The Physics of Local Helicity Injection (LHI) Non-Solenoidal Tokamak Startup

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PEGASUS Toroidal Experiment

Poster Abstract

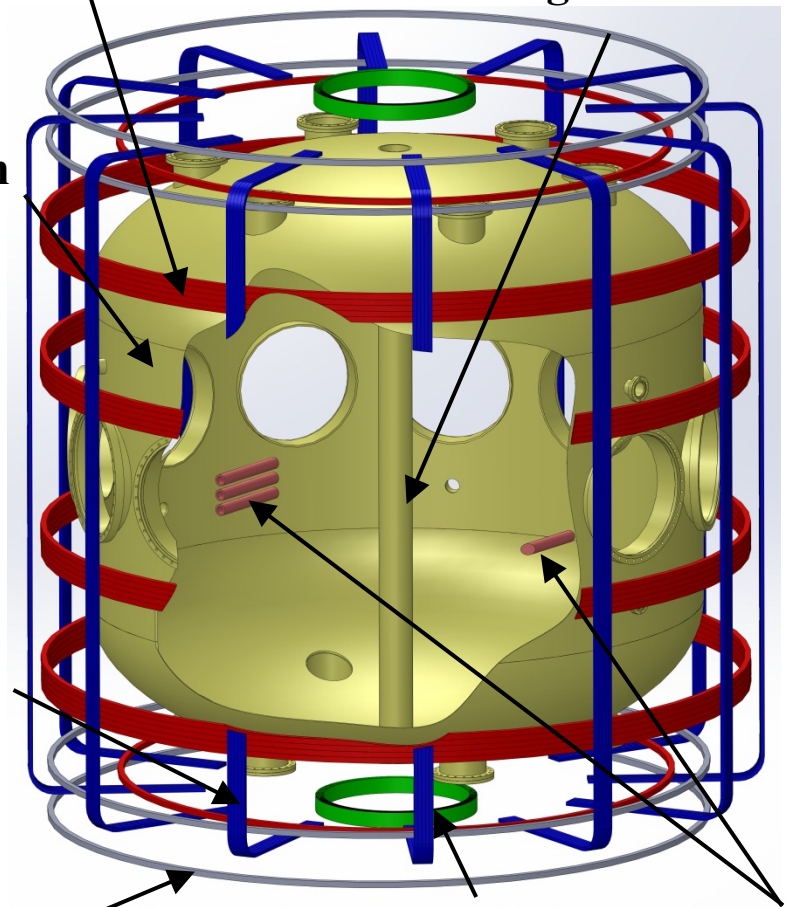
- Non-solenoidal startup via Local Helicity Injection (LHI) uses compact current injectors to produce toroidal plasma currents up to 170 kA in the PEGASUS Toroidal Experiment
  - Driven by 4-8 kA injected current on timescales of 5-20 milliseconds
- Increasing the current buildup duration enables experimental demonstration of operating regimes relevant for high-current startup
- LHI-driven discharges exhibit:
  - Bursty MHD activity (apparently line-tied kinking of the LHI-driven field lines), with the bursts correlating with rapid equilibrium changes, sharp I_p rises, and drops in the injector impedance
- Preliminary NIMROD results suggest:
  - Helical LHI-driven current channels remain coherent
  - Plasma current increases due to reconnection between adjacent helical turns, forming axisymmetric plasmoid rings, with corresponding sharp drops in the bias circuit impedance
- The DC injector impedance is consistent with a space charge limit at low injected current and a magnetic limit at high injected current
- Internal measurements show that the plasma current density starts strongly hollow and rapidly fills in during current buildup
- Simulations of LHI discharges using the Tokamak Simulation Code (TSC) will provide insights into the detailed current drive mechanism and guide experiments on PEGASUS and NSTX-U

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Motivation for this Study

- Motivated by the need to assess the use of LHI for non-solenoidal startup in tokamaks and spherical tokamaks (STs):
  - Non-solenoidal plasma startup is a universal problem for the tokamak concept
  - The LHI technique appears to scale to high-I_p startup in fusion-scale devices
- Particularly, address specific issues of LHI implementation on the PEGASUS and NSTX-U devices:
  - Minimum necessary size of the injector structure
  - Parameters of the external power supply driving the injector current
  - Optimum practical location for the injector structure
- Assessment requires full-physics predictive modeling of LHI startup in both PEGASUS and NSTX-U:
  - Use insights from first-principles NIMROD modeling, where applicable
  - Incorporate best validated physics-based models for current drive and injector impedance
  - Use these models in TSC numerical simulations of LHI-driven discharges

PEGASUS is a compact ultralow-A ST



Experimental Parameters

Parameter	Achieved	Goals
A	1.15 – 1.3	1.12 – 1.3
R(m)	0.2 – 0.45	0.2 – 0.45
I_p (MA)	≤ .21	≤ 0.30
I_N (MA/m-T)	6 – 12	6 – 20
RB_t (T-m)	≤ 0.06	≤ 0.1
κ	1.4 – 3.7	1.4 – 3.7
τ_{shot} (s)	≤ 0.025	≤ 0.05
β_t (%)	≤ 25	> 40
P_{HHFW} (MW)	0.2	1.0

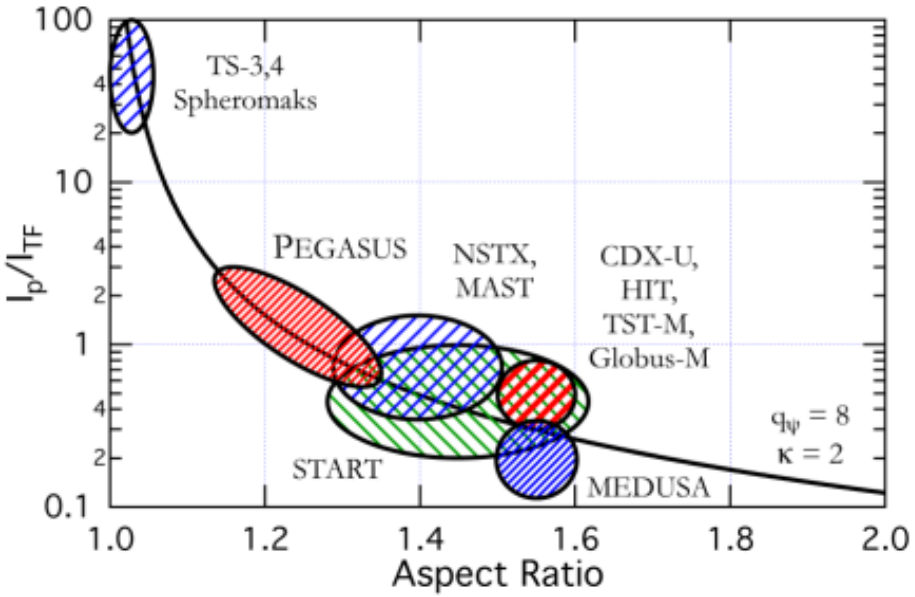
Major research thrusts include:

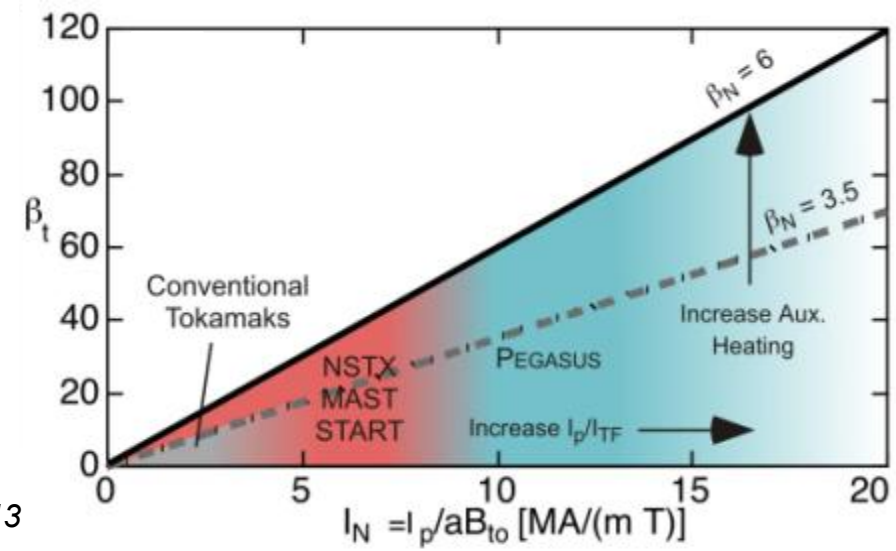
- *Non-inductive startup and sustainment*
- *Tokamak physics in small aspect ratio:*
  - *High-I_N, high-β stability limits*
  - *ELM-relevant edge MHD activity*

