Advances in High Voltage Converter Modulator and Performance

Presented at the

Accelerator Advisory Committee Review

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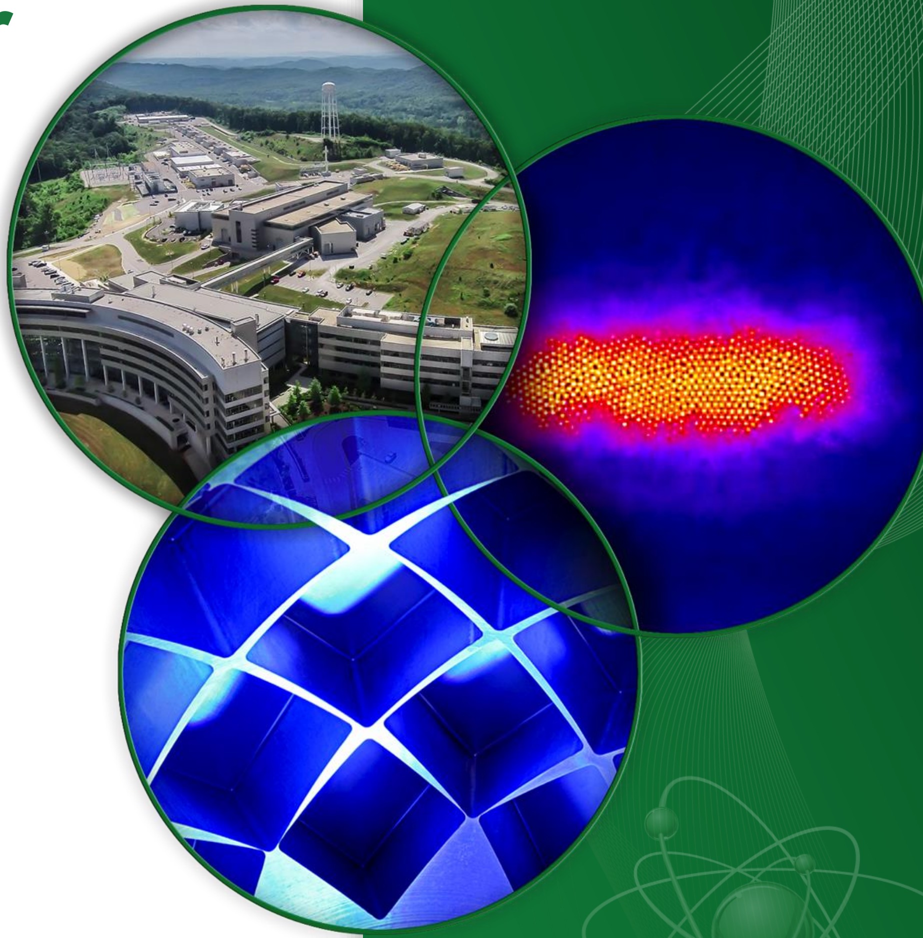
March 2015



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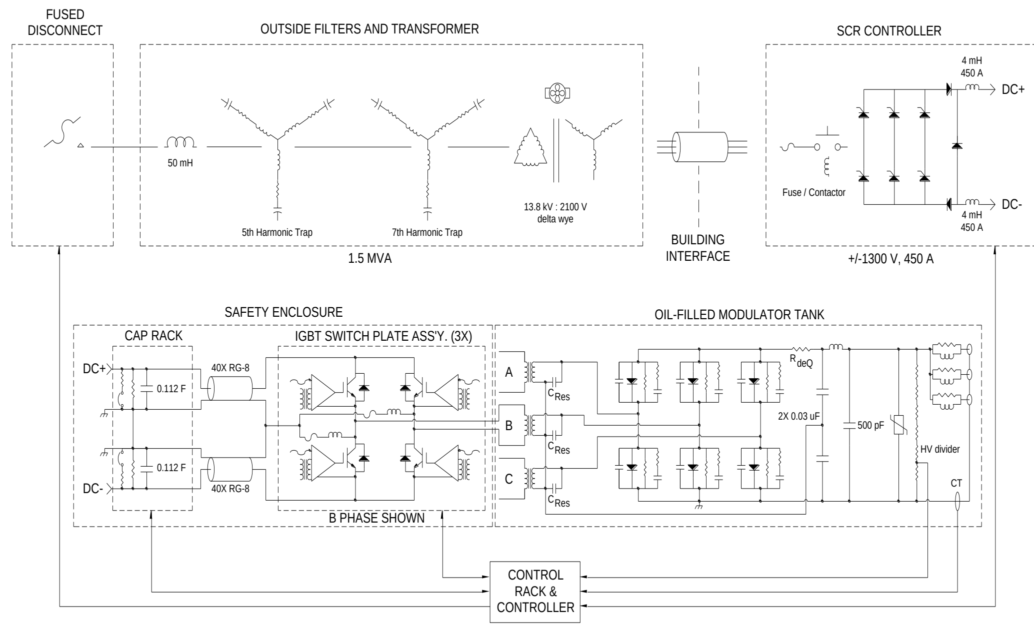
Modulators provide pulsed power to high power RF klystrons using 20 kHz switching with IGBTs

- Provides up to 135 kV, 1.35 ms pulses at 60 Hz to amplify RF to 5 MW
- 3 phases employed to increase output ripple frequency
  - Minimizes output filter requirements
  - Minimizes fault energy available to klystron
- Powers multiple klystrons up to 11 MW peak power
- Currently there is up to a 5% pulse droop operating in open-loop



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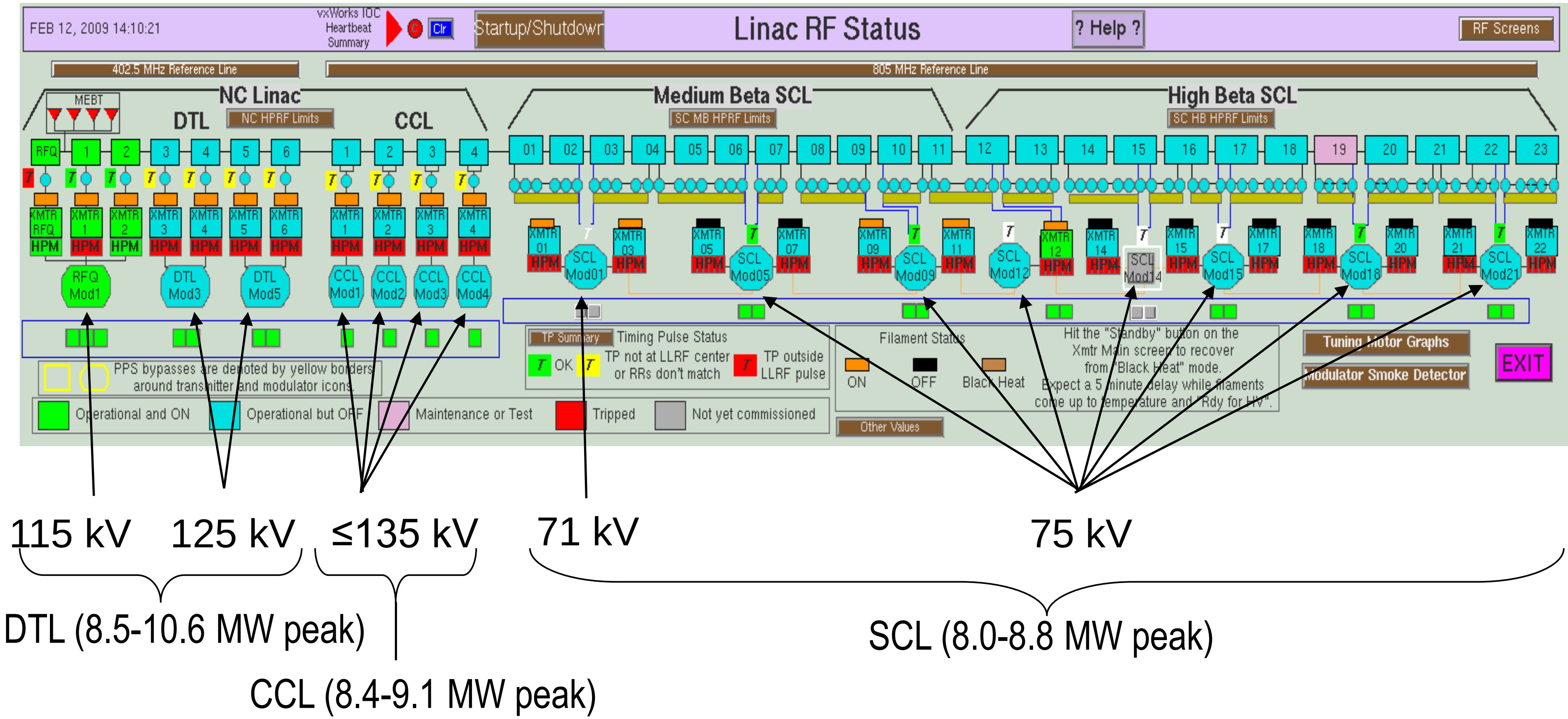
15 Modulators in 3 different configurations power 92 klystrons to support operation of the Linac



