MHD During Relaxation and Growth of DC Helicity Injection Plasmas on PEGASUS

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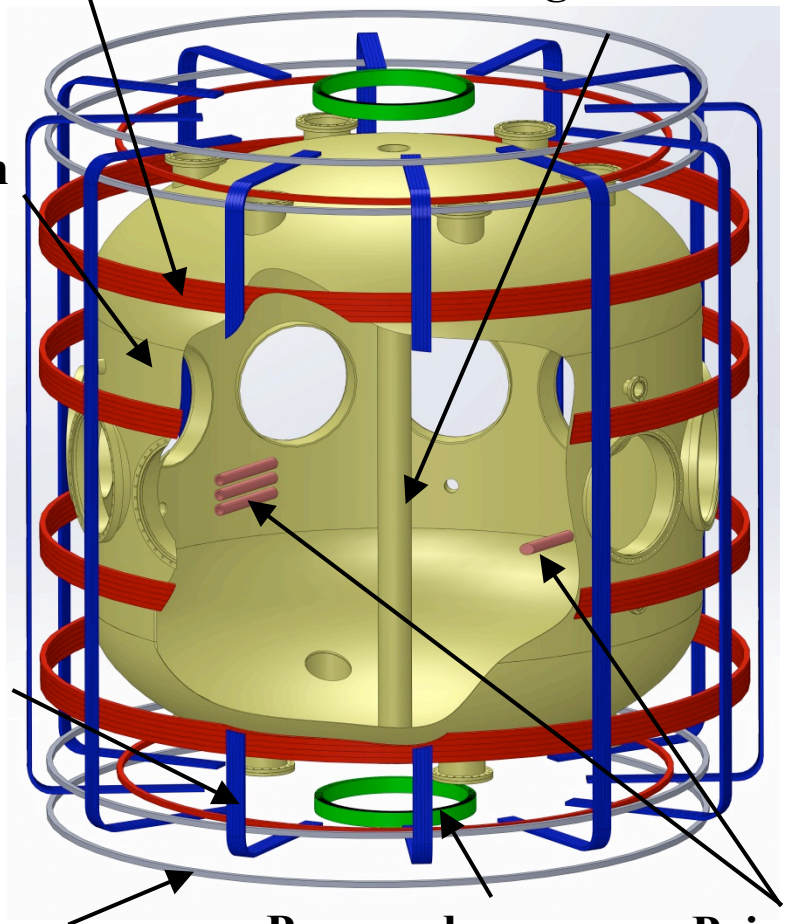
PEGASUS Toroidal Experiment

PEGASUS DC HI MHD Outline

- PEGASUS' DC helicity injection (HI) plasmas exhibit bursts of n=1 MHD while HI drive is applied
  - Additional n=0 oscillations have been identified and could be related to plasma formation or results of n=1 burst side-effects on the plasma
- The n=1 mode structure is peaked in the edge of the plasma near to the DC HI injector radii
  - Bursts exhibit toroidal asymmetries dependent on HI injector geometry suggestive of line-tying at the injector end
- Internal B_z measurements confirm the formation of a null prior to relaxation to a tokamak-like state, and support aspects of the PEGASUS HI plasma evolution model

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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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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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Taylor Relaxation Criteria Sets the Maximum I_p for a Given Magnetic Geometry

Helicity balance in a tokamak geometry:

$$\frac{dK}{dt} = -2\int_V \eta \mathbf{J}\cdot\mathbf{B}\, d^3x - 2\frac{\partial\psi}{\partial t}\Psi - 2\int_A \Phi\mathbf{B}\cdot d\mathbf{s} \quad \Rightarrow \quad I_p \le \frac{A_p}{2\pi R_0\langle\eta\rangle}\left(V_{ind} + V_{eff}\right)$$

- *Helicity injection can be expressed as an effective loop voltage*
- I_p limit depends on the scaling of plasma confinement via the η term

$$V_{eff} \approx \frac{A_{inj}B_{\phi,inj}}{\Psi_T}V_{bias}$$

Taylor relaxation of a force-free equilibrium:

$$\nabla\times B = \mu_0 J = \lambda B$$

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

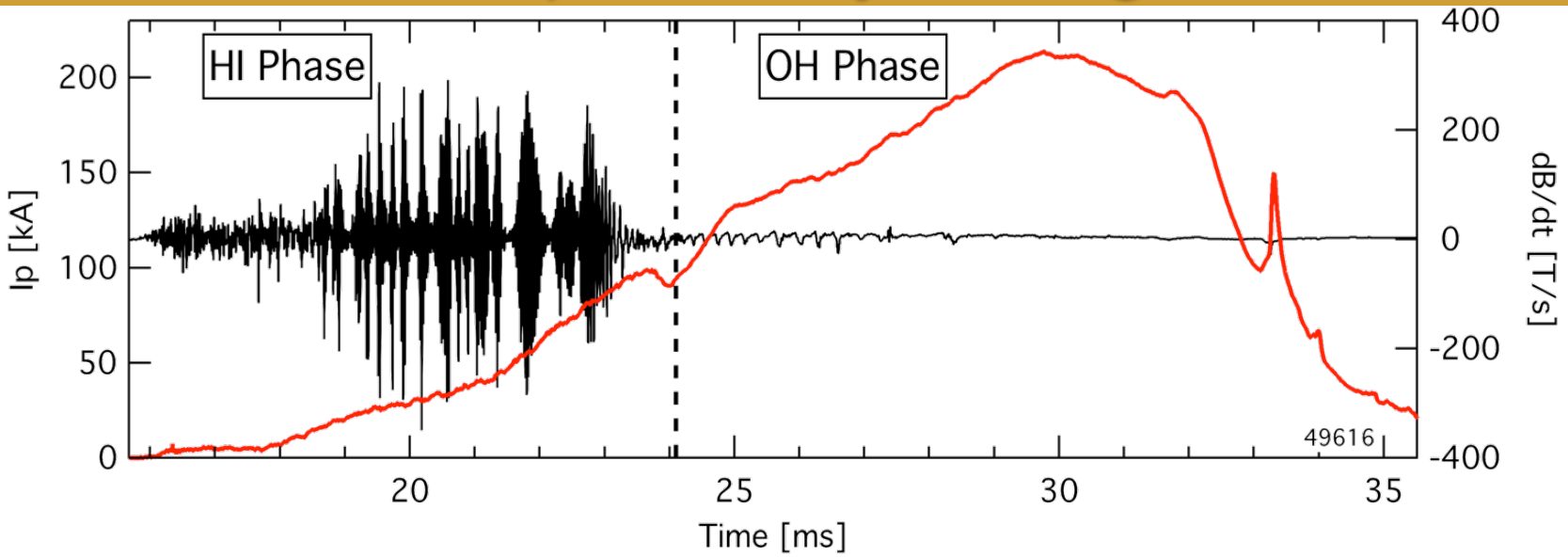
Assumptions:

- Driven edge current mixes uniformly in SOL
- Fields average to tokamak-like structure

A_p Plasma area
C_p Plasma circumference
Ψ_T Plasma toroidal flux
w Edge current channel width