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PEGASUS Mission: Physics of Low A → 1

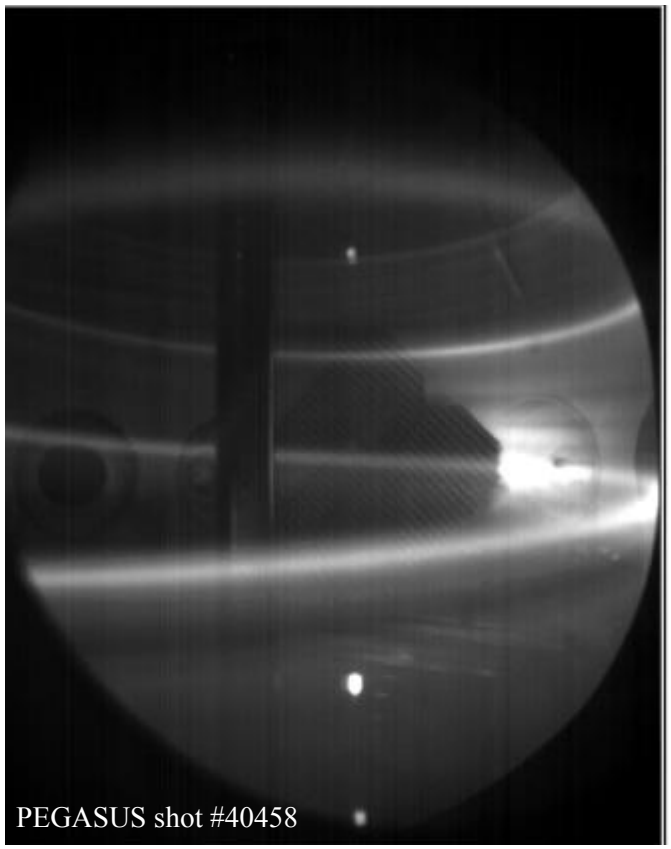
- Non-solenoidal startup
  - Local helicity injection
  - Helicity-initiated discharges readily couple to other current drive methods
- Physics of High I_p/I_{TF}
  - Explore limits of ST operating space
  - Study high β_T plasmas as A → 1
- Tokamak edge stability
  - Tests of peeling-ballooning theory (ELMs)
  - H-mode studies as A → 1



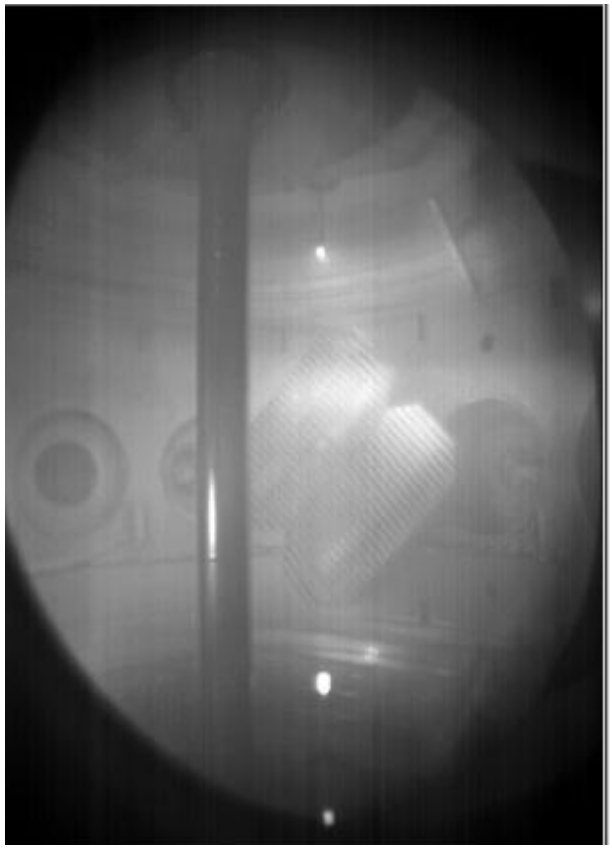


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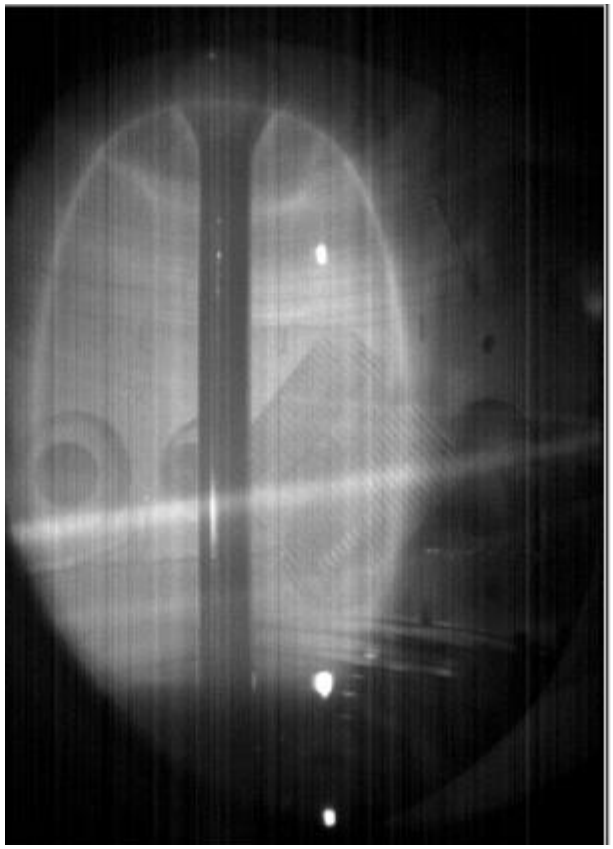
Typical Evolution Yields $I_p >> I_{INJ}$ and Apparent Tokamak-like structure



t=21.1 ms, I_p=2-3 kA
Filaments only



t=28.8 ms, I_p=42 kA
Driven diffuse plasma

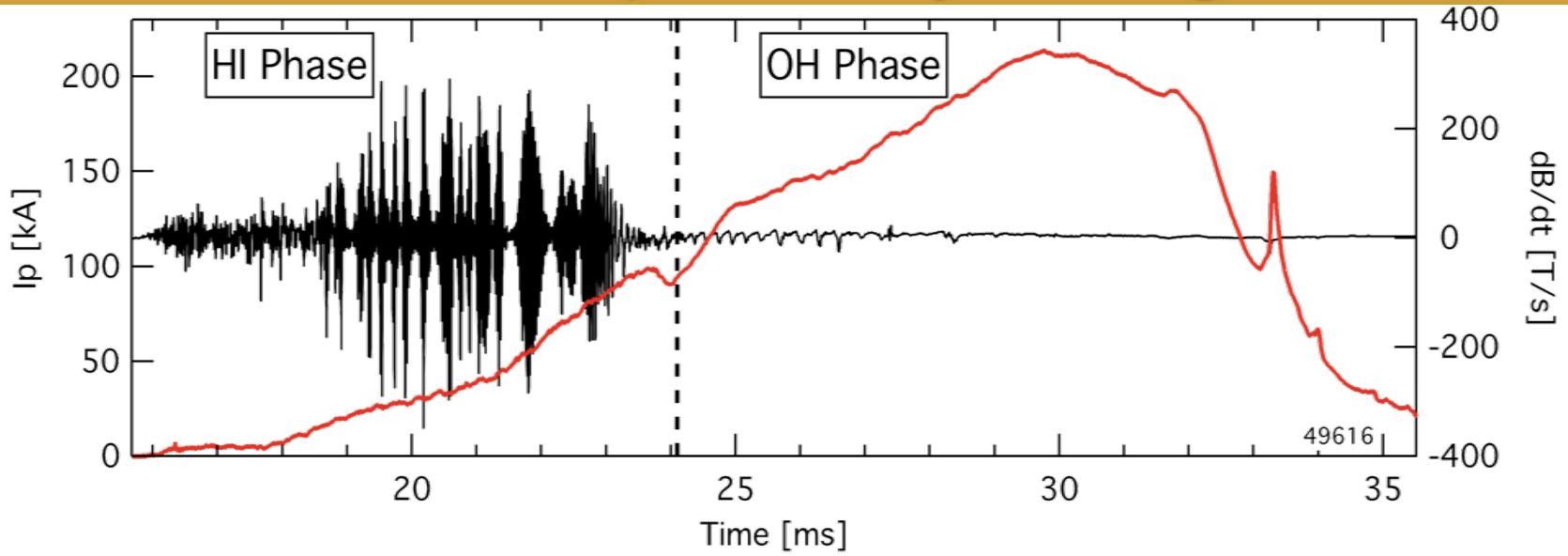


t=30.6 ms, I_p=37 kA
Guns off, Decaying

See Battaglia *et al*., Nucl. Fusion **51**, 073029 (2011)

