Abstract

Magnetic equilibrium analyses of low-A 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 using wall mounted flux loops. With I_{wall}/I_{pmax} up to 2, the poloidal field due to the walls dominates early in the discharge. Plasmas with $A < 1.3$ on the order of 0.15 MA, with $0.2 < \ell_i < 0.8$ and $\beta_t \sim 25\%$ have been analyzed. The presence of low-order rational surfaces in broad regions of low magnetic shear inside the plasma correspond to the growth of large internal tearing modes, which are observed in nearly all discharges. Ideal stability analyses have been performed using DCON. An external kink stability boundary appears to have been reached at $q_{95} = 5$. Poloidal and toroidal Mirnov arrays as well as an 18-channel poloidal soft X-ray diode array are used to observe and characterize the internal fluctuations.

Outline

- **PEGASUS introduction**

- **PEGASUS equilibrium tools**
  - equilibrium code and magnetic diagnostic used for equilibrium fitting
  - uncertainties in the fit parameters have been determined
  - current filament model used to determine induced wall currents

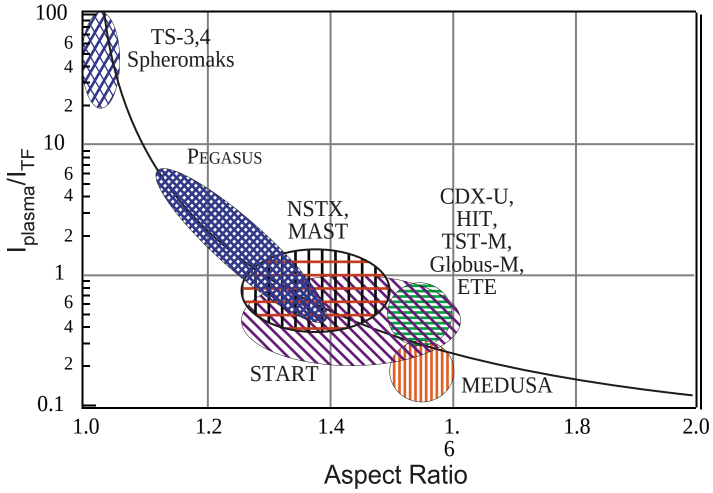
- **PEGASUS low-A ST characteristics**

- **Operational limit of $I_p/I_{TF} \sim 1$**
  - Volt-second limitations
  - MHD activity

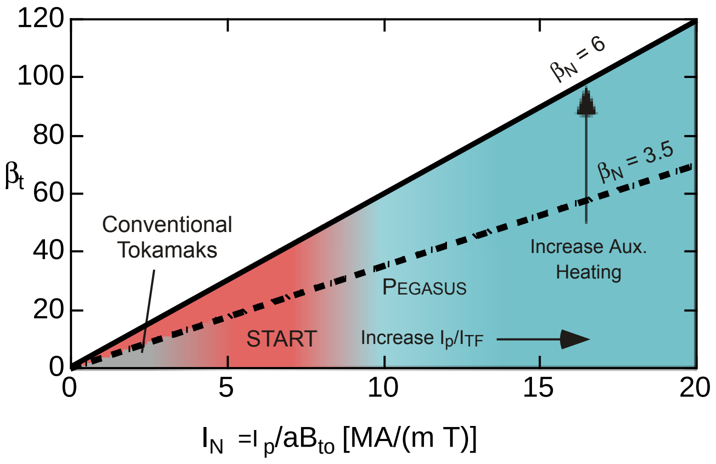
- **Edge kinks observed at $q_a \sim 5$**

Role of Pegasus in the Fusion Community

- **Physics of A ≈ 1 plasmas as an Alternate Concept (low q)**
  - Extreme toroidicity (A → 1)
  - Very high TF utilization (I_P/I_{TF}) > 3
  - Stability at very low TF ($\beta \approx 1$)
  - Relaxation stability at tokamak/spheromak boundary
  - RF heating and CD schemes (HHFW, EBW)
  - Trade-offs:
    CD, recirculating power,
    and A ≈ 1, low-TF operation



- **Contribute to development of the ST (high q)**
  - Stability limits for A → 1
    (vs. I_p/I_{TF}, q_ψ, N_e, β_t,
    β_{pol}, κ, A, etc.)
  - β limit dependencies
  - Access high β_t at extreme I_N w/o conducting shell
  - Confinement A < 1.3
  - New startup schemes
    (e.g., plasma gun, EBW)



Equilibrium Reconstruction Tools Developed for Pegasus

- **New Equilibrium Code Developed:**
  - 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

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

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

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

- **Fit Constraints:**
  - magnetics:
    - *poloidal flux loops (26), poloidal B coils (20), wall mounted poloidal flux loops (6)*
    - *diamagnetic loop, plasma Rogowski*
  - coil currents

Monte Carlo Analysis Gives Uncertainty in Fit Parameters

- **Uncertainty estimate technique:**

  - single time-slice of discharge reconstructed 100 times

  - Gaussian noise added to measurement data

    Gaussian width from diagnostic uncertainty

    starting $\chi^2 \sim 8$ *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%

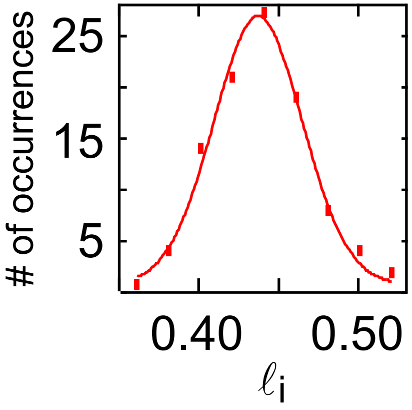
- **Variety of discharges analyzed**

  - wide range of fit parameters covered:

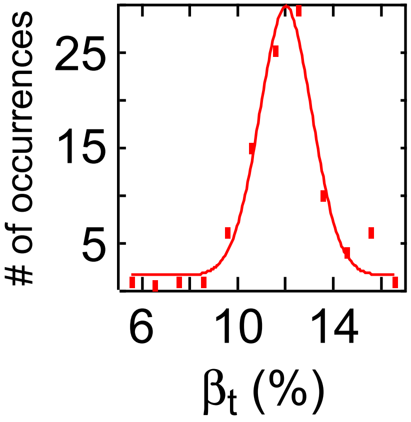
    $75\ \text{kA} < I_p < 150\ \text{kA}$
    $8\% < \beta_t < 18\%$
    $0.2 < \ell_i < 0.4$
    $0.23\ \text{m} < R_0 < 0.33\ \text{m}$

  - no significant variation in relative uncertainty

    ⇒*uncertainty determined by diagnostic uncertainties*



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



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

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)

