The PEGASUS Toroidal Experiment: Results and Recent Upgrades

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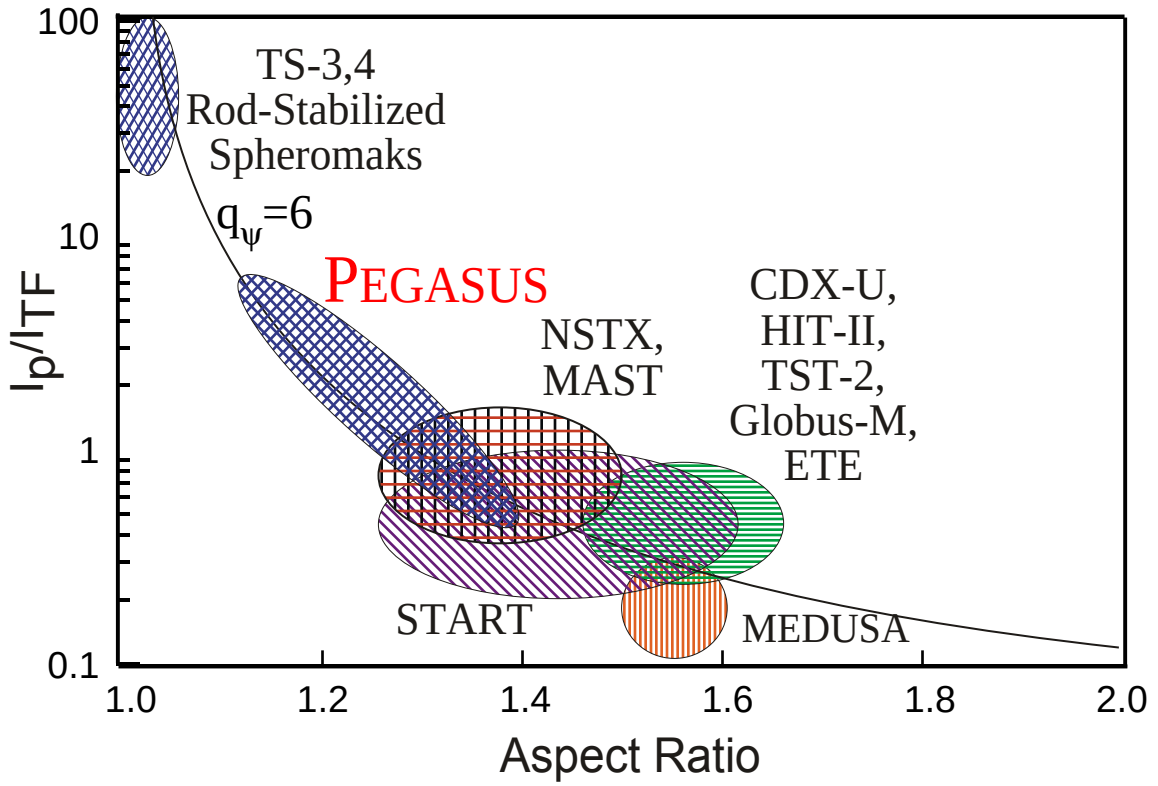


Overview

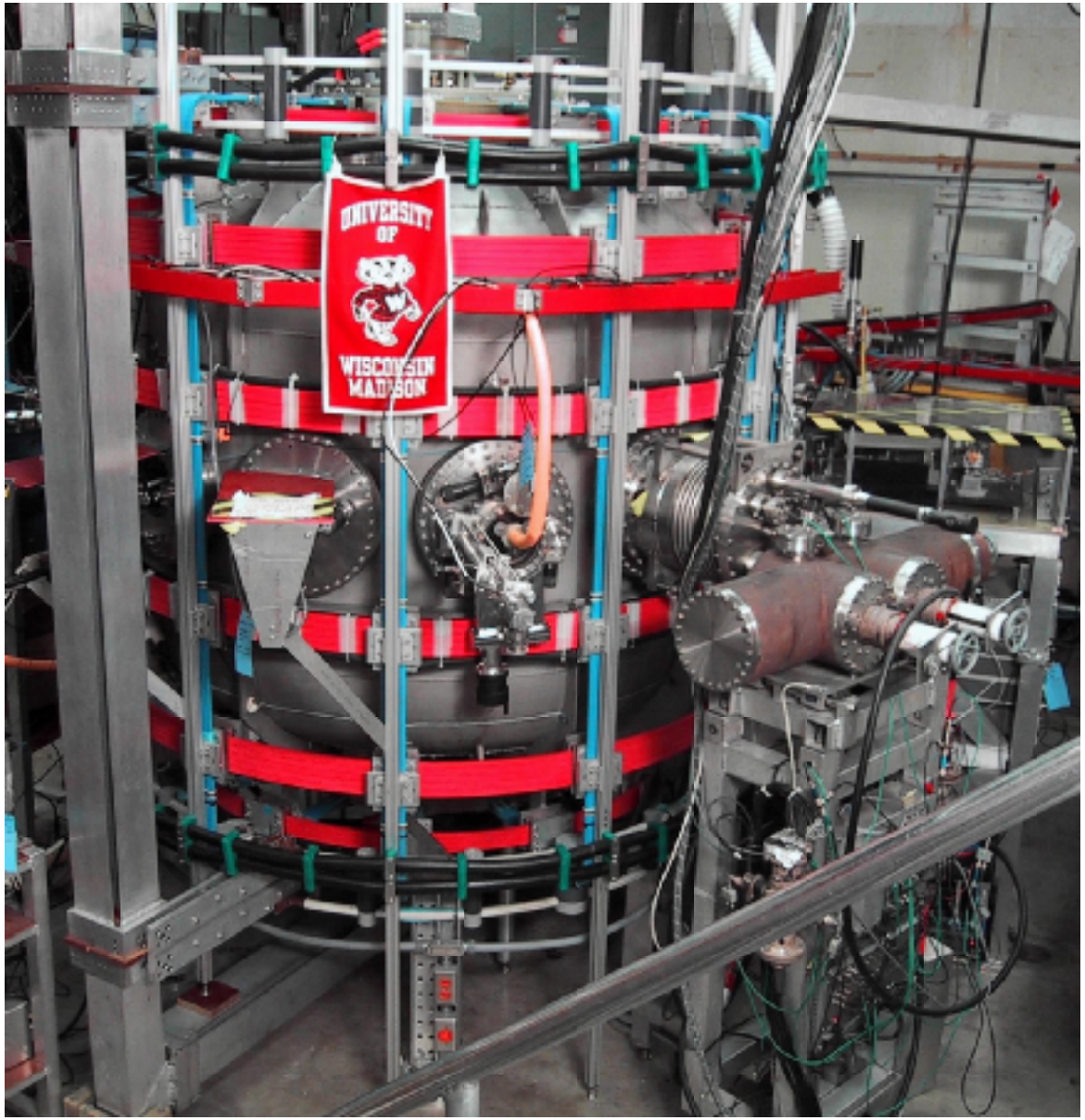
- Pegasus: ultra-low A ST designed to study stability limits as $A \rightarrow 1$ and $I_p/I_{TF} > 1$
- High β_t and $I_p = I_{TF}$ achieved ohmically
- Low-order tearing modes and ideal kinks limit access to higher performance
- Path to high I_p/I_{TF} and β via suppression of instabilities
- Significant upgrades are being conducted
- Upgrades will advance the experiment mission by improving plasma control

Mission: Explore plasma limits as A→1

- 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



Pegasus facility produces ultralow-A plasmas



Phase I: Achieved Parameters

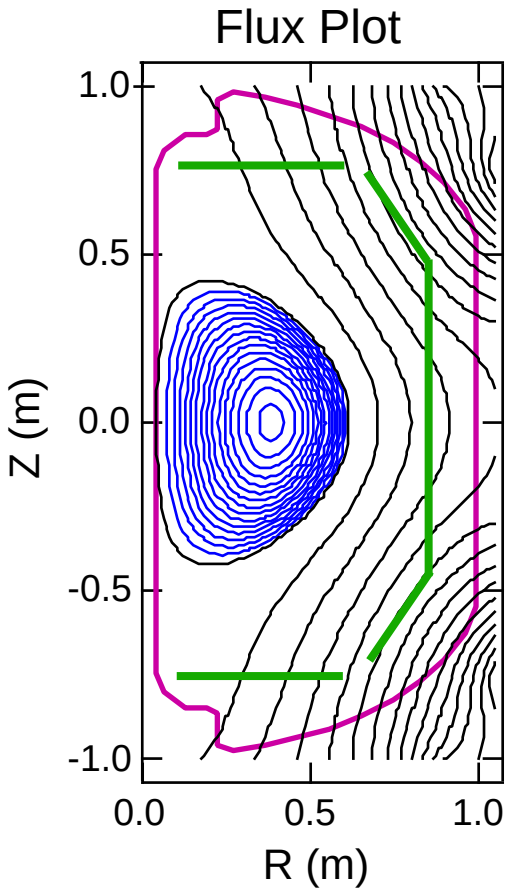
A	1.15-1.3
R	0.2-0.45 m
I_p	0.16 MA
RB_t	≤ 0.03 T-m
κ	1.4 - 3.7
Δt_{pulse}	0.01-0.03 s
$\langle n_e \rangle$	$1\text{-}5 \times 10^{19} m^{-3}$
β_t	≤ 25%

