# Characterization of $T_e$ and $n_e$ Profiles of Discharges Driven Purely By Helicity Injection in the PEGASUS Toroidal Experiment

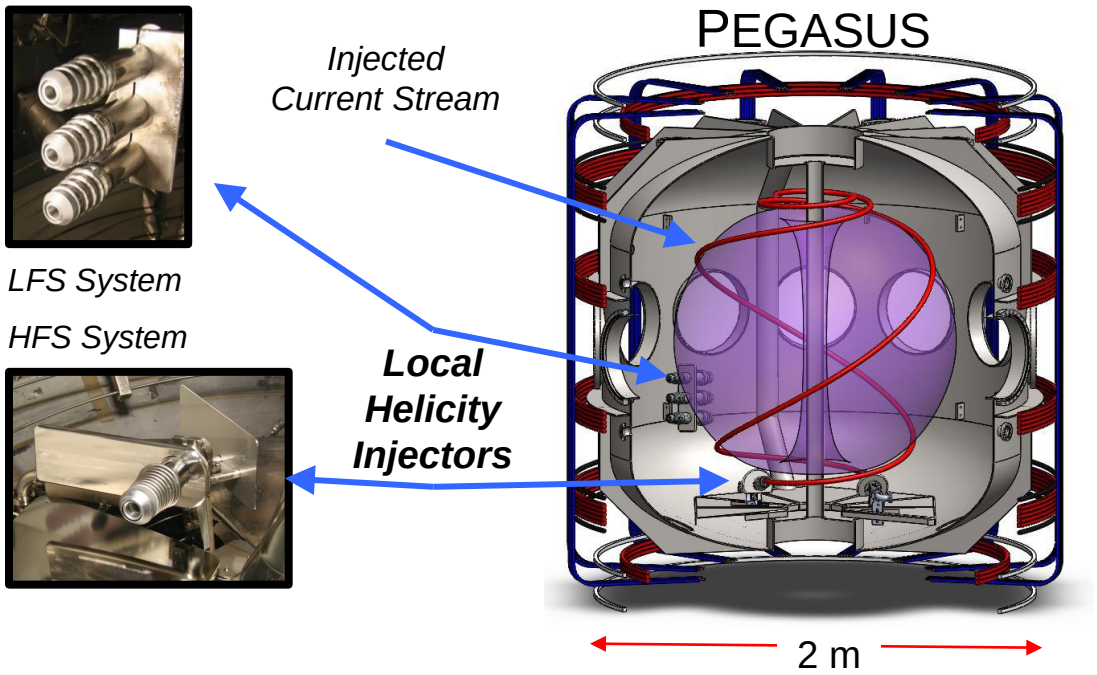
G.M. Bodner, M.W. Bongard, R.J. Fonck, M.D. Nornberg, J.A. Reusch, A.T. Rhodes, N.J. Richner, C. Rodriguez Sanchez, C.E. Schaefer, J.D. Weberski

University of Wisconsin-Madison

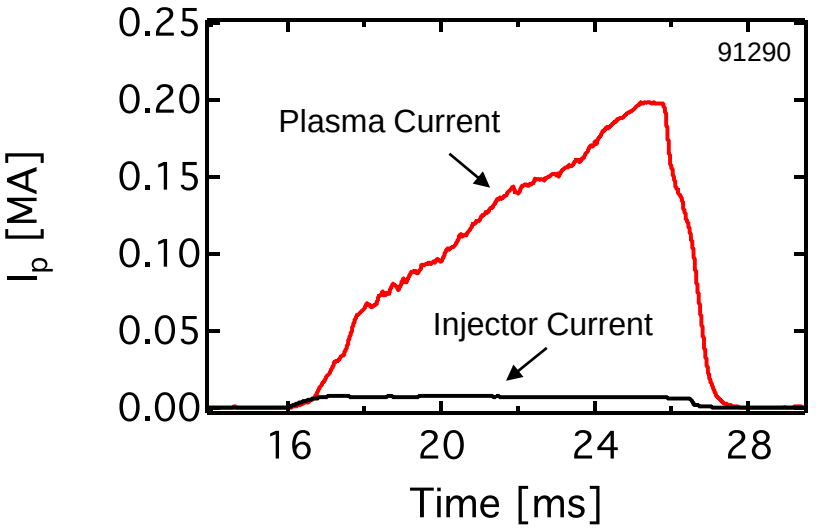
PEGASUS Toroidal Experiment

62nd Annual Meeting of the APS Division of Plasma Physics

# Local Helicity Injection (LHI) Provides Non-Inductive Startup at Low *A*




*Non-Solenoidal $I_p$ = 0.2 MA ($I_{inj}$ ≤ 8 kA)*




*Pegasus Parameters*

| | |
|---|---|
| $A$ | $1.15 - 1.3$ |
| $R$ [m] | $0.2 - 0.45$ |
| $I_p$ [MA] | $\leq 0.25$ |
| $B_T$ [T] | $< 0.15$ |
| $\Delta t_{shot}$ [s] | $\leq 0.025$ |

