Current Drive Scaling of Local Helicity Injection in the Pegasus Toroidal Experiment

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PEGASUS Toroidal Experiment

Layout Slide (Include for Posters)

12:1 scale Panel size: 8’ x 4’

US Legal
8.5 x 14”

US Letter
8.5 x 11”

Populate with section titles, final slide titles

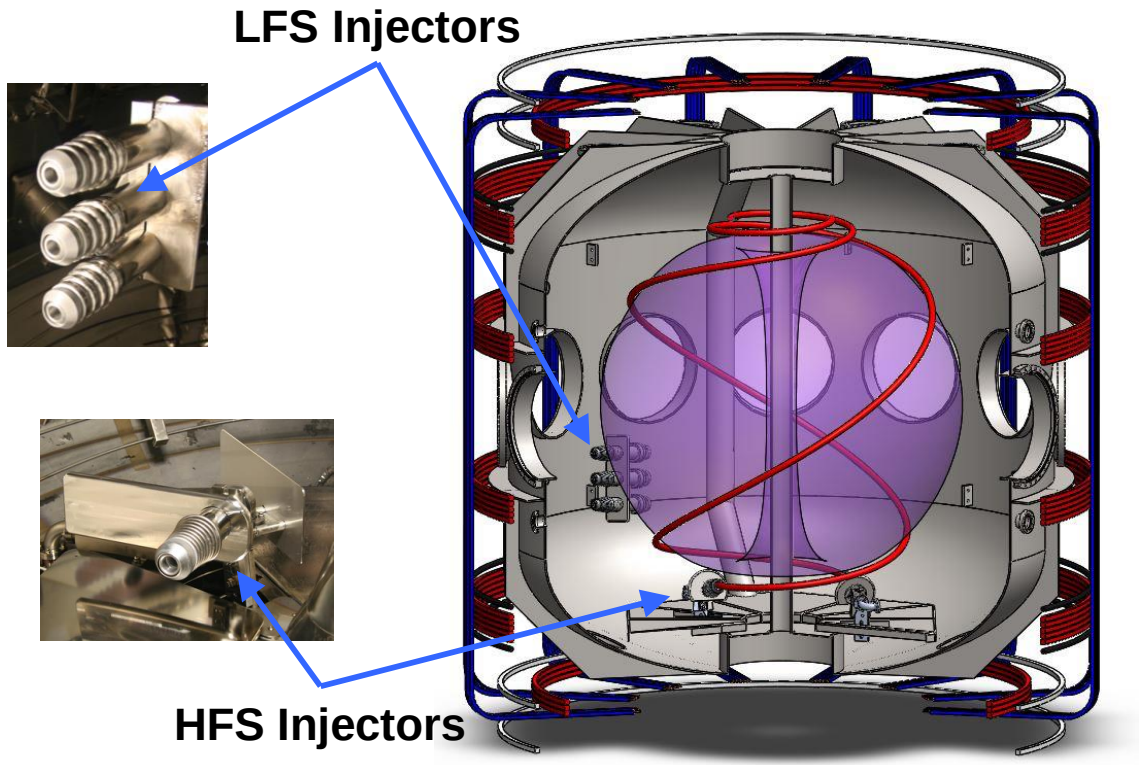
Spacer for Title Strip and Column Headings

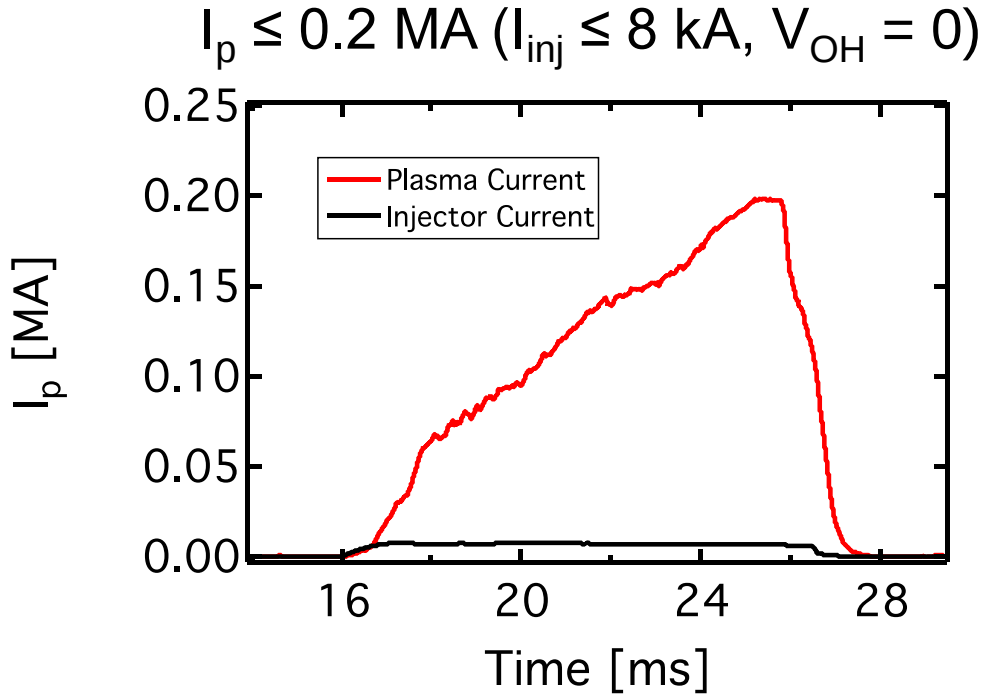
Pegasus Overview	V_{LHI} Experiment Overview (30% TF)	Stochastic Scaling	Impurities in LHI Plasmas	Sustained Hollow T_e Profiles	
HFS Injection	V_{LHI} Experiment Overview (30% TF)	MHD Fluctuation Measurements	Zeff Analysis (1/2)	Ohmic Power Density	Two-Zone Confinement
HFS Confinement Scaling	Current Drive Scaling with B_t	T_e Dependence of Stochastic Scaling	Zeff Analysis (2/2)	LHI vs L-Mode Comparison	Conclusion
Previous V_{LHI} Scaling Experiment	Single Injector Experiment		Zeff Scaling		

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LHI is a Promising Technique for Non-Inductive Tokamak Startup

Local Helicity Injection (LHI) Achieved Using Low-Field-Side and High-Field-Side Injectors





- Edge current extracted from injectors
- Relaxation to tokamak-like state via helicity-conserving instabilities

- Current drive quantified by:

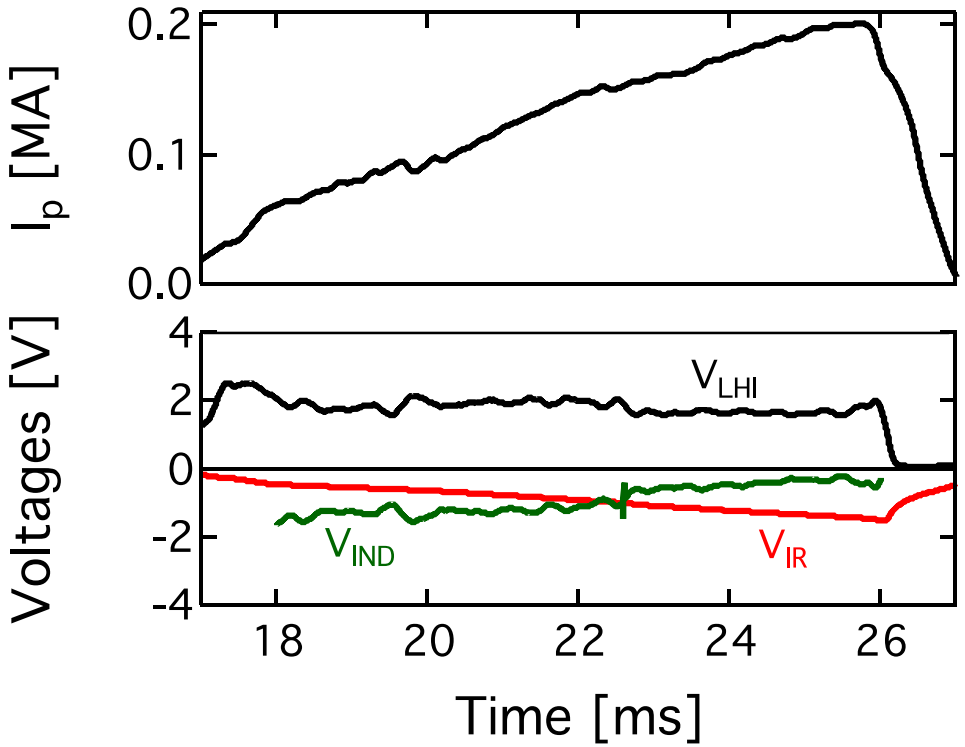
$$V_{LHI} \approx \frac{A_{inj} B_{\varphi,inj} V_{inj}}{\Psi_p}$$

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High Field Side Injection Creates Plasmas Driven Purely by Helicity Injection

High-Field-Side Injection:

