Abstract

A new generation of magnetic field coil set power supplies has been developed and deployed for flexible waveform control of the magnetic fields in the Pegasus ST. In the original configuration, almost all of the power supplies consisted of resonant L-C circuits fired through ignitrons and SCRs. Very limited waveform control was available through commutation of switches, which led to severe constrictions on plasma operations. The new configuration consists of 40 independent power systems switched with PWM (pulse-width modulated) H-bridges. The majority of the coil systems operate at 900 V and utilize IGBT (Insulated Gate Bipolar Transistor) technology. The higher-power ohmic heating system operates at 2700 V and utilizes IGCT (Integrated-Gate Commutated Thyristor) technology. These systems allow for precise preprogrammed wave shaping of current waveforms and active feedback control on ms timescales. Each bridge has an independent electrically isolated capacitor bank and transmission line to allow for parallel operation of multiple switches for higher current needs. Up to 6 MJ of energy is stored in electrolytic capacitor banks located in a vault separate from the research building. The net result of these upgrades is a significant increase in both input power and control. In addition to the new power supplies, significant improvements have been made to the coil sets. The toroidal field has been upgraded to triple the field and reduce the inductance by a factor of 25 over the last configuration. The poloidal field coils have been decoupled from a single set to five independent systems, and two new PF coils have been added. Divertor coils have also been added to allow separatrix operation. Together, these systems provide an unprecedented degree of control and programmability for a mid-sized university based plasma confinement experiment.

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

Overview of PEGASUS and Facility Reconstruction

- **Upgrade Motivation**
  - Soft I_p/I_{TF} limit
  - MHD instabilities

  } need plasma control

- **Facility Reconstruction**
  - Experimental Facility Completely Replaced
  - Toroidal Field Centerstack Assembly Upgraded
  - Equilibrium Field Coils Split

- **New Programmable Coil Power Systems**
  - Pulse Width Modulated (PWM) Control
  - High Power IGBT/IGCT Based H-Bridges
  - HIT PWM Controller collaboration

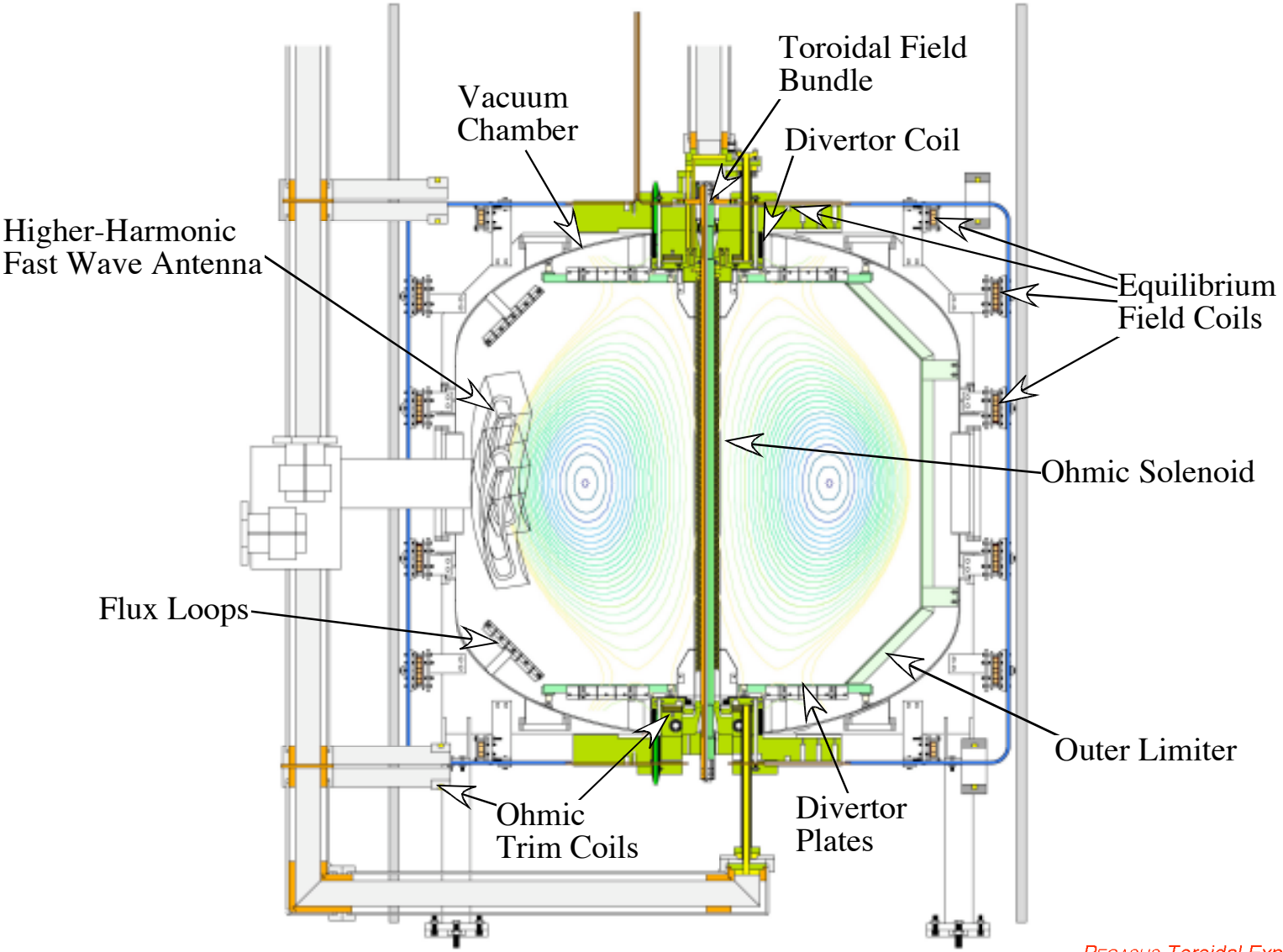
- **Status**
  - Facility Rebuild Complete
  - IGBT H-Bridges Installed and Tested
  - IGBT H-Bridge Systems and Cross-Field Testing in Progress

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 Facility has been Completely Rebuilt

- **Complete Laboratory Reconfiguration**
  - Facility extensively damaged
  - Proposed upgrades frontloaded to be completed during rebuild phase
  - Major energy storage systems were completely replaced and placed in a vault outside of experimental area
- **New Tools Enhance Study of Plasma Stability Boundaries**
  - All coil power systems upgraded to programmable waveform control
  - Increased 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, higher B_T (3x) Toroidal Field bundle for rapid current ramping
  - Divertor coils for separatrix operations
  - Passive compensation coils to reduce stray fields in public areas

