Abstract

A rebuild of the PEGASUS ST facility with several major upgrades is in its final stages, and low-power ohmic operation has begun. A new low-inductance, fast-response toroidal field system allows variation of B_t within a few ms. Additional poloidal field coils, including divertor coils, provide shaping control. New modular IGBT and IGCT switching power supplies have been developed to provide full programmability control of all the magnet coils. The toroidal and poloidal systems are powered by several 900 V/16 KA IGBT switch assemblies, while the OH system requires a 2700 V/48 KA IGCT system. An array of IGBT switch modules has been successfully deployed for low-power OH operation --- albeit with full power for poloidal and toroidal fields --- while initial deployment of the IGCT system is expected this Fall. Together, these systems provide increased V-sec, programmability for V_{loop} and flexible position and shape control, and increased toroidal field strength.

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

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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.



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Overview of PEGASUS and Facility

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

  } need plasma control

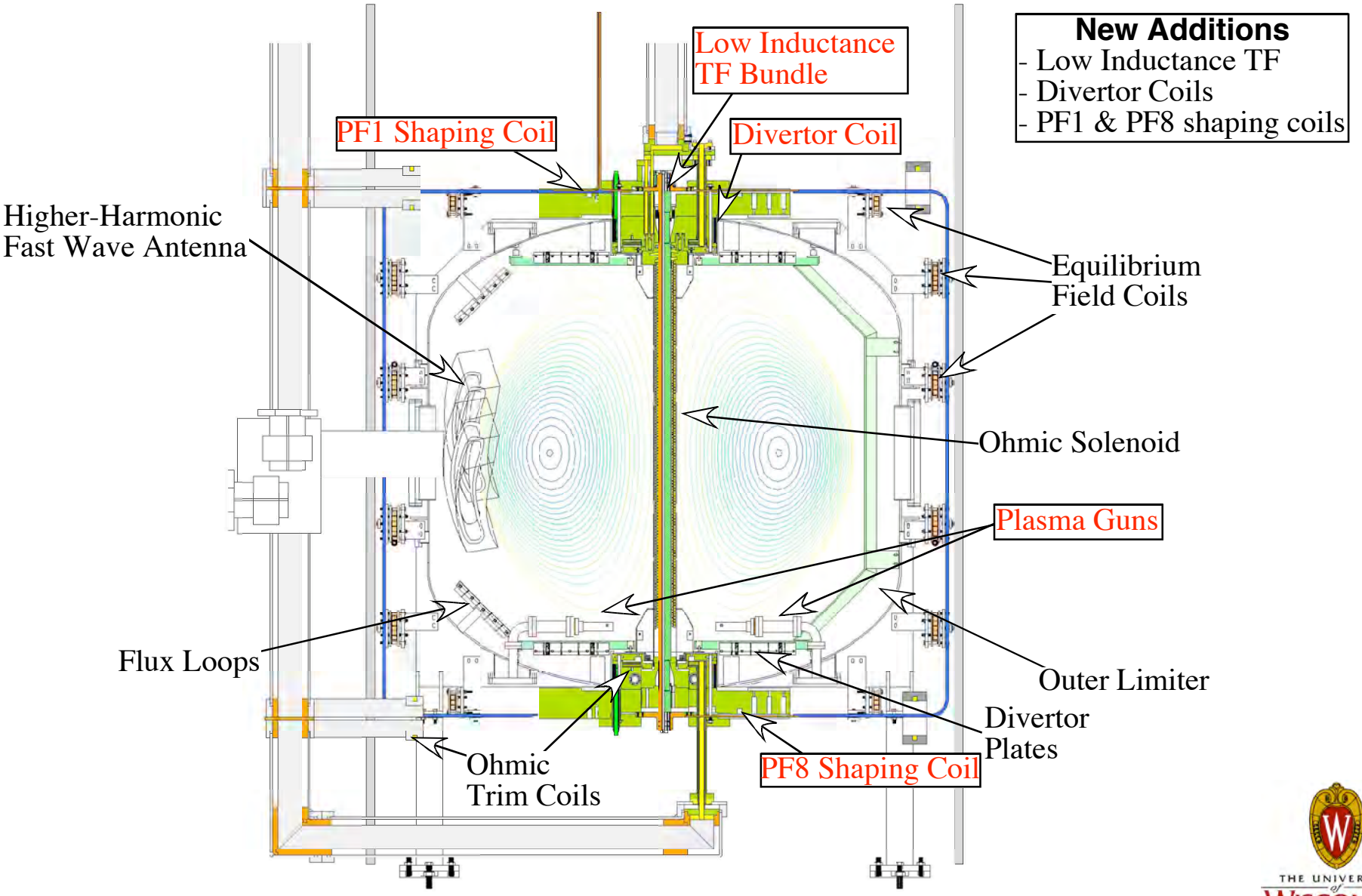
- **Facility Reconstruction**
  - Experimental Facility Completely Replaced
  - Toroidal Field Centerstack Assembly Upgraded
  - Fully shielded data signal runs and DAS

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

- **Status**
  - IGBT H-Bridges in use for low power OH operations (Full TF)
  - IGCT H-Bridge construction awaiting installation

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PEGASUS Toroidal Experiment



New Additions
- Low Inductance TF
- Divertor Coils
- PF1 & PF8 shaping coils

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PEGASUS Facility has been Completely Rebuilt

- **Complete Laboratory Reconfiguration**

  - Facility extensively damaged

  - Proposed upgrades front-loaded 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
    - Active shaping and position programming

  - Increased V-sec (2 - 2.5x) and control during all phases of plasma evolution

  - 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

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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

