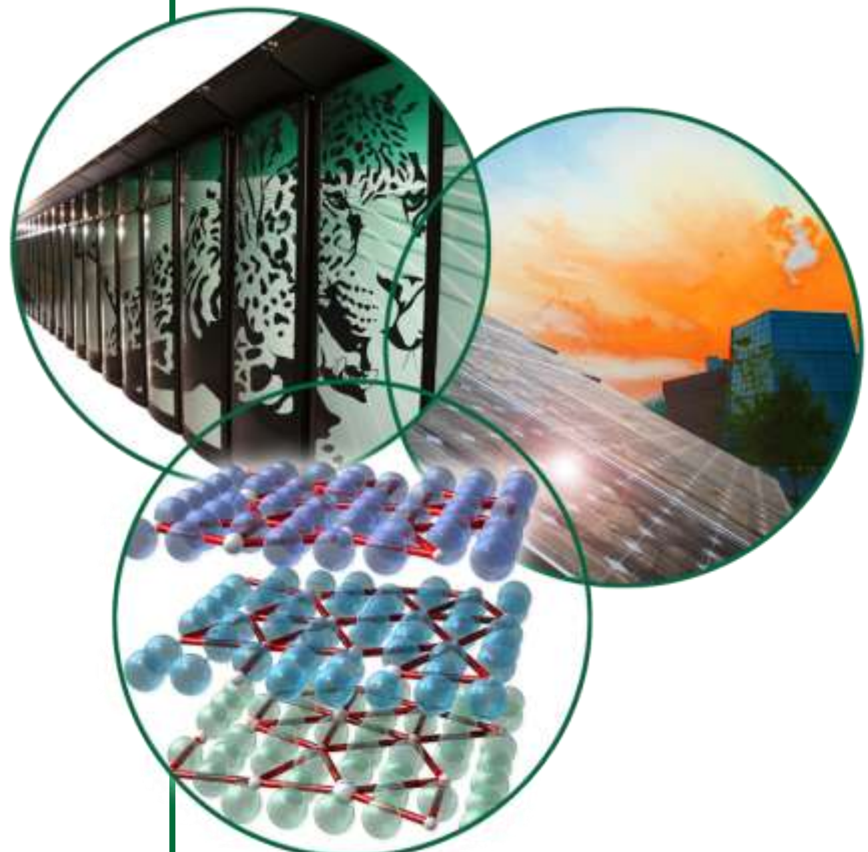
Linac Modulator Upgrades

David E. Anderson



U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY

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Outline

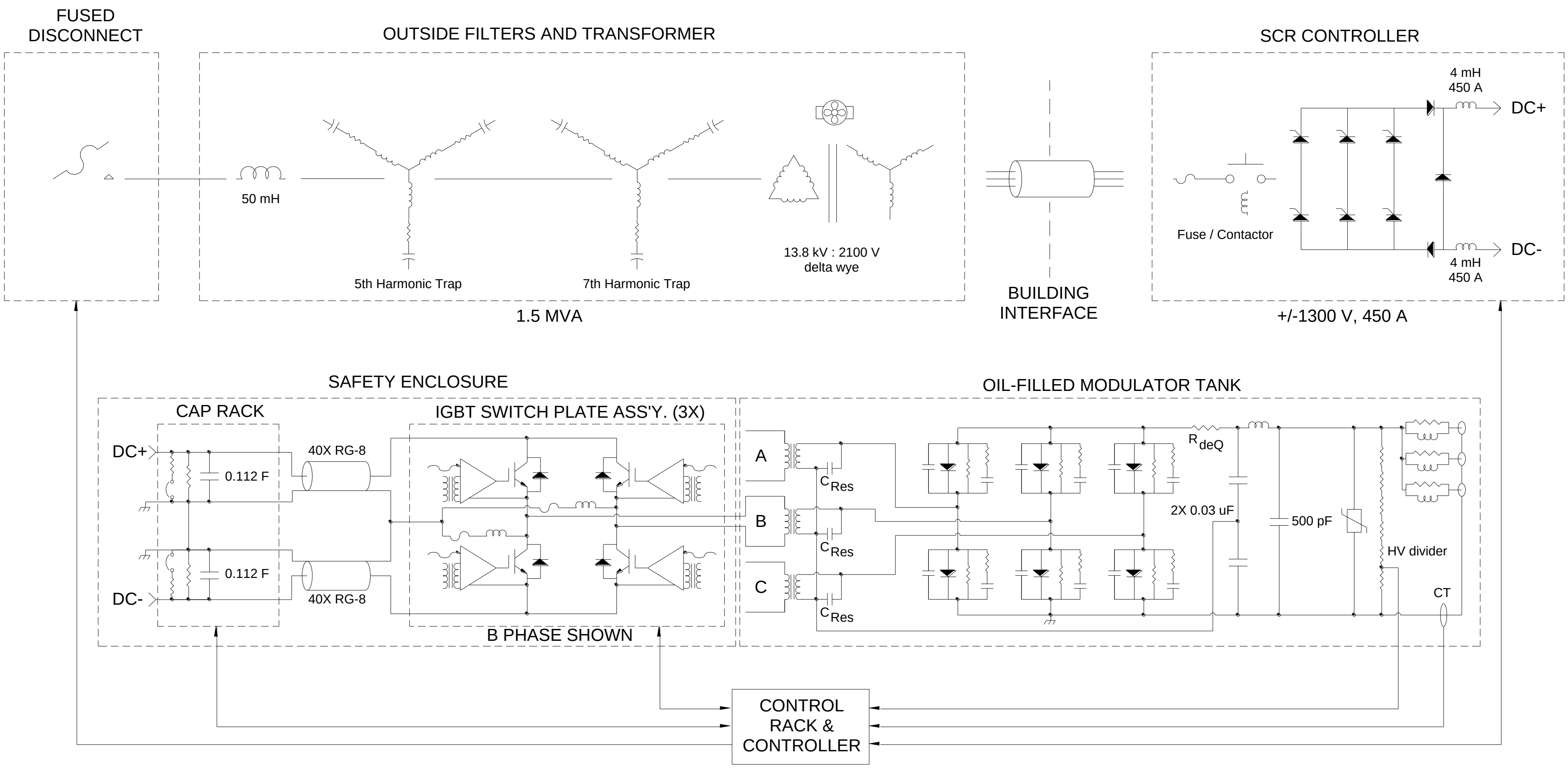
- System Overview
- Past Improvement Efforts – Highlights
- Present Development Efforts
- Planned Future Development Efforts
- Power Upgrade Project Plans and Implications
- Conclusion

High Level Operating Parameters

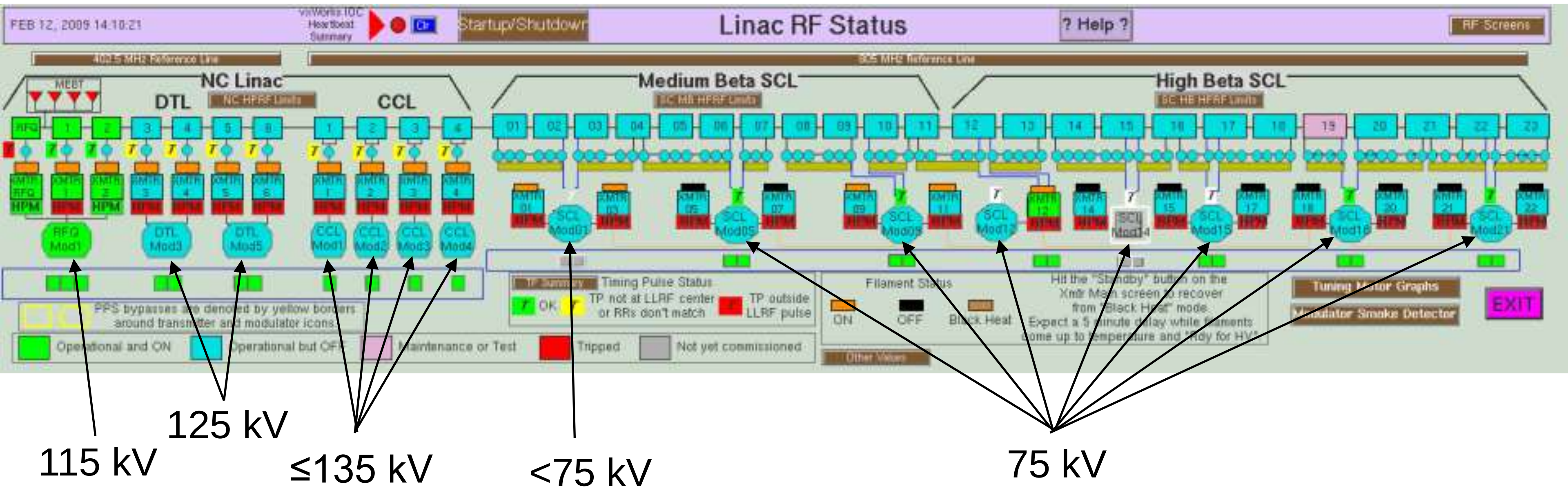
- Input line voltage: 13.8 kV, 60 Hz
- Pulsed output voltage: ≤140 kV[1]
- Peak output current: ≤130 A[1]
- Peak power: 11 MW
- Rated Average power: 1 MW
- Maximum pulse width: 1.35 ms
- Maximum pulse repetition frequency: 60 Hz
- IGBT switching frequency: 20 kHz
- Maximum IGBT bus voltage: 1300 V

