Abstract

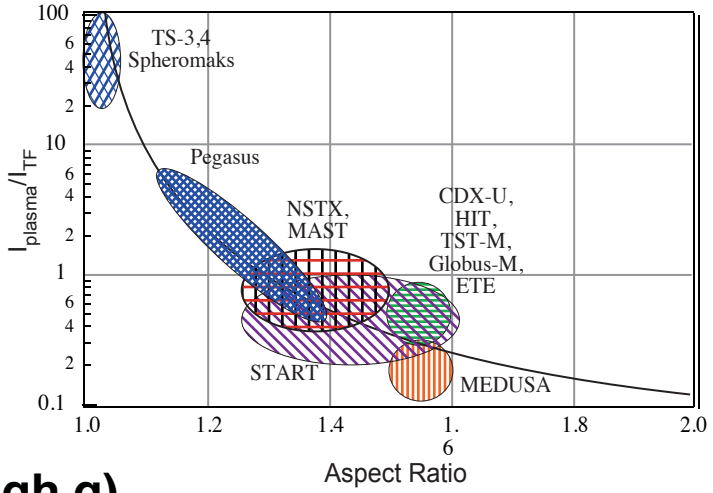
The Pegasus Toroidal Experiment is a mid-sized, extremely low aspect ratio (A) spherical torus. Major parameters are R=0.25-0.45 m, A=1.1-1.4, Ip≤0.15 MA, and BT≤0.07 T. It has the dual roles of exploring the limits of spherical torus plasma behavior as the A approaches 1 and examining alternate confinement concepts in the tokamak-spheromak overlap regime. High beta plasmas are produced with ohmic induction at low toroidal fields, and occupy a region of toroidal beta vs normalized current ($I_N=I_p/aB$) space similar to neutral-beam heated START discharges. Values of toroidal beta up to 25% and normalized beta ($\beta_N=\beta_T/I_N$) up to 5 have been obtained with no evidence of a beta limit. Densities range up to the Greenwald limit. The toroidal field utilization factor, I_p/I_{TF}, reaches values as high as 1, but appears to encounter a "soft" limit at that level. Access to higher beta and increased plasma current appears to be limited by the presence of large amplitude MHD activity. This activity appears to be tearing modes with low order mode numbers (m/n=2/1, 3/2, 4/1, etc.) which rotate in the electron diamagnetic direction at 2-10 kHz. The onset of a mode appears to coincide with the appearance of a flux surface with the corresponding helicity at the low-shear plasma center. This activity is deleterious to plasma performance--discharges with large amplitude MHD have lower values of stored energy and larger Ejima coefficients than more quiescent plasmas. Pegasus experiments are beginning to explore the edge kink stability boundary at low A. High I_p discharges have been observed to terminate in disruptions, with a fast-growing precursor visible on the Mirnov coils. Equilibrium reconstructions indicate q_{95} approaches 5 within 0.5 ms of the growth of the mode, and the DCON code predicts instability to the external kink at this time.

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

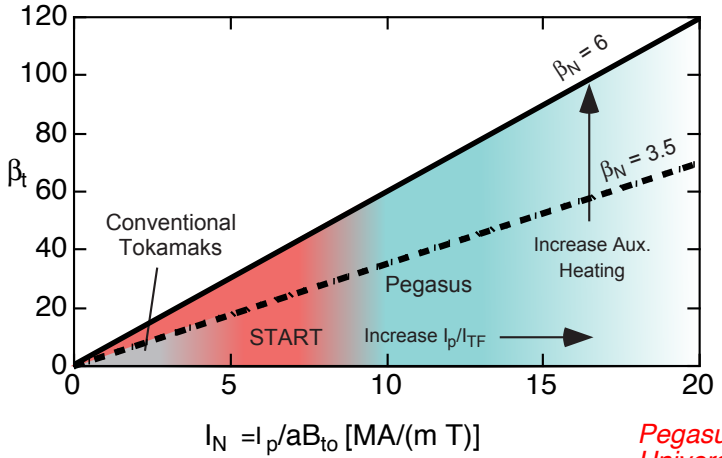
Role of Pegasus in the Fusion Community

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.

- **Physics of A ≈ 1 plasmas as an <u>Alternate Concept</u> (low q)**
  - Extreme toroidicity ($A \rightarrow 1$)
  - 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 $A \rightarrow 1$ (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)

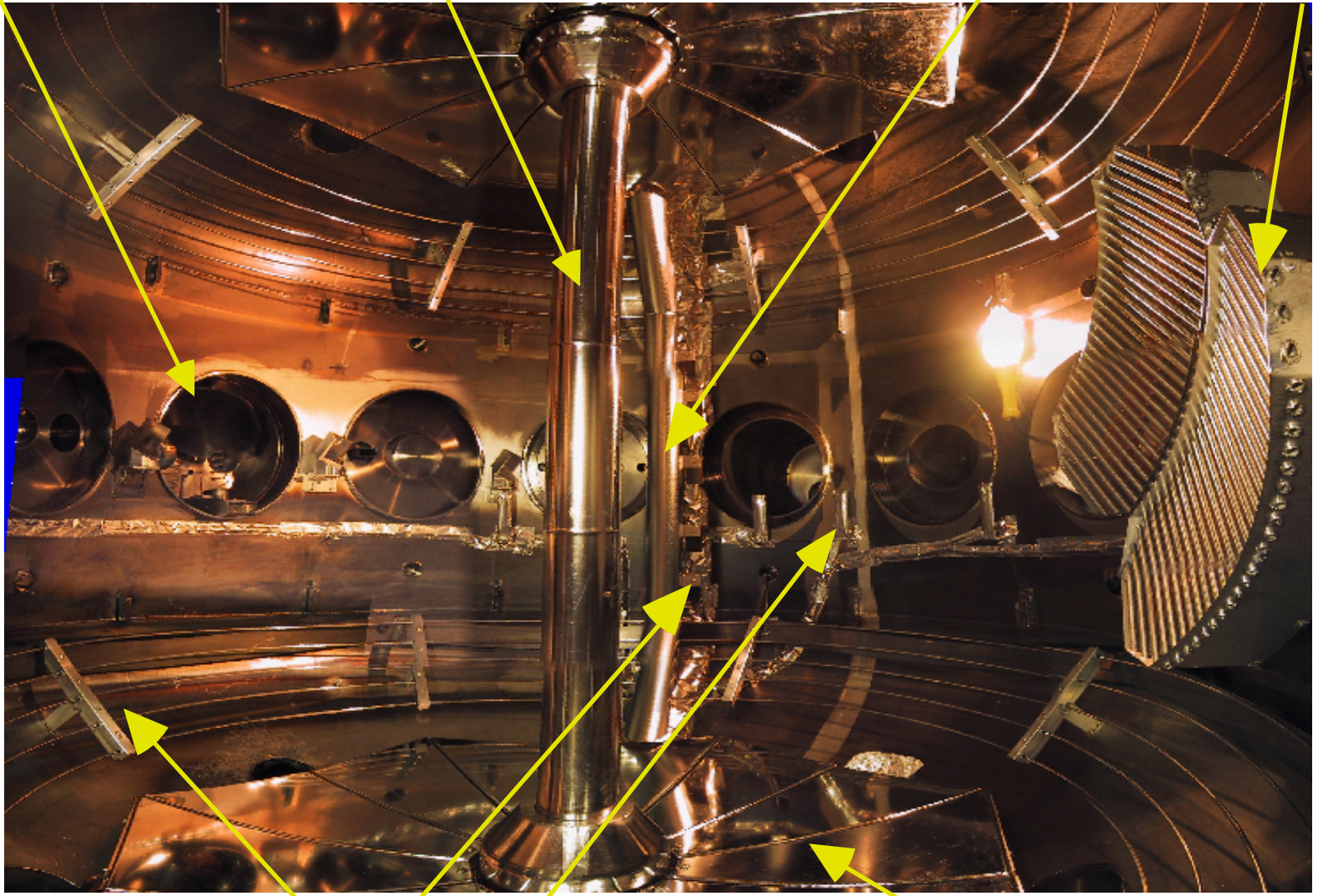


Pegasus is a mid-sized spherical torus

- 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
  - $\langle n_e \rangle = 1 - 5 \times 10^{19} m^{-3}$
  - $\beta_t \leq 25\%$
- High strength solenoid magnet is enabling technology



