Equilibrium and Stability Characterization of $A < 1.3$ Plasmas in the PEGASUS Toroidal Experiment

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STW 2002
November 20, 2002

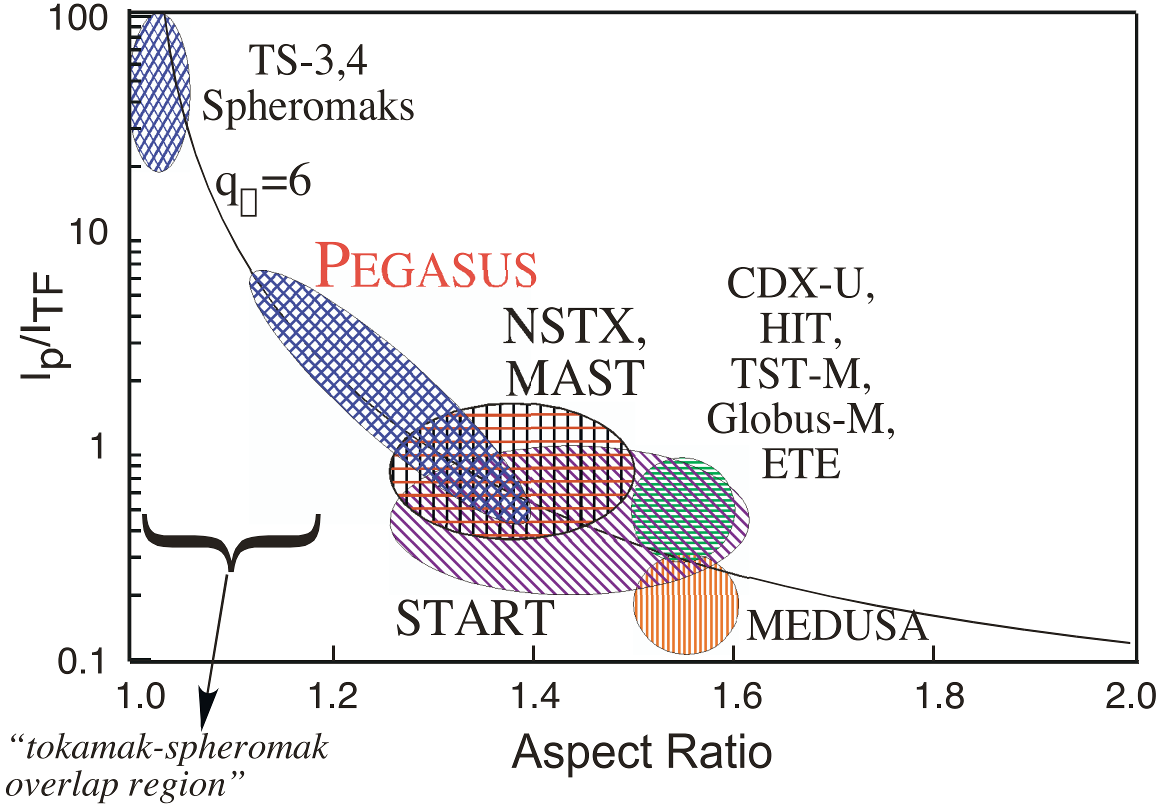
Work supported by U.S. DoE Grant No. DE-FG02-96ER54375

PEGASUS is an ultra-low aspect ratio ST

- Test limits of beta and safety factor as A□ 1
- Access high toroidal beta and high toroidal utilization factor (I_p/I_{tf})
- A “soft limit” occurs at $I_p/I_{tf} \approx 1$
  - *due to MHD activity and some reduction in V-s*
- Beginning to explore the edge kink stability boundary
  - q_{95}*=5 is found unstable*
- Upgrades will allow further challenges to stability limits
  - *tools for increased plasma control*

PEGASUS is exploring the A < 1.3 operating regime

I_p/I_{tf} ≈ figure of merit for access to low-A physics



Achieved Parameters:

- A = 1.12-1.3
- R = 0.2-0.45 m
- I_p = 0.16 MA
- RB_t ≈ 0.03 T-m
- κ = 1.4 - 3.7
- Δt_{pulse} = 0.01-0.03 s
- $\langle n_e \rangle = 1\text{-}5\times10^{19} m^{-3}$
- β_t ≤ 20%
  ($\beta_t \equiv 2\mu_0\langle p\rangle/B_{t0,vac}^2$)

New Equilibrium Reconstruction Code Developed

- **Motivation:**
  - robustness
  - easy incorporation of new diagnostics
  - portability

- **Description:**
  - full solution of Grad-Shafranov equation at each iteration
    G-S solver uses multi-grid Gauss-Seidel PDE solver
  - minimize χ^2 of fit to measurements
    χ^2 minimization via *Levenberg-Marquardt method*
  - has been validated against TokaMac

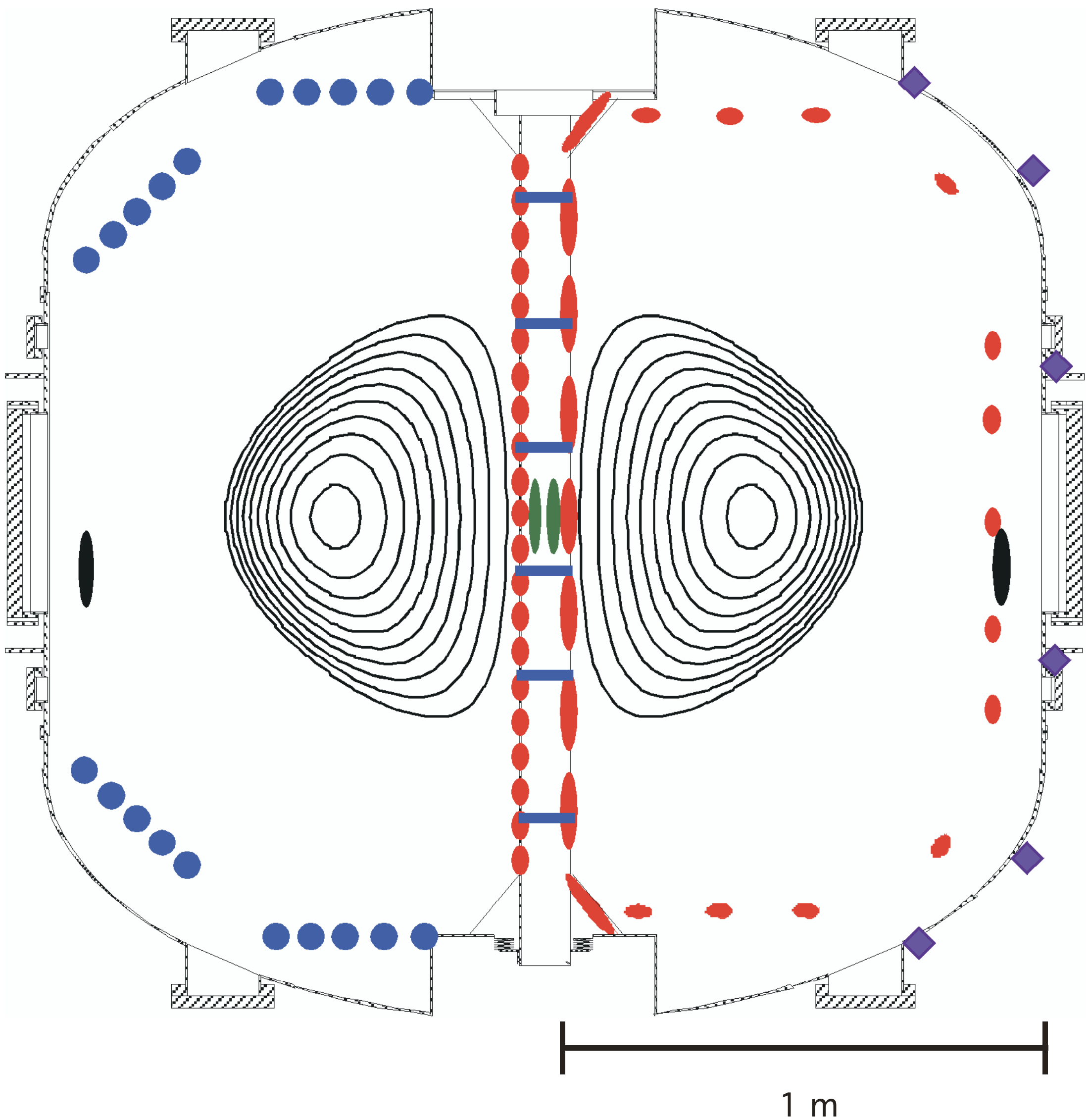
- **Profile parameterization:**
  - GG’ as 3 term polynomial
  - p’ as 2 term polynomial

$$F(x) = F_0 + (F_1 + F_2\psi_N + F_3\psi_N^2 + \ldots + F_n\psi_N^{n-1}) - \psi_N^n(F_1 + F_2 + \ldots + F_n)$$

$$\psi_N = \frac{\psi - \psi_0}{\psi_{\lim} - \psi_0}$$

- **Drawbacks:**
  - computationally intensive $\rightarrow$ slow
  - average fit takes approximately 1.5 minutes with 1.3 GHz Athlon