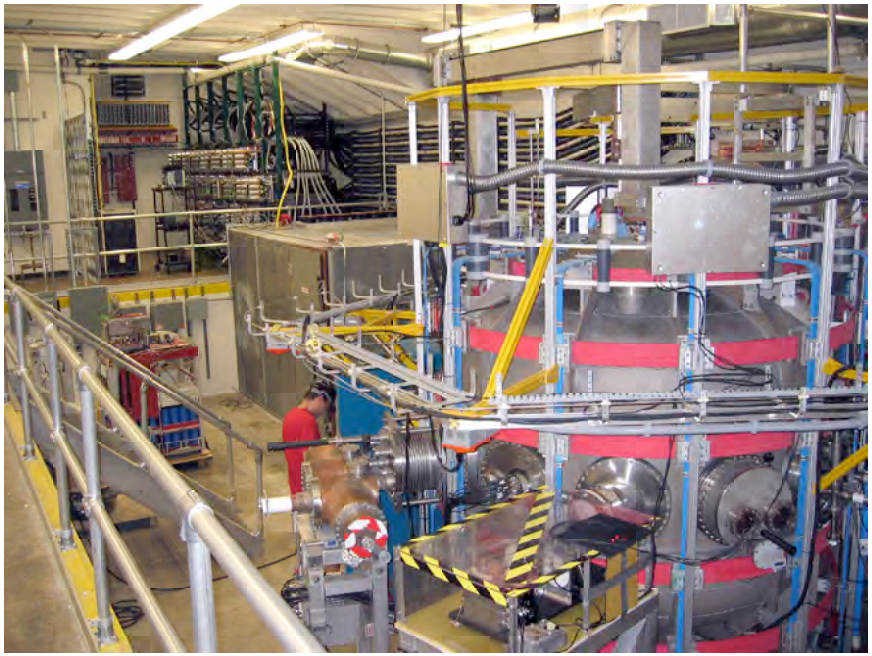
- **Low-inductance Toroidal Field Centerstack Installed**
  - Provides increased, time-variable TF

- **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

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New PEGASUS Experiment Facility





• Accessible Experimental Area

- Energy storage capacitors outside experiment area

- 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.

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Electrolytic Capacitor Banks



Capacitor Bank Installation





Quad Cable Runs and Termination



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Power Systems Operational Status and Waveform

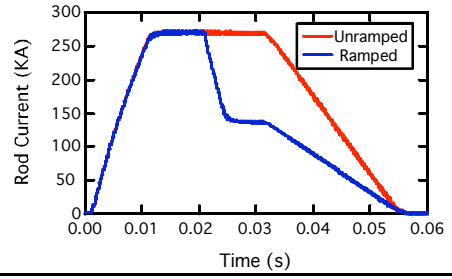
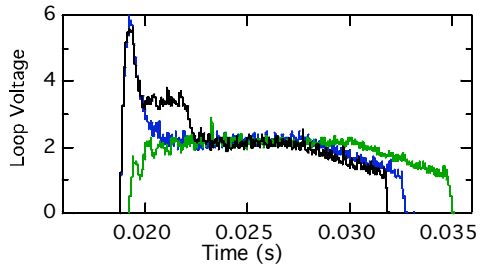
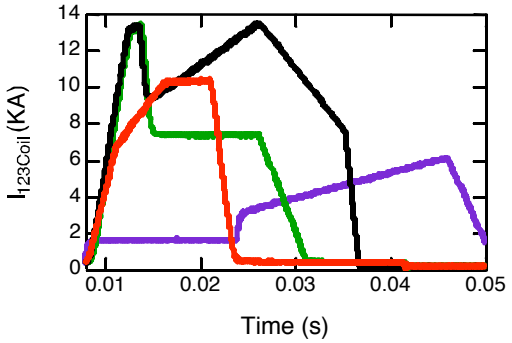
System	Phase II - Low Power	Phase II - Full Power	Example
12 Turn Toroidal Field	• 6 IGBT H-Bridges • 350 kA max • Full Ramp Capability	• 8 IGBT H-Bridges • 450 kA max • Full Ramp Capability	
Ohmic Heating	• 4 IGBT H-Bridges • ±16 kA at 900V • Preprogrammed • LC Filtered	• 12 IGCT H-Bridges • ±48 KA at 2.7kV • Active Ip control • Polyphasic Operations	
Poloidal Field	• 9 IGBT H-Bridges • Two sets @ 16kA • ±4kA bias • No divertor • Preprogrammed	• 20 IGBT H-Bridges • Four sets @16kA • -4/+16kA Bias • ±12kA Divertor • Active feedback	



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

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

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Pulse Width Modulated (PWM) Controlled 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 critical 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

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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

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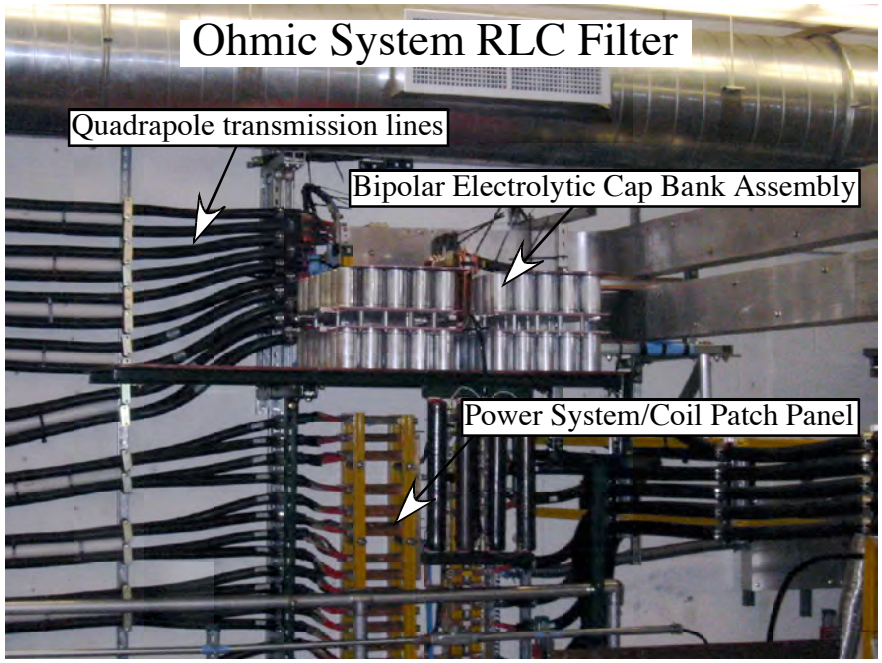
H-Bridge Semiconductor Transient Limits

