Abstract

The PEGASUS Toroidal Experiment is exploring stability limits in the high β_t, low-q operating space at near-unity aspect ratio. Plasmas are characterized by high β_t ($\leq$20% to date); very low toroidal field ($B_t \leq 0.07$ T); densities approaching the Greenwald limit; and low-ℓ_i (0.2-0.5). A soft limit in this operating space is observed at $I_p/I_{tf} \sim 1$ and is related to a combination of MHD activity in the low-shear interior and limited V-s availability. A disruptive external kink limit is observed at $q_{95} \sim 5$, which is verified by DCON analysis of reconstructed equilibria. The experiment has been modified to avoid these limits. Internal tearing mode suppression will use plasma growth control, higher TF during startup, and increased V-s. Manipulation of the external kink limit will employ q(r) tailoring (via time-variable TF and divertor operation) and plasma shaping. Future experiments will focus on exploring extreme values of I_p/I_{tf} with an emphasis on verification of the kink stability limits in the tokamak-spheromak overlap regime.

*Supported by U.S. DoE grant No. DE-FG02-96ER54375

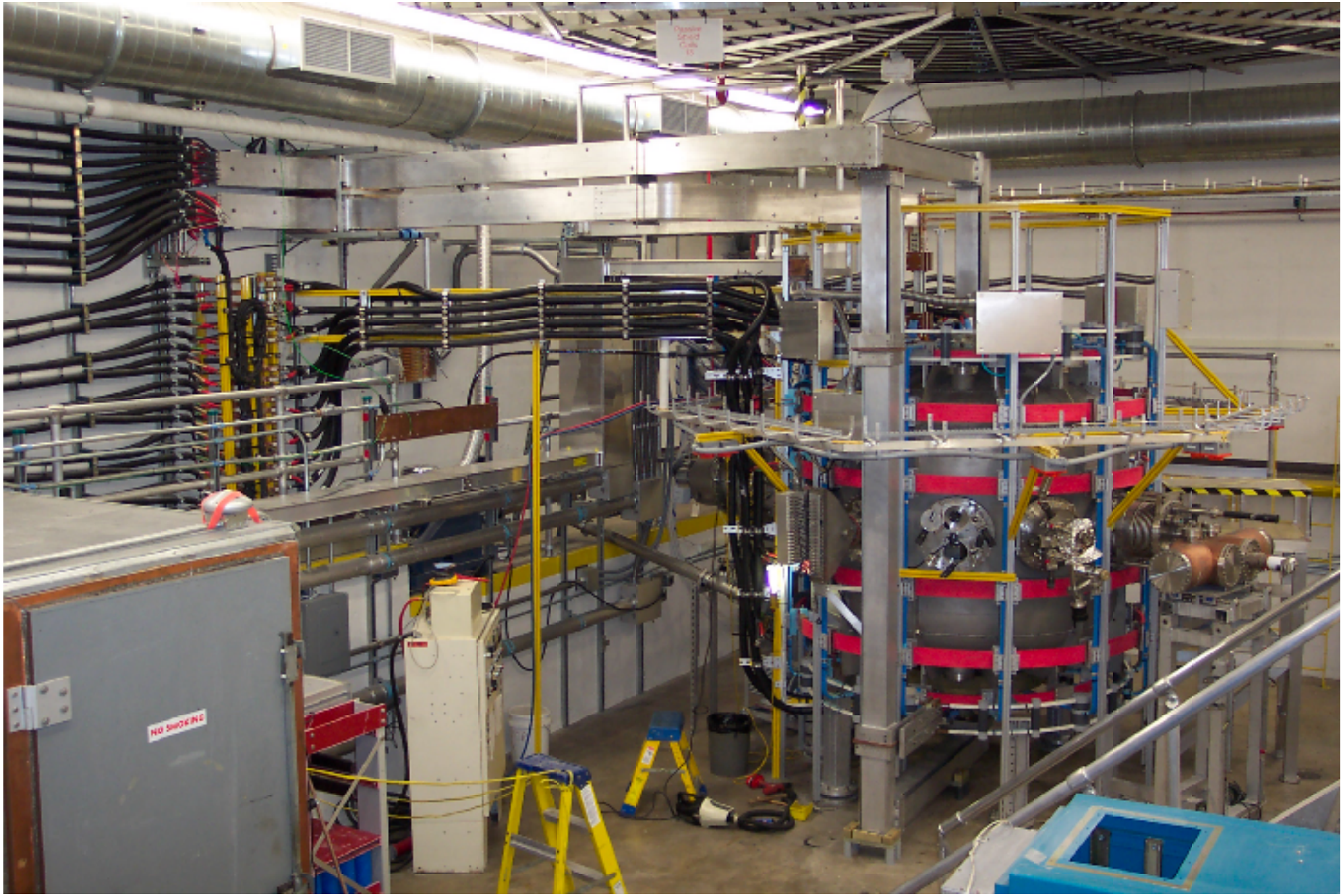
Outline

- **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 I_p/I_{tf} 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*
    - *TSC for shot simulations*
  - Upgrades to increase access to this regime
    - *Increased V-sec.; position and shape control; B_{TF} versus time*
    - *Power testing has commenced*

