The Path to High Field Utilization in the PEGASUS Toroidal Experiment

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Overview

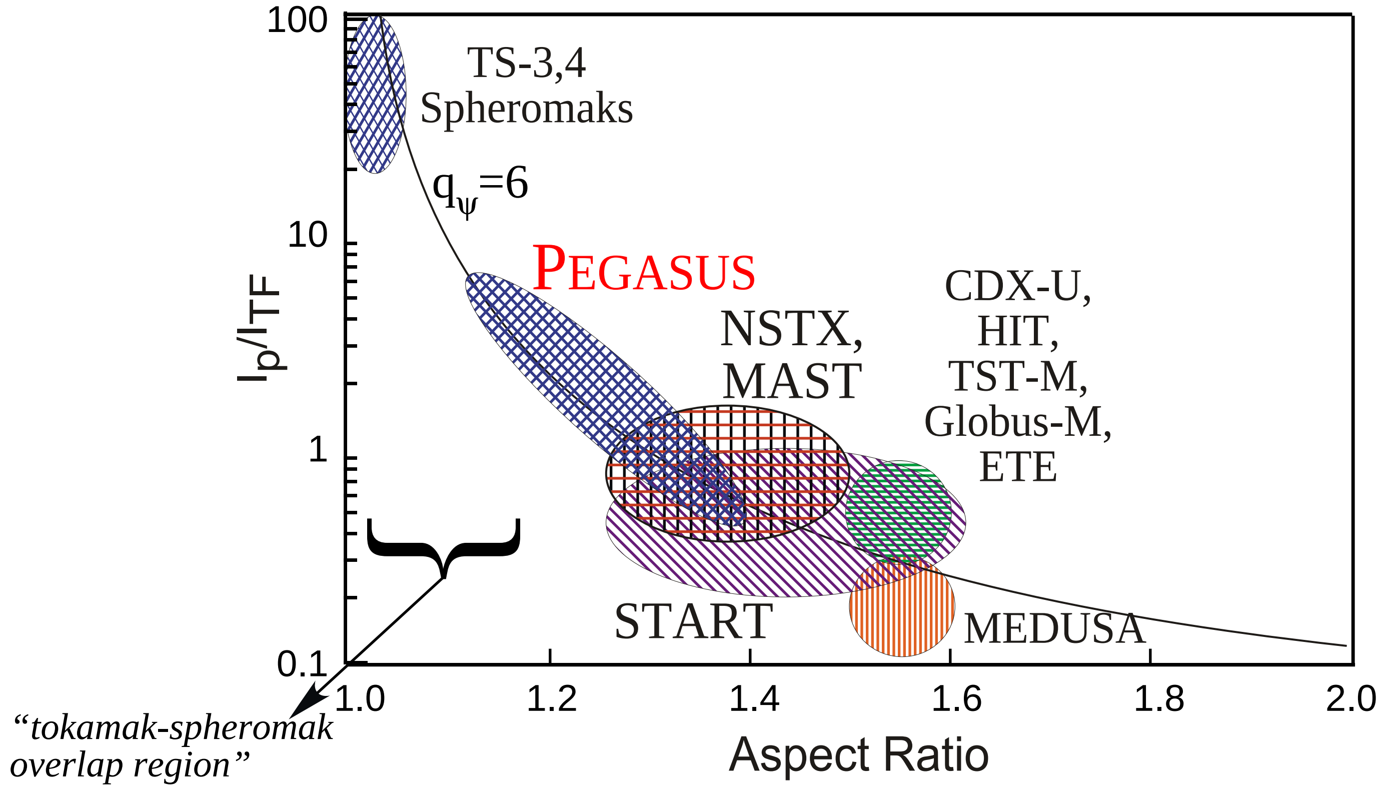
- Pegasus: ultra-low A ST designed to study stability limits as $A \rightarrow 1$ and $I_p/I_{tf} > 1$
- High β_t and $I_p = I_{tf}$ achieved ohmically
- Low-order tearing modes and ideal kinks limit access to higher I_p/I_{tf}
- Path to high I_p/I_{tf} requires suppression of instabilities
- Upgrades will advance the mission by increasing q during startup and 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

- Stability and confinement at high I_p/I_{tf}
- Limits on β_t and I_p/I_{tf} (kink) as $A \rightarrow 1$

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



Pegasus facility produces ultralow-A plasmas

Achieved Parameters:

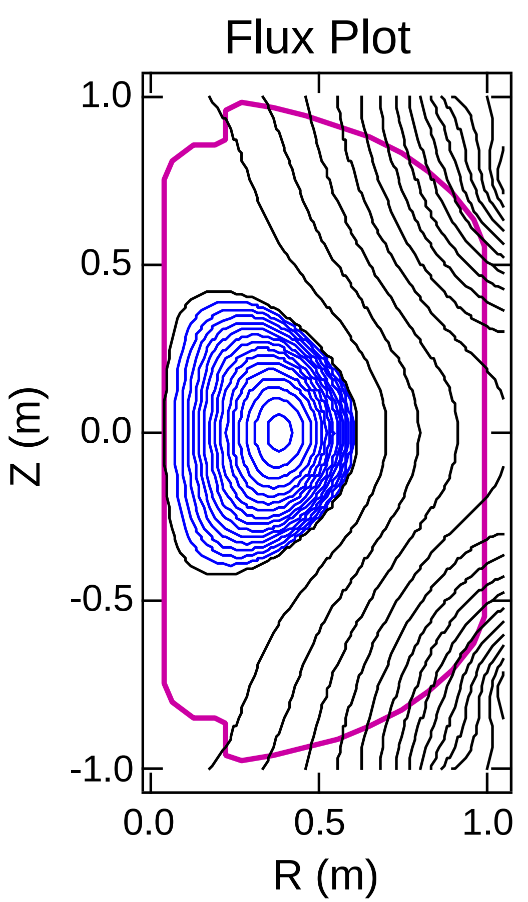
A	1.12-1.3
R	0.2-0.45 m
I_p	0.16 MA
RB_t	$\leq$ 0.03 T-m
κ	1.4 - 3.7
Δt_{pulse}	0.01-0.03 s
$\langle n_e \rangle$	$1\text{-}5 \times 10^{19} m^{-3}$
β_t	$\leq$ 20%

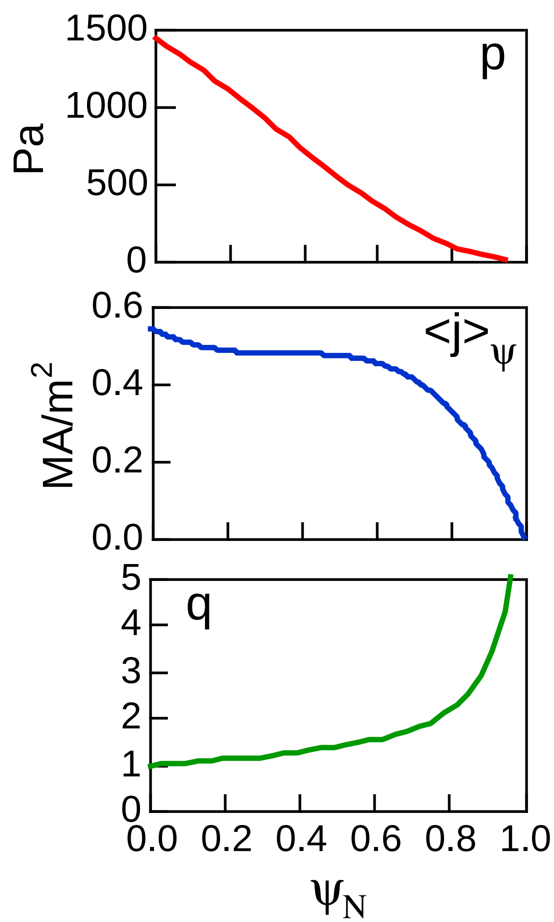
Equilibrium reconstructions show low-A characteristics

Low-A Characteristics

- High-β_t (Ohmic): $\beta_t > 10\%$
- 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: $F/F_{vac} \sim 1.5$ on axis ($\varepsilon\beta_p < 1$)