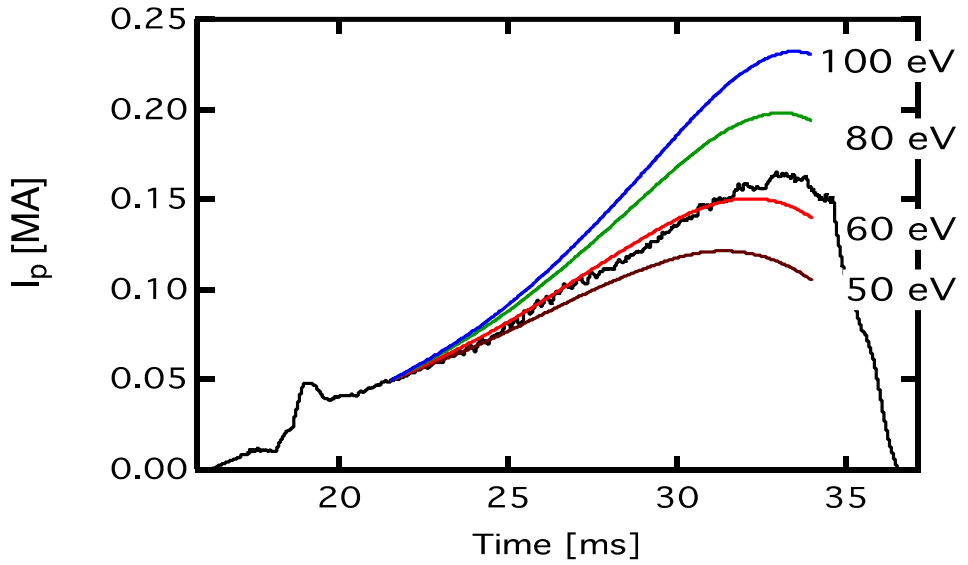
- Injectors in lower divertor
- Low R_{inj} → strong V_{LHI}
- Static shape → minimal V_{IND}



0-D Power Balance Model For $I_p(t)$:

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

Projections from 0-D Power Balance Model Demonstrating Impact of T_e on LHI Performance



G.M. Bodner APS-DPP 2019

J.A. Reusch et al 2018 PoP **25** 056101

J.L. Barr et al 2018 Nucl. Fusion **58** 076011

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Confinement Properties May Set the Current Drive Scaling for HFS Injection

- No validated 1st principle confinement model for LHI
  - Ohmic:

$$I_p = \frac{1}{\langle 2\pi\eta \rangle} \underbrace{\frac{V_{loop} A_p}{R_0}}_{V_{norm\text{-}OH}} \qquad I_p = \frac{1}{\langle 2\pi\eta \rangle} \underbrace{\frac{V_{LHI} A_p}{R_0}}_{V_{norm\text{-}LHI}}$$

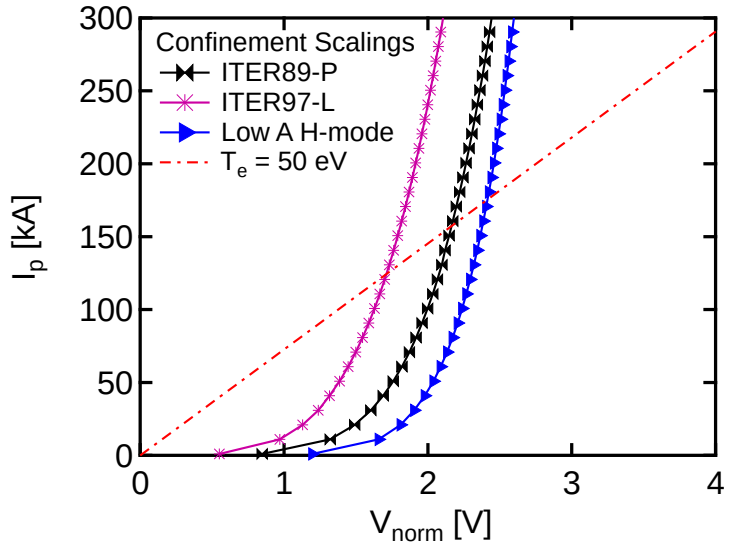
$$V_{norm-LHI} \equiv \frac{V_{inj} A_{inj}}{R_{inj}}$$

  - Collisional Stochastic:

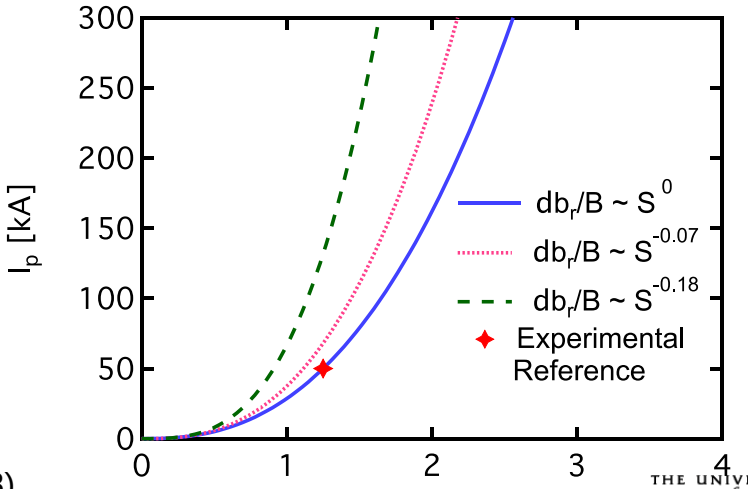
$$P_{in} = I_p V_{LHI} \sim \frac{n_e T_e \chi_e}{a^2} \qquad V_{LHI} = I_p R_p \rightarrow T_e^{3/2}$$

$$I_p \propto \frac{V_{LHI}^{5/2}}{\left(\frac{\delta b_r}{B_{tor}}\right)^{3/2}} \quad , \left(\frac{\delta b_r}{B_{tor}}\right) \sim S^{-\alpha}$$

Ohmic Confinement Scalings



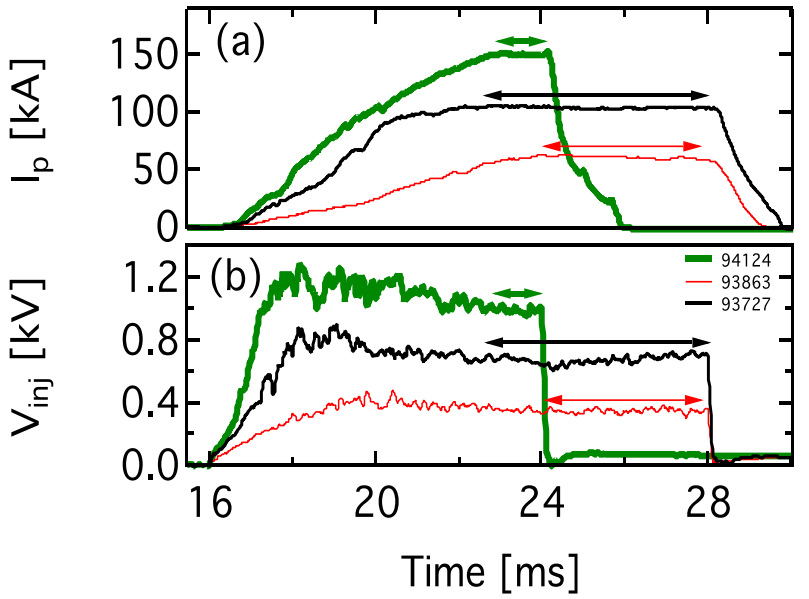
Stochastic Confinement Scalings

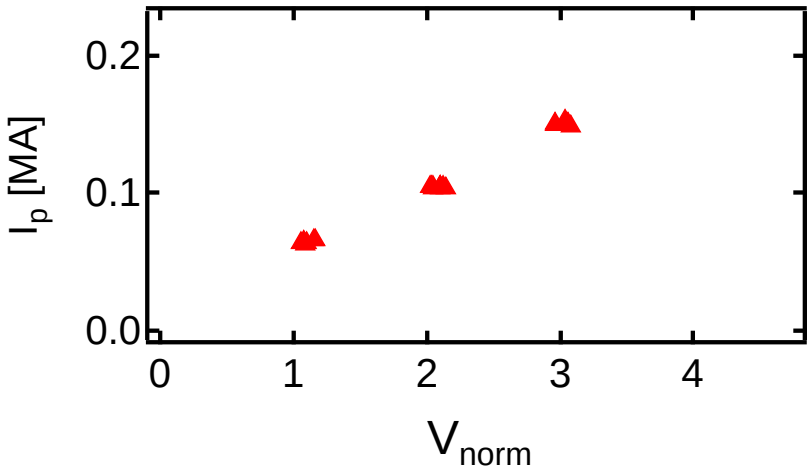


Rechester and Rosenbluth PRL **40** 1 (1978)
Stoneking et al. PoP **5** 4 (1998)

Initial Results Suggest a Linear Current Drive Scaling

- Experiment shows I_p proportional to V_{LHI}
  - Suggests fixed $\langle \eta \rangle$
- May not be fully representative
  - Experiment conducted at low $B_t \sim 0.045$ T
  - Short I_p flat top
  - n_e was not controlled
- All discharges featured an abrupt transition into a reduced MHD state
  - Rapid increase of I_p and n_e





