Electron Temperature Evolution During Local Helicity Injection on the Pegasus Toroidal Experiment

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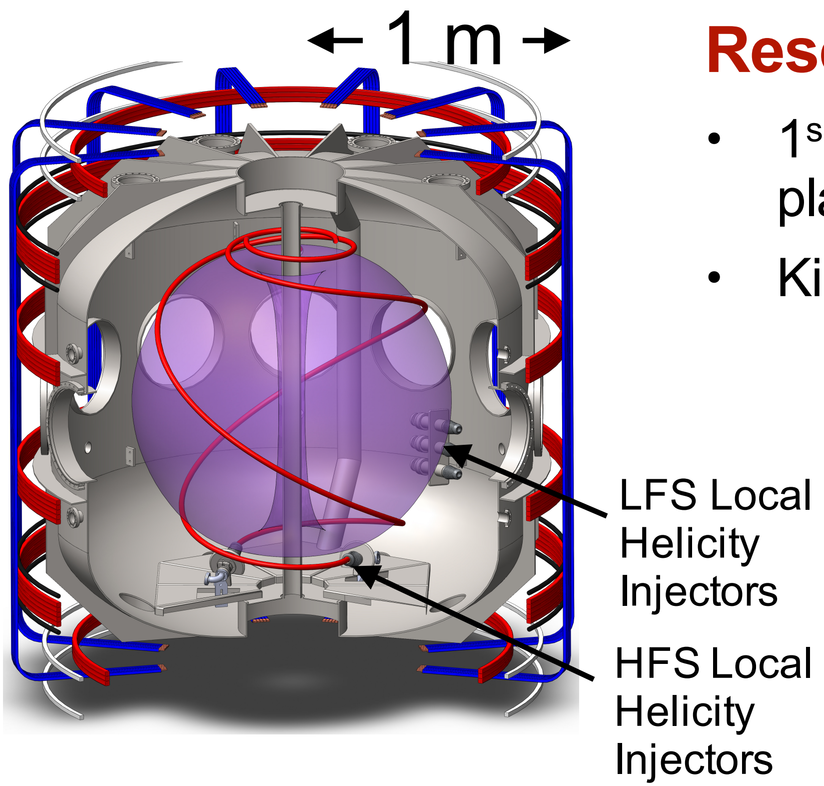
PEGASUS
Toroidal Experiment

Pegasus is a Compact, Ultralow Aspect Ratio Spherical Tokamak

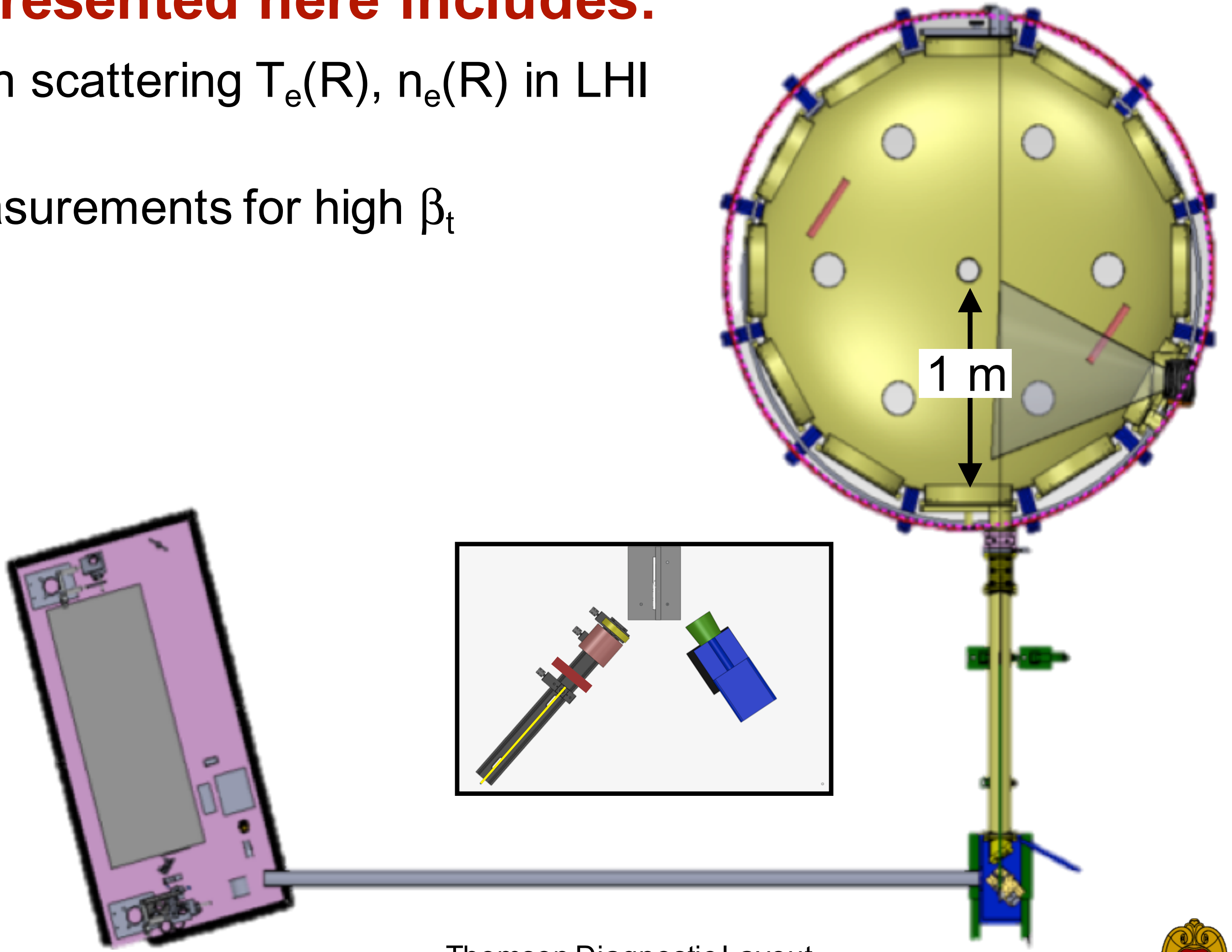


Research presented here includes:

- 1^{st} Thomson scattering $T_e(R)$, $n_e(R)$ in LHI plasmas
- Kinetic measurements for high β_t

Experimental Parameters

A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .21
κ	1.4 – 3.7
β_t (%)	≤ 100



