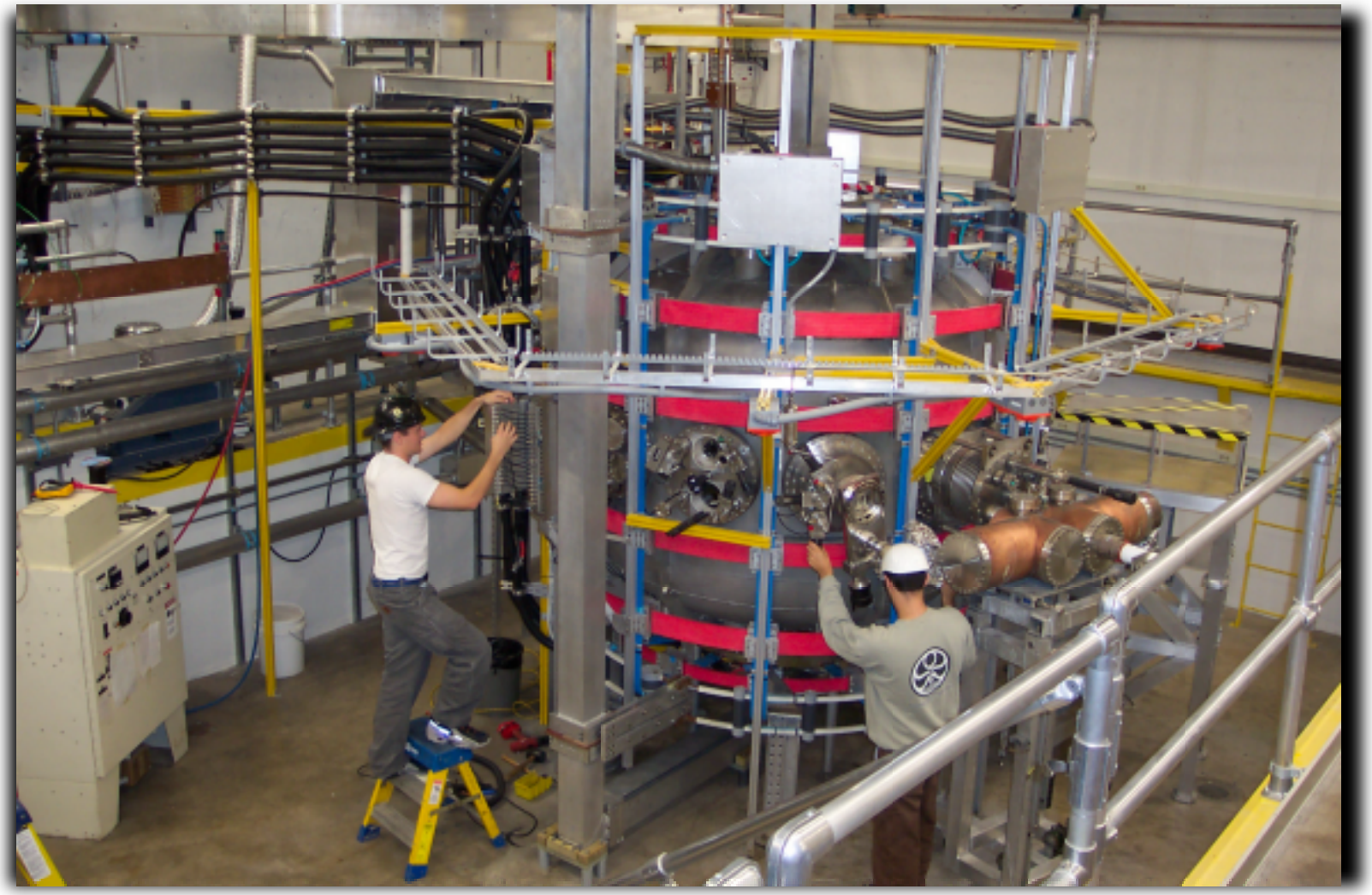
Abstract

The PEGASUS Toroidal Experiment is a near-unity aspect ratio spherical torus. PEGASUS has recently undergone a major upgrade to all of its coil power systems allowing >200 MW of preprogrammed waveform control. 6 MJ of capacitor energy storage feeds up to 40 independent H-bridges. The capacitor bank is modular in construction to allow each bridge system to act independently. Individual H-Bridges can be ganged together and are controlled via linear PWM (Pulse Width Modulation) to supply individual coil sets. All poloidal and toroidal power systems utilize two or four quadrant H-bridges with 1700 V-2400 A IGBTs (Insulated Gate Bipolar Transistor) while the ohmic heating system utilizes four quadrant H-bridges with 2700 V-3800 A IGCT (Integrated Gate Commutated Thyristor) technology. H-Bridge semiconductor transient suppression utilizes simple RC or RCD shunt snubbers. The IGCT H-bridges are to be upgraded to an Undeland type snubber for full power operations. A Plasma Control System (PCS) is to be implemented allowing non-linear real-time feedback control and eventual direct digital control of H-bridge systems. These developments provide the Pegasus experiment with state-of-the-art control capabilities typically only available to large national facilities.