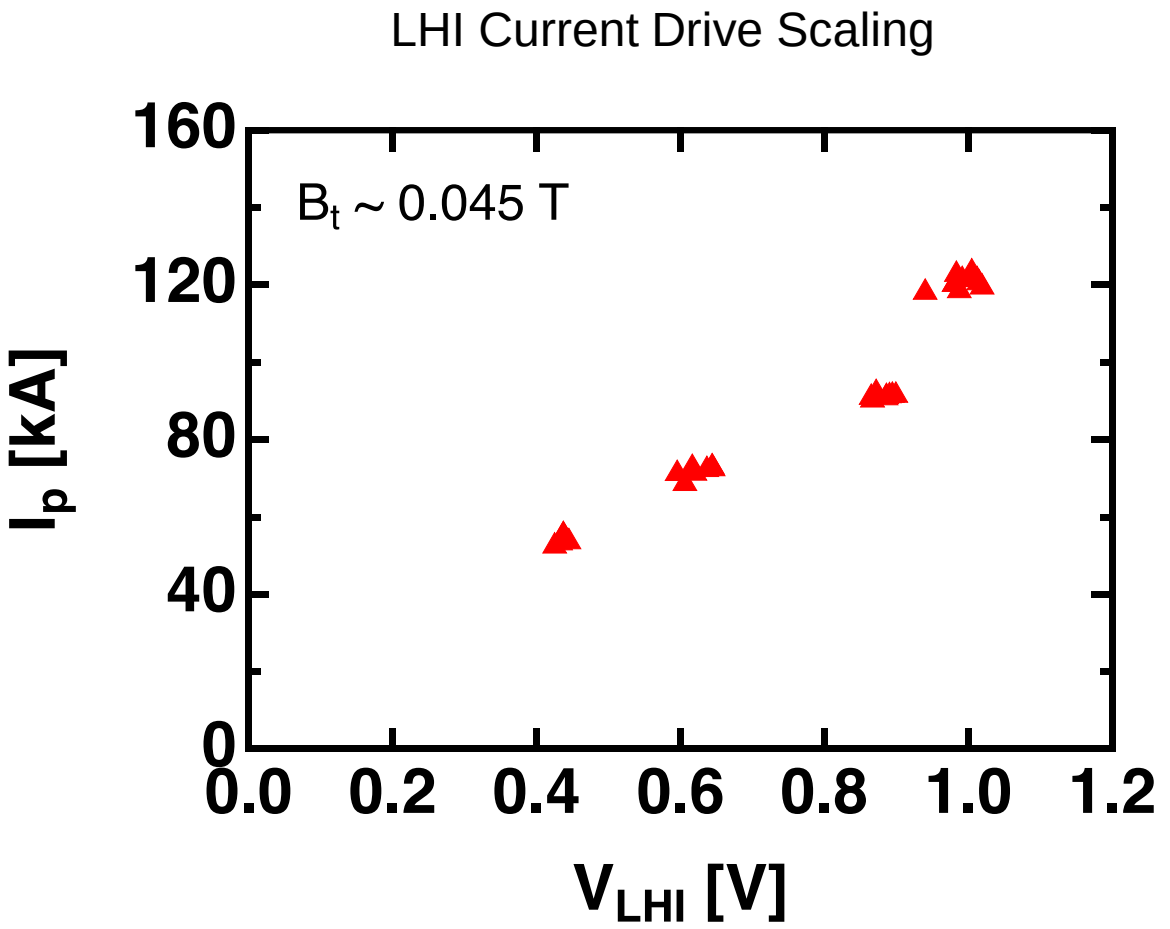
J.M. Perry et al. Nucl. Fusion **58** 096002 (2018)

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V_{LHI} Current Drive Scaling Experiment

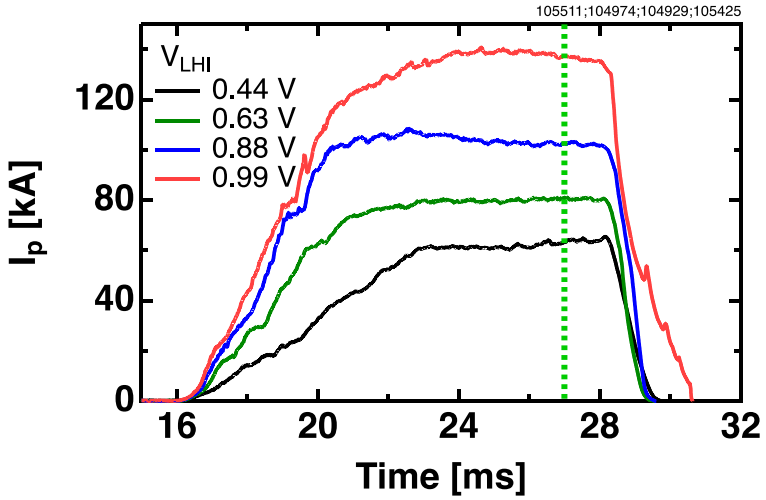
Linear Current Drive Scaling Confirmed at $B_t \sim 0.045$ T

- Current drive scaling experiment repeated, controlling for:
  - Longer I_p Flat top
  - Electron density
  - Static plasma shape
- Scaling consistent with steady-state models, if:
  - Ohmic: Z_{eff} scales with I_p
  - Stochastic: Magnetic fluctuations scale with V_{LHI}

