Performance and Stability of Near-Unity Aspect Ratio Plasmas in the PEGASUS Toroidal Experiment

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Pegasus is an ultra-low aspect ratio ST

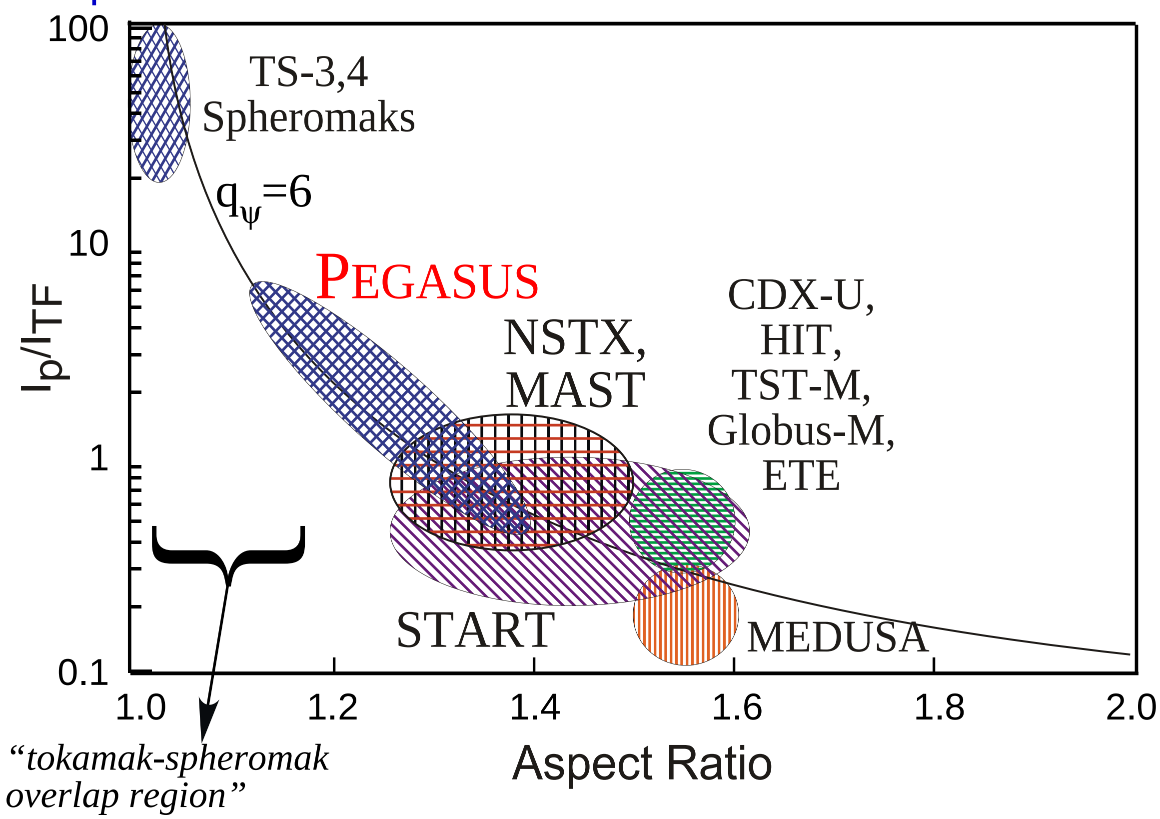
- Test limits of beta and safety factor as A→1
- Access high toroidal beta and high toroidal utilization factor (I_p/I_{tf})
- A "soft limit" occurs at $I_p/I_{tf} \approx 1$
  - *due to MHD activity and some reduction in V-s*
- Beginning to explore the edge kink stability boundary
  - *q_{95}=5 is found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

Mission: Explore plasma limits as A→1

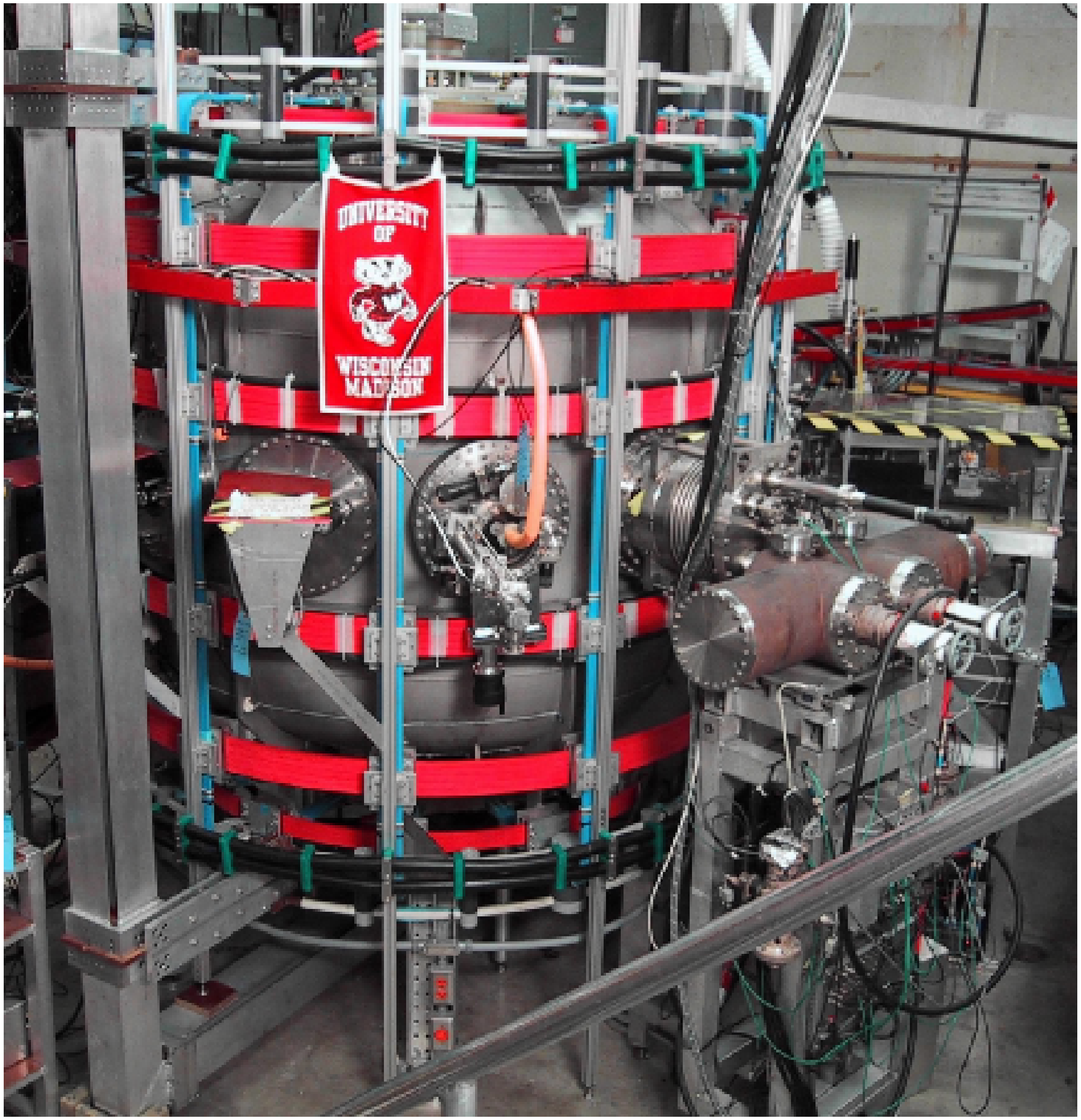
Pegasus is an extremely low-aspect ratio facility exploring quasi-spherical high-pressure plasmas with the goal of minimizing the central column while maintaining good confinement and stability

- Plasma characteristics at high toroidal field utilization
- High toroidal beta at low applied toroidal field
- Edge kink stability at near-unity A

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



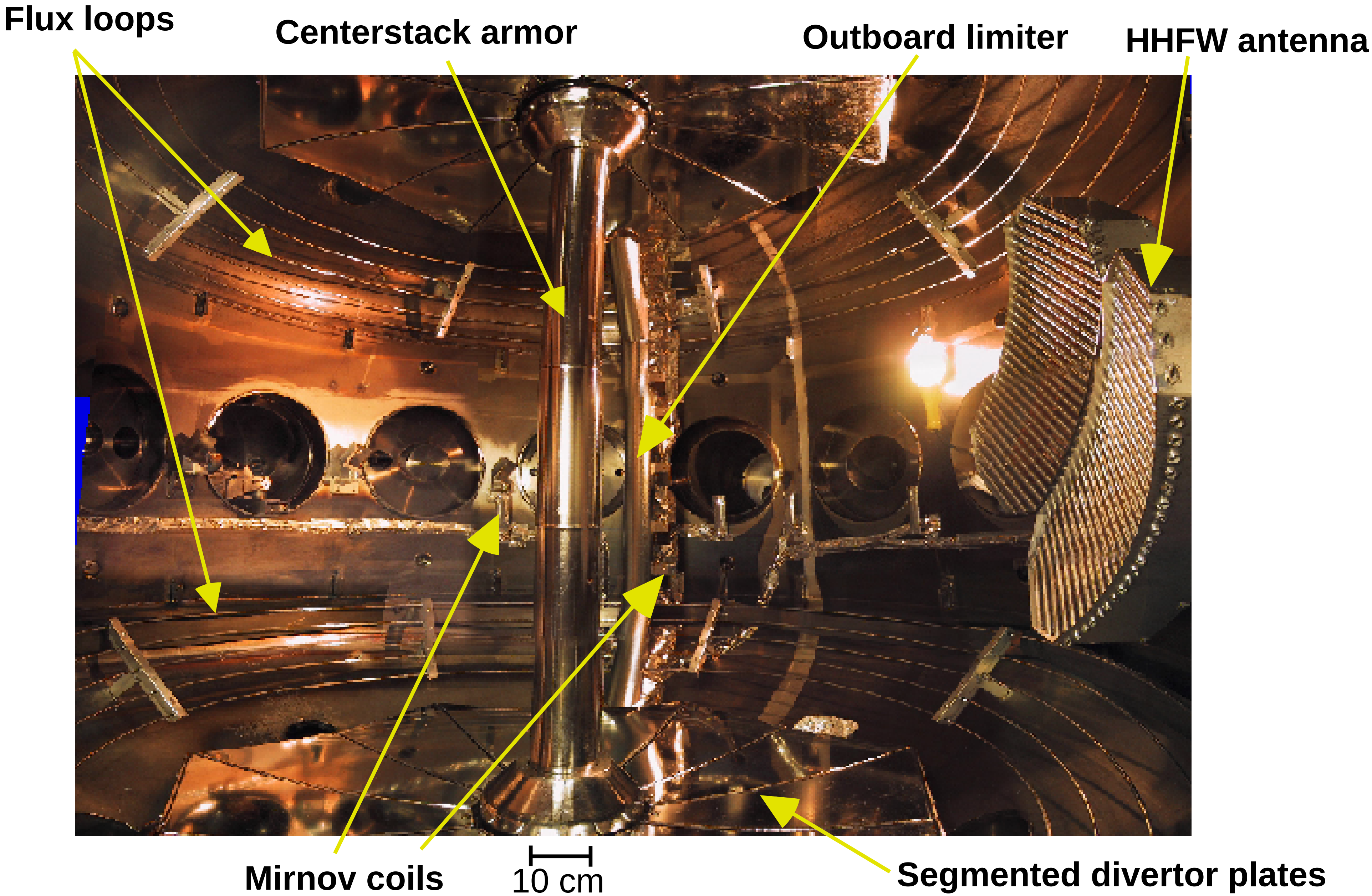
Pegasus facility produces ultralow-A plasmas