A full set of magnetics diagnostics provides equilibrium and stability data

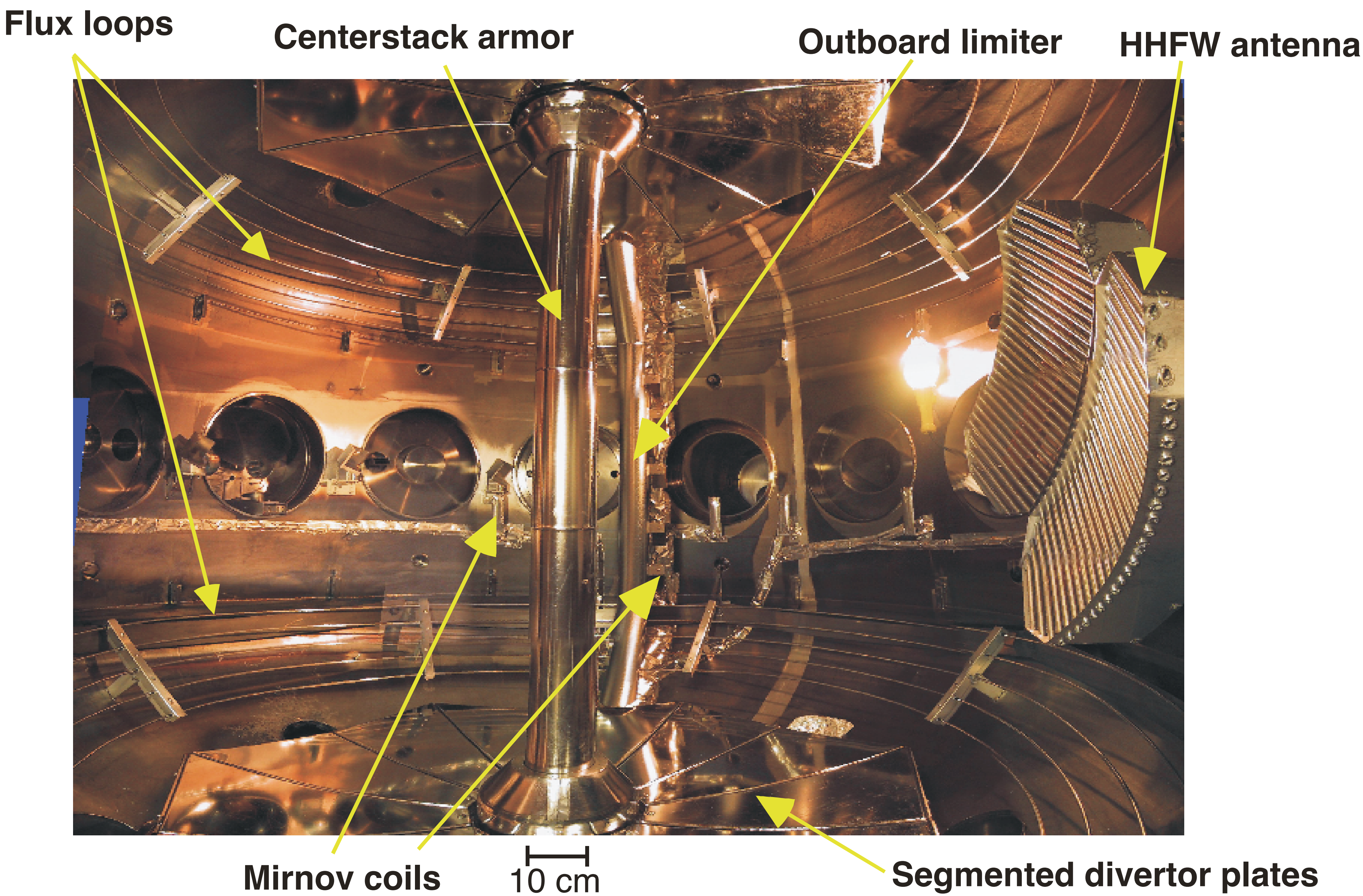


Installed Magnetics

- Flux Loops (26)
- Poloidal Mirnov Coils (22 + 21)
- LFS Toroidal Mirnov Coils (6)
- HFS Toroidal Mirnov Coils (7)
- External Wall Loops (6)

Not shown:
Internal Plasma Rogowski Coils (2)
Internal Diamagnetic Loops (2)
Diamagnetic Compensation Loop

Internal view of PEGASUS shows narrow centerstack



Resistive vacuum vessel wall modeled as set of axisymmetric current filaments

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

  - coupled current filaments described by matrix equation

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

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

inductance of individual filament (wall)

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

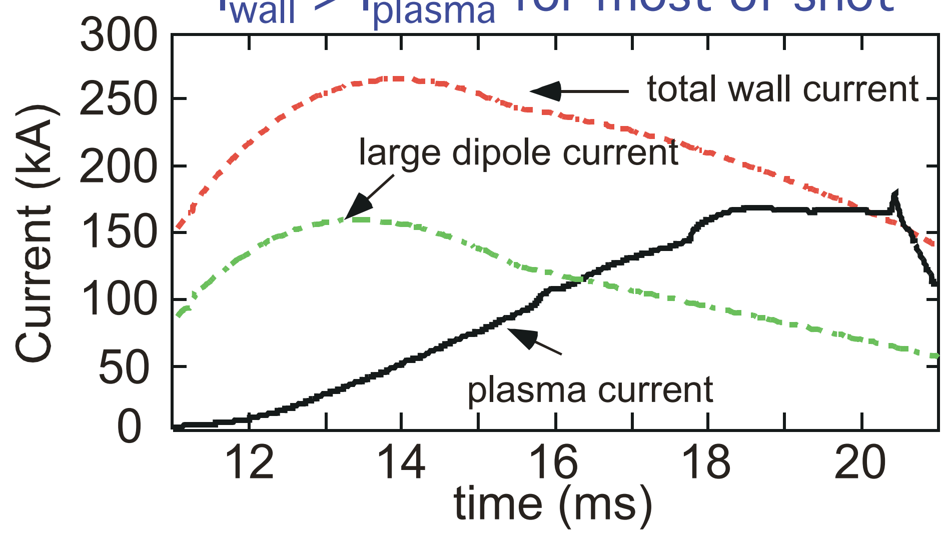
self-inductance of coil set i

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

mutual inductance of coil set i with coil set j

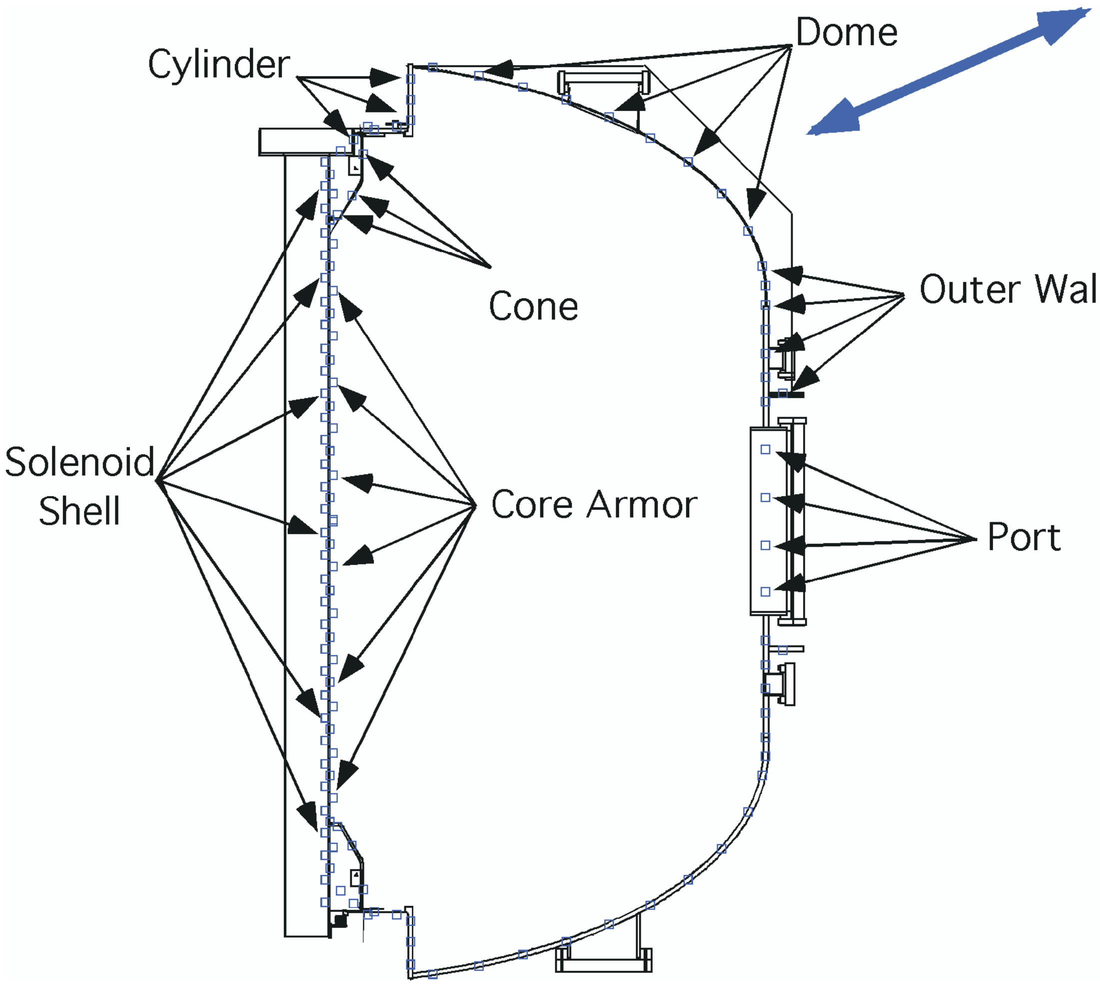
$$M_{ij} I_j = \sum_{k=1}^{N_i} \sum_{l=1}^{N_j} \Phi_{ij}^{k,l}$$

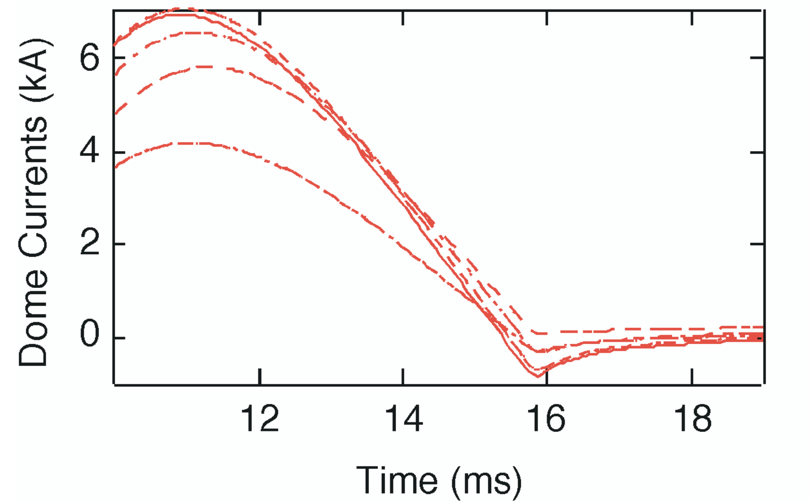
$I_{wall} > I_{plasma}$ for most of shot



Wall filaments are grouped into coil packs

- **Wall modeled as 91 current filaments**
- **Filaments grouped into coil packs**
  - coil pack currents are fit by equilibrium code





pack currents constrained via
mounted flux loops

Dome and outer wall most significant
2 loops on dome, 1 on outer wall

Monte Carlo analysis gives uncertainty in fit parameters

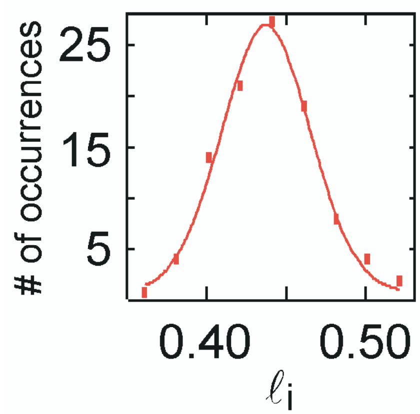
- **Uncertainty estimation technique:**

  - single time-slice of discharge reconstructed 100 times

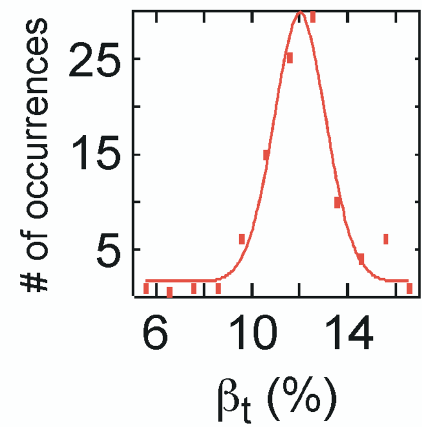
  - Gaussian noise added to measurement data
    Gaussian width from diagnostic uncertainty
    starting χ^2 ~ 8 x final χ^2

