MHD Activity and Analysis at Near-Unity Aspect Ratio in PEGASUS

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Abstract

Several MHD instabilities have been observed on the PEGASUS Toroidal Experiment. A m/n=2/1 resistive mode is observed in nearly all discharges. The appearance of this mode is correlated with a large volume of the plasma at low magnetic shear near the q=2 surface. This mode has a fundamental frequency between 3 and 10 kHz and is highly toroidal, with 1.5 of 2 wavelengths detected along the center column. More recent discharges exhibit a 3/2 mode which is observed to destabilize a 2/1 island. Evidence of external kink modes at q_{95}=5 has been detected. Standard MHD diagnostics are employed for mode detection and identification. Four arrays of Mirnov coils are available: a 7-coil inboard and 6-coil outboard toroidal array, a full poloidal array of 22 coils, and a 21-coil center-stack poloidal array. An 18-channel poloidal soft X-ray array provides data on internal fluctuations.

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Outline - MHD Activity on PEGASUS

- Mirnov Coils
  - *Construction, calibration, and installation*
- Observations of 2/1 magnetic island
  - *Mode structure, correlation with q profile*
- Observations of 3/2 and 2/1 islands
  - *Mode structure, coupling, effect on plasma performance*
- Indications of external kink
  - *Experimental measurements, equilibria, calculations*
- Soft X-ray array
  - *Hardware, correlation with magnetics diagnostics*

Questions to be addressed

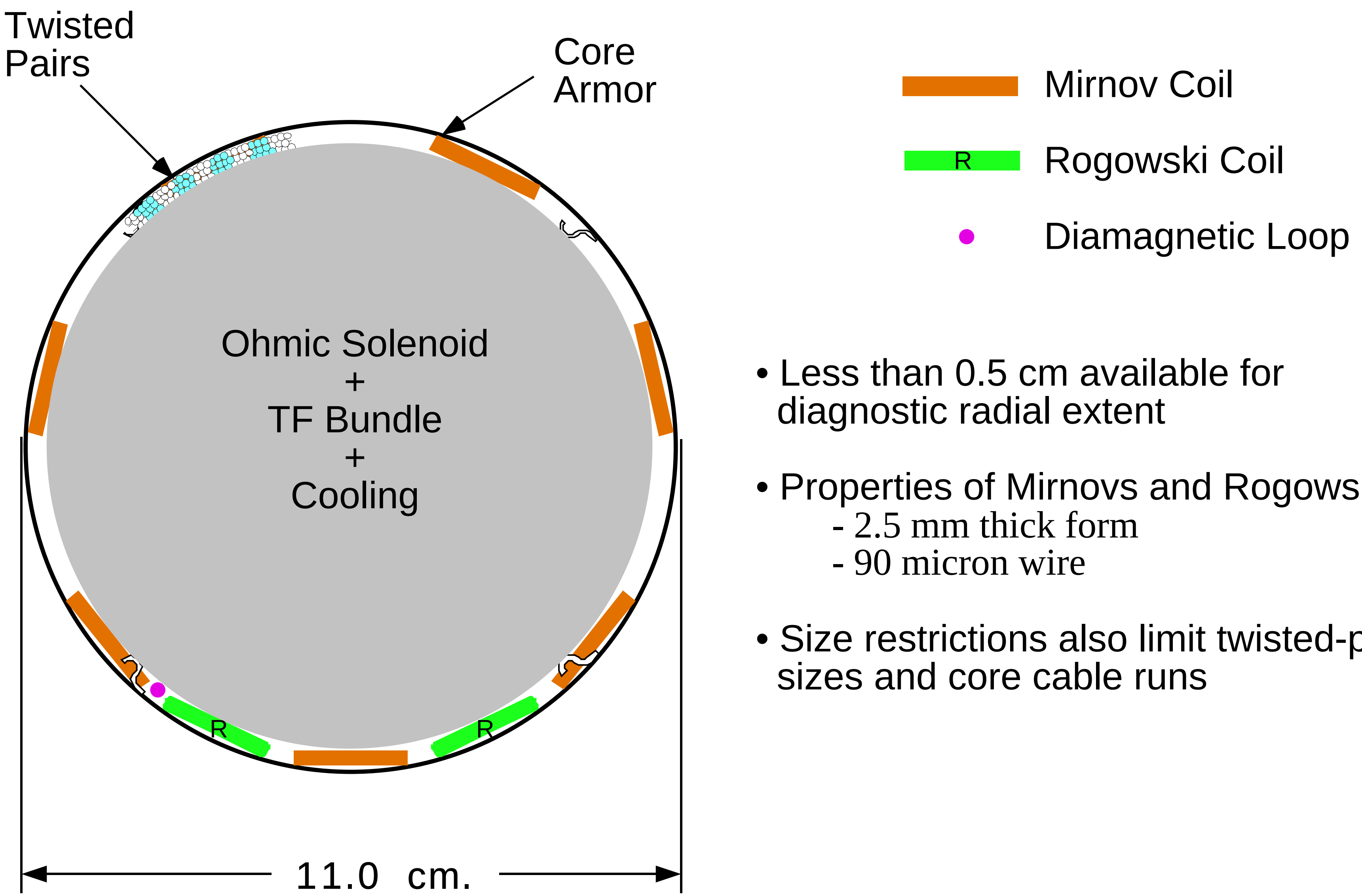
- What resistive, macroscopic MHD instabilities are observed at near-unity aspect ratio?
  - Are magnetic islands present?
  - What mode numbers?

- What is the character of these instabilities?
  - How virulent?
  - What is the poloidal structure?
  - What relationship do the modes have to each other?

- Do these instabilities significantly limit plasma performance?

- Are any ideal MHD limits evident?

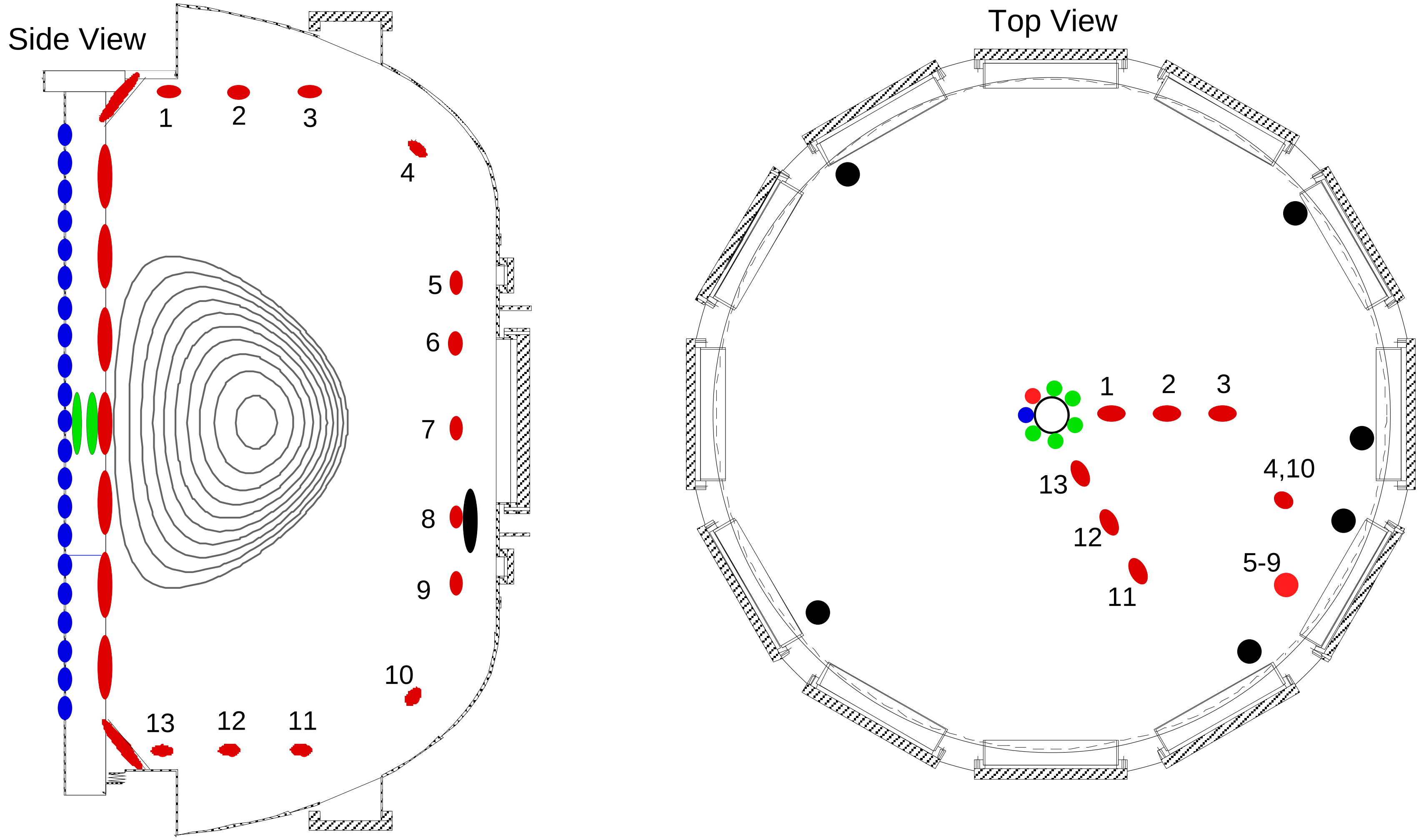
The small size of the centerstack puts tight constraints on core diagnostics