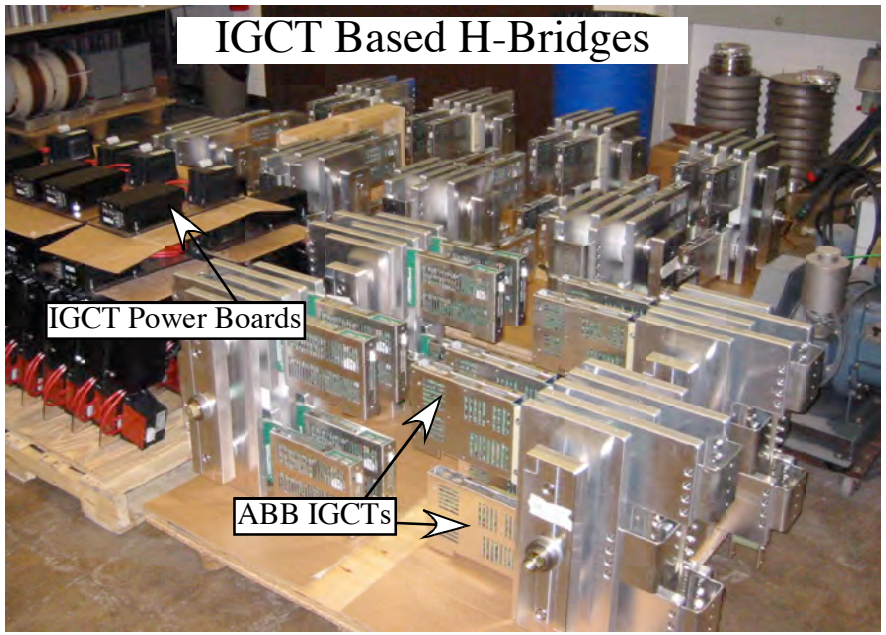
- **ABB 5SHY35L4511 IGCT**
  - Steady State Rating 2.8kV, 4kA at 1kHz
  - Switching Frequency
    - Dependent on current/voltage switched as well as device integrated controller
    - Can switch at 1.0kHz steady state
    - Can switch beyond 1.0kHz for a finite number of pulses (~100s)
  - Switched Voltage
    - 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

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PEGASUS Power System Development





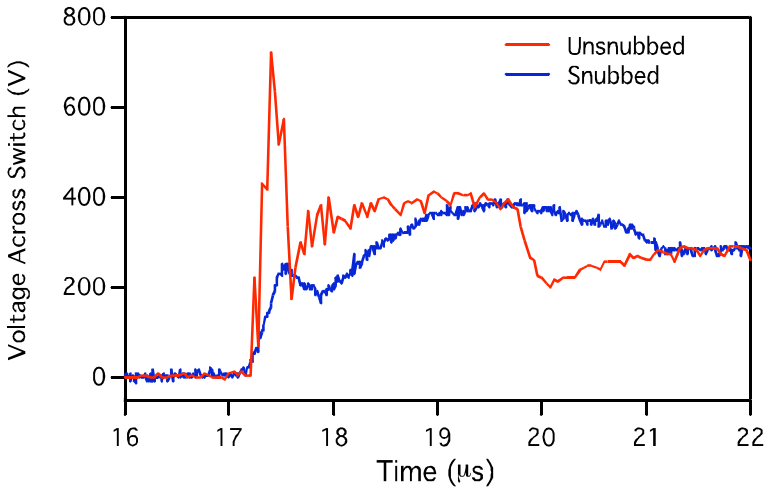
- **April - June 2004**
  - 900V IGBT H-Bridge testing and stabilizing
  - Coil currents increased significantly
  - DC Links
  - H-Bridge and transmission line snubbers
  - Common mode and switch transient symmeterization to suppress transient spikes
- **First low power plasma operations**
  - Four 900V H-Bridge system applied to OH
    - Limited V_{loop} and V-sec
  - Allowed development of new operating scenerios
- **Presently installing full OH power system**
  - Allow full power operations

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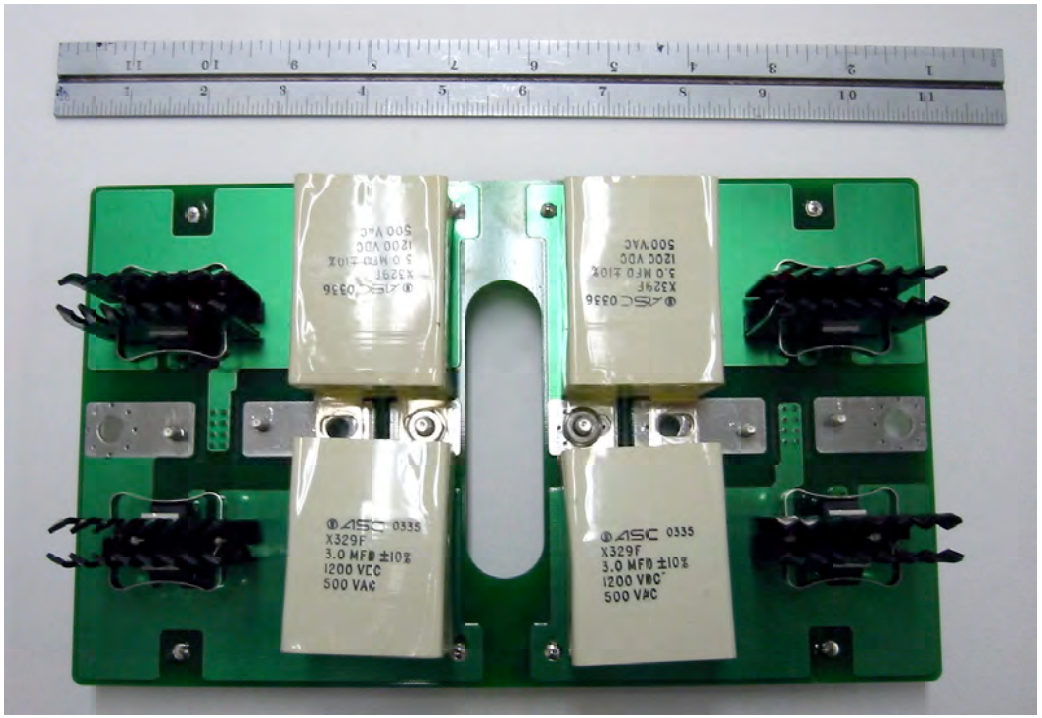
H-Bridge System Transient Supression