  - σ of fit parameter distributions gives uncertainty

Parameter	Rel. Uncertainty
I_p	± 2%
R_0	± 4%
ℓ_i	± 9%
β_t	± 15%
β_p	± 15%
q_{95}	± 6%
q_0	± 20%



$$\frac{\sigma_{\ell i}}{\ell_i} = 9\ \%$$



$$\frac{\sigma_{\beta t}}{\beta_t} = 15\ \%$$

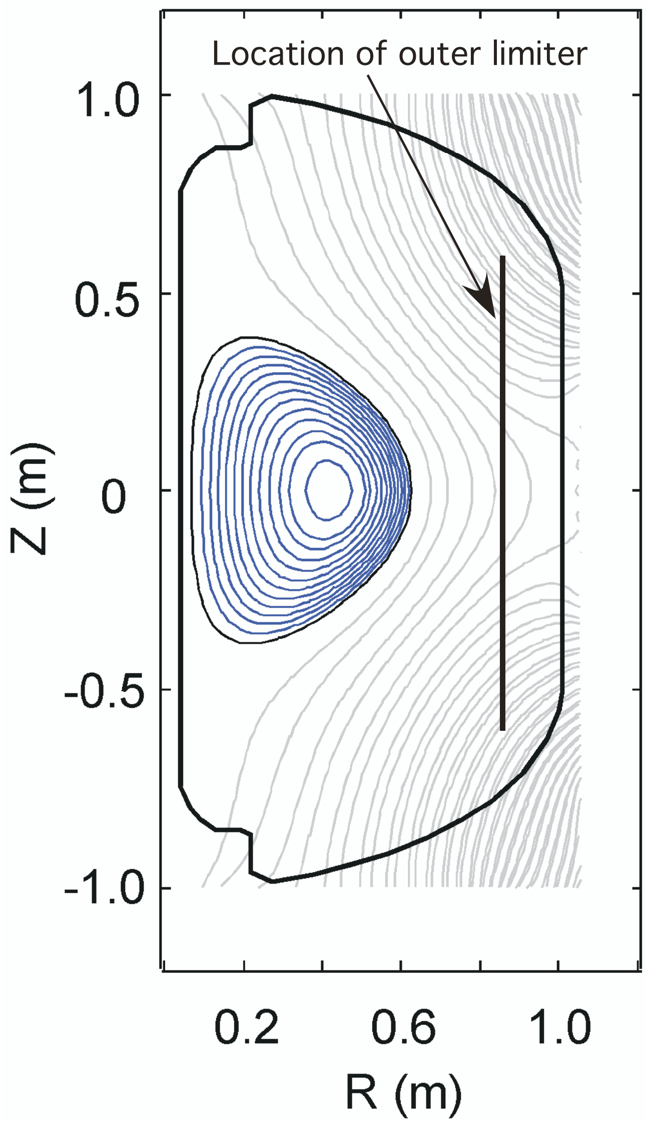
- **Variety of discharges analyzed**

  - wide range of fit parameters covered:

    $75\ \text{kA} < I_p < 150\ \text{kA}$
    $8\% < \beta_t < 18\%$
    $0.2 < \ell_i < 0.4$
    $0.23\ \text{m} < R_0 < 0.33\ \text{m}$

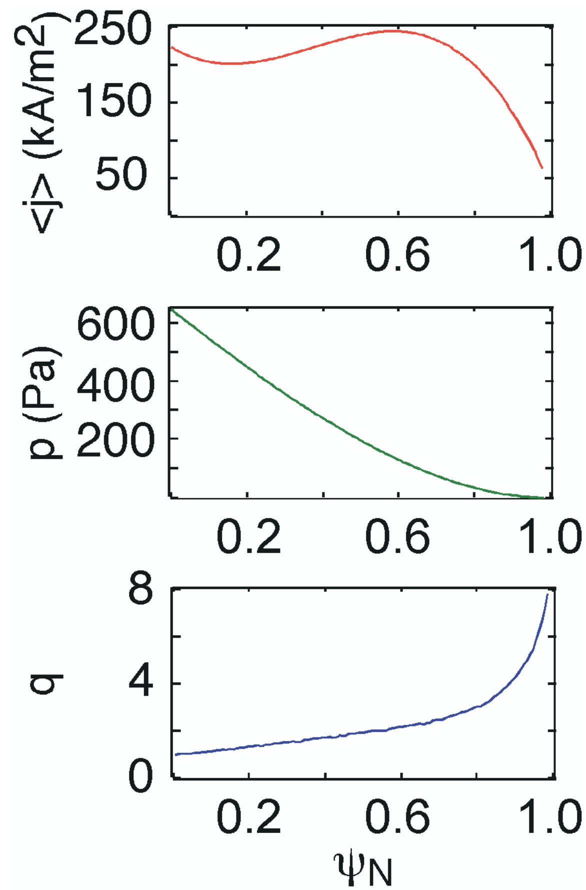
  - no significant variation in relative uncertainty
    ⇒ *uncertainty determined by diagnostic uncertainties*

Sample equilibrium results



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_{98}	7.8



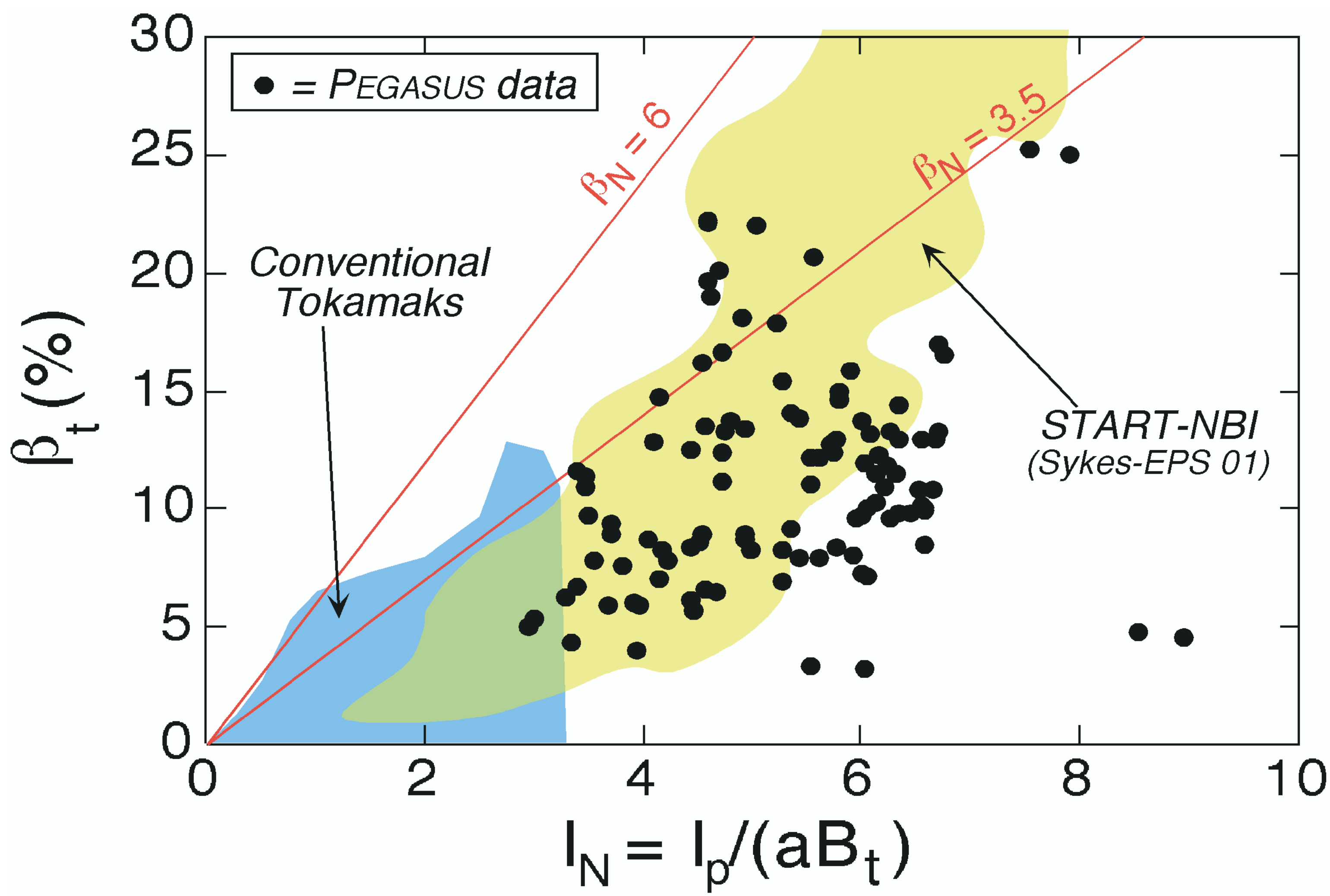
- **Small plasma size due to crude vertical field control**

Equilibrium reconstructions show low-A characteristics

- **High-$\square_t$ (Ohmic):** **$\square_t \sim 20\%$**
- **High-$\square_N$ (Ohmic):** **$\square_N \sim 5$**
- **High-I_N (Ohmic):** **$I_N \sim 6.5$**
- **High I_p/I_{TF}:** **$I_p/I_{TF} \sim 1$**
- **High-$\square$ (natural):** **$\square > 2$**
- **High field windup:** **high q_a at low TF**
- **Paramagnetic:** **$\square_p = 0.3$ at $\square = 0.83$; $F/F_{vac} \sim 1.5$ on axis**

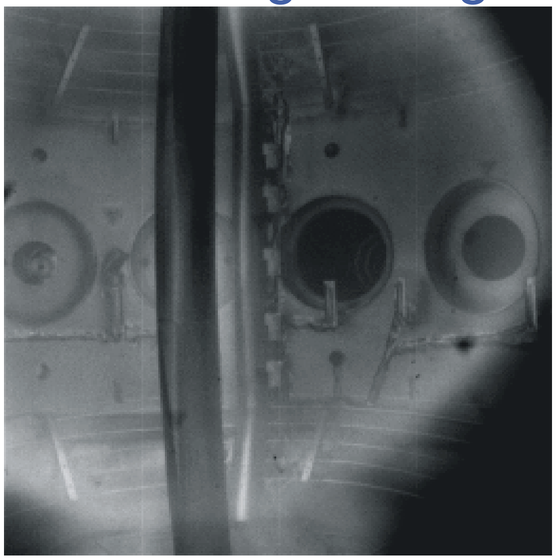
$A < 1.3 \Rightarrow$ ready ohmic access to high β_t

- $\beta_t \sim 20\%$ and $I_N > 6$ achieved ohmically
- Low field $\Rightarrow$ high I_N and β_t

