Equilibrium and Stability Analysis of PEGASUS Plasmas

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Abstract

Magnetic equilibrium analyses of near-unity aspect-ratio discharges in the PEGASUS Toroidal Experiment have been performed using a locally developed code which incorporates a nonlinear least-squares fitting routine coupled to a Grad-Shafranov solver. Induced currents in the continuous, resistive vessel wall are estimated using a time-evolving current filament model and are constrained during the reconstruction by wall-mounted flux loops and B-dot coils. With I_{wall}/I_p up to 2, the wall contribution to the total poloidal field often dominates early in the discharge. An upgrade of the internal magnetics set to include 20 poloidal flux loops, a poloidal array of 20 B-dot coils, and a diamagnetic loop has increased the accuracy of equilibrium reconstructions. Plasmas with $A < 1.3$, $I_p <= 0.15$ MA, $0.2 < l_i < 0.8$, and $\beta_t <$ 25% have been analyzed. The presence of a broad q ~ 2 region inside the plasma corresponds to the growth of a large m=2/n=1 internal mode; at higher values of plasma current an m=3/n=2 mode has been observed. Ideal stability analyses have been performed using DCON; these analyses predict instability to external kink modes in good agreement with observed plasma disruptions.

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Overview

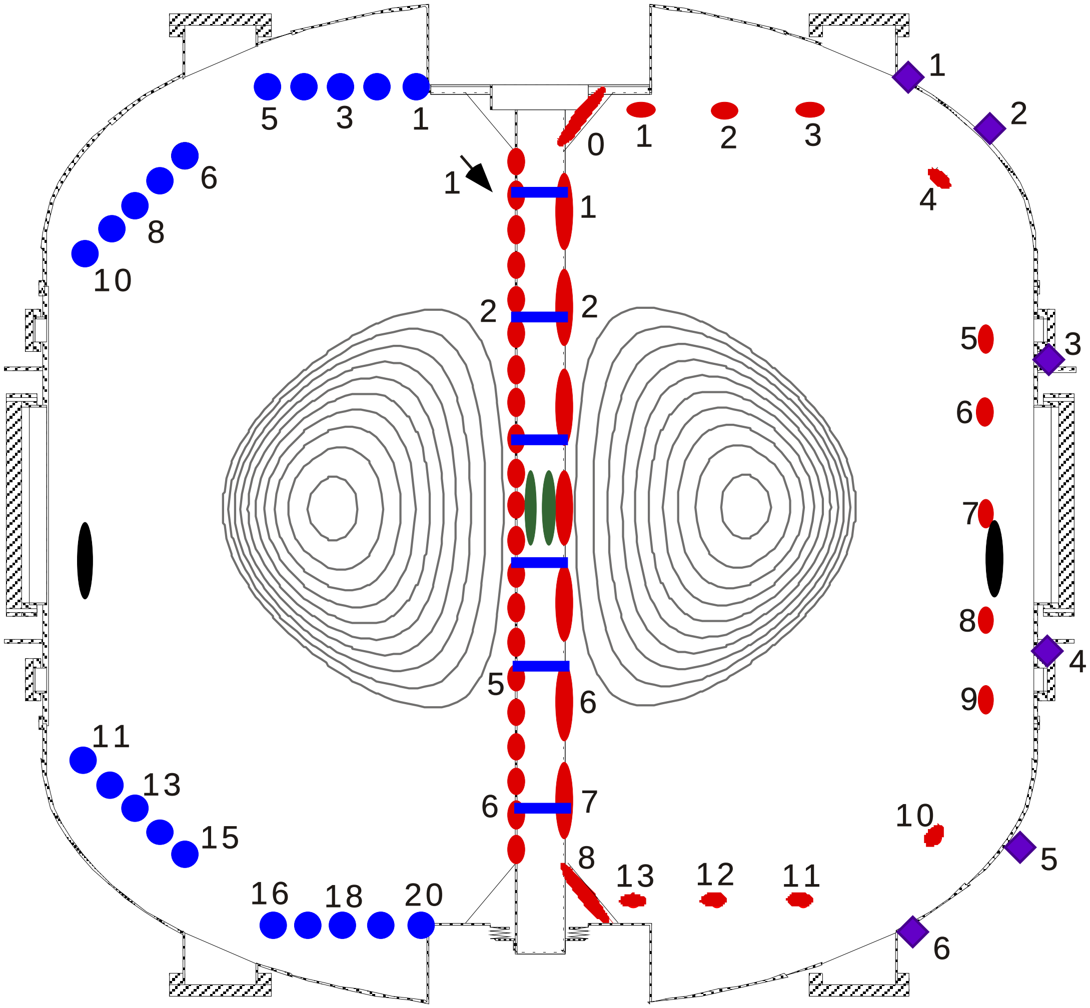
- Equilibrium reconstruction for PEGASUS
  - *- New diagnostics*
  - *- Incorporation of wall currents*
  - *- New equilibrium code*

- Results of equilibrium analysis
  - - β_t <= *25%*
  - *- Observation of low* l_i*, high* κ *plasmas*
  - *- Agreement with observed MHD activity*

- Observations of large-scale resistive MHD
  - *- m/n = 3/2 and 2/1 readily observed*
  - *- Modes consistent with low-central-shear region in ST*

- Indications of external kink mode
  - *- Experiment exhibits disruption when* $q_\psi = 5$
  - *- Calculations suggest instability to external kink*

New Magnetics Diagnostics Installed in 2001



- ● Flux Loops (26)
- ◆ Wall Flux Loops
- ● Poloidal $\dot{B}$ Coils (22 + 21)
- ● LFS Toroidal $\dot{B}$ Coils (6)
- ● HFS Toroidal $\dot{B}$ Coils (7)

Future Diagnostic:

- Wall $\dot{B}_{tan}$ strips

Not shown:

- Plasma Rogowski Coils (2)
- Diamagnetic Loops (2)
- Diamagnetic Compensation Loop
- Internal B_{tan} Coils (15)

  - constrain wall currents

Resistive Vacuum Vessel Wall Modeled as Axisymmetric Current Filaments

- **Induced wall currents calculated by numerically integrating resulting set of differential circuit equations**

  - coupled current filaments described by matrix equation

$$\overline{\overline{M}}\,\frac{d\bar{I}}{dt} + \overline{\overline{R}}\;\bar{I} = \bar{V}$$

  - inductance matrix (*M*) determined by coil set self-inductances and mutual-inductances

inductance of individual filament (wall)