- **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 (DC Links)

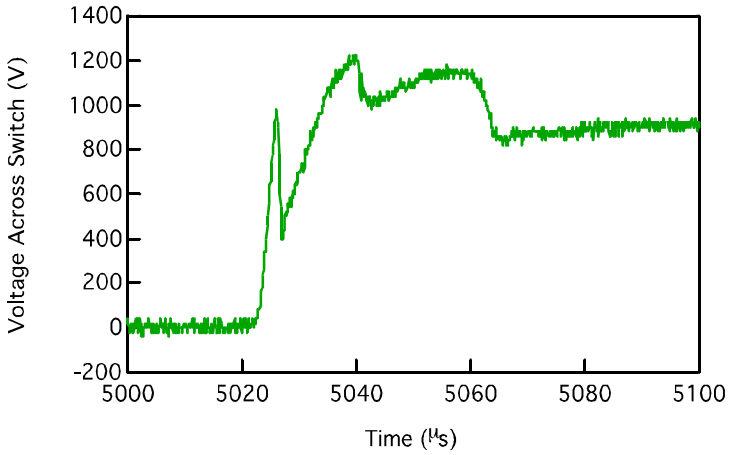
Transients across IGBT at 300V/1kA



IGBT H-Bridge RCD Snubber Board



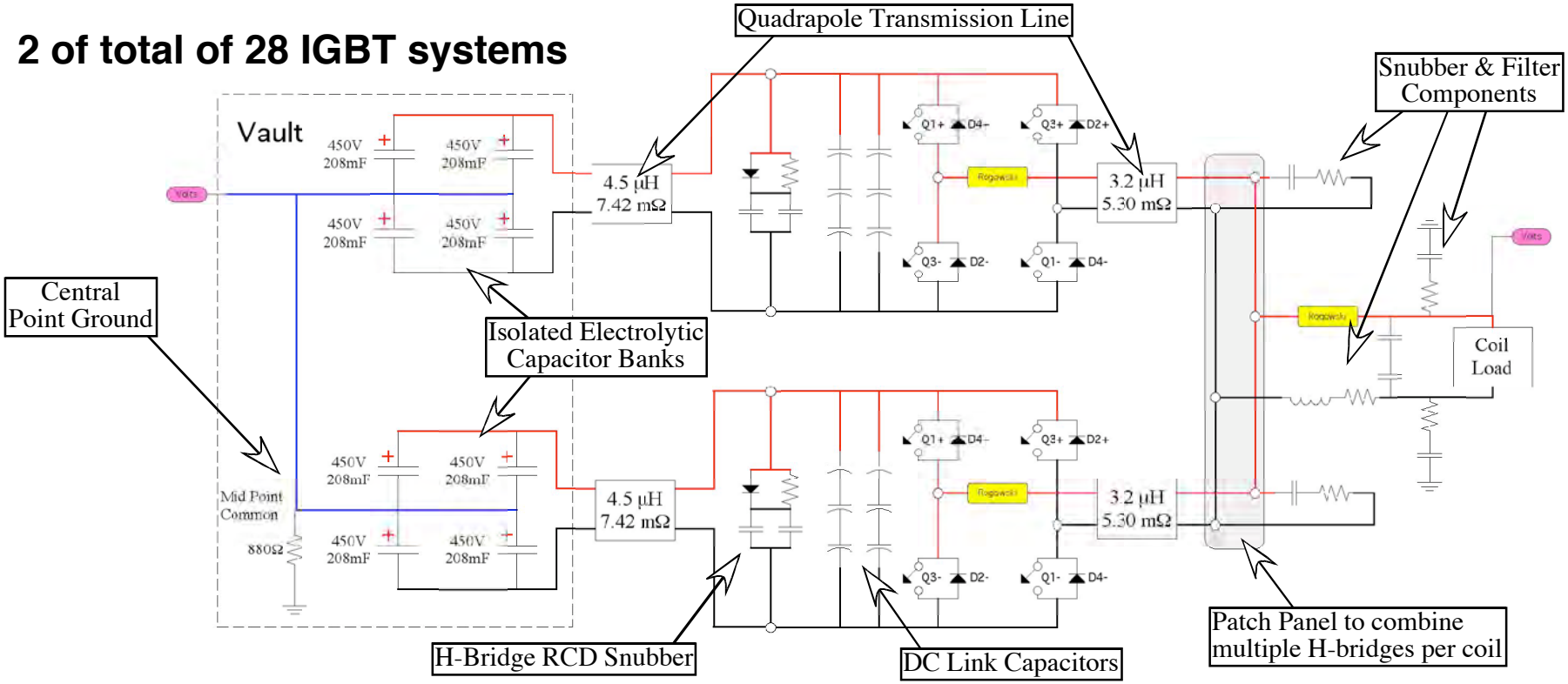
Snubbed Transients across IGBT at 850V/4kA



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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