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

Mission Statement for the PEGASUS Toroidal Experiment

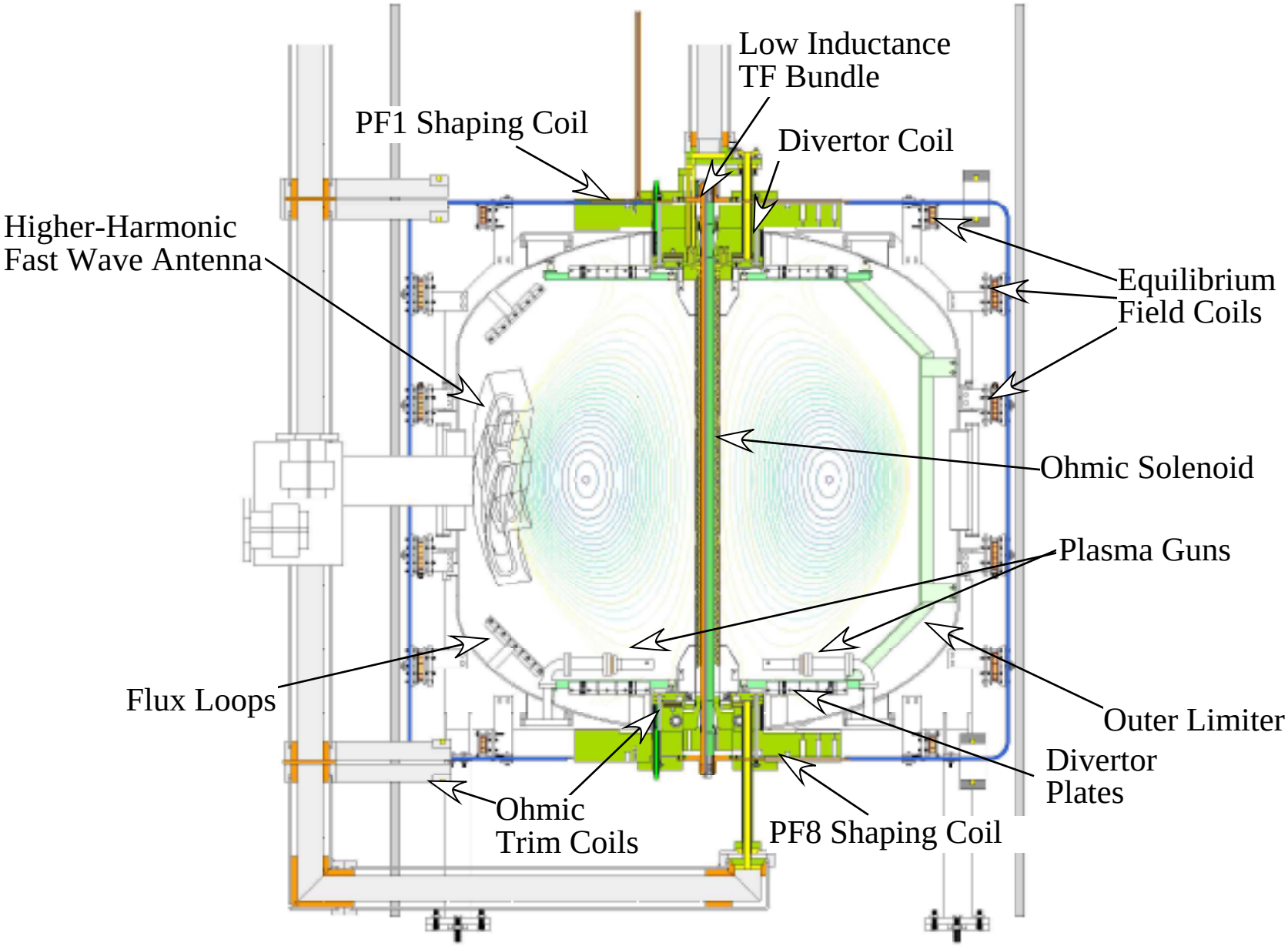
- The PEGASUS Toroidal Experiment is a university based plasma magnetic confinement experiment designed to study high-pressure plasmas in a low aspect ratio axisymetric toroidal geometry.



Overview of PEGASUS Coil Power System

- **Programmable Coil Power Systems**
  - Linear Pulse Width Modulated (PWM) Control
  - High Power IGBT/IGCT Based H-Bridges
  - HIT PWM controller collaboration
  - Undeland snubbers being developed for full power IGCT operations
- **Electrolytic Capacitor Banks**
  - Modular Construction
  - Center Grounded
  - Fully isolated power conduits for each H-Bridge
  - Located outside experimental facility
- **Plasma Control System in development**
  - General Atomics providing technical support for PCS programming
  - Allows non-linear real time feedback
  - PCS to take full advantage of H-bridge power system capabilities
  - Future operation may include direct digital control of H-bridge systems

PEGASUS Toroidal Experiment



PEGASUS Facility has been Completely Rebuilt

- **New Tools Enhance Study of Plasma Stability Boundaries**

  - All coil power systems upgraded to programmable waveform control
    - Active shaping and position programming
    - Modern semiconductor systems allow more control with less stored energy
    - Modular construction allows flexibility to meet needs of experiment

  - Increased V-sec (2 - 2.5x) and control during all phases of plasma evolution
    - H-bridge based power supply uses regeneration capability to minimizes heating of OH coil at the end of the plasma discharge