Overview of PEGASUS Phase II Rebuild

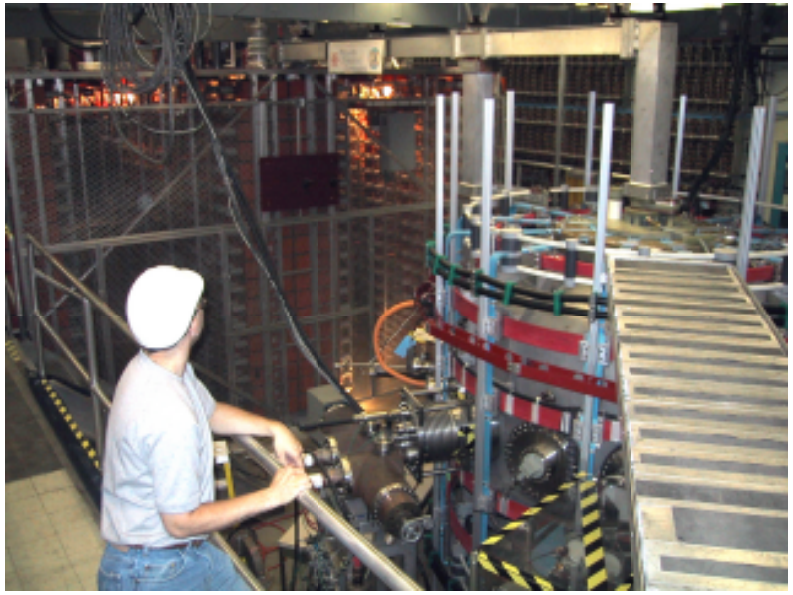
- **Power Systems Entirely Replaced**
  - PWM controlled H-Bridges allow for complete waveform control
  - Coil currents increased significantly
  - 6 MJ of electrolytic capacitors installed outside of experimental area
  - New power buses installed

- **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 - PEGASUS Experiment Facility





• Crowded Experimental Area

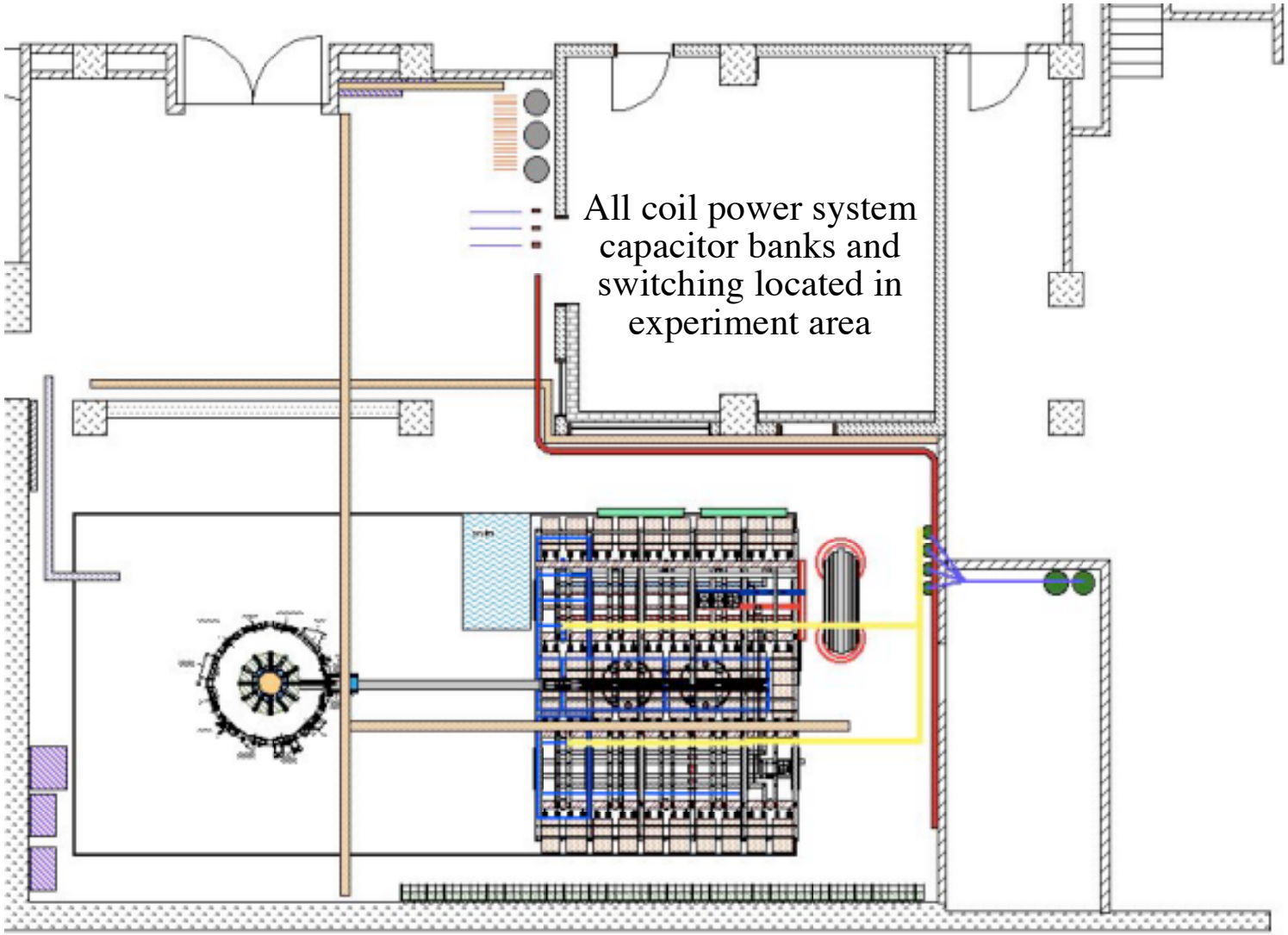
- Energy storage systems took up more than 60% of the usable experiment area.

- Close proximity of power systems to each other and the machine experiment

- Resonant systems required more stored energy and high power coupling components to give coarse waveform control

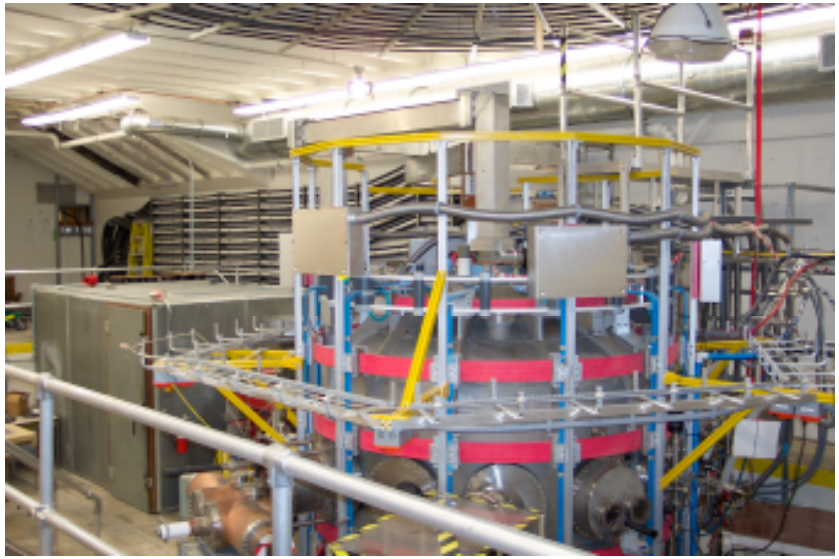
- Outdated facility infrastructure constrained experi ment growth