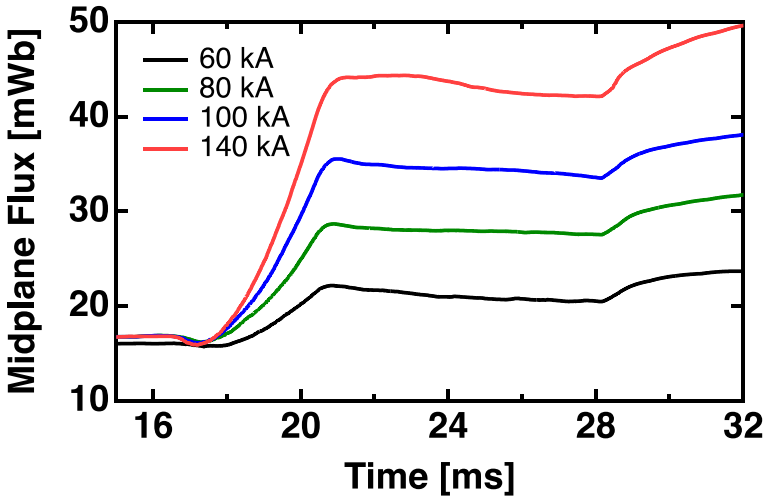


Current Drive Scaling Experiment Repeated At Four Levels of V_{LHI}

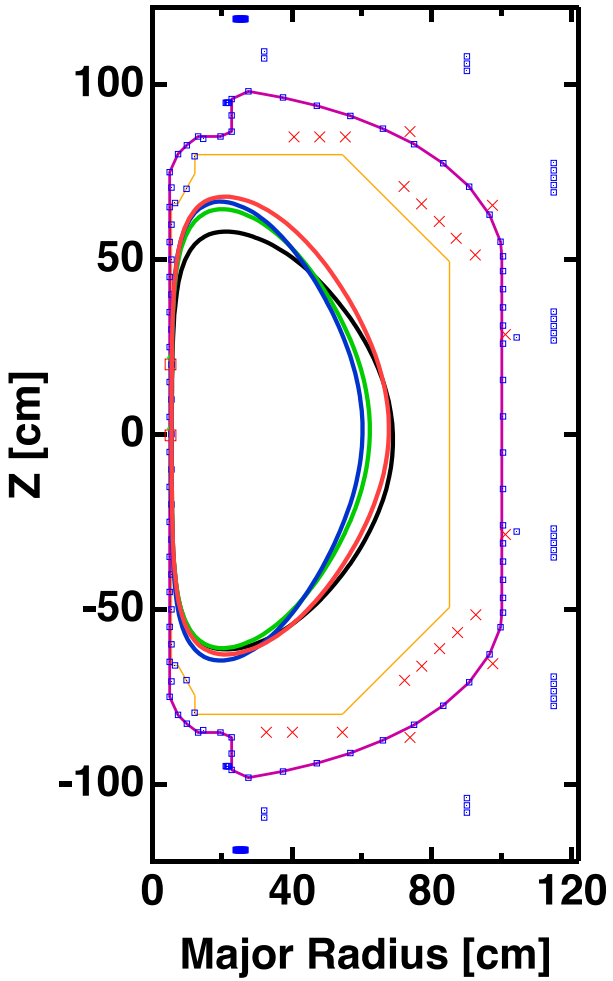
Longer I_p Flat Tops



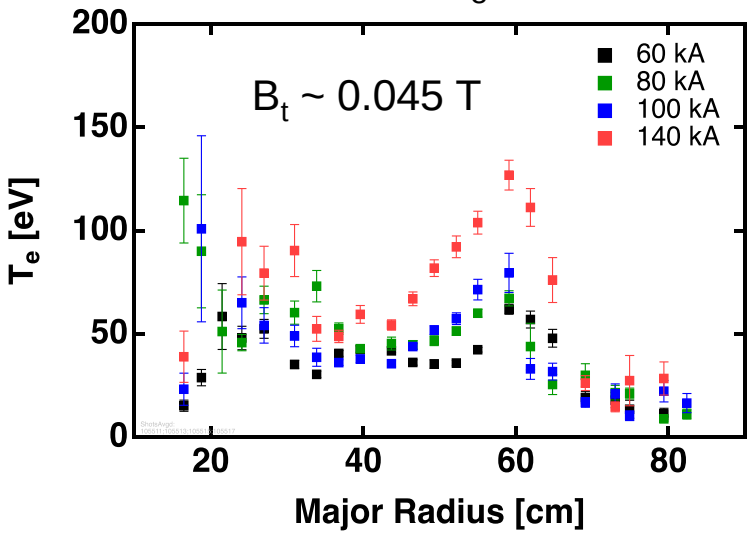
Static Plasma Shape



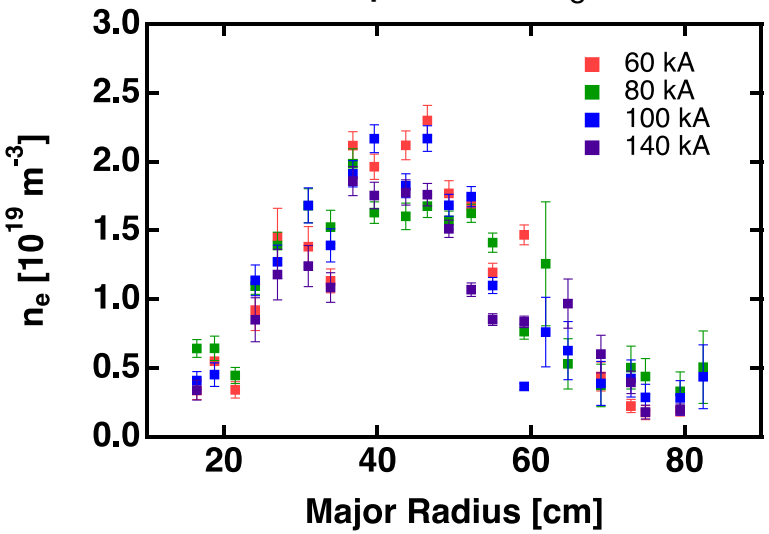
Plasma Shape From Reconstruction



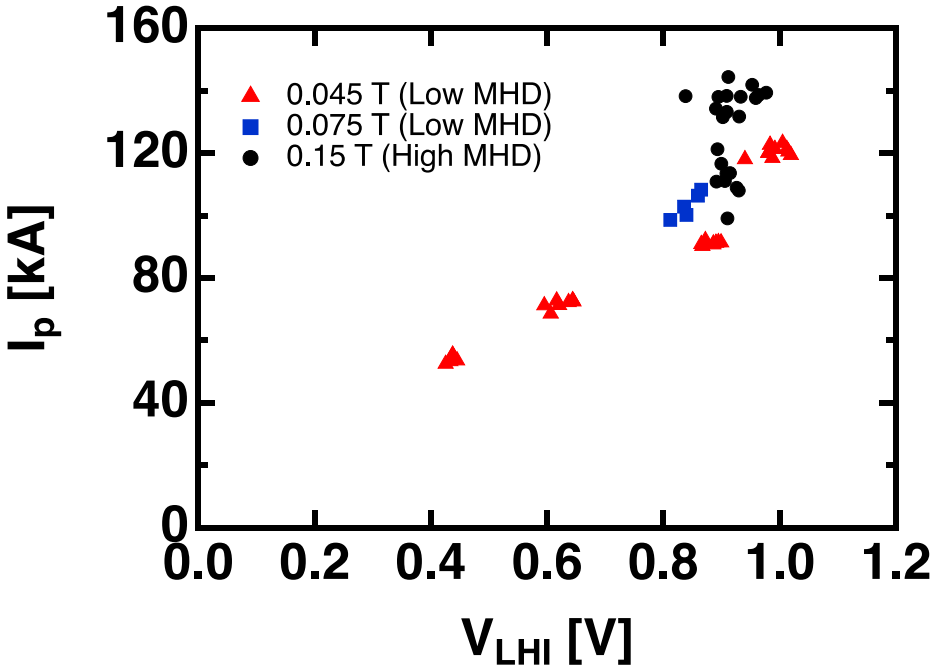
Measured T_e Profiles

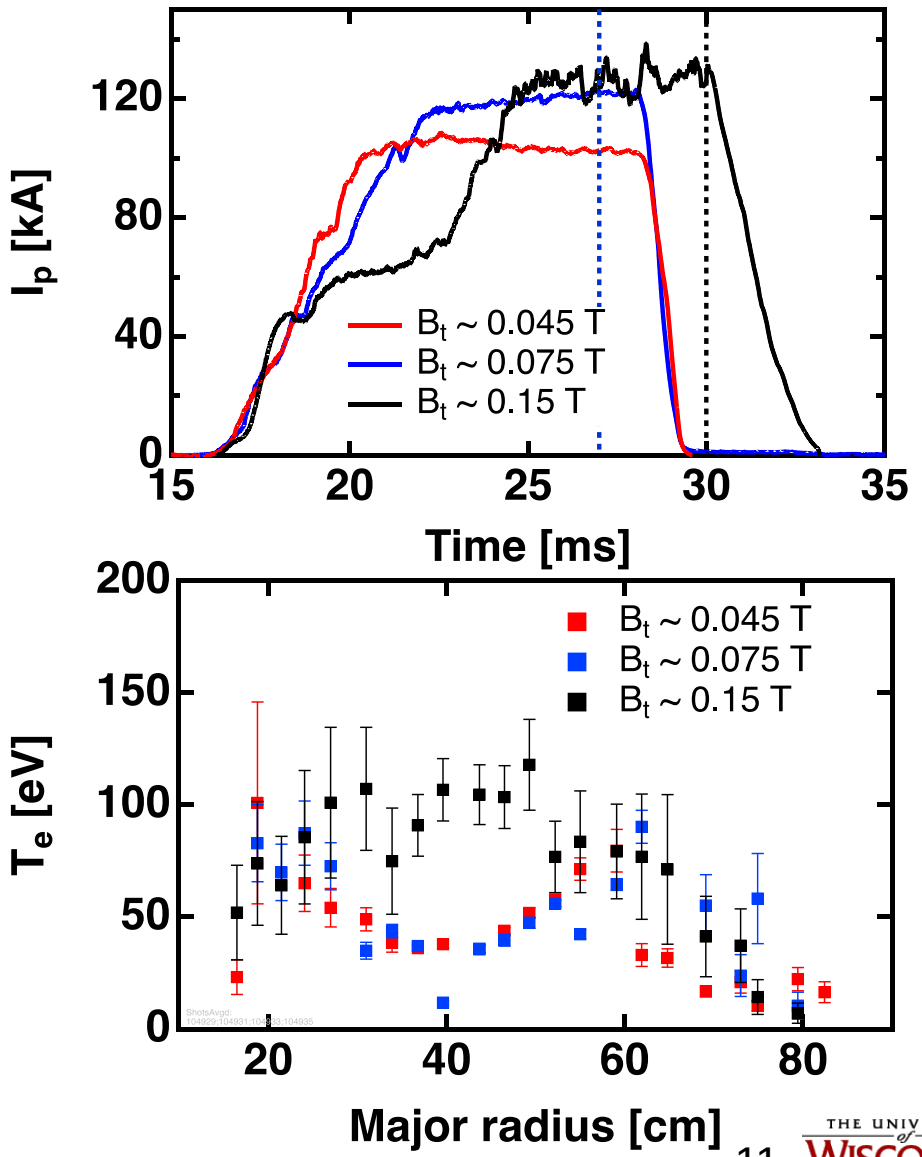


Comparable n_e



Current Drive Scaling Shows Some Dependence on B_t



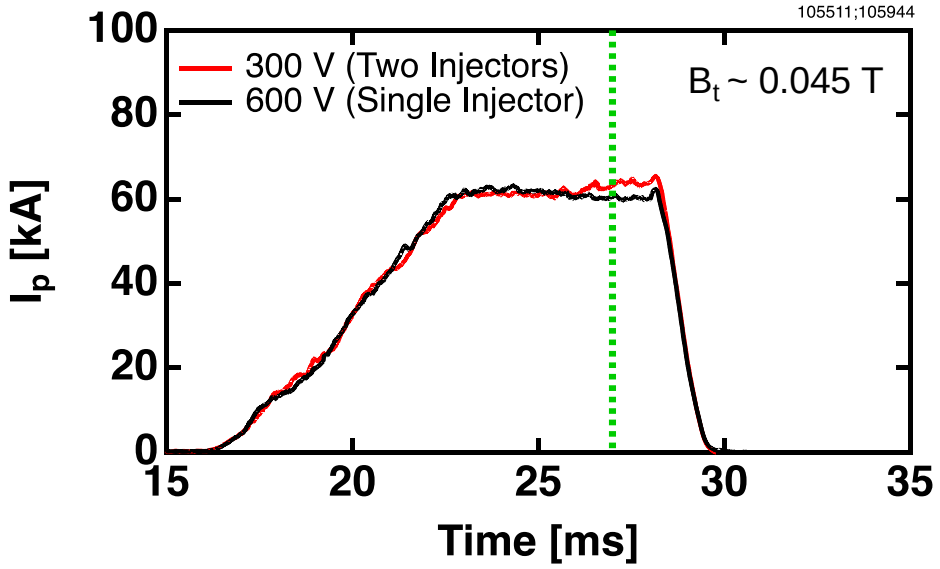


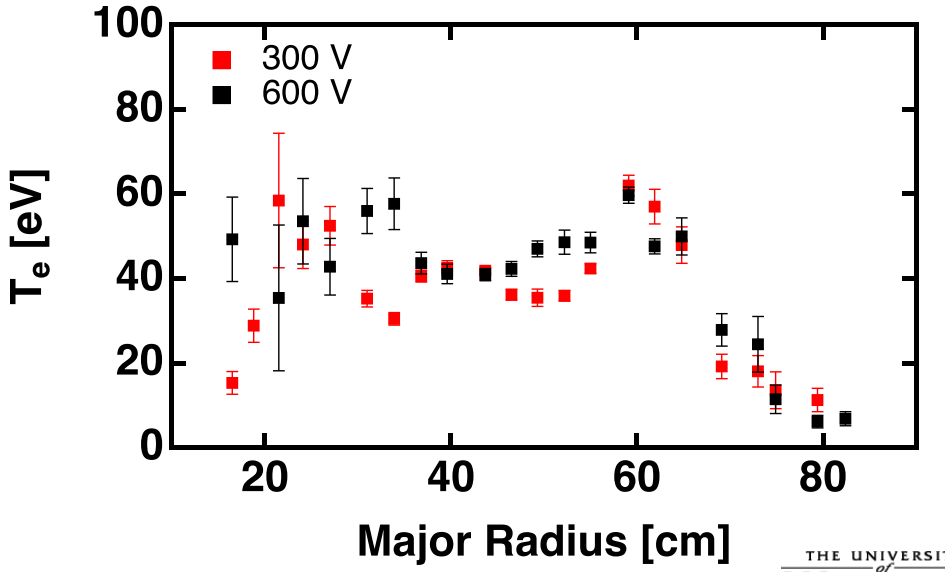
- T_e profile structure peaked at B_t ~ 0.15 T
- Operating space narrows as B_t is increased
  - MHD transition not observed at 0.15 T
  - Relaxation issues with low V_{inj}

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HFS LHI Discharges Are Dependent Upon V_{LHI} Rather Than V_{inj}