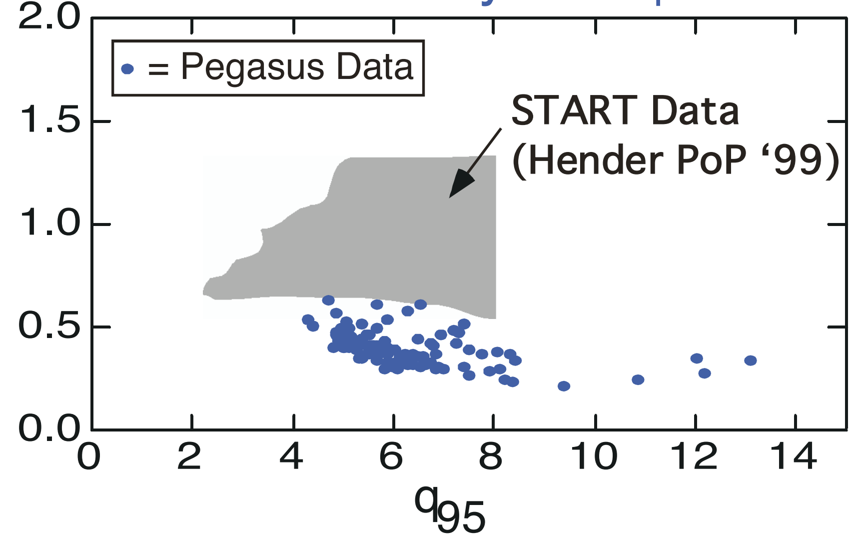


PEGASUS operates in low-ℓ_i, high-density space

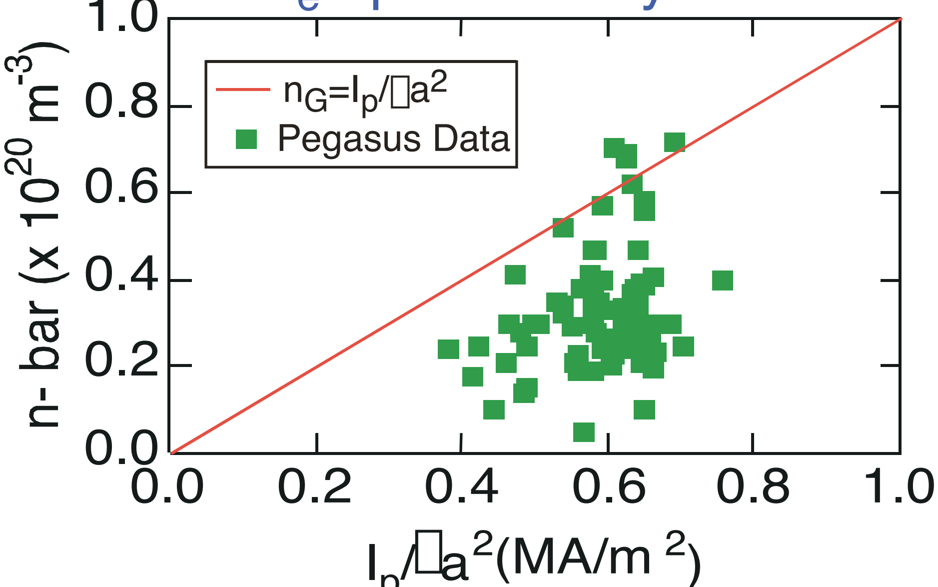
Visible light image



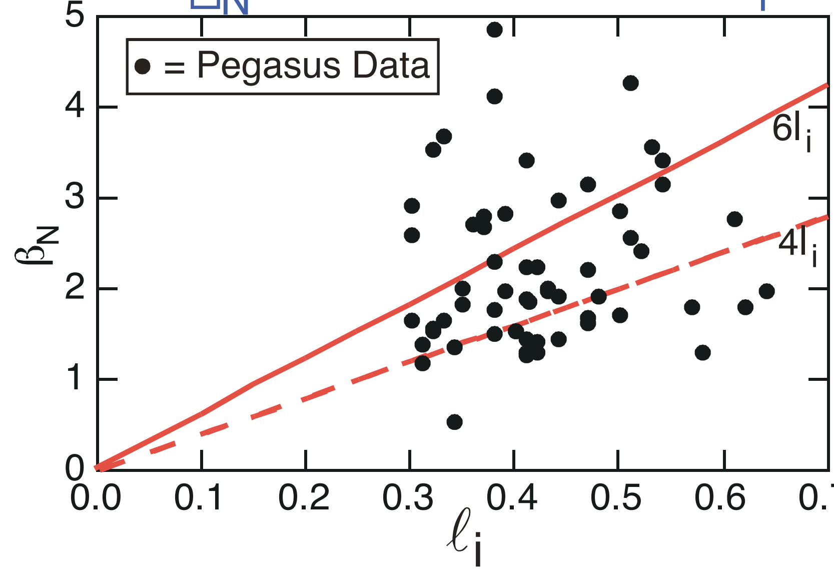
Generally low ℓ_i



$\overline{n_e}$ up to density limit

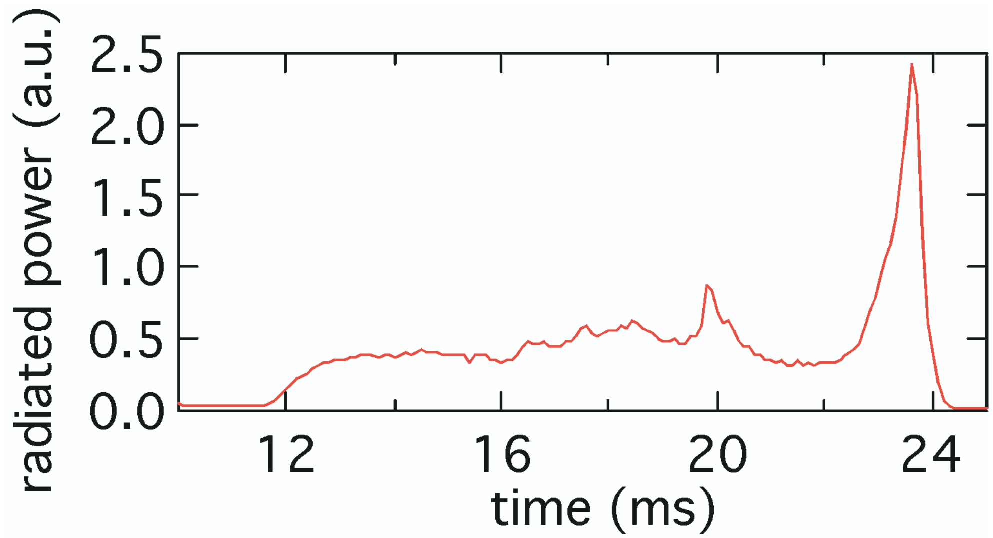


β_N uncorrelated with ℓ_i

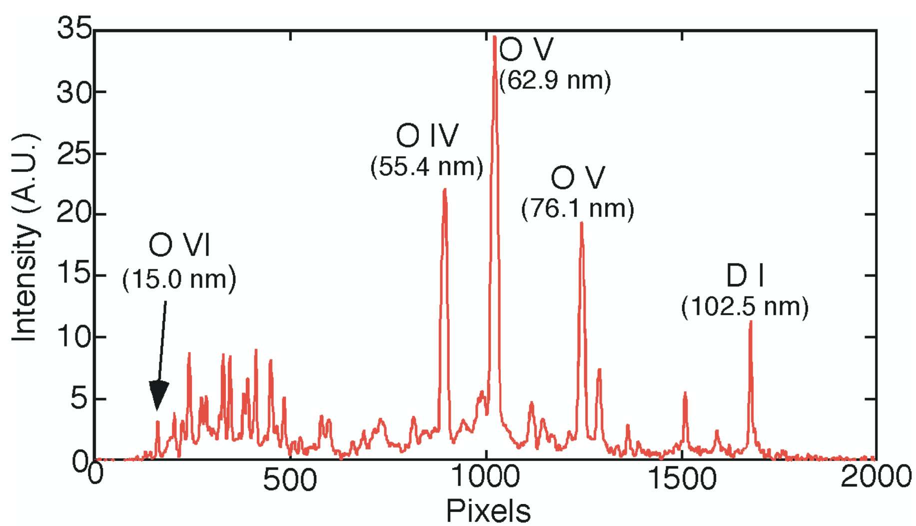


General discharge characteristics

- **Bolometry shows no indications of impurity build-up**



- **SPRED indicates oxygen is dominant impurity species**

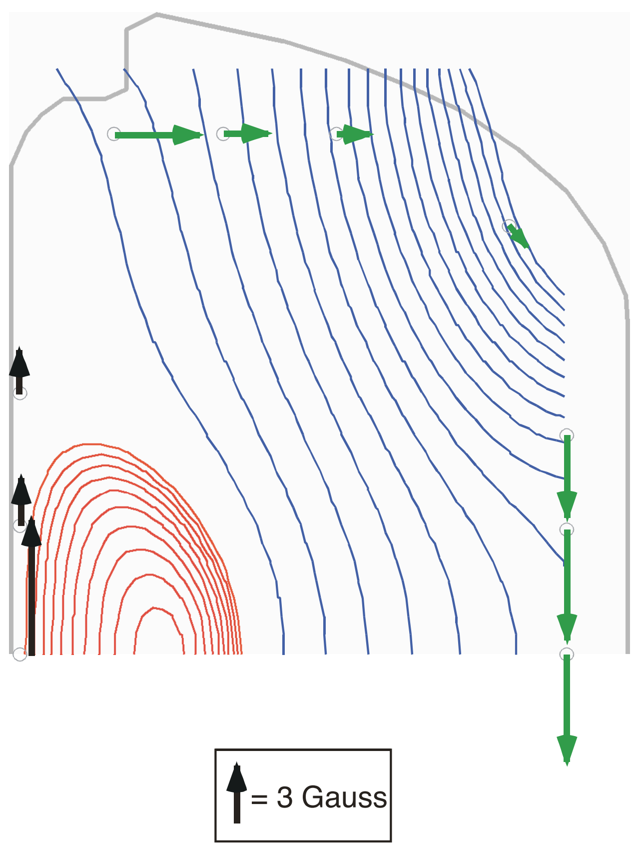


Ultra-low A □ strong poloidal asymmetry to tearing mode

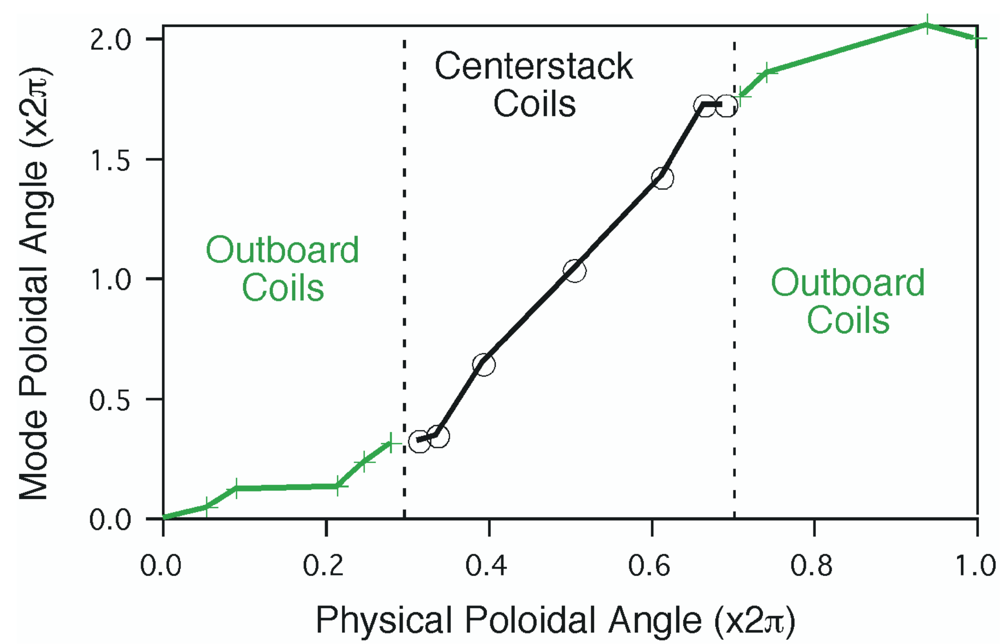
- Large phase shifts observed along centerstack for m/n=2/1
  - 1.5 wavelengths observed across 120° poloidally
  - similar structure observed for 3/2 and higher m/n