Old PEGASUS Experiment Facility



Present PEGASUS Experiment Facility





- Accessible Experimental Area

- No energy storage capacitor banks in experiment area

- Outdated interference from past facility removed

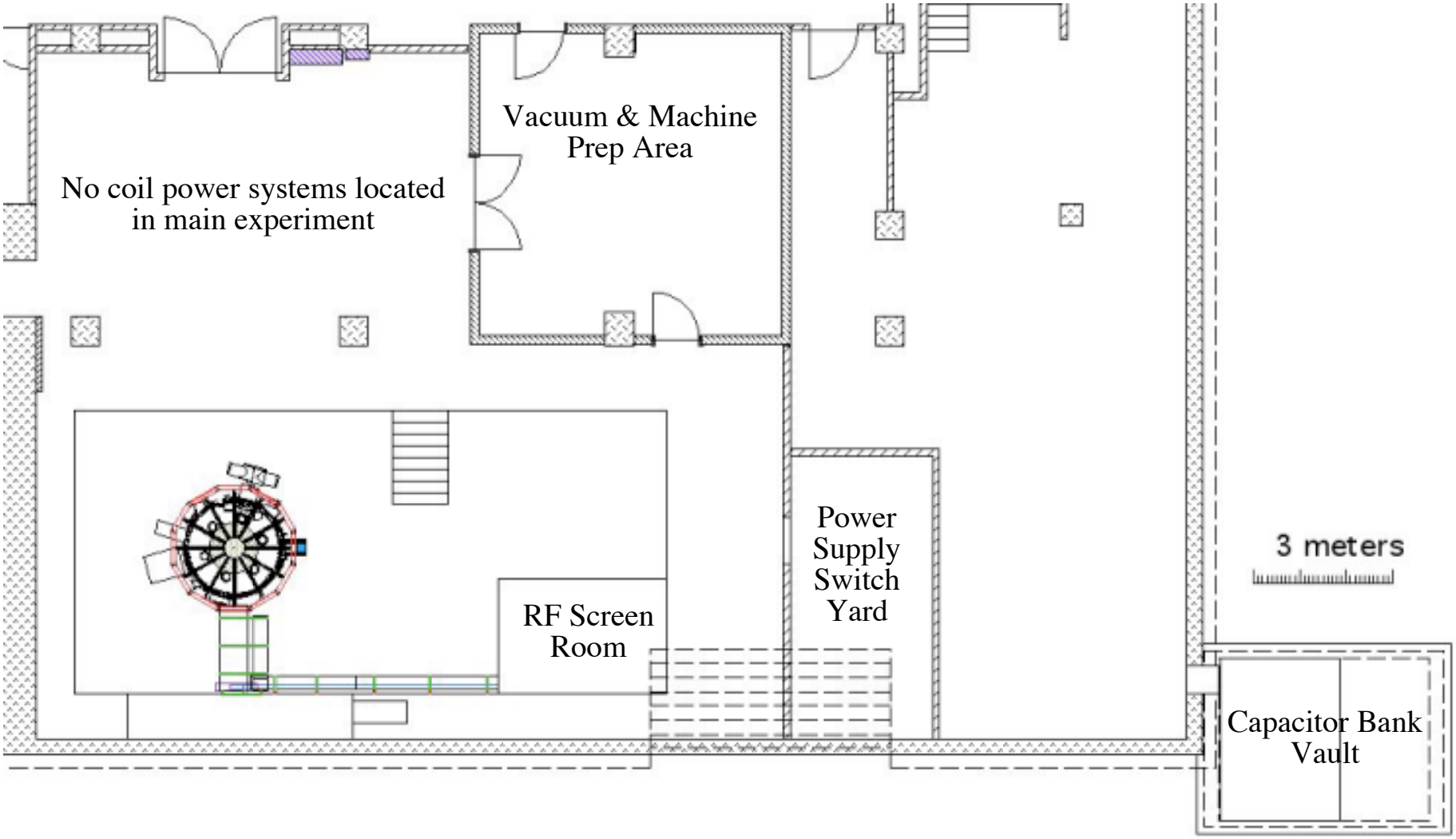
- H-Bridge switches adjacent to experiment area