Sample Reconstruction



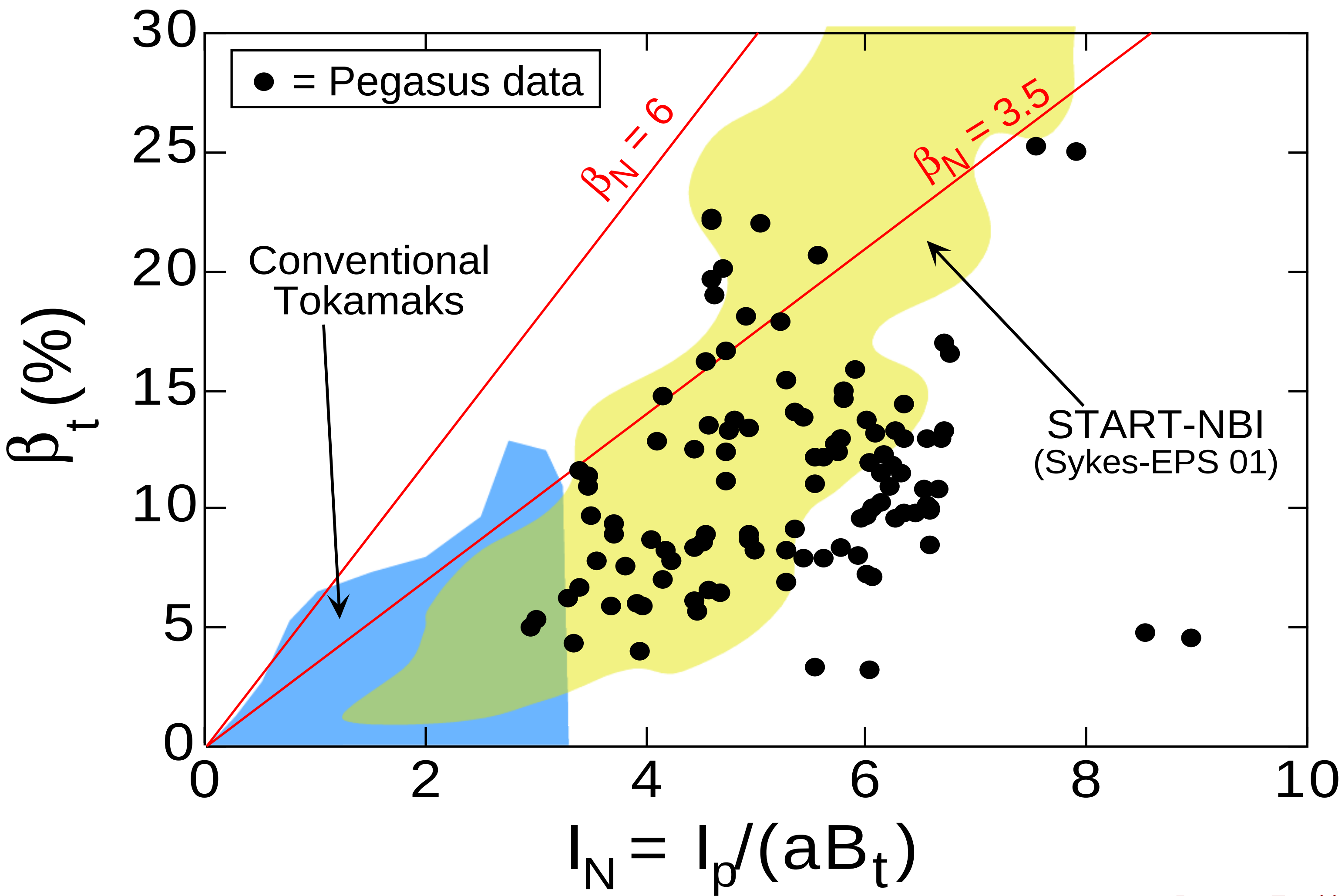


Fit Results

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

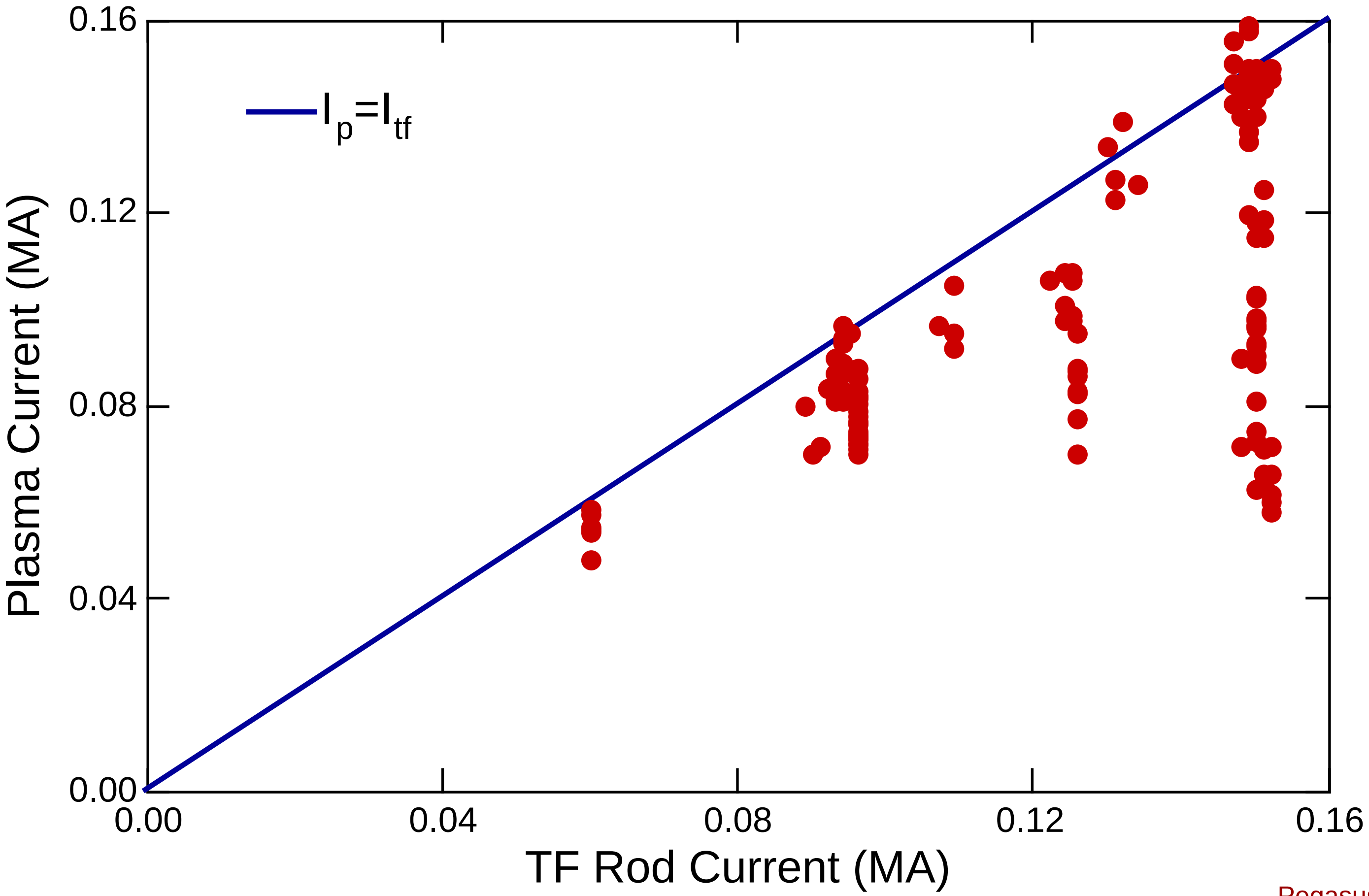
A < 1.3 → ready ohmic access to high β_t

- β_t up to 20% 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



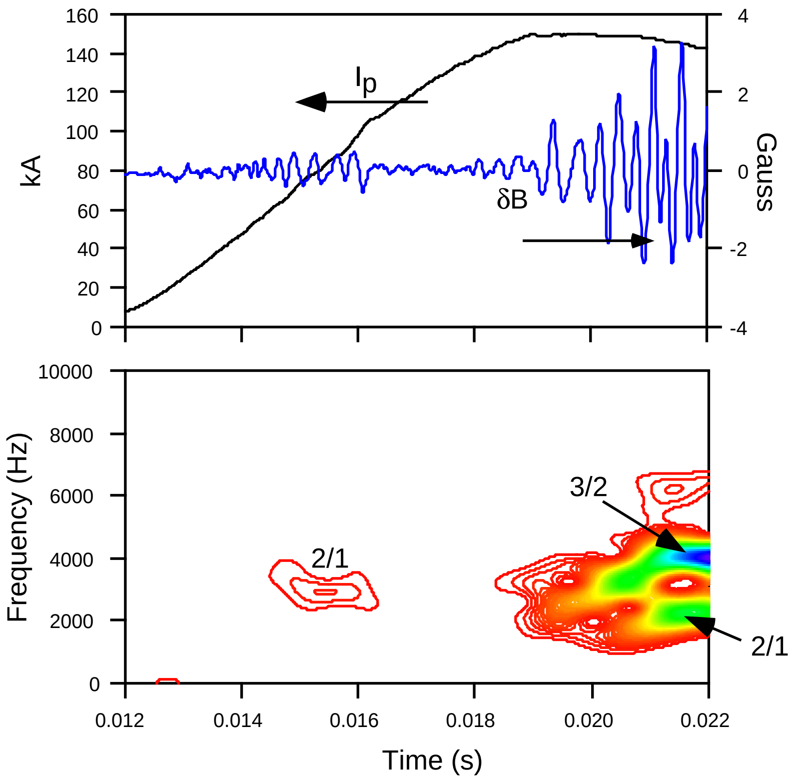
Two factors contribute to the I_p/I_{tf} = 1 soft limit

Large resistive MHD instabilities degrade plasma as TF ↓

- low B_t and fast dI_p/dt → early appearance of low-order q=m/n
- 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*

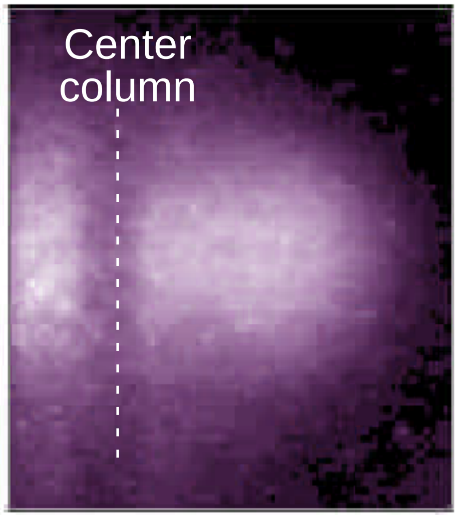


Reduced available Volt-seconds as TF ↓

- reduced toroidal field → delayed startup
- delayed startup + fixed sine V_{loop} waveform → reduced available V-s
- contributes to drop in I_p with reduced I_{tf}