Thomson Diagnostic Layout

I_p Projections for LHI Depend Strongly on Electron Confinement Scaling

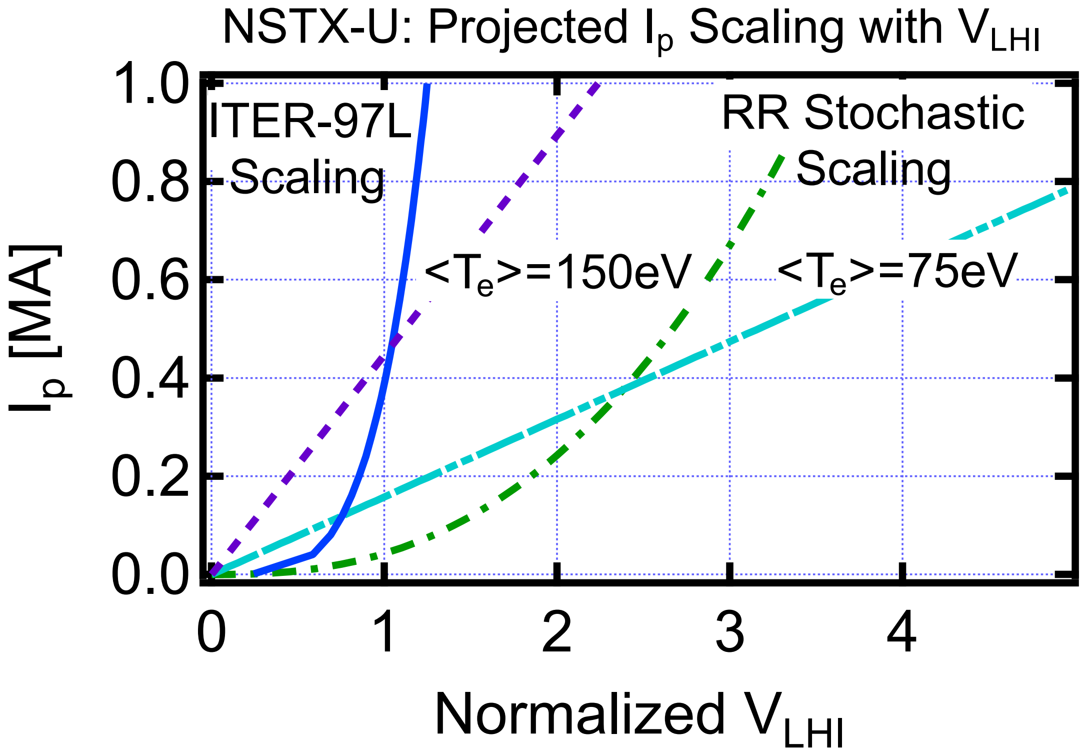
- 0-D power-balance model[1] predicts $I_p(t)$ from Local Helicity Injection (LHI):

$$I_p[\, V_{LHI}+V_{IR}+V_{IND} \,] = 0$$

$$V_{IR} \rightarrow \propto T_e^{-3/2}$$

- Projected T_e, I_p, may vary if:
  - Helicity drive dominates ($V_{LHI} >> V_{IND}$)
  - Inductive drive dominates ($V_{LHI} << V_{IND}$)

- Exploring T_e behavior as dominant drive method varies



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[1] *J.L. Barr, et al. NP10.55, Poster session Wed morning*

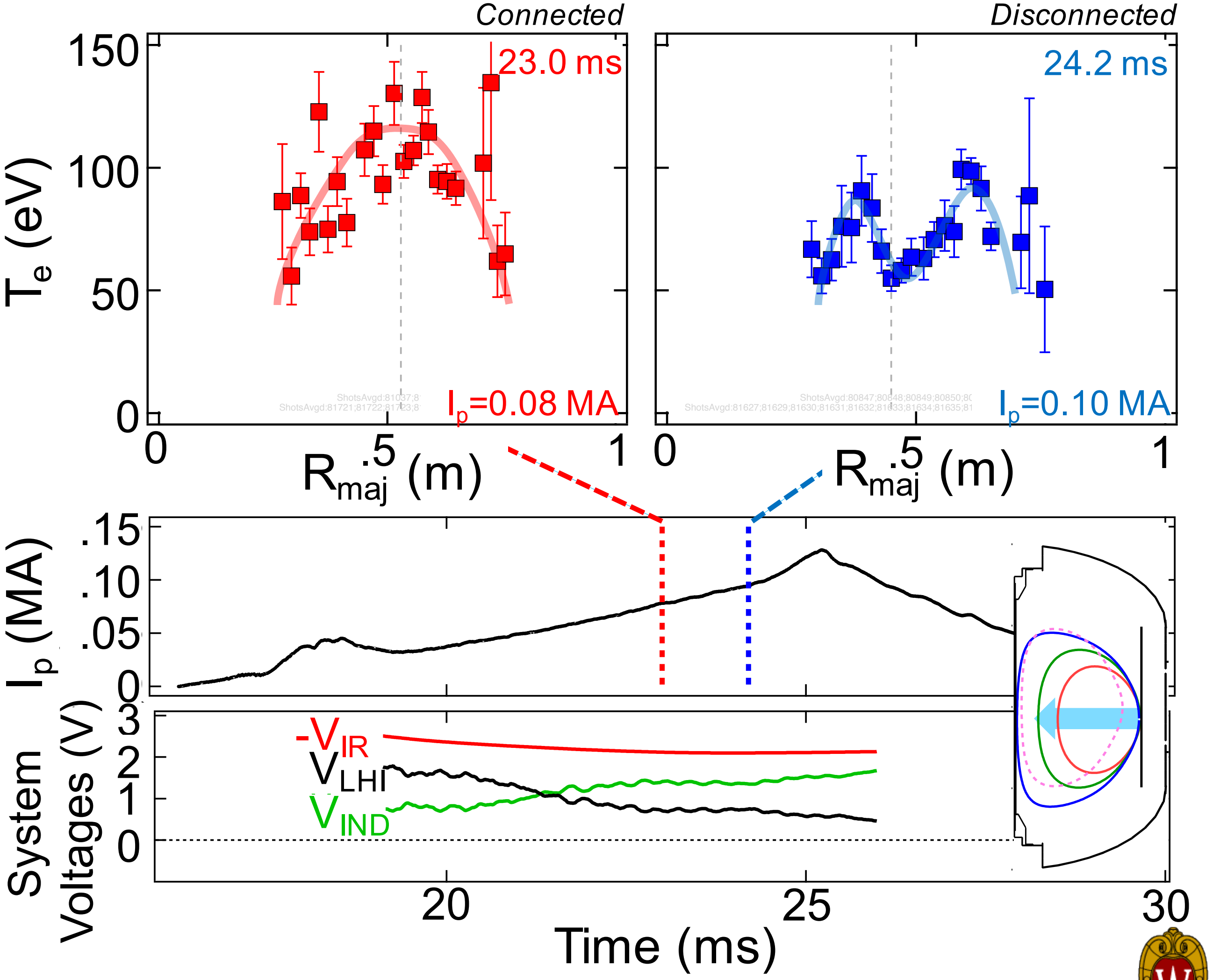
LFS Local Helicity Injection Produces Core T_e > 100 eV

- Plasma position and shape evolve inward from outboard injectors
    - Shape evolution generates V_{IND}
    - $V_{IND} > V_{LHI}$ during high-I_p phase

- Peaked $T_e(R)$ during drive phase (connected)
    - Not strongly stochastic
    - After disconnect radial compression drives skin current

- Core $n_e > 10^{19}$ m^{-3}, $T_e \geq 100$ eV provides target for subsequent CD

