Abstract

Reconstruction of the magnetic equilibrium for recent discharges in Pegasus are obtained with a locally developed code. This code employs a nonlinear least-squares fitting routine combined with a Grad-Shafranov solver. Newly installed set of equilibrium magnetics diagnostics including a poloidal array of 20 magnetic pick-up coils, 20 poloidal flux loops on the outboard, 6 center stack flux loops, a Rogowski coil for the toroidal plasma current, and a diamagnetic loop are used as constraints. Typical plasmas exhibit broad/flat central q(R) profiles with $q_0 < 2$ corresponding to the onset of a large 2/1 mode. The ideal stability limits in q_a and beta to be expected for Pegasus are under study using the DCON code applied to model equilibria. Plasmas with high edge current gradients are unstable to edge kink modes as expected; a constraint on the edge current gradients was implemented to access more realistic plasmas. A systematic mapping of stability space (e.g. ℓ_i vs q_0, ℓ_i vs q_{95}, etc) is in progress.

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Overview

- **Equilibrium reconstruction is an important tool for PEGASUS**
  - determines global plasma parameters
  - provides necessary information for stability analysis

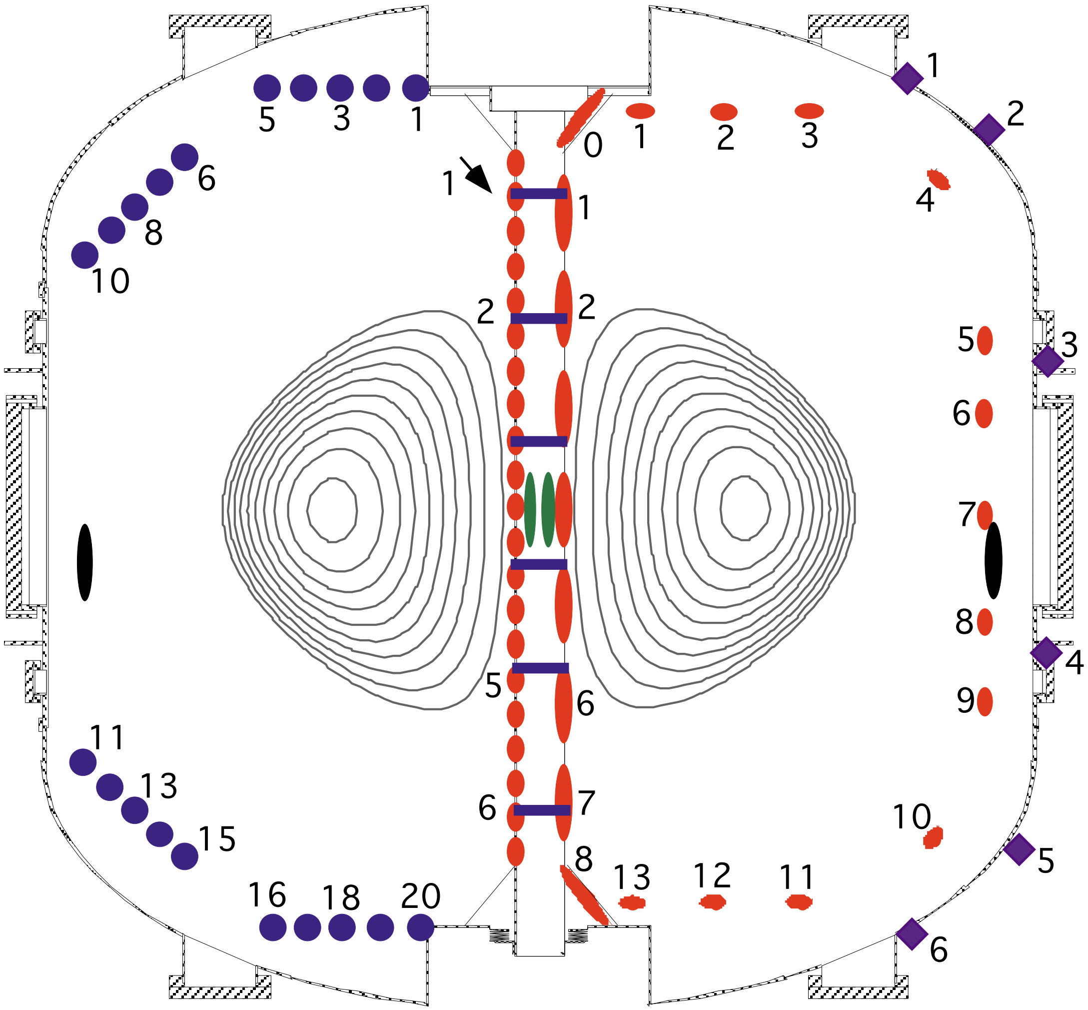
- **New magnetic equilibrium code developed**
  - robust fitting routine for easy convergence
  - new diagnostics easily incorporated

- **A new set of external magnetics diagnostics installed**
  - flux loops and $\dot{B}$ coils on outboard side of plasma as well as core mounted diagnostics
  - diamagnetic loop constrains the plasma pressure

- **Large currents induced in vacuum vessel walls have been accounted for**
  - axisymmetric current filament model for first order correction
  - equilibrium code fits final values (constrained by wall flux loops)

- **Initial results**
  - External kink and internal tearing modes have been identified
  - equilibrium analysis show PEGASUS in designed operational region
    - $_t$ 15%
    - ~ 3

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:

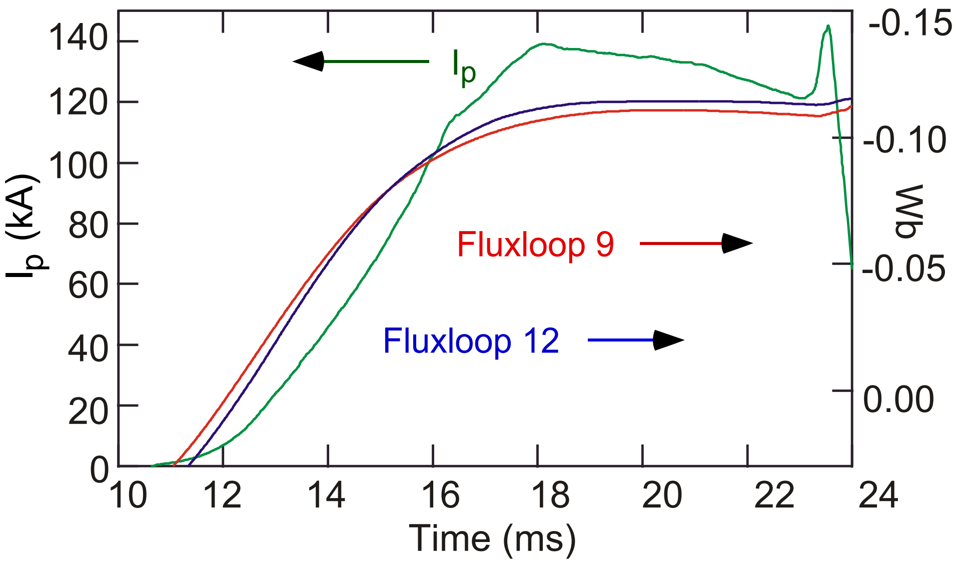
- Wall $\dot{B}_{tan}$ strips

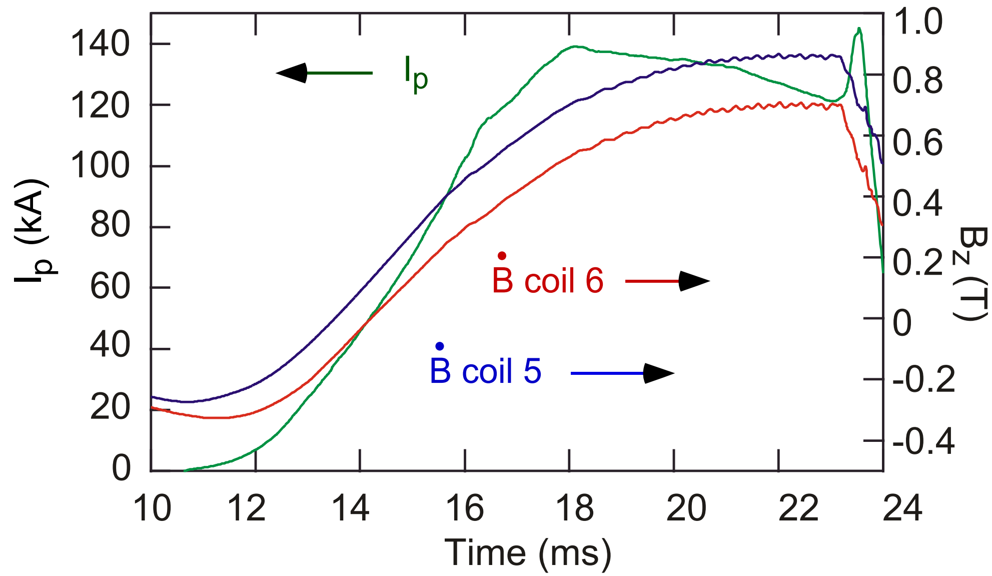
Not shown:

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

Sample Waveforms from New Magnetics

- Fluxloops and $\dot{B}$ coils constrain equilibrium reconstructions.

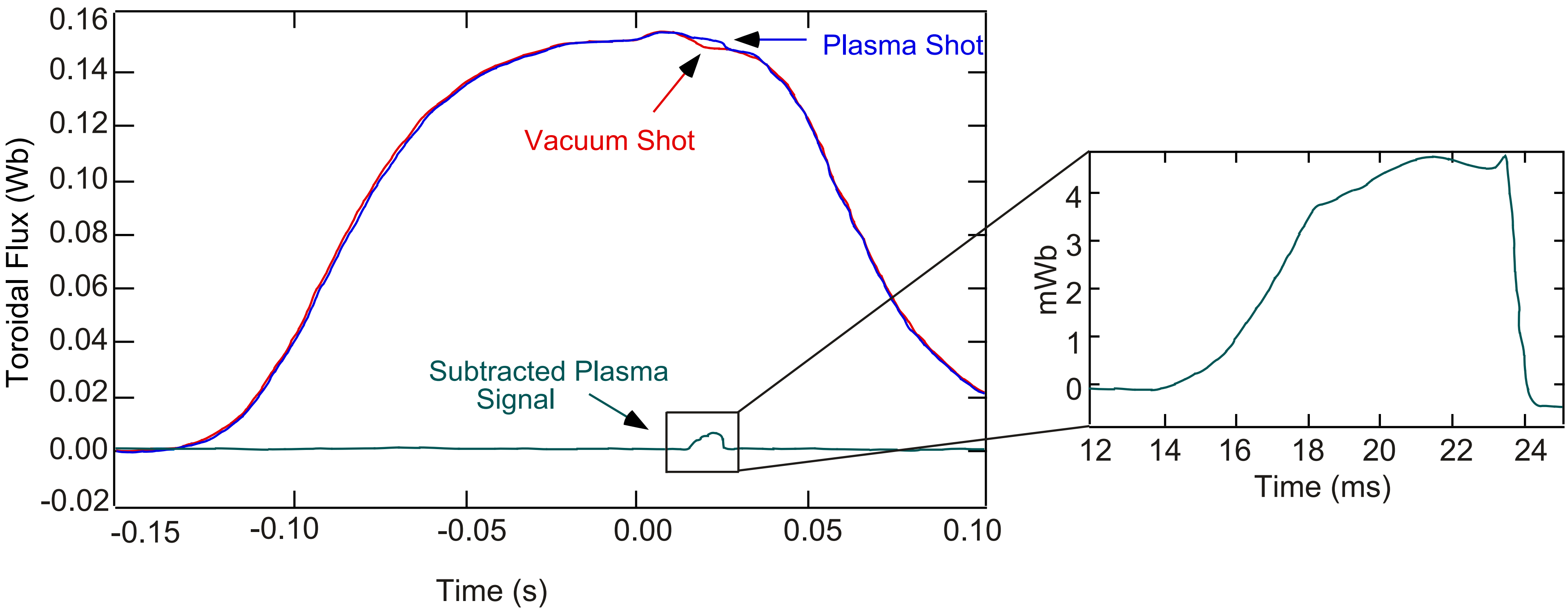




- Typically employ about 20 magnetic measurements.
  - Discard coils with excessive MHD activity

