Abstract

Extensive new capabilities have been installed on the Pegasus ST facility. The laboratory has been completely reconfigured to separate all power systems from the main hall. Data acquisition, control, and support facilties have been replaced. New magnetic field power supplies will allow active waveform programming and control. Unique high-power IGCT switch modules provide bipolar waveform control for the high-stress solenoid magnet, while IGBTs are used for the poloidal and toroidal systems. The voltage or current of each coil set is controlled by phase-width-modulated circuits developed by the HIT group. Capacitor charging, dumping, and monitoring are controlled by a PCI-based multichannel data acquisition and control system. These upgrades will provide: 1) increased V-s and loop voltage control for higher plasma current and suppression of MHD modes; 2) increased toroidal field with fast-ramp capability for improved access to the low-q, high toroidal beta regime; and 3) flexible equilibrium field control for radial position and modest shape control.

Overview of PEGASUS and Facility Upgrades

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

  } need plasma control

- Facility Upgrades Implemented
  - Experimental Facility
  - Toroidal Field Centerstack Assembly
  - Equilibrium Field compensation coils

- New Programable Magnet Coil Power Systems
  - Pulse Width Modulated (PWM) coil supplies
  - HIT power system collaboration

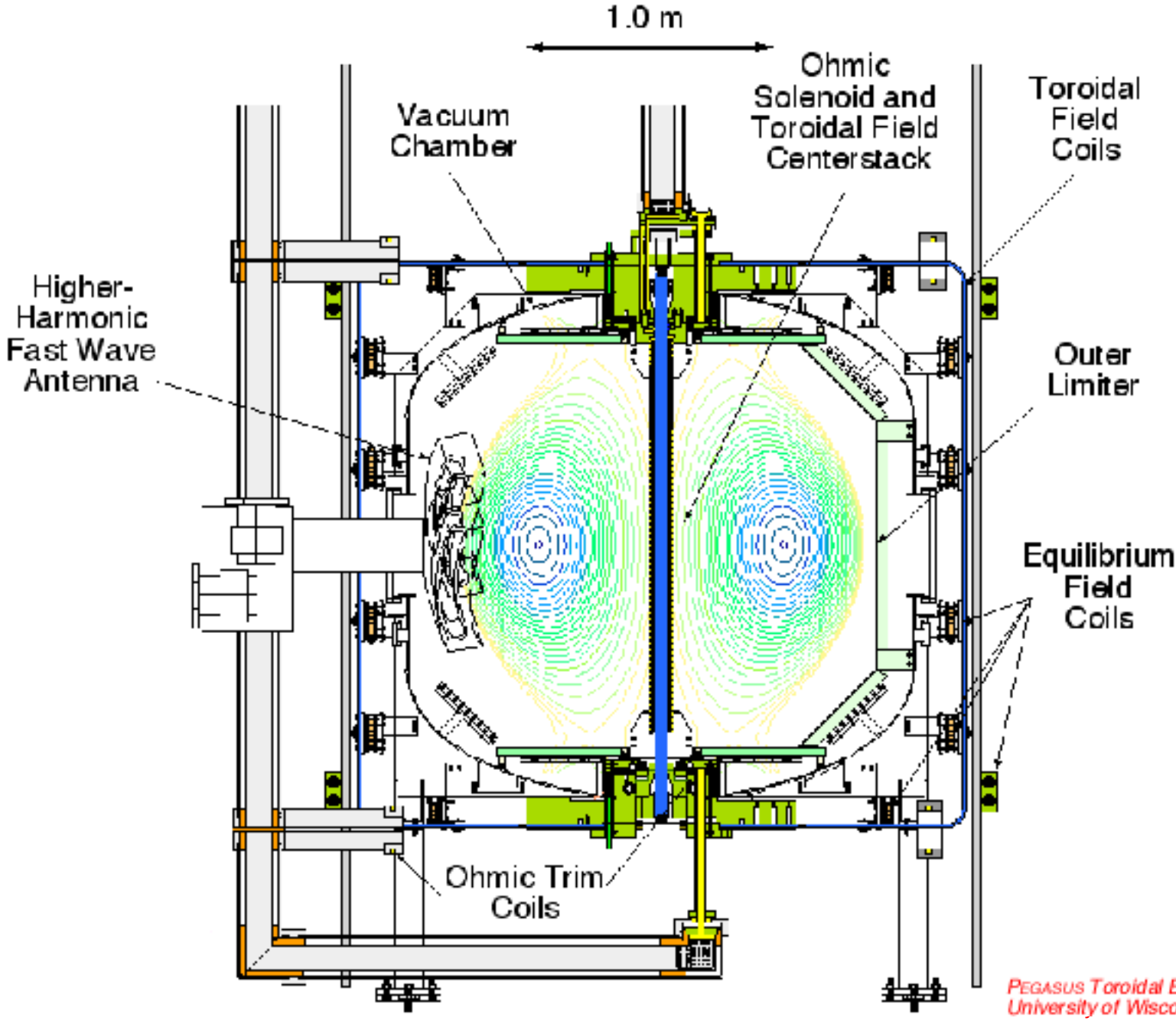
- Status
  - -Facility rebuild complete
  - -Programable power supplies in fabrication/assembly
  - -Power testing in progress

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



Path to high β_t and I_p/I_{TF}: mitigate early MHD

- $I_p > I_{TF}$ regime accessed via suppression of tearing modes

  - Ohmic plasma: $I_p > I_{TF} \Rightarrow$ high β_t, low q

- Approaches and tools to increase I_p/I_{TF}

  - Transiently increase q during startup
    = $B_t(t)$

  - Manipulate current profile
    = V_{loop} control
    = position/shape control
    = $B_t(t)$

  - Reduce η before low-order rationals appear
    = V_{loop} control
    = position/shape control
    = RF heating (HHFW)

PEGASUS Experiment has Undergone a Major Upgrade Phase

- Major Laboratory Reconfiguration
  - Facility damaged in fire following power diode failure
  - -Proposed upgrades frontloaded to single major upgrade phase
  - 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 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 bundle installed for establishing higher B_T (3x) and allowing rapid current ramping capability
  - Divertor coils added for activated separatrix operations
  - Compensation coils reduce stray fields in public areas
- Enhance Poloidal Field System that Includes Stray Field Reduction