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

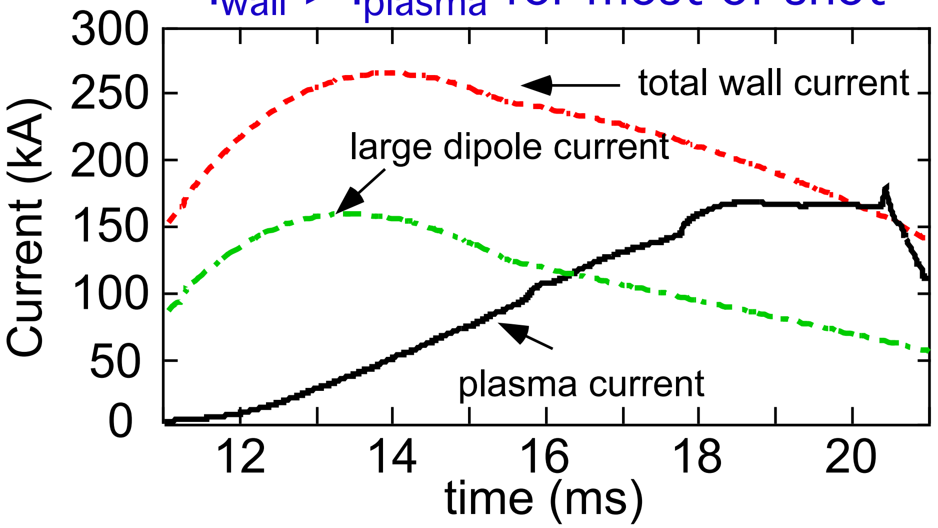
self-inductance of coil set i

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

mutual inductance of coil set i with coil set j

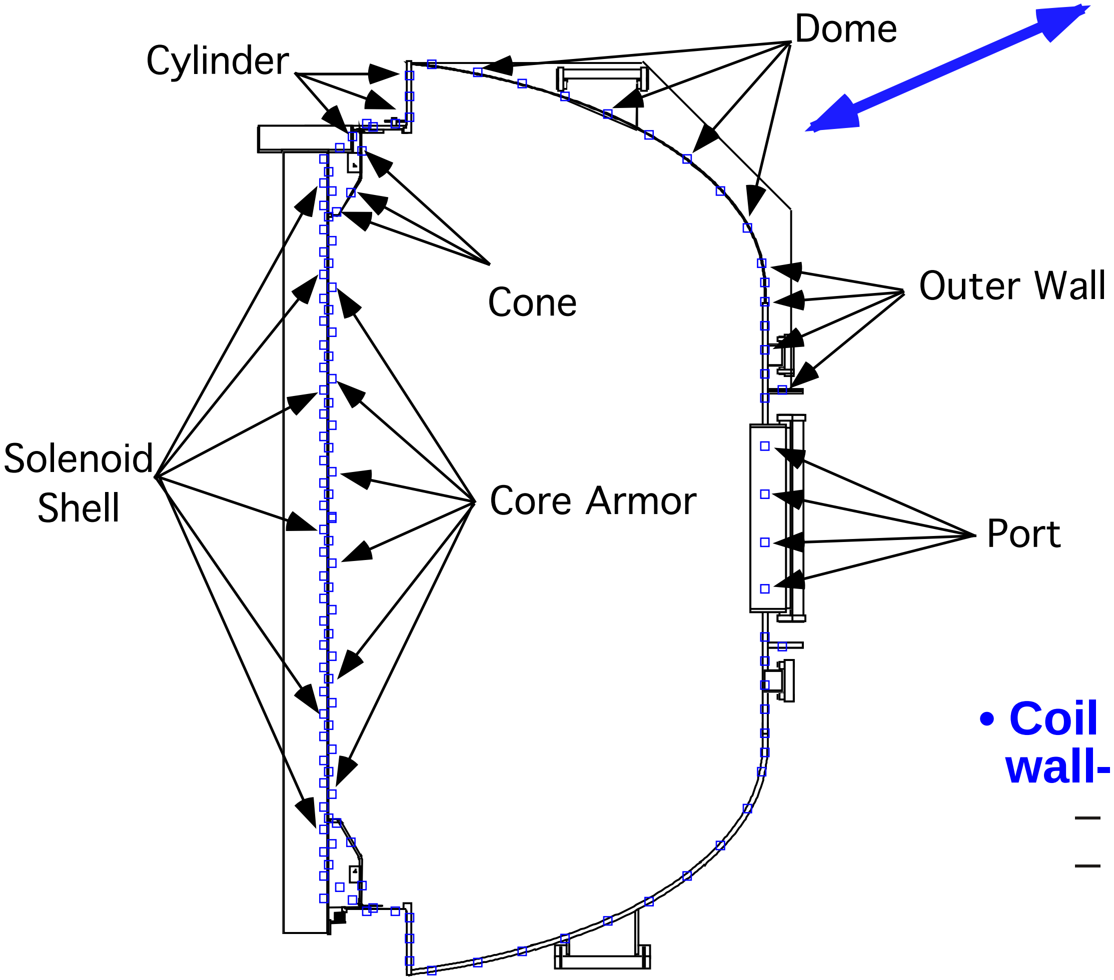
$$M_{ij} I_j = \sum_{k=1}^{N_i} \sum_{l=1}^{N_j} \Phi_{ij}^{k,l}$$

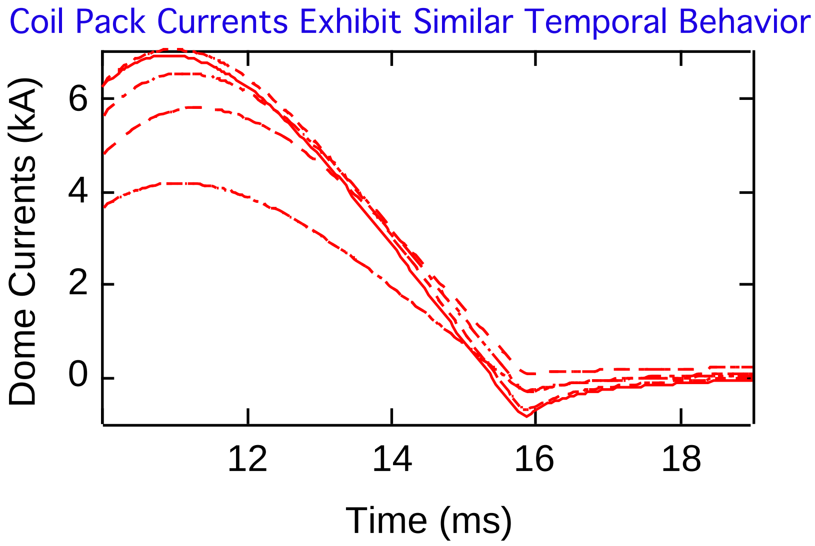
$I_{wall} > I_{plasma}$ for most of shot



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





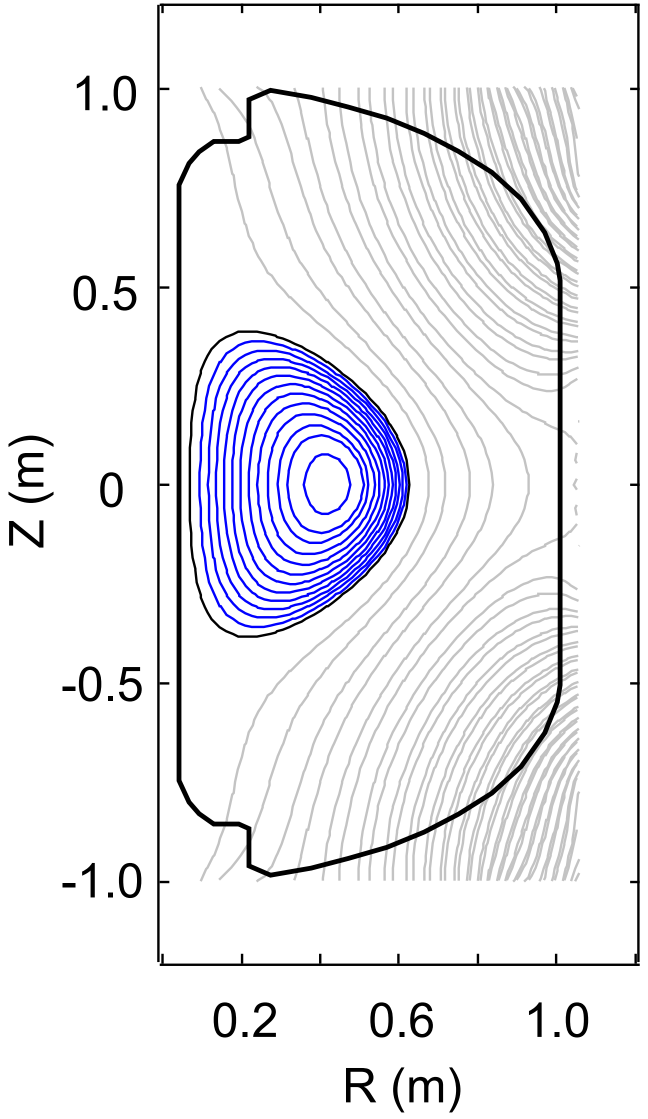
Coil Pack Currents Exhibit Similar Temporal Behavior

- **Coil pack currents constrained via wall-mounted flux loops**
  - – Dome and outer wall most significant
  - – 2 loops on dome, 1 on outer wall