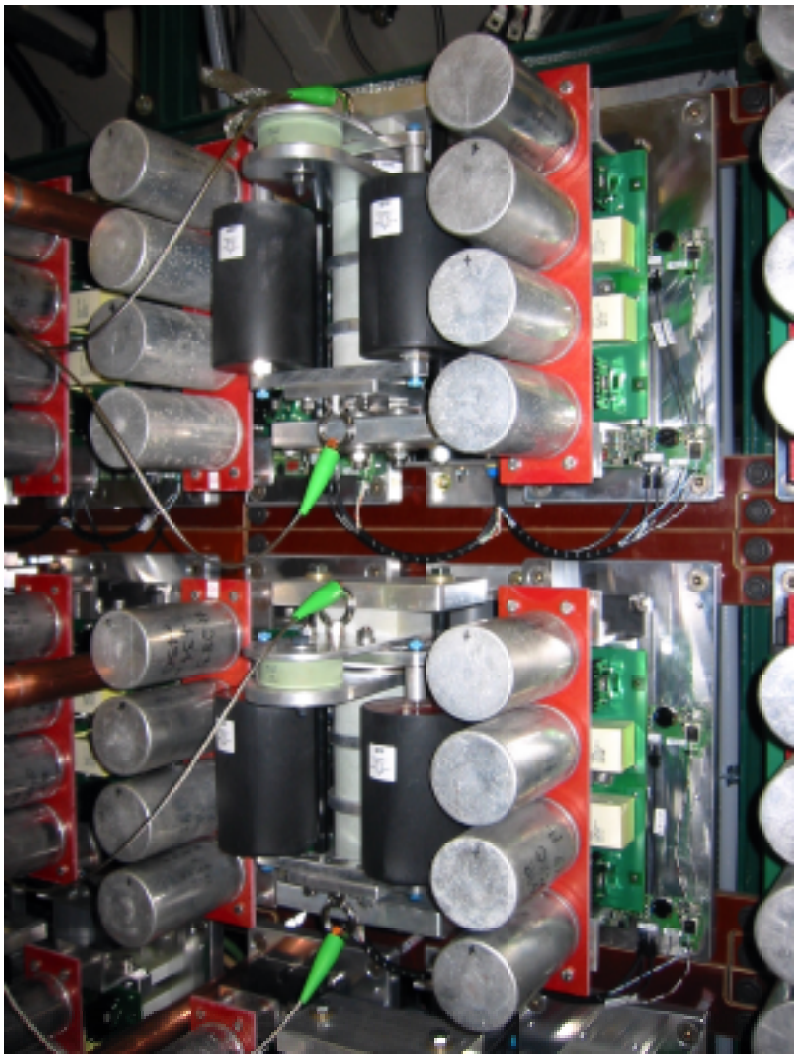
  - Low inductance, higher B_T (3x) Toroidal Field bundle for rapid current ramping

  - Divertor coils for separatrix operations

  - Plasma Guns for plasma startup and current drive
    - H-bridge based gun power supply maximizes gun performance and control

Linear 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

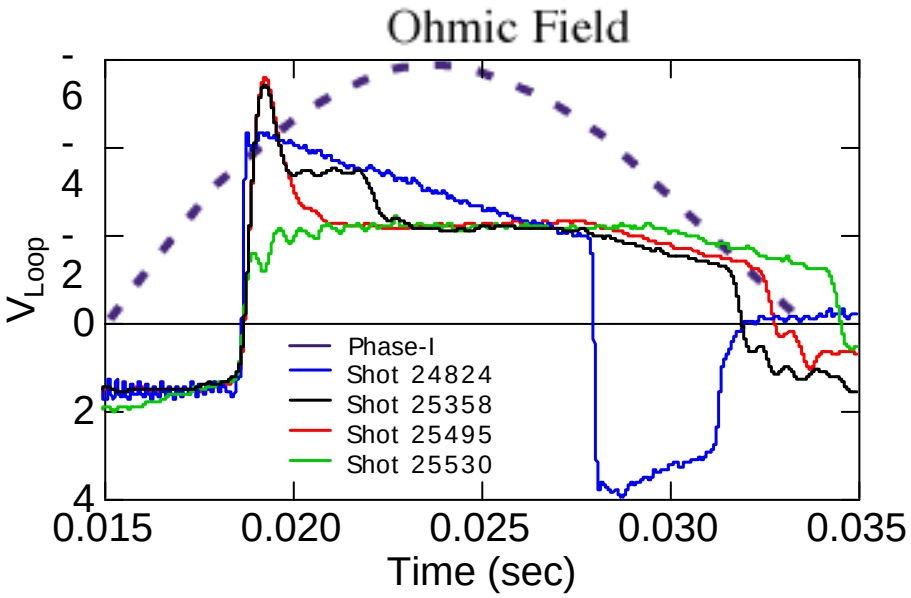
- More reliability and control with less overall stored energy

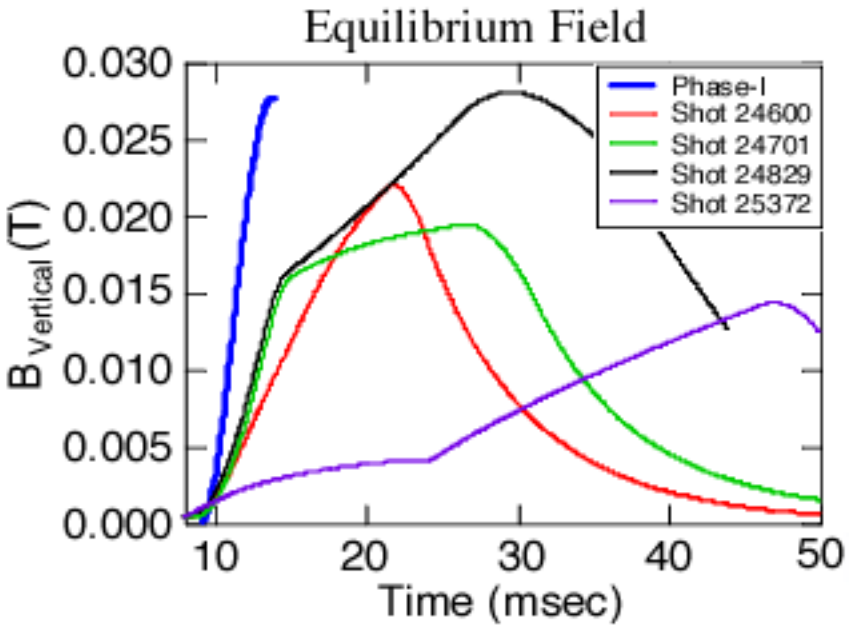
- H-Bridge regeneration mode minimizes heating of critical coil sets

