Abstract

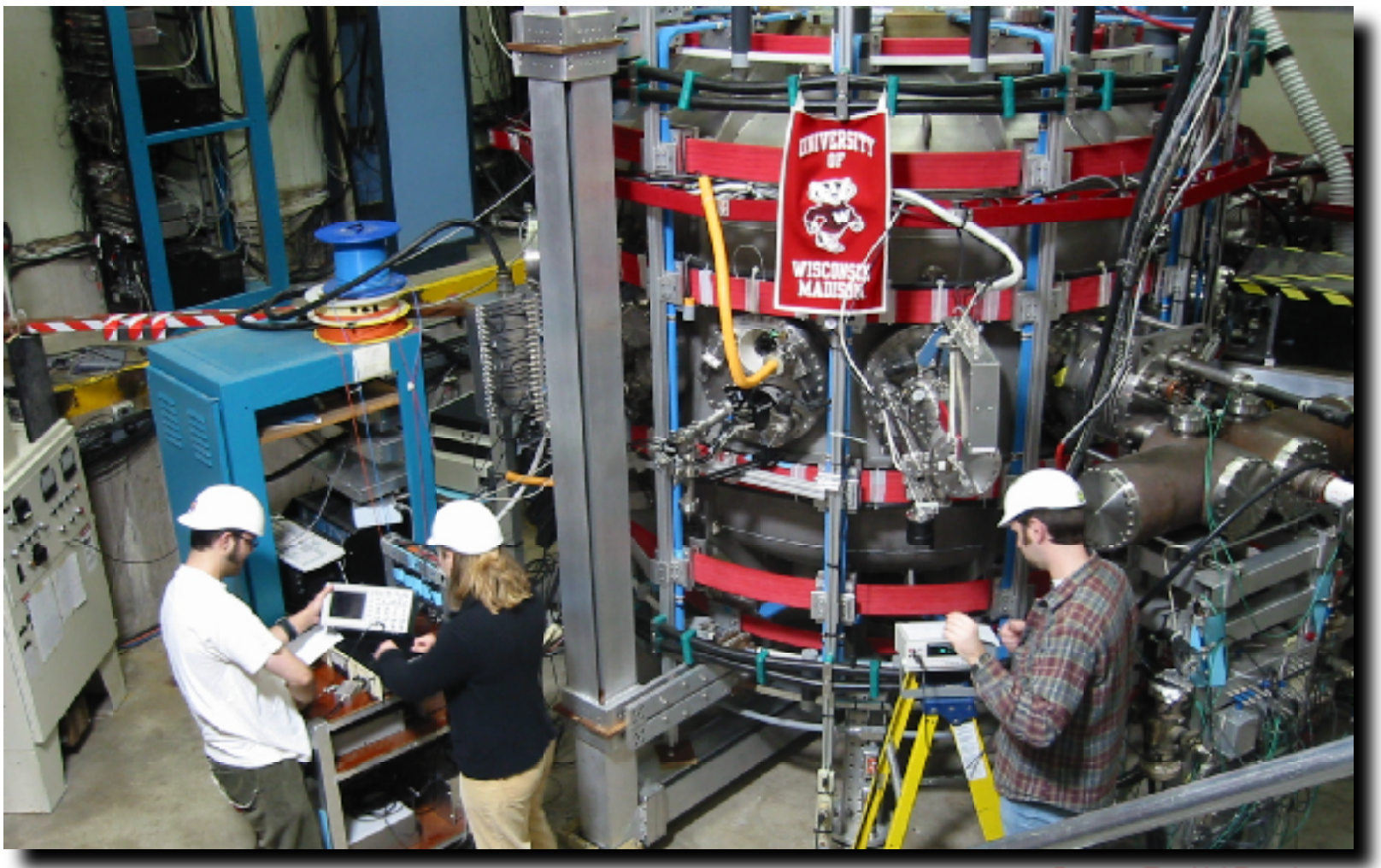
The PEGASUS Toroidal Experiment explores ST plasma behavior focusing on q and beta limits as the aspect ratio approaches unity. Typical plasma parameters are A=1.15-1.4, R=0.2-0.4 m, Ip<0.16 MA, B<0.07 T, and toroidal beta <20%. A 1 MW HHFW system has begun operation and injected 0.2 MW into plasma. Plasma performance is constrained by power supply limitations and low-order resistive instabilities associated with low central shear. Edge kink instabilities have been observed for q_{95}=5 with low internal inductance (0.2-0.4). The magnetic field set power systems are being upgraded to allow for improved waveform control and plasma performance. These upgrades include: 1) increased V-s and loop voltage control for higher plasma current and suppression of observed internal and edge modes; 2) increased toroidal field with fast-ramp capability for improved startup and subsequent access to the low-q, high toroidal beta regime; and 3) improved equilibrium field and waveform control for radial position and modest shape control.

Overview of PEGASUS Results and Facility Upgrades

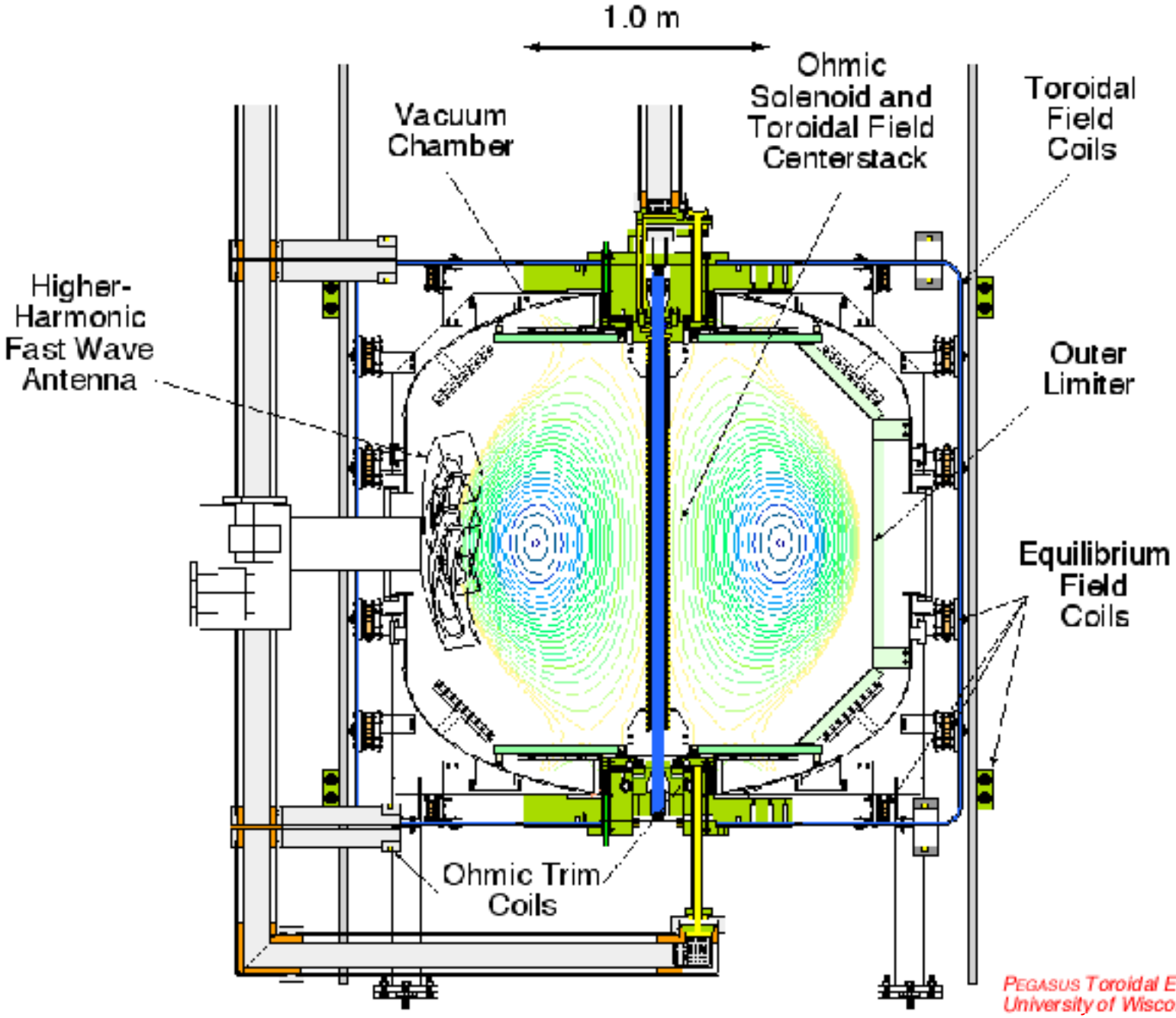
- Introduction
  - *Mission statement for experiment, experiement facility overview*
- PEGASUS Results Summary
  - *High β_t via Ohmic Heating, Soft I_p/I_{TF} limit, MHD*
- Major Upgrades in progress
  - *Experimental Facility, Toroidal Field Centerstack Assembly, Equilibrium Field compensation coils*
- Magnet Coil Power Systems
  - *Pulse Width Modulated (PWM) coil supplies, HIT power system collaboration*
- Summary