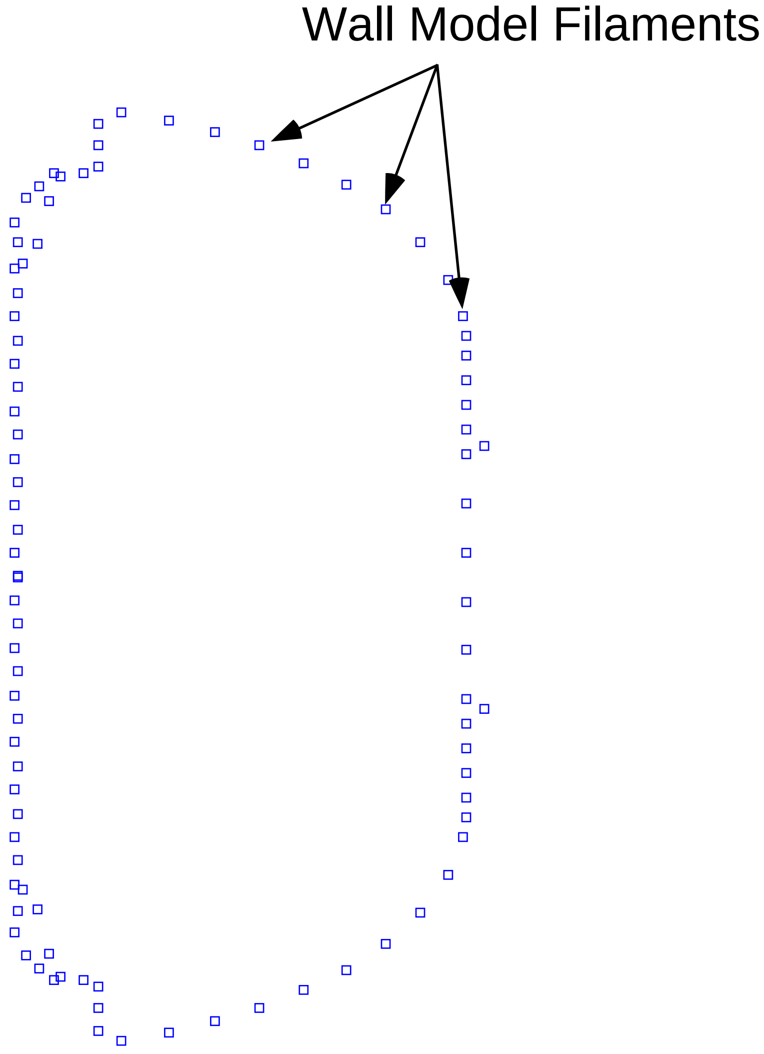
$$L_i = \mu_0 R\left[\ln\left(\frac{8\sqrt{\pi}R}{\sqrt{A}}\right) - \frac{7}{4}\right]$$

self-inductance of coil set i

$$L_i I_i = \sum_{k=1}^{N_i}\sum_{l=1}^{N_i}\Phi_i^{k,l}$$

mutual inductance of coil set i with coil set j

$$M_{ij} I_j = \sum_{k=1}^{N_i}\sum_{l=1}^{N_j}\Phi_{ij}^{k,l}$$

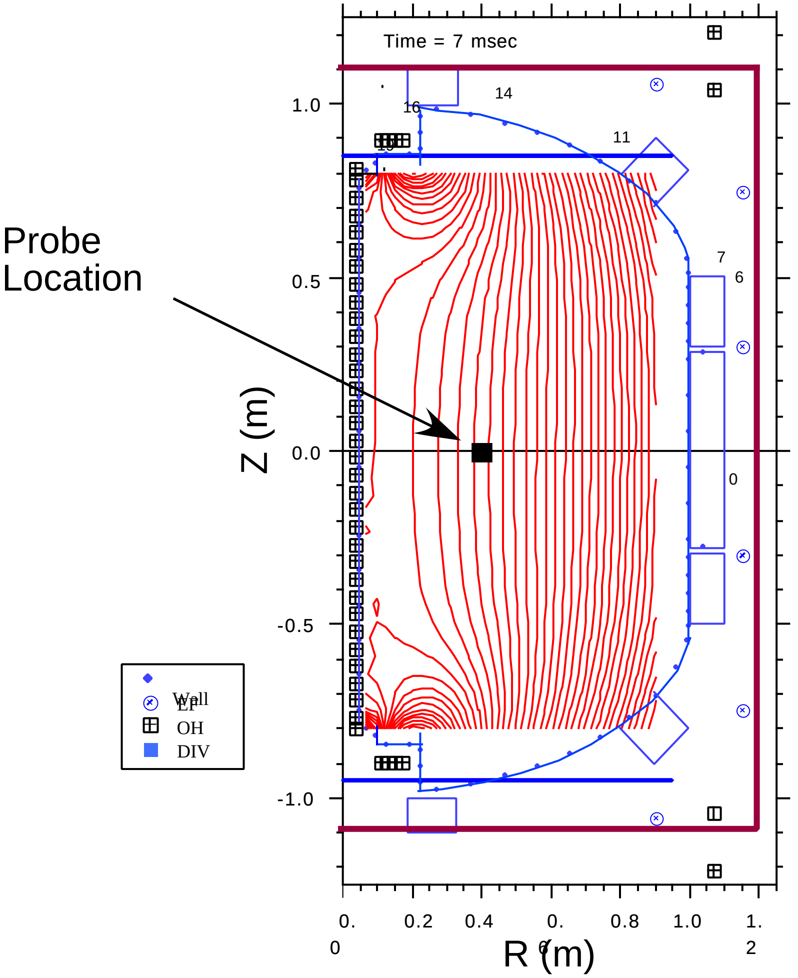


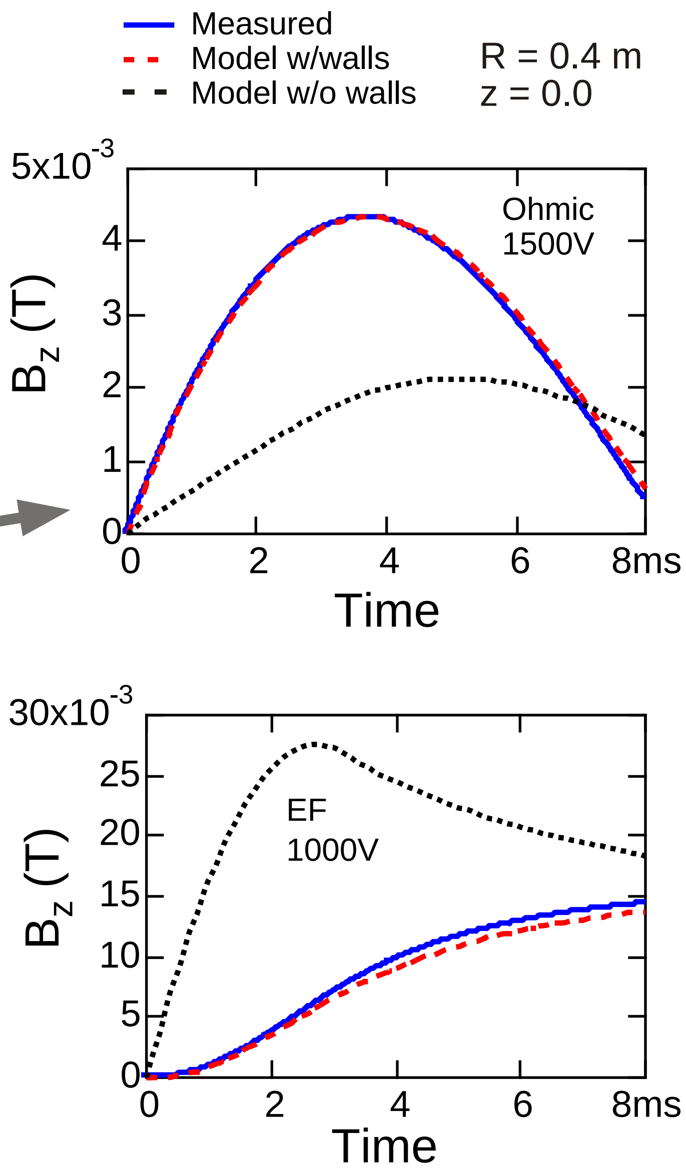
Wall Model Calibrated With Probe Measurements

