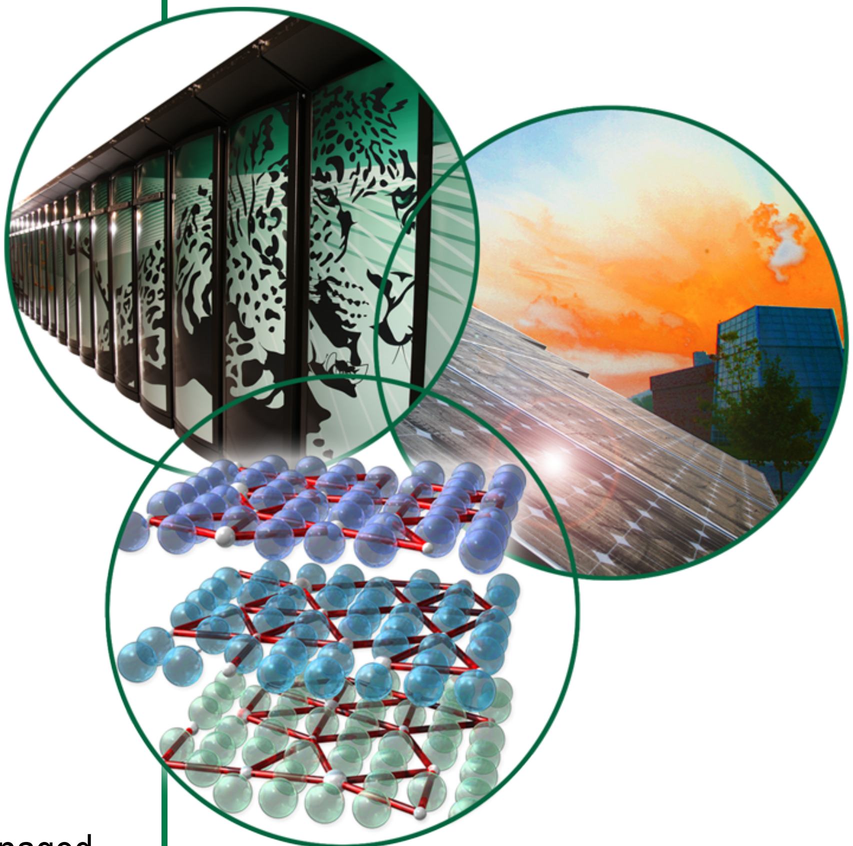
Developments in Solid-State Modulator Technology Towards High Availability*

David E. Anderson



*Work performed at Oak Ridge National Laboratory, which is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy.

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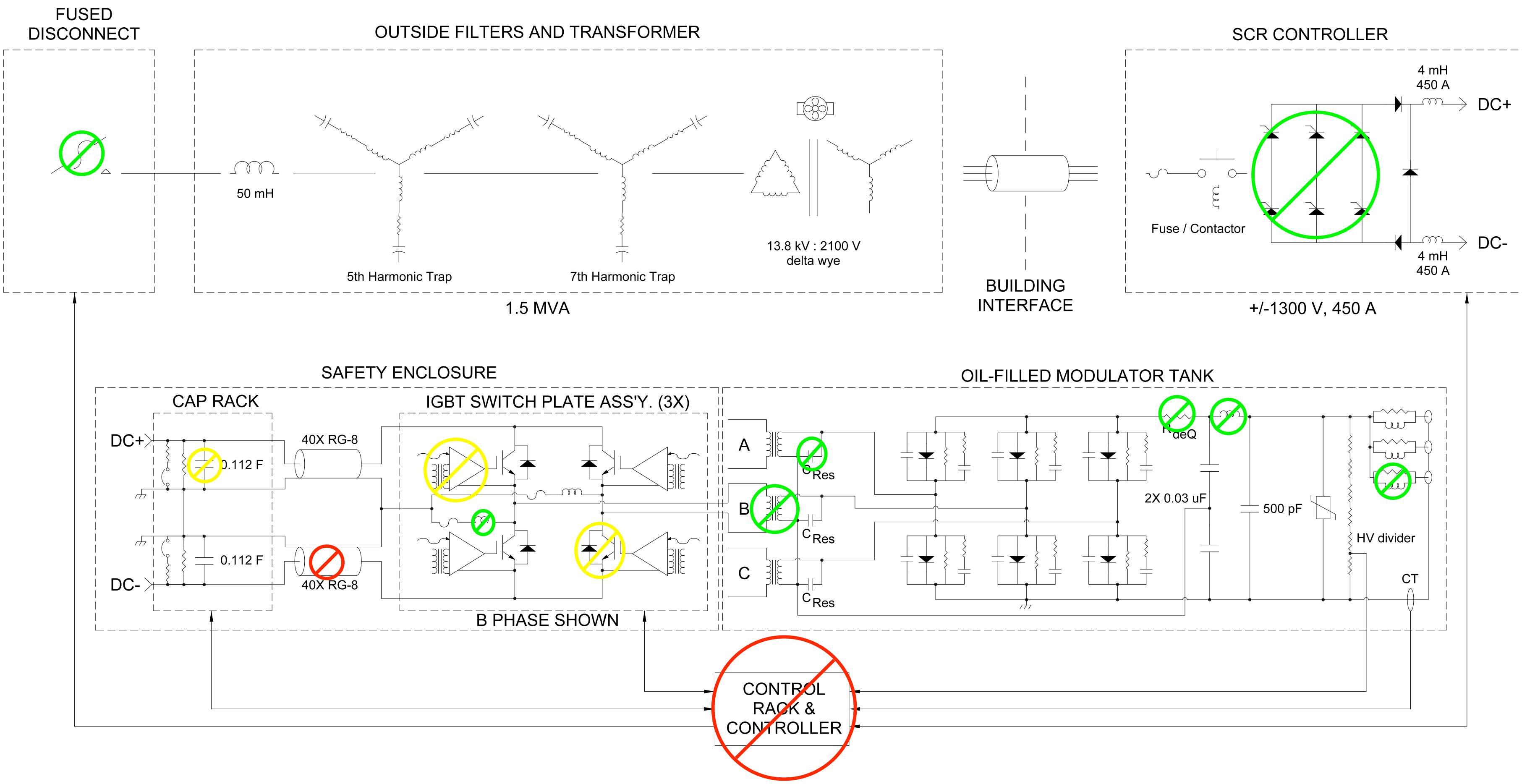
Solid-State Modulators in Vogue

- Inductive Voltage Adder approach
  - DARHT kicker
  - SLAC / LLNL NLC modulator
- "Bouncer" modulator with Hard-Switching
  - CERN / RRCAT modulator
  - Fermilab / DESY bouncer modulator
- Solid-State Marx
  - DTI ILC Marx
  - SLAC Marx
- Traditional scaled converter topology
  - SNS modulators
  - KAERI PEFP modulator
- Others

- HVCM System Overview
- Operational Statistics
- System Improvement Highlights
- Future Plans
- Conclusion