- New data conduits provide better RF shielding and grounding

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

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

Present PEGASUS Experiment Facility



Electrolytic Capacitor Banks

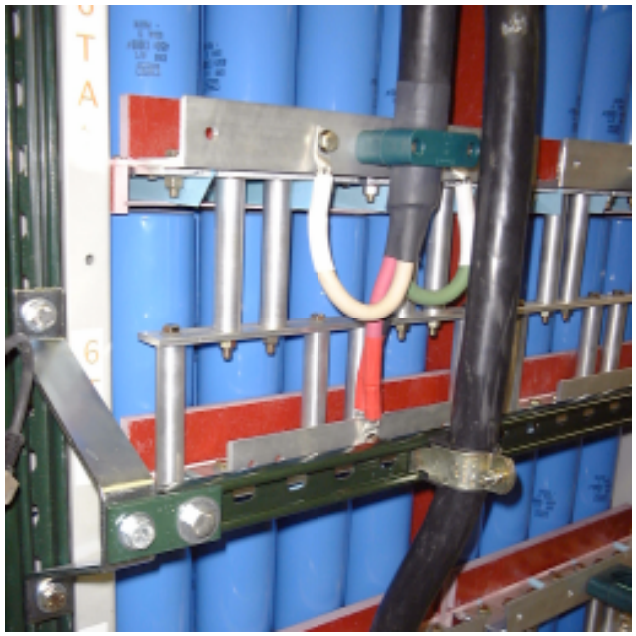


Capacitor Bank Installation





Quad Cable Runs and Termination



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

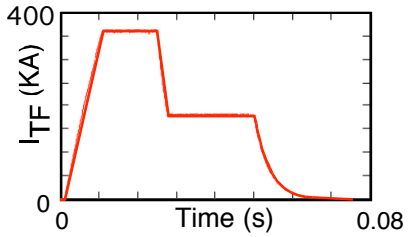
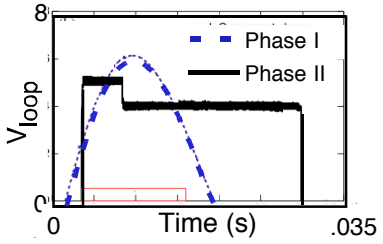
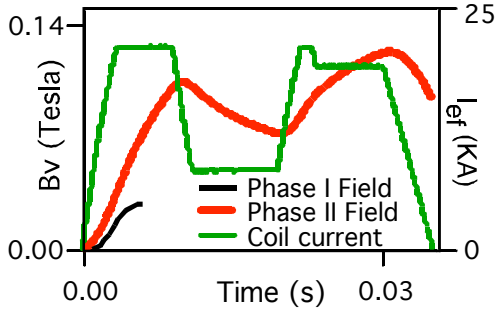
System	Phase I	Phase II	Example
Toroidal Field	• 60 turns • Quasi-DC • 150 kA-t max	• 12 turns • Time-variable • up to 450 kA-t • 8 IGBT Bridges	
Ohmic Heating	• Half-sine Waveform • ±40 KA at 10kV	• Programmable • ±48 KA at 2.7kV • 12 IGCT Bridges	
Equilibrium Field	• Monolithic coil set • 2 Resonant 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

• 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 critcal coil sets

- Fault detection and interruption capability

- HIT group: CAMAC based, optically isolated PWM controller

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



Insulated Gate Bipolar Transistor

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
  - Quadrapole 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

H-Bridge Semiconductor Transient Limits

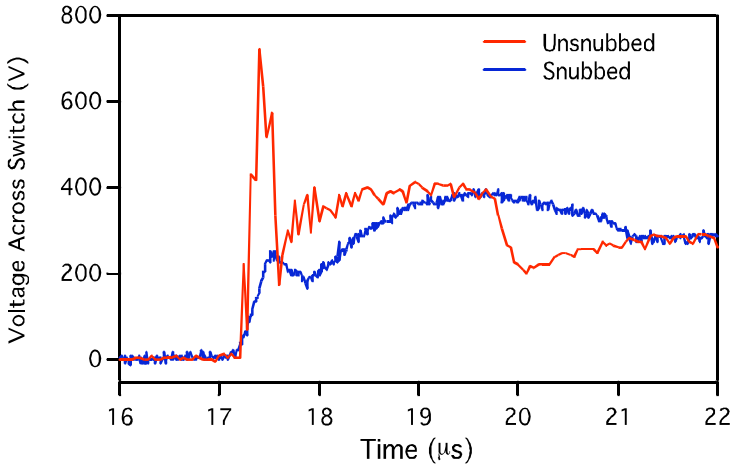
- **ABB 5SHY35L4511 IGCT**
  - Steady State Rating 2.8kV, 4kA at 1kHz
  - Switching Frequency
    - Dependent on current/voltage switched as well as device integrated controller
    - Can switch at 1.0kHz steady state
    - Can switch beyond 1.0kHz for a finite number of pulses (~100s)
  - Switched Voltage
    - Heating is minimized with reduced voltage operation
  - Switched Current
    - Cannot control (turn off) more current than device rating (4kA)
    - Heating is minimized with reduced current
  - Primary heating derived from switching losses

- **Eupec FZ2400R17KE3 IGBT**
  - Steady State Rating 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

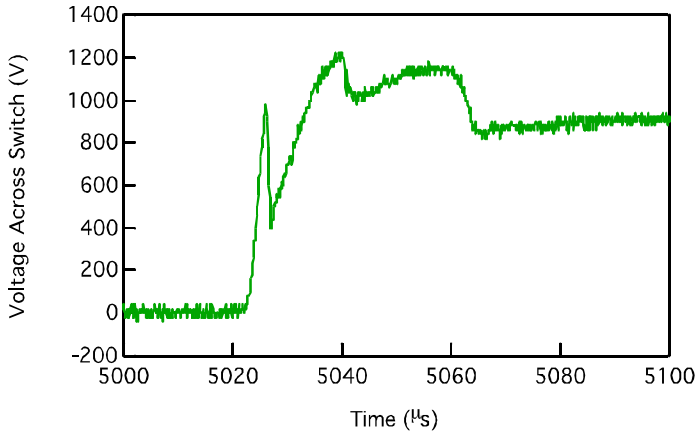
H-Bridge System Transient and Ripple Supression

- **H-Bridge Transient Suppression**
  - Transmission lines have inductive stored energy
  - RCD snubber for overall H-Bridge
  - RCD snubber for individual switching components
  - Local electrolytic capacitors
- **Transmission Line / Coil Suppression**
  - Impedance mismatchs leads to reflections
  - RC snubber on most individual lines and coils
  - Common mode voltage when coil is in freewheel mode
  - RC snubber from high and low side of coil to ground
- **PWM Systems Presents Additional Challenges**
  - Current Ripple on Coils
  - PF and TF systems adequately filtered by Vacuum Vessel
  - Ohmic Systems to neccesitate Polyphasic Multiswitch Operation for higher system switching frequency

Transients across IGBT at 300V/1kA



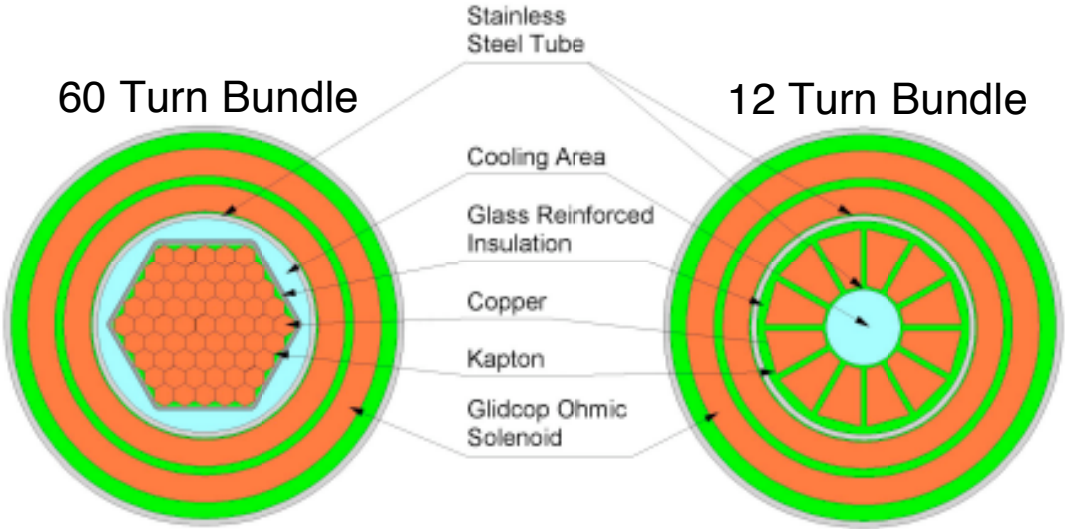
Snubbed Transients across IGBT at 850V/4kA