Midplane Cross-Section of Centerstack

- Less than 0.5 cm available for diagnostic radial extent
- Properties of Mirnovs and Rogowskis:
  - 2.5 mm thick form
  - 90 micron wire
- Size restrictions also limit twisted-pair sizes and core cable runs

Schematic layout of Mirnov coils

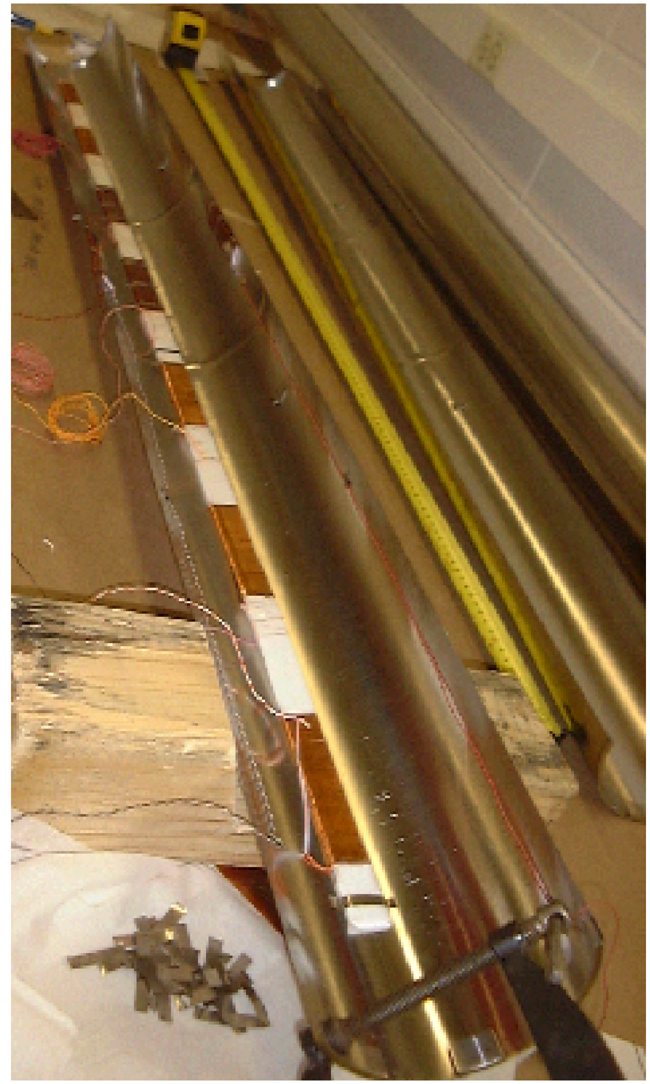


- "High-Res" Core Mirnov Coils (21)
- Poloidal Mirnov Coils (22)
- LFS Toroidal Mirnov Coils (6)
- HFS Toroidal Mirnov Coils (7)

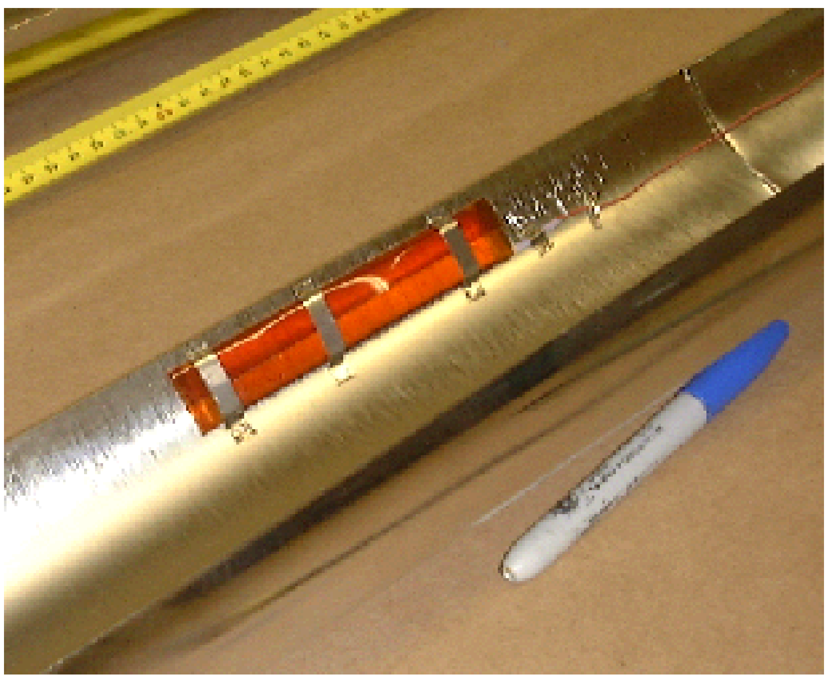
Physical construction of coils

- PEGASUS Mirnov coils are divided into three types
- First type is recycled PDX coils - used for LFS poloidal array
  - *1 cm x 2.7 cm x 3 cm long*
  - *0.5 mm wire, 18 turns/cm, double layer*
  - *330 cm^2 effective area*

- Second and third types are used for the core arrays and external toroidal array
  - *1.9 cm x 0.25 cm x (10 cm or 2 cm) long*
  - *90 micron wire, 60 turns/cm, single layer*
  - *280 or 55 cm^2 effective area*
  - *Core arrays on long strips to facilitate alignment of coils on core armor*