<u>Achieved Parameters:</u>

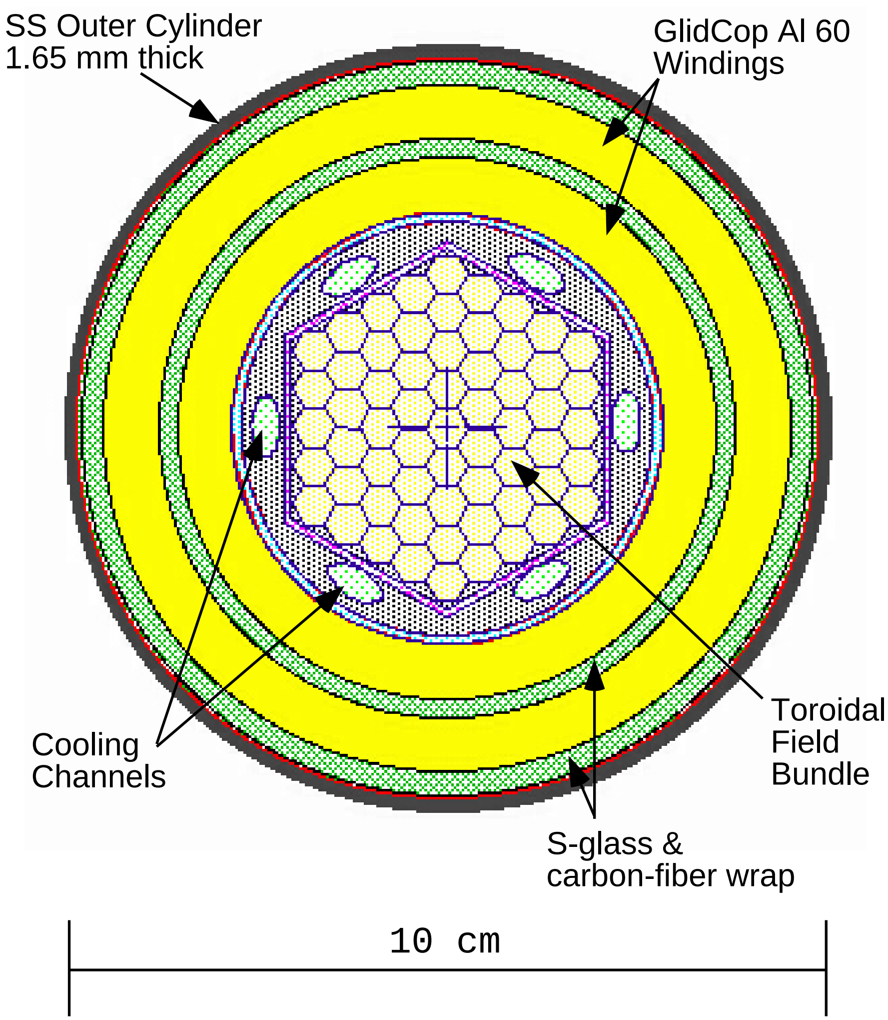
- $A = 1.12\text{-}1.3$
- $R = 0.2\text{-}0.45$ m
- $I_p = 0.16$ MA
- $RB_t \leq 0.03$ T-m
- $\kappa = 1.4 - 3.7$
- $\Delta t_{pulse} = 0.01\text{-}0.03$ s
- $\langle n_e \rangle = 1\text{-}5\times10^{19} m^{-3}$
- $\beta_t \leq 20\%$
  $(\beta_t \equiv 2\mu_0 \langle p \rangle / B_{t0,vac}^2)$

Internal view of Pegasus shows narrow centerstack



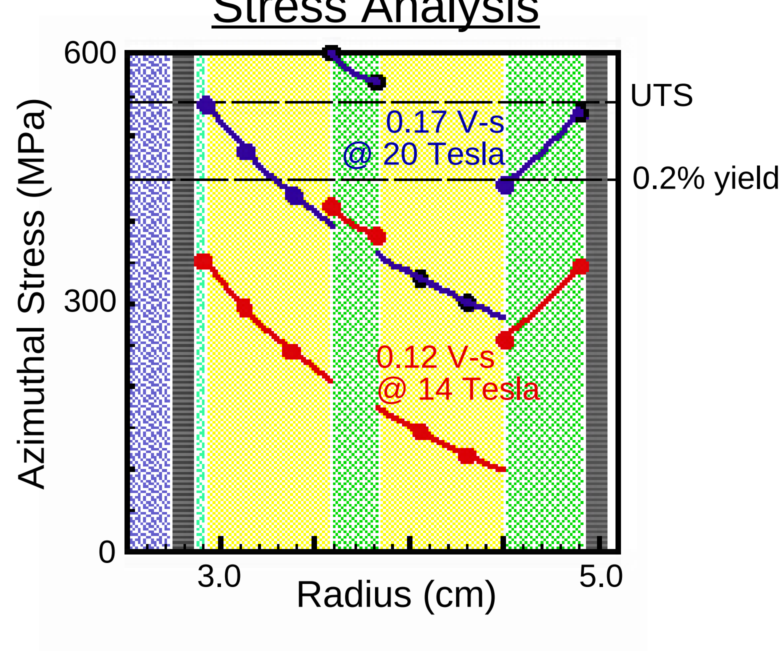
High-stress solenoid is enabling technology

Core Radial Build

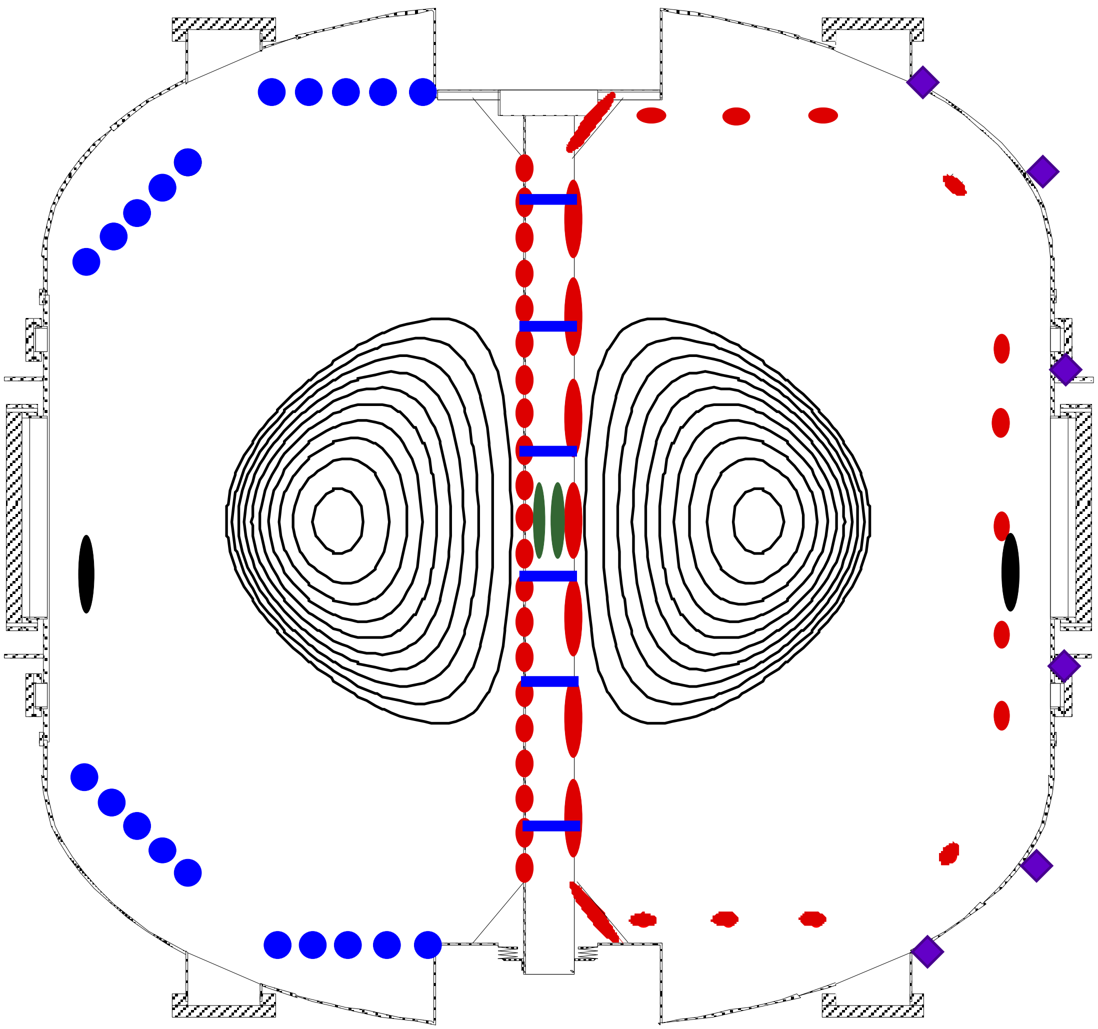


- Solenoid built by the National High Magnetic Field Laboratory
- Composition: GlidCop Al 60
  - *carbon-fiber reinforced*
- Rated at 20 T for 1000 pulses
- Operates routinely ≥ 10 T

