Abstract

The Pegasus Toroidal Experiment is an ultralow aspect ratio ST with a mission to study the limits of magnetohydrodynamic stability at extremely low aspect ratio and high toroidal beta and to explore the transition region between the tokamak and spheromak configurations. The program is now completing a complete redesign of all the coil power systems and supporting infrastructure, and is entering a new operation phase. These upgrades include arbitrary, programmable waveform control for 8 independent coil currents, a factor of 3 increase in toroidal field, a factor of 2 increase in available ohmic flux, divertor coils,and improved pumping and conditioning. Results from earlier campaigns with the original facility showed that persistent low m/n tearing modes were responsible for limiting toroidal field utilization (I_p/I_tf) and toroidal beta. The first phase of operations of the next campaign will involve the development of startup scenarios that suppress the tearing modes. This will be accomplished by lowering the plasma current ramp rate and controlling the growth of the plasma size in order to decrease resistivity, and if necessary startup at transiently high toroidal field. The next phase of experiments will focus on establishing operating points at high toroidal field utilization and high toroidal beta, including limited and diverted configurations. With these operating points established, experiments will be conducted to determine the boundaries of the external kink mode at very low A. Earlier results from Pegasus showed an unstable point at q_95=5, albeit with significant edge currents. Studies will focus on the effects of aspect ratio, elongation, and l_i on the kink stability boundary.

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Outline

- **Pegasus is a mid-size ST built to explore A $\rightarrow$ 1**

- **Experimental results from phase I operations**
  - Plasmas exhibit low-A characteristics
    - *High β_t, I_N, β_N via OH heating*
    - *High I_p/I_{tf}*
    - *low ℓ_i*
  - Characteristics of High Ip/Itf Operation
    - *Large scale internal MHD limit on I_p/I_{tf}*
    - *External Kink at q_{95}=5*

- **Present phase of operations focusing on accessing high I_p/I_{tf}, β_t regimes**
  - Recent modeling has demonstrated existence and accessibility to this regime
    - *DCON and local G-S solver for stability and equilibrium*
    - *TSC for shot simulations*
  - Upgrades complete to increase access to this regime
    - *Increased V-sec.; position and shape control; B_{TF} versus time*
    - *Limited Operations have begun*

PEGASUS Facility

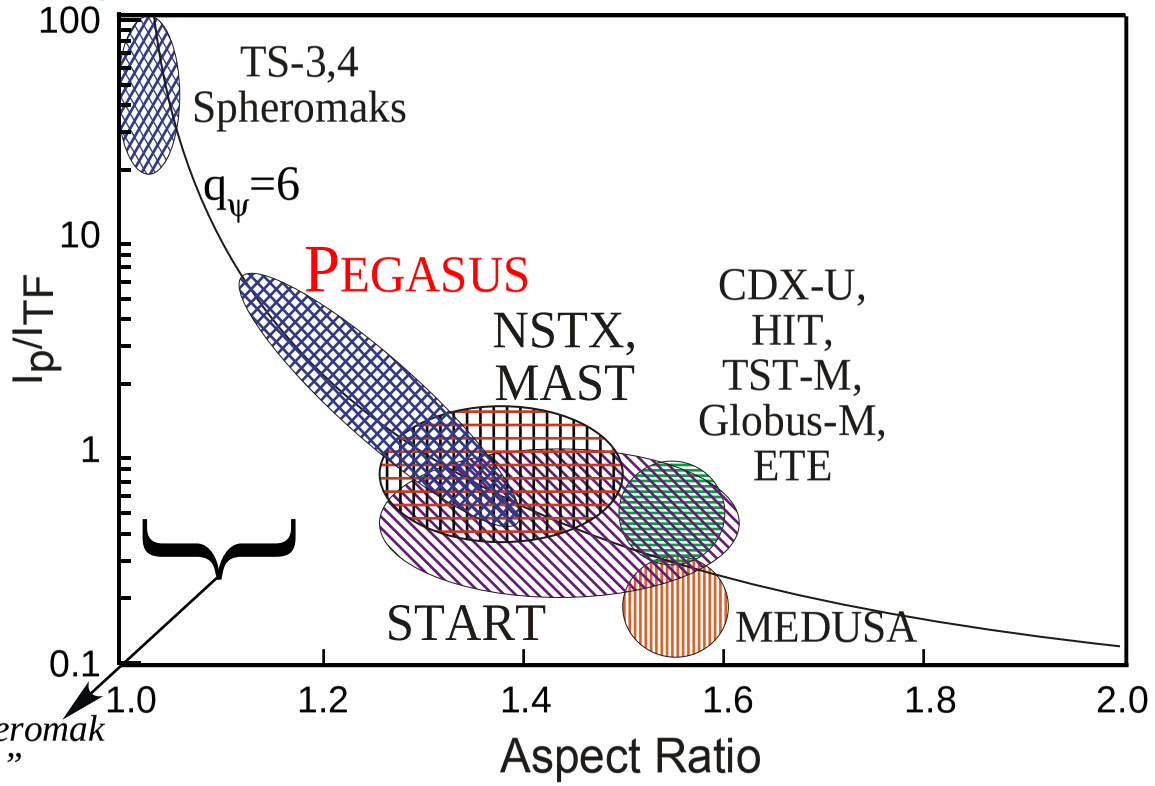


Mission: Explore plasma limits as A→1

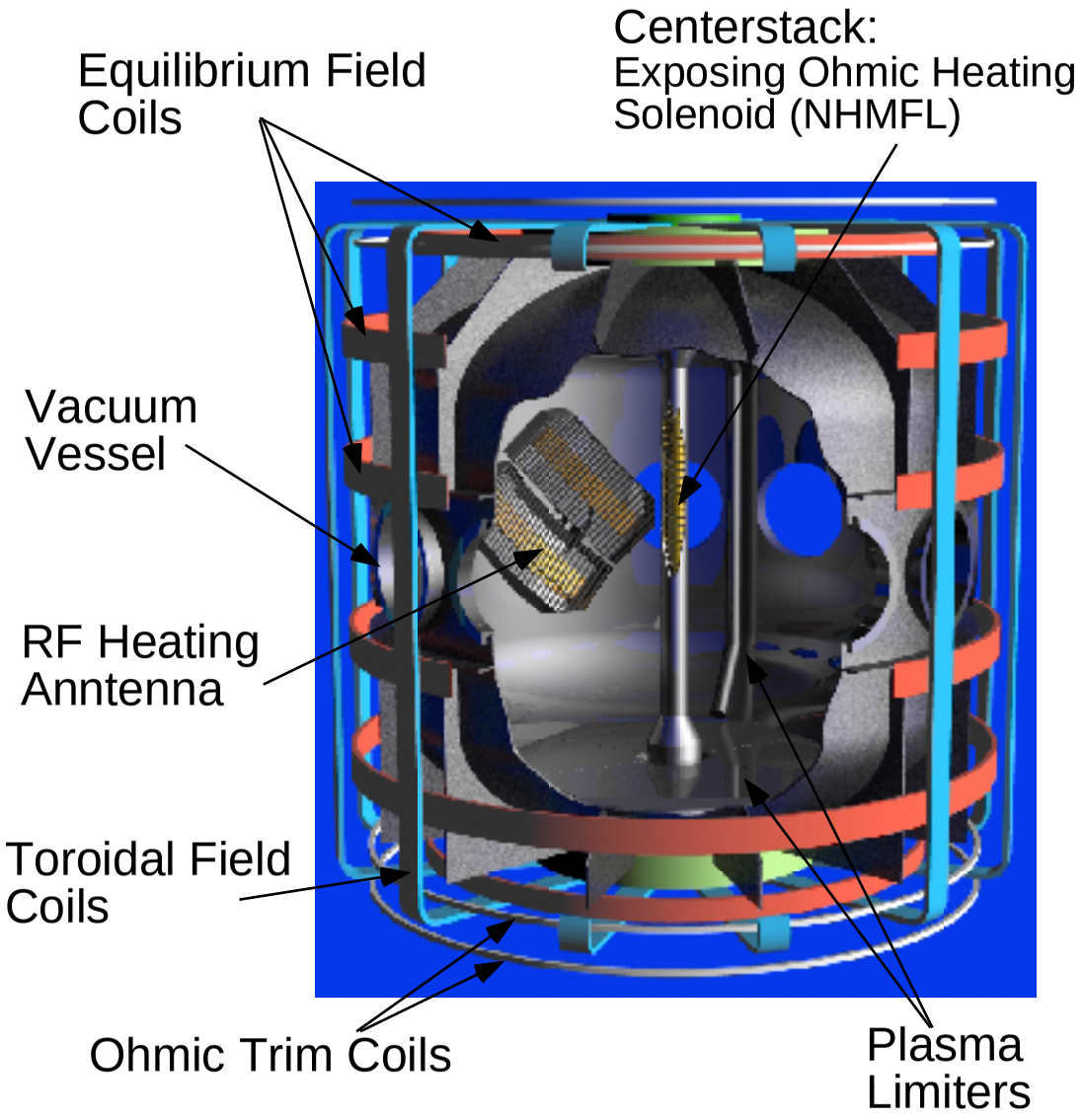
Pegasus is an extremely low-aspect ratio facility exploring quasi-spherical high-pressure plasmas with the goal of minimizing the central column while maintaining good confinement and stability

- Stability and confinement at high I_p/I_{TF}
  - *Extension of tokamak studies*
- Limits on β_t and I_p/I_{TF} (kink) as A→1
  - *Overlap between the tokamak and the spheromak*