Diamagnetic Loop Used to Constrain Pressure

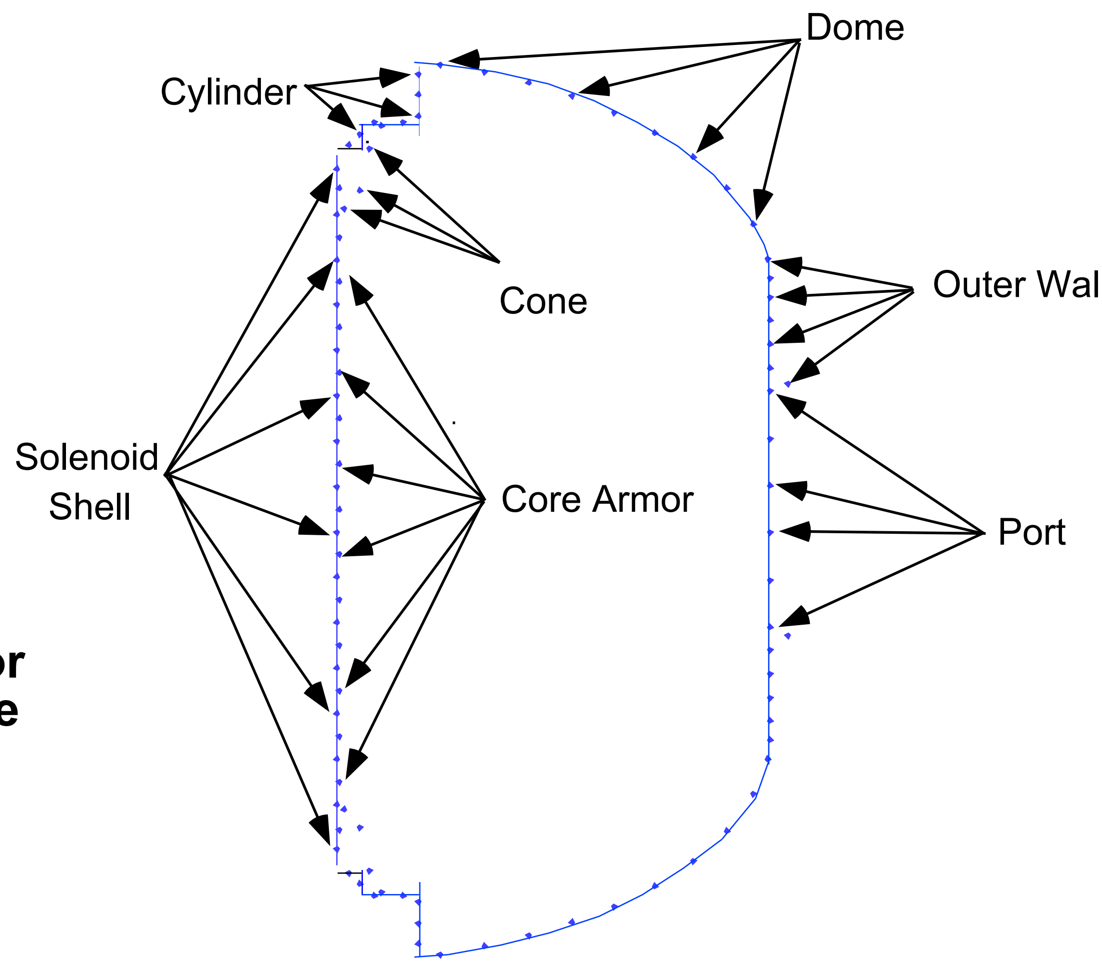
- For Pegasus, B_{tor} due to plasma is relatively large.
  - Alignment to ±1mm is adequate.



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

Wall Model Filaments are Grouped into Coil Packs

- **Wall model breaks vessel into 91 individual axisymmetric current filaments**
- **Filament currents exhibit similar behavior in 7 different sections of vacuum vessel:**
  - Ports, outer wall, domes, reentrant cylinders, solenoid shell, core armor, cones
- **Filaments in each region grouped into a single coil pack**
  - Each coil pack treated as independent poloidal field coil set in equilibrium code
- **Coil pack currents constrained via wall-mounted flux loops**
  - Dome and outer wall most significant
  - 2 loops on dome, 1 on outer wall
- **2 strips of $\dot{B}$ coils mounted on interior and exterior of wall planned for future**
  - Interior strip already installed

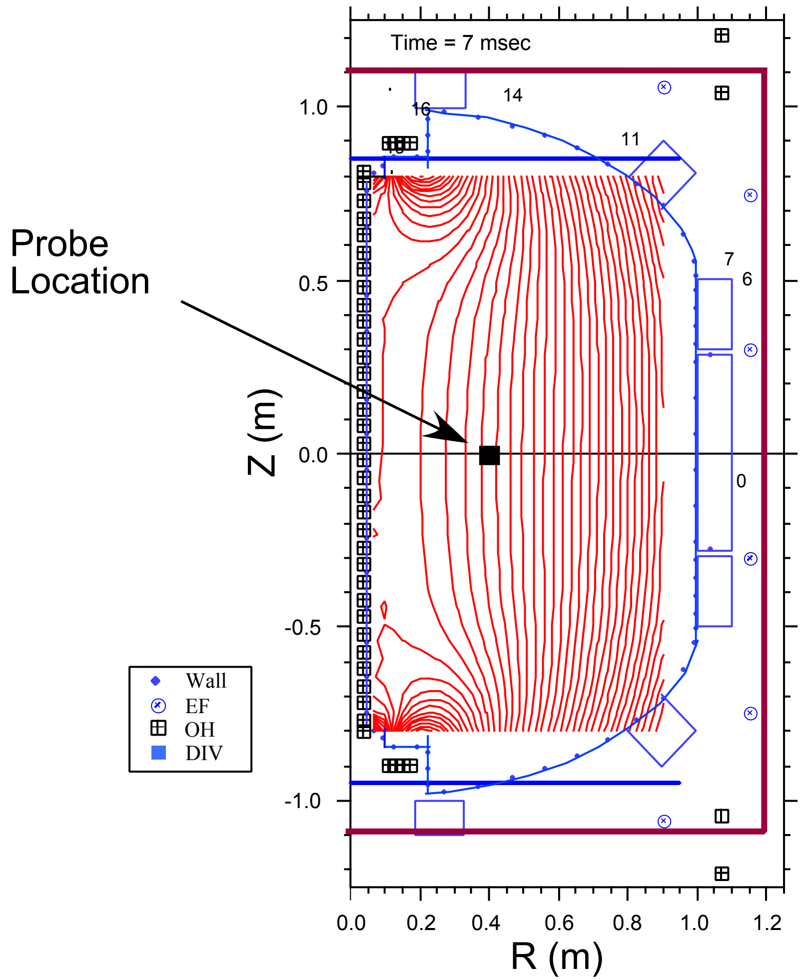


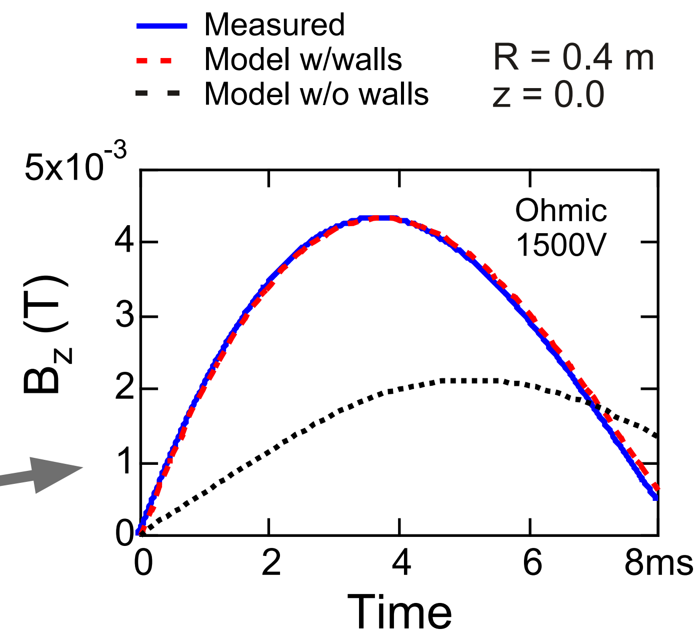
Wall Model Calibrated With $\dot{B}$ Probe Measurements

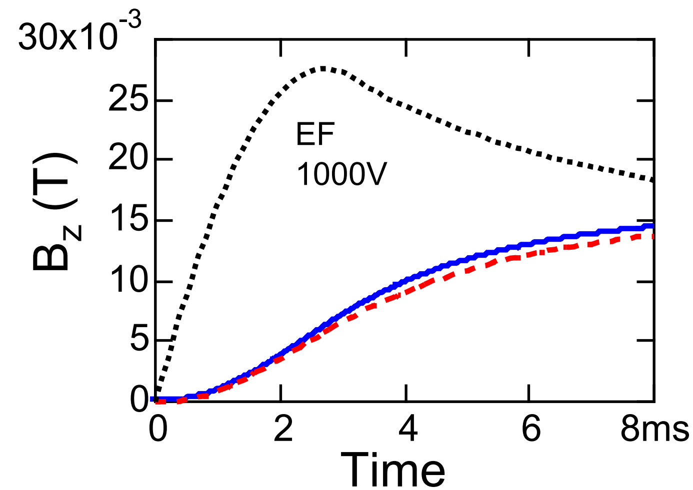
- **Comparison of measured and calculated poloidal fields in agreement**

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

Flux plot for OH only case







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

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

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

inductance of individual filament (wall)