- HFS LHI plasmas are driven purely by helicity injection
- Scaling of LHI may be limited by dissipation $\left(\eta \propto Z_{eff} T_e^{-3/2}\right)$
- Characterization of electron behavior needed to project $T_e(t)$





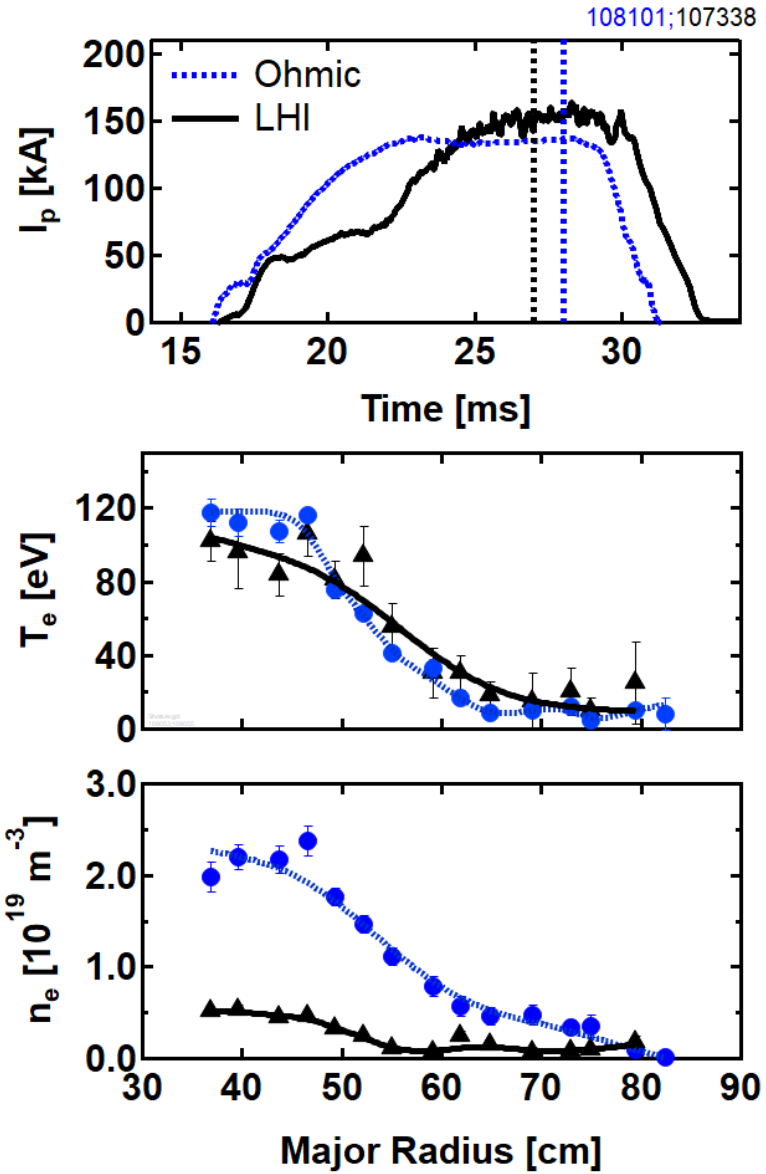
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# At $B_t$ ~ *0.15* T, LHI $T_e$ Profiles Were Comparable to Ohmic $T_e$ Profiles in PEGASUS

- LHI $T_e$ profiles were peaked with $T_{e,0}$ ~ 100 eV
- LHI can achieve Ohmic-like temperatures given comparable operating conditions ($I_p$, $B_t$)
- Low $n_e$ in LHI due to lack of available drive voltage
  - LHI ($V_{LHI}$ ~ 1 V)
  - Ohmic ($V_{loop}$ ~ 3 V)