Peaked $T_e(R)$ while Connected to Injectors



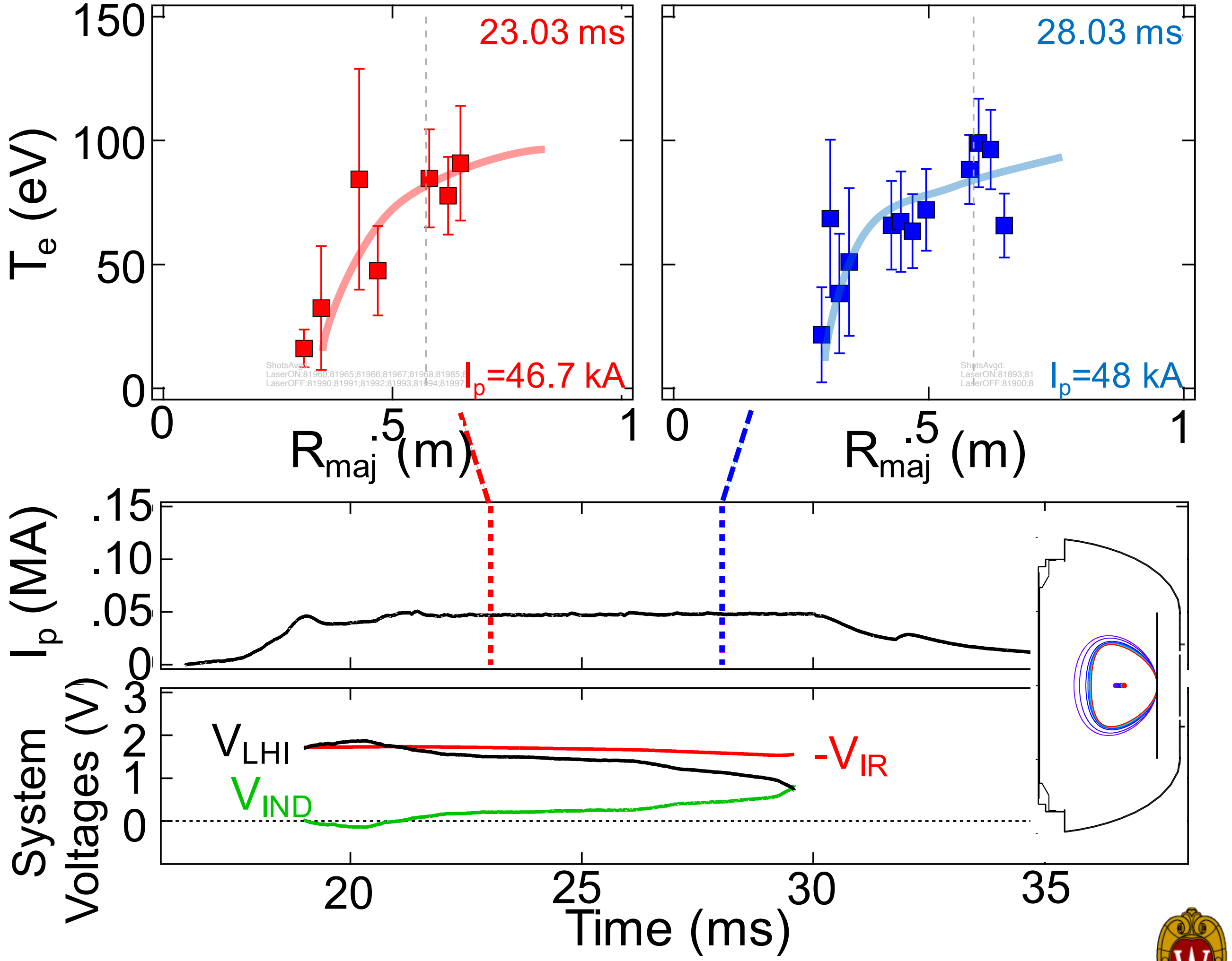
T_e (R_{maj},t) Remains Peaked for LFS LHI when V_{IND} Small

- Same injection location but static, circular plasmas at large R_{maj}
  - Lower performance due to shape constraints

- V_{IND} = 0, $T_e(0)$ ~ 80 eV

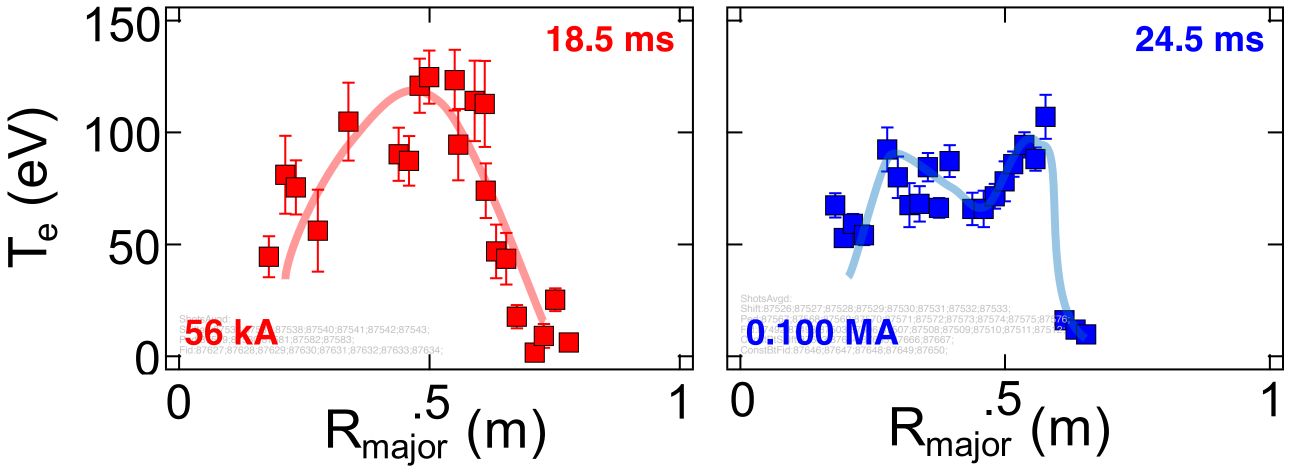
- $T_e(R)$ remains peaked while driven solely by edge LHI

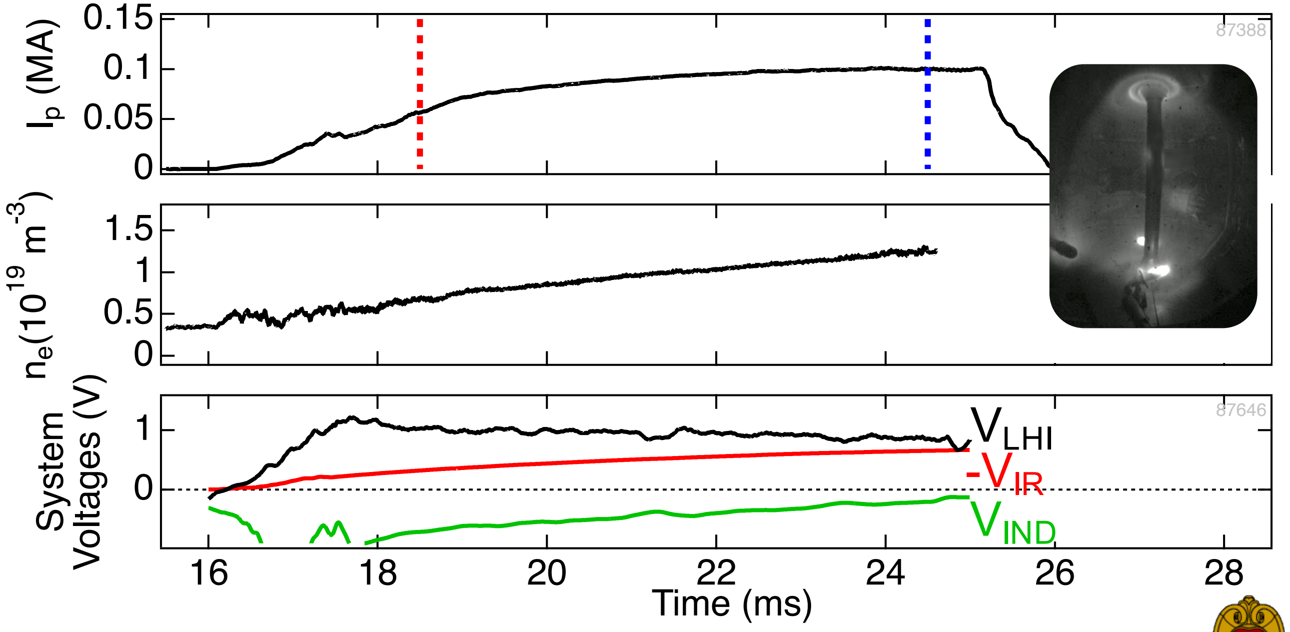
$T_e(R)$ > 85 eV with majority LHI-drive



HFS Injection Gives Peaked $T_e(R)$ for Sustained, Highly Elongated Discharge

- $T_e(0) \geq 100$ eV
- $\bar{n}_e$ increasing to ~1.2×10^{19} m^{-3}
- T_e, n_e comparable to Ohmic plasmas in Pegasus
- V_{LHI}-driven throughout