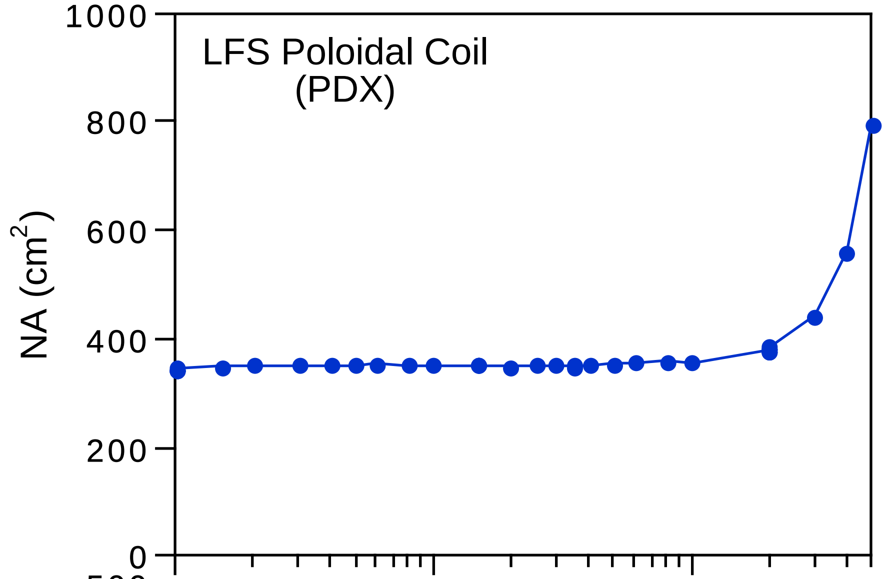


Low-Res array installed on core armor

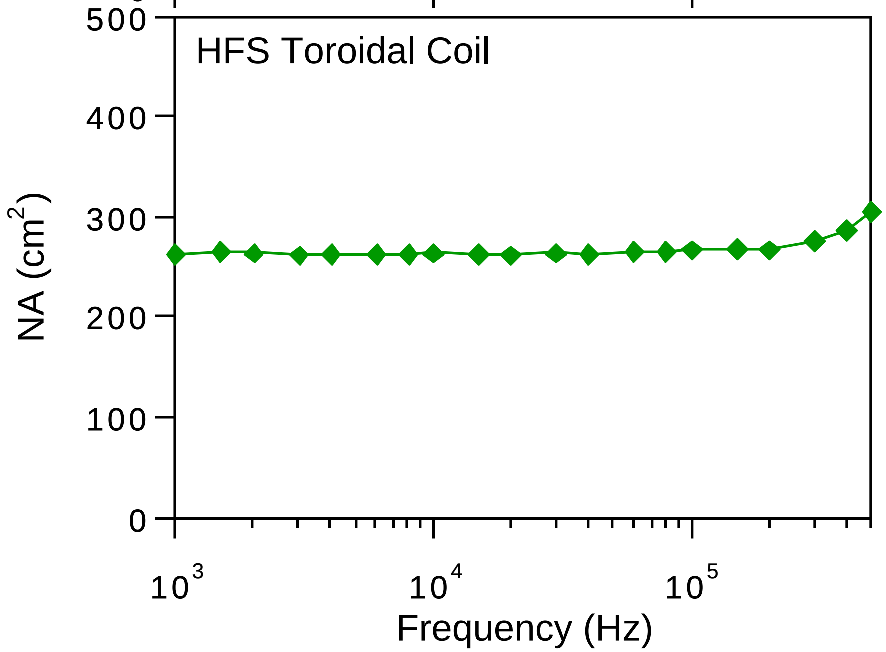


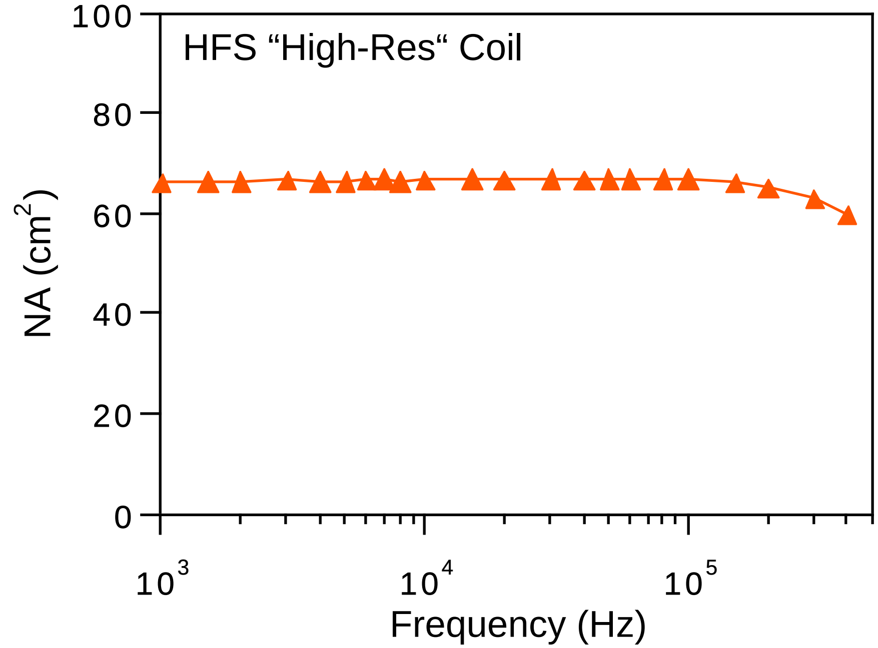
Single Coil from HFS toroidal array

Mirnov coils give flat response below 100 kHz

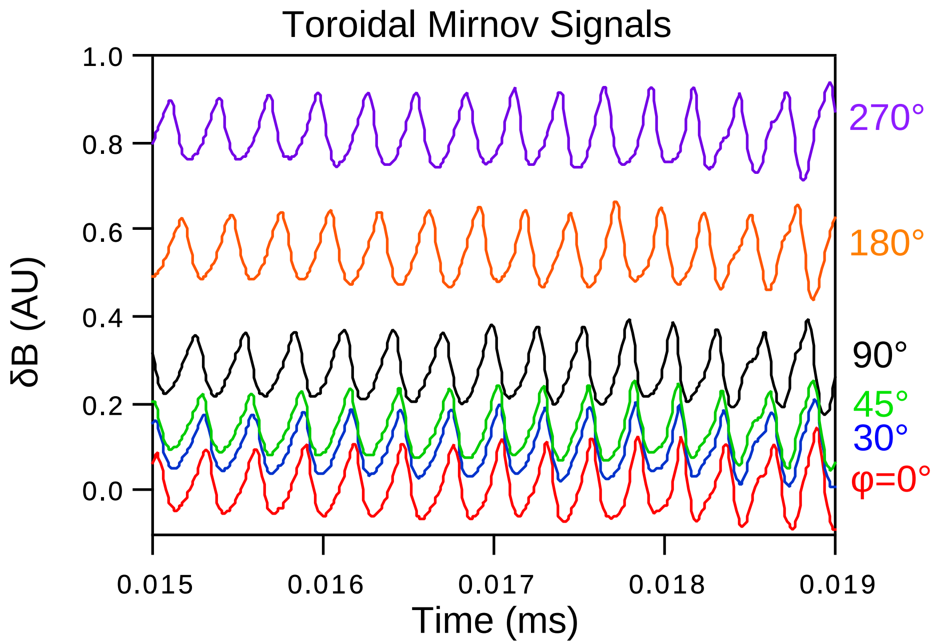


- All coils calibrated on same Helmholtz set
- Typically frequencies of 10 kHz or less are observed on PEGASUS
- Coil resonances are observed at frequencies above 100 kHz
- Coils also function as equilibrium diagnostics (B coils)



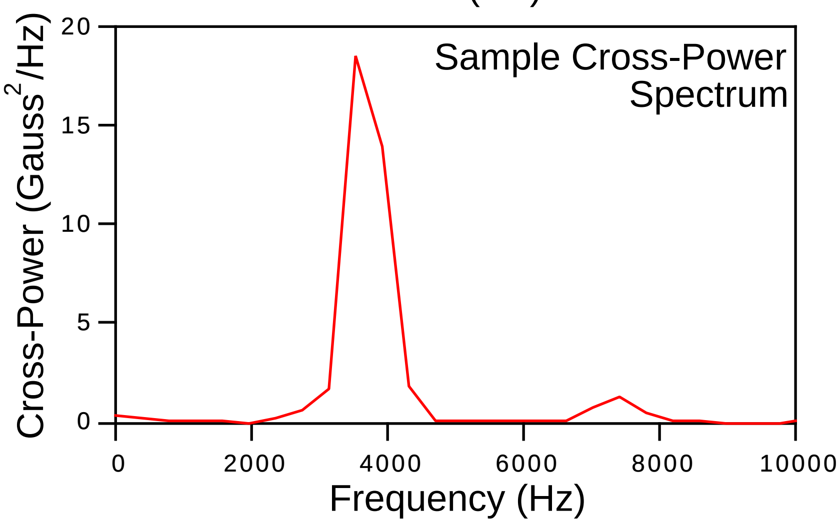


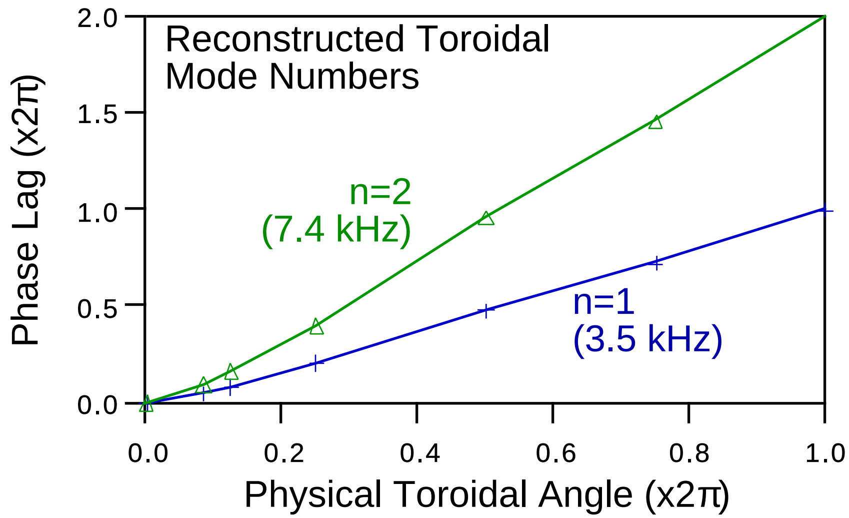
Toroidal mode numbers are readily identified



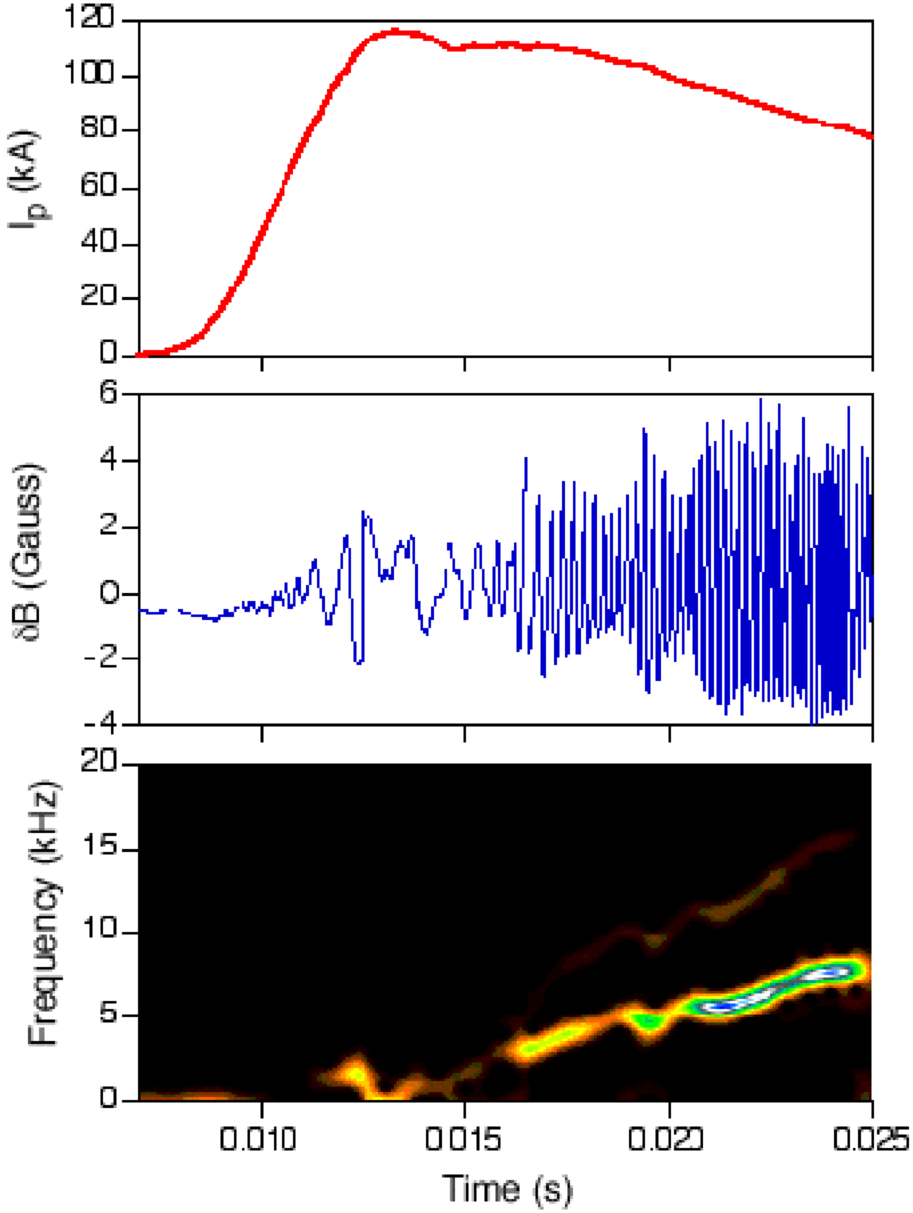
- The 6-coil LFS array is used to obtain values of n
  - Uneven coil spacing allows for resolution up to n=12