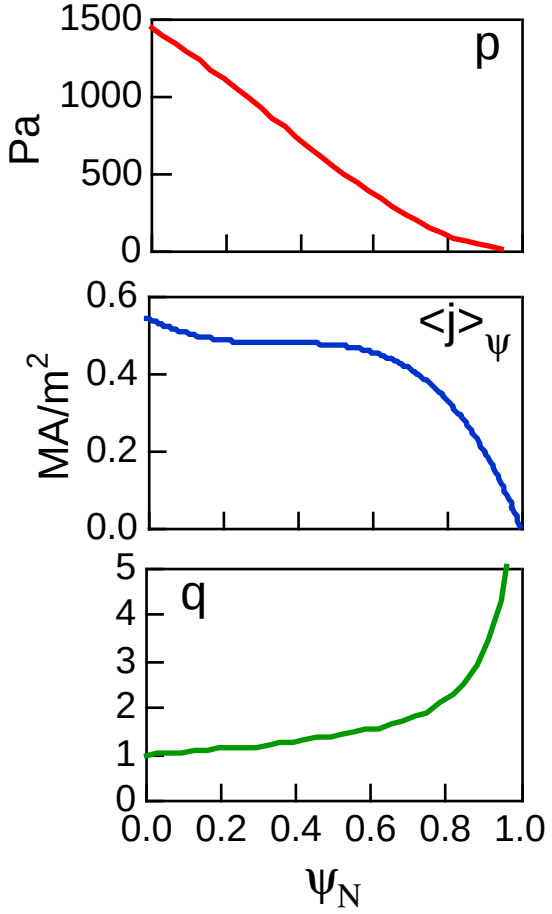
Equilibrium reconstructions show low-A characteristics

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

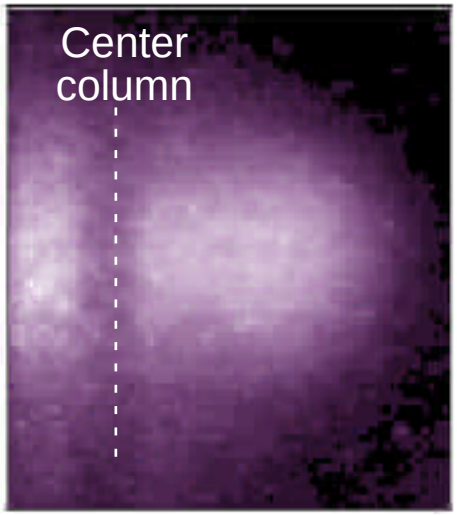




I_p	154 kA
R_0	0.34 m
a	0.29 m
A	1.15
κ	1.33
F_0	0.03 T-m
β_t	18%
W	570 J
l_i	0.54
q_0	1.0
q_{95}	4.3

Measured q-profile indicates low central shear

Tangential PHC SXR image



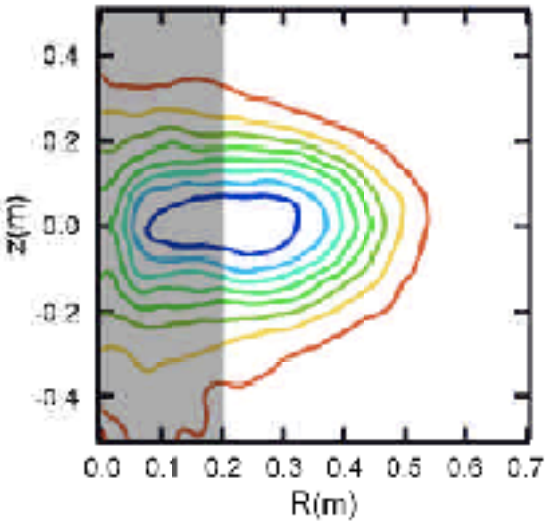
- 2D soft x-ray camera gives q-profile
  - Images soft x-rays
  - Constant-intensity surfaces determined
  - Mapped into flux space
  - G-S equation with SXR constraints
  - Iterate solution until convergence

- Measured q-profile ⇒ low central shear

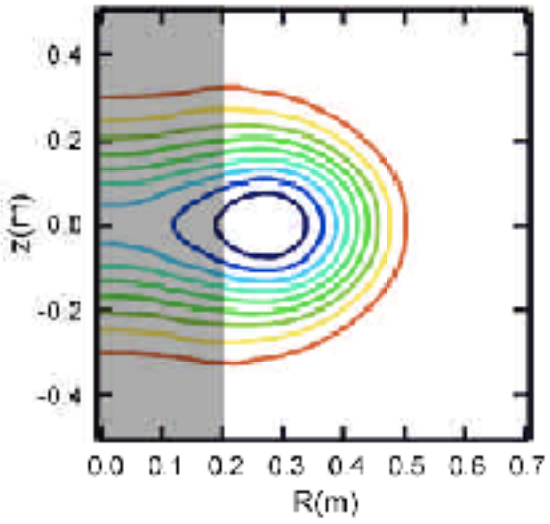
⇓

Image Contours:

Measured

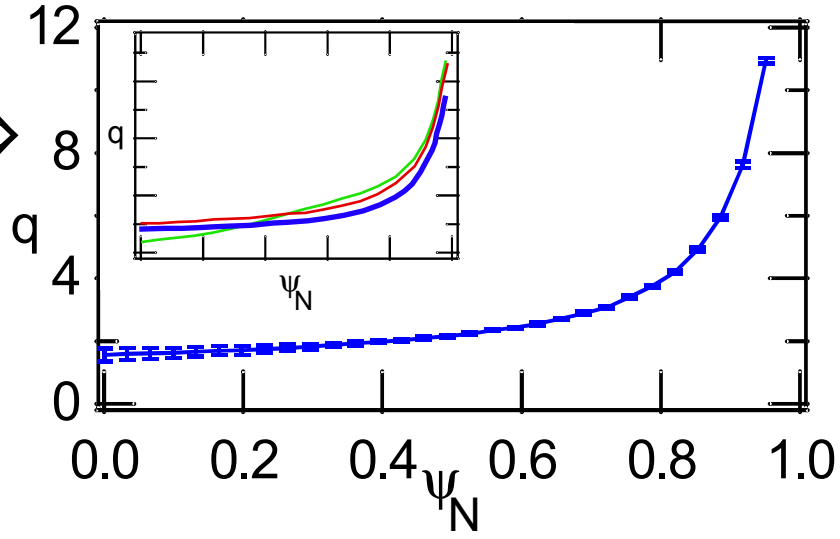


Reconstructed



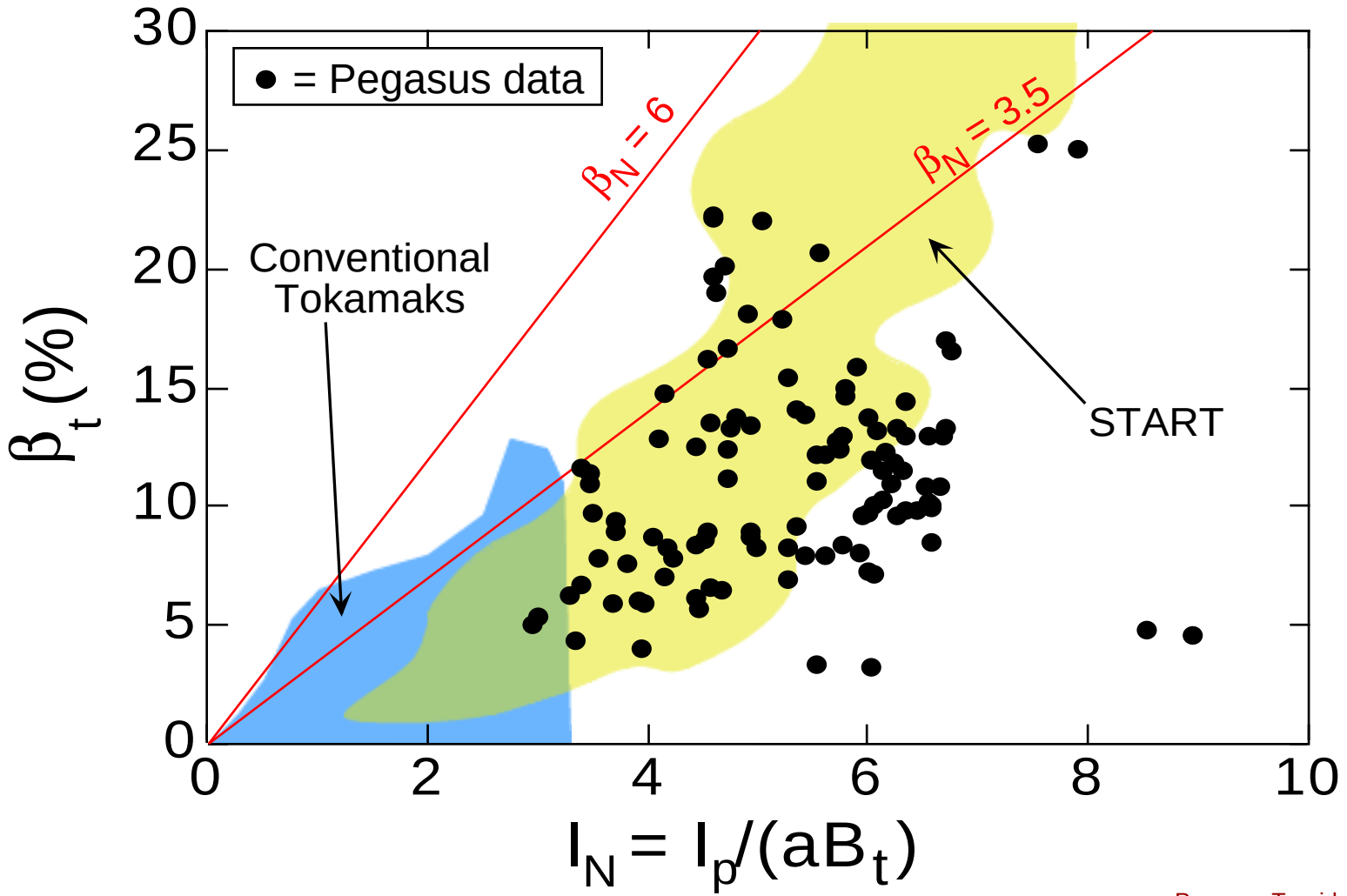
⇒

Reconstructed q-profile



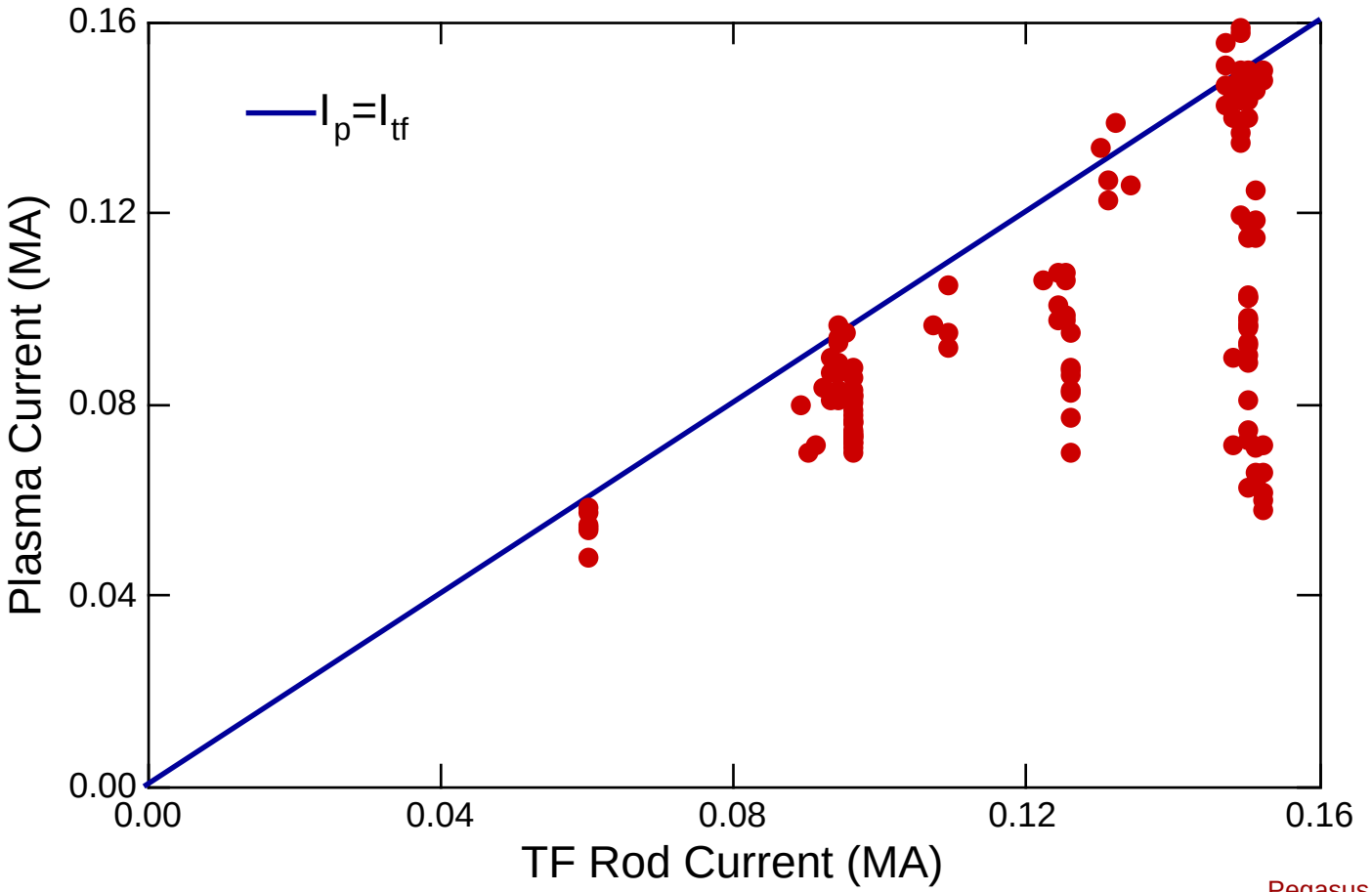
A < 1.3 → ready ohmic access to high β_t

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



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

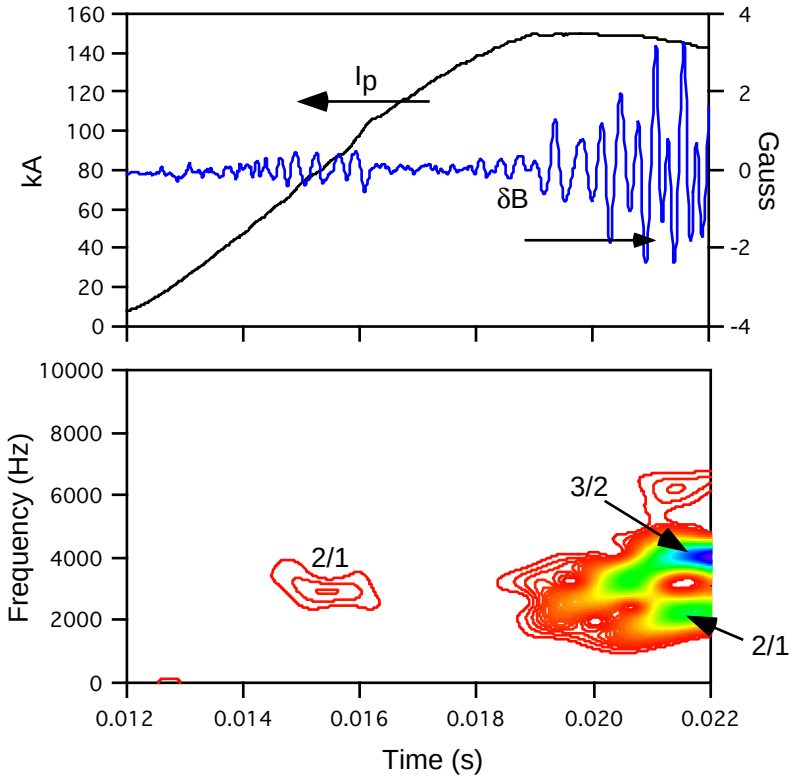
Large resistive MHD instabilities degrade plasma as TF ↓