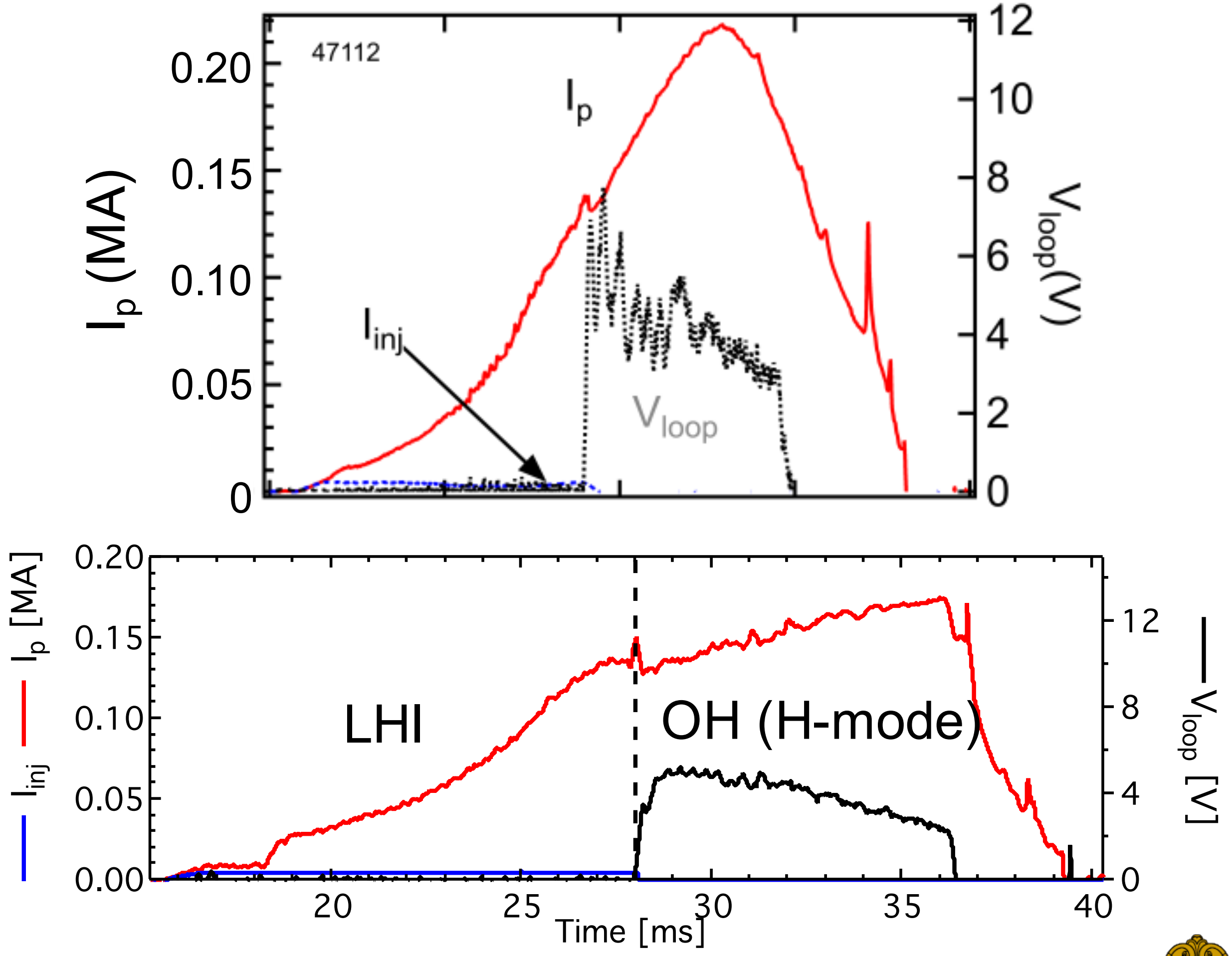
see also: J.M. Perry, et al. NP10.53, Poster session Wed morning

LHI Plasmas Provide Targets for Subsequent Current Drive Schemes

- Coupling to aux. drive is sensitive to I_p ramp-rate:
  - J(ψ) too hollow: ineffective coupling
  - J(ψ) too peaked: MHD unstable
- Pegasus aux. drive = Ohmic
- Upcoming campaign: characterize T_e, n_e through LHI-OH transition

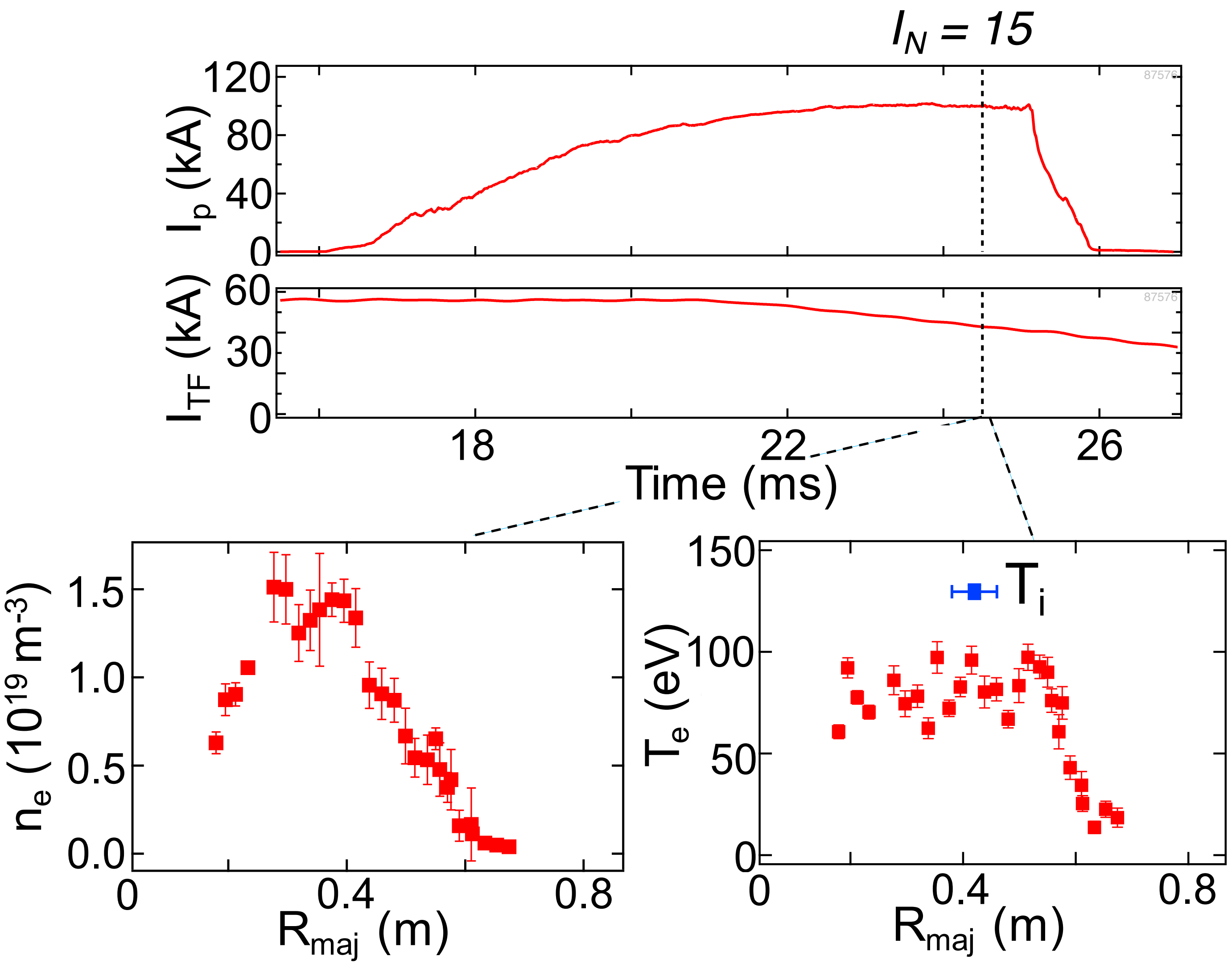
LHI-to OH Handoff Examples

(Pre-Thomson Scattering)