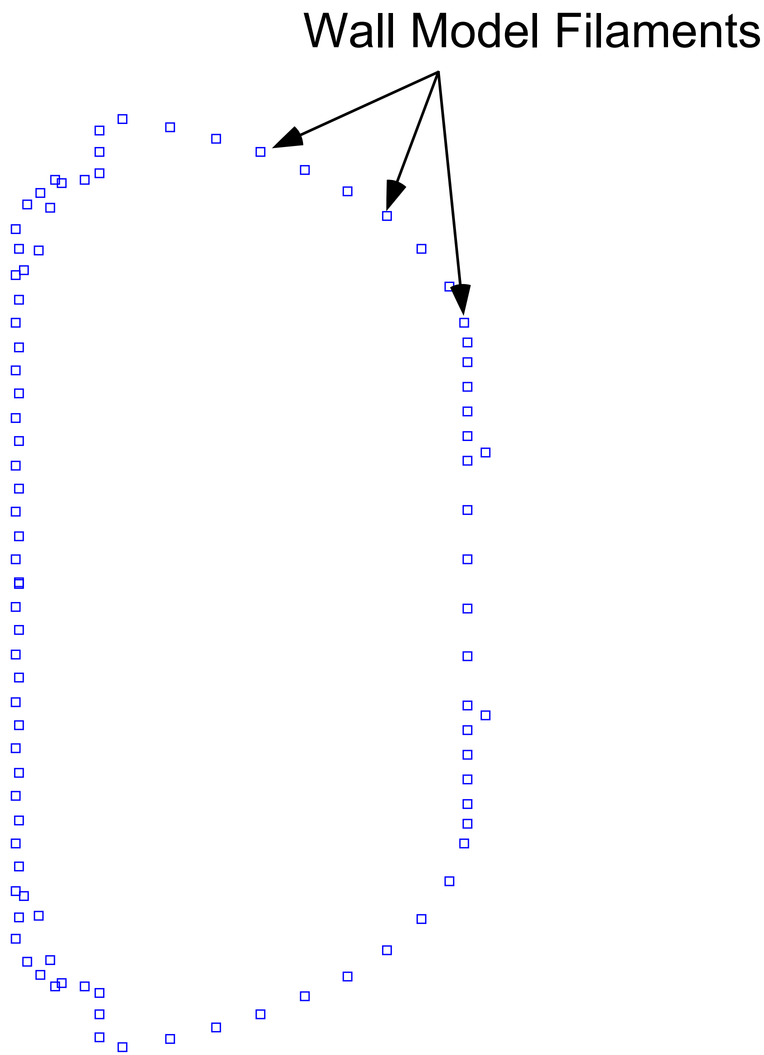
$$L_i = \mu_0 R \left[\ln\left(\frac{8\sqrt{\pi} R}{\sqrt{A}} \right) - \frac{7}{4} \right]$$

self-inductance of coil set i

$$L_i I_i = \mathop{}\limits_{k=1}^{N_i} \mathop{}\limits_{l=1}^{N_i} \quad {}^{k,l}_{i}$$

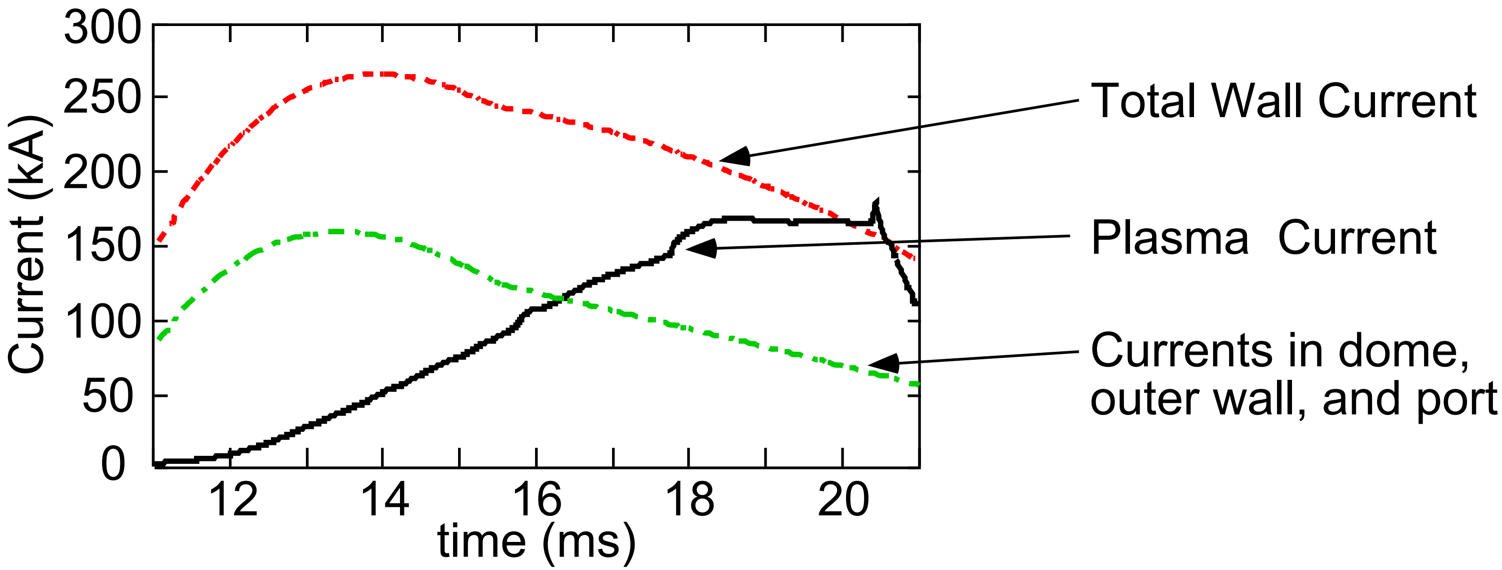
mutual inductance of coil set i with coil set j

$$M_{ij} I_j = \mathop{}\limits_{k=1}^{N_i} \mathop{}\limits_{l=1}^{N_j} \quad {}^{k,l}_{ij}$$

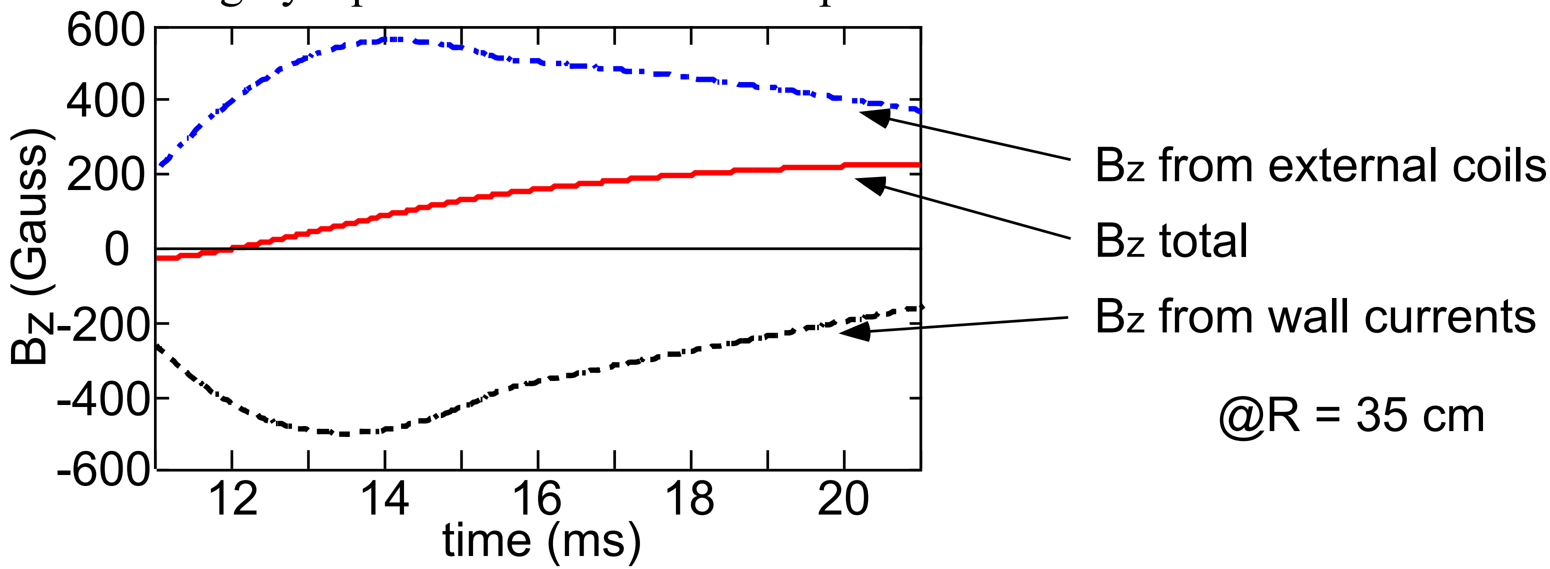


Wall Currents Are Significant During Startup

- **Total current induced in wall is comparable to Ip throughout shot**
  - dome, outer wall, and ports have largest dipole



- **Induced wall currents strongly affect B_z at early times**
  - Field due to walls roughly equal to coil field at startup



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 c^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, $\dot{B}$ coils, diamagnetic loop and plasma Rogowski used routinely**

  - flux and $\dot{B}$ 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	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
$\dot{B}$ 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**

- **$0.8 < \chi^2_\nu < 1.5$ is typical on high-current discharges ($I_P > 90$ kA)**
  - statistically good fit

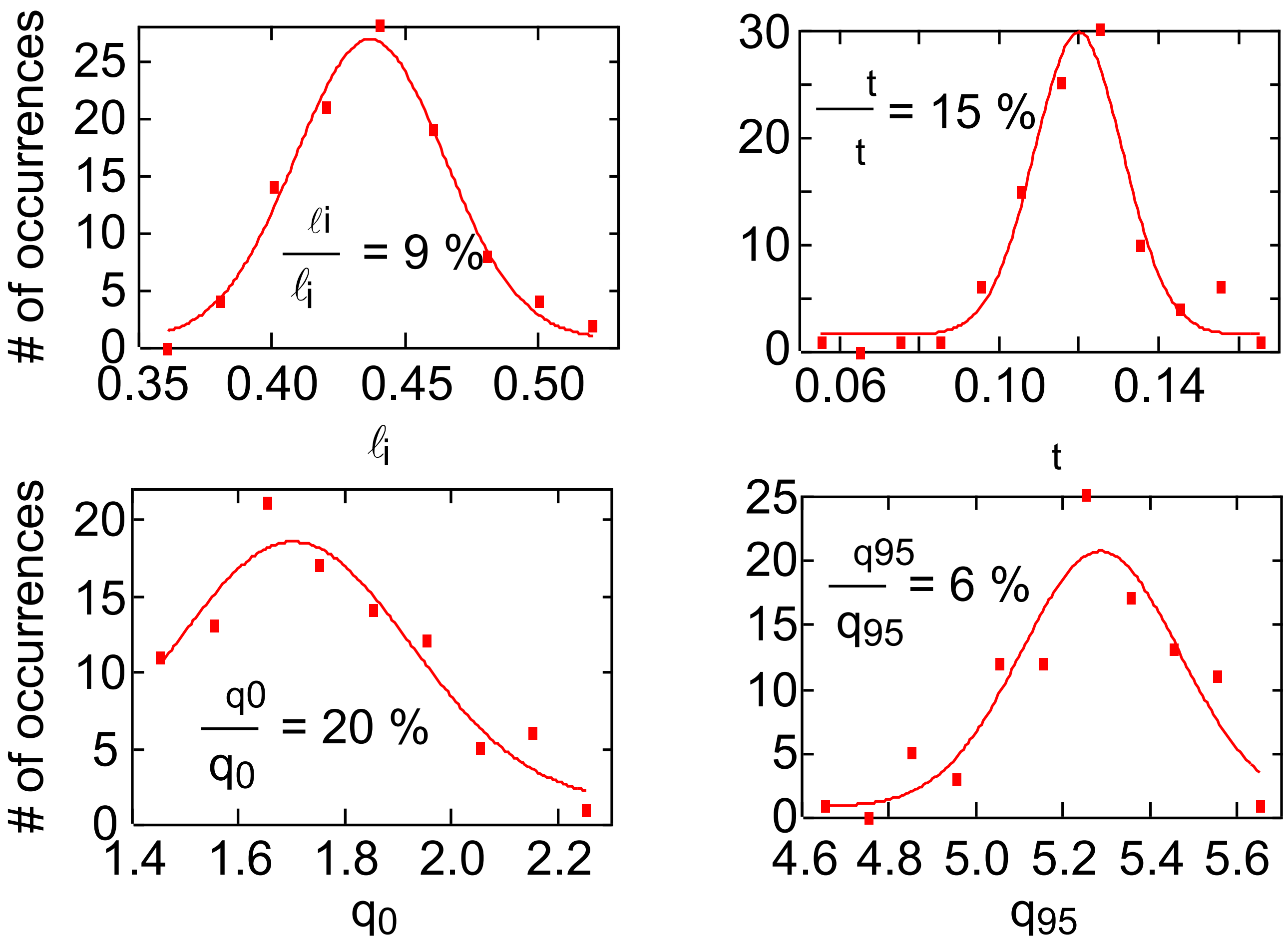
Monte Carlo Analysis Used to Estimate Uncertainty in Fit Parameters