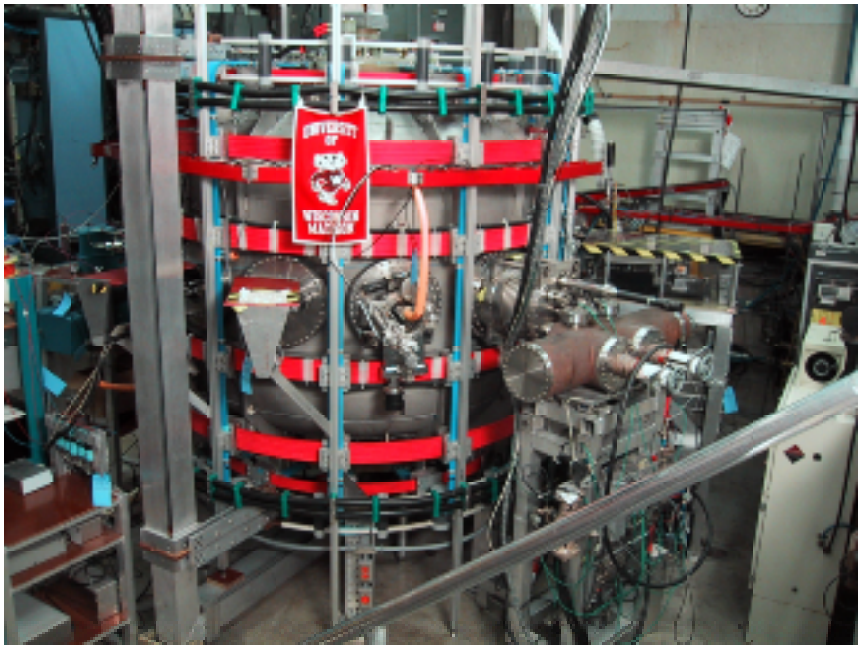
Overview of Pegasus Phase II upgrades

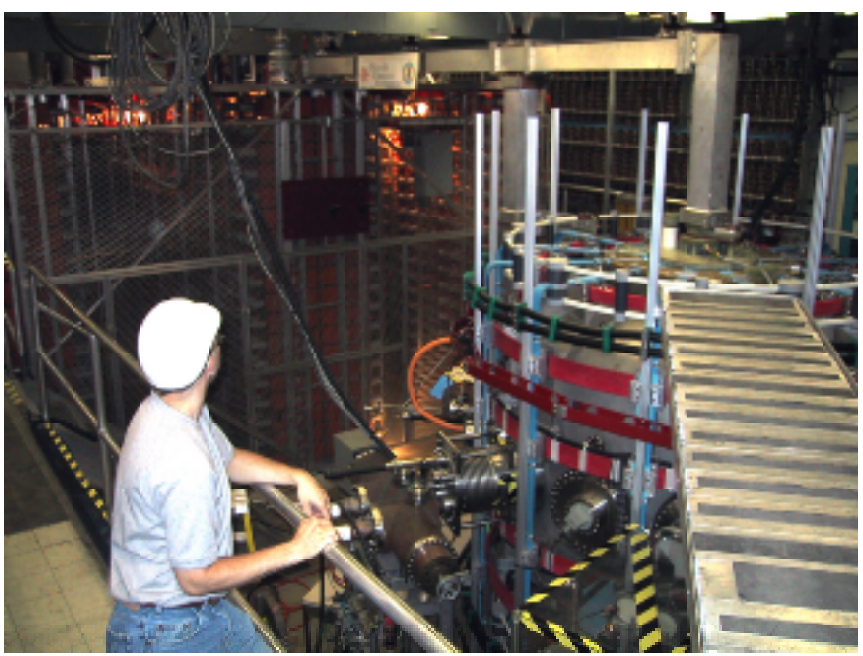
- Power supplies entirely replaced
  - Maximum coil currents increased significantly
  - Solid state switches (SPA's) make waveform control available
  - 6 MJ of electrolytic capacitors installed outside of building
  - New power buses installed
  - Stray field "flux catcher" installed for public safety

- Low-inductance toroidal field centerstack installed
  - Provides increased, time-variable TF

- Lab infrastructure improved or replaced
  - Shielded cable trays installed around lab feeding data to a Screen room
  - New grounding system installed
  - Control system upgraded
  - Bakeable gas system
  - Upgraded AC, air, and water services installed