- Discharges have the same total input helicity rate, V_{LHI}, but different levels of V_{inj}
- Same amount of V_{LHI} results in similar levels of I_p and T_e
- Open field line theory* suggests $T_{e,max} \sim \frac{V_{inj}}{4}$
  - Data doesn't challenge T_e limit
  - Observed T_e not proportional to V_{inj}





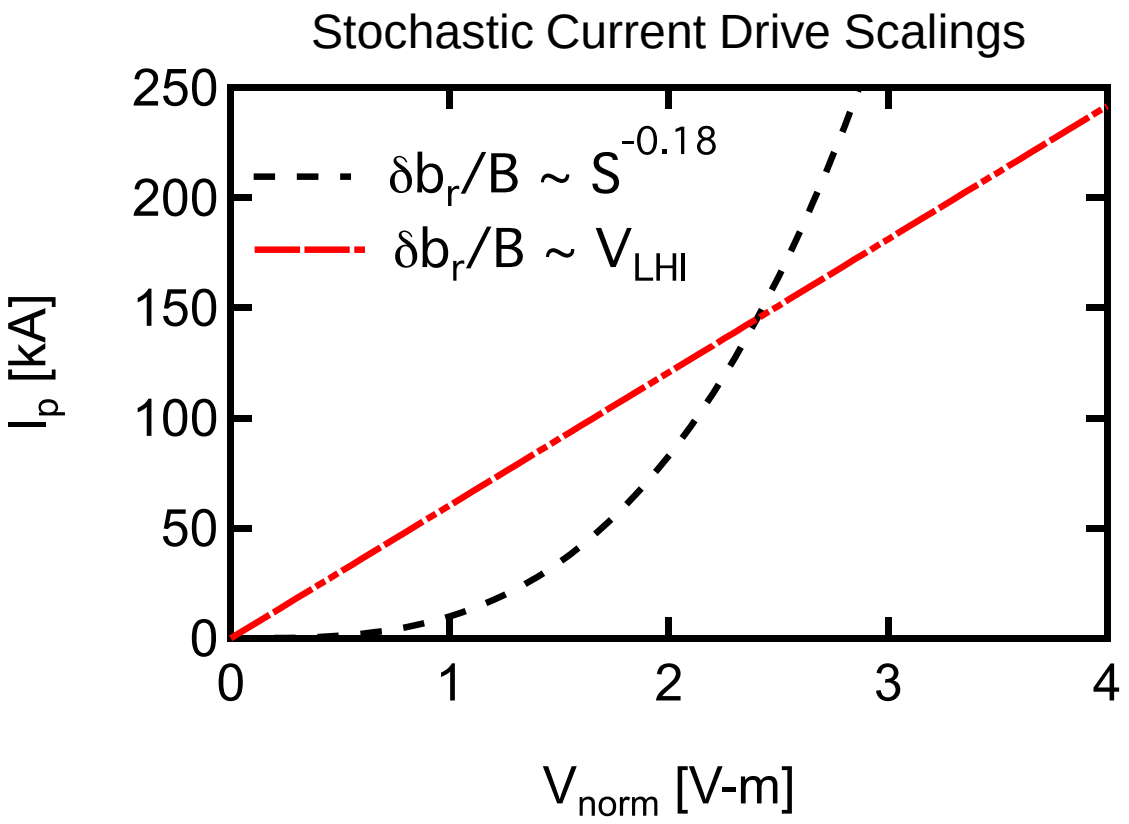
*Moses et al. PoP **8** 4839 (2001)

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Comparison to Collisional Stochastic Scaling Model

Stochastic Transport Model May Account for Linear Current Drive Scaling

- LHI discharges have significant MHD activity; reconnection of current streams
- Scaling of $\left(\frac{\delta b_r}{B_t}\right)$ with S based off of stochastic transport observed in MST
- Linear current drive scaling possible if fluctuations increase with V_{LHI}



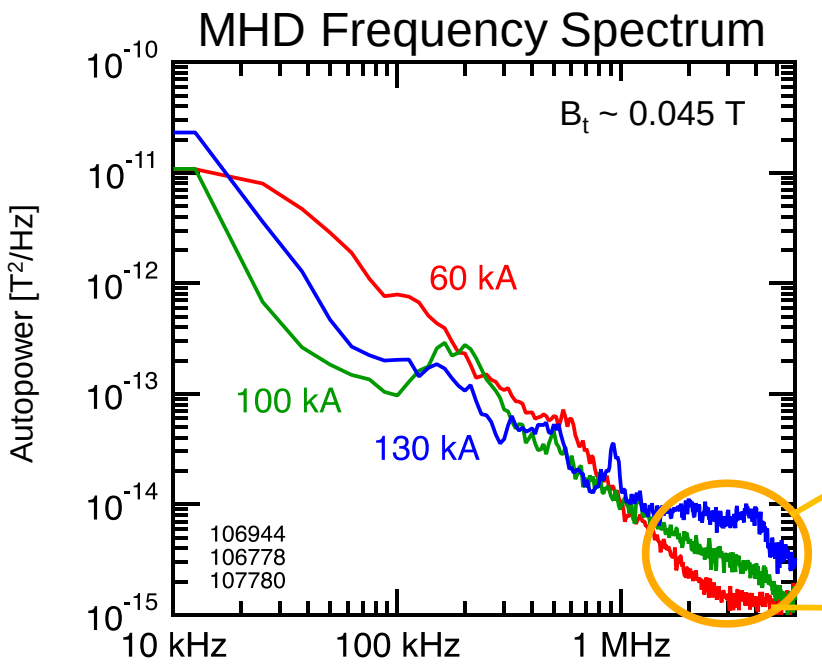
Perry PhD Thesis (2018)

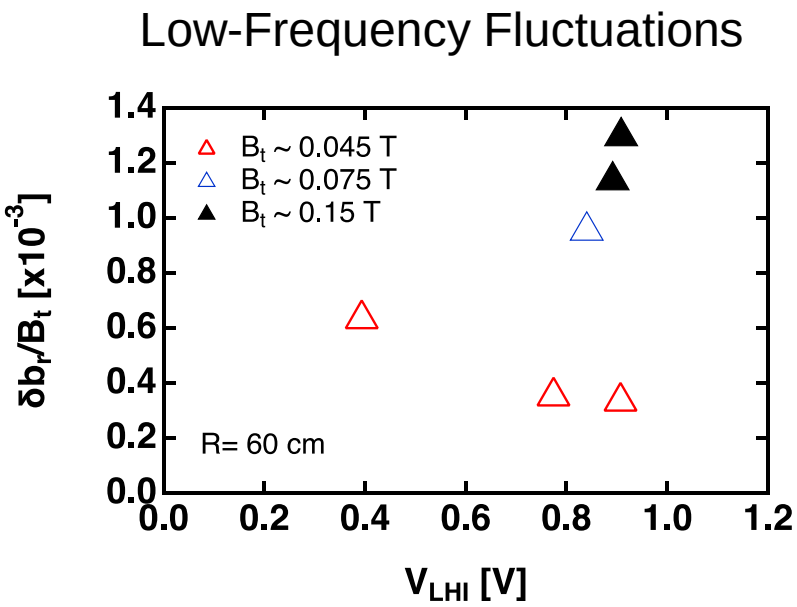
*Stoneking et al. PoP **5** 4 (1998)

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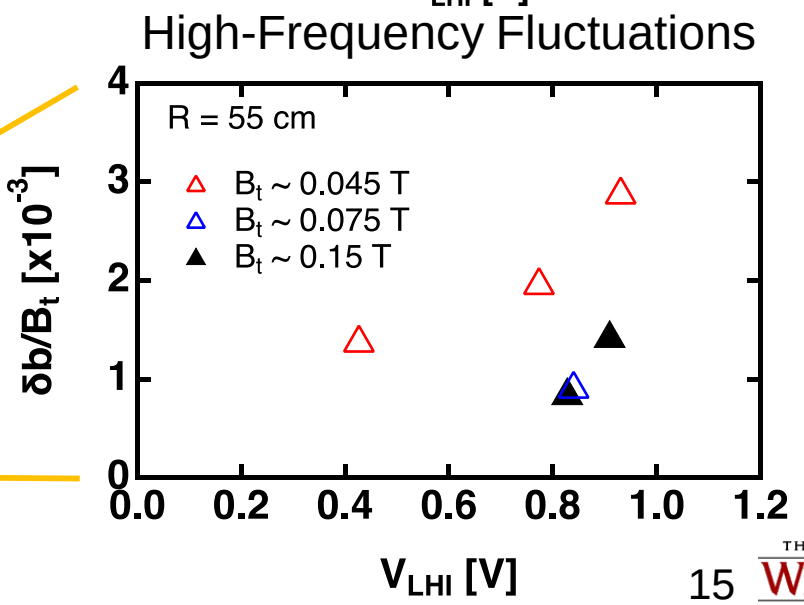
High Edge Magnetic Frequency Fluctuations Scale Linearly with V_{LHI}

- Low freq. fluctuations decrease with V_{LHI}; High freq. fluctuations increase with V_{LHI}
- High frequency activity could account for linear current drive scaling





3-60 kHz



2-3 MHz

Collisional Stochastic Confinement Model Inconsistent with T_e (R) Measurements

- Linear stochastic scaling implies constant T_e if $\left(\frac{\delta b_r}{B_t}\right) \sim V_{LHI}$