PEGASUS Facility

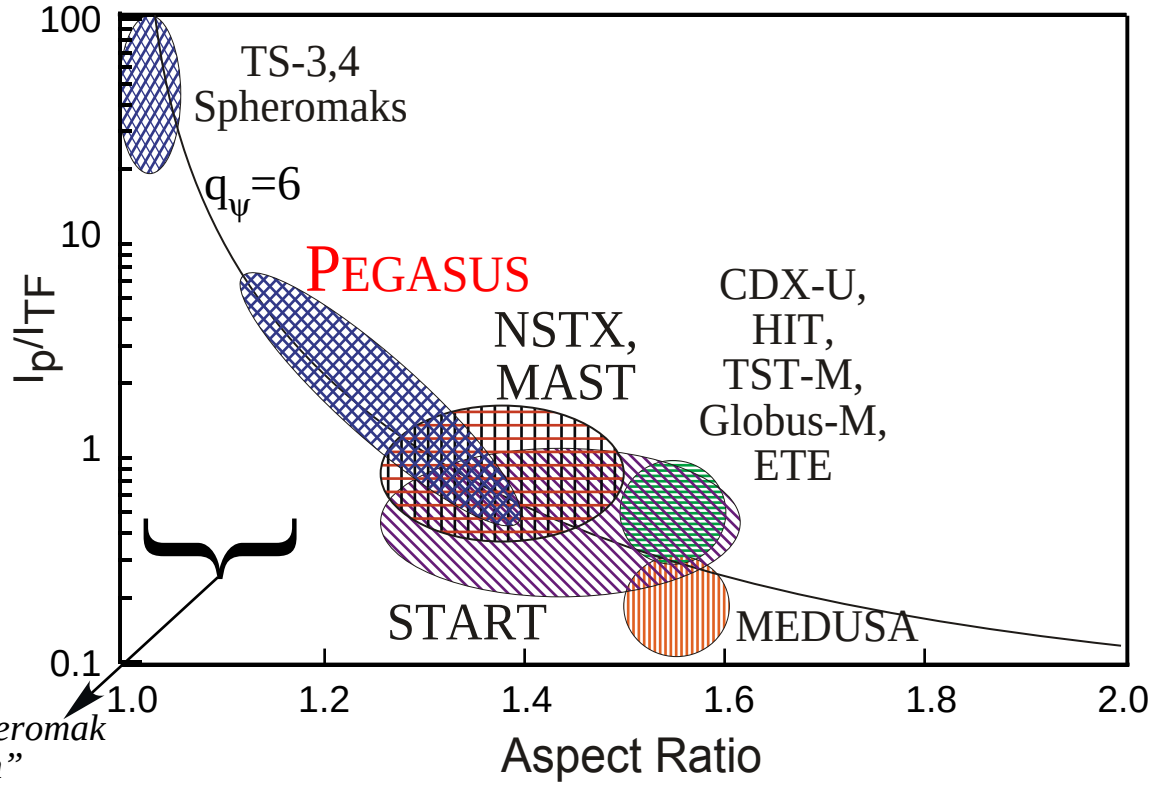


Mission: Explore plasma limits as A→1

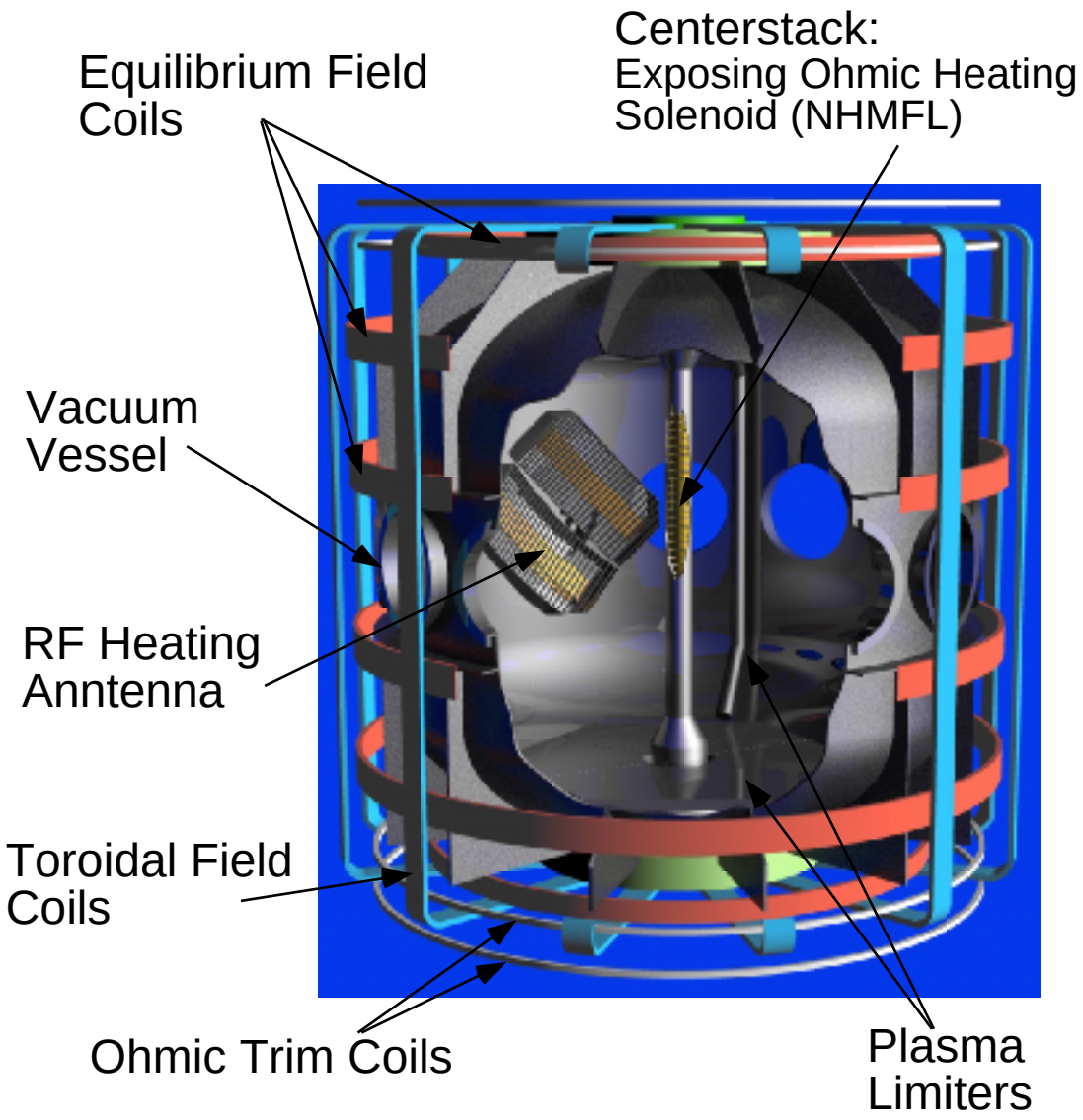
Pegasus is an extremely low-aspect ratio facility exploring quasi-spherical high-pressure plasmas with the goal of minimizing the central column while maintaining good confinement and stability

- 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 a University-Scale, Mid-Sized ST

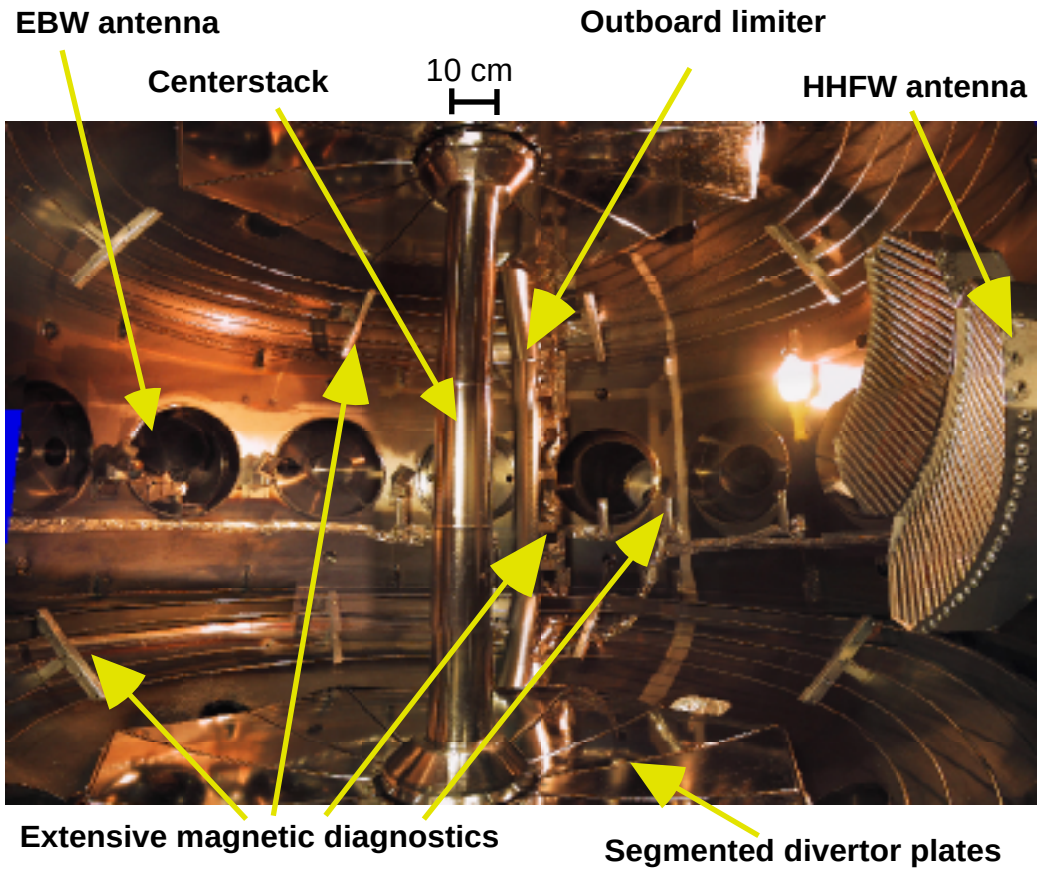


Experimental Parameters

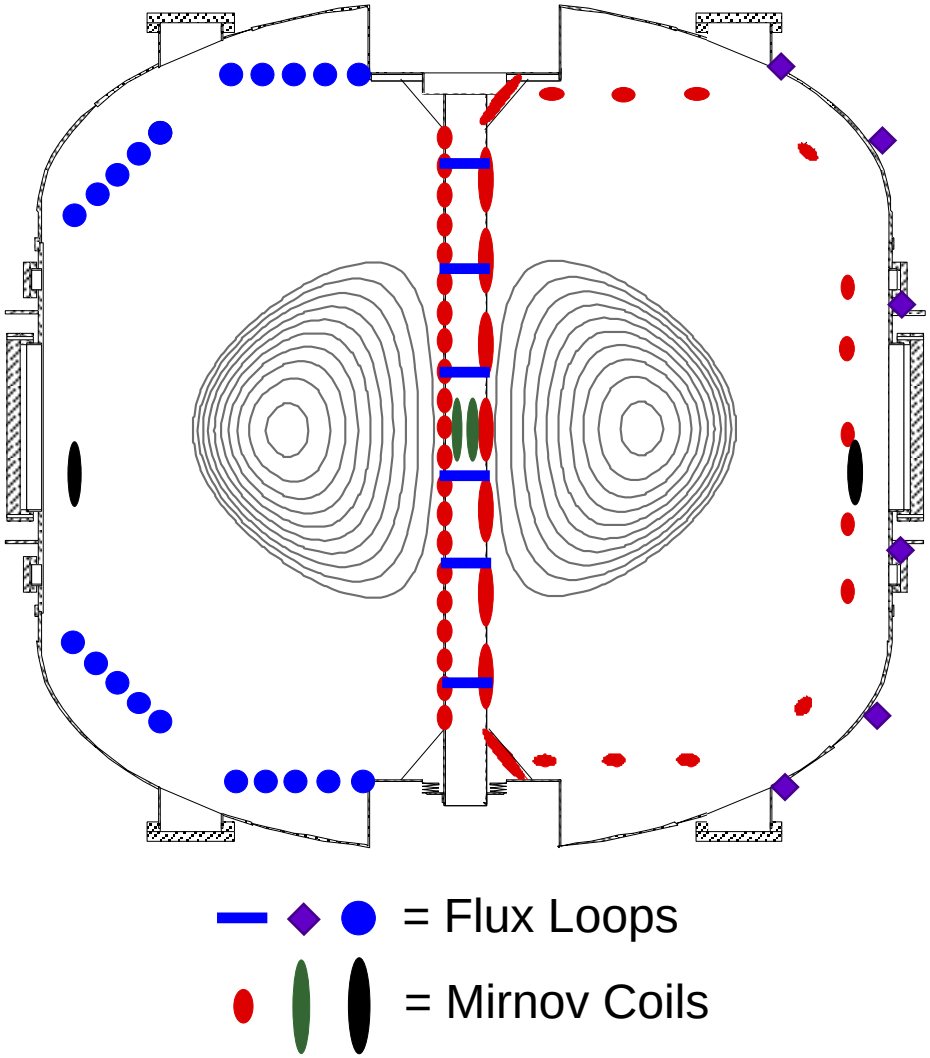
Parameter	Achieved	Phase II Goals
A	1.15-1.3	1.12-1.3
R (m)	0.2-0.38	0.2-0.45
I_p (MA)	≤ 0.16	≤ 0.30
I_N (MA/m-T)	6-8	15-20
RB_t (T-m)	≤ 0.03	≤ 0.1
κ	1.4–3.7	1.4–3.7
τ_{shot} (s)	≤ 0.02	≤ 0.05
n_e (10^{19} m^{-3})	1-5	≤ 10
β_t (%)	≤ 20	> 40
P_{HHFW} (MW)	0.2	1.0

