Initial Operation of the Upgraded Pegasus ST Experiment

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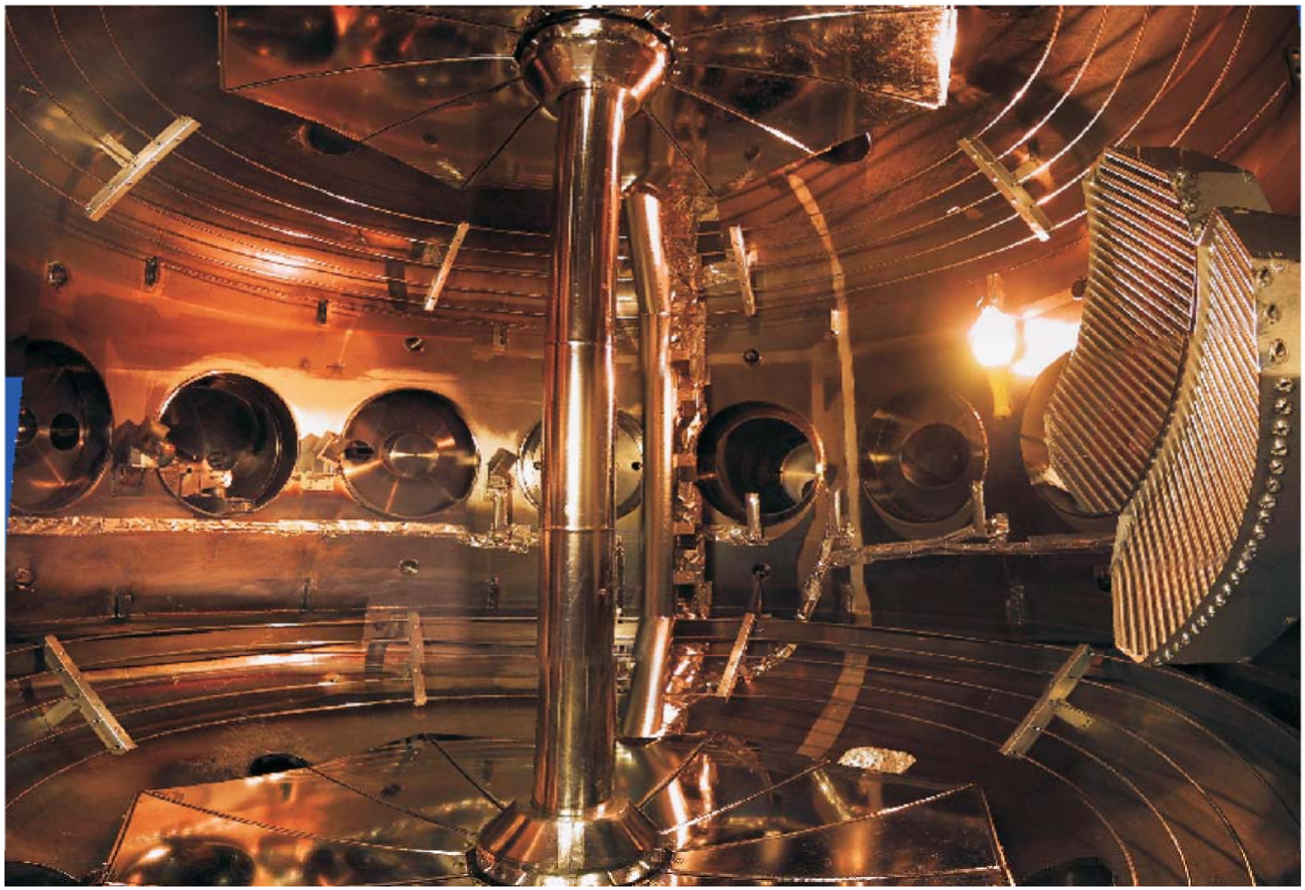

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Overview

- PEGASUS: ultra-low A ST designed to study stability limits as A→1 and $I_p/I_{TF} > 1$
- High β_t and $I_p = I_{TF}$ achieved ohmically
- Low-order tearing modes and ideal kinks limited access to higher I_p/I_{TF}
- Path to high I_p/I_{TF} and β via suppression of instabilities
- After fire: Lab rebuilt with significant upgrades
- Advancing the experiment mission by improving plasma control

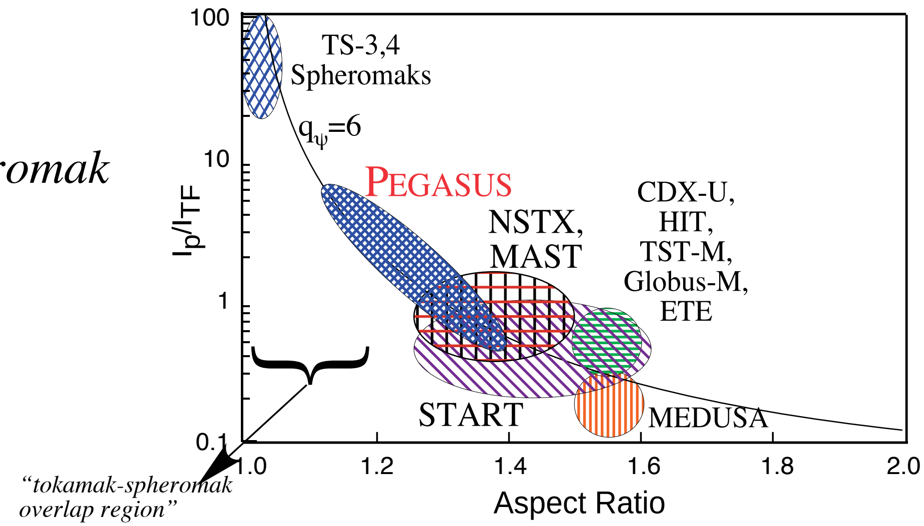
Mission: Explore plasma limits as A→1

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

Original Pegasus Goals:

- 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*

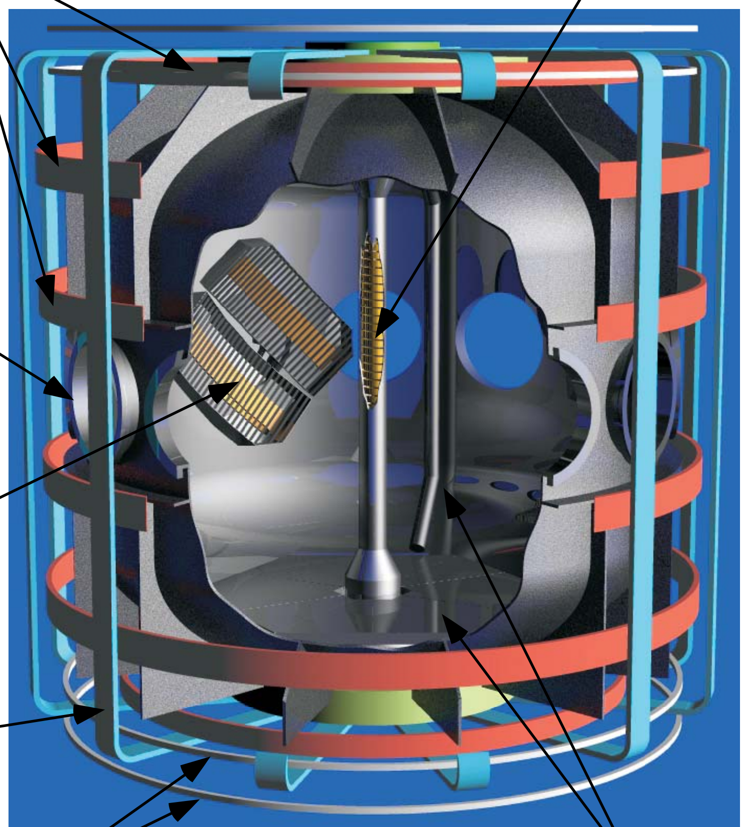
I_p/I_{tf} = figure of merit for access to low-A physics



Planned Future Emphases:

- Support ST program movement to next stages
  - *EBW tests for heating & CD (w/PPPL)*
  - *Noninductive startup tests*
  - *Novel divertor design tests (w/UT)*
  - *CT fueling tests (w/UCD)*
  - *Diagnostics*
  - *High-pressure gas puff for deep fueling*

