MHD Evolution in Point-Source Helicity Injection Driven Plasmas on Pegasus

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53rd APS DPP Annual Meeting

November 14-18, 2011

Salt Lake City, Utah



PEGASUS Toroidal Experiment

Abstract

Point-source helicity injection for non-solenoidal startup on Pegasus produces plasmas with $I_p \leq 0.17$ MA consistent with Taylor relaxation. The helicity injection supplies an effective loop voltage V_{eff} inversely proportional to the plasma toroidal flux Ψ_T . Accurate measurement of the V_{eff} evolution requires equilibrium reconstructions. Helicity injection-driven plasmas originate on the outboard, low-field side and expand inward to fill the vessel. This evolution increases Ψ_T , reducing V_{eff} from ≥ 10 V to ≤ 2 V. Supplemental loop voltage from poloidal field induction is used to obtain higher plasma current. I_p growth is accompanied by bursts of $n = 1$ magnetic activity with frequencies between 10–150 kHz, abrupt inward motion of the plasma, and a drop in internal inductance. This magnetic activity persists during helicity injection. Afterward, MHD quiescence is obtained and persists in discharges subsequently sustained by ohmic induction. The spectral content of these magnetic fluctuations measured with a scanning Mirnov probe does not differ significantly with distance from the plasma edge.

Work supported by US DOE Grant DE-FG02-96ER54375.

Pegasus HI Plasma MHD Outline

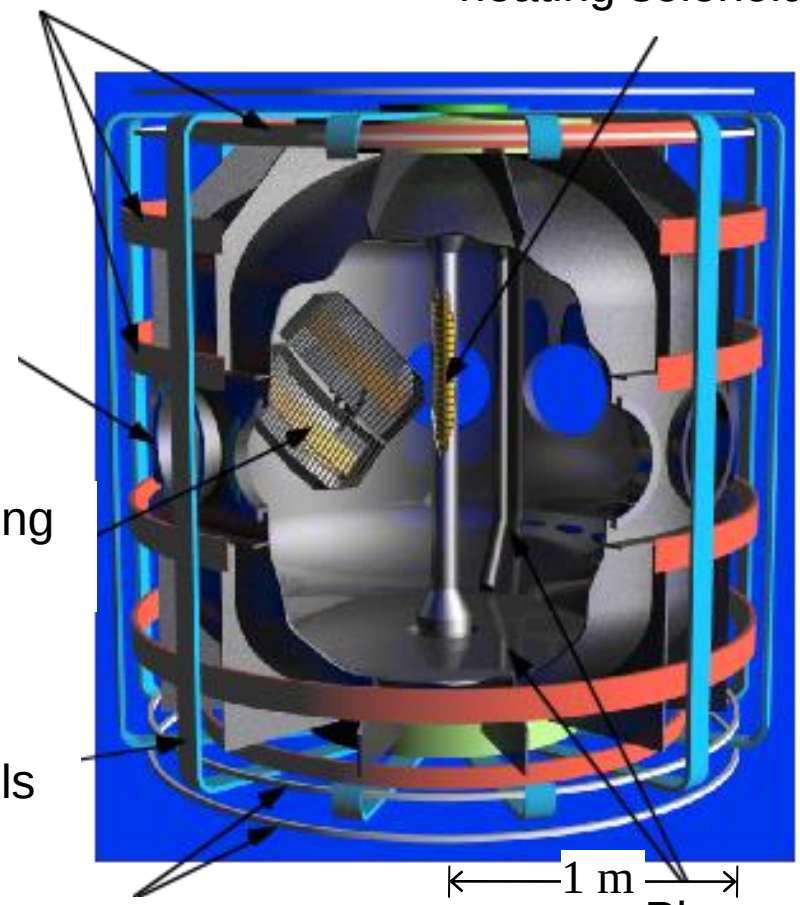
- Magnetic perturbations in PEGASUS Helicity Injection (HI) plasmas are identified by external magnetics as n=1, and continue as long as HI drive is applied

- Internal magnetic measurements indicate that the n=1 mode exists deep in the core of the plasma, and its mode structure is presented

- Internal magnetic measurements have confirmed aspects of the HI plasma formation and evolution model

Work supported by US DOE Grant DE-FG02-96ER54375.

Pegasus is a Compact Ultralow-A ST



Experimental Parameters

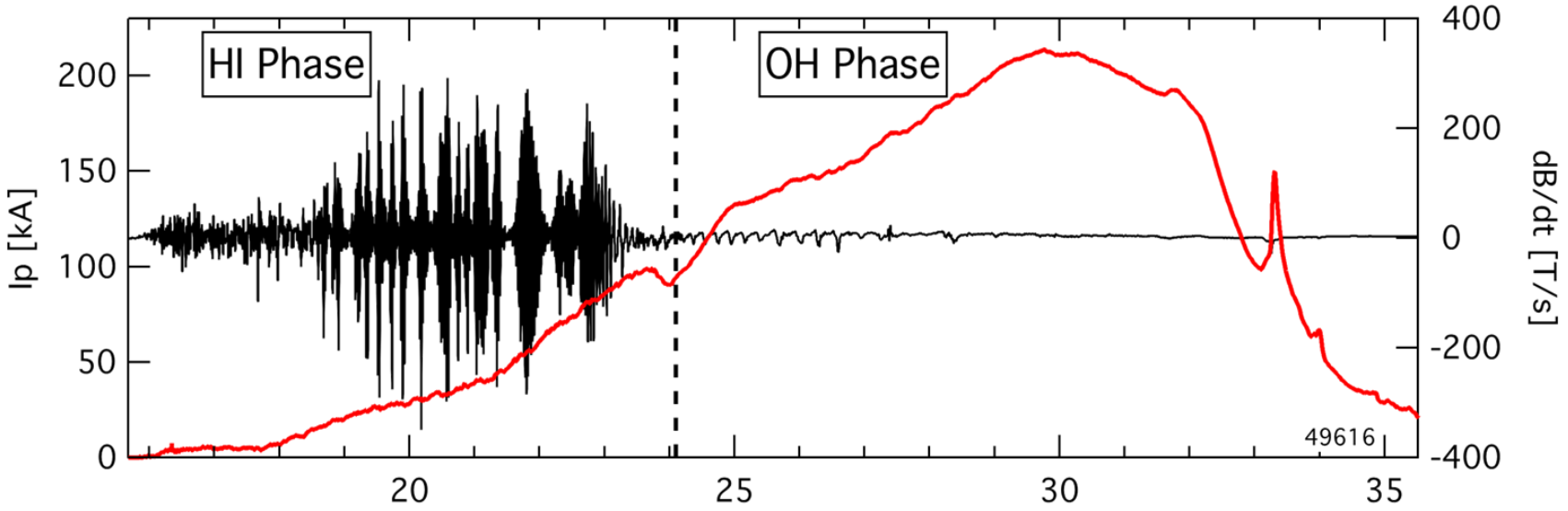
Parameter	To Date
A	1.15 – 1.3
R(m)	0.2 – 0.45
I_p (MA)	≤ .22
I_N (MA/m-T)	6 – 12
l_i	0.2 – 0.5
κ	1.4 – 3.0
τ_{shot} (s)	≤ 0.025
β_t (%)	≤ 25
P_{HHFW} (MW)	0.2