- **100 reconstructions performed with Gaussian noise added to measurements**

  - distributions of fit parameters used to determine random error
  - reconstructions performed using polynomial model for current and pressure profiles

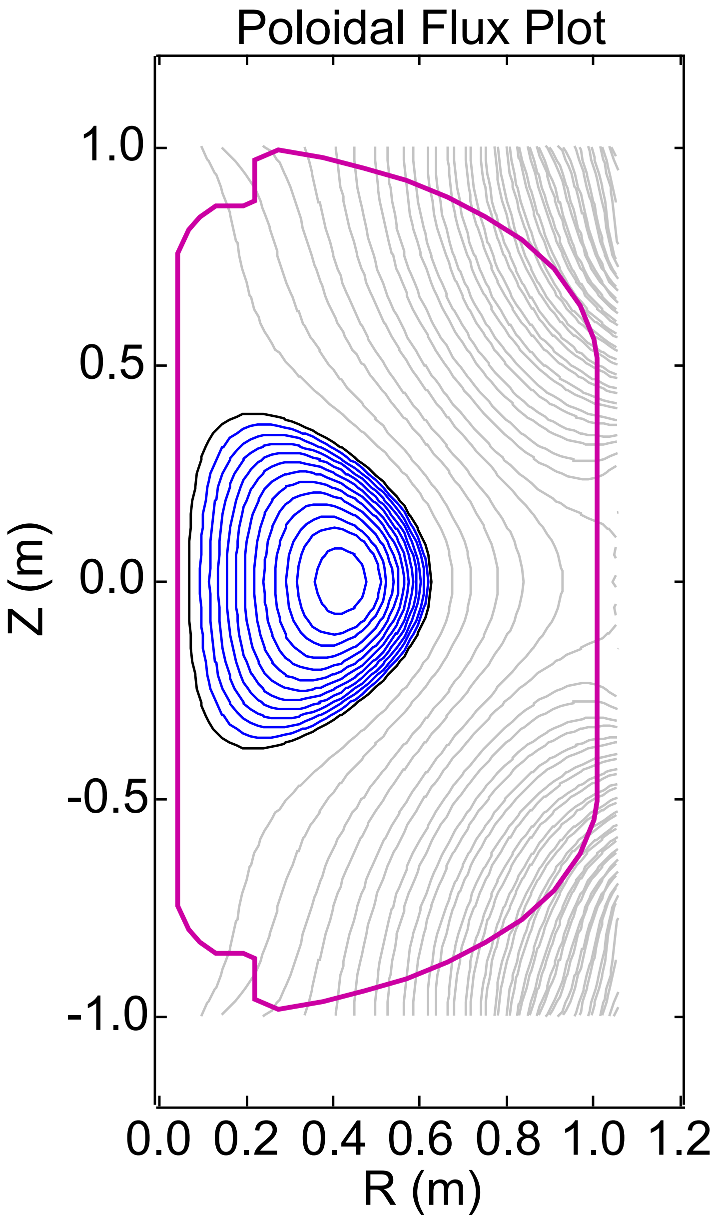
    3 terms for current

    2 terms for pressure



Increased b_t Accessible by Reduction of Toroidal Field

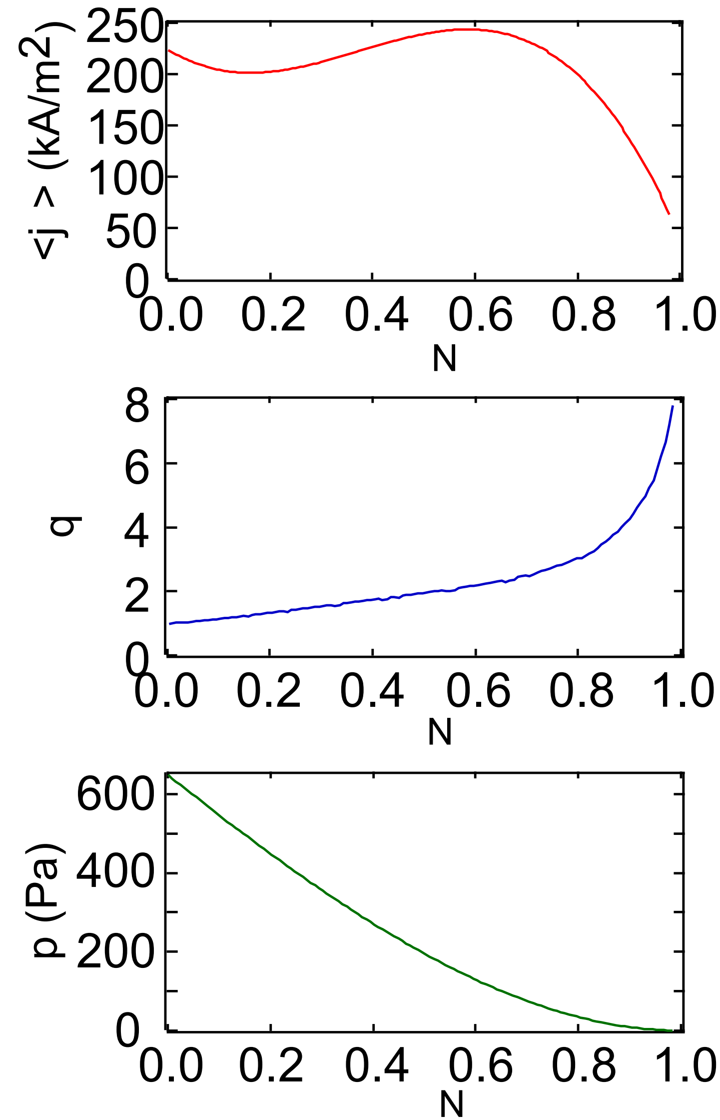
- **Note: This shot was prior to OH modifications which increased available V-s**
  - $_t$ 10% for full field shots with similar OH V-s



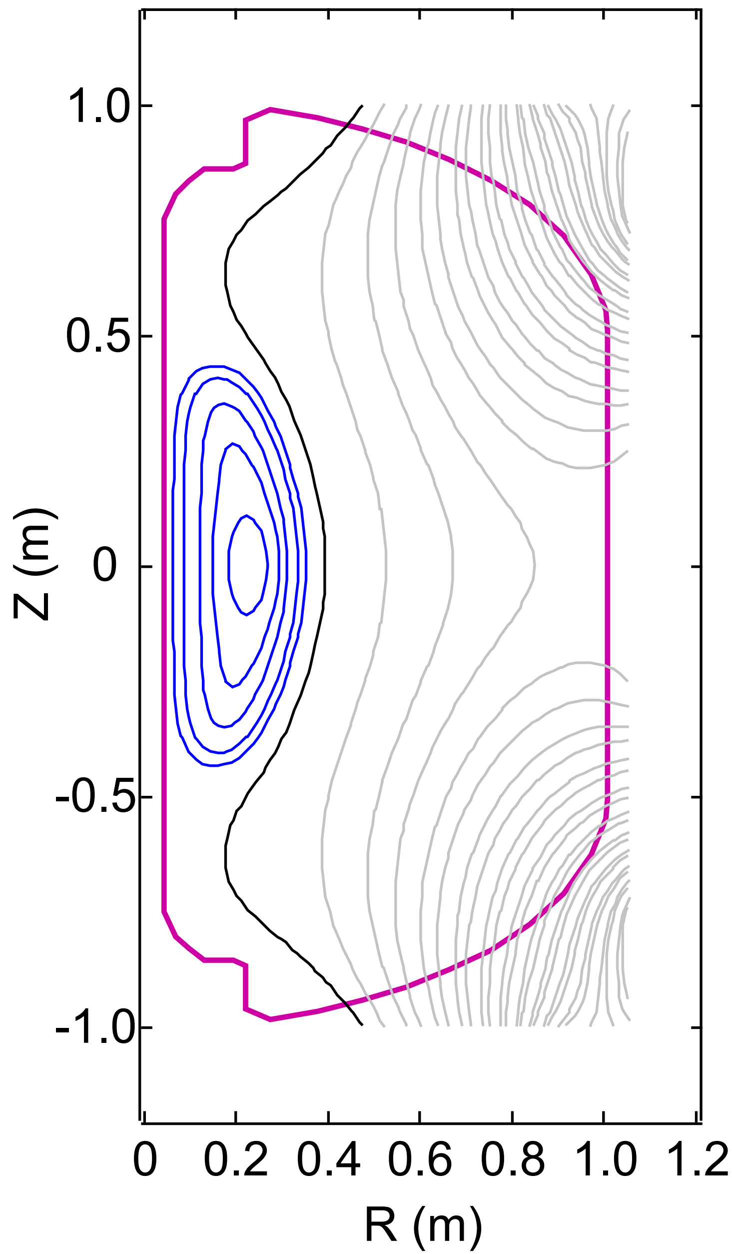
Shot
12445

I_p	78.3 kA
R_0	0.337 m
a	0.274 m
A	1.22
	1.4
B_t (axis)	0.048 T
$_t$	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

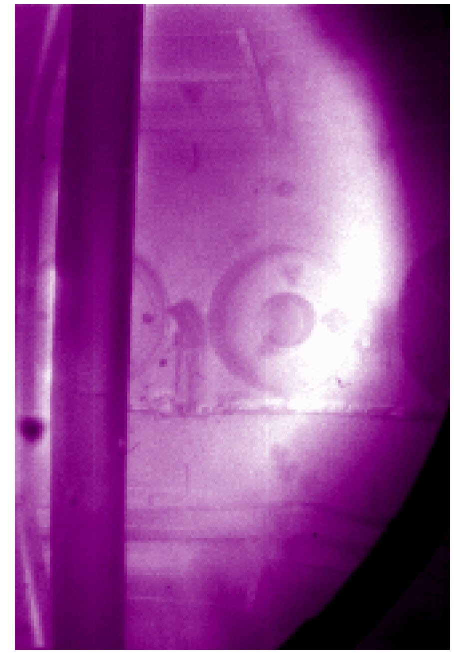


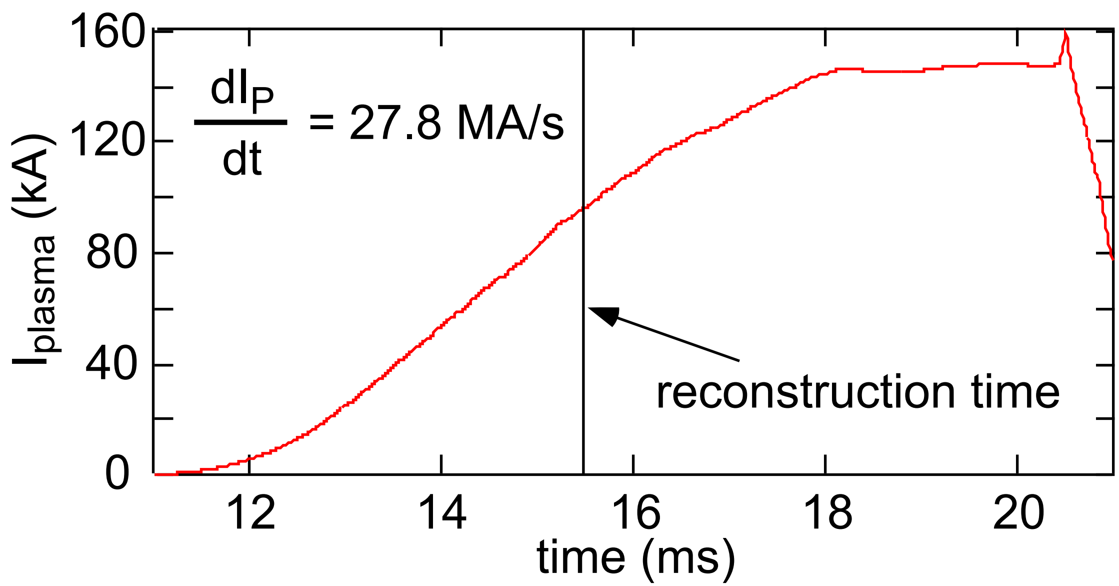
High Elongation Observed During Current Ramp