Measured q-profile indicates low central shear

Tangential PHC SXR image

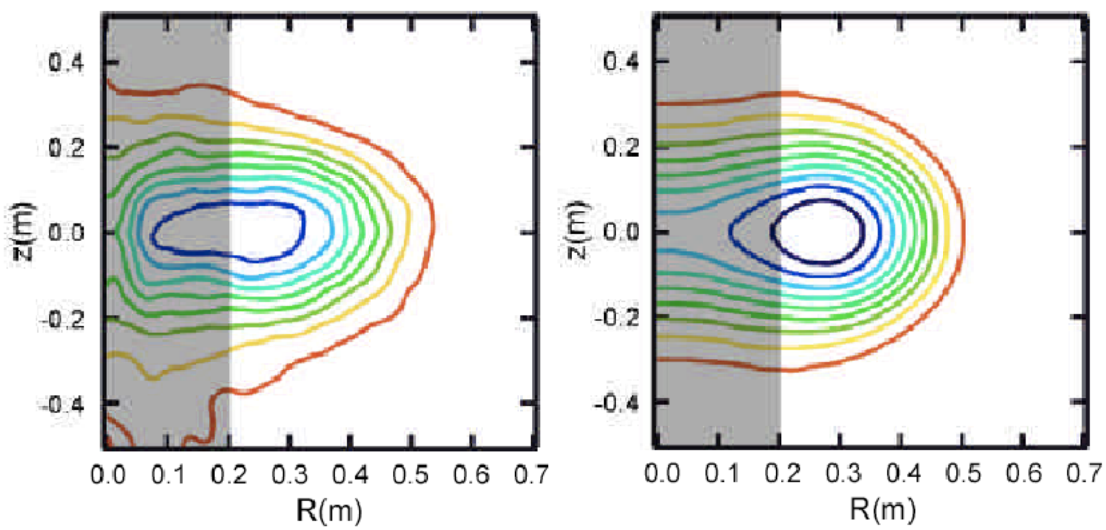


- 2D soft x-ray camera gives q-profile
  - Measures constant-intensity surfaces
  - Used as internal constraint on equilibrium
  - Useful as q-profile diagnostic
- Measured q-profile ⇒ zero central shear
  - Typical of low-A

⇓

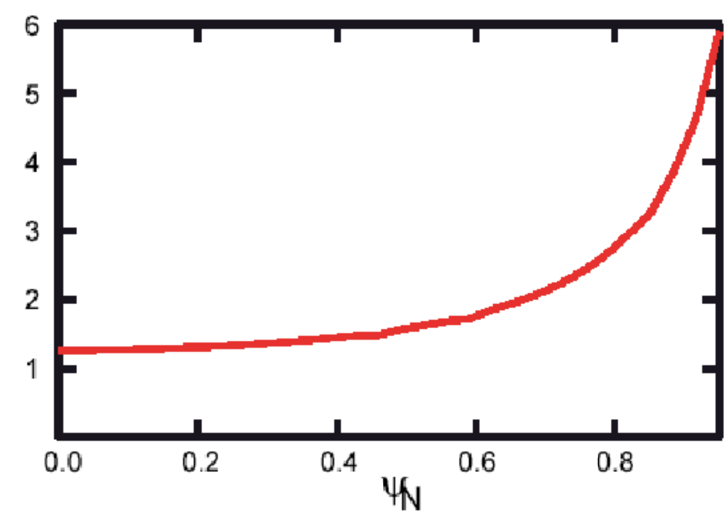
Image Contours:

Measured Reconstructed



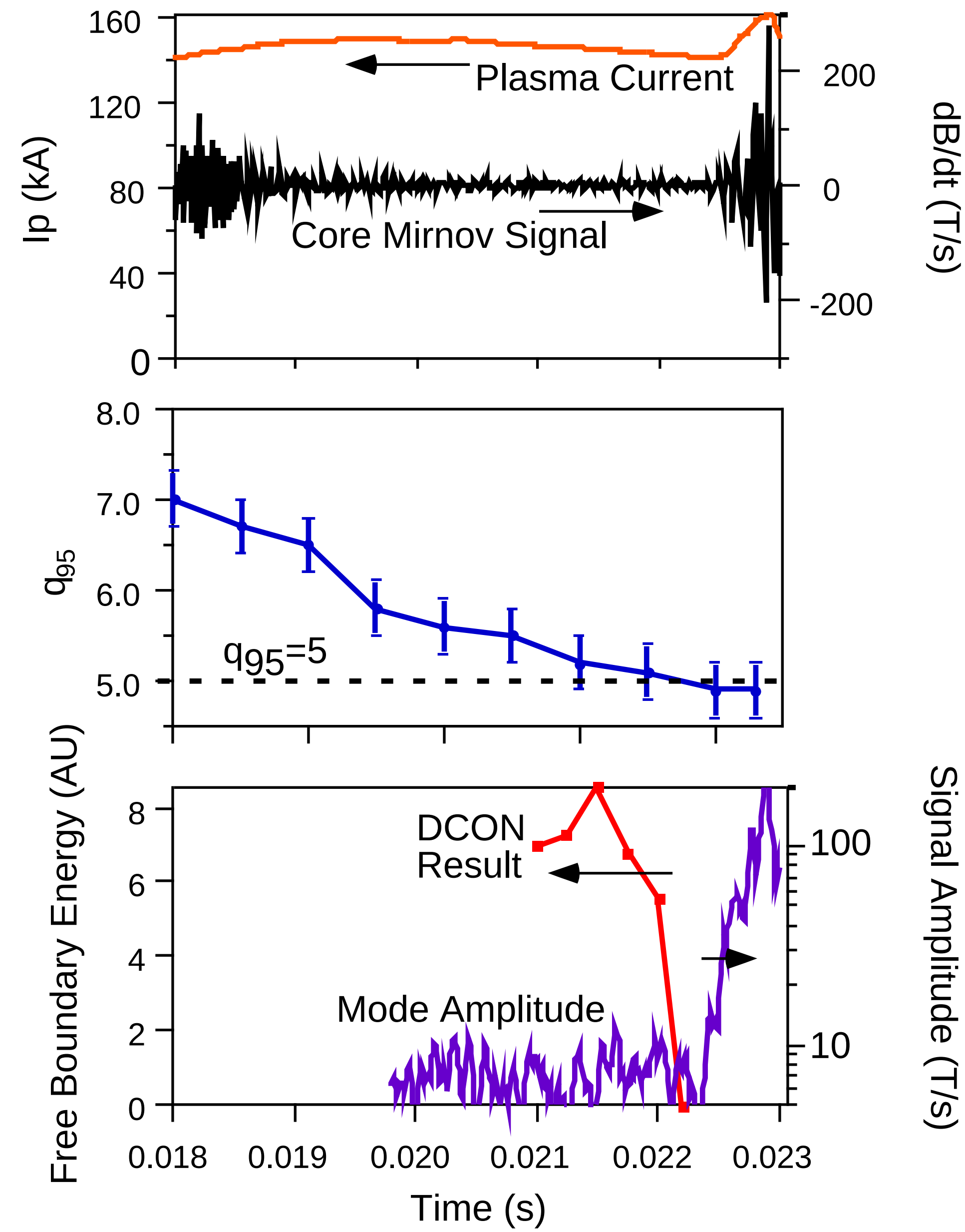
⇒ q

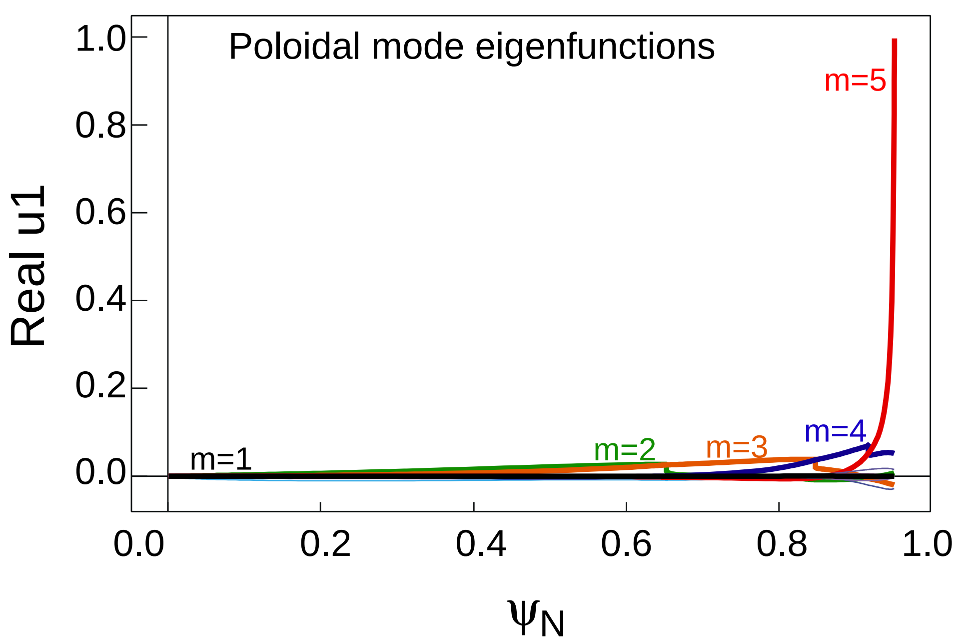
Reconstructed q-profile



External kink stability also limits field utilization

- 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





The path to high field utilization: avoid early MHD

- High field utilization ($I_p > I_{tf}$) requires suppression of tearing modes

    - High β_t, edge kink accessed at high I_p/I_{tf}

- Approaches to increase I_p/I_{tf}

    - Transiently increase q during startup
        = via transient I_{tf} waveform

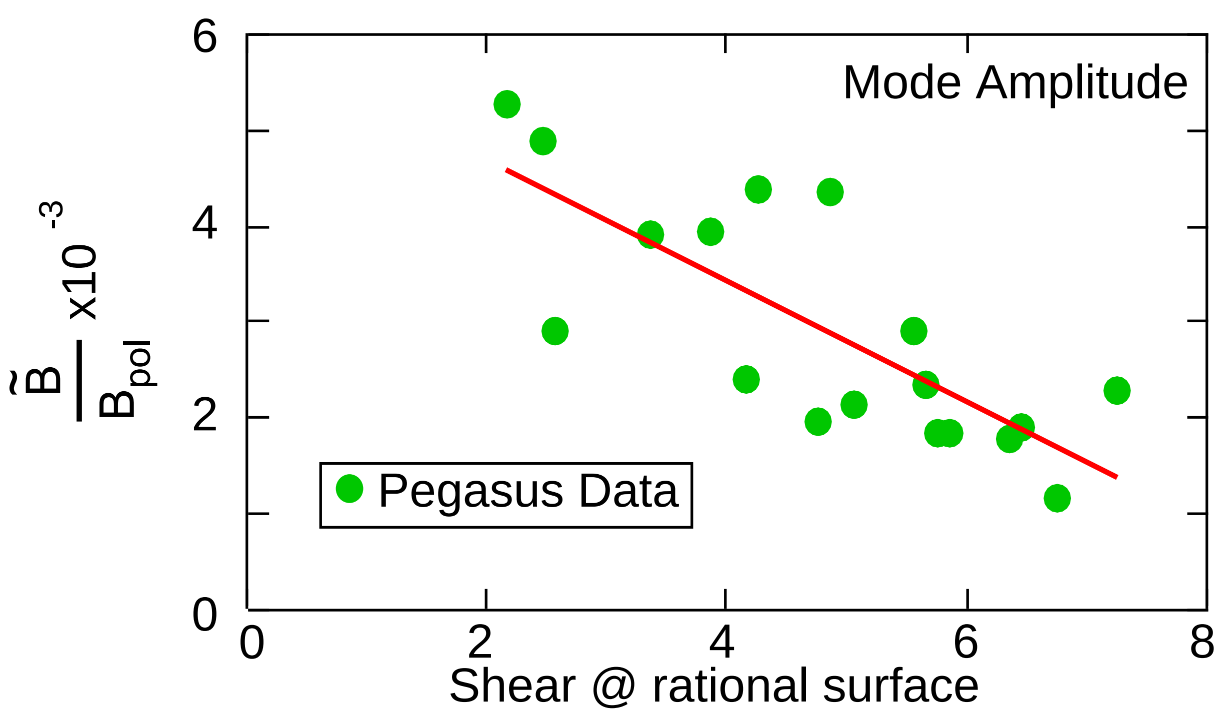
    - Manipulate current profile
        = variable dI_p/dt
        = shape control and separatrix operation
        = transient I_{tf} changes

    - Reduce η before low-order rationals appear
        = V_{loop} control
        = radial position control
            + *R small early* $\Rightarrow$ *large J(r)*
        = RF heating (HHFW)
            + *requires well-controlled edge*

Mode amplitude reduced by manipulation of shear and q_0

- Discharge tailoring → plasmas with reduced MHD activity
  - Increased W, I_p
- Increased shear, increased q_0 ⇒ delay tearing onset
- MHD amplitude decreases with increasing shear

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

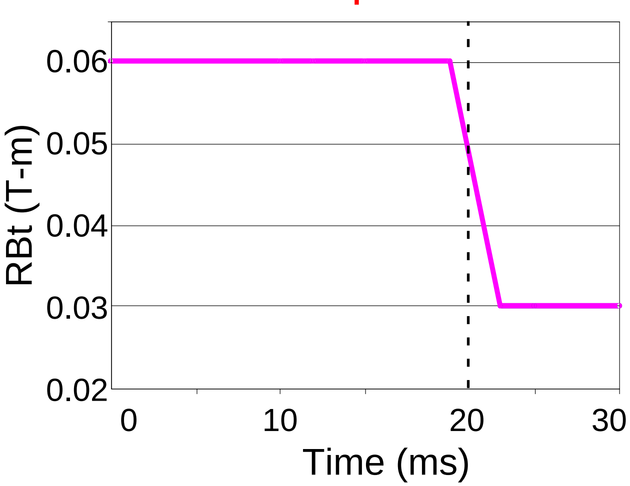


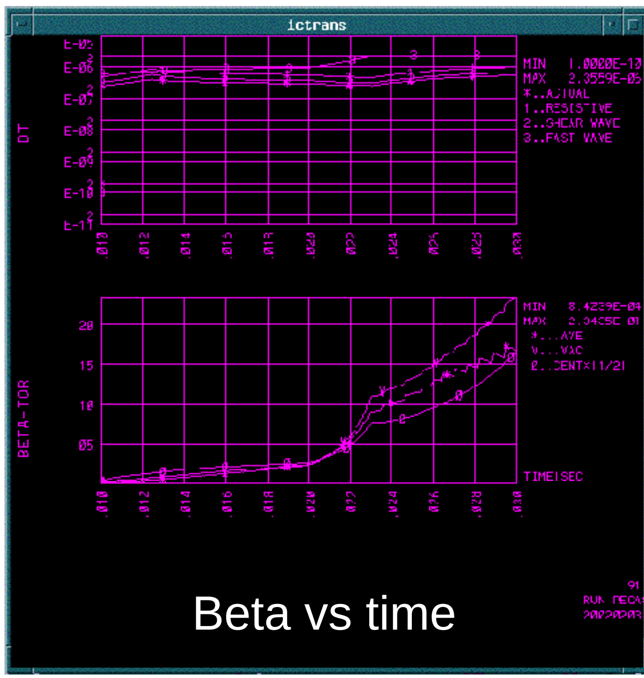
TSC: Fast TF rampdown is tool for q(r) and β manipulation

- Effect of fast ramp:
  - β_t increases
  - q_a drops as B_t, q_0 falls more slowly (on τ_R time scale)
  - Toroidal flux conservation:
    - = edge poloidal currents driven, ℓ_i drops
    - = I_{ef} increases to hold R, I_p increases due to induction and energy conservation

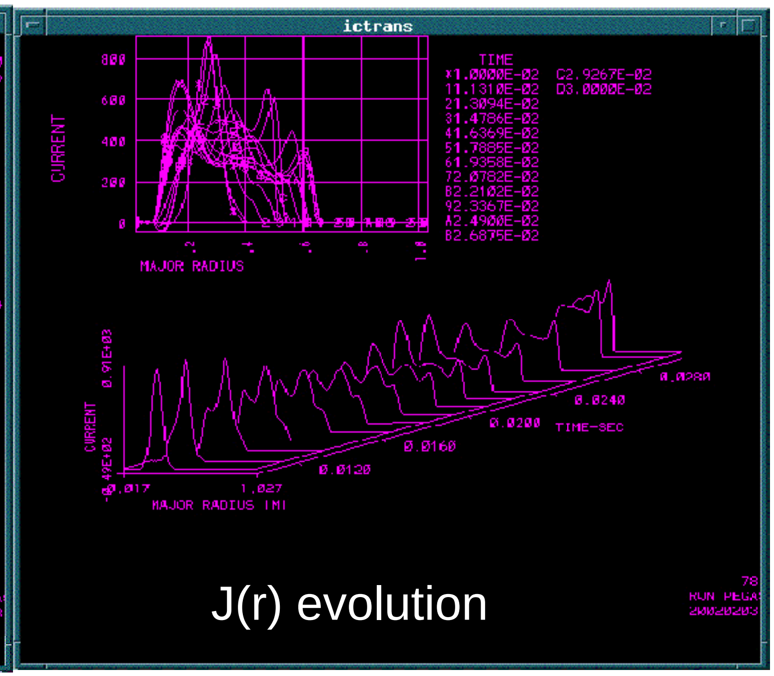
- Results of TSC PEGASUS simulation:
  - RB_t: 0.06 to 0.03 T-m in 2 ms
  - β_t increases from 5% to 16%
  - I_p: up from 90 kA to 140 kA
  - Φ up from 1 to 6 mWb