Vacuum vessel interior hardware



Pegasus diagnostic set

• Presently Operating Diagnostics

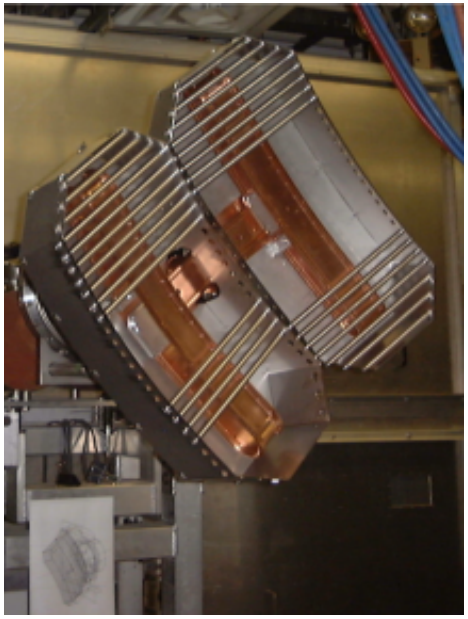
Diagnostic	Capability	Measures
Core Flux Loops	(6)	V_L , Ψ_{pol}
Wall Flux loops	(6)	Vessel currents
Int. Flux loops	(20)	Ψ_{pol}
Rogowski Coils	(2)	I_p
Diamagnetic Loop	(2)	Φ_{tor} / β_p
B_p, Mirnov Coils	(56)	B_r , B_z / MHD activity
VUV (SPRED)	central chord	Impurity monitor
Filterscopes	central chord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

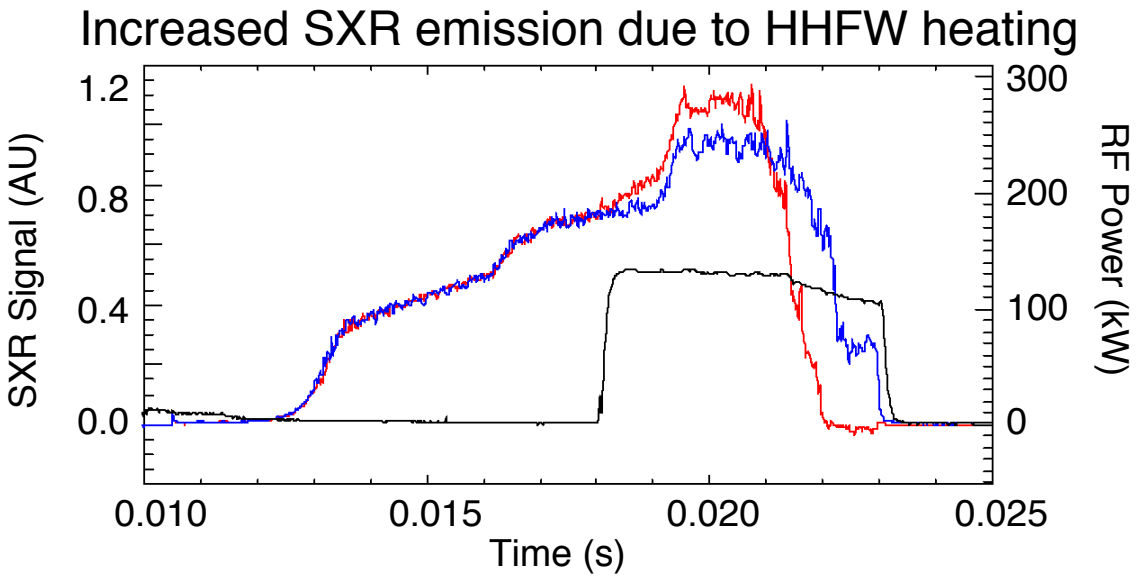
• Near-Future Diagnostics

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

High harmonic fast wave system coming into operation

- Two-strap HHFW system installed and heating tests havebegn
  - P_{RF} = 1-2 MW available; sufficient to access high β_t regime
    - *Up to 200 kW injected into plasmas - some evidence of heating observed*
    - *Forward power limited by coupling to edge*

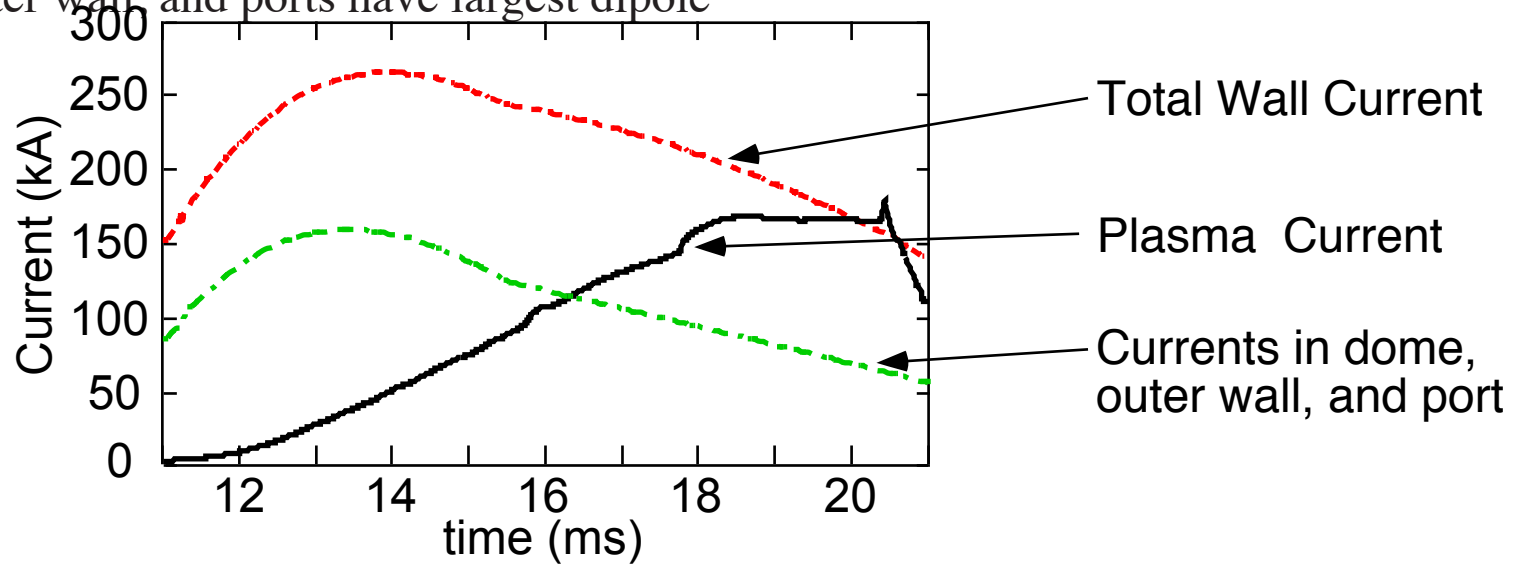




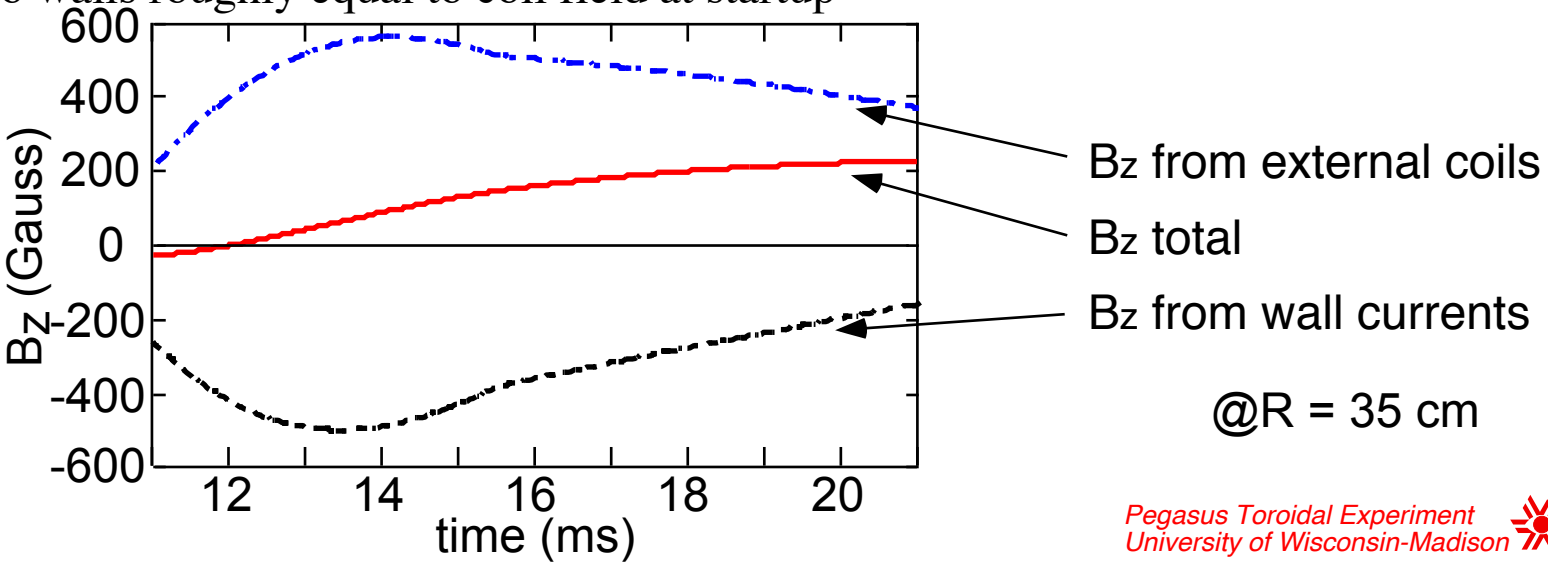
- HHFW Startup and CD applications:
  - Startup assist via preheating and/or current profile "freezing"
    - *Startup plasma phase: 40% single pass absorption*
    - *High β plasma phase: 100% single pass absorption*
  - Current Drive possible with present power supply and new antenna