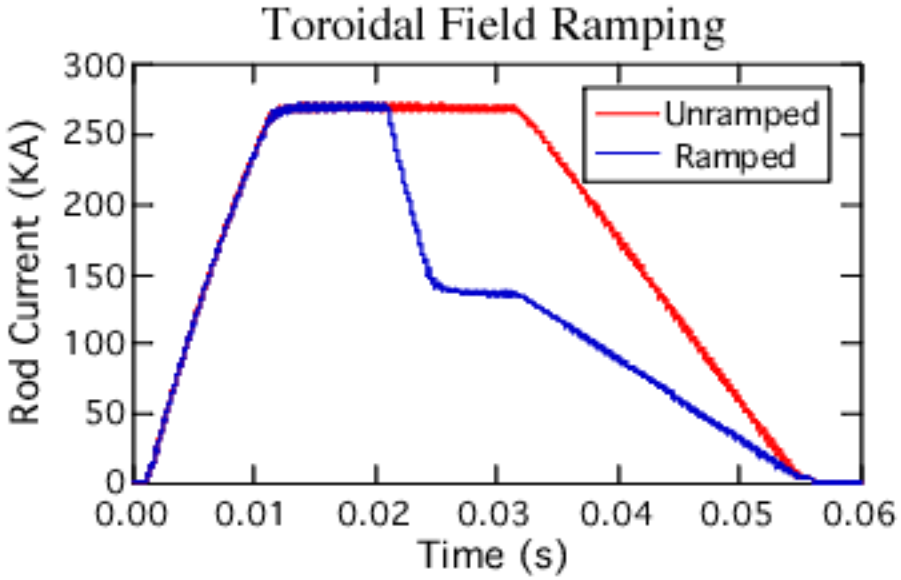
- Fault detection and interruption capability

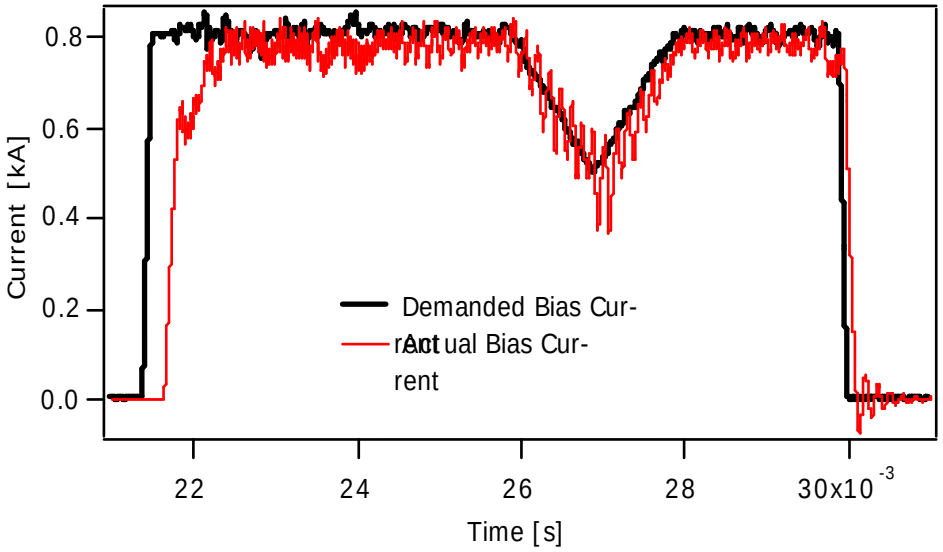
- Many thanks to the **HIT** Group: CAMAC based, optically isolated PWM controller

Power System Waveforms









Highly Flexible H-Bridge Power Systems

- **Designed to operate as independent or parallel sets**

  - 40 Electrolytic Capacitor Banks are fully isolated
    - 12 - 70mF @ 2700V dedicated to Ohmic Heating
    - 8 - 208mF @ 900V dedicated to Toroidal Field System
    - 12 - 208mF @ 900V for remaining PF systems
    - 8 - 104mF @ 900V for remaining PF systems
  - Quad-cable transmission lines provide magnetic and electrical isolation
    - 21m transmission line to capacitor bank vault allows placement of stored energy outside of main experimental hall
    - 15m transmission line provides electrical isolation between parallel H-Bridge systems and the summing patch panel
    - Industrial Type W 1/0 Mining Cable ~ 200nH, 250pF and 350μΩ per meter
    - Provides sufficient impedance to minimize fault currents

Details of PEGASUS Power Supplies

- **Ohmic Heating (OH) [130MVA]**
  - 12 parallel systems can provide ±48kA @ 2700V/3032kJ - Four Quadrant Control
  - Efficient utilization of up to 100mV/sec Ohmic Flux
  - Minimize heating of Ohmic Solenoid by utilizing regeneration mode of H-Bridges
- **Toroidal Field (TF) [35MVA]**
  - 8 parallel systems provide 0 to +38kA @ 900V/673kJ - Two Quadrant Control
  - Allows for rapid current ramping
  - Maximum of 450kA rod current (up from 150kA)
- **Equilibrium Field (EF) [85MVA]**
  - Up to 8 independent coil sets can be powered by up to 20 H-bridge systems
  - 8 - 900V/42kJ and 12 - 900V/84kJ banks for each H-Bridge
  - 0 to ±4.8kA @ 900V - Two or Four Quadrant Control for each H-Bridge system
  - Provides positioning and shaping fields with active feedback control
- **Total of 250MVA of programmable power**