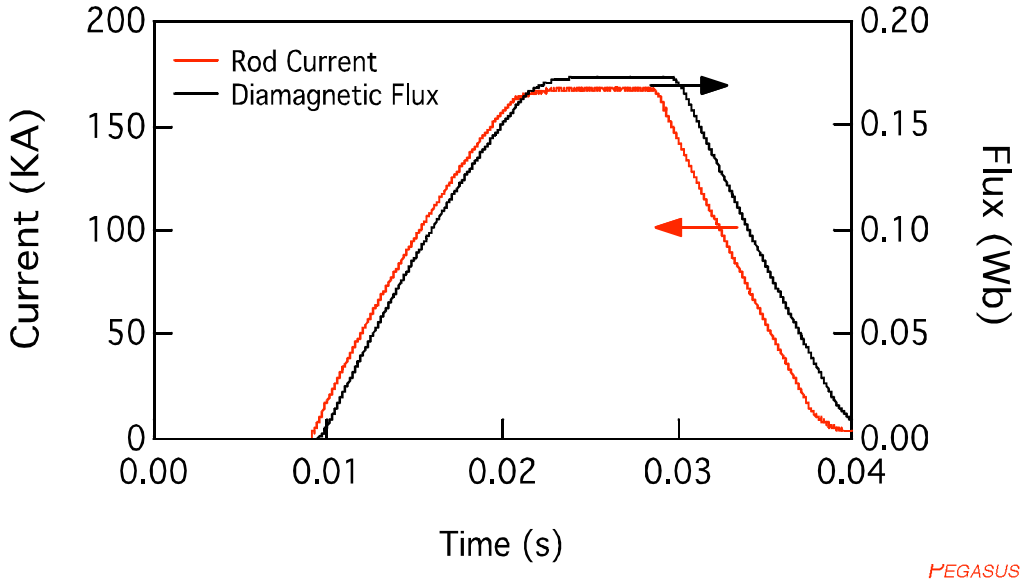


Details of PEGASUS Coil Power Systems

- **Ohmic Heating (OH)**
  - 12 parallel systems 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)**
  - 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)**
  - 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 ±4kA @ 900V - Two or Four Quadrant Control for each H-Bridge system
  - Provides positioning and shaping fields with active feedback control

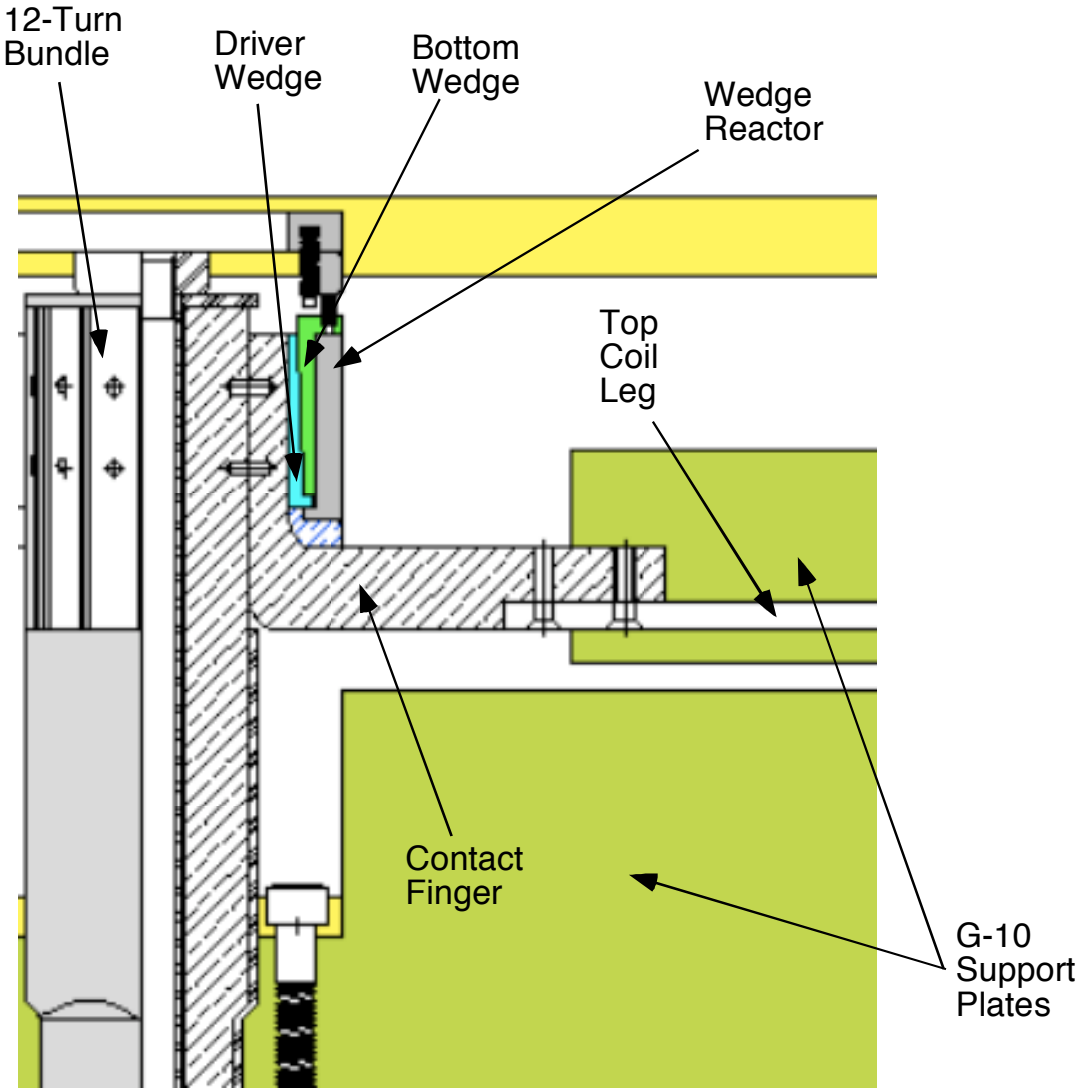
PEGASUS Centerstack Assembly and TF Waveform





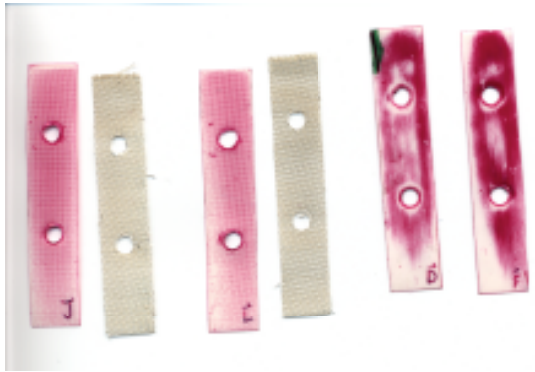
Toroidal Field Joint Area is Critical

Cross-Sectional Drawing (Top)