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



PEGASUS is University-Scale, Mid-Sized ST

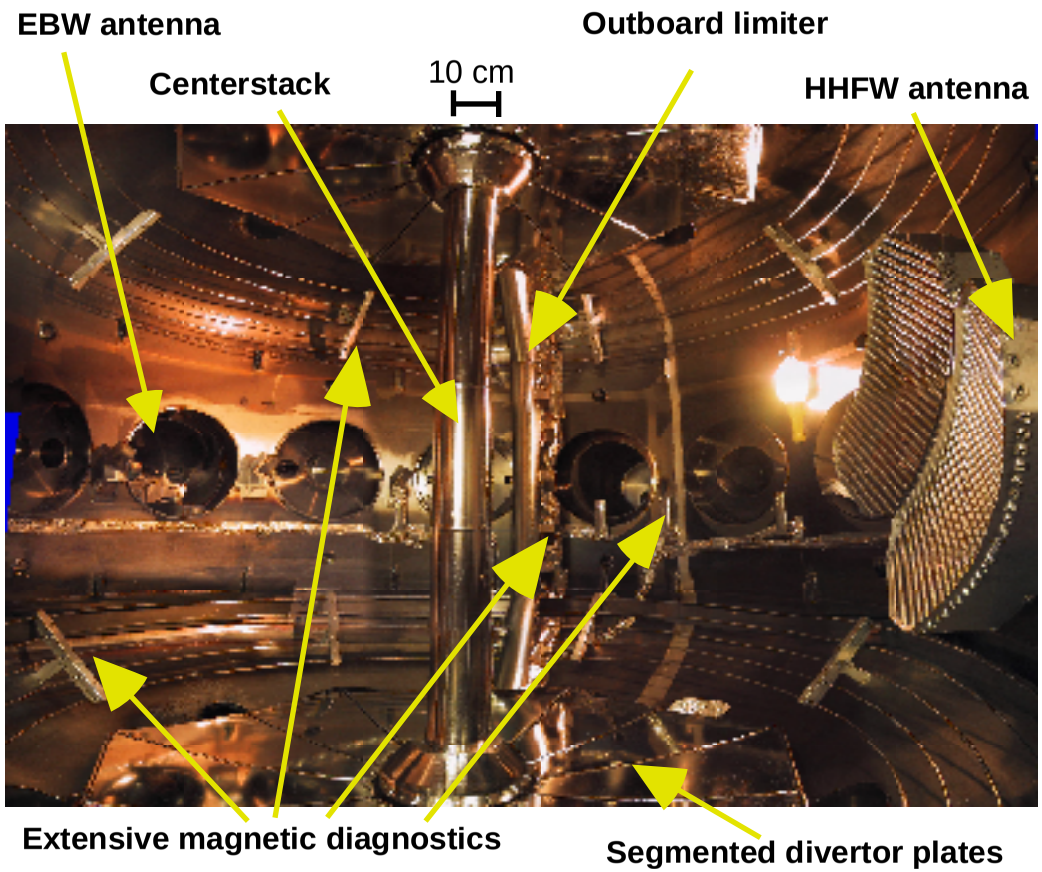


Experimental Parameters

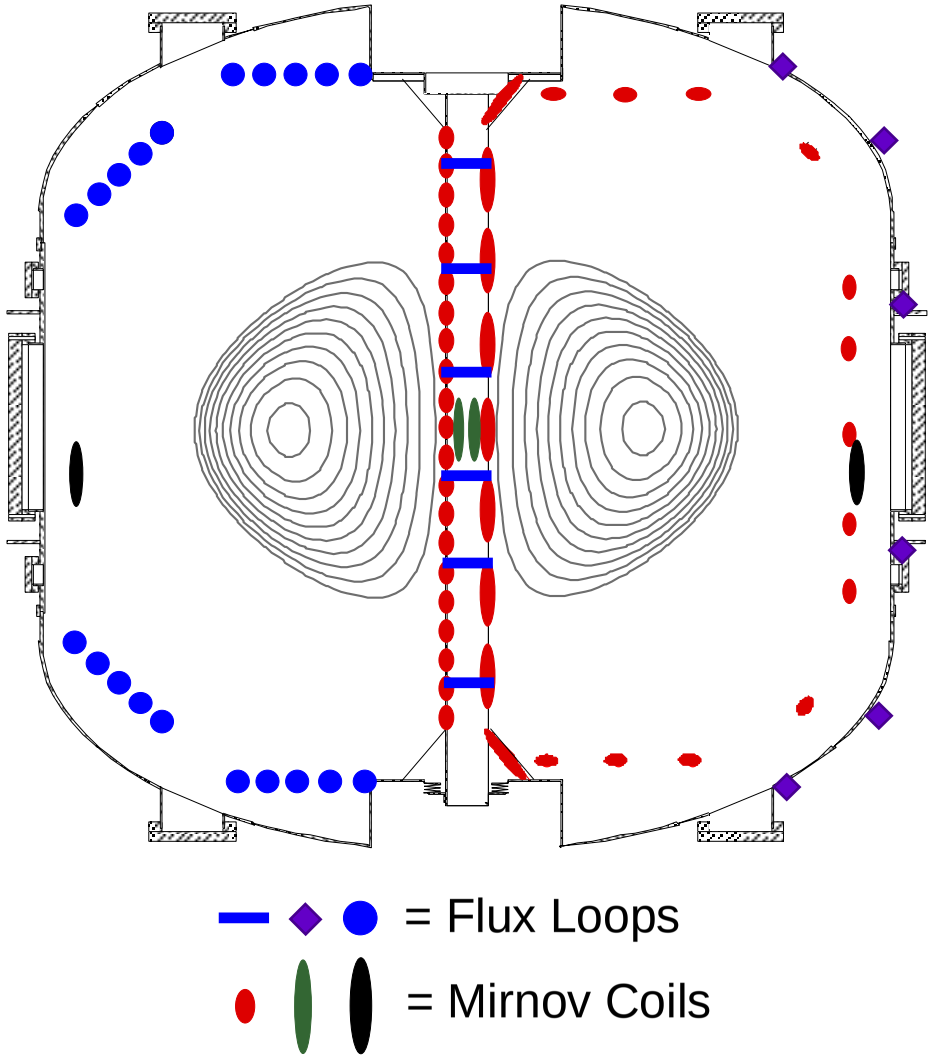
Parameter	Achieved	Phase II Goals
A	1.15-1.3	1.12-1.3
R (m)	0.2-0.38	0.2-0.45
I_p (MA)	≤ 0.16	≤ 0.30
I_N (MA/m-T)	6-8	15-20
RB_t (T-m)	≤ 0.03	≤ 0.1
κ	1.4–3.7	1.4–3.7
τ_{shot} (s)	≤ 0.02	≤ 0.05
n_e (10^{19} m^{-3})	1-5	≤ 10
β_t (%)	≤ 20	> 40
P_{HHFW} (MW)	0.2	1.0

PEGASUS has complete set of magnetic diagnostics

Composite Photograph of Vessel Interior

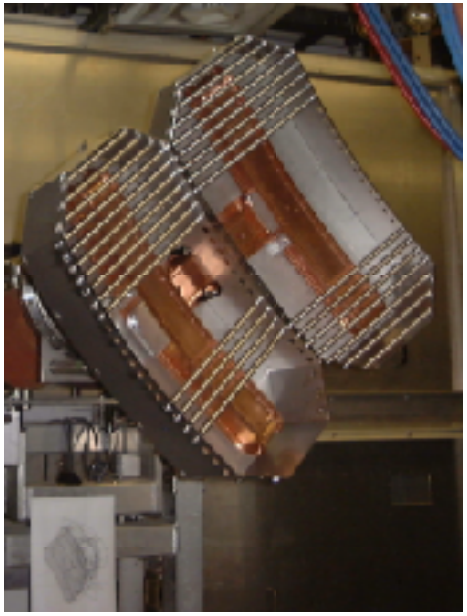


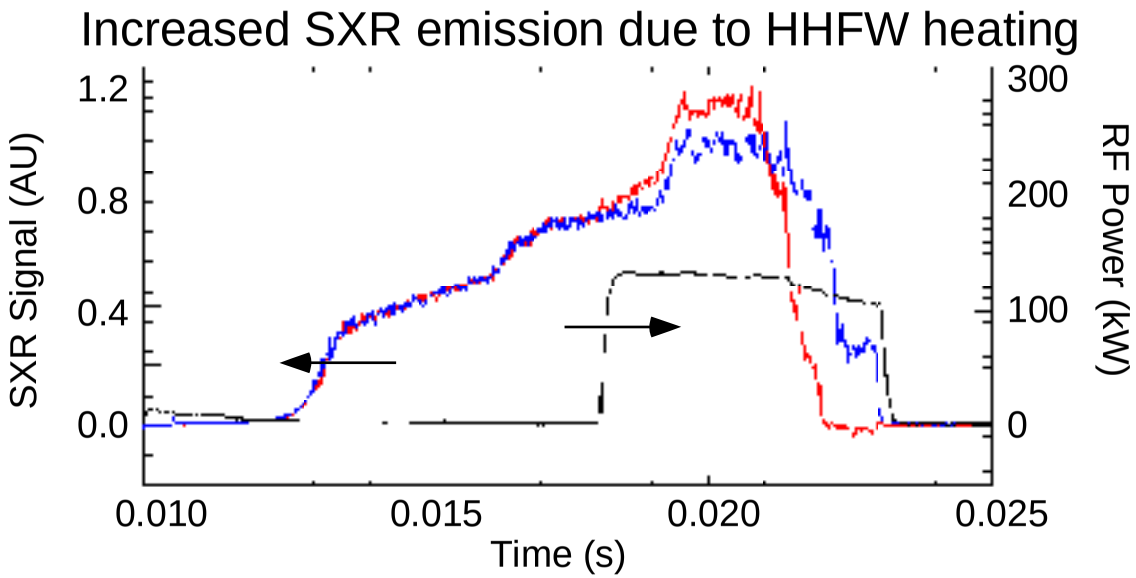
Schematic of Magnetic Diagnostics



HHFW system tested in Phase-I OPS

- Two-strap HHFW system installed and heating tests run
  - 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 in Phase I by plasma shape and position control*

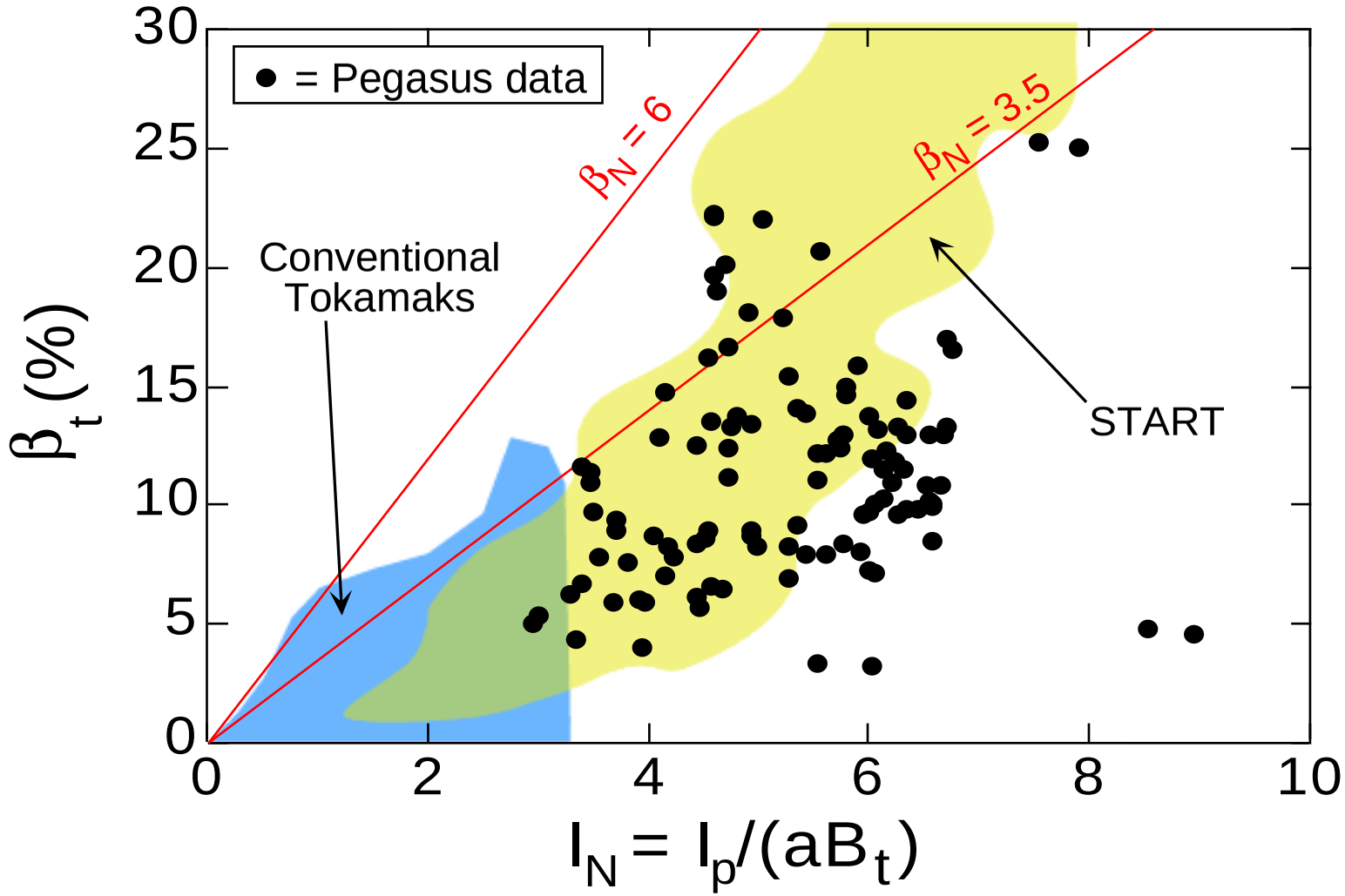




- HHFW Startup and CD applications:
  - Startup assist via preheating and/or current profile "freezing"
    - *Startup plasma phase: 40% single pass absorption*
    - *High β plasma phase: 100% single pass absorption*
  - Current Drive possible with present power supply and new antenna