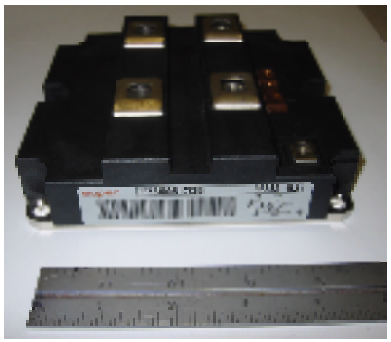
H-Bridge Semiconductor Components

- **ABB 5SHY35L4511 IGCT**
  - Rated 2.8kV, 3.8kA at 1kHz
  - Switching Frequency
    - Dependent on current/voltage switched and integrated controller
    - Can switch at 1.0kHz steady state
    - Can switch beyond 1.0kHz for a finite number of pulses (~100s)
  - Switched Voltage
    - Heating is minimized with reduced voltage operation
  - Switched Current
    - Not rated to interrupt current more than device rating (4kA)
    - Heating is minimized with reduced current
  - Primary heating derived from switching losses



ABB IGCT
2.8kV@4kA
~ 50 cm long

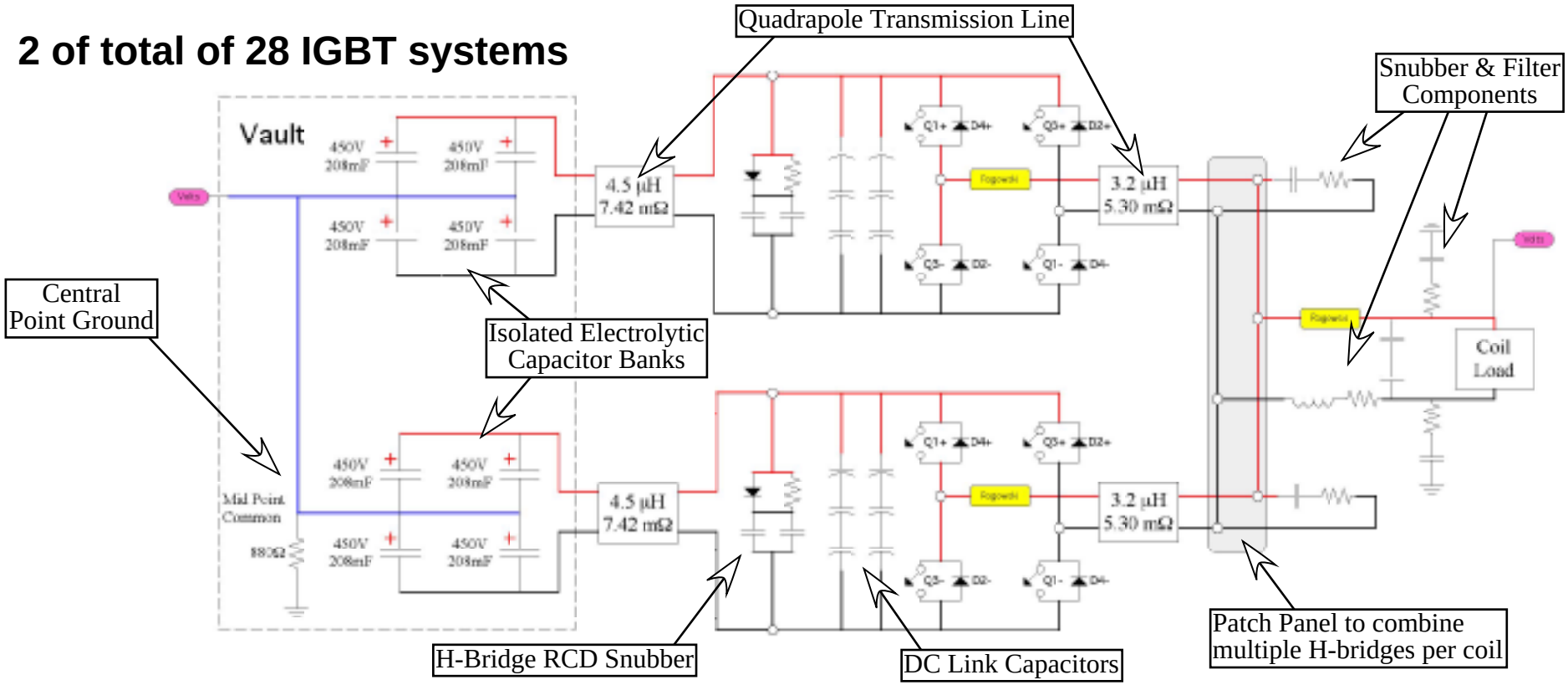
- **Eupec FZ2400R17KE3 IGBT**
  - Rated 900V, 2.4kA at 1kHz
  - Switching Frequency
    - Only dependant on controller (up to 5kHz)
  - Switched Voltage
    - Heating is minimized with reduced voltage operation
  - Switched Current
    - Repeated operation at 2x switch rating (4.8kA)
    - Single fault current interrupt at 9.6kA
  - Primary heating derived from conduction losses