ANSYS Finite Element Stress Analysis



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)

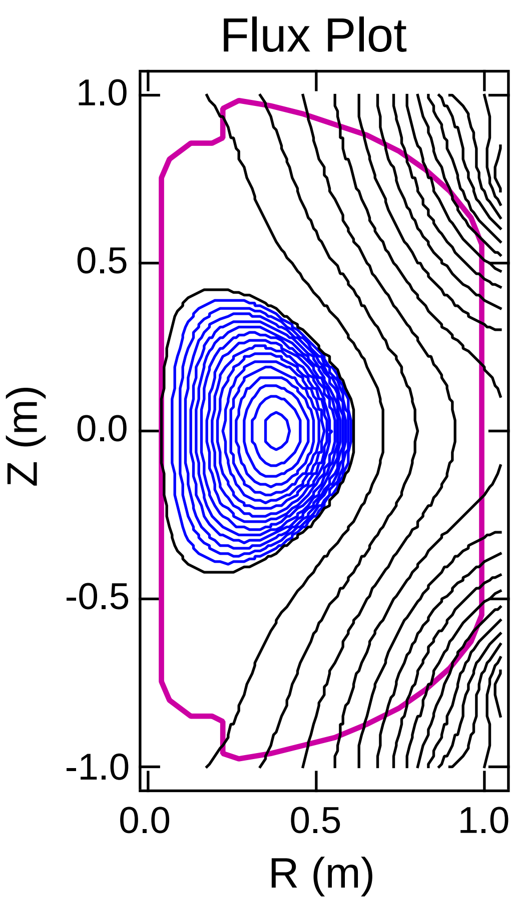
Not shown:
Internal Plasma Rogowski Coils (2)
Internal Diamagnetic Loops (2)
Diamagnetic Compensation Loop

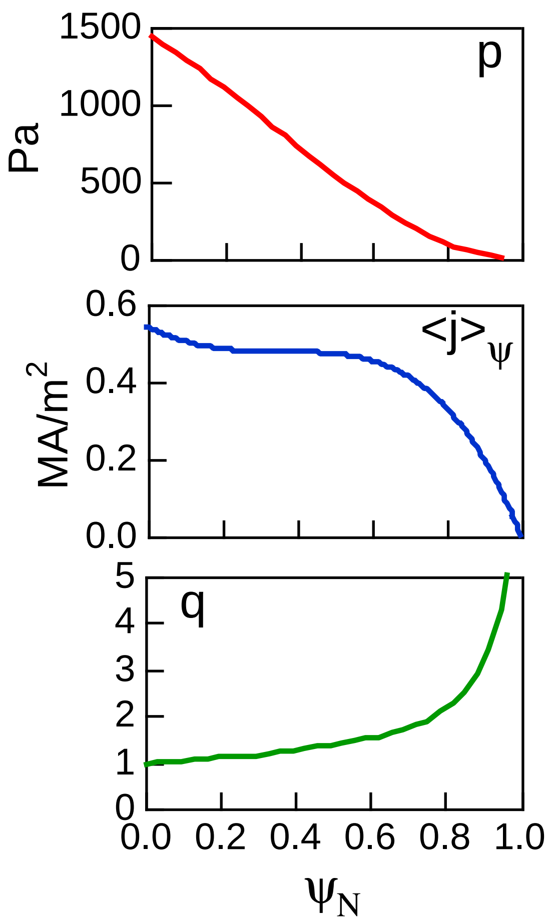
- Diagnostics details in Diem et al., KP1.094

Equilibrium reconstruction is primary analysis tool

- Global/external parameters well-determined by equilibrium reconstruction
- Internal profiles less-well constrained
- Small central shear/high edge shear: feature of ultralow-A
- Equilibrium details in Sontag et al., KP1.093

Sample Reconstruction





Fit Results

I_p	154 kA
R_0	0.34 m
a	0.29 m
A	1.15
κ	1.33
F_0	0.03 T-m
β_t	18%
W	570 J
l_i	0.54
q_0	1.0
q_{95}	4.3

Calculated Uncertainties

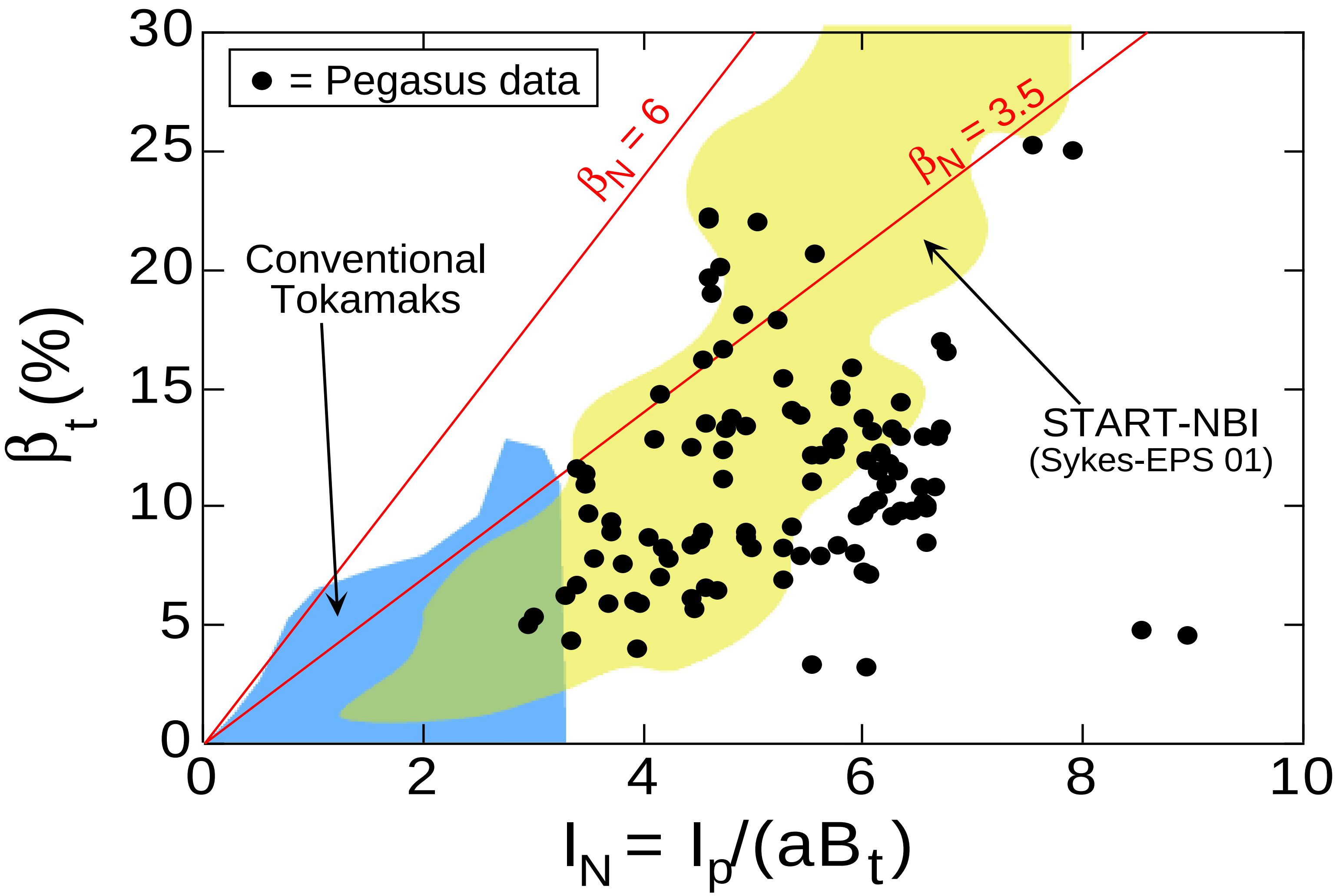
I_p	± 2%
R_0	± 4%
l_i	± 9%
β_t	± 15%
β_p	± 15%
q_{95}	± 6%

Equilibrium reconstructions show low-A characteristics

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

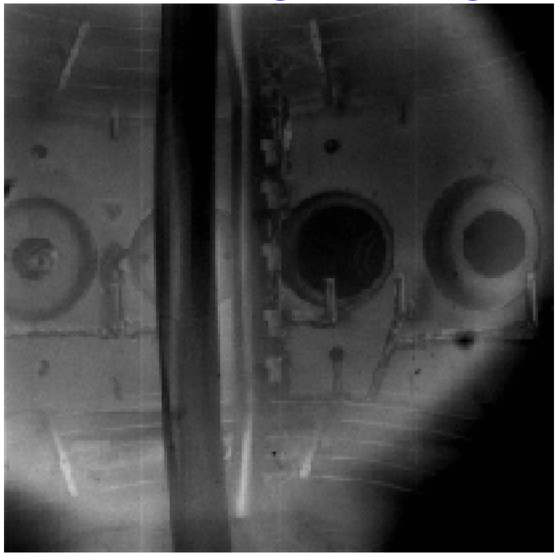
A < 1.3 → ready ohmic access to high β_t