[1]depending on klystron load and location of HVCM system, SCL systems typically run at 75 kV

HVCM Simplified Block Diagram



Cavity / Klystron / Modulator Layout



- Multiple HVCM/Klystron Configurations
- Peak Power 11 MW, Average Power 1 MW design

Upgrade Overview

- Initial focus was on the SCR Controller – brought in manufacturer but little help
- Several SCR upgrades implemented based on failure analysis and observed behavior – rapid improvement resulted
- Early modulator upgrades focused on magnetics & other in-tank components
- Switchplate fires followed quickly, shifted to caps, IGBTs and Safety Enclosure internal construction materials
- Implemented fire mitigation and extinguishing systems, fire response rate improved
- With recommendations from review committees, IGBT improvements and analysis of operational statistics, focus has shifted to power electronics, controller and component derating

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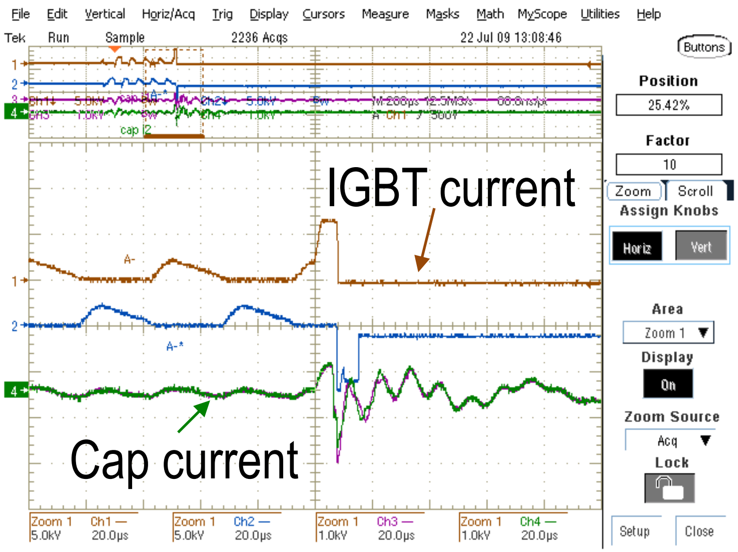
HVCM Modulator Upgrades AIP-02

- Higher duty cycle revealed system limitations, SCL IGBT commutation current issues
  - Retuned SCL resonant circuit parameters
  - Installed new magnetics
  - Installed Dynamic Fault Detection Chassis (DFDC)
    - Protects transformer saturation
    - Protects from dV/dt events
- New Rogowski probes show I_C
- Real time signal monitoring

HVCM Fires – Capacitor Replacement

- Cause of multiple fires, other failures from collateral damage
- Replacing capacitors w/ self-healing AVX units shown
  - 500 fault shots + ~1 year of ops on 12 units and largest $\Delta C \approx 0.2\%$



- Self-clearing = no catastrophic failures, no collateral damage

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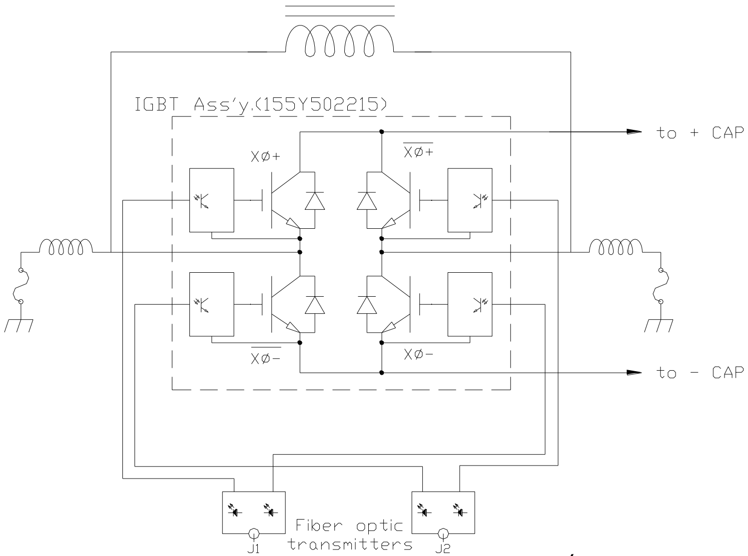
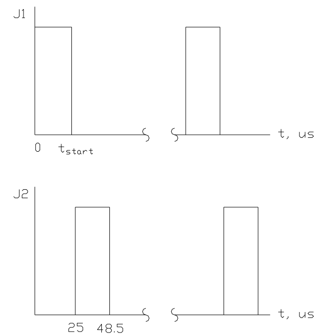
HVCM Development Resources

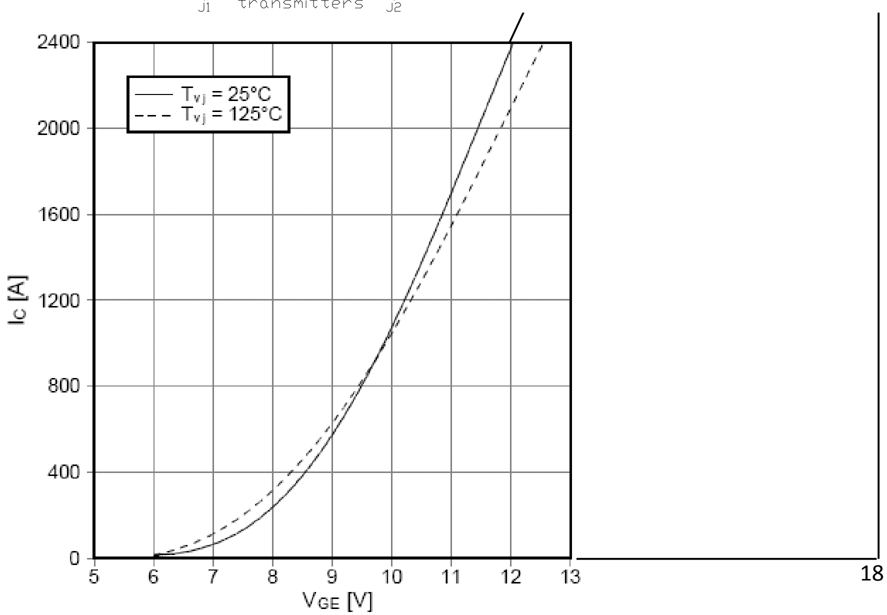
- Dedicated project under Neutron Facilities Development Division effective October 2008
- 3 engineers, 1 new position
  - David Anderson, Team Lead, System Engineer
  - Dennis Solley, specialization in Power Electronics
  - Mark Wezensky, specialization in Control of Electronic Systems
- 2-3 matrixed technicians
  - 1 operating test stand, 1 developing electronic systems, 1 PCB designer
- Help from SLAC team

- HEBT Beamstick Load Test Stand
  - Emulates SCL modulator
  - Dedicated to HVCM Development
- RFTF available (DTL/CCL)
- Installing SLAC Single Phase Test Stand