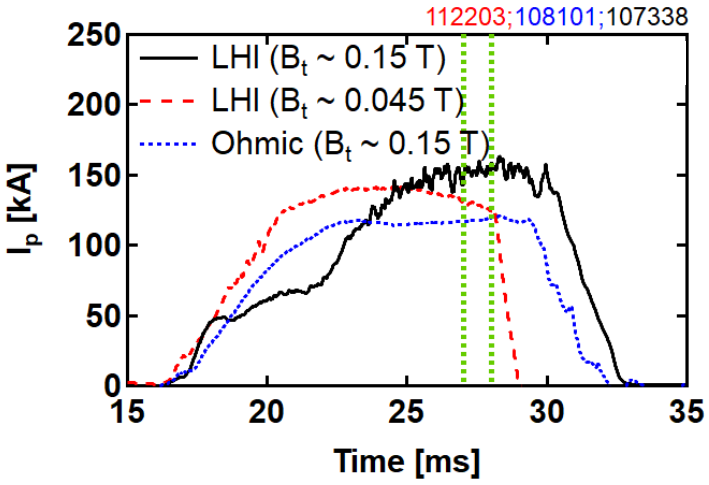
$$V_{LHI} \equiv \frac{N_{inj} A_{inj} B_{t,inj}}{\Psi} V_{inj}$$

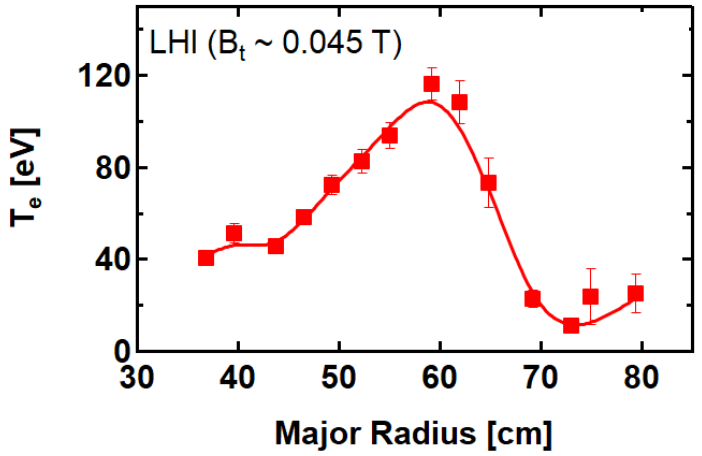
- Profile structure implies some level of core confinement