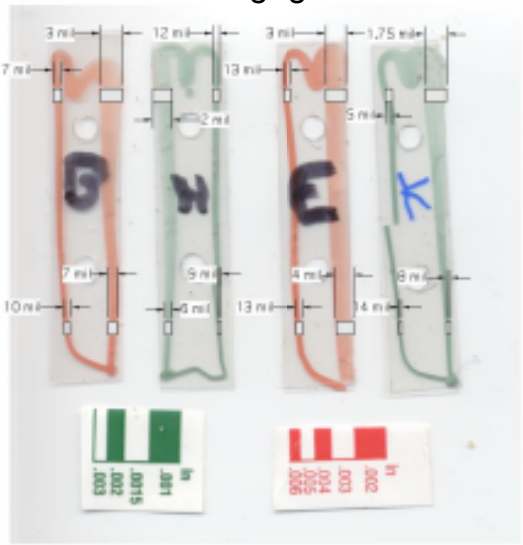


Fit-Check Diagnostics

Pressure Paper

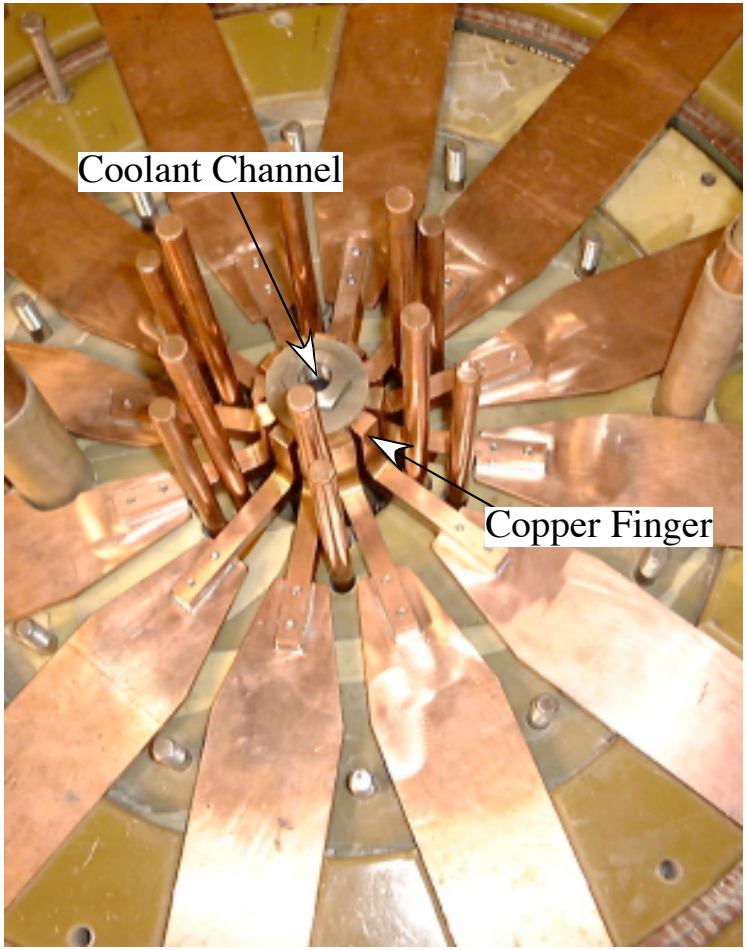


Plastigage™

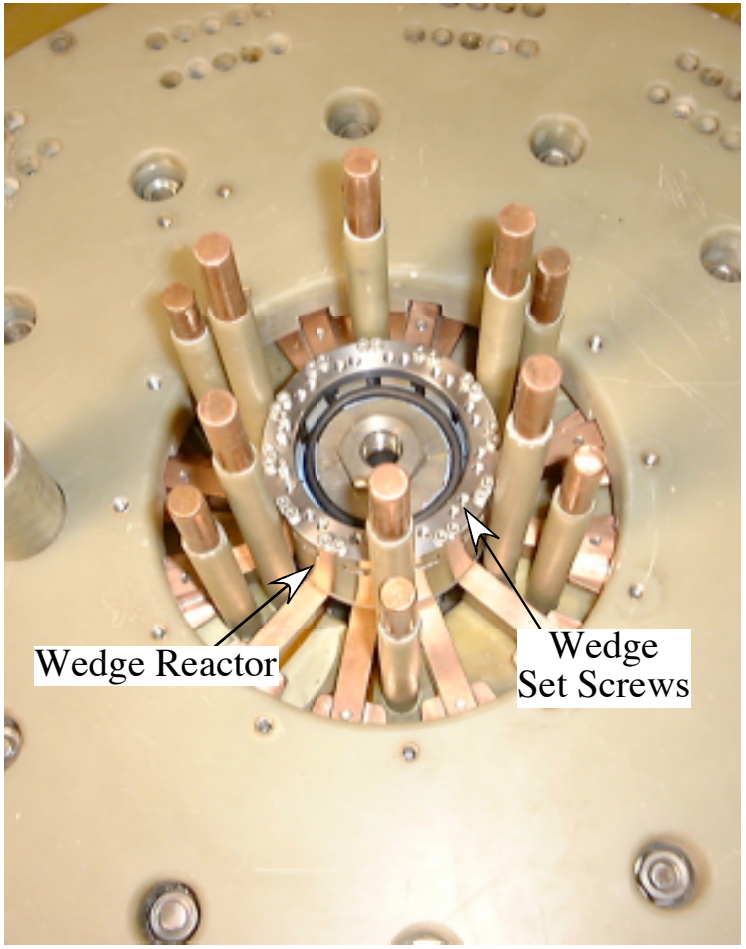


Toroidal Field Upper Joint Assembly

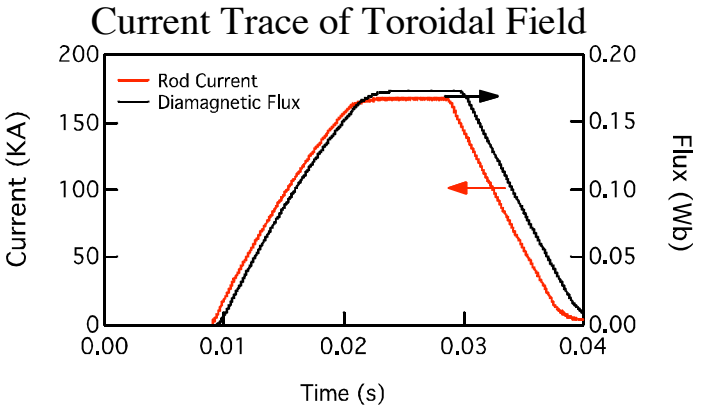
Bare TF Assembly

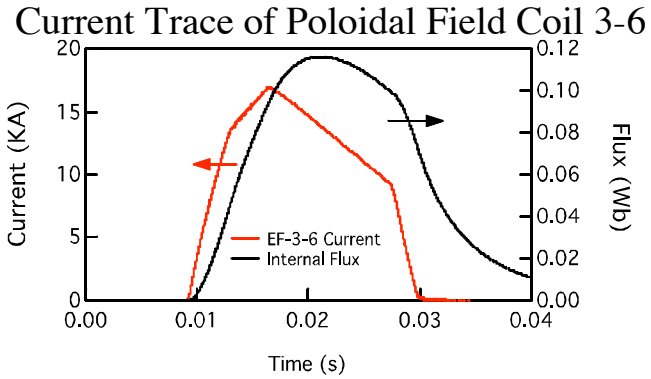


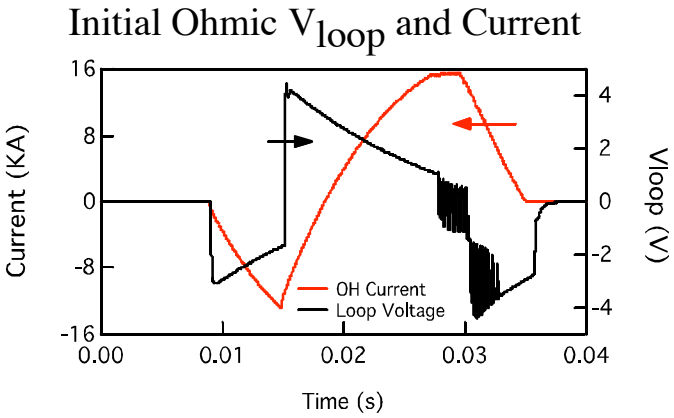
Fully Assembled TF Joint



H-Bridge Systems Shakedown and Coil Power Testing







- **Laboratory Infrastructure Complete**
- **900V IGBT Systems Complete for Initial Plasma Operations**
  - Tested to full power individually
  - Cross Field and Multi-Switch Systems Shakedown in Progress
  - Limited Loop Volts / Volt-Seconds to follow
- **Modest Power Operations - Summer 04**