Old PEGASUS Experiment Facility





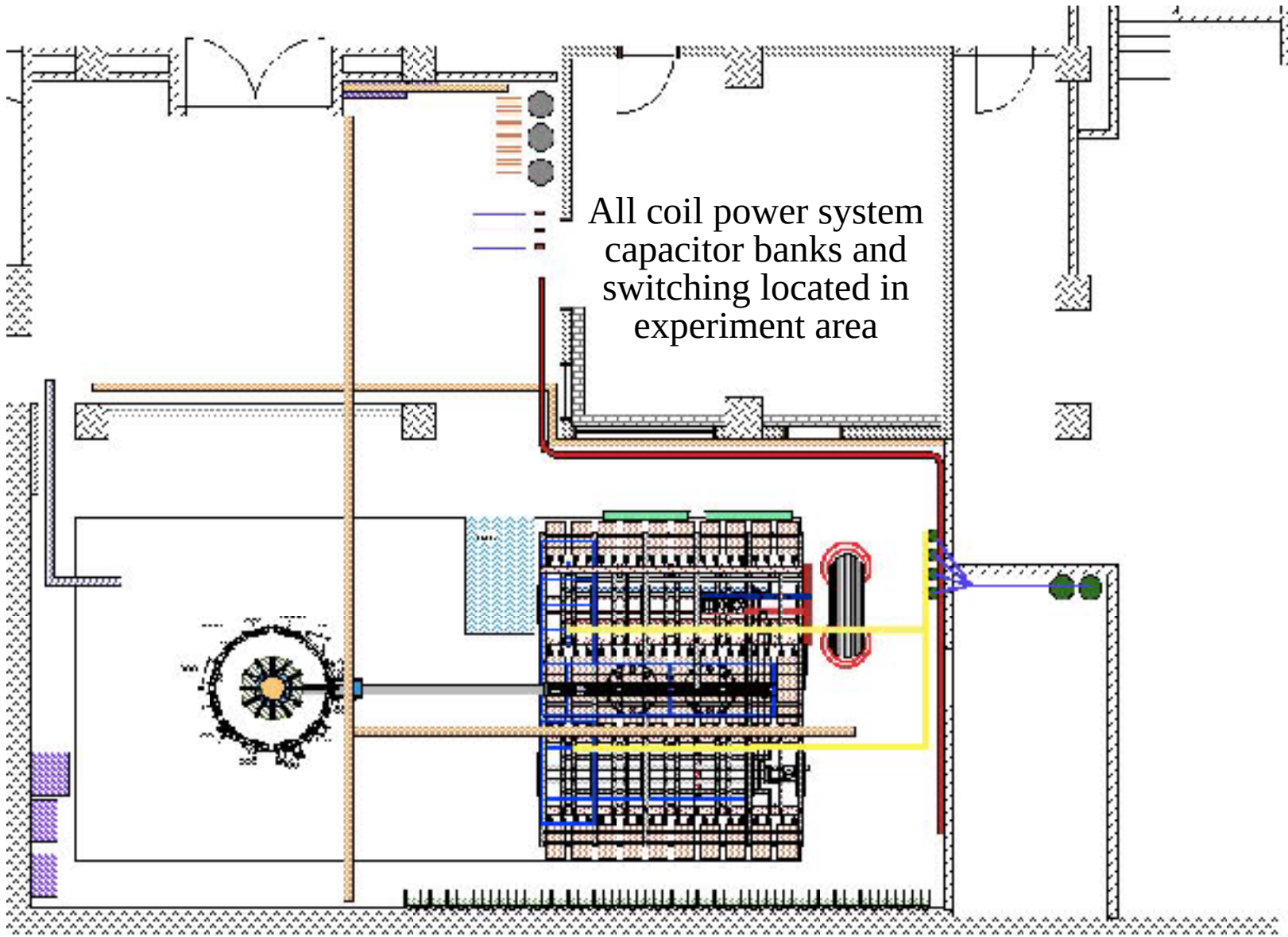
- Crowded Experimental Area

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

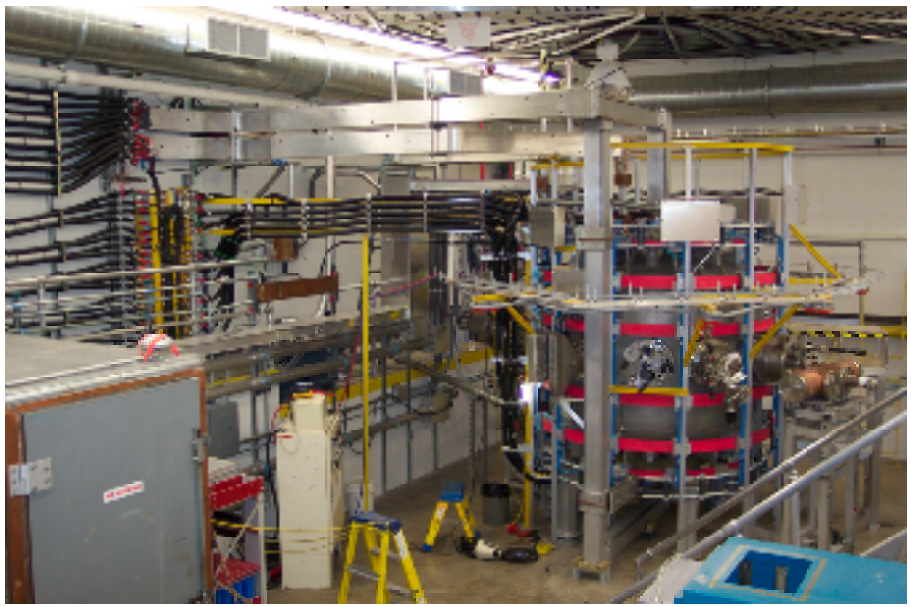
- Close proximity of power systems to each other and the machine experiment

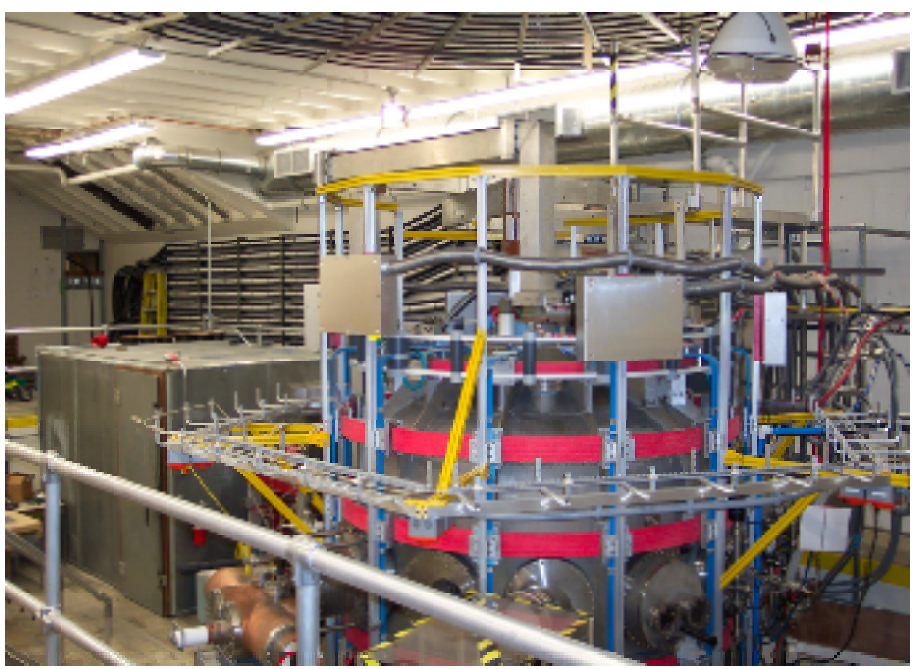
- Resonant systems required more stored energy and high power coupling components to give desired current waveforms

Old PEGASUS Experiment Facility



Present PEGASUS Experiment Facility





• Accessible Experimental Area

- No energy storage capacitor banks in experiment area

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

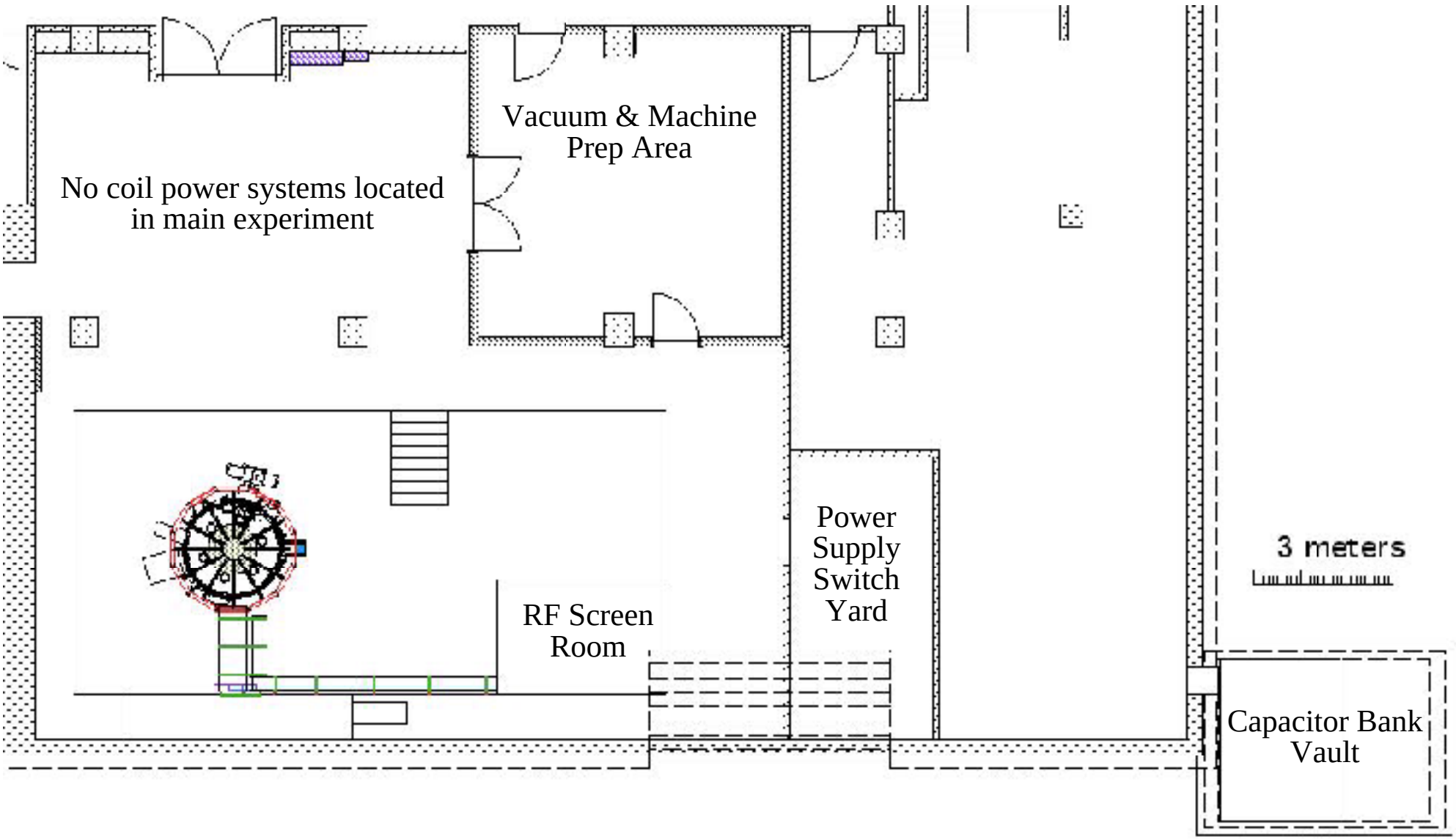
- Removed all outdated interference from past facility.