HVCM Existing IGBT Gate Drive Concerns

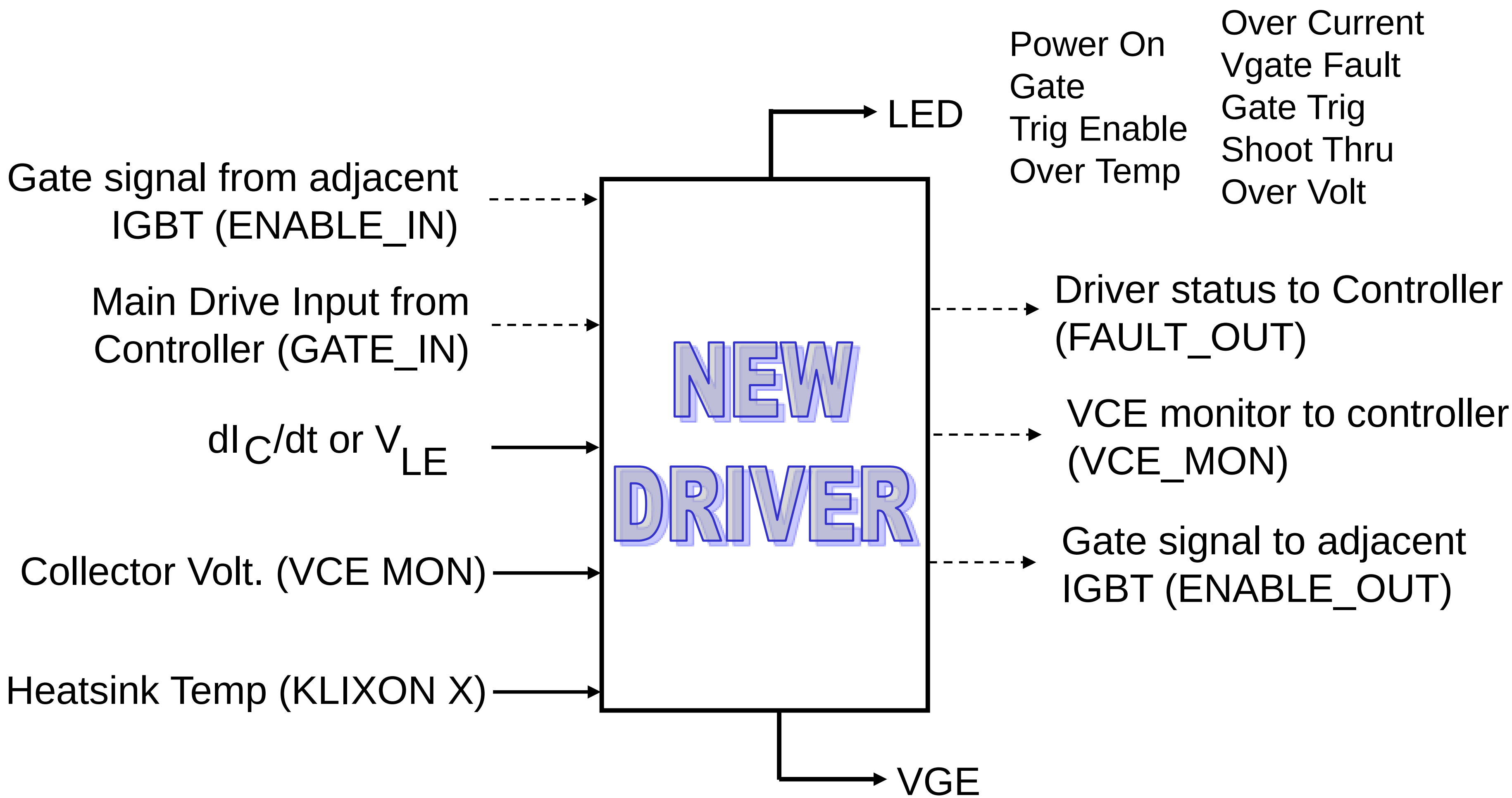




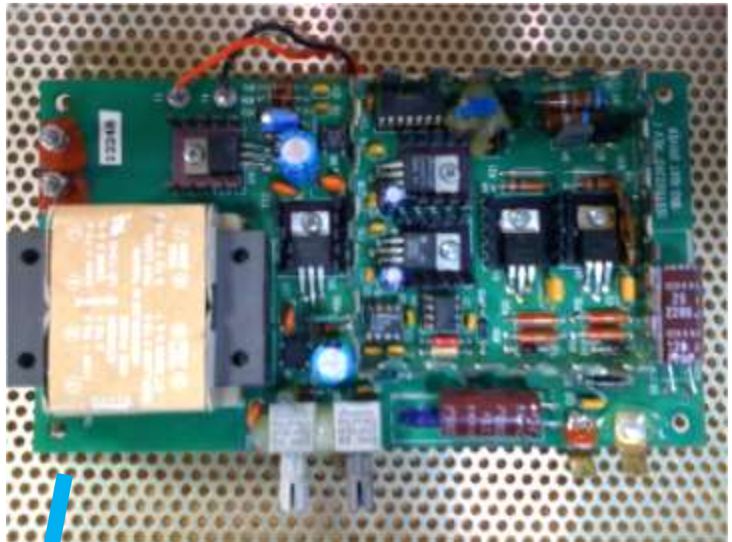


- Severe overdrive increased saturated current levels
  - Fault currents higher
  - Carrier recombination time longer?
- Slow drift of electronic delays
  - Leads to timing skew
  - Leads to flux saturation
- No on-board IGBT fault detection / protection
- 120 V ac distribution safety concerns
- Insufficient isolation derating for operating voltages
- Poor EMI shielding
- Interface w/ new controller

