p, B_{TF}
- Planned Experiments on PEGASUS to develop URANIA operation scenarios
  - Testing non-circular injector design, high J_{inj}, confinement studies
- Work Supported by US DOE grants DE-FG02-96ER54375 and DE-SC0006928

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