Wall currents are dominant 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 vertical field at early times
  - Field due to walls roughly equal to coil field at startup



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

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

  - inductance matrix (M) determined by coil inductances:

inductance of individual filament (wall)

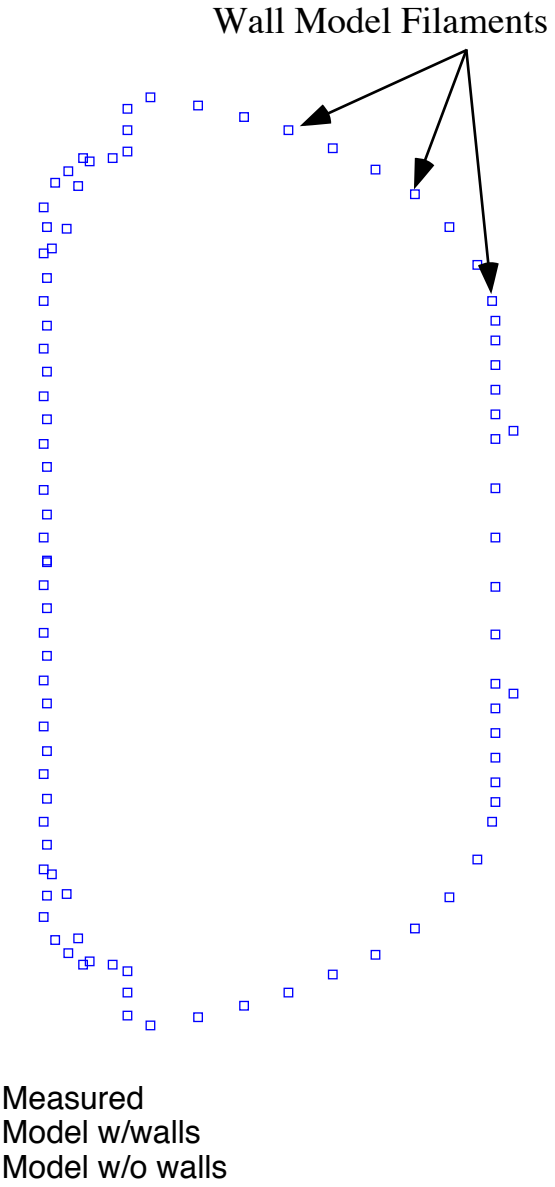
$$L_i = \mu_0 R \left[\ln\left(\frac{8\sqrt{\pi} R}{\sqrt{A}} \right) - \frac{7}{4} \right]$$

self-inductance of coil set i

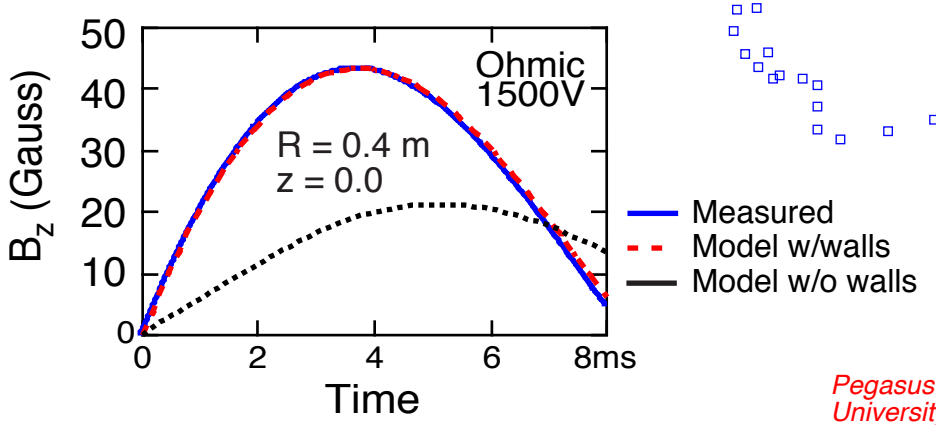
$$L_i I_i = \sum_{k=1}^{N_i} \sum_{l=1}^{N_i} \Phi_i^{k,l}$$

mutual inductance of coil set i with coil set j

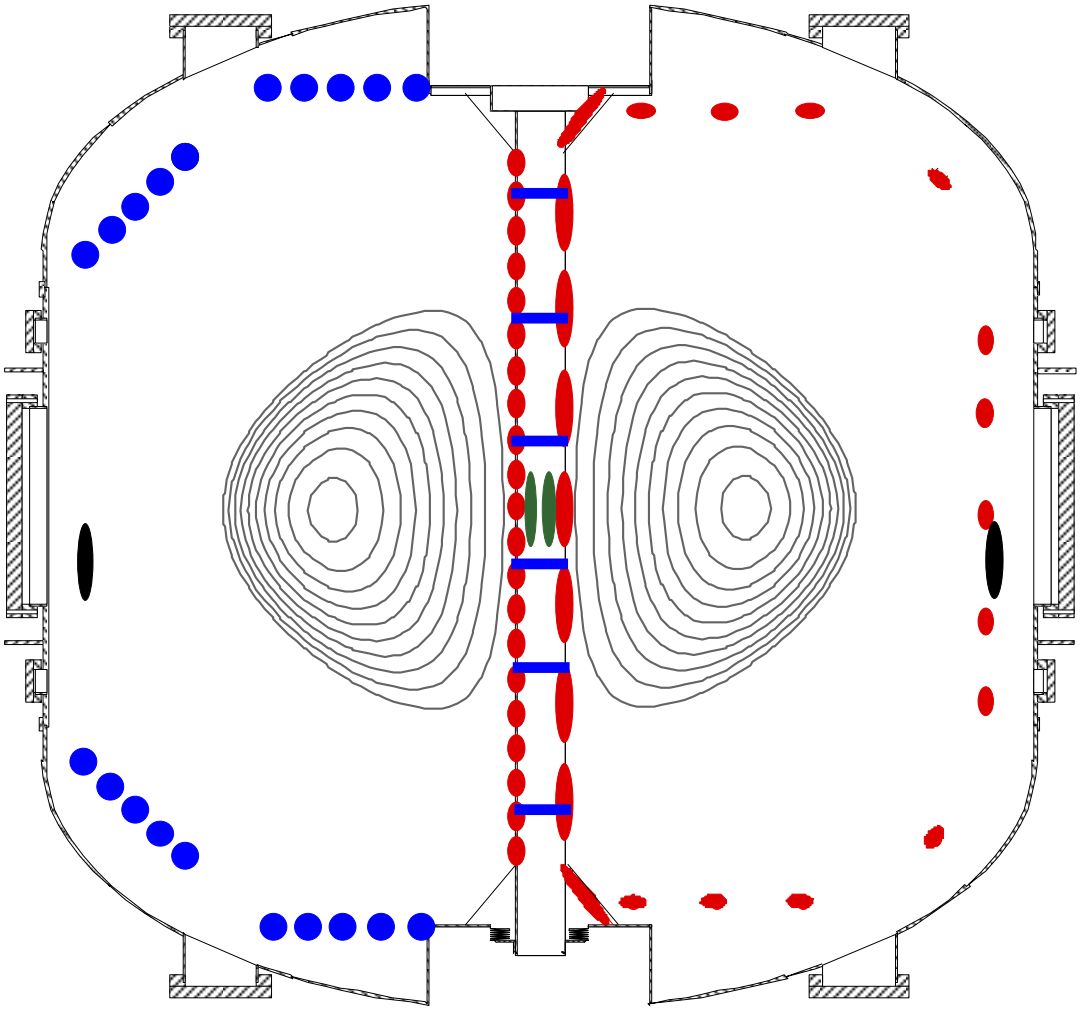
$$M_{ij} I_j = \sum_{k=1}^{N_i} \sum_{l=1}^{N_j} \Phi_{ij}^{k,l}$$



- Measurements agree well with wall model:



Magnetics diagnostics installed in 2001



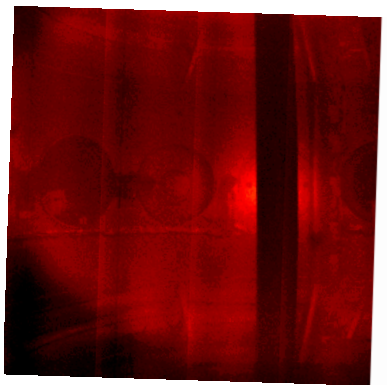
- Flux Loops (26)
- Poloidal Mirnov Coils (22 + 21)
- LFS Toroidal Mirnov Coils (6)
- HFS Toroidal Mirnov Coils (7)

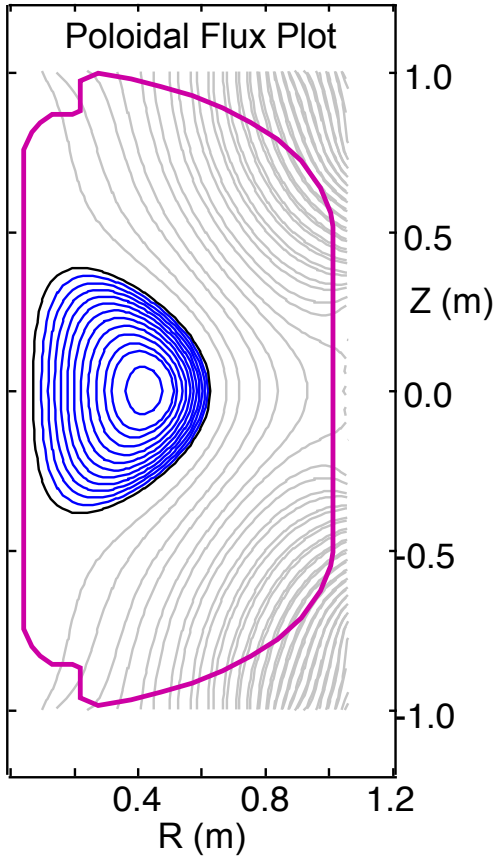
Not shown:
Plasma Rogowski Coils (2)
Diamagnetic Loops (2)
Diamagnetic Compensation Loop
External Flux Loops (6)
Internal B_{tan} Coils (15)

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:

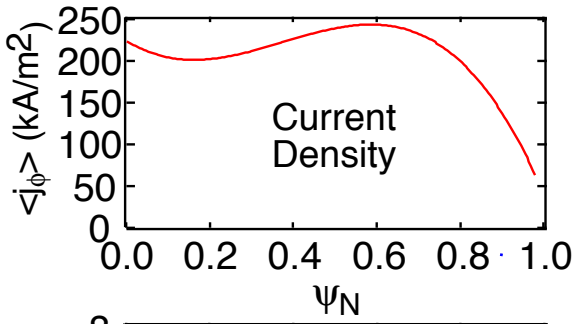
False-Color CCD Image

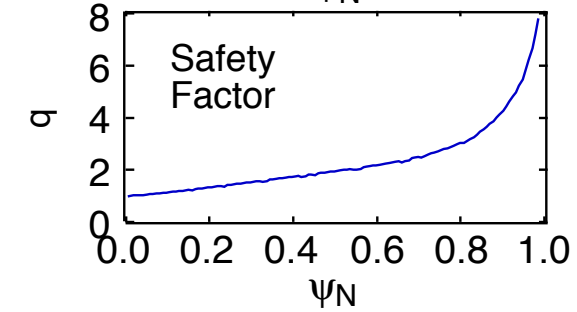


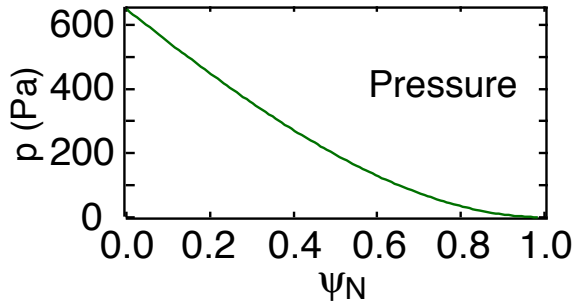


Fit Results

I_p	78.3 kA
R_0	0.34 m
a	0.27 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_{95}	7.8