HVCM Simplified Block Diagram



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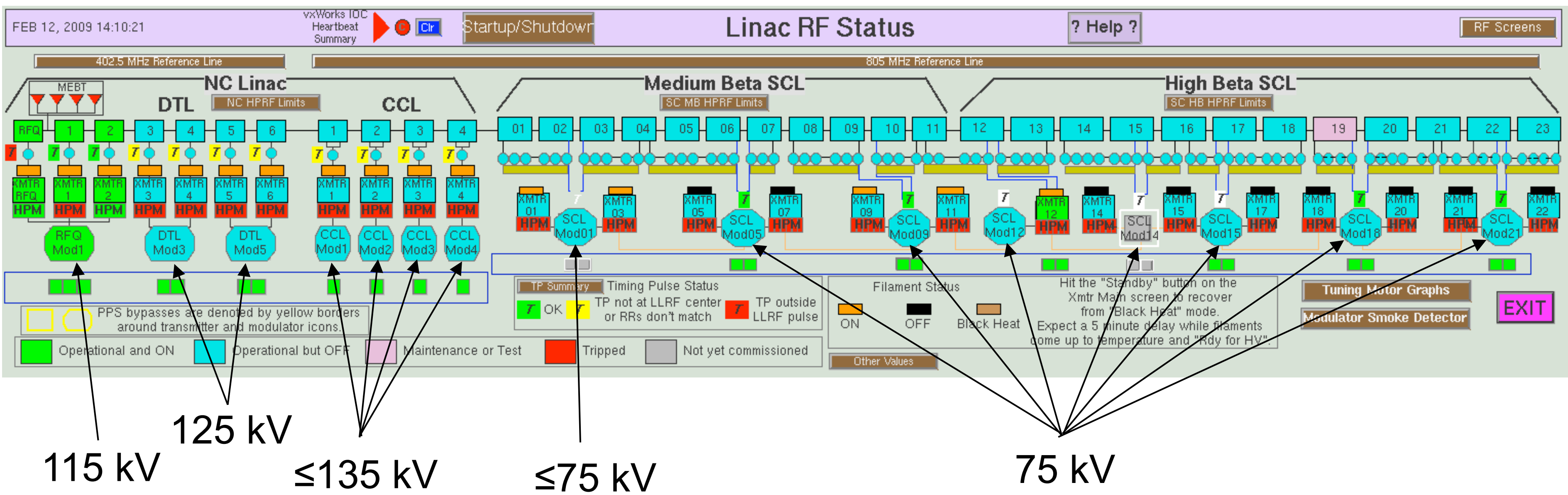
HVCM Major Subsystems

Cavity/Klystron/Modulator Layout



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

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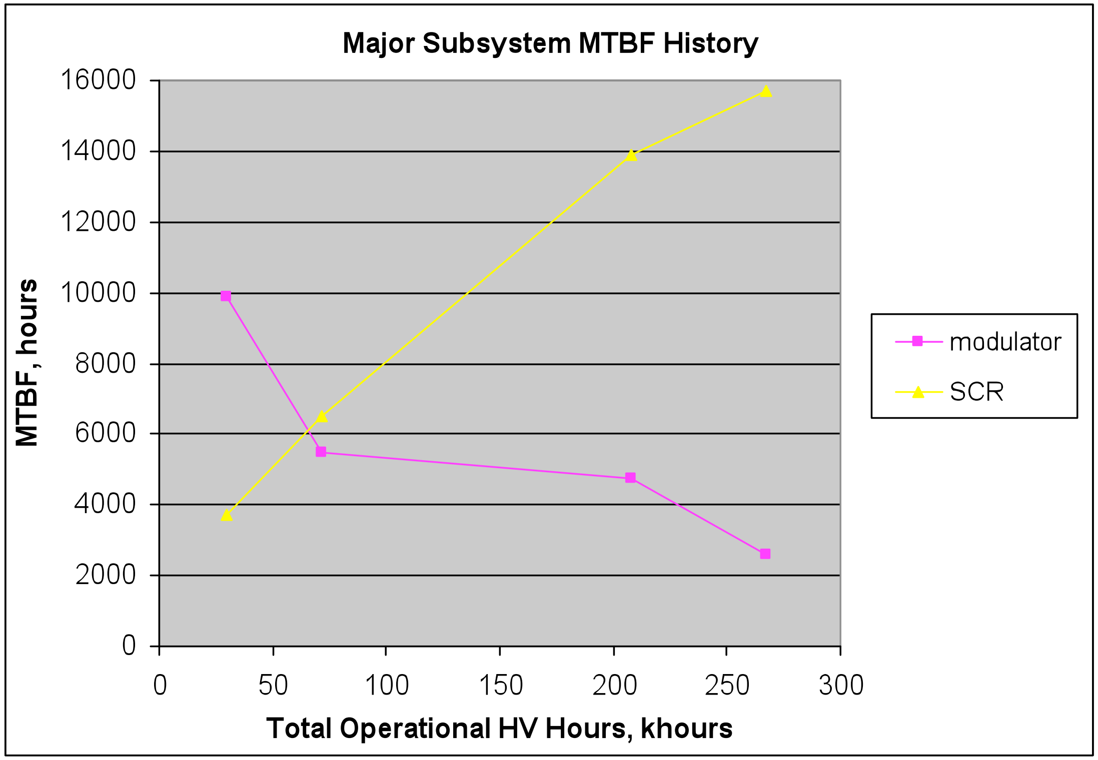
HVCM Lifetime Performance

SYSTEM	SCR Failure*	Mod. Failure*	Hours
DTL-Mod1	5/1	8/7	22,756
DTL-Mod3	2	4/5	20,828
DTL-Mod5		1/7	20,781
CCL-Mod1		3/12	19,831
CCL-Mod2	1	4/5	17,313
CCL-Mod3	2	4/3	19,076
CCL-Mod4		1/3	16,888
SCL-Mod1	1	1/2	18,001
SCL-Mod5		1/2	18,931
SCL-Mod9		3/6	17,281
SCL-Mod12	1	2/3	18,580
SCL-Mod15	1	1/1	18,357
SCL-Mod18	0/1	2/2	17,878
SCL-Mod21		7	18,024
RFTF Mod	2	1	>2,890
TOTAL	15/2	44/58	266,965



- 60 Hz operation began April 2008 at ~200 khours
- Overall system goal of 24,000 hours MTBF

*failure >1 hour downtime, red since 1/1/08, through 1/1/09

HVCM Fault Details

	Cap	in tank	IGBT	DFDC	Phase imbalance	Arc	IGBT drive	OI	Timing	Fiber	RF	Oil pump	Un-known
9/08	5		6	1	1	1	1	2					
10/08	3		2	6			2		1	1	1		2
11/08	4		7	4		1	1			2			
12/08	0	1	1									1	
total	12	1	16	11	1	2	4	2	1	3	1	1	2

Total Faults: 57
Total "nuisance" trip: 20 recorded
Total cap failures: 12

Development and Manufacturing Challenges and Limitations

- Exceed capabilities of circa-2000 power devices
  - Inadequate engineering design margins
  - MTBF analysis based on ideal component lifetimes, actual lifetimes fell short of assumptions
- Manufacturing challenges
  - Magnetics design deficiencies
  - Workmanship/quality concerns
- Expedited schedule didn't allow sufficient testing time, release to manufacturing was premature
- No prototype effort on SCL-variant of system
- Failure modes not sufficiently addressed
  - Power semiconductor fault modes
  - Catastrophic capacitor failures not contained
  - No real-time correction in controller, only fault shutdown capability
- MTTR exceeds estimates

