Performance and Stability Limits at Near-Unity Aspect Ratio in the PEGASUS Toroidal Experiment

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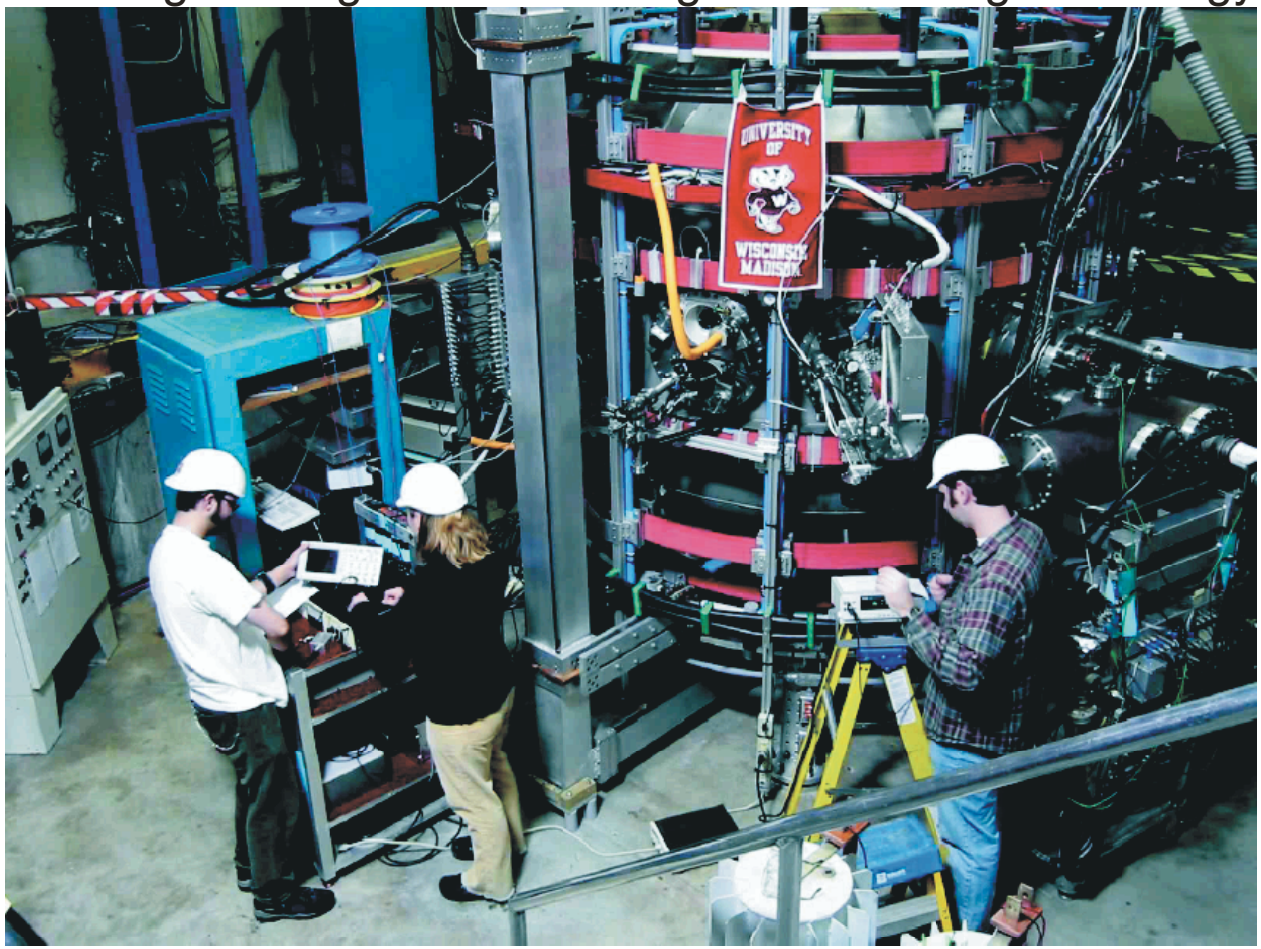
Abstract

The Pegasus Toroidal Experiment is a mid-sized extremely-low aspect ratio (A) spherical torus (ST). It has the dual roles of exploring limits of ST behavior as A approaches 1 and studying the physics of ST plasmas in the tokamak-spheromak overlap regime. Major parameters are R = 0.25 - 0.45 m, A = 1.1 – 1.4, $I_p \leq 0.15$ MA, and $B_T < 0.1$ T. High beta plasmas are produced at very low toroidal field by ohmic heating. Values of $\beta_t > 20\%$ have been obtained, and the operational space of β_t vs I_p/aB_T is similar to that observed for NBI-heated START discharges. Achievable plasma current is subject to an apparent limit of $I_p/I_{TF} \sim 1$. Access to higher-I_p appears to be restricted by the appearance of large internal MHD activity, including m/n=2/1 and 3/2 modes, which extend over a large region of low shear. Recent experiments have begun to access ideal stability limits, with disruptions observed as q_{95} approaches 5, in agreement with numerical predictions for external kink mode onset.

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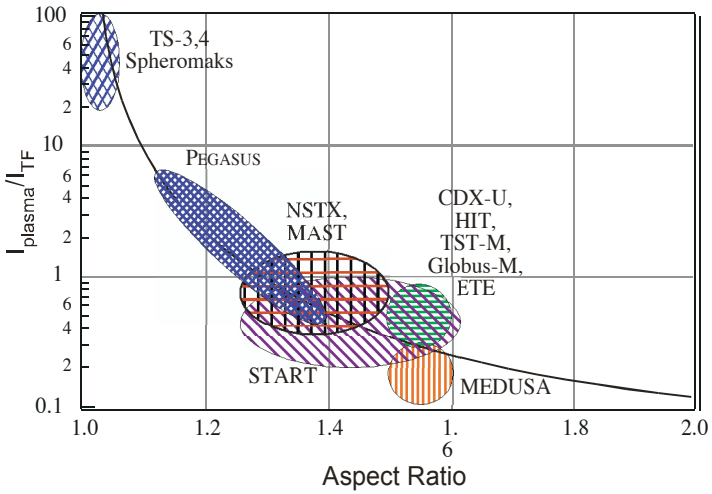
Pegasus is a mid-sized spherical torus

- Major Parameters:
  - $R = 0.2 - 0.45$ m
  - $A = 1.15 - 1.3$
  - $B_t \leq 0.07$ T
  - $I_p \leq 0.15$ MA
  - $\kappa = 1.5 - 3.7$
  - $\Delta t_{pulse} = 10 - 30$ ms
  - $\langle n_e \rangle = 1 - 5 \times 10^{19} m^{-3}$
  - $\beta_t \leq 20\%$
- High strength solenoid magnet is enabling technology

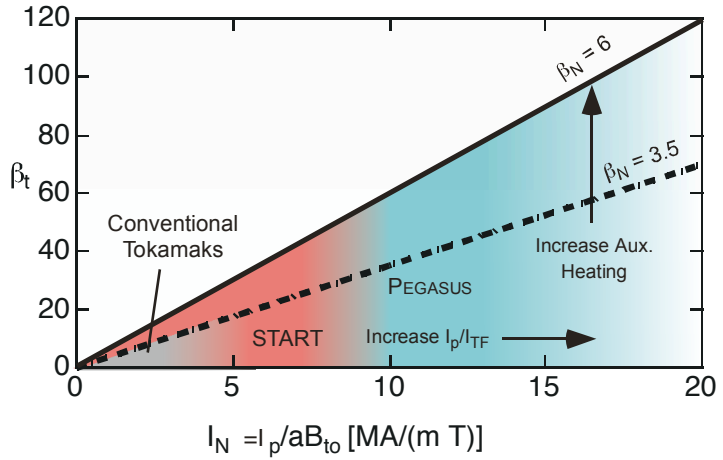


Role of PEGASUS in the Fusion Community

- **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 (β ≈ 1)
  - Relaxation stability at tokamak/spheromak boundary
  - RF heating and CD schemes (HHFW, EBW)
  - Trade-offs: CD, recirculating power,

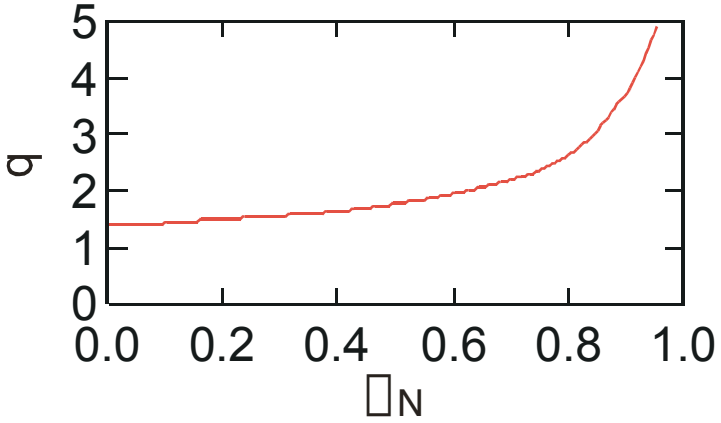


- **Contribute to development of the ST (high q)**
  - Stability limits for A → 1 (vs. I_p/I_{TF}, q_ψ, N_e, β_t, β_{pol}, κ, A, etc.)
  - β limit dependencies
  - Access high β_t at extreme I_N w/o conducting shell
  - Confinement A < 1.3
  - New startup schemes (e.g., plasma gun, EBW)