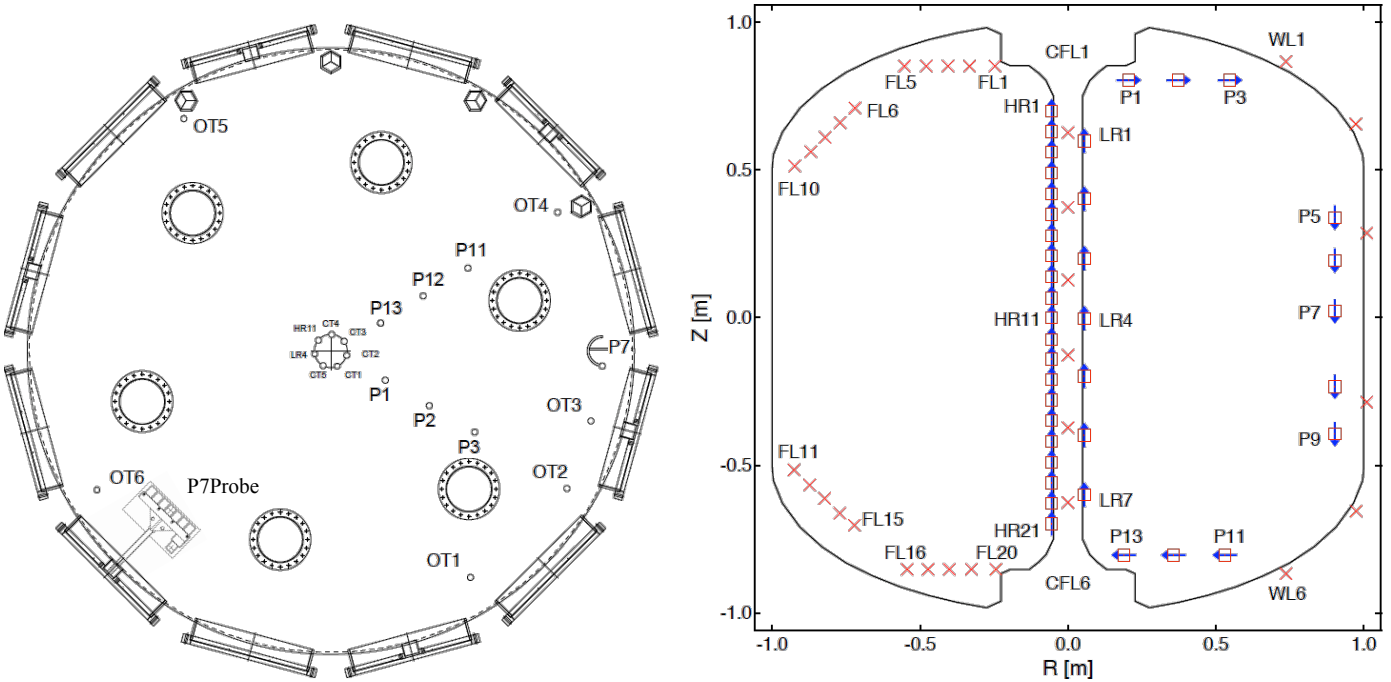
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HI is an Alternative to OH Induction and is Accompanied by Strong MHD



- HI offers an alternative to OH induction for plasma startup
  - HI on PEGASUS has produced plasmas with $I_p \leq 0.17$ MA consistent with Taylor relaxation
- HI on PEGASUS is accompanied by strong MHD activity
- To understand and implement more effective HI current drive, we are motivated to better understand:
  - Relaxation dynamics and the requirements for relaxation
  - The role of the observed magnetic activity in current drive

PEGASUS External Magnetics



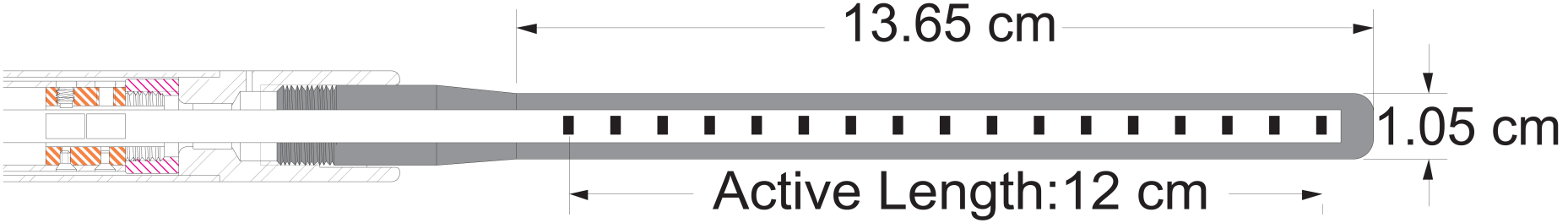
(a) Toroidal Mirnovs

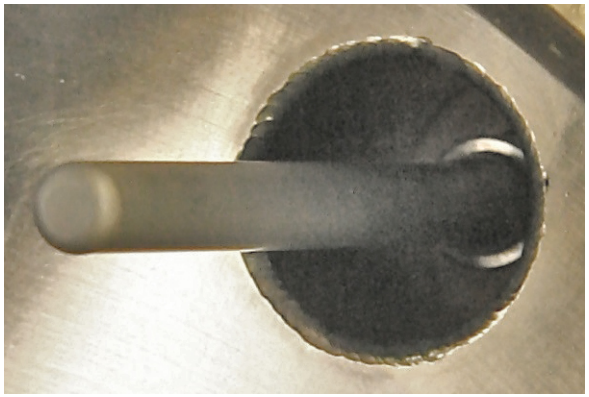
(b) Poloidal Mirnovs and flux loops

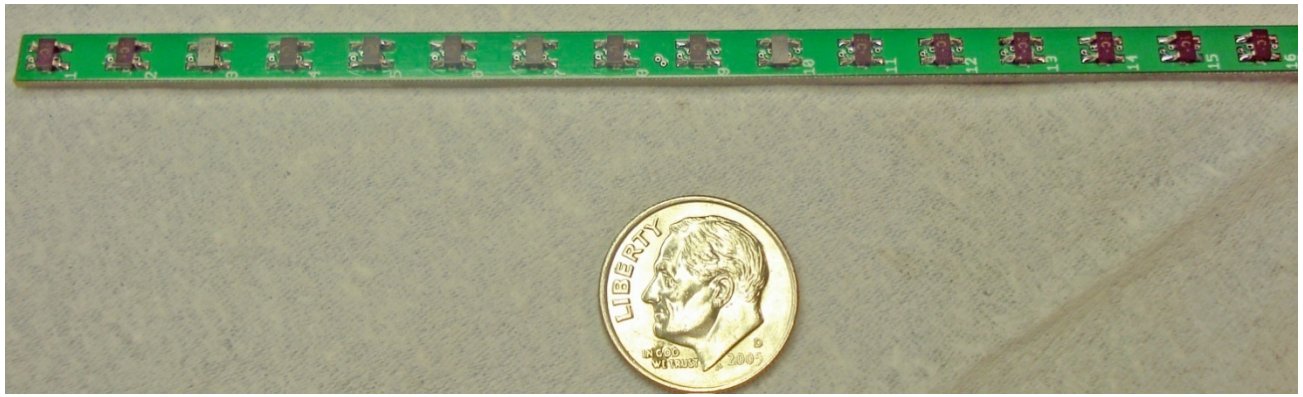
- PEGASUS has an extensive magnetic diagnostics set including:
  - Arrays of toroidal (11) and poloidal (43) Mirnov Coils
  - Insertable toroidal Mirnov Coil probe array
  - Insertable radial Hall sensor probe array