- Spectral techniques are used to extract resonant frequencies and phase delays
  - Cross-power gives spectrum
  - Cross-phase gives phase shift





A dominant feature has been a rotating m/n=2/1 mode

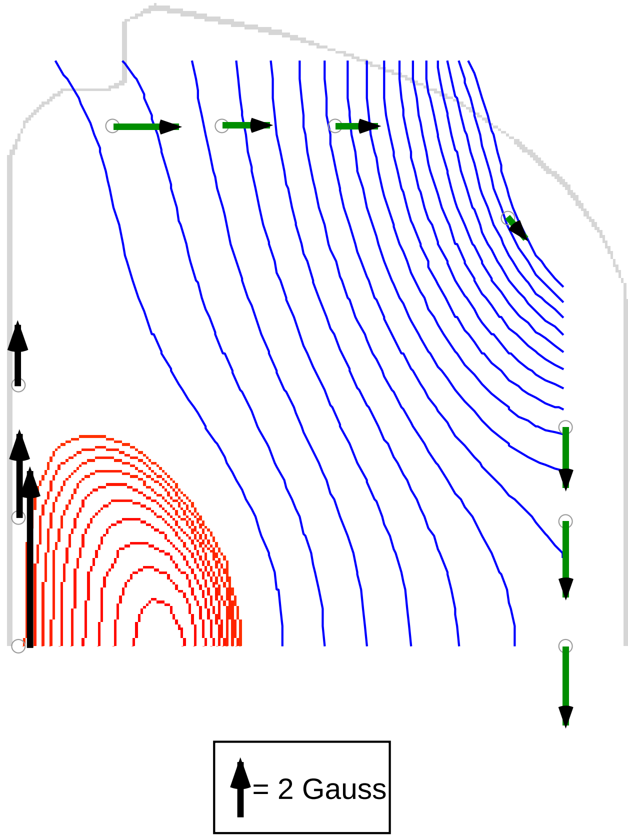


- Mode present in all significant discharges
- Rotates in electron diamagnetic direction
  - Mode is likely magnetic island
- Frequency is typically 4-10 kHz
  - No evidence of mode locking
- Little shear stabilization of island growth
  - Central shear is nearly zero

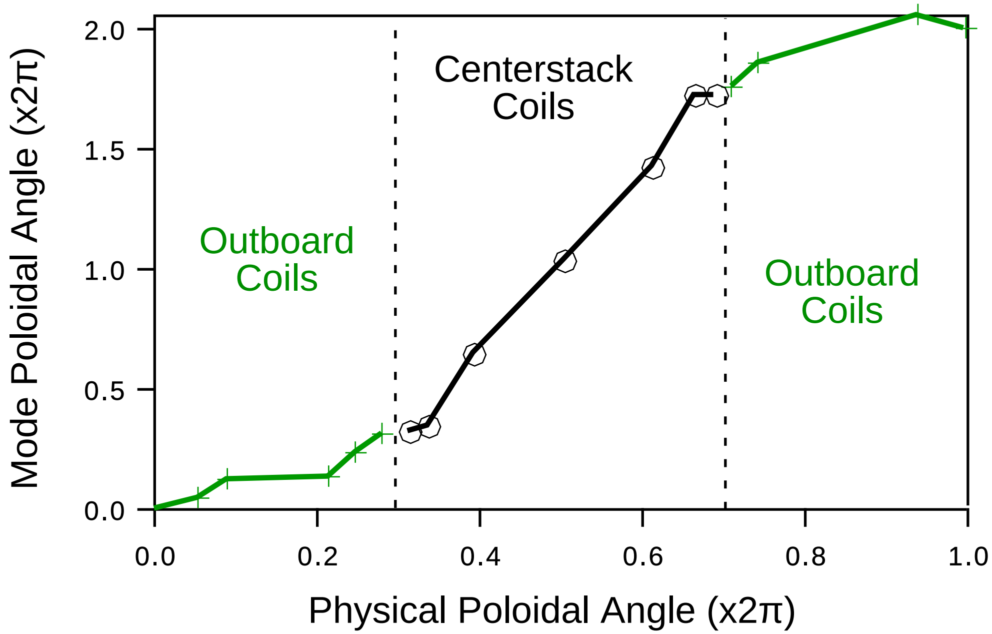
2/1 mode is poloidally asymmetric

- Poloidal and toroidal phase analyses clearly indicate mode is m=2/n=1
- Toroidicity of mode is seen in large phase shifts along centerstack
  - Roughly 1.5 wavelengths observed across 120º poloidally
- Mode is strongest on the low-field side
  - As plasma grows, LFS signal increases and HFS signal decreases