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HI is an Alternative to Solenoidal Startup and is Accompanied by Strong MHD



- Non-solenoidal HI startup produces high I_p with modest drive
  - HI on PEGASUS has produced plasmas with $I_p \leq 0.17$ MA, using 4-8 kA drive
- HI drive phase characterized by strong MHD activity
- Better understanding will enable accurate numerical modeling
  - The role of the MHD activity in HI current drive
  - Impedance for the external circuit driving the injector current
  - Requirements for forming the axisymmetric tokamak-like equilibrium

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Tokamak Current Drive is Helicity Injection

Total helicity K in a tokamak geometry: $K = \int_V (\mathbf{A} + \mathbf{A}_{vac}) \cdot (\mathbf{B} - \mathbf{B}_{vac})\, d^3x$

$$\frac{dK}{dt} = -2\int_V \eta \mathbf{J} \cdot \mathbf{B}\, d^3x - 2\frac{\partial \psi}{\partial t}\Psi - 2\int_A \Phi \mathbf{B} \cdot d\mathbf{s}$$

- Resistive Helicity Dissipation
  - $\mathbf{E} = \eta\mathbf{J} \rightarrow$ much slower than energy dissipation ($\eta\mathbf{J}^2$)
  - Turbulent relaxation processes dissipate energy and conserve helicity
- AC Helicity Injection: $\dot{K}_{AC} = -2\frac{\partial \psi}{\partial t}\Psi = 2V_{loop}\Psi$
  - Ψ is toroidal flux, ψ is poloidal flux (*e.g.*, current drive through solenoid induction)
- DC Helicity Injection $\dot{K}_{DC} = -2\int_A \Phi \mathbf{B} \cdot d\mathbf{s} = 2V_{inj}B_{\perp}A_{inj}$
  - Φ is electrostatic potential

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Helicity Balance and Taylor Relaxation Determine the Maximum Achievable I_p

Helicity balance in a tokamak:

$$\frac{dK}{dt} = -2\int_V \eta \mathbf{J}\cdot\mathbf{B}\,\mathrm{d}^3x - 2\frac{\partial\psi}{\partial t}\Psi - 2\int_A \Phi\mathbf{B}\cdot\mathrm{ds} \quad \Rightarrow \quad V_{eff} \approx \frac{A_{inj}B_{\phi,inj}}{\Psi_T}V_{inj}$$

- *Helicity injection expressed as an effective loop voltage*
- Maximum I_p depends on plasma confinement via η

$$I_p \le \frac{A_p}{2\pi R_0\langle\eta\rangle}\left(V_{ind} + V_{eff}\right)$$

Relaxation to force-free Taylor state:

$$\nabla\times B = \mu_0 J = \lambda B$$
$$\lambda_p \le \lambda_{edge} \quad \Rightarrow \quad \frac{\mu_0 I_p}{\Psi_T} \le \frac{\mu_0 I_{inj}}{2\pi R_{inj} w B_{\theta,inj}} \quad \Rightarrow \quad I_p \le \left[\frac{C_p}{2\pi R_{inj}\mu_0}\frac{\Psi_T I_{inj}}{w}\right]^{1/2}$$

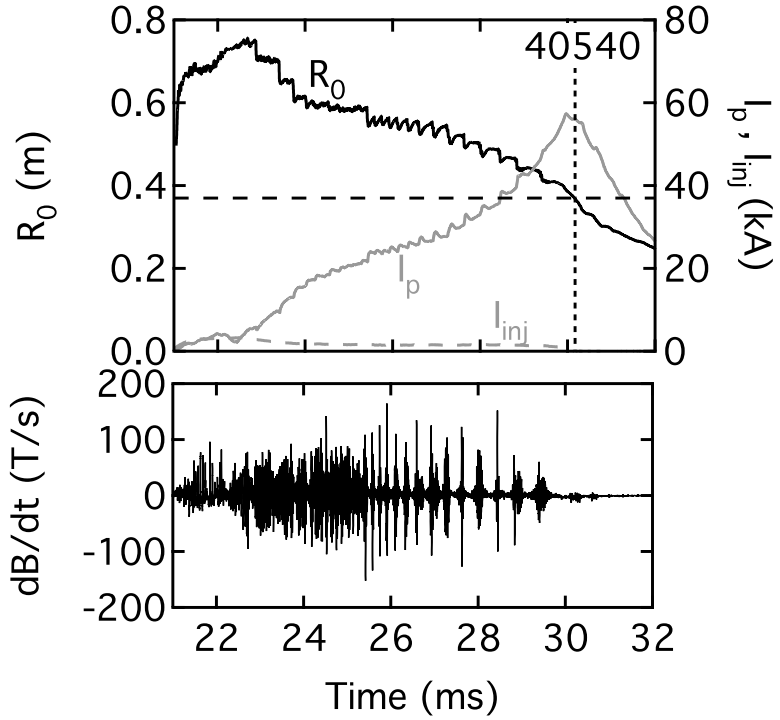
Note that these limits do not determine the plasma evolution.

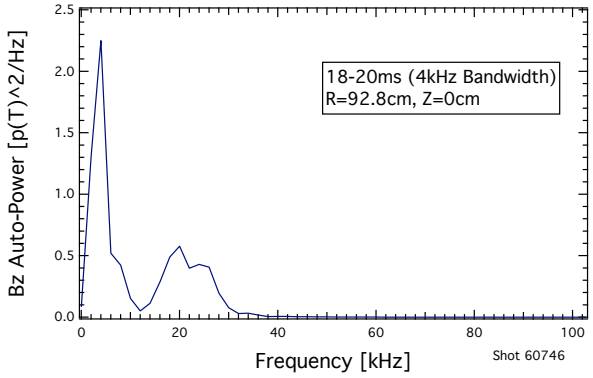
For LHI plasma evolution studies using a power-balance model, see poster TP8.18 by J.L. Barr *et al.*, this session.

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MHD Activity in HI-Driven PEGASUS Plasmas Dominated by Two Main Components

- Most obvious component is bursty n=1:
  - δB/B ~ 1%, 20-80 kHz
  - Bursts coincide with rapid equilibrium changes, including jumps in I_p, sharp drops in both ℓ_i and major radius
- Axisymmetric (n=0) activity correlates with the bursts of n=1:
  - δB/B ~ 0.1-1.0%, 2-10 kHz
- Nonlinear cascade to high frequency may cause ion heating during bursts:
  - See Poster TP8.20 by M.G. Burke *et al.*, this session