TF Rampdown





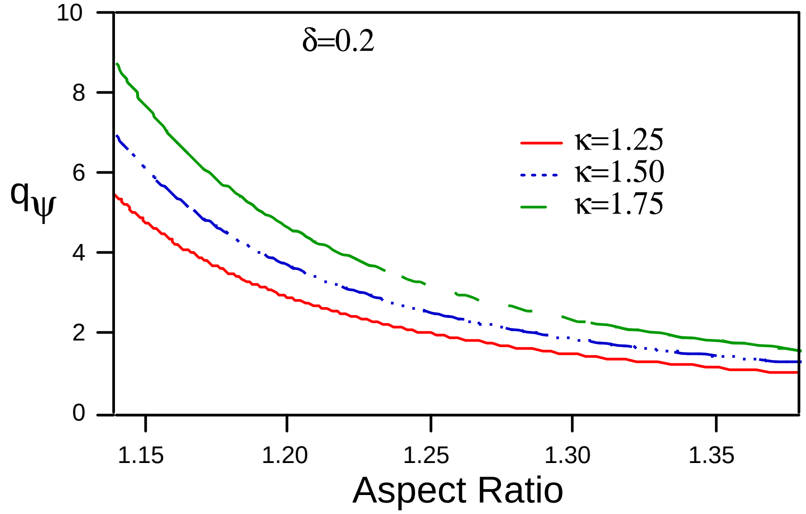
Beta vs time

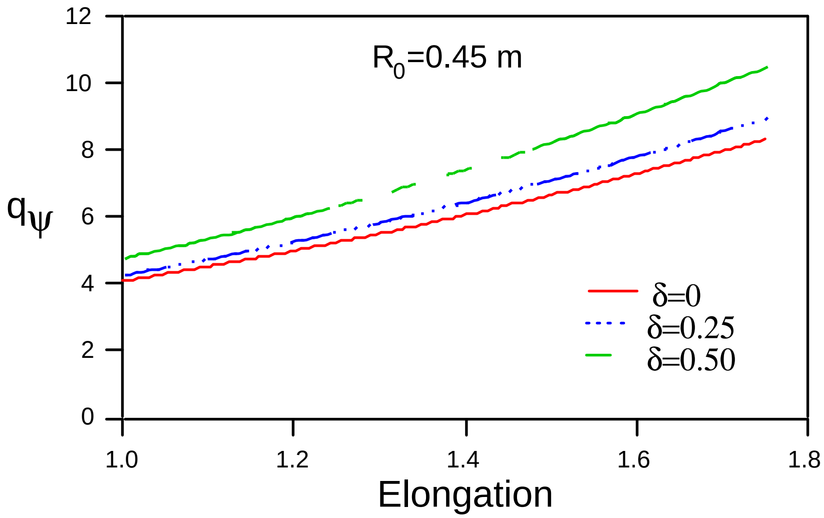


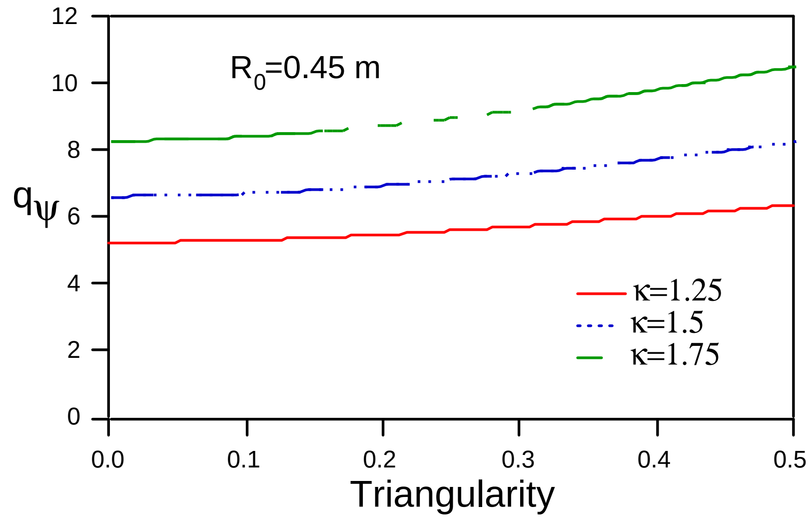
J(r) evolution

Shaping strongly affects edge q

- κ, δ, A strongest effects
- Variation in q => variations in kink stability
- These plots from analytical expression
  - I_p = 300 kA
  - RB_t = 0.028 T-m







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

- Suppress tearing modes early in discharge evolution

  = Transiently increase q during startup:

  - Increased TF => high I_{tf}, low inductance TF bundle

  = 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

- Avoid edge kink modes at low 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

Active power supplies provide experimental flexibility

- New supplies: capacitor banks actively switched by an H-bridge configuration
  - IGCTs and IGBTs used
  - Replaces old RLC supplies using SCRs and ignitrons
  - Cap banks situated outside building

- Enable coil current programming
  - Loop voltage control
  - TF flat-top and fast rampdown
  - Position and shape control
  - Stray field compensation
  - Active divertor control

Ohmic IGCT H-Bridge Switch

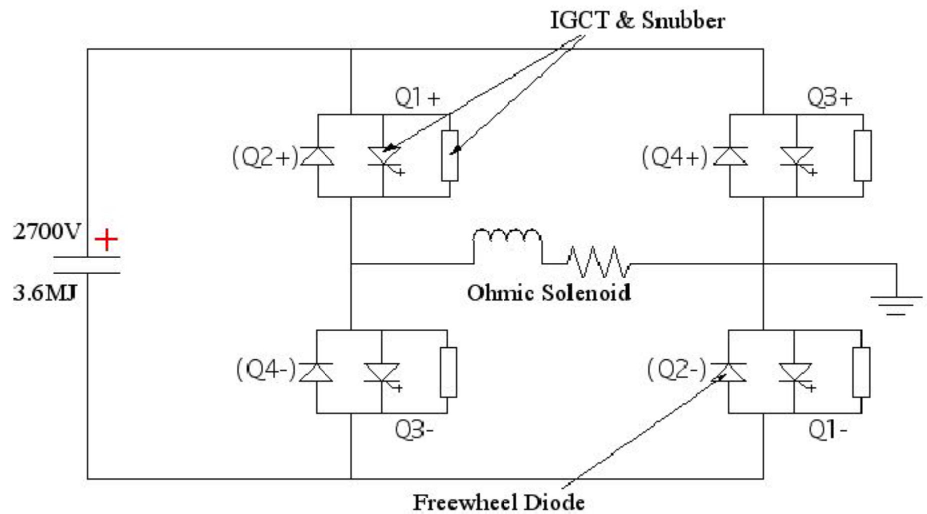


ABB IGCT Presspack with Integrated Gate Unit - Steady State - 2.8kV@4kA

Ohmic heating system provides loop voltage control

• Old waveform: half-sine wave

- non-optimal waveform
- effective plasma time: 15 ms
- effective flux delivered: 40 mV-s