- 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



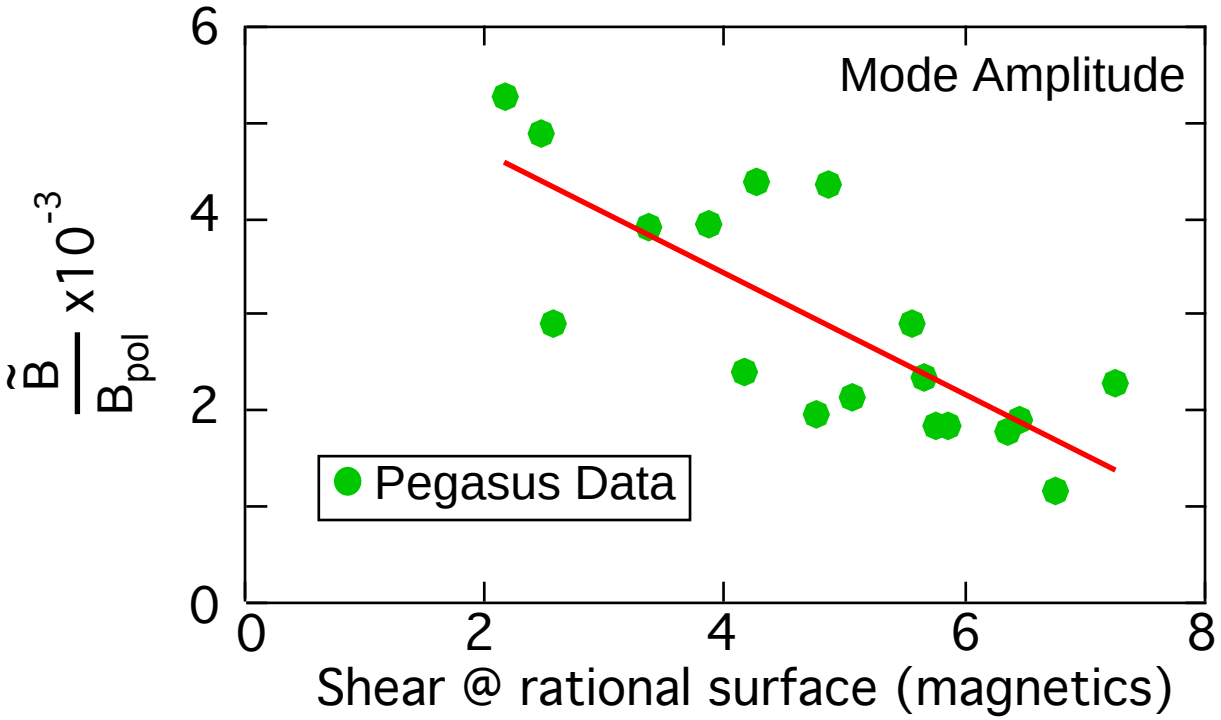
Reduced effective Volt-seconds as TF ↓

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

Mode amplitude reduced by manipulation of shear and q_0

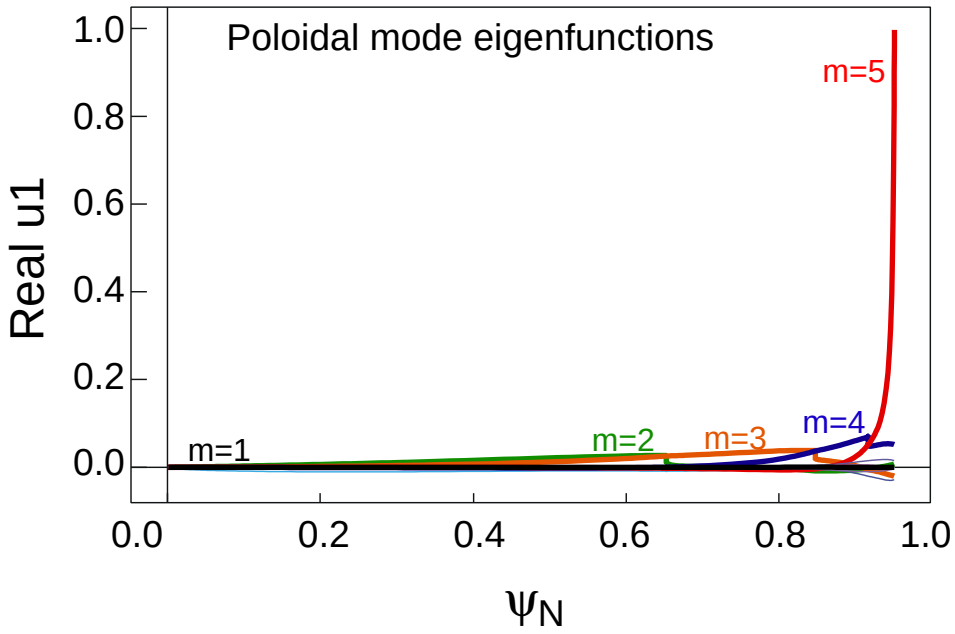
- Discharge tailoring $\rightarrow$ plasmas with reduced MHD activity
  - Increased W, I_p
- Increased shear, increased $q_0 \Rightarrow$ delay tearing onset
- MHD amplitude decreases with increasing shear

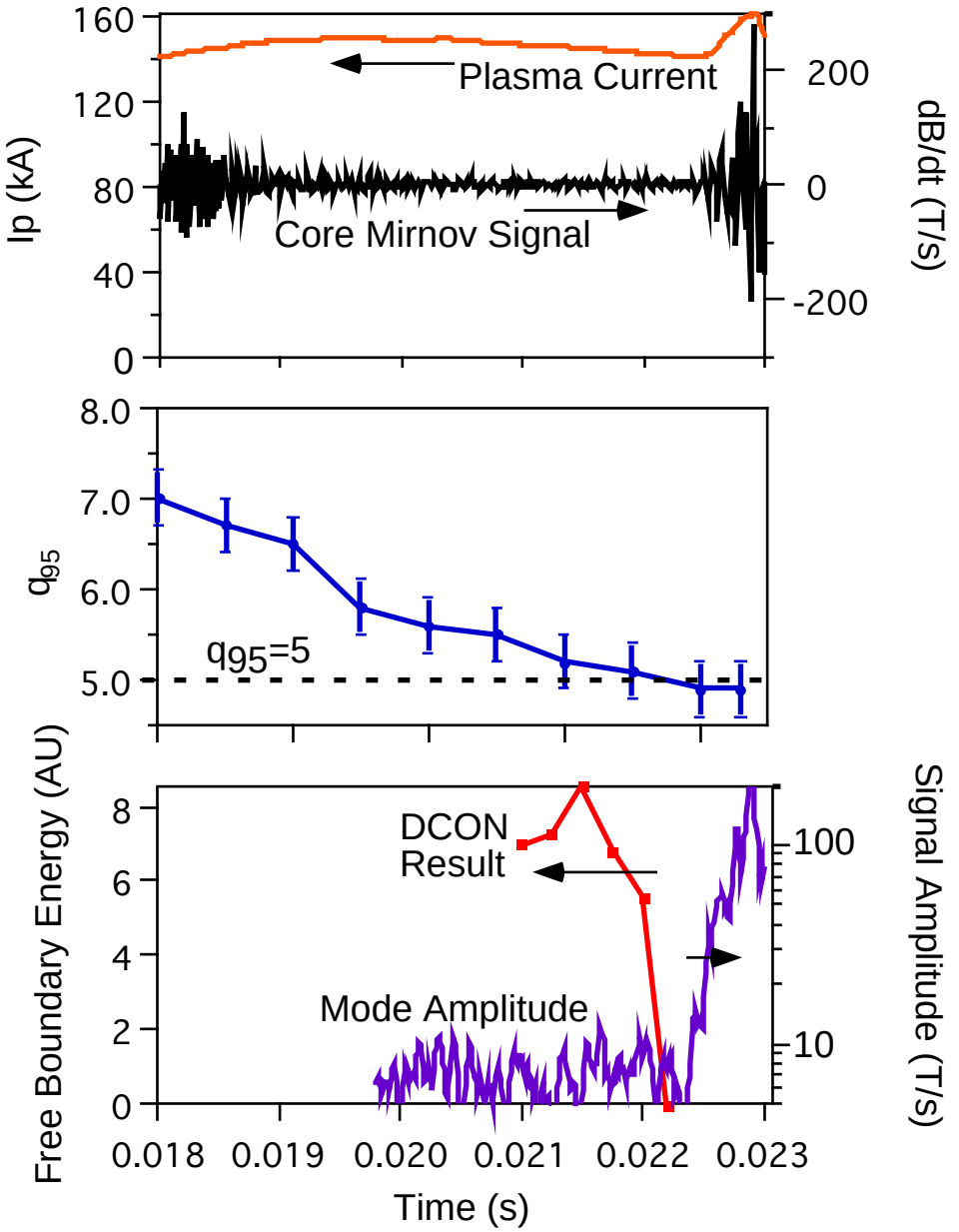
$\Rightarrow$ Access higher I_p/I_{TF}, β_t via increased q_0, T_e, shear