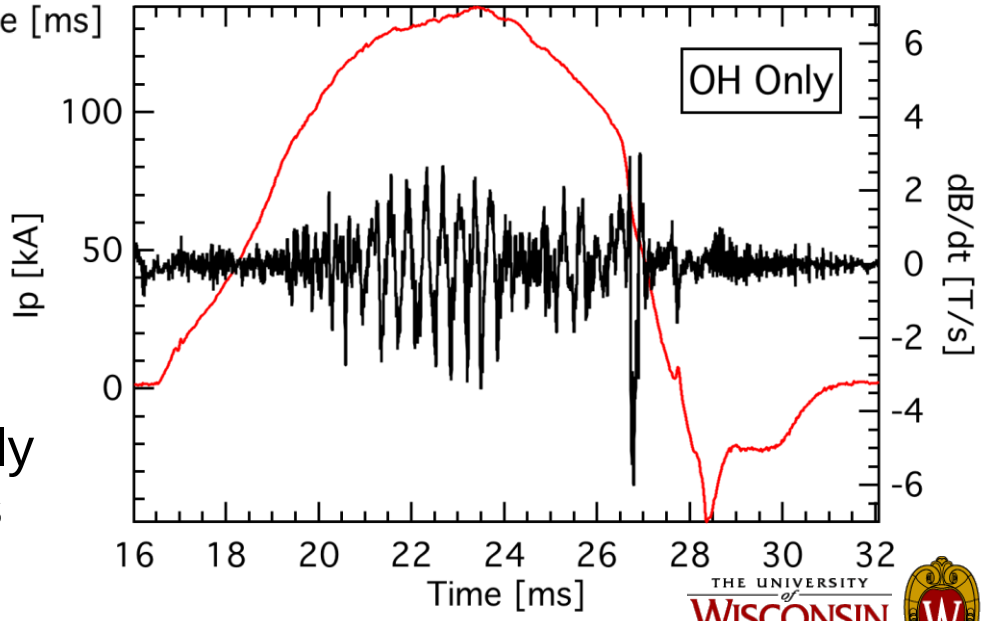
Point-Source DC Helicity Injectors

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



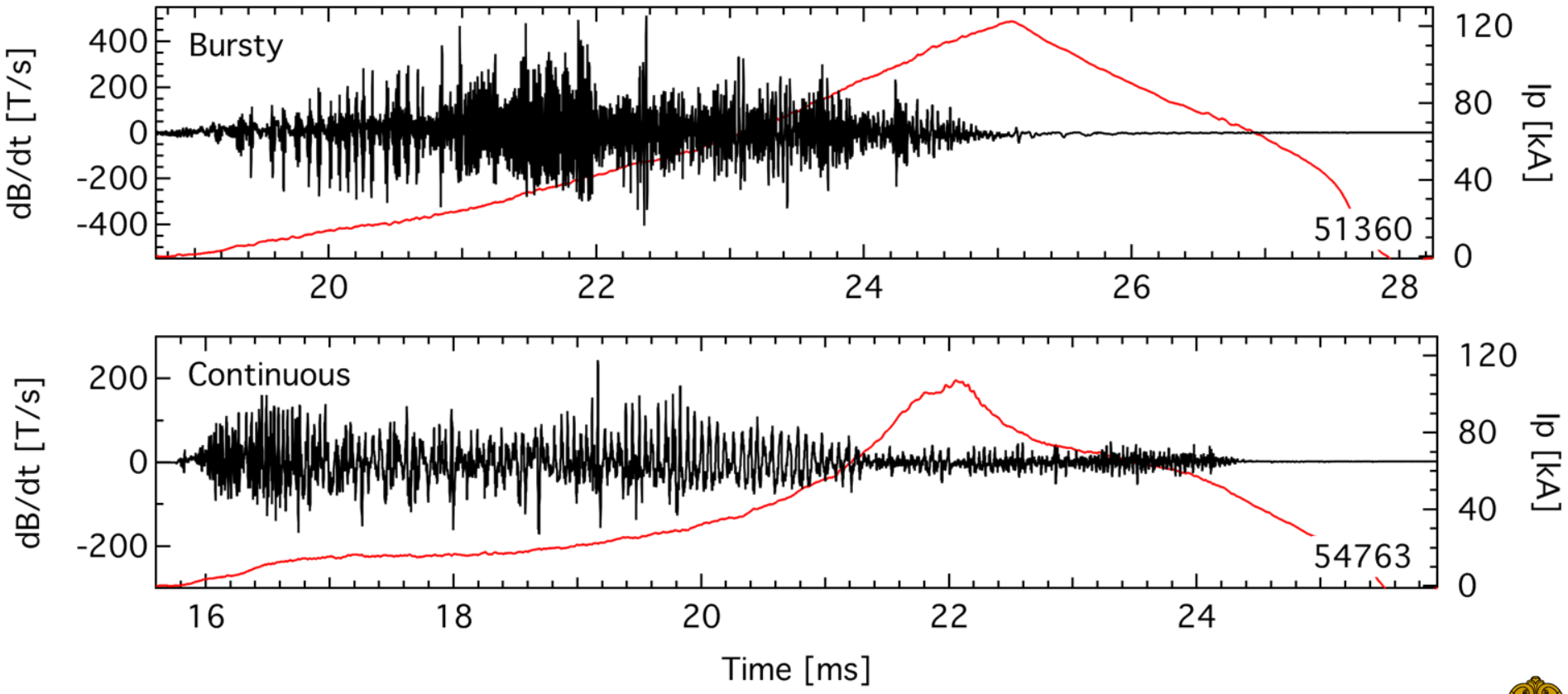
- HI offers an alternative to OH induction for plasma startup
  - HI on Pegasus has produced plasmas with $I_p \leq 0.17$ MA consistent with Taylor relaxation
- HI-to-OH handoff creates plasmas without the low-n MHD that typically limits Pegasus OH driven plasmas



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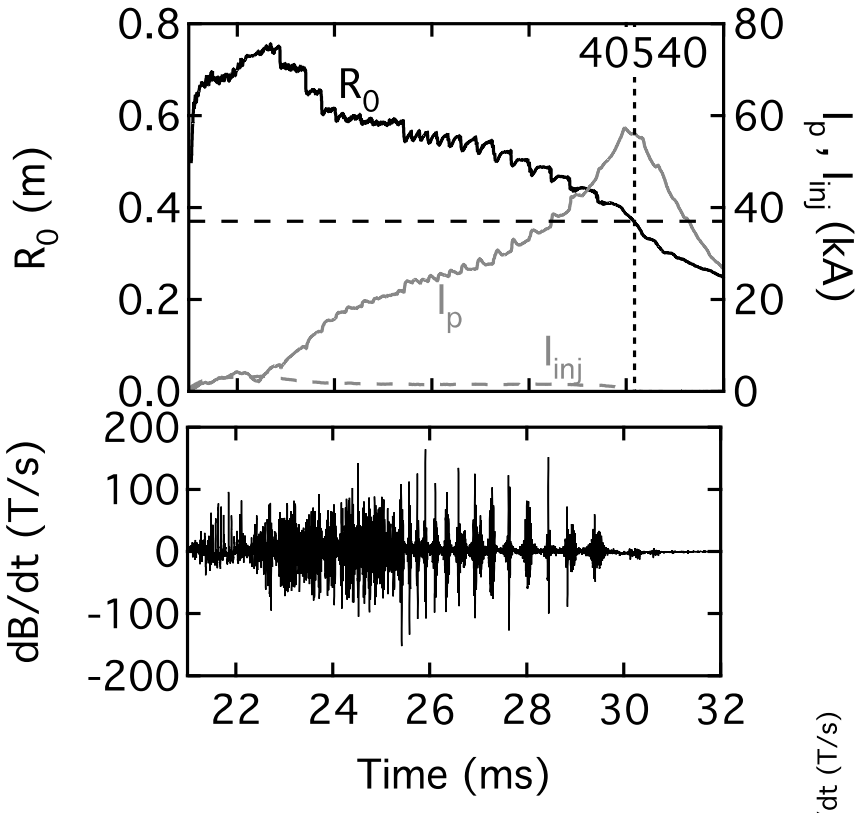
n=1 Magnetic Fluctuations Persist During HI