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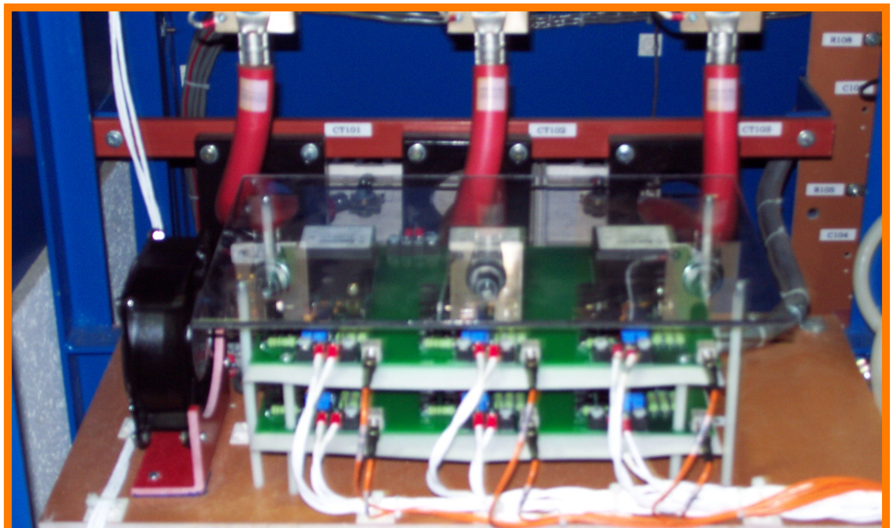
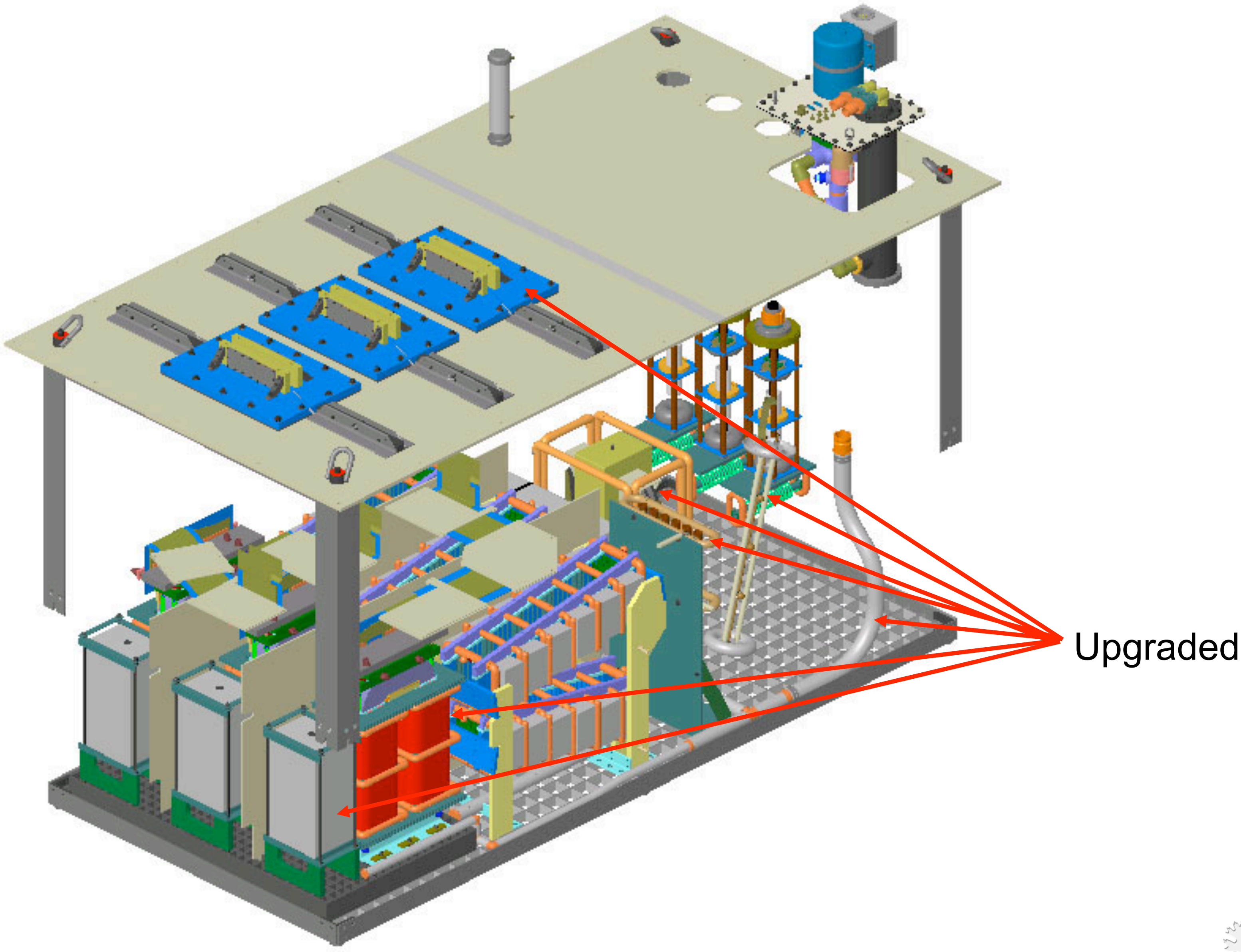
SCR Upgrades, Improved Reliability

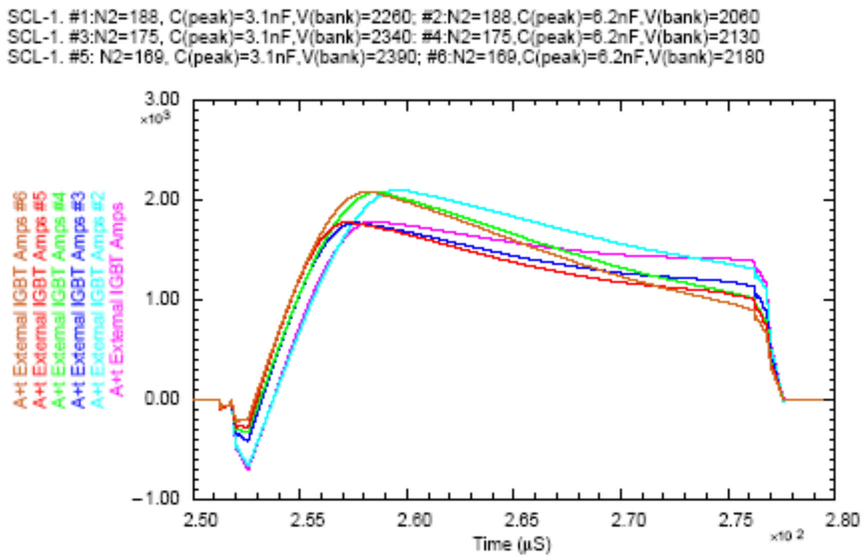


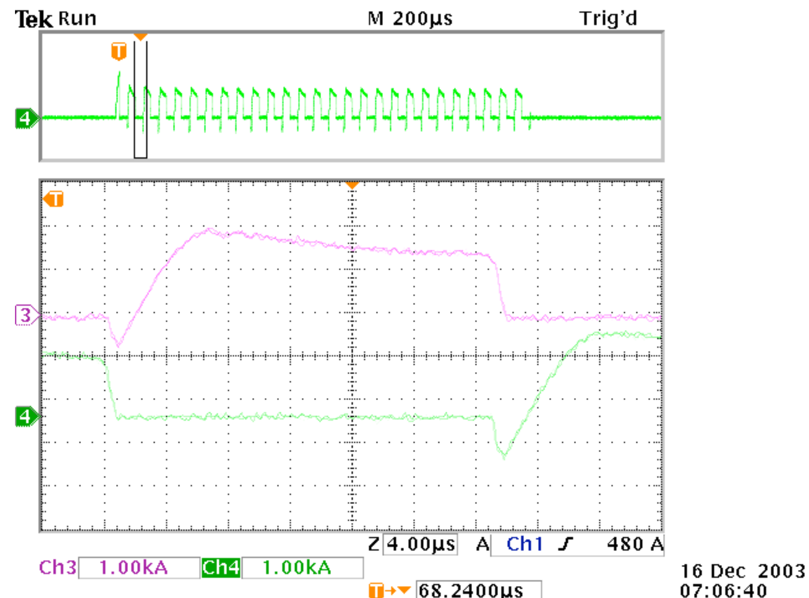
- Wafer punch-through and edge failures reveal different failure modes
- Improved snubbers to prevent over voltages
- Improved gate drive to prevent punch-through
- Miscellaneous improvements
  - Soft start / phase back prior to shutdown
  - Fast over current protection
  - Faster contactor operation in fault modes