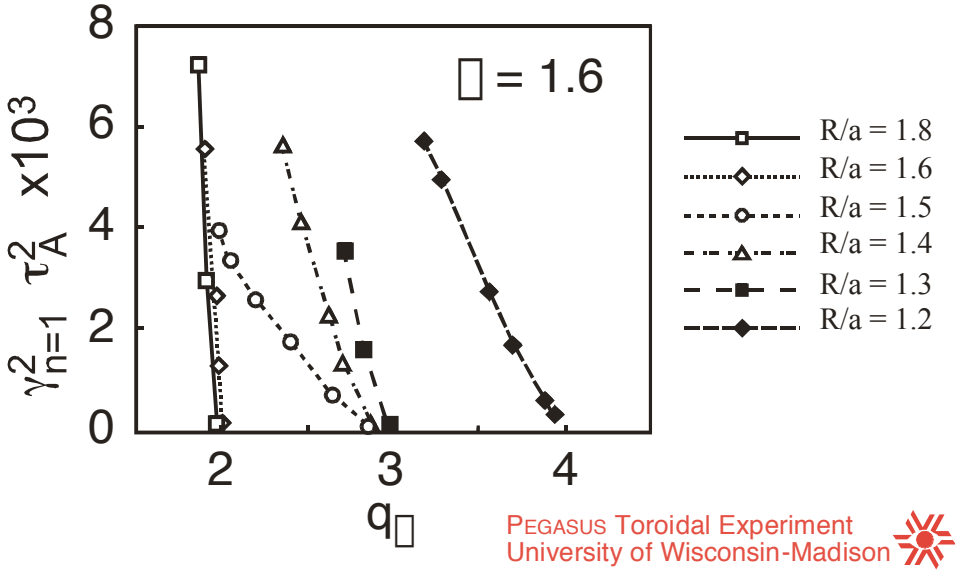


PEGASUS Faces a Variety of Stability Issues

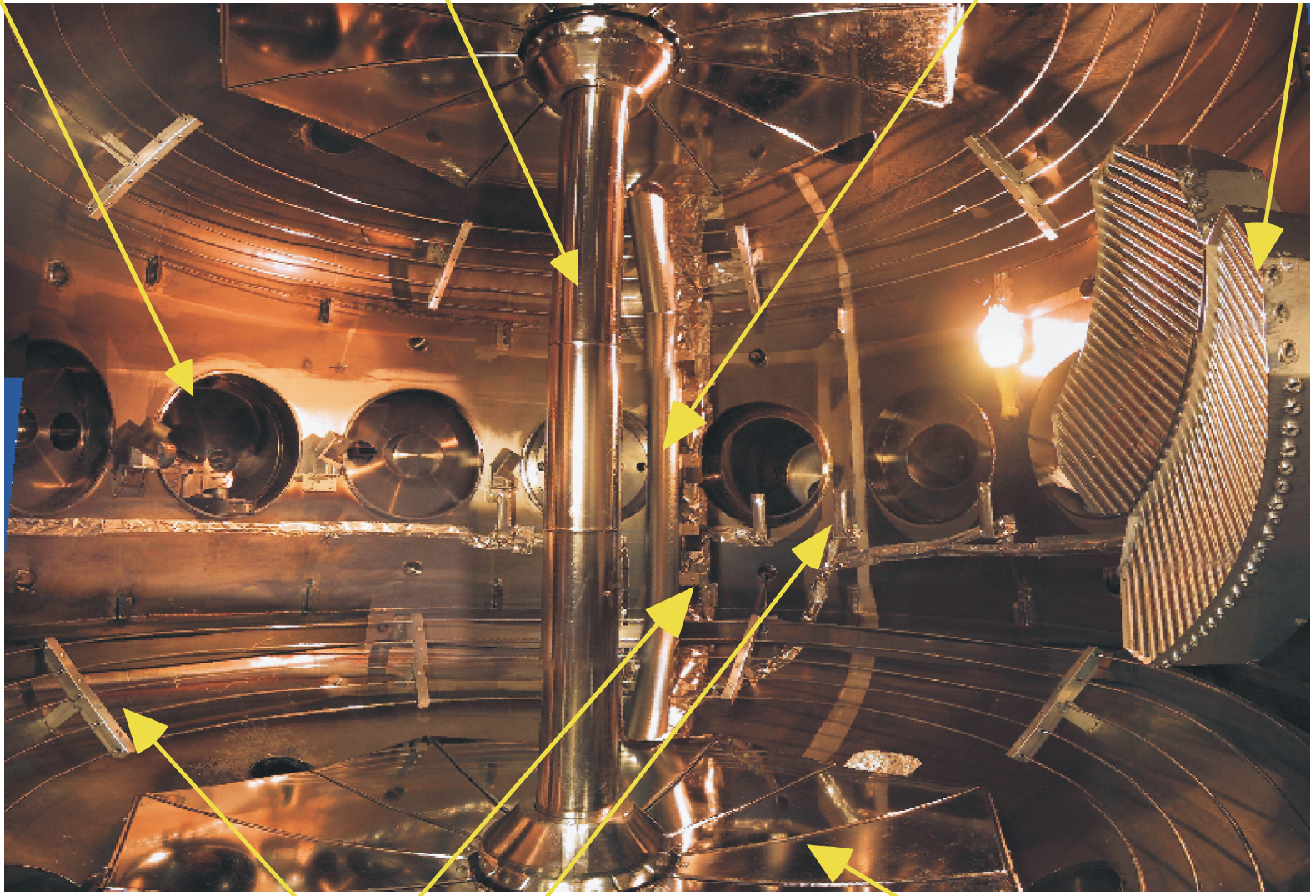
- **Resistive internal modes can be especially severe at low-A**
  - Low T_e at startup increases □
    faster mode growth
  - Broad low-shear region provides little stabilization
    larger saturated island width
  - Confinement degradation dissipates limited OH flux



- **External kink limits more severe for STs**
  - $q_{□}$ for n = 1 kink stability ↑ as A □
  - could cause limit for low-TF operations at A ~ 1



Vacuum vessel interior hardware



Pegasus diagnostic set

• Presently Operating Diagnostics

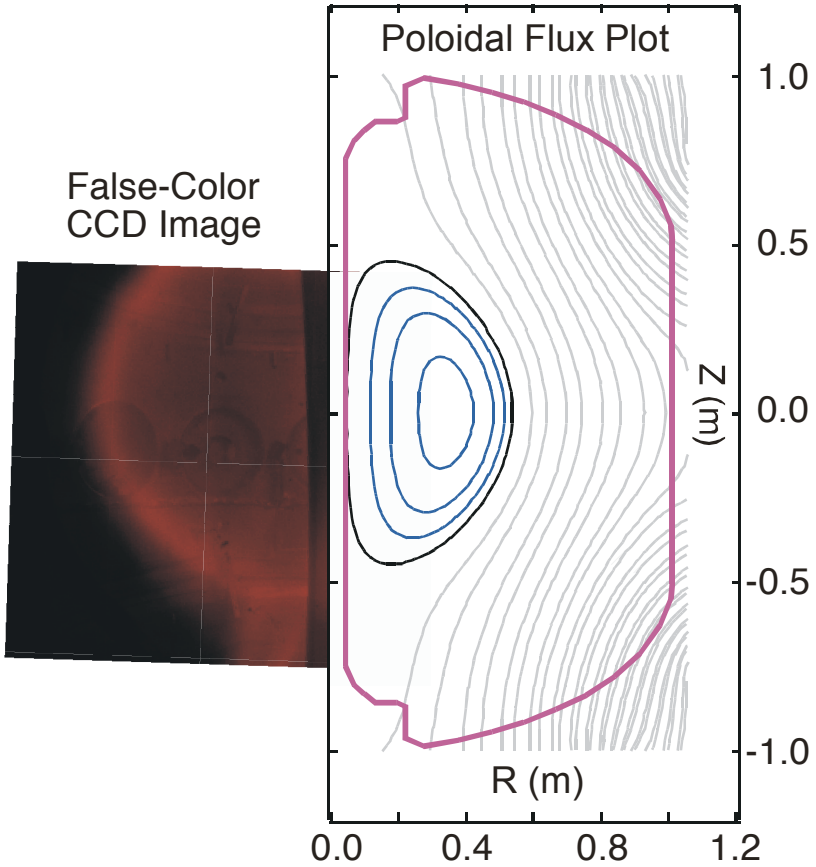
Diagnostic	Capability	Measures
Core Flux Loops	(6)	V_L , Φ_{pol}
Wall Flux loops	(6)	Vessel currents
Int. Flux loops	(20)	Φ_{pol}
Rogowski Coils	(2)	I_p
Diamagnetic Loop	(2)	Φ_{tor} / Φ_p
B_p, Mirnov Coils	(56)	B_r , B_z / MHD activity
VUV (SPRED)	central chord	Impurity monitor
Filterscopes	central chord	Oxygen, Carbon, VB, D_α
Interferometer	single chord	N_el
High Res. Camera	1000 fps	Plasma shape/position
2-D SXR Camera		Internal Shape/ j(R)
Poloidal SXR Diode Array	(19)	MHD Activity

• Near-Future Diagnostics

Diagnostic	Capability	Measures	Status
Tangential CCD PHA	single chord	$T_e(t)$	In Development
Tangential Bolometer Array	~20 chords	P_{rad}	Testing
Ross Filters	4 chords	$T_{e0}(t)$	Testing
2-Color X-ray	4 chords	T_e	Testing
Tangential VB Array	~20 chords	$Z_{eff}(R,t)$, $N_e(R,t)$	Testing
DNB		$N_e(R,t)$, $T_e(R,t)$, j(R)	Proposed
EBW Radiometer		$T_e(t)$	Proposed

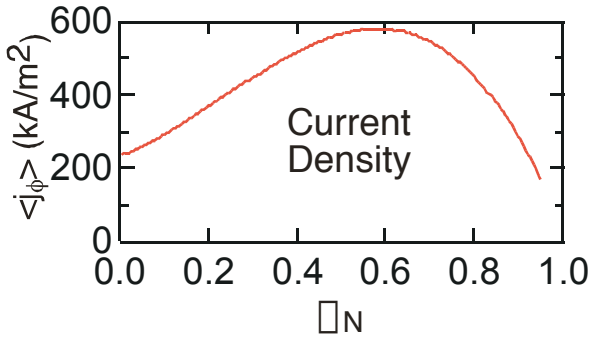
Equilibrium reconstruction is a primary analysis tool

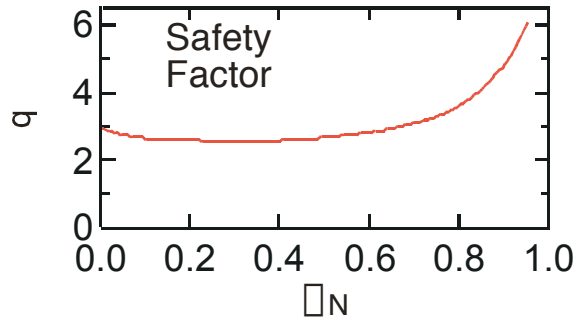
- A new equilibrium code has been developed for Pegasus
  - Robust, cross-platform, easy incorporation of new diagnostics
- Uses a two-step iterative method to determine equilibrium
  - Gauss-Seidel multigrid relaxation to solve Grad-Shafranov equation
  - Levenberg-Marquardt method to minimize χ^2
- Benchmarked against existing codes
- Sample reconstruction:

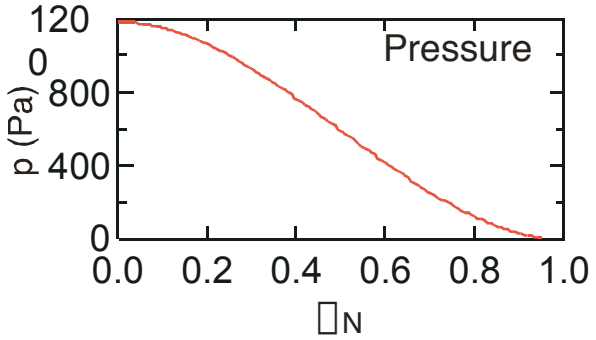


Fit Results

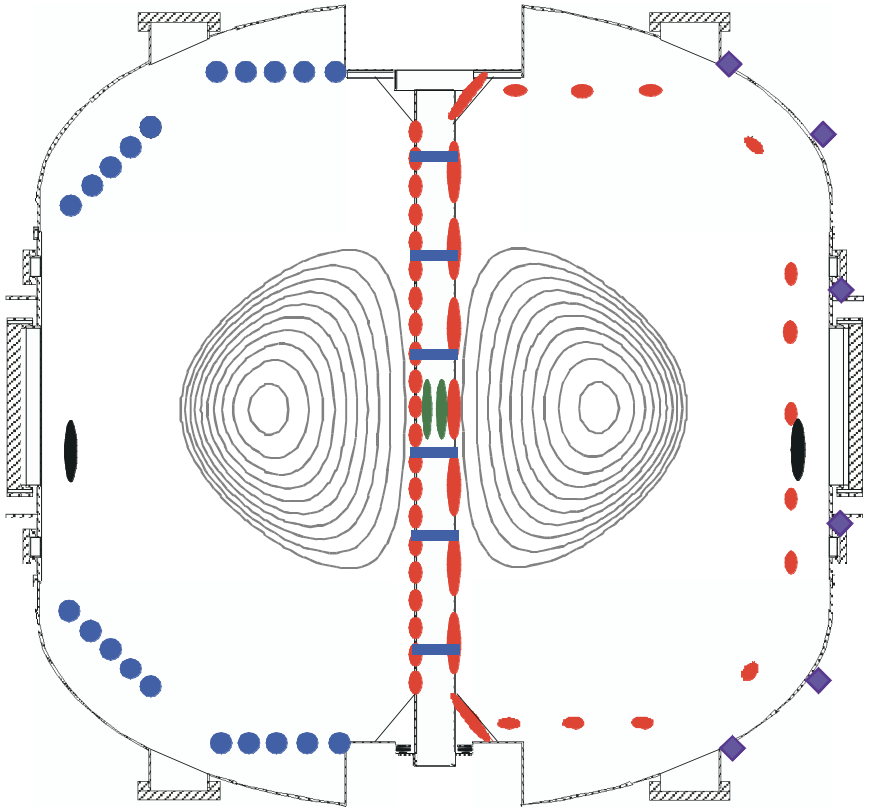
I_p	151.4 kA
R_0	0.305 m
a	0.249 m
A	1.22
κ	1.8
RB_t	0.003 T-m
β_t	16%
ℓ_i	0.35
q_0	2.8
q_{95}	6.2