- Magnetic perturbations observed during PEGASUS HI driven discharges are typically described as bursty
- At times the fluctuations appear to be more continuous, and are likely bursts that are very near in time



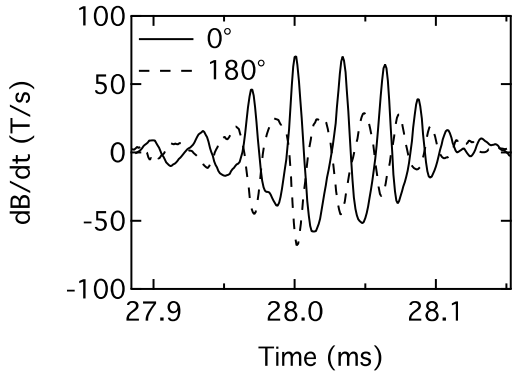
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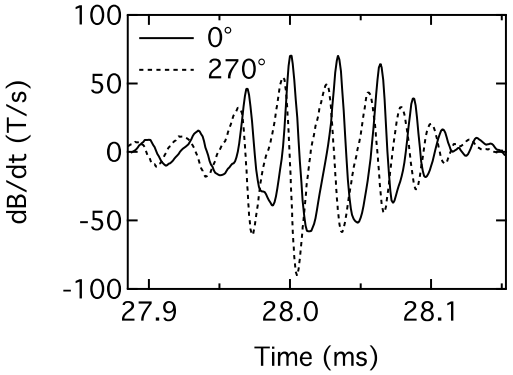
Pegasus HI Bursty MHD is n=1



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

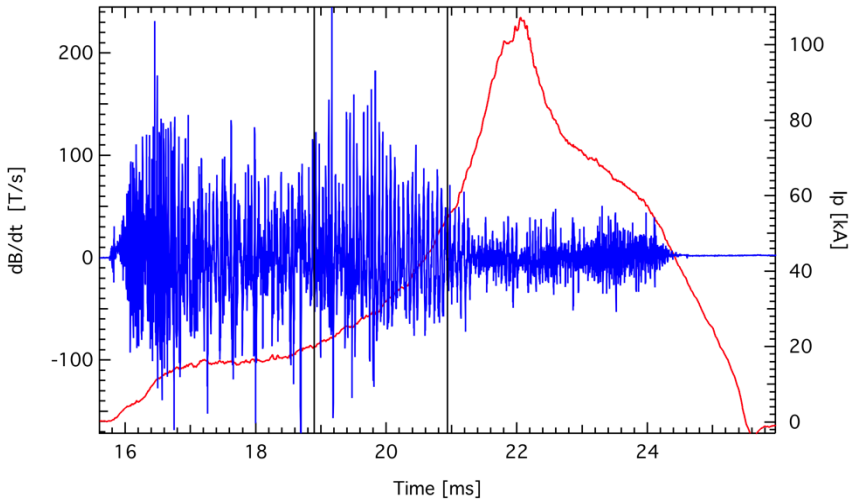




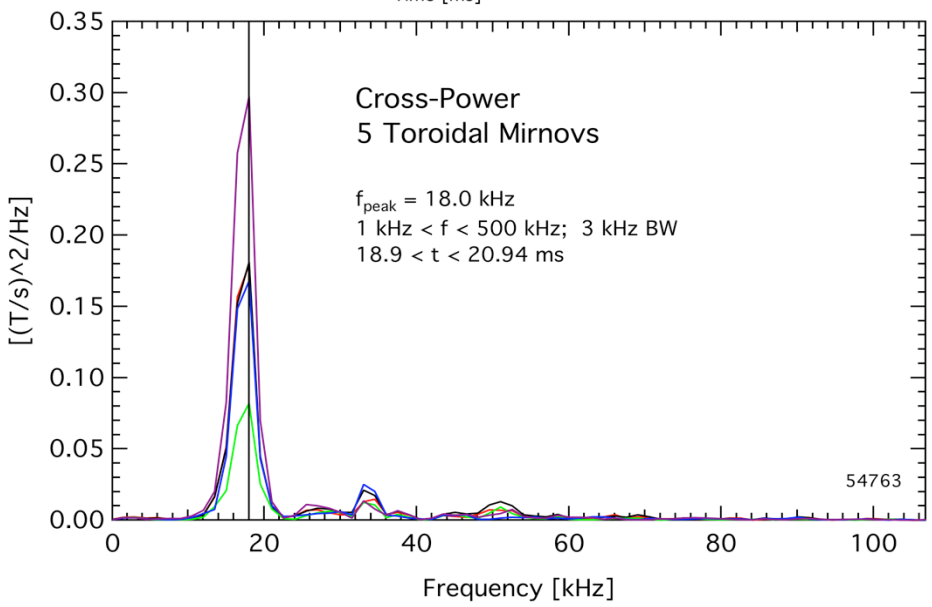
*Figures and analysis from D. Battaglia thesis:
D. Battaglia, *Non-solenoidal startup using localized current sources near the outboard mid-plane*, UW-Madison NEEP (2009)

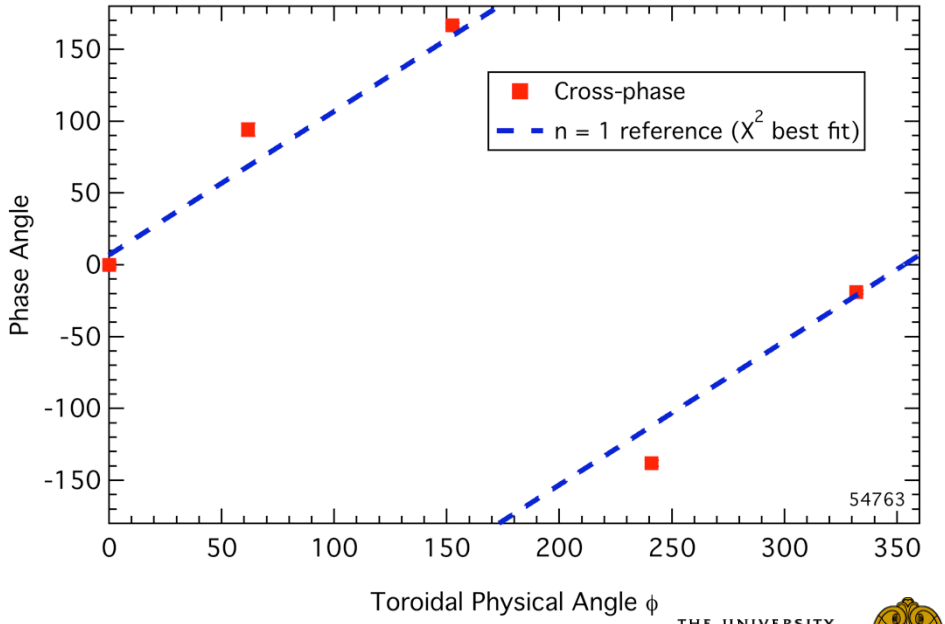
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Pegasus HI Continuous MHD is Also n=1