- 15 modulators: 3 - DTL, 4 - CCL, 8 – SCL (1 added 2008)
- Multiple HVCM/Klystron Configurations
- 690,000 combined operational hours on all modulators

2 additional modulators plus a partial system are available to support modulator development and testing activities

RFTF HVCM

- NCL variant of HVCM
- Primarily to support RF- and cryomodule testing, ISTF (new RFQ)
- Secondary mission is NCL HVCM work
  - Extended run testing

Open frame test stand

- Prototype efforts
  - Alternate topology
  - Laminated bus
- Affords flexibility and more extensive instrumentation @ limited power levels

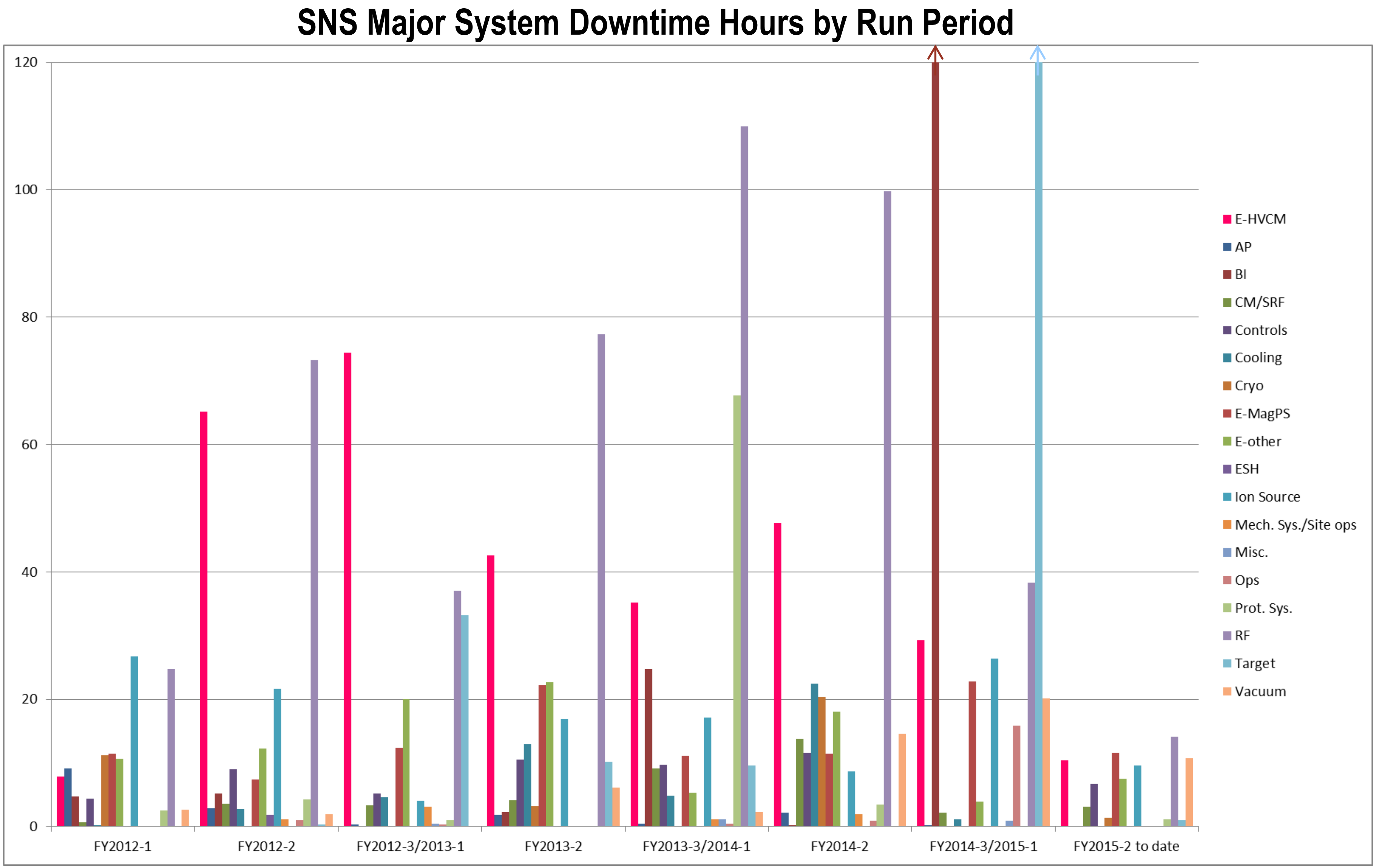
HEBT HVCM

- SCL variant of HVCM STS-rated beam stick load
- Dedicated mission is to support HVCM testing
- Most development work is initiated here

Single Phase Test Stand (not shown)

- Useful to test IGBT assemblies for matched timing on all 4 IGBTs and pre-qualification of spares

The HVCM systems continue to contribute to accelerator downtime but show improvement