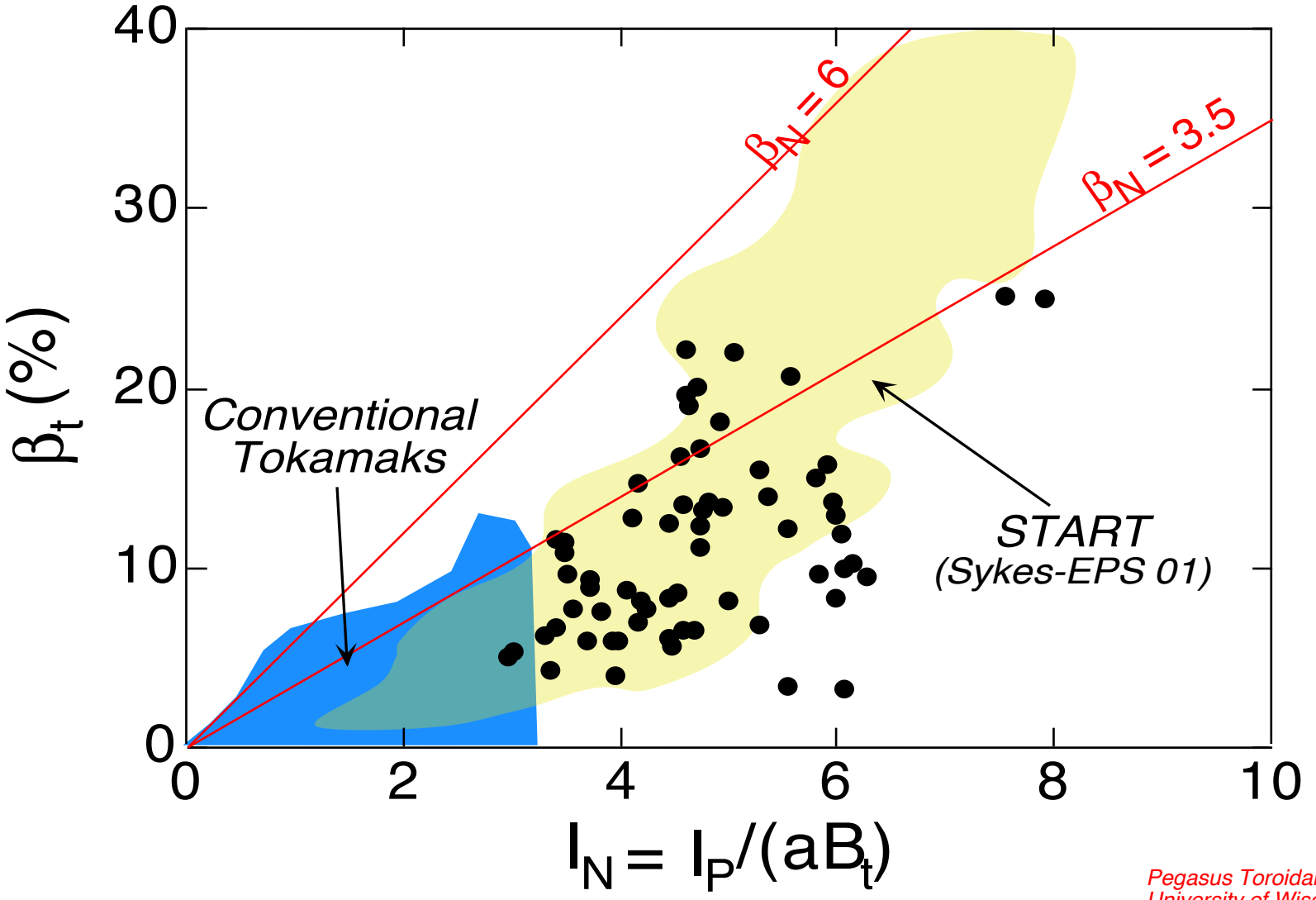






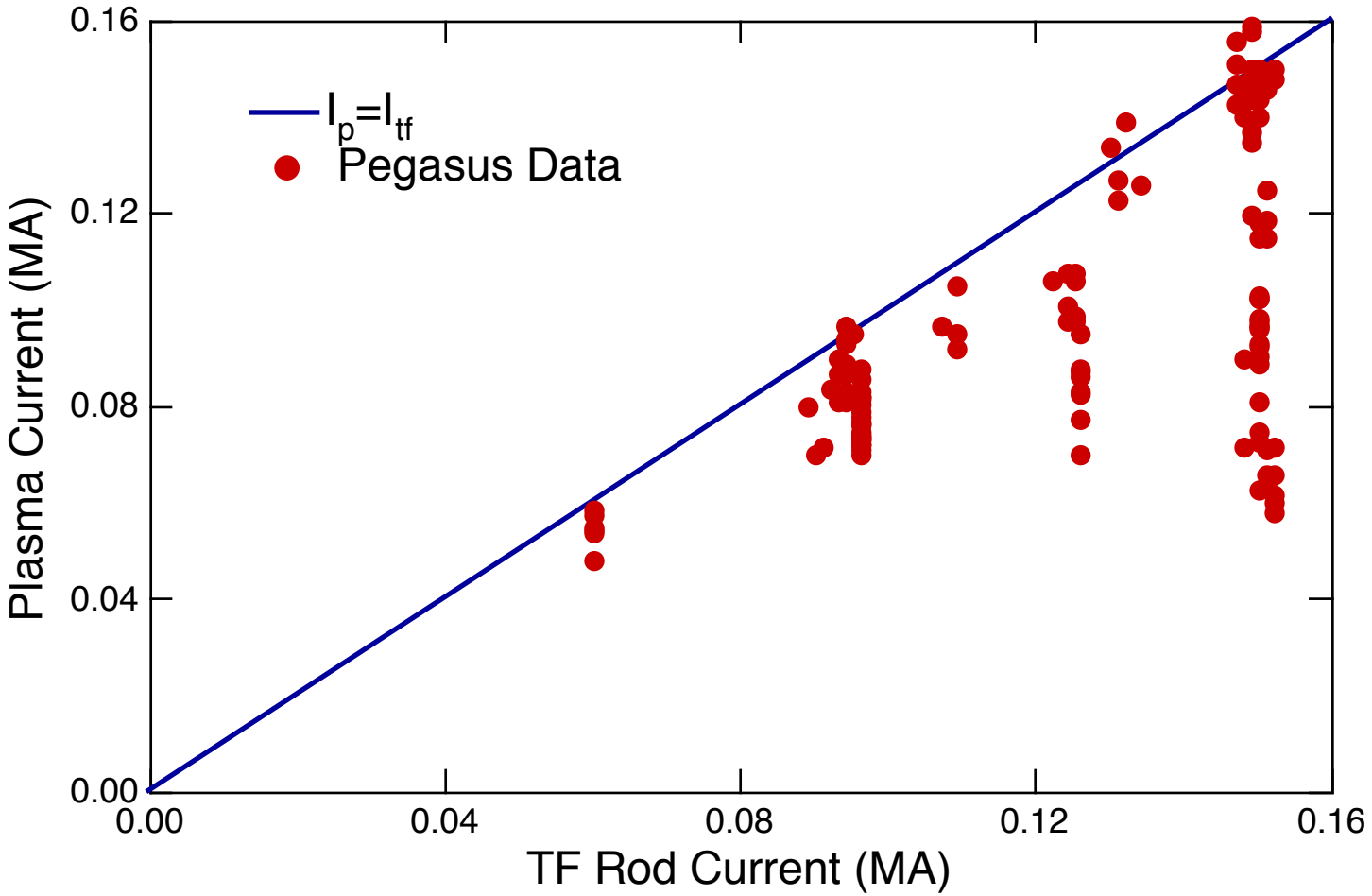
PEGASUS is Accessing High-β_t ST Regime

- 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



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?)

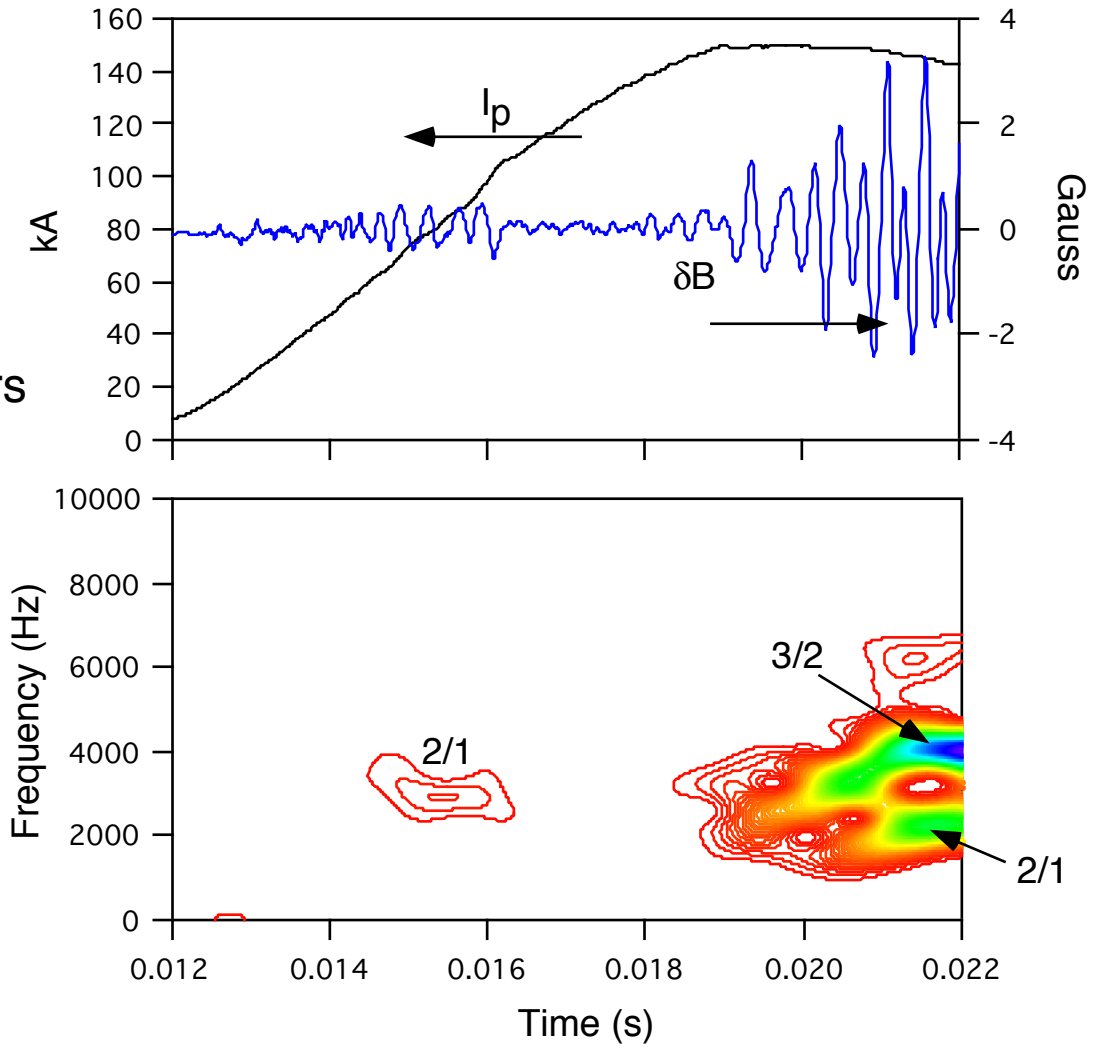


A dominant feature has been a rotating m/n=2/1 mode

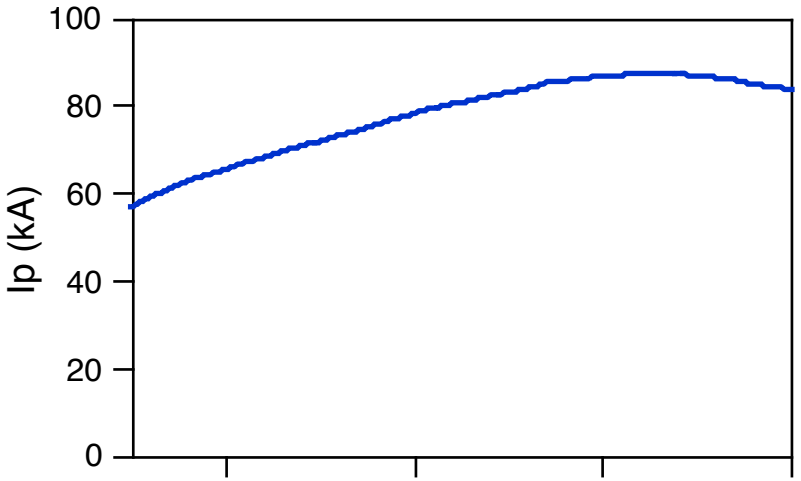
- Mode present in all significant discharges
- Rotates in electron diamagnetic direction
  - Mode is likely magnetic island
- Frequency is typically 2-10 kHz
  - No evidence of mode locking
- Little shear stabilization of island growth
  - Central shear is nearly zero