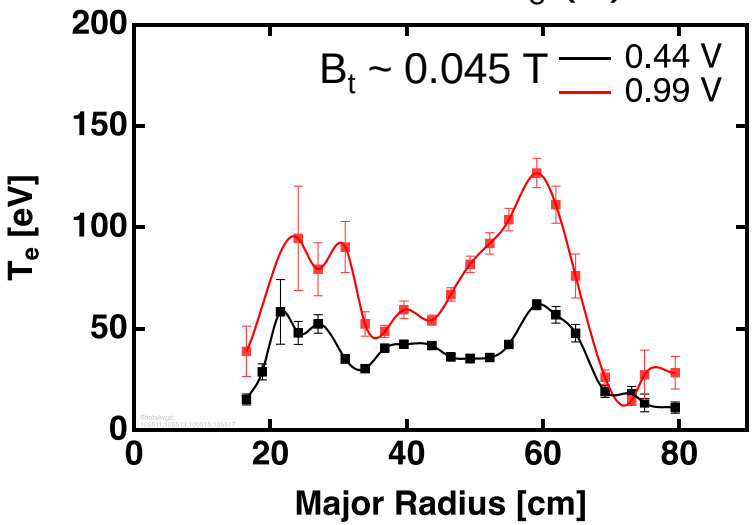
$$I_p V_{LHI} \sim \frac{n_e T_e \chi_e}{a^2} \qquad \chi_e \sim v_{th}^2 \tau_c \left(\frac{\delta b_r}{B_t}\right)^2, \; I_p \sim V_{LHI} T_e^{3/2}$$

$$V_{LHI}^2 \sim T_e^2 \left(\frac{\delta b_r}{B_t}\right)^2 \longrightarrow T_e \sim \frac{V_{LHI}}{\left(\frac{\delta b_r}{B_t}\right)} = const.$$

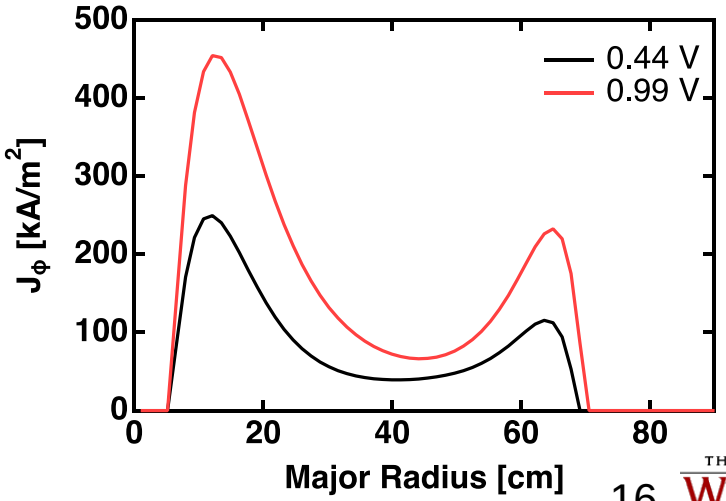
- Experiment: $\left(\frac{\delta b_r}{B_t}\right) \sim V_{LHI}$, $T_e \neq$ const.

- At $B_t \leq 0.075$ T, T_e strongly increases with V_{LHI} in the plasma edge
  - Change in T_e strongest in areas of high current density

Measured T_e (R)



Reconstructed J_ϕ(R)



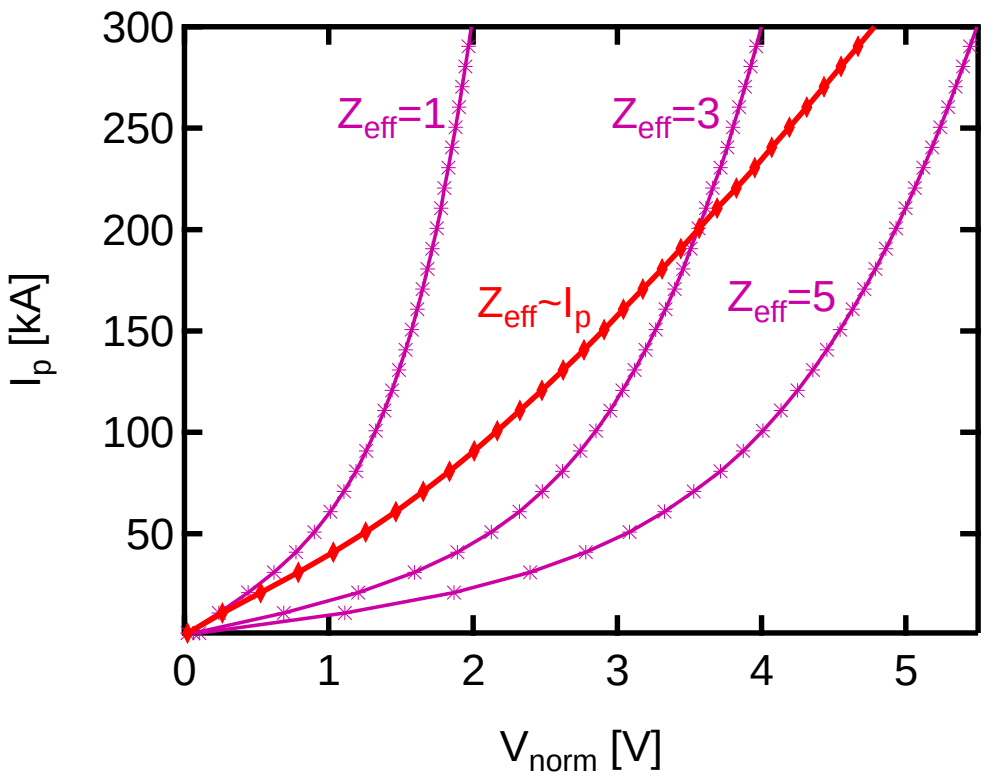
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Comparison to Ohmic L-Mode Confinement Scaling

Ohmic Confinement with $Z_{eff} \sim I_p$ Could Provide Explanation for Linear Current Drive Scaling

- Ohmic confinement represents an upper bound for LHI
- Assumption of $Z_{eff} \sim I_p$ in ITER97-L scaling yields $I_p \propto V_{LHI}$
- SPRED VUV spectrometer shows increased impurity radiation in LHI with increased V_{LHI}

Ohmic L-Mode Scaling as a Function of Z_{eff}



J.M. Perry et al. Nucl. Fusion **58** 096002 (2018)

Approximating Z_{eff} is Necessary to Evaluate Current Drive Scaling

- Visual Bremsstrahlung measurement of Z_{eff} difficult in Pegasus discharges
  - Light pollution due to recombination, H_2 emission, and Electron-Atom Bremsstrahlung
- Assuming transport is neoclassical, Z_{eff} approximated by voltage balance
  - Ohm's Law gives the effective plasma resistance
  - Thomson data gives a resistance through the Sauter calculation of σ_{neo}

Assume V_{LHI} is the only drive mechanism

$$V_{LHI} = I_p R_{eff}$$

$$R_{Thomson} = \left[\sum_i \frac{2\pi\rho_i}{A_i \sigma_{neo,i}}\right]^{-1}$$

i ≡ grid cell from reconstruction

$$\sigma_{neo} = \sigma_{spitz}(T_e, Z_{eff}) F_{33}(Z_{eff}, \nu_e^*, f_t)$$

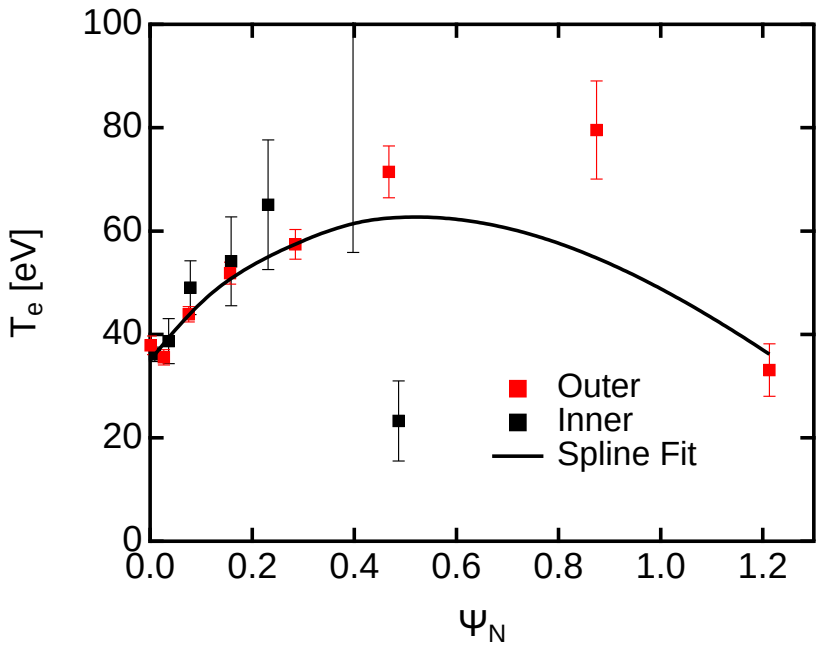
O. Sauter. Physics of Plasmas **6**, 2834 (1999)

Iterate Z_{eff} to match R_{eff} and $R_{Thomson}$

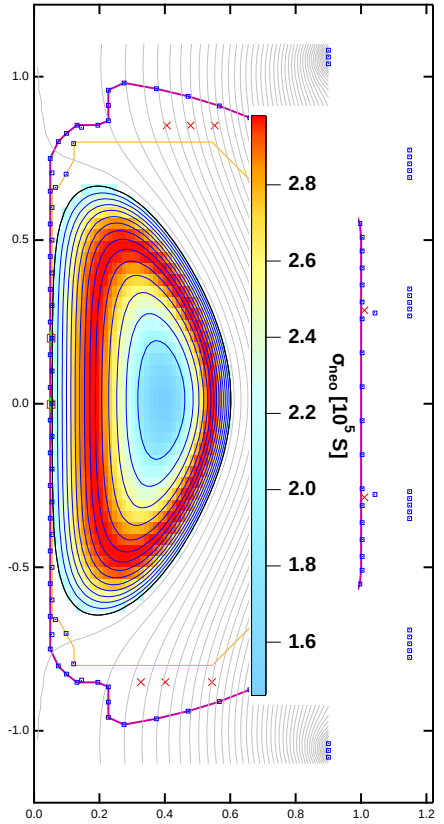
Neoclassical Conductivity Calculated Using Thomson Profiles and Equilibrium Reconstructions