Mission Statement for the PEGASUS Toroidal Experiment

- *The PEGASUS Toroidal Experiment is a university based plasma magnetic confinement experiment designed to study high-pressure plasmas in a low aspect ratio axisymetric toroidal geometry.*



PEGASUS Toroidal Experiment



PEGASUS Results Summary

- **PEGASUS discharges exhibit low-A characteristics**

  - $\beta_t > 10\%$, $\beta_N > 4$, $I_p/I_{TF} \sim 1$, $\kappa > 2$, high edge-q at low TF
  - highly paramagnetic: $\beta_p = 0.3$ at $\varepsilon = 0.83$; $F/F_{vac} \sim 1.5$ on axis

- **I_p/I_{TF} 'soft' limit due to combination of internal tearing modes and limited OH flux**

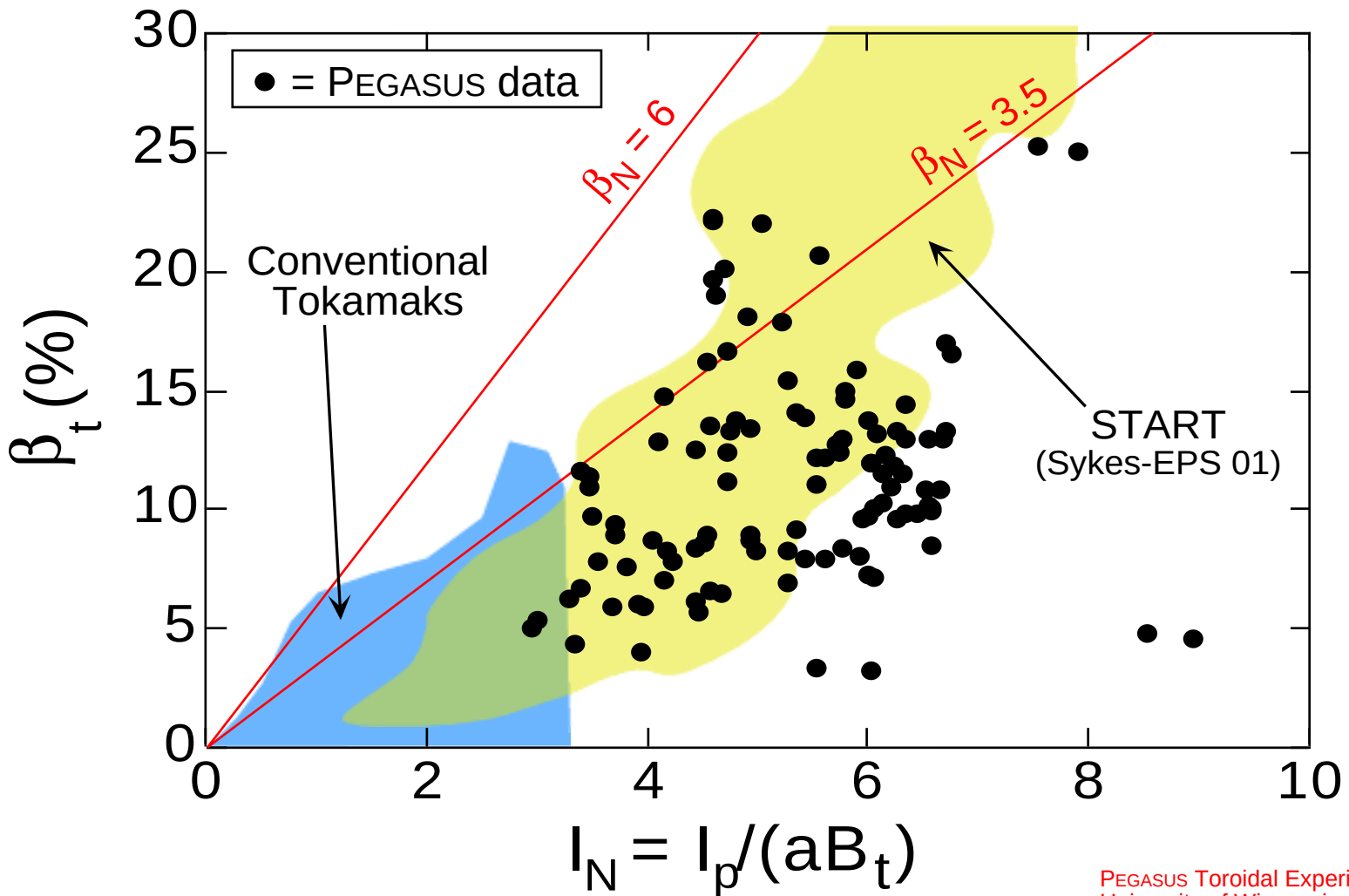
  - internal tearing modes arise when low-order rational surfaces appear
  - low magnetic shear allows large radial extent
  - low TF allows onset early in discharge when η is high

