Confinement Scaling Projections for Local Helicity Injection Plasma Startup on PEGASUS-III

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PEGASUS-III Experiment

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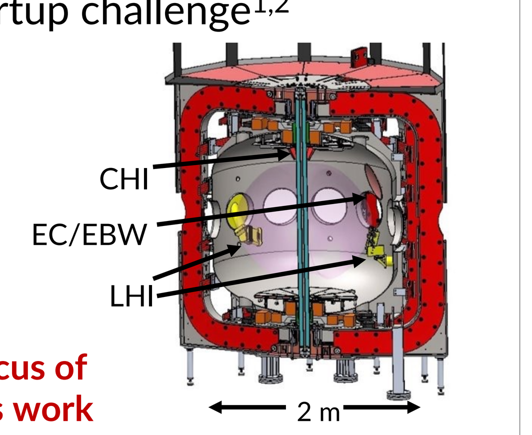
Higher B_T Enables Critical Tests to Advance LHI on PEGASUS-III

Mission: Compare, contrast, and synergistically combine power-plant relevant solenoid-free startup techniques to solve the tokamak startup challenge[1,2]

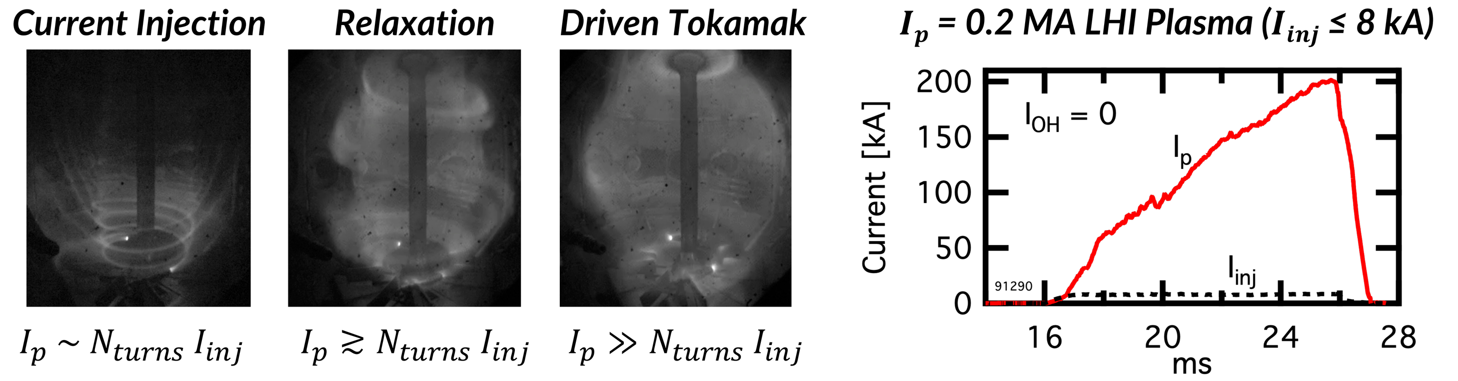
- PEGASUS-III startup systems:
  - Local Helicity Injection (LHI)[3]
  - Coaxial Helicity Injection (CHI)[4,5]
  - Radio-frequency (RF) heating and CD[6]
- LHI physics tested at higher $B_T \leq 0.6$ T
  - Improve extrapolation to higher B_T facilities
  - Demonstrate improved performance: $I_p \geq 0.3$ MA
  - Characterize dissipation and confinement scaling
  - Test current drive models[7]
  - Coupling to RF heating and CD[6]

Focus of this work



[1]M.W. Bongard *et al.*, CP11.00040
[2]S.J. Diem *et al.*, GO03.00002
[3]A.C. Sontag *et al.*, CP11.00045
[4]R. Raman *et al.*, CP11.00053
[5]J.A. Reusch *et al.*, CP11.00044
[6]J.K. Peery *et al.*, CP11.00042
[7]R. Sassella *et al.*, CP11.00048

LHI makes High-I_p Tokamak Plasmas via Edge Current Injection



- **Helicity Balance:** To drive I_p, helicity must be injected faster than it is dissipated