External kink instability also limits field utilization

- High l_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





Path to high β_t and I_p/I_{TF}: mitigate early MHD

- $I_p > I_{TF}$ regime accessed via suppression of tearing modes

  - Ohmic plasma: $I_p > I_{TF} \Rightarrow$ high β_t, low q

- Approaches and tools to increase I_p/I_{TF}

  - Transiently increase q during startup
    = $B_t(t)$

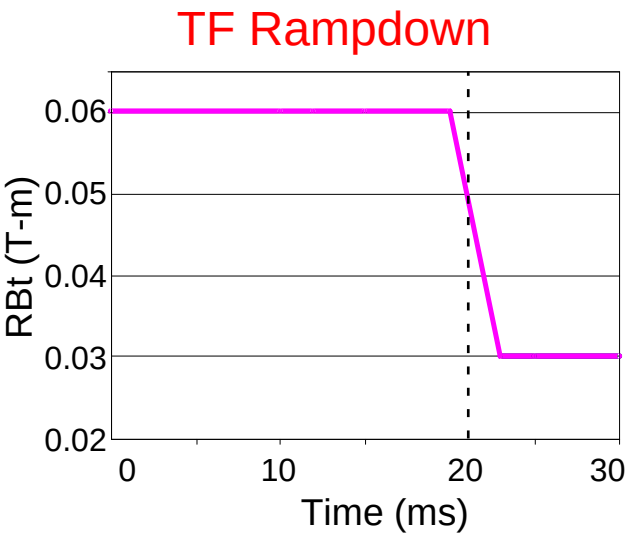
  - Manipulate current profile
    = V_{loop} control
    = position/shape control
    = $B_t(t)$

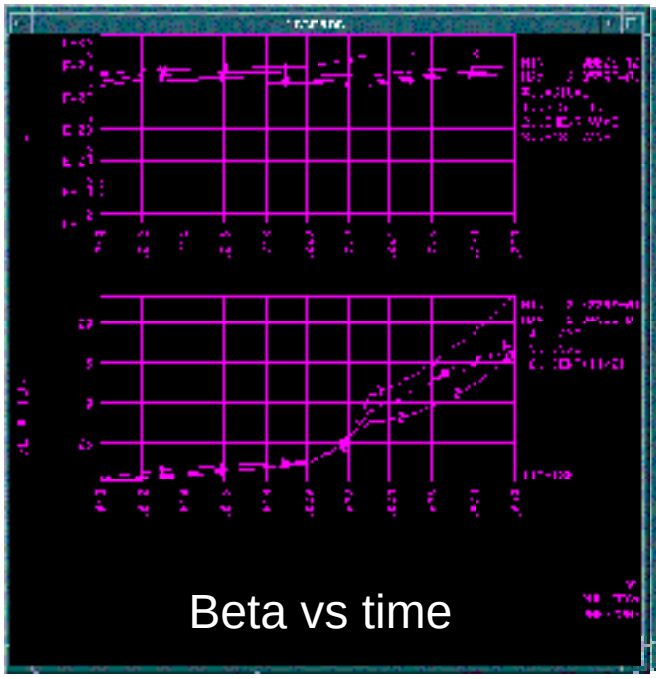
  - Reduce η before low-order rationals appear
    = V_{loop} control
    = position/shape control
    = RF heating (HHFW)

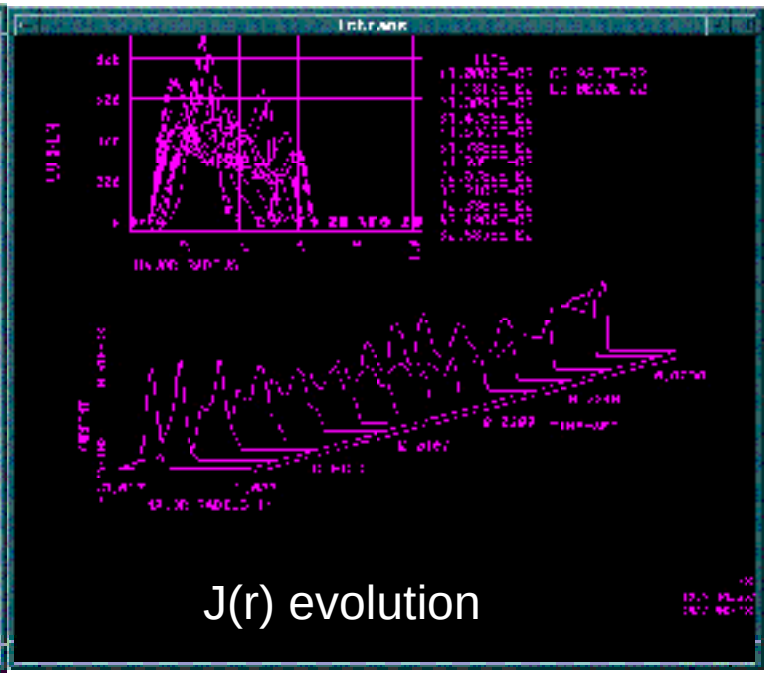
TSC: Fast TF rampdown is tool for q(r) and β manipulation

- 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







Experiment Status - Autumn 2003

- Phase I of plasma operations nearly complete in 2002
- Upgrades proposed for 2002-2005 grant period
- Power supply fire in April 2002
- Decision to “front-load” upgrades with post-fire rebuild
- Experiment hall closed for several months for PCB testing & cleanup
- Rebuild nearly complete - Phase II plasma ops resume late Fall 2003

Overview of Pegasus Phase II upgrades

- Power supplies entirely replaced
  - Maximum coil currents increased significantly
  - Solid state switches (SPA's) make waveform control available
  - 6 MJ of electrolytic capacitors installed outside of building
  - New power buses installed
  - Stray field "flux catcher" installed for public safety
- Low-inductance toroidal field centerstack installed
  - Provides increased, time-variable TF
- Lab infrastructure improved or replaced
  - Screen room installed for control and data acquisition hardware
  - Shielded cable trays installed around lab
  - New grounding system installed
  - Control system upgraded
  - Upgraded AC, air, and water services installed

Power supplies are being entirely replaced

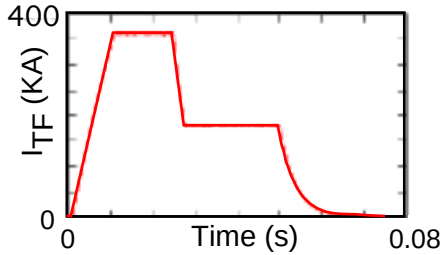
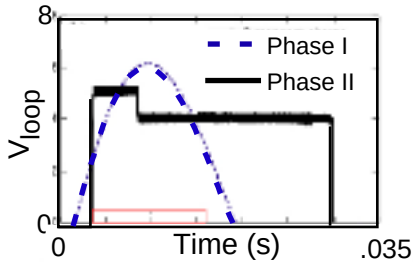
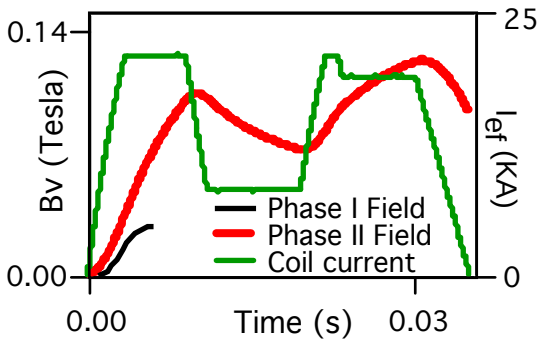
System	Phase I	Phase II	Example
Toroidal Field	• 60 turns • Quasi-DC • 150 kA-t max	• 12 turns • Fast time-variable • 450 kA-t max	
Ohmic Heating	• Half-sine Waveform • ±40 KA	• Programmable Waveform • ±50 KA	
Equilibrium Field	• Monolithic coil set • 2 Resonant banks • Waveform constrained by startup 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 (SPA)
  - Many thanks to the HIT Group for their assistance

Capacitor banks are installed (8/2003)