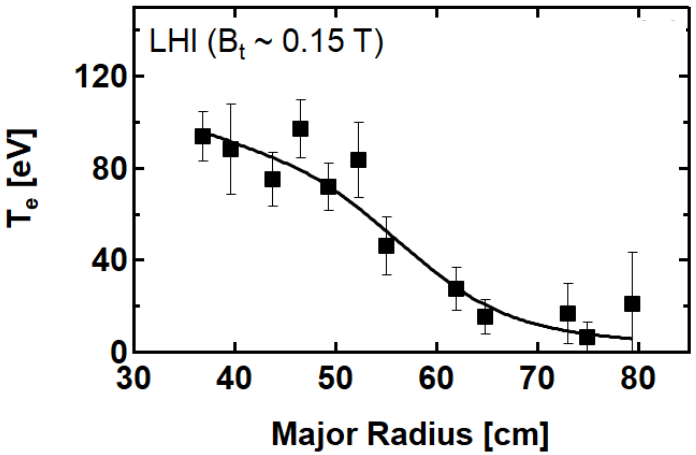


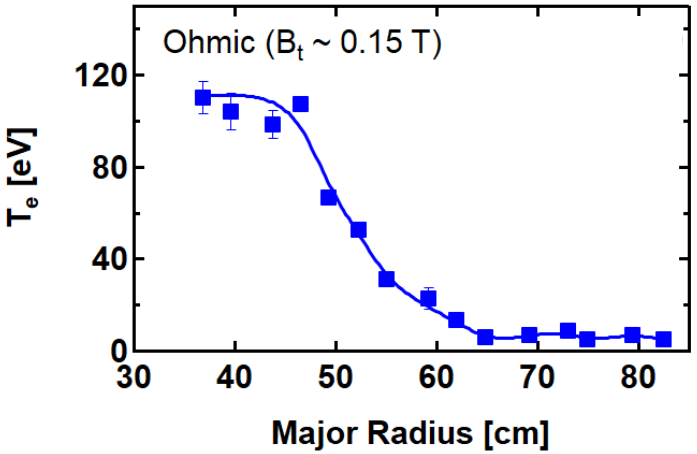

C. Pierren (ZP6:04)

# $T_e$ Profile Sensitive To Balance Between Central Radiation And Central Heating




| $\ell_i$ | $\eta\, j^2(0)$ [kW/m$^3$] | $P_{rad}(0)$ [kW/m$^3$] | $n_{e,0}$ [$10^{19}$ m$^{-3}$] |
|---|---|---|---|
| 0.28 | 11 | ~ 30 | ~1 – 2 |
| 0.26 | 12 | ~ 2 | ~0.5 – 1 |
| 0.56 | 30 | ~ 1 | ~1.5 – 2 |

$P_{rad}(0)$ estimated from XUV radiometry diodes





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# Derived $\langle Z_{eff} \rangle$ Suggests Modest Impurity Concentrations

- Resistive $\langle Z_{eff} \rangle$ approximated
  - Ohm's Law
  - Neoclassical resistance from $\sigma_{neo}$

$$R_{eff} = \frac{V_{LHI}}{I_p} \qquad R_{neo} = \left[ \sum_i \frac{2\pi R_0}{A_i \sigma_{neo,i}} \right]^{-1}$$

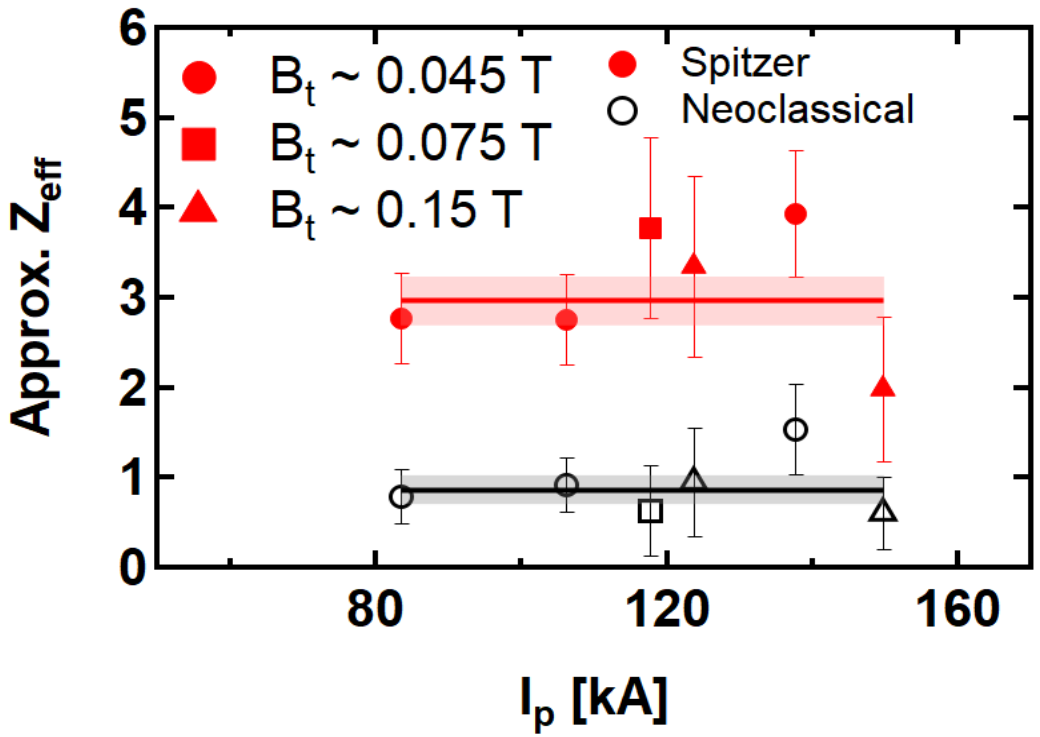
$$\sigma_{neo} = \sigma_{spitz}(T_e, Z_{eff}) m_{neo}(Z_{eff}, \nu_e^*(T_e, n_e, q, \varepsilon), f_t(\varepsilon))$$

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

- $\langle Z_{eff} \rangle$ ~ 1 (neoclassical) and ~ 3 (classical)