HFS Injection at low TF Provides Non-Solenoidal Sustainment at High I_N

- HFS LHI development campaign provides unique operation space
  - Low $I_{TF} \sim 0.6\ I_p$
  - $I_N = 5A\frac{I_p}{I_{TF}} > 10$ accessible
- Enables high β_t access[1]
  - Aided by anomalous ion heating
- Kinetic constraints on magnetic equilibrium fits[2]
  - $P_{tot}(0)$
  - Edge location defined by T_e profiles



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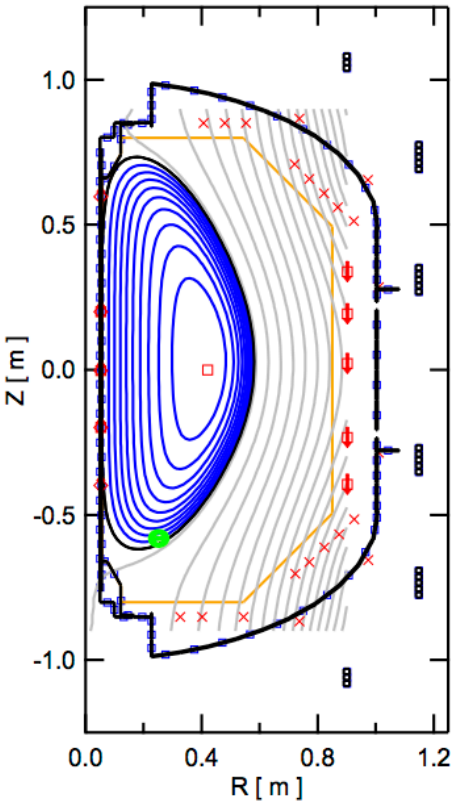
[1] M.W. Bongard, et al. NP10.52 Poster Wed morning

[2] G.M. Bodner, et al. NP10.54, Poster Wed. morning

LHI-Produced Plasmas at low B_t Provide High β_t

- Sample magnetic reconstruction at t = 24.5 ms, using kinetic constraints

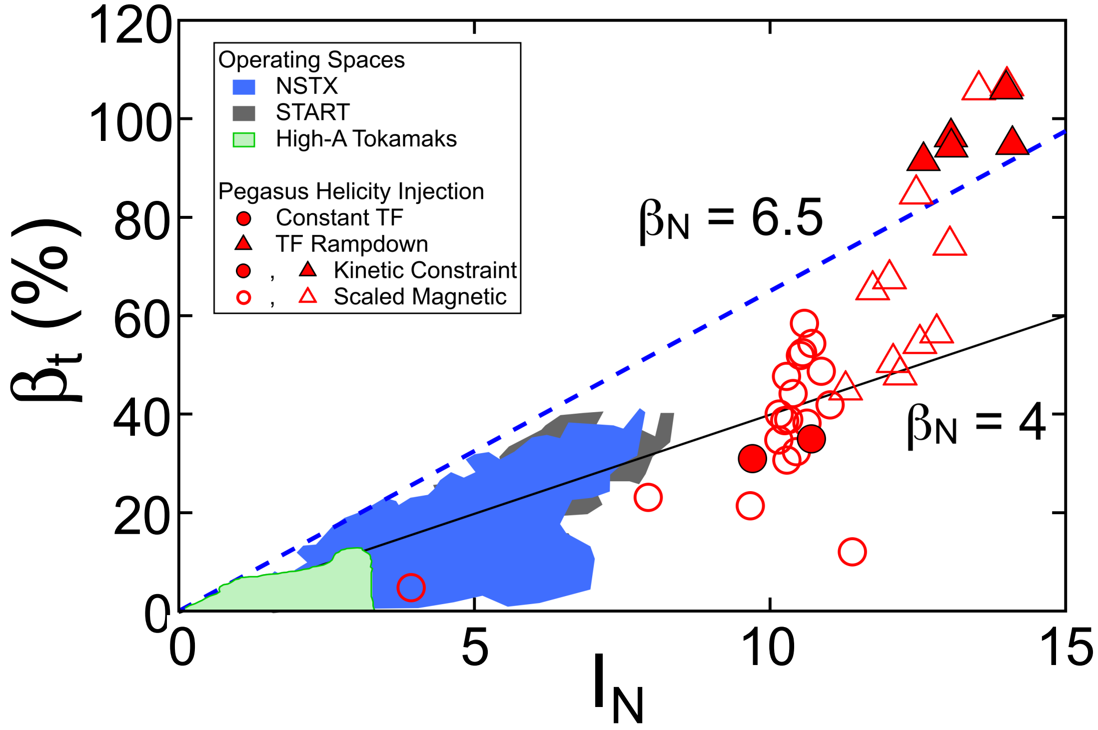


Equilibrium Parameters

Shot 87332, 24.50 ms

I_p	102 kA	R_0	0.317 m
β_t	0.95	a	0.263 m
ℓ_i	0.22	A	1.21
β_p	0.45	κ	2.6
W	545 J	δ	0.54
B_{T0}	0.0249 T	q_{95}	7.24

- β_T for sustained, low-ℓ_i, high-κ, LHI-driven plasmas



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[1] M.W. Bongard, et al. NP10.52 Poster Wed morning

LHI-Driven Plasmas Have $T_e(0)$ ~100 eV and Provide Access to High β_t, High I_N Operating Space

- Local Helicity Injection (LHI) sustains ~100 eV T_e, moderately-high n_e
- No strong $T_e(R_{maj})$ dependence on LHI location and ratio of LHI-to-inductive drive
- Effective startup target for direct OH coupling (Pegasus); Future to NBI (NSTX-U)?
- Very high β_t confirmed by kinetic measurements

Backups:
Taylor Relaxation & Helicity Balance

Physics Models Provide a Predictive Understanding for LHI Startup

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

Taylor Relaxation

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

Helicity Conservation

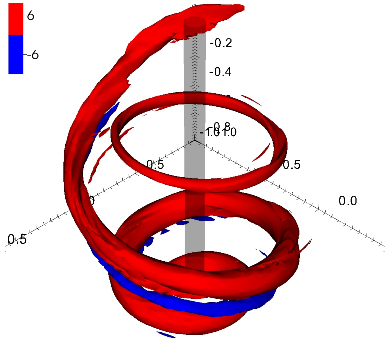
$$V_{LHI} \approx \frac{A_{inj} B_{\varphi,inj}}{\Psi} V_{inj}$$

2. 0-D power-balance $I_p(t)$
   - V_{LHI} for effective LHI current drive

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

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

Reconnecting LHI Current Stream



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)*

Helicity evolution and related plasma current depends strongly on T_e

- In a tokamak, fields and currents are oriented such that helicity injection drives toroidal current:

$$\boxed{\frac{dK}{dt} = \underbrace{2V\Psi}_{AC\ helicity\ injection} - \underbrace{2\oint_S \Phi \mathbf{B}\cdot\hat{n}d^2x}_{DC\ helicity\ injection} \underbrace{-2\int_V \eta \mathbf{J}\cdot\mathbf{B}d^3x}_{dissipation}}$$

  - Formulation analogous to Poynting's Theorem for energy

- Helicity dissipation term depends on resistivity[1], which in turn depends on T_e:

$$\eta_{||}^{(Sp)} = 0.51\frac{m_e}{n_e e^2 \tau_e} = 0.51\frac{m_e^{1/2}e^2 \ln\Lambda}{3\epsilon_0^2 \left(2\pi T_e\right)^{3/2}}$$