Effective loop voltage: $V_{LHI} = V_{inj} A_{inj} B_{T,inj} / \Psi_T$ I_p Limit: $I_p \leq (V_{LHI} + V_{IND})/R_p$

- **Taylor Relaxation:** System driven to minimum energy state that conserves helicity

Taylor/relaxed state: Flat $\lambda(r) \equiv \mu_0 \vec{J} \cdot \vec{B}/B^2 \rightarrow$ In LHI, $\bar{\lambda}_p \leq \bar{\lambda}_{inj}$

Taylor Limit [1]: $I_p \leq I_{TL} \approx f_g \left[\frac{\varepsilon A_p I_{inj} I_{TF}}{2\pi R_{edge} w_{inj}}\right]^{1/2}$ $f_g \equiv$ geometric factor, $1 \lesssim f_g \lesssim 3$

Global limits insufficient for determining $I_p(t)$ → Require predictive models for projecting LHI to MA-class tokamak startup

0-D Power Balance Model Developed to Predict $I_p(t)$

- Circuit model derived from Poynting's theorem [2]
  - Balances input drive with stored magnetic energy and resistive dissipation
  - Inductive effects quantified with analytic, finite-A formulae
  - Solve 1st order ODE for $I_p(t)$ while enforcing Taylor limit: $I_p(t) \leq I_{TL}(t)$
  - **Time-varying inputs:** Plasma shape, injector parameters, β_p, ℓ_i, I_{TF}, assumed $\langle\eta_p\rangle$

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

Inductive Drive from Shape Evolution: $V_{L_e} = -\frac{\partial}{\partial t}\left[L_e I_p\right]$

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

Plasma Magnetic Energy Change: $V_{W_m} = \frac{1}{I_p}\frac{\partial}{\partial t}\left[\frac{1}{2} L_i I_p^2\right] - V_{RTT}$, $V_{RTT} = \frac{I_p}{2\mu_0} \oiint_{S_P} \left(\frac{B_p}{I_p}\right)^2 \vec{v_b}(\theta) \cdot \hat{n} dS$

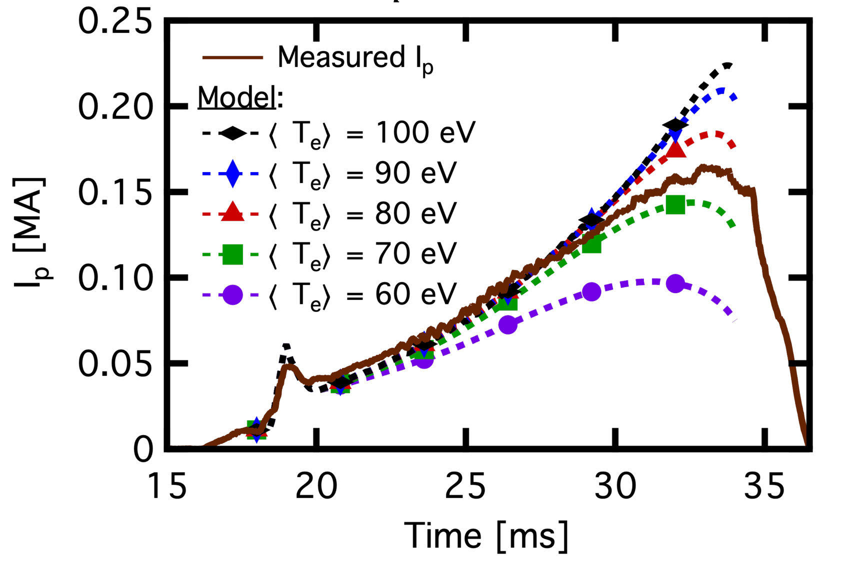
Resistive Dissipation: $V_{IR} = I_p \left(\frac{\langle\eta_p\rangle 2\pi R_0}{A_p}\right)$