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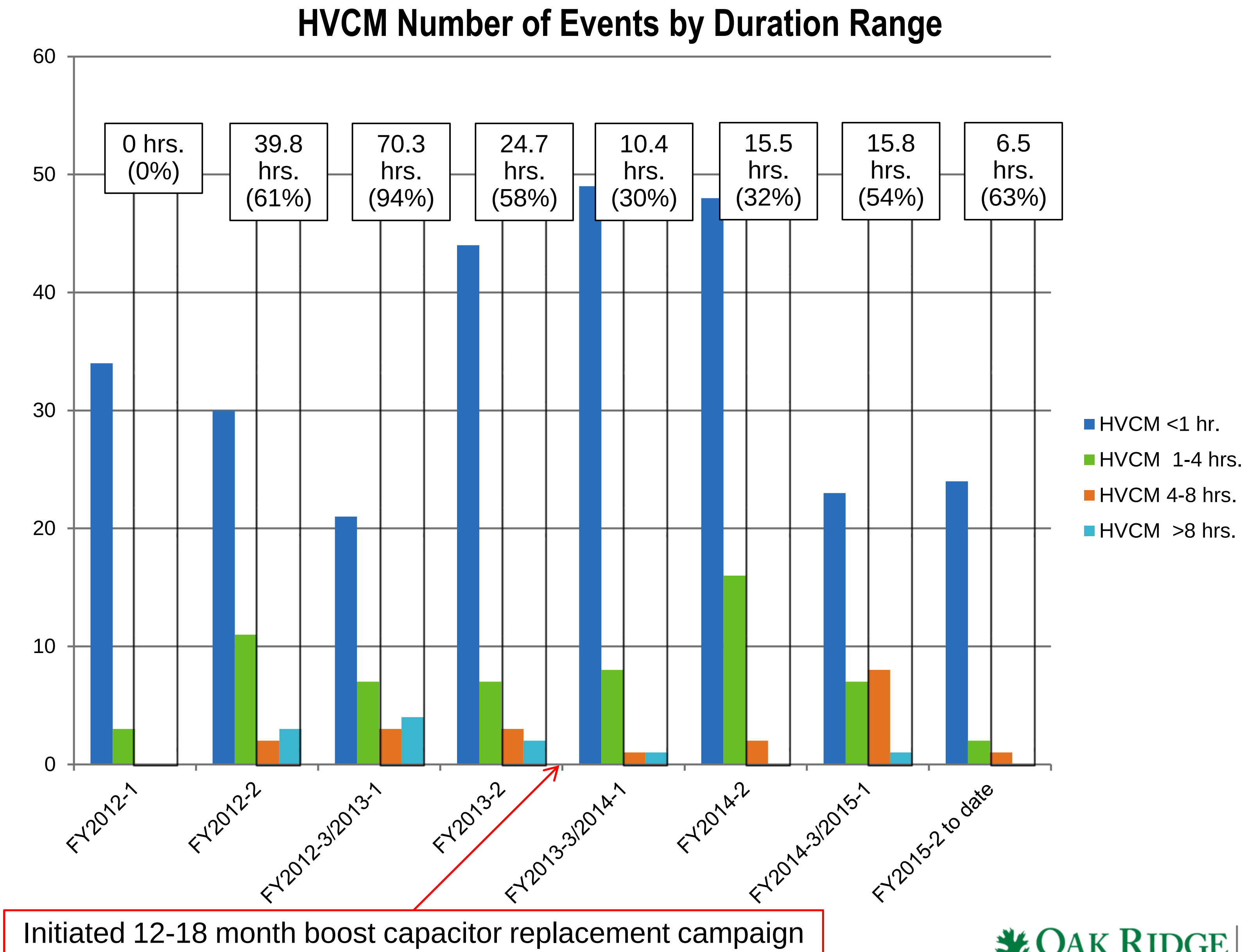
In spite of multiple "nuisance" trips, the HVCM systems' downtimes still dominated by >4 hour duration events



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Analysis of major failures by major component & subsystem is critical to improving overall system availability

Downtime Hours	FY2012-2		FY2012-3/ FY2013-1		FY2013-2		FY2013-3/ FY2014-1		FY2014-2		FY2014-3/ FY2015-1		Σ Hours
Scheduled Beam Hours	3130		1868		3353		2789		3331		3105		17.576
Fault Type	BT	nBT*	BT	nBT*	BT	nBT*	BT	nBT*	BT	nBT*	BT	nBT*	
Boost Capacitor	29.7	7.2	8.9	3.5	20.2	5.5	10.4	-	-	-	-	-	85.4
IGBT/driver	0	5	-	-	-	-	-	-	-	-	0	14.6	19.6
SCR Hardware	10.1	12.7	-	-	-	-	-	-	-	-	7.2	12.9	42.9
Controller / PLC	-	-	23.4	3.5	-	-	0	6.5	8.2	0	-	-	41.6
Mod. Tank	-	-	23.9	0.9	-	-	-	-	-	-	-	-	24.8
SCR Controls	-	-	3.0	0	-	-	-	-	7.3	0	-	-	10.3
Control Cables	-	-	4.0	0	0	6.0	-	-	-	-	-	-	10.0
Water Panel	-	-	0	8.0	-	-	-	-	-	-	-	-	8.0
Ctrl. Electronics	-	-	-	-	4.5	0	-	-	-	-	0	10.1	14.6
Oil Pump	-	-	7.1	0	-	-	-	-	-	-	8.6	0	15.8
Σ	39.8	24.9	70.3	15.9	24.7	11.5	10.4	6.5	15.5	0	15.8	37.6	273 (1.5%)

*non-beam time hours

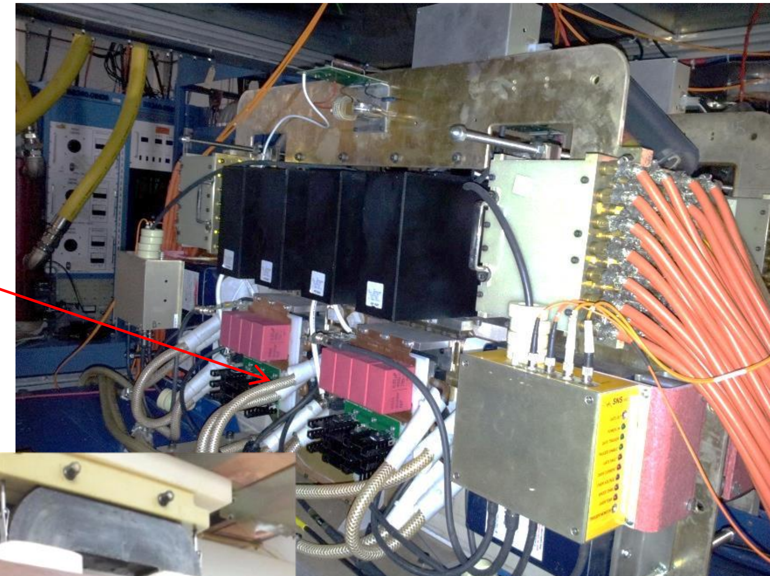
Initiated 12-18 month boost capacitor replacement campaign

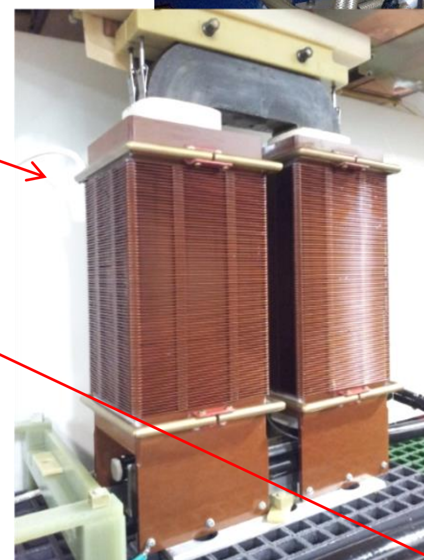
Consolidation of spares inventory should aid in reducing MTTR, improve reliability tracking

- Effort currently underway
- Combined with enhanced barcoding and work control processes with DataStream under development
- Additional troubleshooting tools available with new controller (more later)

Significant upgrades have been performed on the HVCM systems in the past

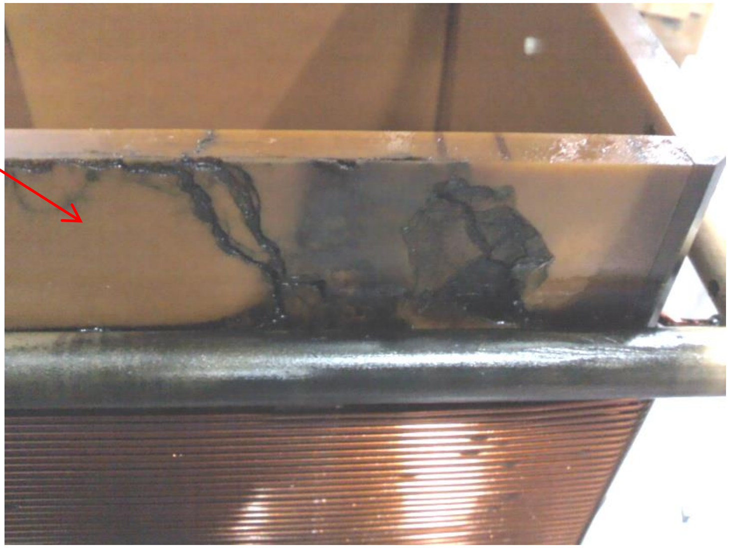
- IGBT Switch Plates
  - Replace bypass capacitors w/ metallized film units
  - Gate drivers (installed 11/15 units)
  - Snubbers (installed 5/15 units)
  - Thorough pre-installation testing
- Transformer and choke winding redesign
- Comprehensive Capacitor Replacement
  - In tank units
  - Switch plate bypass units
- Reduced SCL klystron loading with additional modulator
- Better preventative maintenance plans in place
- Extensive minor improvements