HVCM Basket Assembly

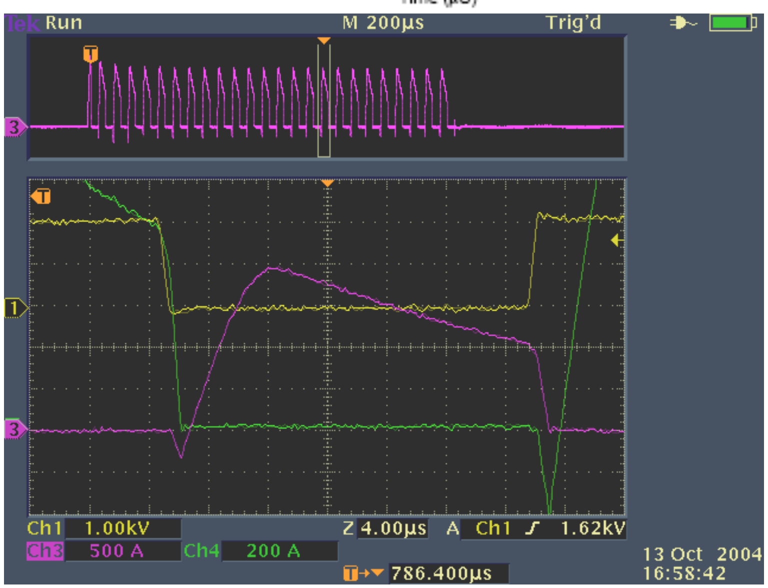


SCL Modulator Re-Tune





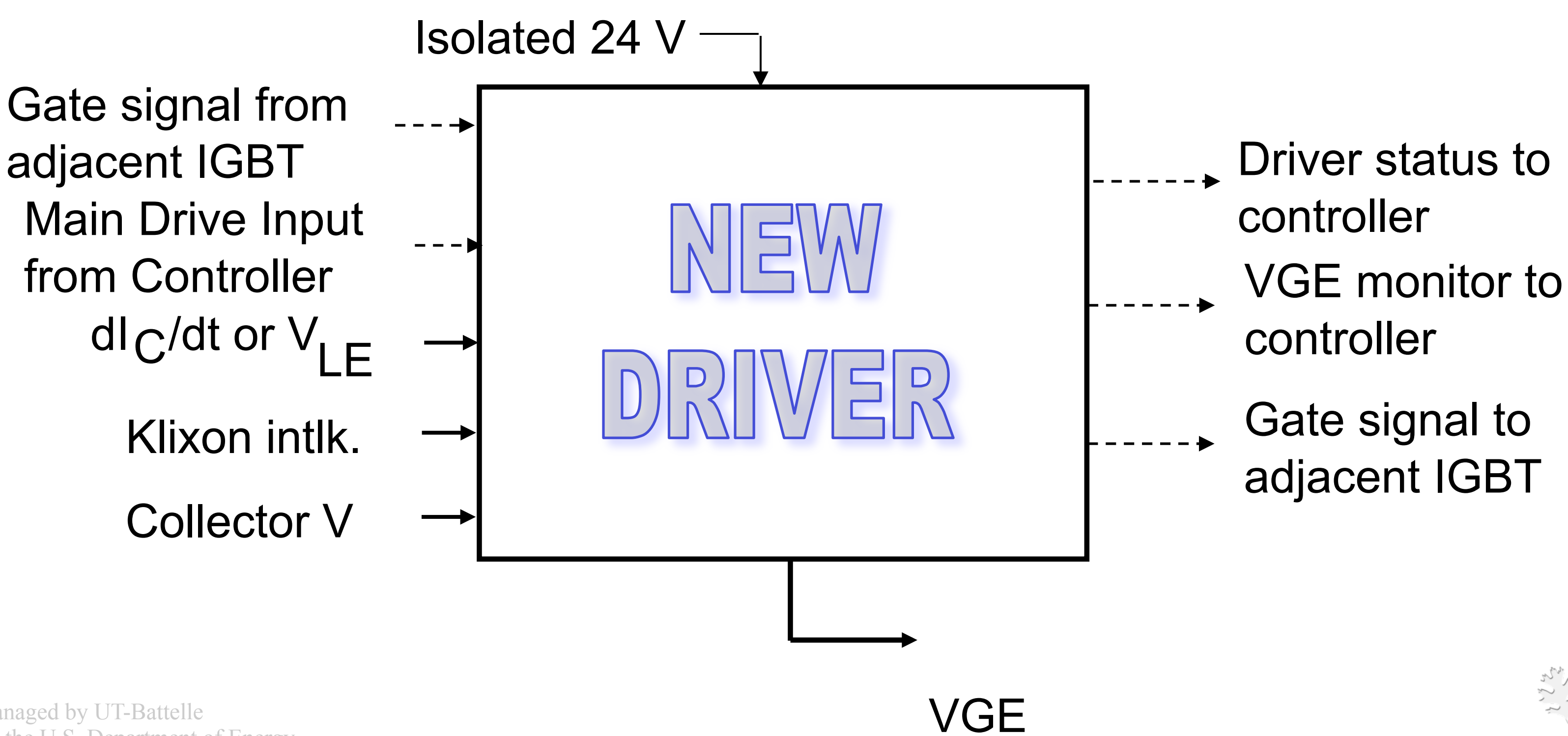
Old configuration



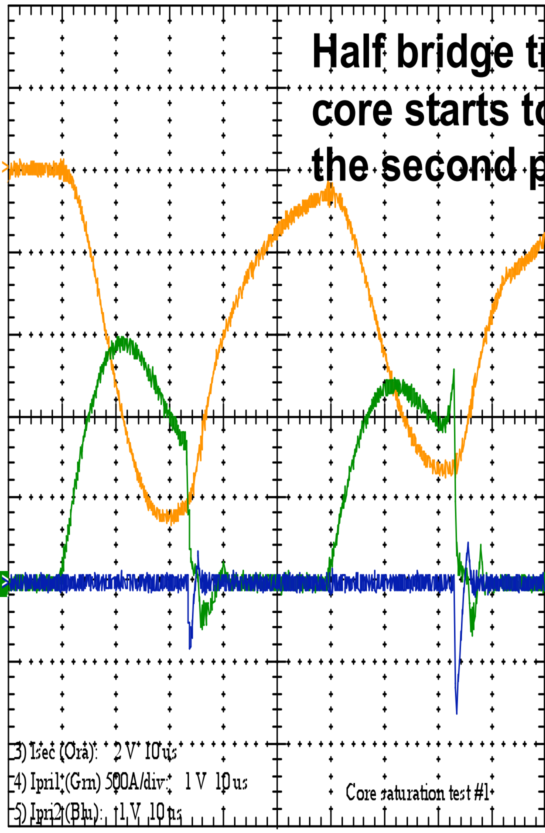
- Switching losses at 60 Hz operation resulted in IGBT failure
- Changing leakage inductance and resonant capacitance improved I_C
- Routine 60 Hz operation now the standard