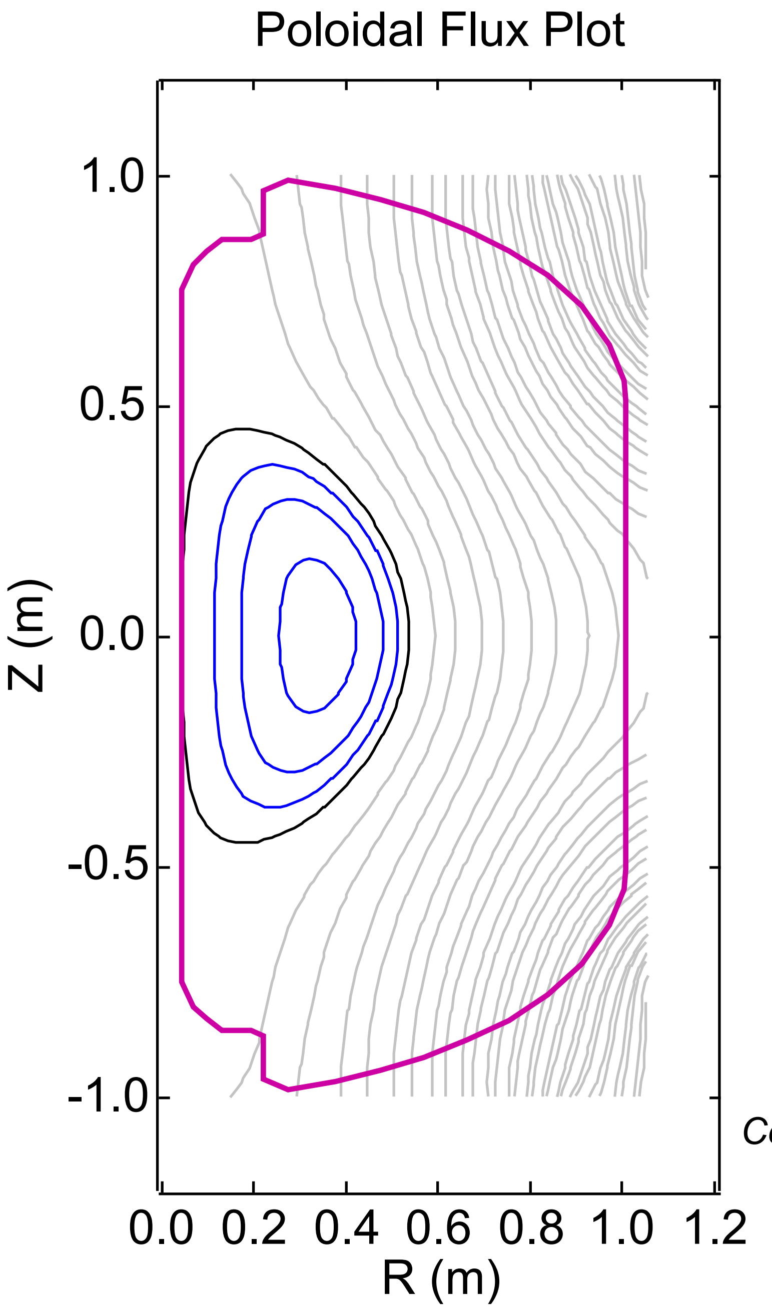
Shot
13231

I_p	93.8 kA
R_0	0.203 m
a	0.147 m
b	0.436 m
A	1.38
	3.0
t	0.1 %
ℓ_i	0.20
q_0	3.8
q_{95}	13.1





Equilibrium Reconstruction Shows High t for Fully Formed Plasmas

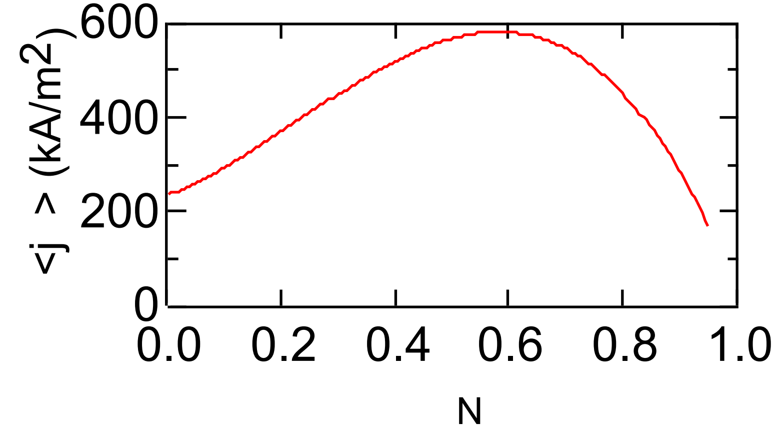


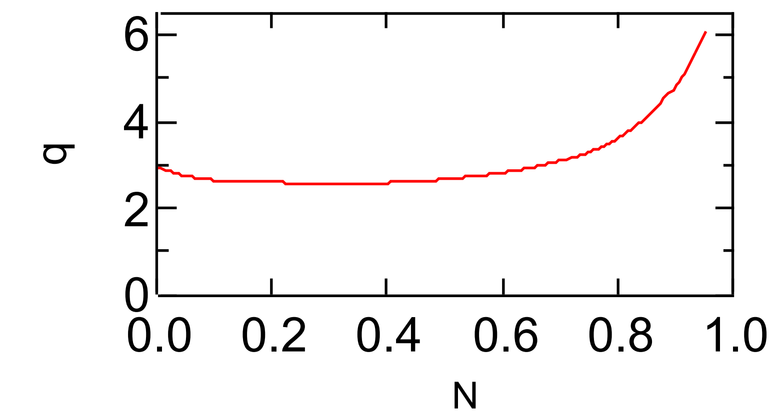
Shot
13064

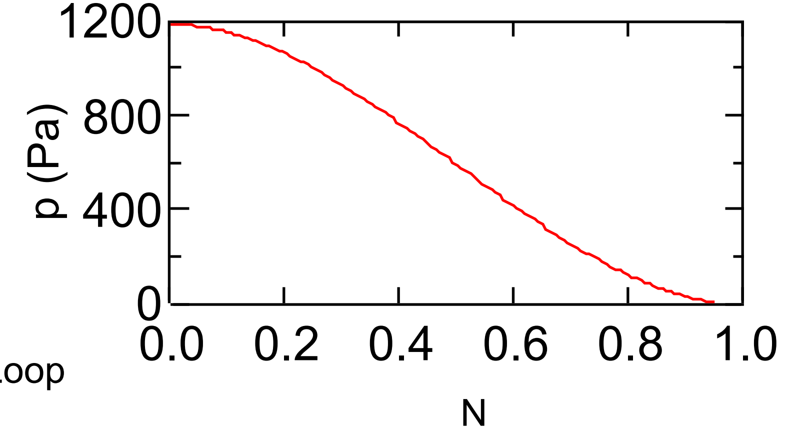
I_p	151.4 kA
R_0	0.305 m
a	0.249 m
A	1.22
	1.8
B_t (axis)	0.1 T
t	16%
ℓ_i	0.35
q_0	2.8
q_{95}	6.2

Constraints:

Rogowski Coil
15 Flux Loops
3 B_p Coils
Diamagnetic Loop

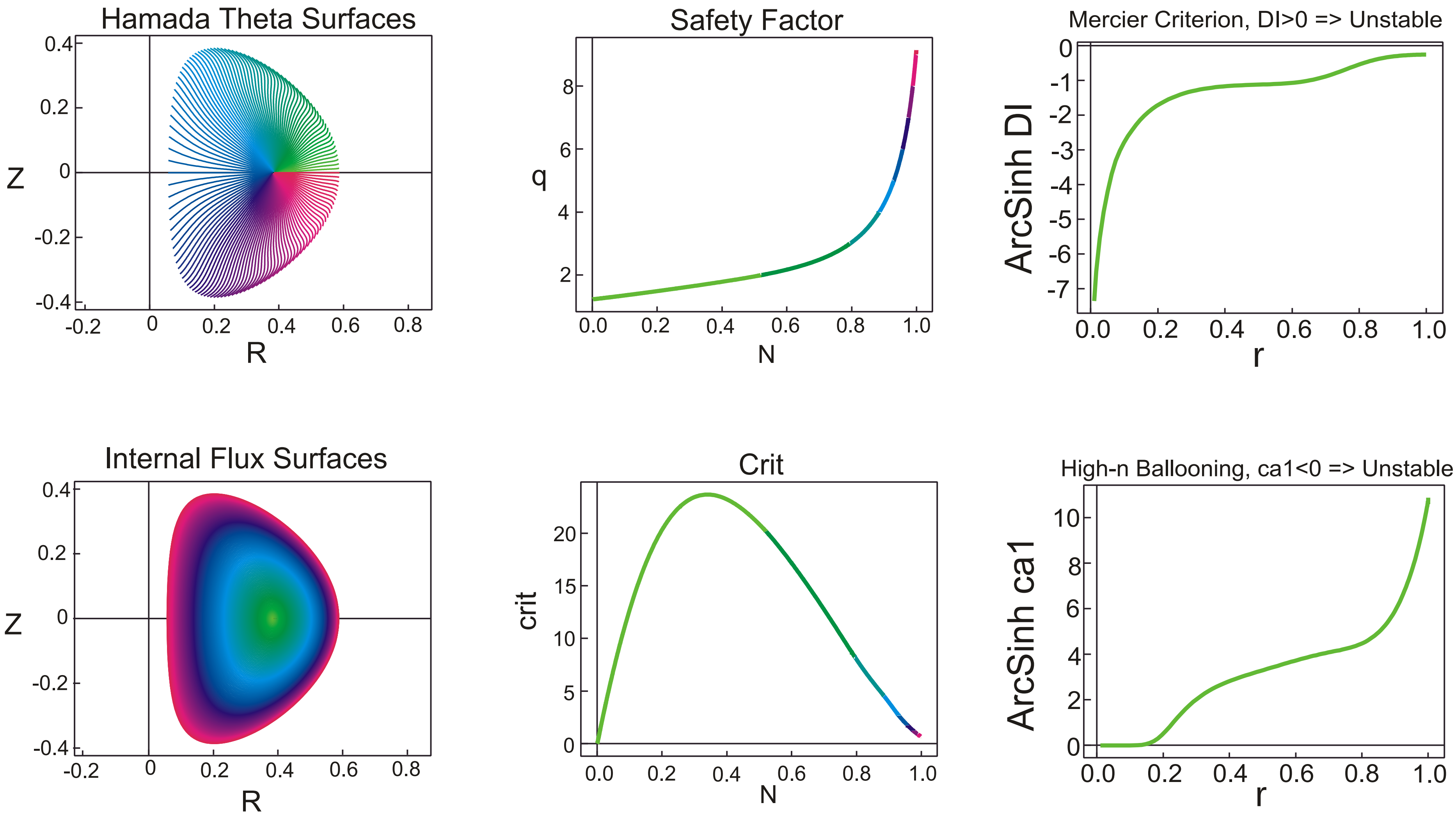






DCON is Being Used to Map Stability Space and Analyze Individual Equilibria

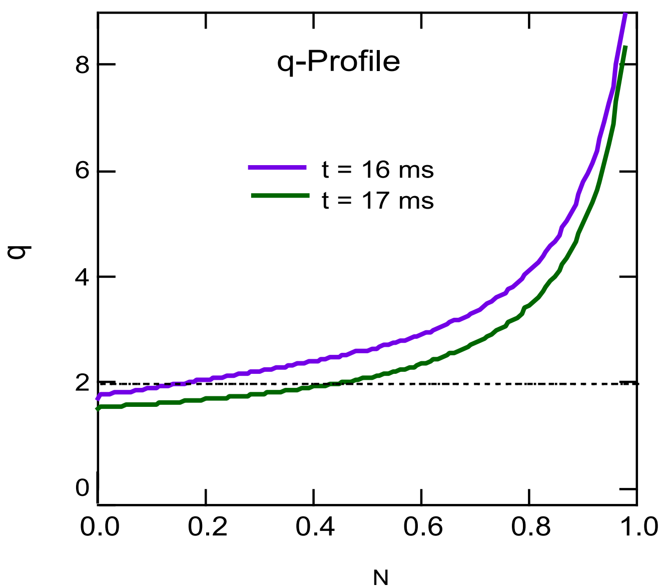
- Shot 12445, 18% t

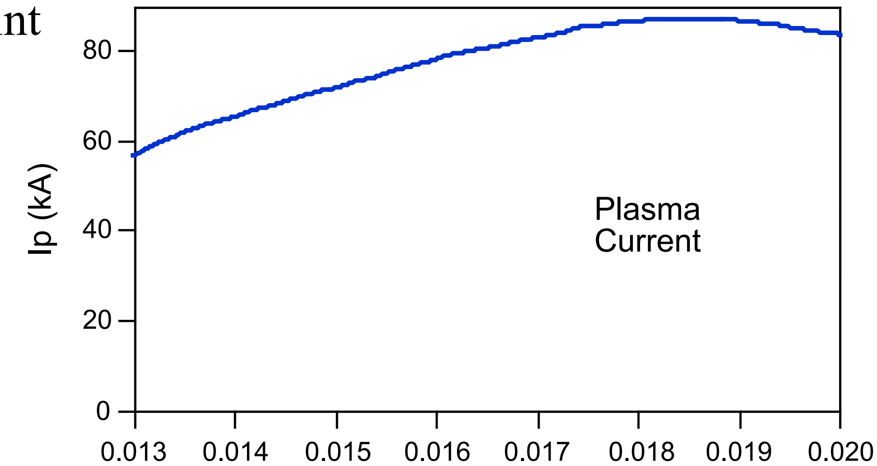


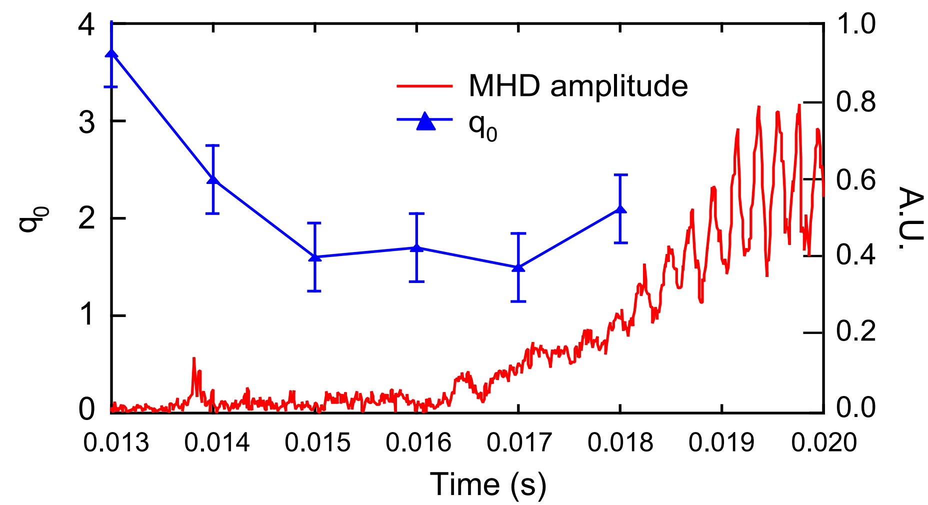
Large Tearing Mode Growth Correlates with q_0 Behavior

- **growth of 2/1 mode observed soon after q_0 passes through 2**
  - often appears to constrain discharge evolution
  - appears correlated with large interior region with low shear

- **q_0 constrained by equilibrium fit to external magnetics**
  - 2D SXR camera will provide better constraint

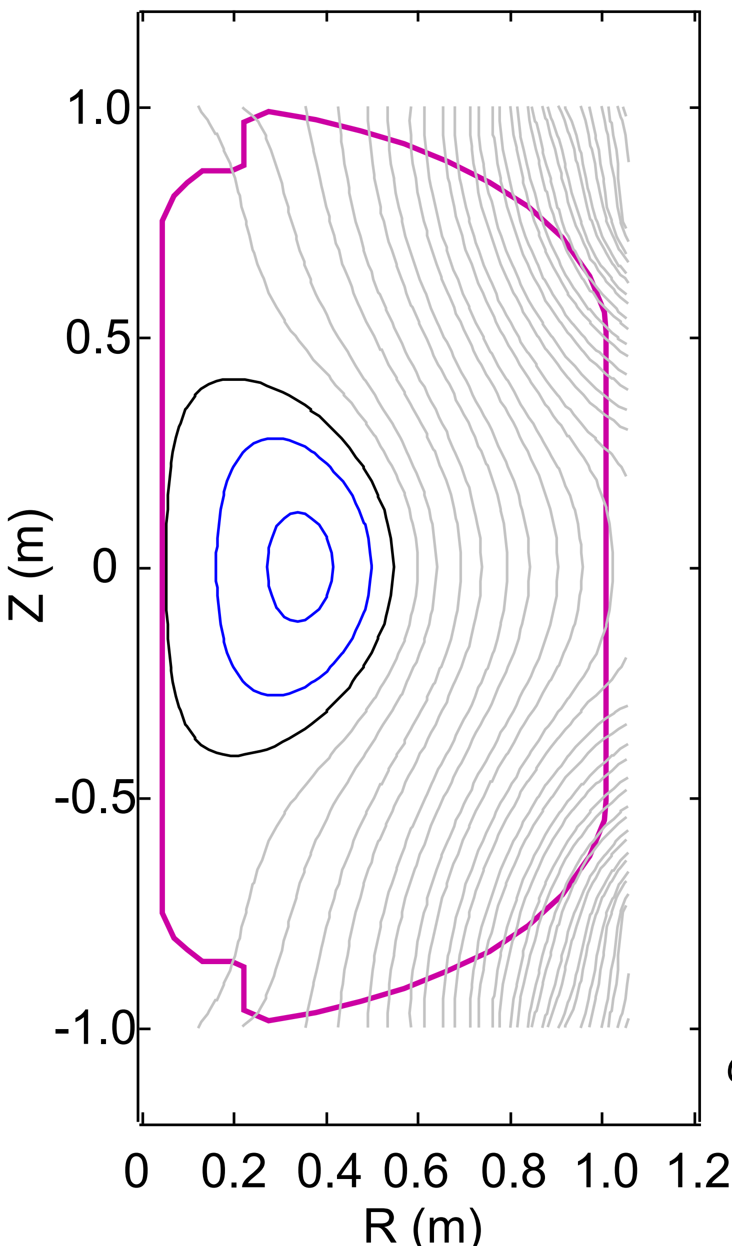






Reconstruction Gives q_{95} ~ 5 Immediately Prior to Disruption

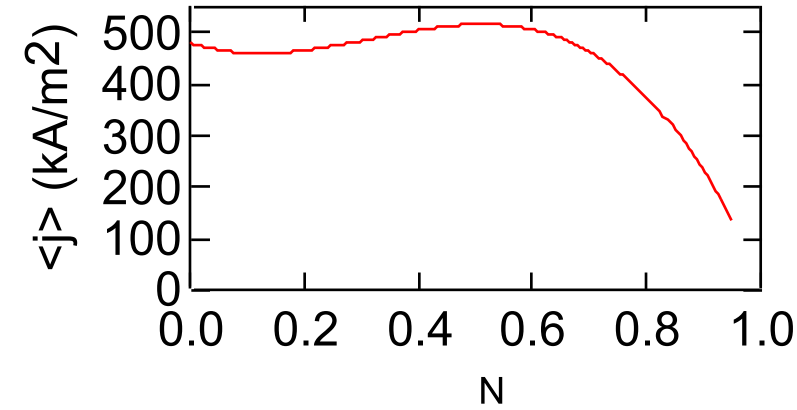
- **Shot 13257 250 μs prior to terminating MHD event**

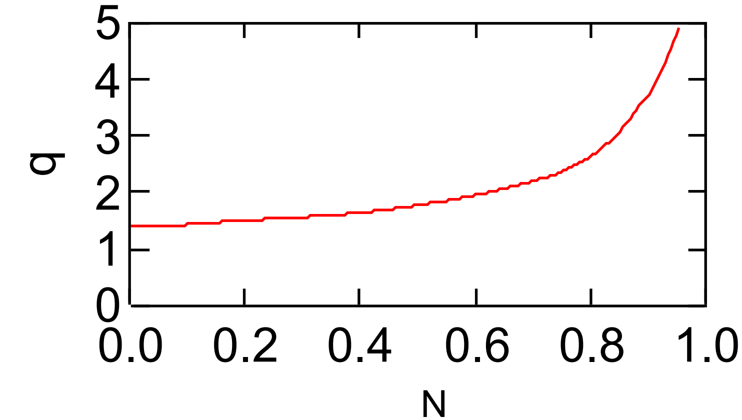


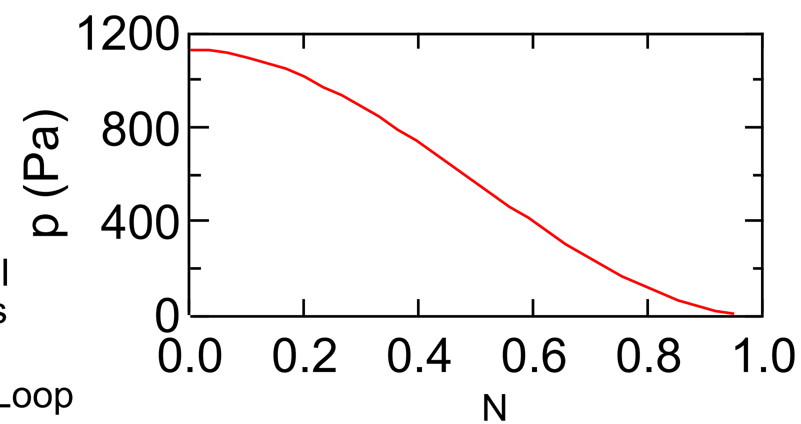
I_p	140 kA
R_0	0.30 m
a	0.25 m
A	1.23
	1.7
B_t (axis)	0.1 T
t	13%
ℓ_i	0.47
q_0	1.4
q_{95}	4.9