Equilibrium Reconstructions Show low-A Characteristics

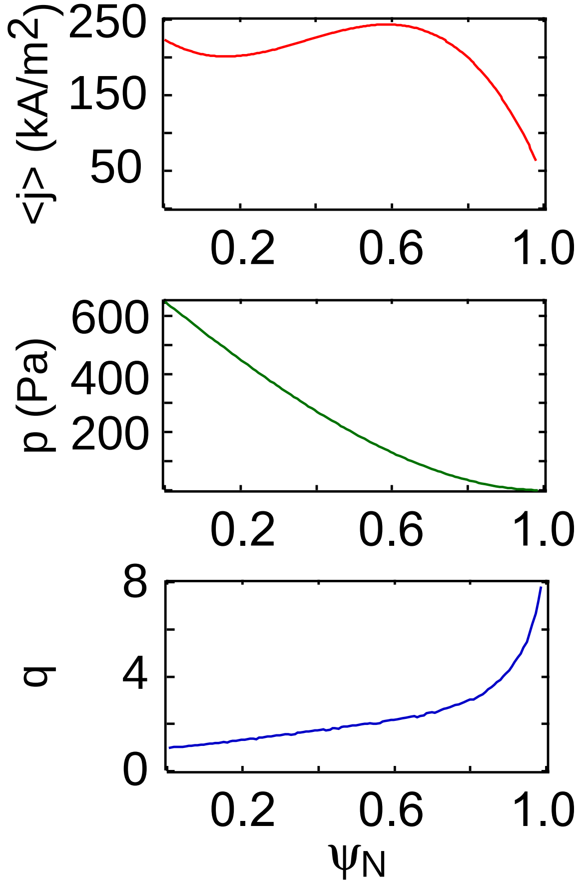
• High-β_t (Ohmic):	**$\beta_t > 10\%$**
• High-β_N (Ohmic):	**$\beta_N > 4$**
• High I_p/I_{TF}:	**$I_p/I_{TF} \sim 1$**
• High-κ (natural):	**$\kappa > 2$**
• High field windup:	**high q_a at low TF**
• Paramagnetic:	**$\beta_p = 0.3$ at $\varepsilon = 0.83$; $F/F_{vac} \sim 1.5$ on axis**

High β_t Obtained at Low TF



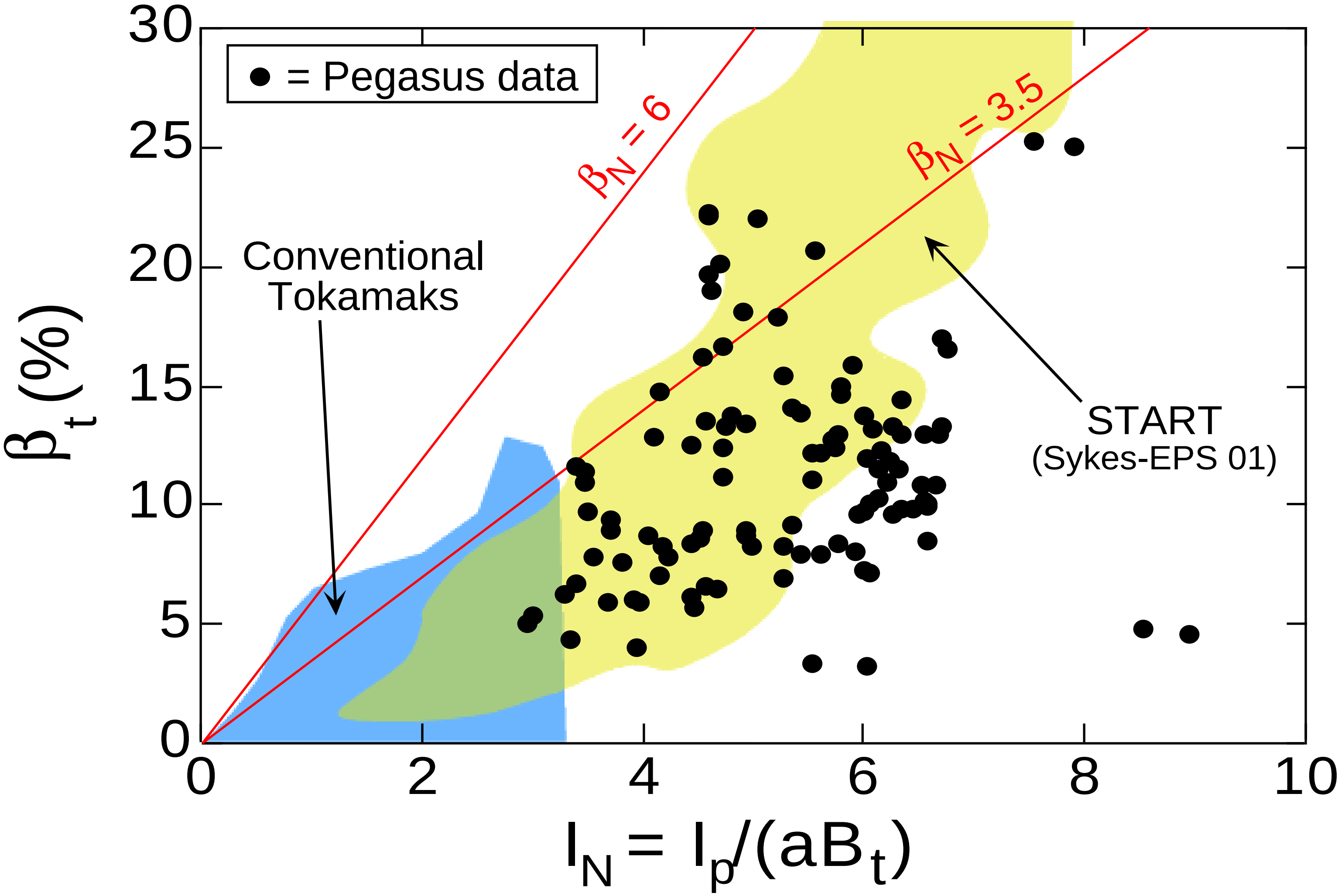
Shot
12445

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



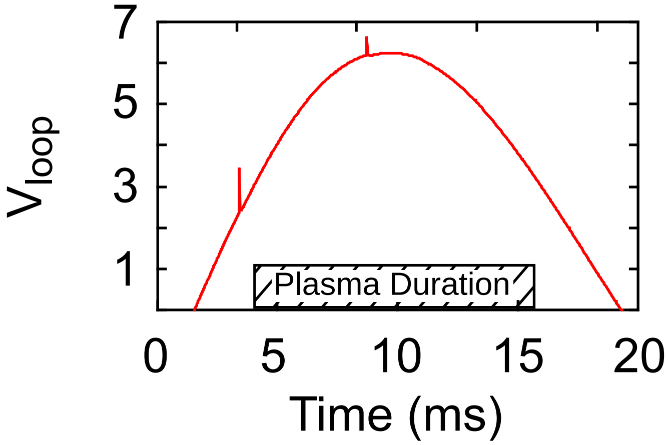
Pegasus is Accessing High-β Operating Space

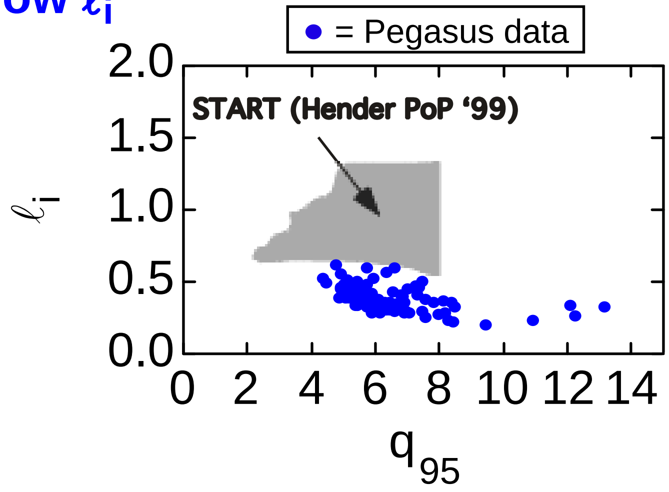
- **High β_t attained at high density, low-TF**
  - *Ohmic heating constant TF*
  - *Highest β_t , I_N at low TF*



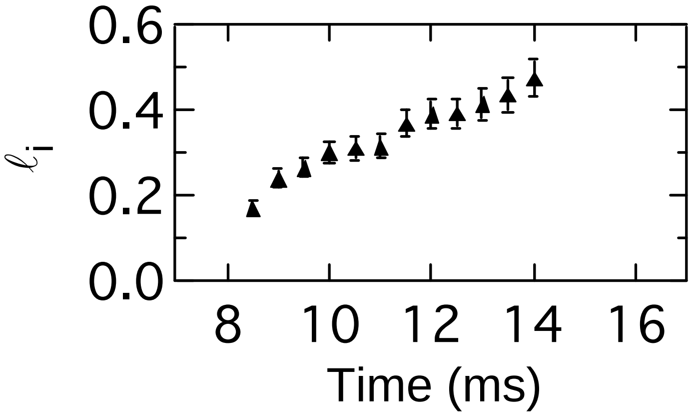
Low-ℓ_i Indicates Unrelaxed Current Profile