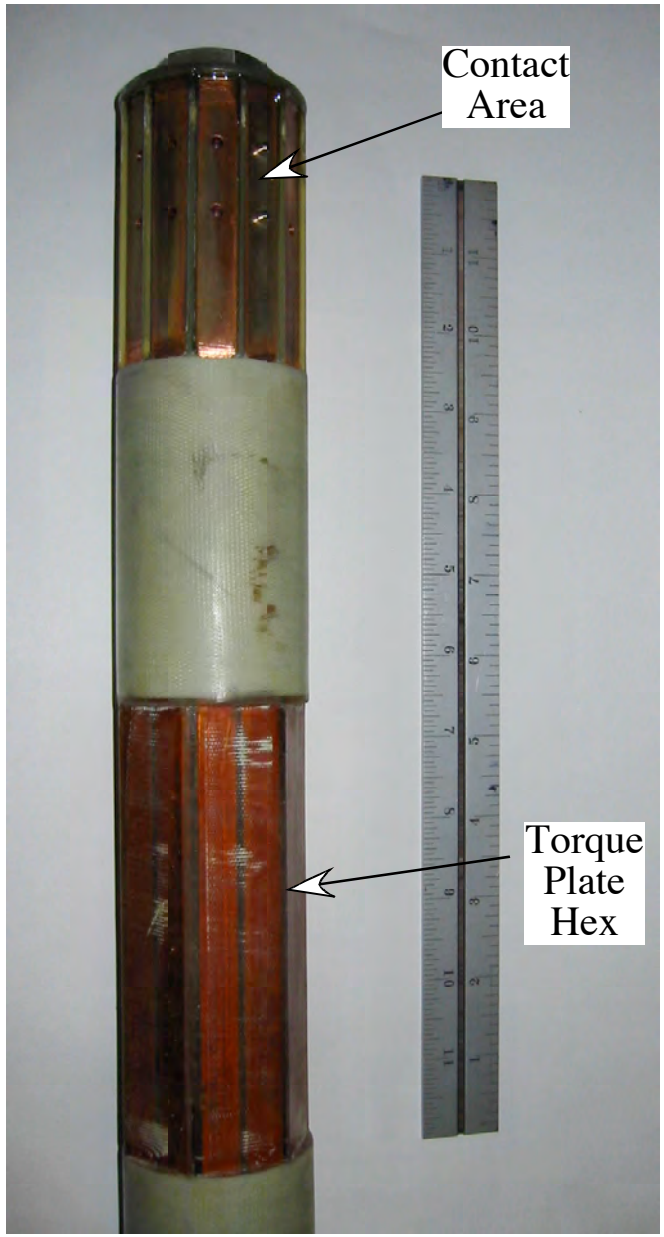
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Details of PEGASUS Power Supplies

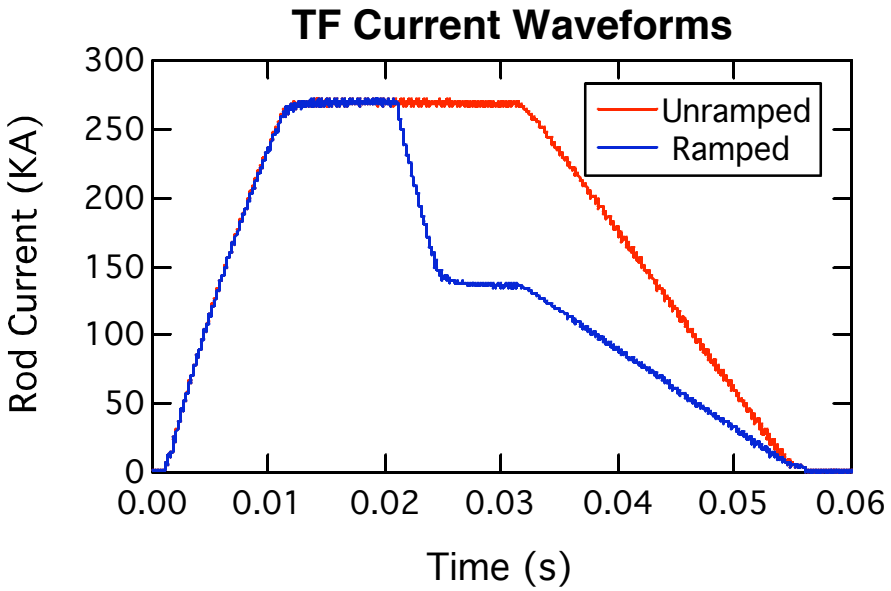
- **Ohmic Heating (OH) [130MVA]**
  - 12 parallel systems provide ±48kA @ 2700V/3032kJ - Four Quadrant Control
  - Efficient utilization of up to 100mV/sec Ohmic Flux
  - Minimize heating of Ohmic Solenoid by utilizing regeneration mode of H-Bridges
- **Toroidal Field (TF) [35MVA]**
  - 8 parallel systems 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**

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PEGASUS TF Center-rod Assembly and Waveform