- Mode is strongest on the low-field side
  - LFS coils ~ a from edge
  - HFS coils ~ a/10 from edge

Perturbed Field Magnitude at the Wall

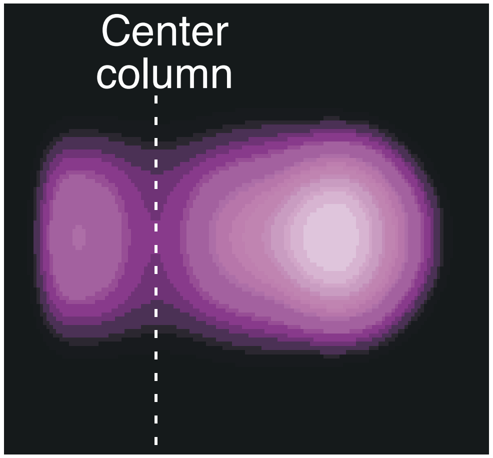


2/1 Poloidal Phase at the Wall



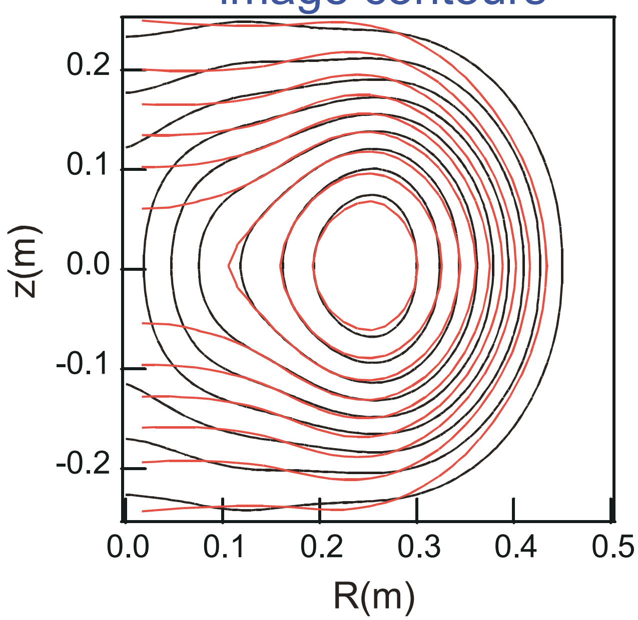
Measured q-profile indicates low central shear

Tangential PHC SXR image



⇓

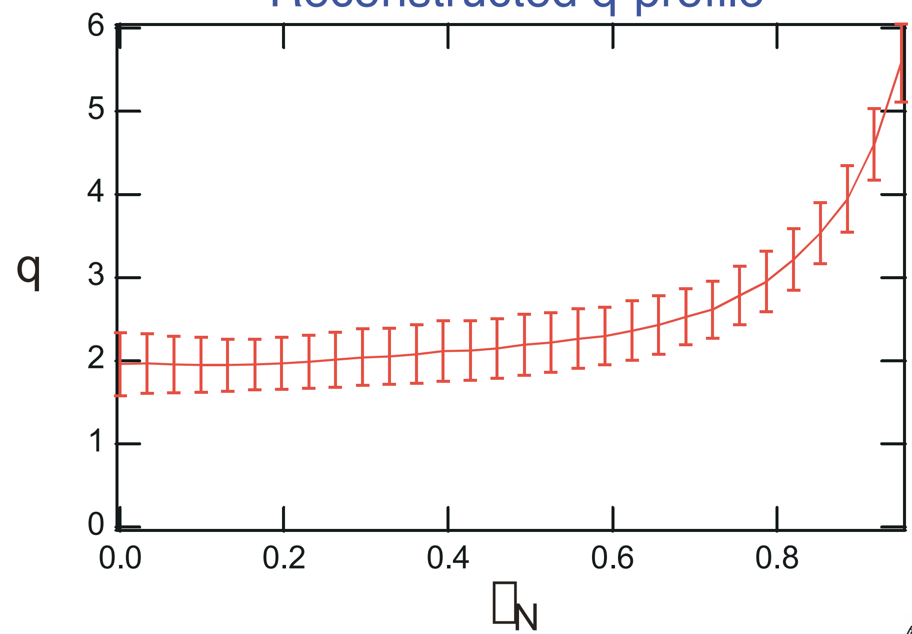
Measured and reconstructed
image contours



- 2D soft x-ray camera gives q-profile
  - Measures constant-intensity surfaces
  - Used as internal constraint on equilibrium
  - Useful as q-profile diagnostic
- Measured q-profile ⇒ zero central shear
  - Typical of low-A
  - Confirms shape predicted by external magnetics

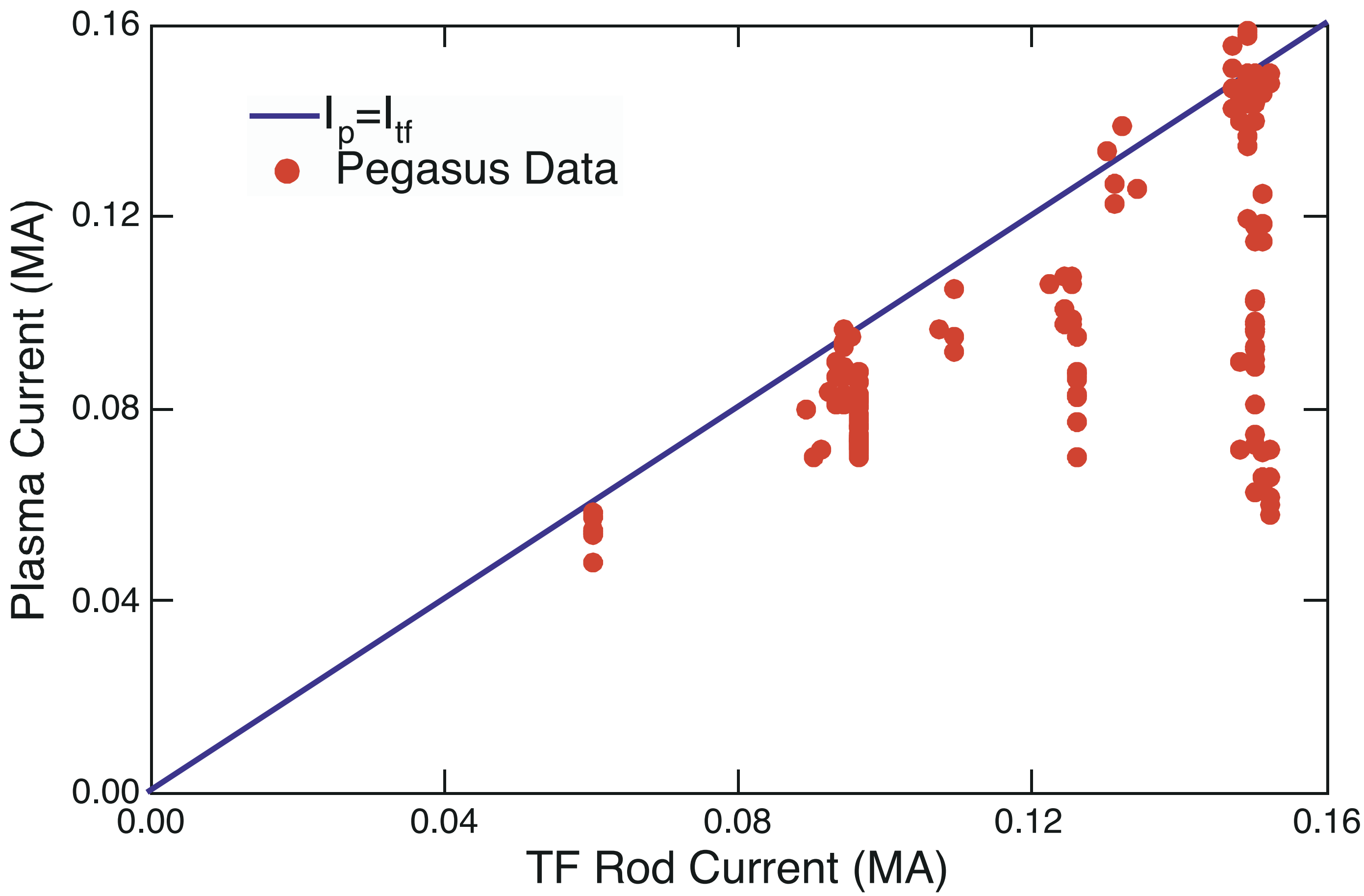
⇒

Reconstructed q-profile



Toroidal field utilization exhibits a "soft limit" around unity

- Maximum $I_p \approx I_{tf}$ in almost all cases
- Limit is not disruptive or abrupt
  - I_p saturates or rolls over



Two factors contribute to the $I_p/I_{tf} \sim 1$ soft limit

Large resistive MHD instabilities degrade plasma as TF □

- low B_t and fast dI_p/dt □ q = low-order m/n early in discharge
- high resistivity early in plasma evolution
- ultra-low A □ low central shear
- in the Rutherford regime:

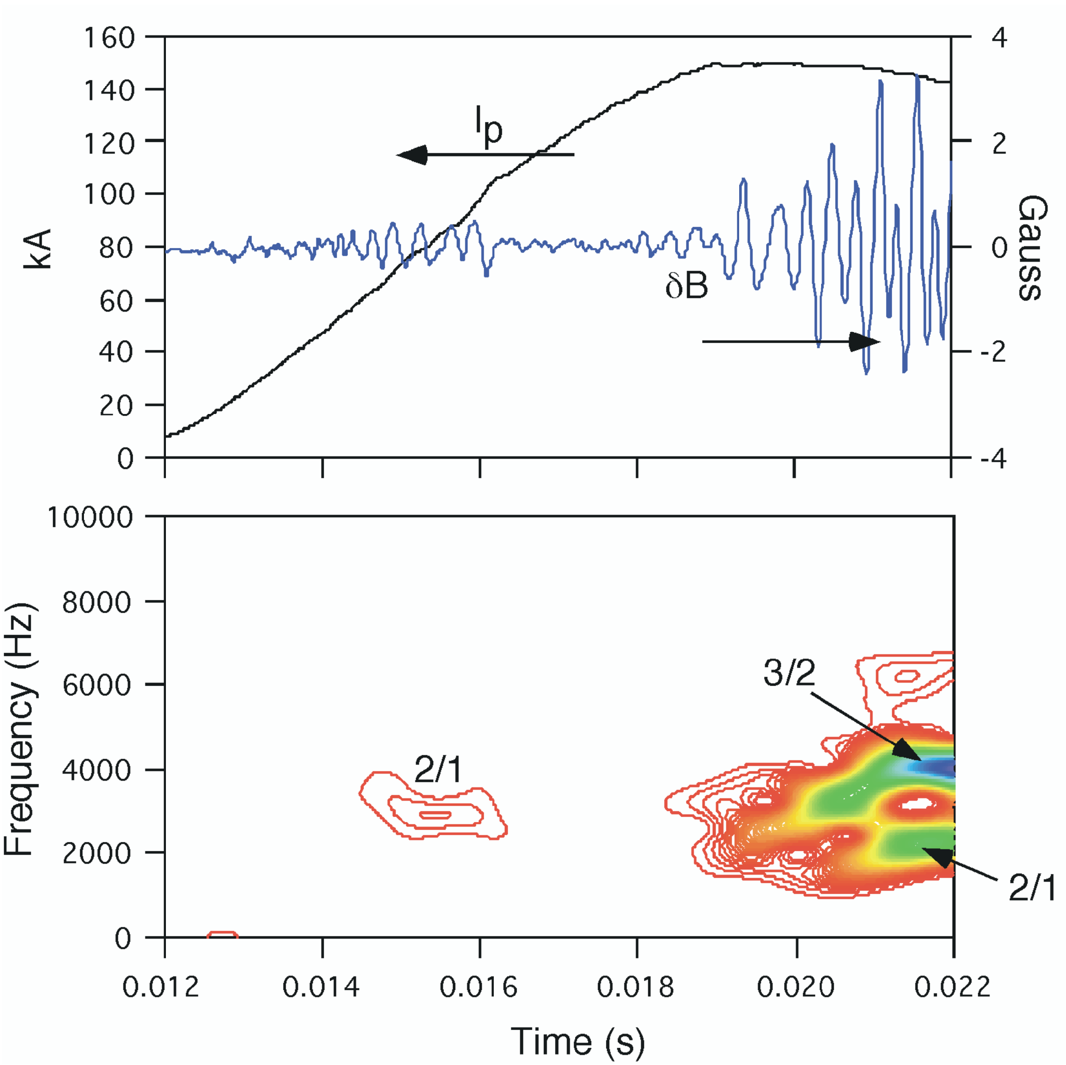
$$\frac{dw}{dt} \sim \square \qquad\qquad w_{sat} \sim q\left(\frac{dq}{dr}\right)^{-1}$$