Diagnostic Set for Reconstructions and Mode Analysis

Composite Photograph of Vessel Interior



Schematic of Magnetic Diagnostics



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

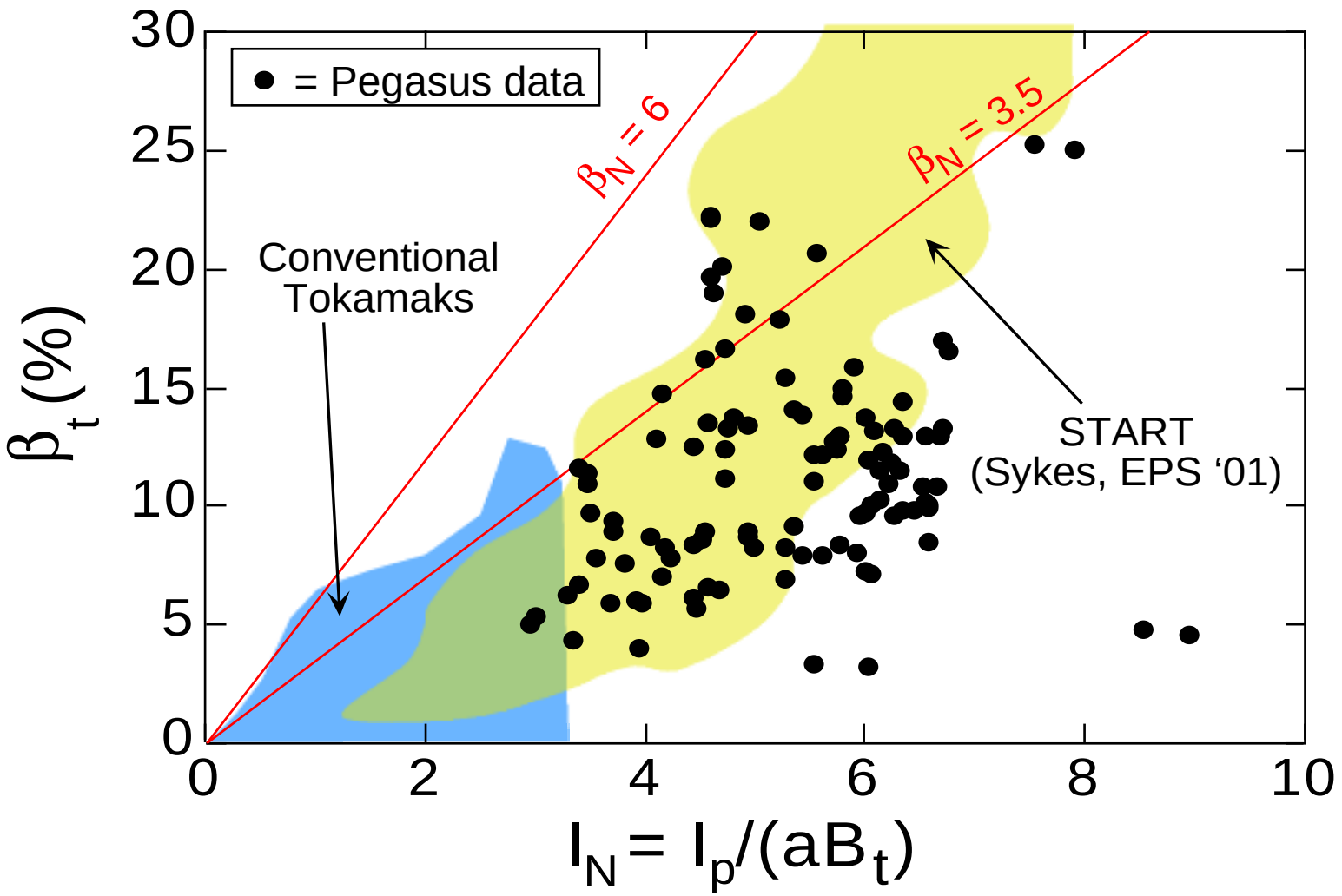
- Near-Future Diagnostics

Diagnostic	Capability	Measures	Status
Tangential PHA	single chord	$T_e(t)$	In Development
Tangential Bolometer Array	~32 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

- See Poster QP1.069-S.P. Burke et al. for details

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

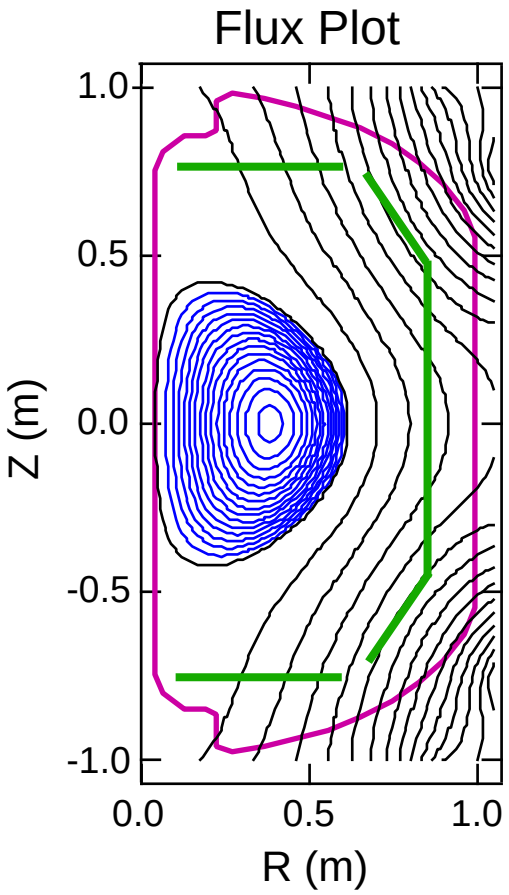


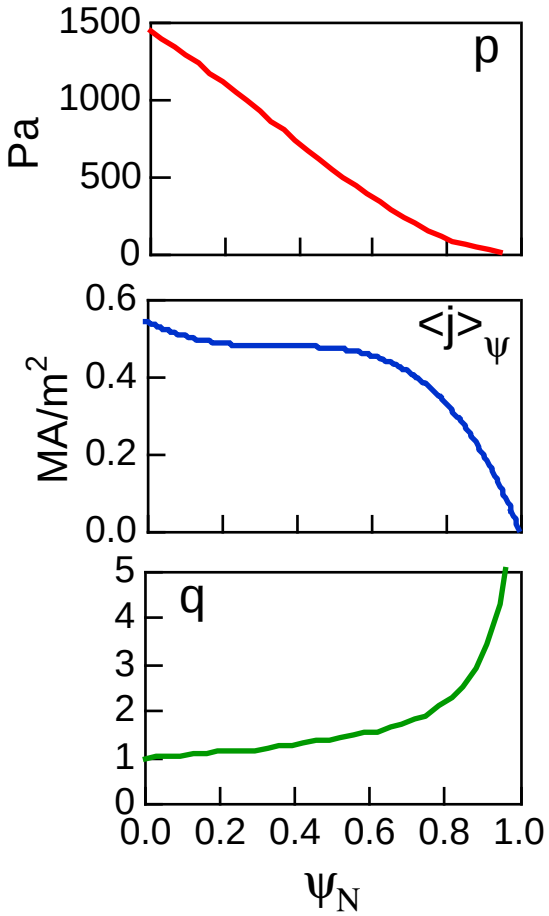
Equilibrium reconstructions show low-A characteristics