- T_e profile fit in flux space
- Plasma resistance, $R_{Thomson}$, derived from sum of $\sigma_{neo,i}$
- Z_{eff} iterated until $R_{Thomson}$ matches the effective resistance from Ohm's Law
  - Model assumes constant Z_{eff} profile

T_e Profile Fit with Akima Spline



Neoclassical Conductivity

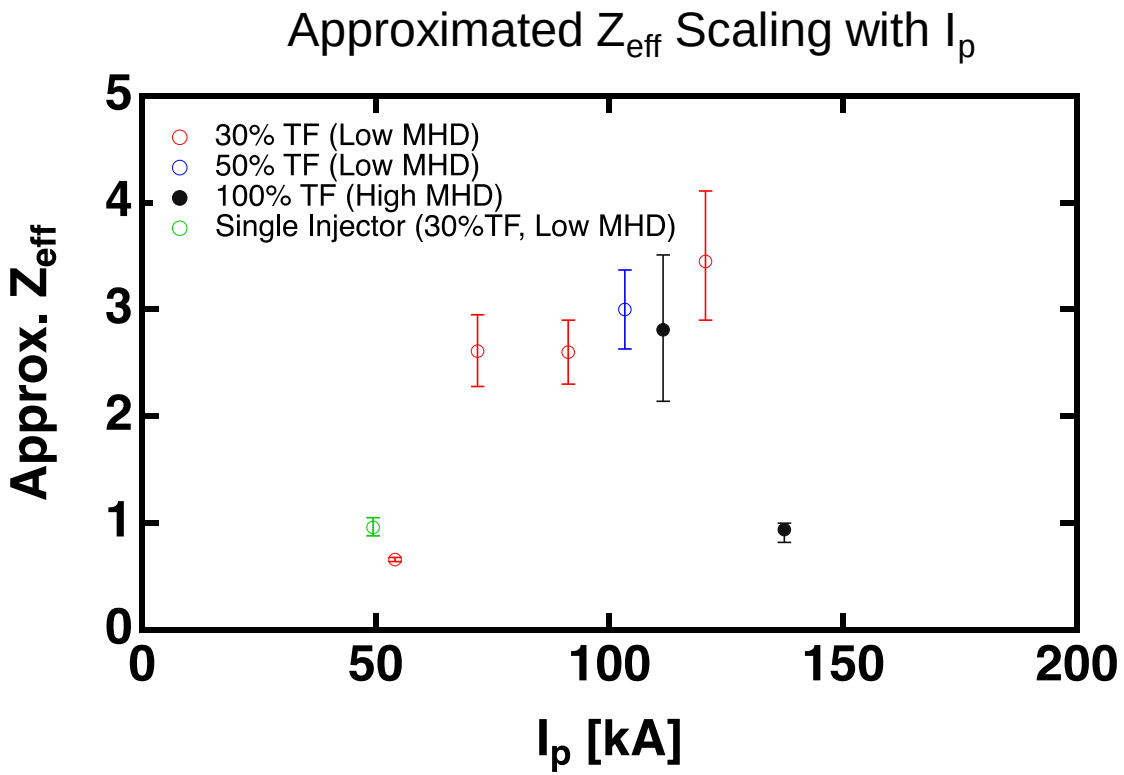


I_p ~ 100 kA
B_t ~ 0.045 T

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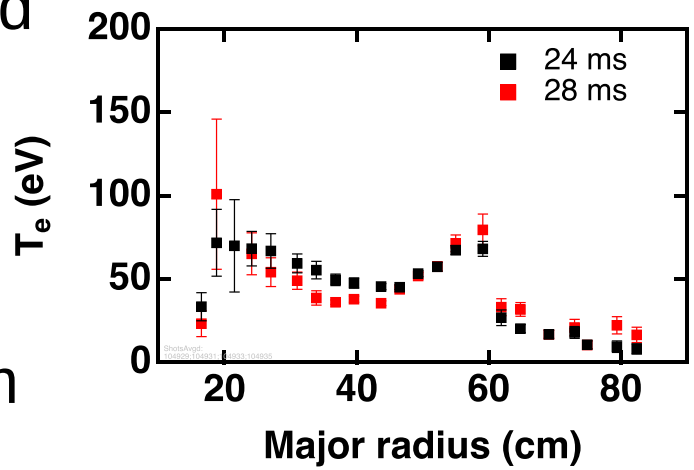
Approximated Z_{eff} Does Not Scale Linearly with I_p

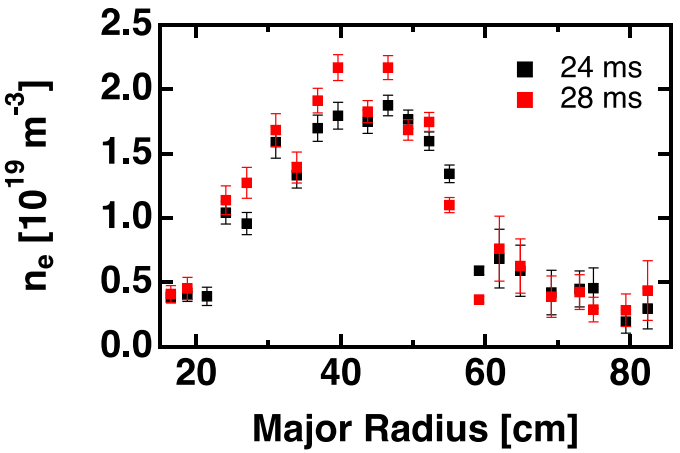
- Analysis technique applied to I_p-V_{LHI} data
  - Z_{eff} (I_p) ~ constant, 2-3 within bounds of model
  - Outliers: Low T_e gives large $R_{thomson}$ which can not be corrected for using Z_{eff}
- Low B_t discharges may not be Ohmic-like
  - Hollow T_e profiles: radiation dominated?
  - Dissipation may not be purely resistive
- Model assumes uniform V_{LHI} distribution and simple magnetic configuration
  - May be an upper limit for Z_{eff}

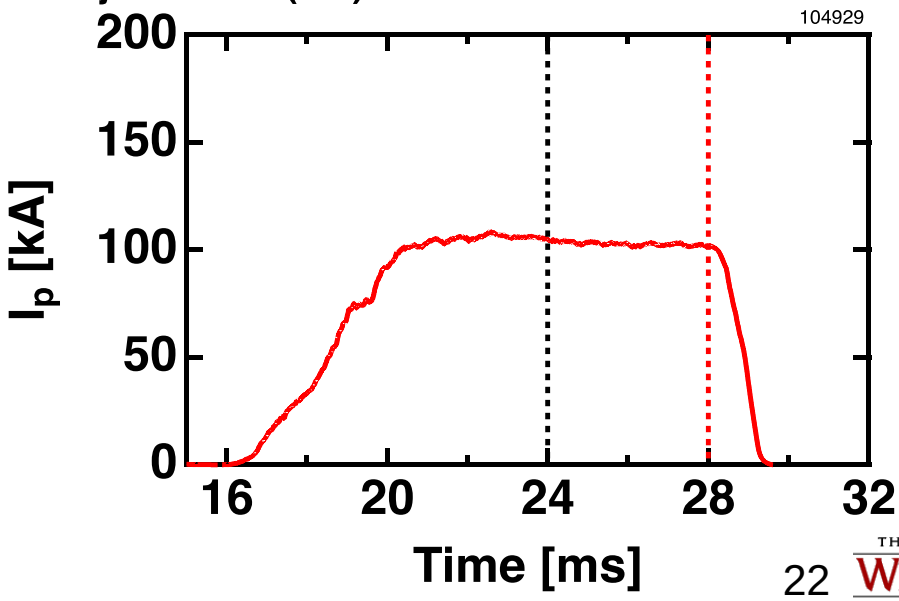


At Low B_t, Hollow T_e Profiles Are Sustained Through the I_p Flat Top

- Minimal T_e profile evolution observed
- Constant I_p, T_e, and n_e imply electrons are in transport equilibrium
- Consistent with typical confinement times in Pegasus of < 1 ms

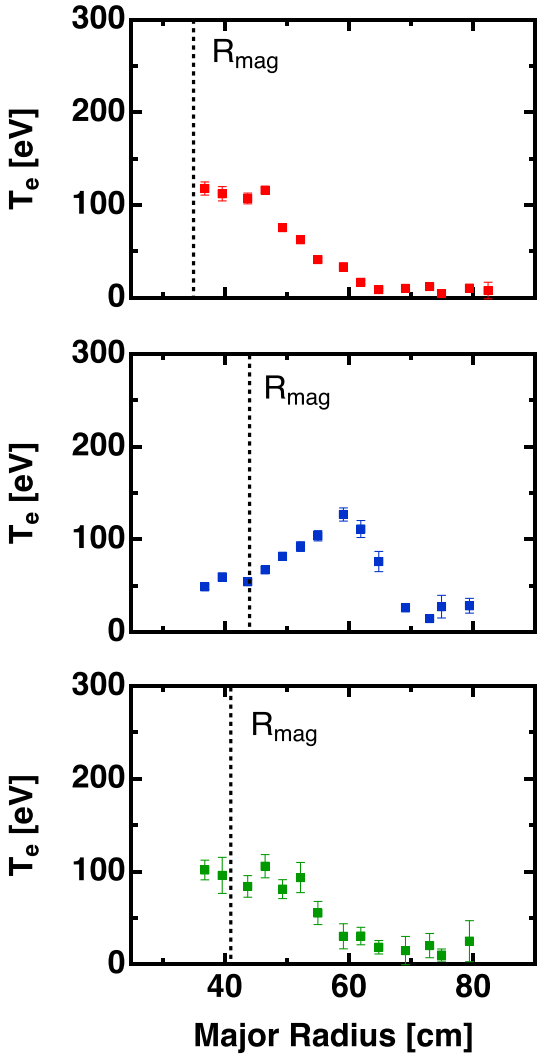






Low Ohmic Heating Power Density in LHI Discharges May Explain Sustained Hollow T_e Profiles