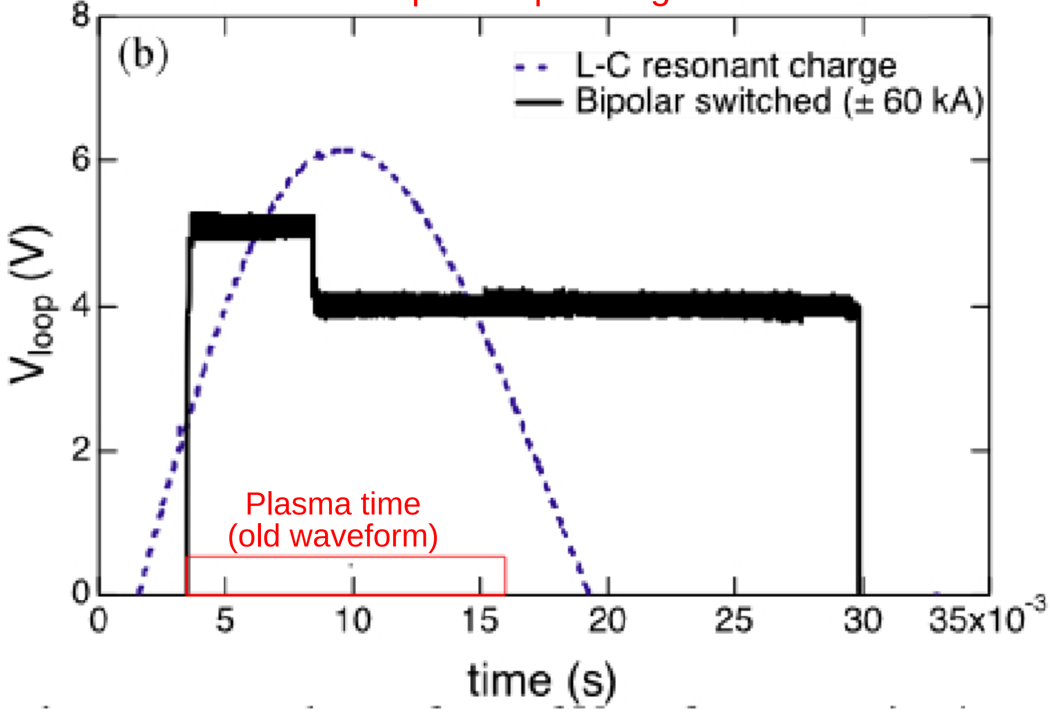
• New waveform: programmable

- can optimize $I_p(t)$ waveform

  = *possible feedback on* I_p

- effective plasma time: 30 ms
- effective flux delivered: 90 mV-s

Sample Loop Voltage Waveform

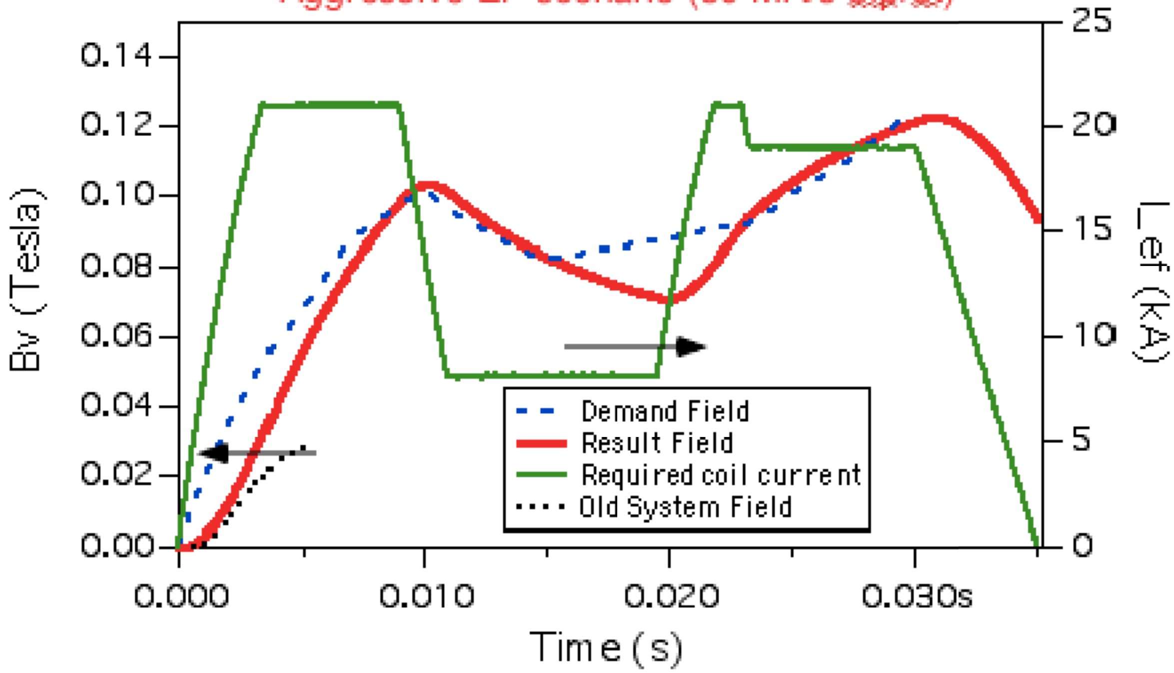


Equilibrium field upgrade provides radial position and shape control

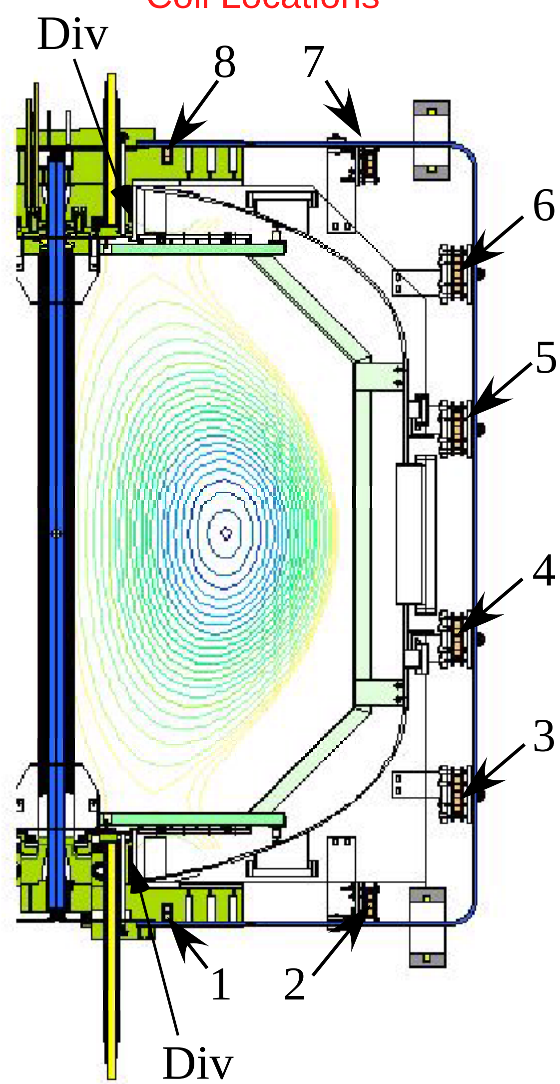
- Upgraded EF system designed with maximum flexibility
  - 8 separate coils + 2 divertor coils
  - 5 independent 20 kA supplies
    - = bipolar divertor coils
    - = 1,2,7,8 coils
    - = 4 and 5 coils
    - = 3 coil
    - = 6 coil (3-6 for up/down control)

- High current and fast response necessary to force field through conducting vessel wall (2 ms skin time)

Aggressive EF scenario (30 MA/s dIp/dt)