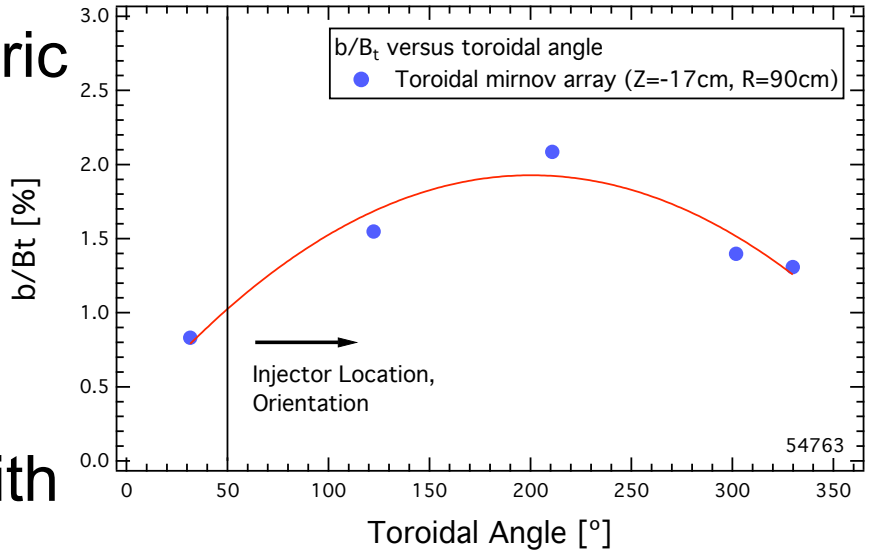


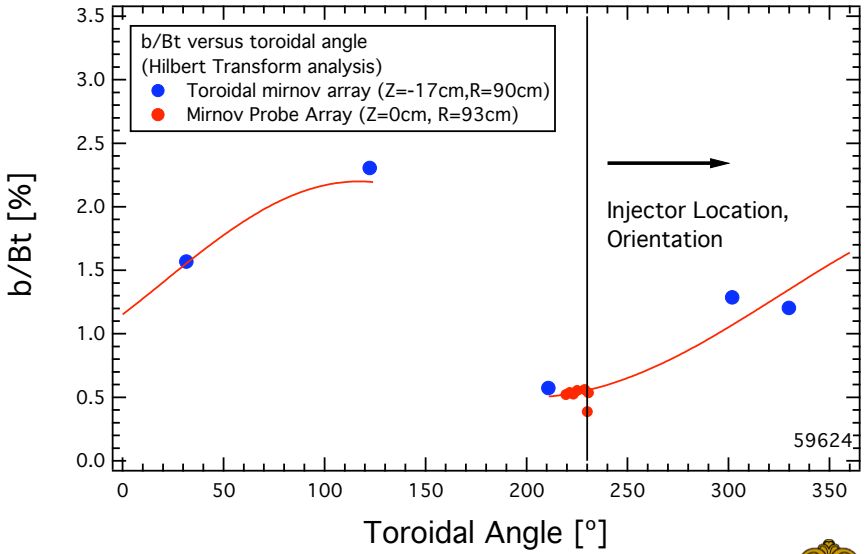


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n=1 Component Appears to be Line-Tied Kink

- n=1 amplitude toroidally asymmetric
  - Smallest near the injector face (cathode)
- n=1 asymmetry follows changes to injector toroidal location
- Observed frequency consistent with Alfvenic oscillation
- Structure suggestive of a line-tied kink mode, tied to the injector*
  - Other end of LHI-driven flux tube may be moving or completely free





*See:

D. D. Ryutuv *et al.*, Phys. Plasmas **13**, 032105 (2006)

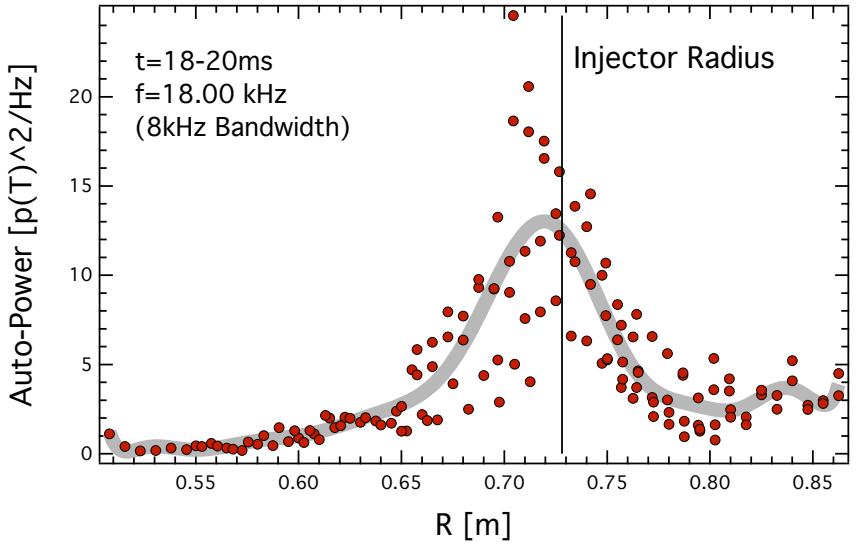
I. Furno *et al.*, Phys. Rev. Lett. 97, 015002 (2006)

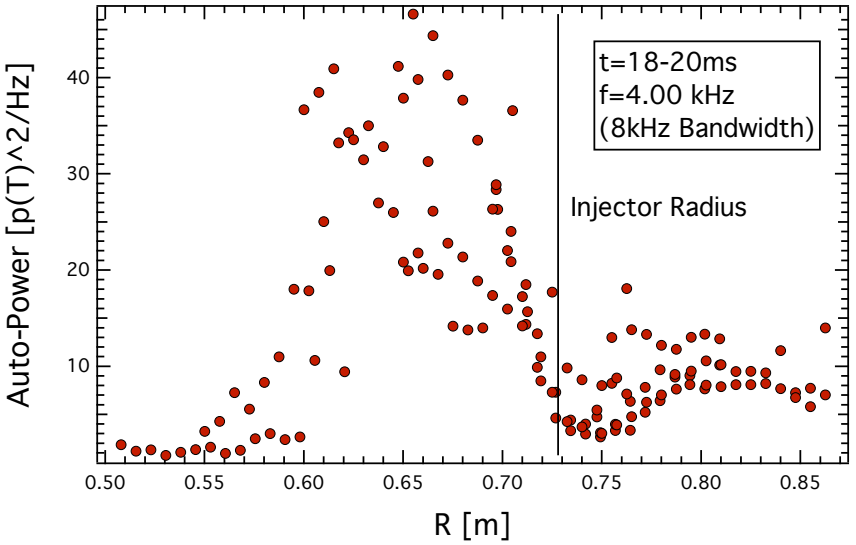
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Bursty n=1 Radially Localized to Injector, n=0 Activity Localized to Interior

- Internal B_z measurements show localization of bursty n=1 mode to the injector

- Axisymmetric activity is localized inside the injector
  - n=0 activity correlates with the bursts of n=1 activity





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Current Injectors for PEGASUS LHI are Intense Electron Beam Sources

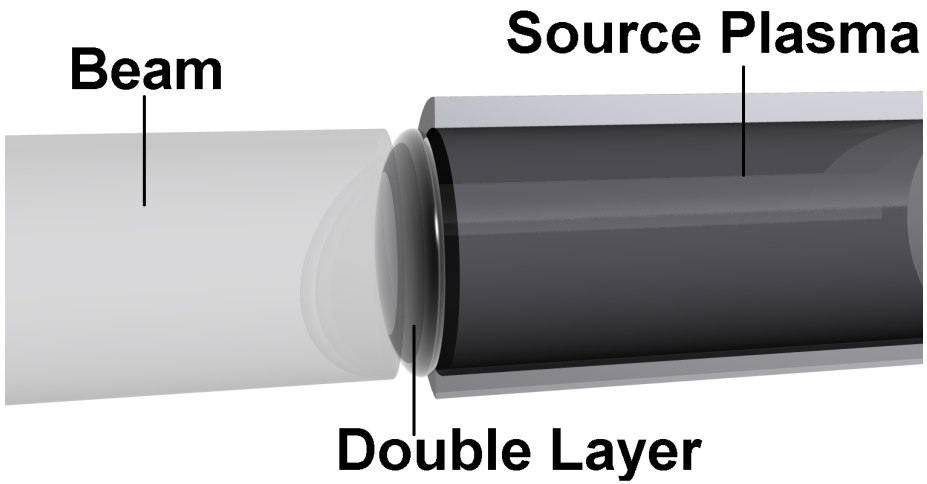
- Two clear operating regimes: $I_{inj} \sim V_{inj}^{3/2}$ at low power, and $I_{inj} \sim V_{inj}^{1/2}$ at high power
- Low-power space-charge limit resulting from double-layer sheath is very low impedance
  - Space-charge gap width is several (micron-scale) Debye lengths
  - Small scale of the gap produces very large currents at low V_{inj}, compared to cm-scale vacuum gaps: Typically $J \sim 0.5$ kA/cm^2 at 100 V
  - Operate as very efficient particle accelerators
- At high power, self-field of the beam is comparable to the local toroidal field
  - Magnetic limit due to self-field may explain more restrictive $V^{1/2}$ scaling
  - Alternatively, extracted current may be limited by quasineutrality to the edge ion density