- β_t up to 20% and I_N up to 6.5 achieved ohmically
- Low field → high I_N and β_t

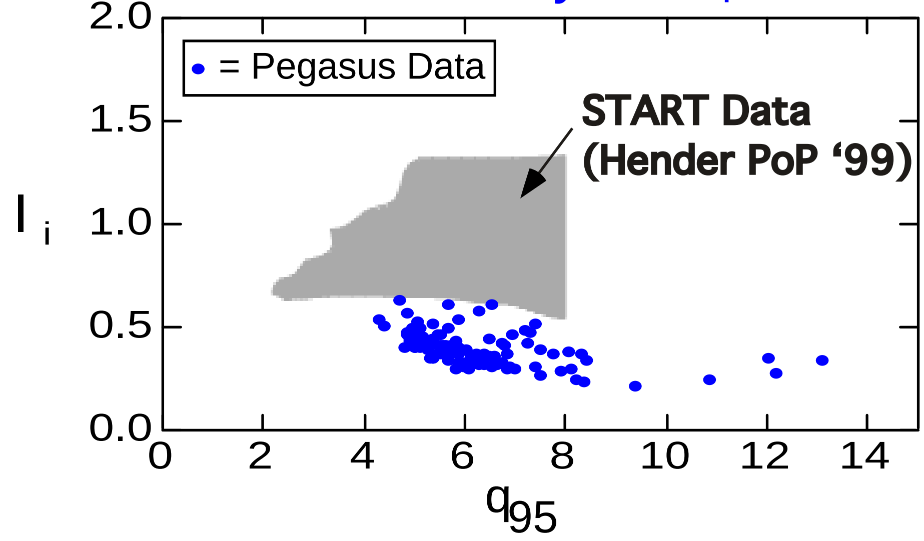


Pegasus operates in low-l_i, high-density space

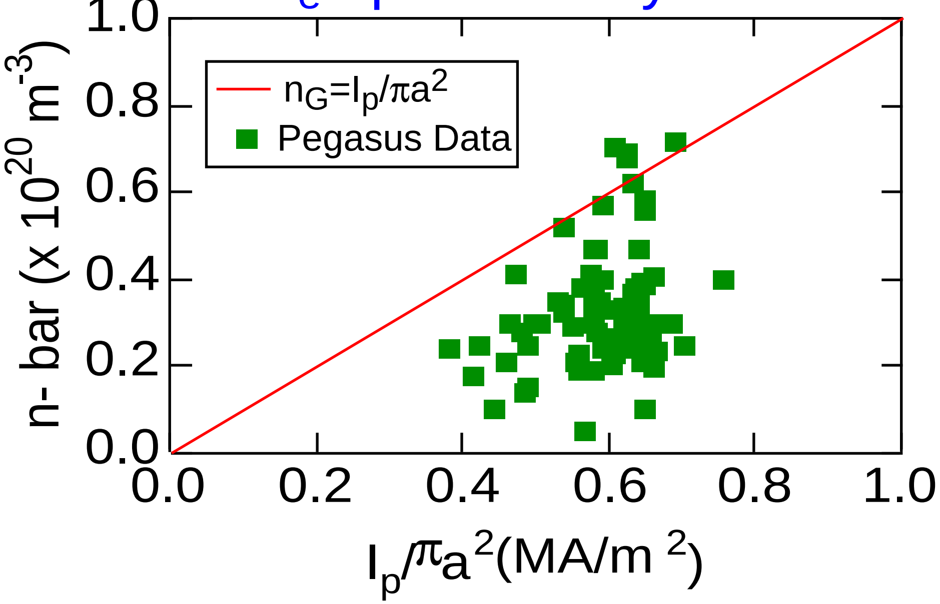
Visible light image



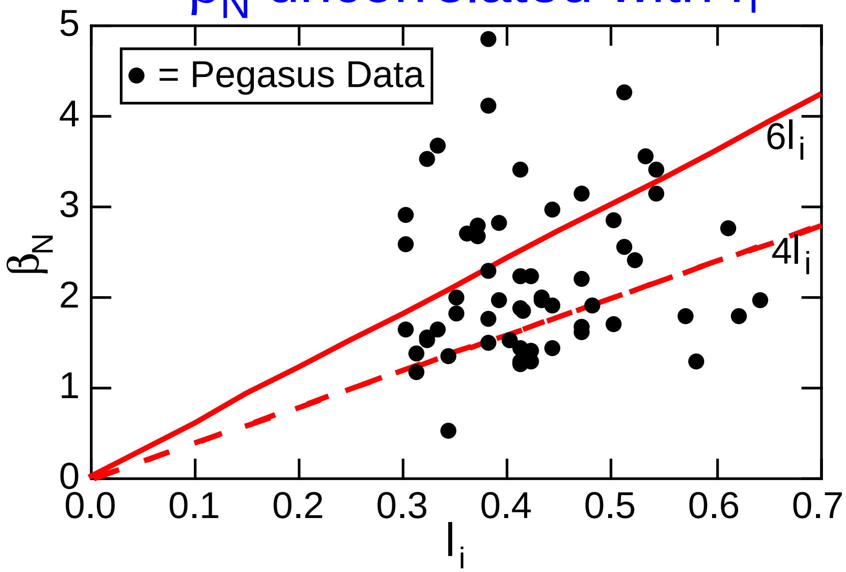
Generally low l_i



$\overline{n_e}$ up to density limit



β_N uncorrelated with l_i

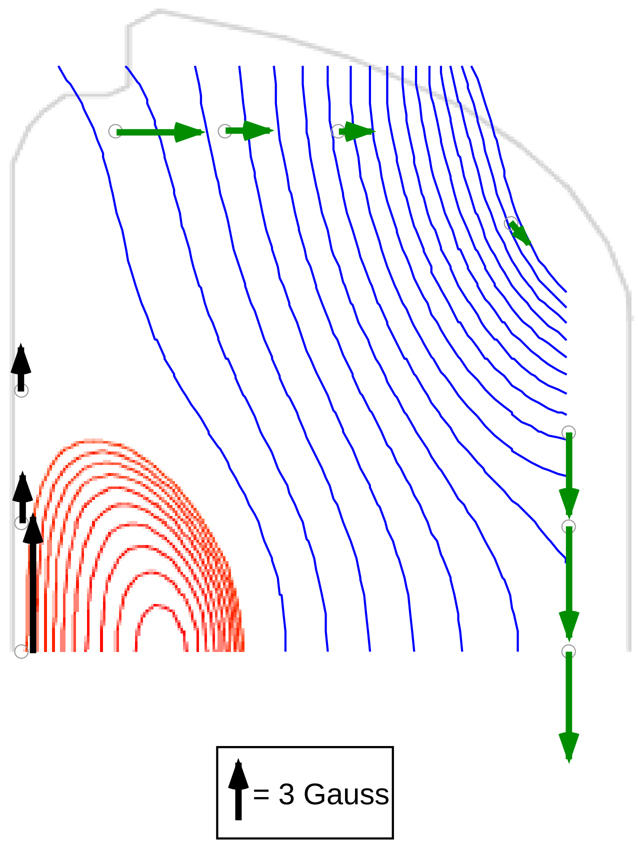


Ultra-low A ⇒ strong poloidal asymmetry to tearing mode

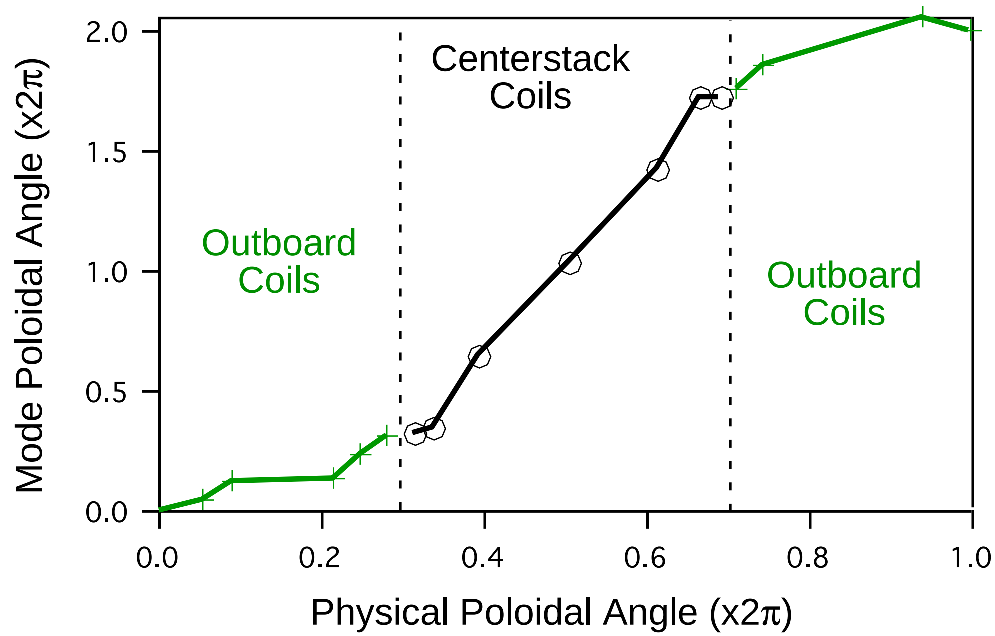
- Large phase shifts observed along centerstack for m/n=2/1
  - 1.5 wavelengths observed across 120º poloidally
  - similar structure observed for 3/2 and higher m/n