- **2700V IGCT Systems for Full Power Operations Summer 04**
  - Resources Permitting

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

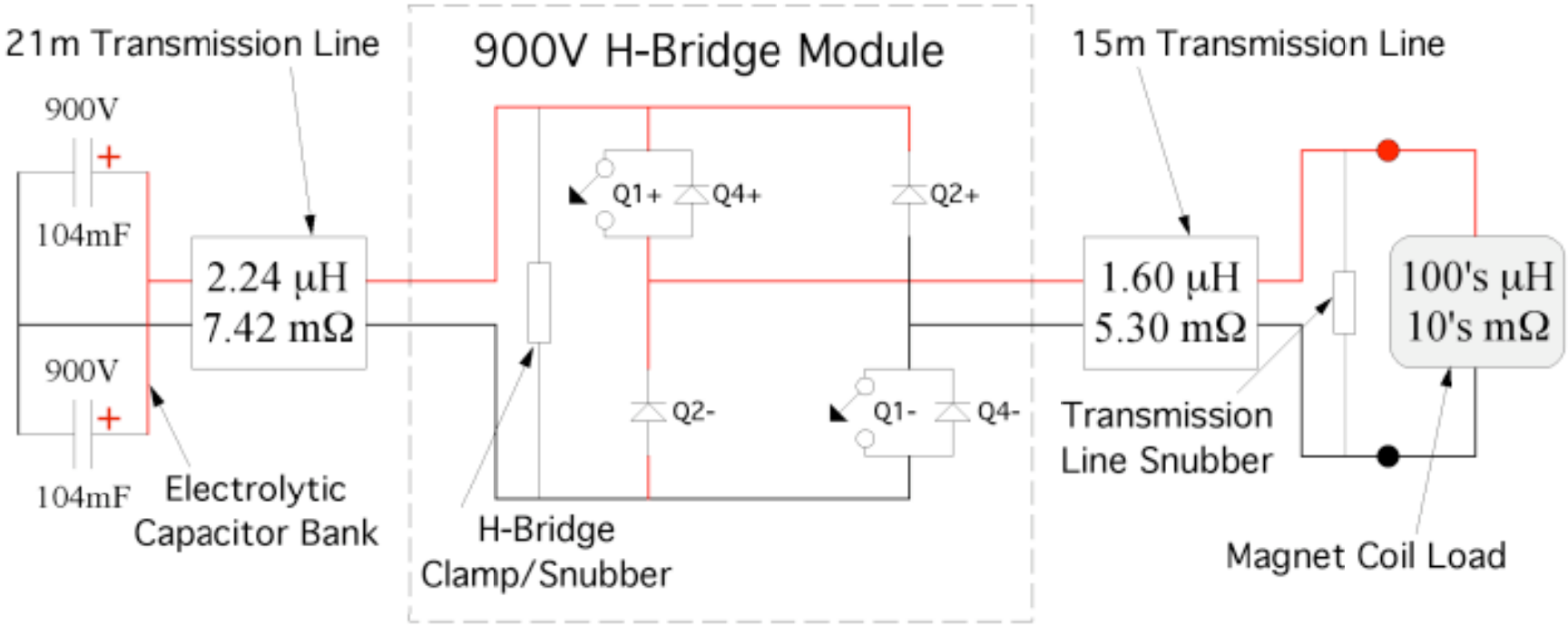
- **New Tools Added to Enhance Study of Plasma Stability Boundaries**
  - Increased ohmic V-sec (2 - 2.5x) and control
  - Programable independent equilibruim field coils for shaping and position control
  - Low inductance toroidal field assembly
  - Divertor coils for separatrix operations

- **PWM Controlled Magnet Coil Power Systems**
  - Coil power systems being upgraded to programmable waveform control
  - HIT power system collaboration greatly reduced development time
  - Provides current waveform control