- Low $Z_{eff}$ consistent with radiation-dominated core
  - STRAHL calculations with $n_N/n_e$ ~ 1%, $T_{e,0}$ ~ 40 eV, $n_{e,0}$ ~ 2x10$^{19}$ m$^{-3}$ predict $Z_{eff}$ ~ 1.03 and $P_{rad}$ ~ 30 kW/m$^3$

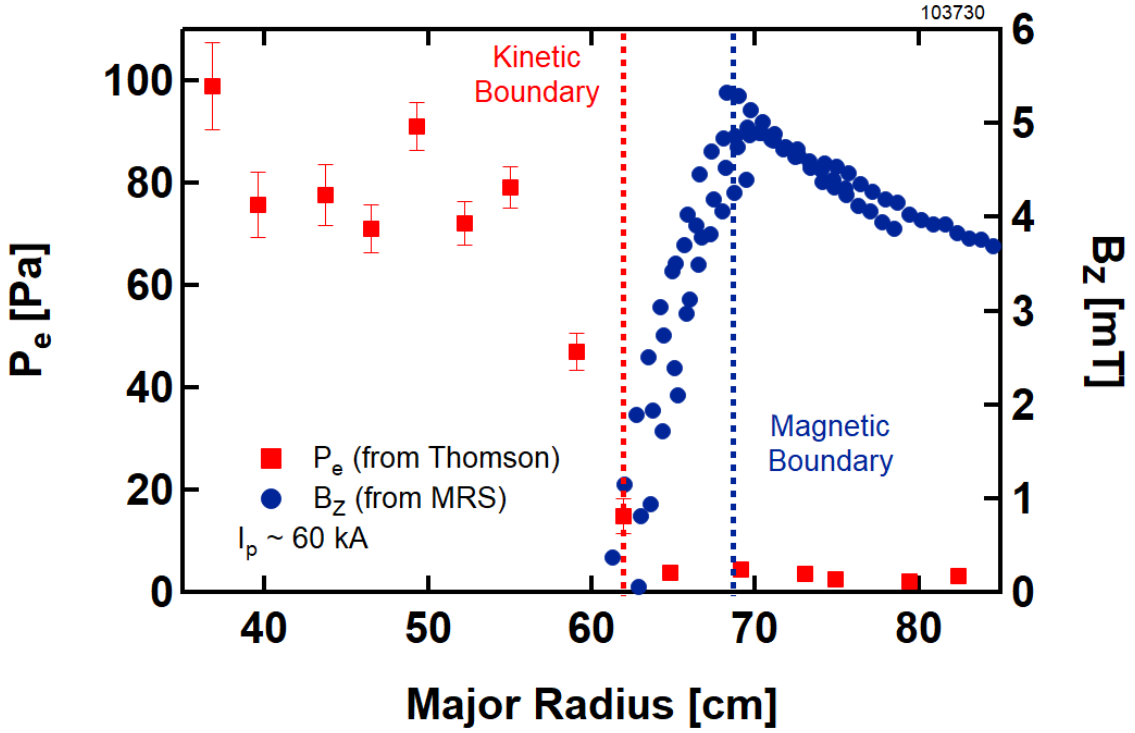
Approximated $Z_{eff}$ Scaling with $I_p$



# Complex Interactions Between the Current Streams and the Plasma Boundary May Affect Electron Behavior

- Separation of the kinetic and magnetic boundaries identified by radially scanning $B_z$ probe and MPTS
  - Kinetic boundary taken from MPTS $P_e$ (R) profile
  - Magnetic boundary taken as peak in time-averaged vacuum corrected poloidal field magnitude

    N. Richner (ZP6:03)
- Simple model: cross-field transport dominated core surrounded by a force-free outer region
  - Reality: current streams maintain their coherence and may act as non-axisymmetric perturbations
- Outer region may provide auxiliary heating to ions and/or electrons in the core from reconnection