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PEGASUS Hall Probe Deployed to Investigate MHD Spatial Variation







- Solid-state InSb Hall Effect sensors
  - Sypris model SH-410
  - Weak variance with T_{sensor} and $B_{||}$ are correctable with calibration
- 16 channels, 7.5 mm radial resolution
- Slim C armor as low-Z PFC
  - Minimizes plasma perturbation
- 25 kHz bandwidth
- Innermost sensor R > 50.8cm
- Used to diagnose both PEGASUS OH and HI plasmas

*See M.W.Bongard, et al., Rev. Sci. Instrum. 81. 10E105, 2010

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Local $J_\varphi(R)$ Can Be Estimated 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

Mode Structure

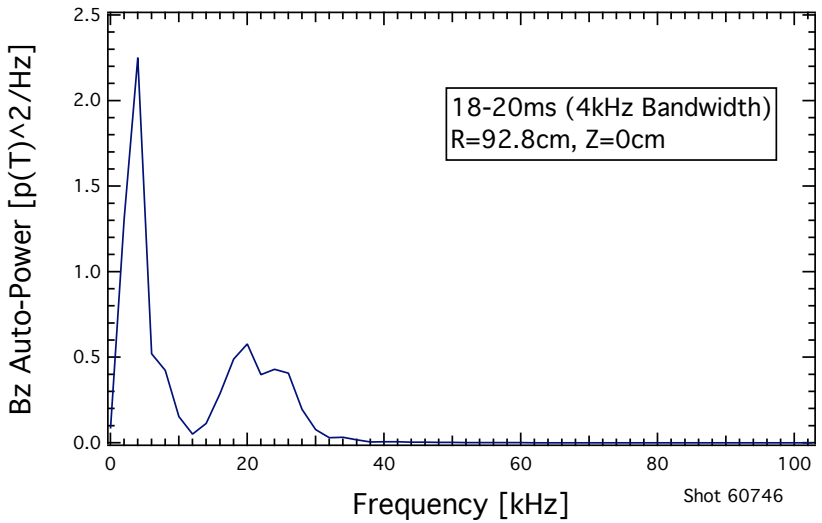


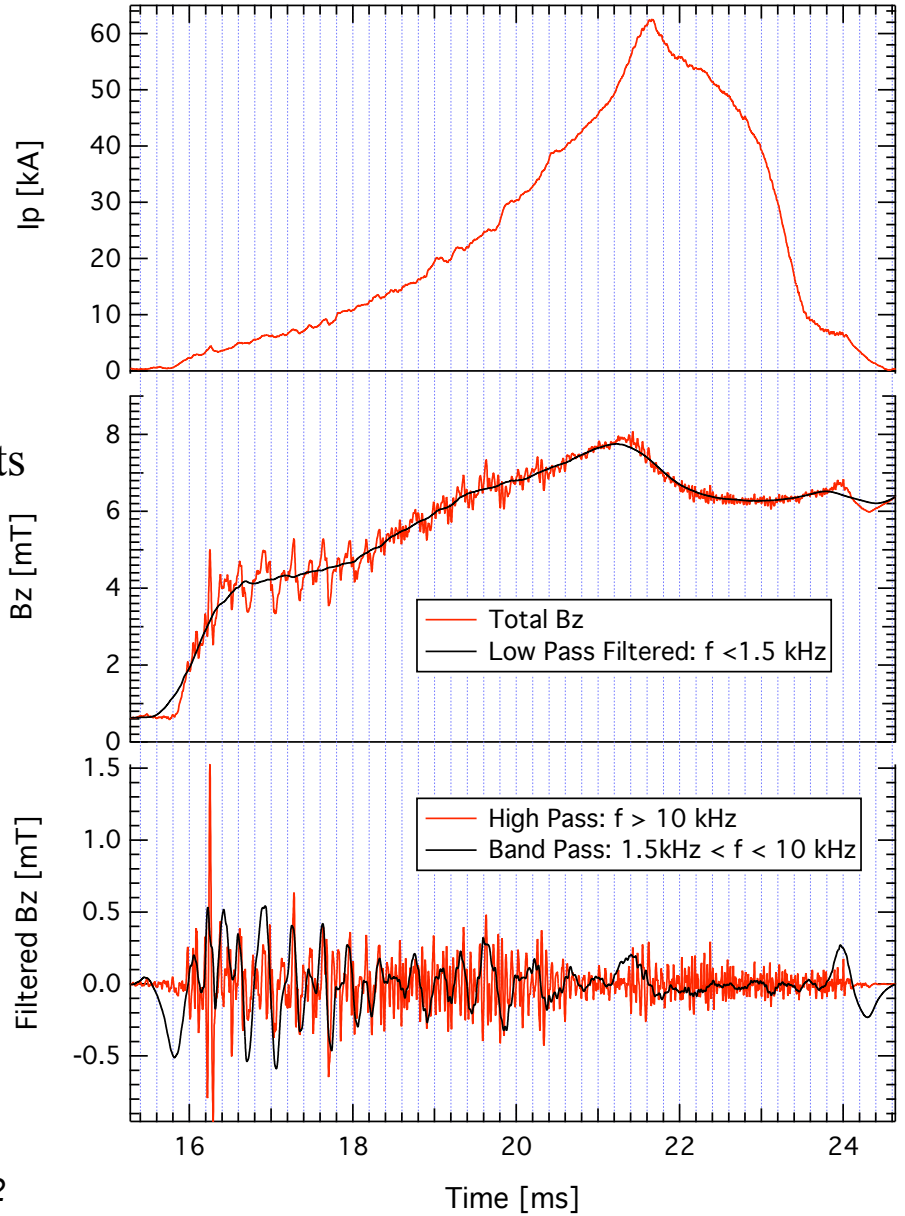
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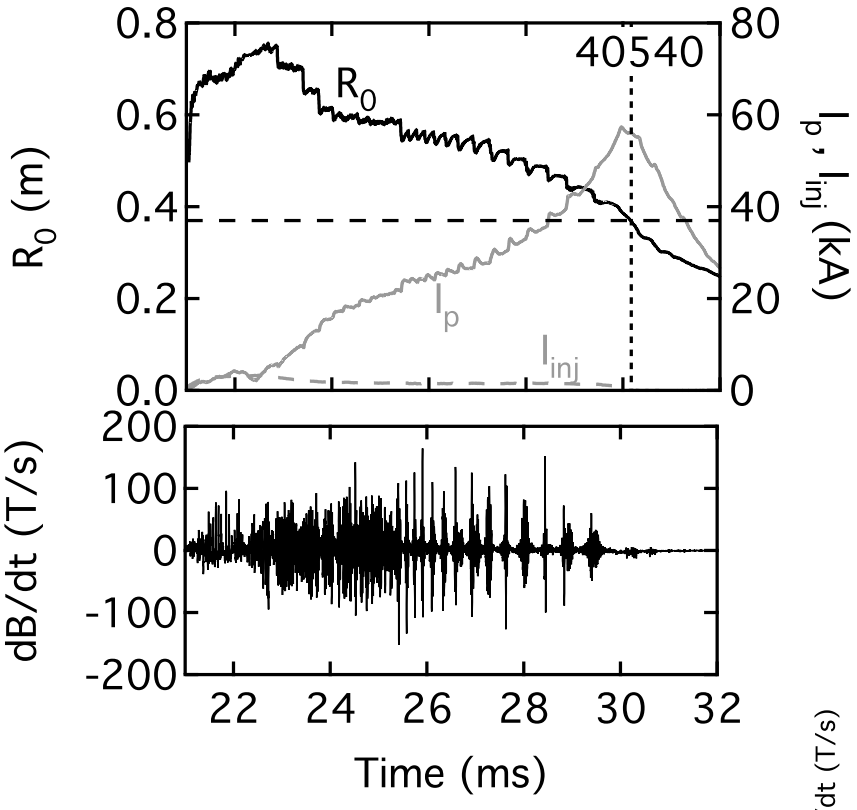
PEGASUS Plasmas Exhibit Two Fluctuating B_{pol} Components