- 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.

Present PEGASUS Experiment Facility



Capacitor banks installed in exterior vault





All power supplies are being replaced/upgraded

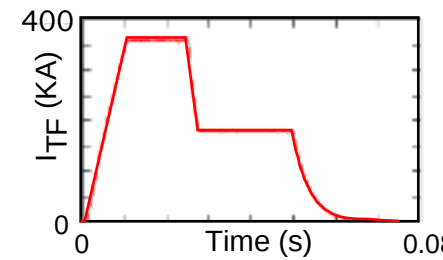
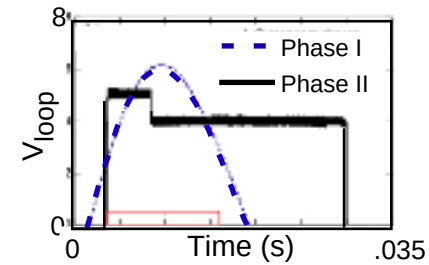
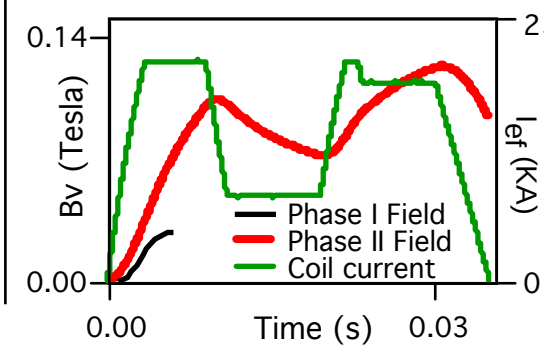
System	Phase I	Phase II	Example
Toroidal Field	• 60 turns • Quasi-DC • 150 kA-t max	• 12 turns • Fast time-variable • 450 kA-t max	
Ohmic Heating	• Half-sine Waveform • ±40 KA	• Programmable Waveform • ±50 KA	
Equilibrium Field	• Monolithic coil set • 2 Resonant banks • Waveform constrained by startup concerns • No divertor	• 5 Independent coils • Programmability • Evolution free from startup constraints • Divertor installed	



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

- All power now driven by solid-state IGBT and IGCT solid-state high power switches
  - Switches arranged in an H-bridge
  - <u>Many thanks to the **HIT** Group</u> for their assistance!

Pulse width Modulated (PWM) Switching Power Amplifiers

- Motivation

- 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

- Fault detection and interruption capability

- HIT group: CAMAC based, optically isolated PWM controller

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



Integrated Gate Commutated Thyristor

Eupec IGBT
Steady State - 900V@2.4kA



Insulated Gate Bipolar Transistor

Details of Coil Power Systems

- Ohmic Heating (OH)
  - Operates up to ±48kA @ 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 450kA 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

New TF Bundle and Waveform

• Motivation & Design

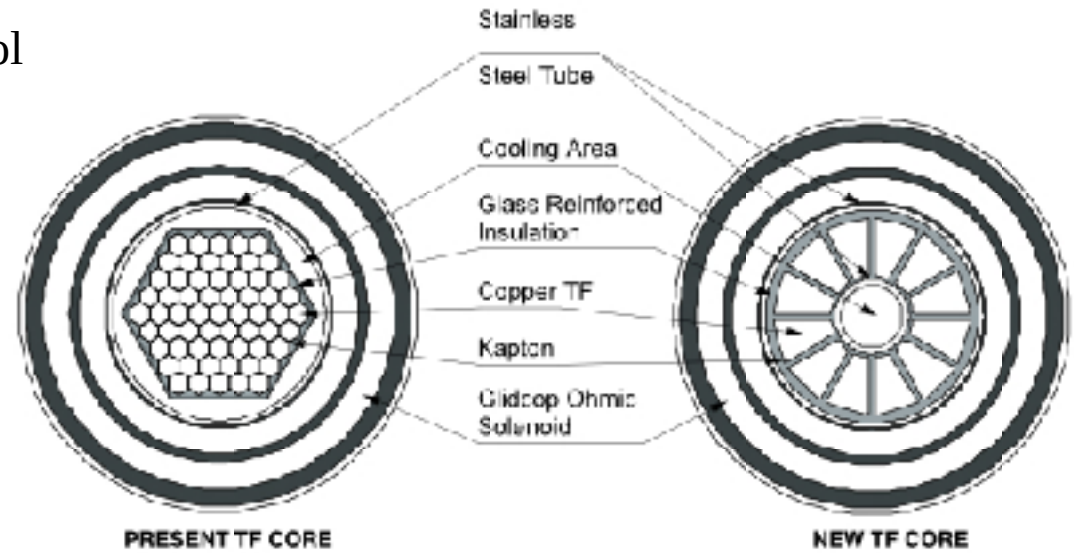
- High-TF for plasma startup and MHD control
- Rapid TF ramp down during shot to provide access to High-β_t, Low-q regime.

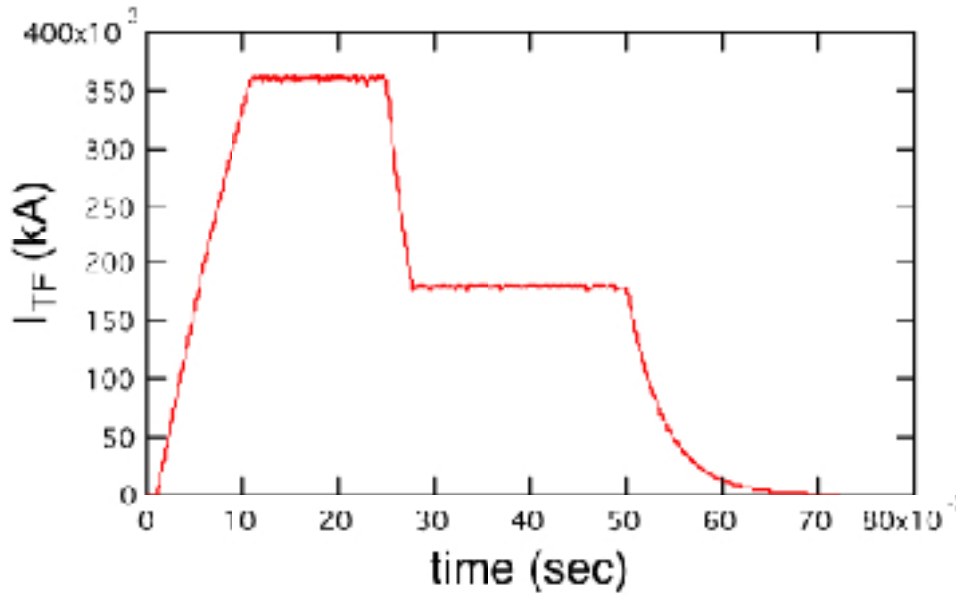
• New TF Bundle

- 12 turn low inductance allows~2-4 msec current ramp down during shot
- Installation without venting machine
- Allow access to high I_{TF} (up to 450 kA) rod current increased from Phase I (150kA)