- **External kink accessed at $q_{95} \sim 5$**

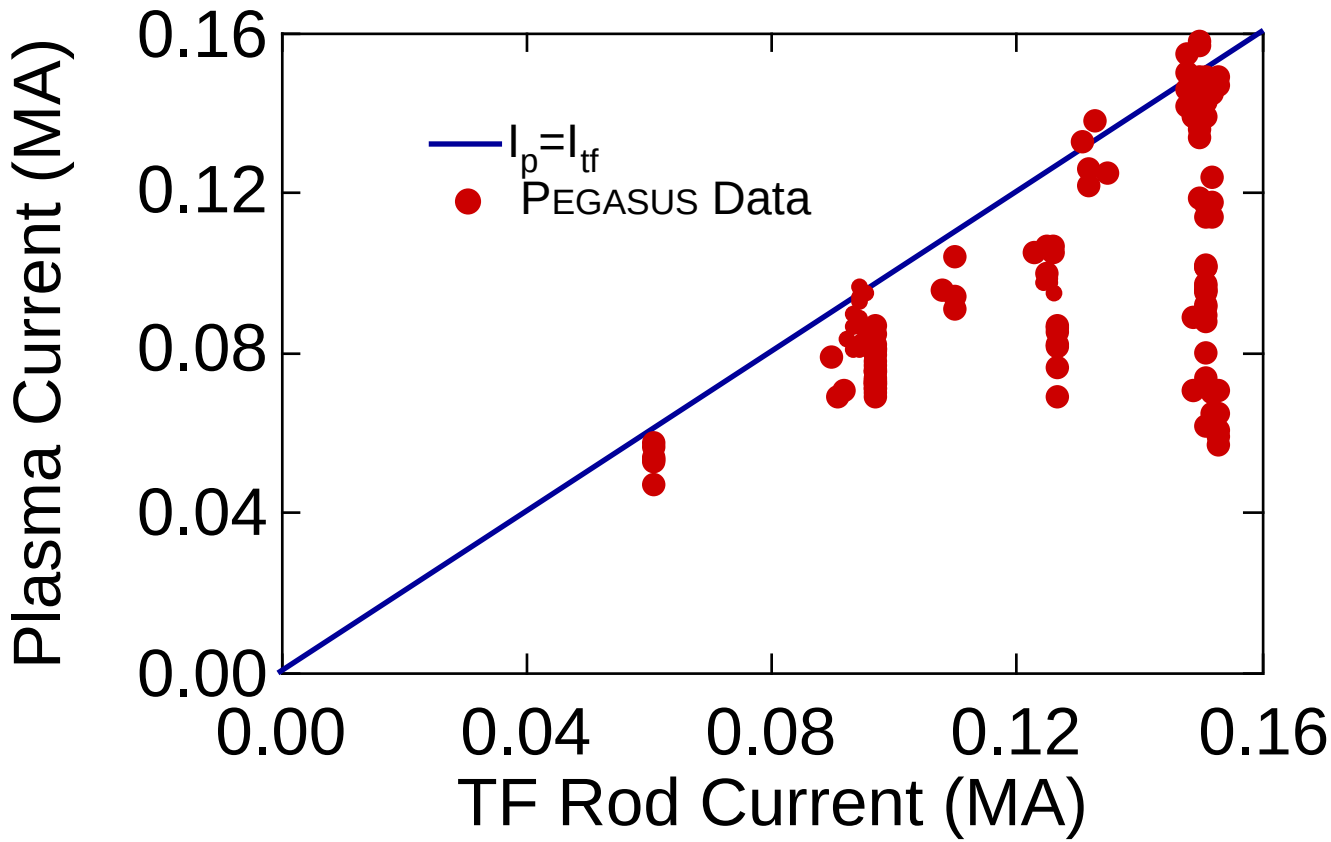
  - theoretical predictions indicate stable q_ψ increases at low-A
  - exacerbated by low-ℓ_i in Pegasus

PEGASUS Routinely Accessing High-β, High I_N via Ohmic Heating

- **High β_t attained at high density, low-TF**
  - *Ohmic heating constant TF*
  - *Highest β_t, I_N at low TF*



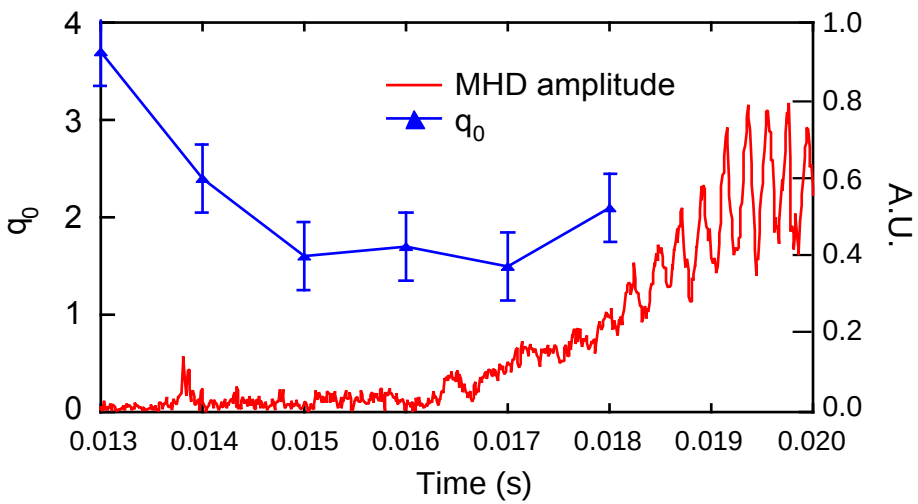
I_p/I_{TF} 'Soft' Limit Observed



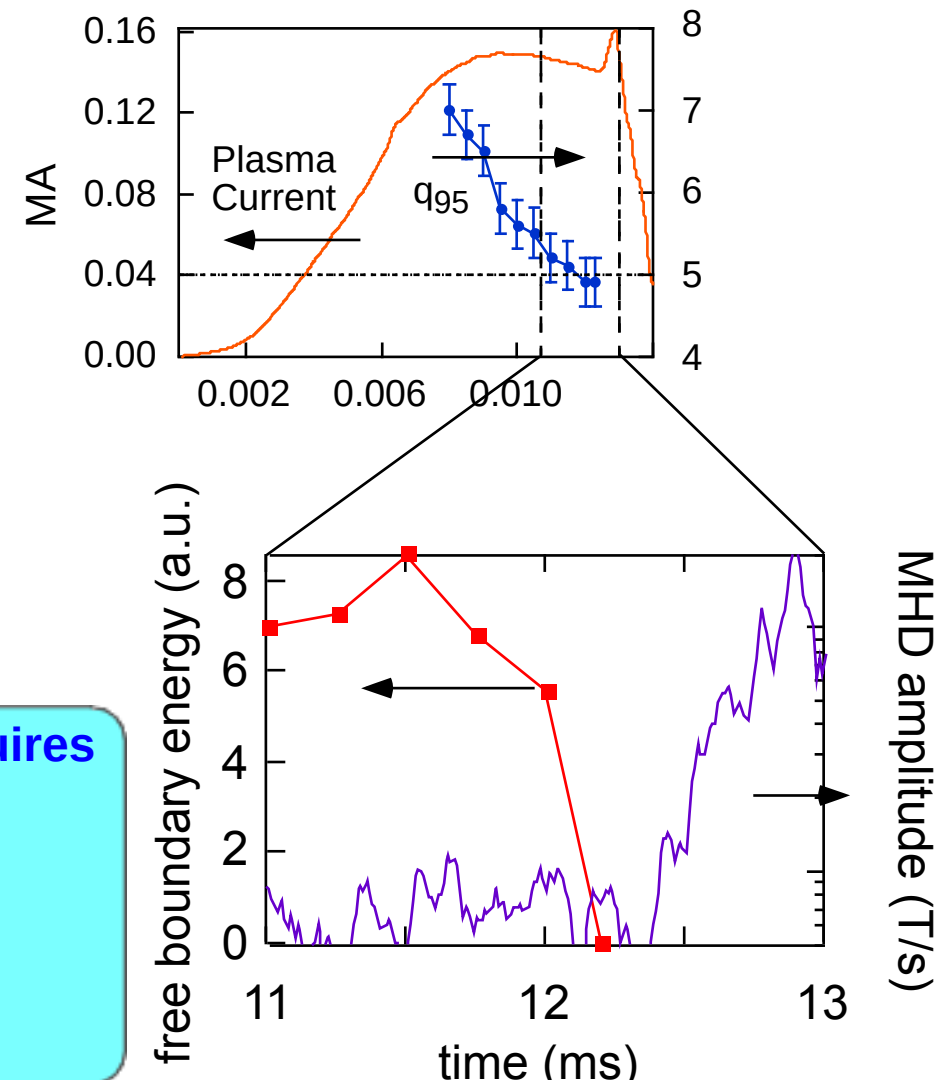
- **Limit manifests as plasma current roll over, not disruption**
- **Internal tearing modes and V-s limitation contribute to limit**
  - extending to $I_p/I_{TF} >> 1$ regime requires tools to supress/manipulate MHD

Pegasus MHD Summary

- **Large scale resistive internal kinks limit $I_p \sim I_{TF}$**
  - mode growth correlates with appearance of low order rational surface in broad region of low magnetic shear