- Continuous type MHD Phenomena is routinely observed in HI discharges
- Typical frequencies: 10kHz < f < 50kHz
- Typically n=1





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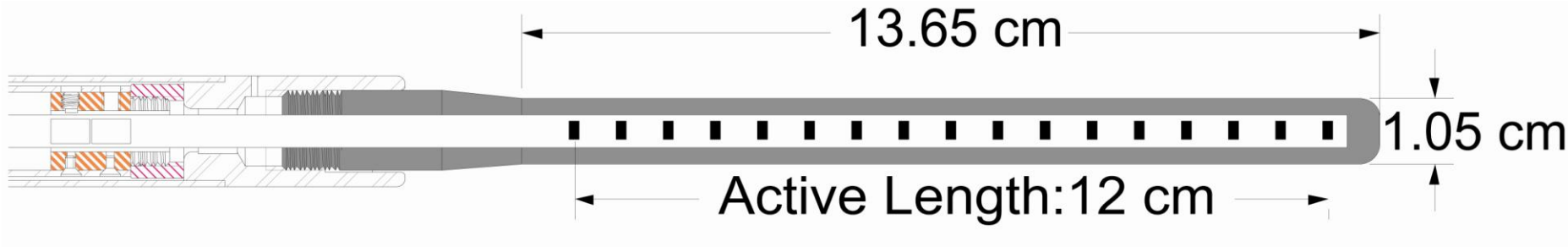
Internal Magnetic Probe Diagnostic Deployed

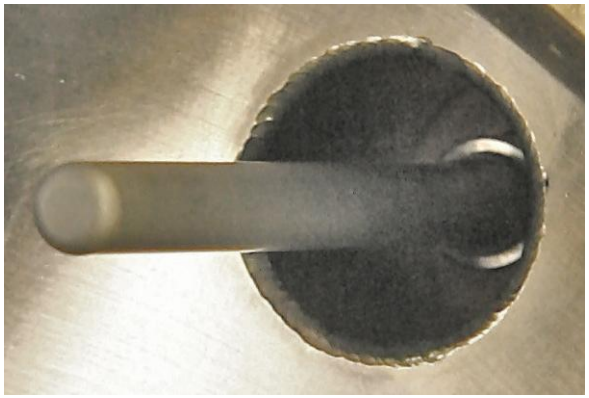
- Some outstanding questions about HI MHD:
  - Where is this mode located in the plasma?
    - What drives the mode? Under what conditions is the mode present?
    - Under the topology of helicity injection, is the mode confined to a flux surface?
  - Does the mode play a role in transport of current to the plasma core?

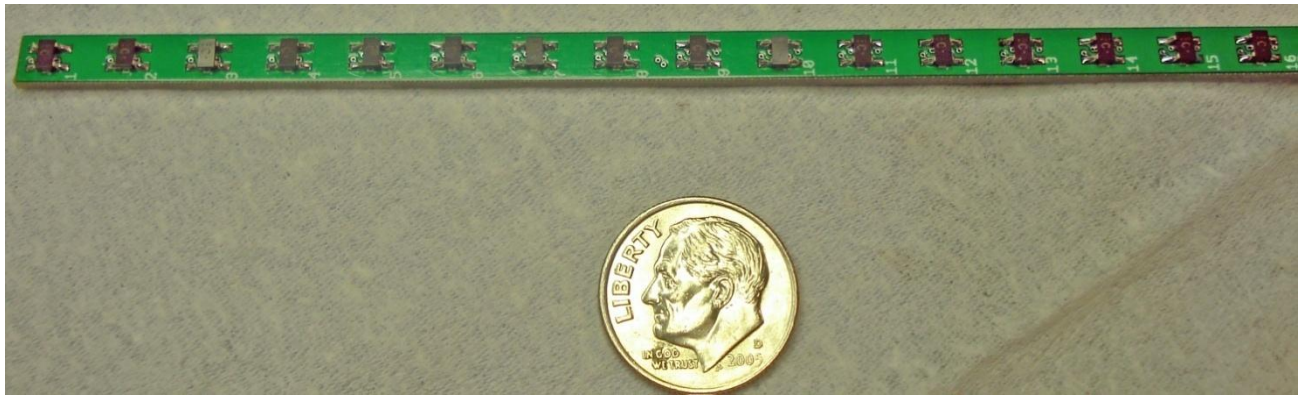
- These questions motivate the use of internal magnetic probes

- The Hall sensor array probe is used to try to answer some of these questions

Pegasus Hall Probe Deployed







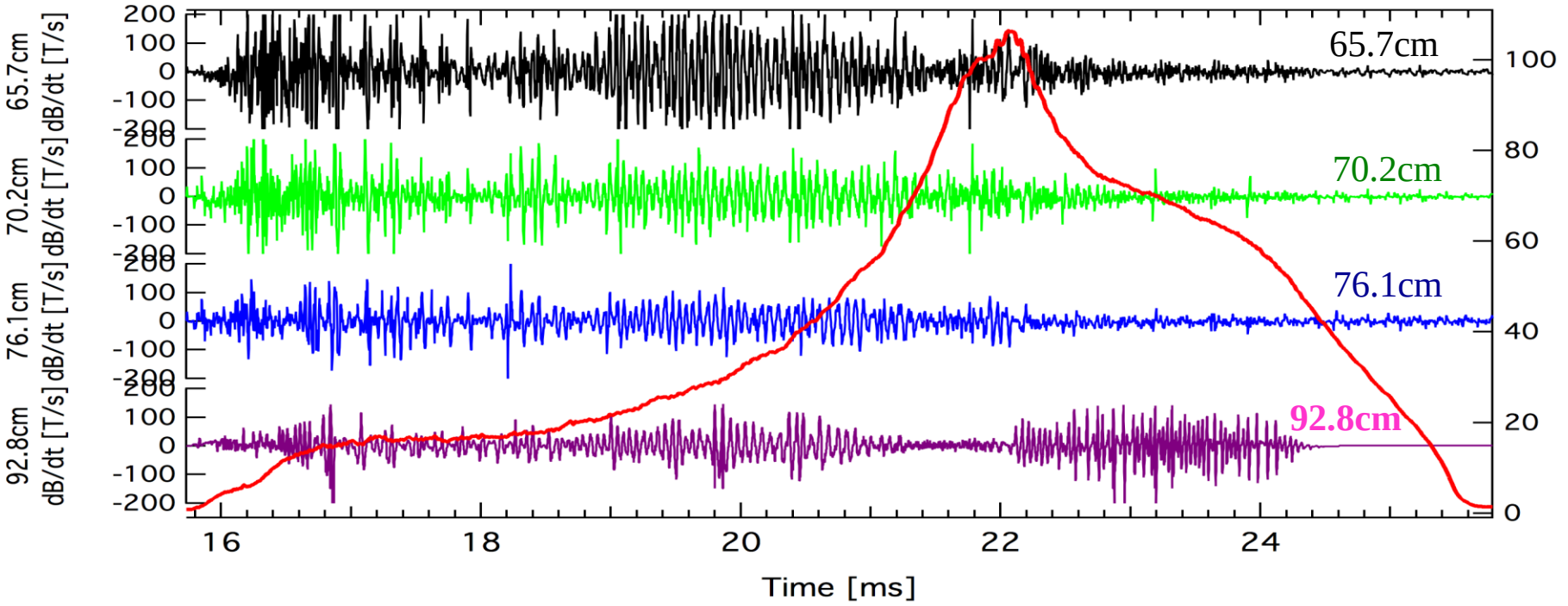
- Solid-state InSb Hall sensors
  - Sypris model SH-410
  - Weak variance with T_{sensor} and $B_{\|}$ are correctable with calibration
- 16 channels, 7.5 mm radial resolution
- Slim C armor as low-Z PFC
  - Minimizes plasma perturbation
- 25 kHz bandwidth
- Previously used to diagnose PEGASUS OH plasmas