• PWM IGBT Half-Bridge

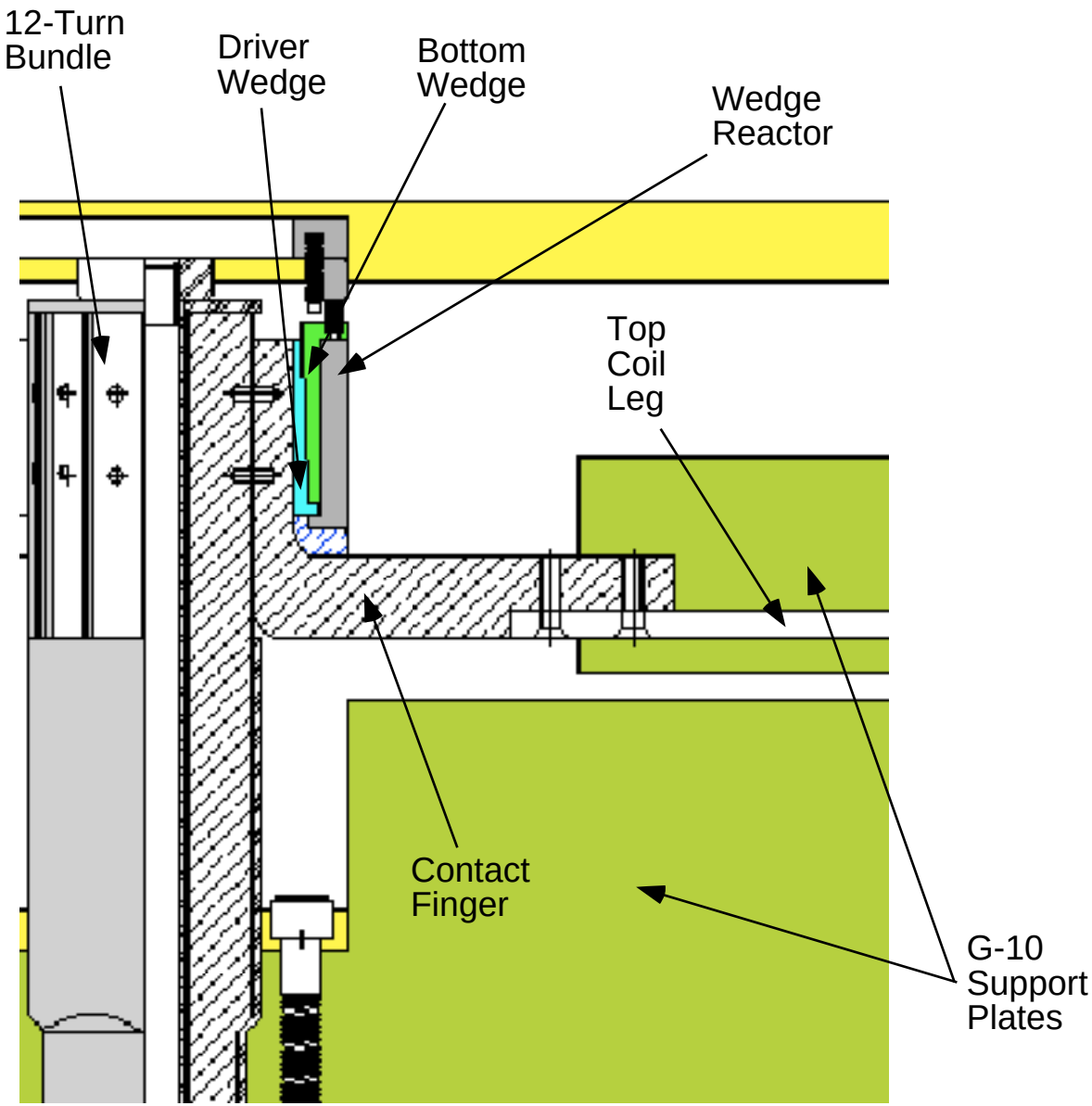
- 900V/584kJ Electrolytic Cap-Bank
- Two quandrant switching capability
- Switch capable of switching 900V @ 4800A at up to 10 kHz
- Feedback control via applied current
- H-Switch requires 4 modules each with 2 IGBTs per module





New toroidal field joint assembly is a critical area

Cross-Sectional Drawing (Top)