Constraints:

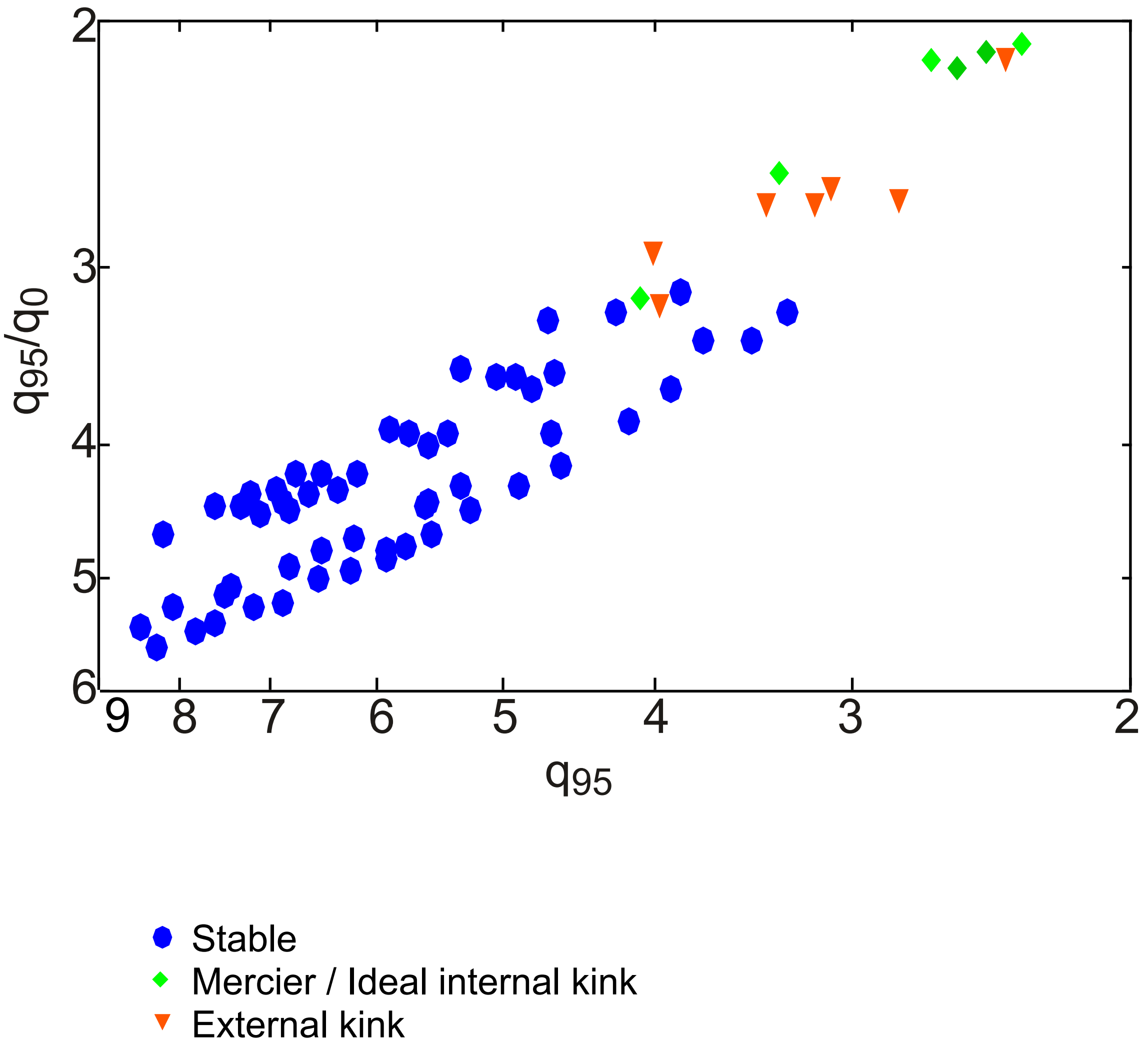
Rogowski Coil
14 Flux Loops
2 B_p Coils
Diamagnetic Loop







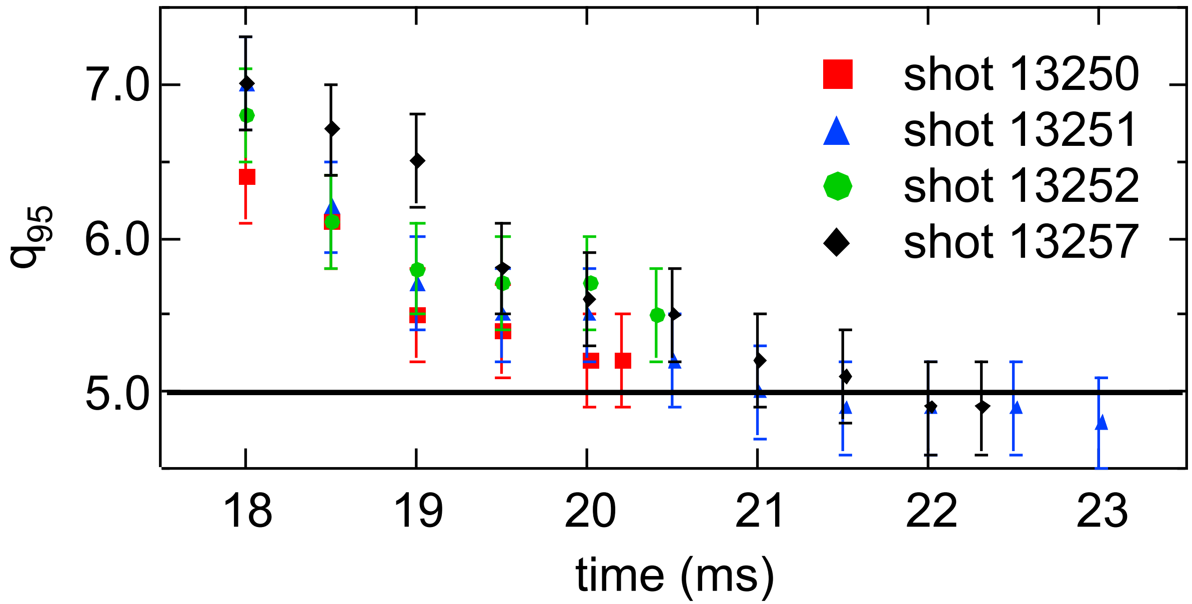
DCON Scans Suggest q_{95} Stability Limit Higher for Low - A than High - A



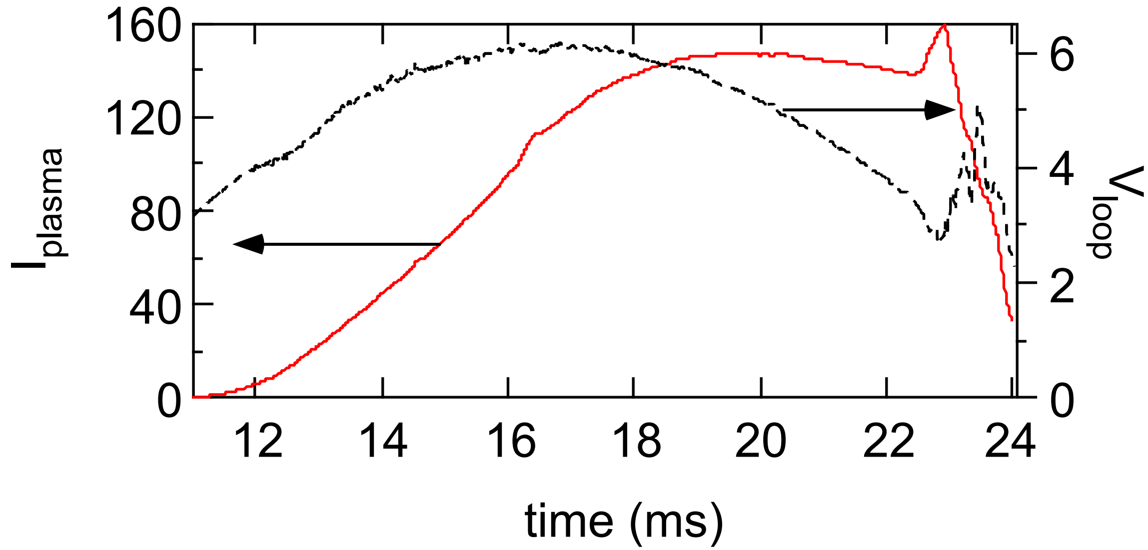
- Scan of ℓ_i and B_t with constraints on:
  - I_p = 120 kA
  - R_{center} = 35 cm
  - q_0 >1
  - low pressure (< 0.5%)
  - A ~ 1.1
- Results:
  - Stable for q_{95}/q_0 3 at A ~ 1.16
  - Higher than usual region for high - A tokamak (i.e., q_{95}/q_0 2)
- More extensive scan and high - A comparisons in progress.