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

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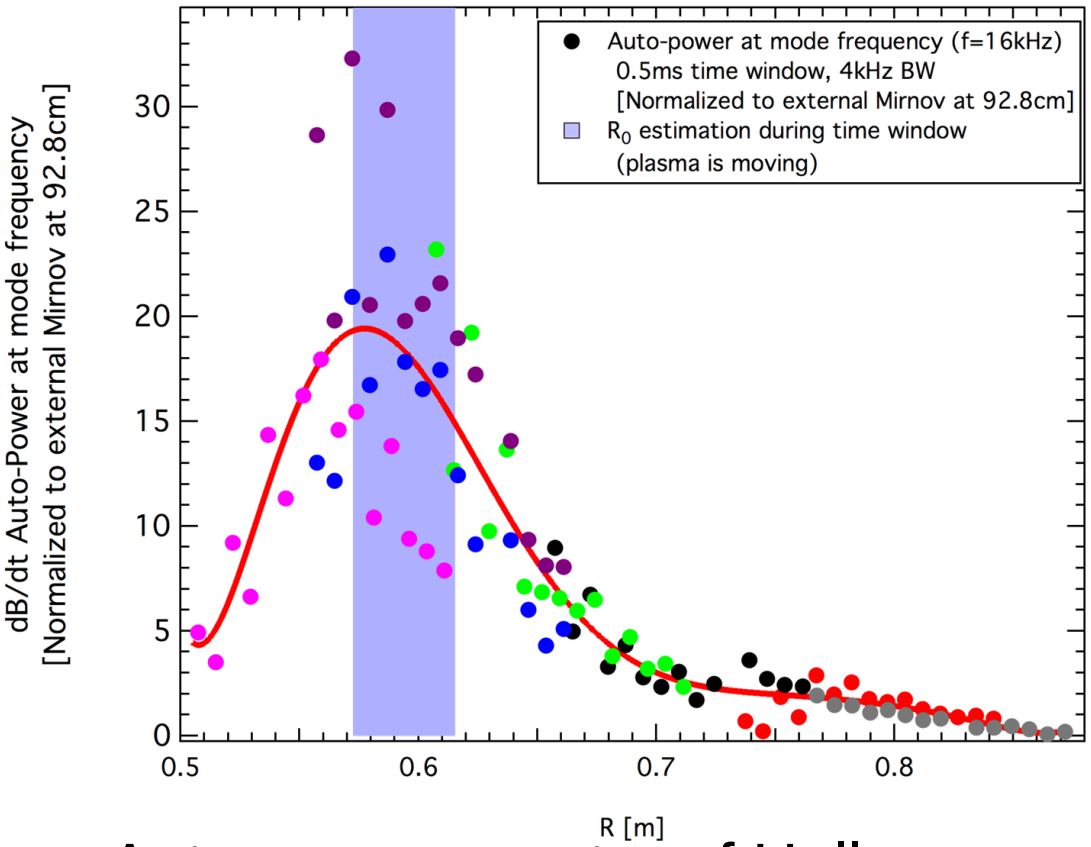
HI MHD is Observed Deep in the Plasma Interior

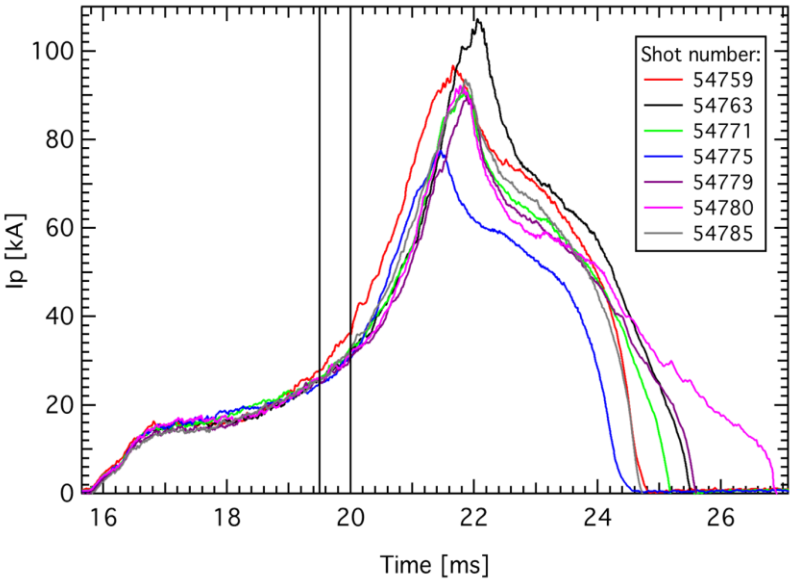
- Radial position of Hall sensor array scanned to R=50cm
  - HI MHD observed and reproduced well shot-to-shot:
    - Mode continues for 2-3 ms during same period in I_p evolution
    - Mode has peak frequency = 16kHz, measured with 4kHz bandwidth
    - All cases showed the mode to be a coherent n=1 at peak frequency as identified by external magnetics



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n=1 Mode Amplitude is Peaked in the Core