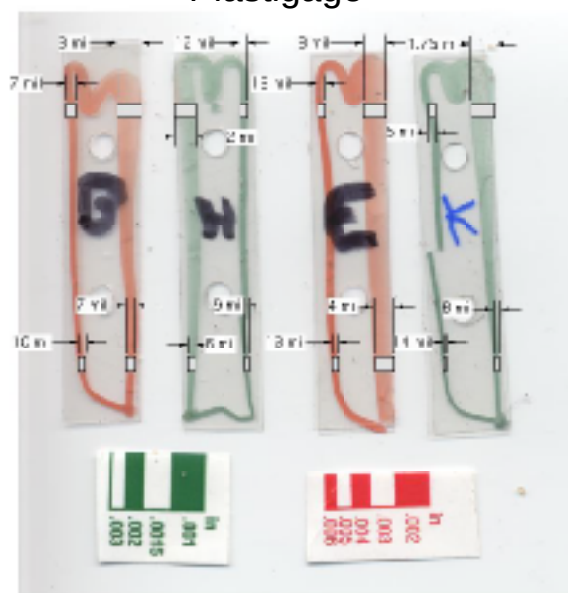


Fit-Check Diagnostics

Pressure Paper

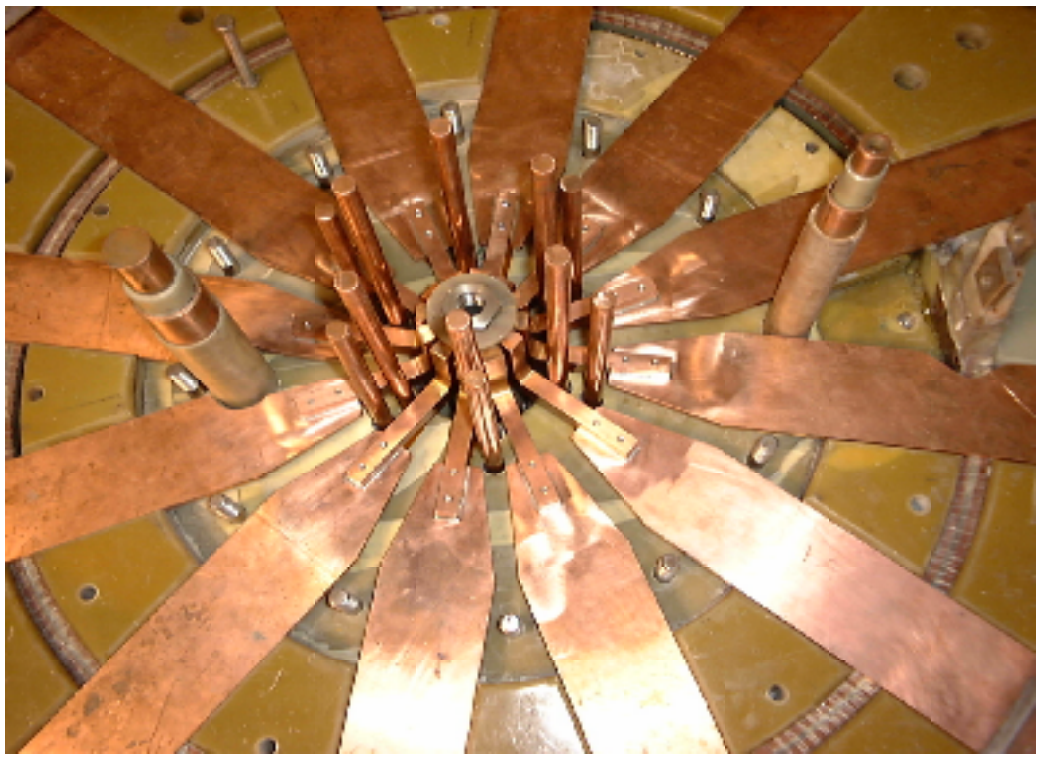


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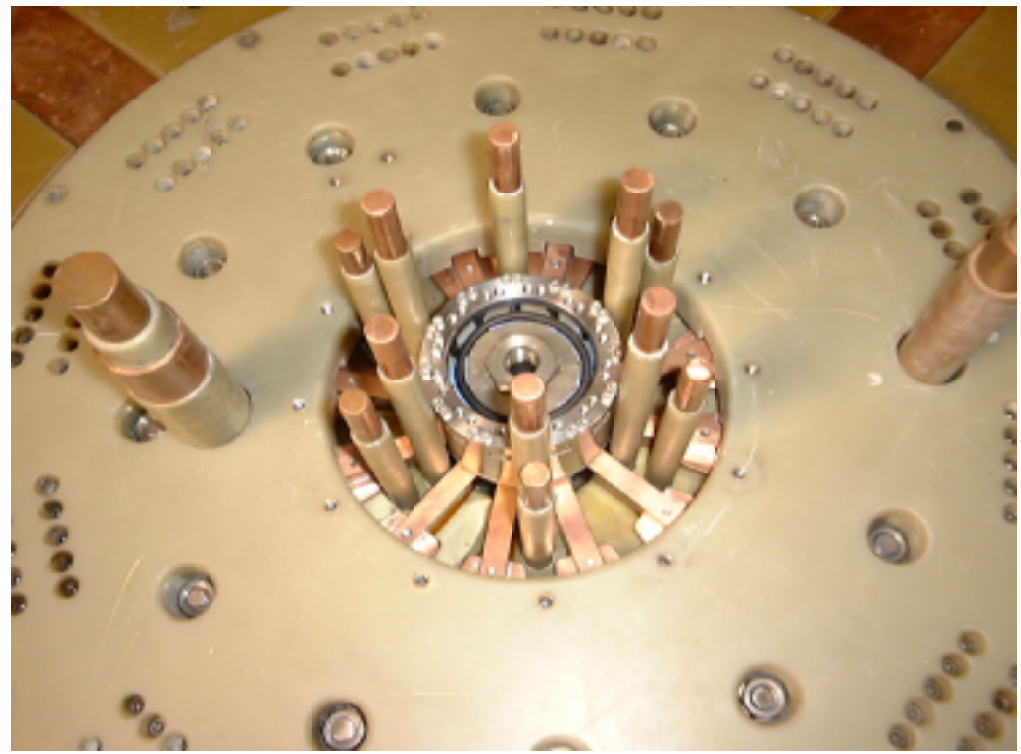


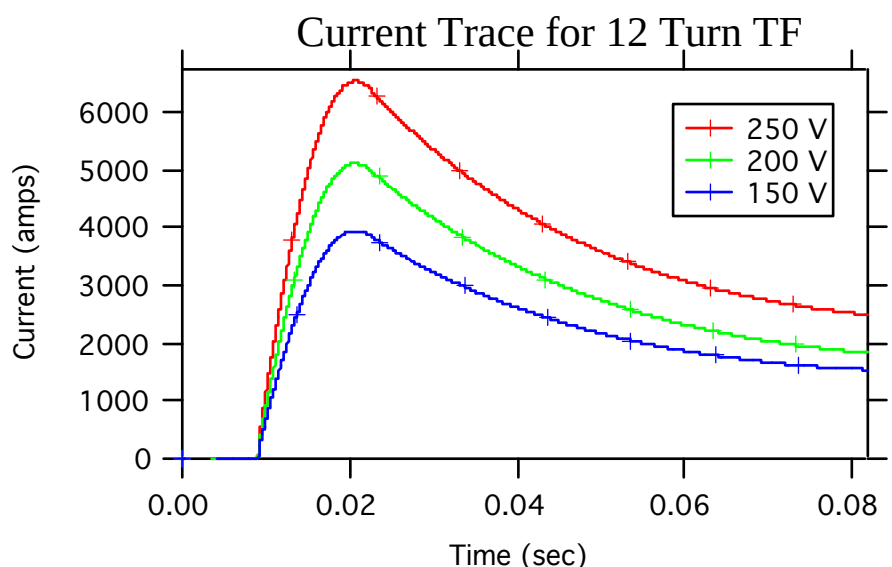
Toroidal Field Assembly and Power Testing