- **External kink observed at $q_{95} \sim 5$**

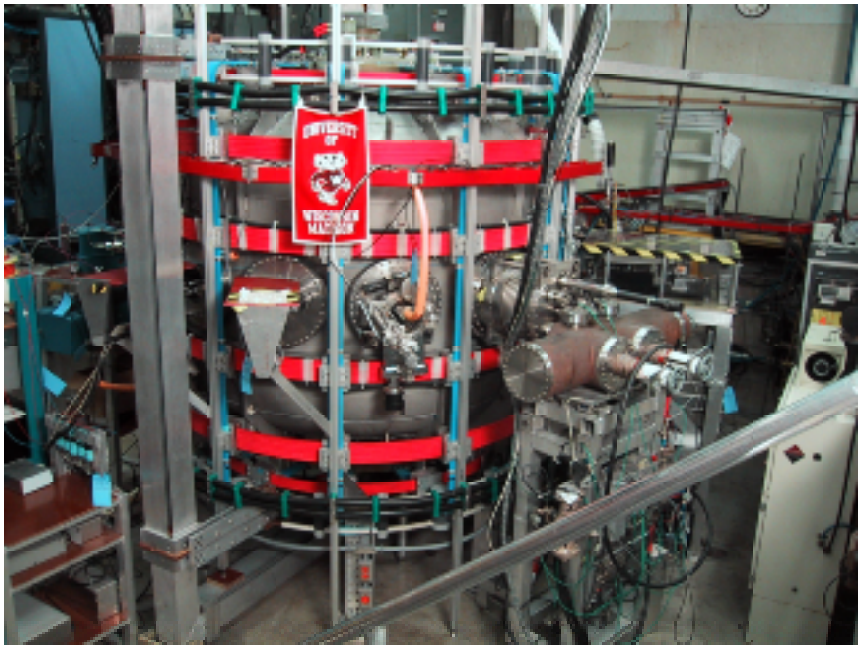


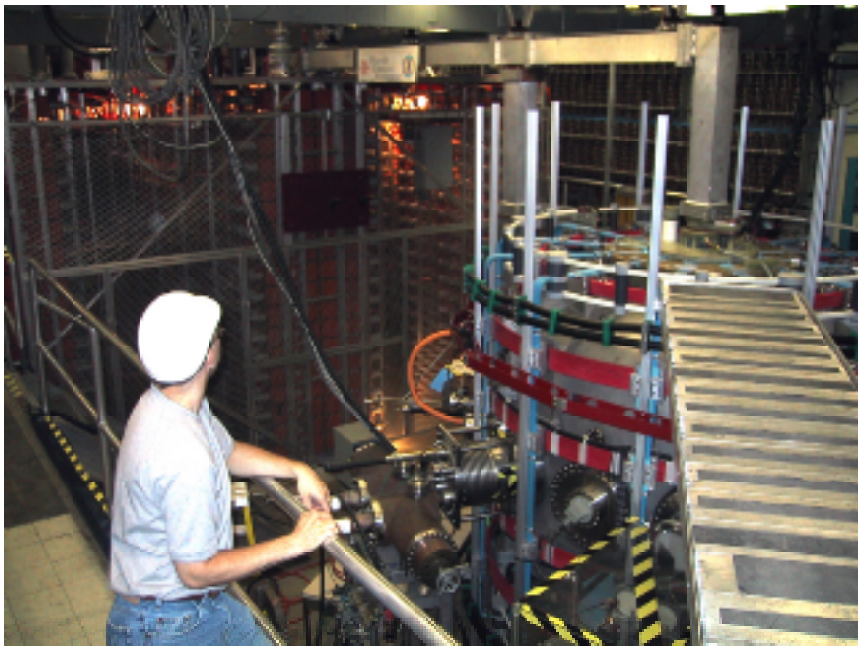
- **Exploration of high I_p / I_{TF}, high β_t regime requires suppression of this MHD**
  - increase T_e, lower η
  - crude control of $q(\psi)$
  - increase V-s and $I_p(t)$
  - allow edge/separatrix control

PEGASUS Experiment is in a Major Upgrade Phase

- Major Laboratory Reconfiguration
  - *Facility damaged in fire following power diode failure*
  - *Improved experiment safety and access in experimental area*
  - *All major energy storage capacitor banks relocated to vault outside building*
- Adding new tools to enhance study of plasma stability boundaries
  - *All coil power systems being upgraded to programmable waveform control*
  - *Independent Equilibruim Field coils to provide active shaping and position control*
  - *Increased V-sec (2 - 2.5x) and control during all phases of plasma evolution*
  - *Low inductance Toroidal Field return bundle being installed for establishing higher B_T (4x) and allowing rapid current ramping capability*
  - *Divertor coils being activated for separatrix operations*
  - *Compensation coil provides additional DC bias field prior to startup*
- Enhance Poloidal Field System to Include Stray Field Reduction

Old PEGASUS Experiment Facility





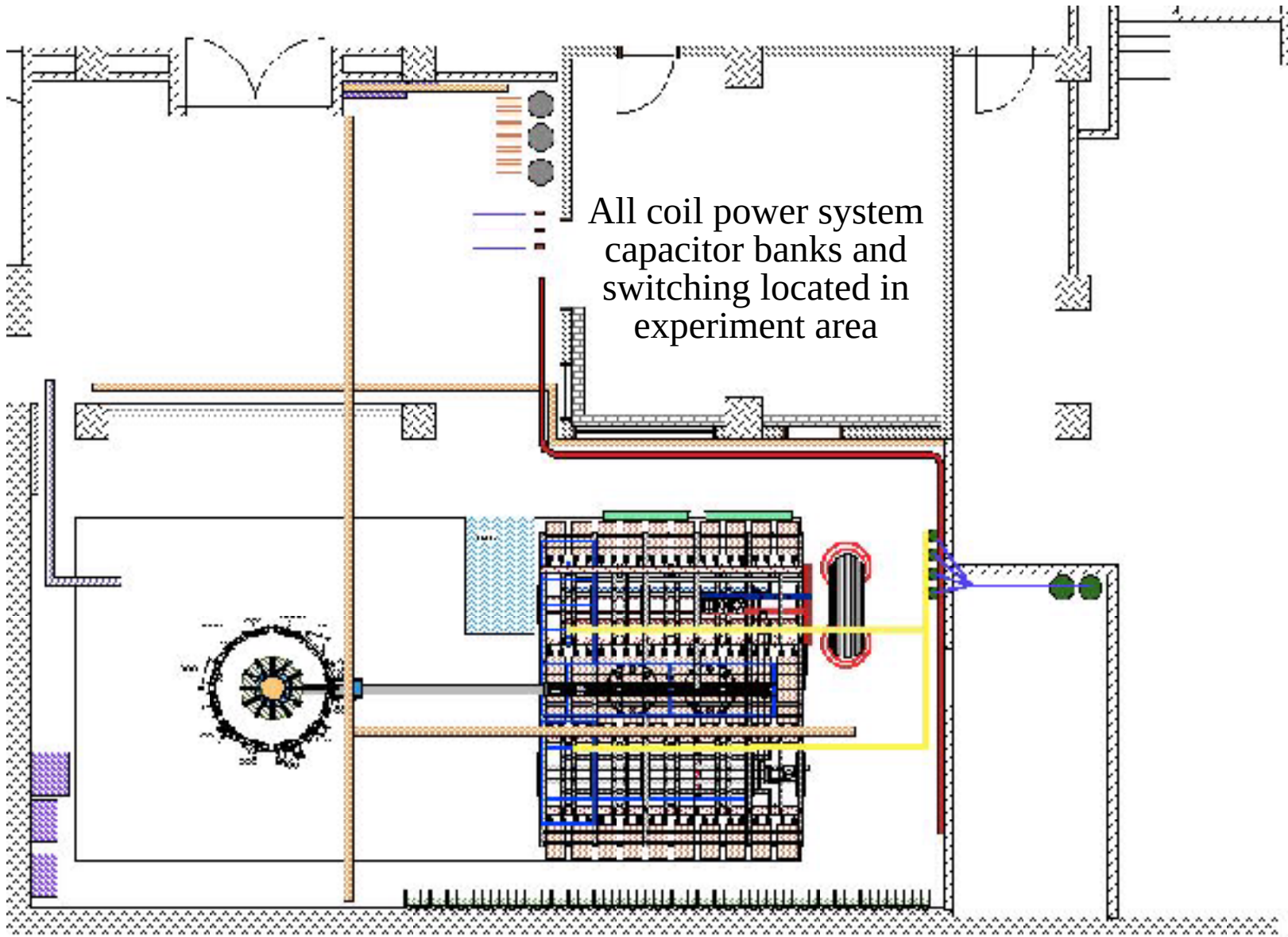
- Crowded Experimental Area

- All high energy coil power systems locate within the experiment hall taking up more than 60% of the usable experiment area.