- 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

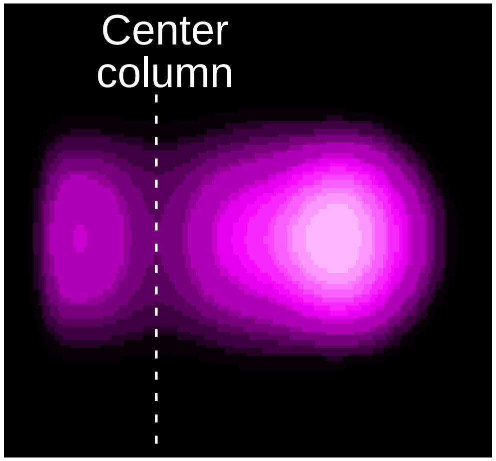


2/1 Poloidal Phase at the Wall



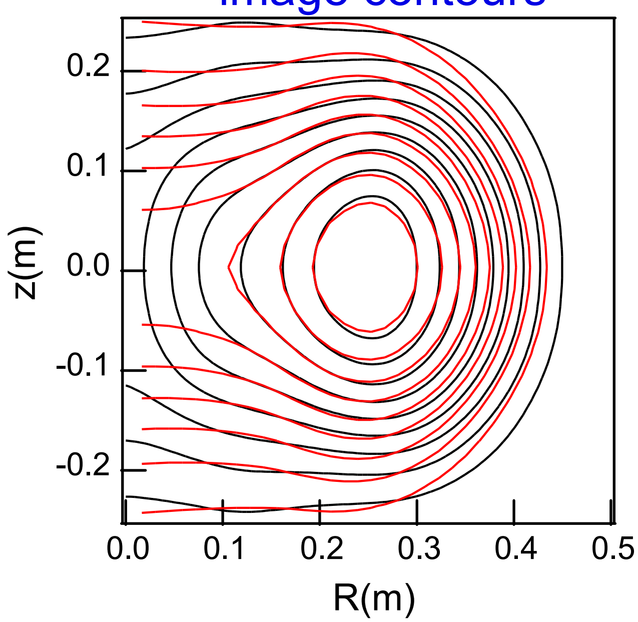
Measured q-profile indicates low central shear

Tangential PHC SXR image



⇓

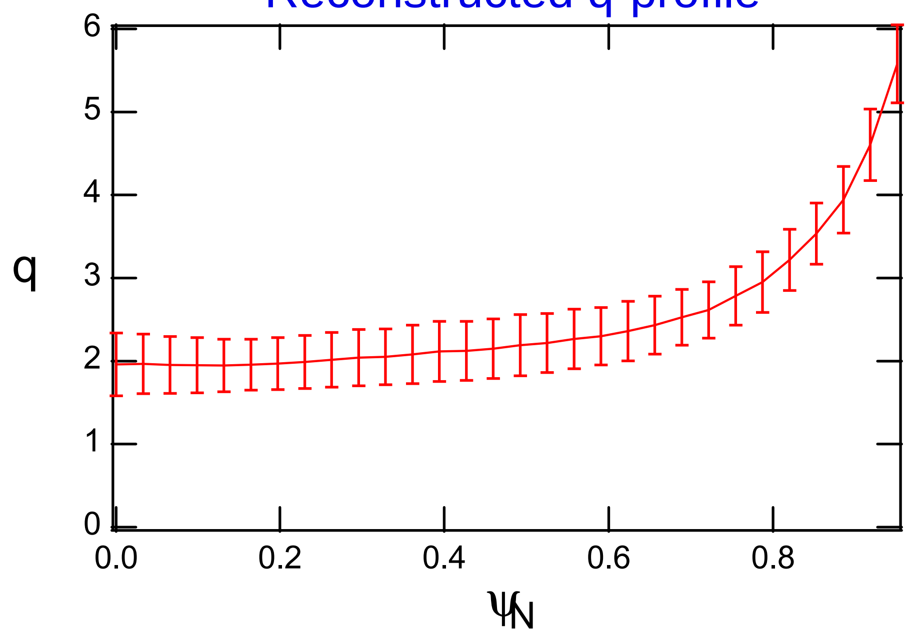
Measured and reconstructed image contours



$\Rightarrow$

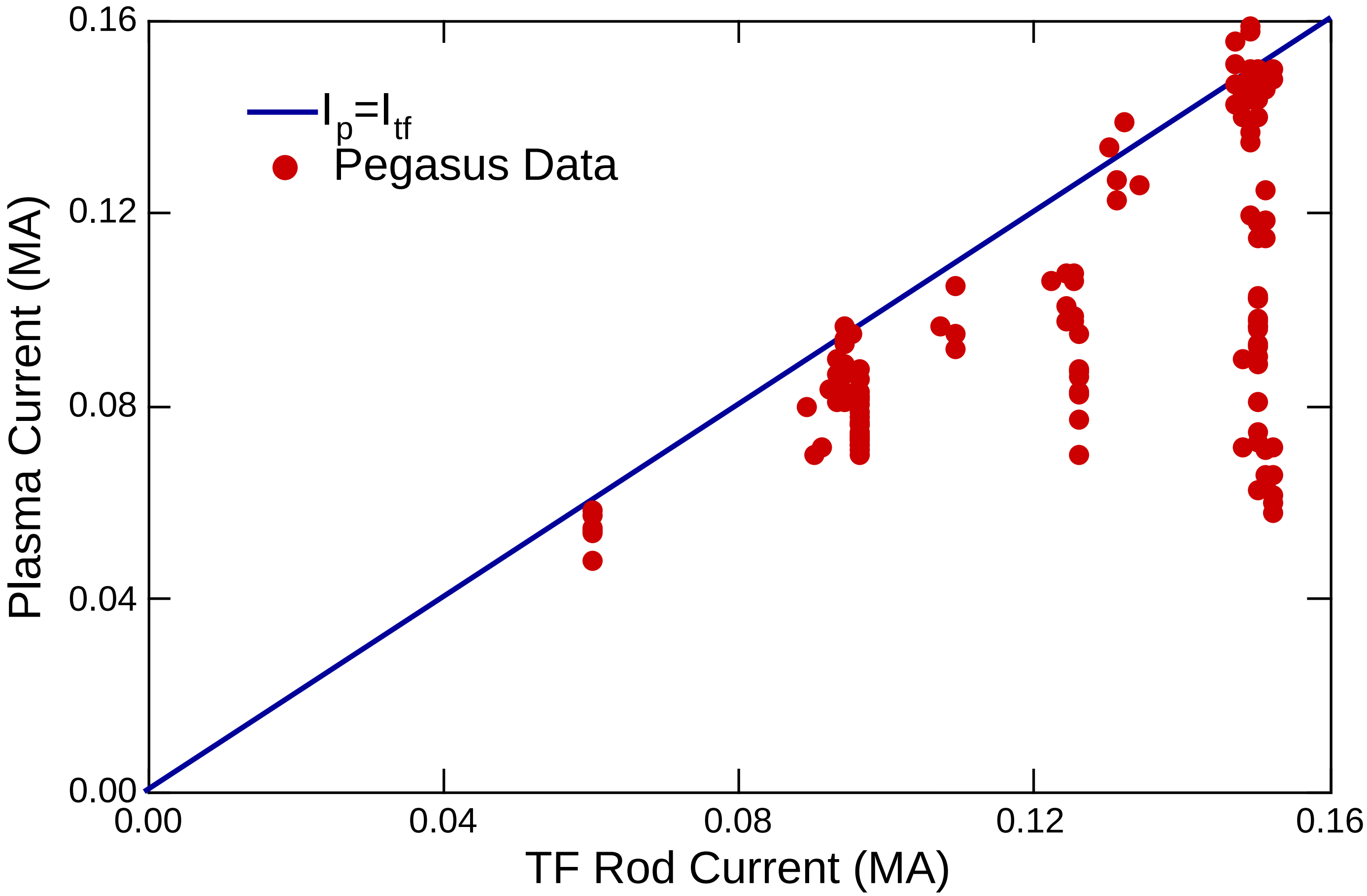
- 2D soft x-ray camera gives q-profile
  - Measures constant-intensity surfaces
  - Used as internal constraint on equilibrium
  - Useful as q-profile diagnostic
- Measured q-profile $\Rightarrow$ zero central shear
  - Typical of low-A
- Details in Tritz et al., KP1.095

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
- Identical V_{loop} waveform along $I_p = I_{tf}$ line