- **High $\dot{I}_p$ and short pulse length result in low ℓ_i**

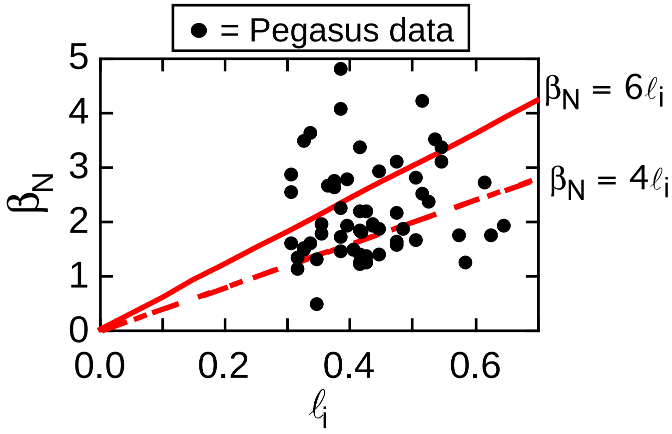




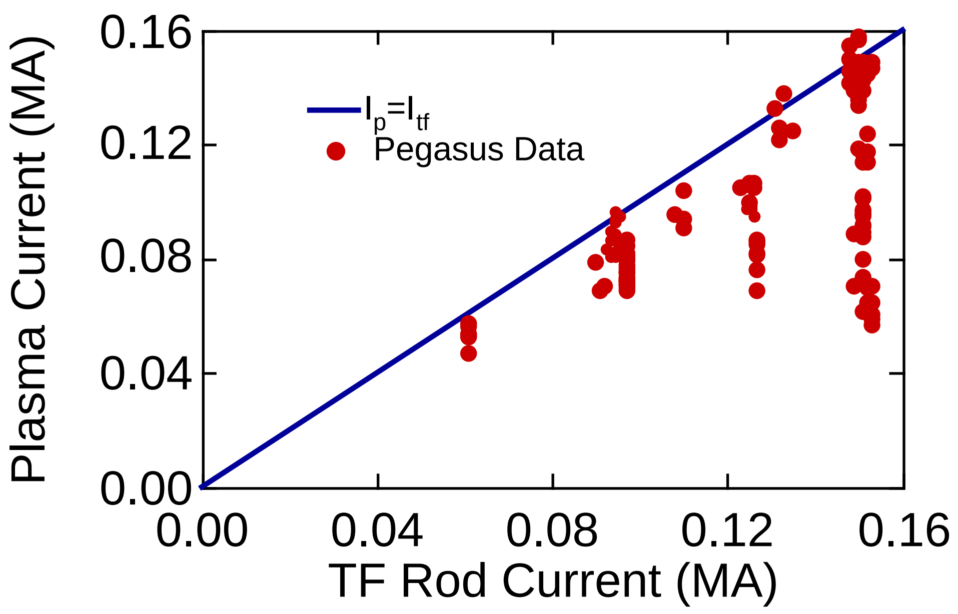
- **Increase in ℓ_i observed during shot**

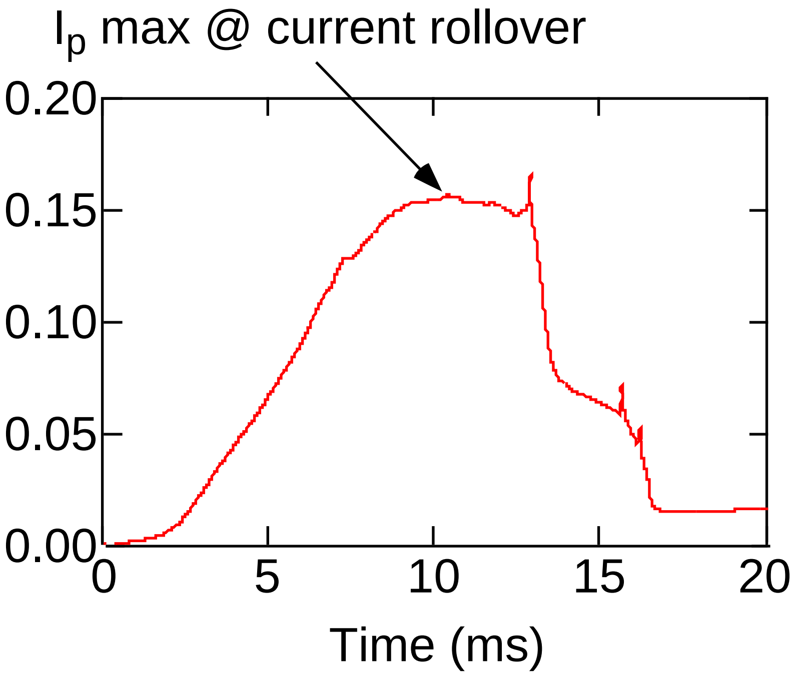


- **No correlation found between ℓ_i and β_N**



I_p/I_{TF} 'Soft' Limit Observed





- **Limit manifests as plasma current roll over, not disruption**

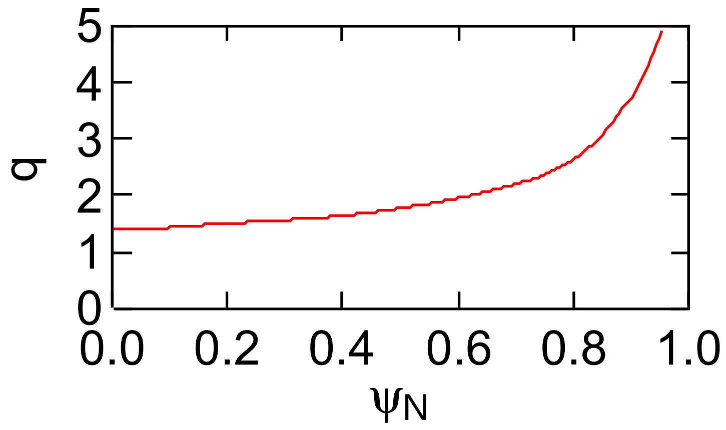
- **Understanding this limit is important to maximizing TF utilization**

  - physical understanding leads to hardware development

What Factors Contribute to $I_p \sim I_{TF}$ Limit: MHD and Volt-seconds

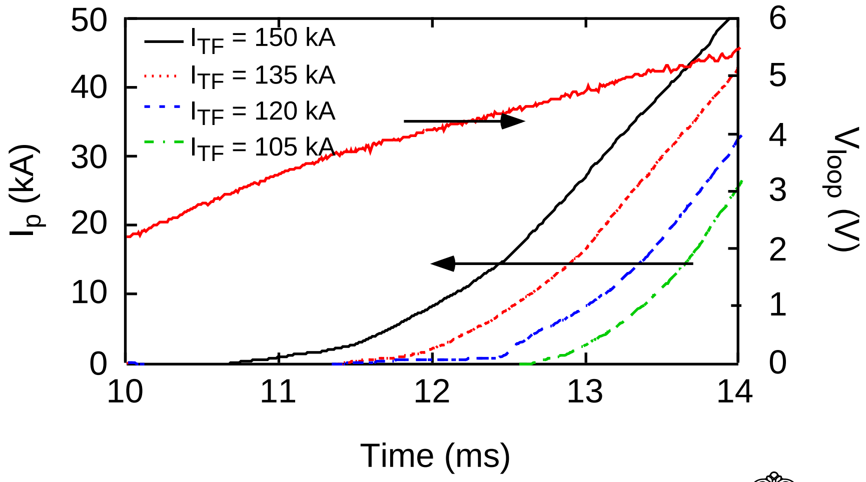
• MHD effects at ultra-low-A & low TF:

- large m/n = 2/1 and 3/2 tearing modes present in most discharges
  known to degrade plasma confinement
- low TF
  → *early appearance of low-order rational surfaces*
- low central magnetic shear
  → *large saturated island width*