- The slowest varying B_{pol} fields are applied B_z and bulk plasma B_{pol}
- Poloidal field measurements show 2 fluctuating components:
  - Bursty activity:
    - 20-80 kHz
    - $\delta b/B_t \sim 0.2 - 3\%$
  - Lower frequency activity, coincide with bursts
    - 2-10 kHz
    - $\delta b/B_t \sim 0.1 - 1\%$



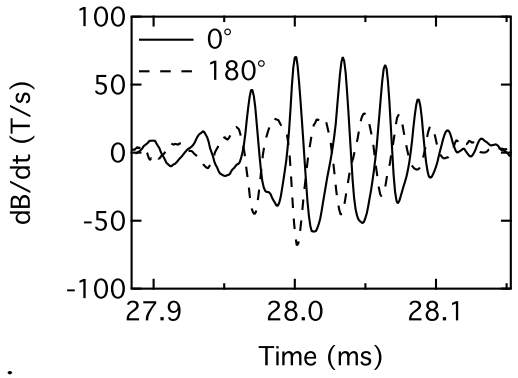


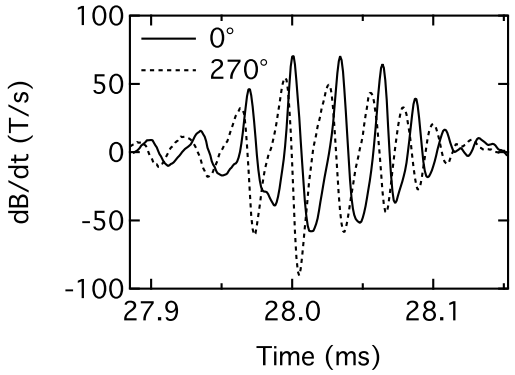
PEGASUS HI Bursty MHD is n=1



Previous study by D. Battaglia* has shown:

- Bursts correspond with:
  - Jumps in I_p
  - Abrupt inward motion of R_0
  - Drop in l_i
- Typical frequencies: 20kHz < f < 80kHz
- Typically n=1



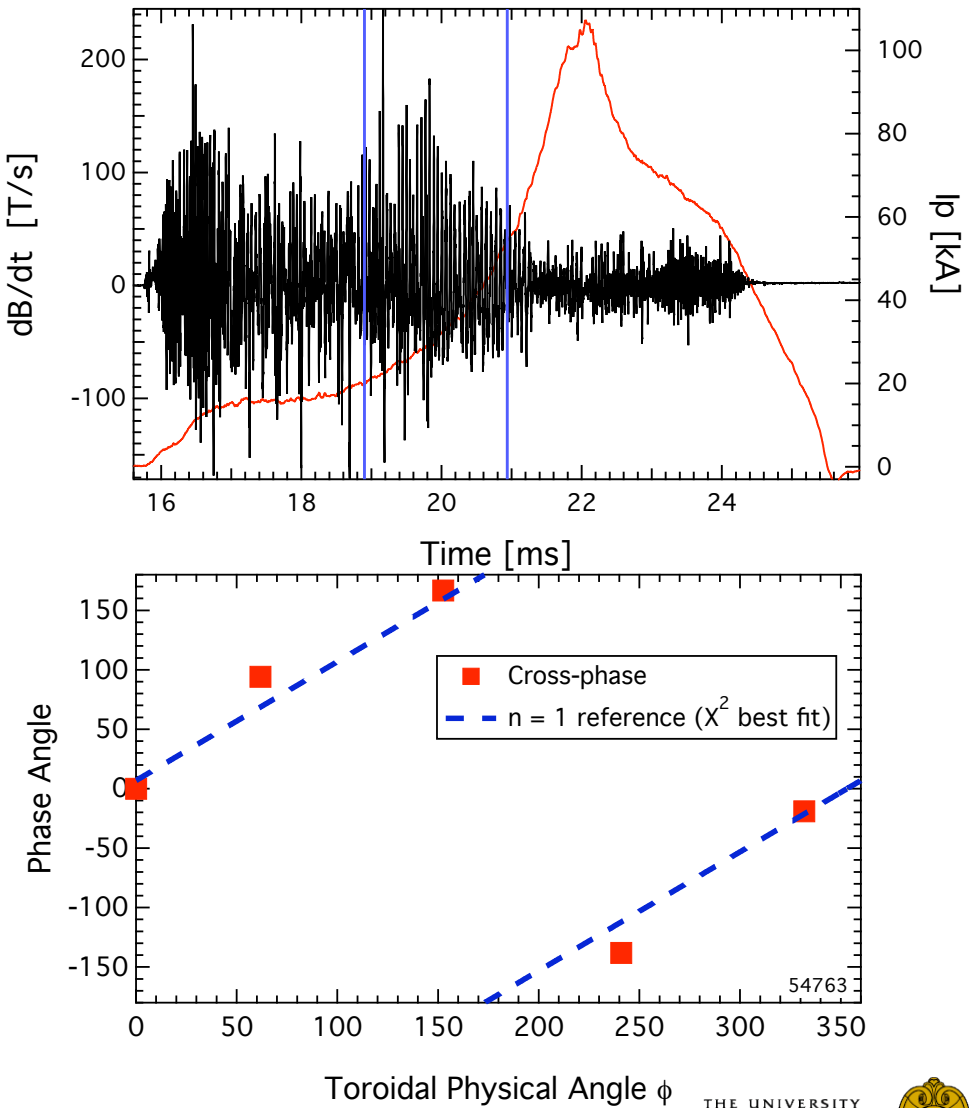


*Figures and analysis from D. Battaglia thesis:
D. Battaglia, *Non-solenoidal startup using localized current sources near the outboard mid-plane*, UW-Madison NEEP (2009)