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

Large resistive MHD instabilities degrade plasma as TF ↓

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

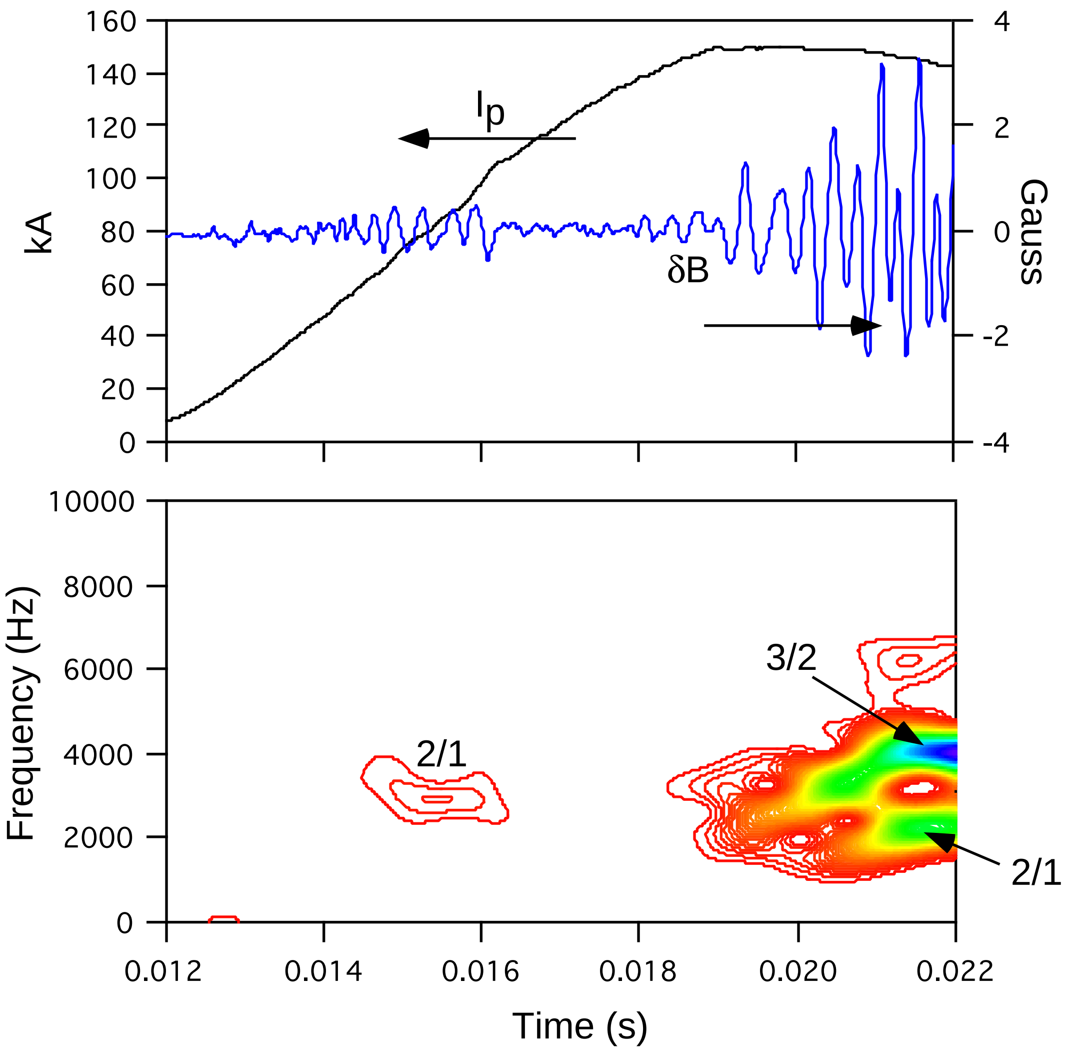
$$\frac{dw}{dt} \sim \eta \qquad\qquad w_{sat} \sim q\left(\frac{dq}{dr}\right)^{-1}$$

⇒ 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



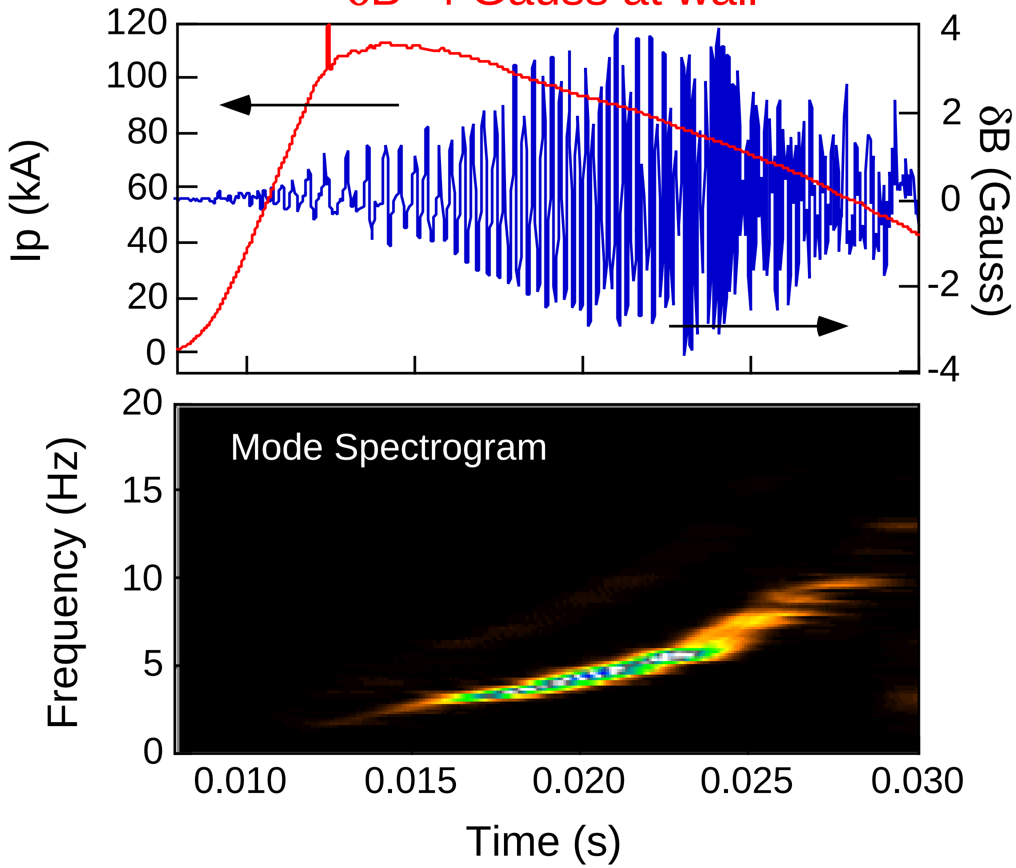
- Most common mode m/n=2/1
  - other m/n also observed
  - evidence of 2/1-3/2 coupling
- Leads to increased C_E, decreased I_p
  - Less efficient flux consumption in presence of internal MHD
  - Degradation of τ_E
  - Decrease in dI_p/dt and I_p
  - Large radial extent
    $\Rightarrow$ affects entire plasma

Island widths are on the order of plasma minor radius

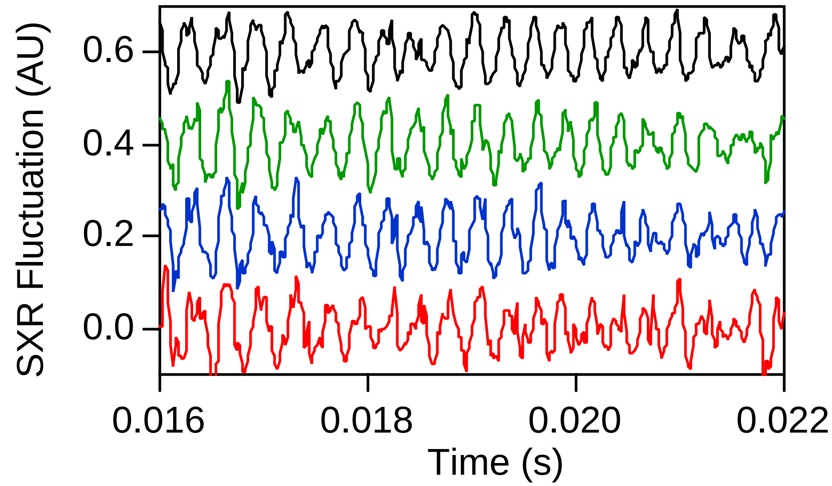
- Island width estimates give w>10 cm

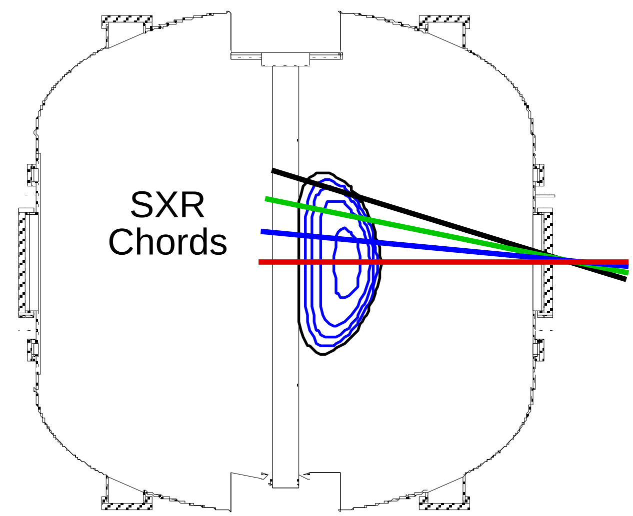
$$w \approx 4\sqrt{\frac{\delta B}{B_t}\frac{qR}{n\frac{dq}{dr}}} \sim \frac{a}{2}$$