Next-Generation IGBT Gate Driver

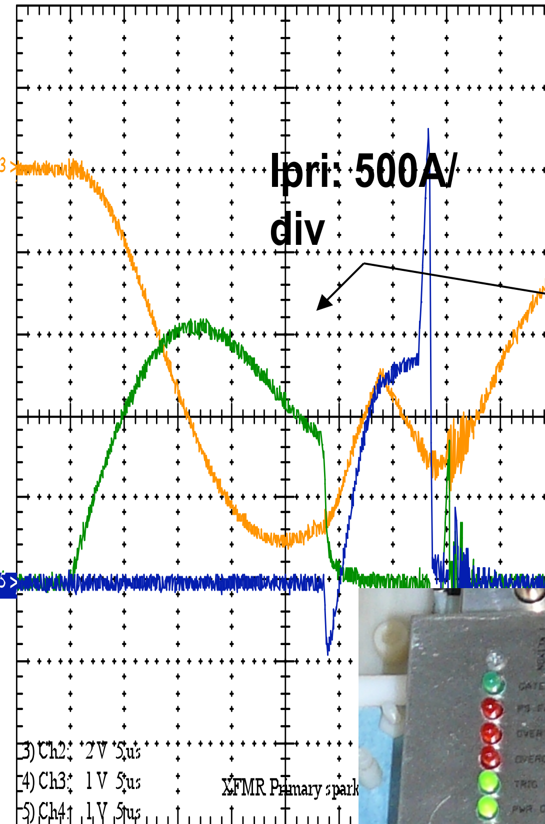
- Over Current protection
- Improved drive levels
- Enhanced handshaking with controller
- Vsat monitoring
- Shoot through interlocking



Next-Generation IGBT Gate Driver Performance



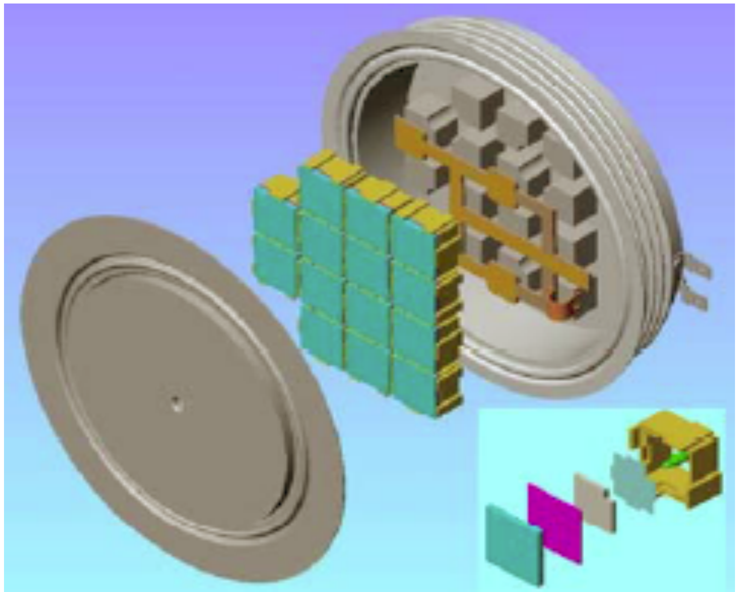
Half bridge triggered – the core starts to saturate on the second pulse

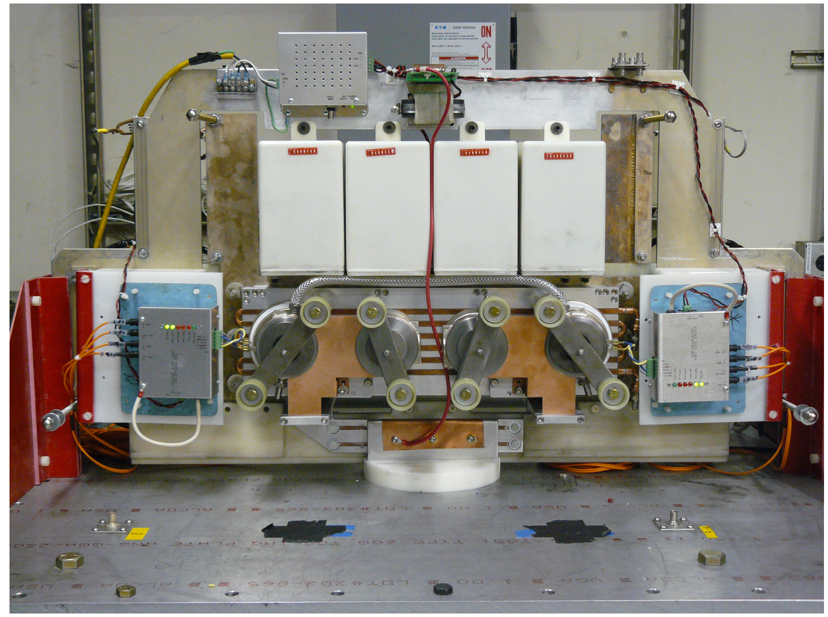


Ipri: 500A/ div

See Nguyen at TU6RFP094 “Advanced Gate Drive for the SNS High Voltage Converter Modulator” for more details