A < 1.3 → Ready Ohmic Access to High β_t

- β_t up to 25% and I_N up to 6.5 achieved ohmically
- Low field → high I_N and β_t

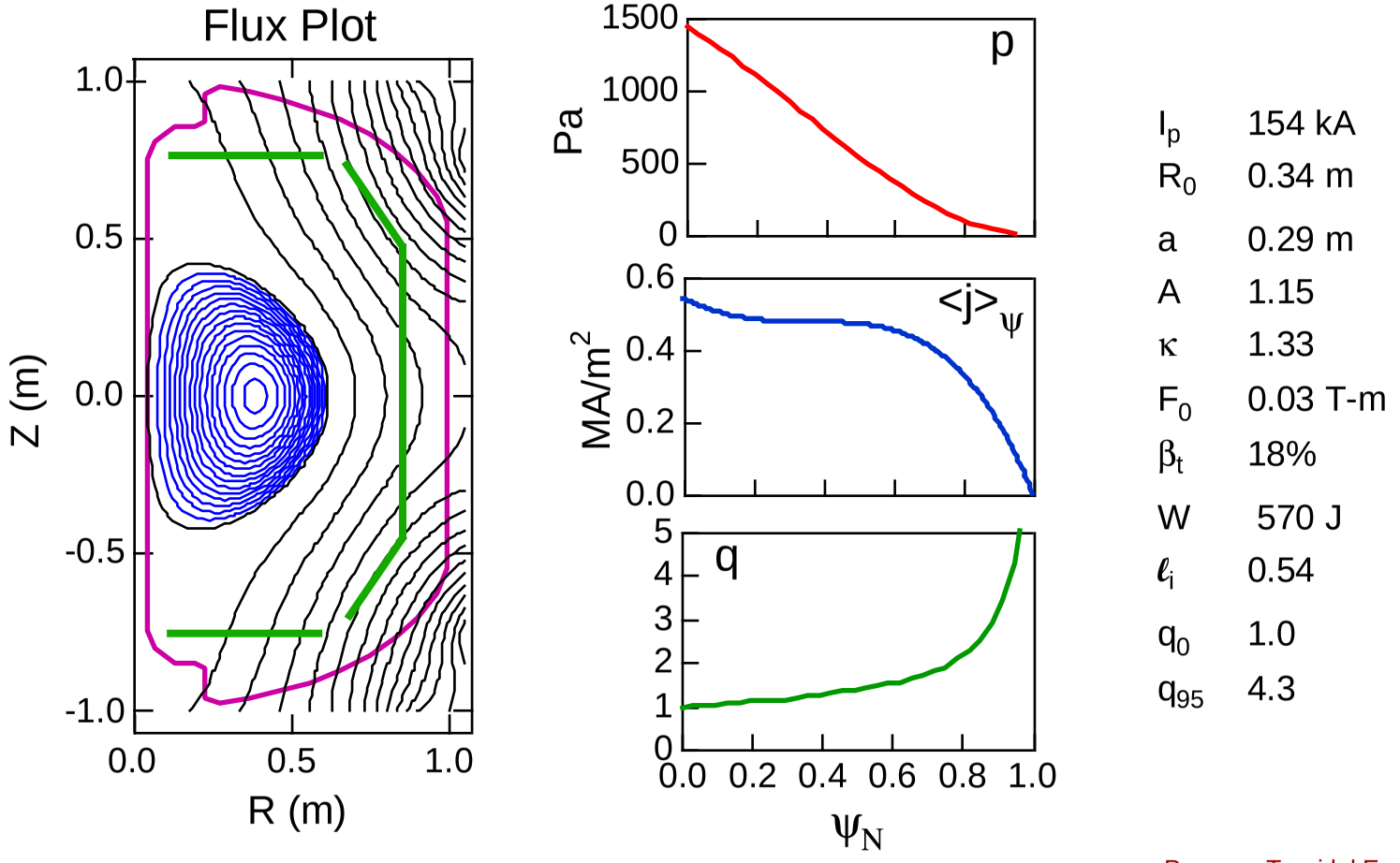


Equilibrium reconstructions show low-A characteristics

Low-A Characteristics

- High-β_t (Ohmic): $\beta_t > 20\%$
- 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: $F/F_{vac} \leq 1.5$ on axis ($\varepsilon\beta_p < 1$)

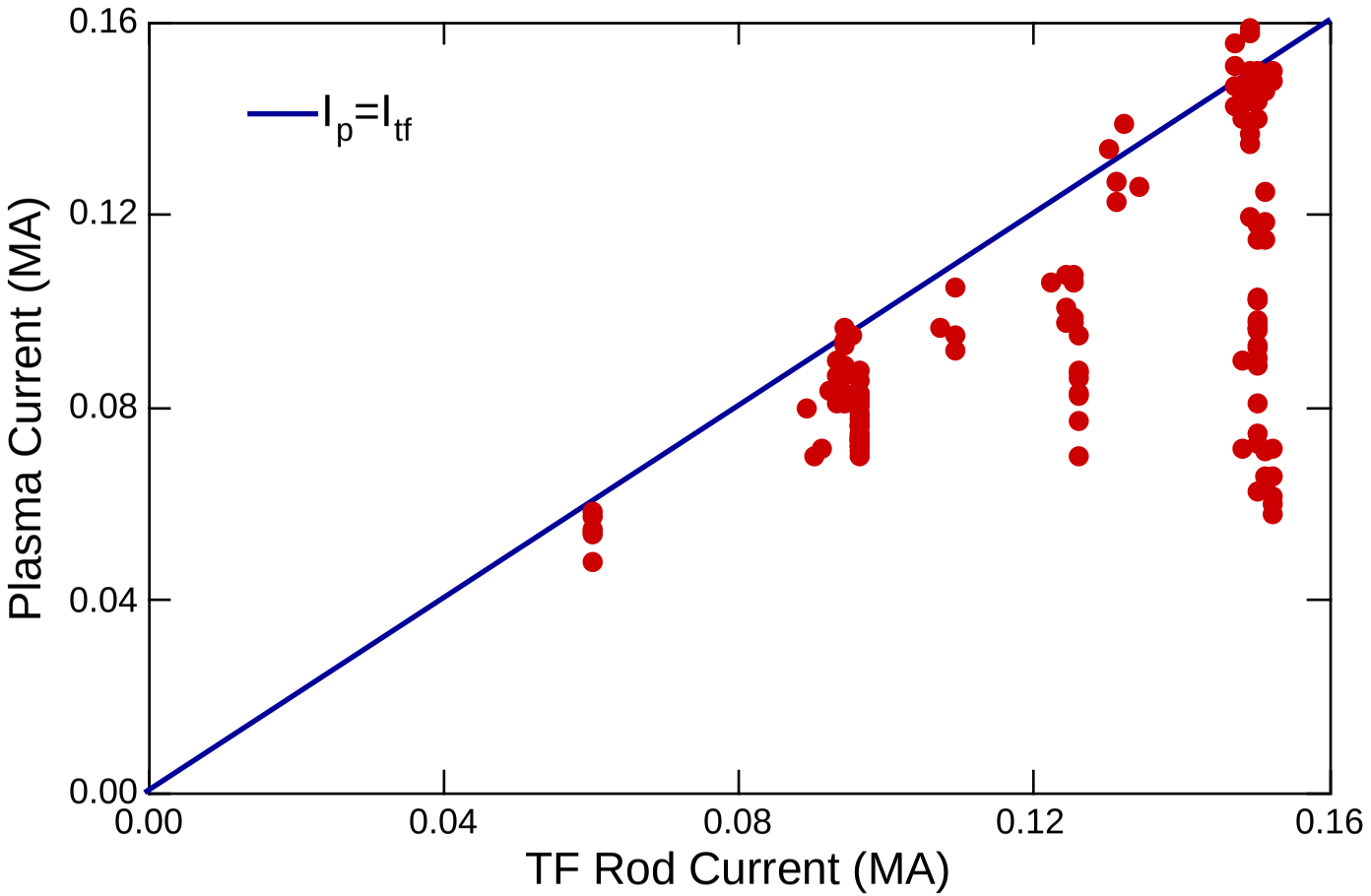
Sample Reconstruction



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

Toroidal field utilization exhibits a “soft limit” around unity

- Maximum $I_p \approx I_{TF}$
- Limit not disruptive or abrupt
  - I_p saturates or rolls over



Two factors contribute to the $I_p/I_{TF} \approx 1$ soft limit

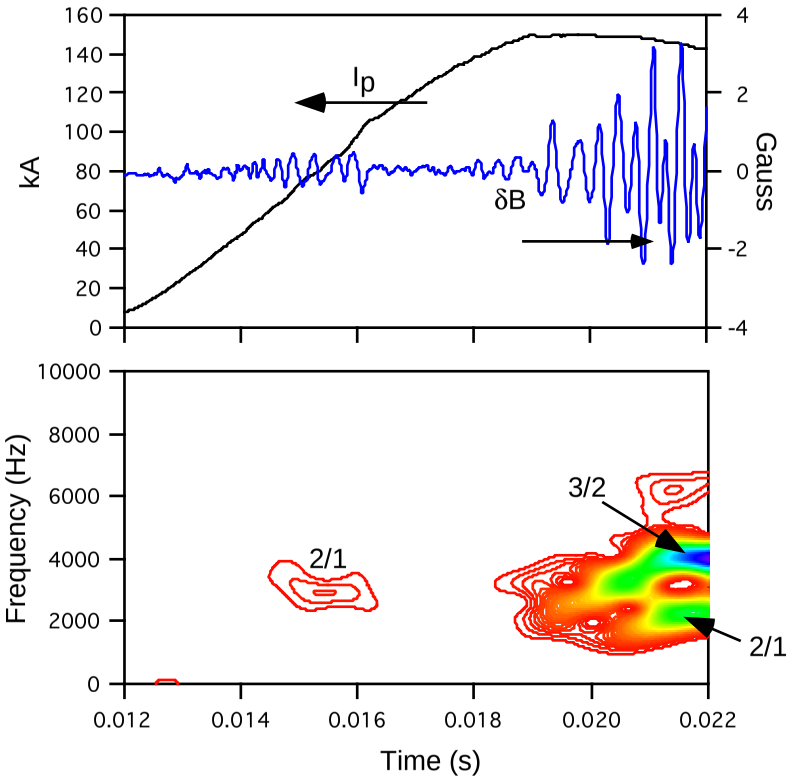
Large resistive MHD instabilities degrade plasma as TF ↓