Higher-current discharges exhibit a variety of MHD activity

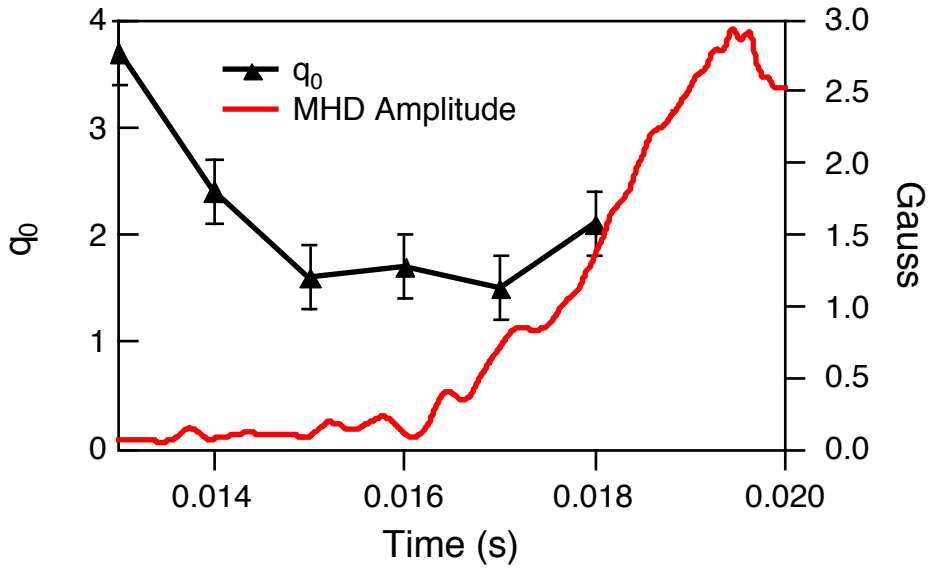
- Recent operations scenarios produce plasmas with I_p ~ 150 kA
  - Improved plasma control
  - Improved conditioning
- 2/1 mode is observed but disappears
  - Is this the reason for improved performance?
- A 3/2 mode appears after a quiescent period
  - 2/1 mode reappears after 3/2 starts; destabilization?
- Appearance of 3/2 mode is correlated with q_{min} dropping below 1.5

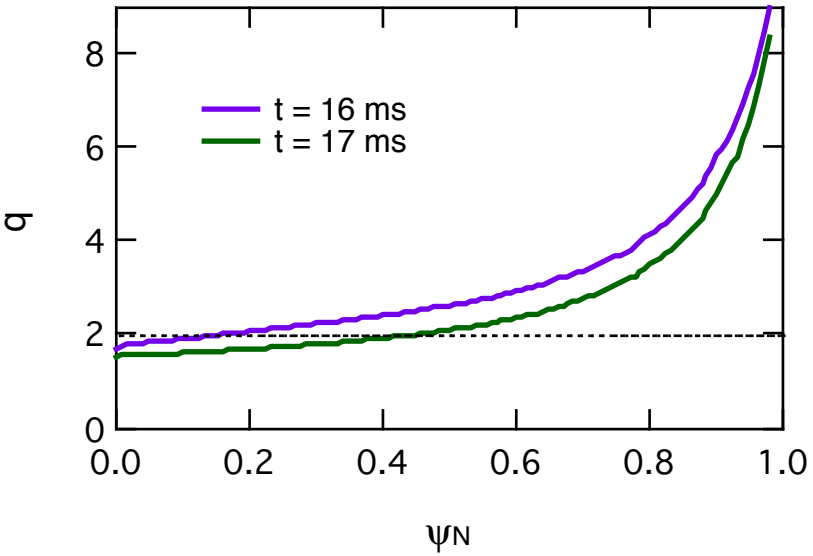


2/1 mode not observed until $q_{min} < 2$



- Consistent with observed helicity of the mode
- A large region of low shear exists about the q=2 surface
- Central q inferred from Equilibrium fit
- In general, strong MHD activity appears to relate to I_p limits