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

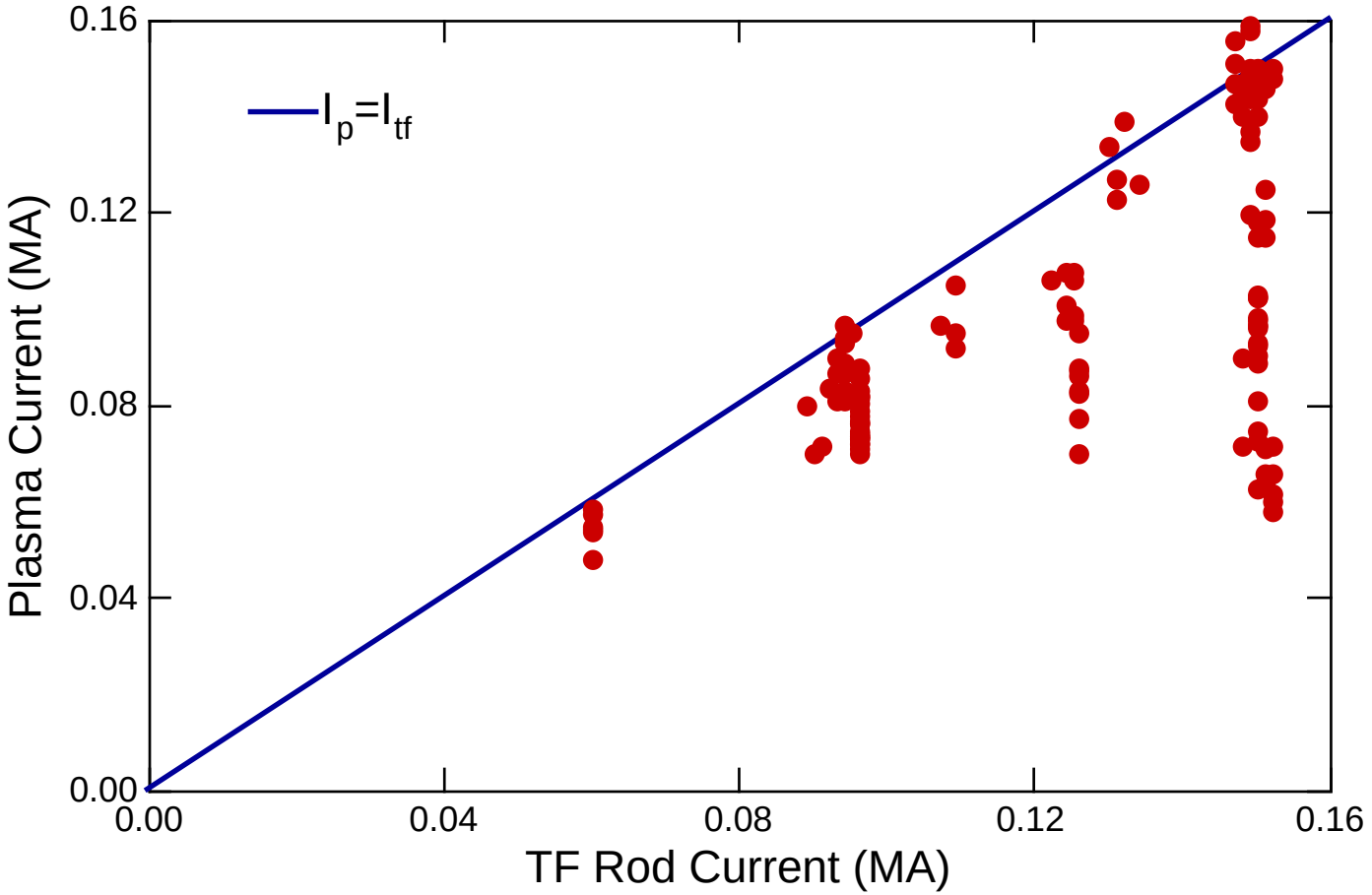




I_p	154 kA
R_0	0.34 m
a	0.29 m
A	1.15
κ	1.33
F_0	0.03 T-m
β_t	18%
W	570 J
l_i	0.54
q_0	1.0
q_{95}	4.3

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

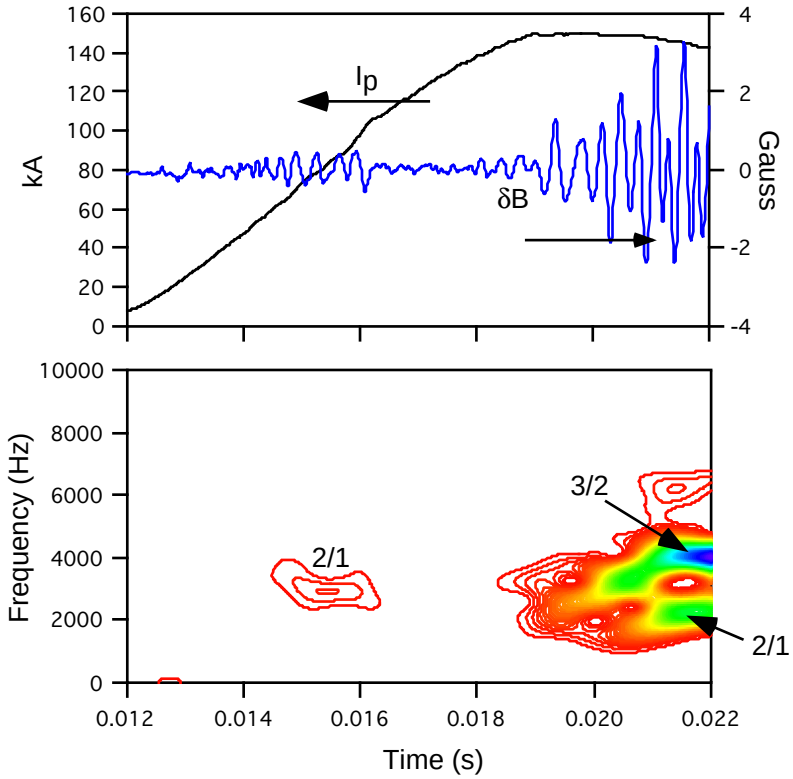
Large resistive MHD instabilities degrade plasma as TF ↓

- 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

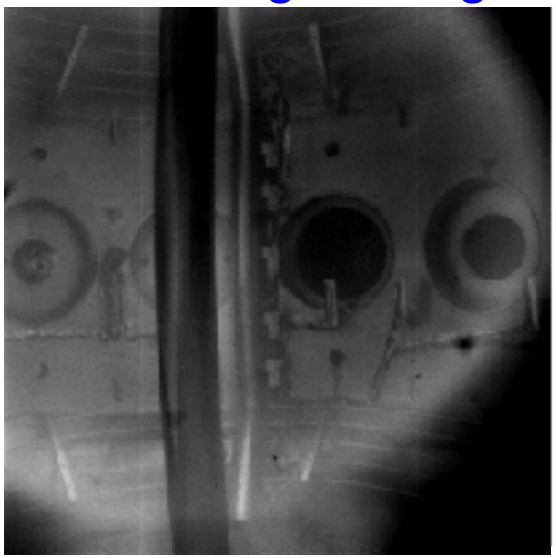


Reduced effective Volt-seconds as TF ↓

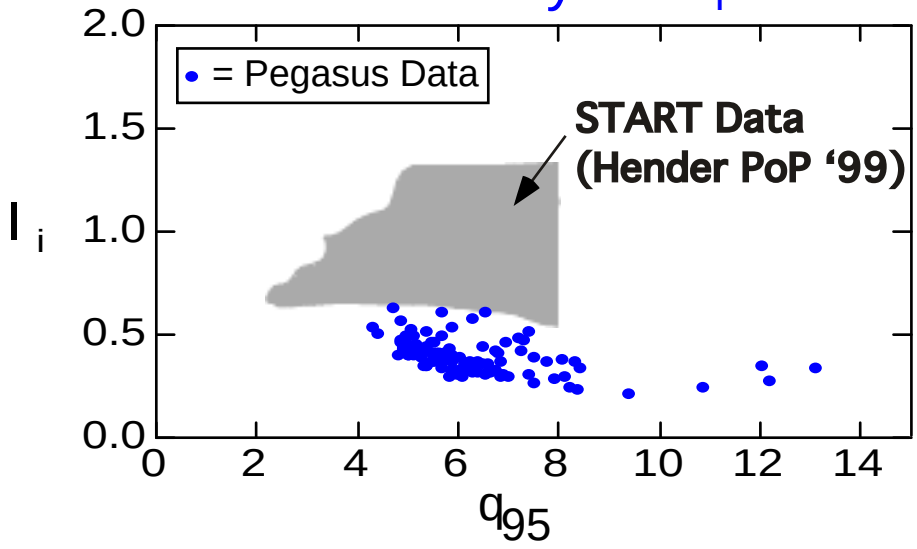
- reduced toroidal field $\rightarrow$ delayed startup
- delayed startup + fixed sine V_{loop} waveform $\rightarrow$ reduced effective V-s