Perturbed Field Magnitude
at the Wall

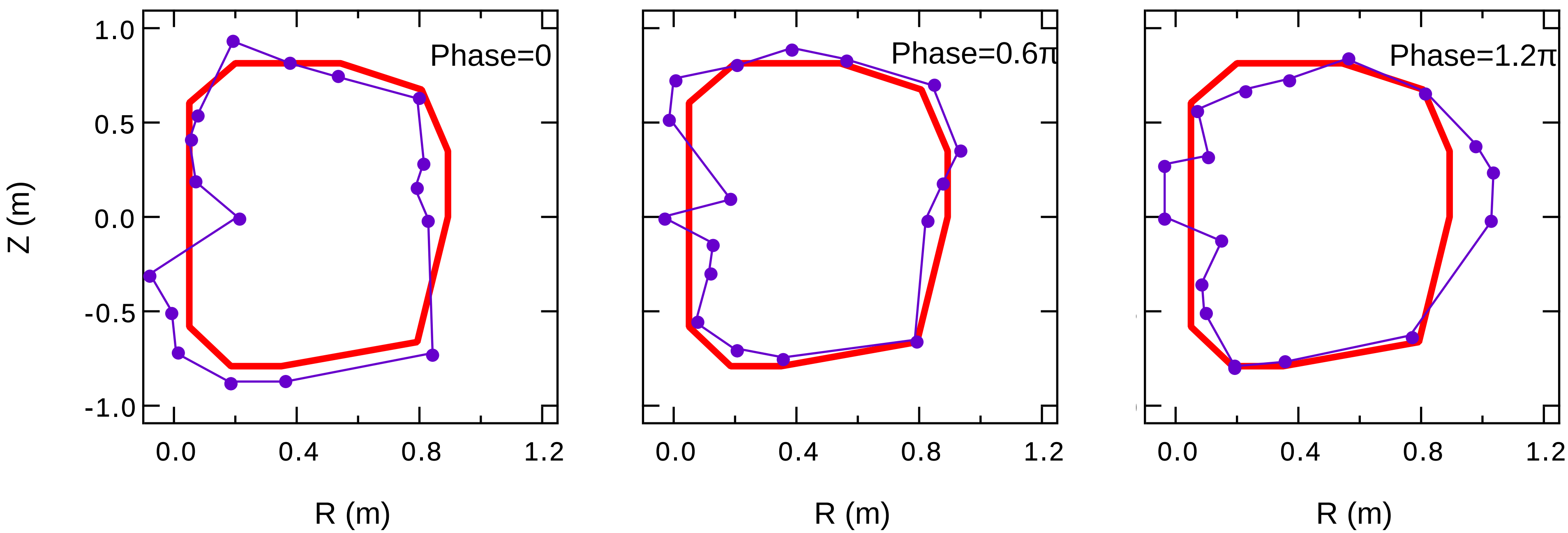


2/1 Poloidal Phase at the Wall

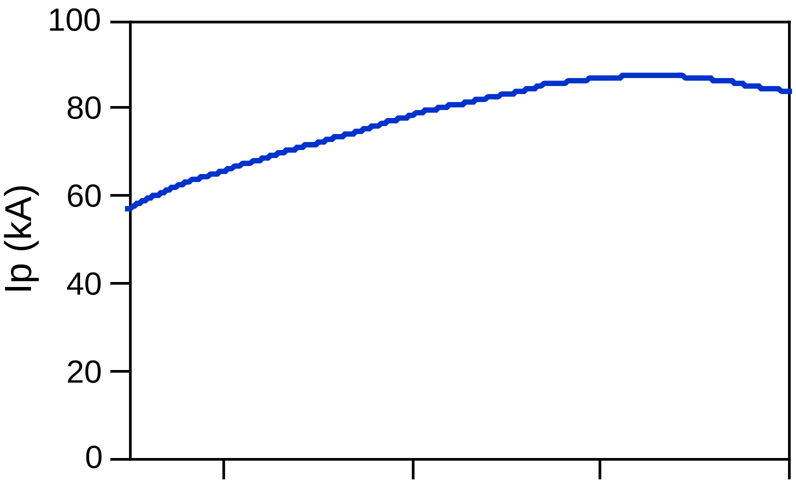


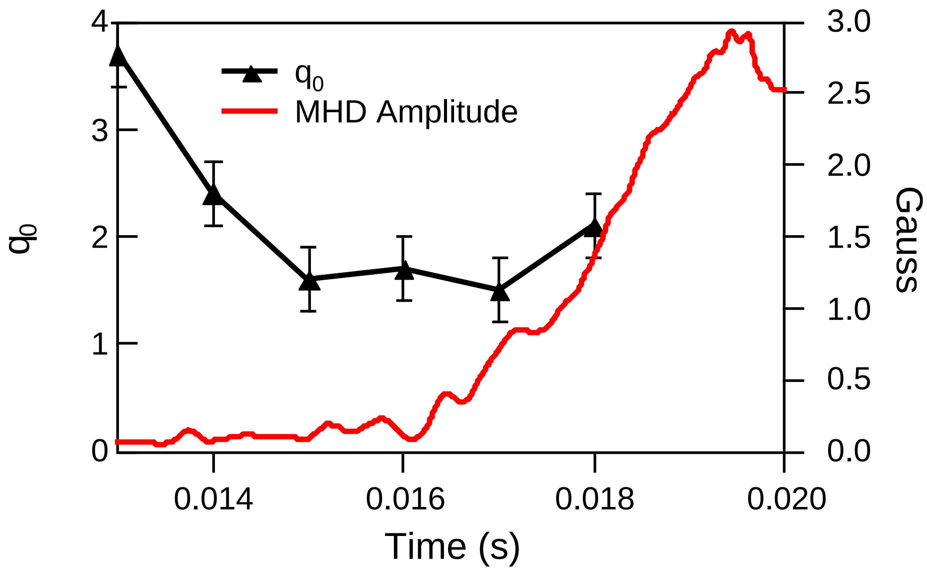
Mode asymmetry demonstrated by magnetic perturbation at coils

- Polar plot shows displacement of B from zero
  - Contains phase and amplitude information
  - Plots based on spectral analysis, not raw data
- This is an example of a 2/1 mode
  - Note two "positive" lobes and two "negative" lobes in each plot
- Efforts underway to model Mirnov coil signals
  - Helically perturb equilibrium with desired m,n
  - Place parallel current on magnetic island
  - Calculate resulting perturbed field with real coil geometry

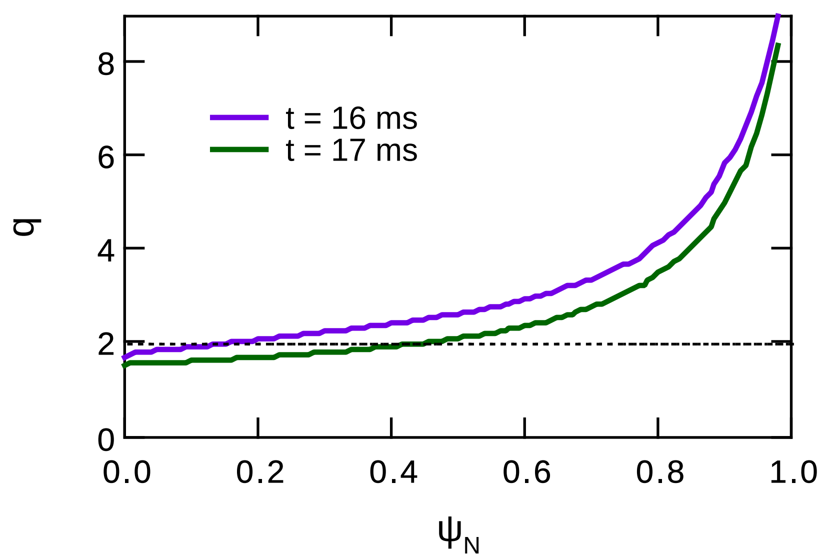


2/1 mode not observed until $q_{min} < 2$



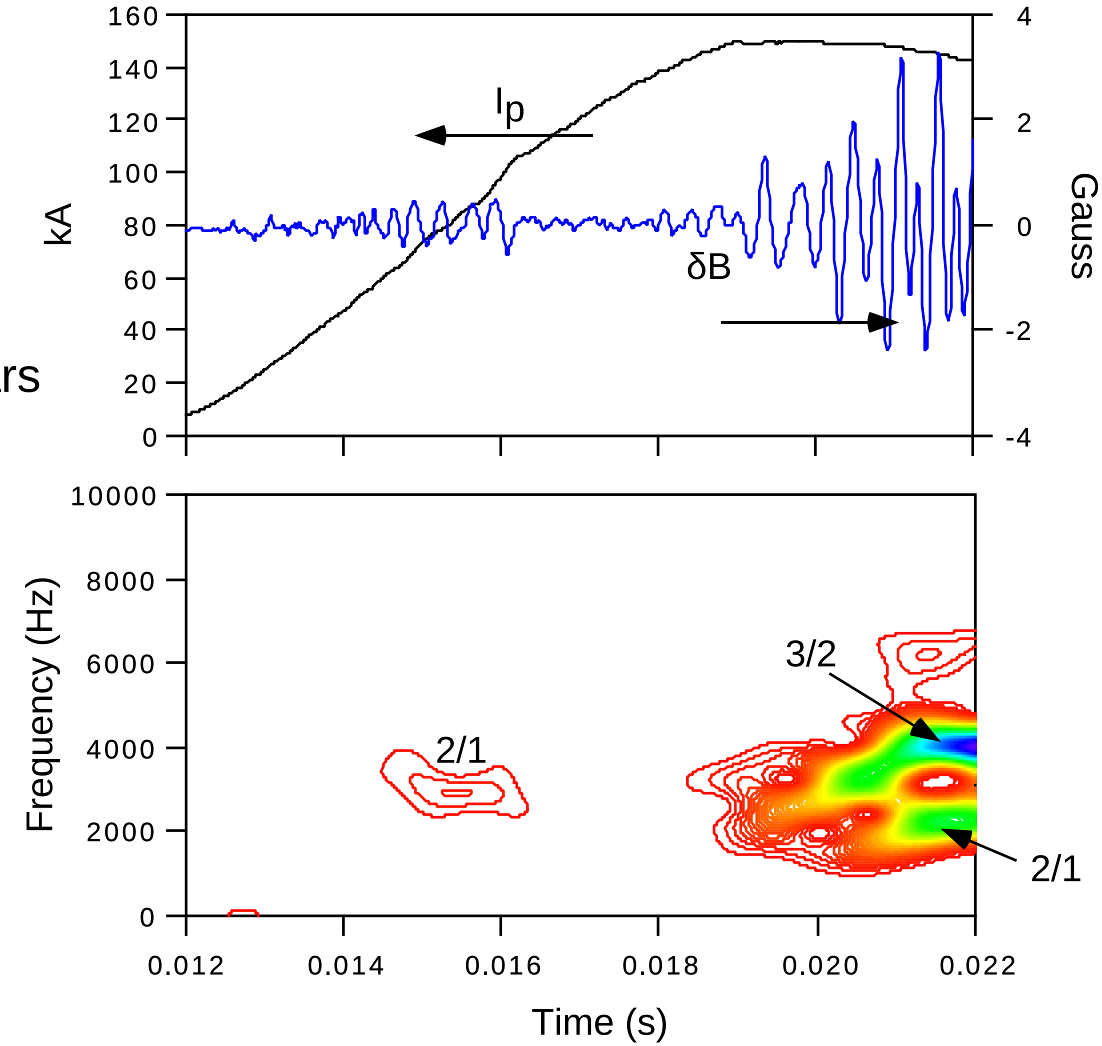


- Consistent with observed helicity of the mode
- A large region of low shear exists about the q=2 surface
- Central q inferred from Equilibrium fit
  - *2D SXR camera will constrain q_0*
  - *See Tritz et al. [RP1.036]*
- In general, strong MHD activity appears to relate to I_p limits



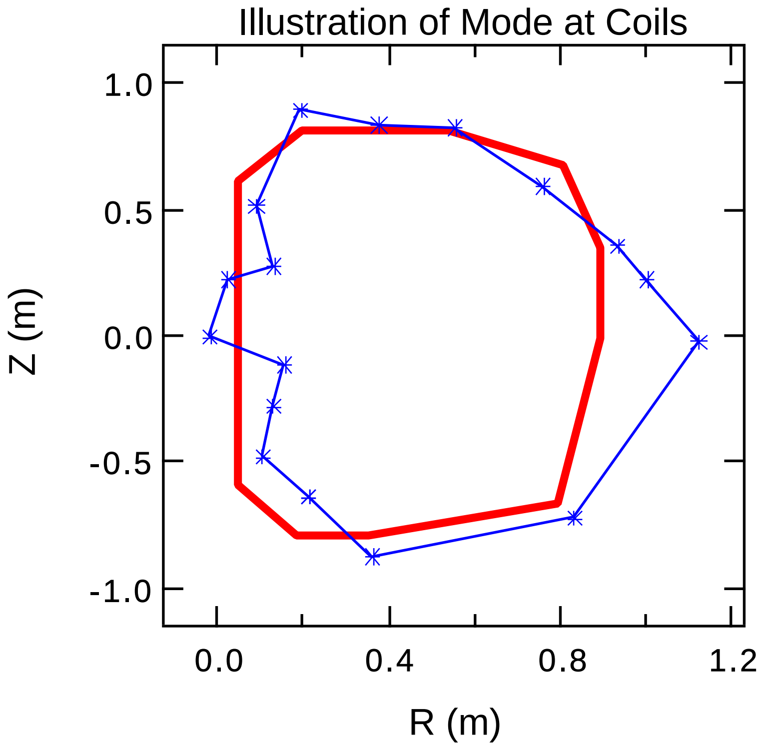
Higher-current discharges exhibit a greater variety of MHD activity