Equilibrium Diagnostics Sufficient for Global Parameter Determination



Installed Magnetics

Flux Loops	(26)
Poloidal Mirnov Coils	(22 + 21)
LFS Toroidal Mirnov Coils	(6)
HFS Toroidal Mirnov Coils	(7)
External Wall Loops	(6)
Total	(88)

- **Plasma - diagnostic separation □ a for many discharges**

  - Flux loops and B-field measurements constrain plasma geometry
  - Diamagnetic loop constrains stored energy □ pressure
  - Wall flux loops constrain wall currents

Monte Carlo Analysis Gives Uncertainty in Fit Parameters

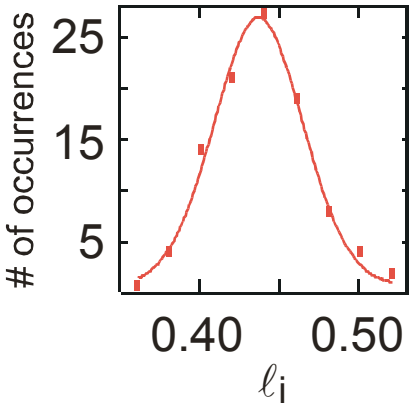
- **Uncertainty estimate technique:**
  - single time-slice of discharge reconstructed 100 times
  - Gaussian noise added to measurement data
    Gaussian width from diagnostic uncertainty
    starting $\chi^2 \sim 8 \times$ final χ^2
  - σ of fit parameter distributions gives uncertainty

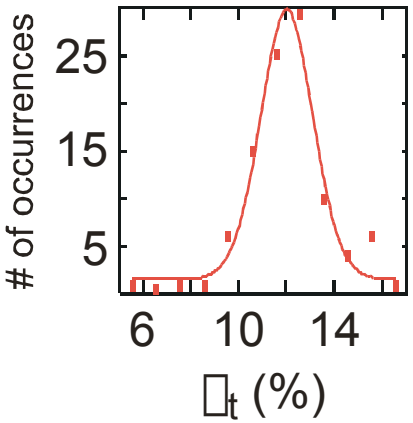
Parameter	Rel. Uncertainty
I_p	± 2%
R_0	± 4%
ℓ_i	± 9%
β_t	± 15%
β_p	± 15%
q_{95}	± 6%
q_0	± 20%

- **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
    σ *uncertainty determined by diagnostic uncertainties*





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

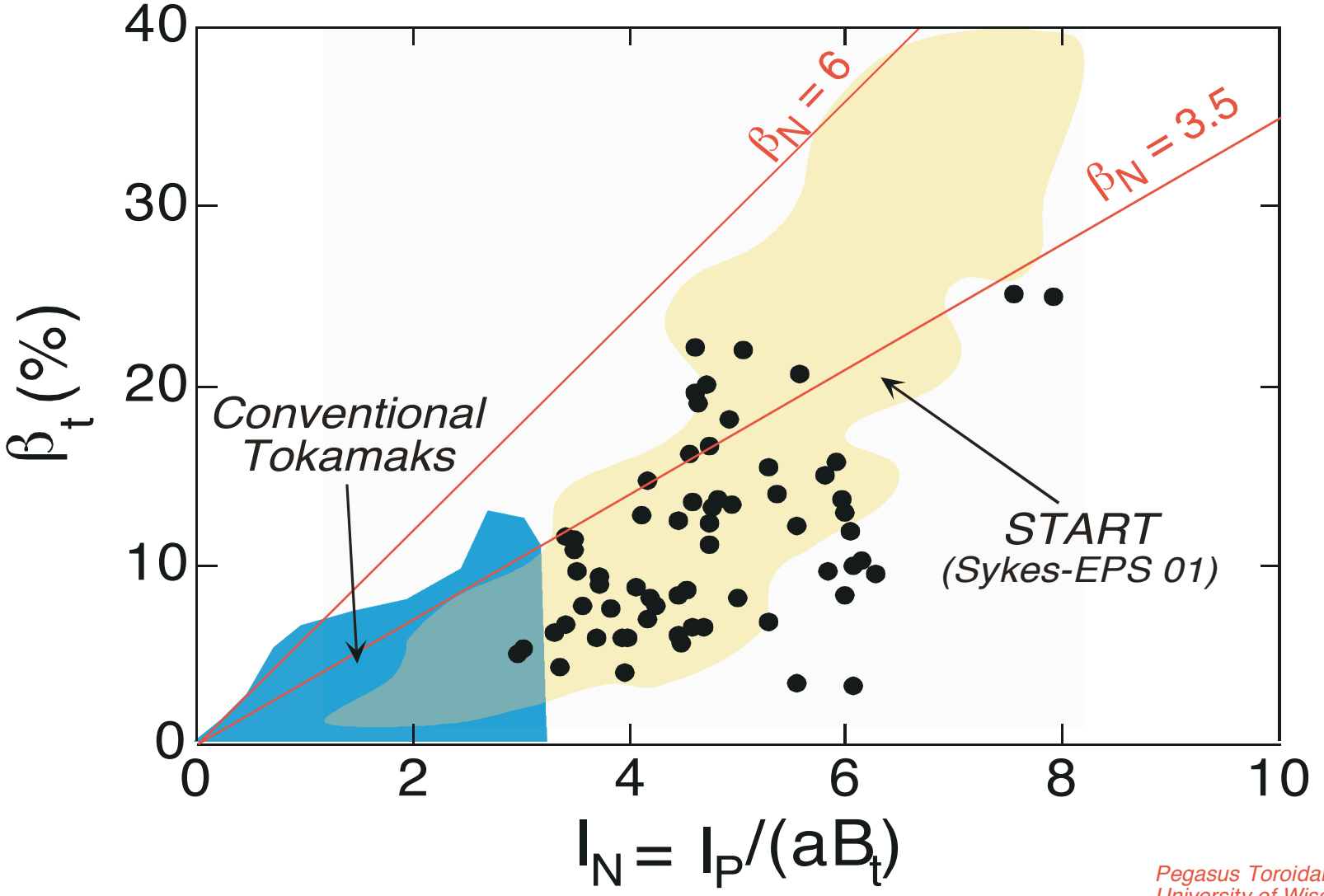
$$\frac{\sigma_{\beta_t}}{\beta_t} = 15\ \%$$

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-β (natural):** $\beta > 2$
- **High field windup:** high q_a at low TF
- **Paramagnetic:** $\beta_p = 0.3$ at $\rho = 0.83$; $G/G_{vac} \sim 1.25$ on axis

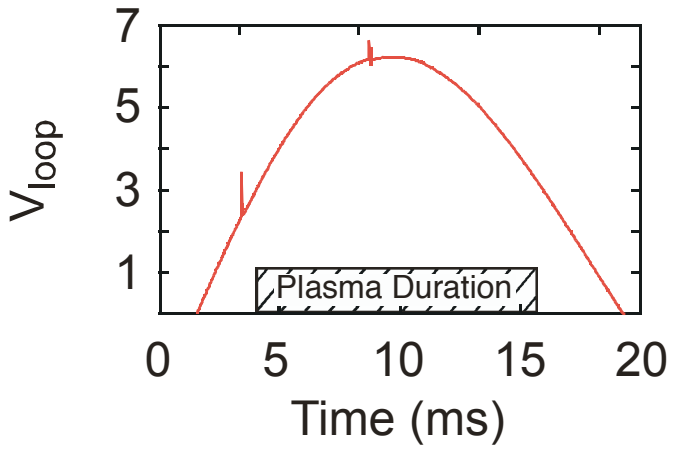
PEGASUS is Accessing High-β_t ST Regime

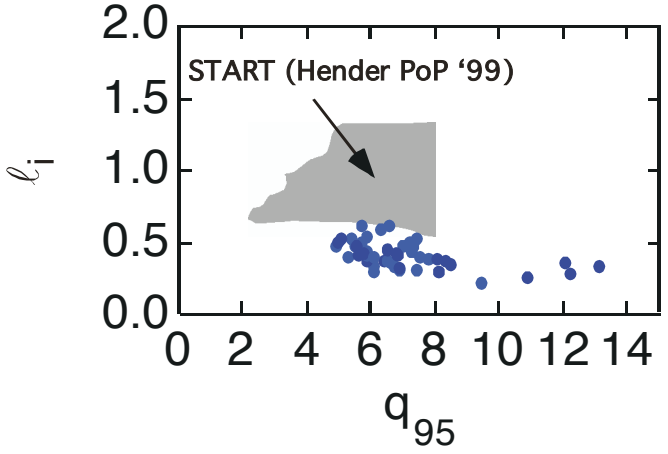
- High β_t achieved at high density and low toroidal field
  - All results achieved with ohmic heating only
  - Highest normalized currents achieved at low field



Low-ℓ_i Indicates Unrelaxed Current Profile

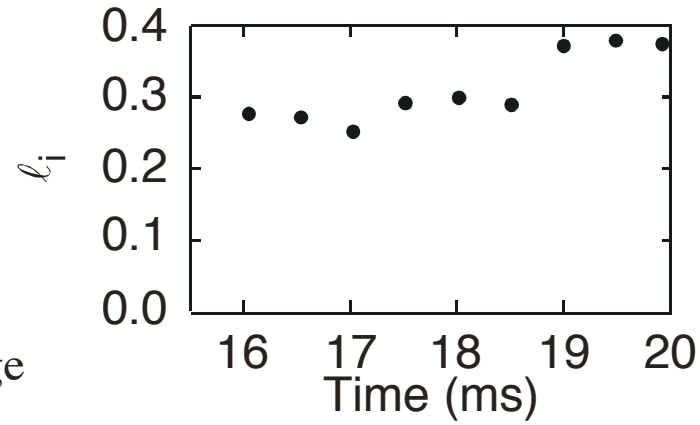
- **High $\dot{I}_p$ and short pulse length result in low ℓ_i**