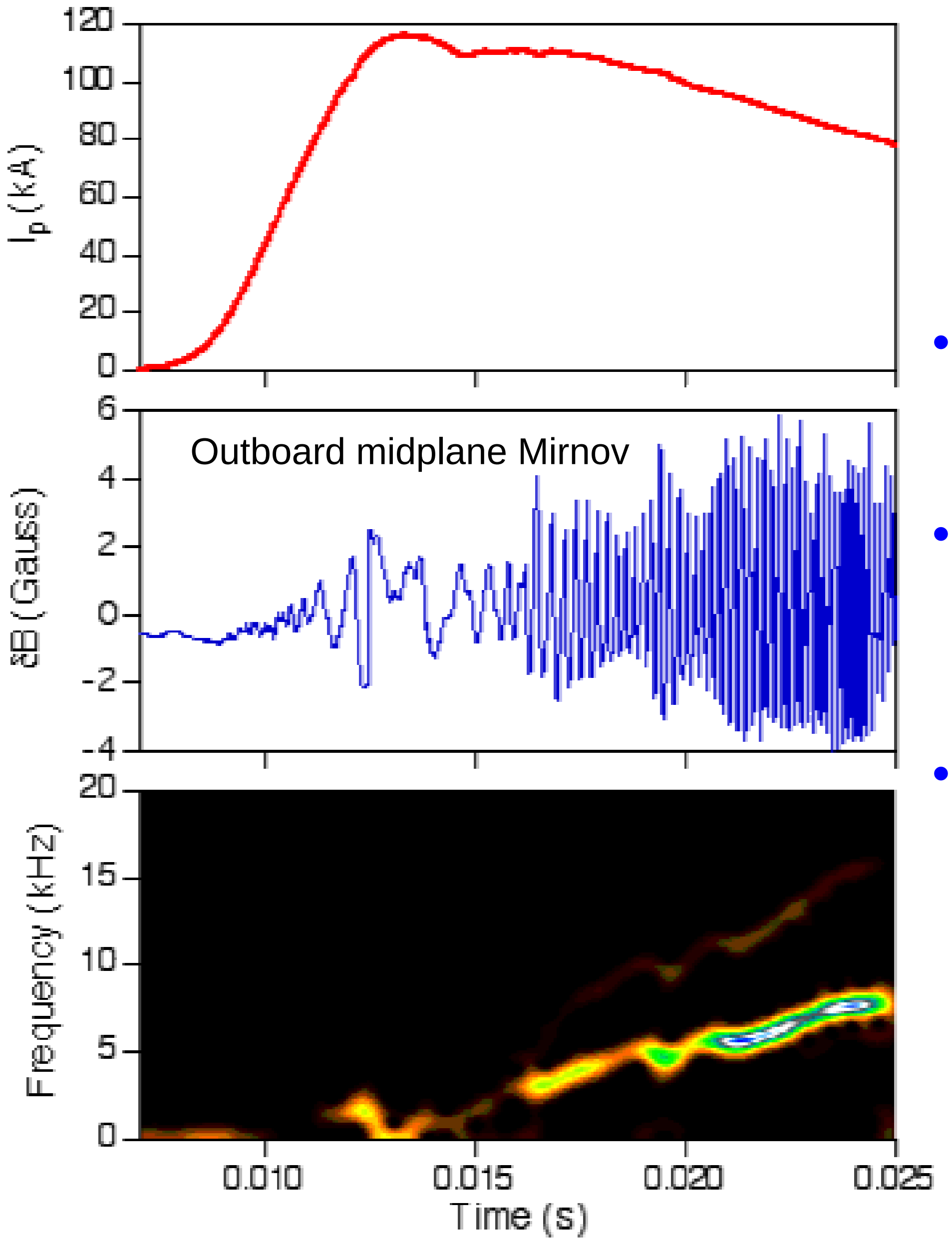


• Volt-second limitation at ultra-low-A:

- limited flux available to drive plasma
  inherent limit due to v_{loop} waveform
- late start up decreases availability at low-TF
  35% drop in TF rod current gives ~20% drop in available OH flux
- efficiency of flux usage



Rotating 2/1 Mode Observed in Most Discharges



- **Mode present in most significant discharges**
- **Frequency is typically 4-10 kHz**

  - no evidence of mode locking

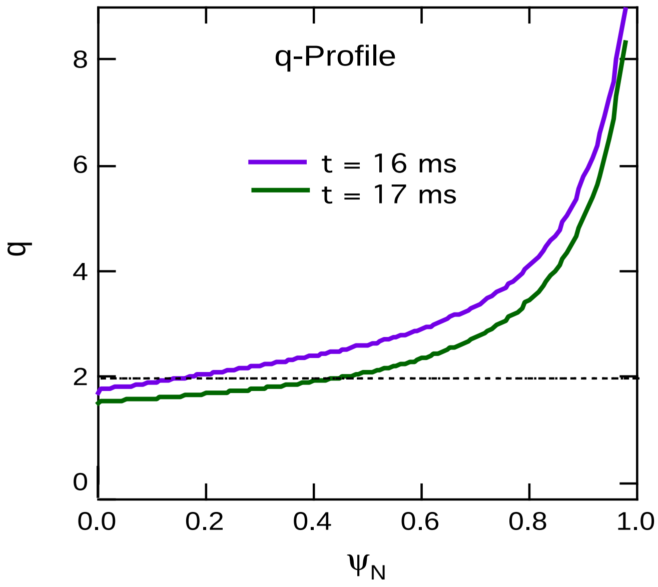
- **Island width estimates indicate w > 10 cm**

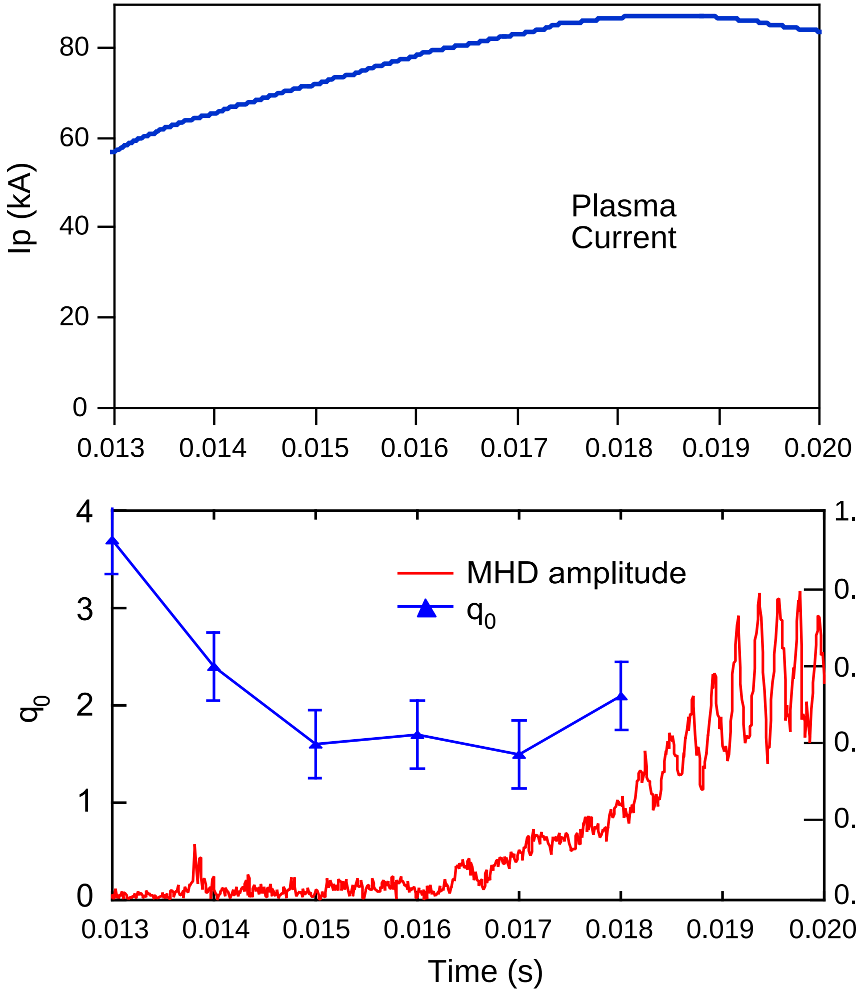
$$w = 4\sqrt{\frac{\delta B}{B_t}\frac{qR}{n\frac{dq}{dr}}}$$

Growth of Large Tearing Mode Correlates with q_0 Behavior

- **Growth of 2/1 mode observed soon after q_0 passes through 2**
  - often appears to constrain discharge evolution