IGBT Next-Generation Development



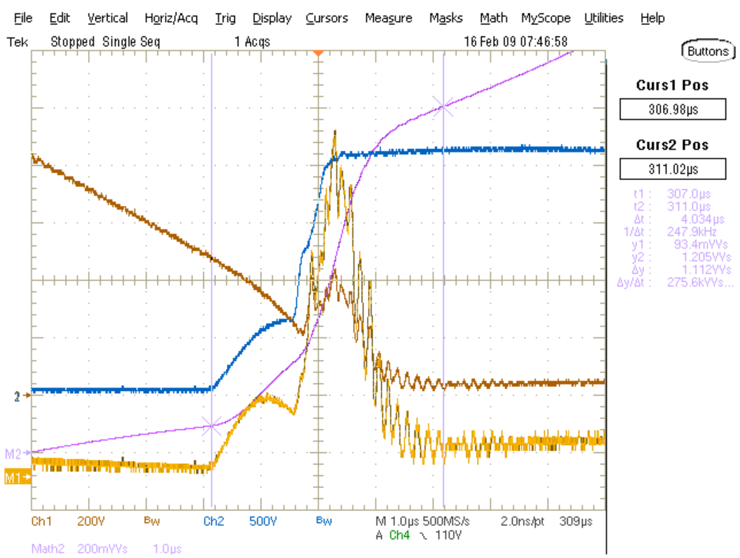


Next-generation Westcode Press-Pac IGBT devices

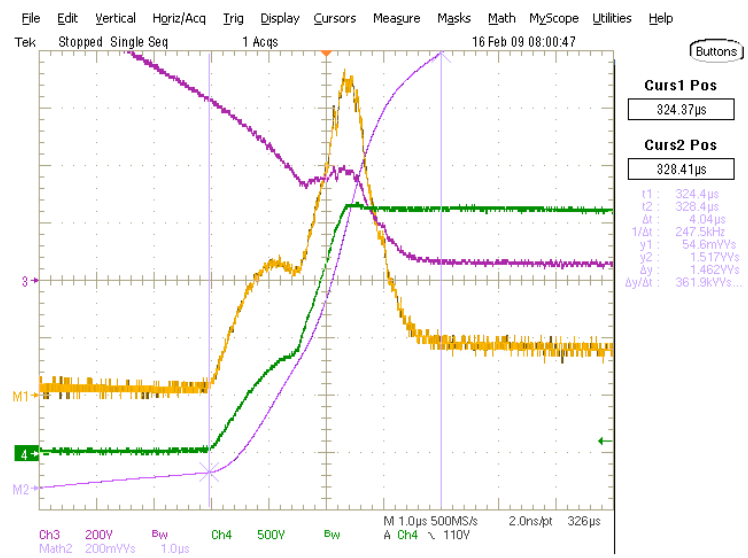
- Higher voltage rating (4500 vs. 3300 V), higher current rated recently available (2400, 1800 vs. 1200 A)
- External anti-parallel diode required
- Developed at SLAC with full power testing at ORNL
- See Kemp "Redesign of the H-Bridge Switch Plate of the SNS High Voltage Converter Modulator" at TU6RFP093 for more details

IGBT Alternate Solutions

- Existing 3300 V, 1500 A devices (Eupec/Mitsubushi)
  - ~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 releasing CM1200HG-90R 4500 V/1200 A power module late June 2009
  - Easier to retrofit into existing hardware
  - Needs to be evaluated before choosing a final upgrade
  - No external anti-parallel diode required



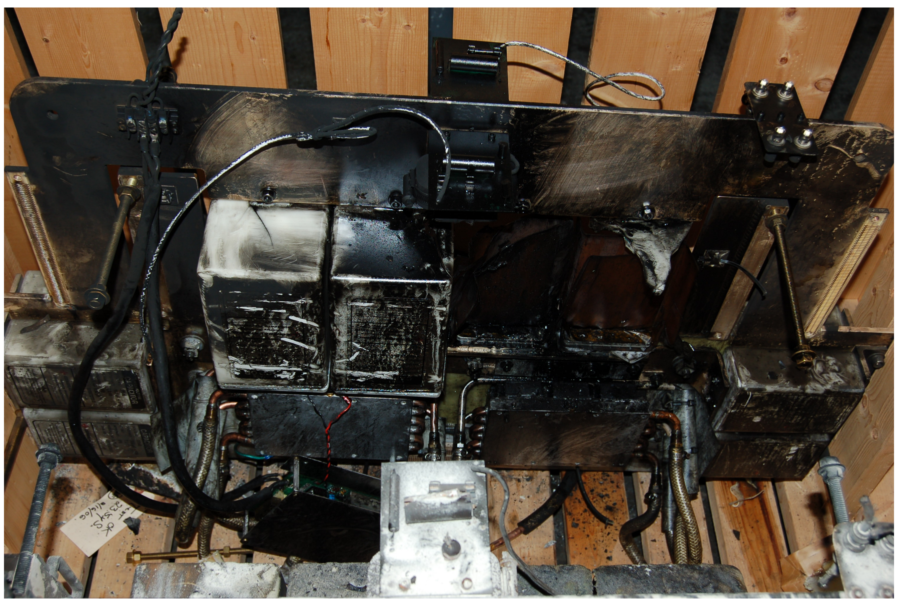
Eupec 1200 A



Eupec 1500 A

Capacitor Failures

- Mfgr.'s cap lifetime ratings 100,000 hours @ 3000 V, Expanded the lifetime on the spec. to 1 million hours
- Experience indicates 10-15 khours @ ≤ 2300 V
- Replaced all warm linac caps w/ higher lifetime spec caps
- Replacing all other caps with new caps, some with poor lifetime history, to "restart" the clock and remove end-of-life units

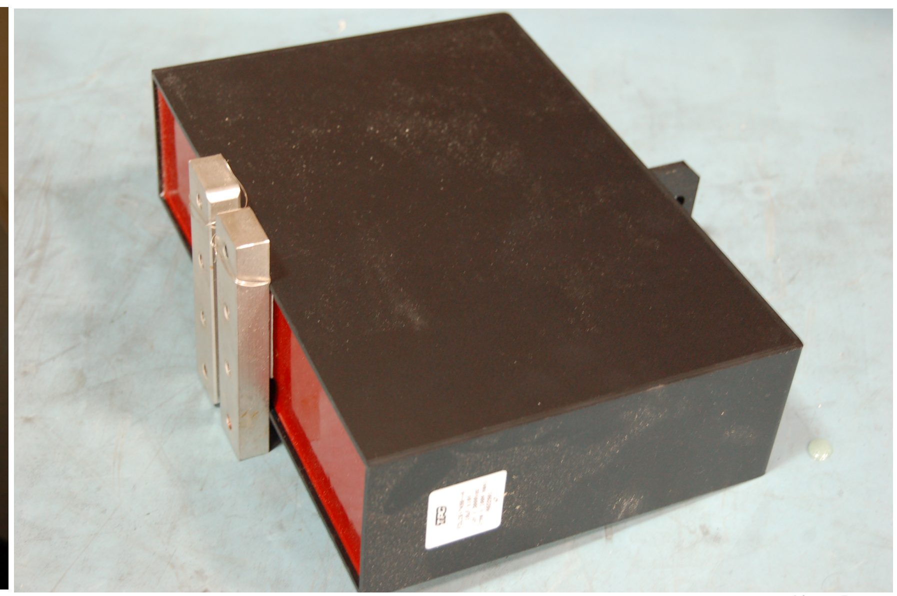


Future Capacitor Replacement

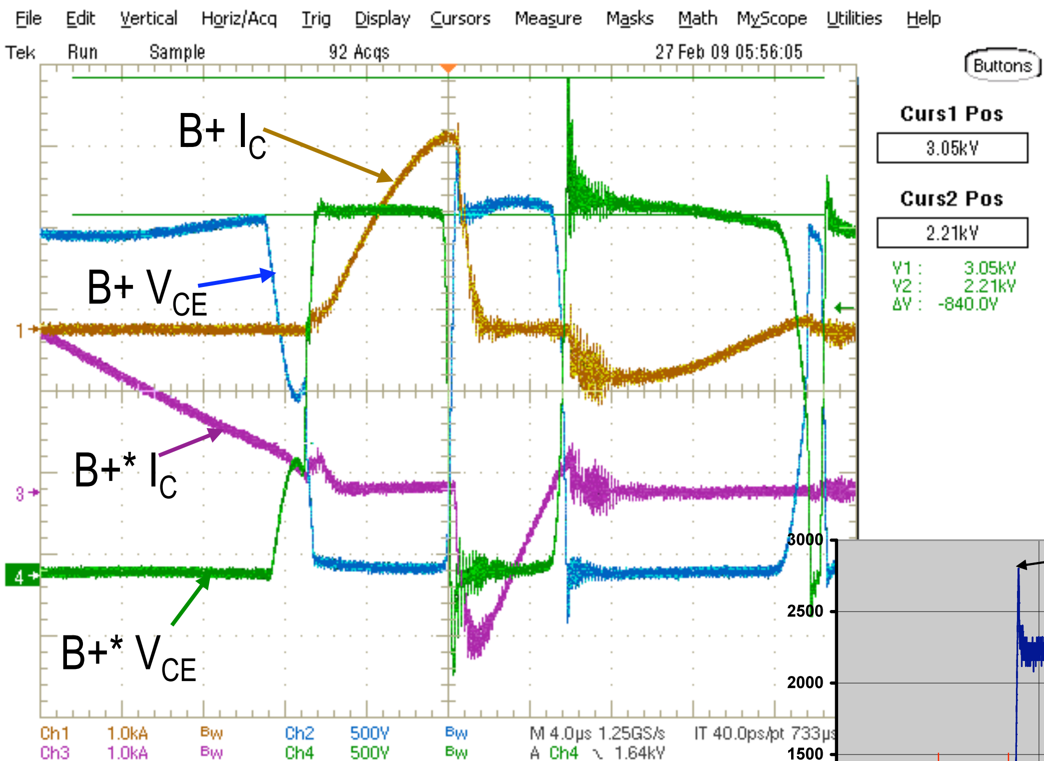
- Run capacitors until July shutdown
- Assess self-clearing capacitor degradation
- Choose and order capacitor selected
- Install when delivered during 1st FY10 Extended Shutdown Period