□ Result is early rapid growth of tearing modes and large saturated island widths

Reduced available Volt-seconds as TF □

- reduction in toroidal field □ delayed startup
- delayed startup □ reduction in available volt-seconds
- only partially explains drop in I_p with reduced I_{tf}

Significant tearing activity is observed in most discharges

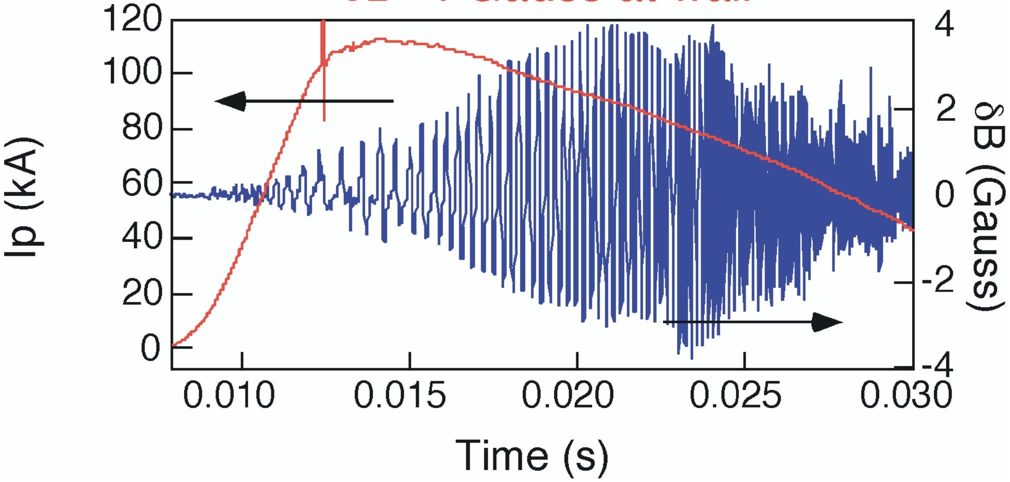


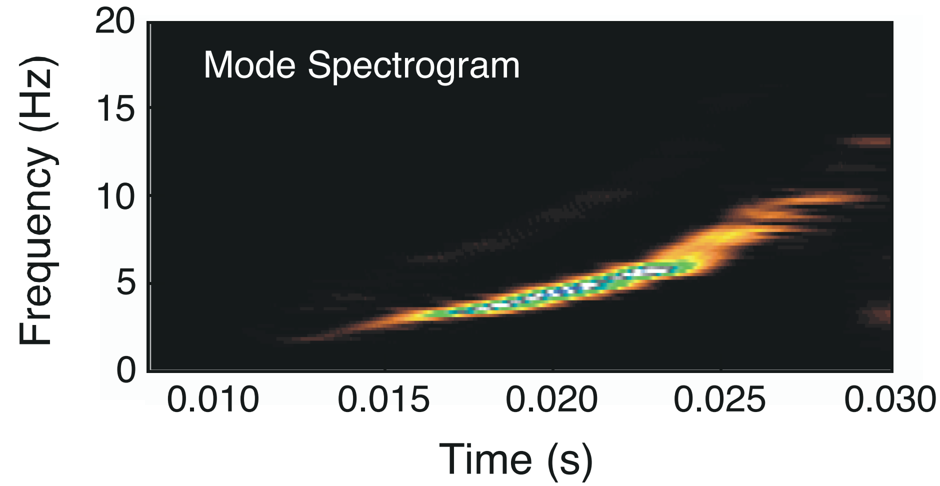
- Most common mode m/n=2/1
  - other m/n also observed
  - evidence of 2/1-3/2 coupling

- Leads to increased C_E, decreased I_p
  - Less efficient flux consumption in presence of internal MHD
  - Degradation of □$_E$
  - Decrease in dI_p/dt and I_p
  - Large radial extent
    □ affects entire plasma

Island widths are on the order of plasma minor radius

• δB=4 Gauss at wall

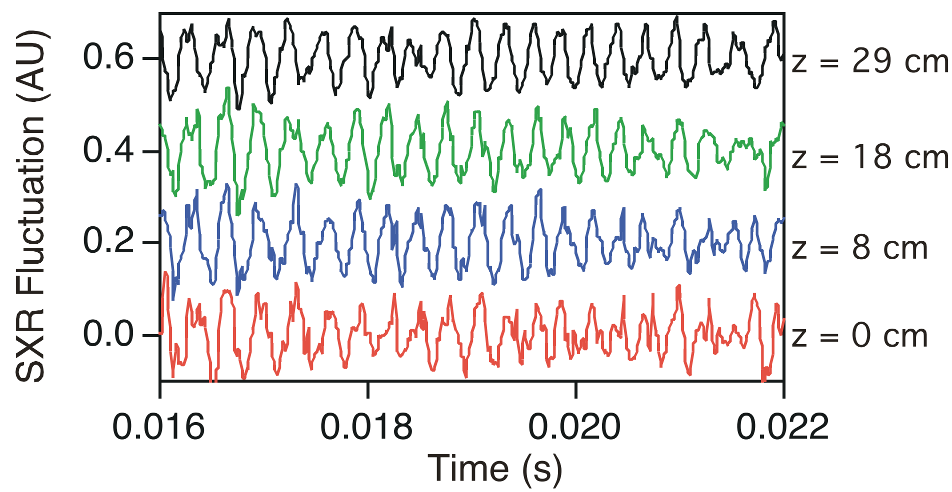




• Island width estimates give w>10 cm

$$w \approx 4\sqrt{\frac{\delta B}{B_t}\frac{qR}{n\frac{dq}{dr}}} \sim a$$

• SXR large radial extent of mode

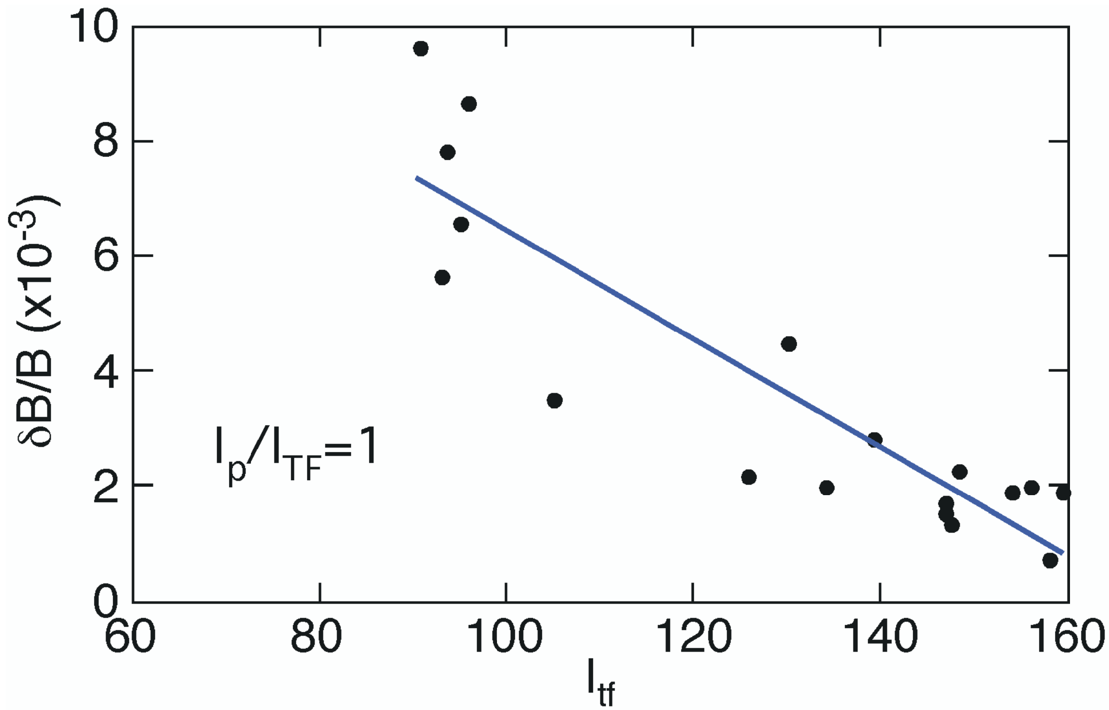


Mode amplitude decreases as I_{TF} is increased

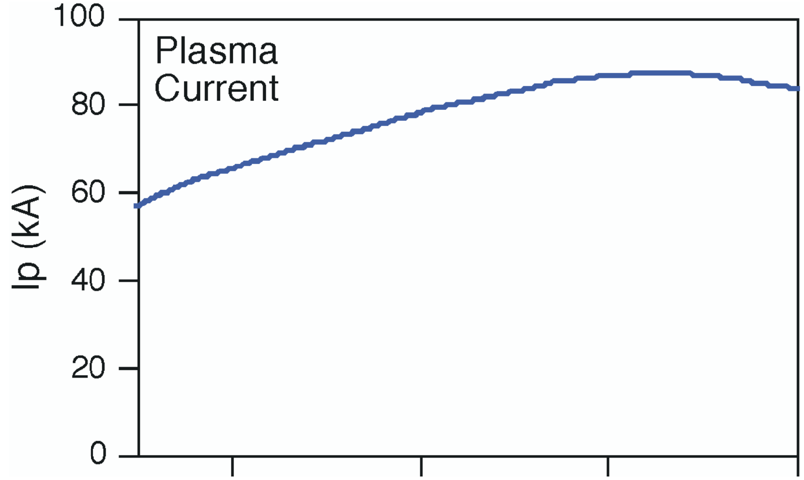
- Along $I_p \sim I_{TF}$ contour: B ↑ as TF