- **q_0 constrained by equilibrium fit to external magnetics**



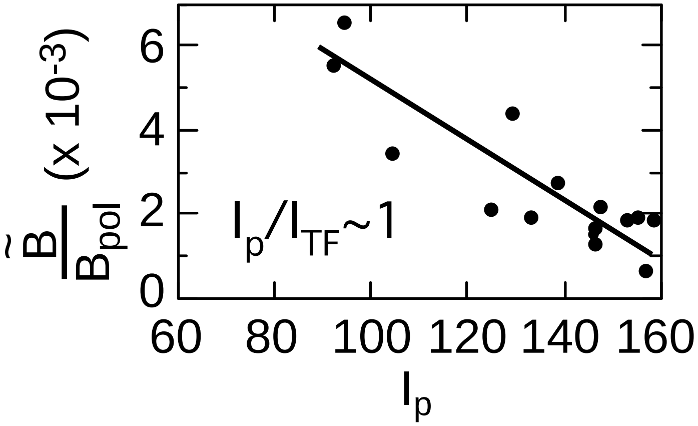


- **Broad low-shear region gives mode large radial extent**

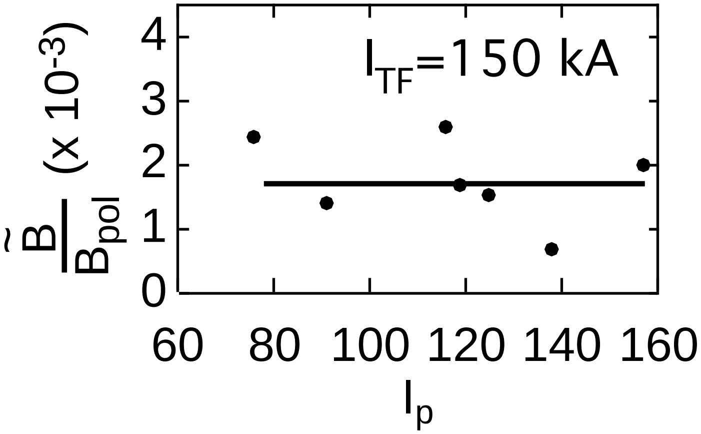
MHD Amplitude Increases at Lower TF

- **MHD amplitude measured with core Mirnov**
  - all discharges core limited

- **Fluctuations increase rapidly at low TF**



- **Fluctuations relatively constant at constant TF**



Scaling Argument Supports Internal Tearing Modes as Contributor to I_p/I_{TF} ~ 1 Soft Limit

$$q = \frac{2\pi r^2 B_t}{\mu_0 R I_p}\,\frac{1+\kappa^2}{2}\, f(A) \qquad f(A) = 1 + \frac{1}{A^2}\left[1 + \frac{\left(\beta_p + {l_i}/{2}\right)^2}{2}\right]$$

$$I_p(r) = \pi r^2 j(r) \quad \Longrightarrow \quad q_0 \cong \frac{2B_t}{\mu_0 R j_0}\,\frac{1+\kappa^2}{2}$$

$$B_t = \frac{\mu_0 I_{TF}}{2\pi R} \quad \Longrightarrow \quad q_0 \sim \frac{1}{A^2}\,\frac{I_{TF}}{I_p}\,\frac{1+\kappa^2}{2}$$

assume j(r) = j_0

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

- **For Pegasus:**

A ~ 1   κ ~ 1.7 @q_0 = 3/2 - 2: $\frac{I_p}{I_{TF}} \sim \frac{1}{1^2}\,\frac{1}{2}\,\frac{1+1.7^2}{2} \cong 1$

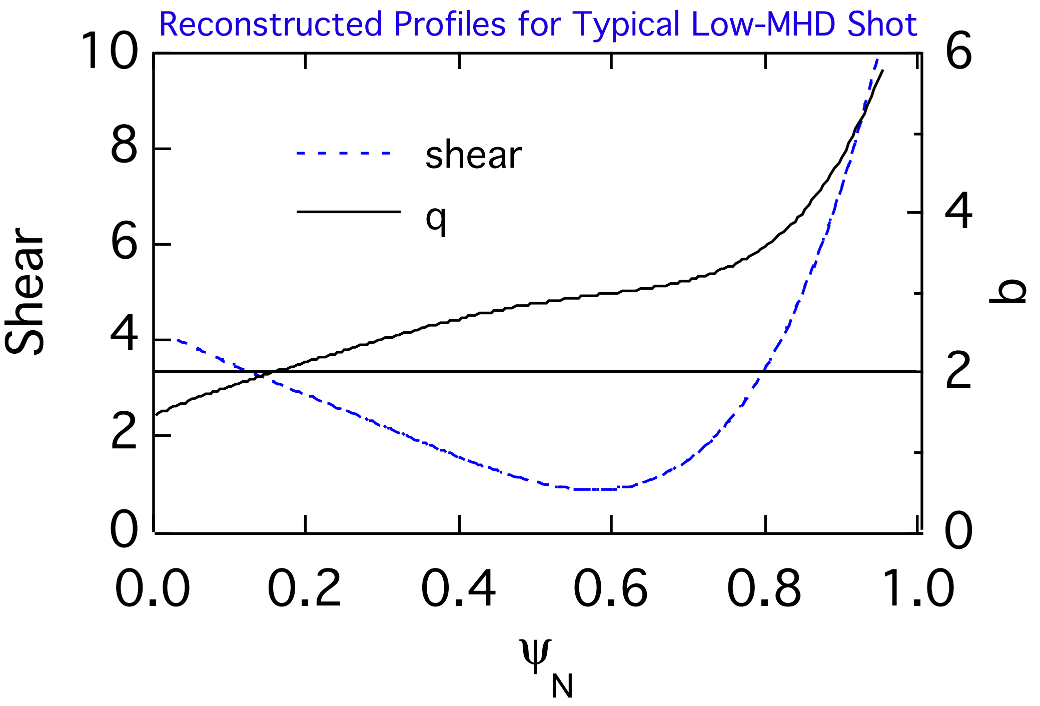
Hence I_p/I_{TF} = 1 for q_0 = 3/2 - 2

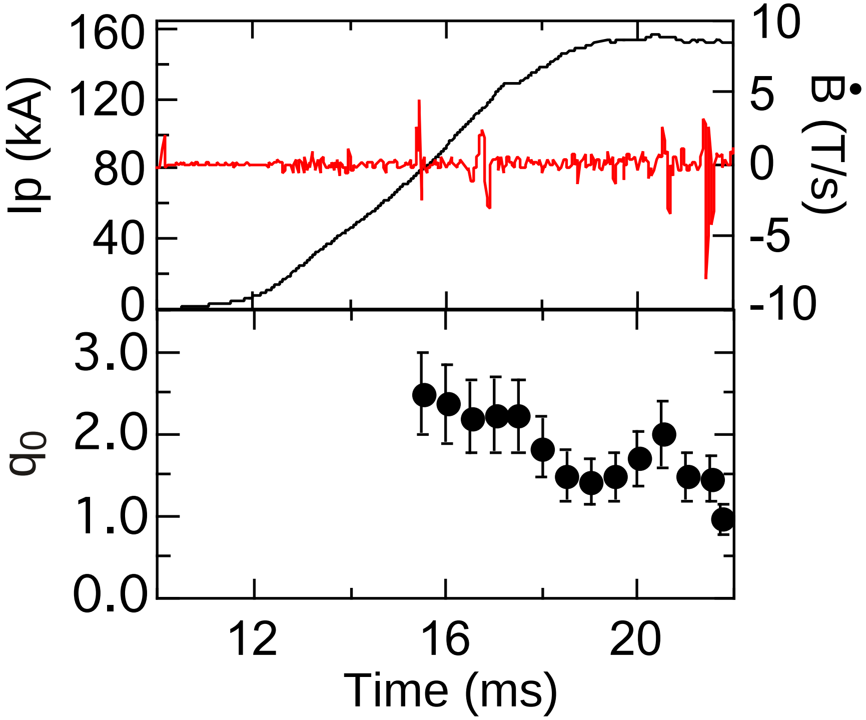
- **I_p/I_{TF} ~ 1 due to q(ψ_N ~ 0.5) = 2**

MHD Inhibited by Combination of Location of Rational Surfaces & Magnetic Shear

- **q = 2 surface is close to center of discharge**
  - appearance of mode will not cause severe confinement degradation

- **no q = 2 surface before 5 ms into discharge**
  - η lower before mode can appear