- δB=4 Gauss at wall

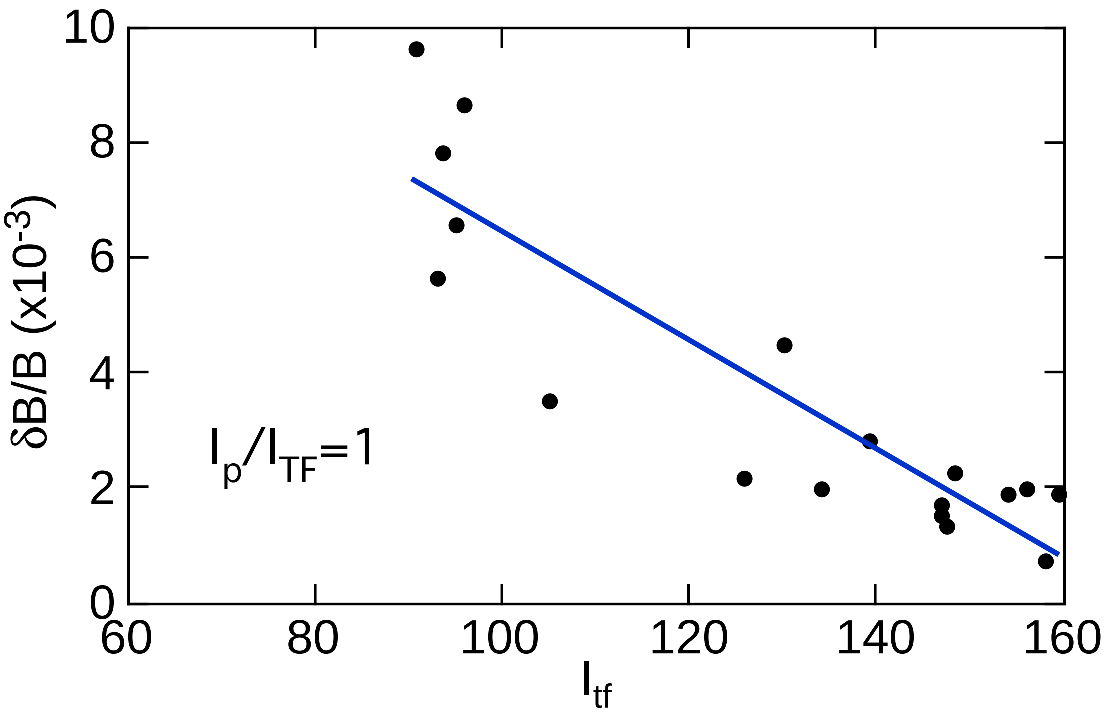


- SXR→ large radial extent of mode





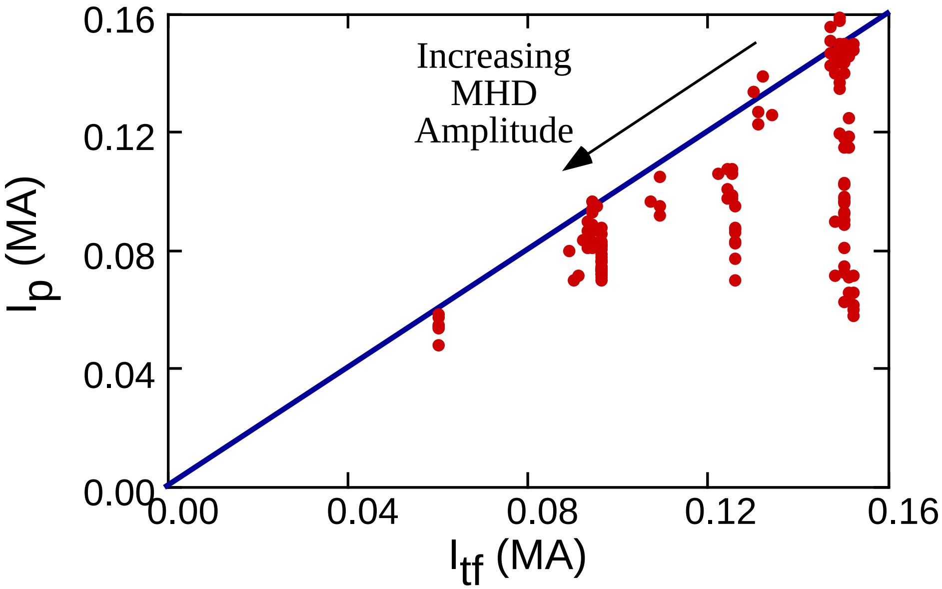
Mode amplitude decreases as I_{tf} is increased



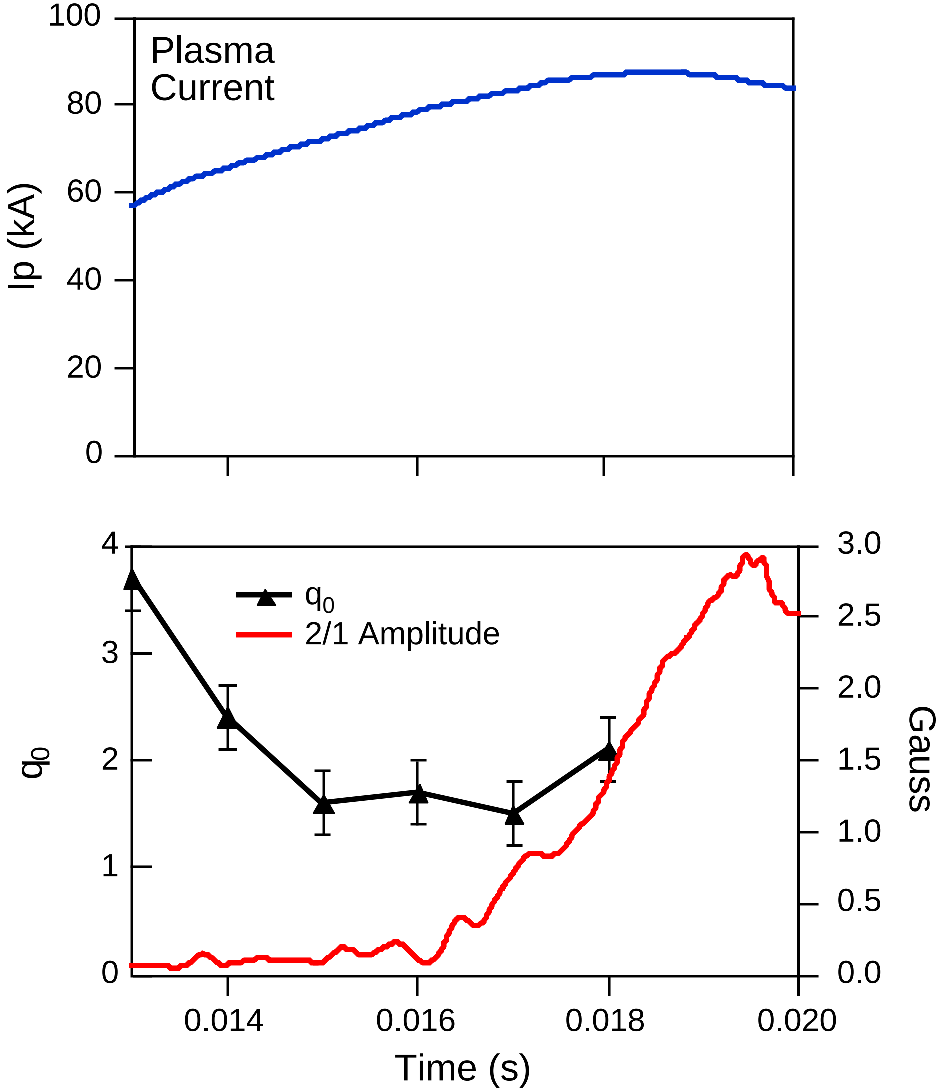
- Along I_p=I_{tf} contour: δB ↑ as TF ↓

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

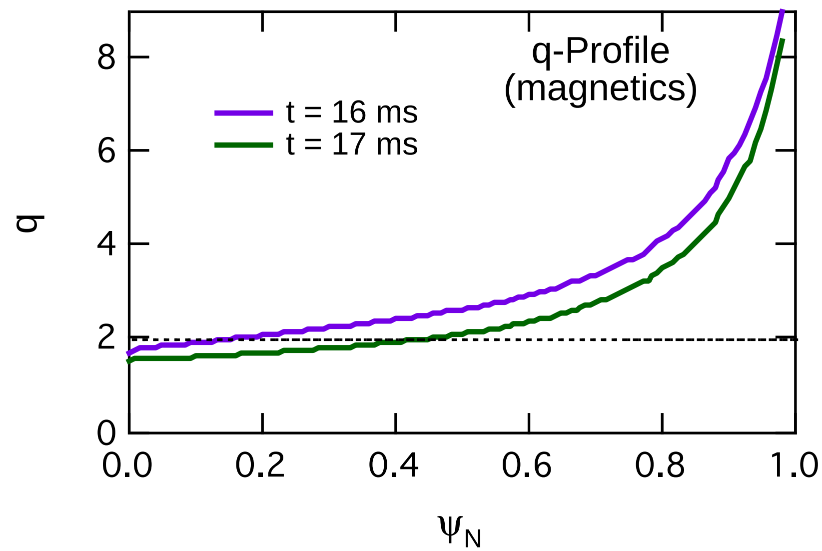
- At lower TF MHD amplitude increases
  - C_E increases
  - Stored energy decreases



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
- η high early in shot
- Broad low-shear region gives large radial extent of mode
  - 2D SXR imaging shows low central shear



$I_p/I_{tf} = 1$ 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:

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

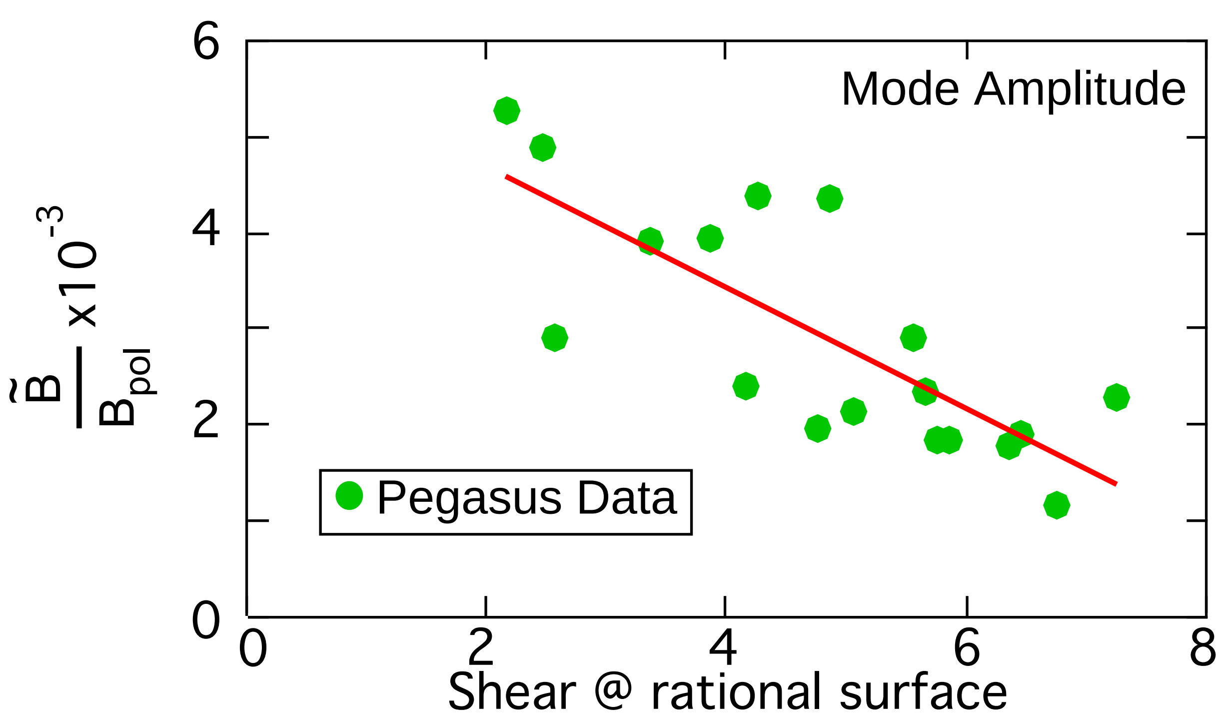
- For Pegasus at $I_p = I_{tf} \Rightarrow q_0 = 1.5 - 2$