- Close proximity of power systems to each other and the machine experiment could lead to high collatoral damage.

- Resonant systems required more stored energy and high power coupling comnents to give desired current waveforms

Old PEGASUS Experiment Facility



Improved PEGASUS Experiment Facility

• Facility Upgrades

- No energy storage capacitor banks in experiment area

- High power PWM switching located in room adjacent to the experiment area

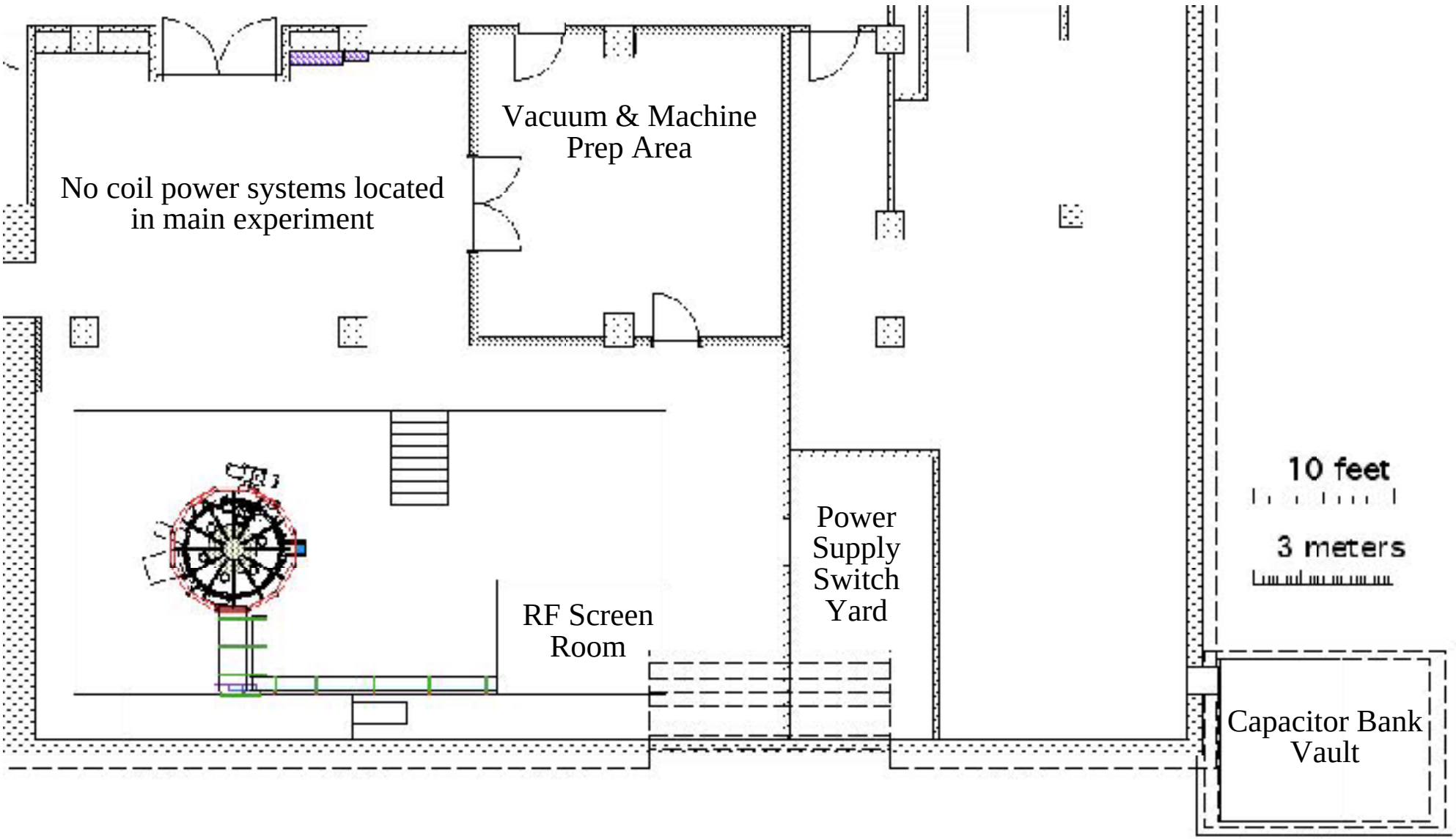
- Removed all outdated interference from past facility.

- Diagnostic transmission lines completely replaced for better RF shielding and grounding

- All oil-dieletric/insulated components replaced with aluminum-electrolytic or dry, self-healing type technology.

- Increased machine capability includes additional Poloidal Field coil to compensate for increased stray field in public areas.

Improved PEGASUS Experiment Facility



Proposed Pulse Width Modulated (PWM) Power Systems

- Ohmic Heating (OH)
  - *Operates up to ±50kA @ 2700V/3500kJ - Four Quadrant Control*
  - *Ohmic Trim provides high order vacuum null for plasma formation*
  - *Allows full controlled utilization of up to 100mV/sec Ohmic Flux*
  - *Regenerative nature of H-bridge allows for resonant termination of Ohmic Current to minimize heating of Ohmic Solenoid*
- Toroidal Field (TF)
  - *Operates up to +50kA @ 900V/584kJ - Two Quadrant Control*
  - *Will allow rapid current ramp down during the shot*
  - *Will allow up to 600kA of TF rod current (up from 150kA)*
- Equilibrium Field (EF)
  - *5 independent systems operate up to +20kA @ 900V/146kJ - Two Quadrant Control*
  - *Provides positioning and shaping fields with active feedback control*
  - *Coil set is adaptable for shaping and positioning concerns*

Helicity Injected Torus Power Systems Collaboration

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

Integrated Gate Commutated Thyristor

- Motivation

- Need better control coil power systems to tailor the current waveform to match the needs of the plasma with active feed back control.