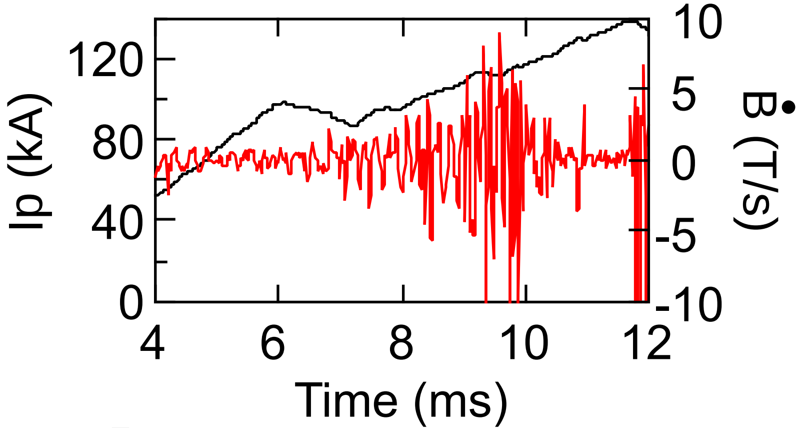


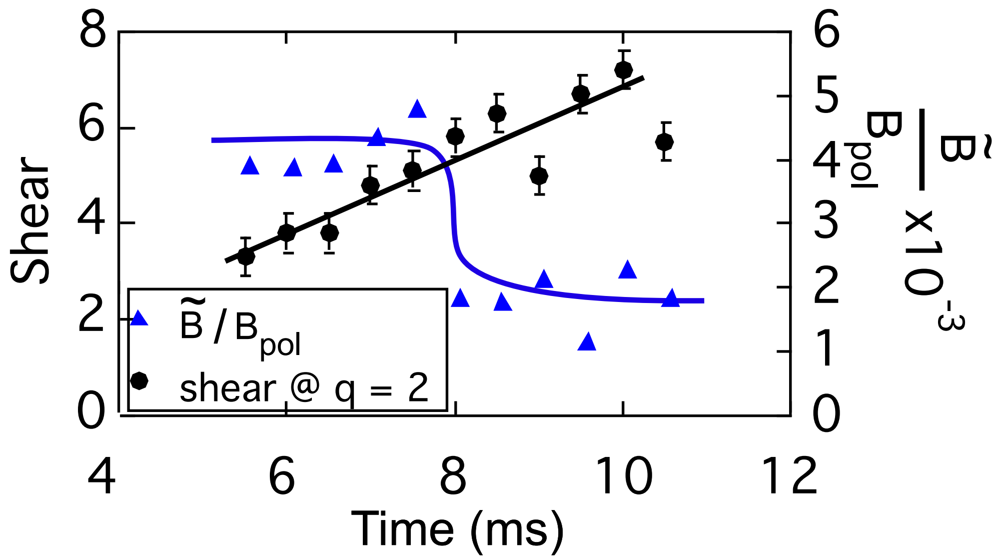


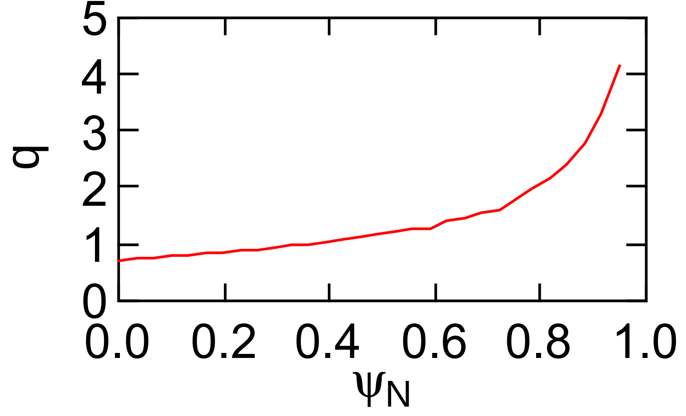
- **q = 2 surface located in region of higher shear**
  - island width will be reduced
  - σ_{shear} ~ 30% in core of plasma

Increased Magnetic Shear Reduces MHD Amplitude

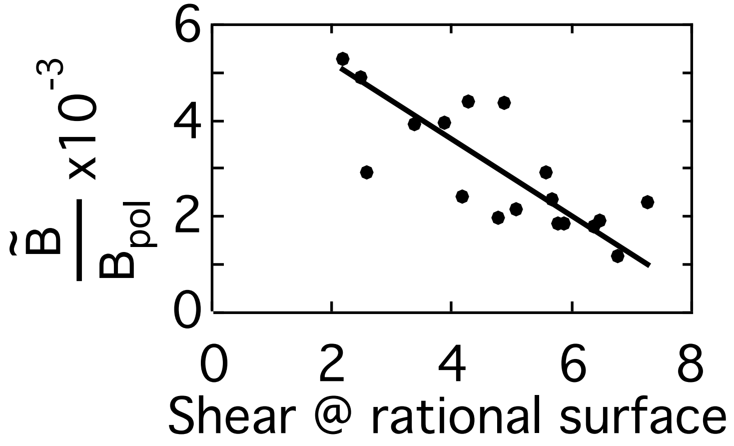
- **Mode stabilized as rational surface moves to higher shear region**







- **Similar stabilization observed for several shots**
  - both 2/1 and 3/2 modes



⇒Increased internal magnetic shear helps to mitigate confinement degrading MHD

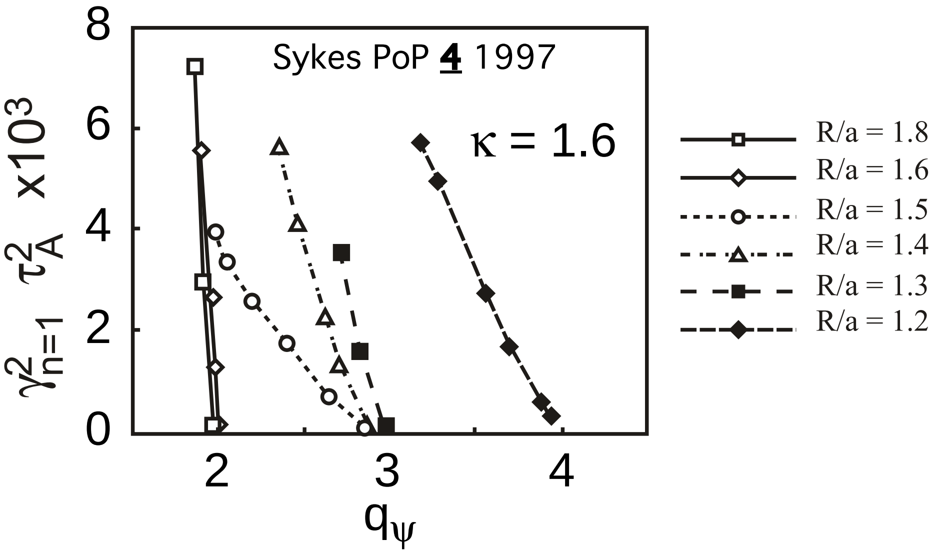
External Kink Stability Limits More Severe for STs