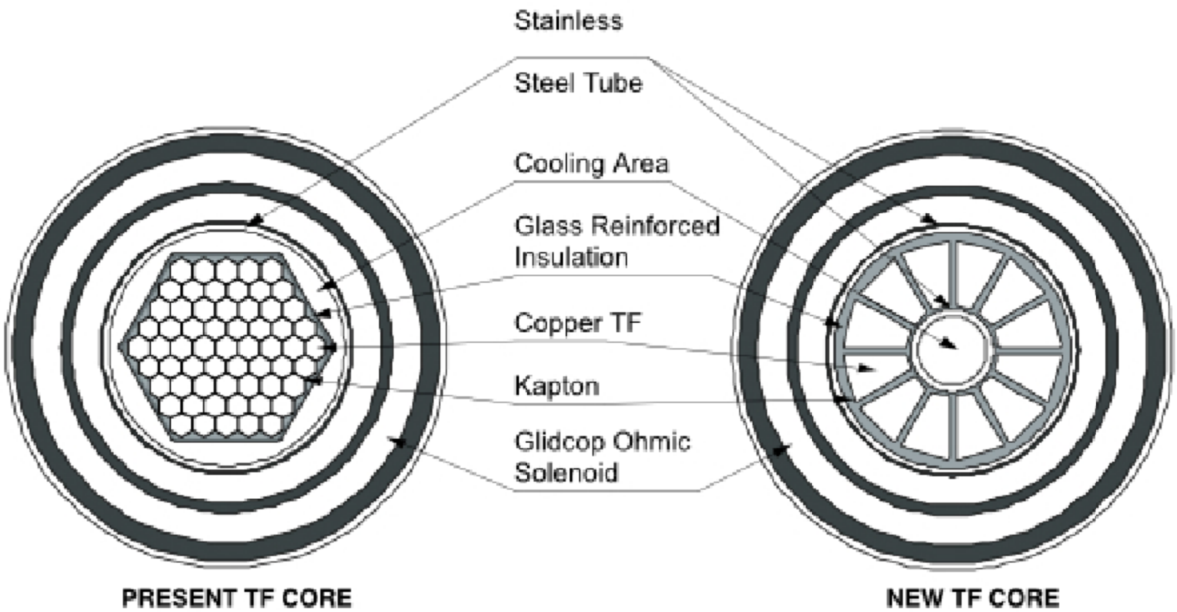


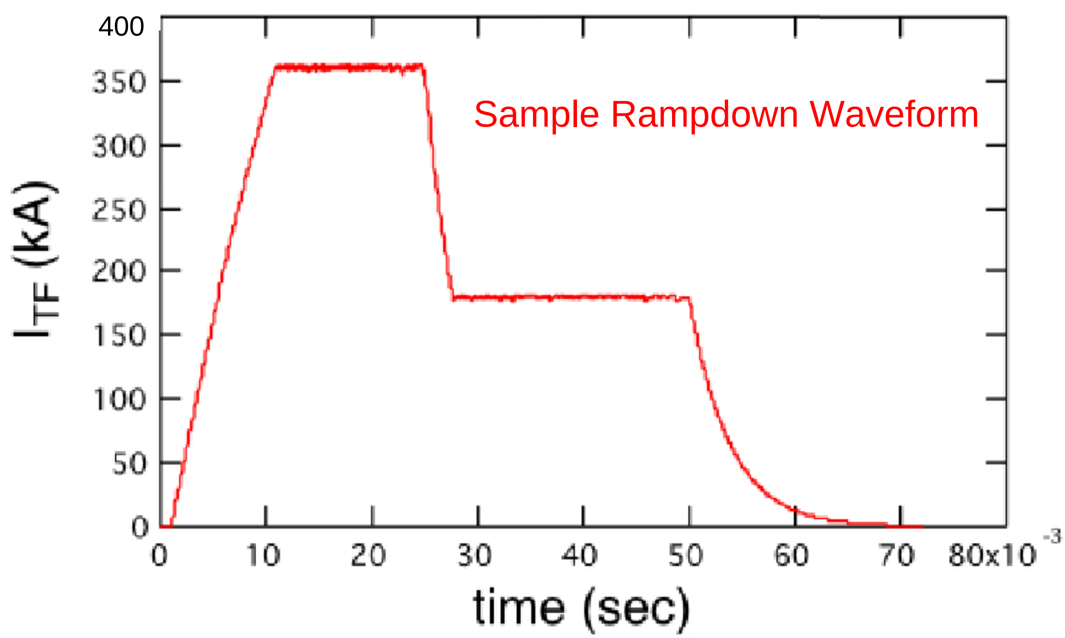
Coil Locations



Toroidal Field: Increased field and fast rampdown

Comparison: old core vs new core

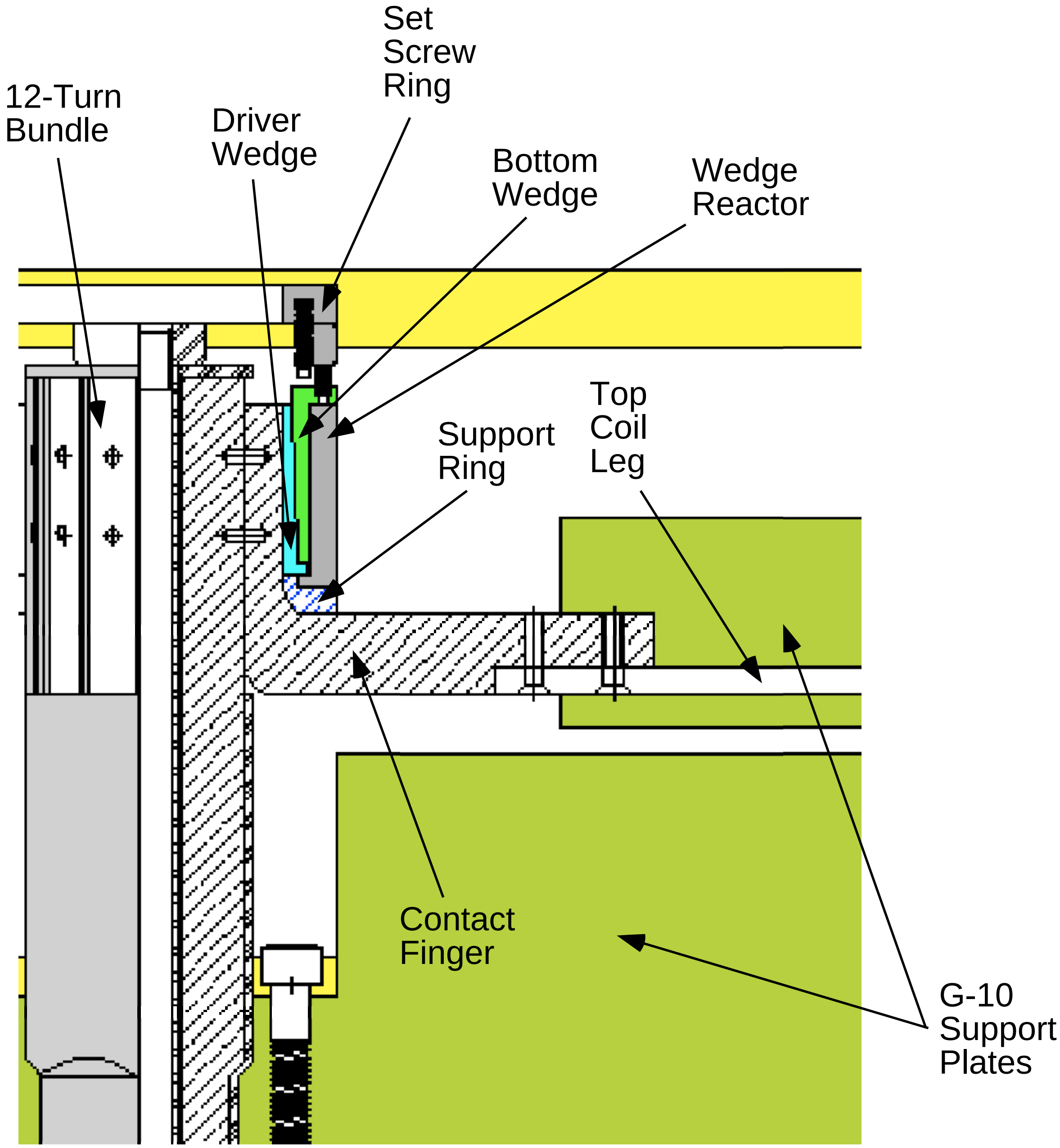




- Previous system
  - 60 turns
  - 2.5 kA/turn
  - Limited by resistivity
    $= I_{tf} \leq 150\ kA$

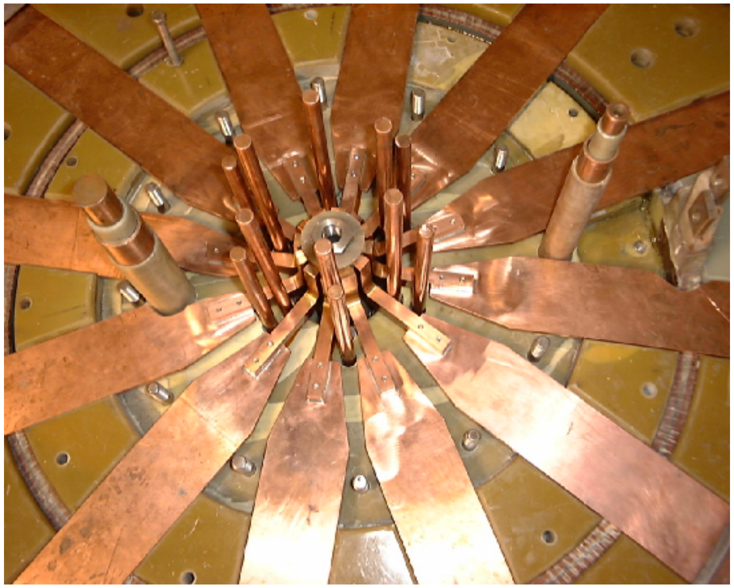
- New system
  - 12 turns
  - > 40 kA/turn
  - Limited by switches
    $= I_{tf} \leq 500\ kA$

Toroidal Field Centerstack Assembly

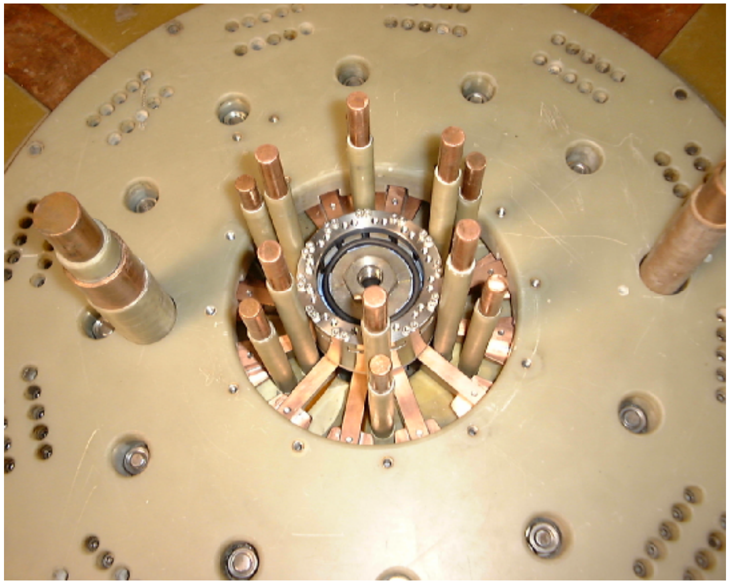


Cross-Sectional Drawing (Top)

Partial Assembly Showing Fingers (Top)



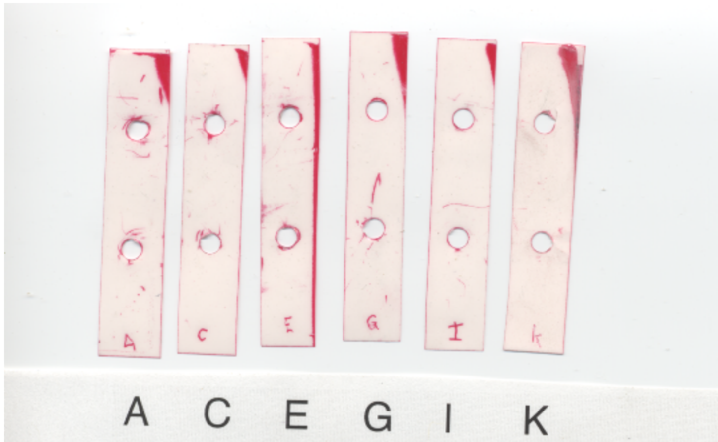
Finished Assembly with Wedge Reactor (Top)



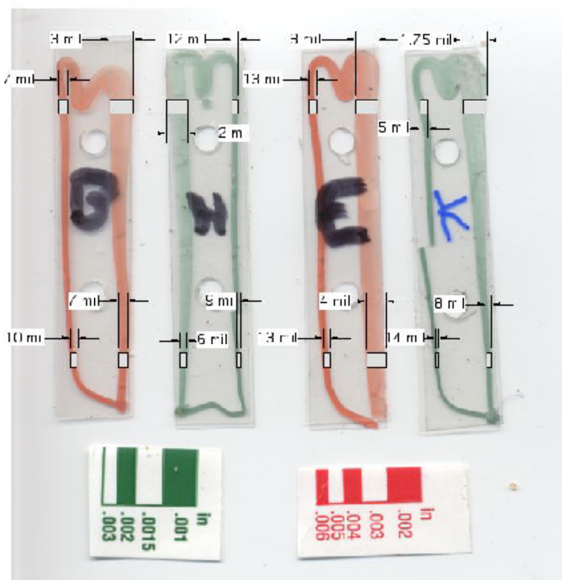
TF assembly in close quarters of small centerstack region

Initial Fit

Pressure Paper

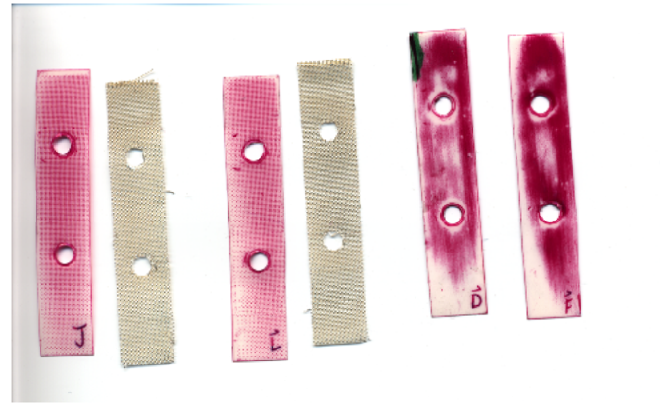


Plastigage™



Final Fit

Pressure Paper



- New diagnostic tools aid joint assembly
  - Pressure sensitive paper
    - = *Turns red when compressed*
    - = *Indicates surface area in contact*
  - Plastigage™
    - = *Plastic wire compressed in joint*
    - = *Width after compression indicates gap*

- Pegasus joint assembly
  - Initial fit: good resistivity, but poor alignment & gap
  - Surfaces honed to improve alignment
  - Ag mesh inserted to distribute load
  - Final fit: good contact over finger area