- Use PWM Controlled modern IGCT/IGBT semiconductors

- More reliability and control with less overall stored energy

- Fault detection and interuption capability

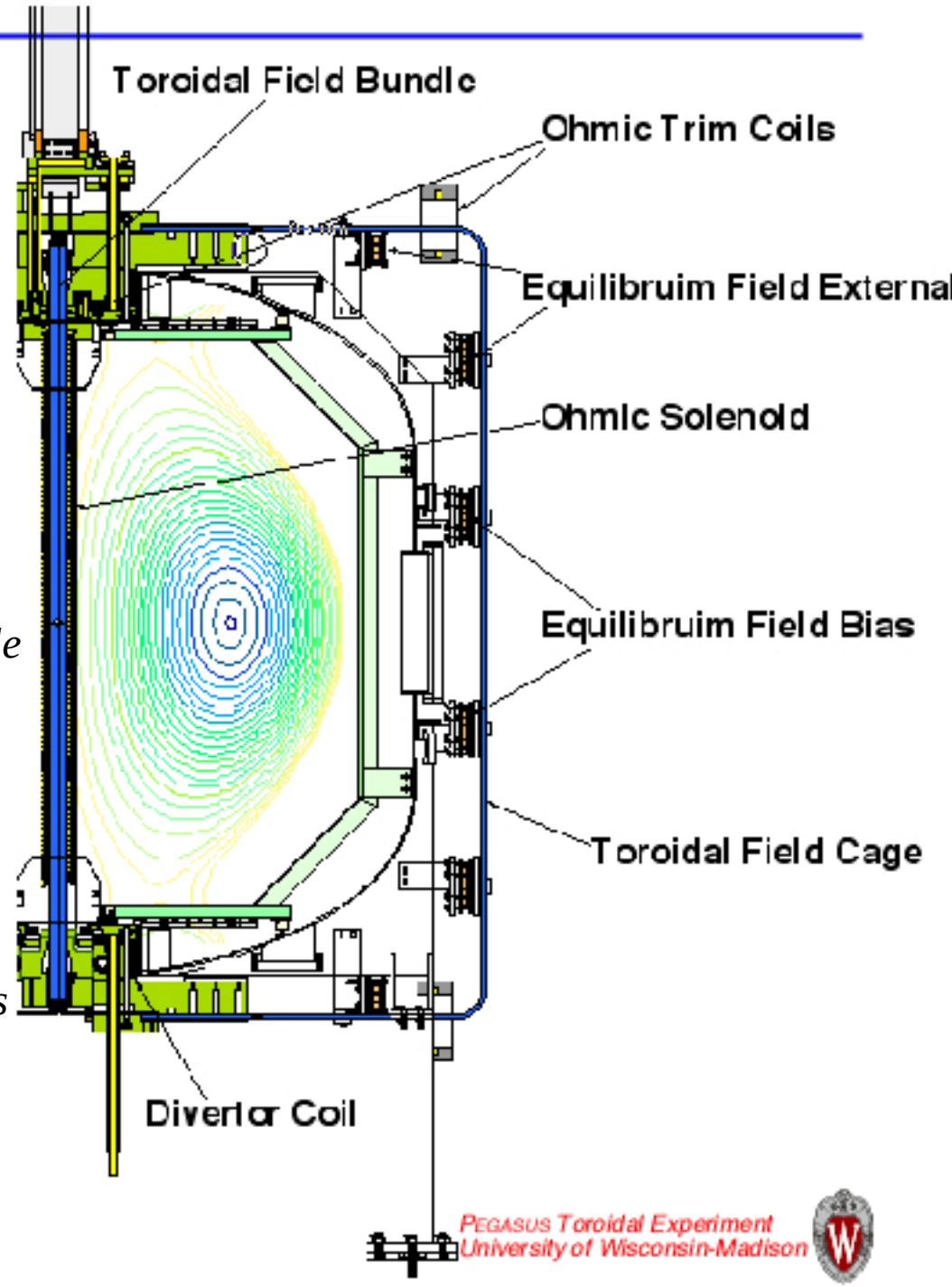
- HIT has developed and utilizes a CAMAC based, optically isolated PWM controller for IGBT semiconductors

Eupec IGBT
Steady State - 900V@2.4kA

Insulated Gate Bipolar Transistor

PEGASUS Coil Systems

- Ohmic Heating (OH)
  - *Solenoid provides primary heating for the plasma*
  - *Ohmic Trim provides high order vacuum null for plasma formation*
  - *Operates up to 3kV at ±60kA*
- Toroidal Field (TF)
  - *Coil Set provides main confining field*
  - *New, low inductance 12 turn return bundle*
  - *Operates up to 900V at 50kA (600kA rod current)*
- Equilibrium Field (EF)
  - *Provides positioning and shaping fields*
  - *Coil set is adaptable for shaping concerns*
  - *Operates up to 900V at 20kA*



Ohmic Power System Upgrades

• Motivation

- Need better control over formation and growing stages of the plasma.

- Need to minimize Ohmic solenoid heating while maximizing loop volt utilization.

• PWM IGCT H-Bridge

- 2700V/3500kJ Electrolytic Cap-Bank

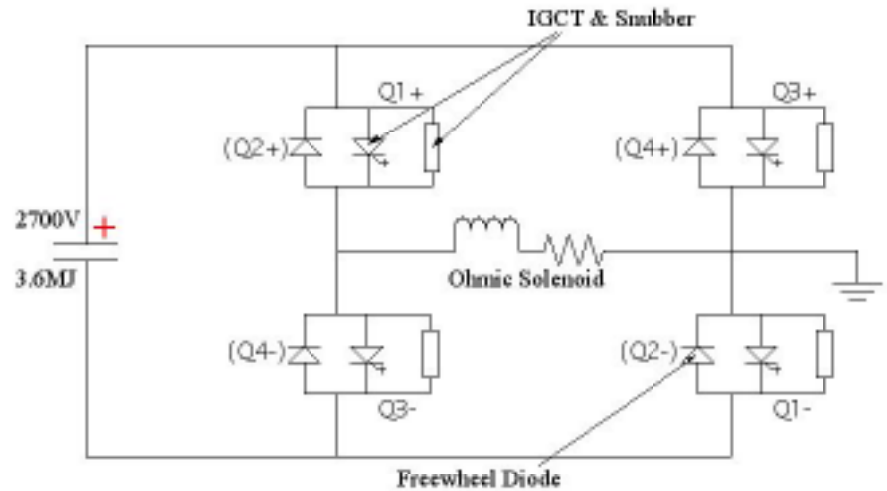
- Full four quandrant switching capability

- ABB 5SHY 35L4510 IGCT capable of switching 2800V @ 6000A at up to 25kHz

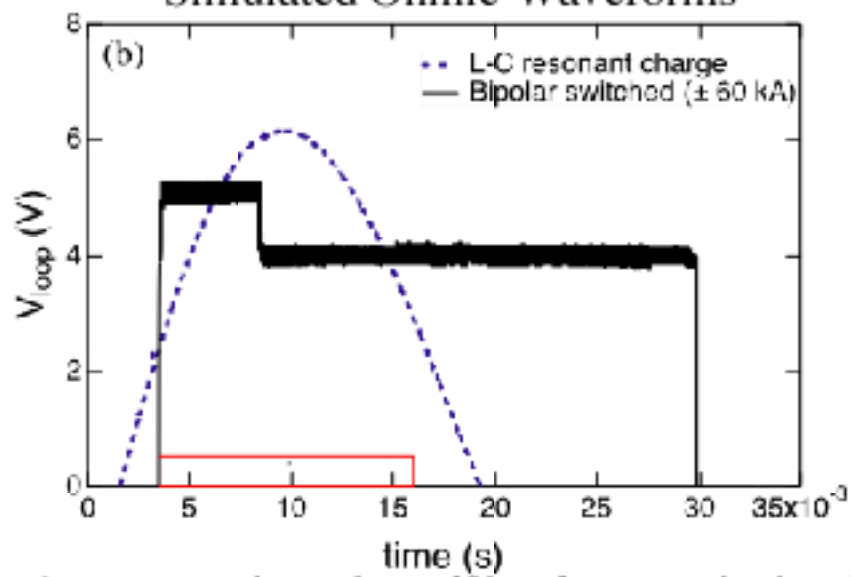
- Feedback control via applied loopvolts with possible future control via plasma current