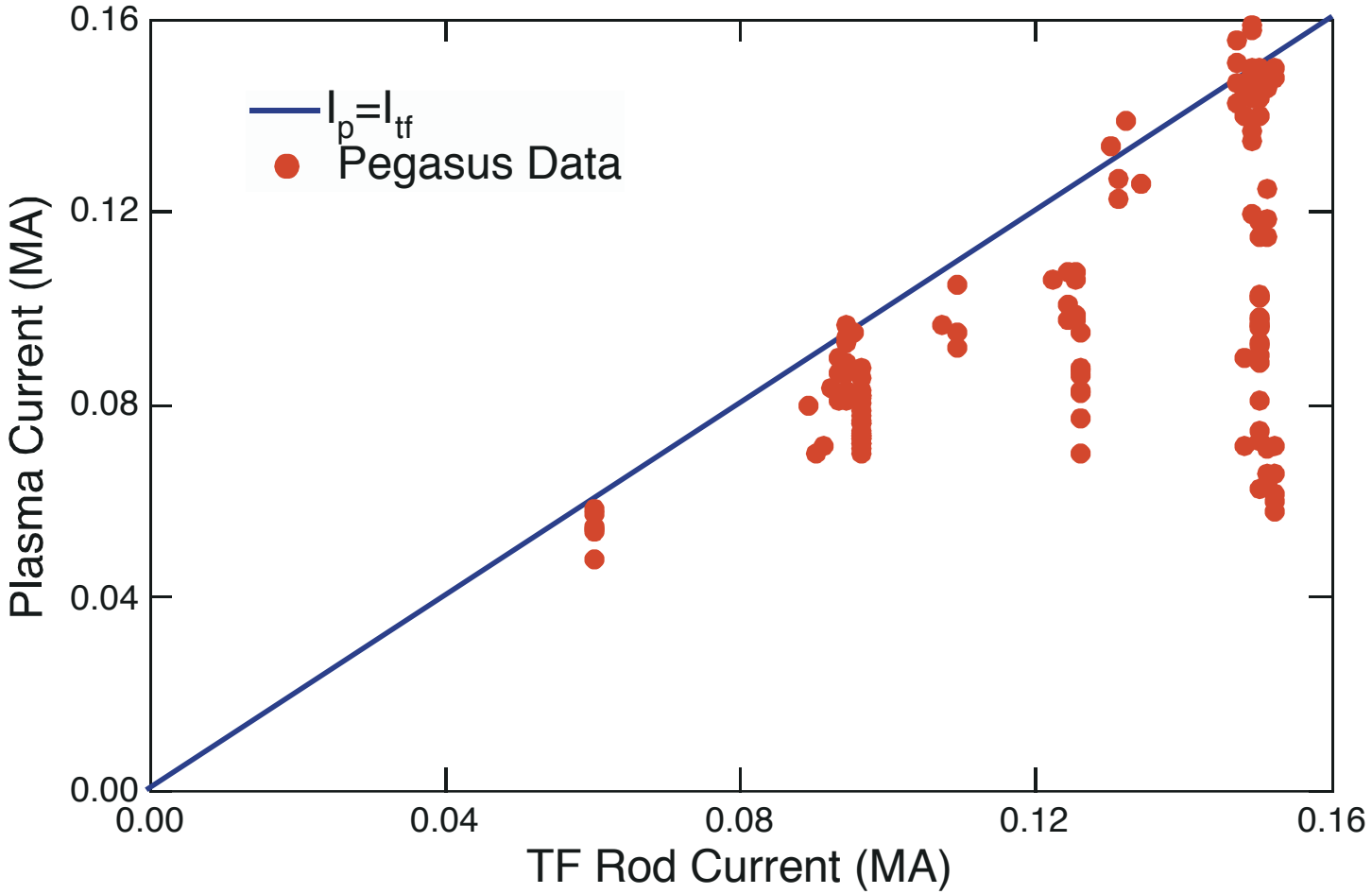
- **Some hints of increasing ℓ_i as pulse length increases**

- τ_R is on the order of discharge length or greater
  - $\tau_R \sim 30$ *ms for following conditions:*
  - $Z_{eff} = 2$, $n_e = n_i = 2 \times 10^{19}$
  - $\bar{T}_e = 2\,\bar{T}_i = 150$ *eV (linear profile)*
  - $a = 25$ *cm*
- these conditions typical for t ~ 5 ms into discharge



Toroidal field utilization exhibits a “soft limit” around unity

- Maximum plasma current generally does not exceed rod current
- This holds for a variety of loop voltage waveforms
- Appears to relate to two factors:
  - Increased V-s consumption required for breakdown at lower TF
  - Large-scale resistive MHD during current ramp (exacerbated by low ℓ_i?)



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

- **Volt-second effects:**

  - total flux available to drive plasma
    inherent limit due to v_{loop} waveform

  - late start up decreases availability at low-TF

  - efficiency of flux usage

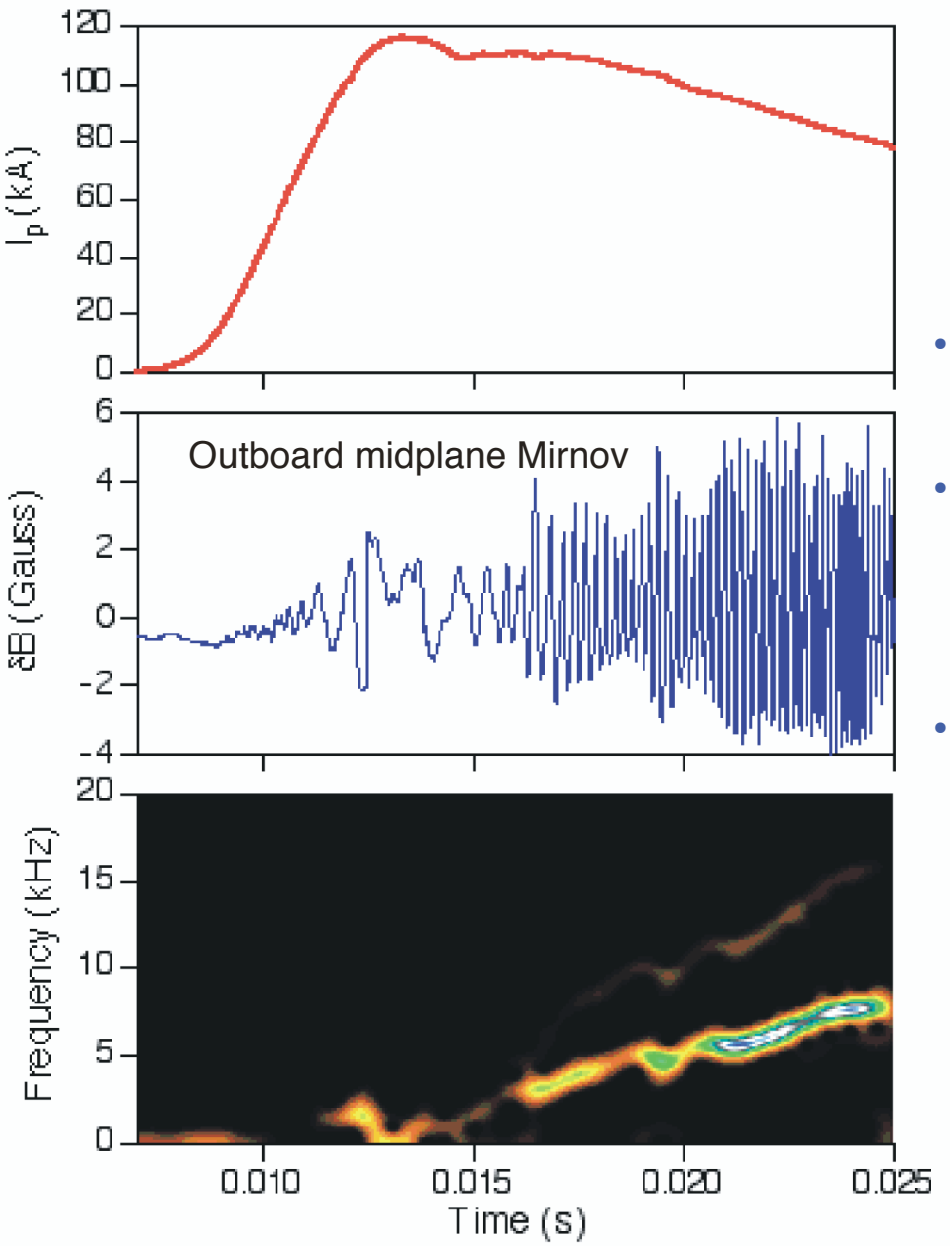
- **MHD effects:**

  - large m/n = 2/1 and 3/2 tearing modes present in most discharges
    known to degrade plasma confinement

  - low-shear & high-β lead to quick growth of large modes

$$\beta = \frac{0.55}{\beta_R^{3/5}\beta_A^{2/5}}\left[n\frac{a}{R}\frac{aq'}{q}\right]^{2/5}(a\beta')^{4/5} \qquad \beta_R = \frac{\beta_0 a^2}{\beta} \qquad w_s \mu \frac{q}{q'}$$

Rotating 2/1 Mode Observed in Most Discharges



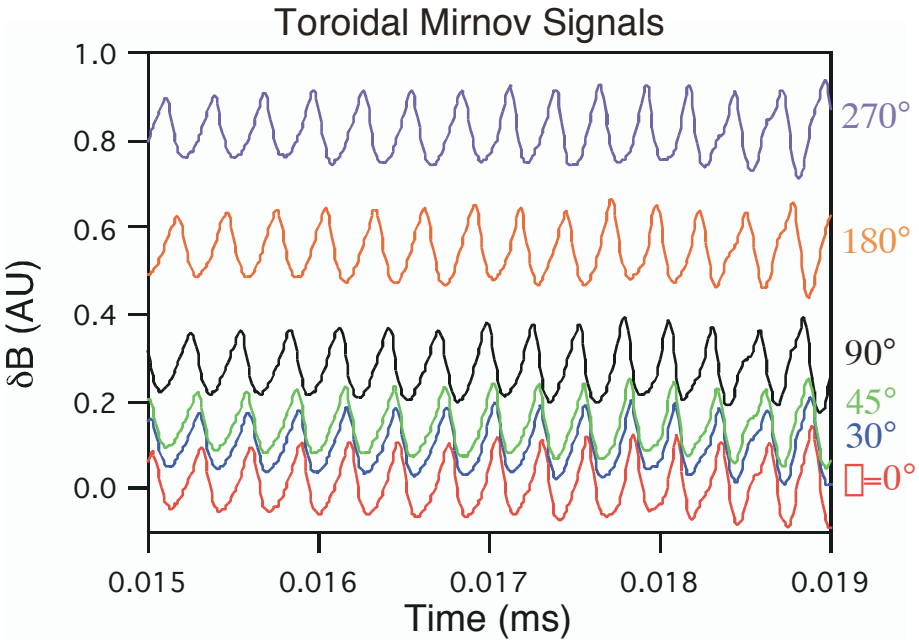
- **Mode present in most significant discharg**
- **Frequency is typically 4-10 kHz**

  - no evidence of mode locking

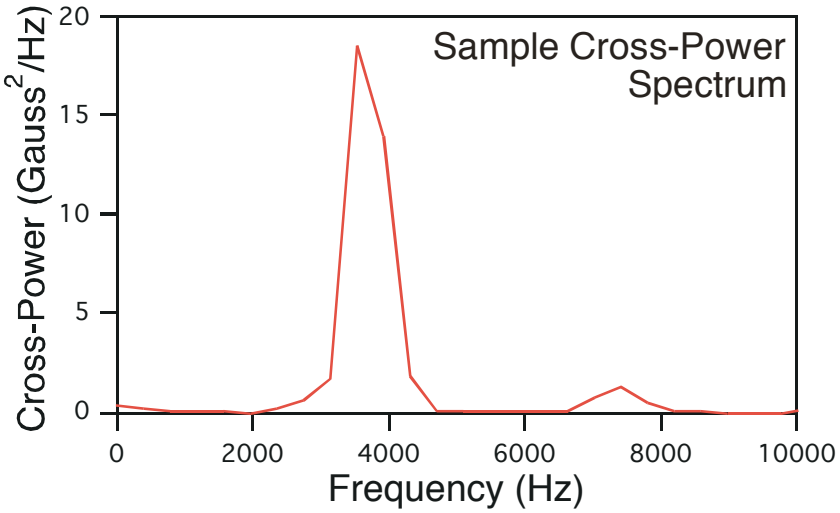
- **Island width estimates indicate *w* > 10 cm**