- Thomson scattering will be used to quantify T_e, and thereby helicity dissipation

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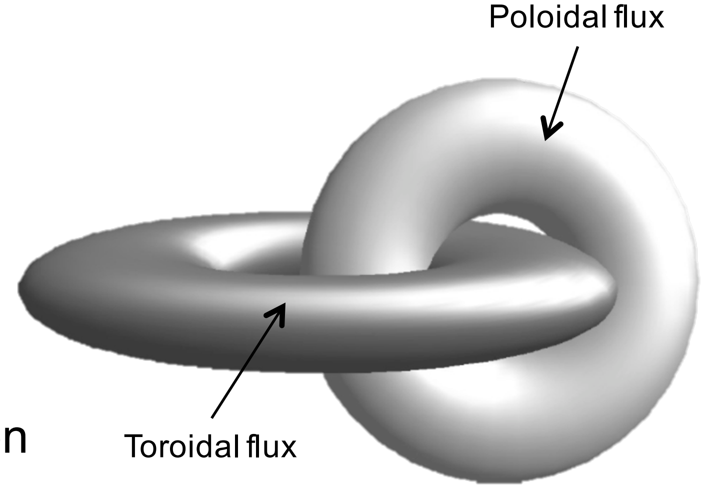
[1] Spitzer, Lyman, Jr. et al. Phys. Rev. 1953.

Helicity is a conserved quantity in magnetic systems, and directly relates to current drive



- Helicity describes linkage between magnetic flux tubes:

$$K = \int \mathbf{A} \cdot \mathbf{B} dV$$

- Helicity is conserved on resistive time scales even when magnetic energy is not

- System's minimum energy state, *given constant helicity constraint*, can be represented by:

$$\nabla \times \mathbf{B} = \lambda \mathbf{B}$$

  - λ represents system eigenstates ("Taylor states")
  - Unstable systems relax to this minimum energy state

J.B. Taylor, *Phys. Rev. Lett.*, 1974.
Woltjer, L., *Proc. Natl. Acad. Sci.*, 1958.
Brown, M.R. et al. *Geophys. Monograph*, 1999.

Backups: Power Balance Model

Backups:
Power Balance Model

Power-Balance, Taylor Relaxation Applied to Predict LHI $I_p(t)$

0-D LHI model predicts $I_p(t)$ based on lowest of two limits:

- Poynting's Theorem at plasma boundary sets $I_p(t)$:

$$\underbrace{I_p V_s}_{\text{Plasma surface-voltage}} \approx \underbrace{\iiint \frac{\partial}{\partial t}\left(\frac{B_\theta^2}{2\mu_0}\right) dV}_{\text{Internal magnetic energy storage}} + \underbrace{I_p^2 R_p}_{\text{Resistive Dissipation}} - \underbrace{I_p V_{LHI}}_{\text{Non-inductive current drive (LHI)}}$$

- Taylor relaxation limit strictly enforced as maximum I_p

Power Balance Model Incorporates Analytic Plasma Inductance Formulae

$$I_p\left[\underbrace{V_{PF}+V_{geo}-V_{W_m}}_{V_{IND}}-V_{IR}+V_{LHI}\right]=0$$

Analytic low-*A* descriptions of L_p*, B_z**

$$V_{PF}=-\sum_{coils}\frac{d}{dt}\left[\psi_{PF}\right]\approx-\frac{\partial}{\partial t}\left[M_V\,\pi R_0^2\,B_V\big|_{R_0}\right]$$

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

$$M_V(\varepsilon,\kappa)=\frac{(1-\varepsilon)^2}{(1-\varepsilon)^2 c(\varepsilon)+d(\varepsilon)\sqrt{\kappa}}$$

$$c(\varepsilon)=1+0.98\varepsilon^2+0.49\varepsilon^4+1.47\varepsilon^6$$

$$d(\varepsilon)=0.25\varepsilon\left(1+0.84\varepsilon-1.44\varepsilon^2\right)$$

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

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

$$V_{geo}=-\frac{d}{dt}\left[L_eI_p\right]=-L_e\frac{dI_p}{dt}-I_p\frac{dL_e}{dt}$$

$$L_e=\mu_0R_0\frac{a(\varepsilon)(1-\varepsilon)}{1-\varepsilon+\kappa b(\varepsilon)}$$

$$a(\varepsilon)=\left(1+1.81\sqrt{\varepsilon}+2.05\varepsilon\right)\ln\left(\frac{8}{\varepsilon}\right)-\left(2.0+9.25\sqrt{\varepsilon}+1.21\varepsilon\right)$$

$$b(\varepsilon)=0.73\sqrt{\varepsilon}\left(1+2\varepsilon^4-6\varepsilon^5+3.7\varepsilon^6\right)$$

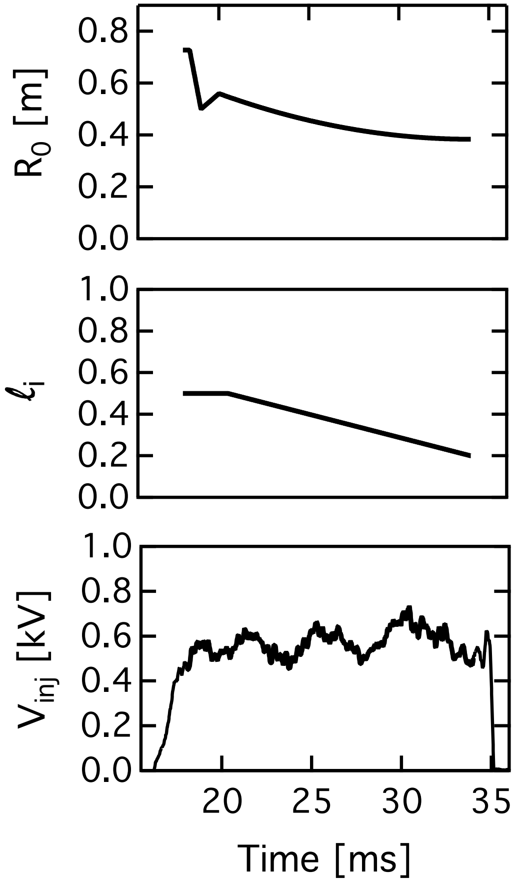
$$V_{W_m}\approx-\frac{1}{I_p}\frac{d}{dt}\left(\frac{1}{2}L_iI_p^2\right)$$

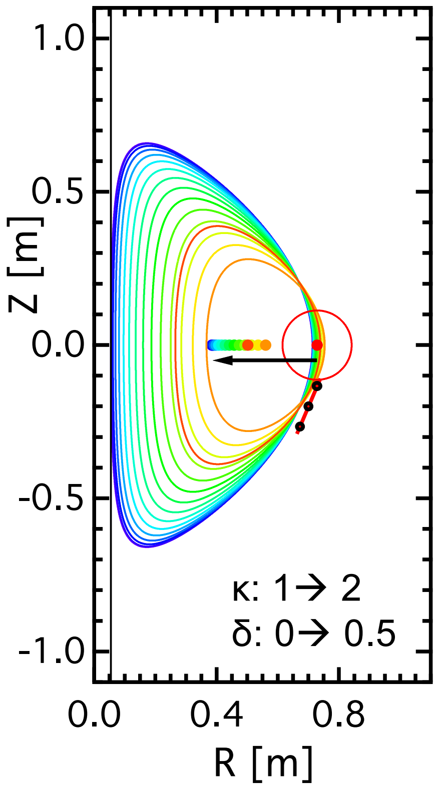
$$\ell_i=\frac{C_p^2}{\mu_0V_p}L_i$$

* *S.P. Hirshman and G.H. Nielson 1986 Phys. Fluids* ***29*** *790*
** O. Mitarai and Y. Takase 2003 *Fusion Sci. Technol.*
S. Ejima et al 1982 Nucl. Fusion ***22*** *1313*
J.A. Romero and JET-EFDA Contributors 2010 Nucl. Fusion ***50*** *115002*