PEGASUS is University-Scale, Mid-Sized ST

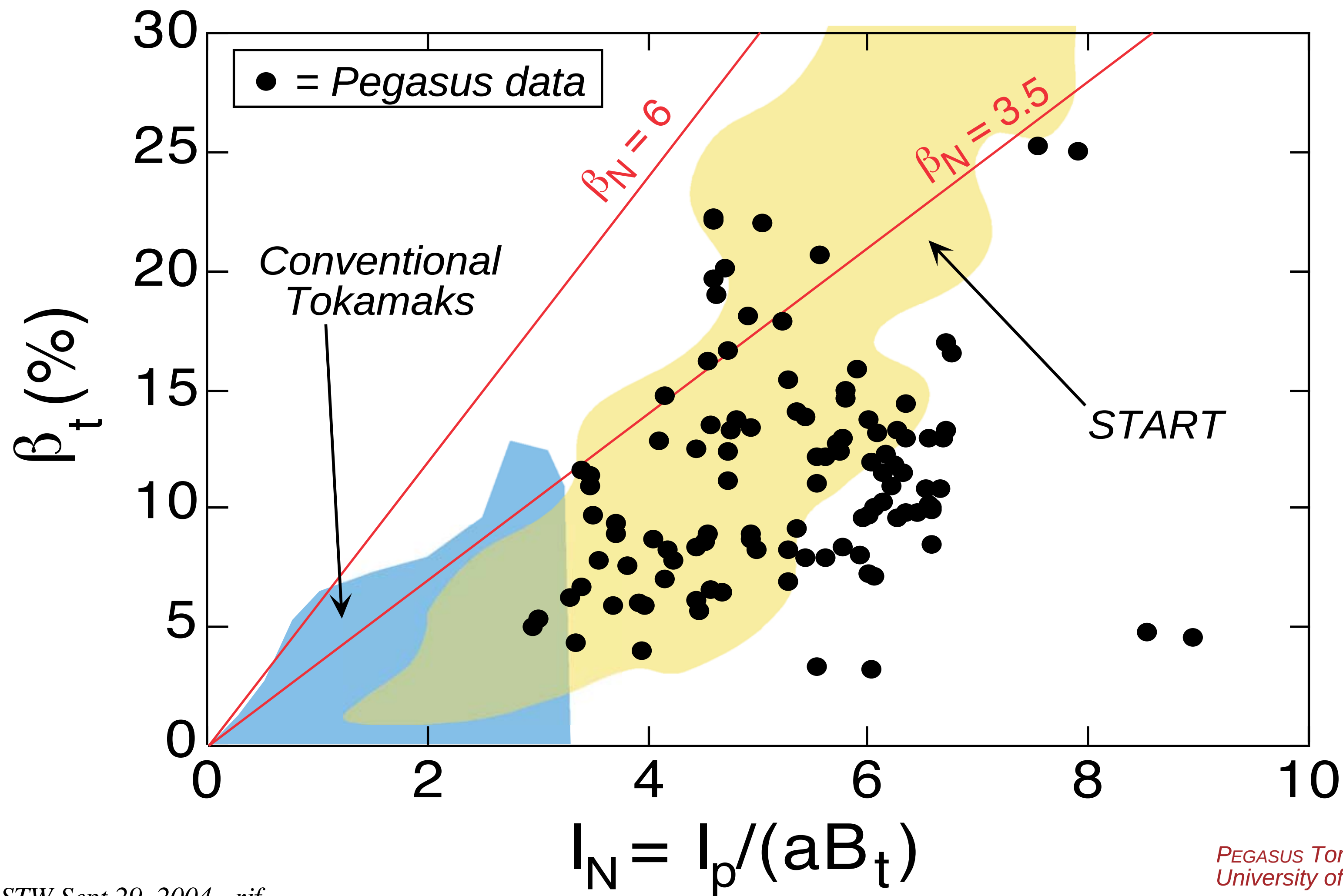


Experimental Parameters

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

A < 1.3 → Ready Ohmic Access to High β_t

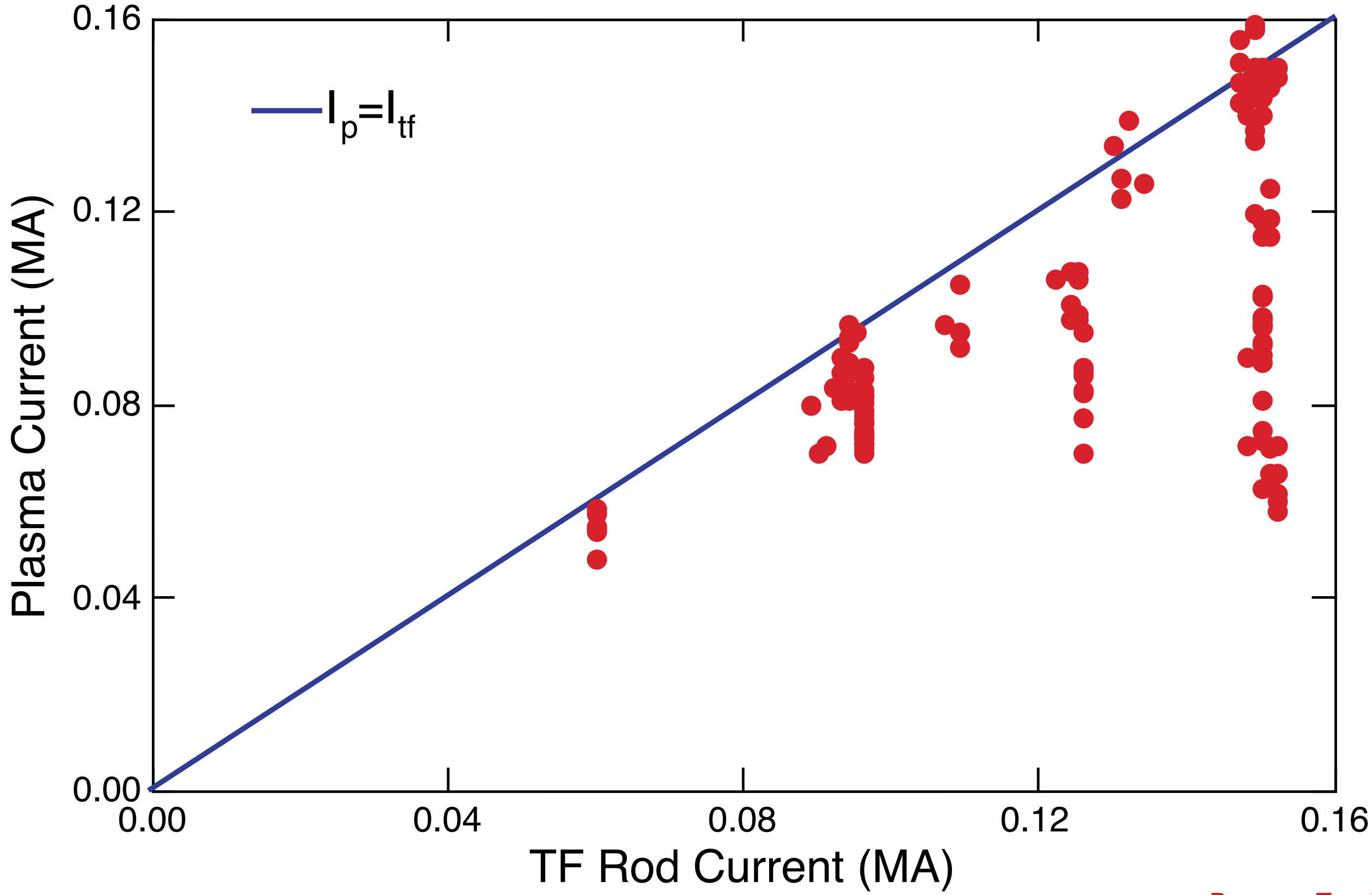
- β_t up to 25% and I_N up to 6.5 achieved ohmically
- Low field → high I_N and β_t



Toroidal field utilization exhibits a "soft limit" around unity

- Maximum $I_p \approx I_{TF}$

- Soft limit due to two factors:
  - Large, internal 2/1, 3/2 tearing modes degrade plasma
    - *Low shear over most of plasma, high resistivity*
  - Reduced Volt-sec as TF decreases



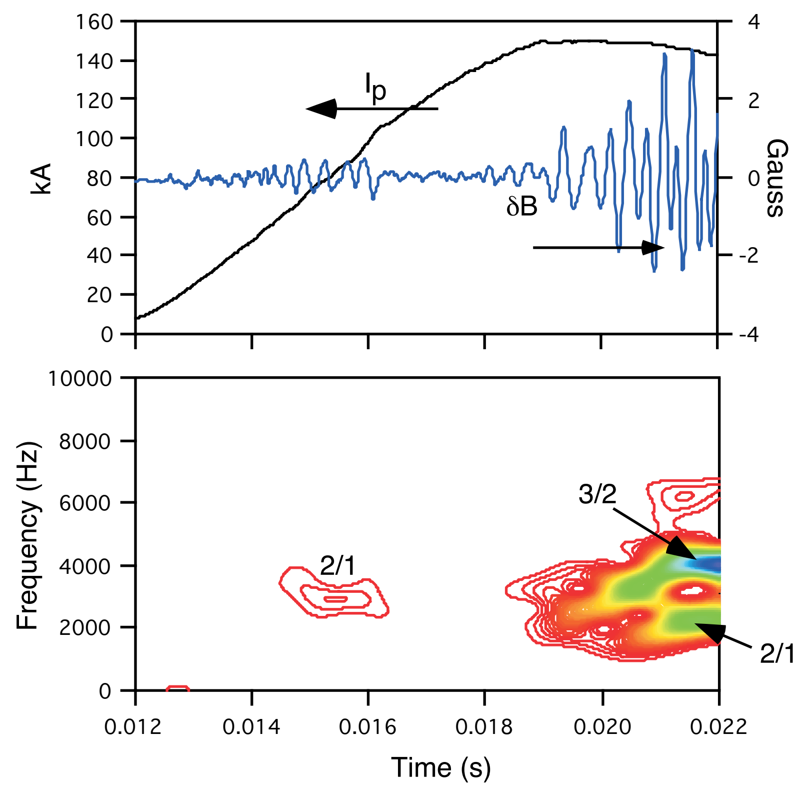
Two factors contributed to the $I_p/I_{TF} \approx 1$ soft limit

Large resistive MHD instabilities degrade plasma as TF ↓

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

⇒ 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 → delayed startup
- delayed startup + fixed sine V_{loop} waveform → reduced effective V-s

Measured q-profile indicates low central shear

Tangential PHC SXR image

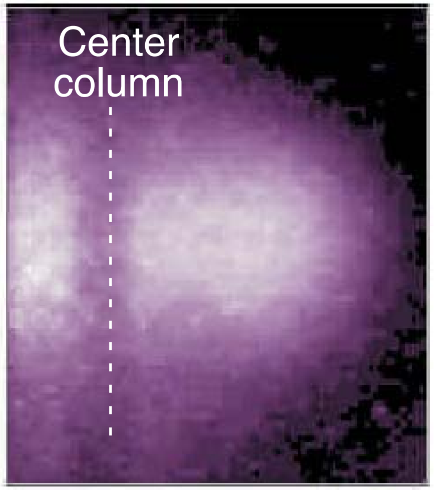


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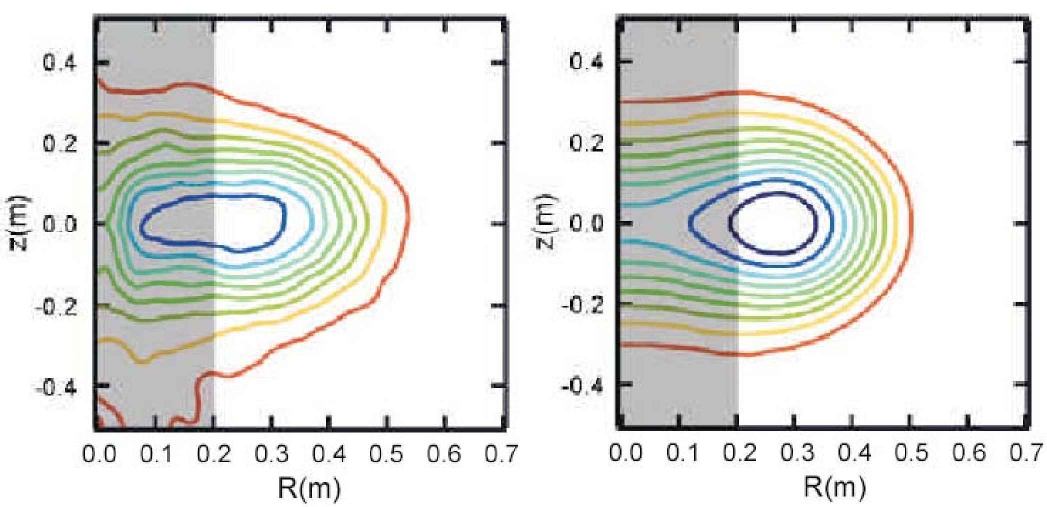
Image Contours:

Measured | Reconstructed



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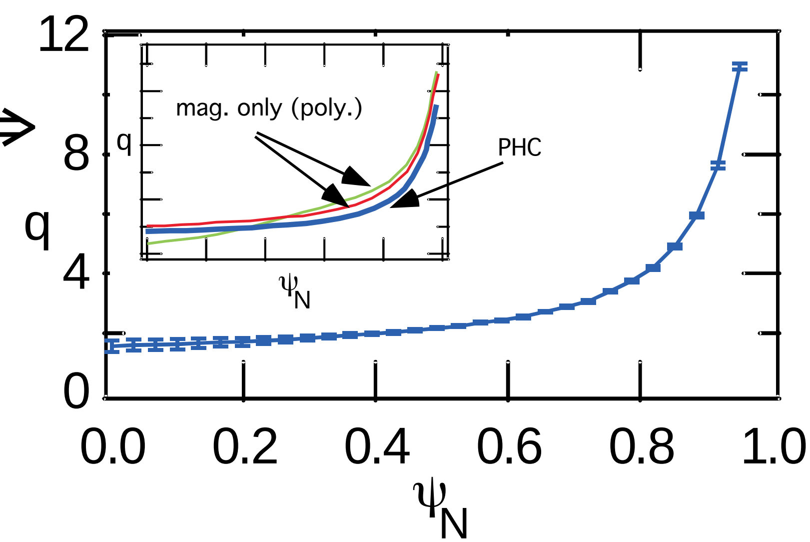