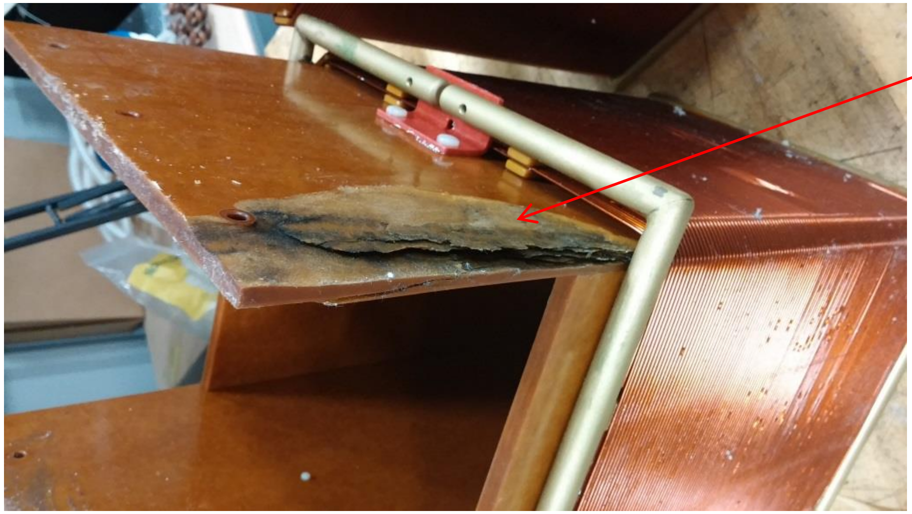


A past discovery of transformer failures mitigated but subsequent problem discovered

- A combination of materials selection, winding placement, corona ring placement & possibly temperature cause the problem



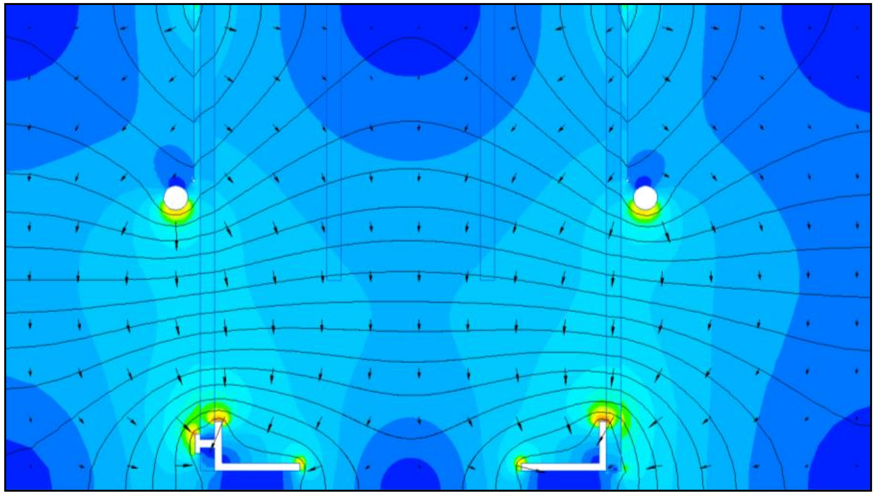
- Mitigation implemented
  - Moved inner winding layer away from surface of coil form
  - Increased corona ring dimension
  - Eliminated potential trapped air sites
- No additional failures at top of winding



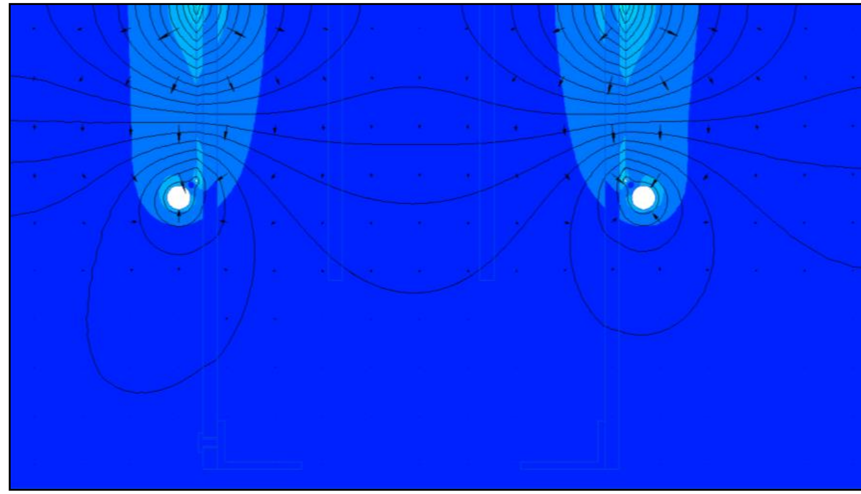
- Subsequent faults at bottom of winding assembly
- 2 instances of failures in NCL HVCMs
- Used field simulation to determine cause
- Failure in G-10 laminations leads to an alternate choice of material

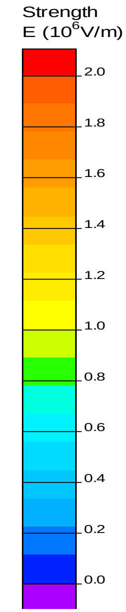
Resolution of the lower winding failure is summarized in FEA results