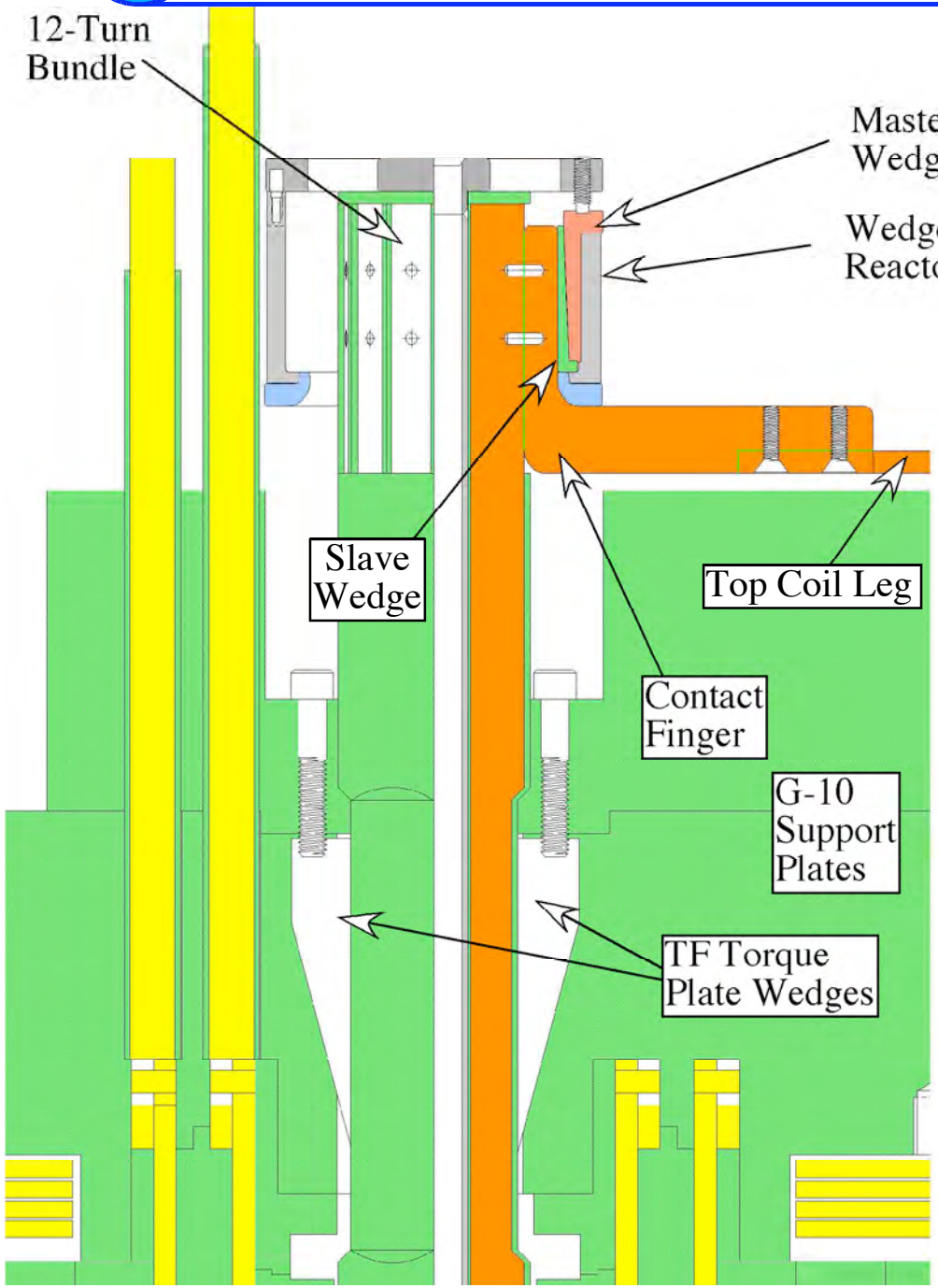


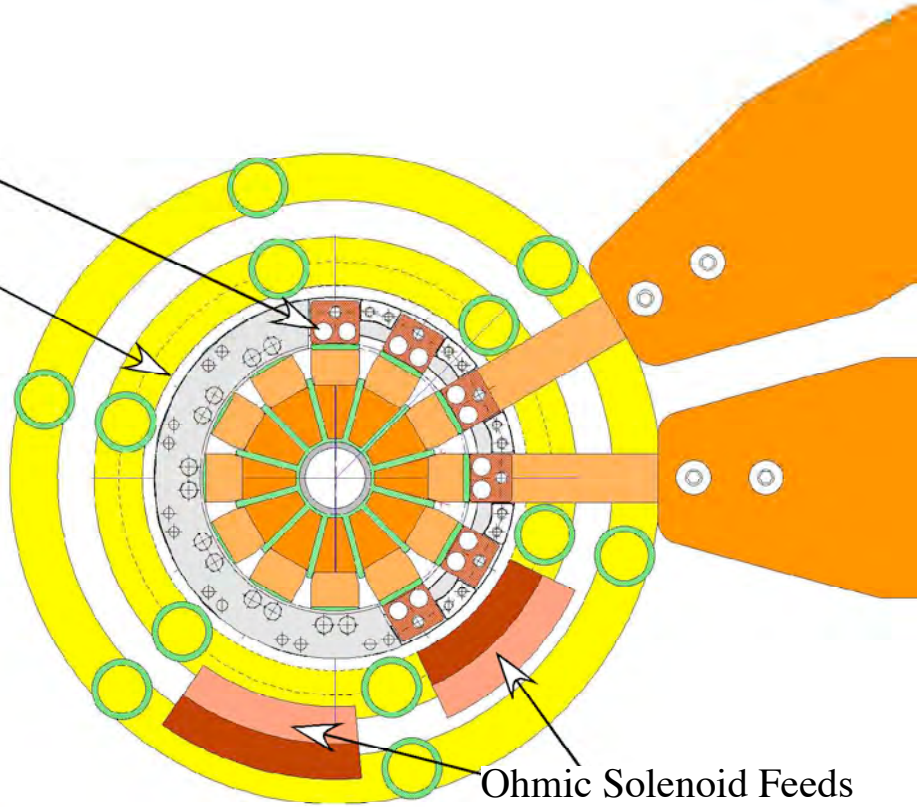
- New 12-Turn low inductance center-rod assembly
  -Allows for rapid current ramping
- Supplied via 8 parallel IGBT H-Bridges systems
- 0 to +38kA @ 900V/673kJ - 2 quadrant control
- Maximum of 450kA rod current (up from 150kA)



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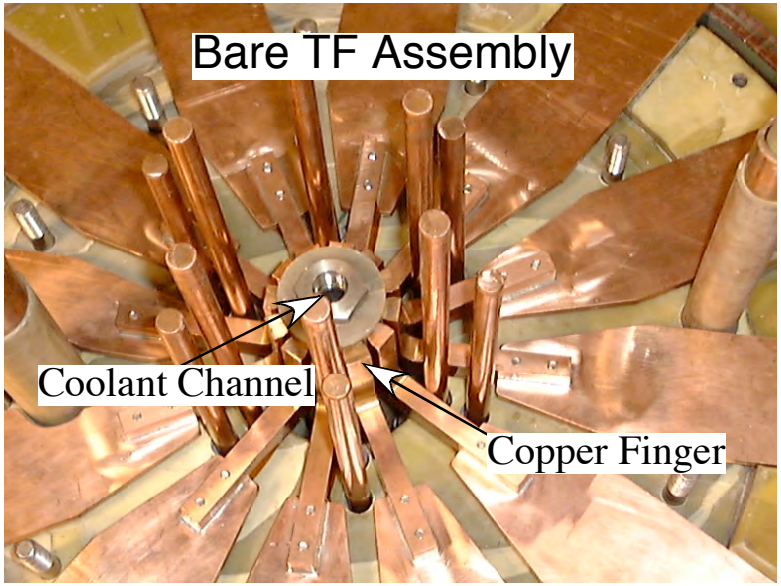
Toroidal Field Joint Area is Critical