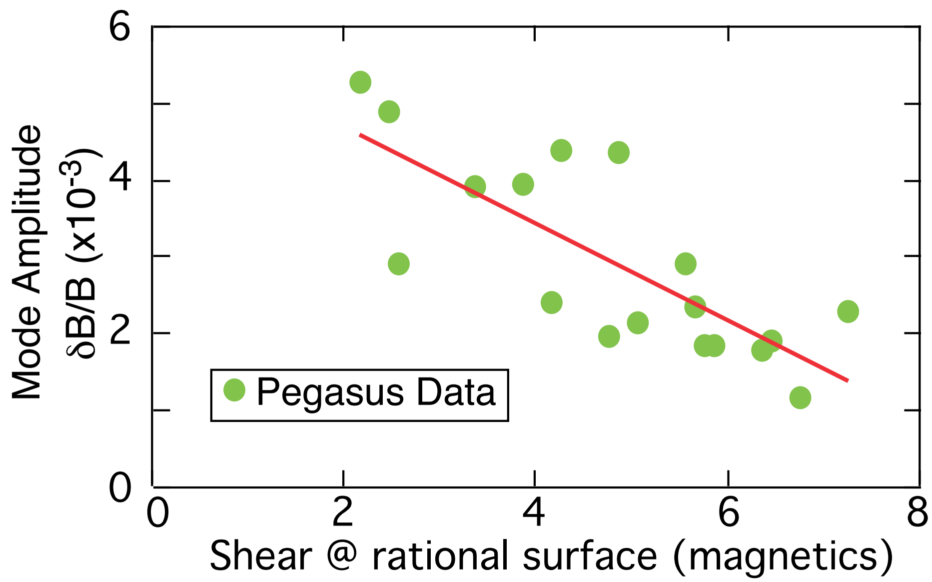
- 2D soft x-ray camera gives q-profile
  - Images soft x-rays
  - Constant-intensity surfaces determined
  - Mapped into flux space
  - G-S equation with SXR constraints
  - Iterate solution until convergence

- Measured q-profile ⇒ low central shear

MHD affected 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*

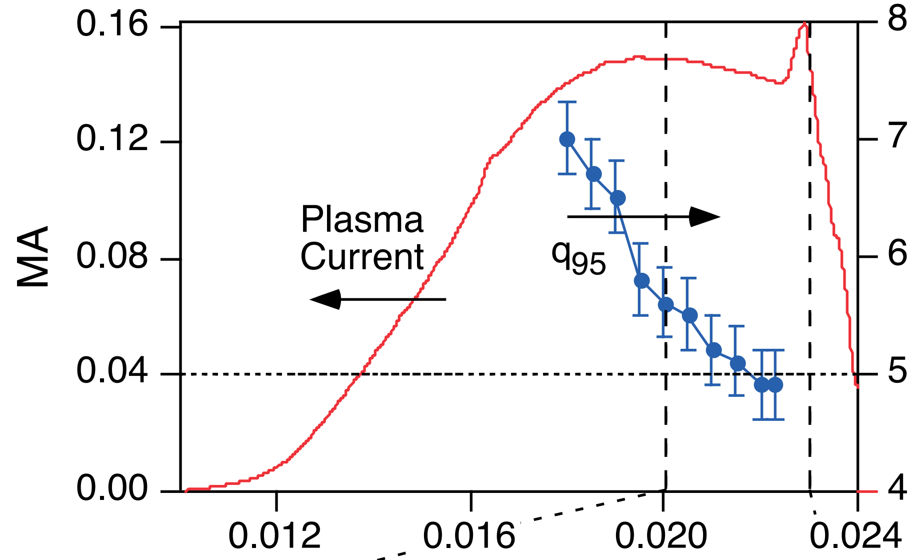
⇒ Access higher I_p/I_{TF}, β_t via increased q_0, T_e, shear

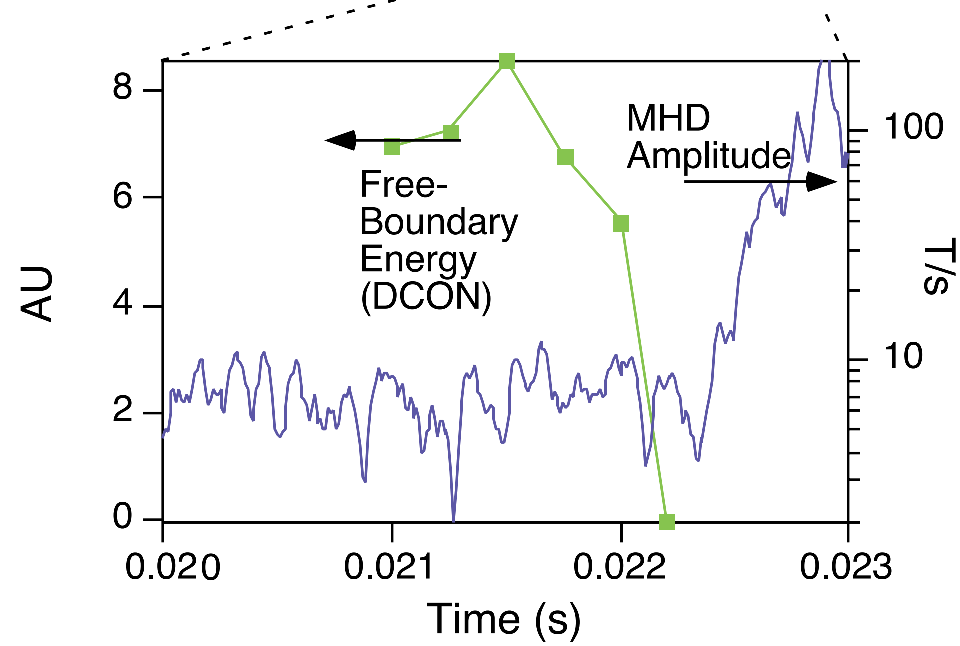


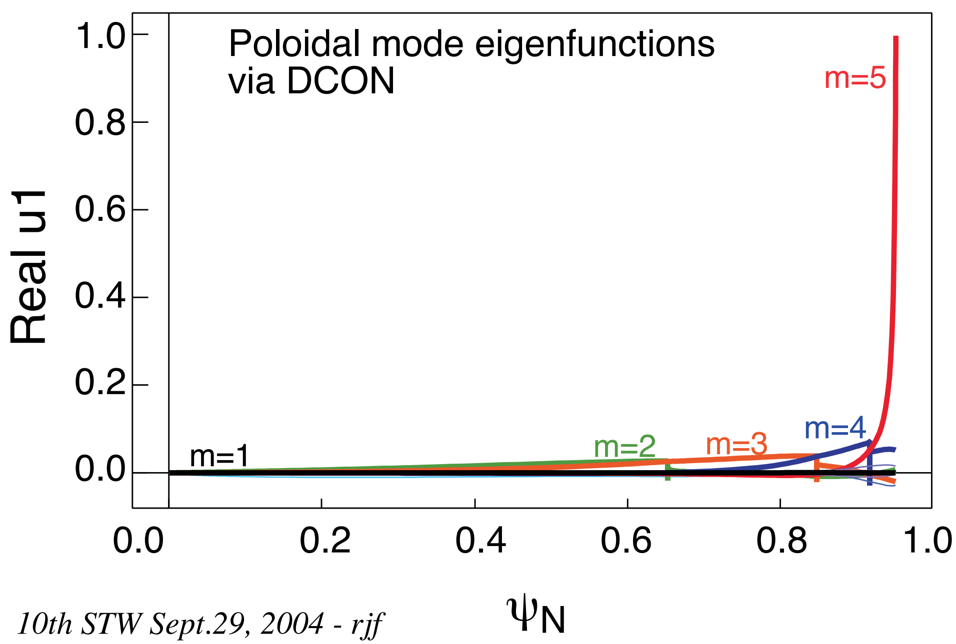
PEGASUS Toroidal Experiment
University of Wisconsin-Madison

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







Planned path to 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 availability

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

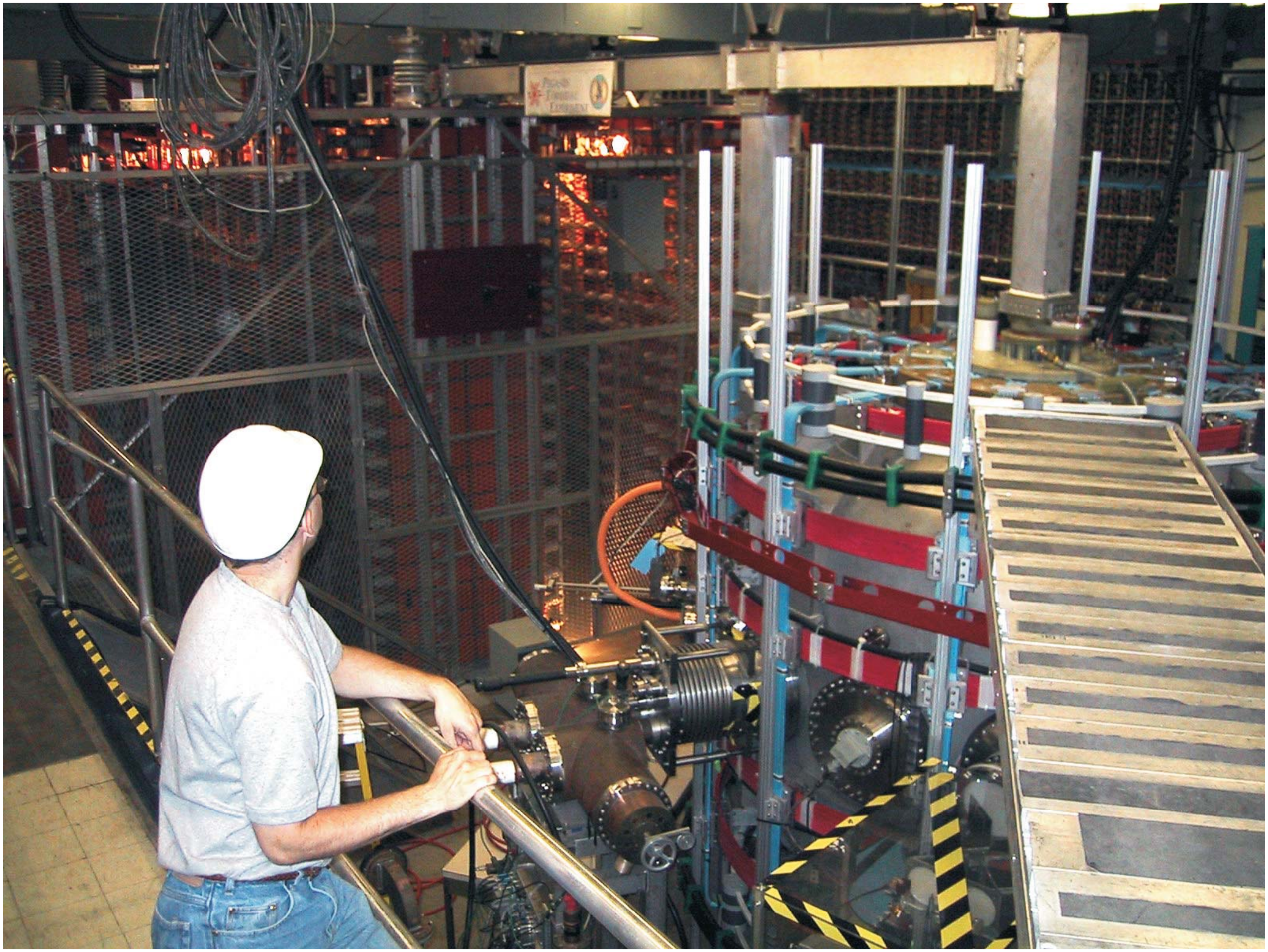
Overview of PEGASUS Phase II Rebuild

- **Power Systems Entirely Replaced**
  - PWM controlled H-Bridges allow for complete waveform control
  - Coil currents increased significantly
  - 6 MJ of electrolytic capacitors installed outside of experimental building
  - New power buses installed