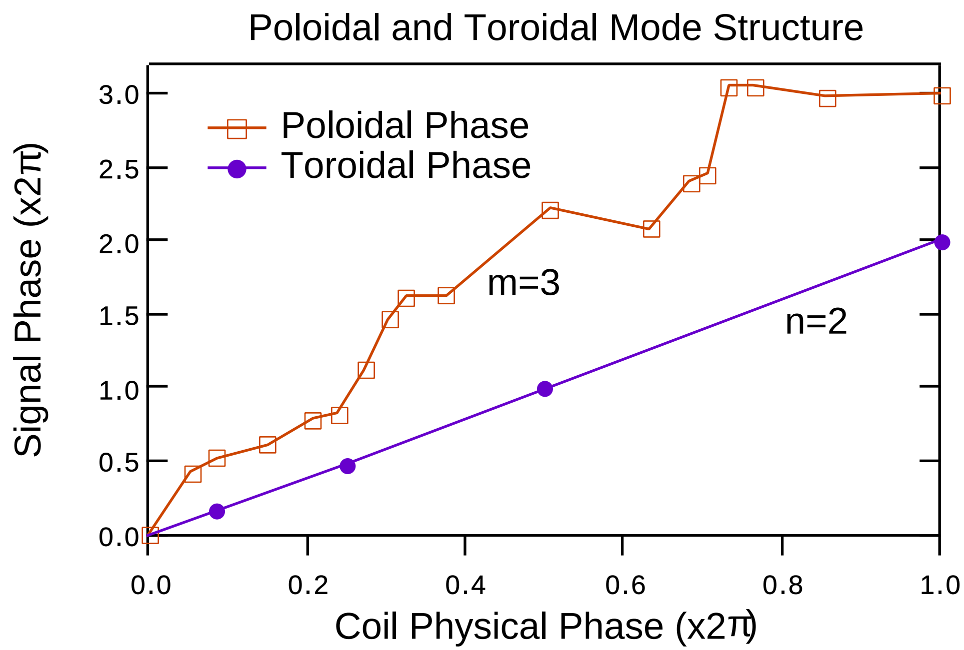
- Recent operations scenarios produce plasmas with I_p 150 kA
    - Improved plasma control
    - Improved conditioning
- 2/1 mode is observed but disappears
    - Is this the reason for improved performance?
- A 3/2 mode appears after a quiescent period
- Appearance of 3/2 mode is correlated with q_0 dropping below 1.5



An m/n=3/2 mode arises as I_p increases over 130 kA

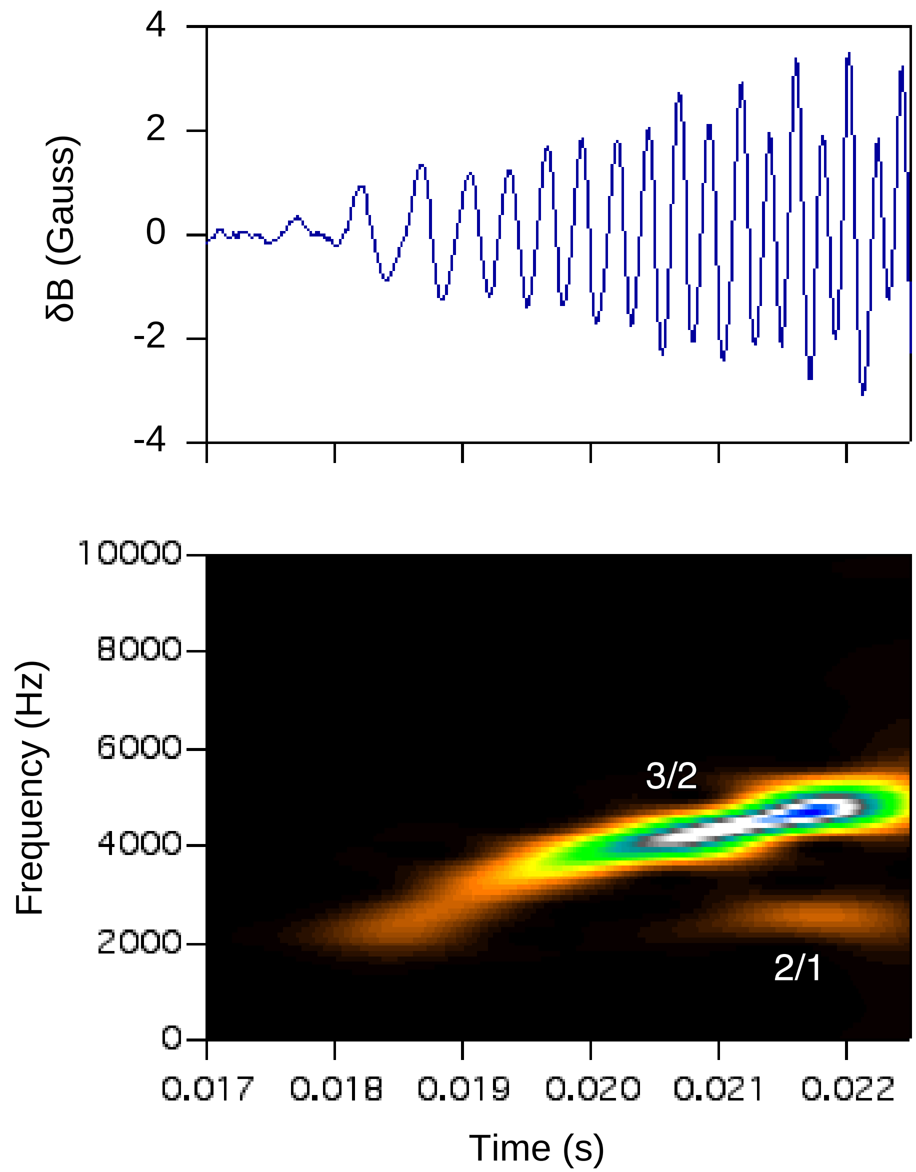
- Mode is observed in essentially all discharges over roughly 130 kA
- Toroidal structure (n=2) is clearly and unambiguously present
- Poloidal mode structure is more circular than 2/1
  - 3/2 island deeper in the core than 2/1
  - Poloidal reconstruction is less robust than 2/1 case
  - Some up/down asymmetry is observed