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PEGASUS HI Continuous MHD is Also n=1

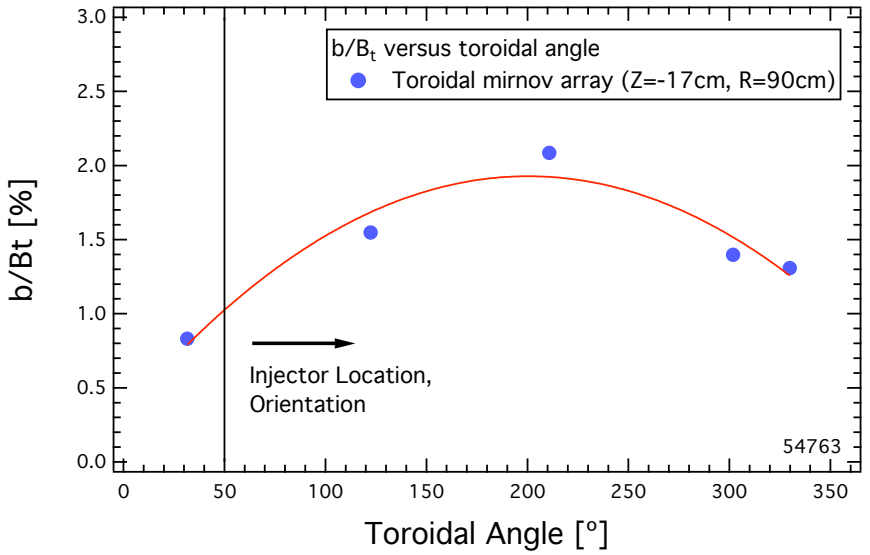
- Continuous type MHD is also observed in HI PEGASUS discharges
  - Likely a series of many bursts, or similar phenomenon
- Typical frequencies:
  10kHz < f < 50kHz
- Typically n=1

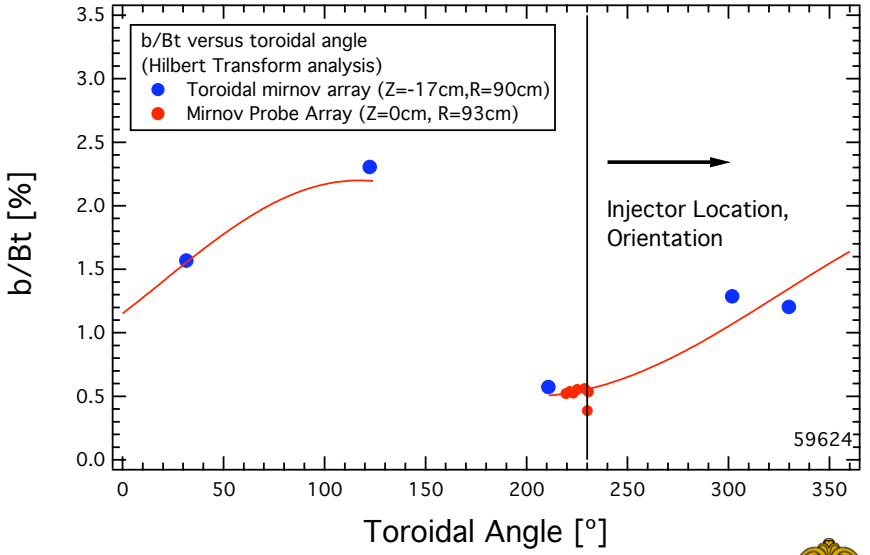


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n=1 Mode Amplitude is Toroidally Asymmetric

- The n=1 mode amplitude is toroidally asymmetric
  - Smallest near the injector face (cathode)
- n=1 toroidal asymmetry follows changes to injector toroidal location
- This structure is suggestive of a line-tied kink mode with one end moving*
  - Line-tying at the injector face with the other end free or moving





*See:

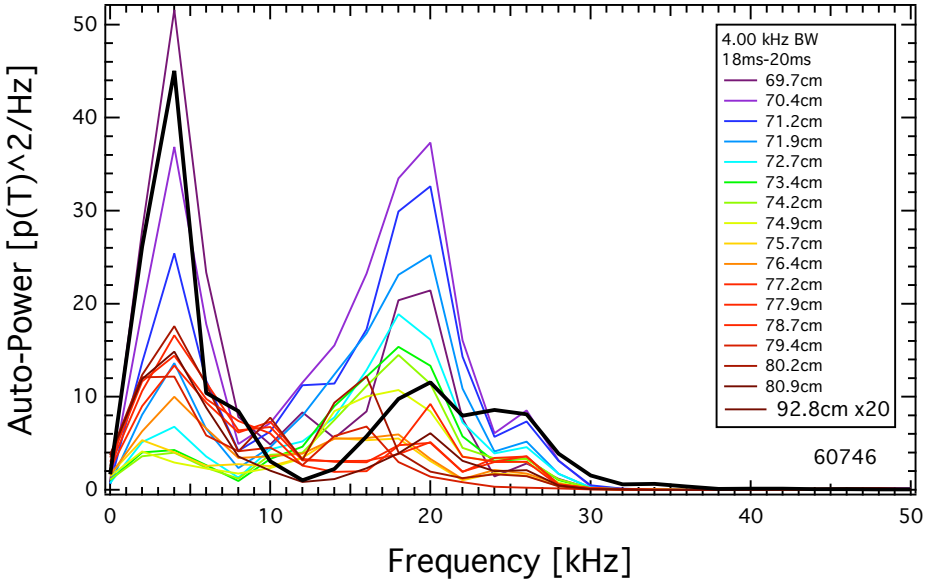
D. D. Ryutuv *et al.*, Phys. Plasmas **13**, 032105 (2006)

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

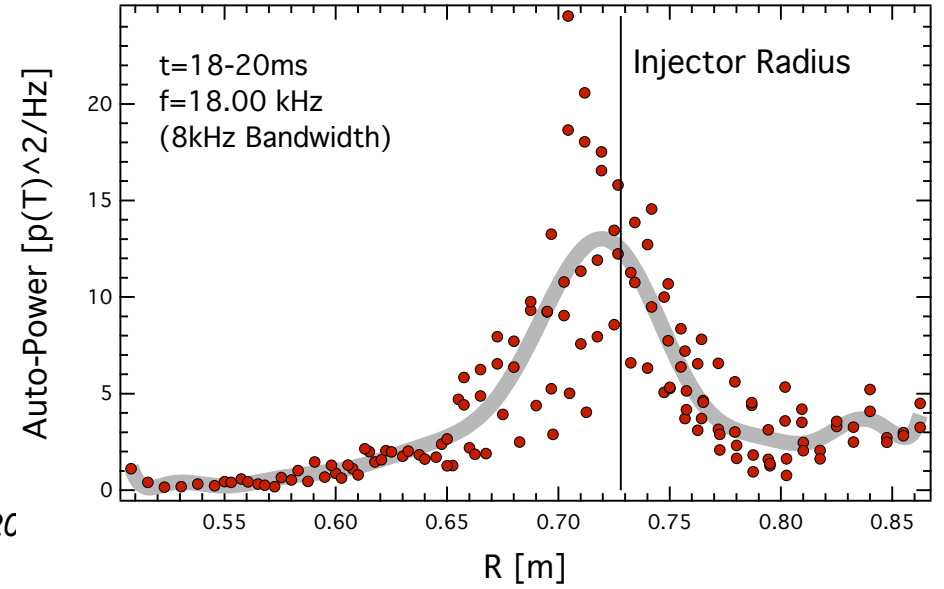
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n=1 MHD Activity is Localized Near the Injector Radius