- **Low-inductance Toroidal Field Centerstack Installed**
  - Provides increased, time-variable TF

- **Lab Infrastructure Improved or Replaced**
  - Shielded conduits and cable trays installed
  - New grounding system installed
  - Control and Safety systems upgraded
  - Bakeable gas system
  - Upgraded AC, air, and water services installed
  - Passive Stray field “flux catcher” installed for public safety

Phase I laboratory layout (2002)



Laboratory before rebuild (October 2002)

Rebuilt laboratory (June 2004)

Power Systems consist of IGBT/IGCT Solid State H-Bridges

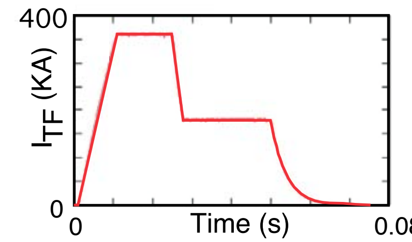
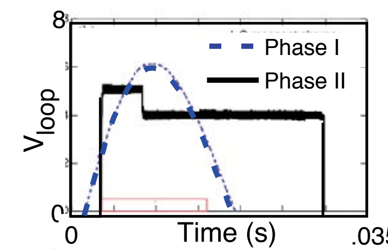
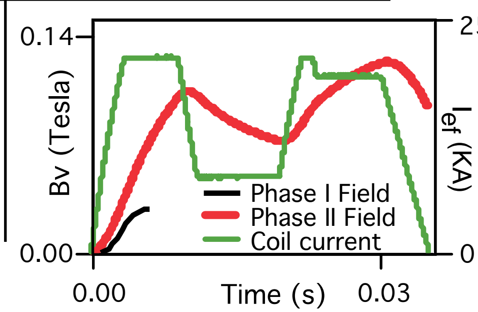
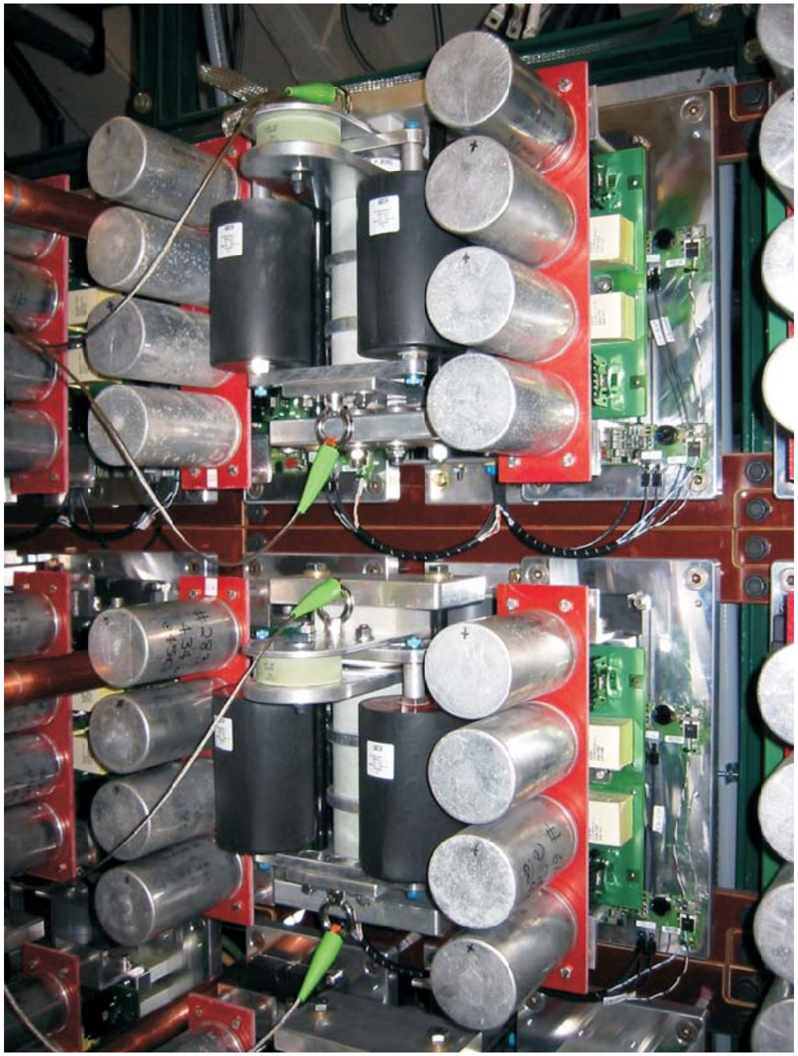
System	Phase I	Phase II	Example
Toroidal Field	• 60 turns • Quasi-DC • 150 kA-t max	• 12 turns • Time-variable • up to 450 kA-t • 8 IGBT Bridges	
Ohmic Heating	• Half-sine Waveform • ±40 KA at 10kV	• Programmable • ±48 KA at 2.7kV • 12 IGCT Bridges	
Equilibrium Field	• Monolithic coil set • 2 Resonant banks • Waveform constrained by startup concerns • No divertor	• Independent coils • 20 IGBT Bridges • Evolution free from startup constraints • Divertor installed	

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

- Many thanks to the **HIT** Group for their assistance!

Pulse Width Modulated (PWM) H-Bridges

IGBT H-Bridge (2 of up to 28)
900V, 4kA at up to 5kHz

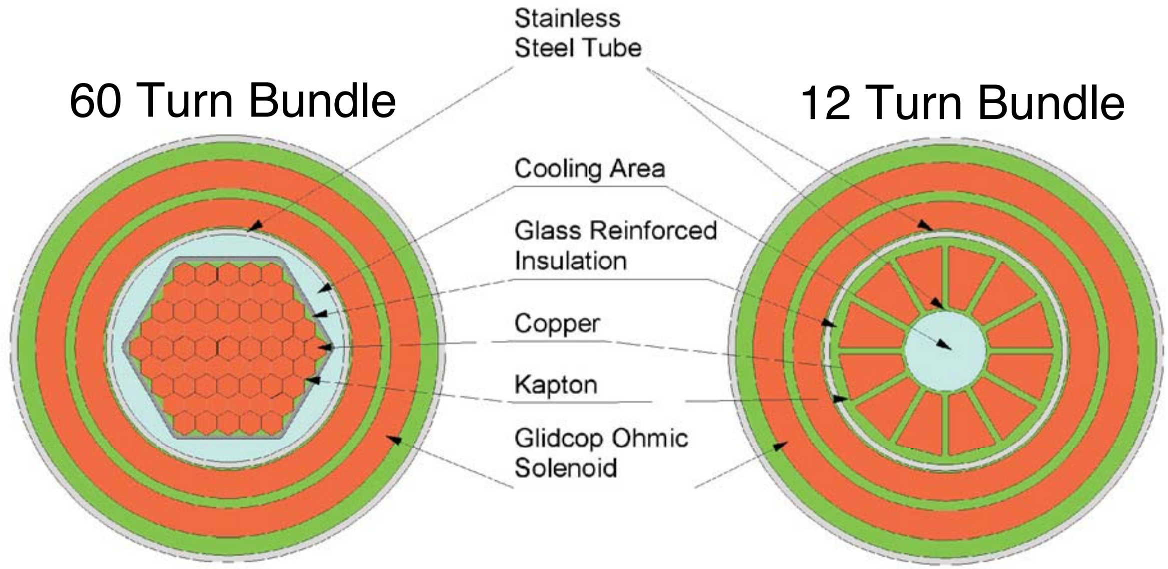


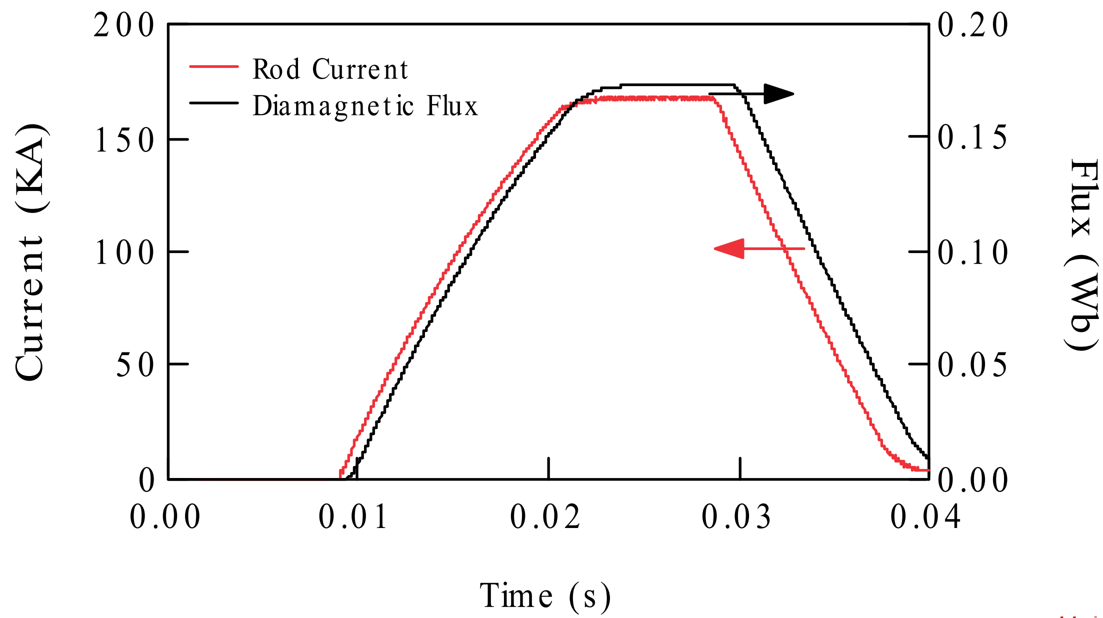
Insulated Gate Bipolar Transistor

• Benefits

- Tailor the current waveform to match the needs of the desired plasma evolution
- PWM controlled modern IGCT/IGBT semiconductors
- More reliability and control with less overall stored energy
- H-Bridge regeneration mode minimizes heating of critical coil sets
- Fault detection and interruption capability
- HIT group: CAMAC based, optically isolated PWM controller