PEGASUS operates in low-l_i, high-density space

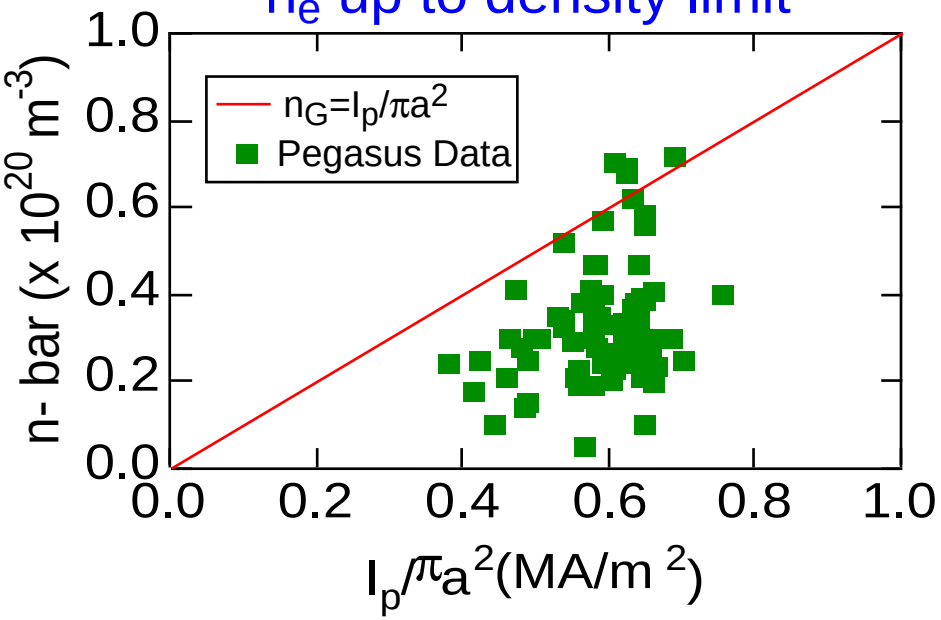
Visible light image



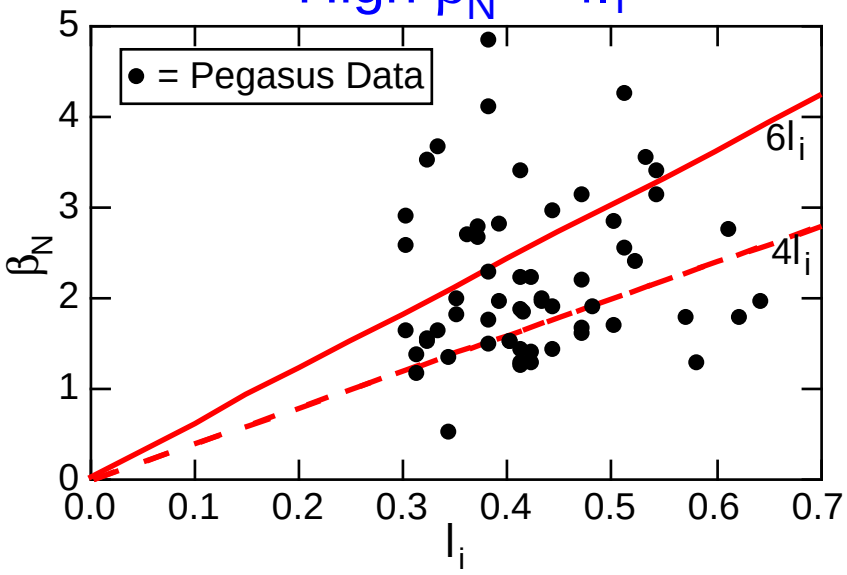
Generally low l_i



$\overline{n_e}$ up to density limit

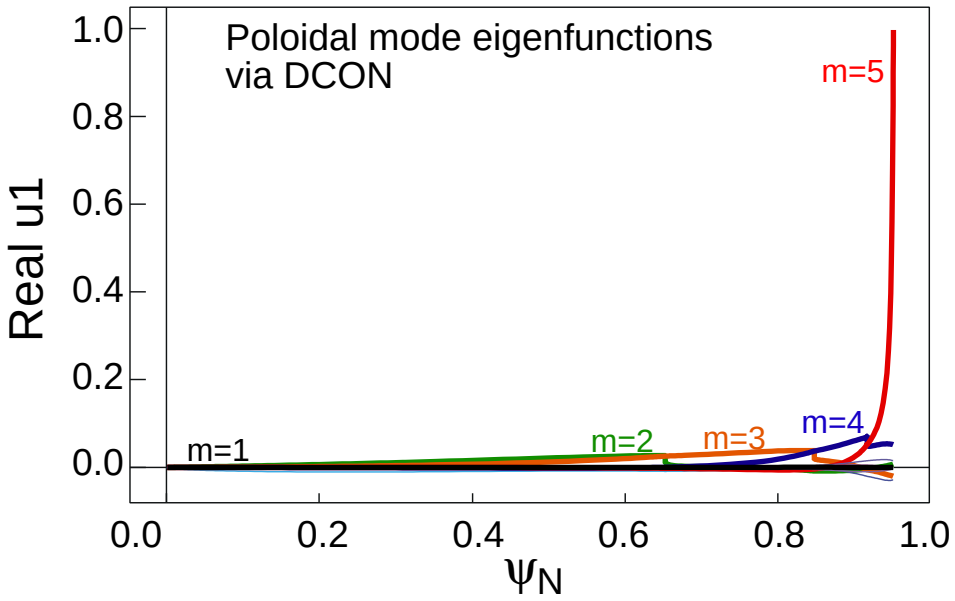


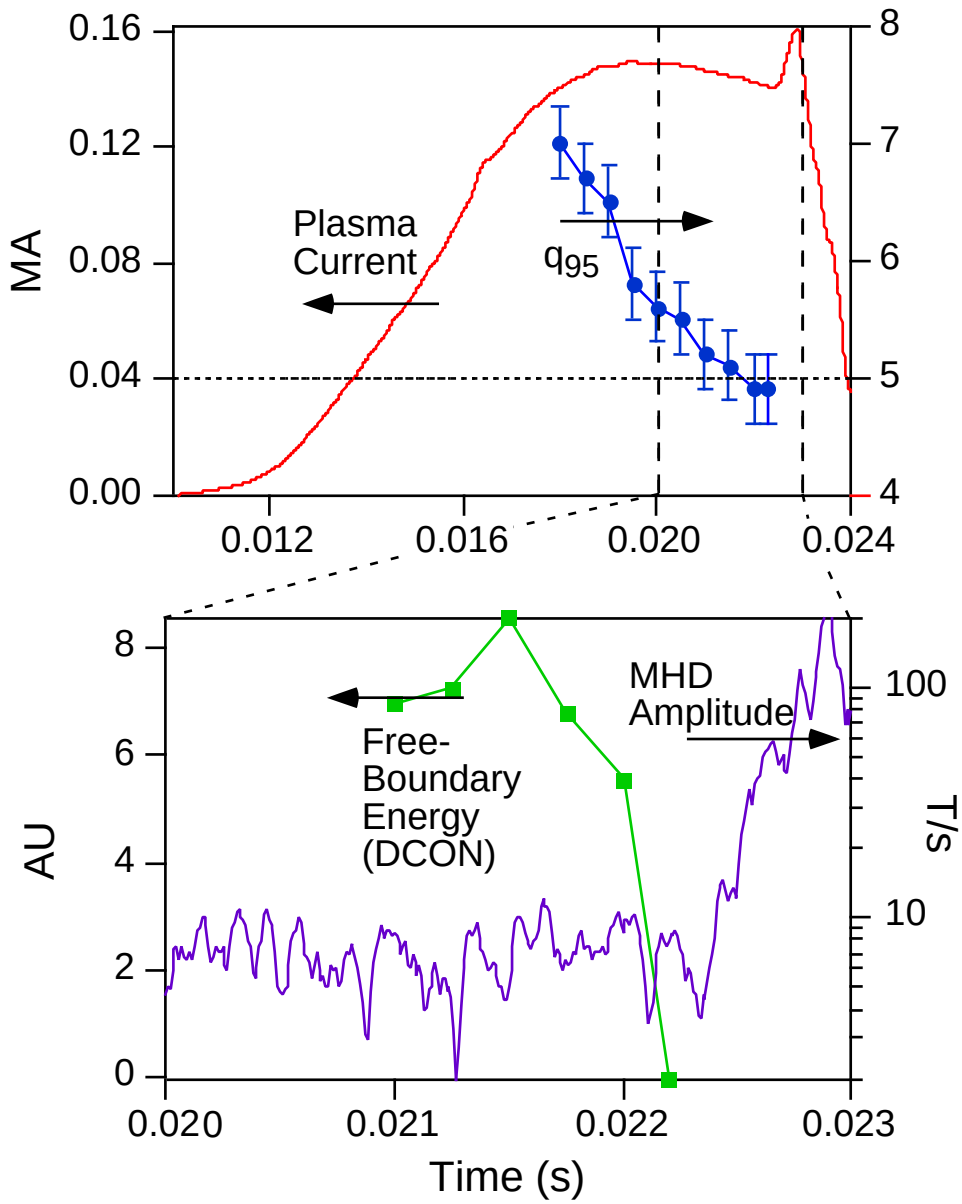
High $\beta_N > 4l_i$



High q_{95} external kink limit observed

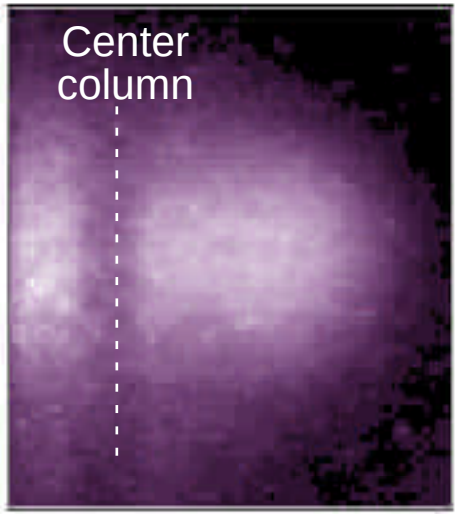
- High I_p plasmas often disrupt
- q_{95} = 5 observed preceding disruption
  - l_i=0.5 at this time
- DCON analysis ⇒ unstable to n=1 external kink
  - m=5 most unstable mode
- Consistent with theory expectation





Measured q-profile indicates low central shear

Tangential PHC SXR image



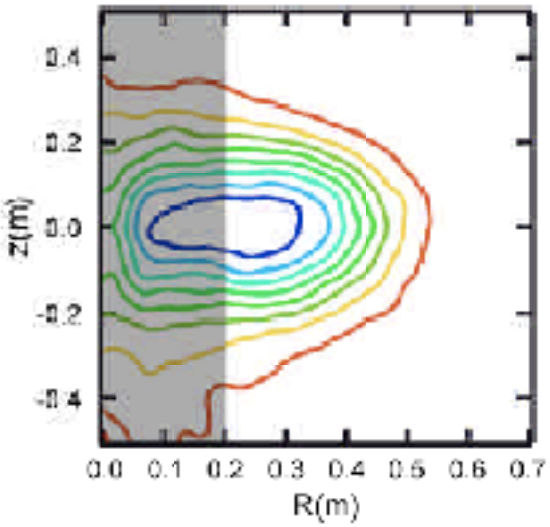
- 2D soft x-ray camera gives q-profile
  - Images soft x-rays
  - Constant-intensity surfaces determined
  - Mapped into flux space
  - G-S equation with SXR constraints
  - Iterate solution until convergence

- Measured q-profile ⇒ low central shear

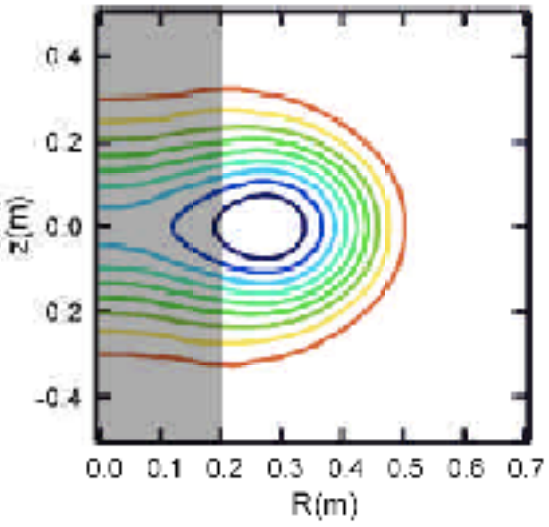
⇓

Image Contours:

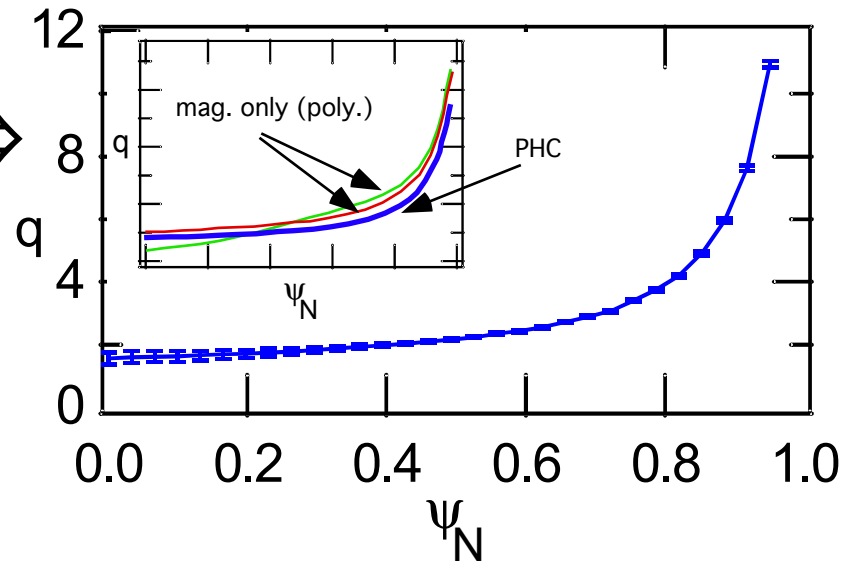
Measured



Reconstructed



⇒

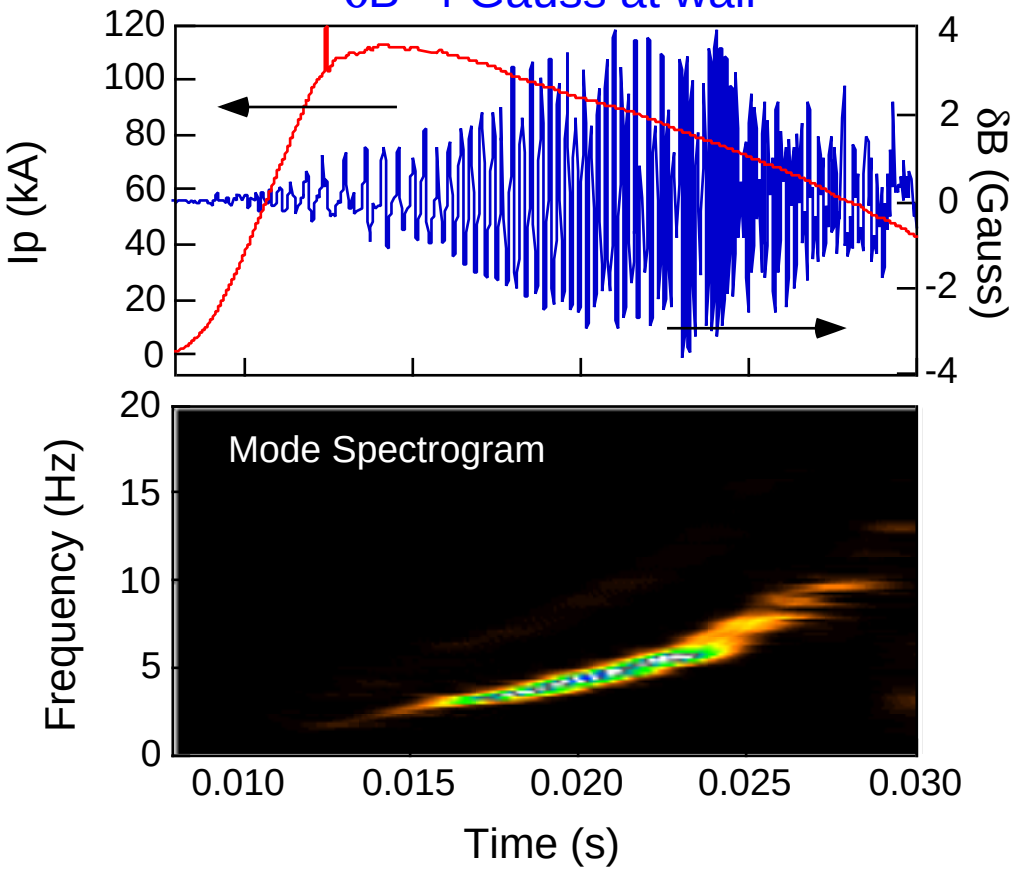


Island widths are on the order of plasma minor radius

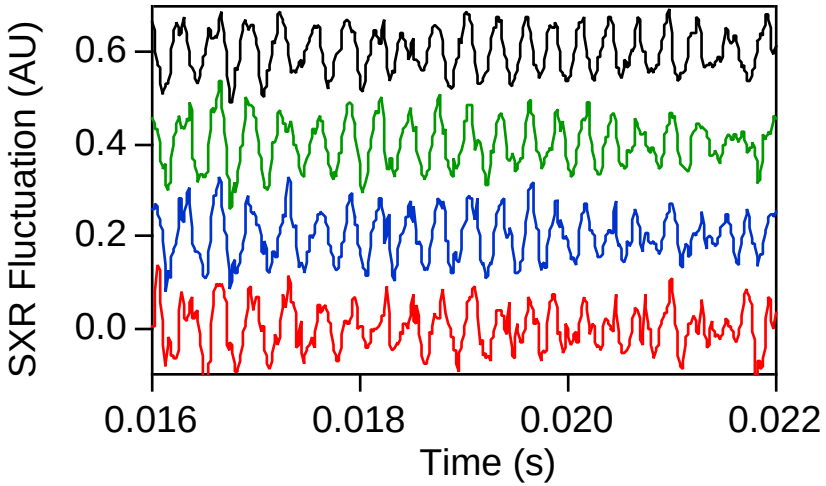
- Island width estimates give w>10 cm

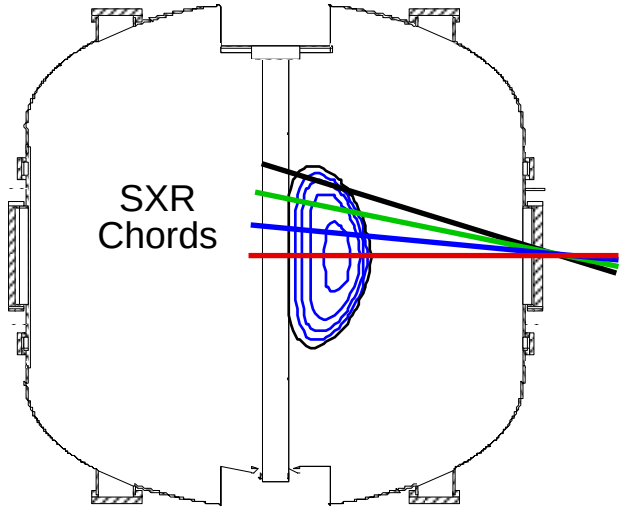
$$w \approx 4\sqrt{\frac{\delta B}{B_t}\frac{qR}{n\frac{dq}{dr}}} \sim \frac{a}{2}$$

- 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 $q(\psi)$
  - Lower η before $q(\psi)$ approaches low-order rational mode surfaces

- **Expand access to external kink modes studies**
  - Plasma time evolution, shape
  - Edge conditions and edge currents

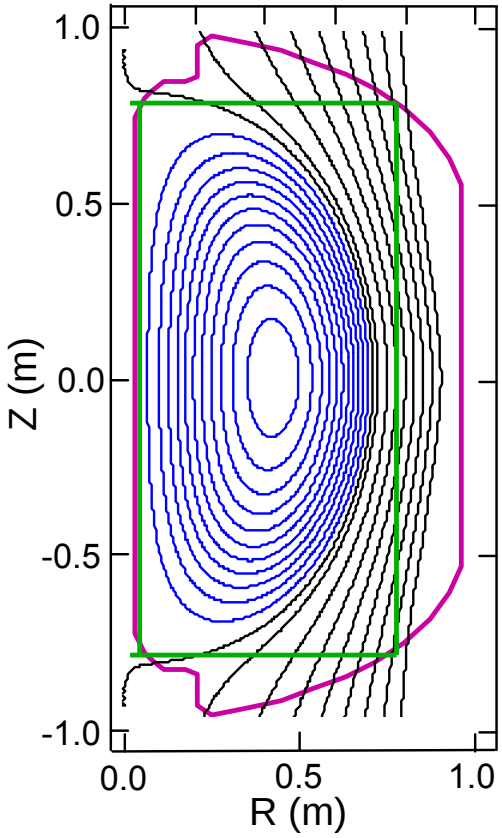
- **Access to very high β_t regime for stability analysis**
  - OH access and HHFW heating availible