Bare TF Assembly



Fully assembled TF joint



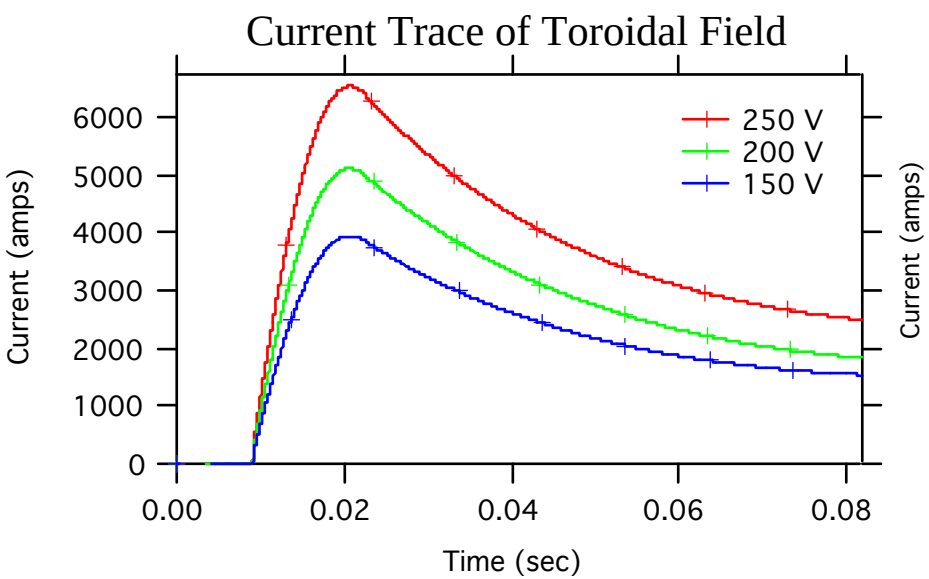


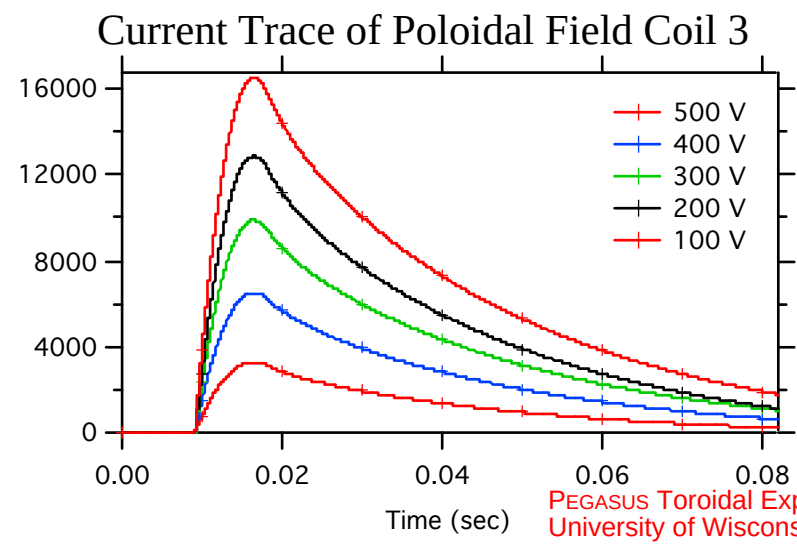
Status: Entering Power Testing and Shakedown



- Facility Construction **Complete** (infrastructure)
  - -New high Current bus work
  - -New bakeable gas system
  - -New control system
  - -New shielded signal system
- Machine under Vacuum
- Internal diagnostics operational
- External diagnostic installation ongoing
- Programmable Power Supply Switches coming online
  - -First Test in November/December
  - -Full expansion through January/February

- New Toroidal and Poloidal field joints assembled and testing in progress





Summary

- Major laboratory reconfiguration essentially complete
  - All major energy storage capacitor banks relocated to vault outside building
  - Improved diagnostic infrastructure to be ready for high power RF operations

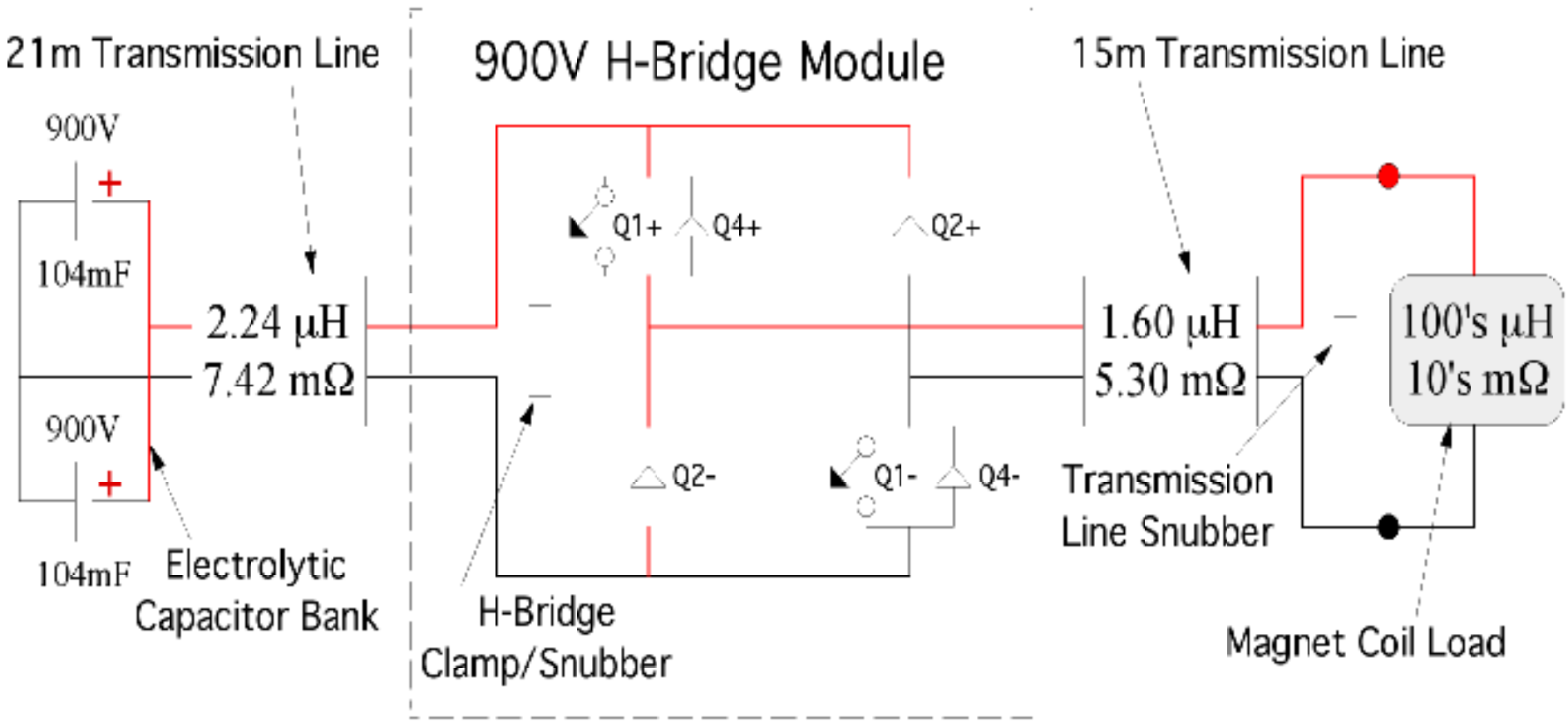
- New tools added to enhance study of plasma stability boundaries
  - Increased ohmic V-sec (2 - 2.5x) and control
  - Programable independent equilibruim field coils for shaping and position control
  - Low inductance toroidal field assembly
  - Divertor coils for separatrix operations