- low B_t and fast $dI_p/dt \rightarrow$ early appearance of low-order q=m/n
  - *fixed sine-wave loop voltage*
- high resistivity early
- ultra-low A $\rightarrow$ low central shear

$\Rightarrow$ Result: rapid growth of tearing modes and large saturated island widths

- *Most common modes: m/n=2/1, 3/2*
- *Leads to decreased C_E, I_p*

- $I_p/I_{TF} \approx 1 \Rightarrow q_0 \approx 1.5$ - 2



Reduced effective Volt-seconds as TF ↓

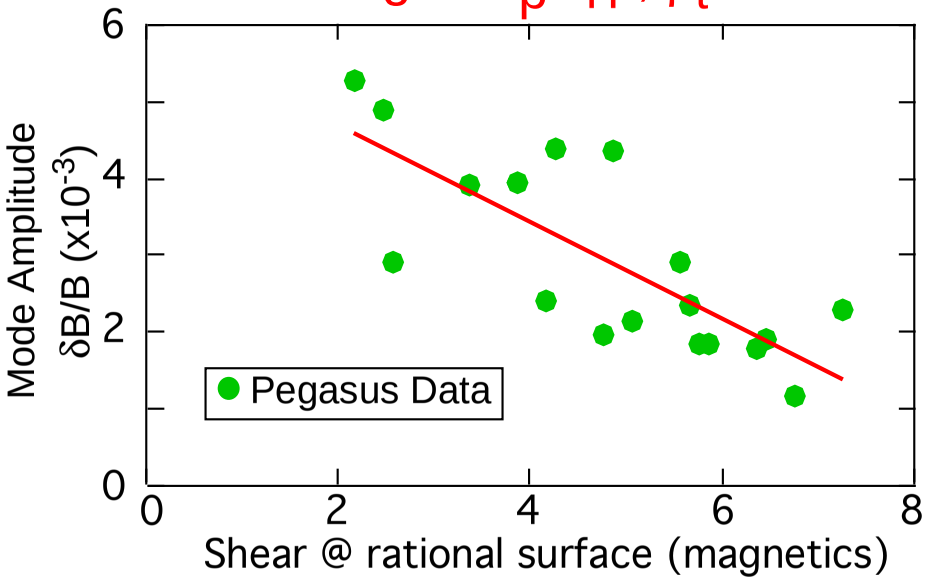
- reduced toroidal field $\rightarrow$ delayed startup
- delayed startup + fixed sine V_{loop} waveform $\rightarrow$ reduced effective V-s

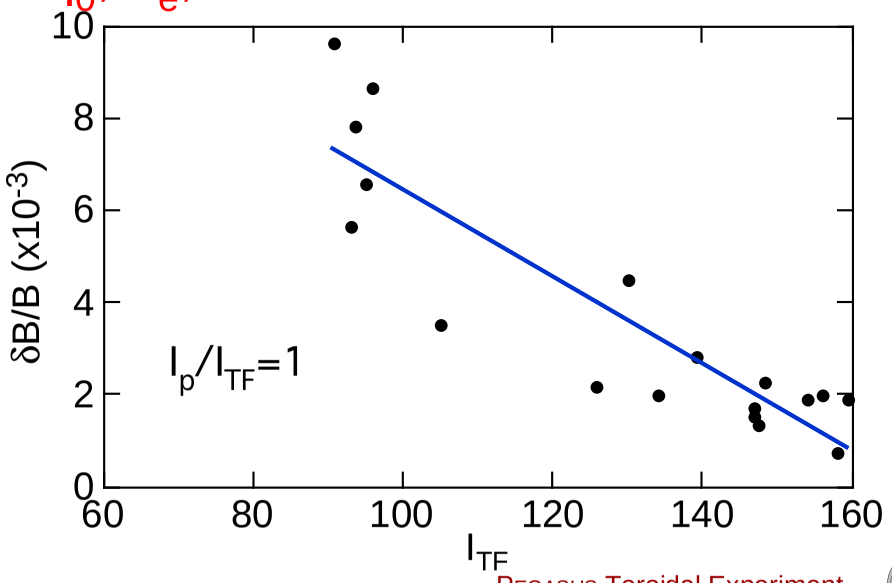
MHD Effected by q-profile Tailoring and TF Strength

- q-profile tailoring increases plasma performance
  - Discharge tailoring → plasmas with reduced MHD activity, increase W and I_p
  - Increased shear, increased q_0 ⇒ delay tearing onset
  - MHD amplitude decreases with increasing shear

- Increased toroidal field strength also reduces MHD activity
  - 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*

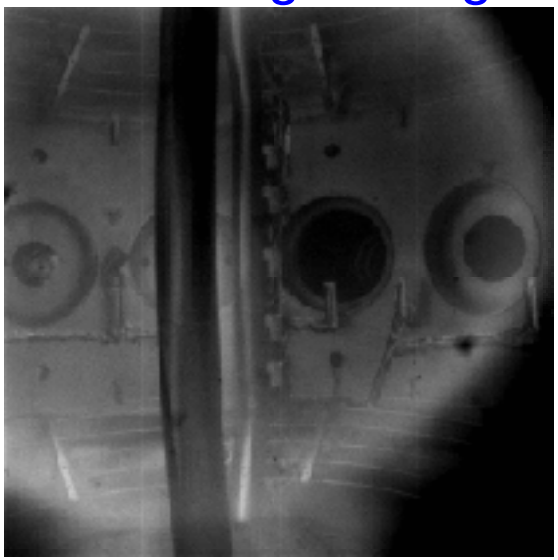
⇒ Access higher I_p/I_{TF}, β_t via increased q_0, T_e, shear