0-D Model Takes Plasma, Injector Parameters as Inputs

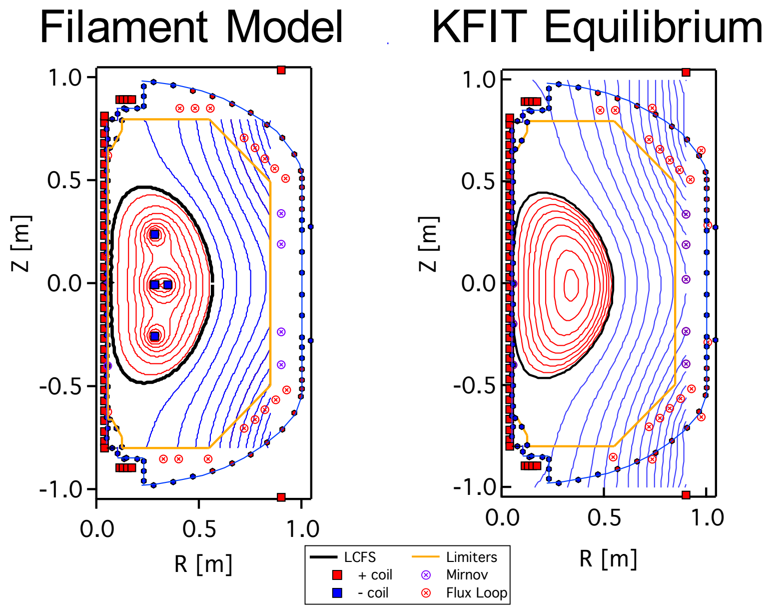
- Initial condition: $I_p(t_0)=I_{TL}$
- Shape(t)
    - $R_0(t)$, $a(t)$, $\kappa(t)$, $\delta(t)$
    - Vertical symmetry
- $\langle\eta\rangle(t)$, $\ell_i(t)$, $\beta_p(t)$
    - Constant $\langle\eta\rangle$ assumed
        - Spitzer
    - $\beta_p = 0$
    - ℓ_i dropping: 0.5 → 0.2
- Injector Inputs:
    - $A_{inj}(t)$, $V_{inj}(t)$, $R_{inj}(t)$

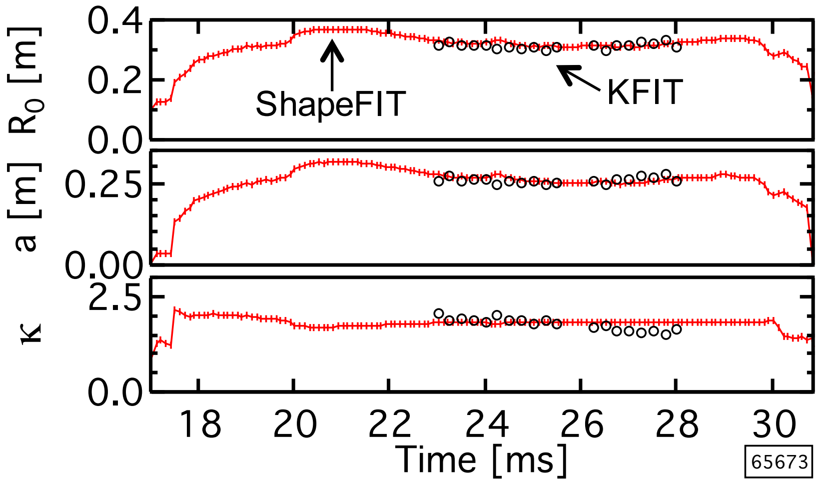




ShapeFIT: Fast Boundary Reconstruction Code Provides Shape(t)

- Plasma treated as 4-6 filaments
  - Positions, currents fit to magnetics
- Wall currents modeled
  - Same model used in KFIT equilibrium code
- Validating against reconstructions
  - $R_0 \pm 1.5$ cm
  - $a \pm 1.5$ cm
  - $\kappa \pm 15\%$
  - $\delta \pm 25\%$



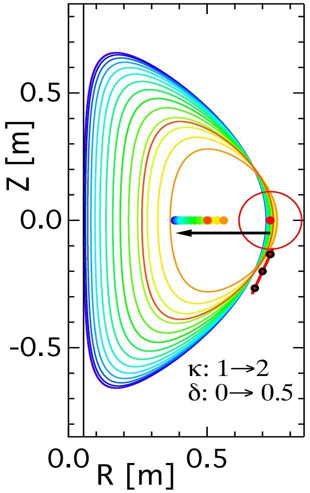


Power Balance Model Provides Predictive Tool for $I_p(t)$

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

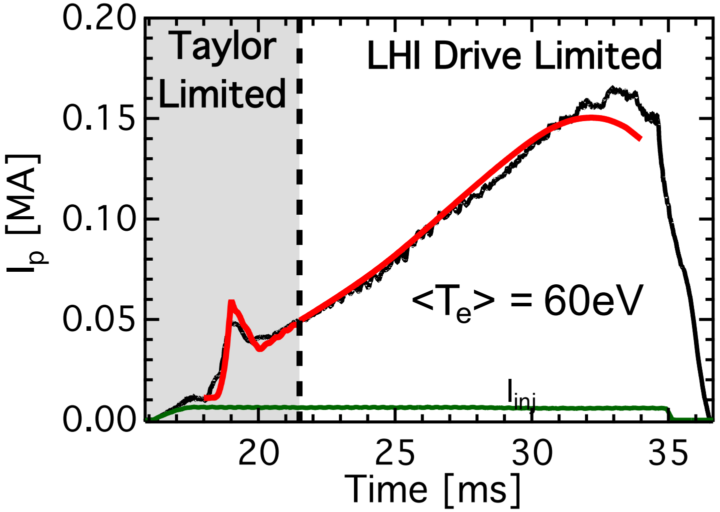
- V_{LHI}: effective drive
- V_{IR}: resistive dissipation
- V_{IND}: analytic, from shape(t)
- Taylor relaxation limit: $I_p \leq I_{TL}$

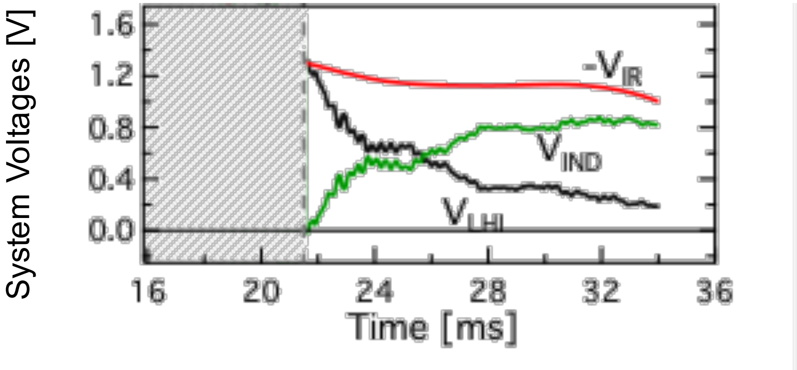
Shape Evolution



- V_{IND} dominates current drive

- Model reasonably recreates $I_p(t)$



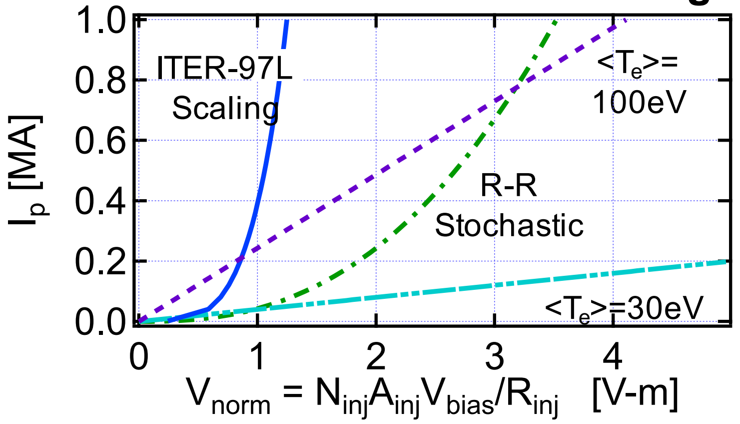


Eidietis et al., J. Fusion Energ. ***26****, 43 (2007)*
S.P. Hirshman and G.H. Nielson 1986 Phys. Fluids ***29*** *790*
O. Mitarai and Y. Takase 2003 Fusion Sci. Technol.
Battaglia et al., Nucl. Fusion ***51****, 073029 (2011)*