Eupec IGBT
900V@4kA

PWM Systems Present Additional Challenges

2 of total of 28 IGBT systems

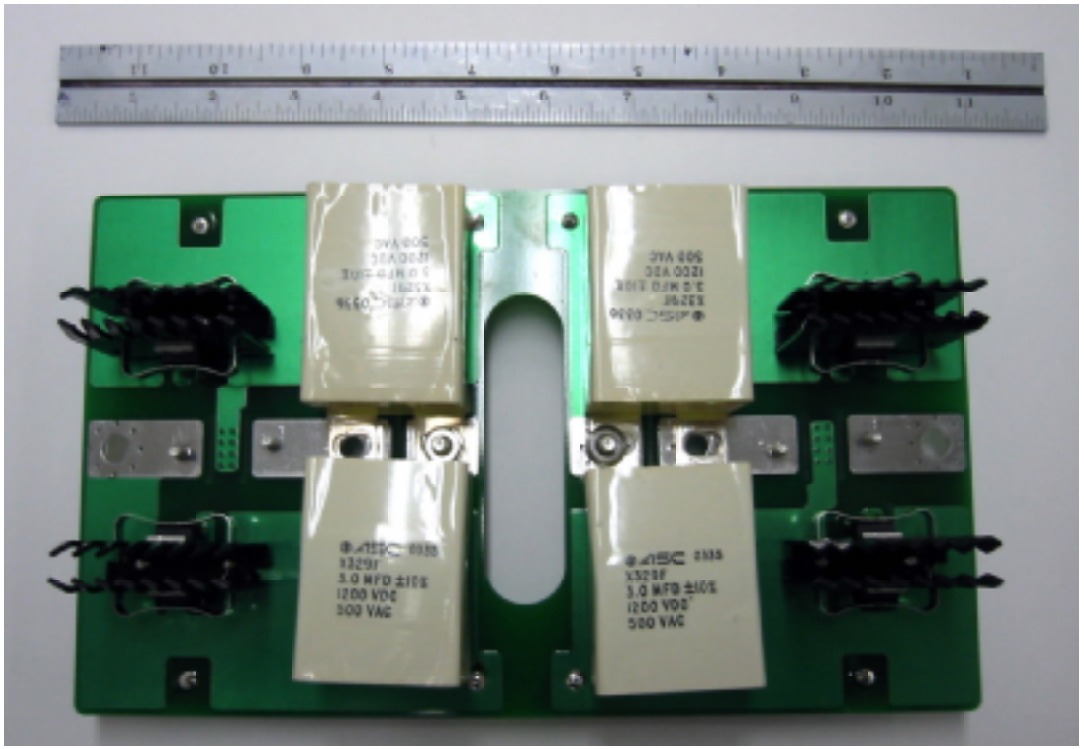


1. Current Ripple on Coils may require high power line filtering
2. Common mode voltage when coil is in freewheel mode
3. Impedance mismatch of transmission lines to coils leads to reflections
4. RC snubbers on most individual lines and coils
5. Requires fully isolated capacitor banks to supply individual IGBT systems
   - Center point ground required to symmeterize common mode and switching transients
   - Required fully isolated capacitor bank charging supplies

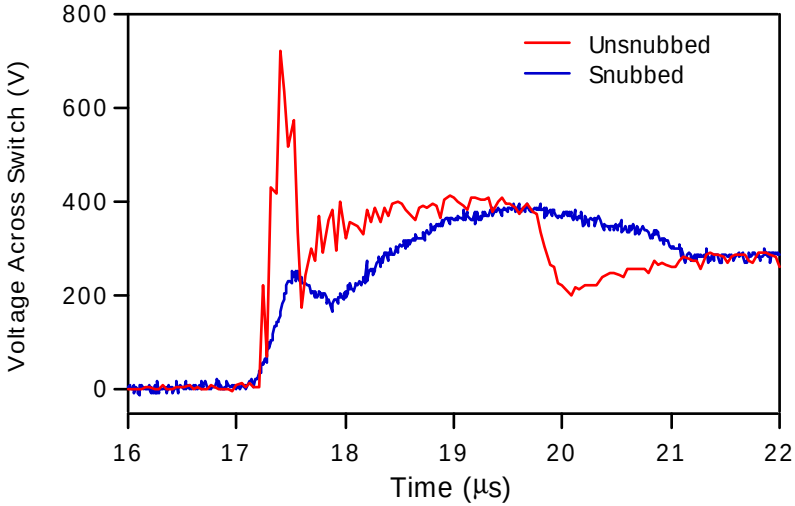
IGBT H-Bridge System Transient Suppression

- **Switching Transient Suppression**
  - Transmission lines have inductive stored energy
  - Stray inductance in H-bridge assembly
  - RCD snubber for overall H-Bridge
  - RCD snubber for individual switching components
  - Local electrolytic capacitors (DC Links)