- At high TF effect of MHD minimal
  - $C_E = 0.4$

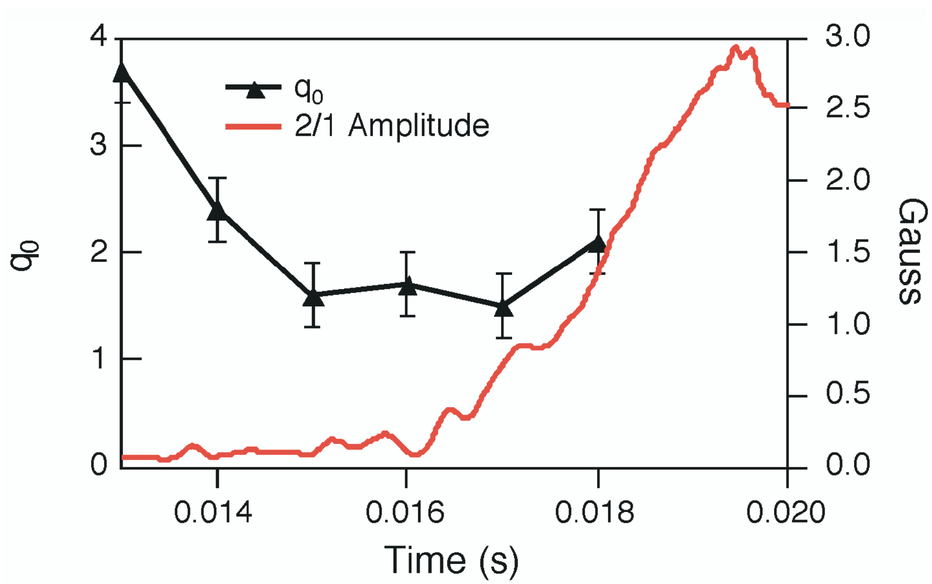
- At lower TF MHD amplitude increases
  - C_E increases
  - Stored energy decreases

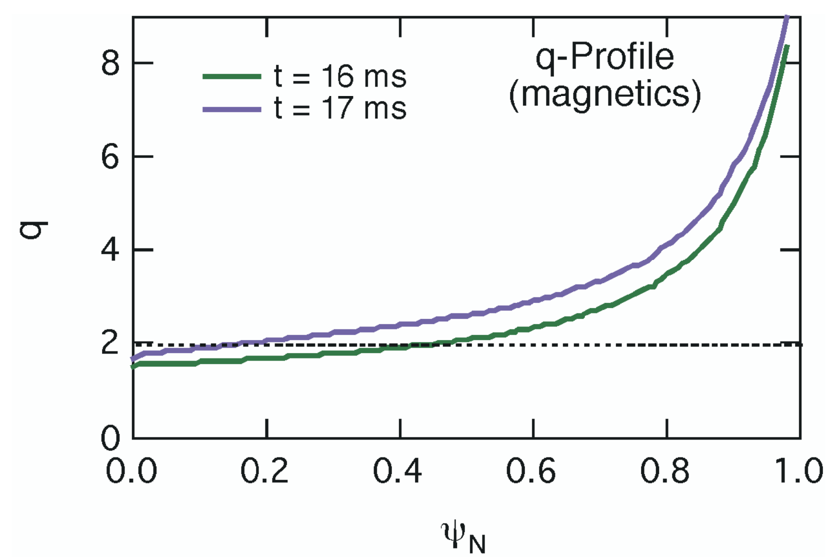


Tearing modes correlated with appearance of low q=m/n in broad low-shear region



- Low-A and low toroidal field
  □ appearance of q=2 surface early in discharge
- □ high early in shot
- Broad low-shear region gives large radial extent of mode
  - 2D SXR imaging shows low central shear





$I_p/I_{TF} \sim 1$ implies low-order q_0

- Cylindrical approximation OK for central flux surfaces:

$$q(r) = \frac{2\pi r^2 B_t}{\mu_0 R I(r)} \frac{1+\kappa^2}{2}$$

- Assuming flat j(r) implies:

$$q_0 \sim \frac{1}{A^2} \frac{I_{TF}}{I_p} \left(\frac{1+\kappa^2}{2} \right)$$

- For PEGASUS at $I_p \sim I_{TF}$ ⇒ $q_0 = 1.5 - 2$

⇒ Low-order rationals in low-shear region for $I_p = I_{TF}$

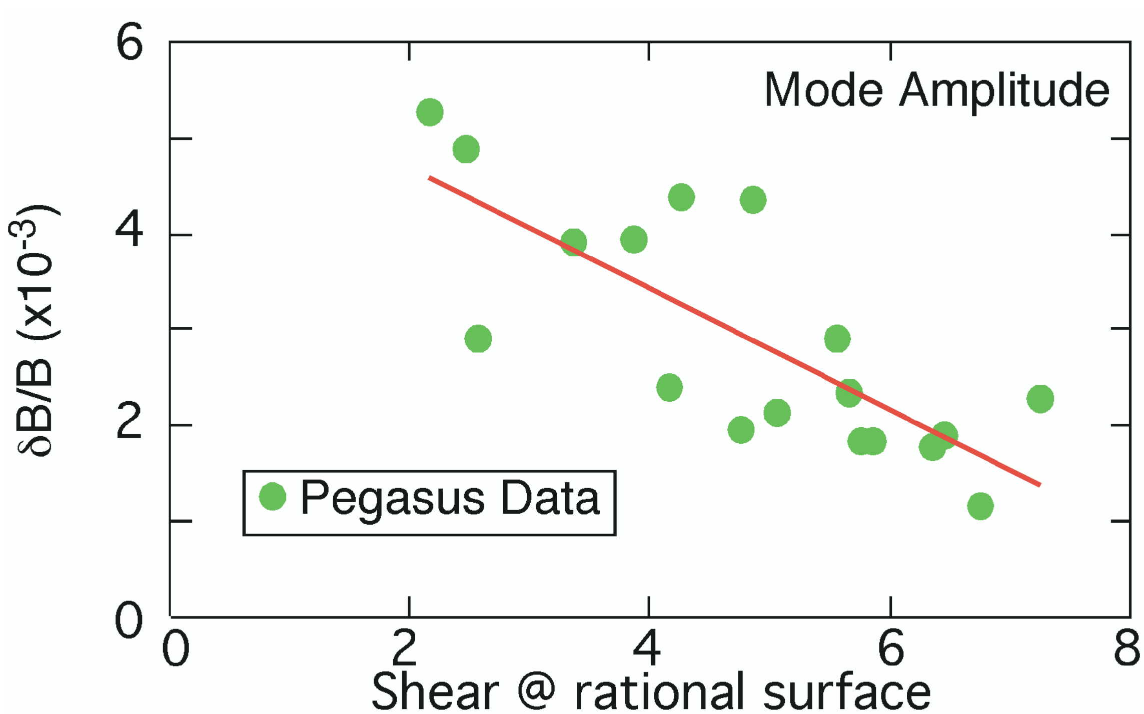
Mode amplitude reduced by manipulation of shear and q_0

- Improved wall conditions & EF control □ plasmas with reduced MHD activity
  - Increased W, I_p

- Increased shear, increased q_0 □ delay tearing onset

- MHD amplitude decreases with increasing shear @ mode rational surface

□ Access higher toroidal field utilization via higher q_0, T_e, shear



Summary of internal MHD effects

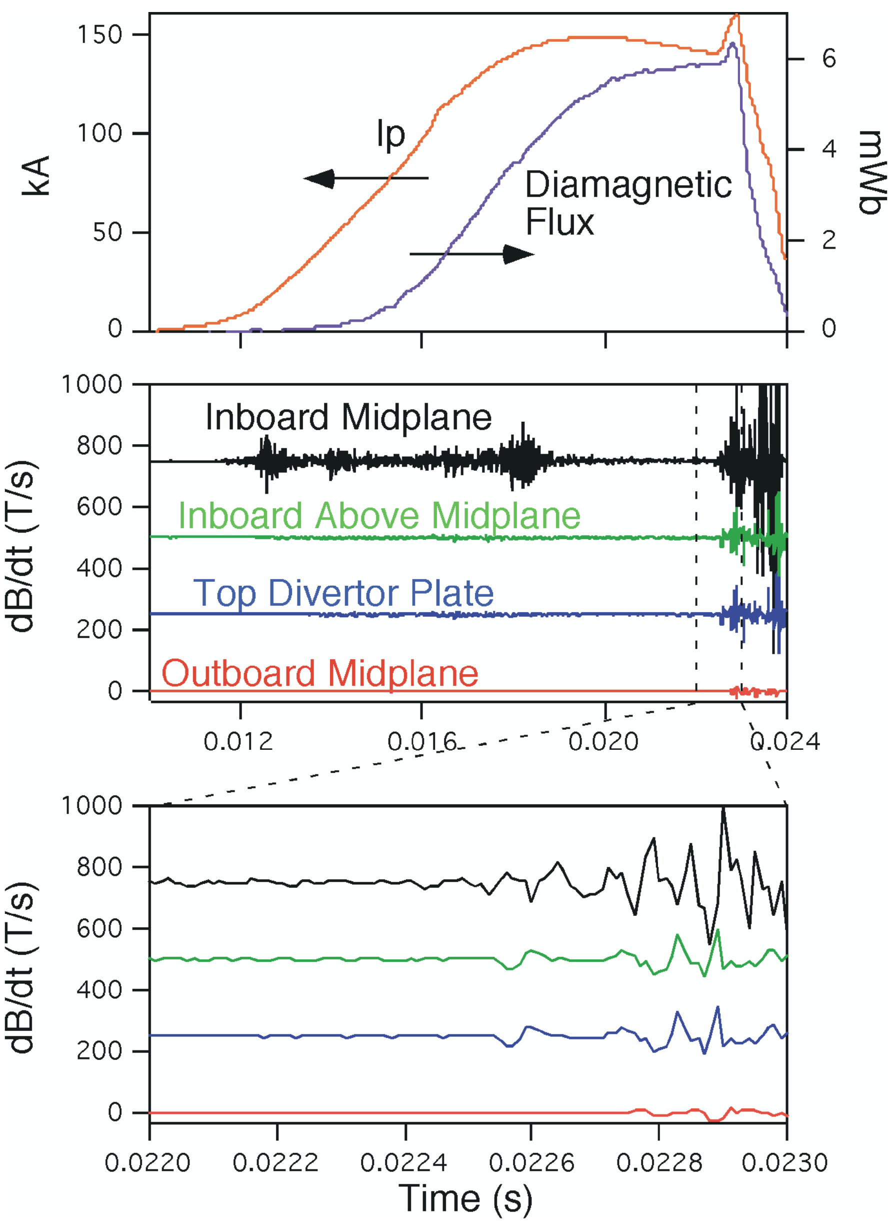
- **Large scale tearing modes observed in almost all plasmas**
  - low B_t and fast dI_p/dt □ low q early in discharge
  - high resistivity early in plasma evolution □ fast island growth
  - ultra-low A □ large island widths