- Local B_z measurements show radial localization of bursty n=1 mode



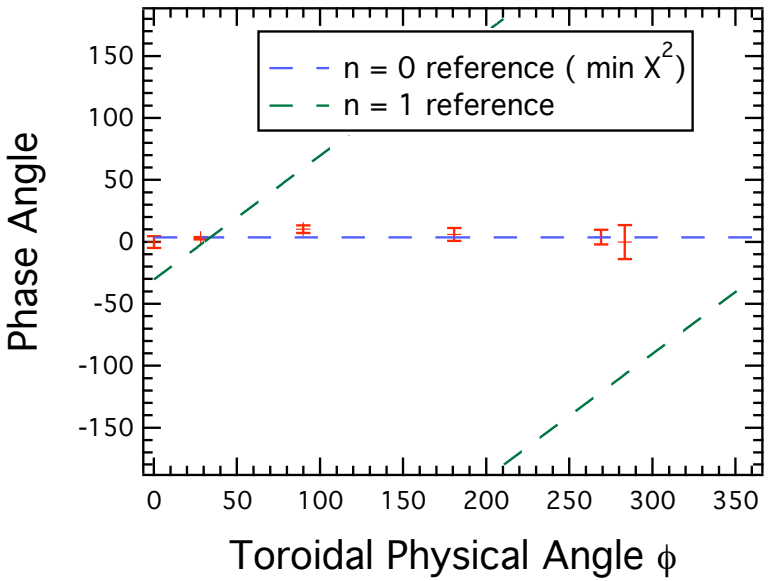
- The n=1 mode is localized near the injector radius

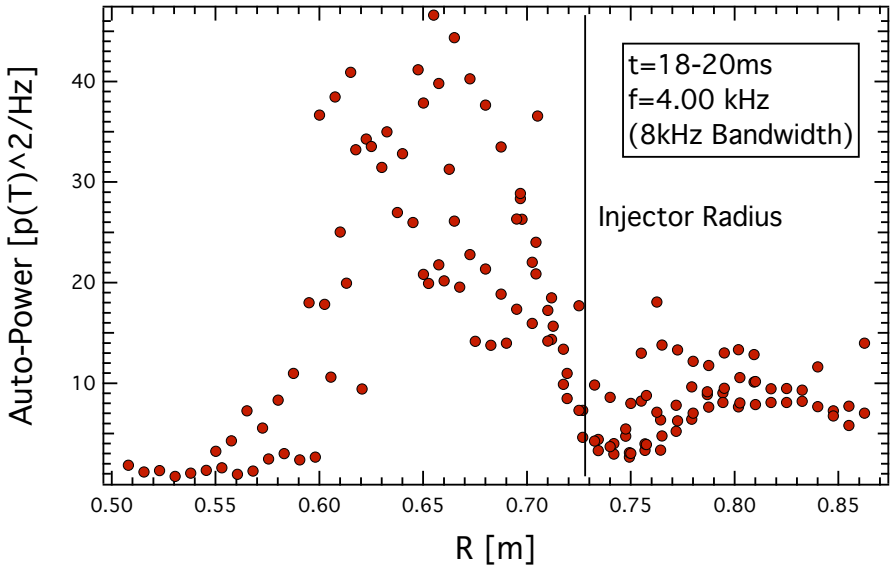


PEGASUS Lower Frequency Magnetic Activity is n=0

- Slower 2-10 kHz magnetic fluctuations are n=0, and strongest in the plasma interior

- Possible or likely causes:
  - Expected inward expansion (strongest in early relaxation phase)
  - Known radial plasma motion, current profile changes caused by n=1 bursts

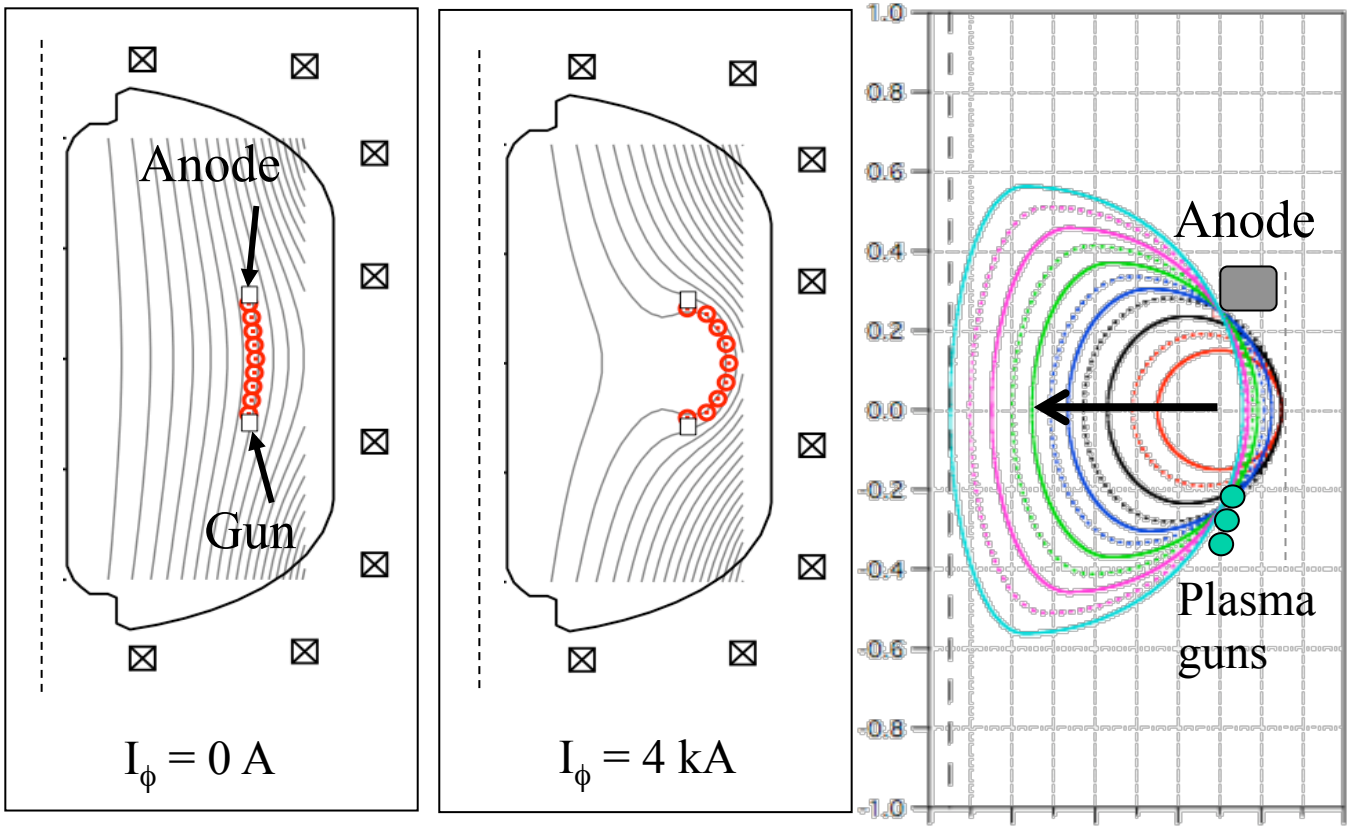




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Internal Magnetic Measurements Confirm Field Null Creation at Plasma Formation