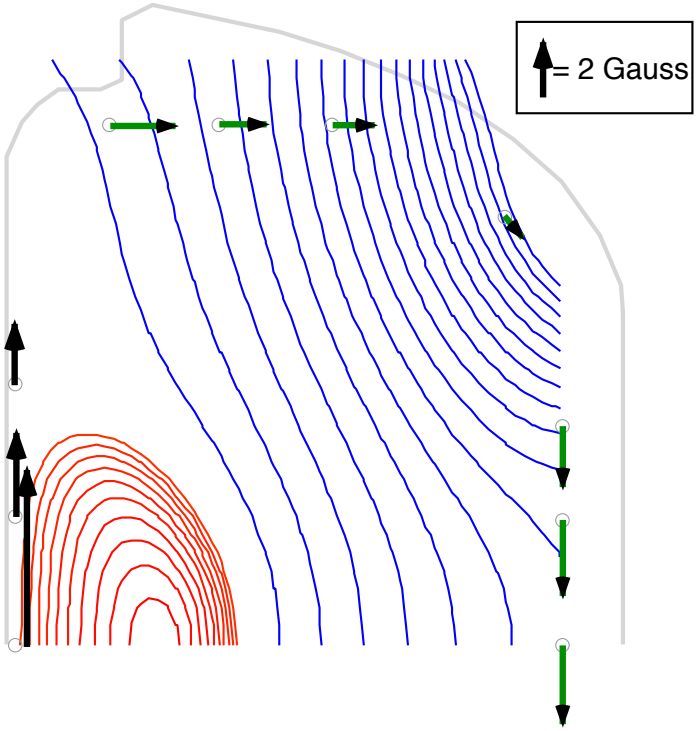


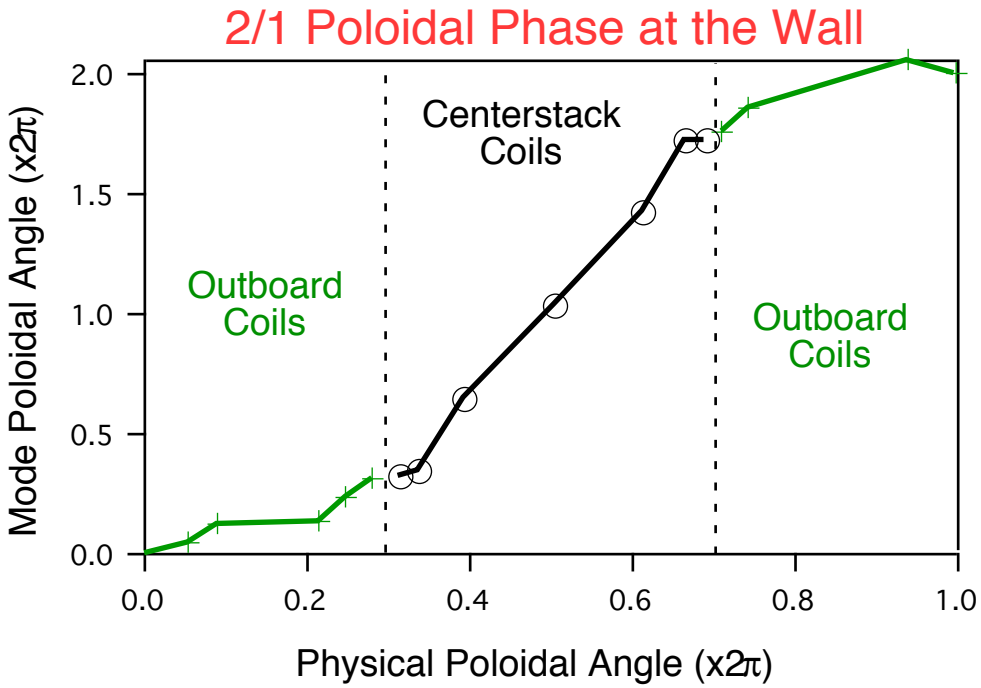


2/1 mode is poloidally asymmetric

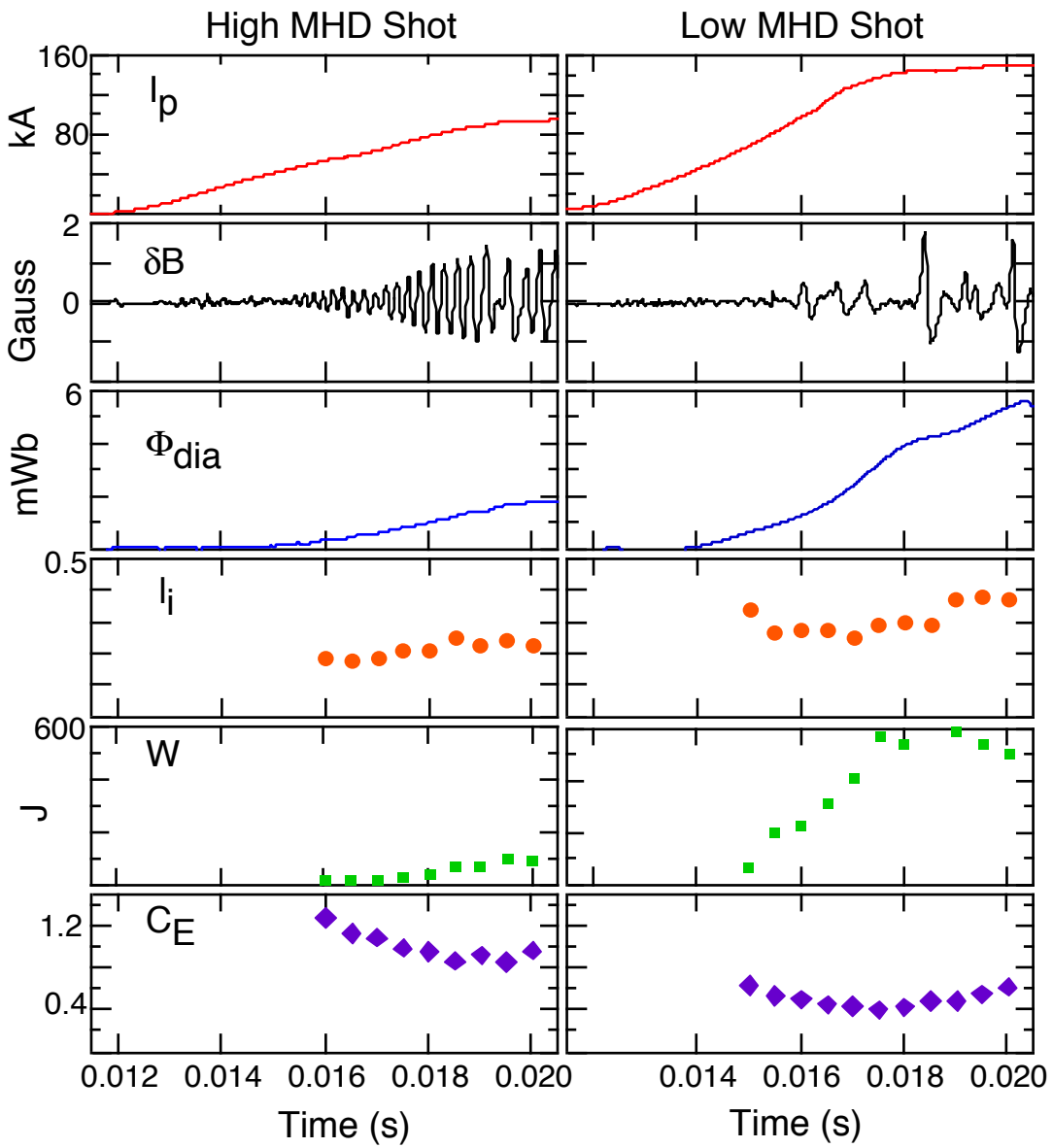
- Poloidal and toroidal phase analyses clearly indicate mode is m=2/n=1
- Toroidicity of mode is seen in large phase shifts along centerstack
  - Roughly 1.5 wavelengths observed across 120° poloidally
- Mode is typically strongest on the plasma outboard
  - As plasma grows, LFS signal increases and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

Perturbed Field Magnitude
at the Wall





MHD activity appears to limit plasma performance

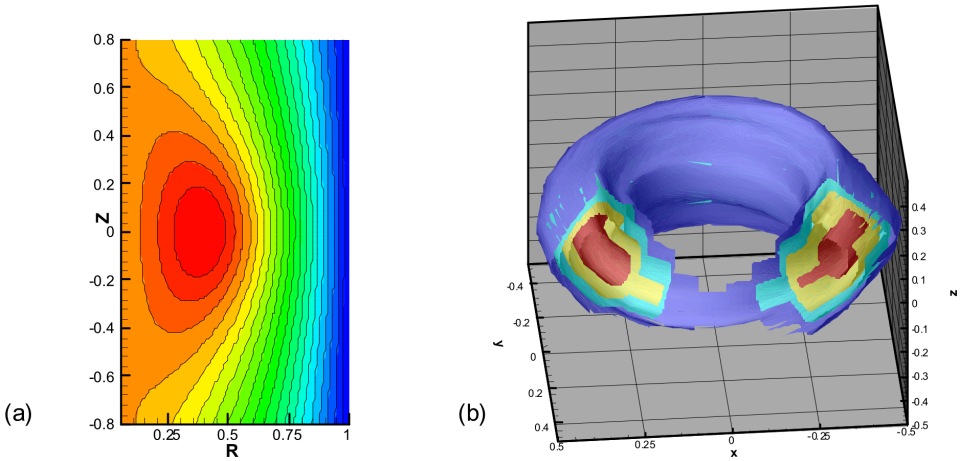


- Reduction in MHD typically results in improved plasma performance
- In "High MHD" Case:
  - l_i stays low (0.3)
  - Stored energy stays < 100 J
  - Ejima coefficient > 0.8
- In "Low MHD" Case:
  - l_i climbs higher (despite higher V_{loop})
  - Stored energy climbs to 600 J
  - Ejima coefficient ~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

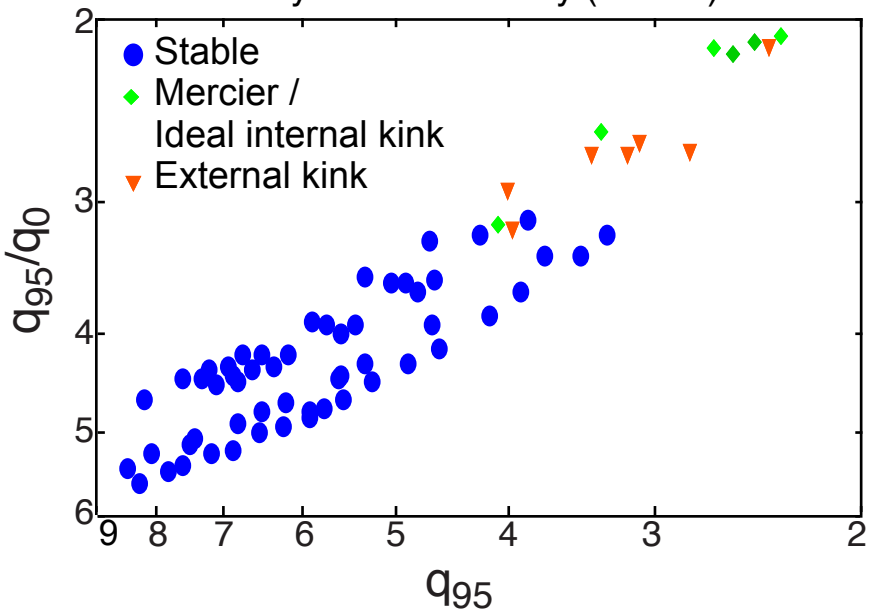
A variety of computational tools are being implemented

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

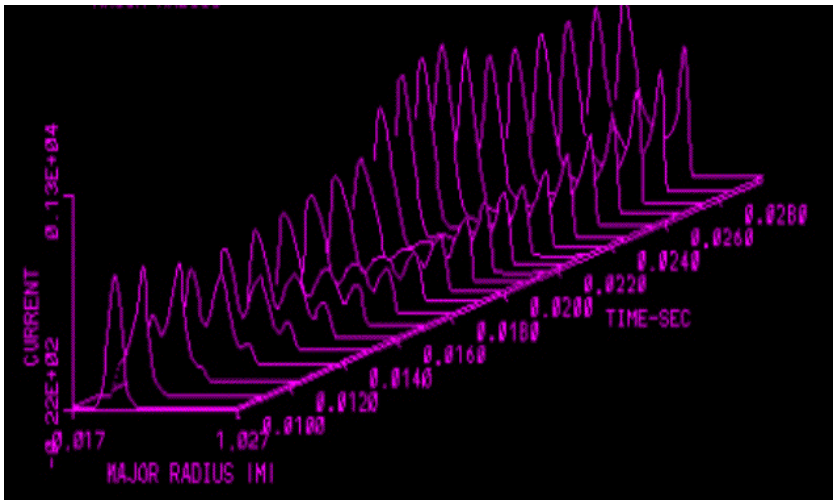
Preliminary Model of Resistive Stability (NIMROD)



Study of Kink Stability (DCON)