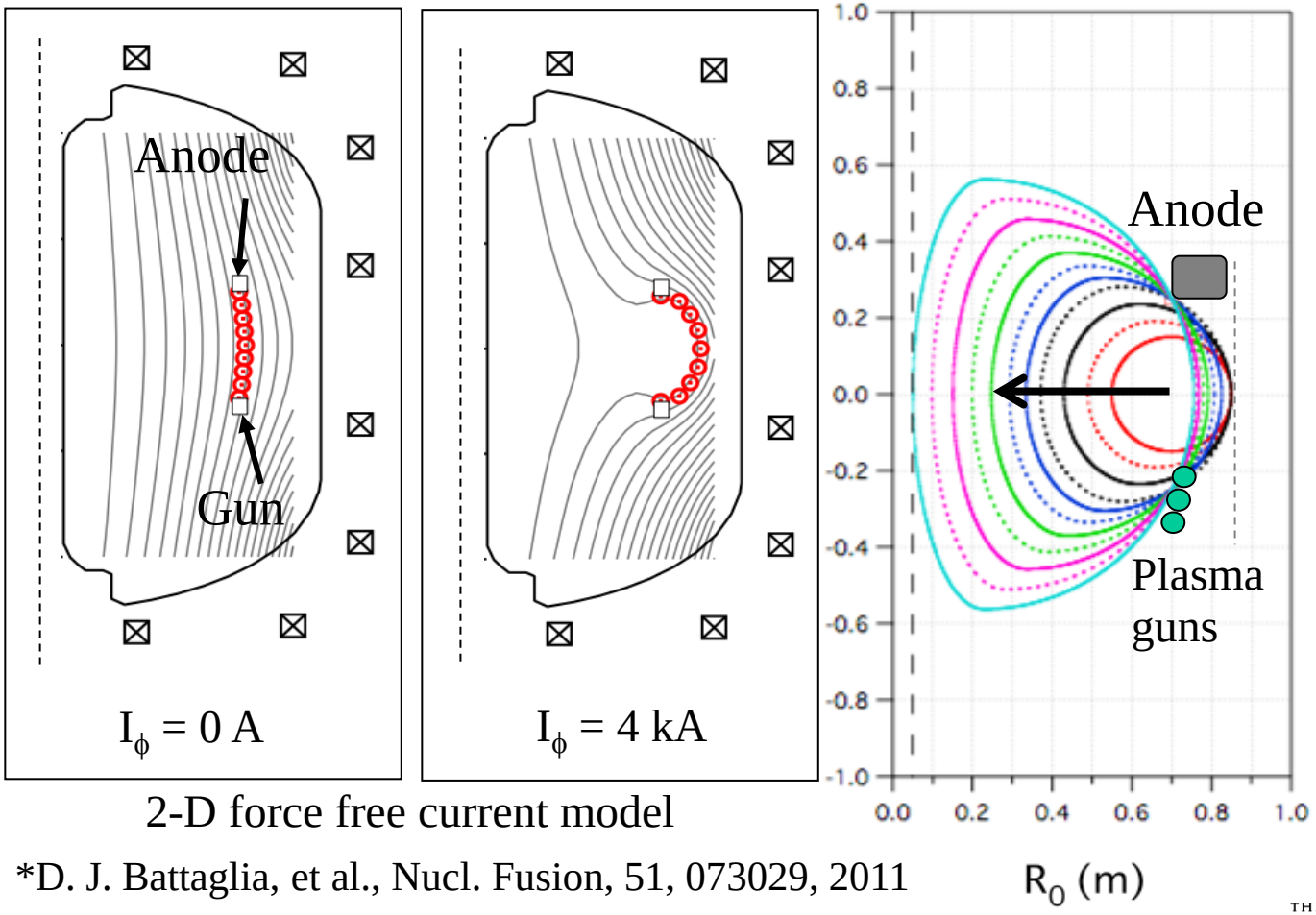




- Auto-power spectra of Hall sensors during 1ms window of mode activity show a strong radial dependence
  - The instability is as much as 20x stronger deep in the plasma interior