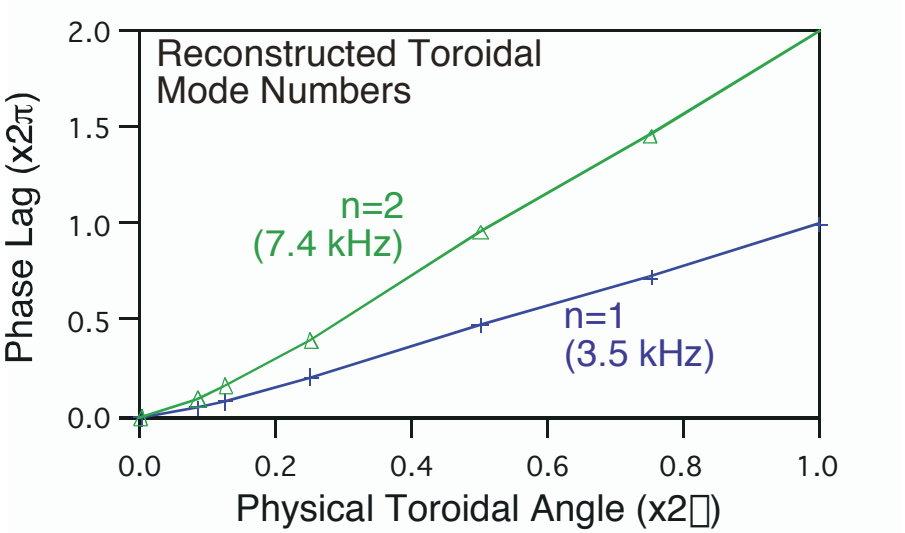
$$w = 4\sqrt{\frac{\tilde{B}}{B_t}\frac{qR}{n\frac{dq}{dr}}}$$

Toroidal mode numbers are readily identified



- The 6-coil LFS array is used to obtain values of n
  - Uneven coil spacing allows for resolution up to n=12
- Spectral techniques are used to extract resonant frequencies and phase delays
  - Cross-power gives spectrum
  - Cross-phase gives phase shift

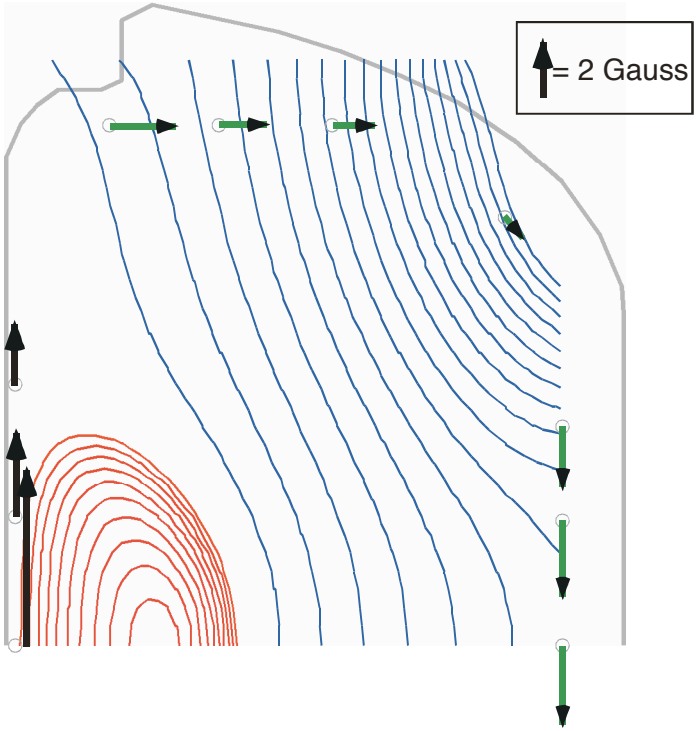


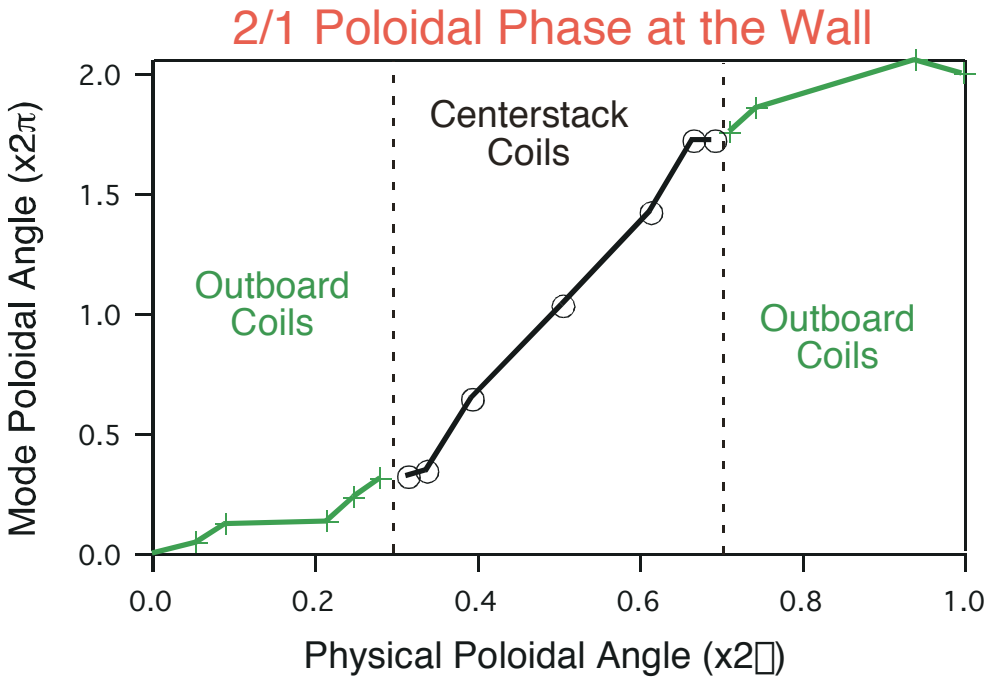


2/1 mode is poloidally asymmetric

- Poloidal and toroidal phase analyses clearly indicate mode is m=2/n=1
- Toroidicity of mode is seen in large phase shifts along centerstack
  - Roughly 1.5 wavelengths observed across 120° poloidally
- Mode is typically strongest on the plasma outboard
  - As plasma grows, LFS signal increases and HFS signal decreases

Perturbed Field Magnitude
at the Wall

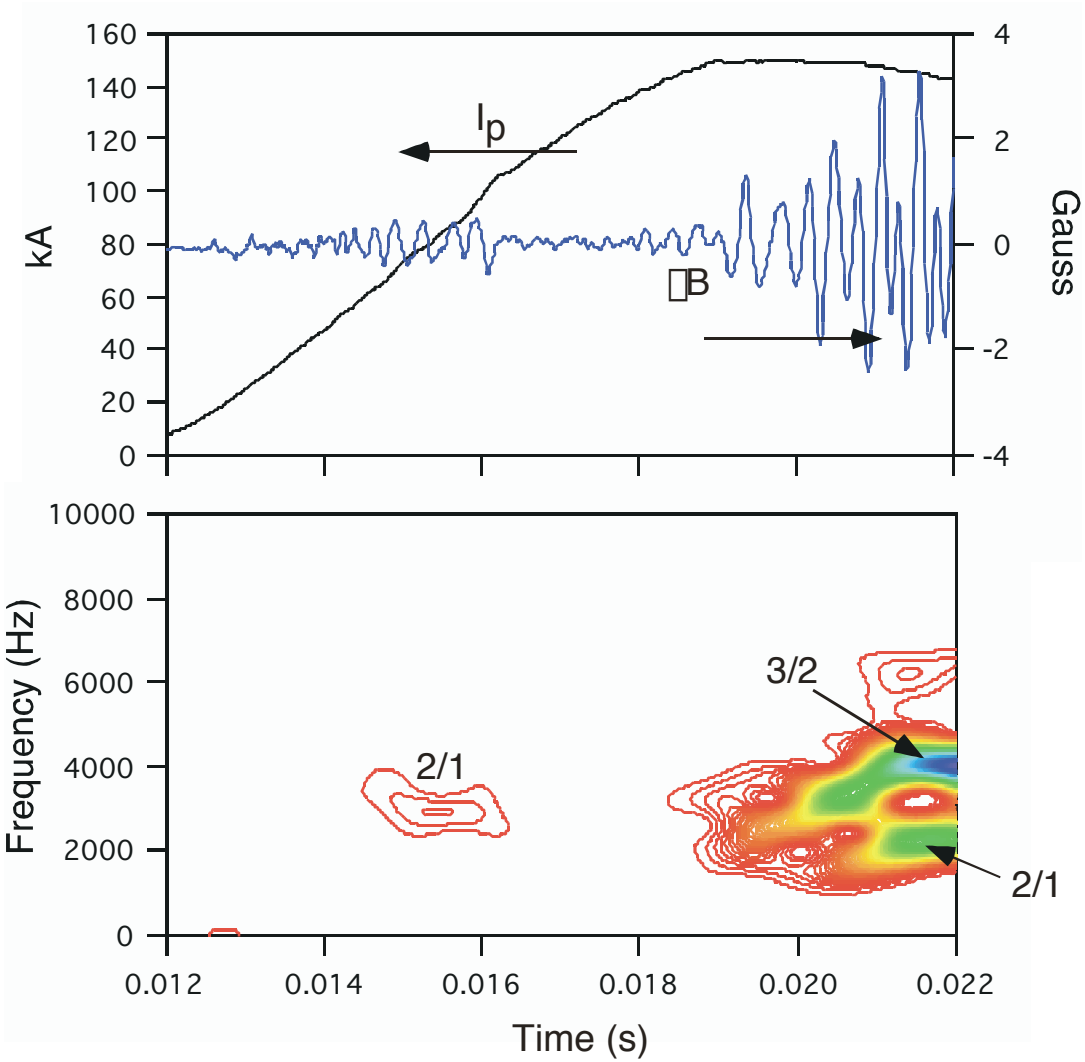




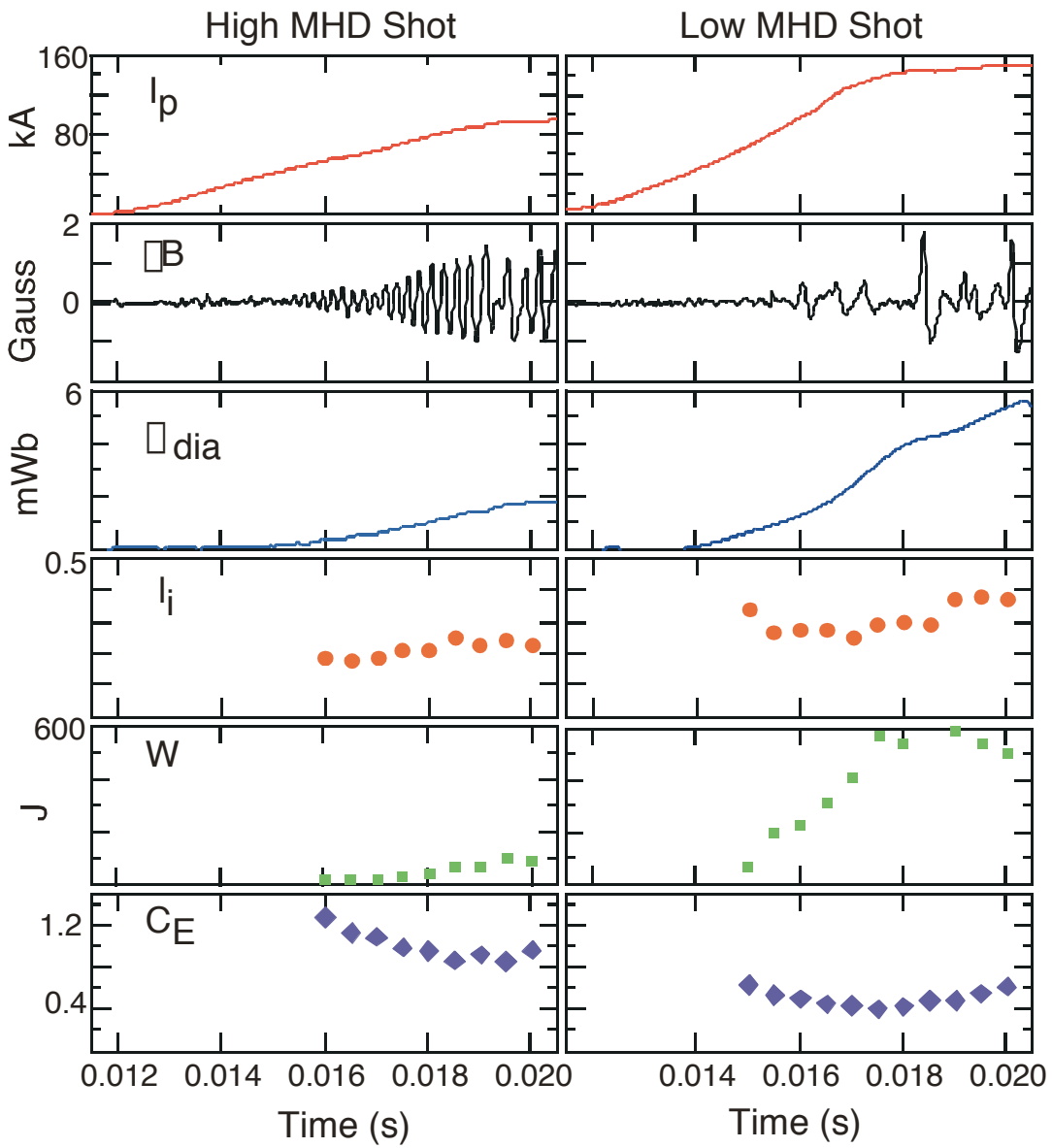
Higher Current Discharges Exhibit Greater Variety of Modes