New Gate Driver Improvements

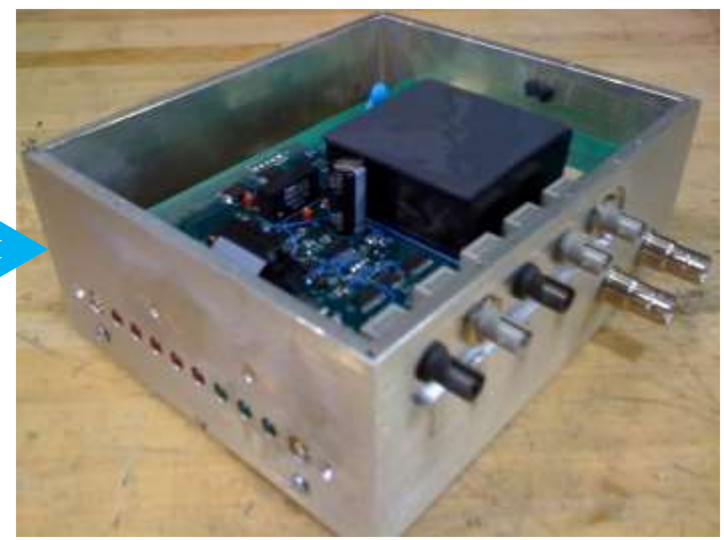


IGBT New Gate Drive Card Evolution



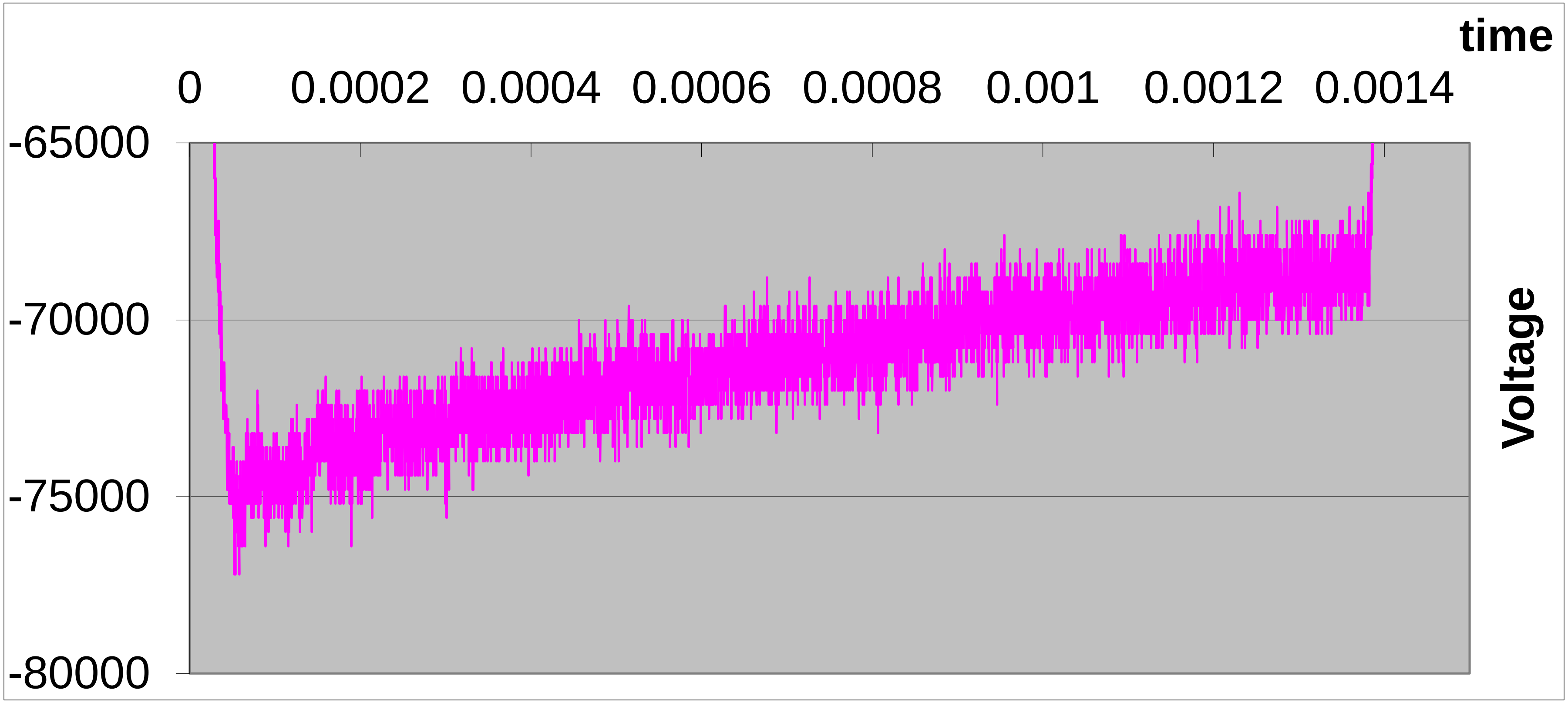
Original LANL Driver

Original SLAC Driver



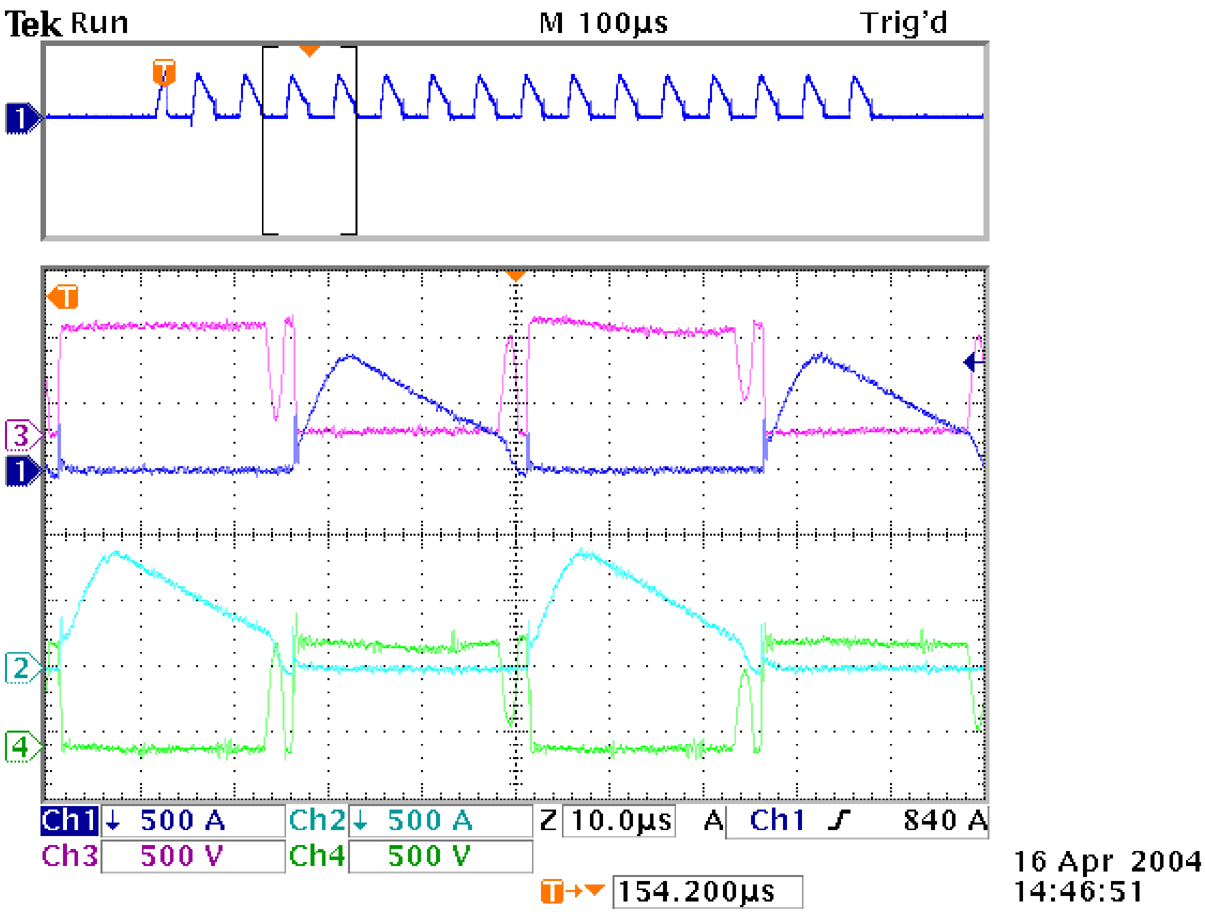
First Article ORNL Driver

Modulator Droop Problem



- Example of SCL-Mod1 Output Voltage Waveform
- ~8.3% droop over 1.35 ms pulse width
- RF power reduction at end of pulse