- **Comparison of measured and calculated poloidal fields in agreement**

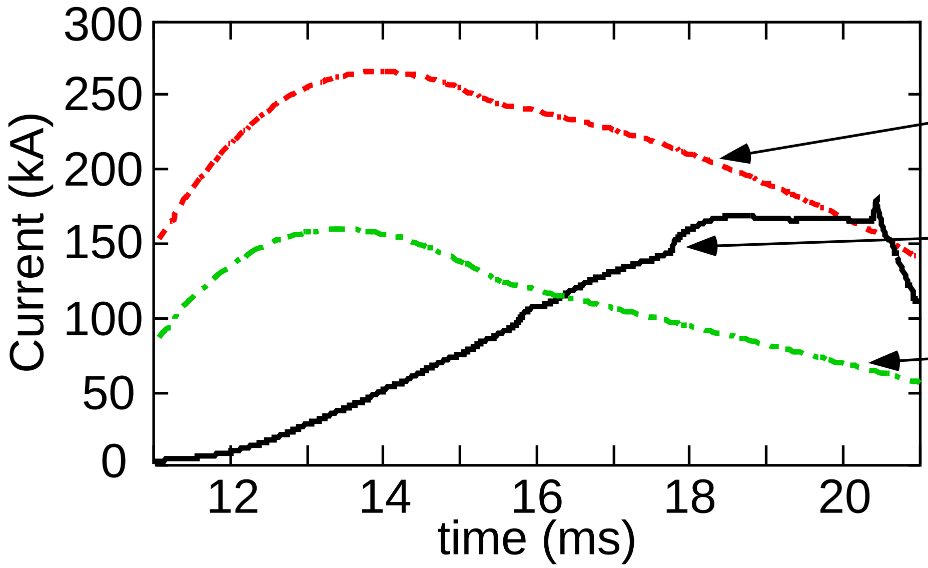
- **Good first-order estimate of wall currents**
  - equilibrium code used to fit these currents

Flux plot for OH only case





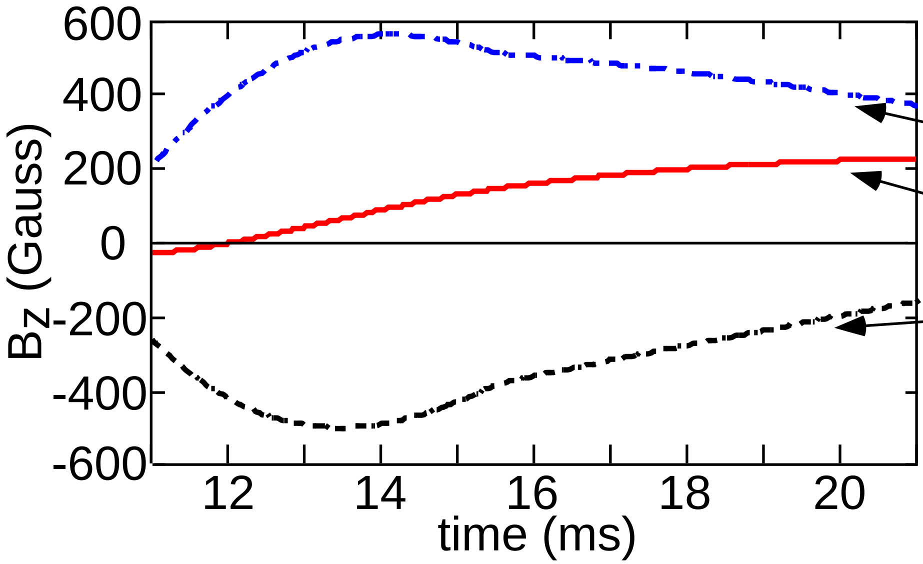
Wall Currents Are Significant During Startup



Total Wall Current

Plasma Current

Currents in dome,
outer wall, and port



B_z from external coils

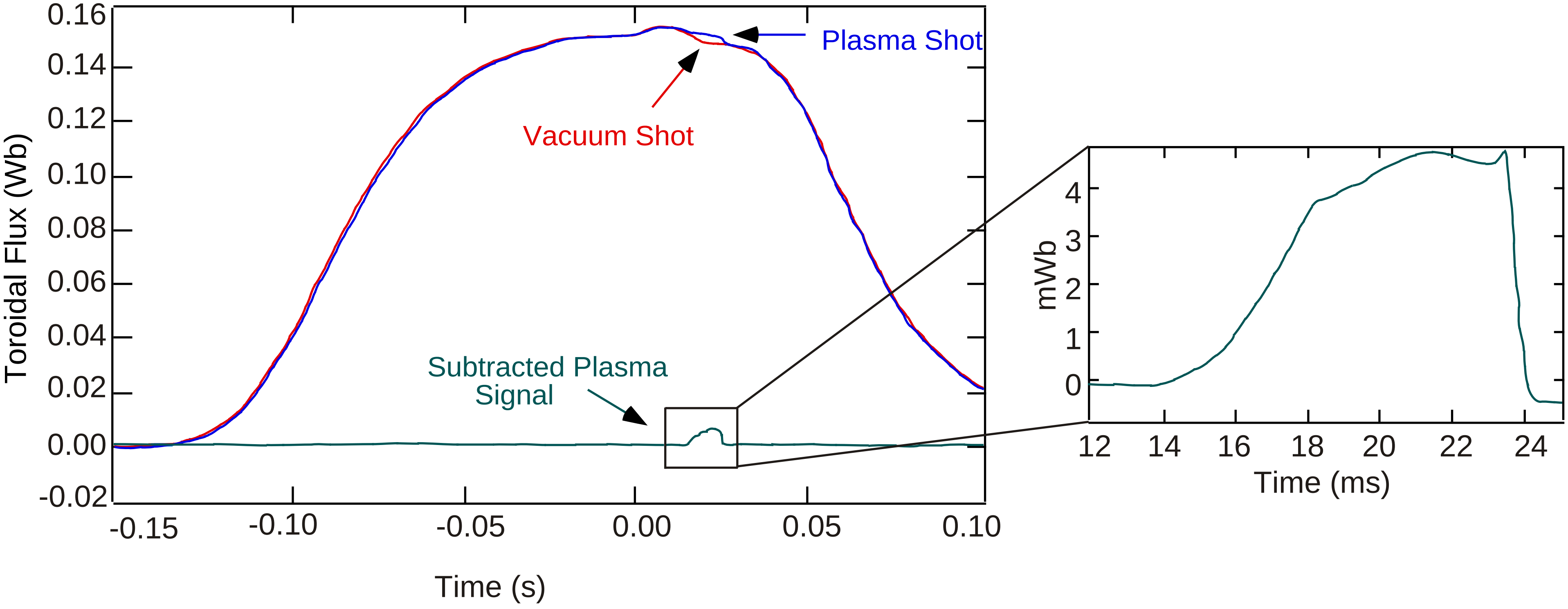
B_z total

B_z from wall currents

@R = 35 cm

Diamagnetic Loop Used to Constrain Pressure

- For Pegasus, ΔB_{tor} due to plasma is relatively large.
  - Alignment to ±1mm is adequate.



- A compensation loop is used to remove signal noise due to TF switching transients

New Equilibrium Code Developed for PEGASUS

- **Motivation:**
  - robustness
  - easy incorporation of new diagnostics
  - cross-platform

- **Description:**
  - full solution of Grad-Shafranov equation at each iteration
    - Gauss - Seidal multigrid relaxation on 2-D grid
  - minimize χ^2 of fit to measurements
    - via Levenberg-Marquardt method

- **Implementation:**
  - IGOR Pro routine interfaced to an ANSI C G-S solver
  - built-in graphics capabilities for data display
  - has been validated against TokaMac

- **Drawbacks:**
  - computationally intensive → relatively slow
  - average fit takes approximately 1.5 minutes on 1.3 GHz Athlon

Upgraded Diagnostic Set Constrains Equilibrium Fits

- **Flux loops, B coils, diamagnetic loop and plasma Rogowski used routinely**

  - flux and B errors estimated from uncertainty in diagnostic positions
  - error in plasma Rogowski from uncertainty in subtraction of core armor currents