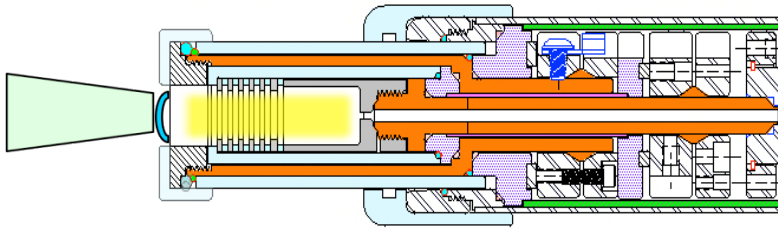
Current Through Double Layer is Predicted to scale as ~$V^{3/2}$ and ~n_e

- Space-charge limited current through the double layer
  - Expression depends on plasma parameters n_e and T_e
  - Current proportional to injector cross-section

$$J = \frac{4}{9} 1.865 \varepsilon_0 \left(1 + \sqrt{\frac{m_e}{m_i}}\right) \left(\frac{2e}{m_e}\right)^{\frac{1}{2}} \frac{V^{\frac{3}{2}}}{l^2}$$

where l is the sheath thickness, some number of λ_{De}





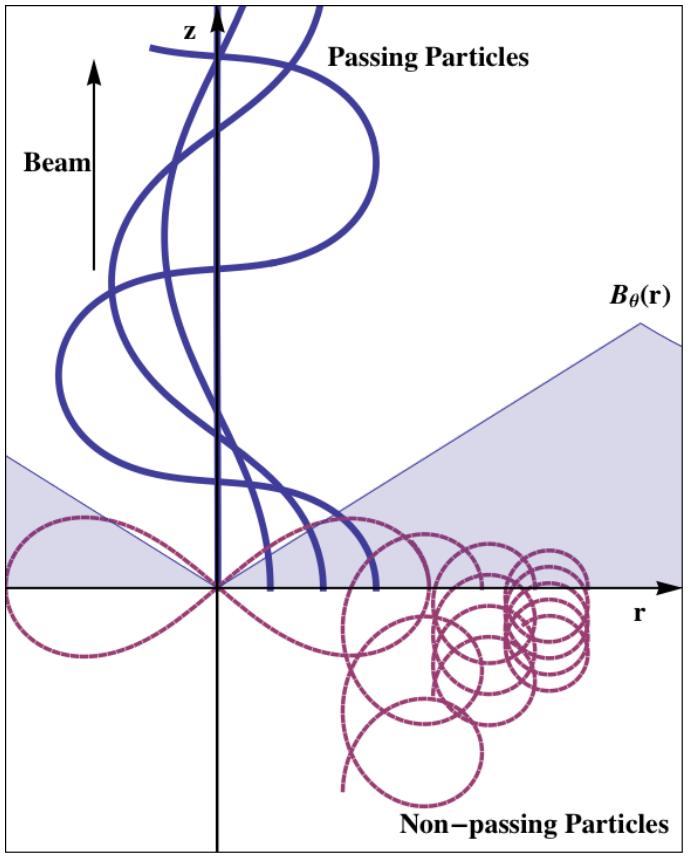
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At Higher Currents, Magnetic Limiting Due to Beam Self-Fields is Expected

- LHI-Driven currents are Intense Beams
  - "Intense" can be defined in terms of the beam energy (kinetic energy = magnetic energy) or the beam size (beam radius comparable to electron Larmor radius in beam field)
  - Defines Alfven current I_A:

$$I_A = \frac{4\pi m v}{e\mu_0} = \frac{4\pi m_e}{e\mu_0}\sqrt{\frac{2eV_{Bias}}{m_e}}$$

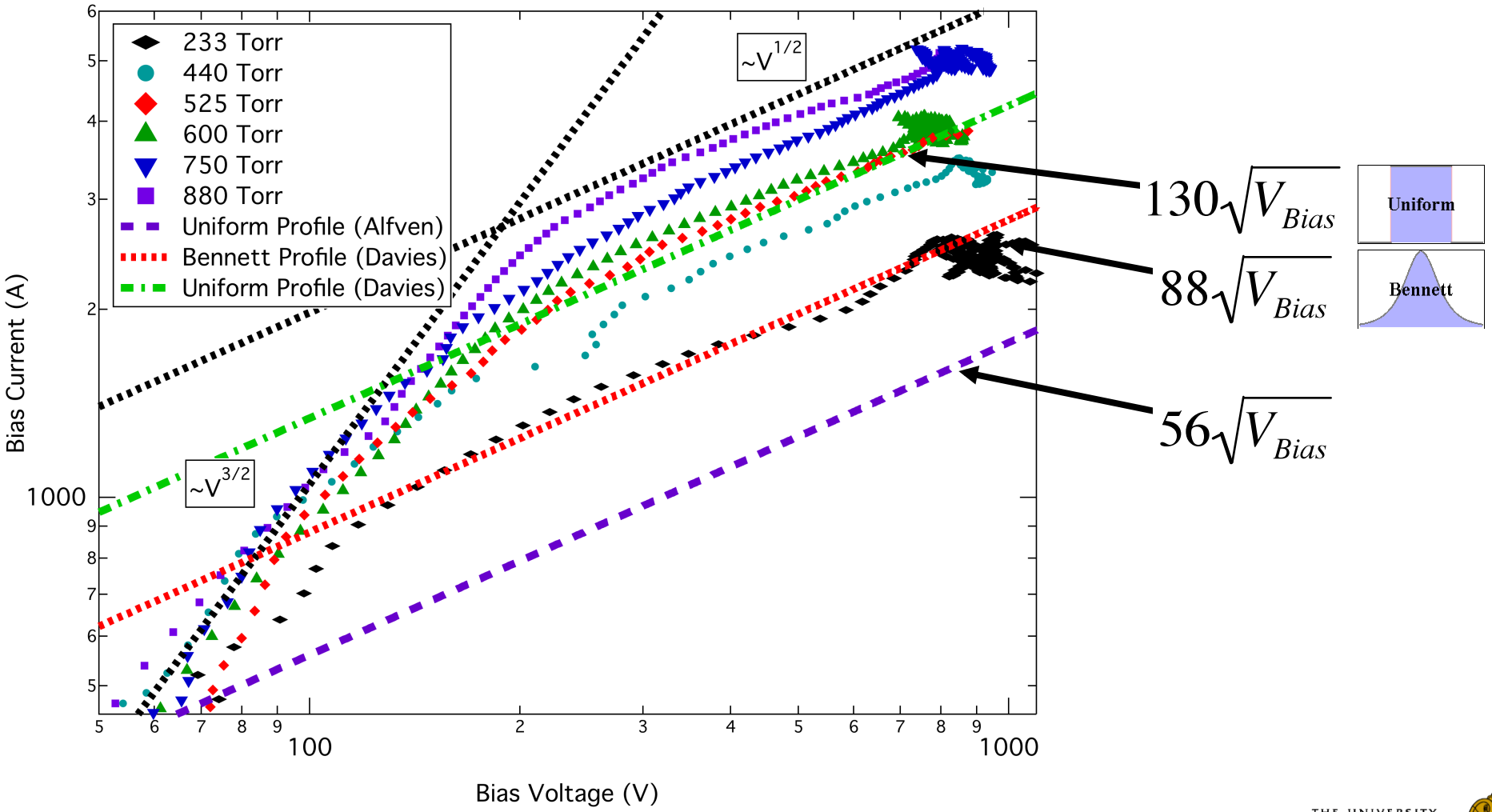
- Alfven current I_A is a "soft" limit
  - PEGASUS injectors typically achieve $I_{inj} \sim 3I_A$
- Physical mechanism for magnetic limit may be the Alfven-Lawson limit (1939)
  - Particles reverse direction in beam self-field
  - $I_{AL} = 1.65I_A = 56V_{inj}^{1/2}$