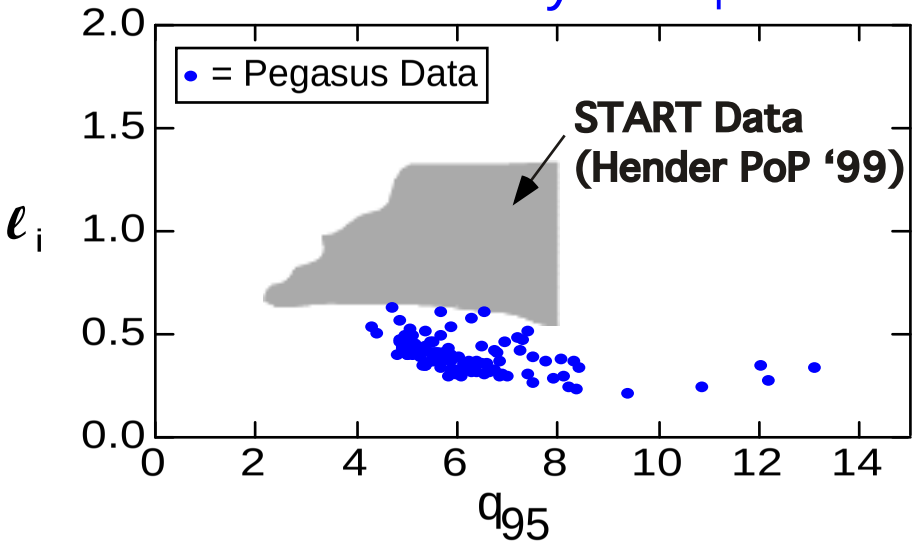


PEGASUS operates in low-ℓ_i, high-density space

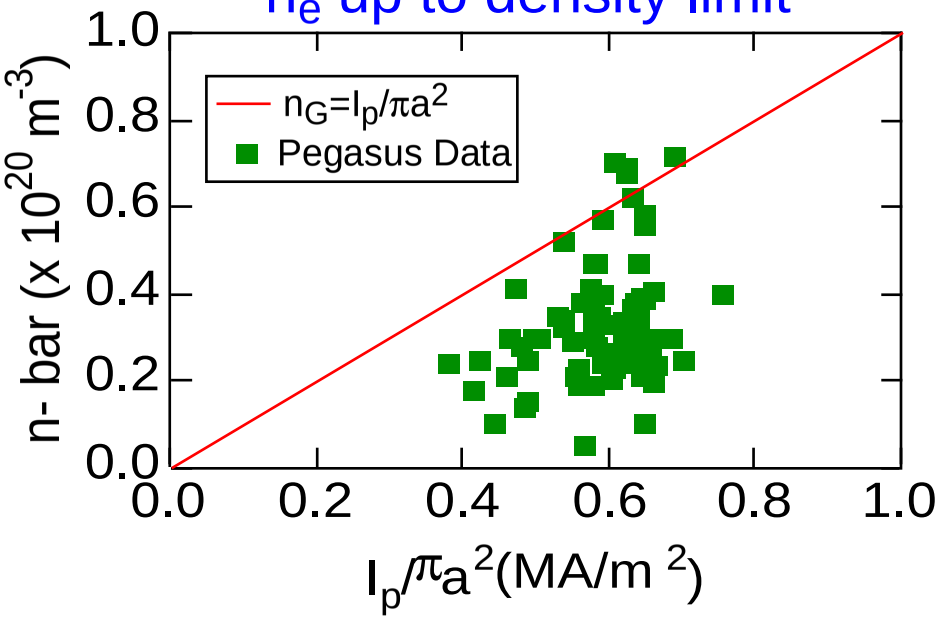
Visible light image



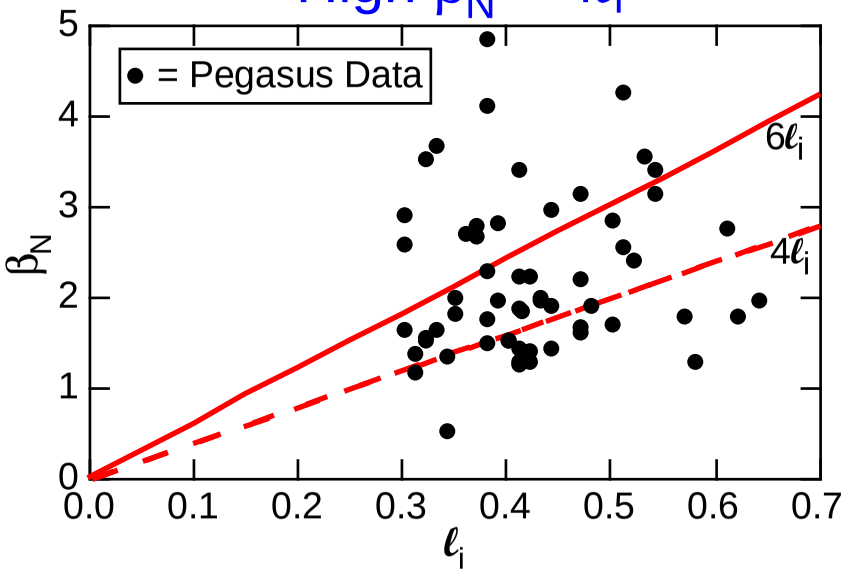
Generally low ℓ_i



$\overline{n}_e$ up to density limit

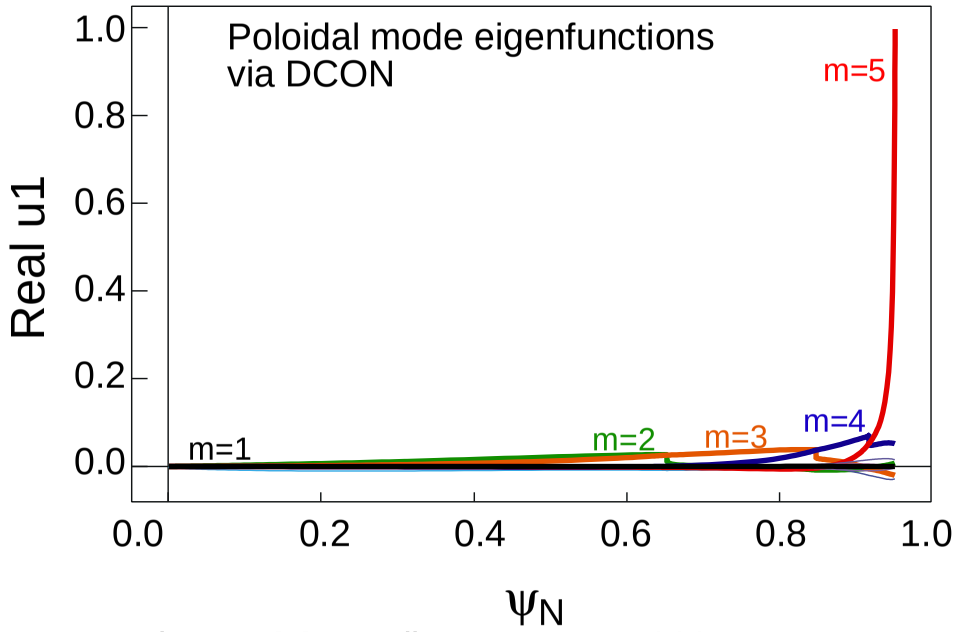


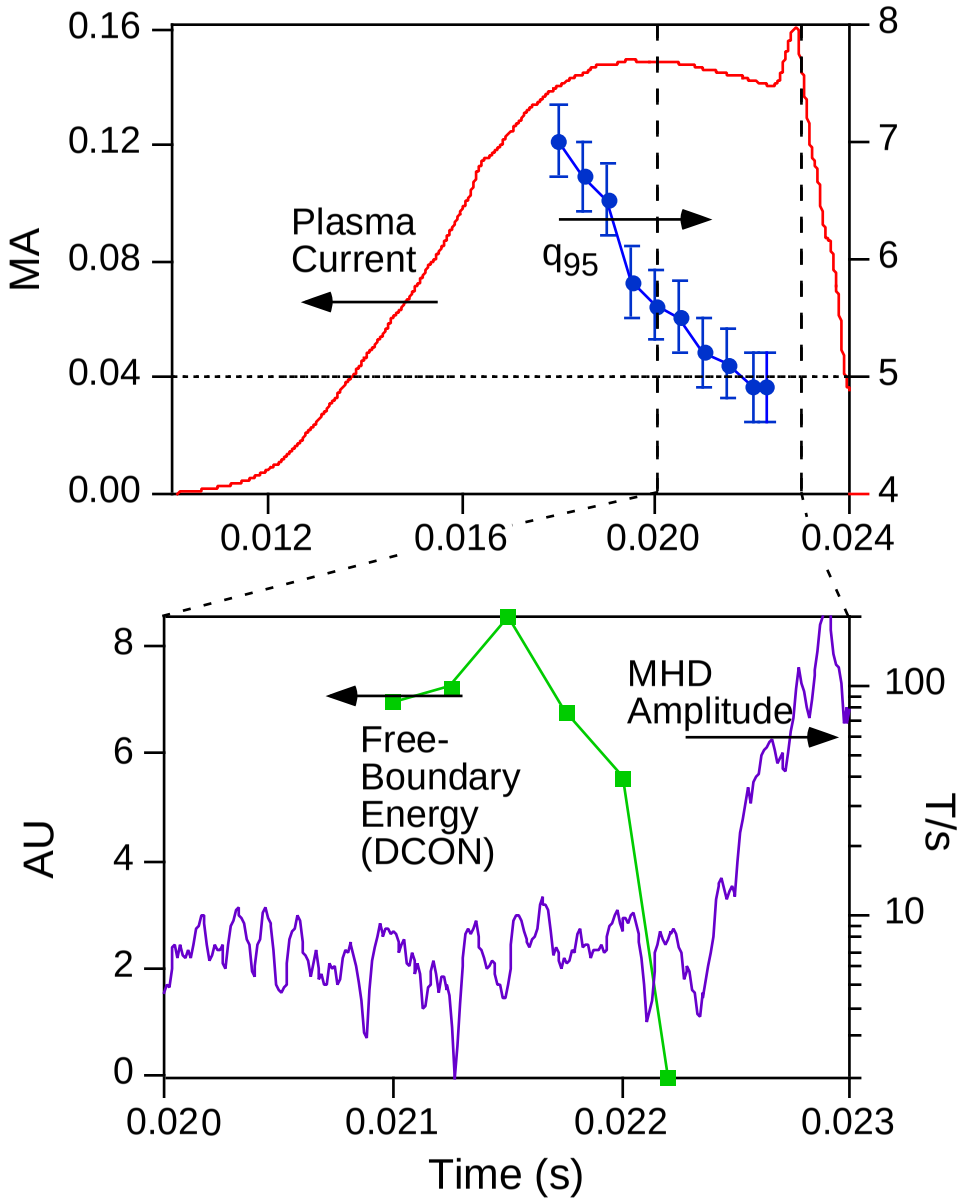
High $\beta_N > 4\ell_i$



High q_{95} external kink limit observed

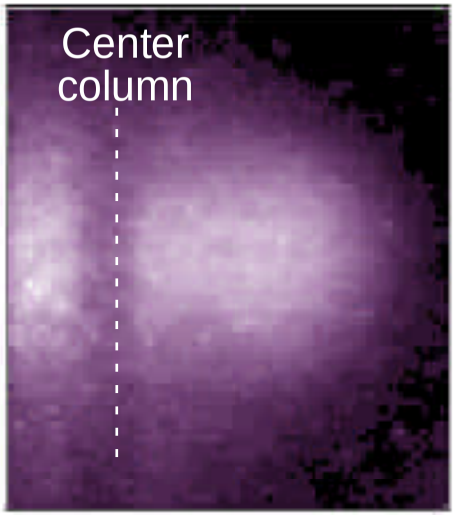
- High I_p plasmas often disrupt
- q_{95} = 5 observed preceding disruption
  - ℓ_i=0.5 at this time
- DCON analysis ⇒ unstable to n=1 external kink
  - m=5 most unstable mode
- Consistent with theory expectation





Measured q-profile indicates low central shear

Tangential PHC SXR image



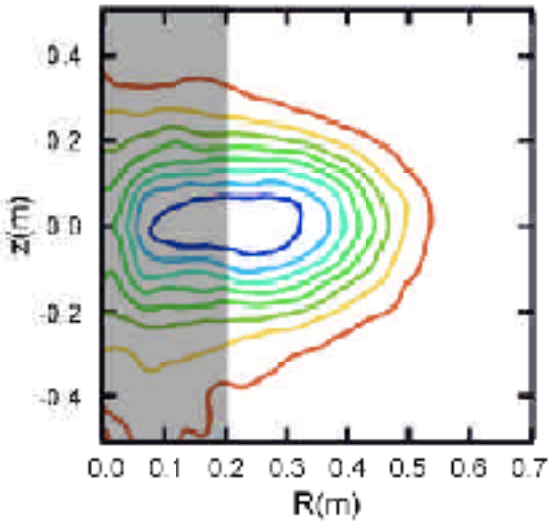
- 2D soft x-ray camera gives q-profile
  - Images soft x-rays
  - Constant-intensity surfaces determined
  - Mapped into flux space
  - G-S equation with SXR constraints
  - Iterate solution until convergence

- Measured q-profile ⇒ low central shear

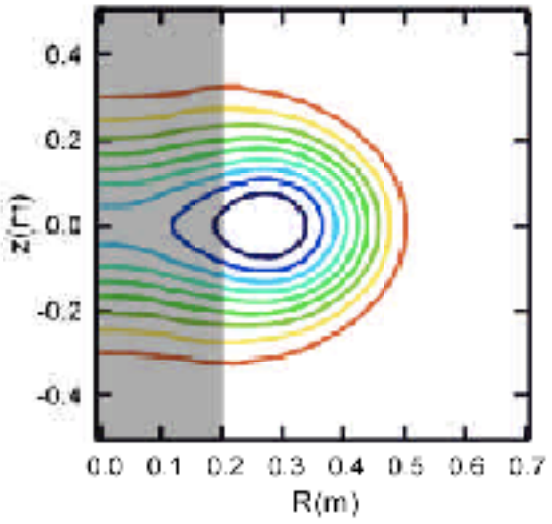
⇓

Image Contours:

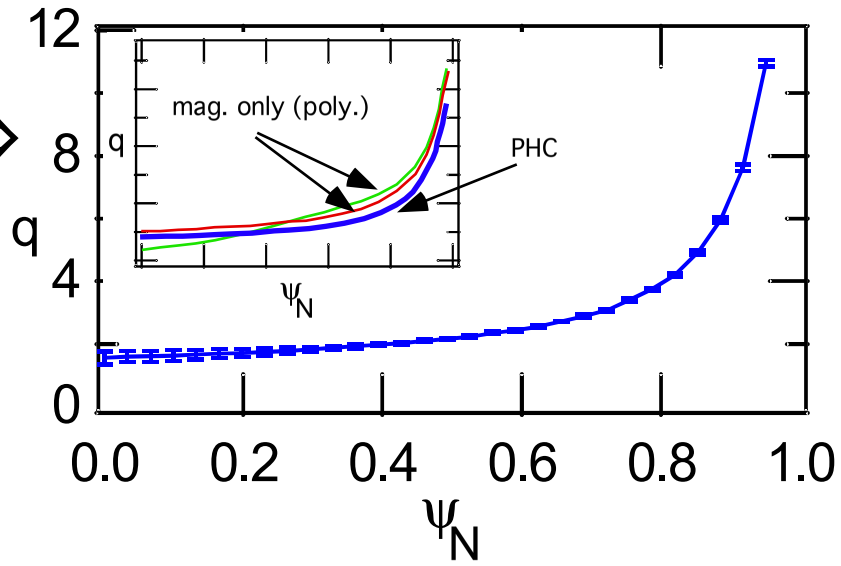
Measured



Reconstructed



⇒

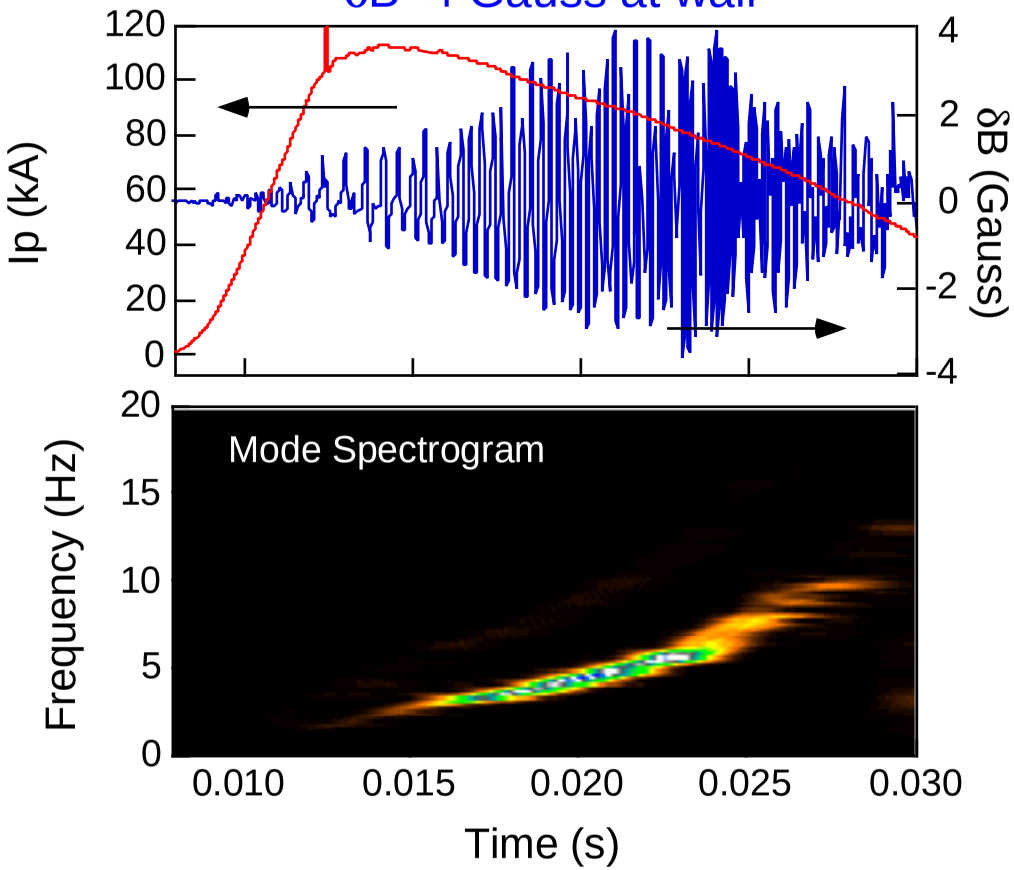


Island widths are on the order of plasma minor radius

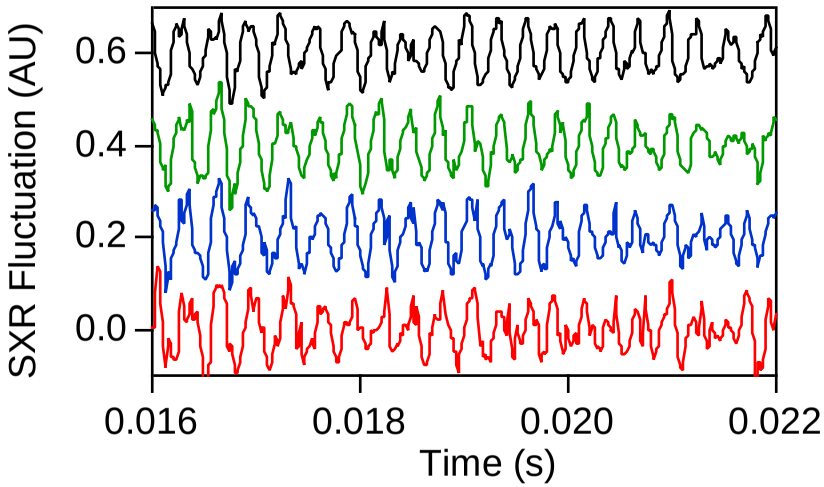
- Island width estimates give w>10 cm

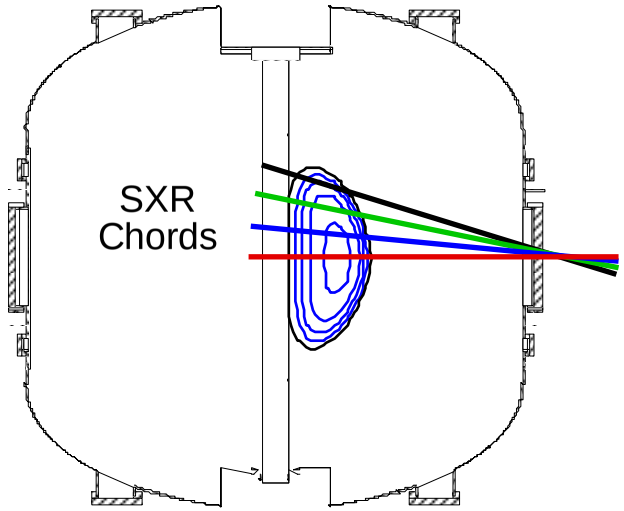
$$w \approx 4\sqrt{\frac{\delta B}{B_t}\frac{qR}{n\frac{dq}{dr}}} \sim \frac{a}{2}$$

- δB=4 Gauss at wall



- SXR→ large radial extent of mode





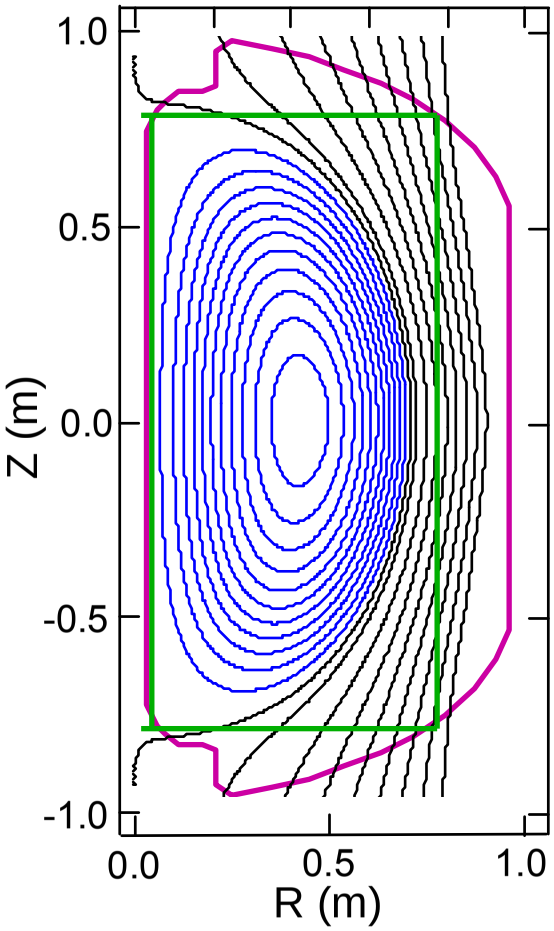
Access to High I_p/I_{tf}, β_t Operation

- **Suppression of large internal MHD modes**
  - Vary q(ψ)
  - Lower η before q(ψ) approaches low-order rational mode surfaces
- **Expand access to external kink modes studies**
  - Plasma time evolution, shape
  - Edge conditions and edge currents
- **Access to very high β_t regime for stability analysis**
  - OH access and HHFW heating availibility

Stable $l_p/l_{tf} > 1$ Equilibrium Found

- "zero"-β Equilibria showing $l_p/l_{tf} = 1.93$
- Predicted Stable with DCON

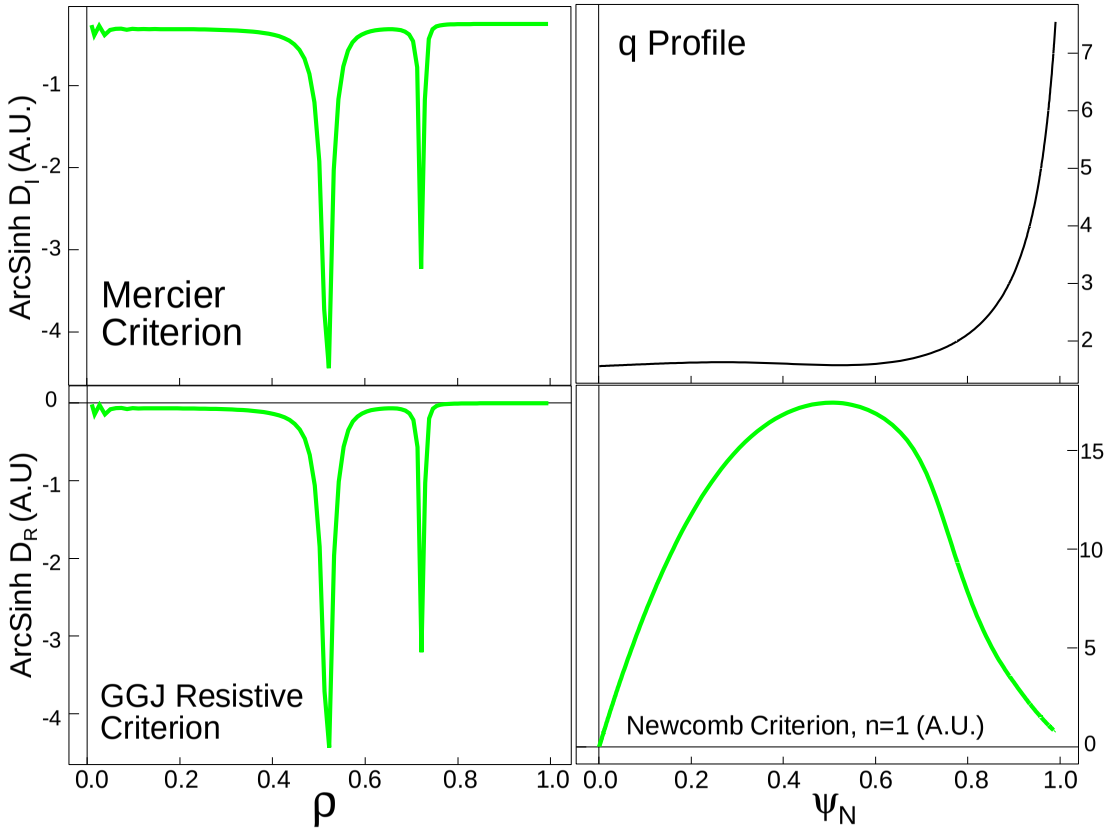
Flux Plot



Equil. Paramters

I_p	290000
I_N	12
I_p/I_{tf}	1.93
ℓ_i	0.59
q_0	1.5
R_0	0.39
a	0.34
Elongation	2.2
q_{95}	4.8