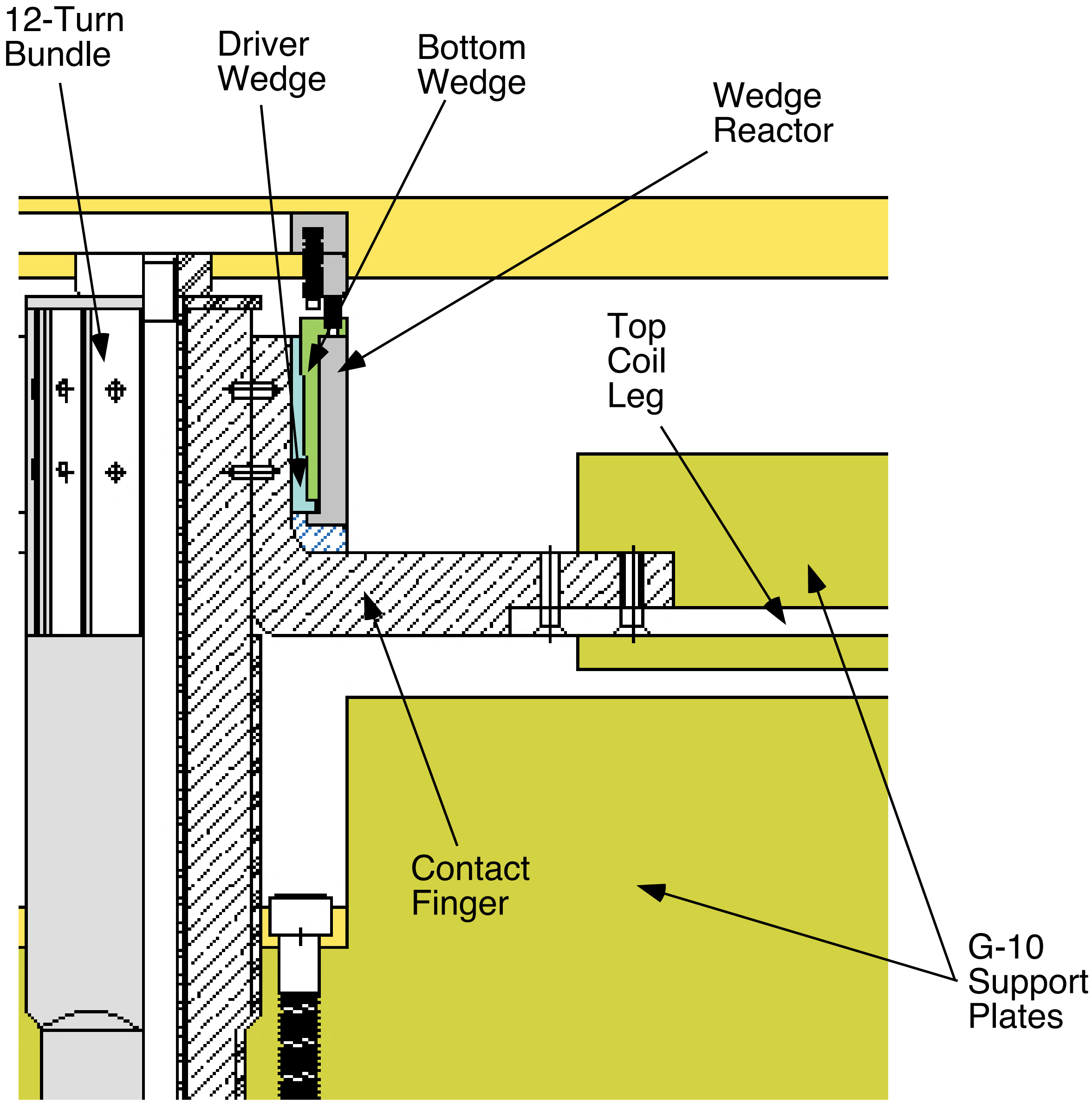
PEGASUS Centerstack Assembly and TF Waveform





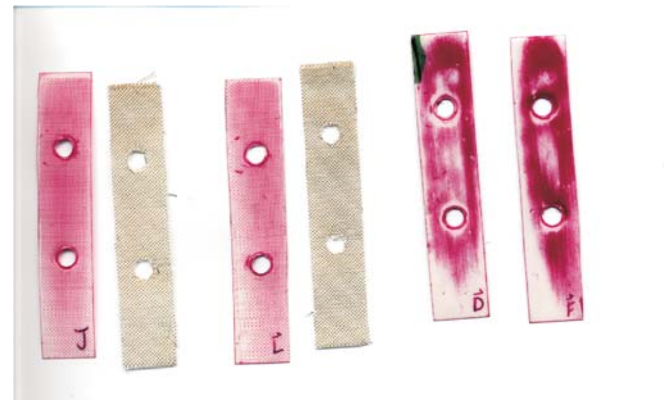
Toroidal Field Joint Area is Critical

Cross-Sectional Drawing (Top)

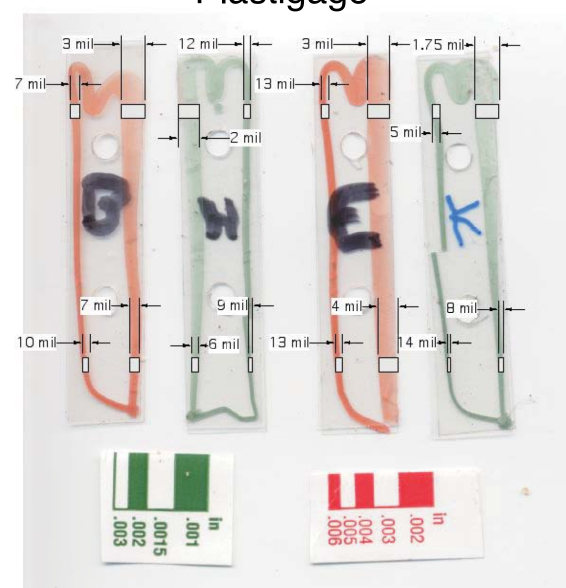


Fit-Check Diagnostics

Pressure Paper

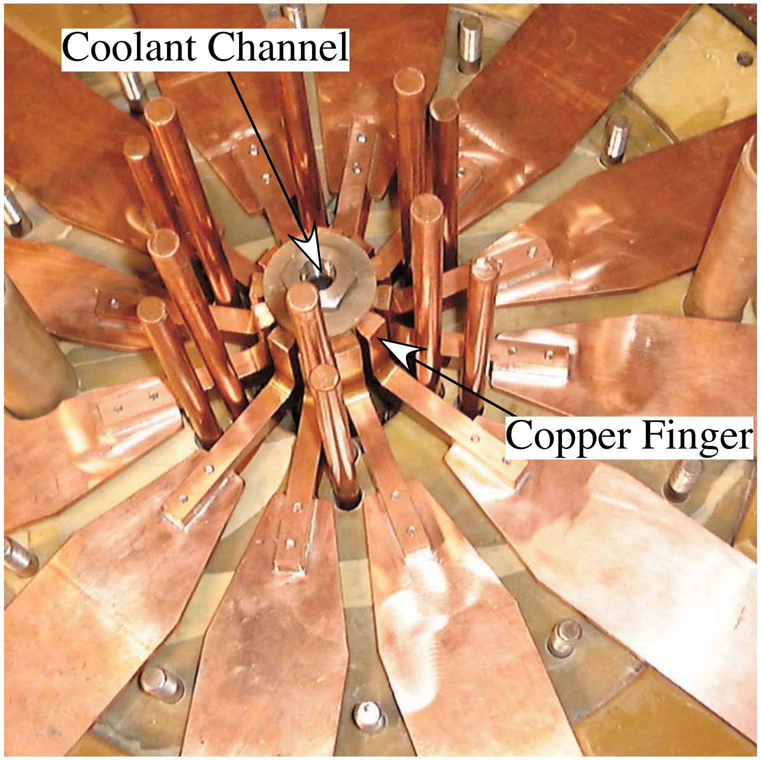


Plastigage™

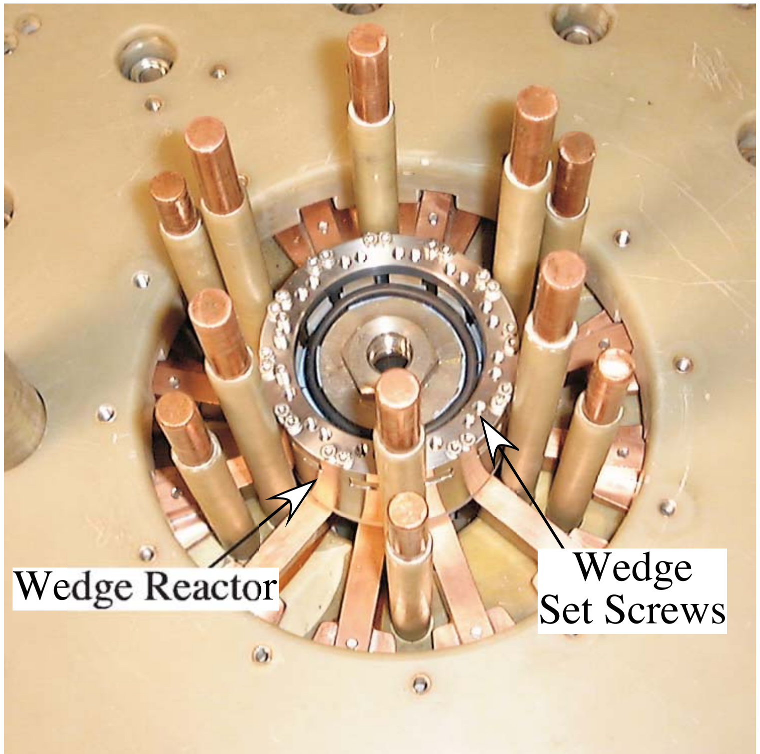


Toroidal Field Upper Joint Assembly

Bare TF Assembly

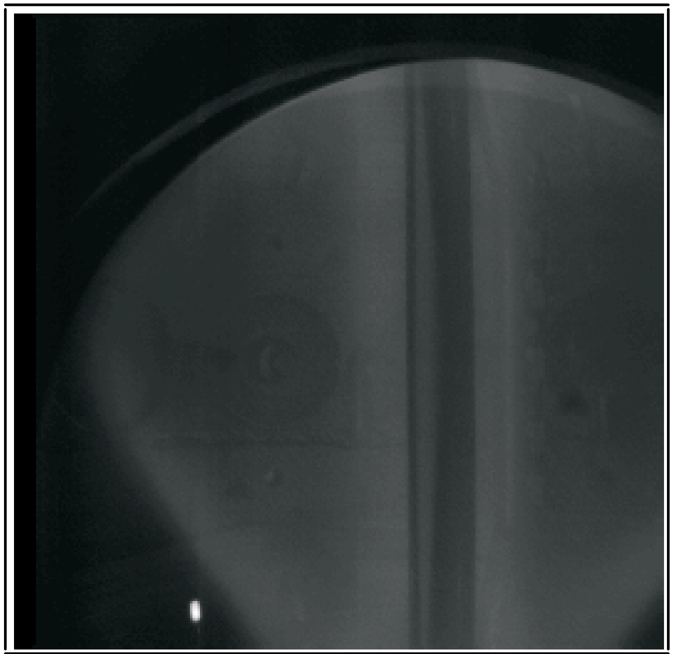


Fully Assembled TF Joint



Present Status - Coming into full power ops

- Initially using PF power supplies for OH ⇒ limited Volt-s and V_{loop}
  - 1st plasma in late May
  - 2 month campaign in Summer 2004
    - *Transient suppression and PS stabilization*
    - *New facility tests and systems shakedown*
    - *Effects of wall currents with new waveforms*
    - *Low power startup studies*