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Transition to $V^{1/2}$ Injector Operating Regime Consistent with Magnetic Limit

- Data consistent with current profile changing with density

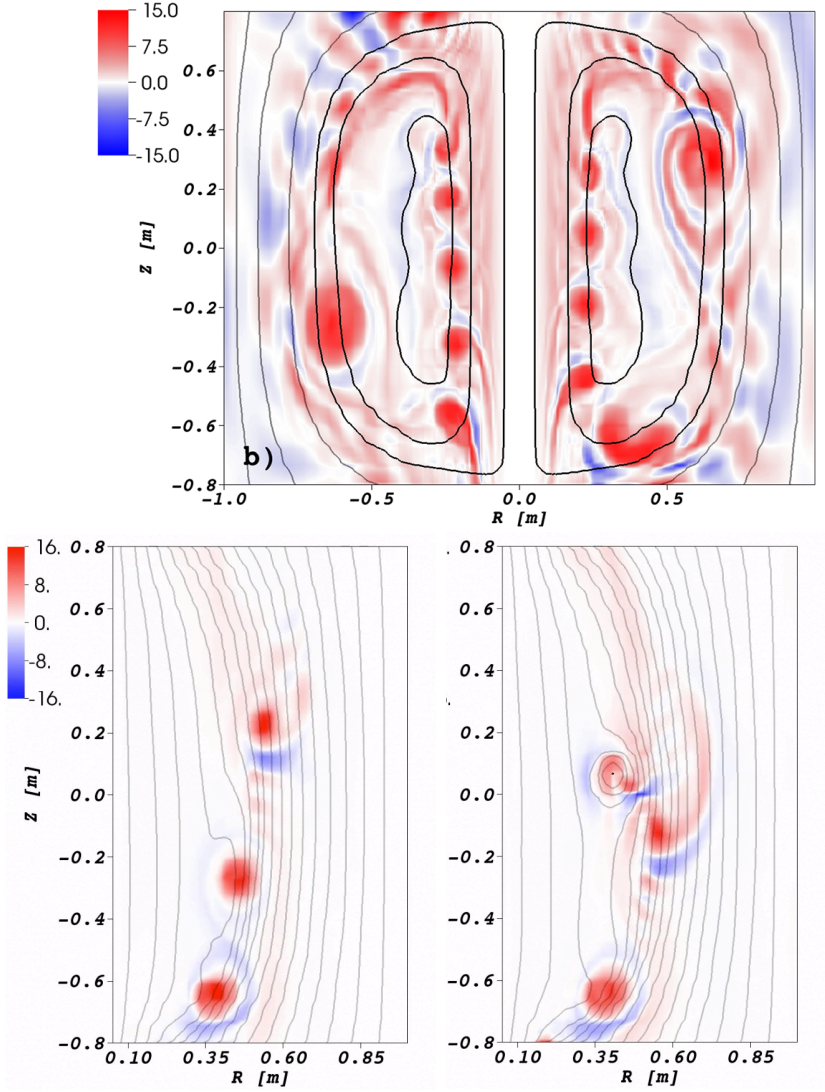


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NIMROD Simulations Show Helical LHI-Driven Streams are Persistent

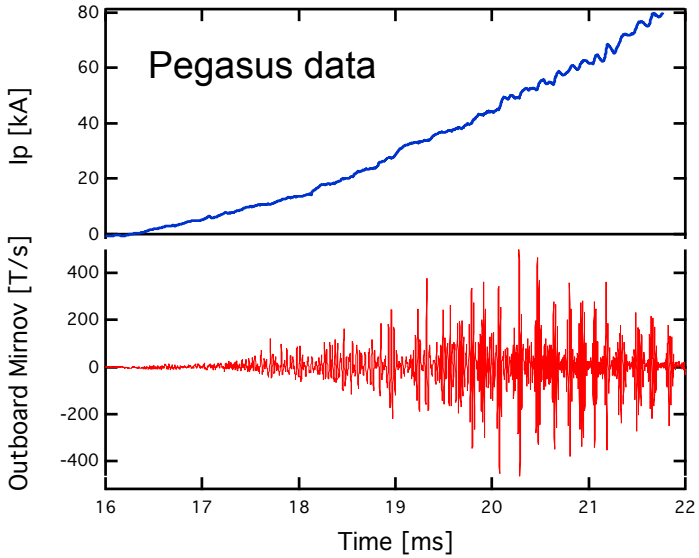
- LHI-driven current streams persist during helicity injection phase
- Adjacent turns of the helix are pulled together and reconnect
- Each reconnection event creates an axisymmetric ring of current
  - See O'Bryan and Sovinec, *Physics of Plasmas* **19** (2012)
- Axisymmetric rings observed in some PEGASUS discharges

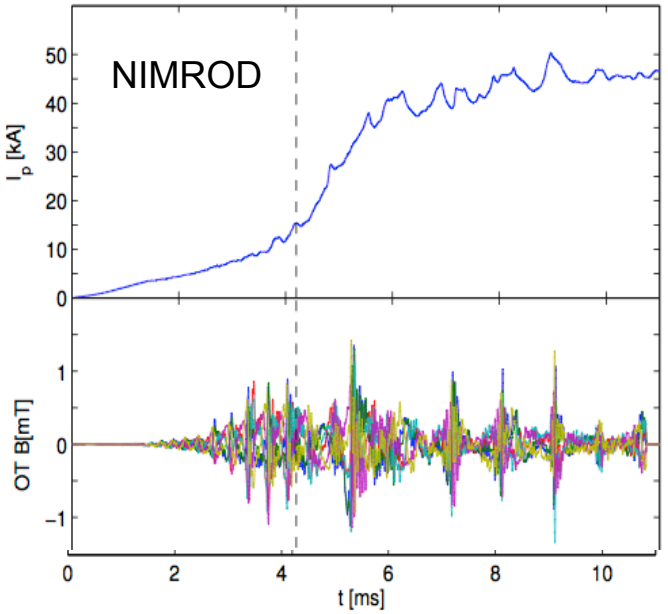


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NIMROD Simulations Show Bursts of MHD Activity Similar to Experiment

- Bursts of MHD activity in NIMROD simulations in qualitative agreement with experiment:
  - Similar frequencies and amplitudes
  - Correlated with I_p rises
- In NIMROD, MHD bursts due to the reconnection events:
  - Primarily due to MHD dynamo
  - Hall dynamo plays a secondary role



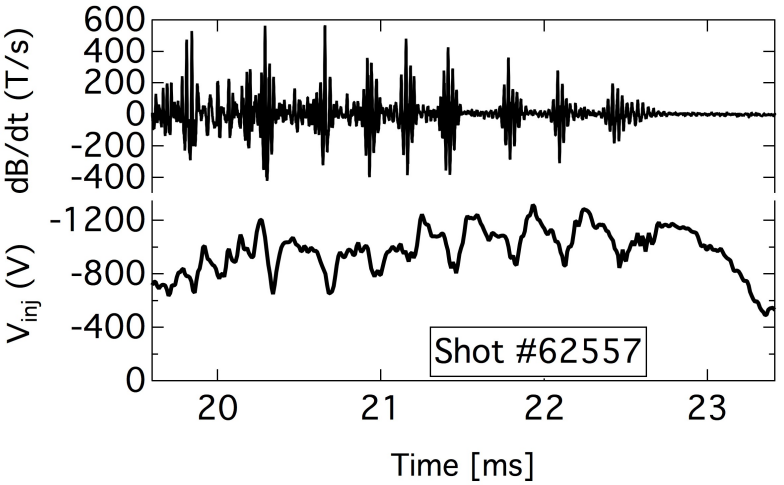


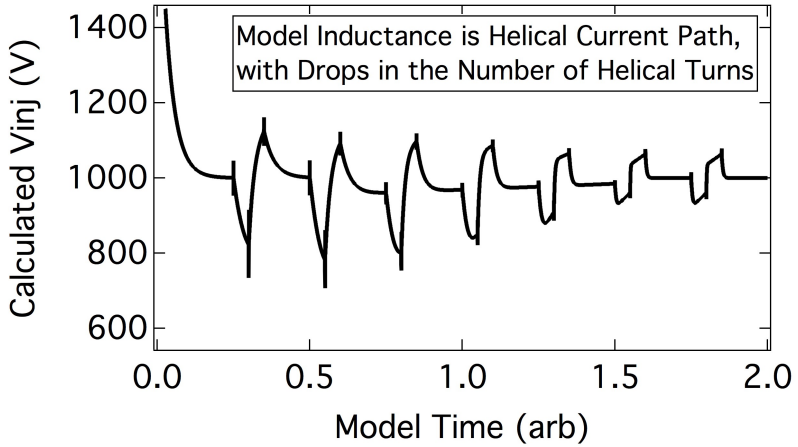
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Bursty n=1 Correlates with V_{inj} Drops, Consistent with an Inductance Model