- **2/1 and 3/2 modes correlate with q_0 passing through 2 and 1.5 respectively**

  - low central shear allows modes to have large radial extent



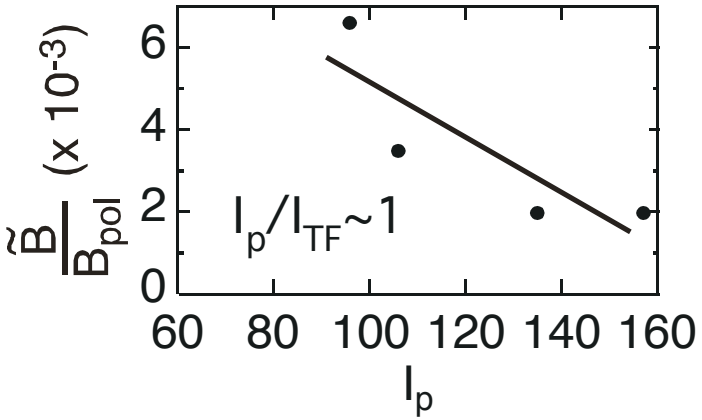
MHD activity appears to limit plasma performance



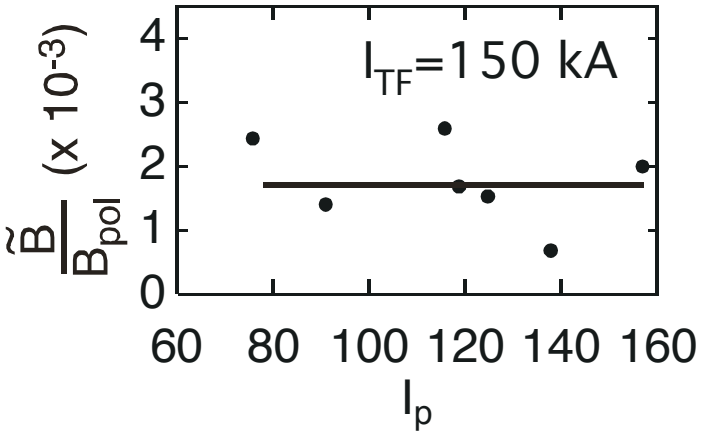
- Reduction in MHD typically results in improved plasma performance
- In "High MHD" Case:
  - ℓ_i stays low (0.3)
  - Stored energy stays < 100 J
  - Ejima coefficient > 0.8
- In "Low MHD" Case:
  - ℓ_i climbs higher (despite higher V_{loop})
  - Stored energy climbs to 600 J
  - Ejima coefficient ~ 0.4
- Reduction of 2/1 mode was important for improved plasma performance
- Further data analysis is ongoing

MHD Amplitude Increases at Lower TF

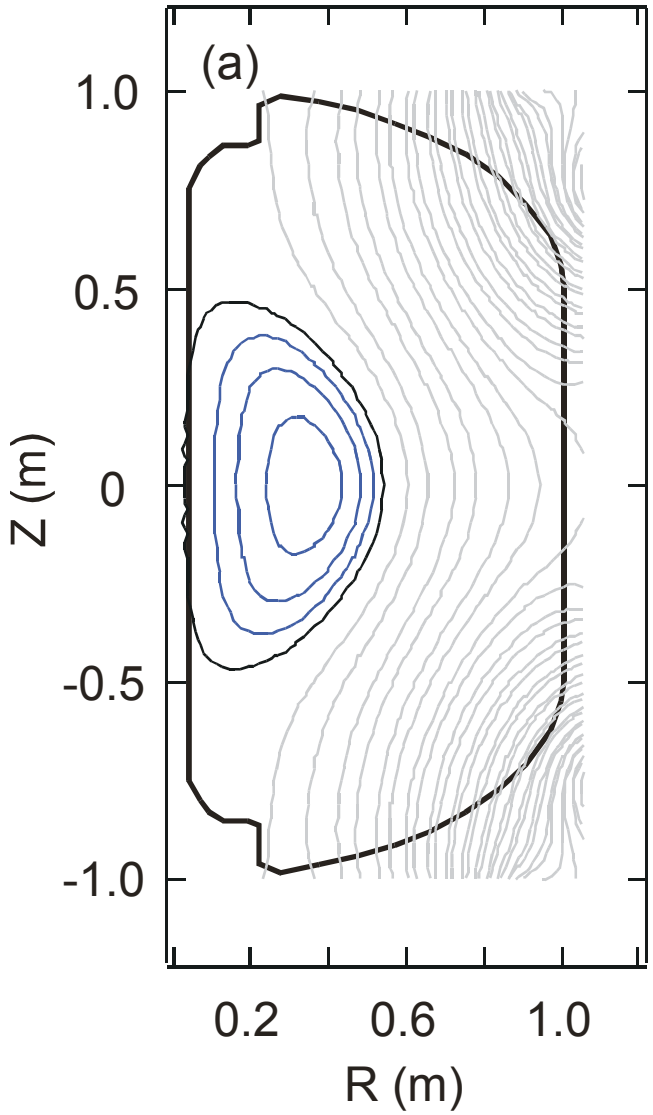
- **MHD amplitude measured with core Mirnov**
  - all discharges core limited
- **Fluctuations increase rapidly at low TF**



- **Fluctuations relatively constant at constant TF**



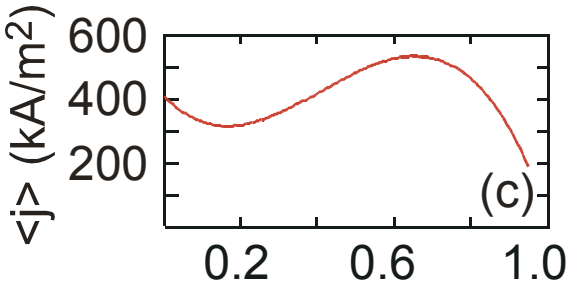
In Some Discharges I_p Exceeds I_{TF}

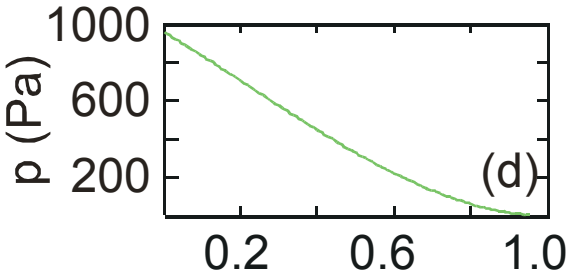


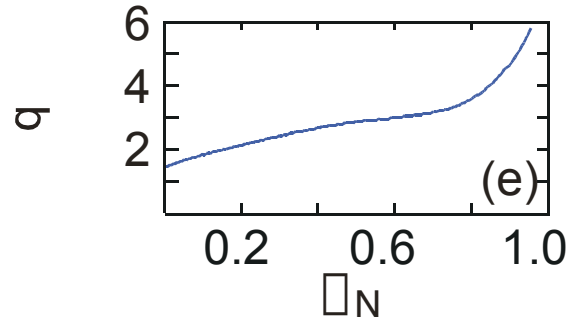
Shot 14697

(b)

I_p	157 kA
R_0	0.29 m
a	0.25 m
A	1.17
□	1.6
B_t (axis)	0.1 T
□$_t$	9%
ℓ_i	0.32
q_0	1.5
q_{95}	5.9