Experiment Status: Power Supplies and Lab Reconfiguration

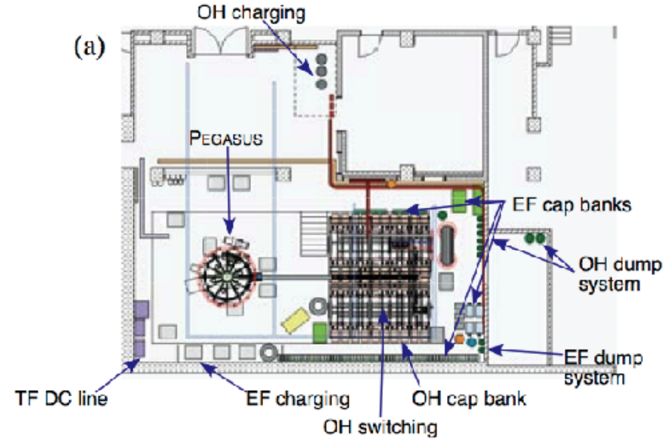
- Power supplies
  - Capacitors relocated to outside vault
  - Capacitors in-house
  - Switches on order
  - Buswork all installed

- Lab reconfiguration
  - Control and DAS centralized in shielded room
  - All signals run in shielded conduit
  - New water and AC lines run

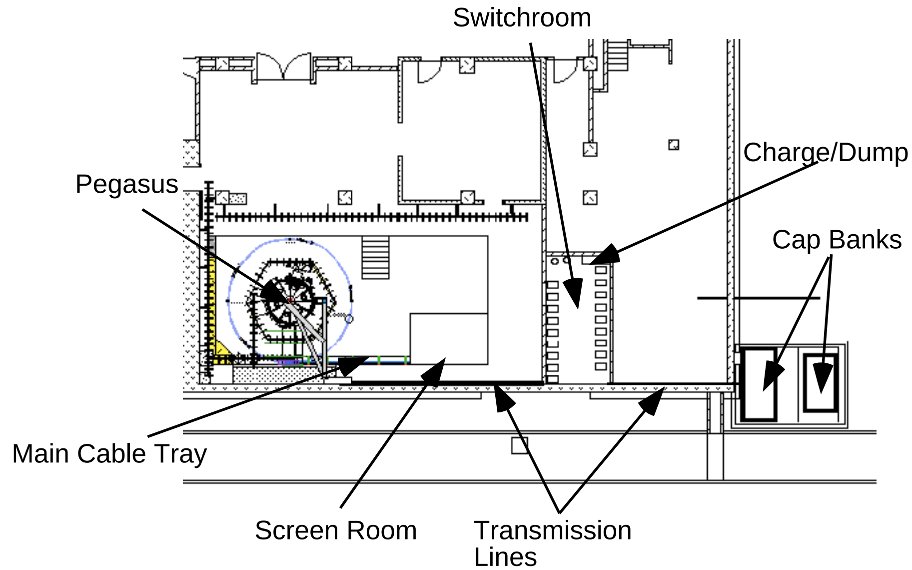
- New diagnostics
  - Pulse height analysis (T_e)
  - Visible bremsstrahlung ($n_e(r)$)
  - 31-channel bolometer ($P_{rad}(r)$)
  - Upgraded 2D SXR camera ($q(r)$)
  - Upgraded 270 GHz interferometer (n_e)

- Status - May 2003
  - TF reassembly complete
  - Pumpdown imminent
  - Capacitors installed: June 2003
  - Power testing: Summer 2003
  - Plasma ops resume: Fall 2003

Lab Configuration - 2002

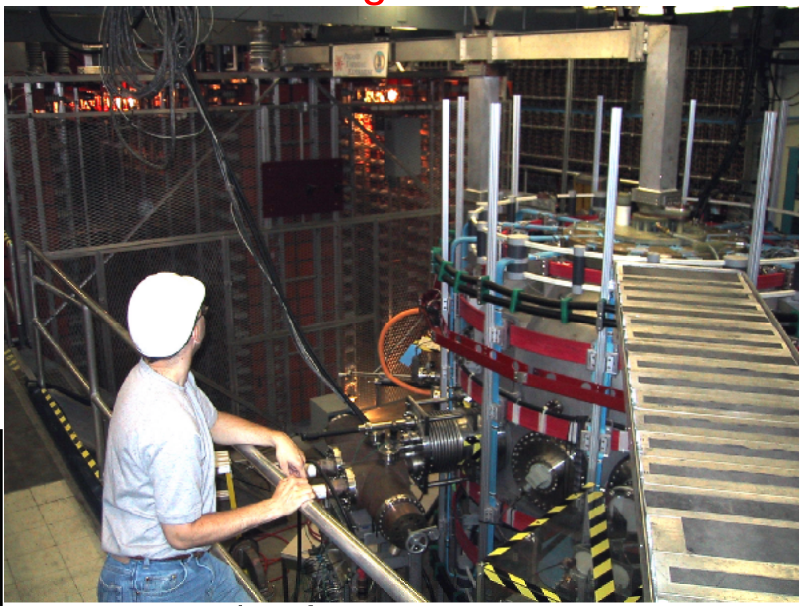


Lab Configuration - 2003



Photos of lab reconfiguration

Old Configuration



View from NW corner

View from pit entrance

New Configuration

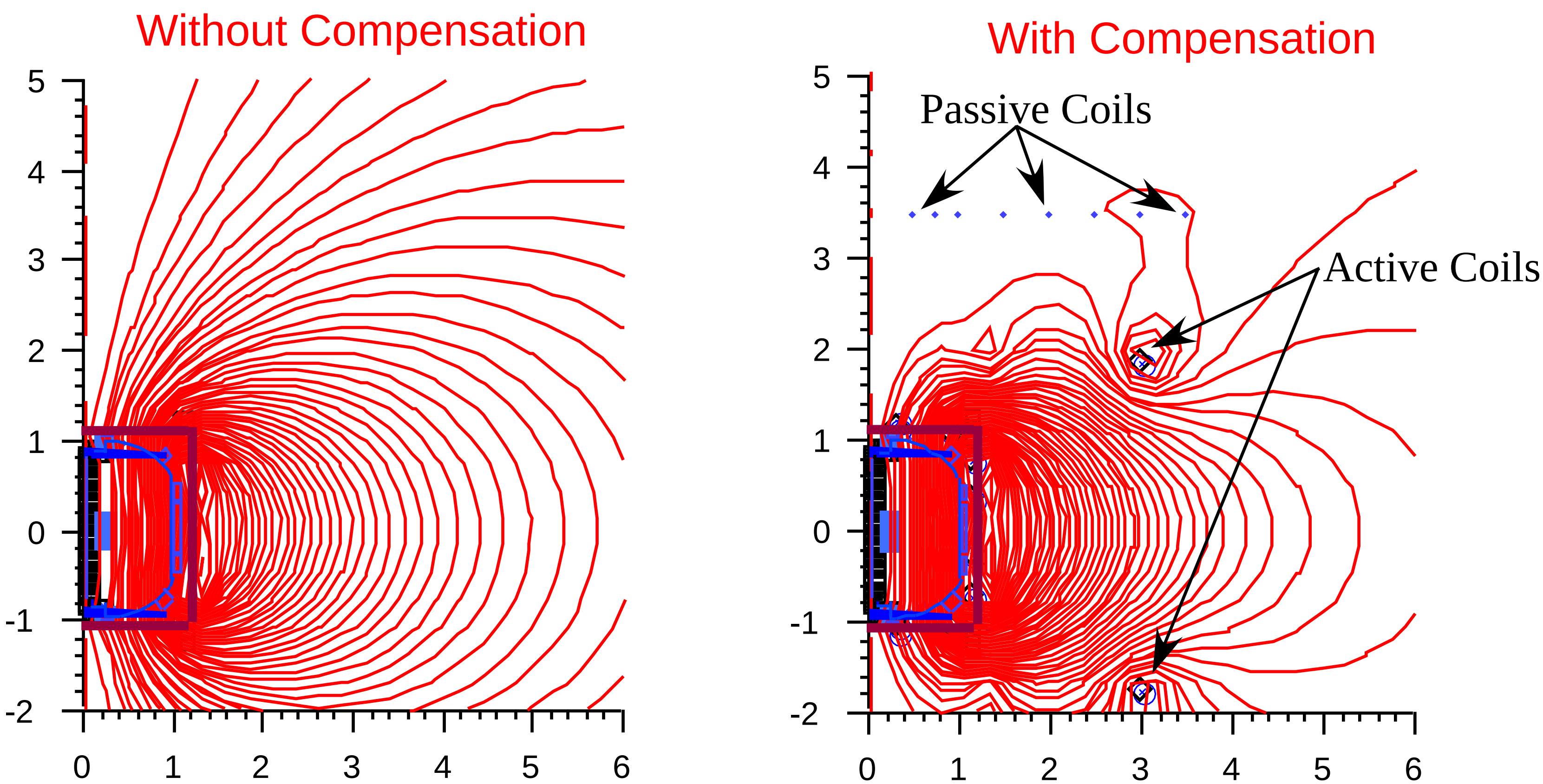
View from NW corner

View from E wall

Equilibrium field must be compensated for public safety

- Increased EF will lead to large fields around the machine
  - 4 m above, and 6 m South, are public places
  - Uncompensated field can be as high as 50 Gauss
  - Possibly hazardous to pacemaker users

- Implement “compensation coils” to reduce this field
  - 8 passive coils on ceiling + 2 active coils at 3 m radius



All axes in meters