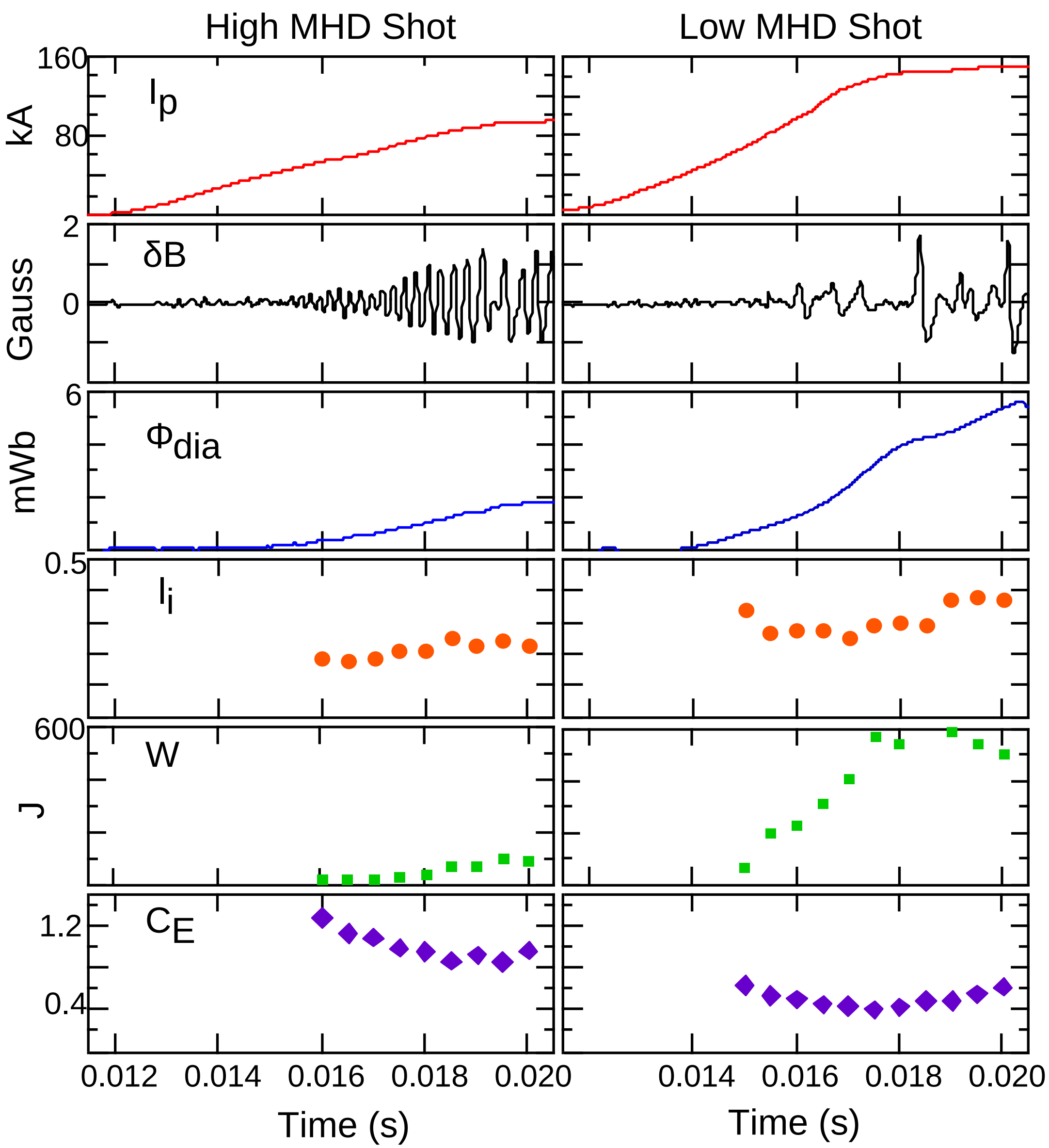


A 2/1 mode is destabilized after the 3/2 mode appears

- 3/2 mode appears after a quiescent period following the end of the 2/1 mode
  - l_i and I_p rise in this period
- Frequency of 3/2 mode typically increases throughout its lifetime
- 2/1 island re-appears after 3/2 mode begins
  - Delay is 1-3 ms
  - 2 modes are discernible in the raw data
- Why does 2/1 become destabilized?
  - Profile modification due to 3/2?
  - Mode coupling with an unobserved 1/1 mode?
- Can these modes be stabilized by optimizing the run scenario?

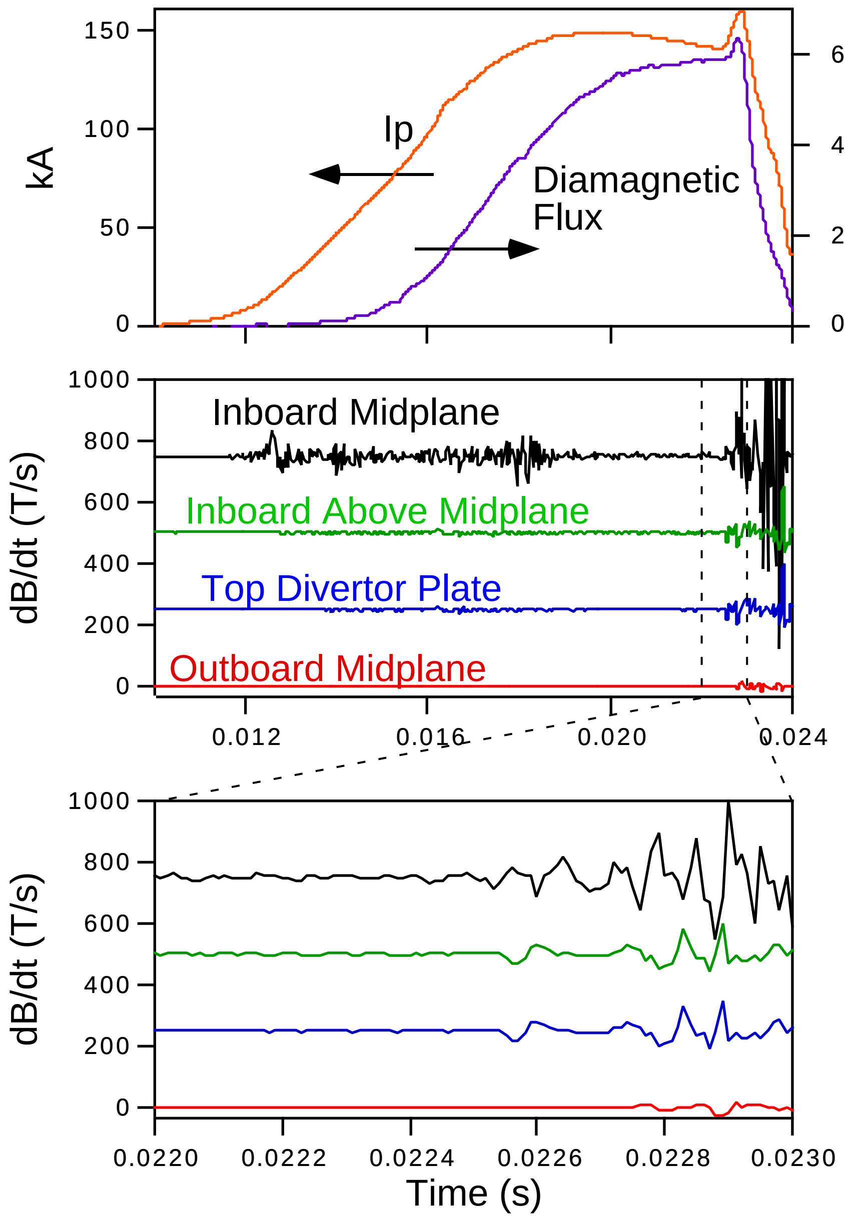


MHD activity appears to limit plasma performance



- Reduction in MHD typically results in improved plasma performance
- In "High MHD" Case:
  - l_i stays low (0.3)
  - Stored energy stays < 100 J
  - Ejima coefficient > 0.8
- In "Low MHD" Case:
  - l_i climbs higher (despite higher V_{loop})
  - Stored energy climbs to 600J
  - Ejima coefficient ~ 0.4
- Reduction of 2/1 mode was important for improved plasma performance
- Further studies are planned to elucidate relative roles of MHD and flux consumption on startup

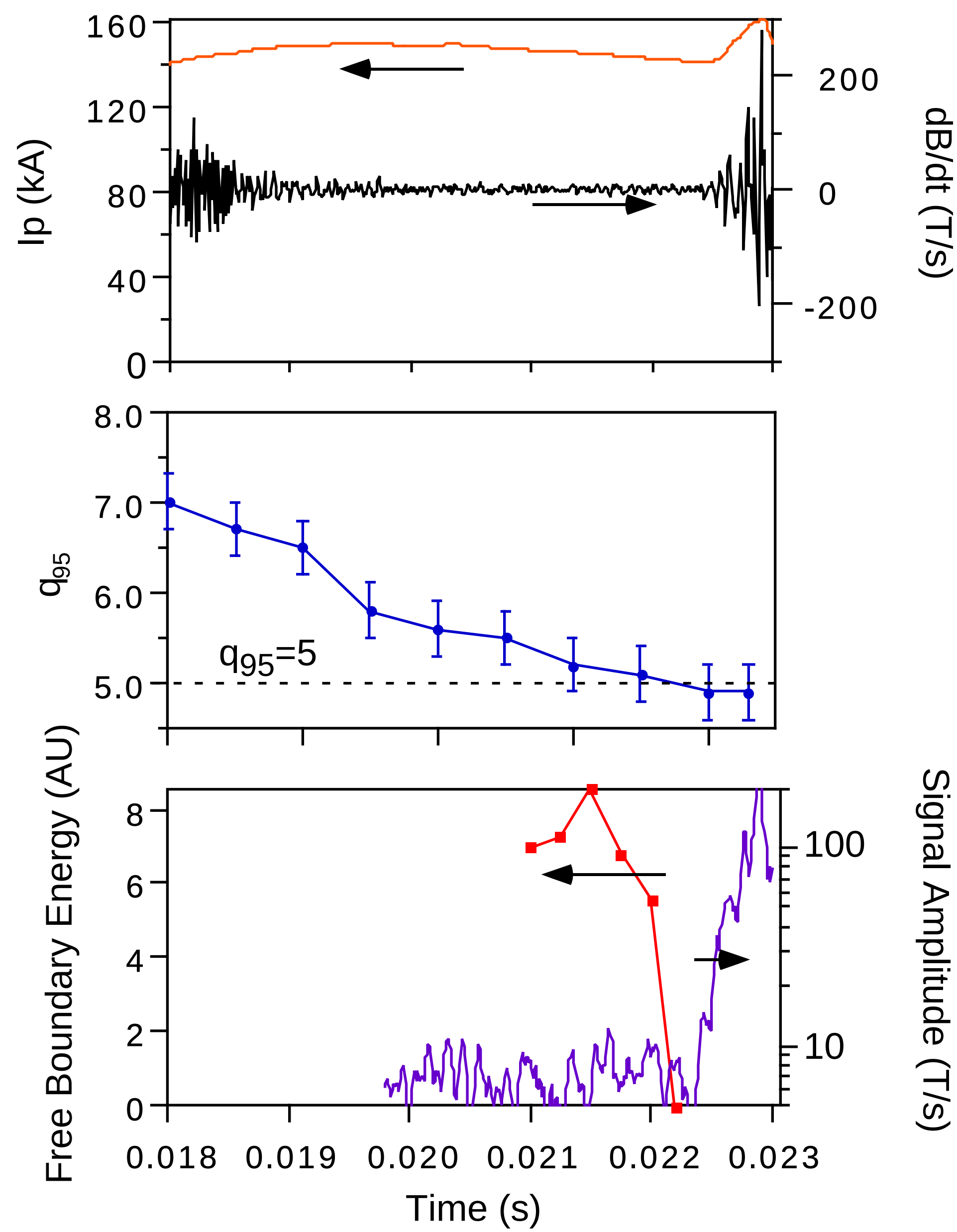
Fluctuations are observed on coils prior to disruption