Pulse Droop Compensation

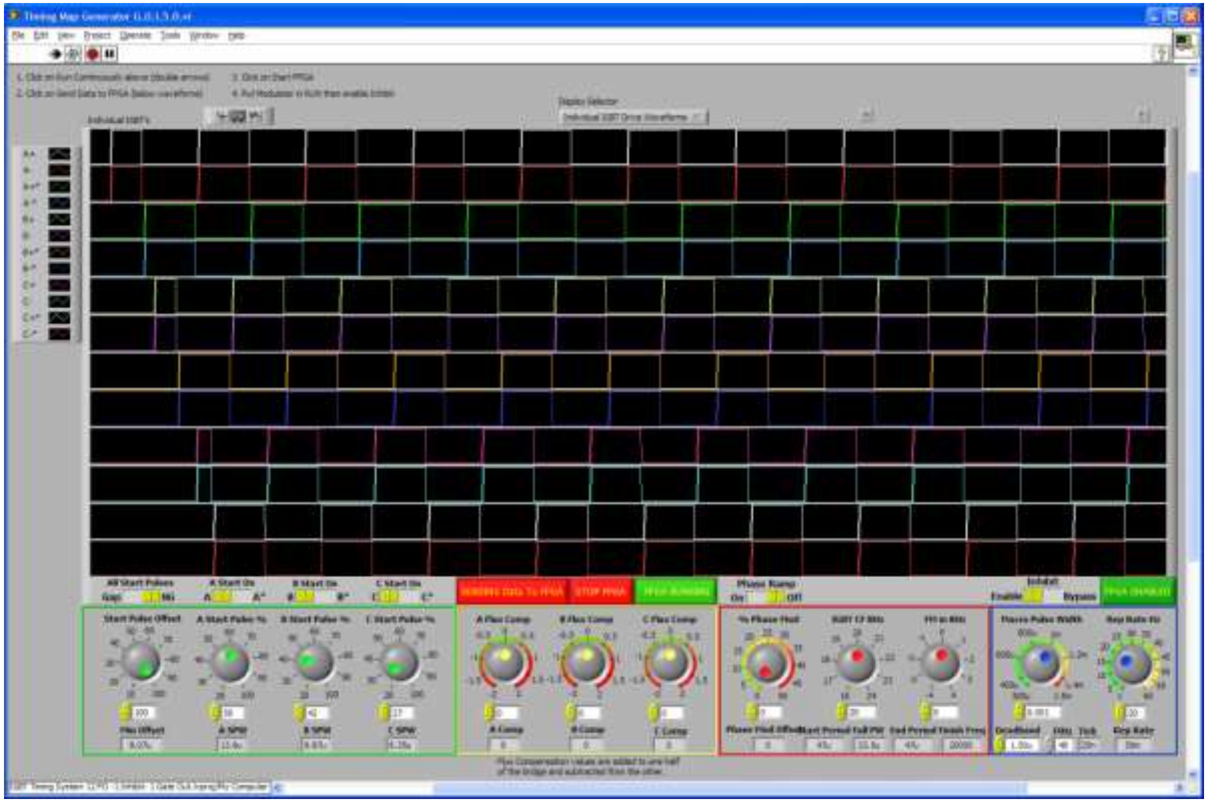


69 kV "phased back" – PWM doesn't work

•Turn-off switching losses too high in initial tests

•Oscillations with device capacitance make constant dead band desirable

New Controller Development



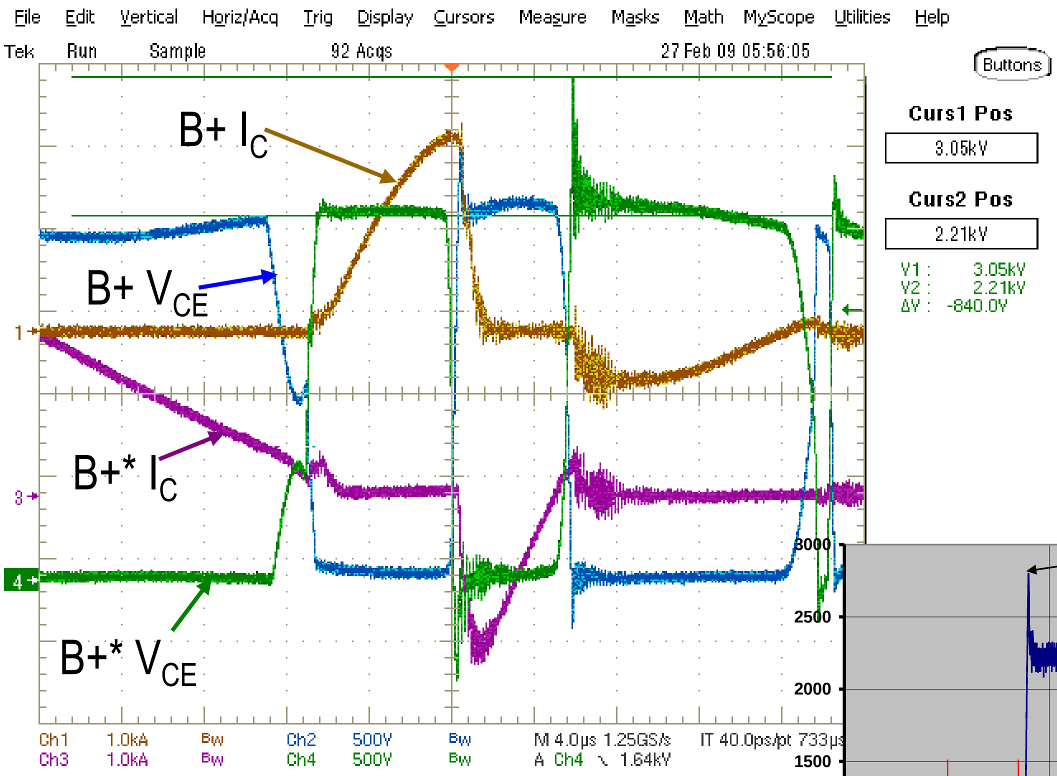
- LabView / FPGA based development system for IGBT timing pulses
- Start pulse adjustment capability
- Flux Compensation feature
- Phase shift & frequency adjustment capabilities
- Presently characterizing IGBT performance under different conditions

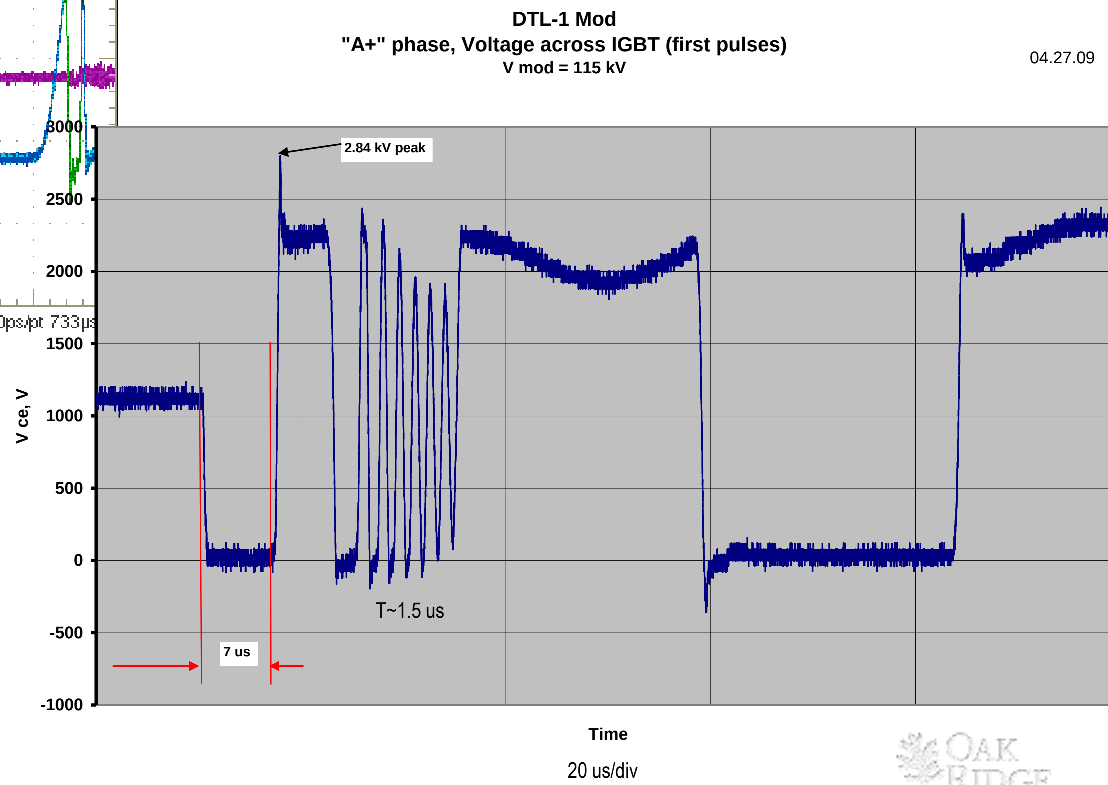
New Controller Functionality & Path Forward

- Integrates several existing chassis & provides additional monitoring, including first fault capture
- Provides data capture, logging, and EPICS retrieval
- With new driver, provides auto. gate timing corrections & monitors IGBTs
- Provides pulse flattening, flux compensation, and drift correction
- Allows for 4 phase operation
- Modular and easily reconfigured
- Interim testing supported with reduced existing controller functionality