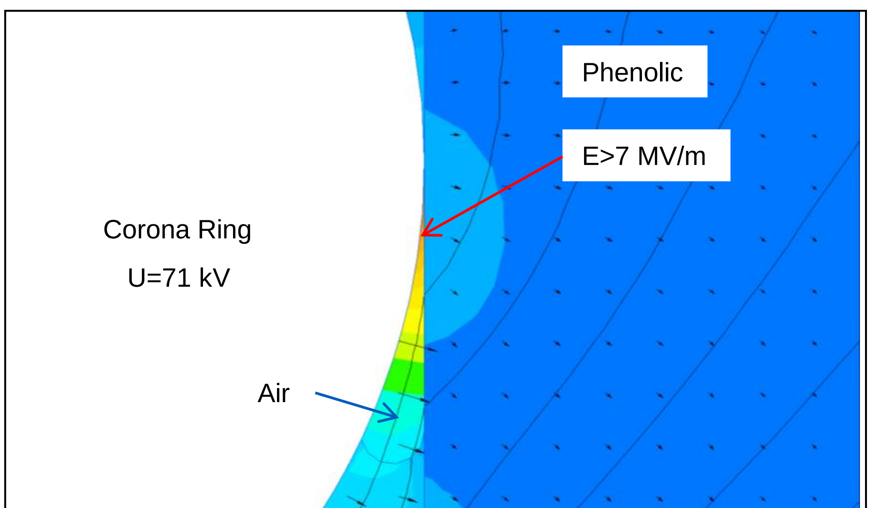
Al Secondary Angle

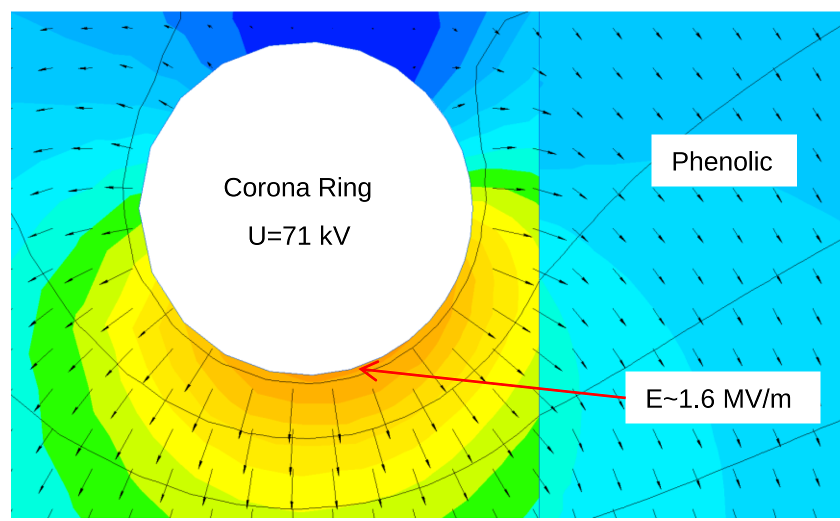


PVC Secondary Angle









A key vulnerability to continuing reliable operation are the NCL HVCM boost capacitors

- CSI capacitors continued to exhibit corona breakdown, failure of case at plastic welds, were eliminated from operation Summer 2013

- Condenser Products capacitors have proven more reliable but still have exhibited some problems
  - Case failure / small leaks
    - Weld and material tested to 65°C
    - Possible chemical interaction with FR3?
      - Cargill says not based on their analysis

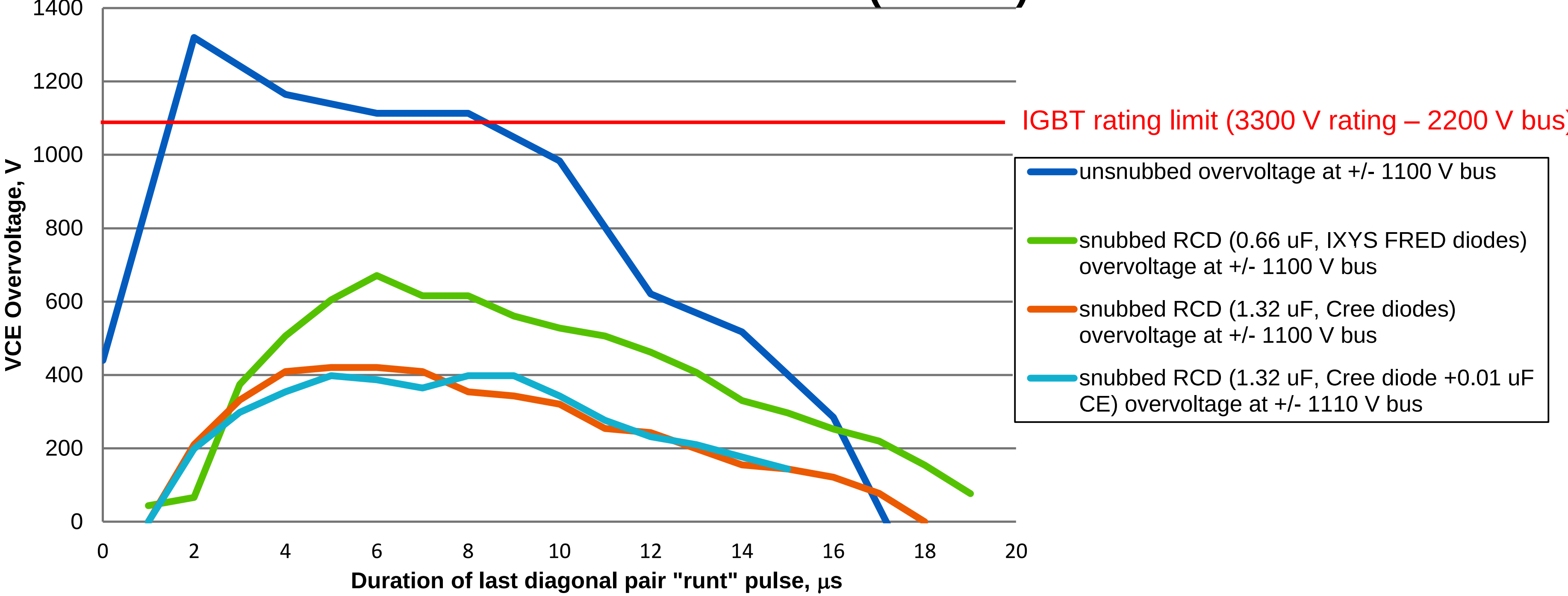
- NWL capacitors currently under evaluation in RFTF

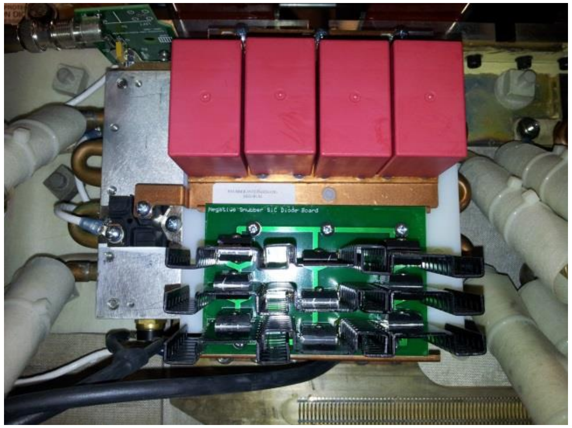
- Current strategy is to replace every 12-18 months proactively
  - Hardware costs ~$50k
  - Effort ~2 days each × 7 units (~2.5 weeks!)

- Recently saw evidence of small case leaks on CSI capacitor in SCL HVCMs (lower voltage operation)

Adding IGBT snubbers permits higher voltage operation, reliable higher current IGBT operation & eliminates fault over-voltage problem

End Of Pulse IGBT Over Voltage at +/- 1100 V bus Operation, worst measurable case (to date)





- Installed on 5 of 15 operational modulators, 2 test stands
- Combined >5000 operational hours w/ no issues
- Necessary for reliable pulse flattening and improved IGBT reliability

Necessary steps to achieve reliable 1.4 MW operation, provide additional LLRF control margin and ultimately to support 2nd Target Station are under development

- Currently, klystrons are at saturation at the end of the pulse with no remaining control margin due to cap bank droop in open-loop

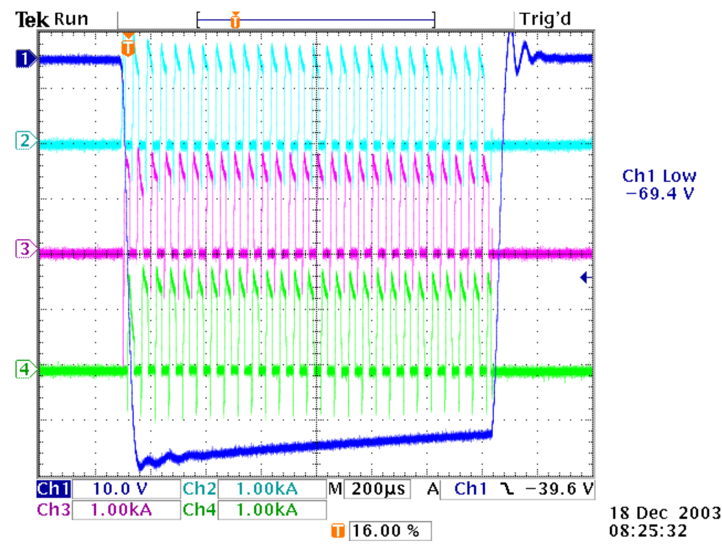
- Increasing klystron voltage with no additional changes will significantly degrade HVCM reliability