- 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

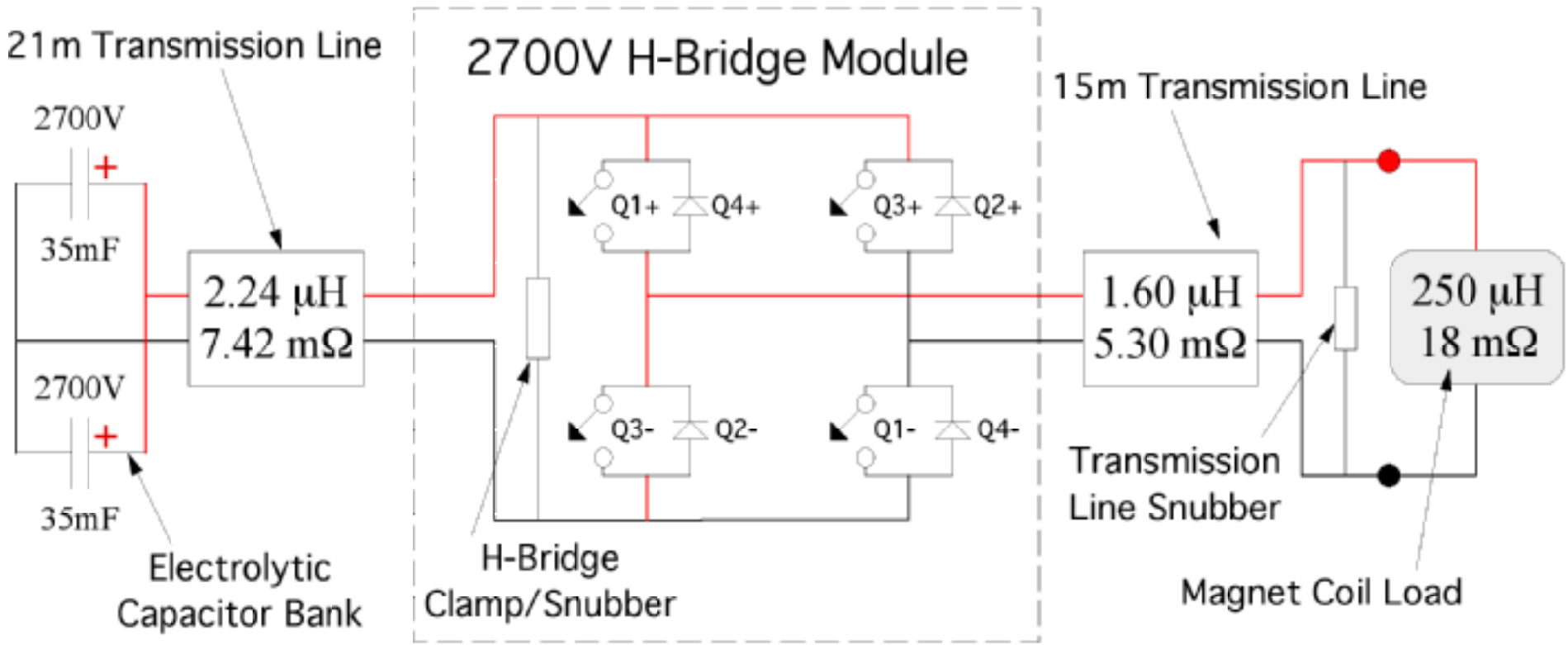
PEGASUS 900V 2-Quadrant H-Bridge System

- Unipolar power systems for EF, Div, and TF coil sets
  - Use lower power IGBT switchs (900 V, 4.8 kA)



PEGASUS 2700V 4-Quadrant H-Bridge System

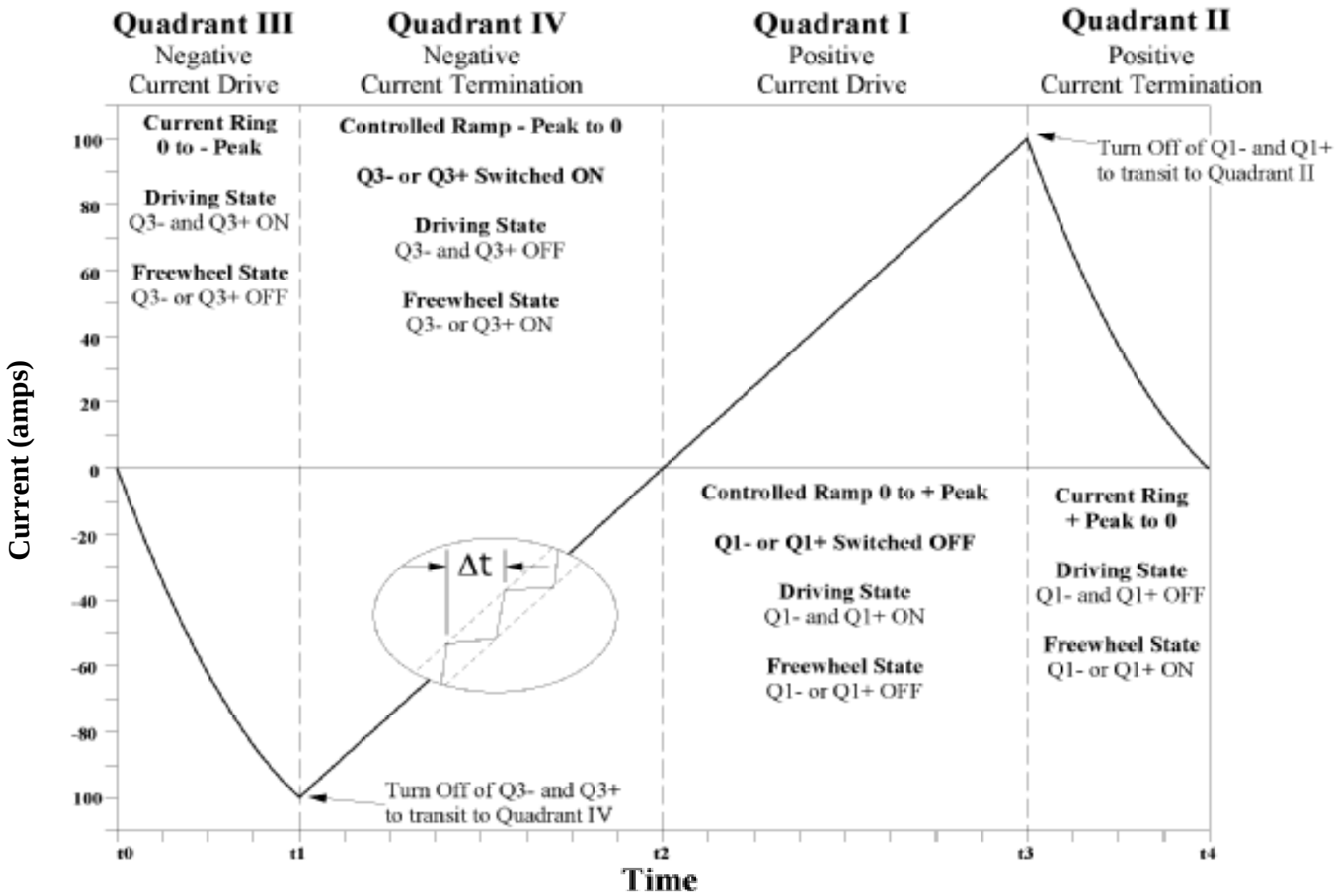
- OH solenoid system schematic for single H-bridge switch
  - -Full OH (±48kA) uses 12 in parallel
  - -Usea high power IGCT (2.8 kV, 4 kA)



- Similar, 900 V system with IGBT to drive single bipolar EF bias coils

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 unipole switch