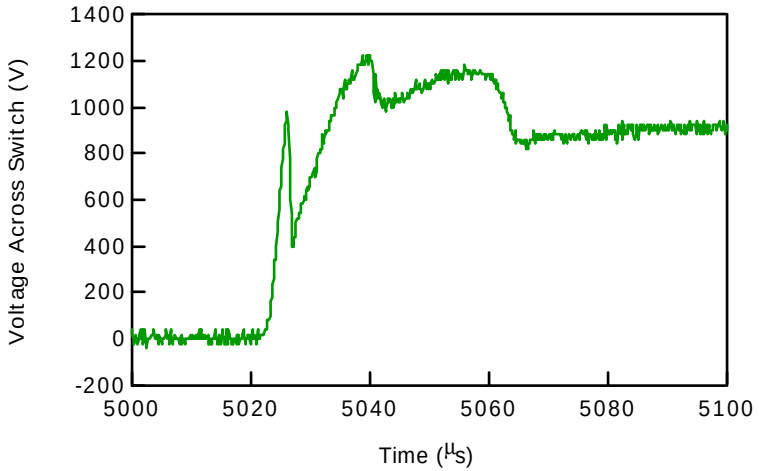
IGBT H-Bridge RCD Snubber Board



Transients across IGBT at 300V/1kA

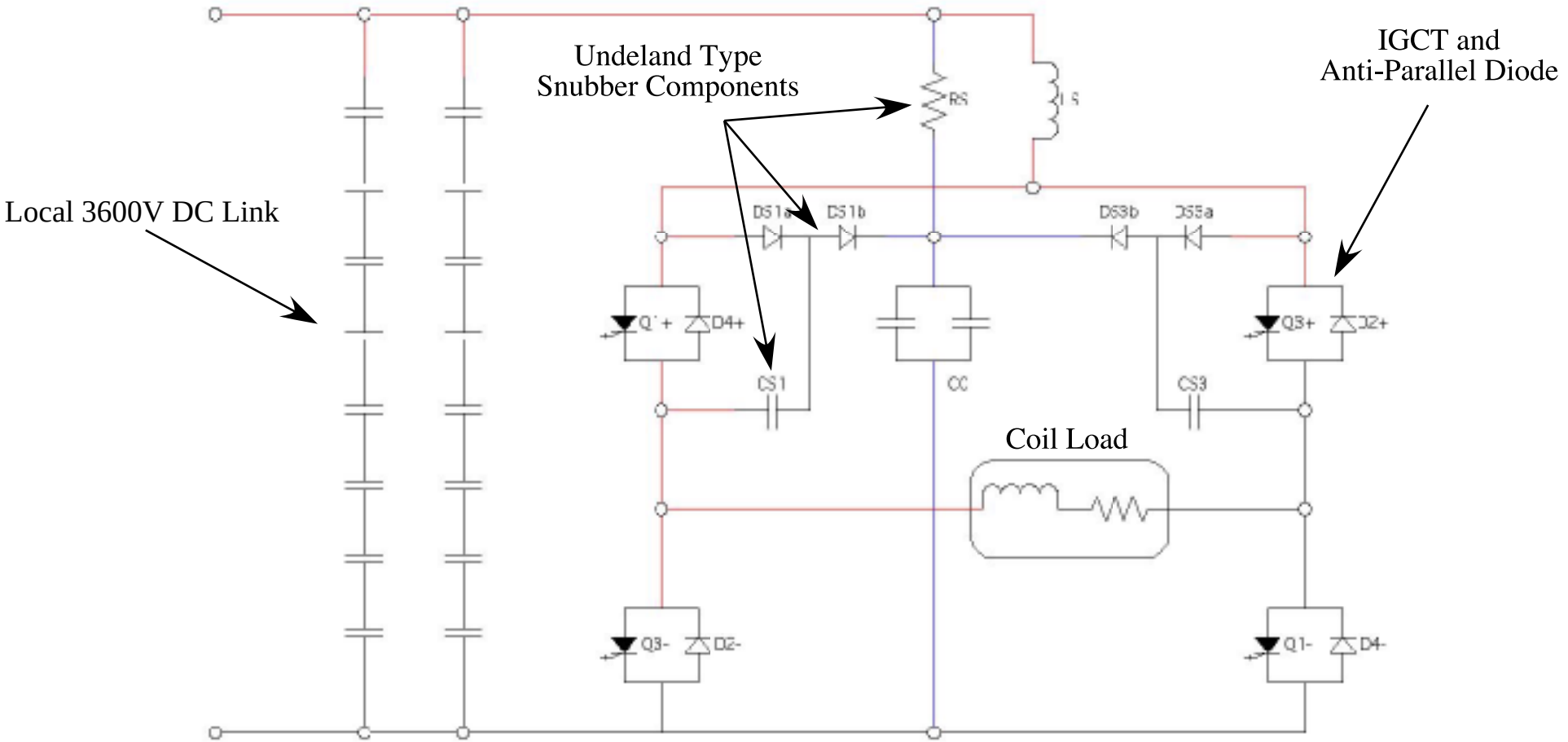


Snubbed Transients across IGBT at 850V/4kA



Undeland Type Snubber development for IGCTs

- **IGCT H-bridge high power diodes present special challenges**
  - Undeland snubber can control both turn-on and turn off transients
  - Overall losses are less than typical RC and RCD shunt snubbers