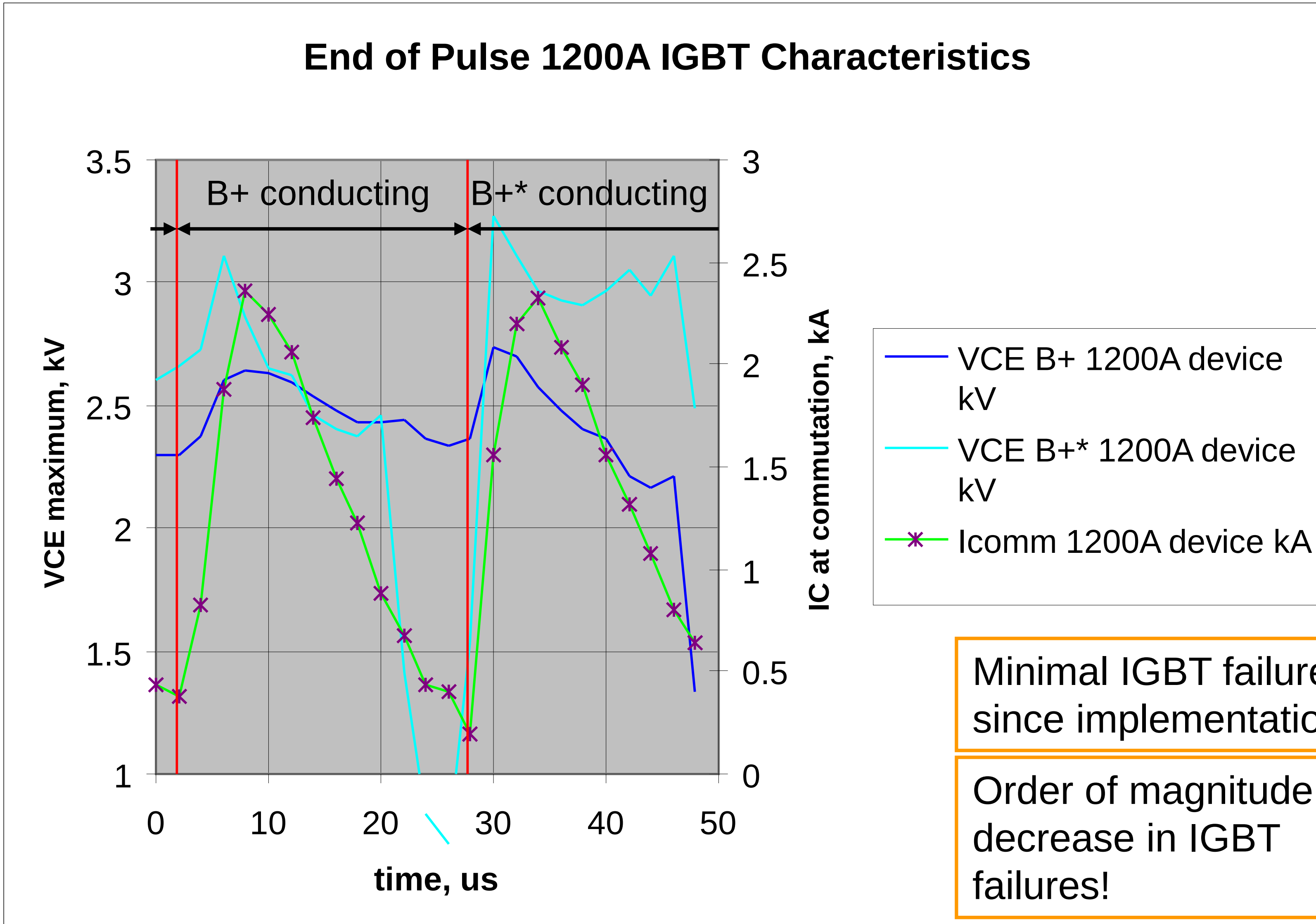
1. Freq. & Phase control developed
2. Develop IGBT fault handling
3. Develop analog hardware & code
4. Develop fiber interface
5. Develop digital I/O interface
6. Digital firmware
7. EPICS interface & code
8. Gate timing firmware
9. Modulation / feedback code
10. Integrated testing

Start & Finish Pulse IGBT Stress





End of Pulse Over Voltage



Minimal IGBT failures since implementation!

Order of magnitude decrease in IGBT failures!

In-tank Component Reliability

- Study of in-tank components revealed that several did not possess proper engineering de-ratings
  - Capacitors – dissipation factor resulted in thermal failure – estimated ~200 W dissipation, 100°C
  - De-Qing resistor – operating power exceeds rating
  - Divider capacitors – inadequate voltage rating
  - Connecting wires/cables – high current density
- Analysis based on PSpice simulations & device datasheets
- Redesign/replacement process started
- Test capacitors ordered from vendors, testing planned for thermal performance
- Major effort planned for upcoming Summer shutdown

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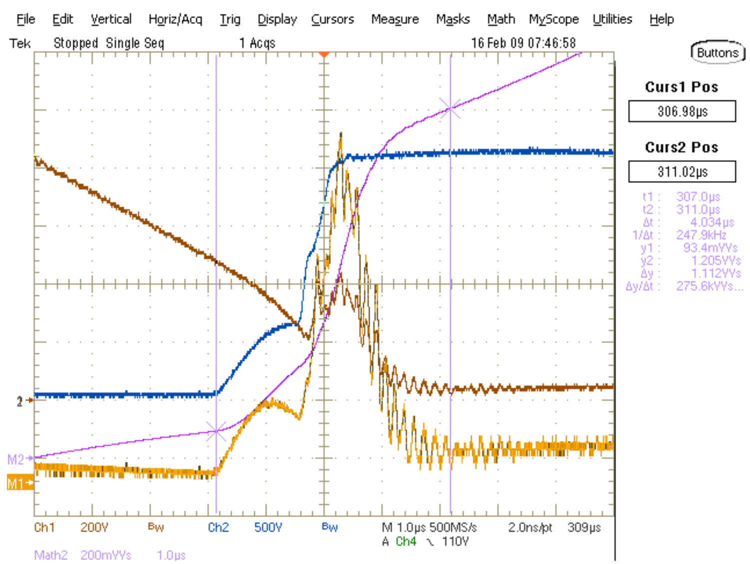
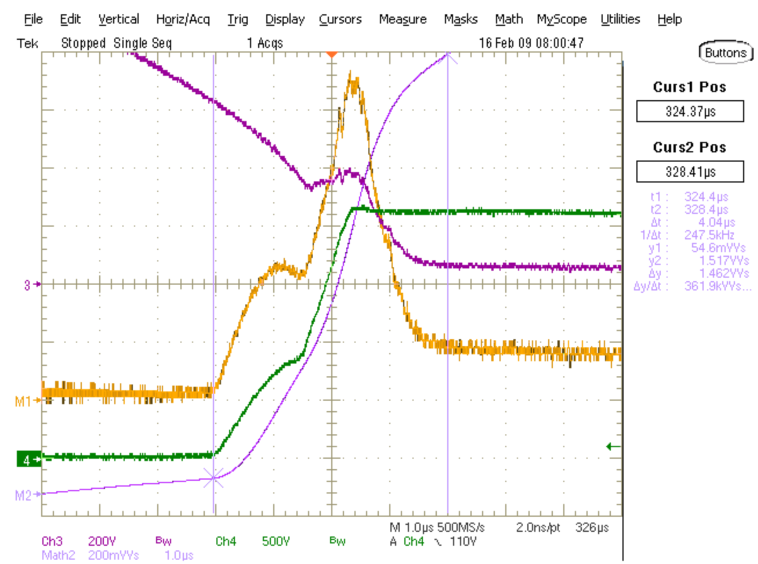
IGBT Alternate Solutions

- Existing 3300 V, 1500 A devices (Eupec/Mitsubishi)
  - ~30% higher switching losses, mainly at turn-off
  - Longer current tails at turn-off
  - Increased losses likely offset any reliability gains from higher current rating…
- Mitsubishi CM1200HG-90R 4500 V / 1200 A power module
- Westcode Press Pack 4500 V / 1200 A IGBT
- …more to come…

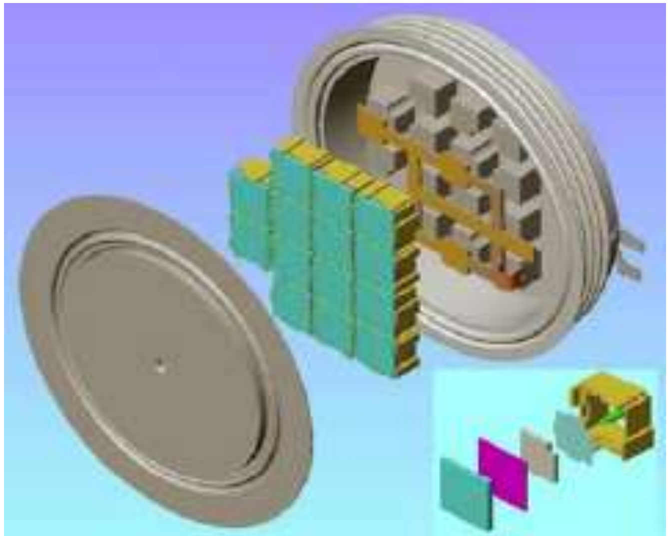


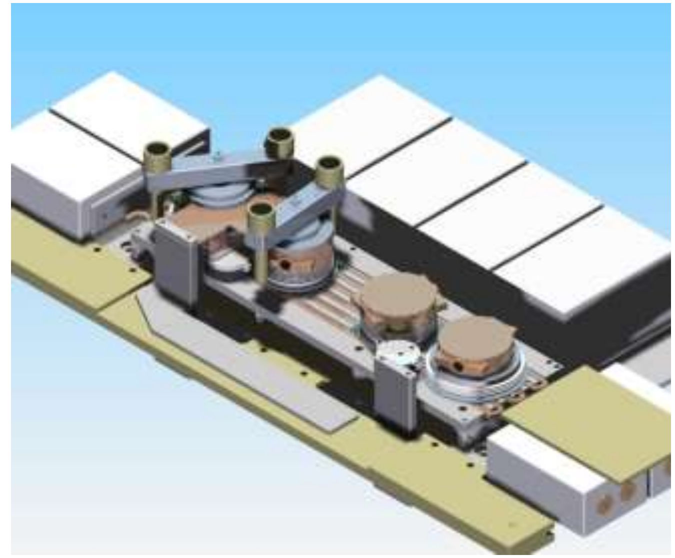
Eupec 1200 A



Eupec 1500 A

Next Generation IGBTs





Next-generation Press-Pac IGBT devices

- Higher voltage rating (4500 vs. 3300 V), higher current rated recently available
- External anti-parallel diode required
- Developed and peak power tested at SLAC and in testing at ORNL
- Under consideration for MTBF on RFQ HVCM, higher operating voltages on SCL modulators, ultimately PUP
- ~$40k semiconductors per modulator + switch plate mods and development costs