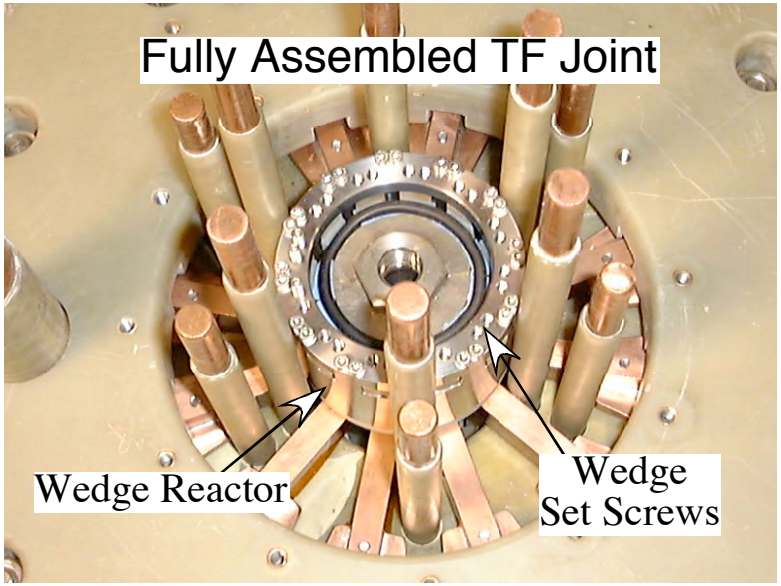


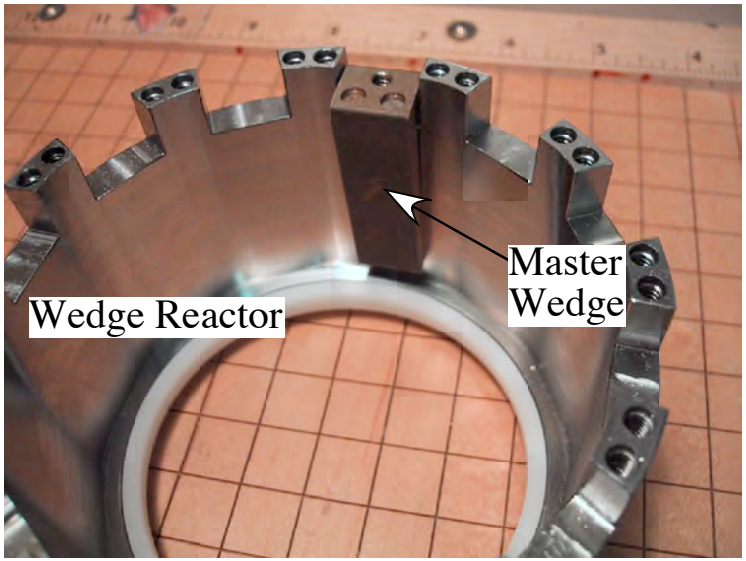


- Wedge Reactor Joint Compressor
  - Provides ~10ksi of joint compression
  - Acts as spring to allow system to flex while maintaining ≥ 4ksi compression
  - Wedges are self locking
  - Compressor "floats" with TF bundle

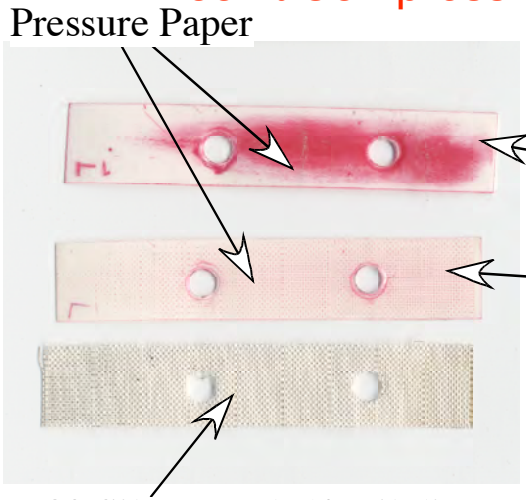
Toroidal Field Upper Joint Assembly







TF Joint Compression Diagnostics



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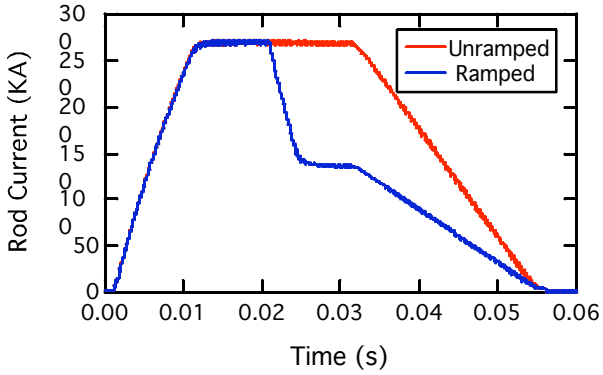
Future Directions

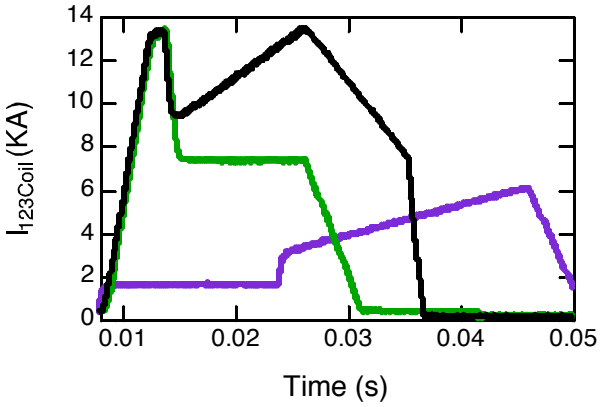
- **Commission IGCT Systems and commence full power operations**
  - 9X available stored energy for OH drive
  - Up to 3X available voltage
- **Active Feedback Control**
  - V_{loop}/Ip for plasma evolution and sustainment
  - Radial Position Control
  - Plasma Elongation
- **Pulse Length Extension**
  - 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