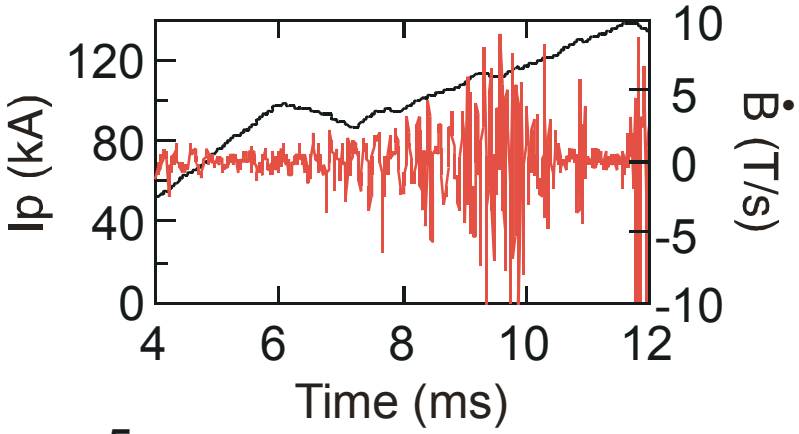


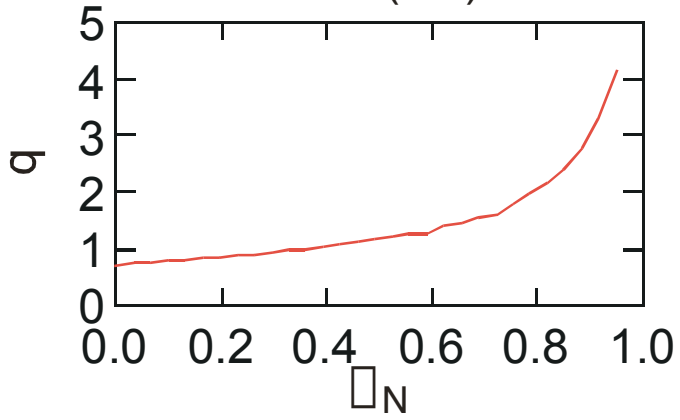


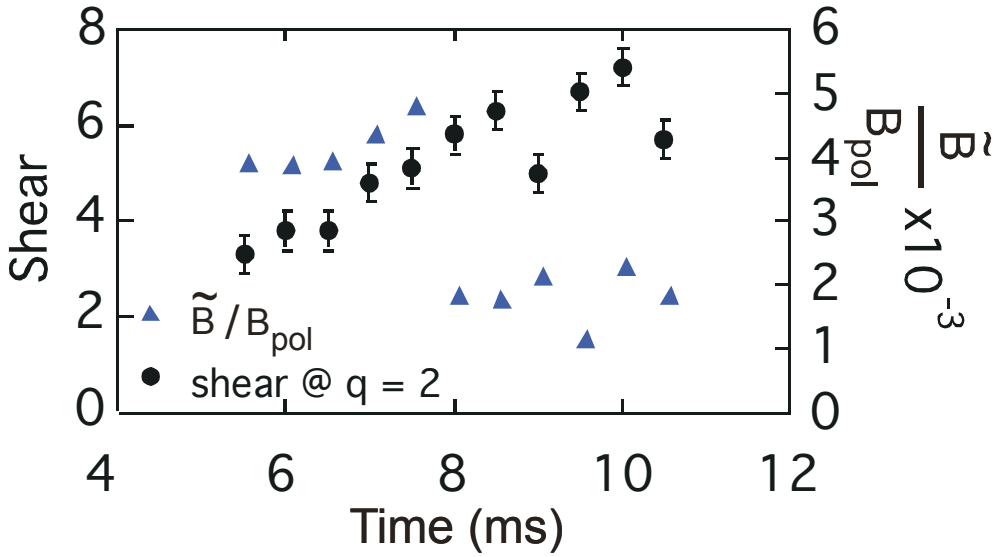
- Discharge appears to be V-s limited

Increased Magnetic Shear Reduces MHD Amplitude

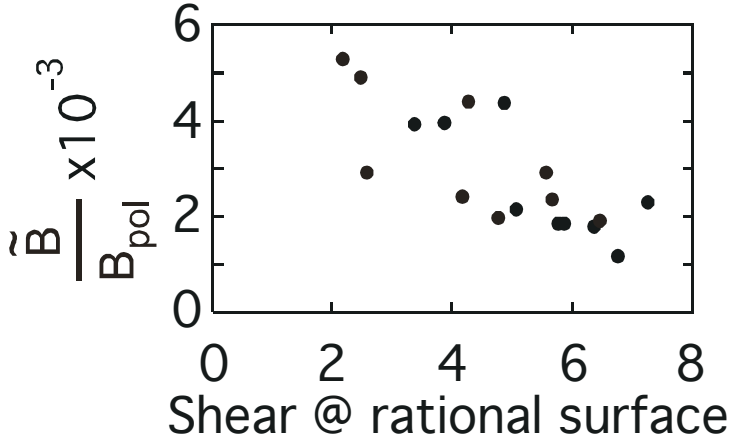
- **Mode stabilized as rational surface moves to higher shear region**







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



 Increased magnetic shear helps to mitigate confinement degrading MHD

$I_p \sim I_{TF}$ Limit Due to Combination of Factors

- **Decreased V-s at lower TF reduces ultimate plasma current**

  - 20% decrease in V-s explains ~ half of drop in plasma current

- **Increased MHD at lower TF degrades plasma**

  - large tearing modes dissipate input flux
  - mode onset is related to appearance of q = 2 surface
    onset at lower I_p for lower TF
  - mitigated by lower □, increased shear

$I_p/I_{TF} \sim 1$ limit arises from large-scale internal modes resonant in regions of low shear

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

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

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

assume $j(r) = j_0$

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

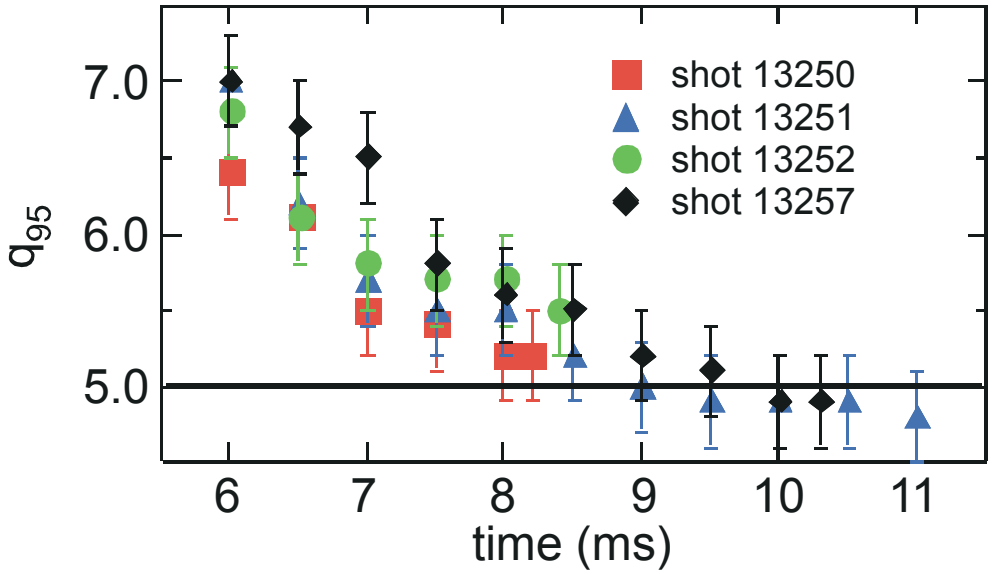
- **For PEGASUS:**

  $A \sim 1.2$ $\quad \kappa \sim 1.7$ $\quad @ q_0 \sim 1.5 - 2$: $\quad \frac{I_p}{I_{TF}} \sim \frac{1}{1^2}\frac{1}{2}\frac{1+1.7^2}{2} \approx 1$

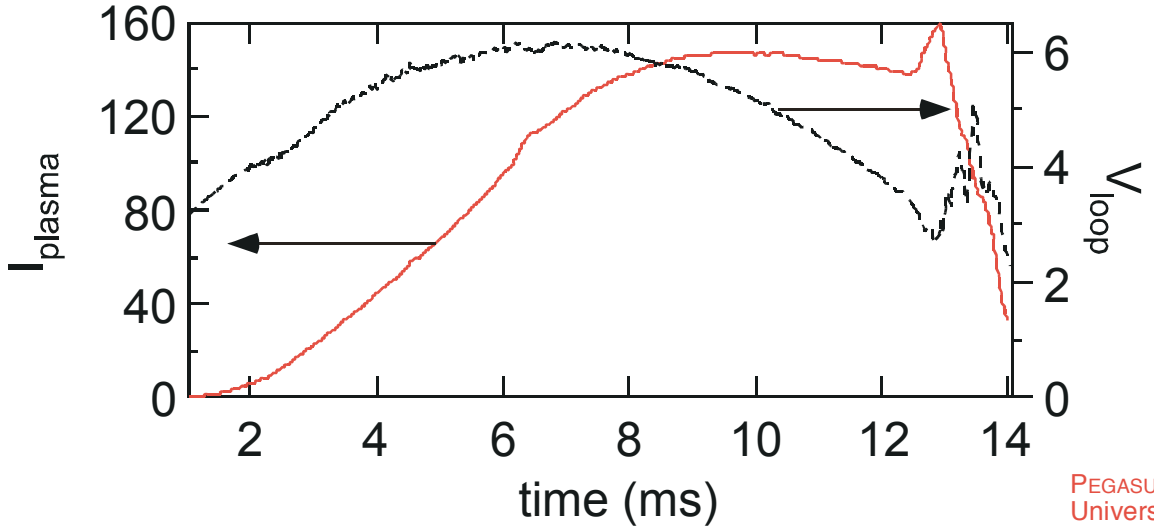
$\Rightarrow$ $I_p/I_{TF} \sim 1$ reflects limit due to $q_0 \approx 2$

Abrupt Discharge Termination Due to Apparent Edge Kink Mode

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

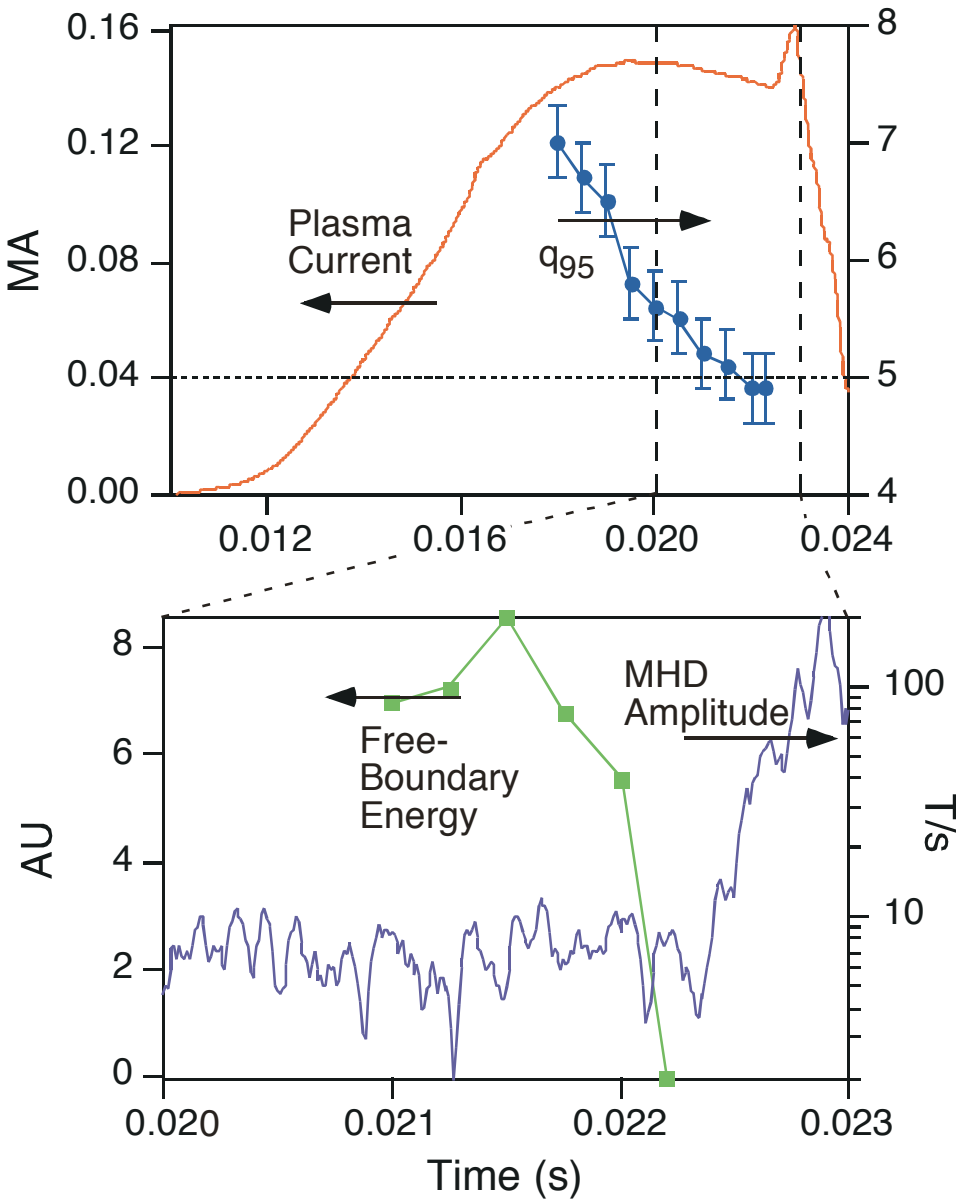


- Shot 13257 is typical of these discharges



External kink modes observed in highest-current shots

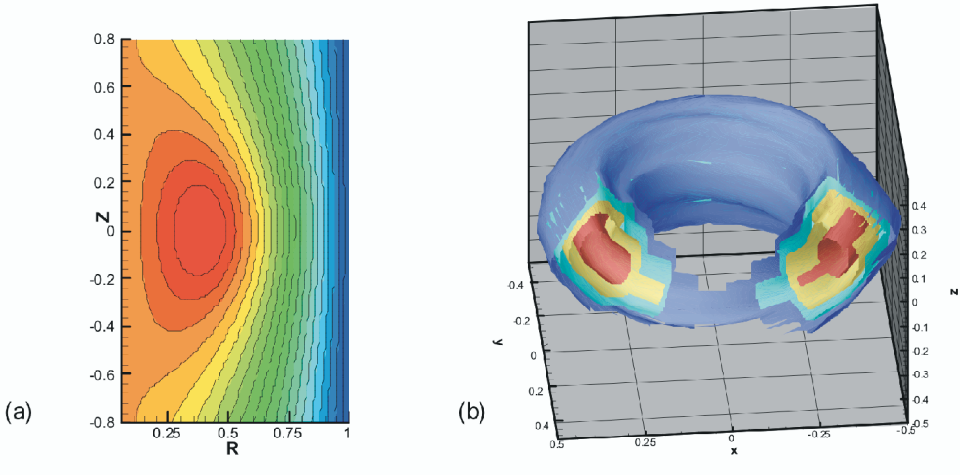
- Higher-current discharges (150 kA class) often terminate in abrupt disruptions
  - Lower-current shots have IREs followed by gradual plasma termination
- n=1 fluctuations are observed on Mirnov coils immediately prior to disruption
  - Dominant frequency is roughly 10 kHz
  - Mode observed a few 100 μs before IRE
- Observed disruptions are associated with edge kink limits
  - Oscillations not observed until $q_{95} \approx 5$
- Calculated free-boundary energy (DCON) approaches zero as oscillations begin
  - Negative value indicates instability to external kink
- Consistent with theoretical understanding of ideal kink stability at near-unity A
  - As A → 1, unstable q_a increases
  - Roles of finite β, low ℓ_i under study