Recent Plasma

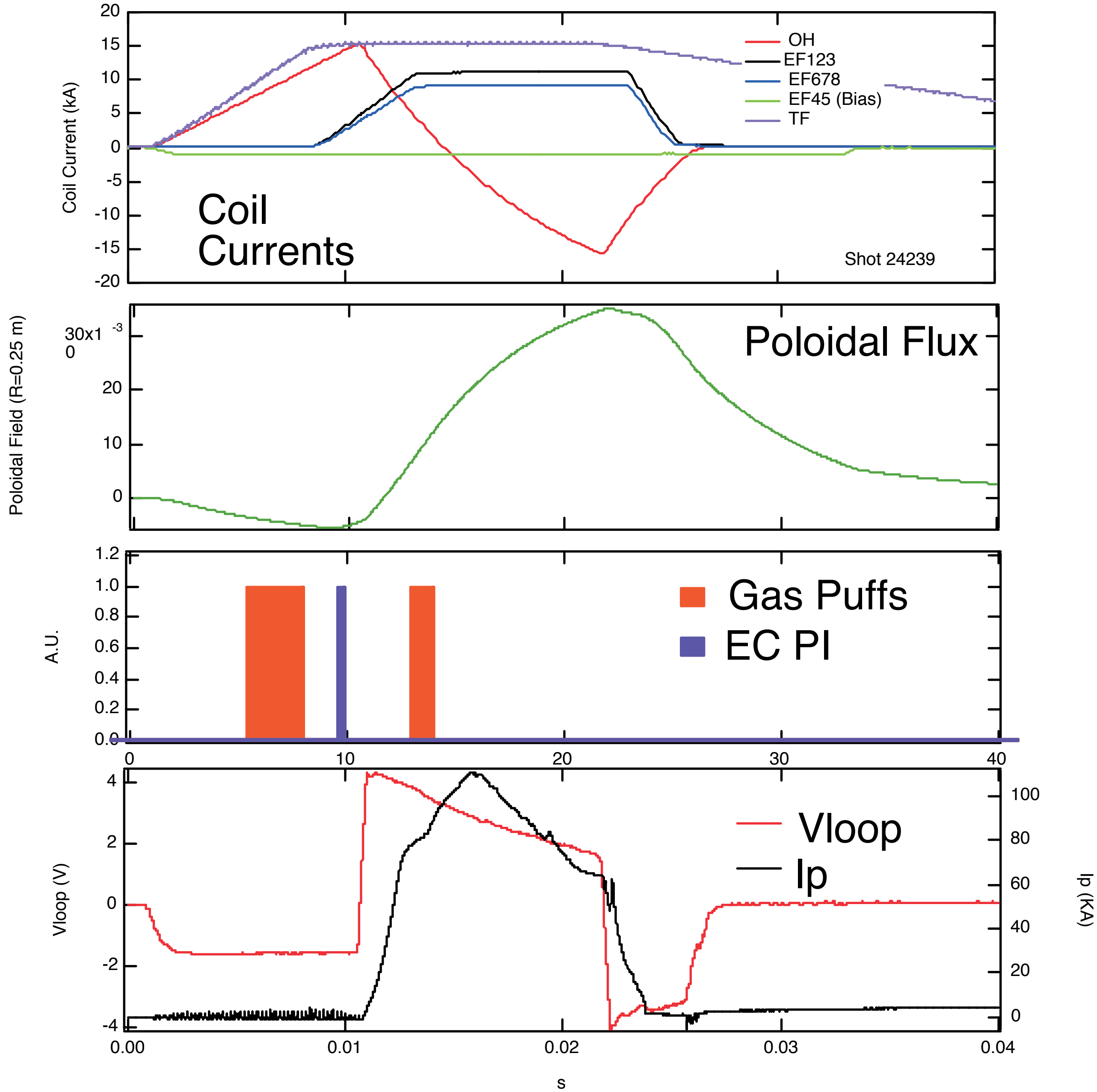
- Stabilizing operations
  - New power systems stabilized and working as desired
    - *Robust to major failures*

- Recent upgrades to enhance operations
  - Major grounding change to stabilize PS
  - New diagnostics installed
  - Single plasma gun installed for tests of CD and fueling

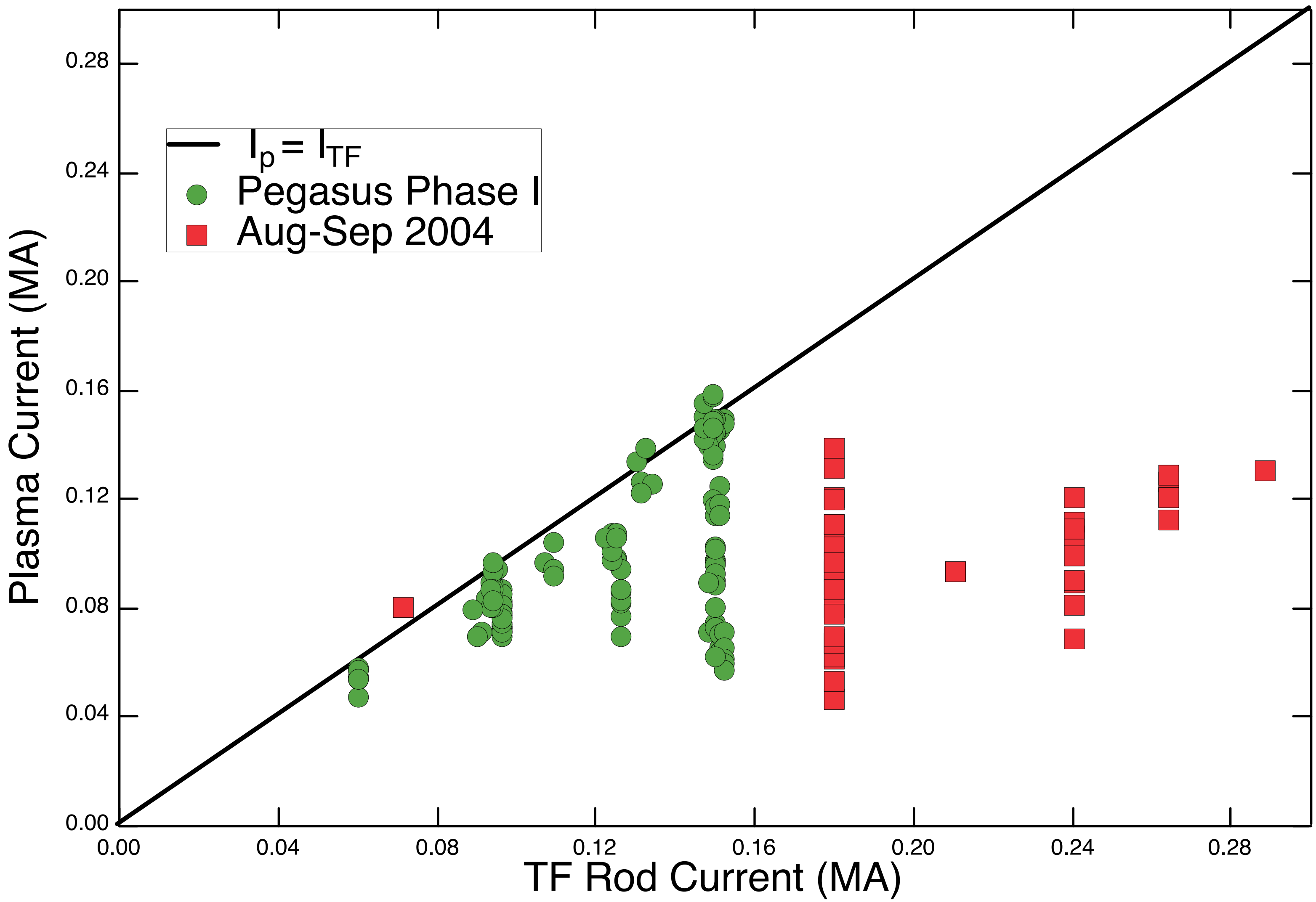
- Late Sep - Early Oct: Installation of first High-V OH power supplies

- Upcoming campaign in Fall-Winter 2004-2005: Use New Tools
  - Commission new OH system for high-power ops
  - Access to $I_p/I_{tf} > 1$, low-q, high I_N, high β_t regime
  - Introduce separatrix
  - Use gun for startup assist
  - Tearing mode suppression
  - Characterize ext kink limits
  - Install more guns