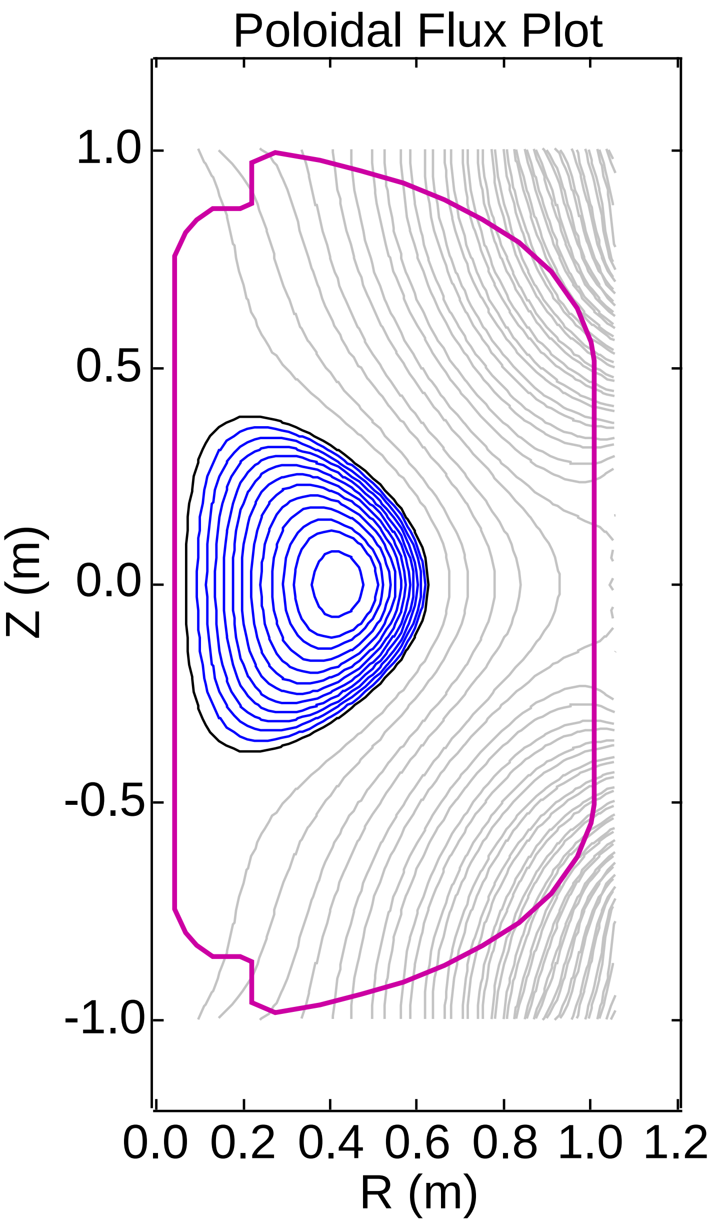
Measurement	value	fit	% difference	meas. error	χ^2
Flux Loops: # 5	0.0552 Wb	0.0547 Wb	0.9 %	3 %	0.1
# 6	0.0938 Wb	0.0950 Wb	1.3 %	3 %	0.2
# 8	0.1151 Wb	0.1147 Wb	0.3 %	3 %	0.01
# 9	0.1187 Wb	0.1220 Wb	2.8 %	3 %	0.9
# 12	0.1264 Wb	0.1240 Wb	1.9 %	3 %	0.4
# 13	0.1164 Wb	0.1159 Wb	0.4 %	3 %	0.02
# 15	0.1012 Wb	0.0954 Wb	5.7 %	3 %	3.7
# 16	0.0537 Wb	0.0528 Wb	1.7 %	3 %	0.3
wall # 1	0.1205 Wb	0.1139 Wb	5.5 %	5 %	1.2
wall # 2	0.1988 Wb	0.1867 Wb	6.1 %	5 %	1.5
wall # 3	0.1033 Wb	0.0932 Wb	9.8 %	5 %	3.8
wall # 4	0.1004 Wb	0.0932 Wb	7.2 %	5 %	2.0
wall # 5	0.1976 Wb	0.1872 Wb	5.3 %	5 %	1.1
wall # 6	0.1164 Wb	0.1139 Wb	2.1 %	5 %	0.2
B coils: outboard # 5	-0.0296 T	-0.0312 T	5.4 %	5 %	1.3
outboard # 6	-0.0264 T	-0.0256 T	3.0 %	5 %	0.4
core low-res # 4	0.1818 T	0.1811 T	0.4 %	5 %	0.01
diamagnetic loop	**0.00515 Wb**	**0.00524 Wb**	**1.7 %**	**5 %**	**0.1**
plasma Rogowski	**149370 A**	**152107 A**	**1.8 %**	**2 %**	**0.8**

- **0.8 < χ^2_ν < 1.5 is typical on high-current discharges (I_P > 90 kA)**

  - statistically good fit

Increased β_t Accessible by Reduction of Toroidal Field

- **Note: This shot was prior to OH modifications which increased available V-s**
  - $\beta_t \leq 10\%$ for full field shots with similar OH V-s

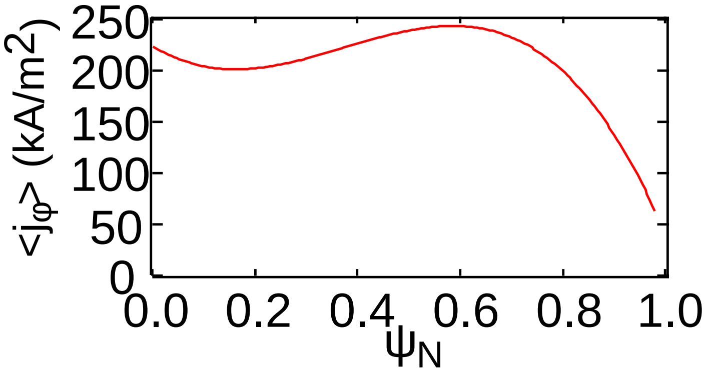


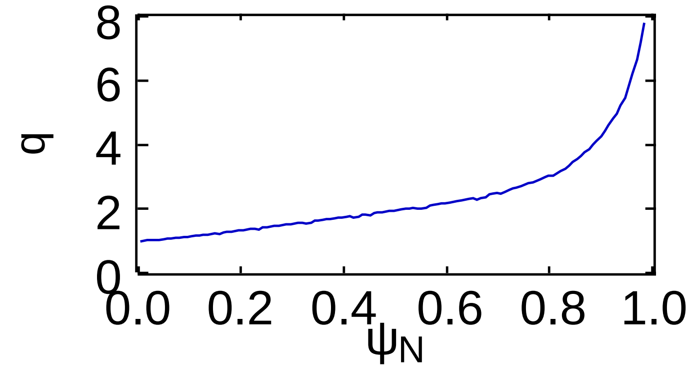
Shot
12445

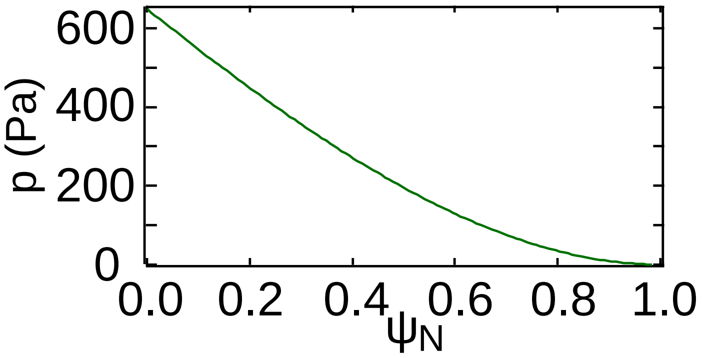
I_p	78.3 kA
R_0	0.337 m
a	0.274 m
A	1.22
κ	1.4
B_t (axis)	0.048 T
β_t	18%
l_i	0.40
q_0	0.98
q_{95}	7.8

Constraints:

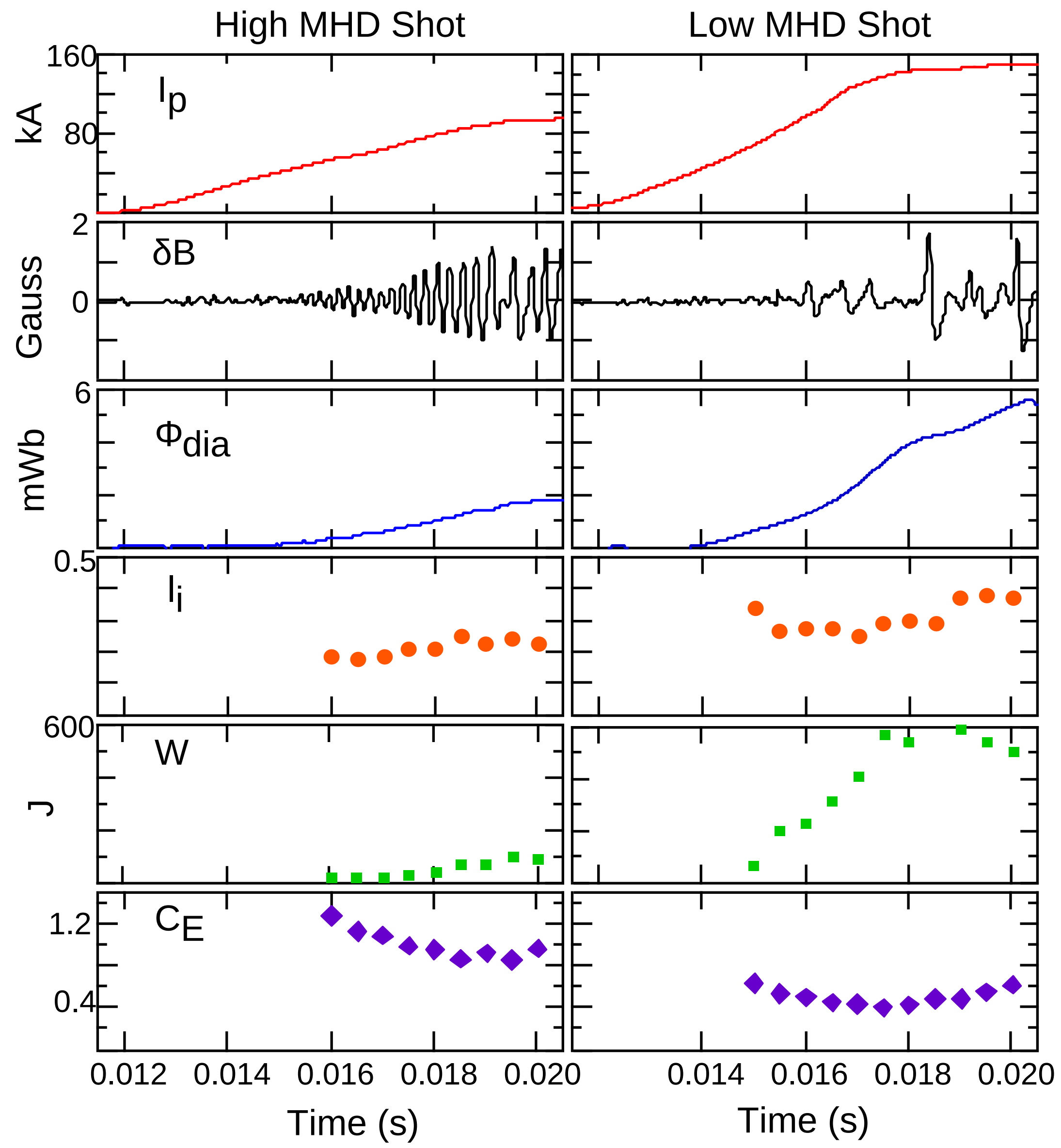
Rogowski Coil
18 Flux Loops
3 B_p Coils
Diamagnetic Loop







MHD activity appears to limit plasma performance



- Reduction in MHD typically results in improved plasma performance

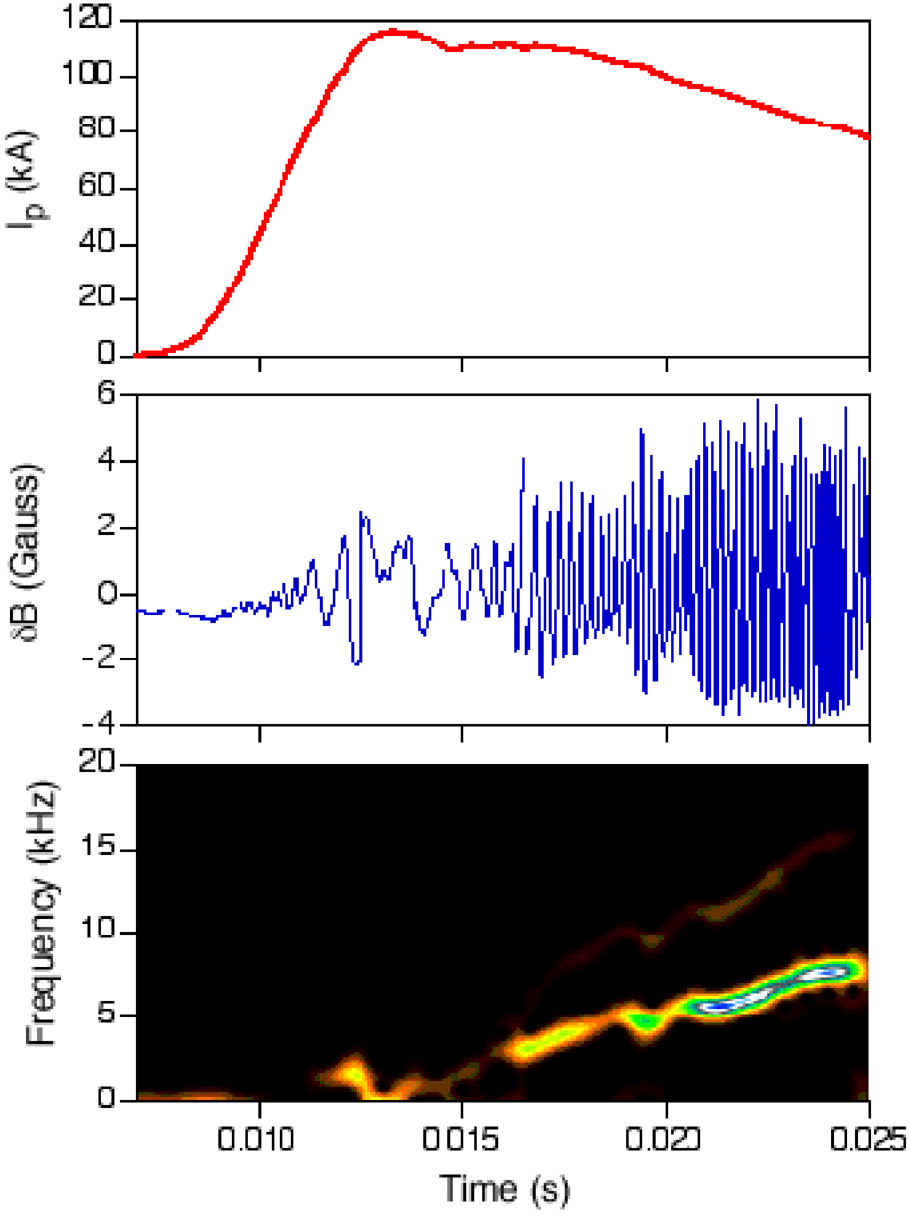
- In “High MHD” Case:
  - l_i stays low (0.3)
  - Stored energy stays < 100 J
  - Ejima coefficient > 0.8