- Upgrades of cooling system underway
  - Provide higher component reliability
  - Reduce MTTR of key subsystems

- Pulse flattening for improved LLRF control margin demonstrated but without RF loop closed
  - Frequency modulation
  - Phase shift modulation

- Transitioning to even higher power presents other unique challenges
  - The current circuit topology creates excessive stresses on components
  - Switching losses in the IGBTs will significantly degrade their reliability

- Voltage ripple poor with current system



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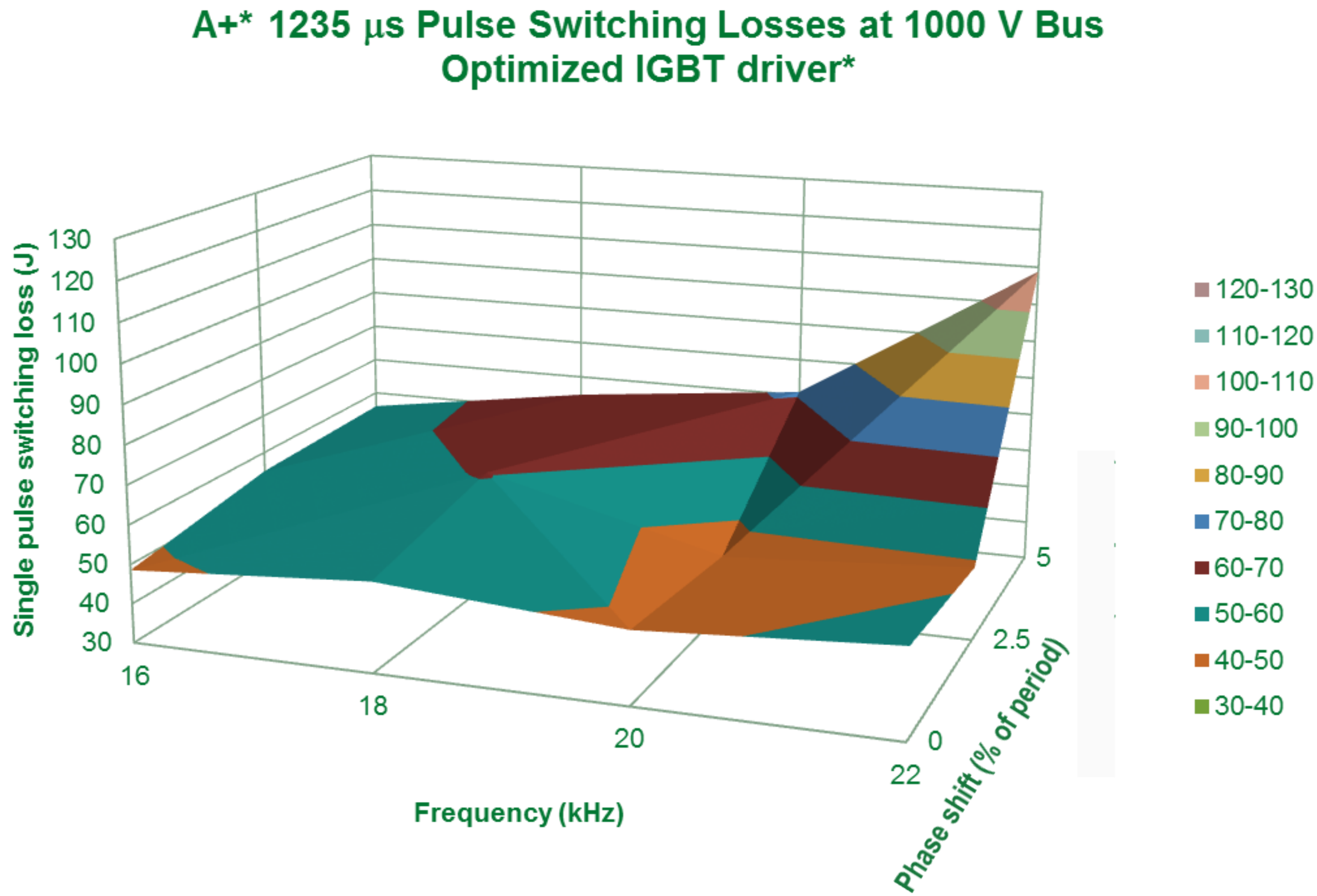
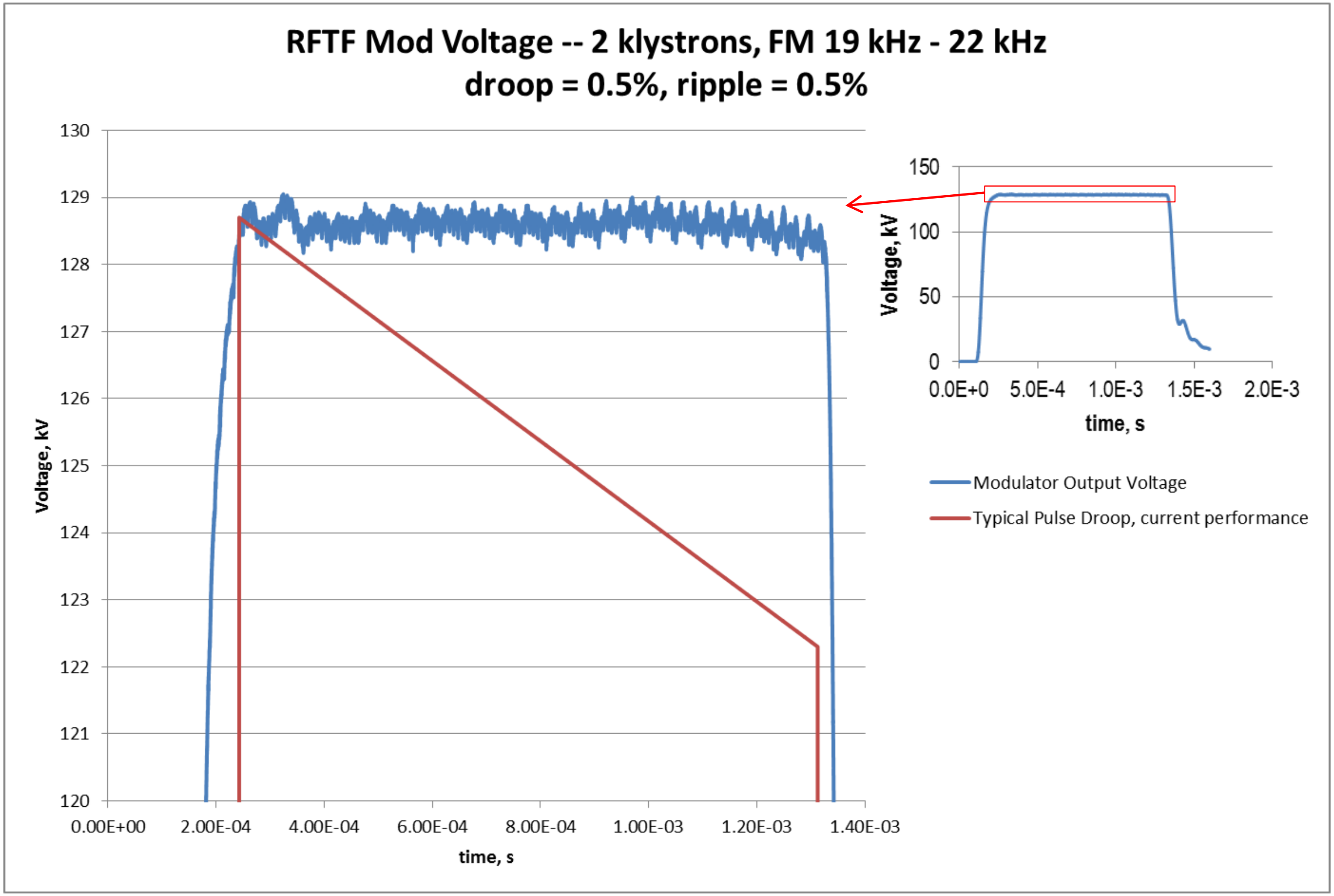
Switching losses measured over range of safe operating areas support minimal use of phase shift modulation