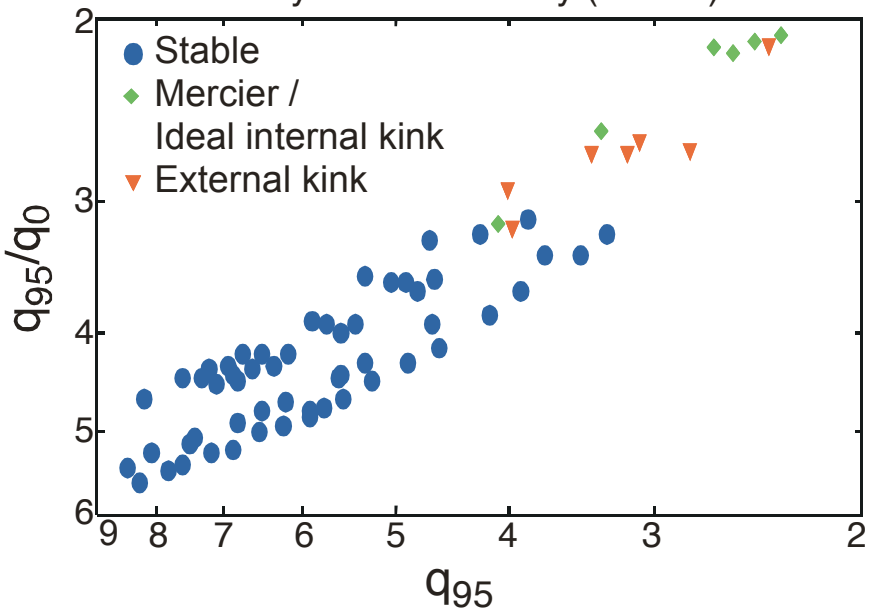
A variety of computational tools are being implemented

- Equilibrium code
- Wall currents code
- Energy confinement code
- DCON: ideal stability analysis
- TSC: predictive discharge modelling
- GATO: instability growth rates
- NIMROD: resistive MHD analysis

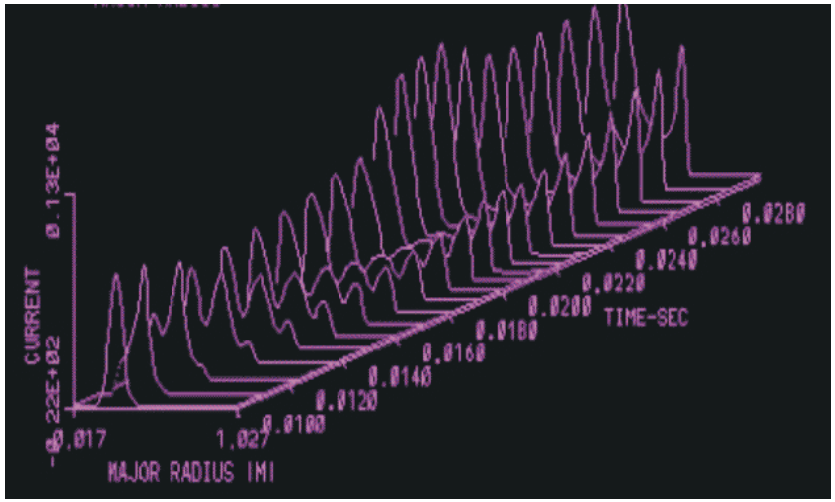
Preliminary Model of Resistive Stability (NIMROD)



Study of Kink Stability (DCON)



Evolution of J(r) during TF rampdown (TSC)



Planned upgrades will allow further study of low-q high-□ plasmas

- **Goals require increased control of plasma conditions**
  - *Density control and shot reproducibility = between-shot gettering*
  - *Improved equilibrium field control*

- **Suppression of large internal MHD modes**
  - *Increasing I_p ramp time = increased programmable V-sec from ohmic solenoid*
  - *Attain higher $T_e(0)$ during formation = increased B_T, improved position control*
  - *HHFW heating = increased RF power operation, improved position control*
  - *Maintain $q(0) > 2$ during plasma formation = increased B_T*

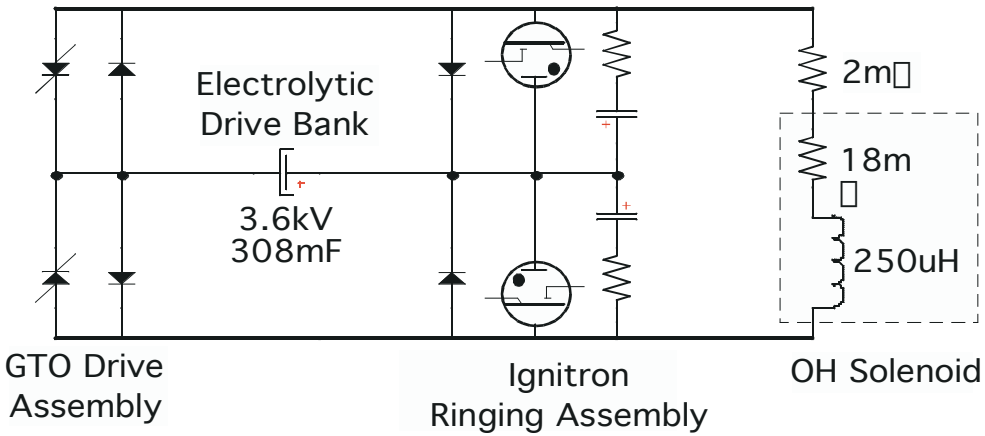
- **Control onset of suspected external kink modes**
  - *Maintain I_p ramp time = increased programmable V-sec from ohmic solenoid*
  - *Maintain high q_{95} during formation = increased B_T w/rampdown*
  - *Controlled gas puff for edge cooling = continuous gettering*
  - *Separatrix operation = energize divertor coils*

- **Access to very high □T regime**
  - *Increase $T_e(0)$ during formation = increased B_T w/fast-rampdown*
  - *Increase I_p and N_e = increased V-sec*
  - *High-power HHFW heating = increased RF power operation*

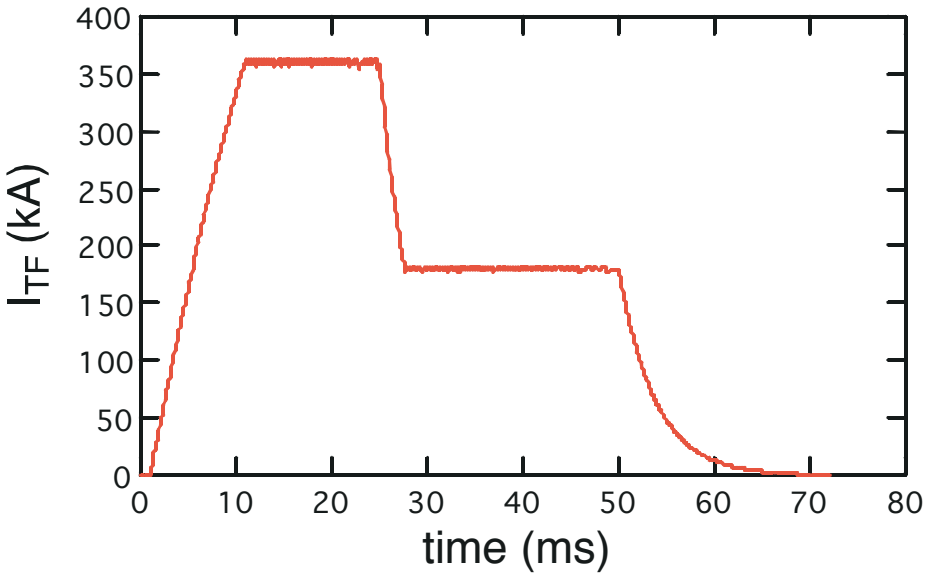
New power supplies will provide dramatically improved waveform control

- Supplies will use electrolytic capacitors switched by GTOs or IGBTs
  - Switches modulate power to coil
  - Provide very flexible waveform control
- Represents a major improvement over resonantly-driven coil sets
  - TF: much higher I_{rod} and fast rampdown capability
  - OH: enables near full use of magnet flux and real V_{loop} control
  - EF: active position control

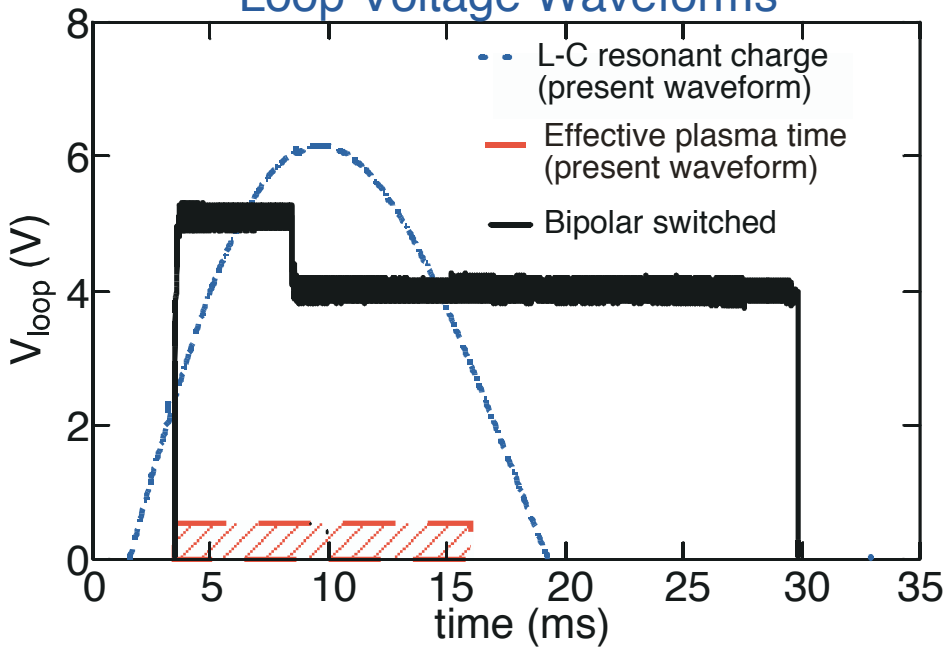
Four Quadrant Ohmic Switch



TF Waveform with Fast Rampdown



Present and New Loop Voltage Waveforms



Summary

- PEGASUS is a university-scale spherical torus plasma experiment designed to explore the limits of plasma behavior as aspect ratio is reduced to near unity
- Results from ohmic operation at very low field include values of $\square_t$ of ~20% and toroidal field utilization factors up to and slightly above 1
- Large-scale low m/n MHD activity is observed in all high-power plasmas; this activity is believed to be resistive in nature and is a limiting mechanism in the current Pegasus configuration
- Experiments have begun to find evidence of external kink limits at very-low-A, with q_{95}=5 found to be unstable for low l_i plasmas
- Upgrades will provide improved plasma performance to higher I_p/I_{TF} by increasing control over toroidal field, loop voltage, and radial position