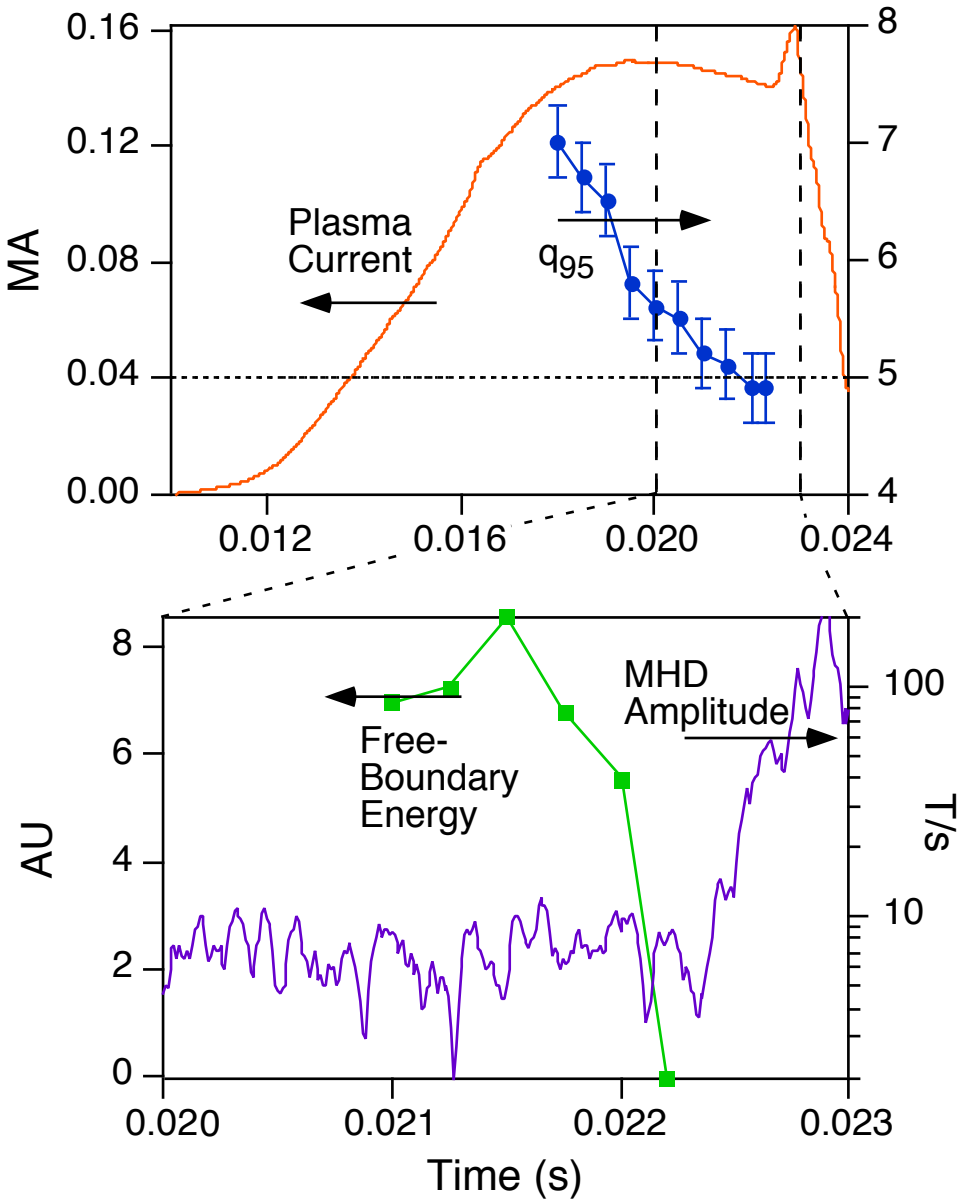


Evolution of J(r) during TF rampdown (TSC)



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 $A \rightarrow 1$, unstable q_a increases
  - Roles of finite β, low l_i under study



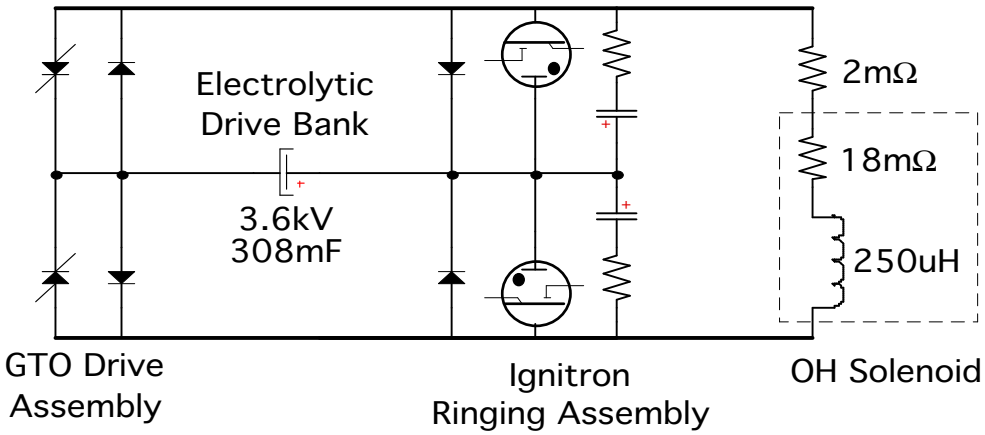
Planned upgrades will allow further study of low-q high-β plasmas

- **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 β_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*

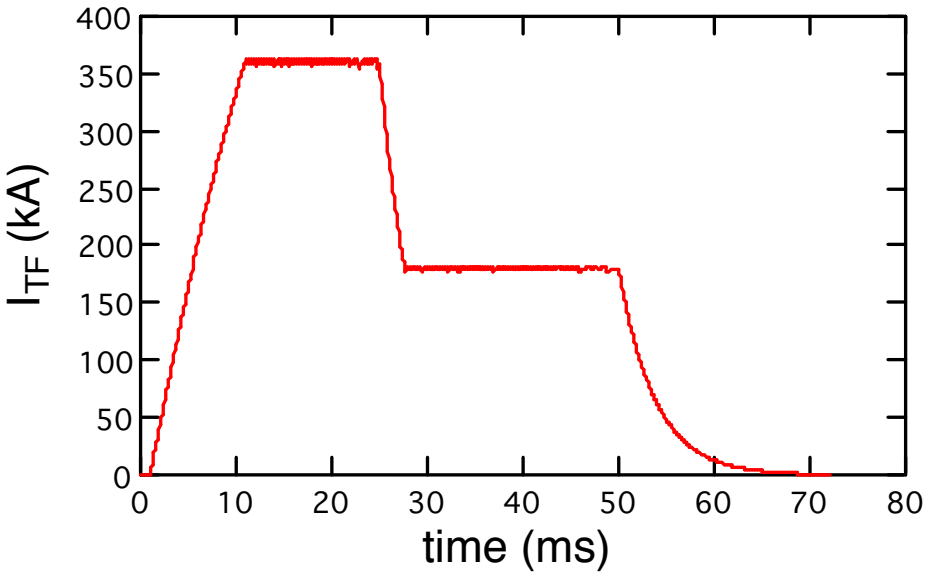
New power supplies will provide dramatically improved waveform control

- 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

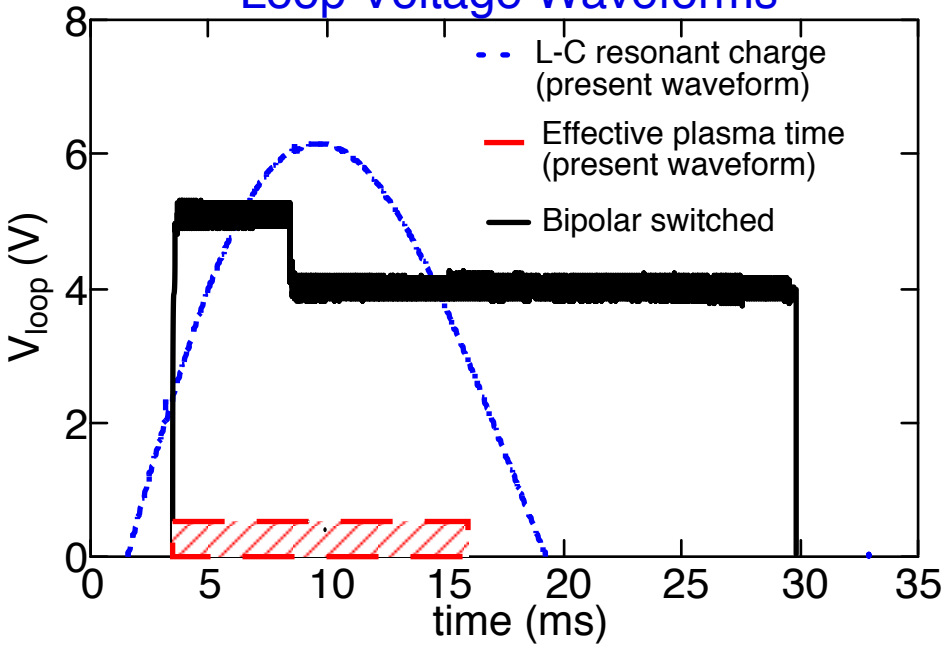
Four Quadrant Ohmic Switch



TF Waveform with Fast Rampdown



Present and New Loop Voltage Waveforms



Summary

- Pegasus is a university-scale spherical torus plasma facility 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 toroidal beta up to 25% 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
- Extensive upgrades will provide significantly improved plasma performance by increasing control over toroidal field, loop voltage, radial position, and the scrape-off