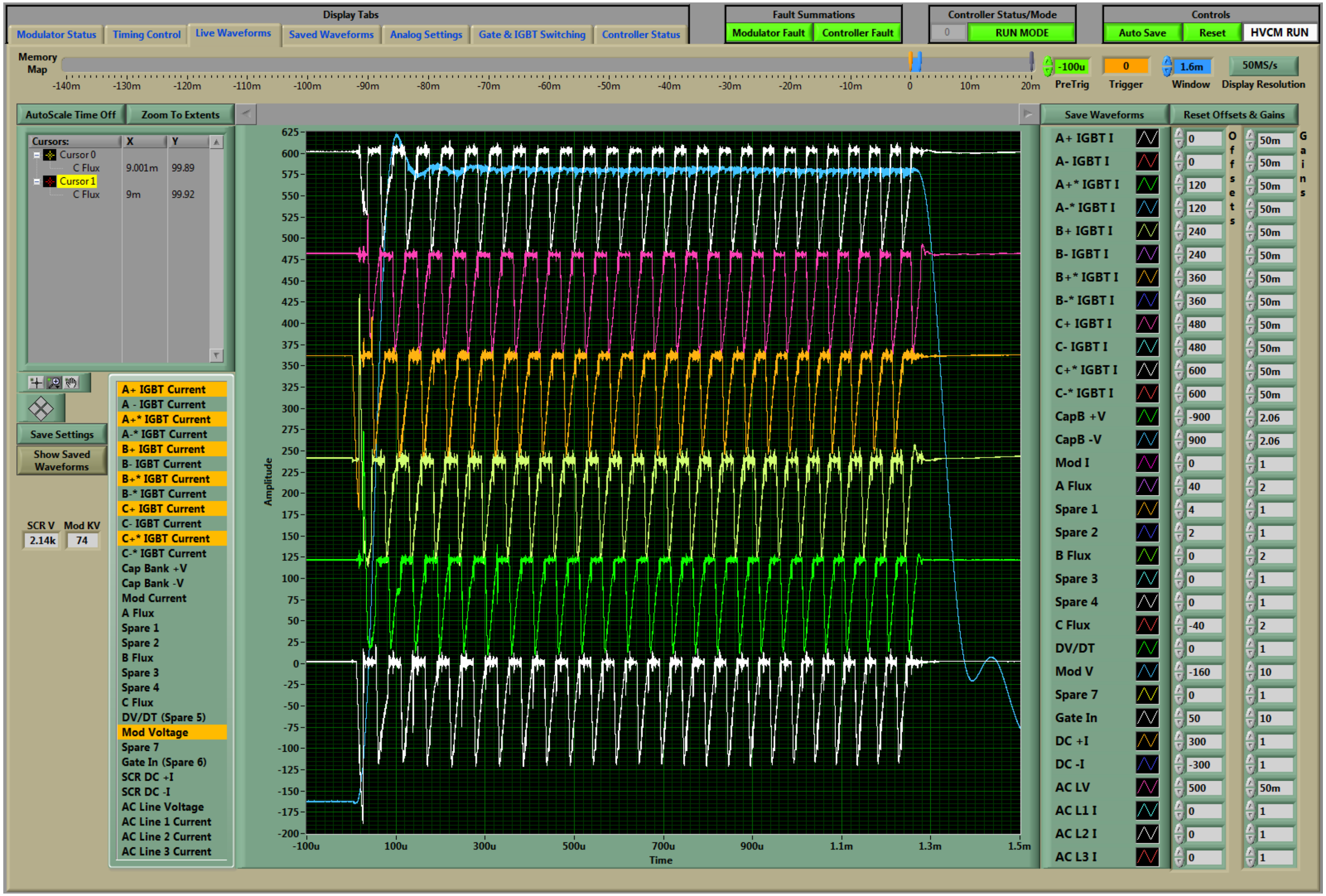
Switching losses increase greatly when employing any significant degree of phase shift modulation but are virtually unchanged over the spectrum of frequency modulation

Frequency Modulation alone can achieve flat top goals with minimal increases in switching losses

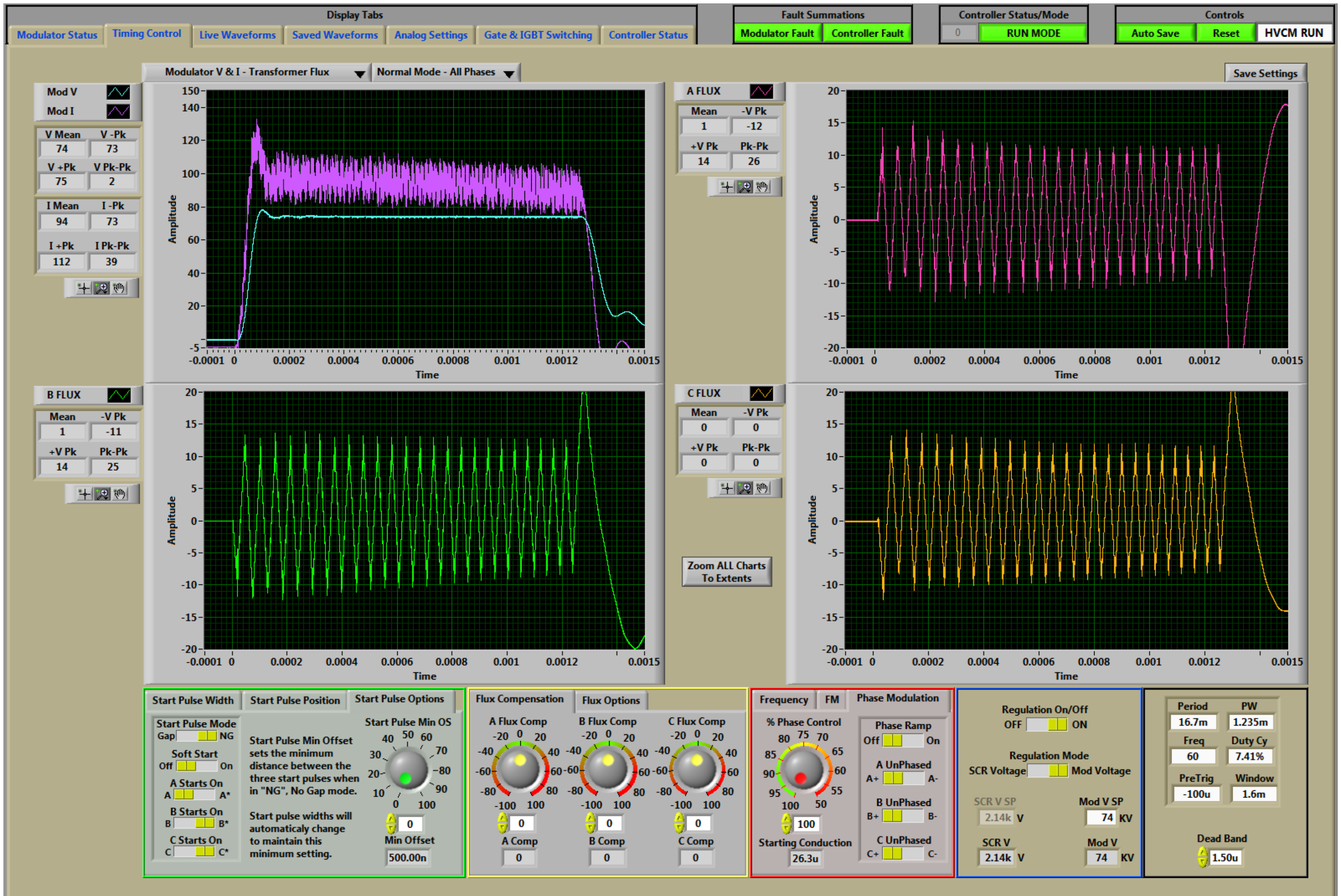


Operational for 100s of hours on NCL HVCMs, 1000s of hours on SCL HVCMs on test stands at full power