$\Rightarrow$ Low-order rationals in low-shear region for $I_p = I_{tf}$

Mode amplitude reduced by manipulation of shear and q_0

- Discharge tailoring → plasmas with reduced MHD activity
  - Increased W, I_p
- Increased shear, increased q_0 ⇒ delay tearing onset
- MHD amplitude decreases with increasing shear

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



Summary of resistive MHD effects

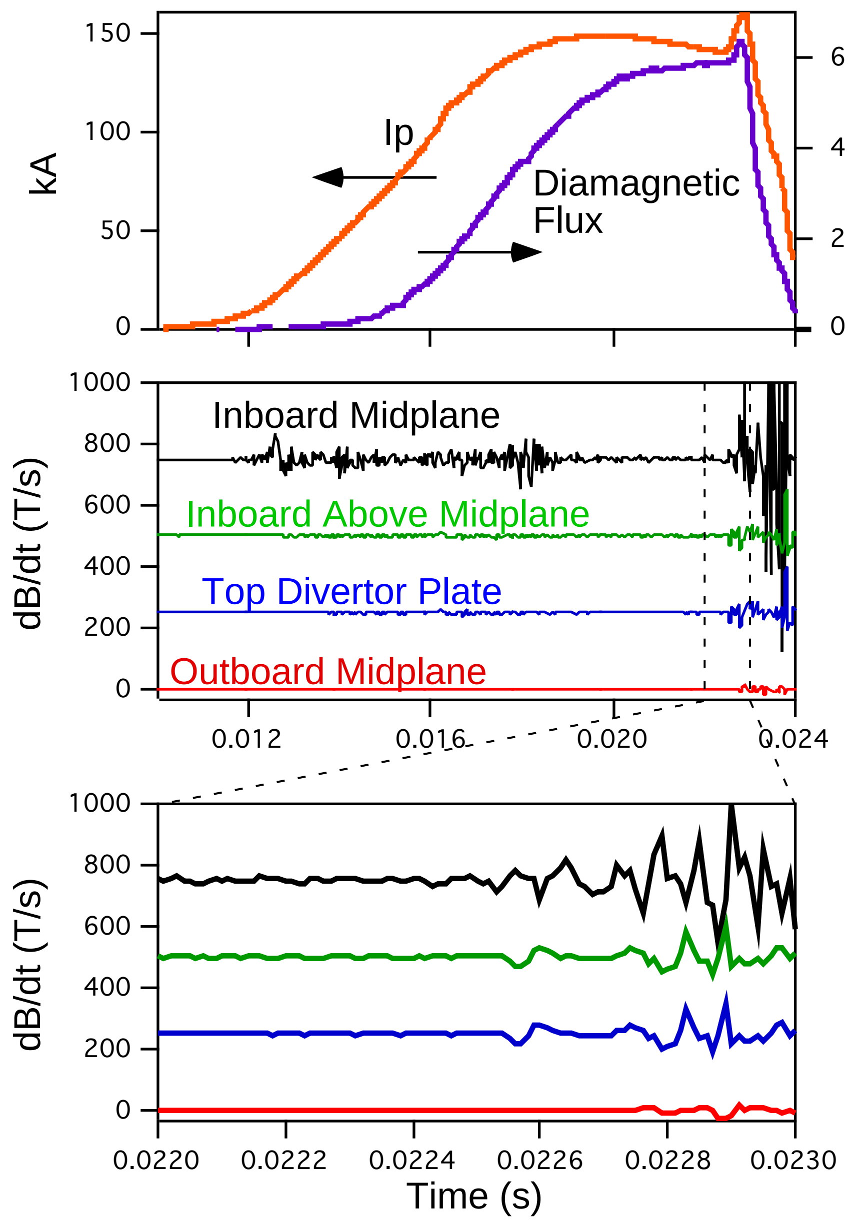
- **Tearing modes observed in almost all plasmas**
  - low B_t and fast $dI_p/dt \rightarrow$ low q early in discharge
  - high resistivity early in plasma evolution $\rightarrow$ fast island growth
  - ultra-low A $\rightarrow$ large island widths

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

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

- **At highest levels of I_p an ideal instability is observed**

Accessing external kink stability boundary at ultralow-A



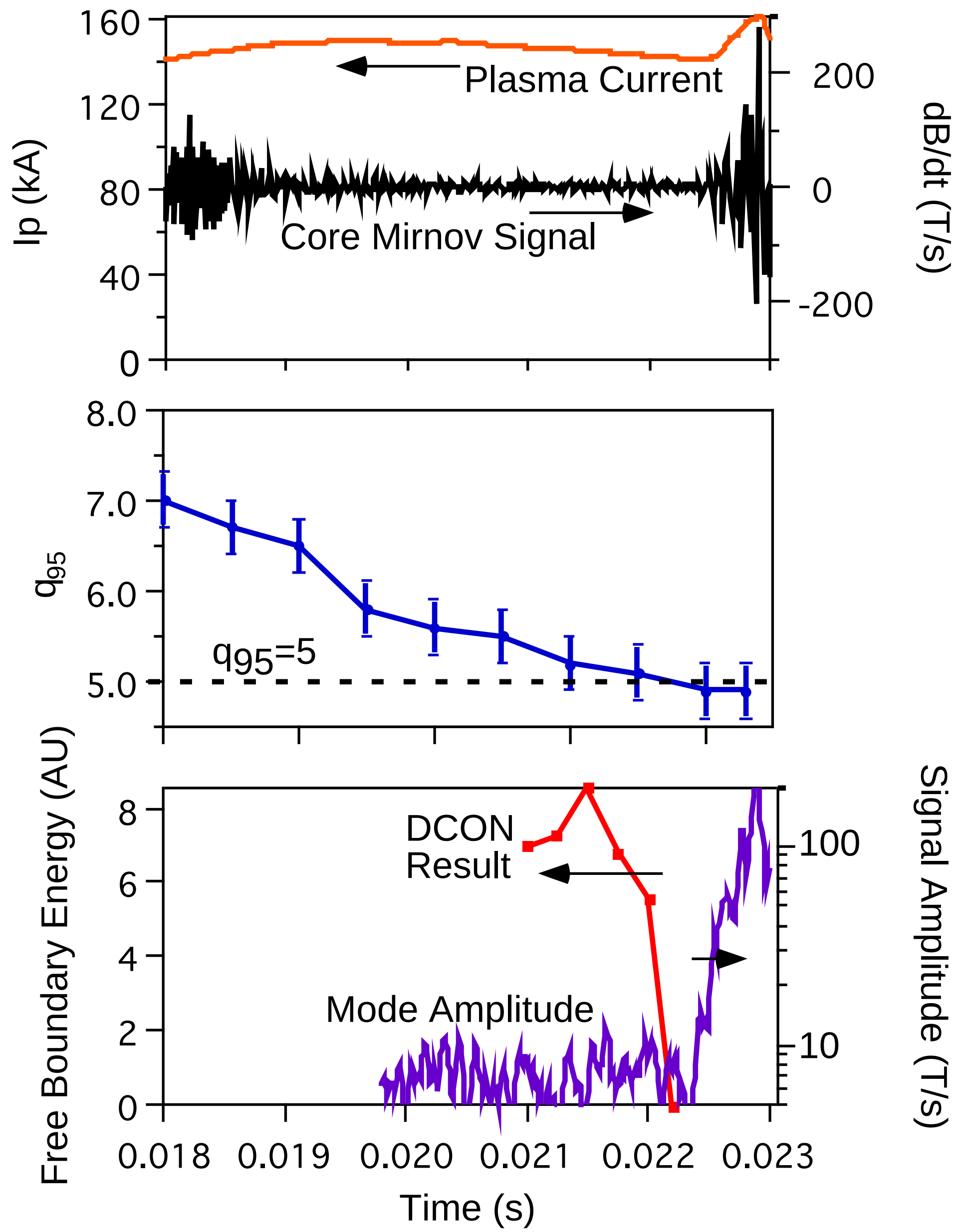
- Higher-current plasmas often terminate in disruptions
- n=1 fluctuations observed on core toroidal Mirnov array
- Fluctuations not observed in lower-current shots

External kink modes unstable for q_{95}=5 at A=1.2

- Equilibria indicate q_{95}=5 preceding disruption
  - l_i=0.5 at this time

- DCON analysis ⇒ instability to external kink at this time
  - Plasma-free boundary energy < 0 as mode grows

- Elevated unstable q_ψ as expected for very-low A
  - consider influences of low l_i, finite β



Upgrades will allow access to high I_p/I_{tf}, β_t operation

Goals:

- Manipulate q-profile: suppression of large internal modes
- Lower η during plasma formation: suppression of large internal modes
- Manipulate edge current: Expand access to external kink modes
- Access to very high β_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

Details of upgrades in Lewicki et al., KP1.092

Summary of Pegasus Ultralow-A Results

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

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

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

Other Pegasus presentations at this meeting

Posters - Wednesday Morning

KP1.092 - Lewicki
Overview of Pegasus Results and Facility Upgrades

KP1.093 - Sontag
Equilibrium and Stability Analysis of Pegasus Plasmas

KP1.094 - Diem
Diagnostic Systems on the Pegasus Toroidal Experiment

KP1.095 - Tritz
Tangential Soft X-ray Imaging for Current Profile Reconstruction on Pegasus

Oral - Thursday Morning

QO1.003 - Unterberg
Characteristics of OH Plasmas in the Pegasus Toroidal Experiment