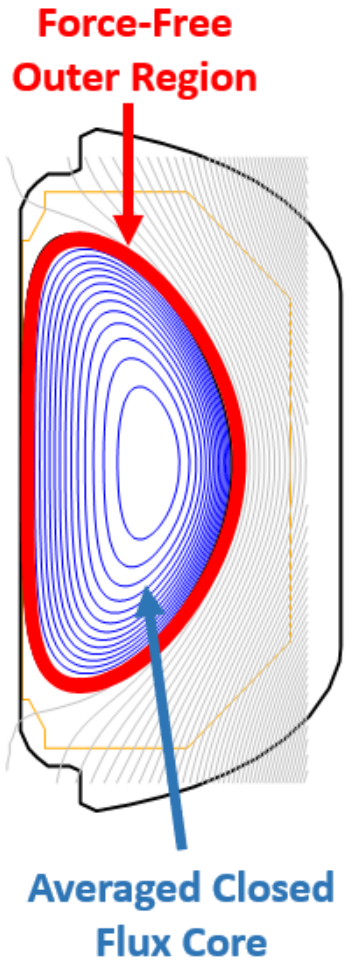



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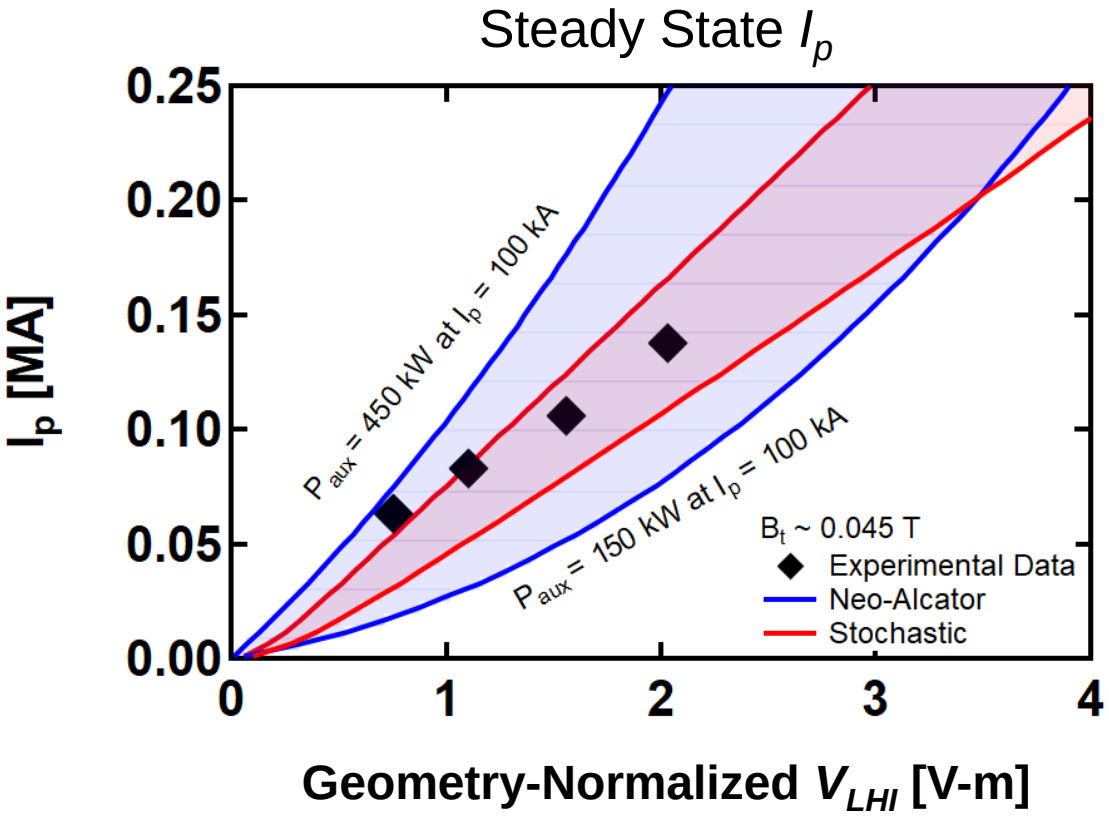

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# LHI Current Drive Scaling Within Bounds of LOC Assuming $P_{aux}$ From Reconnection

- 1-D cylindrical code used to determine drive voltage necessary to sustain steady-state $I_p$ consistent with global confinement scalings
- Measurements of anomalous ion heating in LHI have indicated up to 300 kW of $P_{aux}$ to the ions
  - Exact contributions to ions and/or electrons is not known (Range of auxiliary power was considered)

M.G. Burke et al. 2017 *Nucl. Fusion* **57** 076010

- Proximity of experimental data and neo-Alcator scaling with no free parameters is suggestive
  - Consistency between stochastic scaling and experimental data expected due to normalization