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

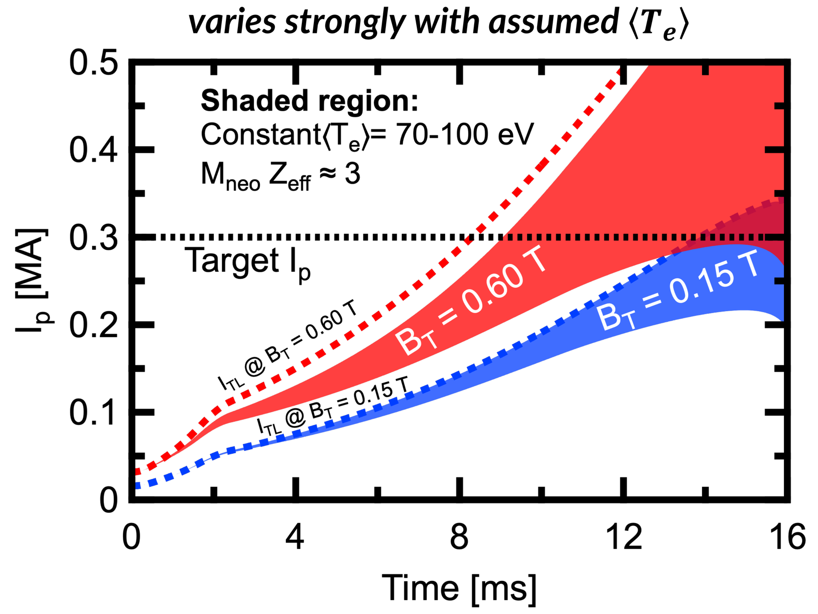
Helicity Dissipation Remains a Major Uncertainty in Projecting LHI Performance

- Presently, dissipation treated resistively
  - $\langle\eta_p\rangle \propto Z_{eff} m_{neo} T_e^{-3/2}$
- $\langle\eta_p\rangle$ adjusted to match experimental $I_p(t)$
  - Assume constant $\langle\eta_p\rangle$, $Z_{eff} m_{neo} \approx 3$
  - In PEGASUS, $\langle T_e\rangle = 60-90$ eV at $B_T \leq 0.15$ T
    - Consistent with Thomson Scattering $T_e(R)$ [2]
- Uncertainty in $\langle\eta_p\rangle$ yields range of projected $I_p(t)$
  - Varies strongly with assumed $\langle T_e\rangle$
- Favorable implications for PEGASUS-III at higher B_T
  - Increased I_{TL} via $B_T \rightarrow I_p$ increases
  - If higher B_T increases $\langle T_e\rangle \rightarrow I_p$ significantly increased

Assumed model $\langle\eta_p\rangle$ varied via $\langle T_e\rangle$ to best match measured $I_p(t)$ on PEGASUS [2]



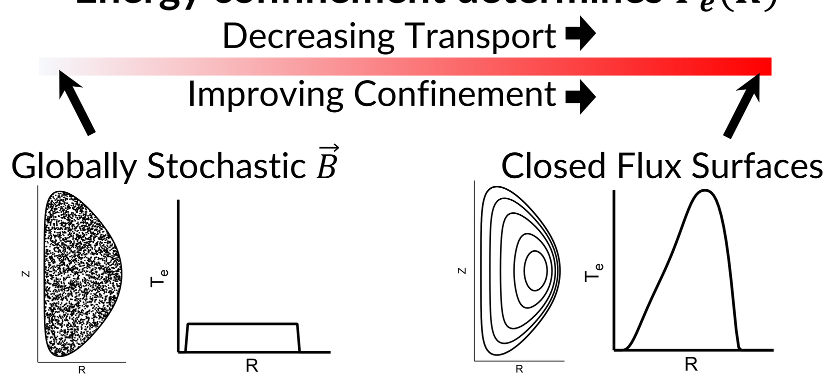
Projected PEGASUS-III I_p increases with B_T and varies strongly with assumed $\langle T_e\rangle$