- Previous work* has shown that sufficient current supplied from the helicity injectors is expected to perturb the local magnetic field to create a field null, which is required for relaxation to a tokamak-like state



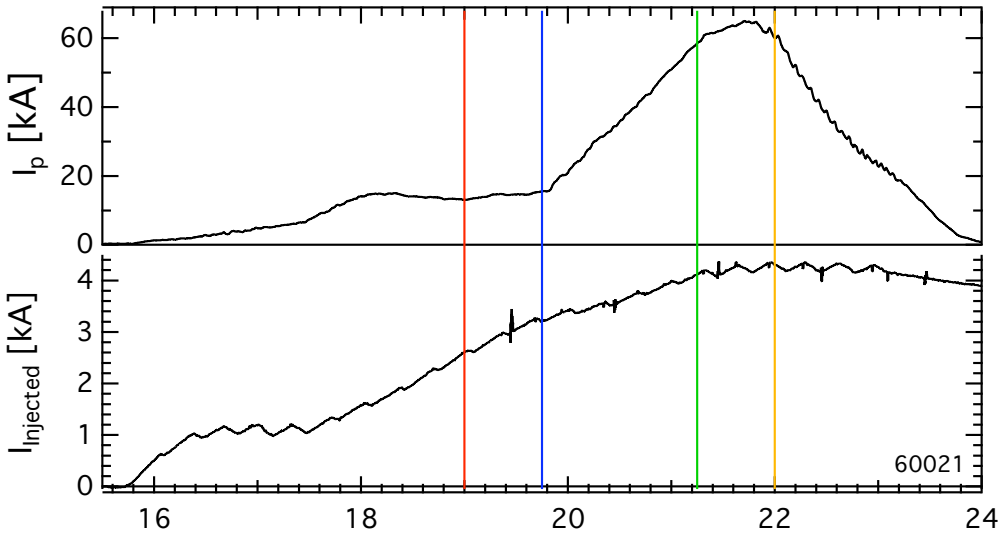
2-D force free current model

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

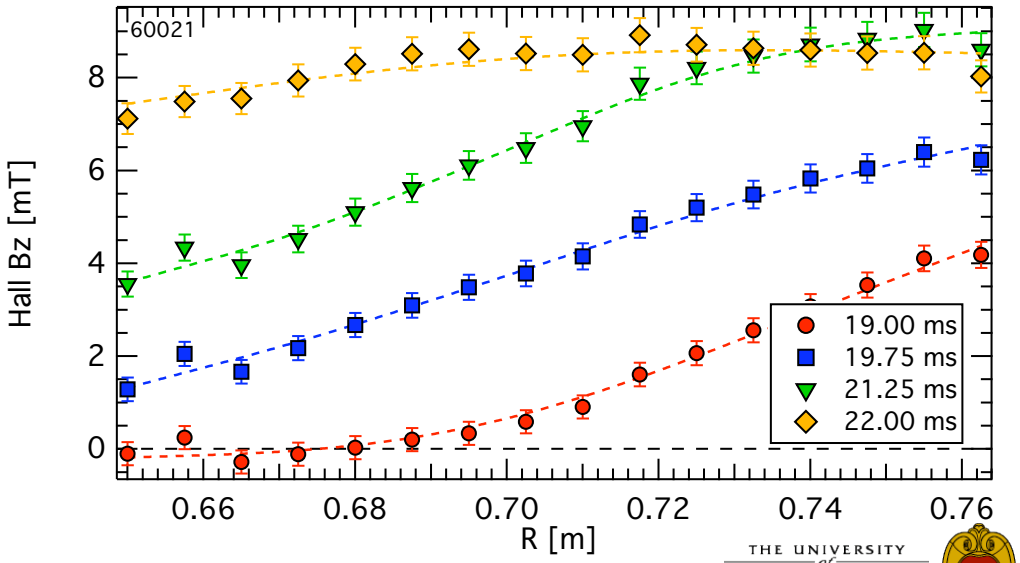
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Representative Discharge Probed to Study Relaxation

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



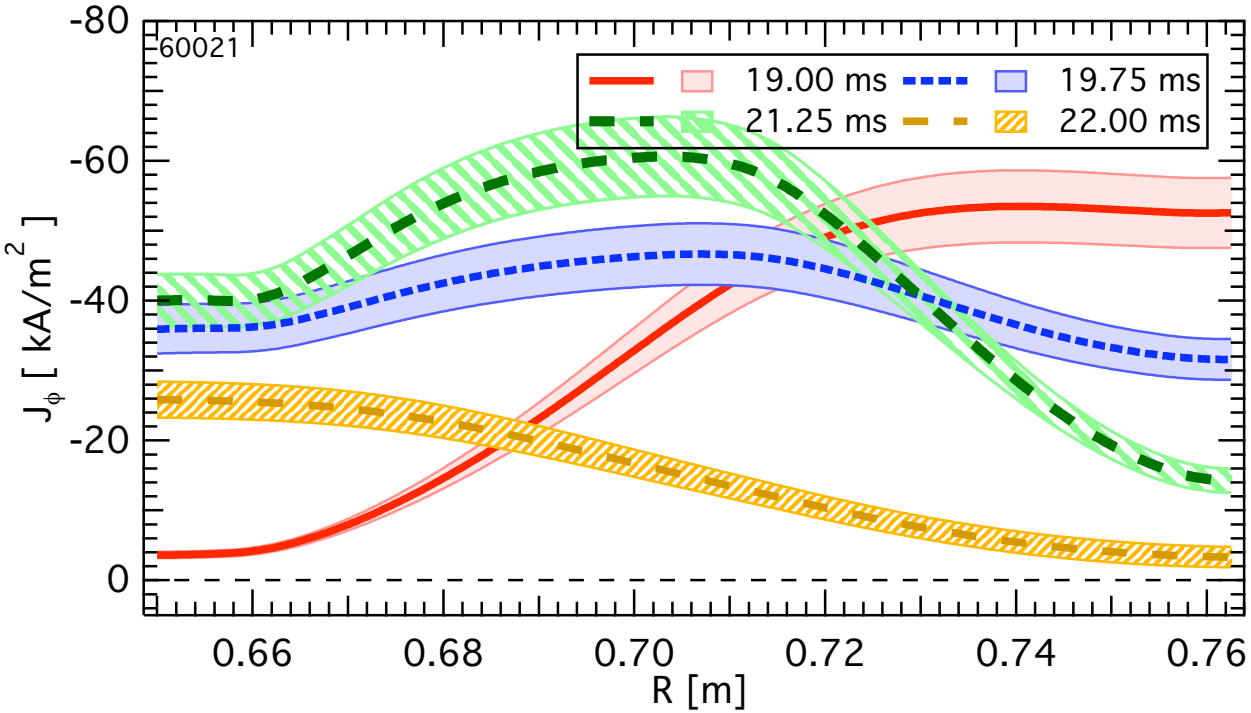
- Internal B_z measurements confirm predicted poloidal field null formation