- **MHD activity contributes to $I_p \sim I_{tf}$ soft limit**
  - large tearing modes dissipate input flux
  - mode onset is related to appearance of low-order rational q surfaces

    onset at lower I_p for lower TF
  - MHD amplitude increases as TF decreased
  - mitigated by lower □, increased q_0, increased shear

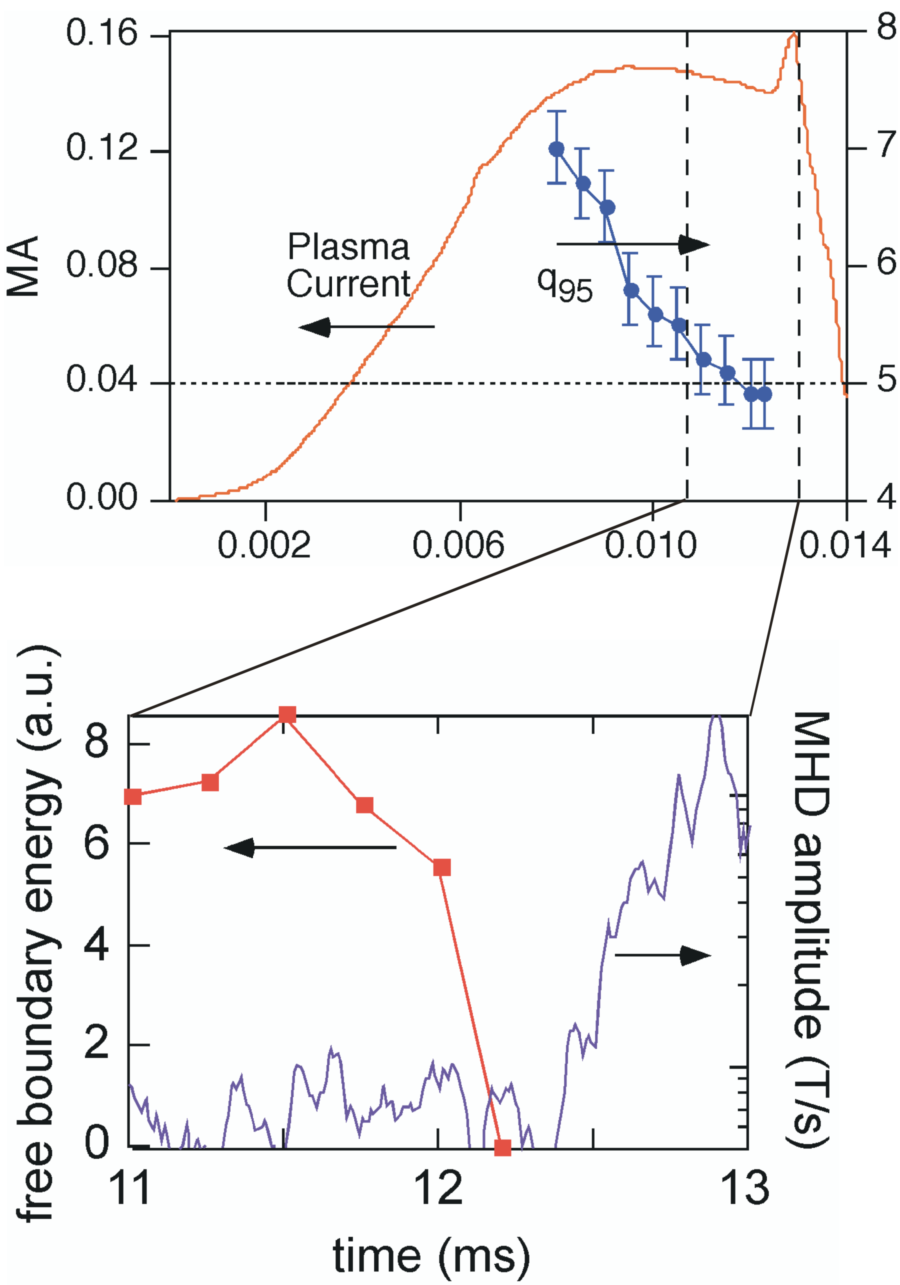
- **At highest I_p ideal external kink is observed ...**

Disruptive instabilities end discharge in some cases

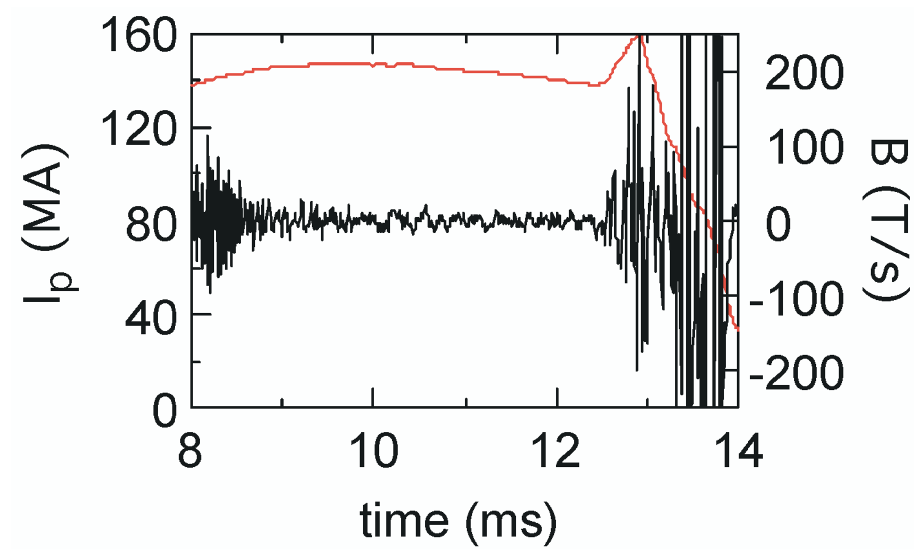


- Higher-current plasmas (150 kA class) often terminate in abrupt disruptions
- n=1 fluctuations are observed on core Mirnov coils immediately prior to disruption
  - Dominant frequency is order of 10 kHz
  - Mode is observed a few 100 μs before IRE
- These fluctuations are not observed in lower-current shots

External kink observed at $q_{95} \sim 5$



- **tearing modes suppressed**
- **free boundary energy → 0 as q_{95} → 5**
- **disruption immediately follows**
- **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



Upgrades will allow access to high I_p/I_{tf}, $□_t$, low-q operation

Goals:

- Manipulate q-profile: suppression of large internal modes
- Lower □ during plasma formation: suppression of large internal modes
- Manipulate edge conditions: Expand access to external kink modes
- Access to very high $□_t$ regime for stability analysis

Additional tools being deployed:

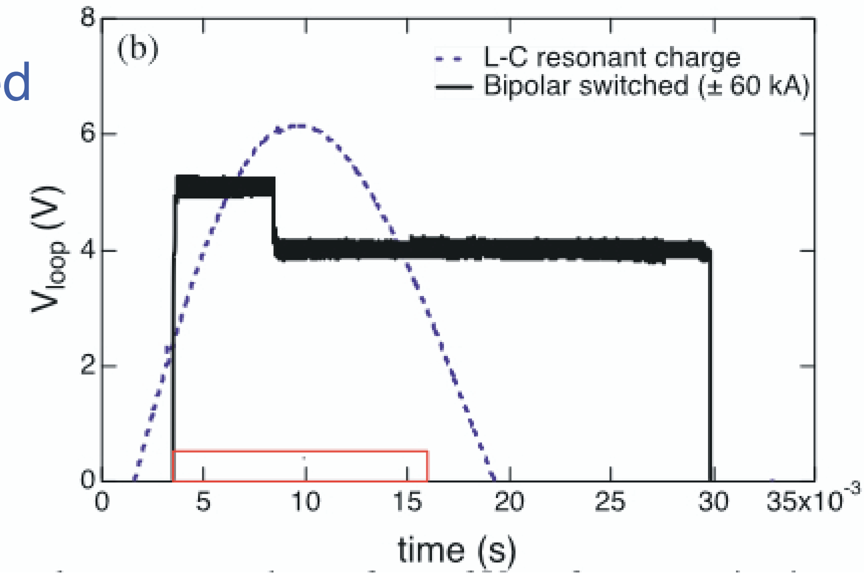
- Programmable waveform power systems
  - Increase V-sec, B_t; position and shape control
- Fast-response $B_t(t)$ system
- Separatrix operation
- Increased HHFW power

Flexible power systems in fabrication

Ohmic Upgrade:

- Programmable waveform being implemented
  - will increase V-s capability
  - eliminates overdrive after breakdown

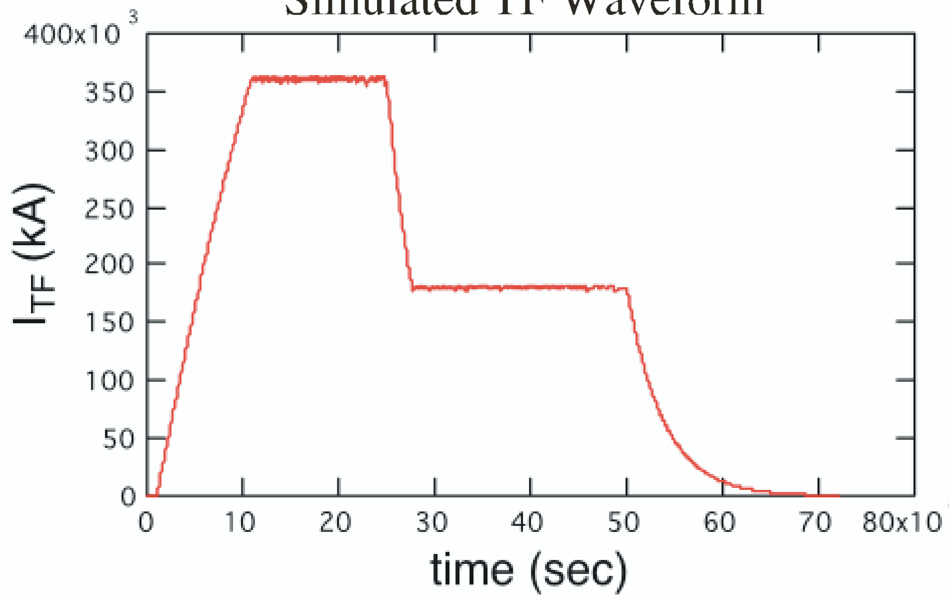
Simulated Ohmic Waveforms



TF Upgrade:

- Allows operation at > 3X present I_{TF}
  - hold off q = 2 surface until □ is decreased
- Fast ramp-down capability

Simulated TF Waveform



EF Upgrade:

- Flexibility added to coil set
  - pre-programmable shape control
  - position control for improved HHFW coupling
  - energize divertor for separatrix operation

Summary of PEGASUS ultralow-A results

- Mission: Study characteristics of plasmas as $A \rightarrow 1$

- Ready access to low-A physics with ohmic heating:
  - $\beta_t = 20\%$, $\beta_N > 4$, $n_e \sim n_{GW}$, low central shear, paramagnetic: $F/F_{vac}=1.5$

- Resistive MHD activity and some Volt-second reduction result in a "soft limit" of $I_p \sim I_{TF}$
  - Associated with central $q(0) = 1.5$-2

- Beginning to explore the edge kink stability boundary
  - external kink observed at $q_{95} = 5$

- Upgrades now underway will provide improved plasma control and allow access to high-β_t, high I_p/I_{TF} regime