- Experimentally, n=1 bursts typically correlate with significant V_{inj} drops
- Model the LHI-driven stream as a helix of N turns; sharply reduce to N-1 turns
  - For constant injected current, the inductance change manifests as a V_{inj} transient with a distinctive waveform
  - Similar waveforms are observed in many LHI discharges in PEGASUS

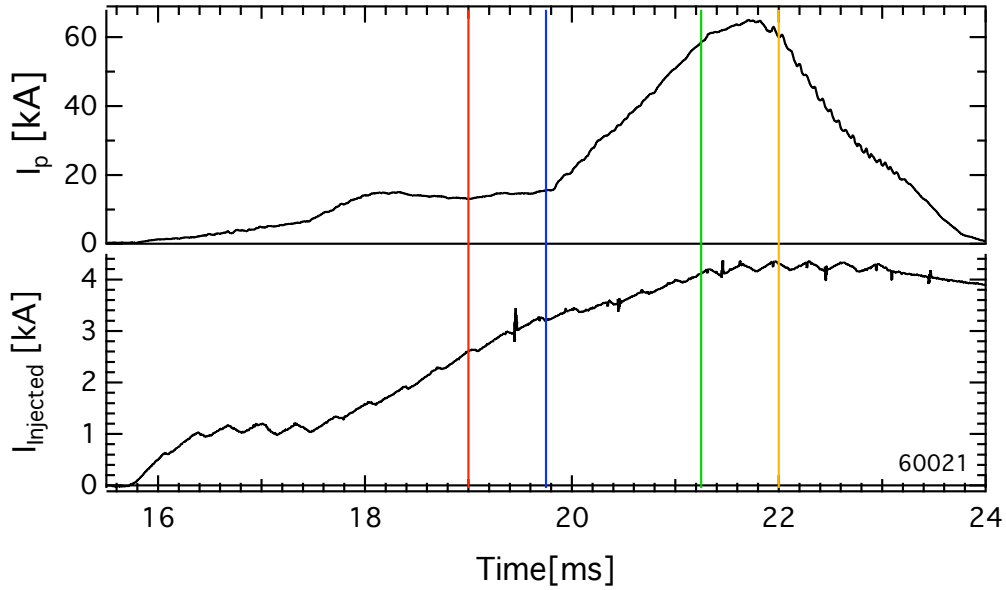




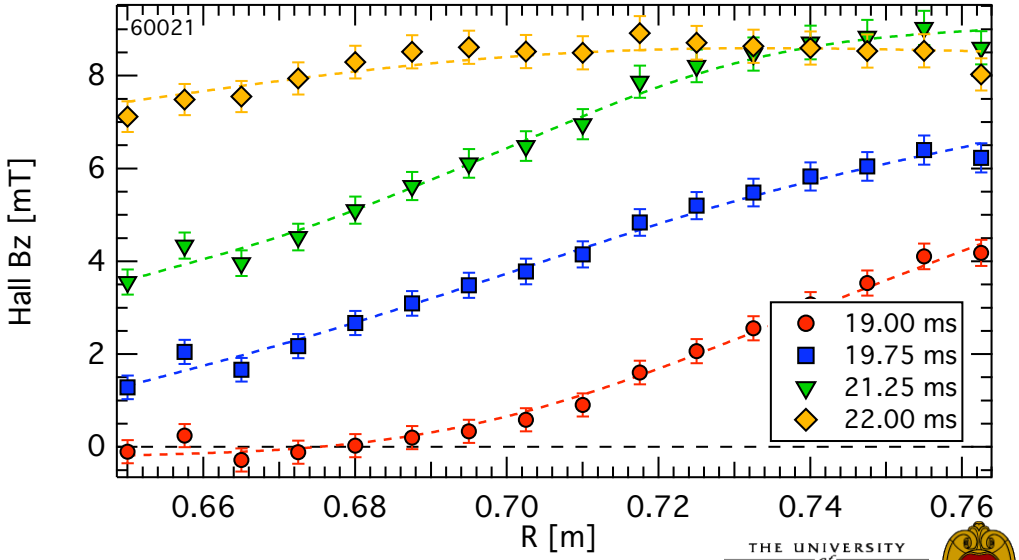
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Direct Measurements Show Current Profile Evolution in Typical PEGASUS LHI Discharge

- Relaxation occurs soon after null formation in initial low-B_z period



- Internal B_z measurements confirm predicted poloidal field null formation



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Local $J_\varphi(R)$ Can Be Calculated From Hall Sensor Array B_z Measurements

- Petty, *et al.** showed that J_φ for a plasma with elliptical cross-section can be calculated from on-midplane B_z measurements:

$$\mu_0 J_\varphi = -\left(\frac{B_Z}{\kappa^2 (R - R_0)} + \frac{\partial B_Z}{\partial R} \right)$$

*Petty, C. C., *et al.*, Nuclear Fusion, 42, 1124, 2002

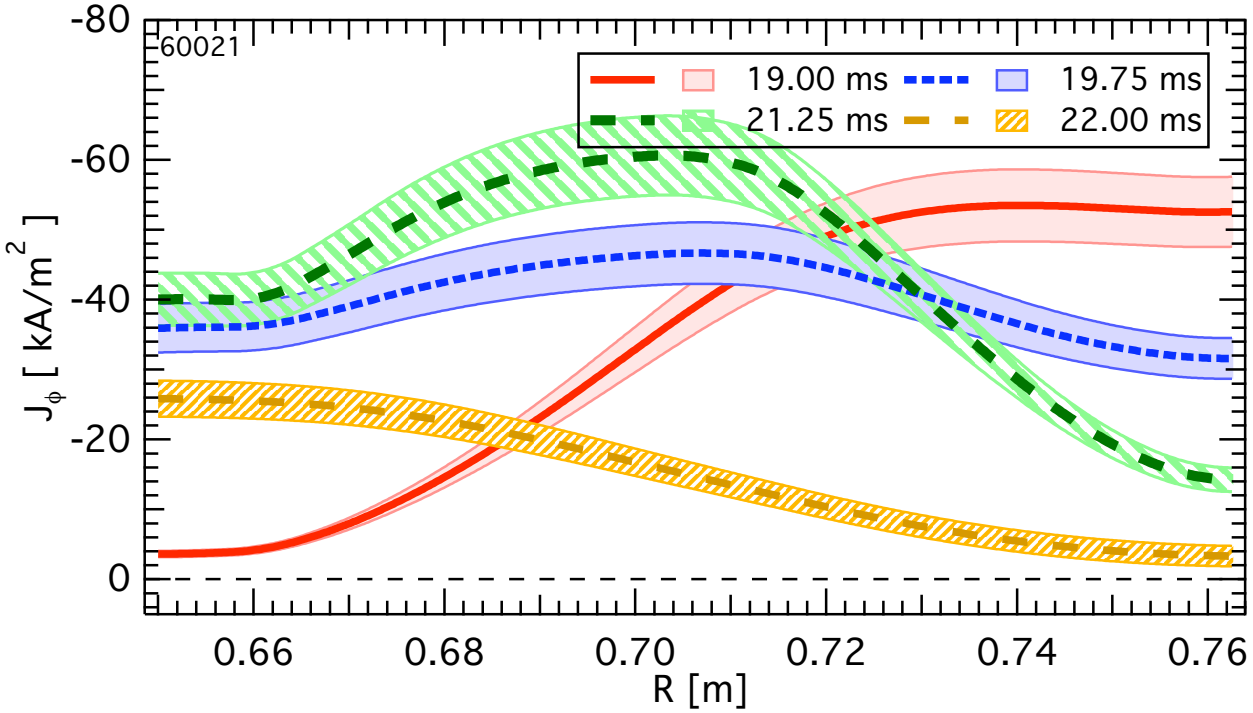
- Assumes a Grad-Shafranov equilibrium
  - Note that this is an estimate, and during helicity injection this is not assured