- 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

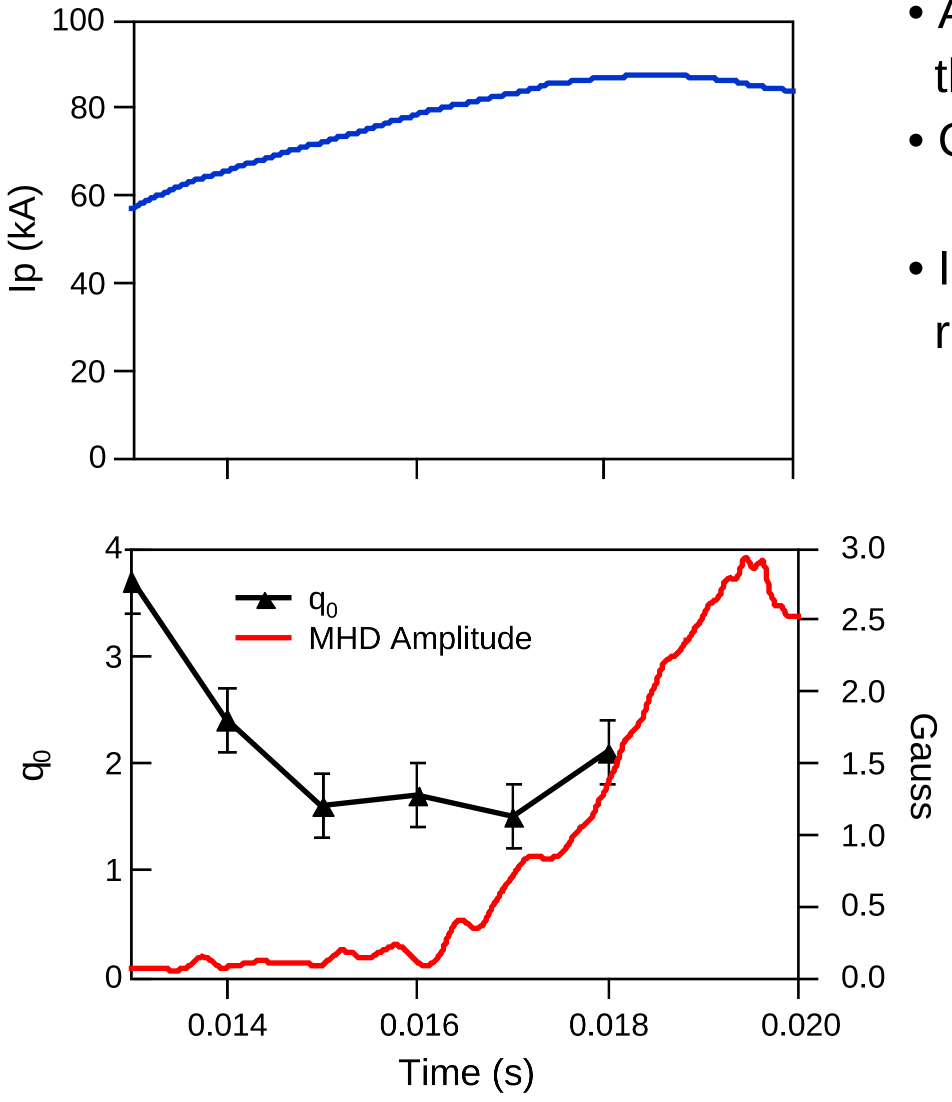
- Further studies are planned to elucidate relative roles of MHD and flux consumption on startup

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

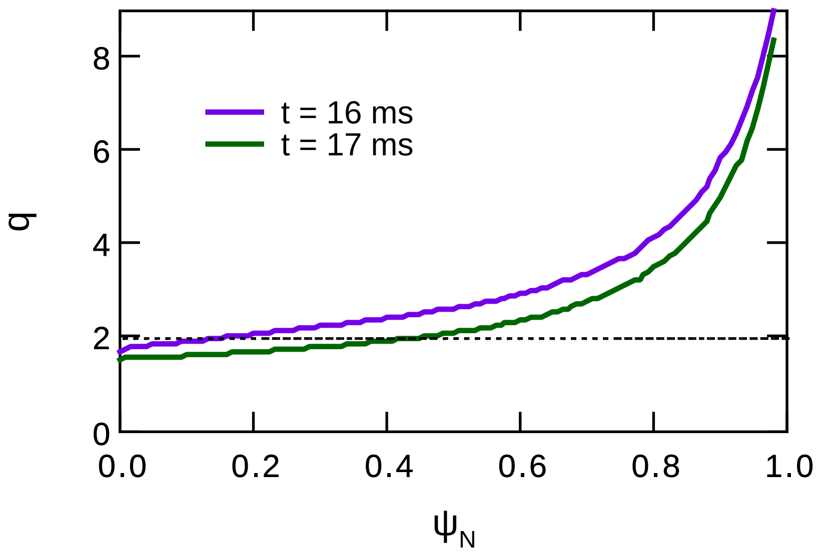


- Mode present in all significant discharges
- Rotates in electron diamagnetic direction
  - Mode is likely magnetic island
- Frequency is typically 4-10 kHz
  - No evidence of mode locking
- Little shear stabilization of island growth
  - Central shear is nearly zero

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

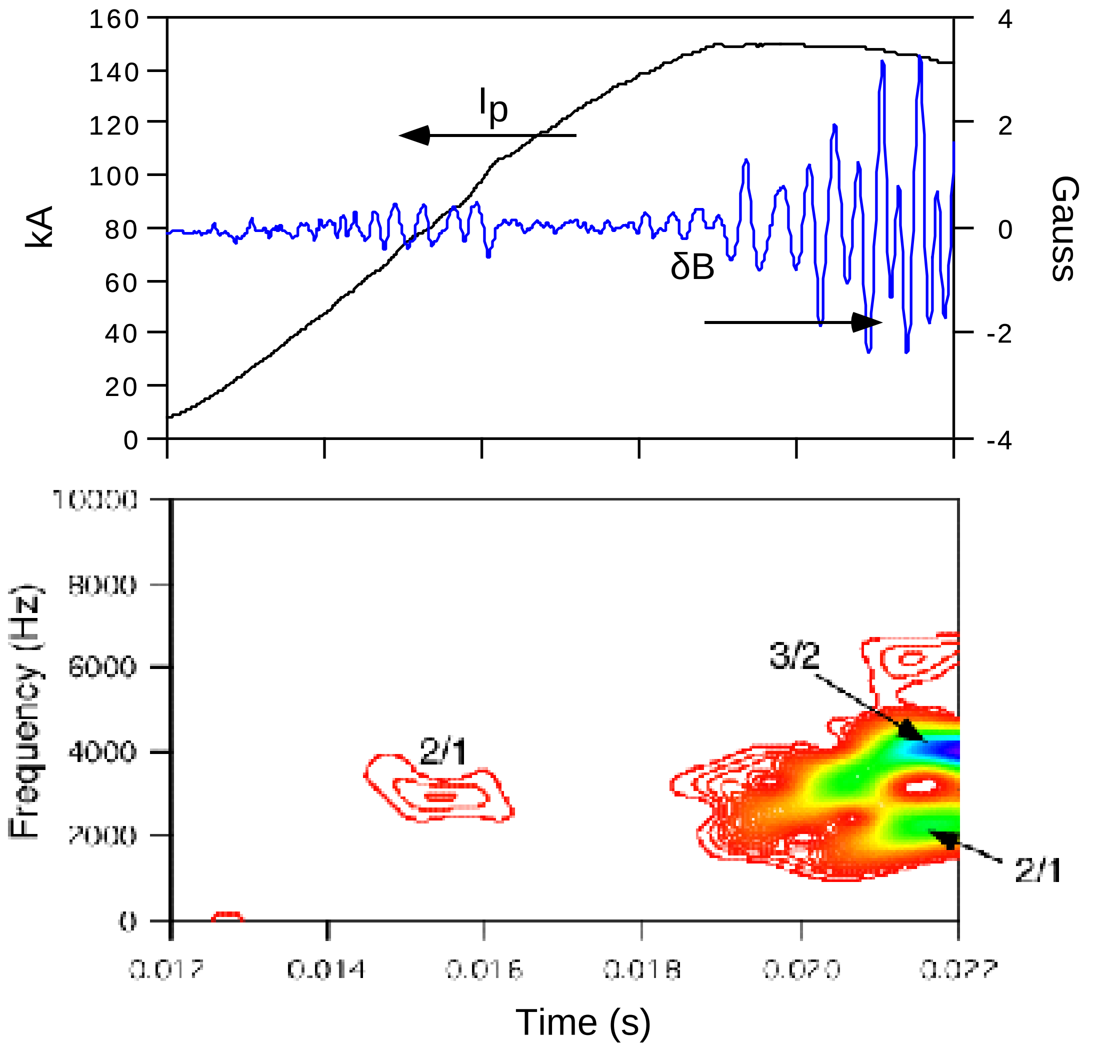


- Consistent with observed helicity of the mode
- A large region of low shear exists about the q=2 surface
- Central q inferred from Equilibrium fit
  - *2D SXR camera will constrain q_0*
- In general, strong MHD activity appears to relate to I_p limits