Abrupt Discharge Termination Possibly due to Edge Kink Mode

- **q_{95} ~ 5 as large MHD event terminates discharge**

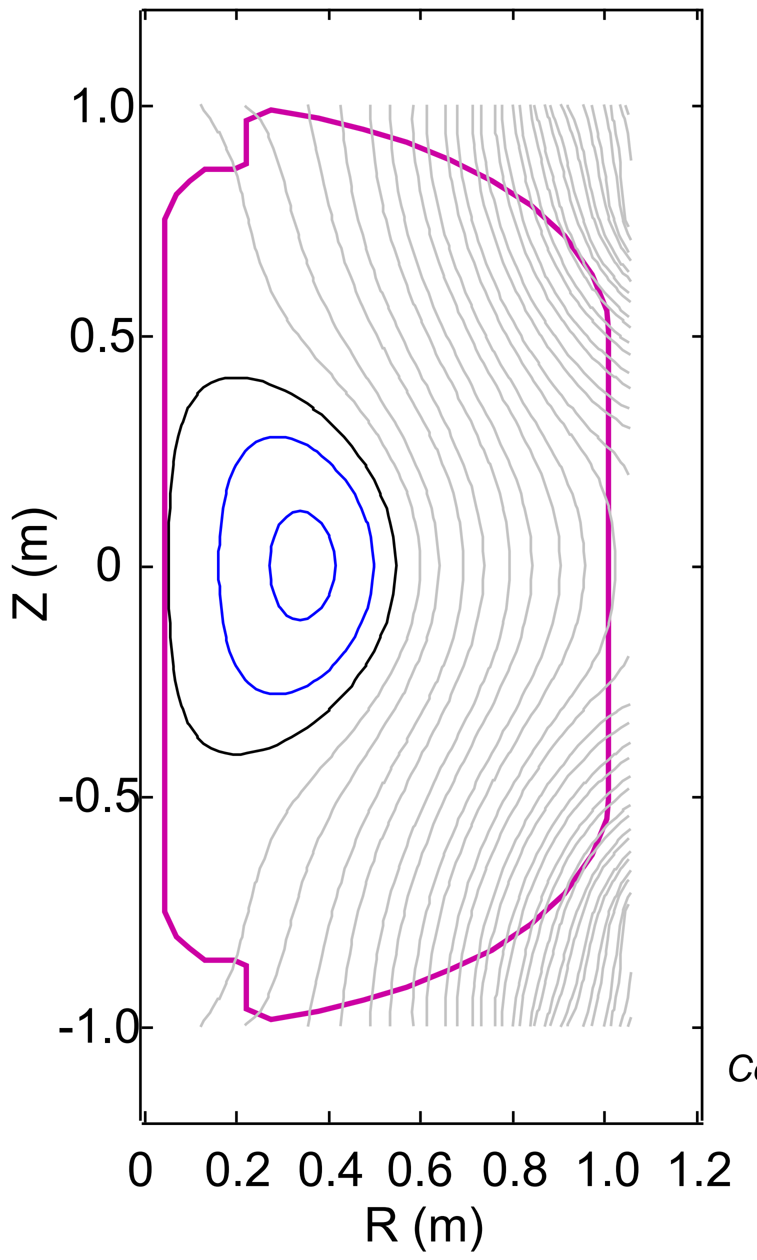


- **Shot 13257 is typical of these discharges**



Reconstruction Gives q_{95} ~ 5 Immediately Prior to Disruption

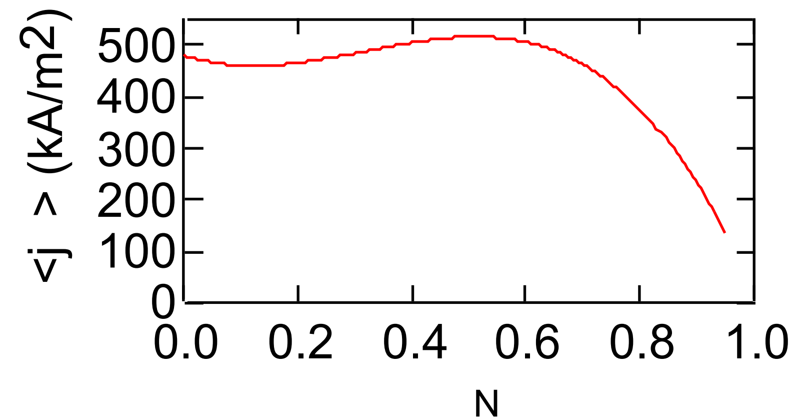
- **Shot 13257 250 μs prior to terminating MHD event**

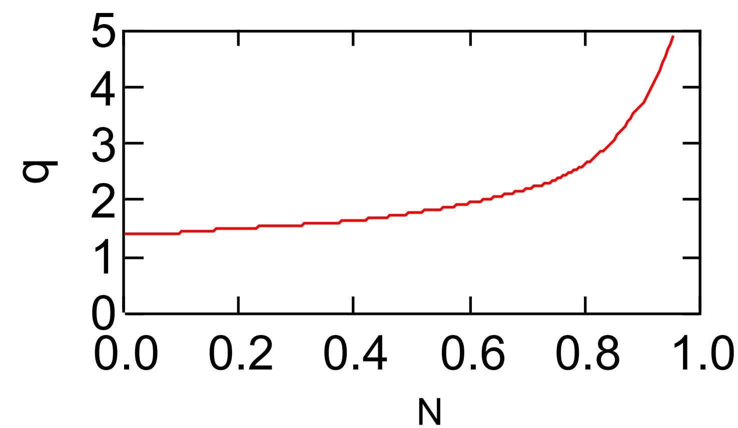


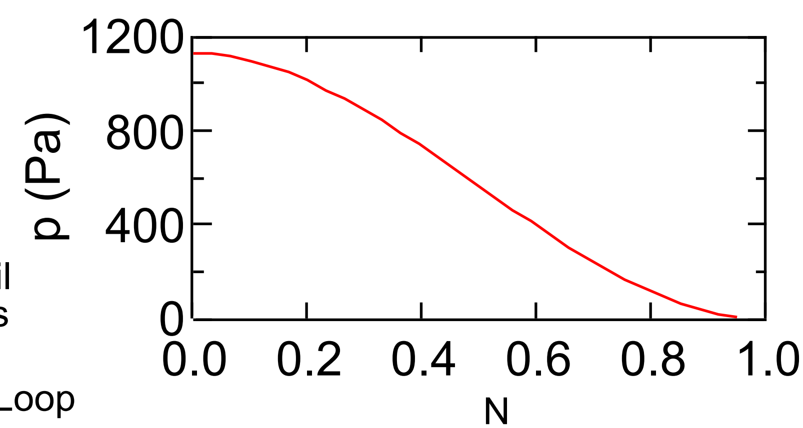
I_p	140 kA
R_0	0.30 m
a	0.25 m
A	1.23
	1.7
B_t (axis)	0.1 T
t	13%
ℓ_i	0.47
q_0	1.4
q_{95}	4.9

Constraints:

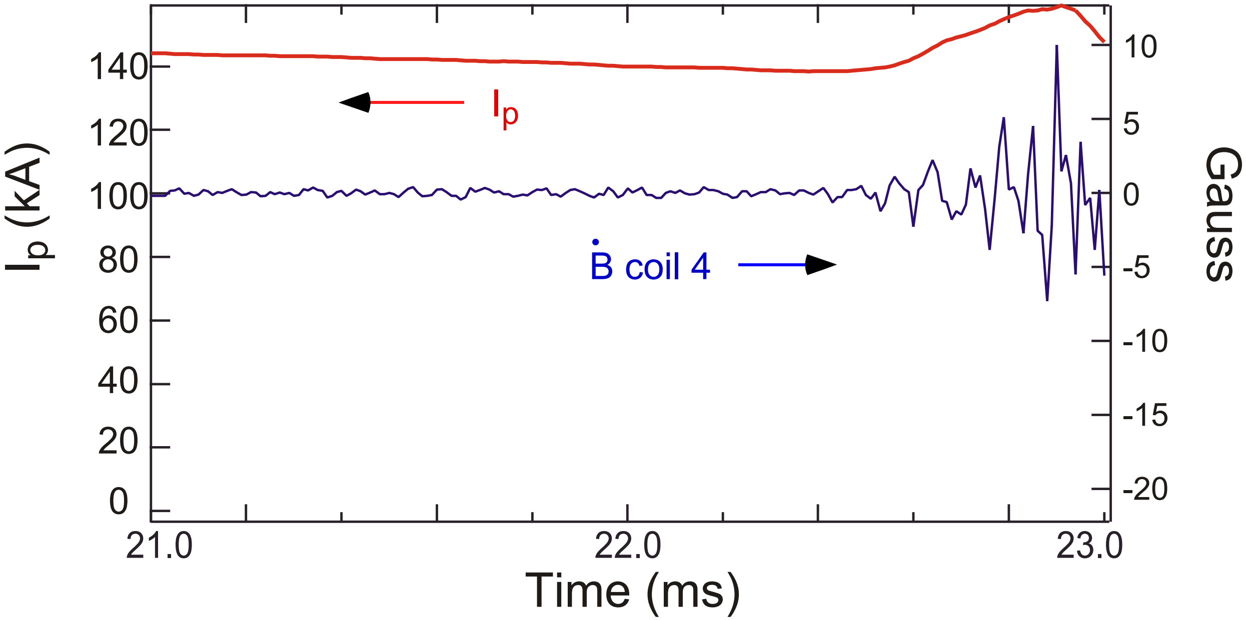
Rogowski Coil
14 Flux Loops
2 B_p Coils
Diamagnetic Loop

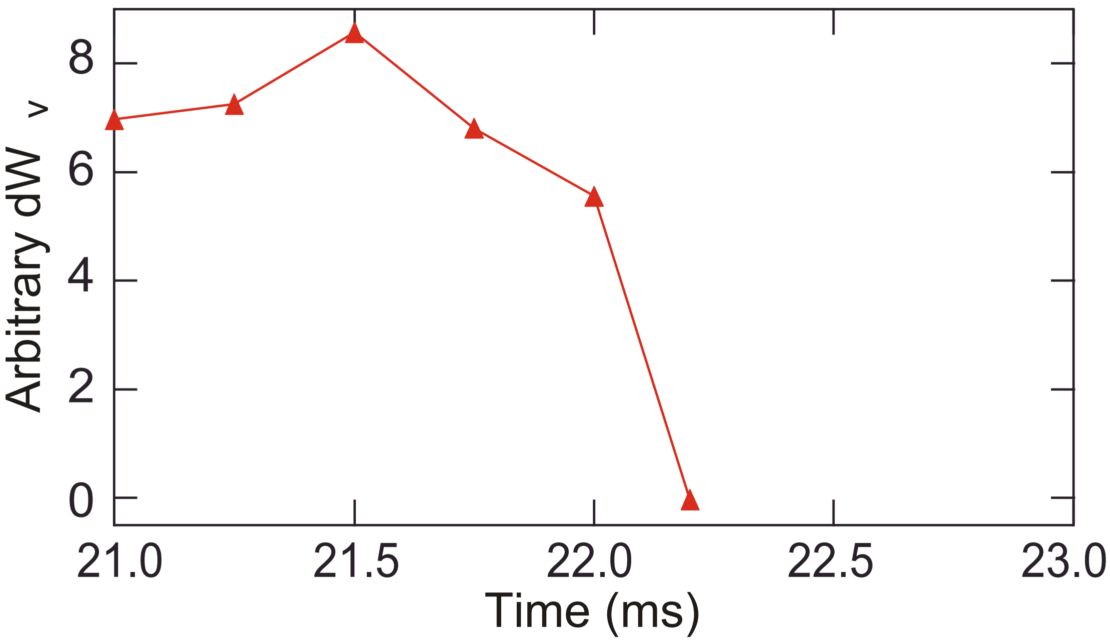






DCON Analysis Suggest Ideal Kink Instability





- Total energy approaches zero as q95 approaches 5.
- Plasma disrupts as vacuum energy approaches zero.

Future Work

- **Incorporate new diagnostics as available**
  - T_e and density for further pressure constraint
  - q_0 constraint from SXR camera
  - SXR wave array for internal MHD activity

- **Continue stability analysis with DCON**
  - resolve remaining issues with incorporation of Pegasus data
  - further explore parameter space

- **Cross-comparison of equilibrium fit results**
  - compare PEGASUS equilibrium code with EFIT from GA/Columbia
  - EFIT has been compiled and a data interface developed for PEGASUS
  - more amenable to evaluating up-down asymmetry in PEGASUS plasmas

Summary

- **Upgraded external magnetics diagnostics constrain PEGASUS equilibria**
  - provides global parameter determination

- **Wall currents contribute significantly to equilibrium field**
  - time evolution from integrated coupled circuit equations, with final fit via equilibrium code

- **A new equilibrium code provides magnetic reconstructions for PEGASUS**
  - new diagnostics easily incorporated; robust convergence

- **Equilibrium analysis indicates PEGASUS is entering designed-for parameter regime**
  - $_t$ up to 25%
  - MHD limits:
    - *large internal tearing mode with m/n = 2*
    - *external kink limit becoming evident*
  - Low ℓ_i, high observed

- **Stability analysis of PEGASUS plasmas has begun**
  - new equilibrium code coupled to DCON