Initial Performance Comparison of 4500 V IGBTs

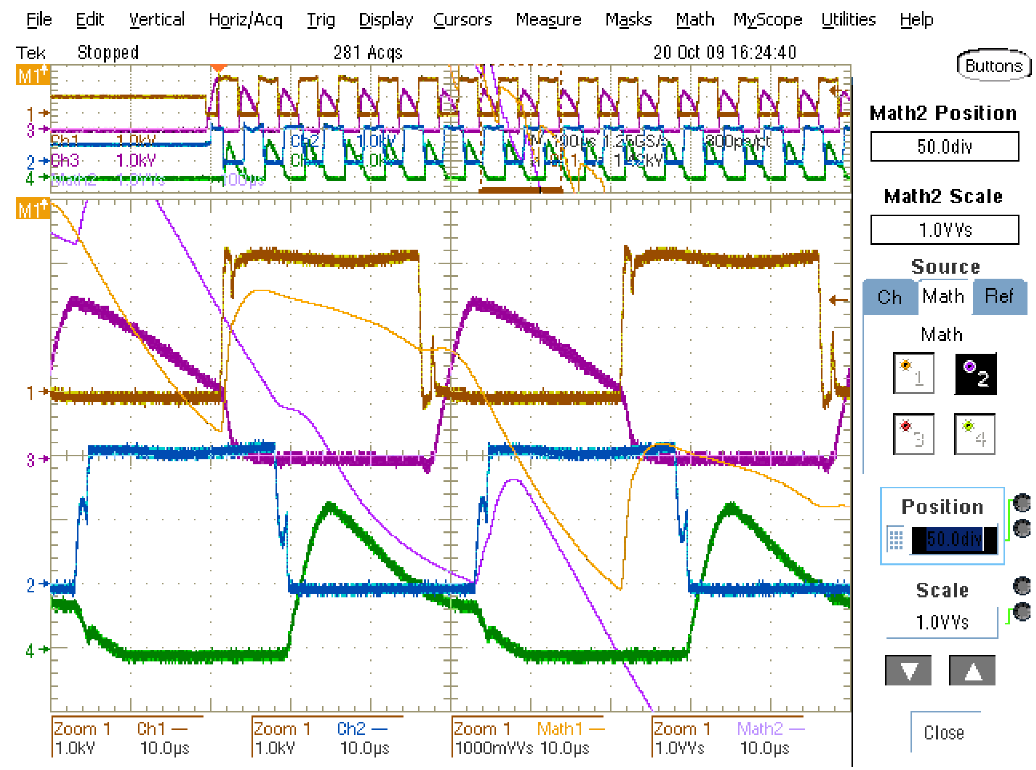
Calorimetry results (±1100 V, 71 kV, 1335 ms, 30 Hz):

Mitsubishi ‹P› = 2.1 kW

Westcode ‹P› = 1.8 kW

$E_{off,\,M}$ = 2.3 J, $E_{off,\,P}$ = 1.6 J

Long tail on Westcode



Ch. 1, 3: Mitsubishi 4500 V IGBT

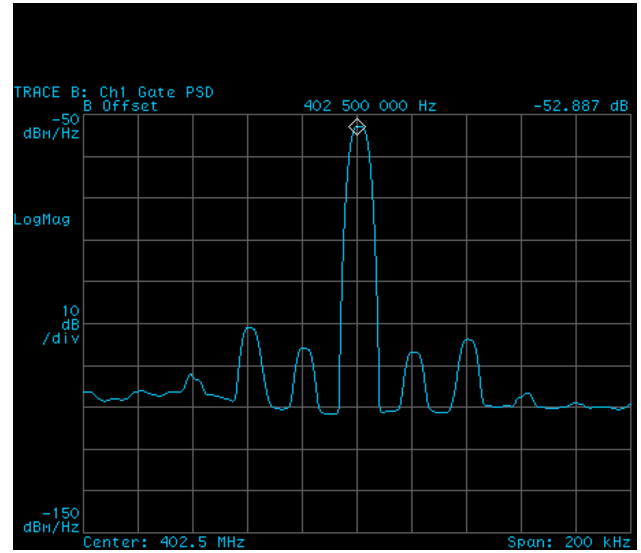
Ch. 2, 4: Westcode 4500 V IGBT

M1: Mitsubishi energy losses

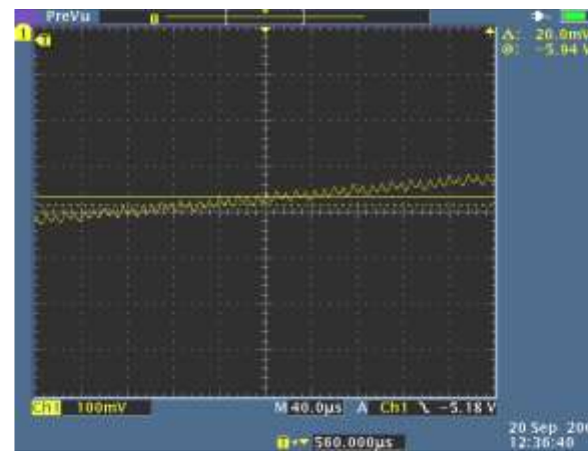
M2: Westcode energy losses

More work needed!

20/40 kHz Harmonic Filter for Ripple Reduction

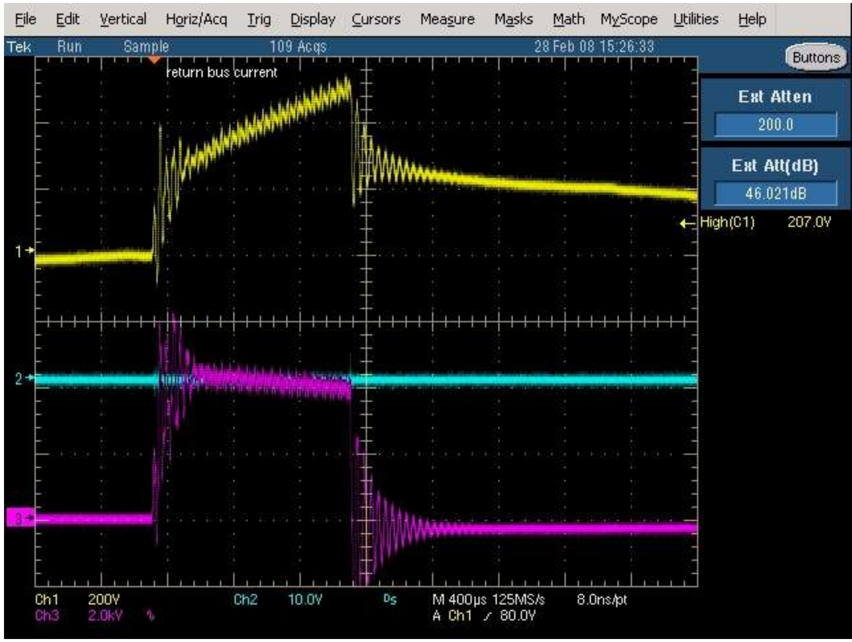


- 20/40 kHz Harmonic Filters on output section to reduce ripple
  - Factor of 2 improvement in ripple (0.33% p-p)
  - Design exists and tested on a DTL & CCL modulator



Additional Planned Development

1. Main energy storage cap bank fast disconnect switch
   - Minimize fault energy available at switch plate
   - Necessary to support possible redundant H-bridge in the future
   - Instrumentation already in place, developed at SLAC
2. External and redundant oil pumping
   – Eliminates long MTTR in event of water leak
   – Heat exchanger is contaminating DI water system so needs replacing
   – Faulty pump can be rapidly switched out of system and recovered quickly
3. Capacitor bussing improvements to eliminate current ringing
4. Improved IGBT Thermal mgmt.
5. 20/40 kHz Harmonic Traps on modulator outputs