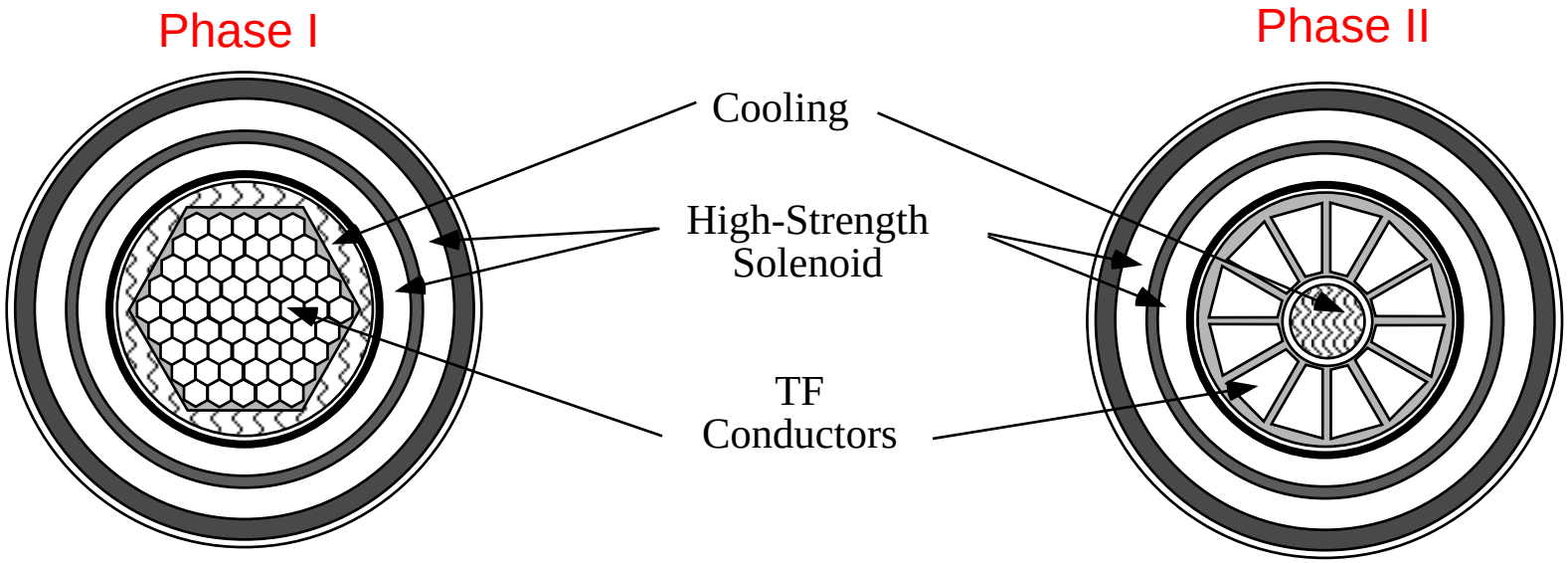


Capacitor banks installed in vault

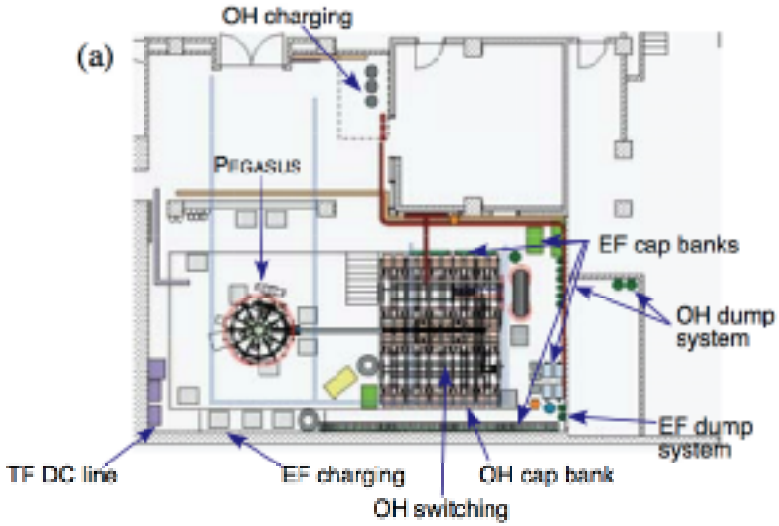


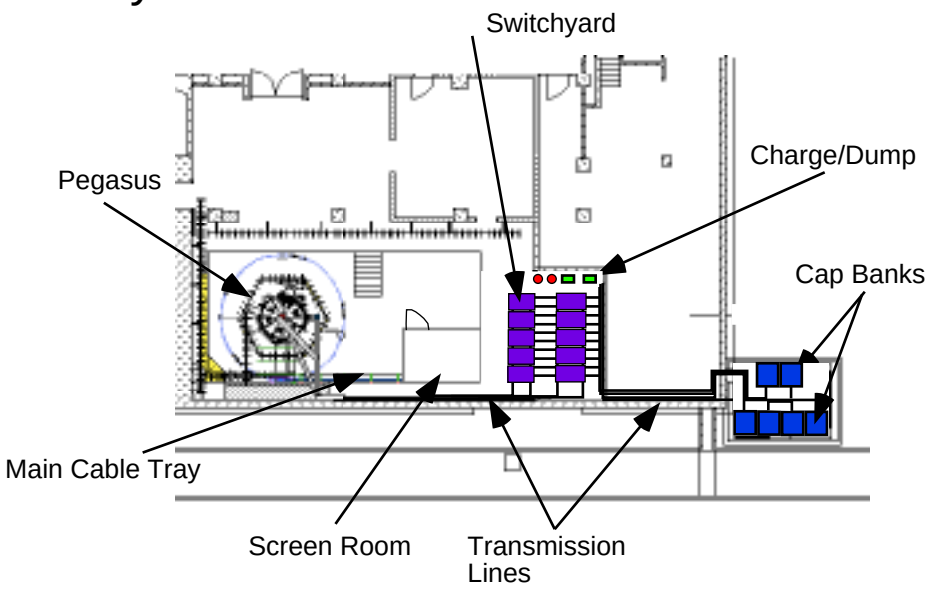
Extensive upgrades conducted on the facility

- Toroidal field centerstack replaced



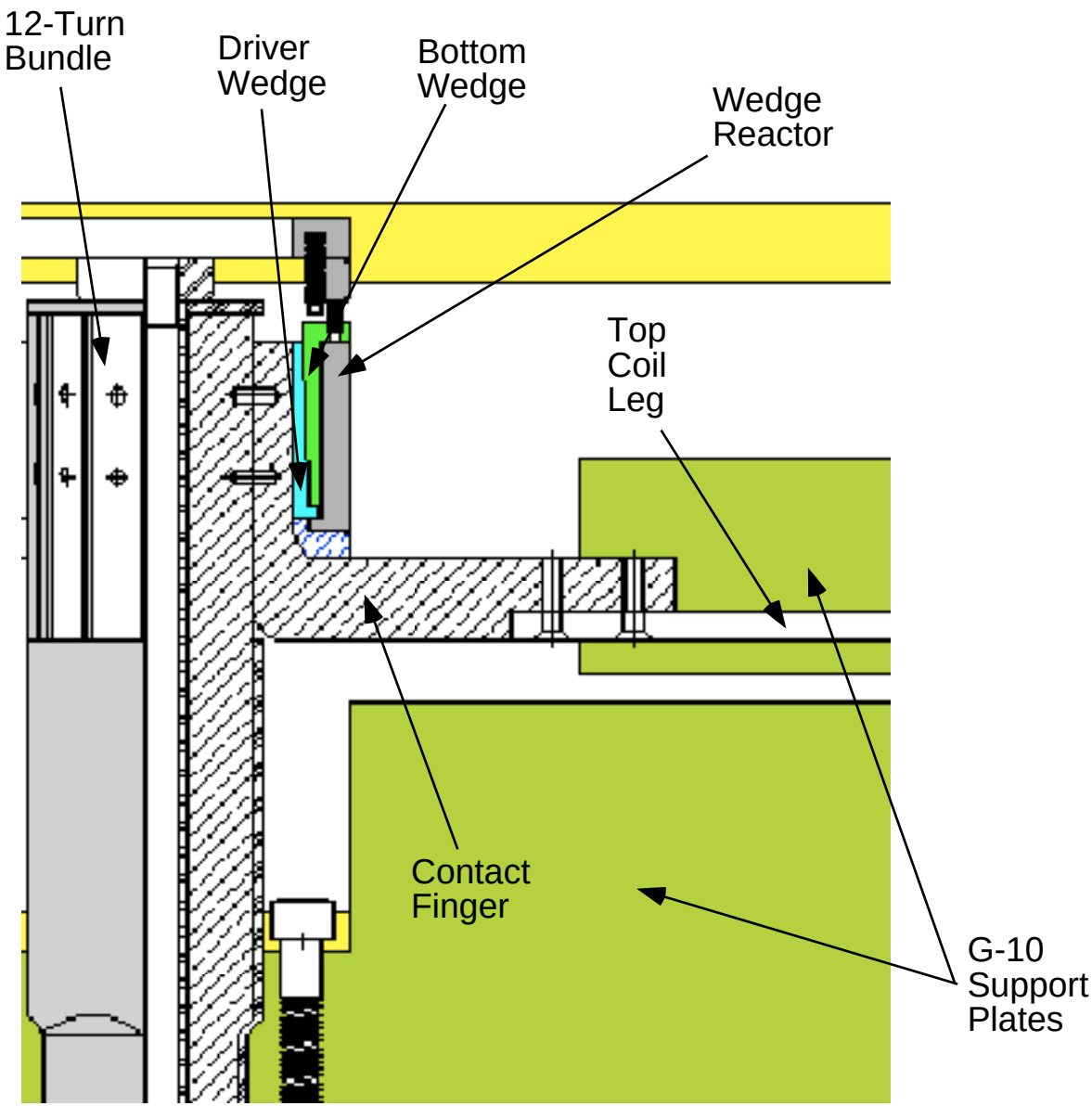
- Major upgrades conducted on the laboratory