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



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

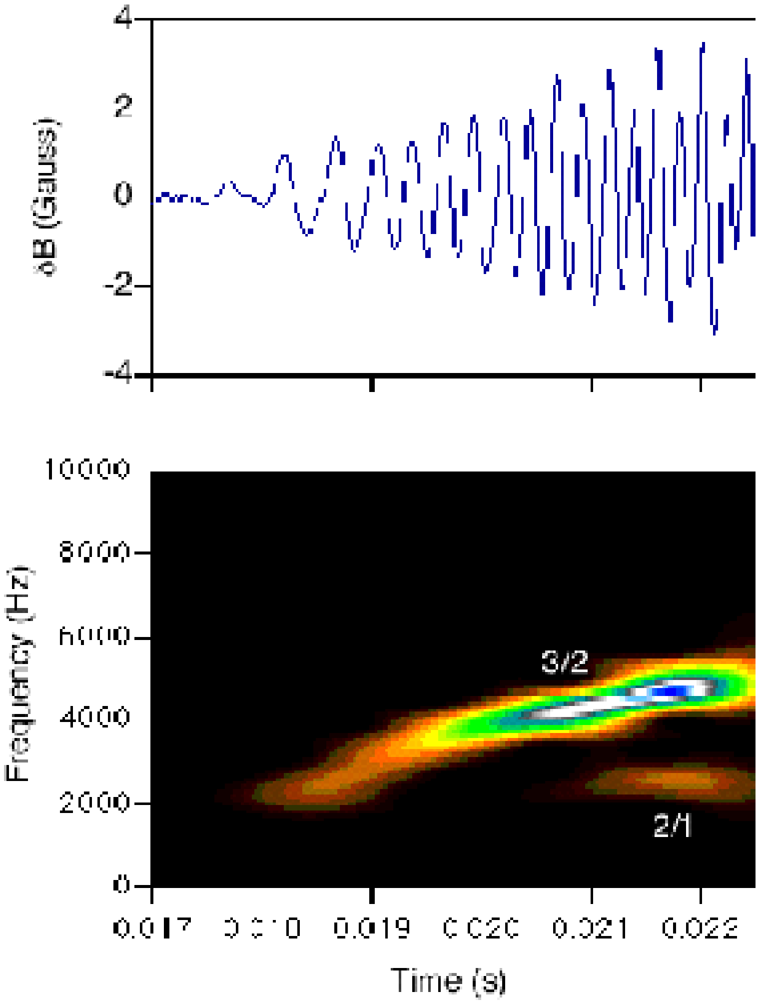
- 3/2 mode appears after a quiescent period following the end of the 2/1 mode
  - l_i and I_p rise in this period

- Frequency of 3/2 mode typically increases throughout its lifetime

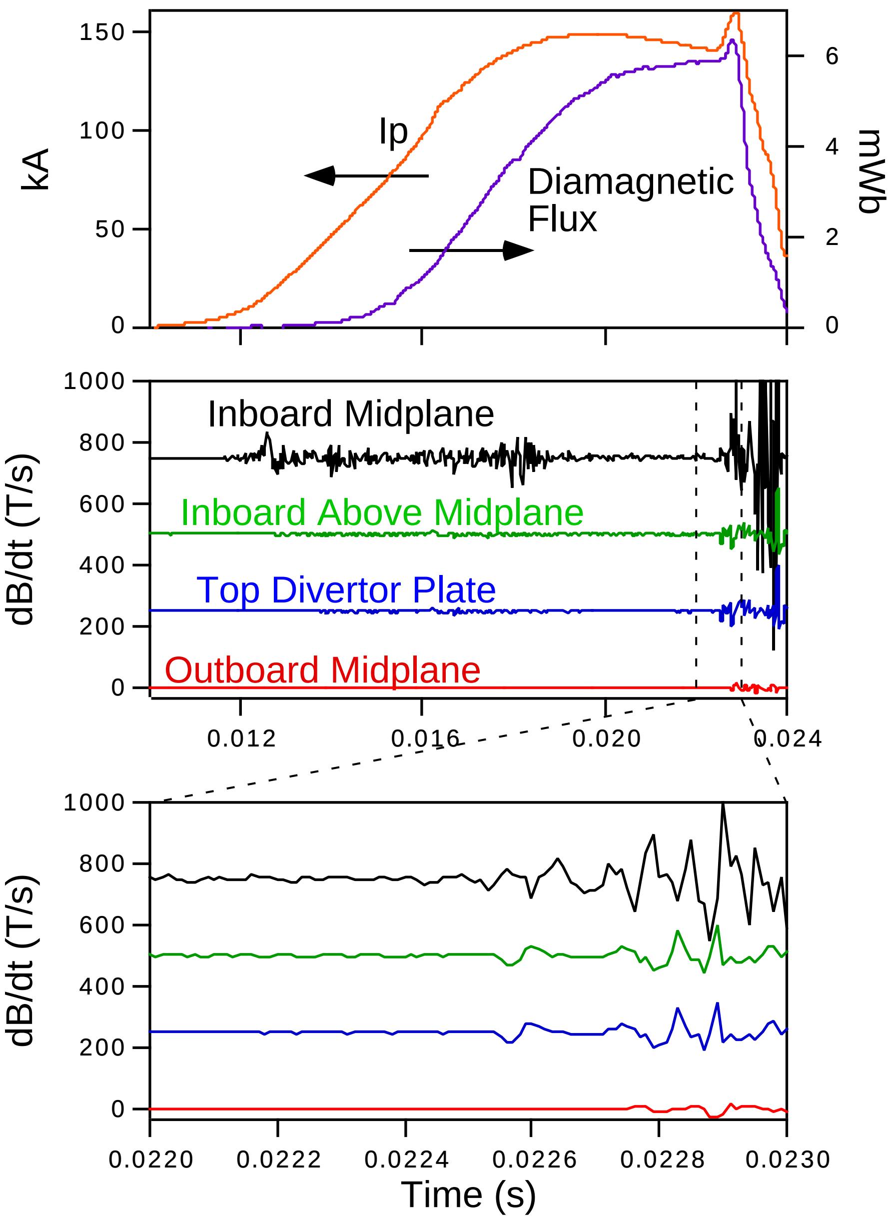
- 2/1 island re-appears after 3/2 mode begins
  - Delay is 1-3 ms
  - 2 modes are discernible in the raw data

- 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?