- Ohmic H-Switch requires 8 parallel modules each with 4 IGCTs per module

Ohmic IGCT H-Bridge Switch



Simulated Ohmic Waveforms



New TF Bundle and Waveform

• Motivation & Design

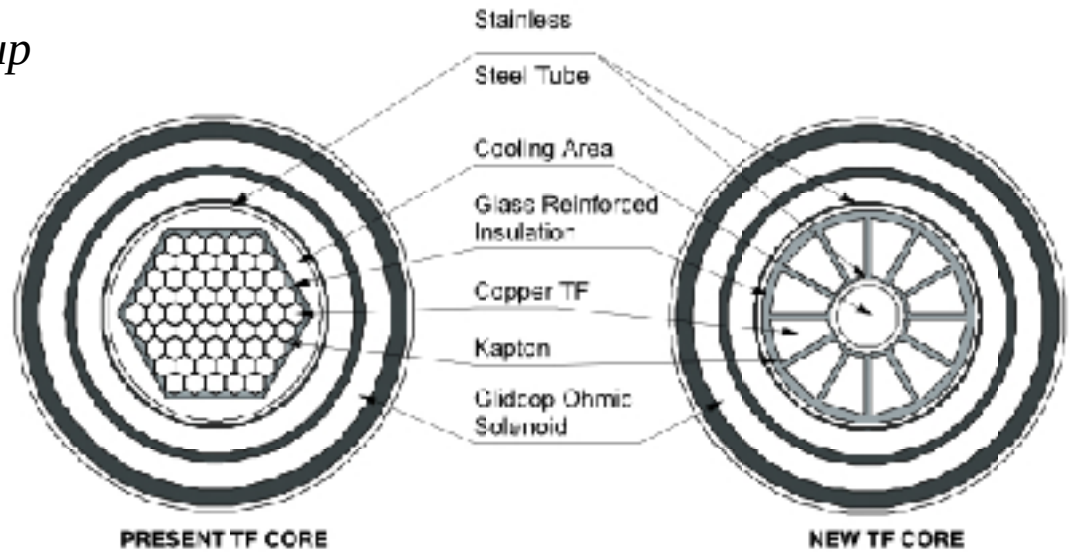
- *Provide High-TF for improved plasma startup and MHD control*
- *Rapid TF ramp down during shot to provide access to High-β, Low-Q regime.*

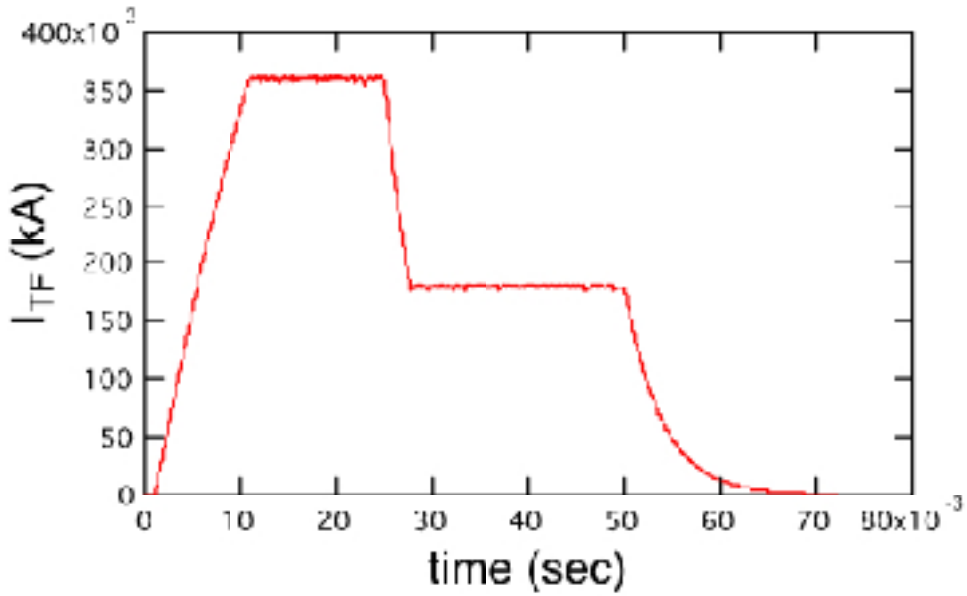
• New TF Bundle

- *12 turn high current, low inductance*
- *Installation without venting machine*
- *Will allow access to high I_{TF} (>500kA) rod current - increased from present 150kA*
- *Low inductance allows ~2msec current ramp down during shot*

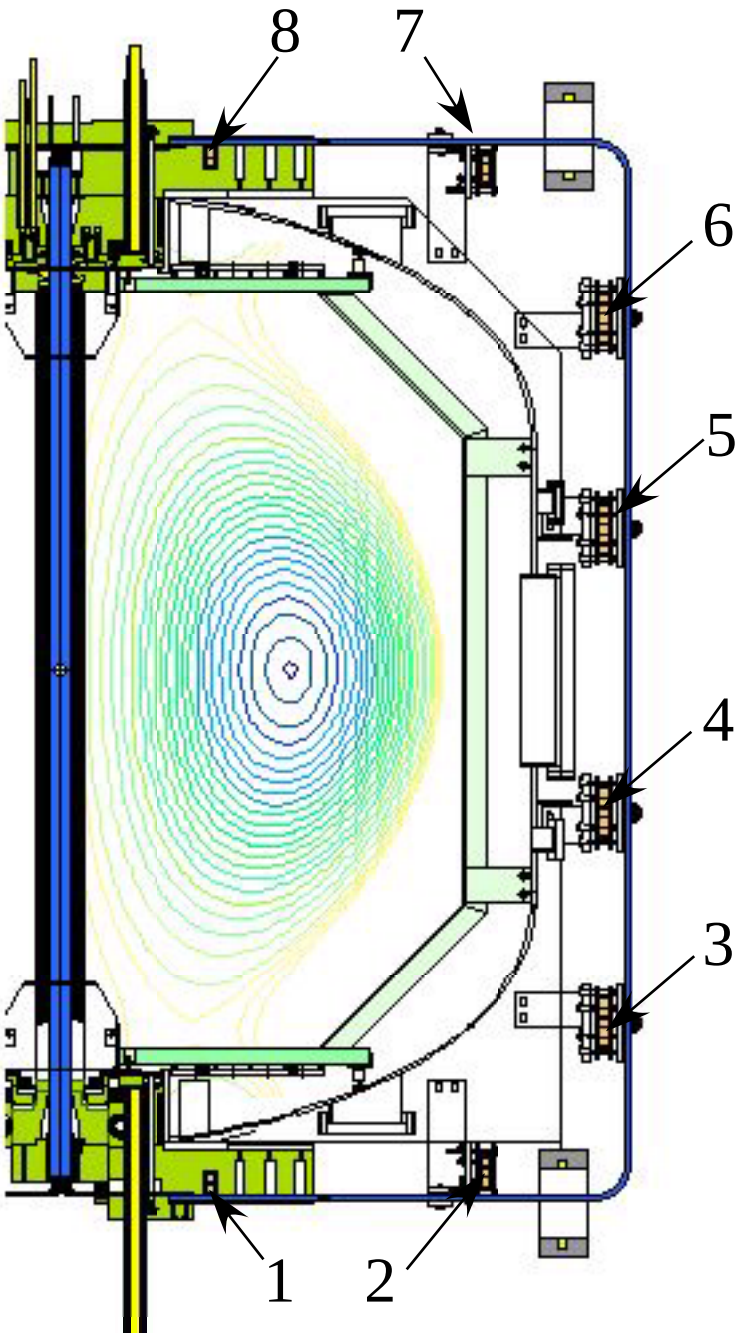
• PWM IGCT Half-Bridge

- *900V/584kJ Electrolytic Cap-Bank*
- *Two quantrant switching capability*
- *ABB 5SHY 35L4510 IGCT capable of switching 900V @ 12000A at up to 25kHz*
- *Feedback control via applied current*
- *H-Switch requires 4 modules each with 2 IGCTs per module*





Equilibruim Field Power System Upgrade



Coil Systems

- Coils 1,2,7,&8 provide shaping and n=0 stability and operate up to +20kA w/ 2msec control - operate as a series connected set

- Coils 3 & 6 provide Up/Down symmetry and operate up to +20kA w/ 2msec control - operate as two independent coils