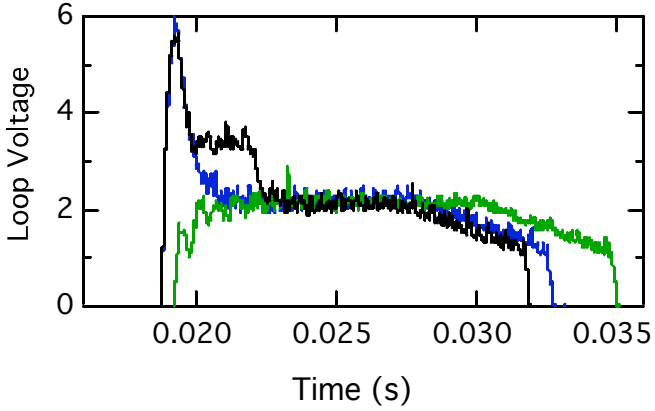
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Initial Plasma Operations with 900V IGBT systems

Example Waveforms







- **900V IGBT Systems Configured for low Plasma Operations**
  - OH up to ±16kA at ≤ 2 loop volts
  - TF up to 350kA rod current
  - 9 remaining IGBT systems allocated for EF
- **2700V IGCT Systems for Full Power**
  - OH up to ±48kA at ≤ 6 loop volts
  - TF up to 450kA rod current
  - 20 remaining IGBT systems allocated for EF

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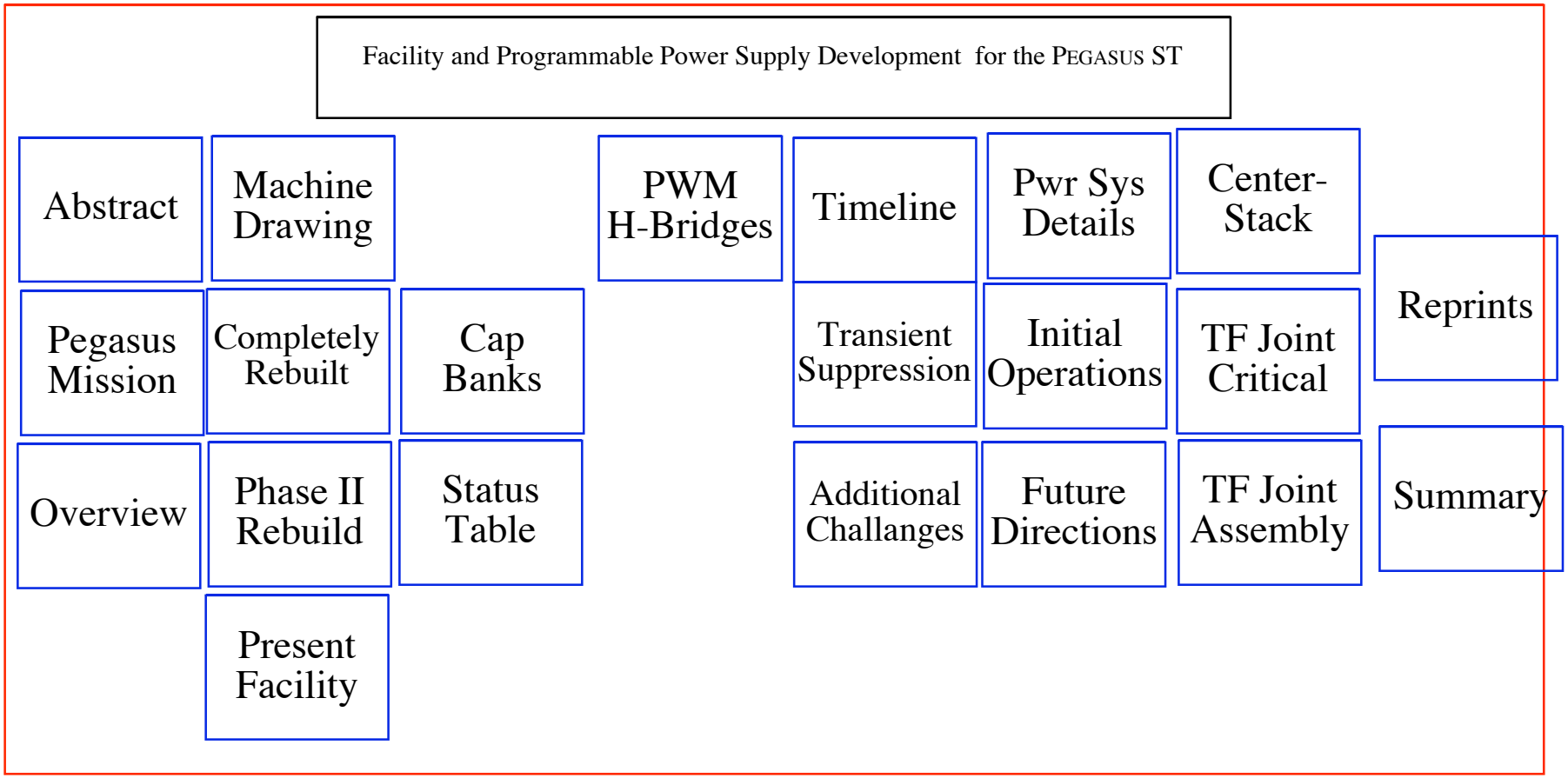
Summary

- **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
  - 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 being upgraded to programmable waveform control
  - HIT power system collaboration greatly reduced development time
  - Provides current waveform control
- **Plasma operation started with low voltage IGBT power supplies**
  - Commissioned new capabilities and developed operating scenerios
  - Now installing final high-voltage power supplied to allow full power operations

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Reprints

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Highly Flexible

Transient Limits

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