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

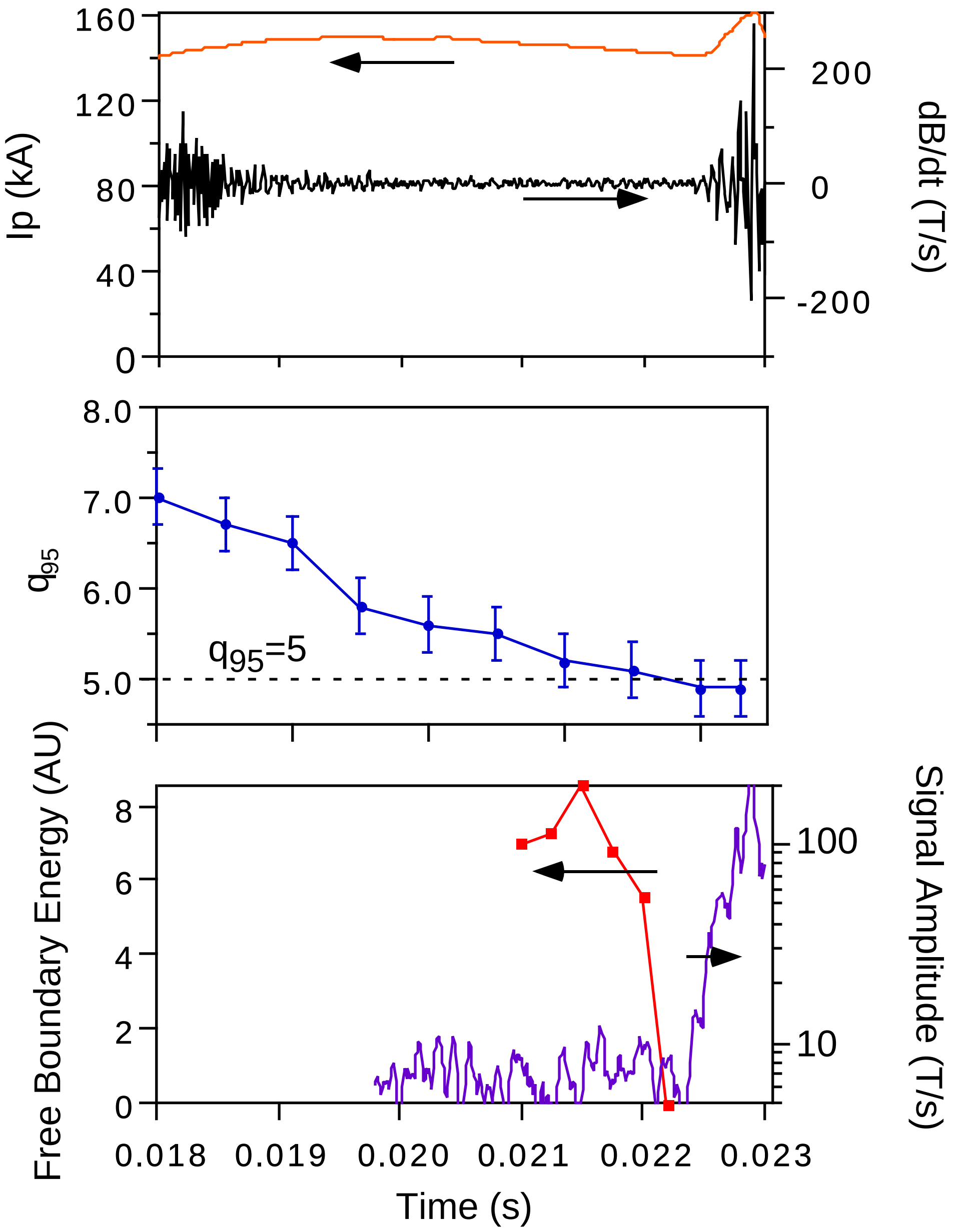
- Fluctuations are observed on Mirnov coils immediately prior to disruption
  - Dominant frequency is order of 10 kHz
  - Mode is observed a few 100 μs before IRE

- These fluctuations are not observed in lower-current shots

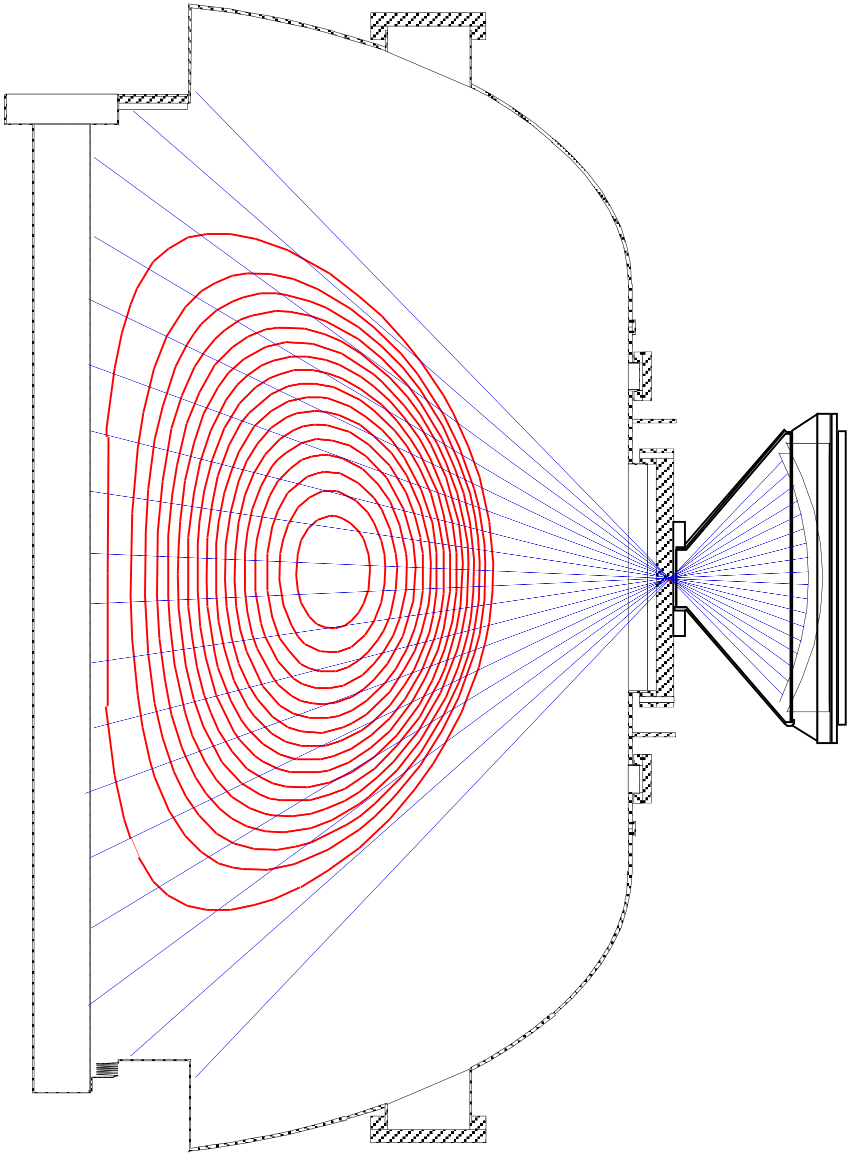
Pegasus Toroidal Experiment
University of Wisconsin-Madison

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 is now operational

Summary

- Pegasus equilibria are well characterized
  - *New magnetics added (including diamagnetic loop)*
  - *Wall currents characterized*
  - *New code developed -- robust convergence, new diagnostics easily incorporated*

- Equilibrium analysis indicates interesting physics
  - *Values of* β_t *up to 25% confirmed*
  - *Reconstructions correlate with observed MHD activity*

- Magnetic islands appear in all high-power shots
  - *Associated with low central shear of ST plasmas*
  - *2/1 mode nearly always seen, 3/2 mode observed in 0.15 MA shots*
  - *Mode helicities consistent with* $q_{min} < m/n$
  - *Islands appear to degrade plasma performance*

- Disruptions in high-power shots are associated with external kinks
  - *Equilibria suggest q=5 is culpable surface*
  - *DCON predicts instability at the correct time*