Reliable $I_p(t)$ projections require a model to scale helicity dissipation

Assessing LHI Performance via Tokamak Global Confinement Scalings

Energy confinement determines $T_e(R)$



LHI likely lies between these extremes

- Observe peaked $T_e(R)$ and $P_e(R)$ [3]
  - Comparable to ohmic discharges
- Reconnection and 3D $\vec{B} \rightarrow$ stochasticity
  - Reconnection evidence: NIMROD modeling [4] and observed anomalous ion heating [5]

No model for LHI confinement currently exists

- Estimate $\langle T_e\rangle$ from global power balance [3]

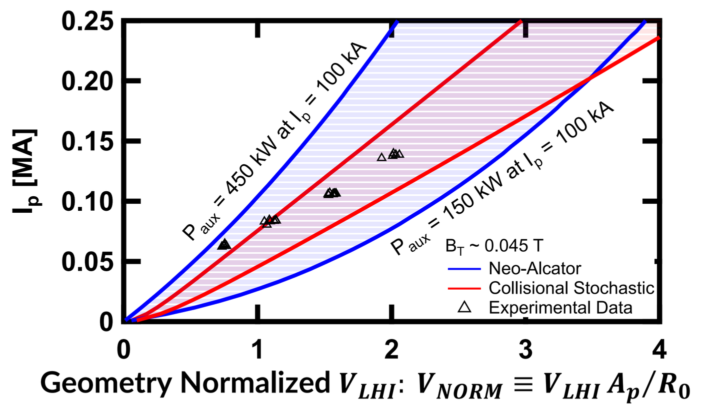
Global power balance: $\frac{d(W_M + W_k)}{dt} = P_{in} - P_{rad} - \frac{W_k}{\tau_E}$ → Steady-state, $d/dt = 0$ → $P_{in} - P_{rad} = \frac{W_k}{\tau_E}$

- Assume τ_E from various confinement models

Confinement Type	Regime	τ_E Scaling
Standard Ohmic Tokamak	LOC	τ_E^{neo-A} [6]
	SOC	$\tau_E^{ITER97Lth}$ [7]
RR stochastic [8] ($\tau_E \sim a^2/\chi_e$)	Collisional	$\sim \frac{a^2}{v_{th,e}{}^2 \tau_{col} (\delta B_r/B_T)^2}$ *
	Collisionless	$\sim \frac{a^2}{v_{th,e} L_c (\delta B_r/B_T)^2}$ *

*Assume $\frac{\delta B_r}{B_T} \sim \left(\frac{\tau_R}{\tau_A}\right)^{-\alpha}$, $\alpha = [0.07, 0.18]$ from work on MST [9]

PEGASUS data consistent with LOC and collisional stochastic scalings [3]