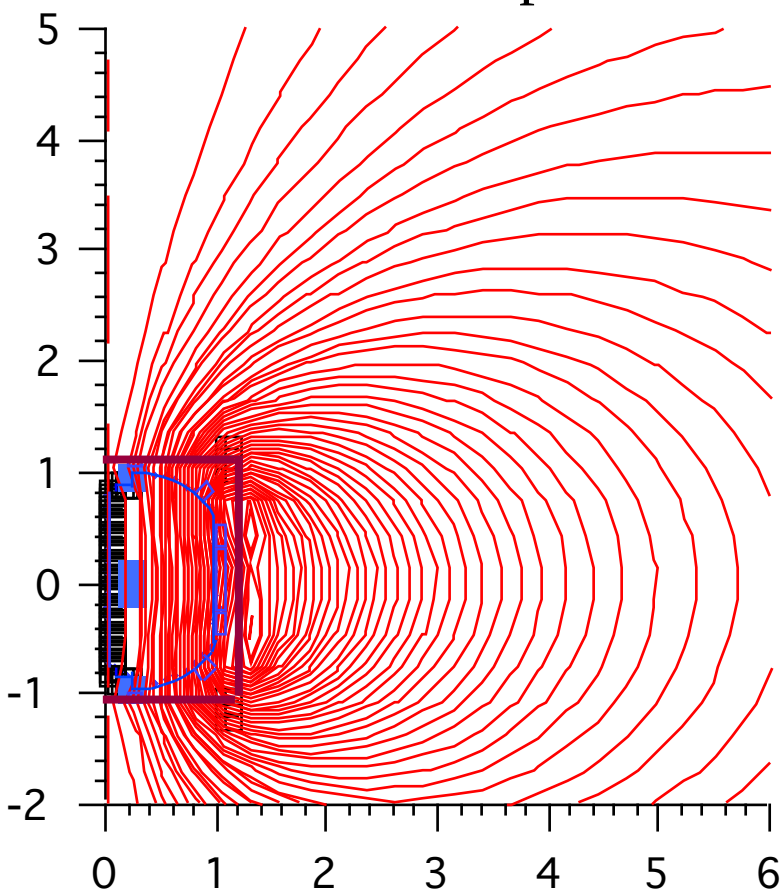
- Coils 4 & 5 provide additional shape and position control and operates up to +20kA w/ 2msec control - operate as series connected set

- Compensation coils provide bias field and stray field compensation and operate up to -20kA w/ 2msec control - operate as series connected set

Equilibruim Field Stray Field Compensation

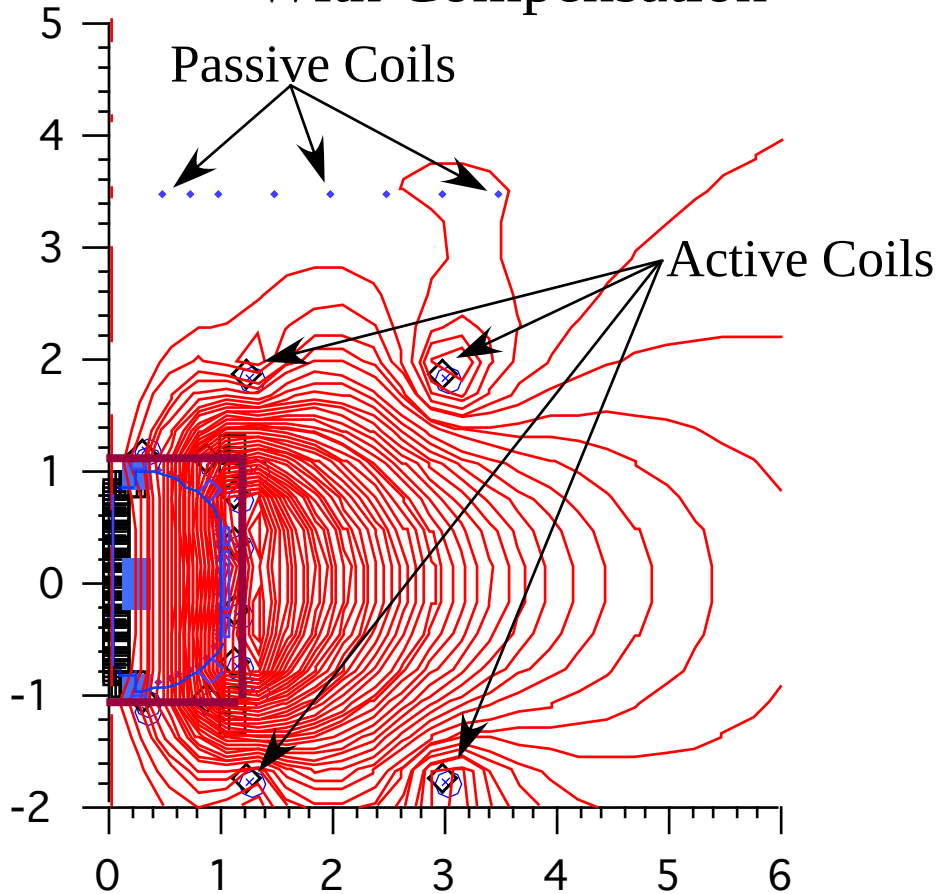
- Motivation & Design
  - *The desired increased Equilibrium Field capability would raise stray B-field in public areas*
  - *The addition of a symetric set of actively controlled 'bucking'coils and passive coil set mounted above the machine reduce the stray B-field to less than 5 Gauss in public exposure areas*

Without Compensation



Both axes are in meters

With Compensation



Summary

- Major Laboratory Reconfiguration

- *All major energy storage capacitor banks relocated to vault outside building*
- *Improved experiment safety and access in experimental area*
- *Improved diagnostic infrastructure to be ready for high power RF operations*

- New tools added to enhance study of plasma stability boundaries

- *All coil power systems being upgraded to programmable waveform control*
- *Increased Ohmic V-sec (2 - 2.5x) and control during all phases of plasma evolution*
- *Independent Equilibruim Field coils to provide active shaping and position control*
- *Low inductance Toroidal Field return bundle being installed for establishing higher B_T (4x) and allowing rapid current ramping capability*
- *Divertor coils being activated for separatrix operations*
- *Compensation coil provides additional DC bias field prior to startup*

- PWM controlled Magnet Coil Power Systems

- *HIT power system collaboration greatly reduced development time*
- *Allows for precise current waveform with feedback control*

- Enhance Equilibruim Field System to Include Stray Field Reduction

- *Compensation coil provides additional DC bias field prior to startup*

Reprints

Abstract

Overview of PEGASUS Results and Facility Upgrades*

B.T. Lewicki, S.J. Diem, R.J. Fonck, B.A. Ford, G.D. Garstka, M.W. Kissick, P.H. Probert, A.C. Sontag, E.A. Unterberg, G.R. Winz
University of Wisconsin-Madison

The PEGASUS Toroidal Experiment explores ST plasma behavior focusing on q and beta limits as the aspect ratio approaches unity. Typical plasma parameters are A=1.15-1.4, R=0.2-0.4 m, Ip<0.16 MA, B<0.07 T, and toroidal beta <20%. A 1 MW HHFW system has begun operation and injected 0.2 MW into plasma. Plasma performance is constrained by power supply limitations and low-order resistive instabilities associated with low central shear. Edge kink instabilities have been observed for q_{95}=5 with low internal inductance (0.2-0.4). The magnetic field set power systems are being upgraded to allow for improved waveform control and plasma performance. These upgrades include: 1) increased V-s and loop voltage control for higher plasma current and suppression of observed internal and edge modes; 2) increased toroidal field with fast-ramp capability for improved startup and subsequent access to the low-q, high toroidal beta regime; and 3) improved equilibrium field and waveform control for radial position and modest shape control.

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