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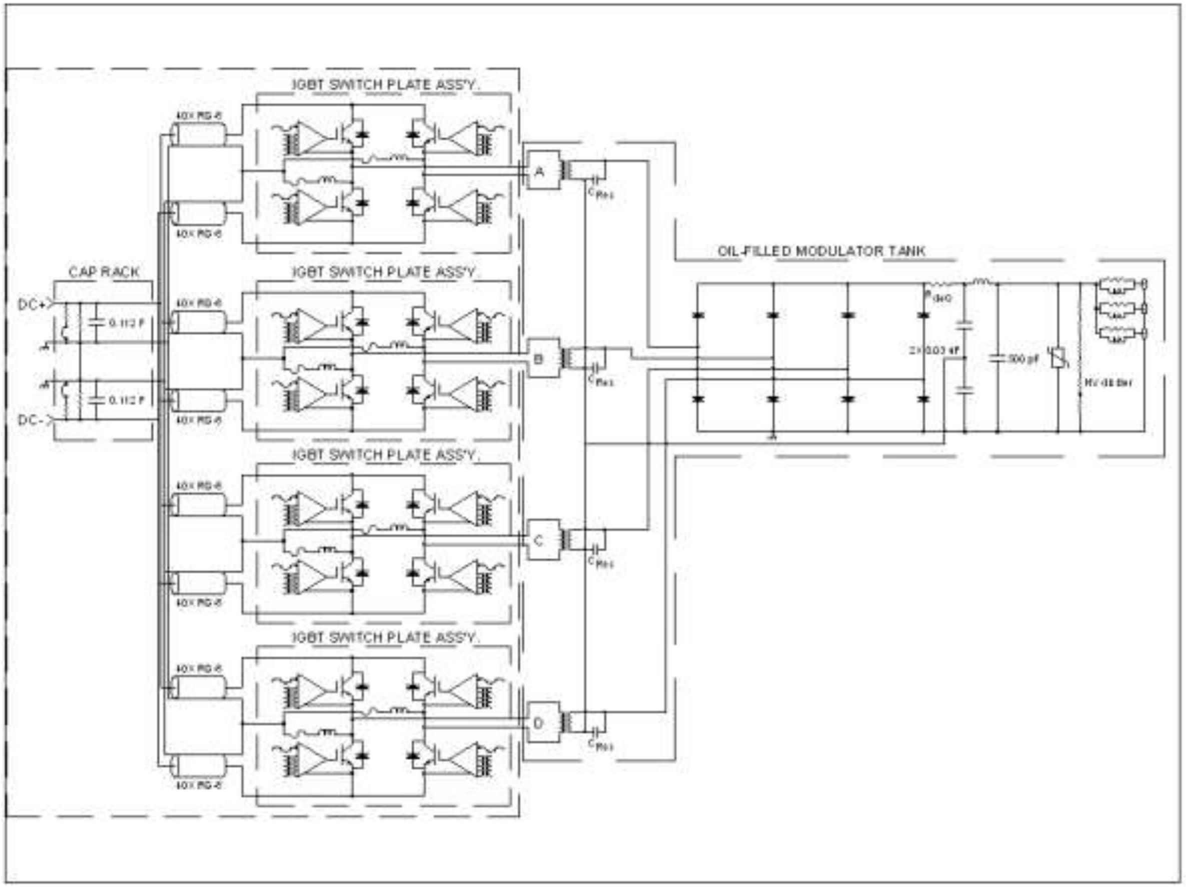
PUP Implications

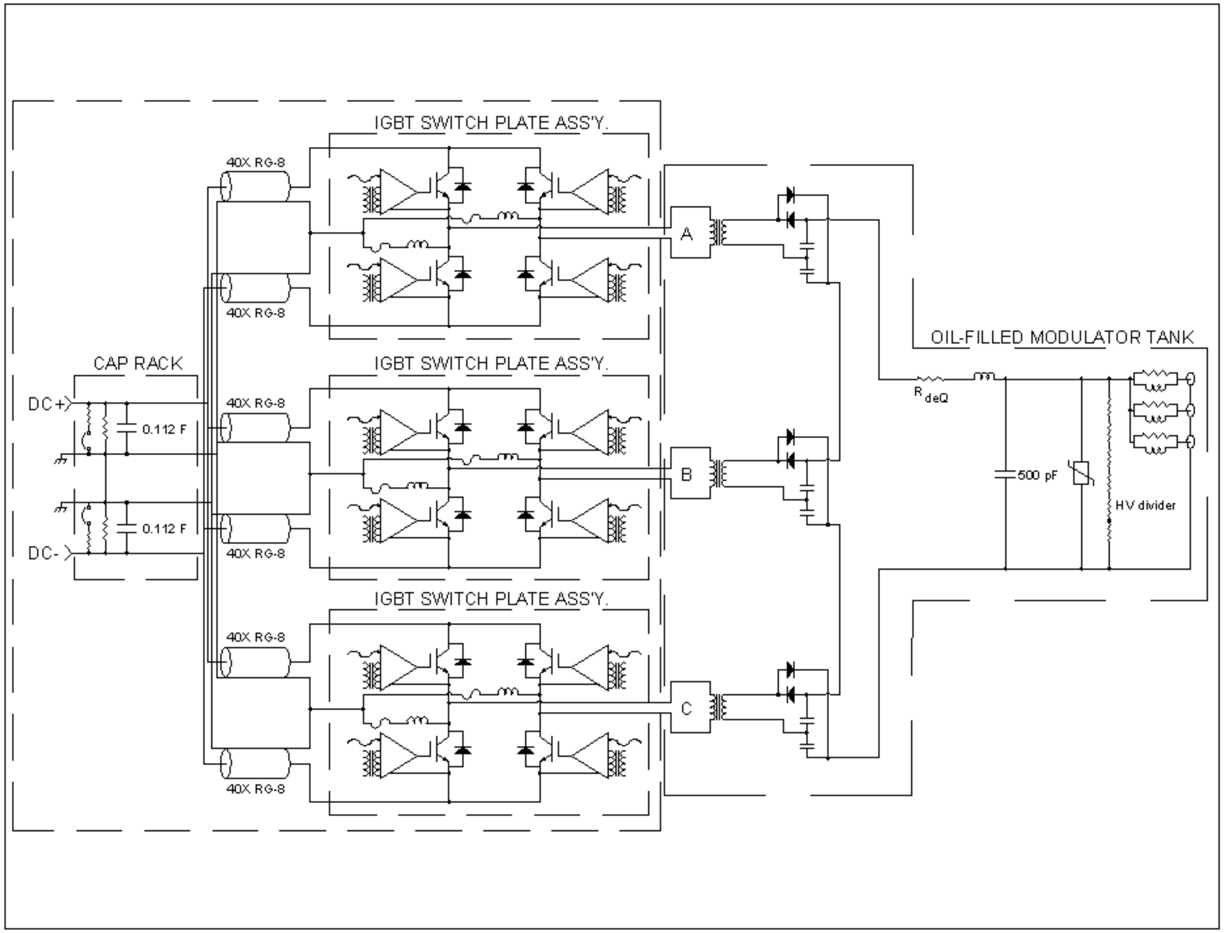
- Desire to run 36 klystrons at up to 700 kW peak (~85 kV modulator output)
- Excess stress on IGBTs of concern, expect MTBF reduction
- 4 modulators / 9-packs helps but possible Second Target Station places additional requirements on modulators
- IGBT improvements may help but compromise reliability gains
- Considering topology modifications
- If successful, mods can be implemented throughout Gallery

4-phase system



- Can achieve true ZCS at turn-off w/ existing components
- Reduces operating voltage levels by about 100 V compared to previous
- New controller design capable of supporting this topology
- Can run w/ 3 phases if switch plate fails

Series-stacked half-bridge system



- Move filter cap after rectifier
- May realize better control of IGBT currents with this topology
- Parallel connection of outputs also viable

Conclusion

- Many subsystems in modulator have been modified and/or replaced
- Early improvements resulted in increased SCR availability
- 60 Hz operation revealed several problems with modulator
  - Over-stressed components
  - Fires
  - Poor overall reliability
- Improvements have helped but still work to do
- Several additional improvements pending