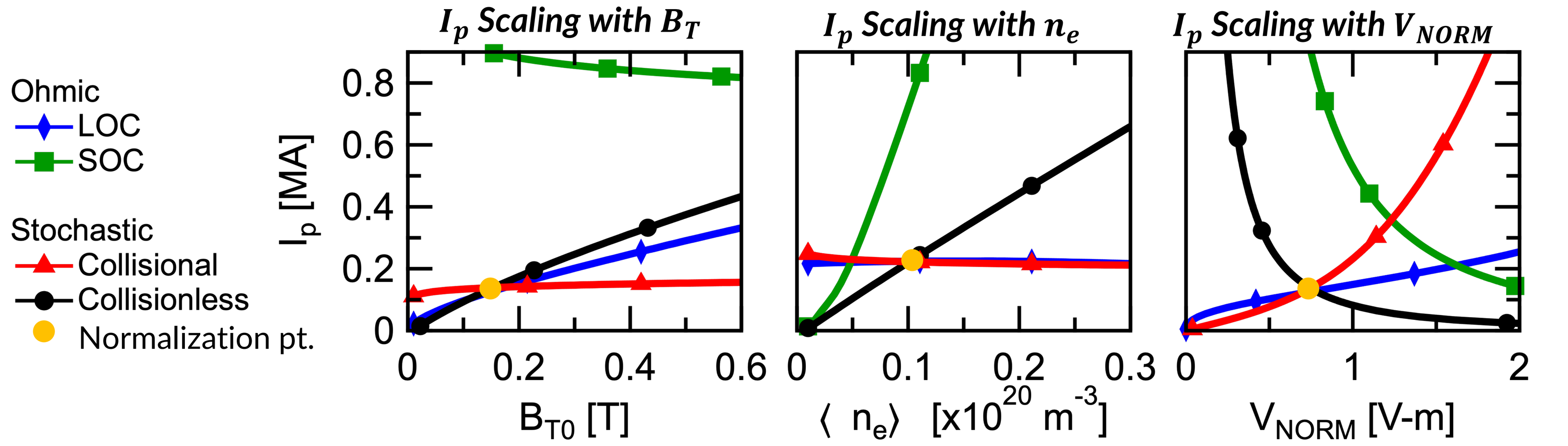


- Requires reconnection $P_{aux} \propto I_{inj} V_{inj}^{1/2}$
- LOC: No free parameters
- Stochastic: Normalized to data
- Data unable to distinguish models

Steady-State I_p Projections Motivate PEGASUS-III Confinement Scaling Experiments

Steady-state confinement model used to predict PEGASUS-III I_p scaling trends

- Calculations assume reference low-A PEGASUS-III plasma
  - $A = 1.2$, $R_0 = 0.4$ m, $\kappa = 2$, $m_{neo} = 2.4$, $Z_{eff} = 1$, $F_{RAD} = 10\%$, $P_{aux} = 0.3$ MW and $T_i/T_e = 2$
  - Stochastic model only provides relative scaling, not absolute I_p predictions → compare qualitative trends
- Varied B_T, $\langle n_e\rangle$, and V_{NORM}: Experimentally accessible and discernable



Summary of predicted qualitative I_p trends for various confinement scalings

Confinement Scaling Estimates	I_p Trend w/ Increasing B_T	Increasing n_e	Increasing V_{NORM}
LOC	↑	–	↑
SOC	–	↑	↓
Collisional stochastic	–	–	↑
Collisionless stochastic	↑	↑	↓

- Unique combination of expected trends for each model
  - Can experimentally discern between models
- PEGASUS-III will test these models via B_T and n_e scans

Incorporating Global Confinement Scalings into 0-D Power Balance Model

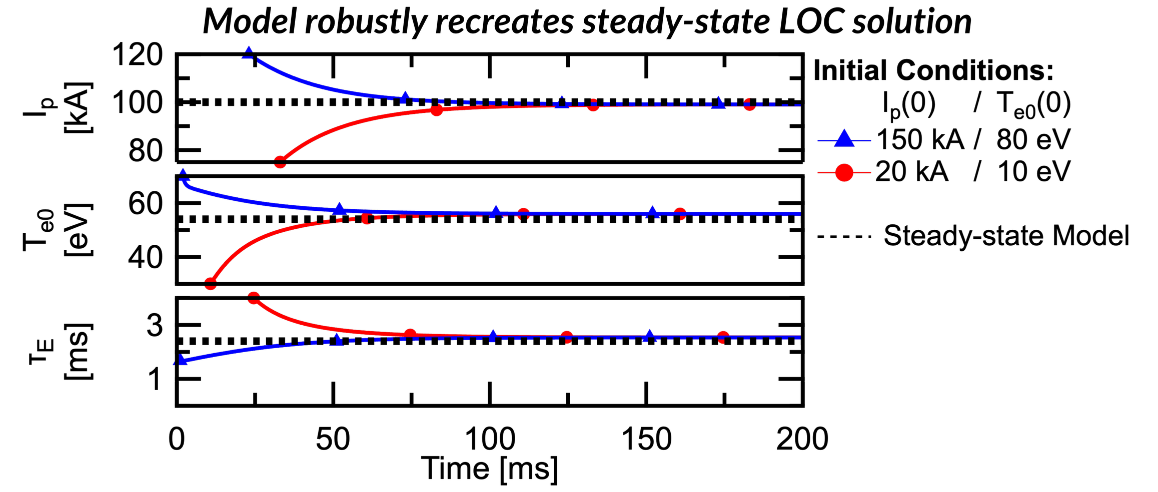
- High-I_p LHI scenarios in PEGASUS-III leverage dynamic shape evolution and significant inductive drive (V_{IND}) [2]
  - Not described by steady-state model
- Extended 0-D power balance model to incorporate global confinement scalings into dynamic $I_p(t)$ predictions