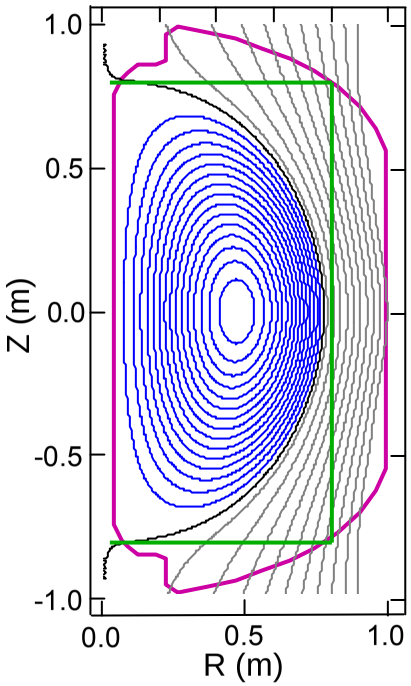
$D_I, D_R > 0$ => Unstable



Plasma Limits Modeled at $I_p/I_{tf} \sim 3$

- High-I_p/I_{tf}, "zero"-β Equilibria

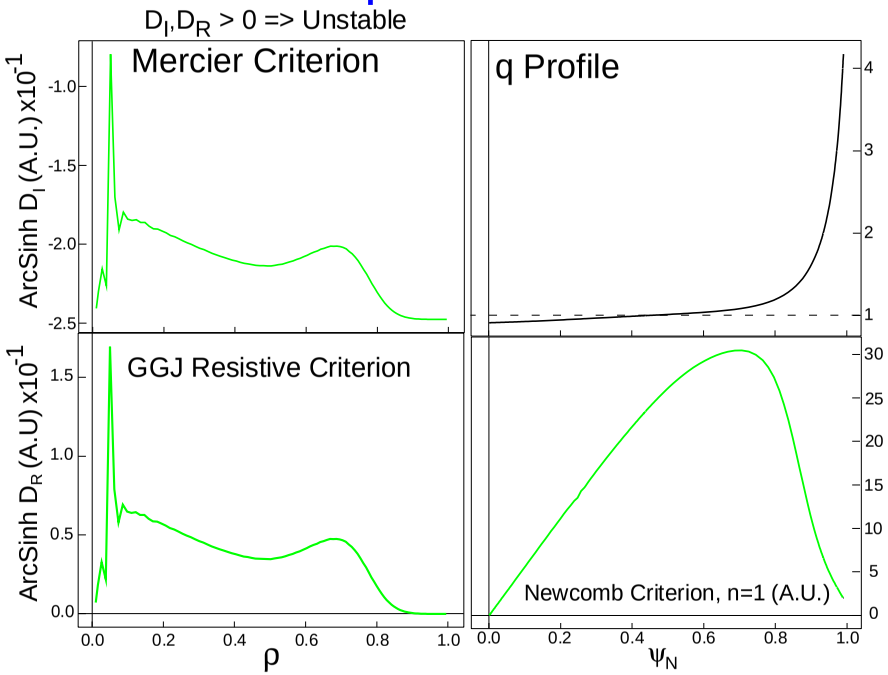
Flux Plot



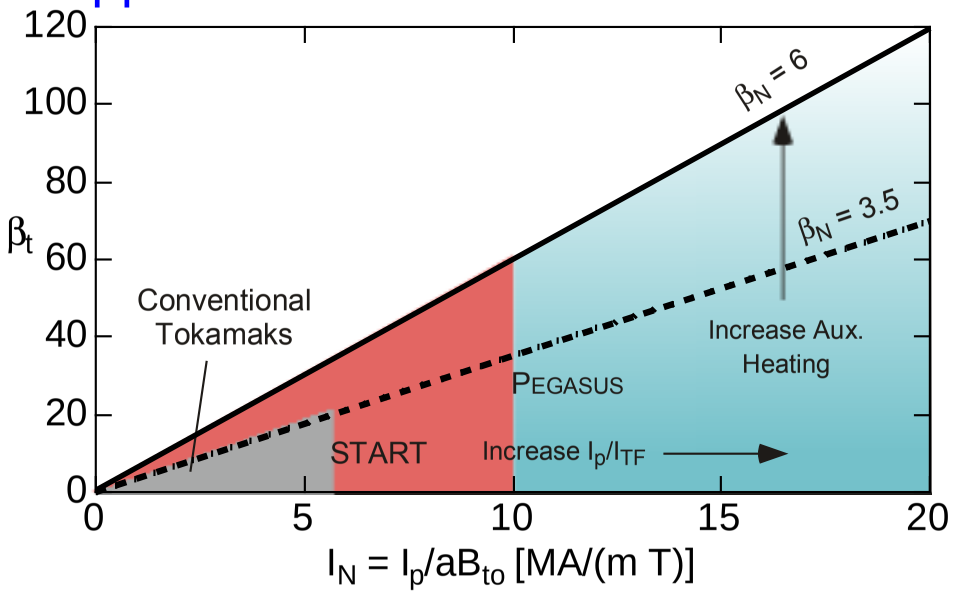
Equilibria Parameters

Ip	296000
I_{tf}	90000
I_N	18.9
li	0.68
q_0	0.91
R_0	0.41
a	0.36
Elongation	1.98
q_{95}	2.3

- DCON Output



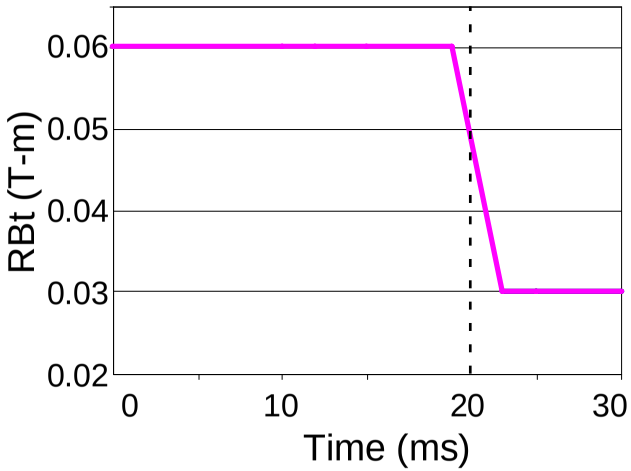
- Approaches Phase II Goals of PEGASUS

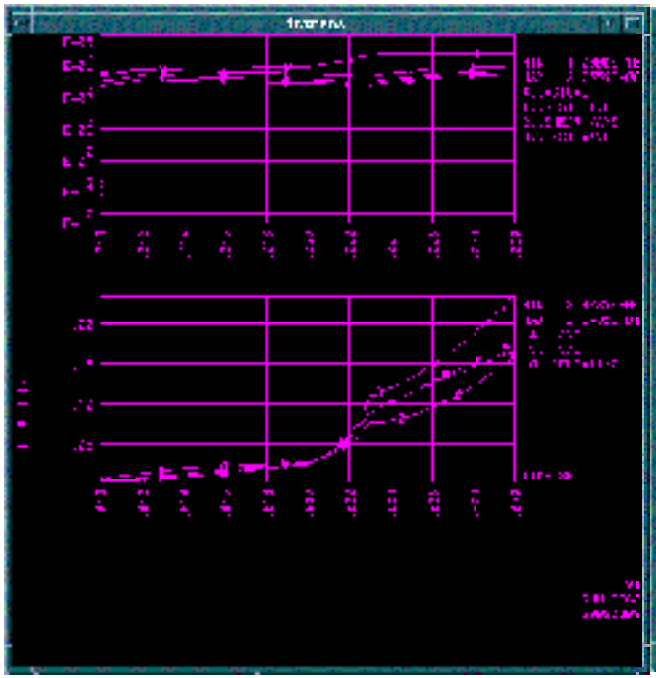


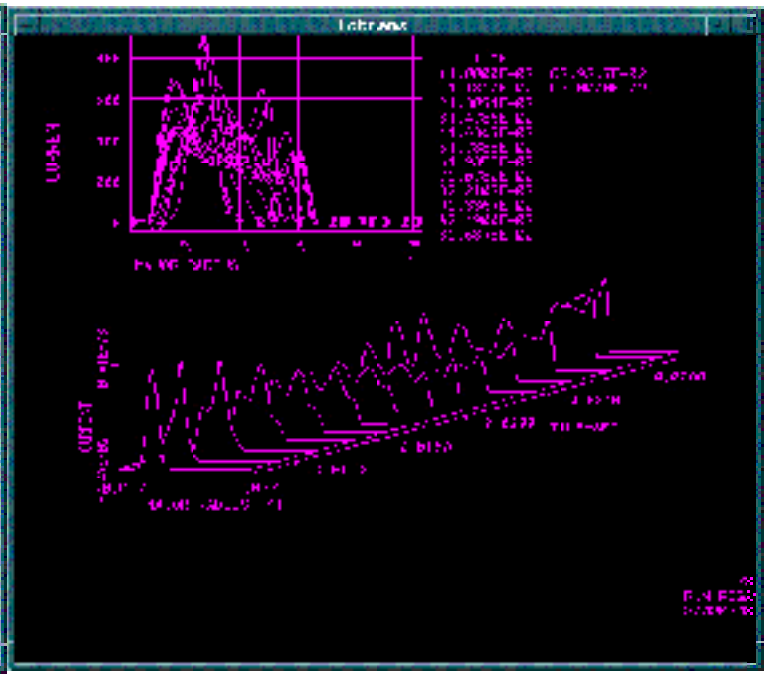
TSC: Fast TF Rampdown is tool for q(r) and β manipulation

- Effect of fast ramp:
  - β_t increases
  - q_a drops as B_t, q_0 falls more slowly (on τ_R time scale)
  - Energy conservation:
    - = J_θ driven, ℓ_i drops
    - = I_{ef} and I_p increase

- Results of TSC PEGASUS simulation:
  - RB_t: 0.06 to 0.03 T-m in 2 ms
  - β_t increases from 5% to 16%
  - I_p: up from 90 kA to 140 kA
  - Φ up from 1 to 6 mWb







New tools to access $I_p > I_{tf}$

- Suppress tearing modes early in discharge evolution

  = Transiently manipulate q during discharge:

  - Increased TF at startup => high I_{tf}, low inductance TF bundle
  - Variable $\dot{I}_p$ and R_0 control => coil-current-waveform control

  = Reduce resistivity before low-order rationals appear

  - Maximize J => V_{loop} control, position & shape control
  - Increase ohmic flux => new ohmic power supply
  - Use HHFW system => position control, V_{loop} control

- Explore edge kink boundary at high field utilization

  - Manipulate edge shear => divertor coils & PF shape control
  - Decrease edge currents => loop voltage control
  - Manipulate plasma shape => shape control
  - Manipulate current profile => V_{loop} control, position control