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

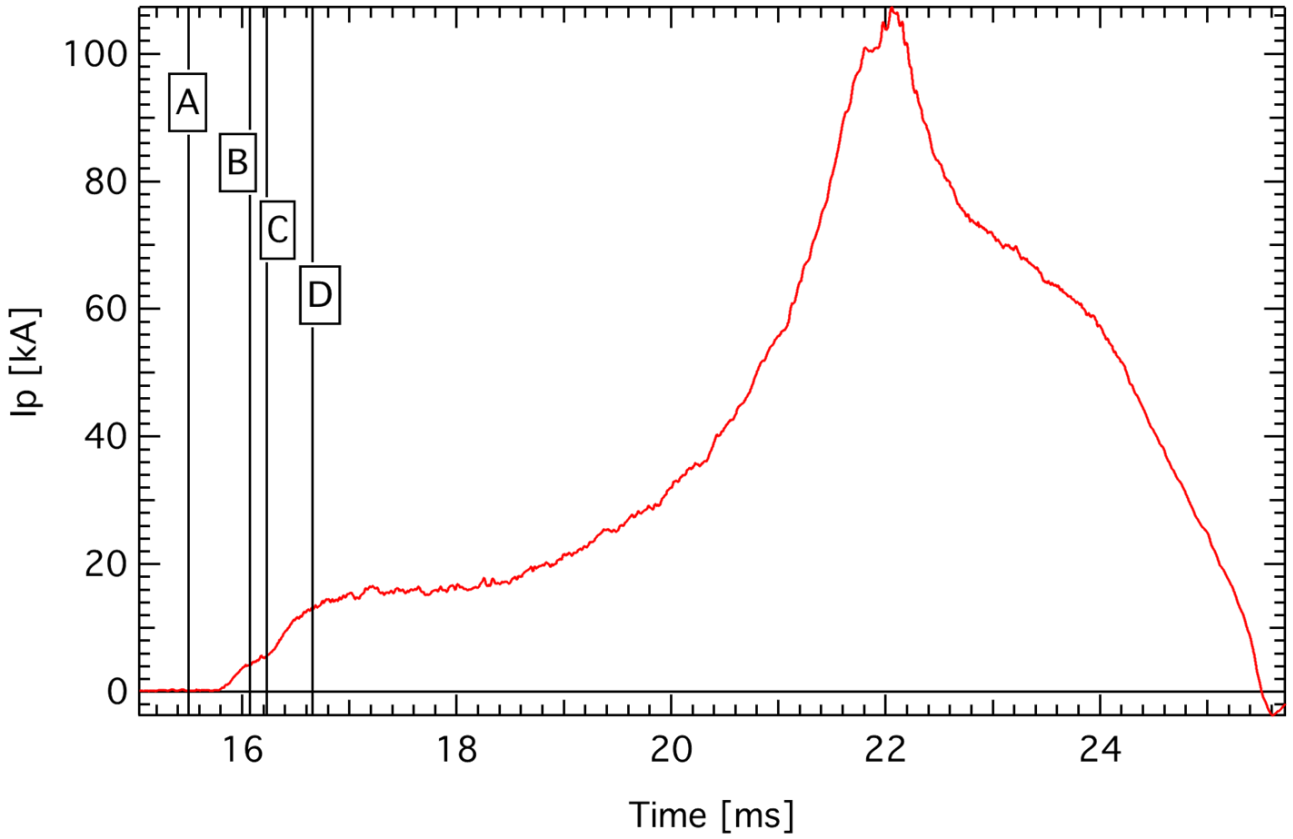


2-D force free current model

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

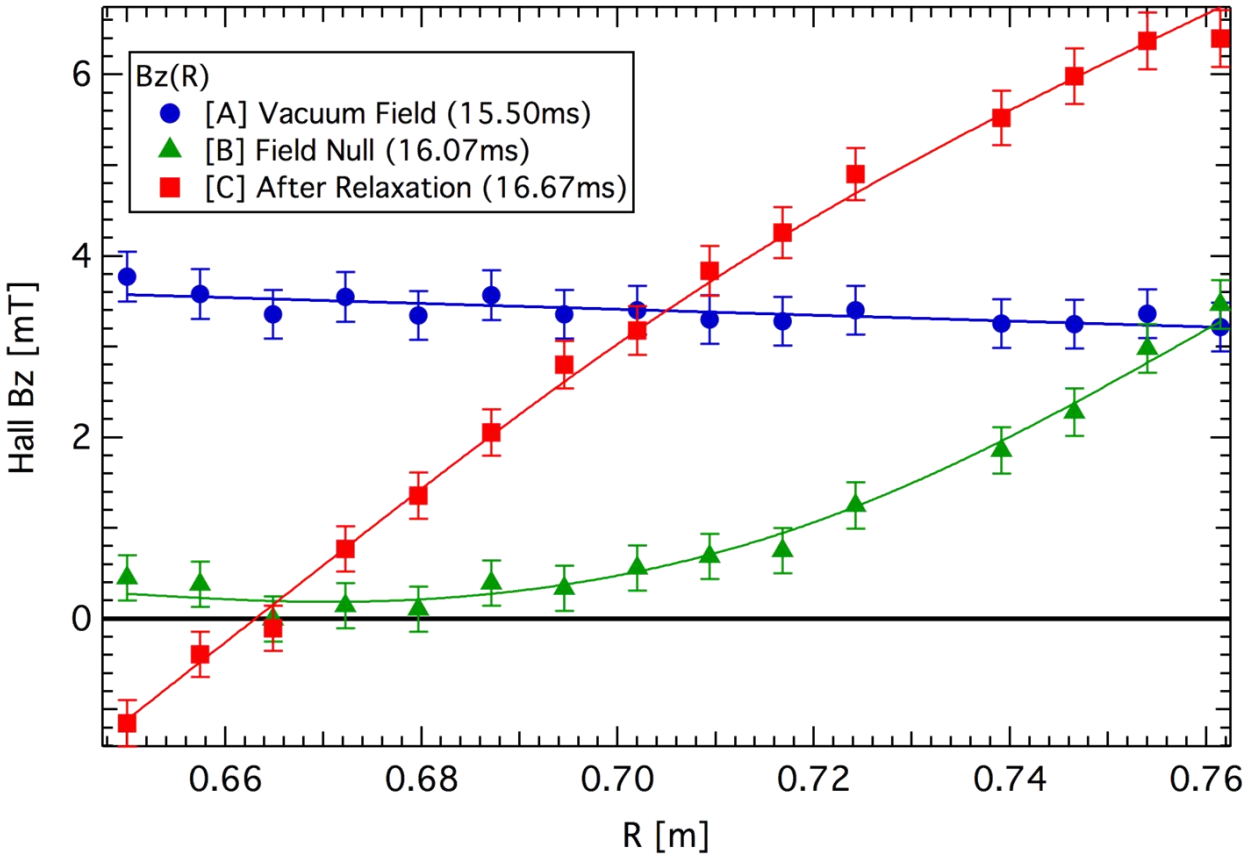
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Representative Discharge Probed to Study Relaxation



- Relaxation occurs at the beginning of the discharge during the programmed low initial field period

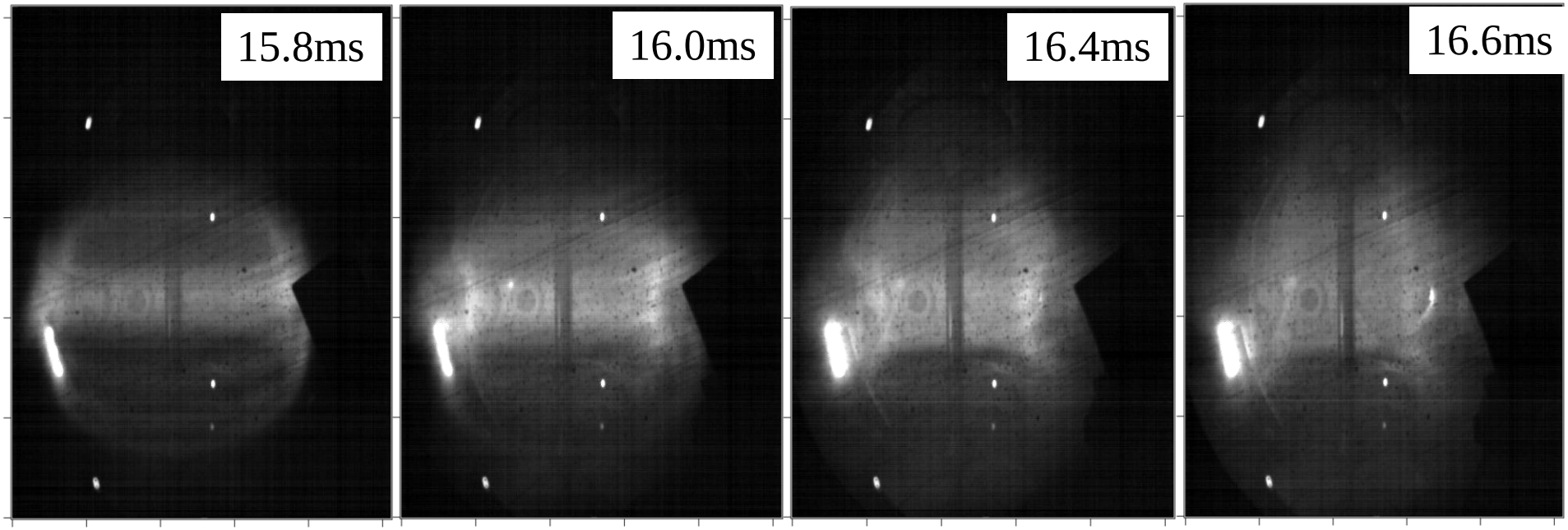
Internal B_z Measurements Confirm Field Null Creation



- Direct measurements of B_z at the Hall probe confirms the creation of a field null at relaxation, predicted by plasma formation and evolution

Fast Imaging Supports Timing of Relaxation Event

- Fast imaging is suggestive of inward expansion near in time to field null creation



Current streams combine into current sheet

Field null is formed and the tokamak-like state expands towards the central column

- Note: imaging from D-alpha camera with fish-eye lens

*See K. E. Thome poster, *Ohmic Confinement in the Pegasus Toroidal Experiment*, for more information on this diagnostic

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Local $J_\varphi(R)$ 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 an off-midplane B_z measurement:

$$\mu_0 J_\varphi = -\frac{B_Z}{\kappa^2(R-R_0)}\left(1-\frac{Z^2R_0}{\kappa^2R(R-R_0)^2}\right)-\frac{\partial B_Z}{\partial R}\left(1+\frac{Z^2}{\kappa^4(R-R_0)^2}\right)$$

*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 parameters (R_0=40cm, κ=1.75) the J_φ over the range of the Hall sensor array can be estimated
  - Note that this is also an estimation as R_0 and κ are changing with time

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Local $J_\varphi(R)$ Estimated From Hall Sensor Array B_z Measurements