Typical waveforms for ohmic operations

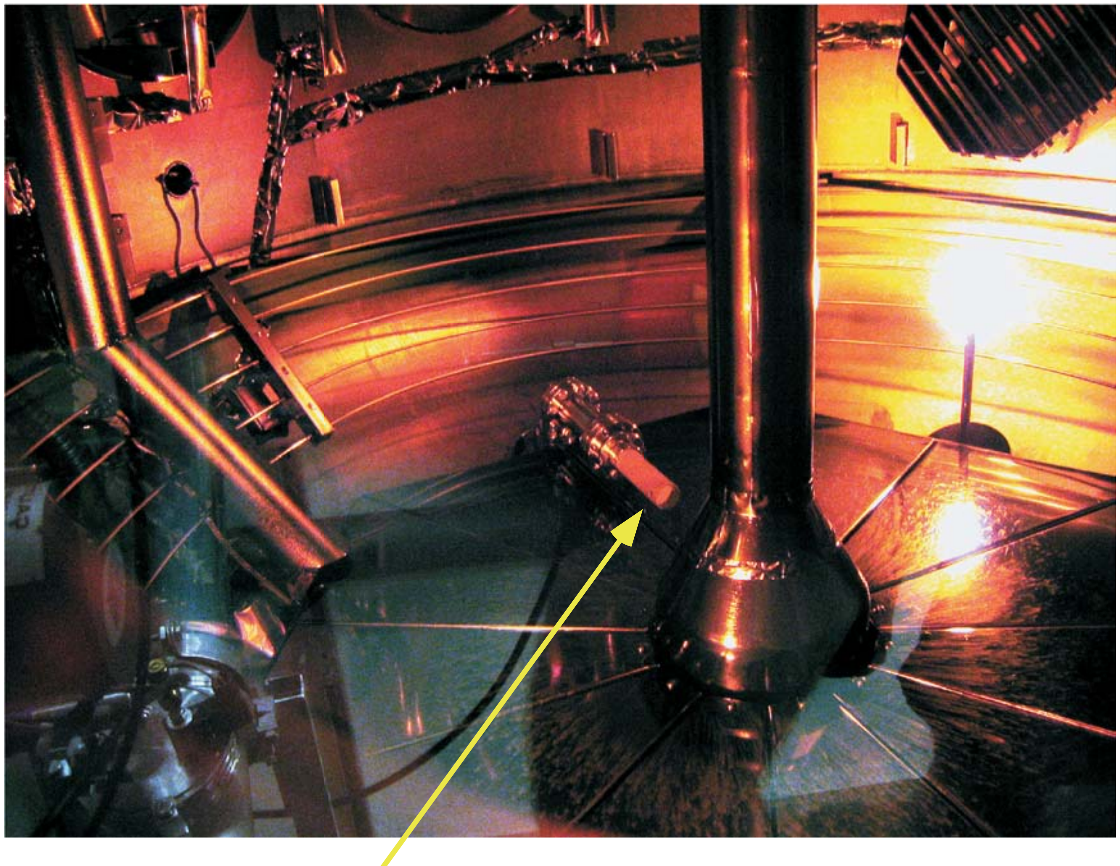


I_p/I_{tf} space expanded



Plasma guns being tested for startup and fueling

Gun installed in lower divertor region



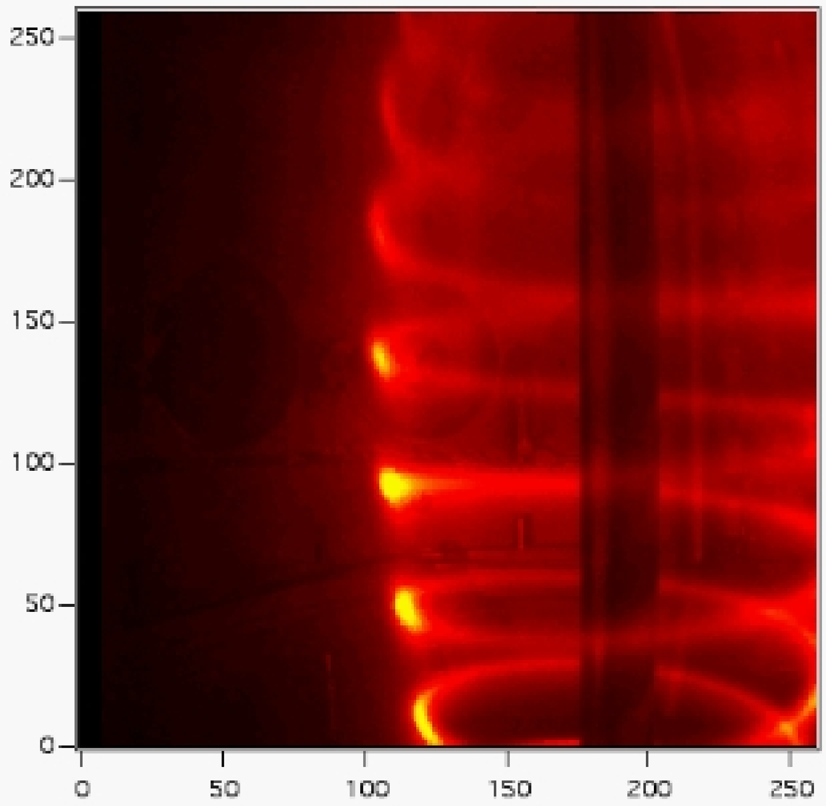
Gun orifice

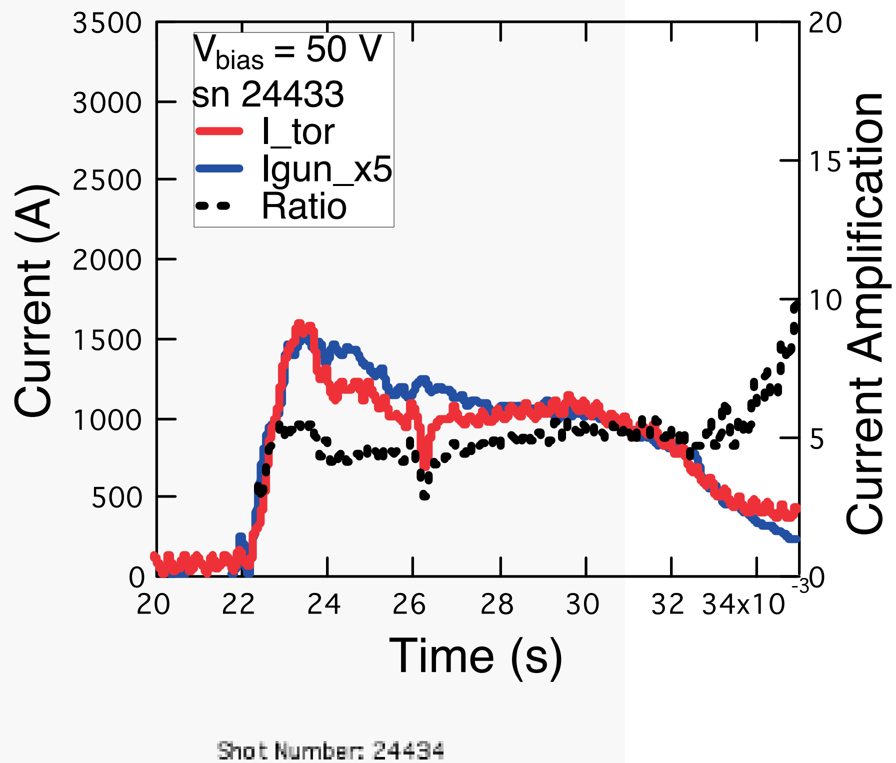
Time-integrated plasma image

Low Gun Current/Power --> Linear Current Scaling

- Current channel follows field line
  - *Maintains helical nature*

- Total toroidal current ~ 5 x gun current
  - $I_p/I_g \approx constant$



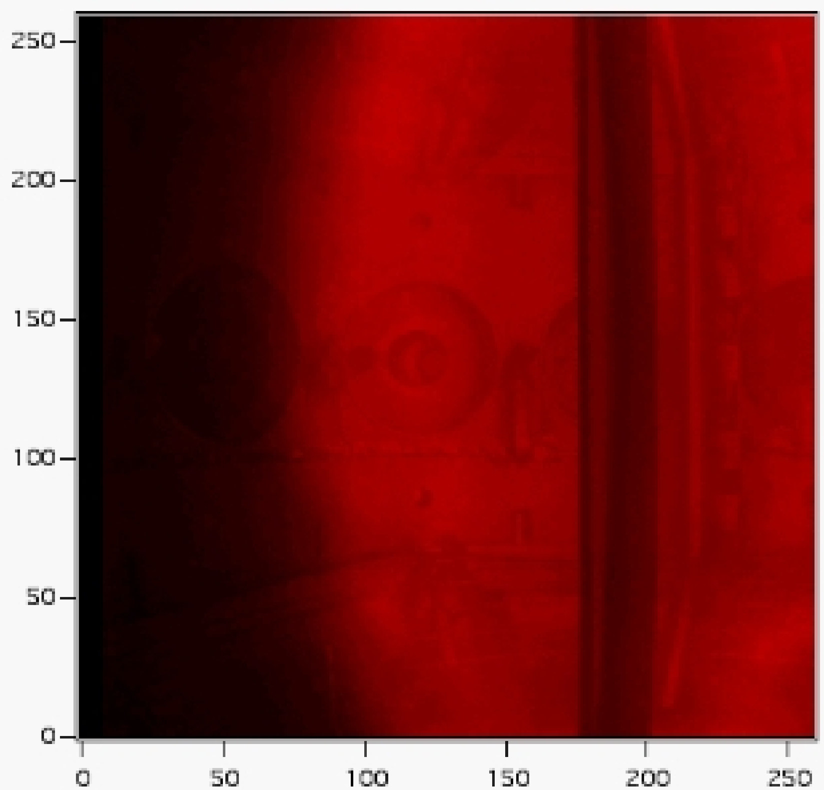


Low Gun Current/Power --> Linear Current Scaling

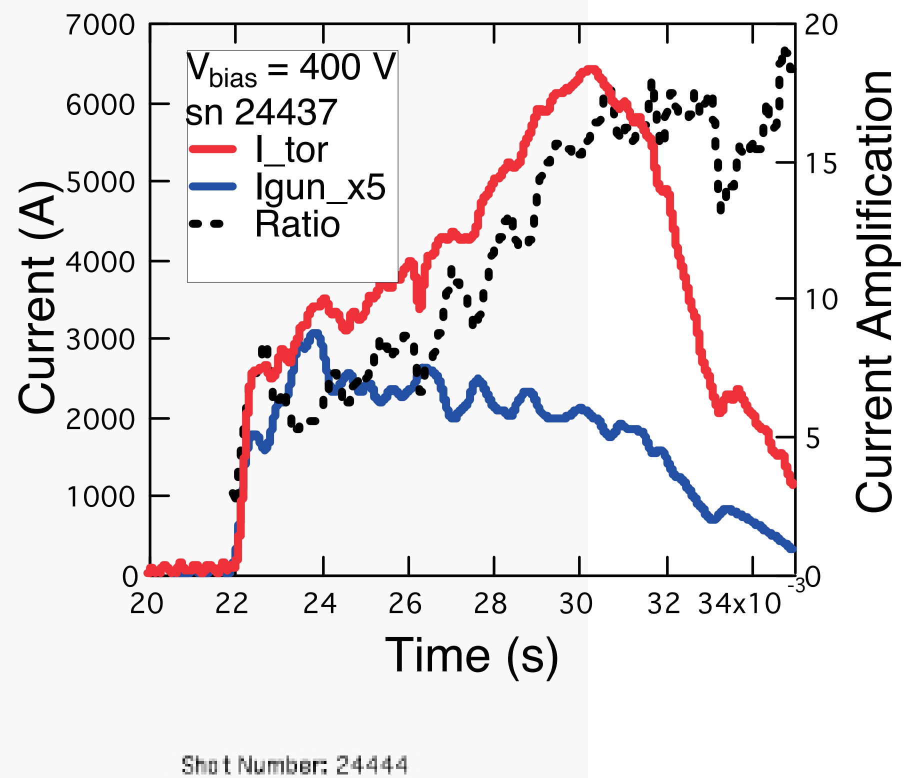
- Current channel follows field line
  - *Maintains helical nature*