Upgrades Near Complete to All Coil Sets

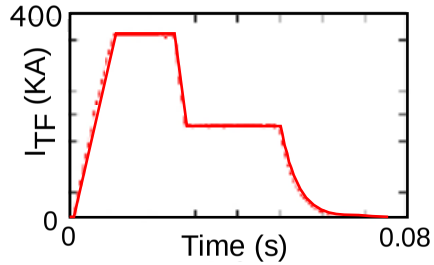
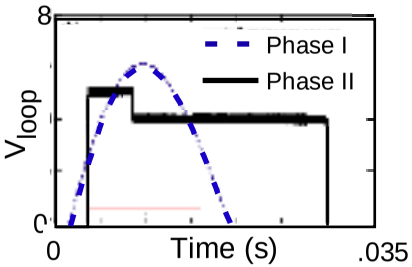
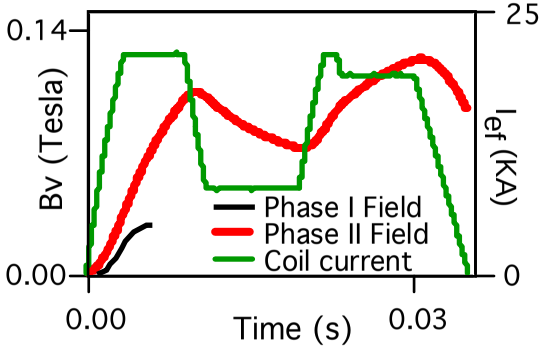
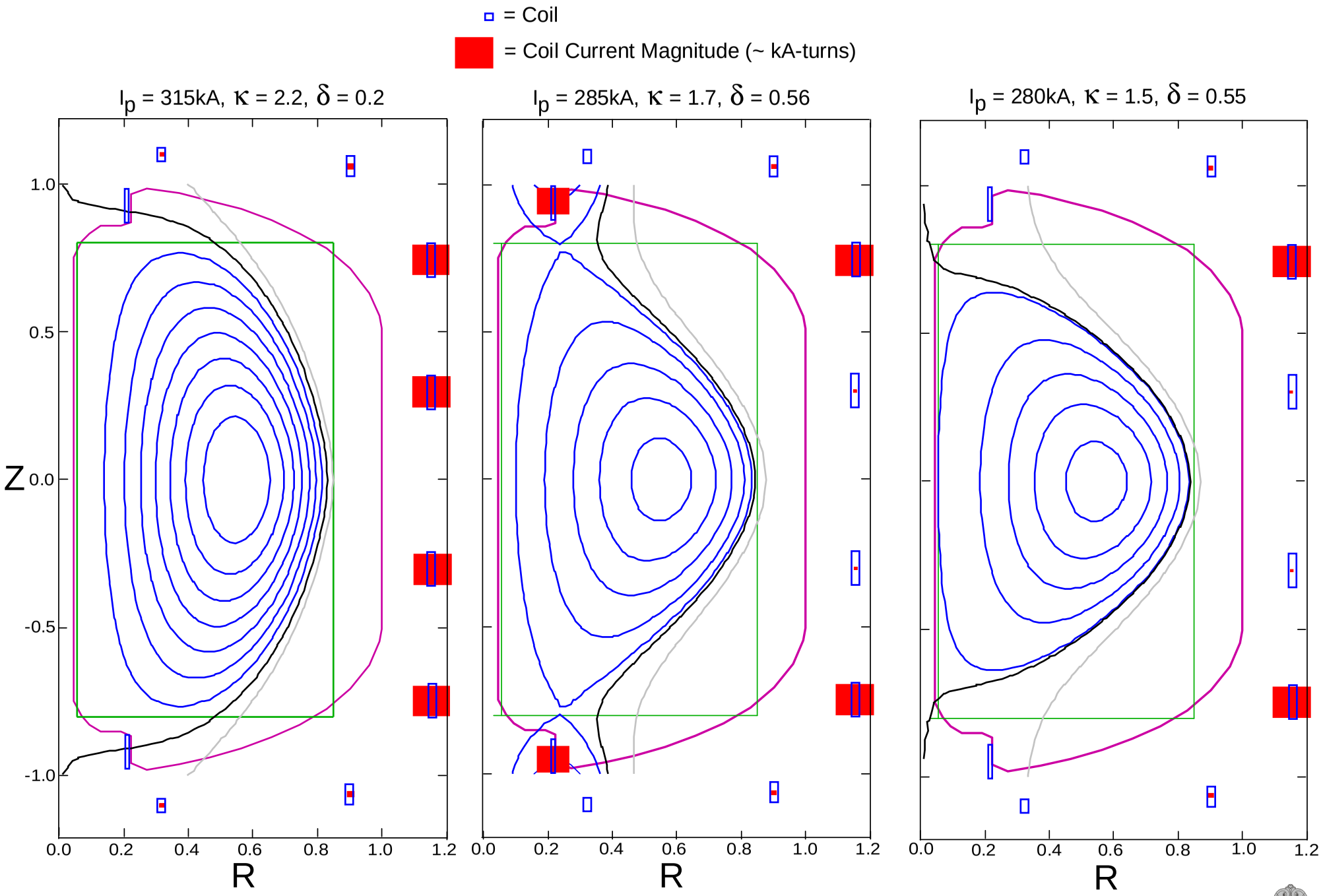
System	Phase I	Phase II	Example
Toroidal Field	• 60 turns • Quasi-DC • 150 kA-t max	• 12 turns • Fast time-variable • 450 kA-t max	
Ohmic Heating	• Half-sine Waveform • ±40 KA	• Programmable Waveform • ±15 kA (availible) • ±50 kA (full power)	
Equilibrium Field	• Monolithic coil set • 2 Resonant banks • Waveform constrained by startup concerns • No divertor	• 5 Independent coils • Programmability • Evolution free from startup constraints • Divertor installed	



ABB IGCT
2.8kV@4kA
Steady-State
~ 50 cm long

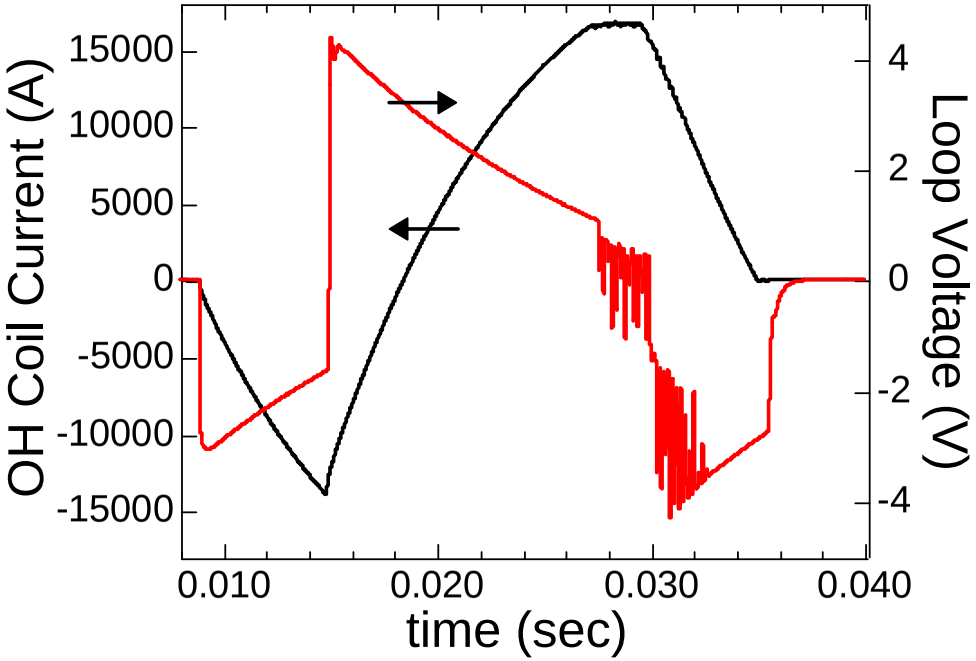
- All power now driven by solid-state IGBT and IGCT solid-state high power switches
  - Switches arranged in an H-bridge
  - Assistance from HIT Group @U. of Washington

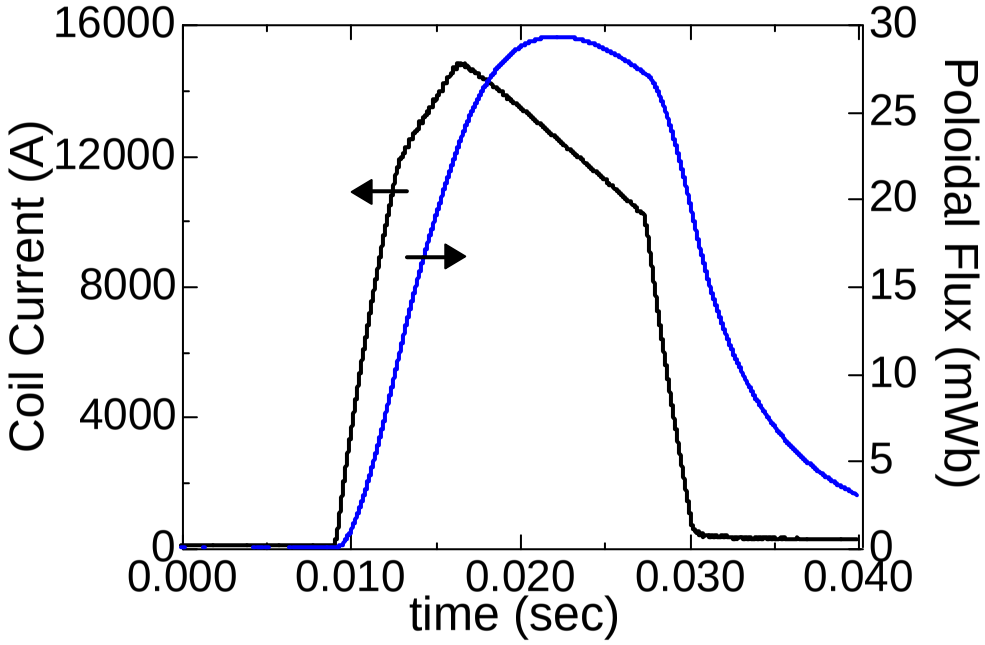
Modelled Equilibria Shows Flexibility of Phase-II PF



Current Status

- **Power testing complete**
- **Cross field testing in progress; Plasma Ops to follow**
- **All coils tested to nominal operating currents**
  - Waveform control demonstrated with EF coil set
  - OH tested to 900V; +/- 15 kA (design = 2700V;+/- 50 kA)
    - *30 mV-sec. manageable OH flux demonstrated vs. 40mV-sec. increasing flux in Phase-I Ops*





Summary

- **Pegasus is a mid-size ST built to explore A $\rightarrow$ 1**

- **Experimental results from phase I operations**
  - Plasmas exhibit low-A characteristics
    - $\beta_t \sim 20\%$, $I_N \sim 6$, $\beta_N > 4$ *via OH heating*
    - $I_p/I_{tf} \sim 1$
    - $\ell_i \sim 0.4$
  - Characteristics of High Ip/Itf Operation
    - *Large scale internal MHD limit on* I_p/I_{tf}
    - *External Kink at* $q_{95}=5$

- **Next phase of operations will focus on accessing high I_p/I_{tf}, β_t regimes**
  - Recent modeling has demonstrated existence and accessibility to this regime
    - *DCON and local G-S solver for stability and equilibrium => found* $I_p/I_{tf} \sim 2 - 3$
    - *TSC for shot simulations*
  - Upgrades to increase access to this regime
    - *Increased V-sec.; position and shape control;* B_{TF} *versus time*
    - *Power supply and cross-field testing in progress; limited plasma operation to follow*