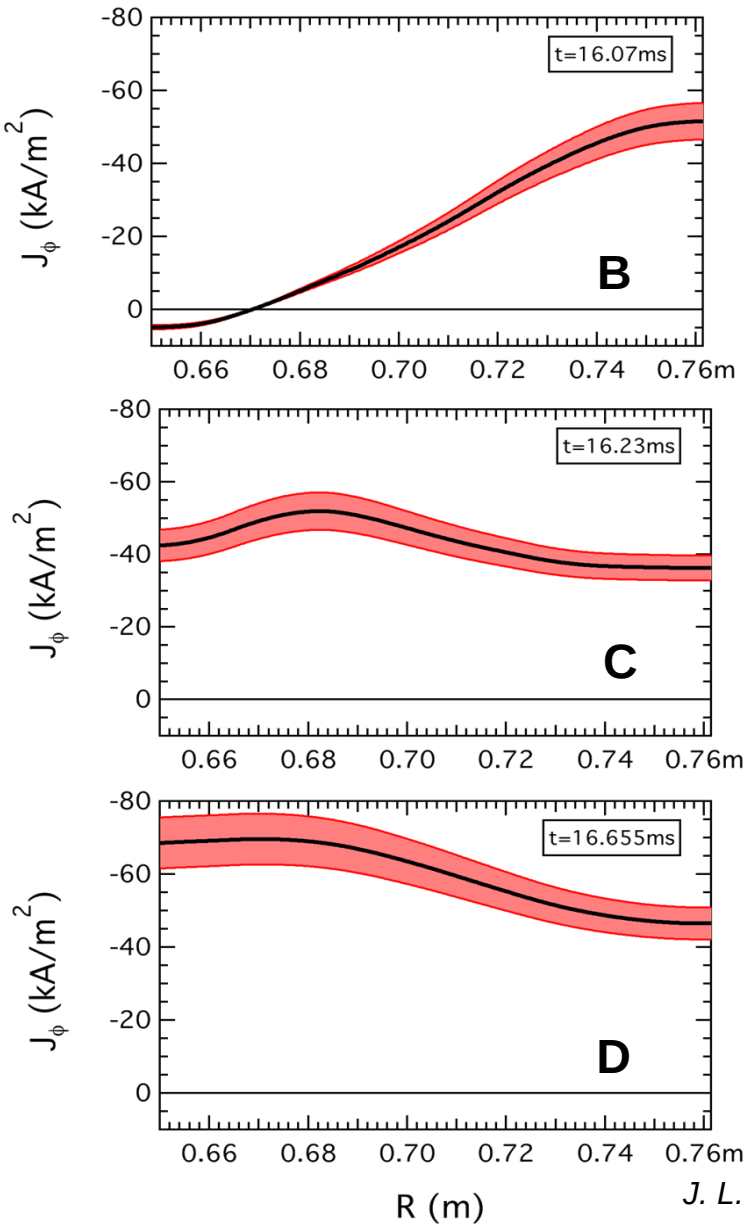
- Petty, *et al.** showed that J_φ for a plasma with elliptical cross-section can be calculated from an off-midplane B_z measurement near $R=R_0$:

$$\mu_0 J_\varphi = -\left(1+\frac{1}{\kappa^2}\right)\frac{\partial B_Z}{\partial R} - \frac{Z^2}{3\kappa^4 R_0}\frac{\partial^3 R B_Z}{\partial R^3}$$

*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 κ=1.75 the J_φ over the range of the Hall sensor array can be estimated
  - Note that this is also an estimation as κ is likely changing with time

$J_\varphi(R)$ Estimates Show Formation of Tokamak Discharge Following Relaxation

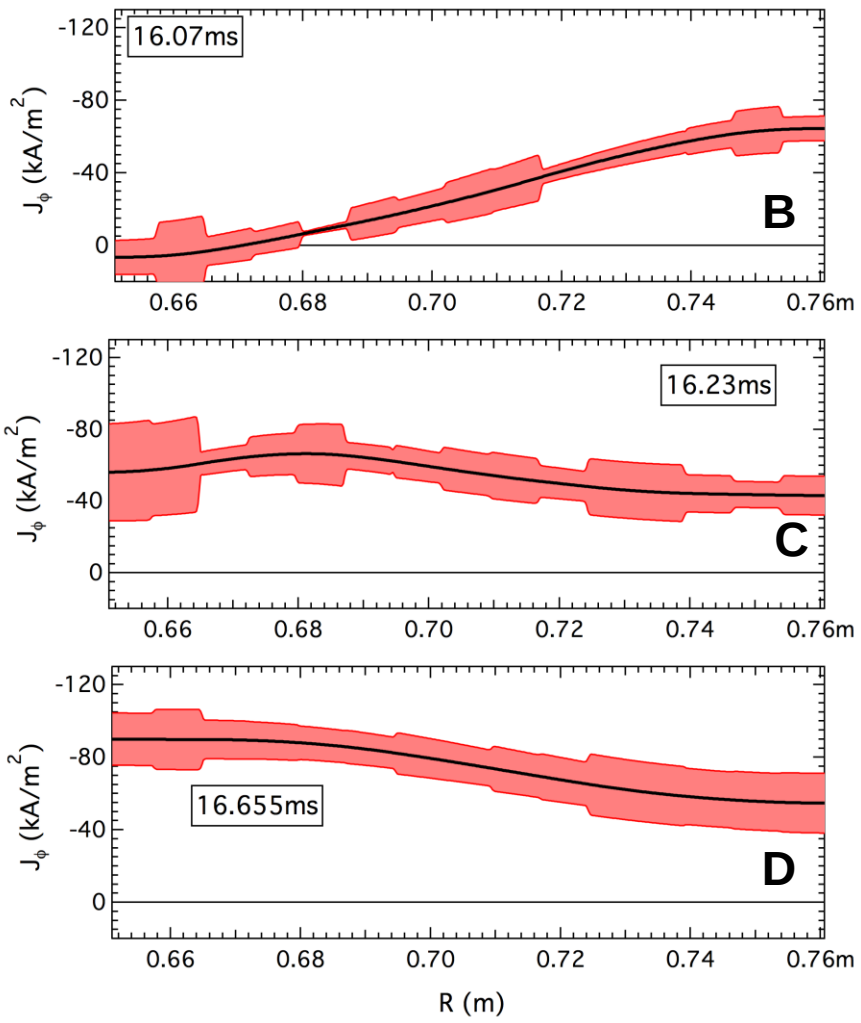


B) HI creates an initial current profile that is very hollow

C) The current profile relaxes, carrying current towards the core

D) A tokamak-like, peaked current profile is formed

$J_\varphi(R)$ Estimates Show Formation of Tokamak Discharge Following Relaxation



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C) The current profile relaxes, carrying current towards the core

D) A tokamak-like, peaked current profile is formed

κ=1.75±0.5

Conclusions

- Strong magnetic perturbations are ubiquitous in PEGASUS HI driven discharges
  - Structure is n=1
  - Bursty and/or continuous behavior
  - Mode structure is internally peaked in the plasma.

- First internal B_z measurements on PEGASUS HI plasmas confirm creation of a field null near the plasma helicity injectors at plasma formation

- Current profile estimates suggest hollow current profiles relaxing to be more tokamak-like - peaked in the plasma core
  - The timescale of this process is on the order of < 1ms.