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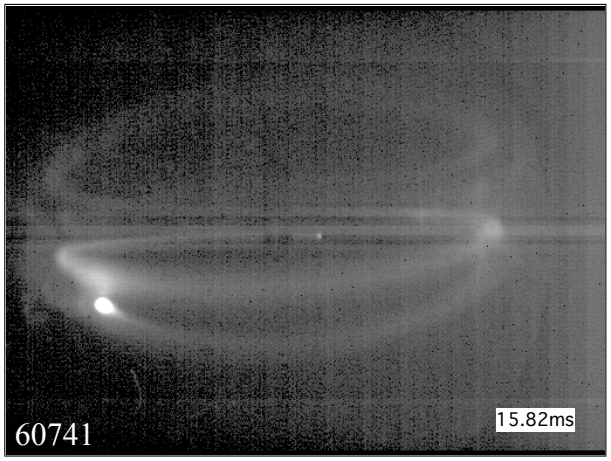
Internal $B_z(R)$ Measurements Allow for Calculation of Current Profile Evolution

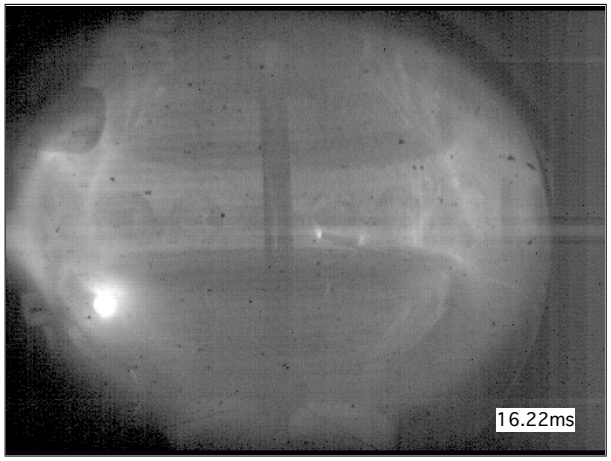
- $J_\varphi(R)$ calculation shows current build in plasma interior:
  - Initially, current is concentrated in the edge region (**red**)
  - Current simultaneously builds in the plasma core while dropping in the edge (**red** to **blue** to **green**)
  - Finally, $J_\varphi(R)$ becomes peaks in the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



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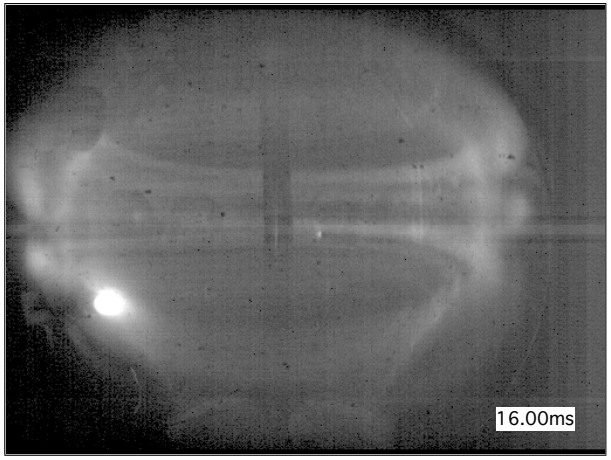
Fast Imaging Illustrates Plasma Evolution

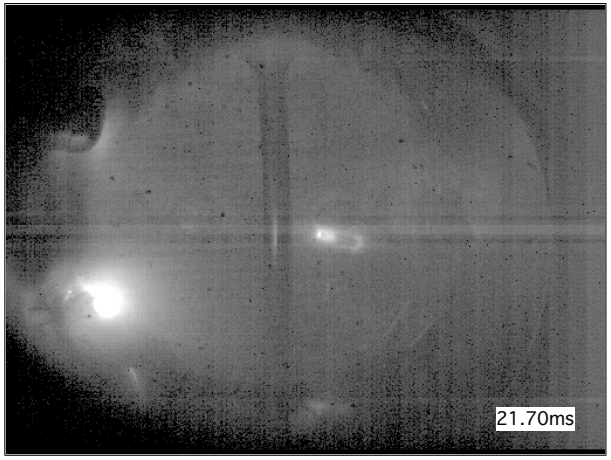






Tokamak-like state is formed, detaches from injectors





Current streams combine into diffusive current layer

Field null is formed and current builds in plasma interior

*D-alpha camera imaging with fish-eye lens. See K. E. Thome poster, *Improved density control in the Pegasus Toroidal Experiment using internal fueling*, for information on this diagnostic

n=1 Modes are Common in HI Driven Plasmas

- Continuous n=1 modes are commonly observed in HI-driven toroidal plasmas (STs and Spheromaks)
  - The observed n=1 structure is thought to be a kink mode

See:

A.J. Redd, Phys. Plasmas **14**, 112511 (2007).

B.A. Nelson, T.R. Jarboe, D.J. Orvis, L.A. McCullough, J. Xie, C. Zhang, L. Zhou, Phys. Plasmas, **2**, 2337 (1995).

- Relevant MHD simulations for PEGASUS are underway:
  - See poster:

    J.B. O'Bryan, C.R. Sovinec, "Simulation of current-filament dynamics and relaxation in the Pegasus ST"

Future Work

- Upgrade radial B_z probe diagnostic for faster frequency response to measure and relate J_φ to local MHD fluctuations
  - Movable or multiple diagnostics could provide further detail of n=1 mode structure
  - Details of n=1 mode relation to current drive is still under investigation
- Comparison to numerical simulations
- Considering local MHD and Hall dynamo measurements
  - Faster, localized PEGASUS T_i spectrometer measurements could resolve v-fluctuations for MHD Dynamo measurements
  - Local, fast J_φ fluctuation measurements for Hall Dynamo measurements

Conclusions

- PEGASUS' DC helicity injection plasmas exhibit bursts of n=1 magnetic perturbations while HI drive is applied
  - Mode structure is toroidally asymmetric – suggestive of line-tying on-or-near the injector
  - The n=1 mode is also radially localized near to the injector
- n=0 magnetic fluctuations are also observed during helicity drive on PEGASUS
  - The n=0 fluctuations are largest in the plasma interior, and likely related to plasma inward expansion and/or motion associated with n=1 burst activity
- Internal B_z measurements confirm poloidal null formation prior to relaxation, and corresponding J_φ calculations show buildup of current density into the plasma interior during HI
  - Calculations show tokamak-like, peaked profile after detachment