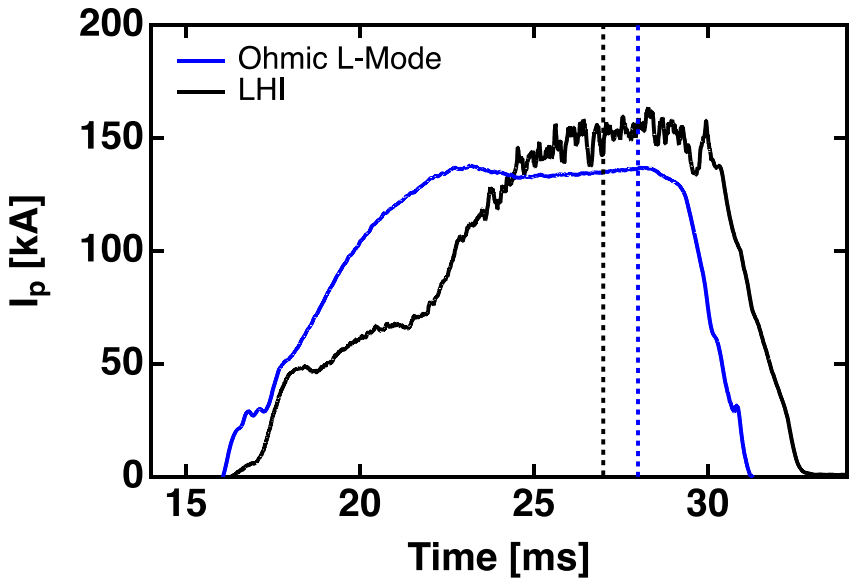
- Low ℓ_i of LHI → low $\eta^* j^2$ in core
- Minimum P_{rad} estimated from AXUV bolometers ($P_{AXUV} \leq P_{RAD}$)
  - Ohmic, LHI ($B_t \sim 0.15$ T) core $\eta^* j^2 \geq P_{AXUV}$
  - LHI ($B_t \sim 0.045$ T) core $\eta^* j^2 \leq P_{AXUV}$
- Suggests higher I_p and/or adding P_{aux} would yield peaked T_e profile
  - Not impurity problem; heating power problem

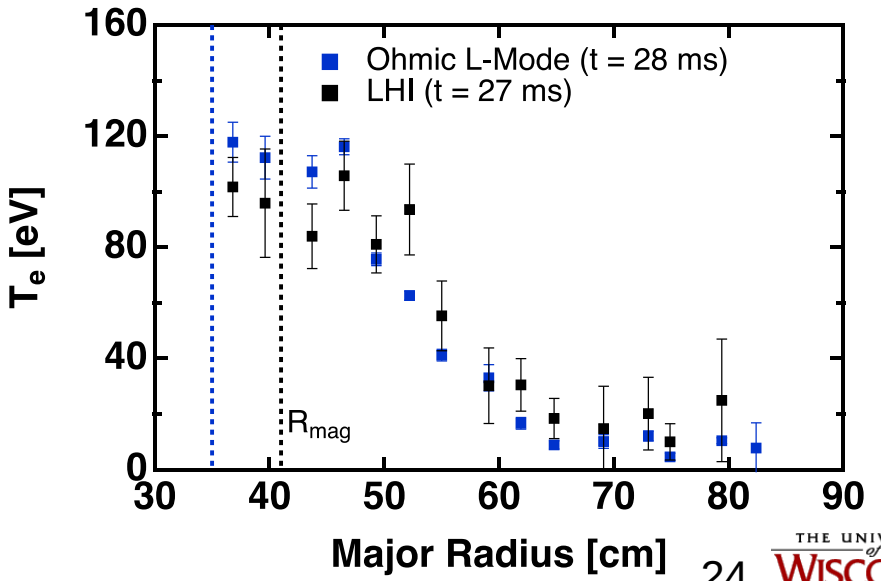


ℓ_i [H]	$\eta^* j^2_{(0)}$ [kW/m^3]	P_{AXUV} [kW/m^3]
0.44	45	1
0.28	7.4	25
0.22	2	2

At B_t ~ 0.15 T, LHI T_e Profiles Comparable to L-Mode Profiles

- First Thomson measurements made in ohmic discharges on Pegasus
- Similarity of T_e (R) suggests high B_t LHI may resemble L-mode like confinement
- Ability to test V_{LHI} scaling at B_t ~ 0.15 T limited
  - Geometric constraints of LHI system
  - Operation limits of V_{LHI}

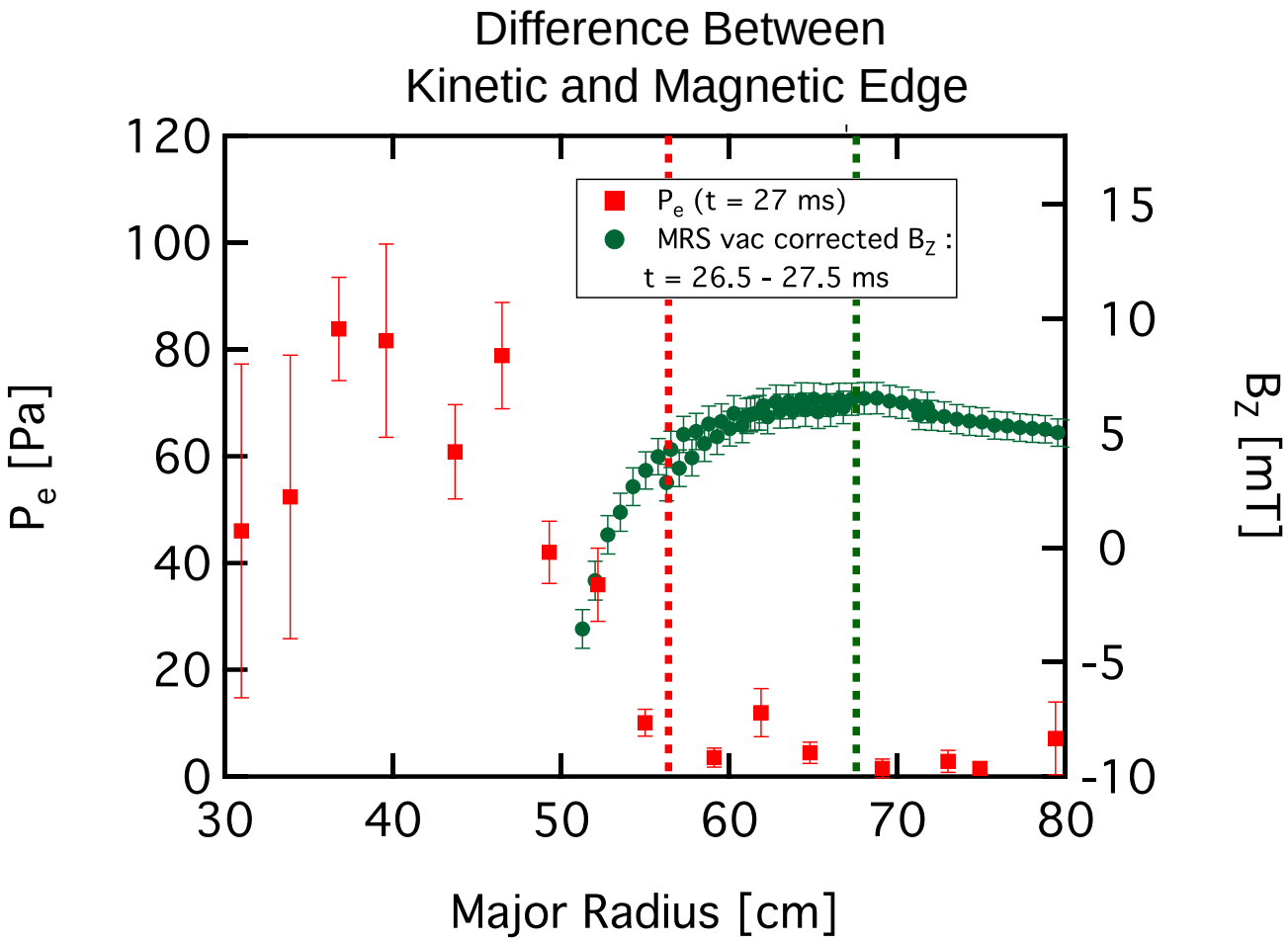




LHI Confinement May Be A Combination of the Two Models

LHI Confinement is May Be a Combination of Stochastic and Ohmic-like Transport

- Magnetic probes indicate a separation of plasma kinetic and magnetic edge
- LHI discharges may have Ohmic-like core surrounded by stochastic edge
  - Force free region between boundaries
  - C.E. Schaefer Poster GP10.00123



Progress Has Been Made to Build The Experimental Basis For a LHI Confinement Model

- Linear current drive scaling confirmed at B_t ~ 0.045 T for helicity driven plasmas
- Current drive scaling can not solely be accounted for by simple collisional stochastic model or L-mode confinement model at low B_t
- Peaked LHI T_e profiles at B_t ~ 0.15 T comparable to Ohmic L-mode
  - Impurity radiation may contribute to steady-state hollow T_e profiles at low B_t
  - Hollow T_e (R) may be due to low Ohmic heating power density in the core
- LHI confinement may have contributions from two characteristic zones:
  - Ohmic-like core
  - Force-free stochastic region

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