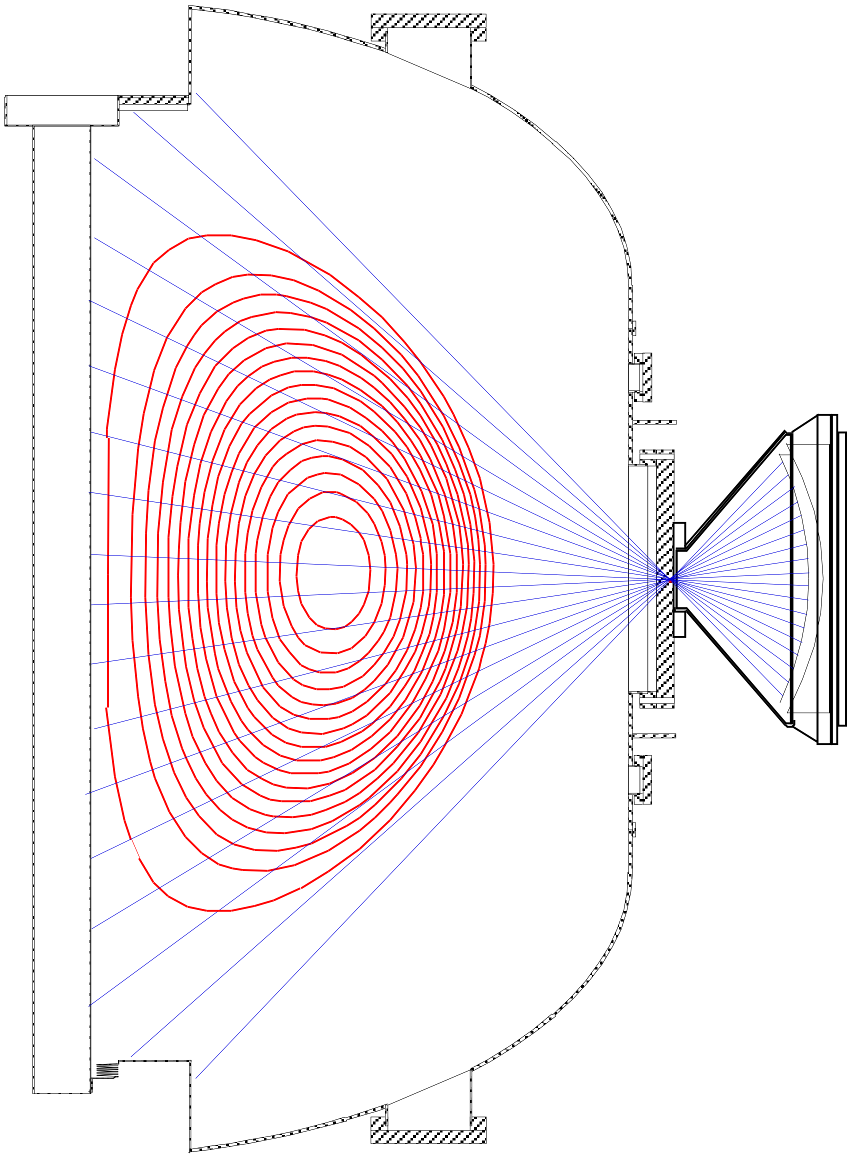
- Higher-current discharges (150 kA class) often terminate in abrupt disruptions
  - Lower-current shots have IREs followed by gradual plasma termination
- Fluctuations are observed on Mirnov coils immediately prior to disruption
  - Dominant frequency is order of 10 kHz
  - Mode is observed a few 100 μs before IRE
- These fluctuations are not observed in lower-current shots

Data and calculations indicate external kink modes

- Observed disruptions are associated with edge kink limits
  - Oscillations not observed until $q_{95} \approx 5$
- Calculated free-boundary energy approaches zero as oscillations begin
  - Negative value indicates instability to external kink
  - Calculations made with DCON and VACUUM
- Consistent with theoretical understanding of ideal kink stability at near-unity A
  - As $A \rightarrow 1$, stable q_a increases
  - Does finite β play a role?
- Mode grows on a hybrid time scale between τ_A and $q(dq/dt)^{-1}$
  - Roughly as expected for a plasma slowly crossing instability boundary

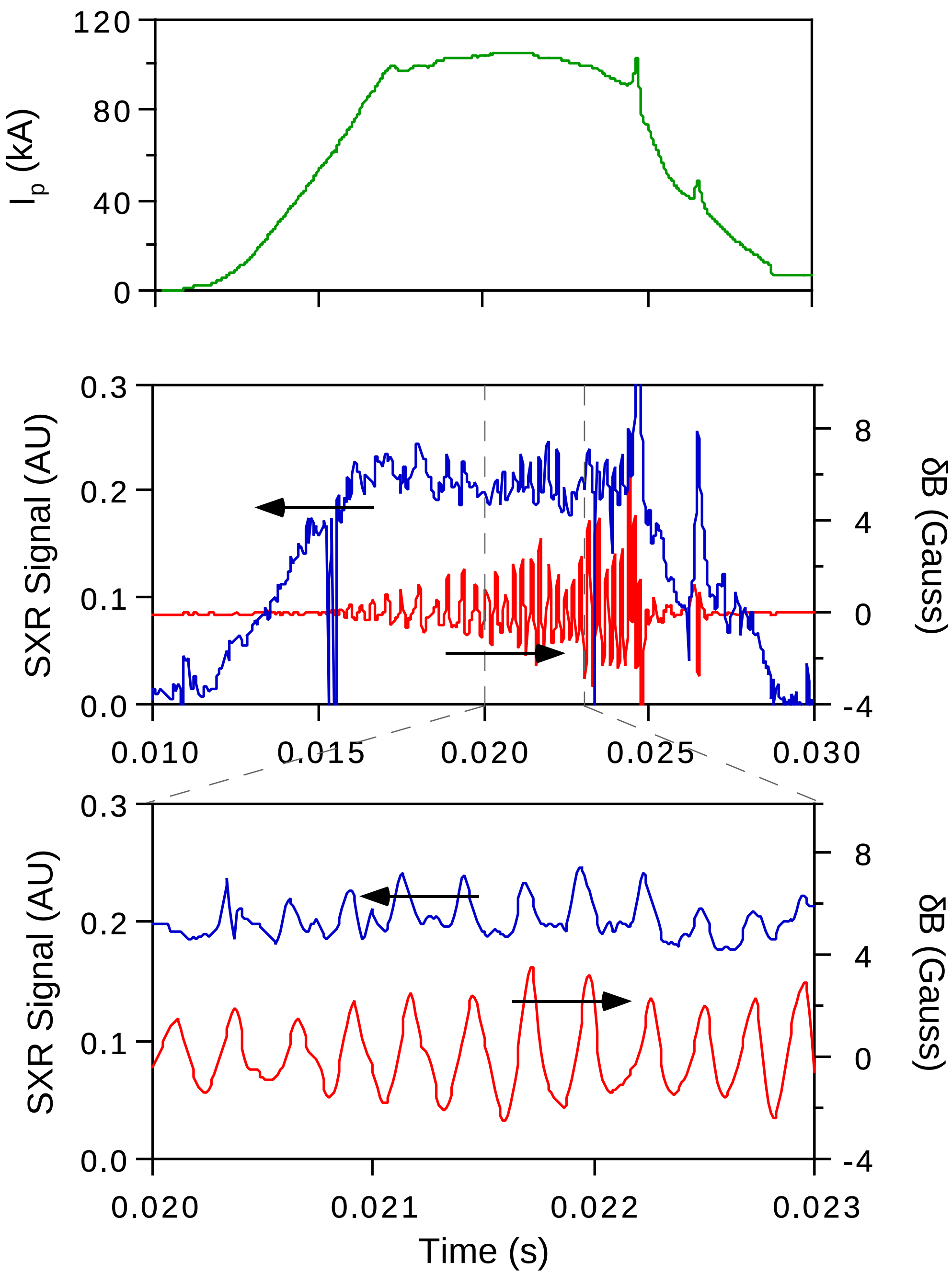


Poloidal soft X-ray diagnostic will aid MHD diagnosis



- 18-channel array
  - Originally from S-1 spheromak
  - Vacuum can modified for PEGASUS
- Standard detector technology
  - Reverse-biased SiLi diodes
  - 2-stage amplifiers
- Metal foil filters placed on each diode
  - Shielded from Ti gettering
- Full array will be made operational later this year

SXR array observes 2/1 mode



- SXR array was tested using a single central channel
- Diagnostic observes bulk plasma signal
- Also observes fluctuations associated with 2/1 magnetic island
  - Fluctuations on the order of dS/S=10-20%
  - Clear phase relationship with outboard Mirnov coil
  - Phase between island O-point and peak of X-ray emission is as expected

Summary of MHD activity on PEGASUS

- Large magnetic islands are observed
  - *2/1 mode seen in all high-power shots*
  - *3/2 mode observed in 150 kA class shots*
  - *Mode helicities consistent with* $q_{min} < m/n$
  - *3/2 mode associated with destabilization of 2/1*
  - *Soft X-ray array will provide details of internal structure*

- These islands appear to degrade plasma performance
  - *More quiescent plasmas exhibit lower* C_E
  - *Discharge tailoring can reduce effects of modes*

- Disruptions in higher-power plasmas are associated with external kinks
  - *Equilibria suggest q=5 is culpable surface*
  - *Rapidly-growing oscillation observed immediately prior to disruption*
  - *DCON and VACUUM predict instability at correct time*