**Assuming:** *A = 1.17, R = 0.35 m, κ = 2.2,* $n_e \sim 1.8 \times 10^{19}\ m^{-3}$, $m_{neo} = 2.4$, $Z_{eff} = 1$, $P_{rad}/P_{tot} = 10\%$, $P_{aux} = 150\text{-}450$ *kW* at 100 kA, $T_i/T_e = 2$





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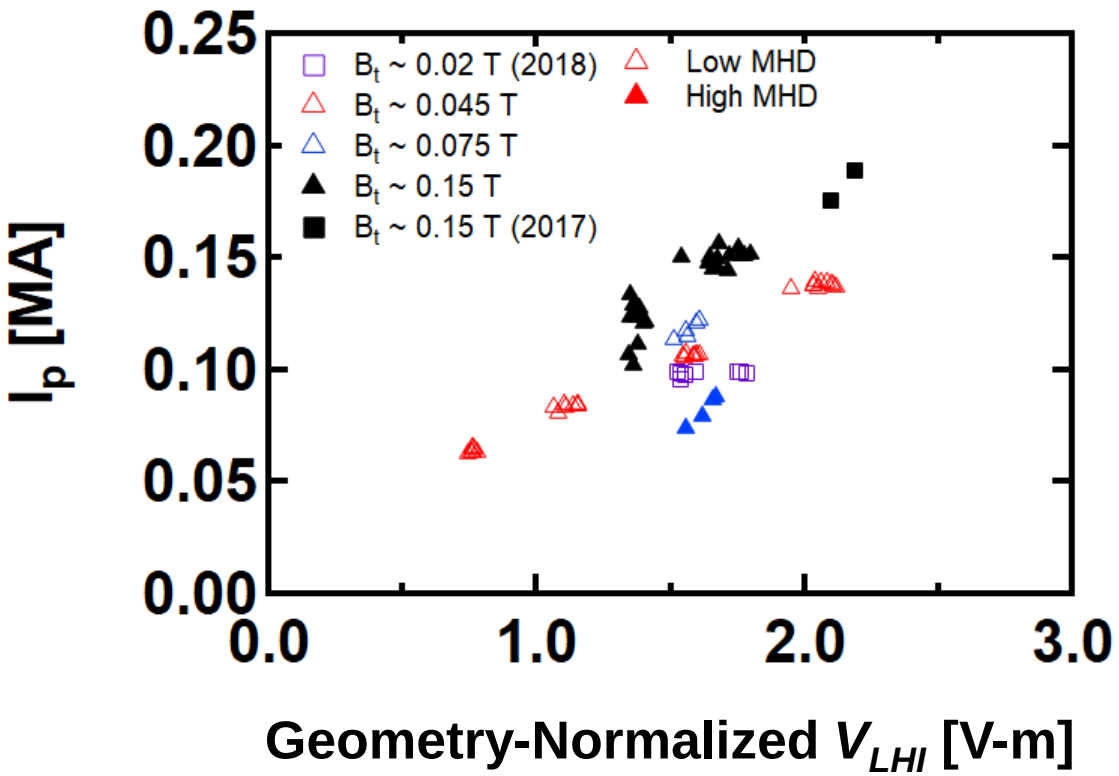
# Weak Scaling of $I_p$ with $B_t$ Implies A More Nuanced Confinement Picture of LHI

- Only modest increase in $I_p$ with $B_t$
  - Much weaker than predicted from Neo-Alcator scaling ($\tau_{neo-A} \sim q$)
  - However, picture clouded by MHD activity
- LHI discharges may transition from LOC to SOC regime:
  - As $B_t$ is increased
  - As $n_e$ is decreased
- Necessitates investigation over wider parameter regime: PEGASUS-III
  - Increased $B_t$ and $P_{aux}$

S. Diem (NO7:02)

M. Nornberg (ZP6:01)

LHI Current Drive Scaling at Various Levels of $B_t$








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

- LHI $T_e$ profiles comparable to Ohmic $T_e$ profiles under the right conditions
- Working model: cross-field transport dominated core surrounded by zero-pressure outer region
- Sustained hollow $T_e$ profiles observed at lower levels of $B_t$
  - Hollow J(r) → low core resistive heating
- Modest low-Z impurity radiation can dominate low core heating
  - Low $T_{e,0}$ of LHI discharges can result in highly radiative plasmas with low $Z_{eff}$
- Low $B_t$ LHI: consistent with LOC estimates
  - Must include auxiliary power from reconnection
- LHI performance and scaling will be further evaluated on PEGASUS-III





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