Electrolytic Capacitor Banks

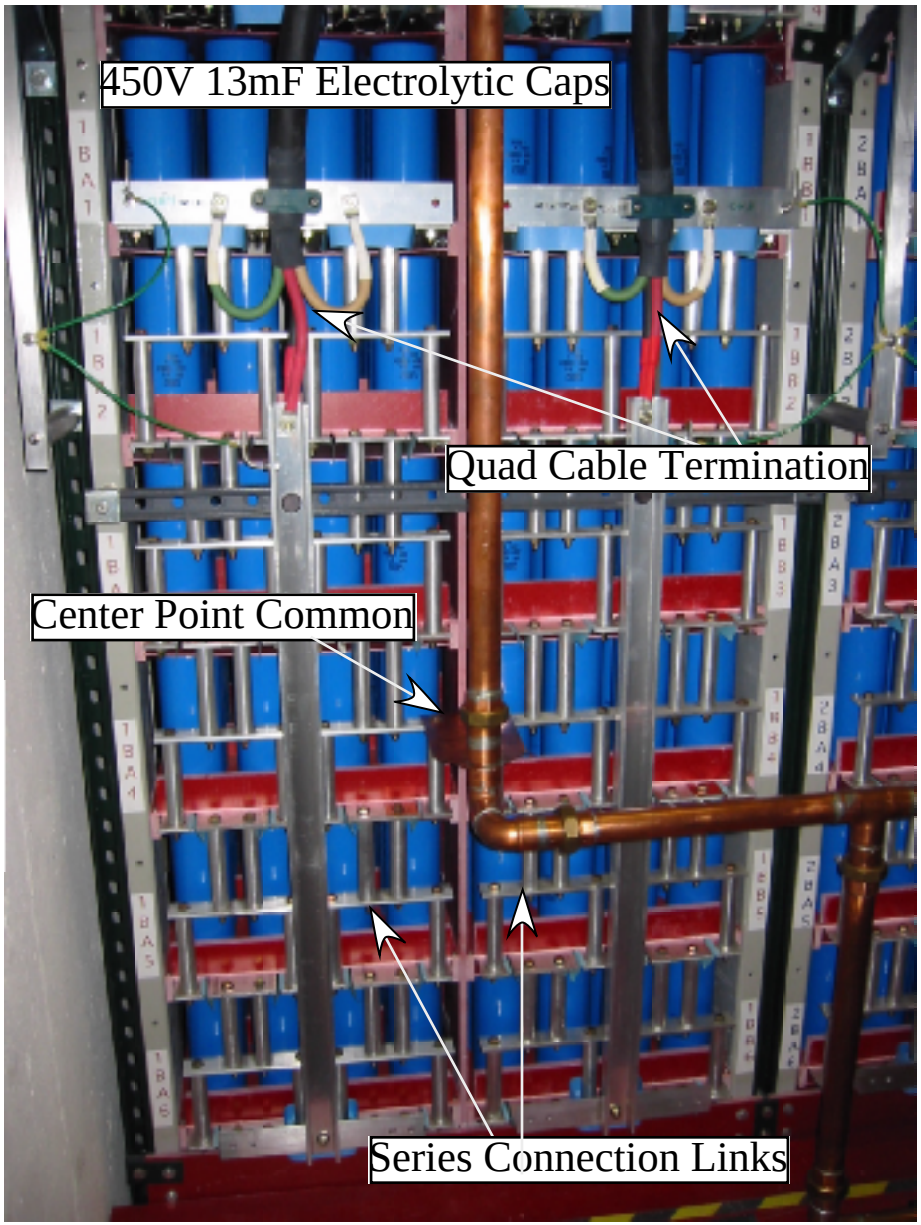


Capacitor Bank Installation

- Modular system allows for flexibility in voltage and stored energy to be supplied to H-bridge systems

- 40 isolated quad cable feeders

- Center point common



2700V, 250kJ OH Section (2 of 12 shown)

Plasma Control System (PCS)

- **Plasma Control System to provide national lab level capability**
  - Natural fit for IGBT & IGCT based H-bridge power systems
  - Real time control will greatly enhance experimental production
  - Modern PCS hardware is powerful and relatively inexpensive

- **General Atomics is providing hardware and software support**
  - Providing base software
  - Aid in the development of system models
    - Vacuum vessel
    - Power supply response
    - Coil response
  - Aid in converting operations from pre-programmed to PCS control
  - System is nearly identical to PCS currently in service at General Atomics

- **PCS hardware is currently being installed**
  - 96 analog in - 500kHz simultaneous at 16-Bit
  - 16 analog out
  - 32 digital I/O

Future Directions

- **IGCT Undeland snubber install for full power operations**
  - Implementation of Undeland snubbers to optimize switching stresses
  - 2X available stored energy for OH drive
  - Utilize full OH voltage of 2700V
- **Active Feedback Control with Plasma Control System**
  - Vloop/Ip for plasma evolution and sustainment
  - Radial Position Control
  - Plasma Shaping for RF studies
- **Pulse Length Extension**
  - Upgrade IGBT RCD snubber for long pulse operation
  - Pre-chill OH solenoid to less than ambient dew point
    - Supply -70C dew point air to TF joint region for condensation control
    - Local chiller loop to take solenoid temperature to -40C

Summary

- **Laboratory infrastructure complete**
  - All major energy storage capacitor banks relocated to vault outside building
  - Improved diagnostic infrastructure to be ready for high power RF operations
  - New power systems enhance capability as well as overall lab and machine safety

- **New tools added to enhance study of plasma stability boundaries**
  - Increased available ohmic V-sec (2 - 2.5x) and control from Phase I operations
  - Programmable independent equilibrium field coils for shaping and position control
  - Low inductance toroidal field assembly
  - Divertor coils for separatrix operations

- **PWM controlled magnet coil power systems**
  - Coil power systems have been completely upgraded to programmable waveform control
  - HIT power system collaboration greatly reduced development time
  - Provides current waveform control

- **Plasma operations continuing to improve with added capability**
  - New capabilities aid in developed broader operating scenerios
  - Plasma Control System final programming and installation nearly complete
  - PCS operations to be implemented late Fall 2005

Reprints

PROGRAMMABLE COIL POWER SYSTEMS FOR PEGASUS EXPERIMENT

Abstract	Pegasus Toroidal Experiment	Highly Flexible	Additional Challanges	Semiconductors	Future Directions
Pegasus Mission Statement	Facility Rebuild	Supply Details	IGBT Snubbers	Cap Banks	Summary
Overview	PWM H-Bridges	Waveforms	Undeland Snubber	PCS	Reprints