Extended 0-D power balance model governing equations

Poynting's theorem:	$I_p[V_{IND} + V_{LHI} - V_{IR}] = 0$
NEW Global power balance:	$\frac{d(W_M + W_k)}{dt} = P_{in} - P_{rad} - \frac{W_k}{\tau_E}$
Taylor Limit:	$I_p \leq I_{TL}$

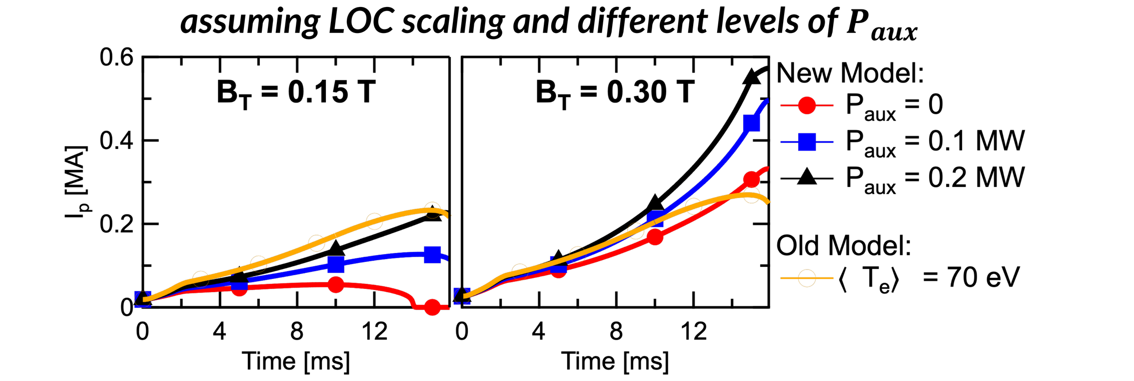
- Recast into coupled set of 1st order, non-linear ODEs
  - Solve for $I_p(t)$ and $T_e(t)$ while enforcing Taylor Limit
- Successfully benchmarked against steady-state model

Model robustly recreates steady-state LOC solution



- Assumed P_{aux} strongly impacts LOC $I_p(t)$ projections
  - Lower B_T: Need P_{aux} to reach previously projected I_p
  - Higher B_T: Improved confinement → higher I_p projected

Comparing previous PEGASUS-III projections with new extended model assuming LOC scaling and different levels of P_{aux}



PEGASUS-III will Validate LHI Predictive Tools

- Experiments will characterize helicity dissipation scaling
  - Reduce uncertainty in 0-D model to enable $I_p(t)$ predictions
- Steady-state I_p projections motivate B_T and n_e scans
  - Assess if global confinement scalings are descriptive of LHI
  - Distinguish between competing confinement scalings
- Incorporated τ_E scalings into 0-D power balance model
  - Provides self-consistent $T_e(t)$ via global confinement scalings

References: [1] D.J. Battaglia, *et al.* Nucl. Fusion **51** 073029 (2011); [2] J.L. Barr, *et al.* Nucl. Fusion **58**, 076011 (2018); [3] G.M. Bodner *et al.*, Phys. Plasmas **28**, (2021); [4] J.B. O'Bryan and C.R. Sovinec, Plasma Phys. Control. Fusion **56** 064005 (2014) [5] M.G. Burke *et al.*, Nucl. Fusion **57**, (2017); [6] R. J. Goldston, Plasma Phys. Control. Fusion **26**, (1984); [7] S.M. Kaye *et al.*, Nucl. Fusion **37**, (1997); [8] B. Rechester and M. N. Rosenbluth, Phys. Rev. Lett. **40**, (1978); [9] M. R. Stoneking *et al.*, Phys. Plasmas **5**, (1998)

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