HIgh Gun Current/Power --> Nonlinear Current Scaling

- Current channels merge/reconnect
  - *Generates extended plasma*



- Total toroidal current > 5 x gun current
  - *I_p/I_g increases*

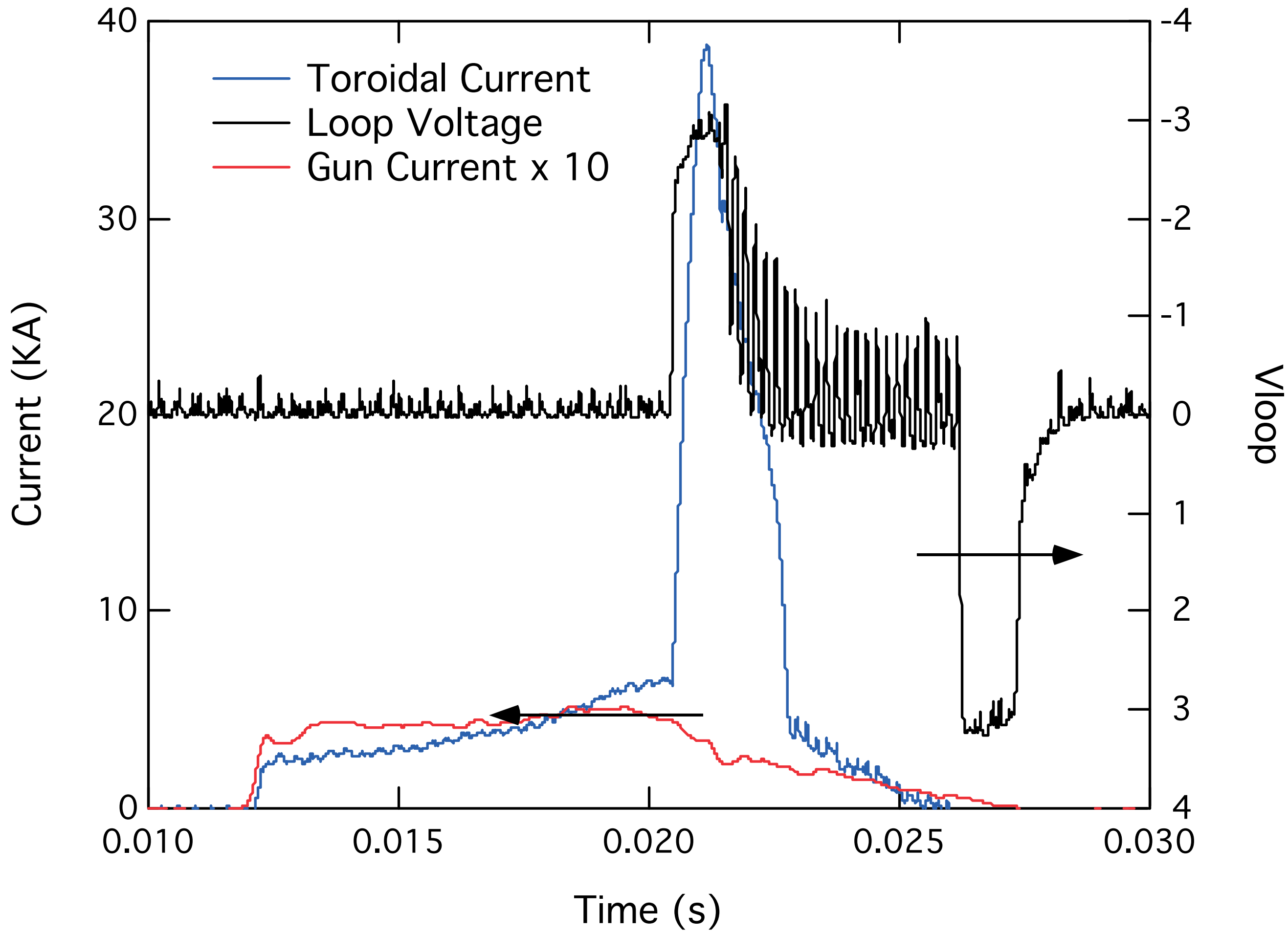


HIgh Gun Current/Power --> Nonlinear Current Scaling

• Current channels merge/reconnect

- Generates extended plasma

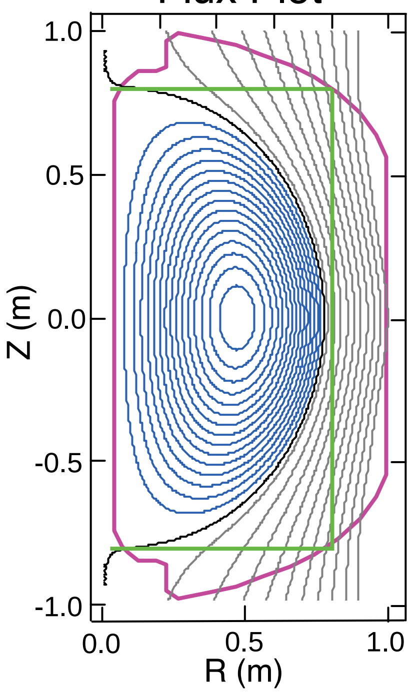
Early indications: gun startup compatible with OH



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

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

Flux Plot

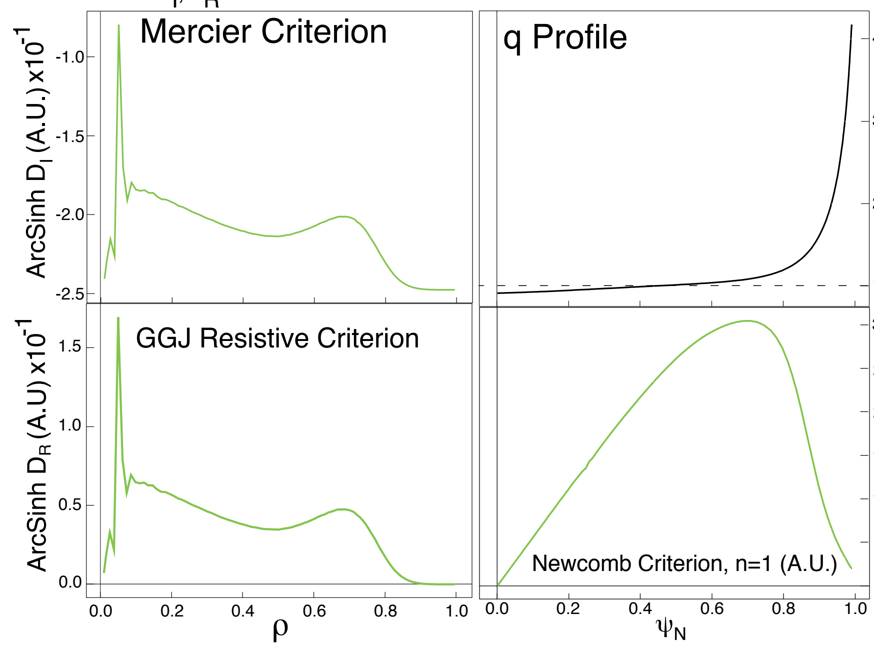


Equilibria Parameters

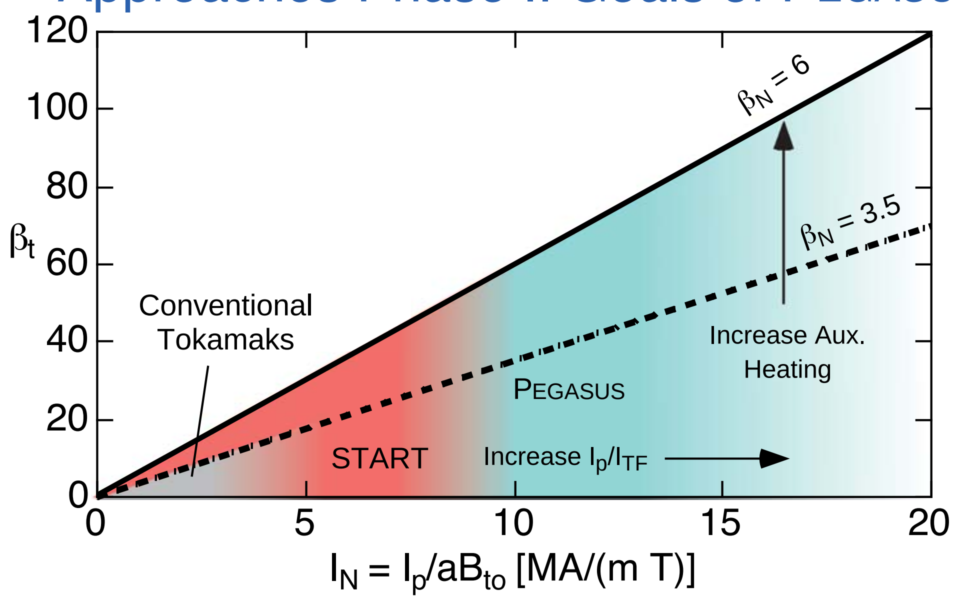
Ip	296000
I_{tf}	90000
I_N	18.9
li	0.68
q_0	0.91
R_0	0.41
a	0.36
Elongation	1.98
q_{95}	2.3

- DCON Output

$D_I, D_R > 0$ => Unstable



- Approaches Phase II Goals of PEGASUS



Economical Tests of EBW Possible on PEGASUS

EBW heating and current drive of interest for ST regime

- Plasma startup, sustainment
- Applicable to low-field, overdense plasmas
- Of interest to future NSTX development

Basic principles tested on W-7S and CDX

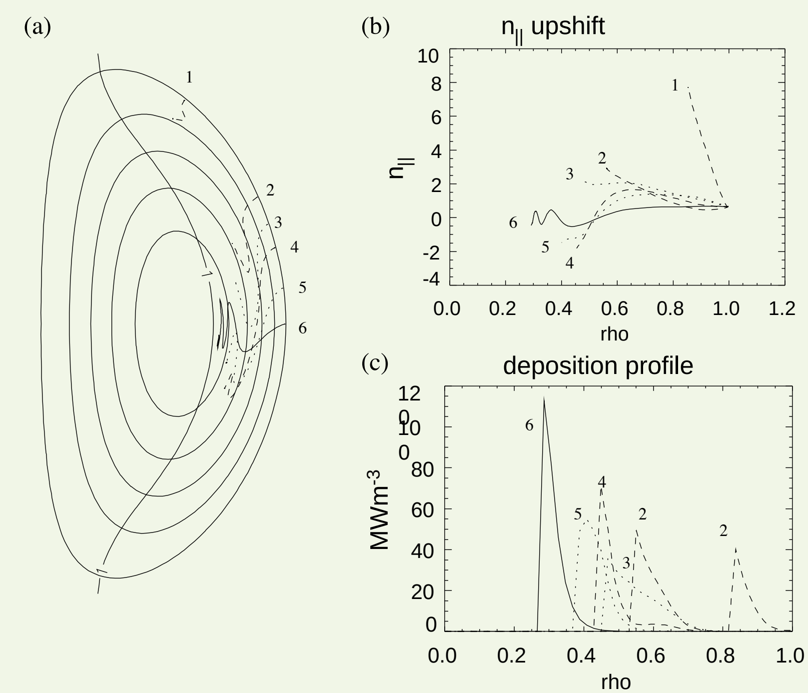
- Need to be tested at significant power levels

Pegasus good candidate for EBW development

- Low-cost 2.45 GHz technology
- Klystrons and waveguide available from PLT
- Need to demonstrate good target plasma control

Working with PPPL to develop best approach

- Modeling
- Hardware
- Experiments



(a) EBW ray tracing calculations for a 250 kA PEGASUS equilibrium, central density of ne(0) = 10^{13} cm^{-3}. (b) $n_{||}$ along the ray path, showing the up-shift depends upon launch position. (c) Power deposition profiles corresponding to the rays in (a) and (b).

PEGASUS now poised to exploit its unique niche

- Phase I ops finished Spring 2002
  - $I_p/I_{tf} = 1.1$
  - $\beta_t = 25\%$
  - Factors found limiting plasma current:
    + *internal resistive modes*
    + *V-s limitations*
    + *external kinks*

- Staged upgrades were proposed to suppress limiting mechanisms
  - Fire initiated a "front-loading" of upgrades

- Upgrades are mostly completed
  - New switching power supplies (final installation now)
  - New capacitor banks
  - New TF centerstack
  - New control code
  - New signal runs and screen room

- Phase II ops have begun
  - Low power OH
  - Plasma gun tests
  - New diagnostic installations