Reprints

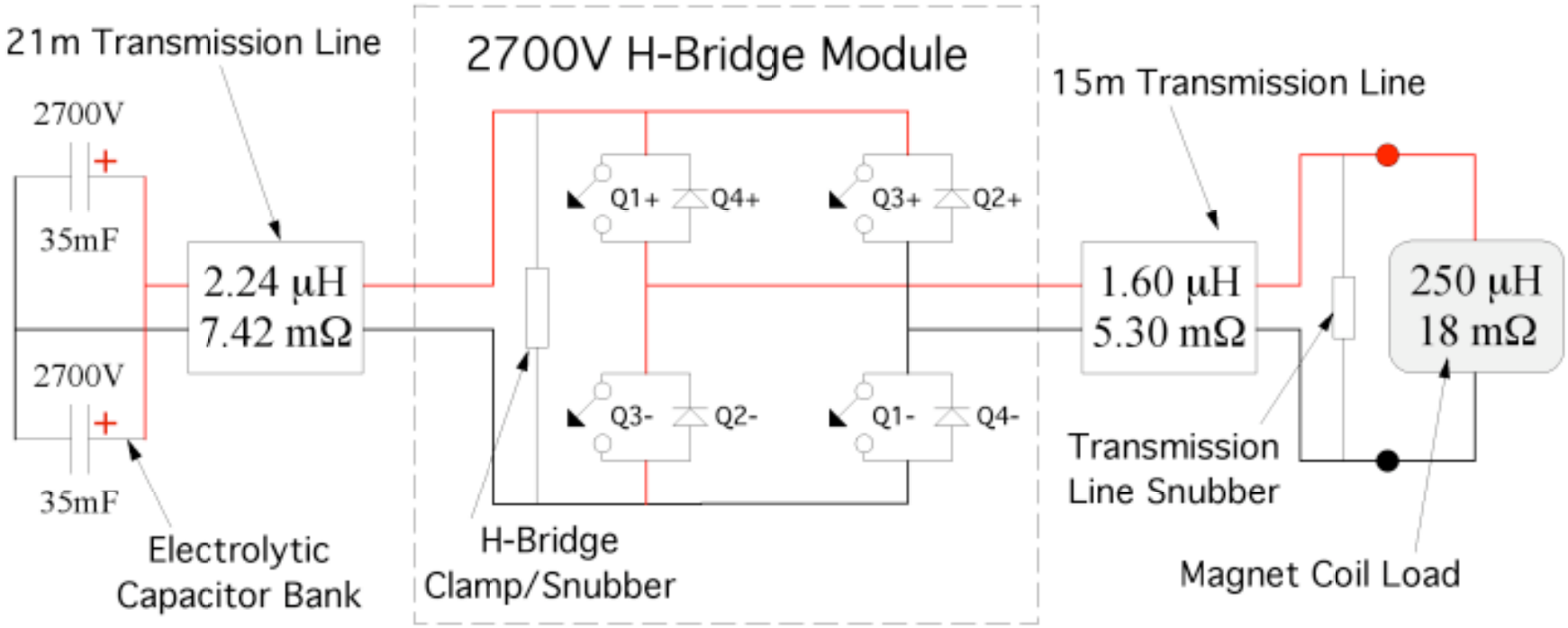
PEGASUS 900V 2-Quadrant H-Bridge System

- Unipolar power systems for EF, Div, and TF coil sets
  - Uses IGBT switches (900 V, 4.8 kA)



PEGASUS 2700V 4-Quadrant H-Bridge System

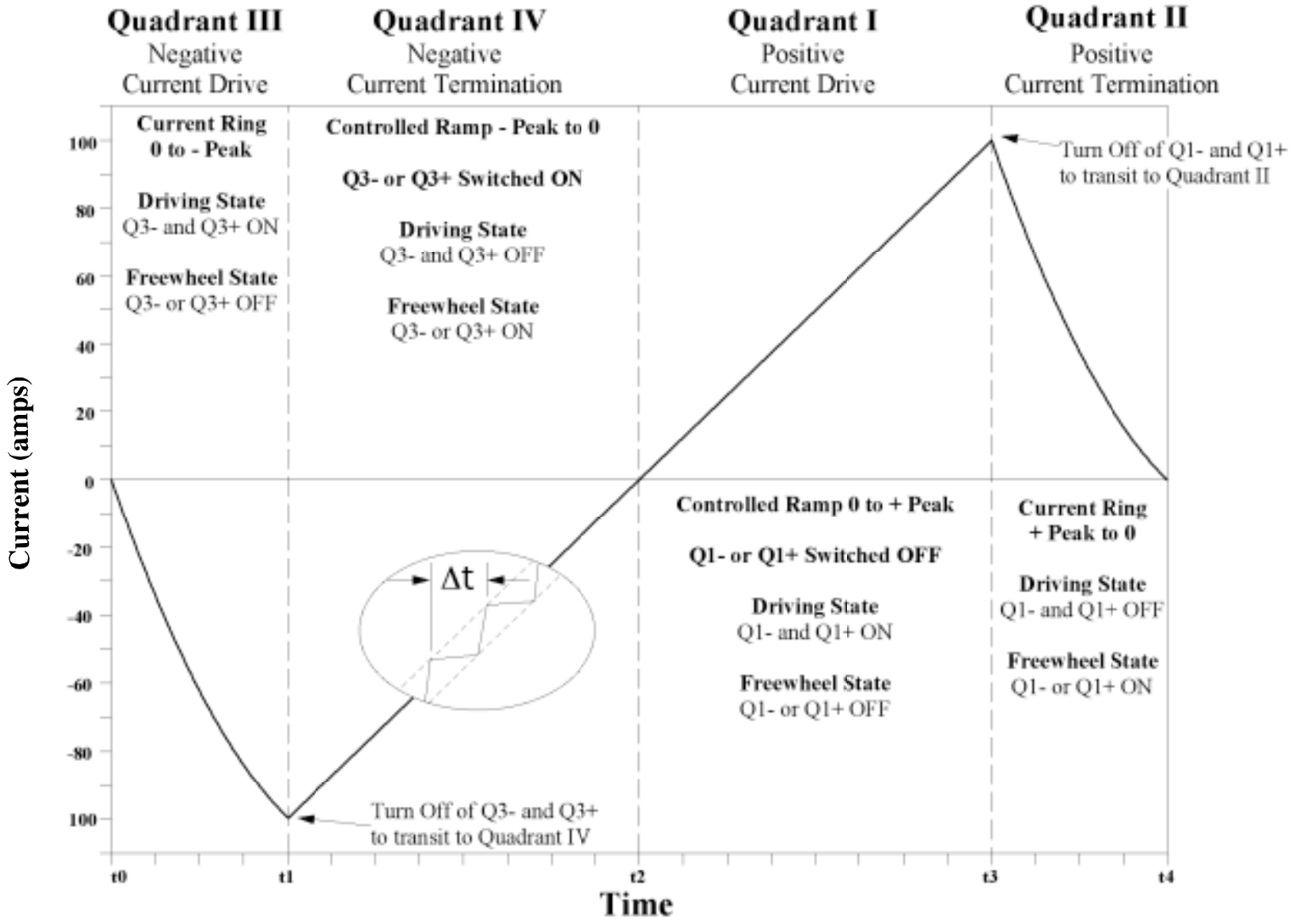
- OH solenoid system schematic for single H-bridge switch
  - -Full OH (±48kA) uses 12 in parallel
  - -Use high power IGCTs (2.8 kV, 4 kA)



- Similar, 900 V system with IGBTs

PEGASUS 4-Quadrant Switching Waveform (Bipolar)

- Switch logic and sequencing for 4-quadrant H-bridge



PEGASUS 2-Quadrant Switching Waveform

- Switch logic and sequencing for 2-quadrant H-Bridge