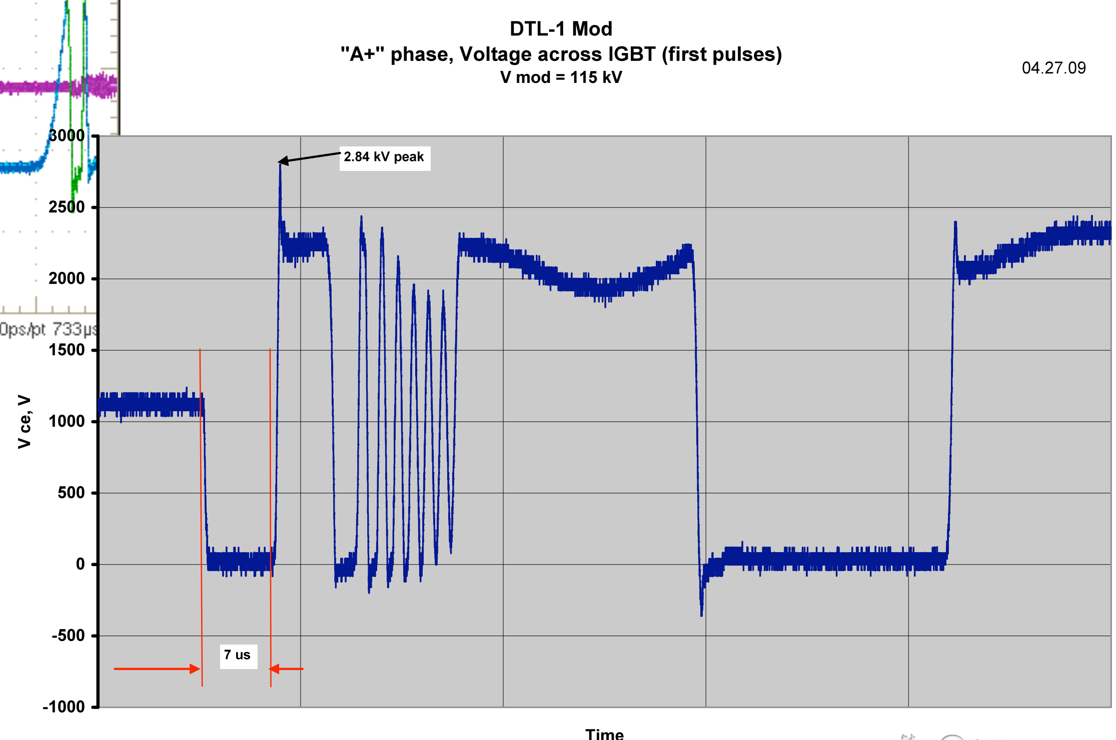
RSO Plastic Case

Self-Clearing Metallized Hazy Polypropylene

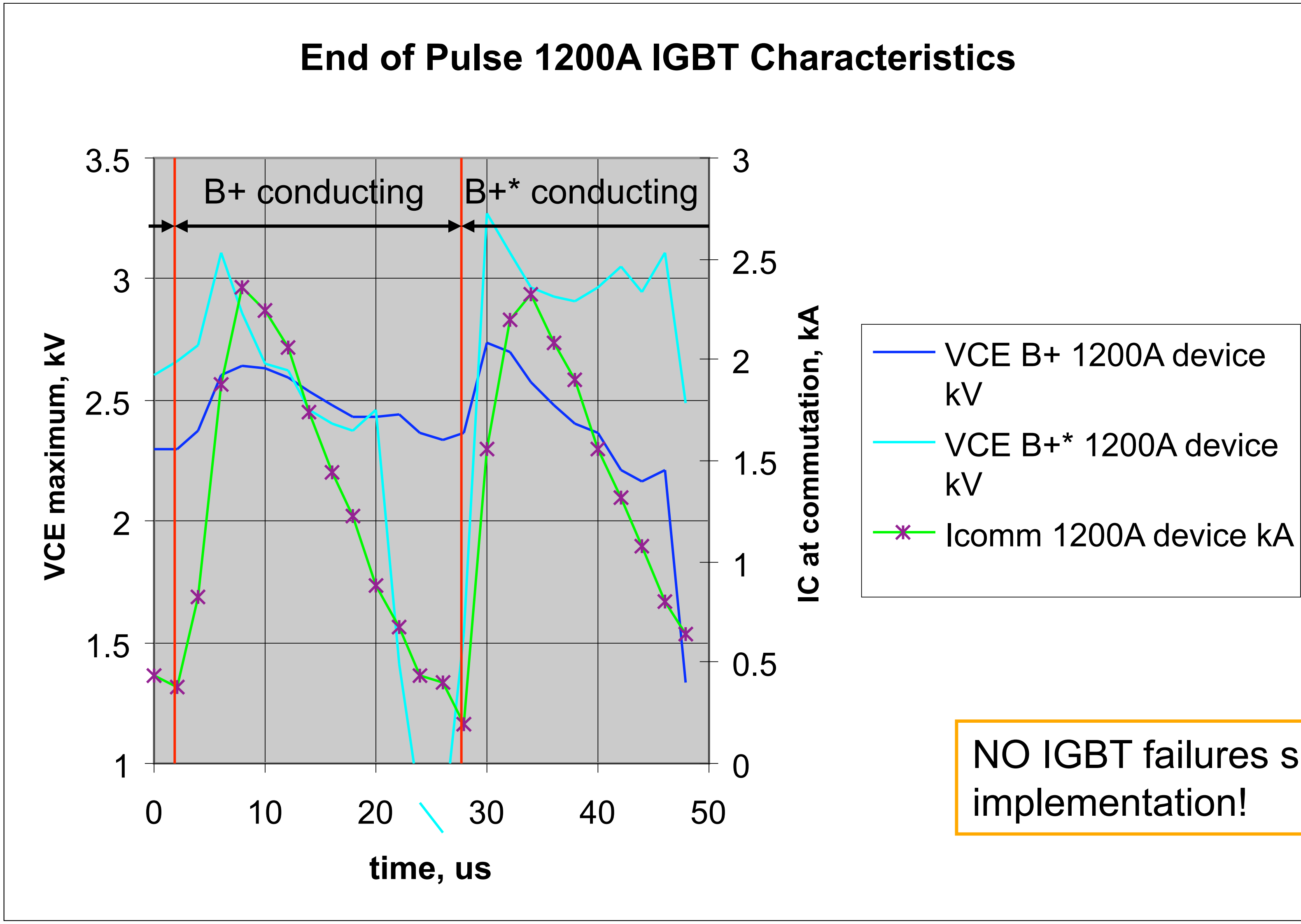


Start & Finish Pulse IGBT Stress





End of Pulse Over Voltage



NO IGBT failures since implementation!