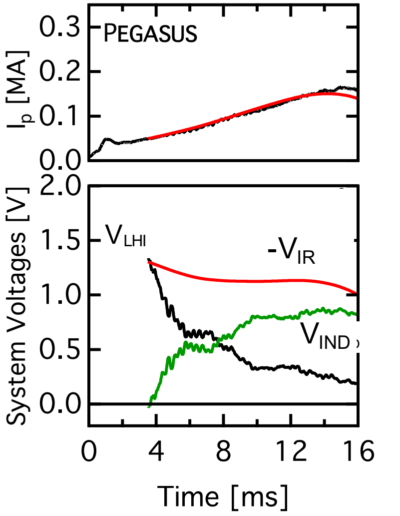
Understanding Confinement Scaling in LHI is Critical for Predicting to NSTX-U and Beyond

- Rapid improvement with V_{LHI} under favorable scalings
  - Possible reduction in injector requirements
- Current projections: I_p~1 MA on NSTX-U accessible
- Will need $V_{LHI} \sim V_{IND}$
  - Confinement studies needed when sustained by V_{LHI}

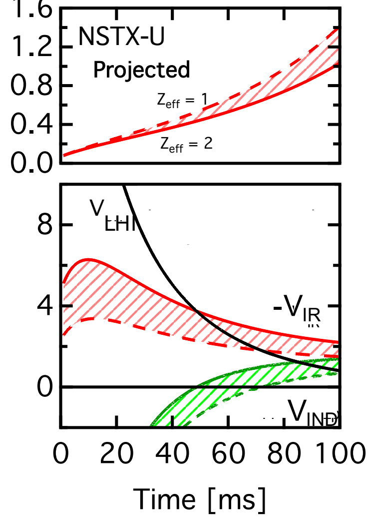
NSTX-U: Confinement Scalings



PEGASUS: $V_{LHI} < V_{IND}$



NSTX-U: $V_{LHI} \sim V_{IND}$



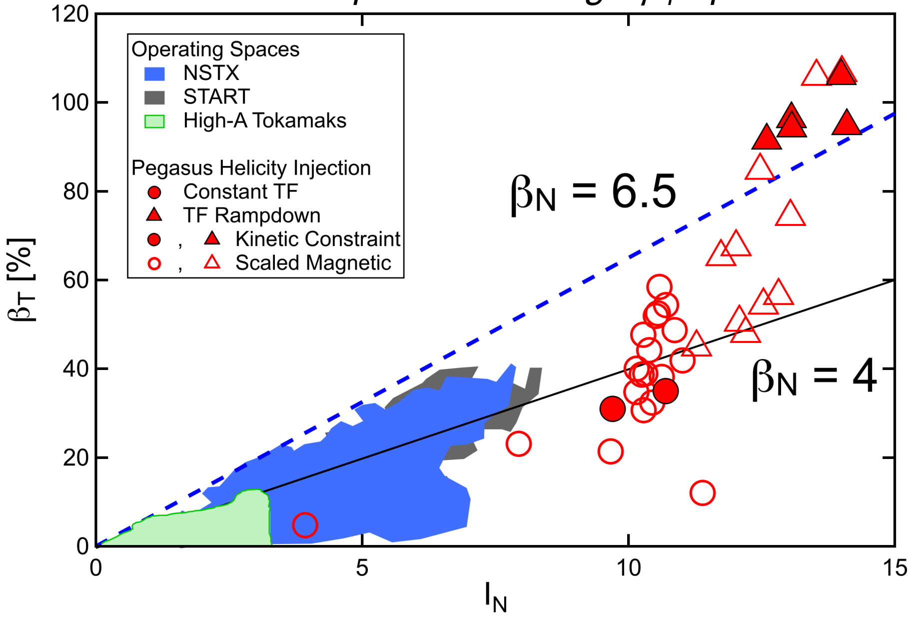
Backups: High Beta

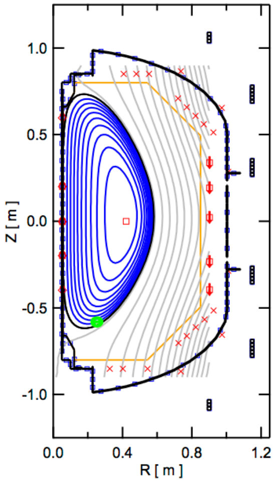
Backups:
High Beta

LHI Provides Access to High-β_T at A ~ 1 with Non-Solenoidal Sustainment and Anomalous Ion Heating

- Equilibrium reconstructions estimate β_T (~<P>/B_{T0}^2)
  - Matches external magnetics, $P_{tot}(0)$, and edge in $T_e(R)$
  - Includes anomalous $T_i(0)$
  - Some caveats for these initial results
    - Assumes closed flux surfaces inboard of injectors
    - Role of SOL edge current
    - Magnetics-only reconstructions scaled via comparison to those with kinetic constraints
    - Need full kinetic profiles in future
- High β_T plasmas often terminated by disruption
  - n = 1, low-m precursors
- Expands accessible high I_N, β_T space for tokamak stability studies at extreme toroidicity
  - Campaign underway to document, extend to higher I_p
  - Improved LHI injector hardware to increase I_p, B_{TF} access

Initial Exploration of High-β_T Space





Equilibrium Parameters

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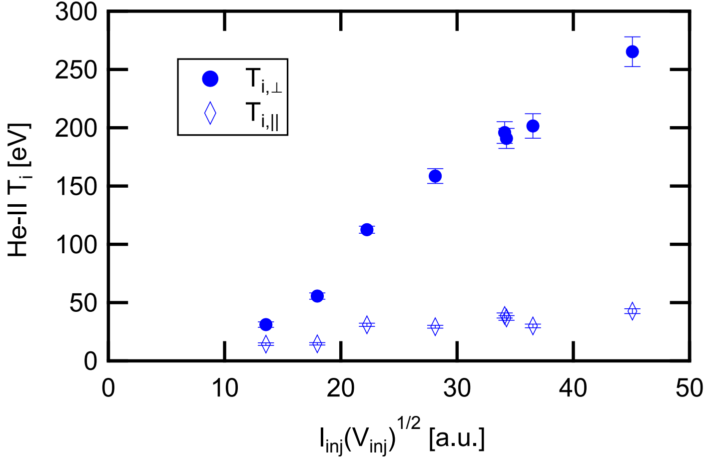
Backups: Ion Heating

Backups:
Ion Heating

Reconnection-driven Ion Heating Gives $T_i > T_e$ During LHI

- Impurity $T_i(0) \sim 100 - 500$ eV > T_e routinely observed during LHI
- Continuous ion heating from reconnection between collinear current streams
  - No effect on current drive efficiency
  - Significant ion heating (~ few 0.1 MW)

Ion heating consistent with 2-fluid reconnection theory



Ion heating correlated with high frequency MHD fluctuations, not with discrete reconnection between helical streams