- **Numerical studies show STs require edge q > 2**

  - q_ψ for n = 1 kink stability ↑ as A ↓

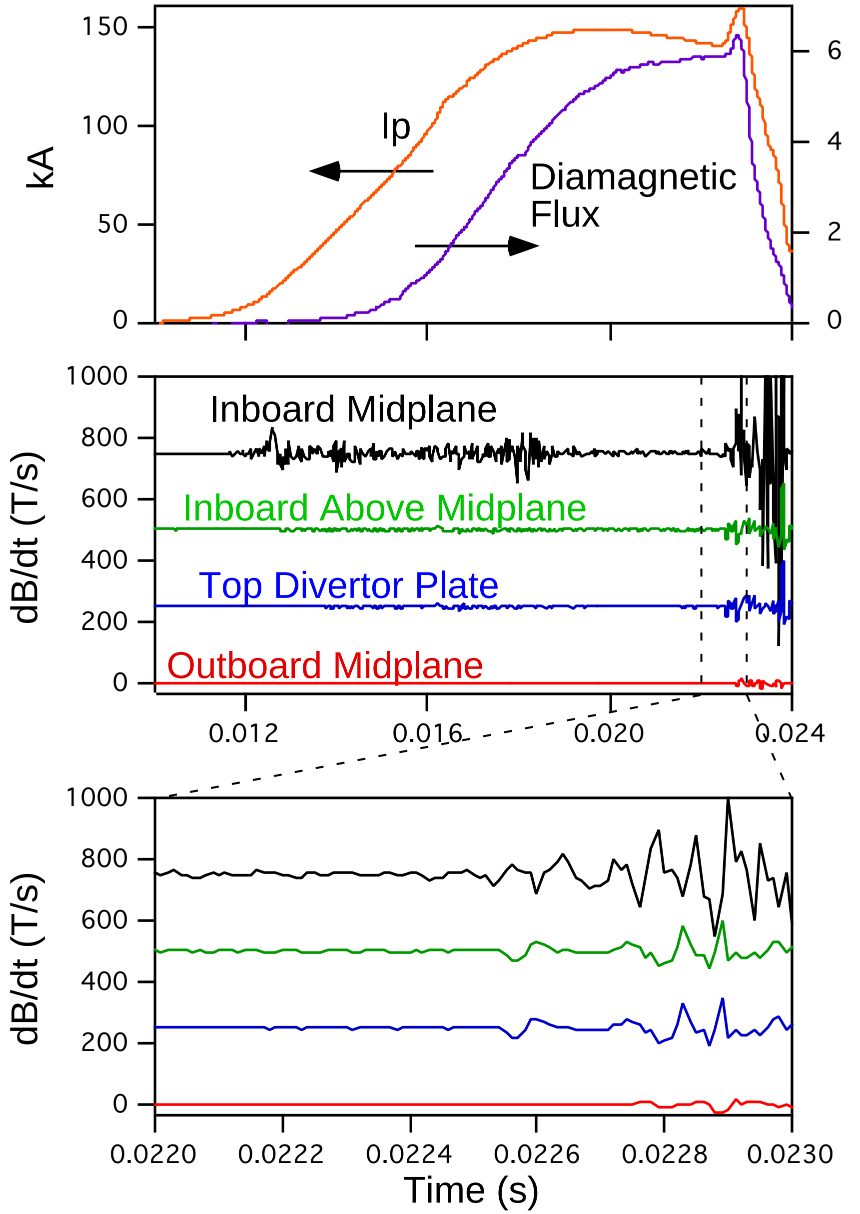
  - could cause limit for low-TF operations at A ~ 1

    determines maximum TF utilization?



- **Pegasus is exploring ultra-low-A regime where limit is most restrictive**

In Some Cases Disruptive Instabilities End Discharge

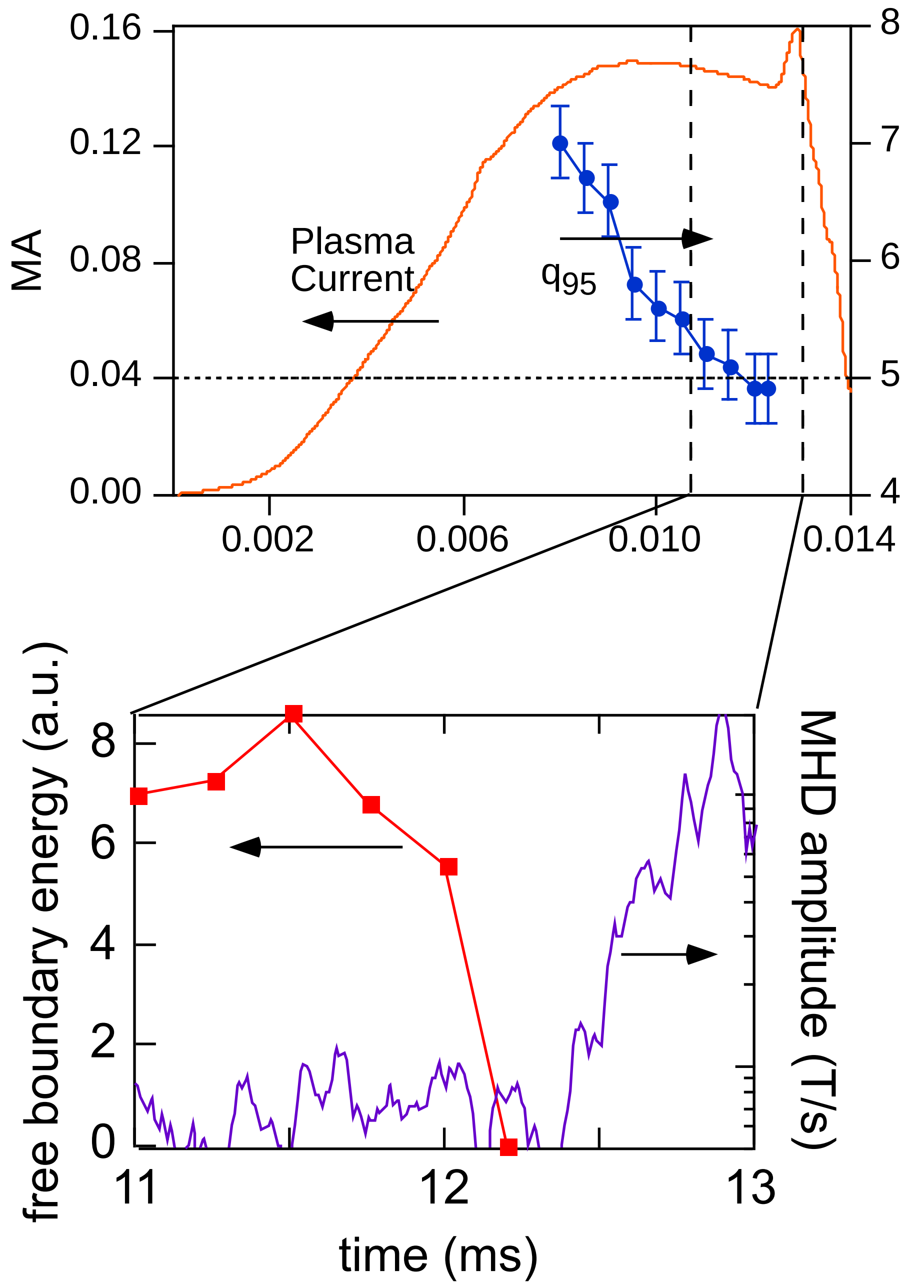


- Higher-current plasmas (150 kA class) often terminate in abrupt disruptions

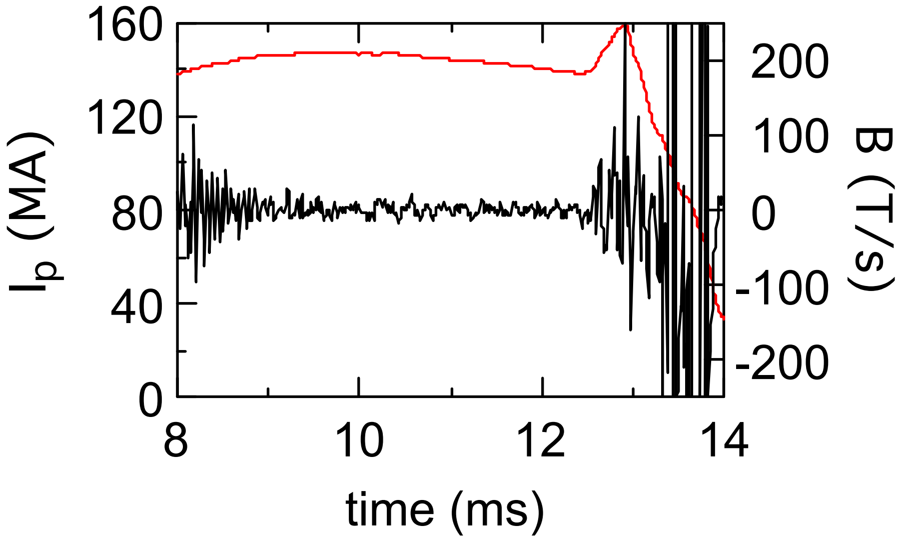
- n=1 fluctuations are observed on core Mirnov coils immediately prior to disruption
  - Dominant frequency is order of 10 kHz
  - Mode is observed a few 100 μs before IRE

- These fluctuations are not observed in lower-current shots

External Kink Observed for q_{95} ~ 5



- **2/1 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



Summary

- **Tools have been developed to perform reliable equilibrium and stability analysis of PEGASUS ST discharges.**

- **Many equilibria have been reconstructed, showing low-A plasma characteristics in PEGASUS.**
  - high β_t, β_N and I_N achieved ohmically
  - high edge q at low toroidal field
  - high paramagnetism

- **A combination of internal tearing modes and V-s limitation has caused a soft I_p/I_{TF} ~ 1 limit.**
  - tearing modes present in nearly all discharges
  - modes exacerbated by high η, low central magnetic shear
  - mode onset at lower I_p for lower TF

- **Pegasus is beginning to access the external kink stability boundary.**
  - $q_\psi \sim 5$ is limit in some cases
  - confirmed with DCON analysis

Reprints