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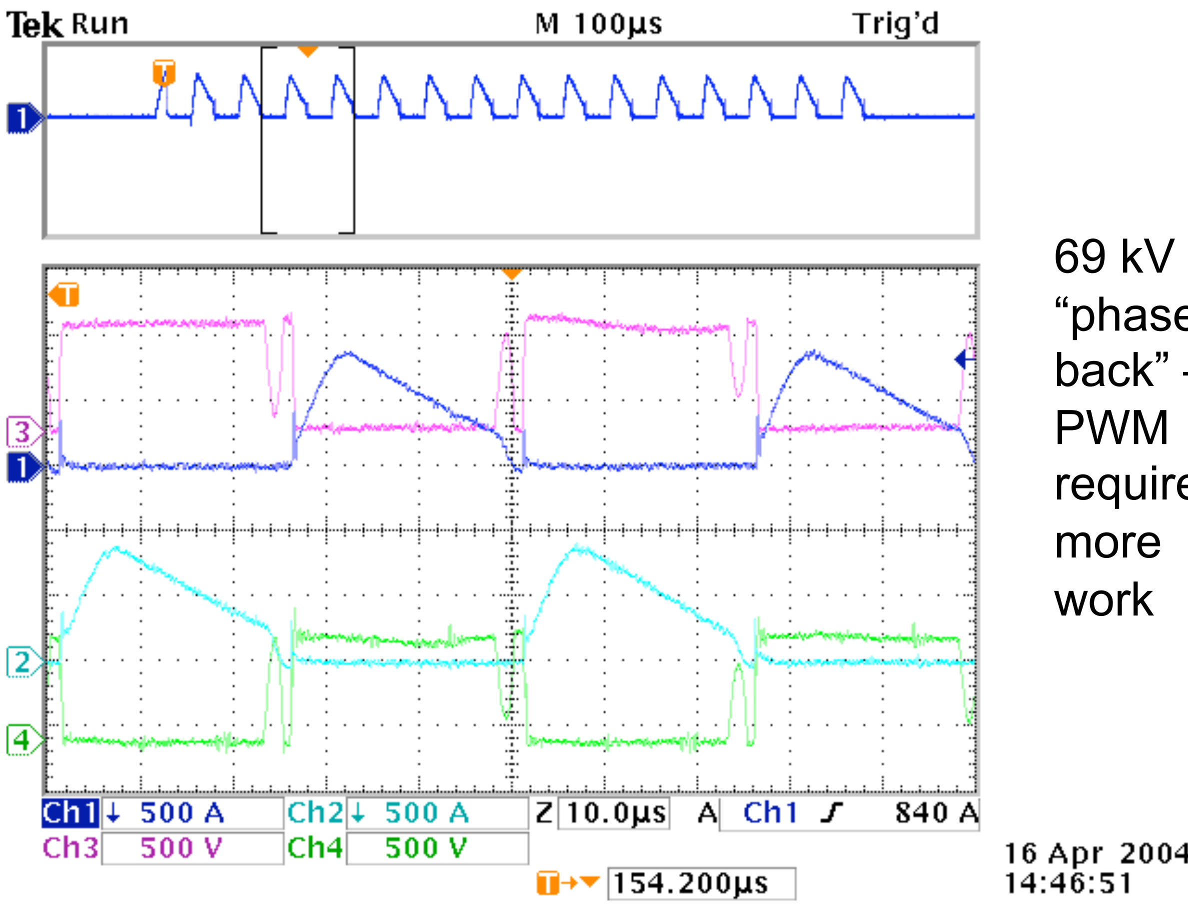
Pulse Droop Compensation



69 kV "phased back" – PWM requires more work

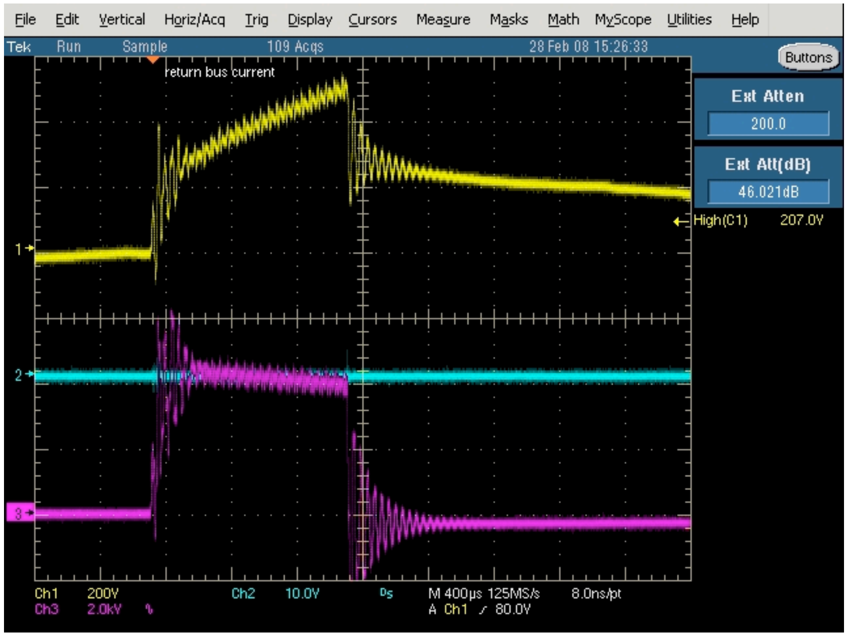
- Turn-off switching losses too high in initial tests
- Alternative droop compensation scheme – frequency modulation, phase shift modulation, ???

Next-Generation Controller

1. On-board signal analysis and timing feedback
   - Eliminates many nuisance trips, self-correcting
   - Compensates for component drift
   - Flux, VGE, IGBT status, etc. as inputs
   - Allows each phase to terminate 20 kHz half-cycle at end of pulse
2. Implement pulse droop feedback
   - Pulse width modulation, frequency modulation, and/or phase modulation
   - Study effects on IGBT and circuit performance
   - True ZCS/ZVS possible? Minimize switching losses?
3. National Instruments development tools in-house, need to do system simulations and integrated testing
4. Ultimately produce stand-alone dedicated FPGA-based controller units to replace
5. Other upgrades incorporate features to support this new controller
6. Design for possible redundant IGBT H-bridge in future

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, develop 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



???Redundant H-Bridge???

- Only conceptual at this point, need to study system interactions
- Could be switched into modulator if another switch plate fails
- Faulty switch plate could be replaced/repaired during scheduled down time
- Controller could perform the “switch” seamlessly between pulses
- Would require oil tank modifications to support an additional phase
- Other planned upgrades support this and are being designed accordingly

Conclusion

- Many of the HVCM subsystems/components have been or will be upgraded to improve reliability
  - Under existing AIP programs
  - Under approved HVCM development work package
- Test stand in place but removed – recover in June
- R&D Efforts underway to support future activities
- Collaborative efforts utilized to extend available resources
- Thanks to the SNS HVCM Development Team and the SLAC Power Conversion Department for help with these activities