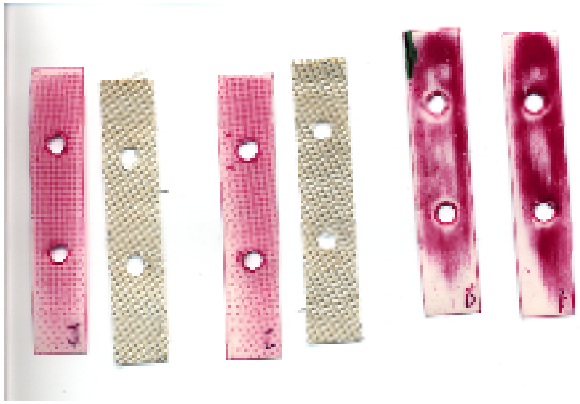
New toroidal field joint assembly is a critical area

Cross-Sectional Drawing (Top)

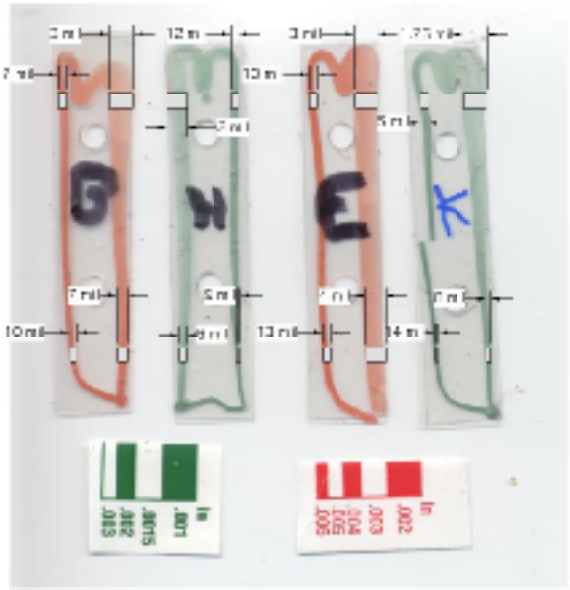


Fit-Check Diagnostics

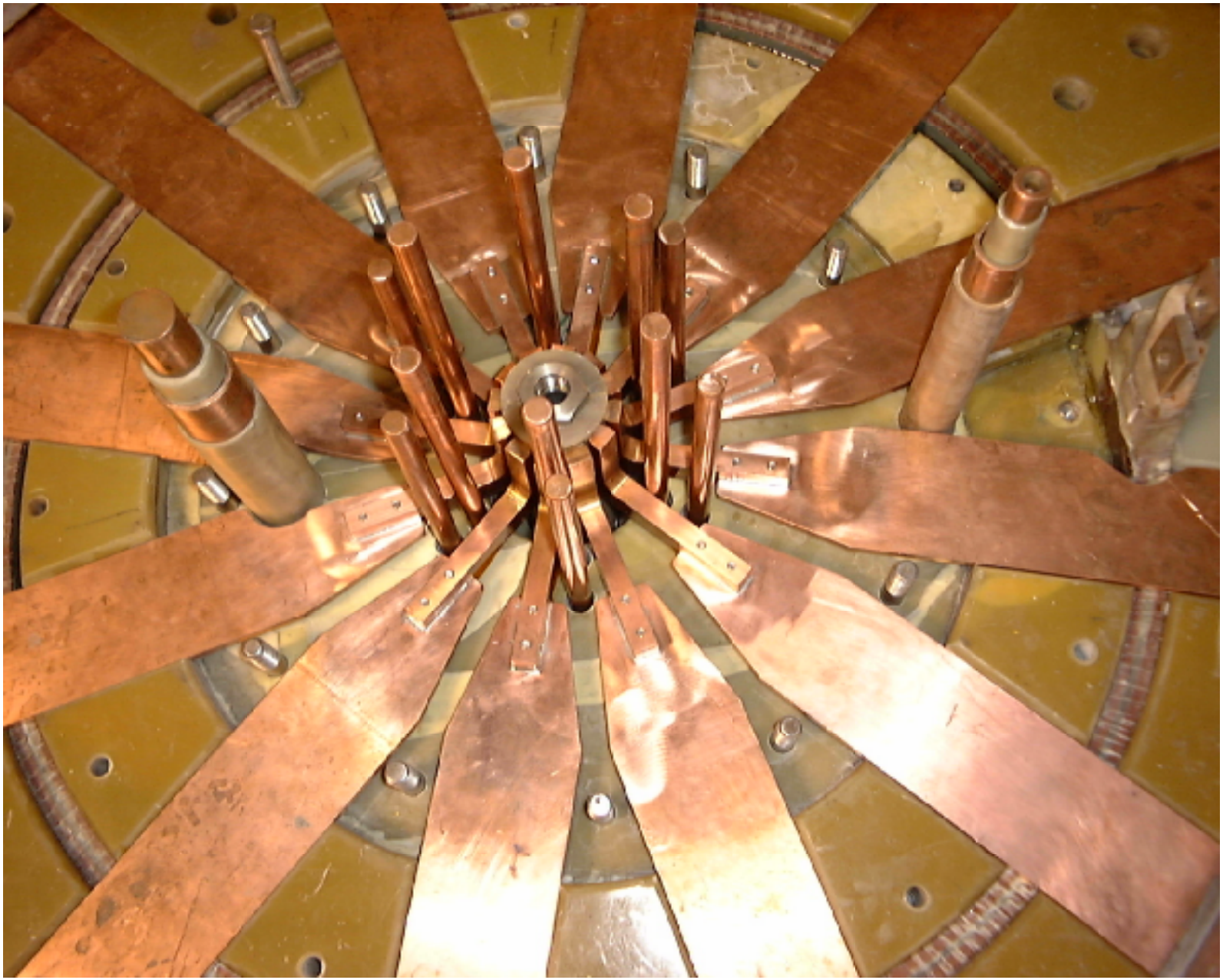
Pressure Paper



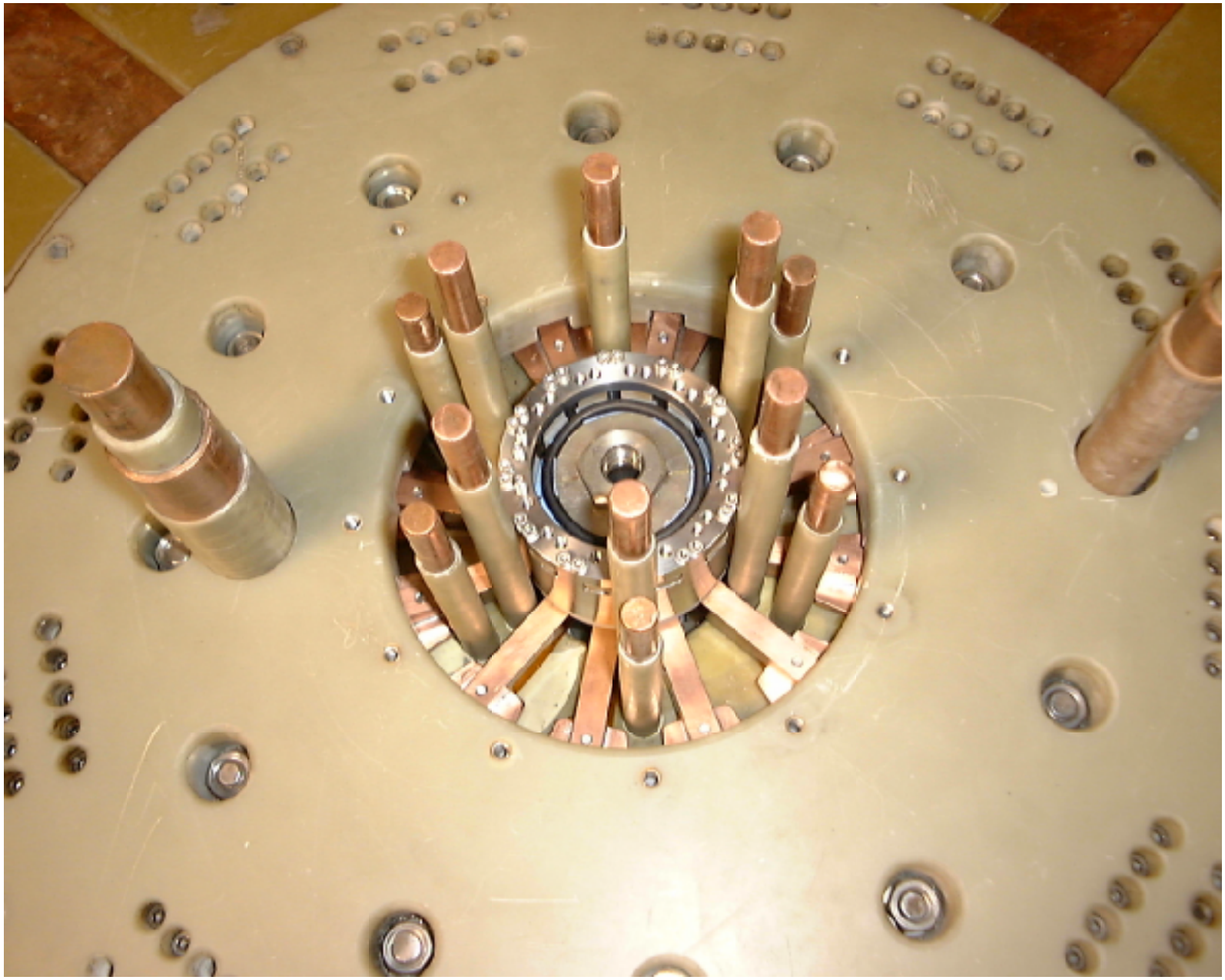
Plastigage™



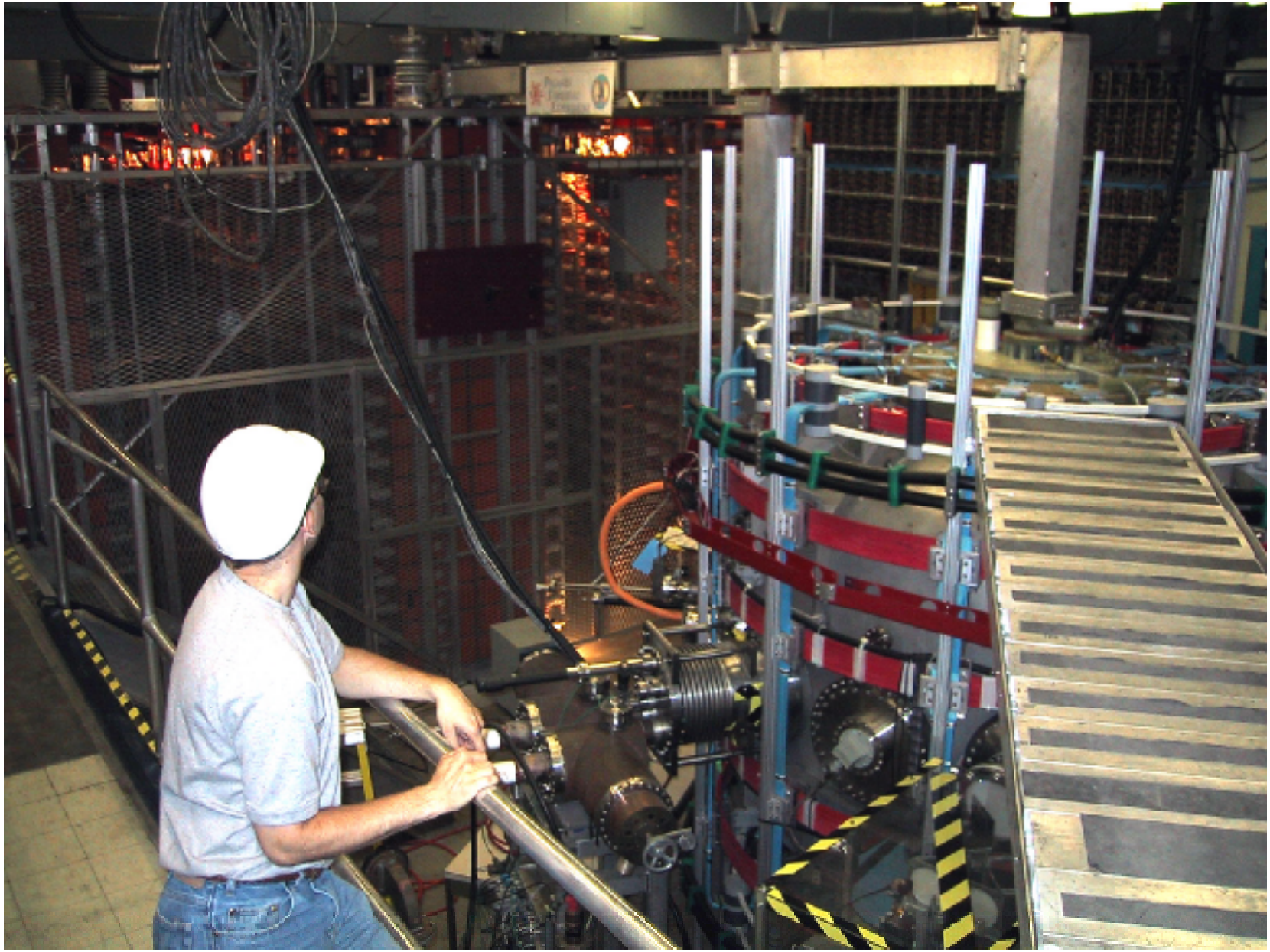
Partially assembled TF joints



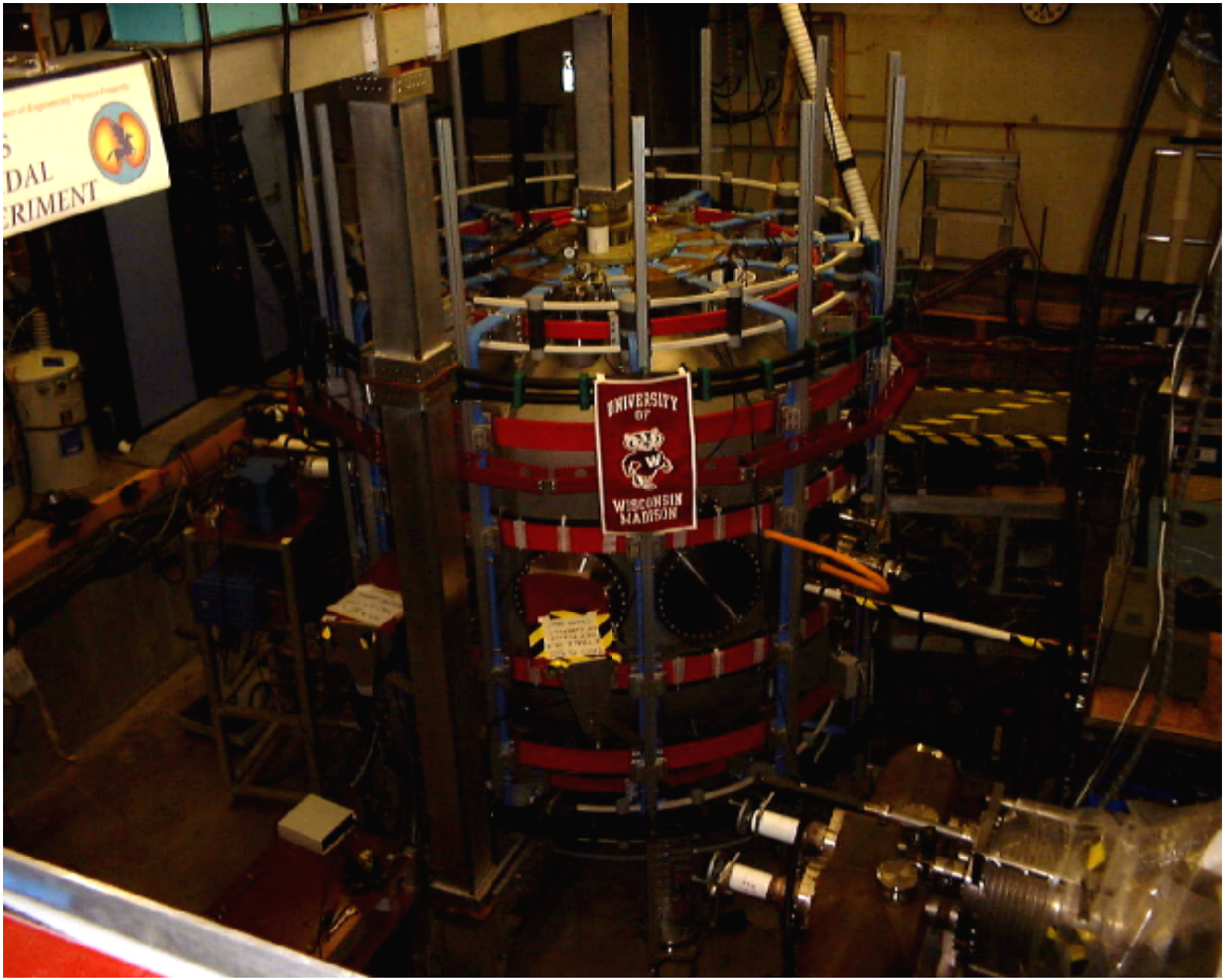
Completed TF assembly



Phase I laboratory layout (2001)



Phase I laboratory layout (2000)



Laboratory after pressure washing (October 2002)



Rebuilt laboratory (May 2003)



Rebuilt laboratory (September 2003)



Summary

- PEGASUS is an ultra-low A ST with a mission to explore plasma limits as $A \rightarrow 1$
- Phase I of plasma operations has demonstrated high β_t and $I_p = I_{TF}$ ohmically
- Tearing modes and external kinks are observed to limit plasma performance
- To pursue the experimental mission, MHD instabilities must be mitigated or avoided
- Upgrades being conducted will significantly increase experimental flexibility and power for Phase II of operations in late Fall 2003