- Assuming typical PEGASUS shaping parameters (κ=1.75, R_0=0.4), J_φ over the Hall sensor array can be estimated
  - Note that R_0 and κ are changing with time

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Measured $J_\phi(R,t)$ Evolution Must Be Matched by Integrated Simulations of LHI Plasmas

- $J_\varphi(R)$ calculation shows current buildup in plasma interior:
  - Initially, current is concentrated in the edge region (**red**)
  - Current simultaneously builds in the plasma core while dropping in the edge (**red** to **blue** to **green**)
  - Finally, $J_\varphi(R)$ becomes peaked in the plasma core after detaching from the injectors (**yellow**)



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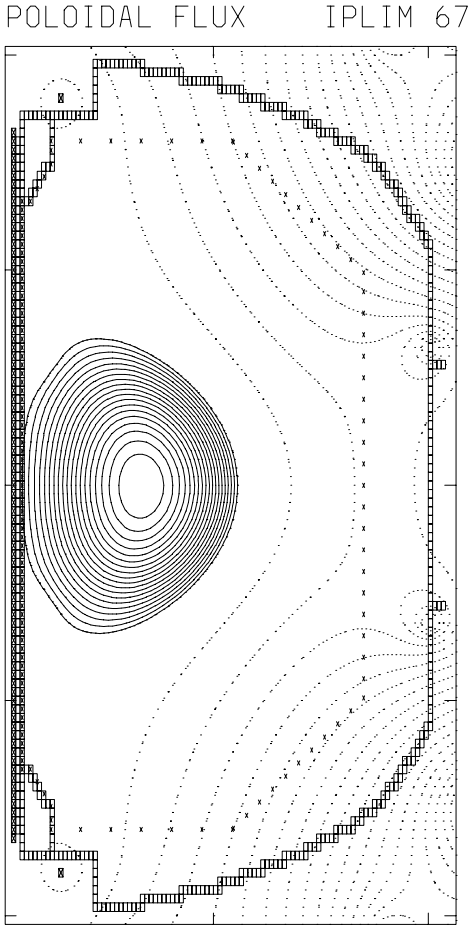
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Validated Integrated Modeling of LHI Needed for Extrapolation to High I_p

- High-I_p startup may be physically distinct operating regime
  - LHI current drive dominates over inductive effects
- 0D modeling neglects possibly important physical effects:
  - Transport and confinement, and profile effects
  - Machine response (due to passive current-carrying elements)
  - Self-consistent plasma shape evolution
  - Self-consistent calculation of V_{inj} from I_{inj} and other parameters
- Integrated modeling will be a key tool for defining high-I_p startup scenarios on NSTX-U and other devices
  - Dependence of startup performance on injector location
  - Define power supply parameters: I_{inj}, V_{inj}, and stored energy

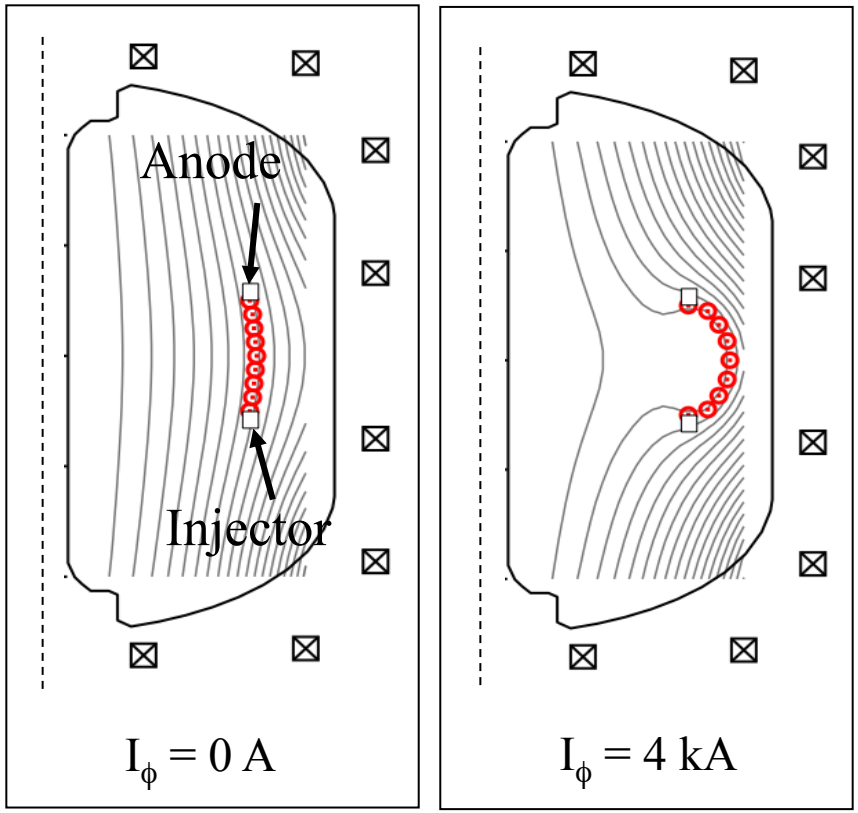
Integrated Modeling of PEGASUS LHI Using Tokamak Simulation Code (TSC)

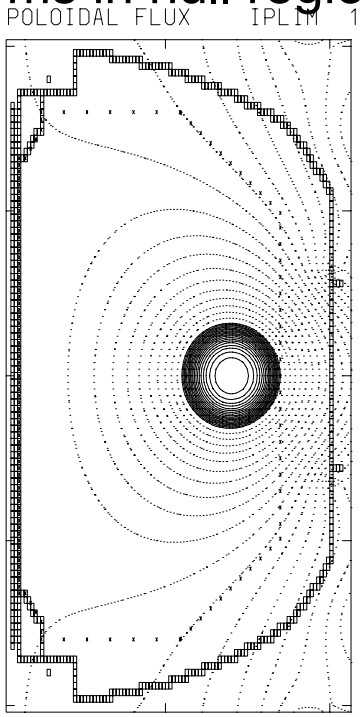
- TSC calculates plasma evolution self-consistently, given:
  - Device definition (coils, passive elements)
  - Coil currents and other drive
  - Transport/confinement model, including sources
- Validation of TSC PEGASUS simulations via modeling of Ohmic discharges
  - Poloidal flux contours for TSC simulation of PEGASUS #54305 shown at right
  - Also via simplified modeling of some LHI cases



Initial Equilibrium for LHI Simulation Mimics Previous Poloidal Null Formation Result

- Sufficient toroidal current in LHI-driven streams will distort the vacuum field, forming a poloidal null region
- Hypothesize that axisymmetric equilibrium forms in null region





Equilibrium with $I_p = 15$ kA

2-D force free current model

*D. J. Battaglia, et al., Nucl. Fusion, 51, 073029, 2011

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Simulation of PEGASUS LHI Discharges is Progressing

- Previous experimental work implies that LHI current drive is equivalent to a simple toroidal surface voltage
  - $V_{eff} = V_{inj}\ A_{inj}/A_{plas}$
- NIMROD simulations imply current drive via reconnection
  - Model many reconnection events via time-averaging
- Also need validated model for injector impedance
- Predictions of LHI current drive models validated against
  - I_p evolution and V_{inj} evolution in typical LHI discharges
  - $J_\phi(R,t)$ evolution for case(s) with internal probing
  - $T_i(R,t)$ evolution for case(s) with ion spectroscopy

Summary

- Non-solenoidal startup using LHI is a technique that may scale to high-I_p startup in PEGASUS and NSTX-U
- LHI-driven discharges are characterized by bursty MHD:
  - Bursts of n=1 activity, apparently a line-tied kink mode
  - Bursts correlate with rapid equilibrium changes, including I_p jumps
- NIMROD resistive-MHD simulations qualitatively agree with experimental results, and imply that LHI current drive mechanism is reconnection during MHD bursts
- Integrated modeling of PEGASUS discharges underway
  - Working toward proper physical model for LHI current drive
  - Model predictions will be validated against PEGASUS database
  - Extrapolate to high-I_p startup in both PEGASUS and NSTX-U