DCON: Stable $l_p/l_{tf} > 1$ Equilibrium

- DCON modeling used to develop operating spaces for future run campaigns

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

Flux Plot

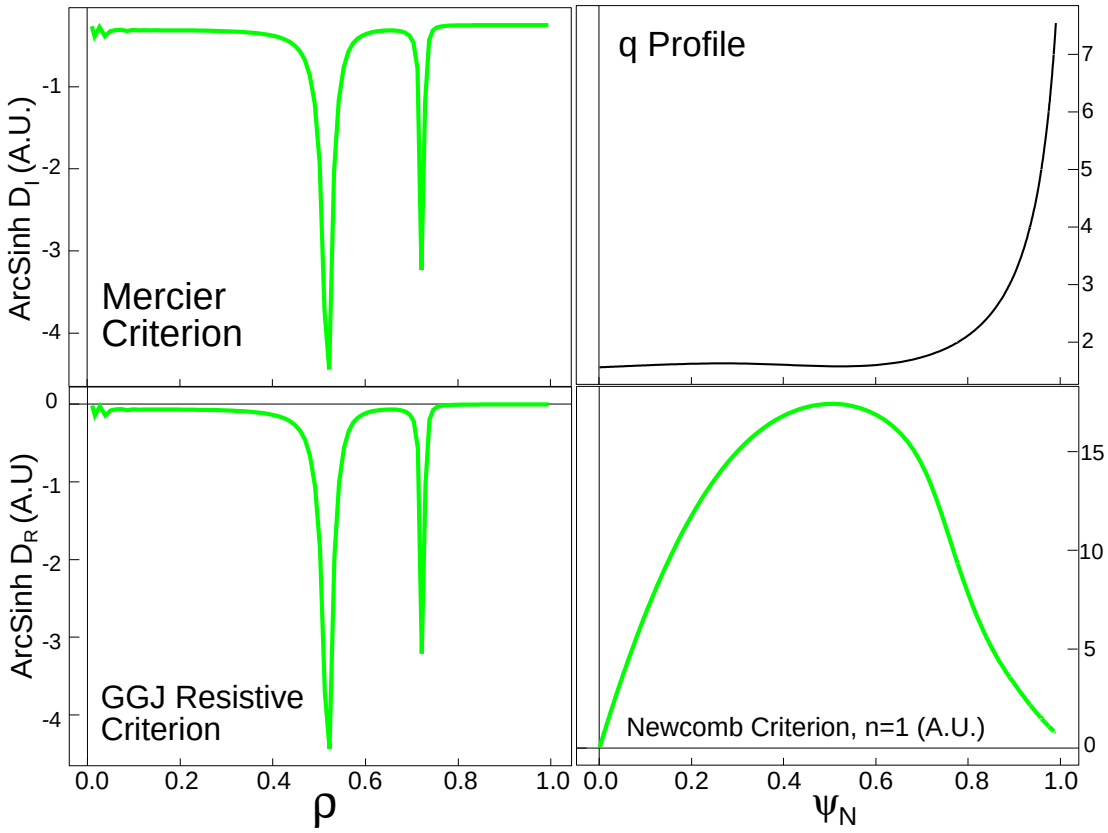


Equil. Paramters

I_p(kA)	290
I_N(MA/T-m)	12
I_p/I_{tf}	1.93
l_i	0.59
q_0	1.5
R_0(m)	0.39
a(m)	0.34
Elongation	2.2
q_{95}	4.8

DCON output

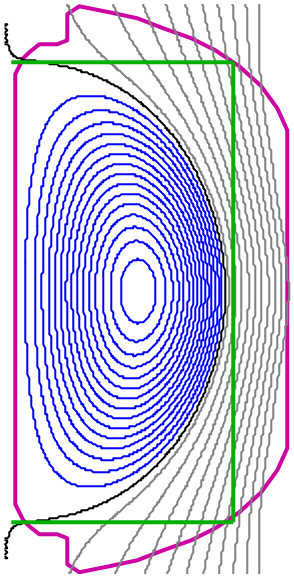
$D_I, D_R > 0$ => Unstable



I_p/I_{tf} ~ 3, I_N ~ 19 Modeled

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

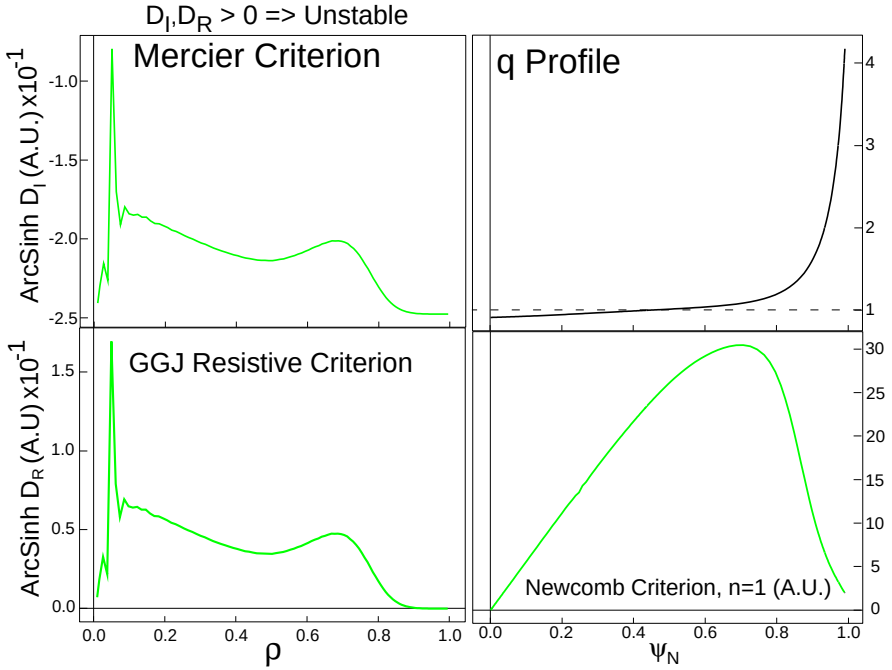
Flux Plot



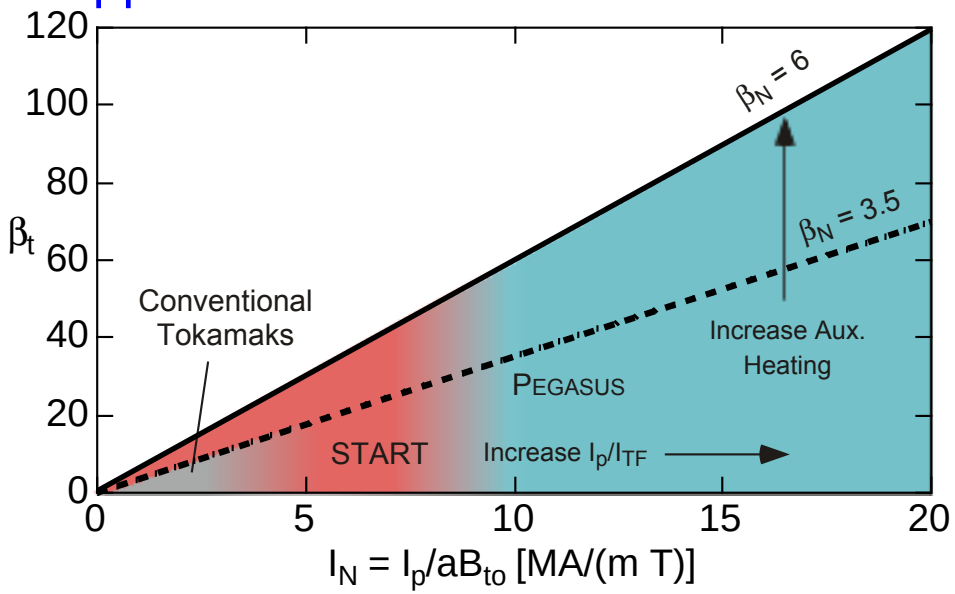
Equilibria Parameters

Ip(kA)	295
I_{tf}(kA)	90
I_N(MA/T-m)	18.9
li	0.68
q_0	0.91
R_0(m)	0.41
a(m)	0.36
Elongation	1.98
q_{95}	2.3

- DCON Output



- Approaches Phase II Goals of PEGASUS



st TF Rampdown is tool for q(r) and β manipulation

mp:

B_t, q_0 falls more slowly (on τ_R time scale)

ervation:

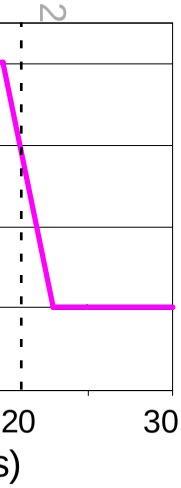
ven, l_i drops

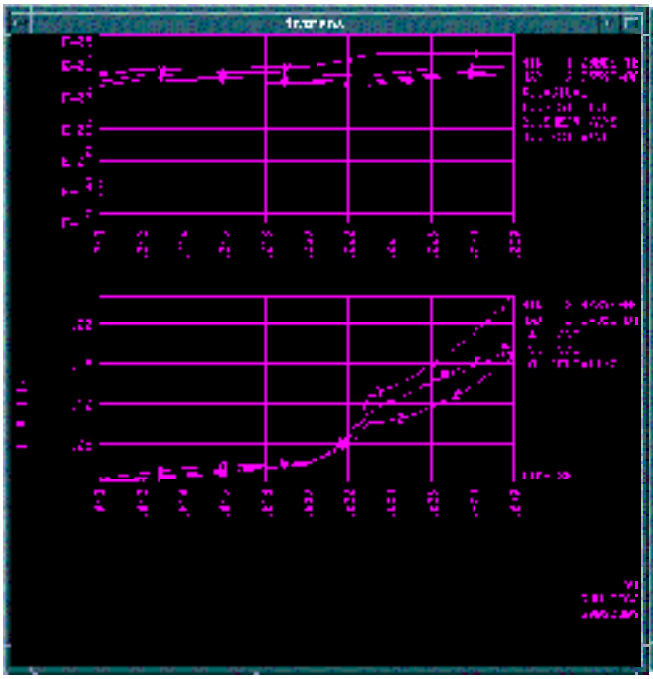
l I_p increase

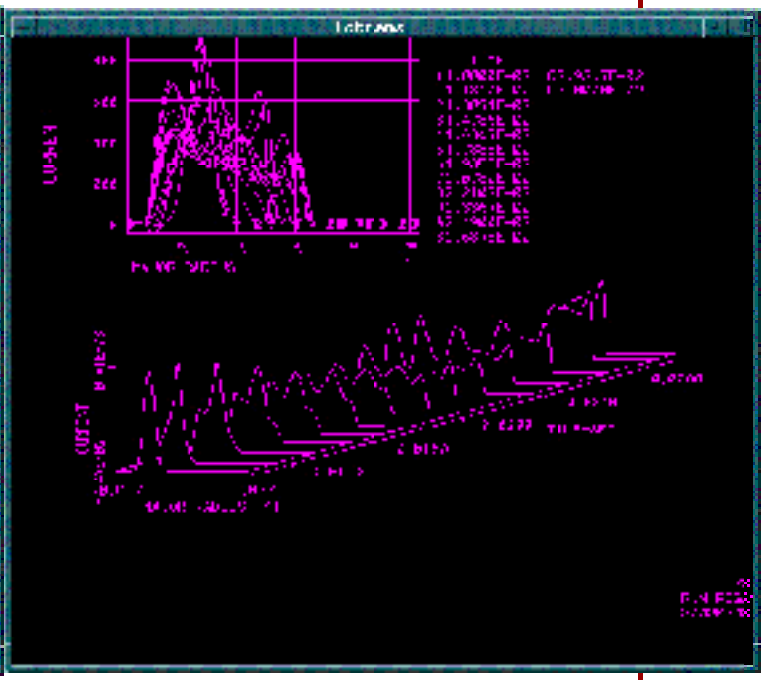
PEGASUS simulation:

- 0.03 T-m in 2 ms
- from 5% to 16%
- I_p: up from 90 kA to 140 kA
- Φ up from 1 to 6 mWb

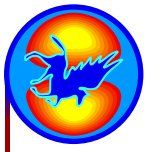
wn







New tools to access $l_p > l_{tf}$



T.A. Unterberg APS-DDP Albuquerque N.M. October 2003

earing modes early in discharge evolution

ently manipulate q during discharge:

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

e resistivity before low-order rationals appear

aximize J	=>	V_{loop} control, position & shape control
crease ohmic flux	=>	new ohmic power supply
e HHFW system	=>	position control, V_{loop} control

ge kink boundary at high field utilization

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



rades in Progress for All Coil Sets

E. A. Unterberg, APS-DDP, Albuquerque, N.M. October 2003

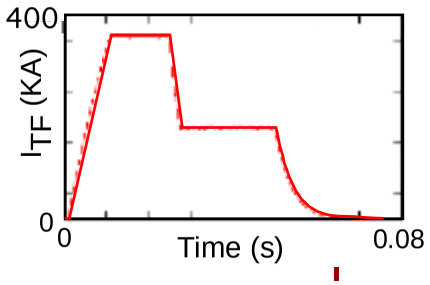
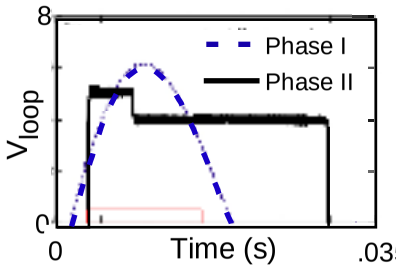
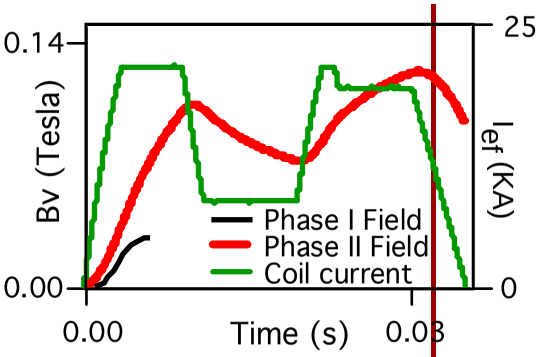
Phase I	Phase II	Example
• 60 turns	• 12 turns	
• Quasi-DC	• Fast time-variable	
• 150 kA-t max	• 450 kA-t max	
• Half-sine Waveform	• Programmable Waveform	
• ±40 KA	• ±50 KA	
• Monolithic coil set	• 5 Independent coils	
• 2 Resonant banks	• Programmability	
• Waveform constrained by startup concerns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



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

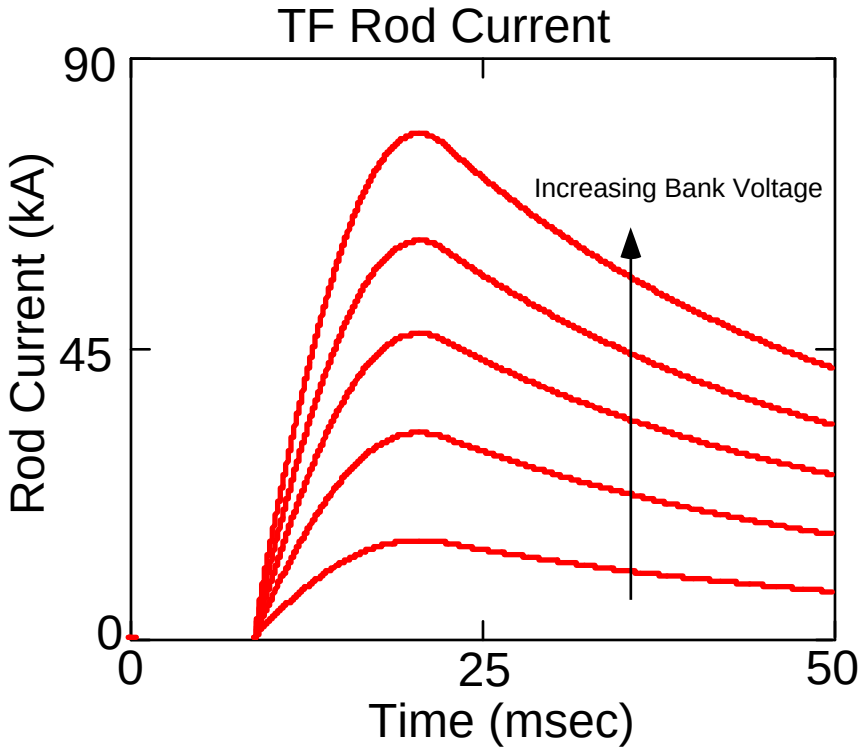
- All power now driven by solid-state IGBT and IGCT solid-state high power switches
  - Switches arranged in an H-bridge (SPA)
  - Many thanks to the HIT Group for their assistance
- See Poster QP1.068; J.C. Quinn for details

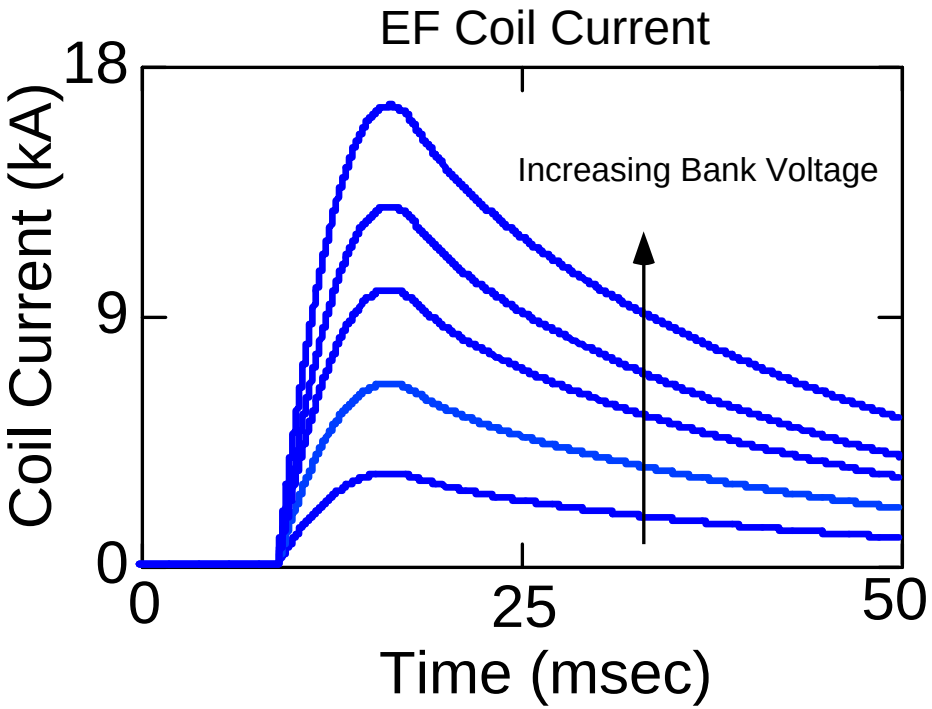




Current Status

- **Power testing has begun**
- **EF and TF coils tested to nominal currents**
  - Full stress and cross-field testing to follow
  - OH cooling and cross-field tests in winter 2003
- **Scheduled first plasma: winter 2003**





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*
    - $I_p/I_{tf} \sim 1$
    - $l_i \sim 0.4$
  - Characteristics of High I_p/I_{tf} 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 => modeled* $I_p/I_{tf} \sim 2$ - 3
    - *TSC for shot simulations and high* I_p/I_{tf} *accessibility*
  - Upgrades to increase access to this regime
    - *Increased V-sec.; position and shape control;* B_{TF} *versus time*
    - *EF and TF power testing has started; full-stress, cross-field, and OH testing to follow*



Reprints