The existing controller does not support the proposed modulation scheme but the new controller does and can provide additional functionality…



The new controller enables all types of modulation and provides real-time waveforms for immediate assessment of timing changes…



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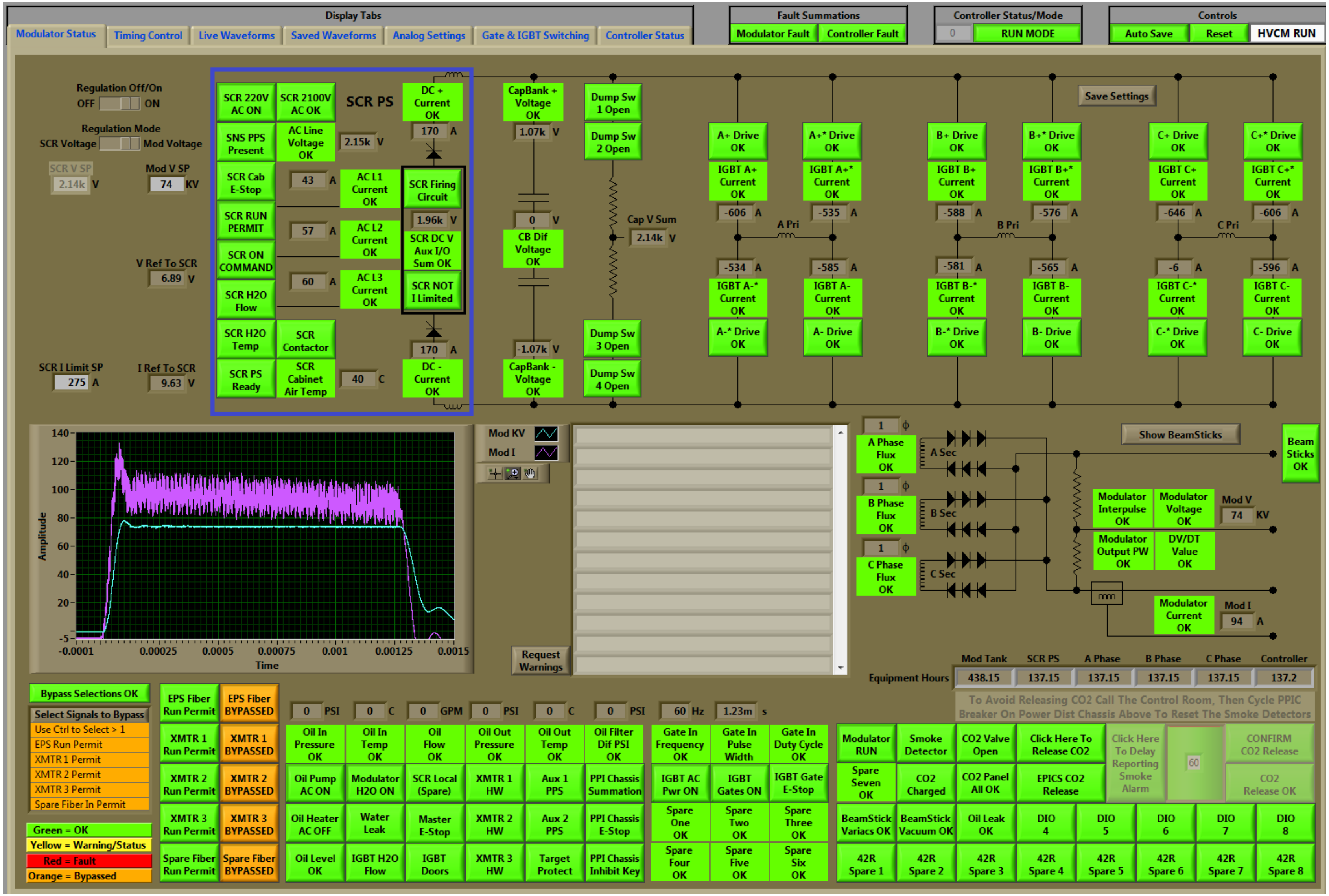
The new controller mimics current user interfaces and enhances them…



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All these features available in a COTS package utilizing LabView for programming flexibility and ORNL ownership

FlexRIO systems consists of:

- An embedded controller for communication and processing
- **Reconfigurable** chassis housing the user-programmable FPGA
- Hot-swappable I/O modules
- Graphical LabVIEW software for rapid real-time, Windows, and FPGA programming

Upgraded version (currently available) of the new controller provides:

EPICS interface

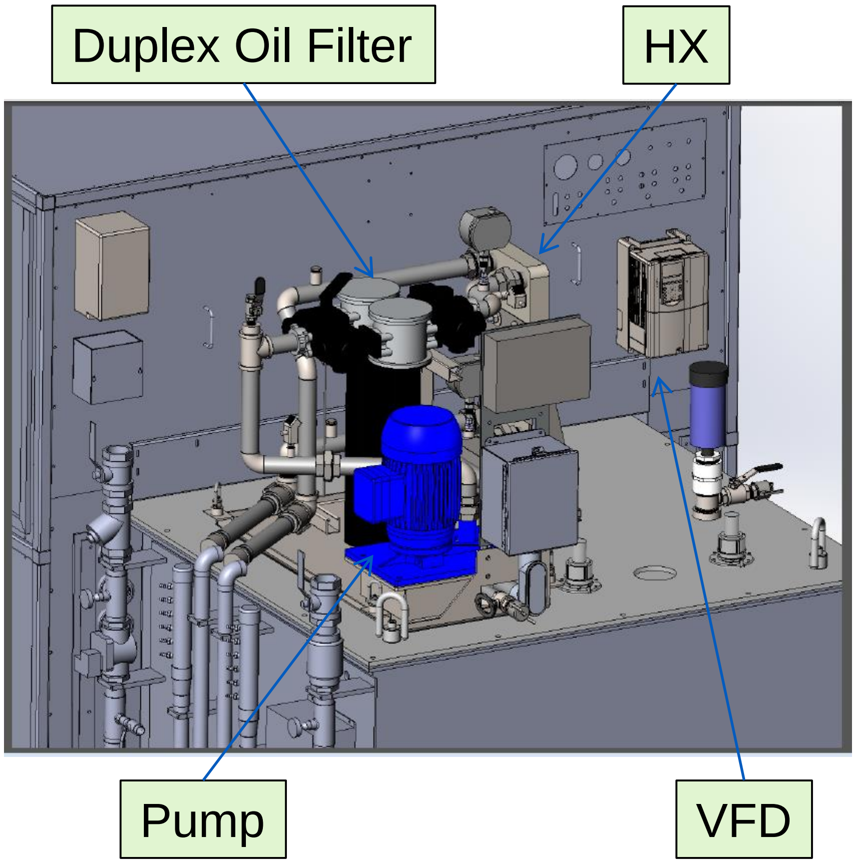
Flexible smoke detector logic

Enhanced IGBT monitoring (need to integrate with new drivers):

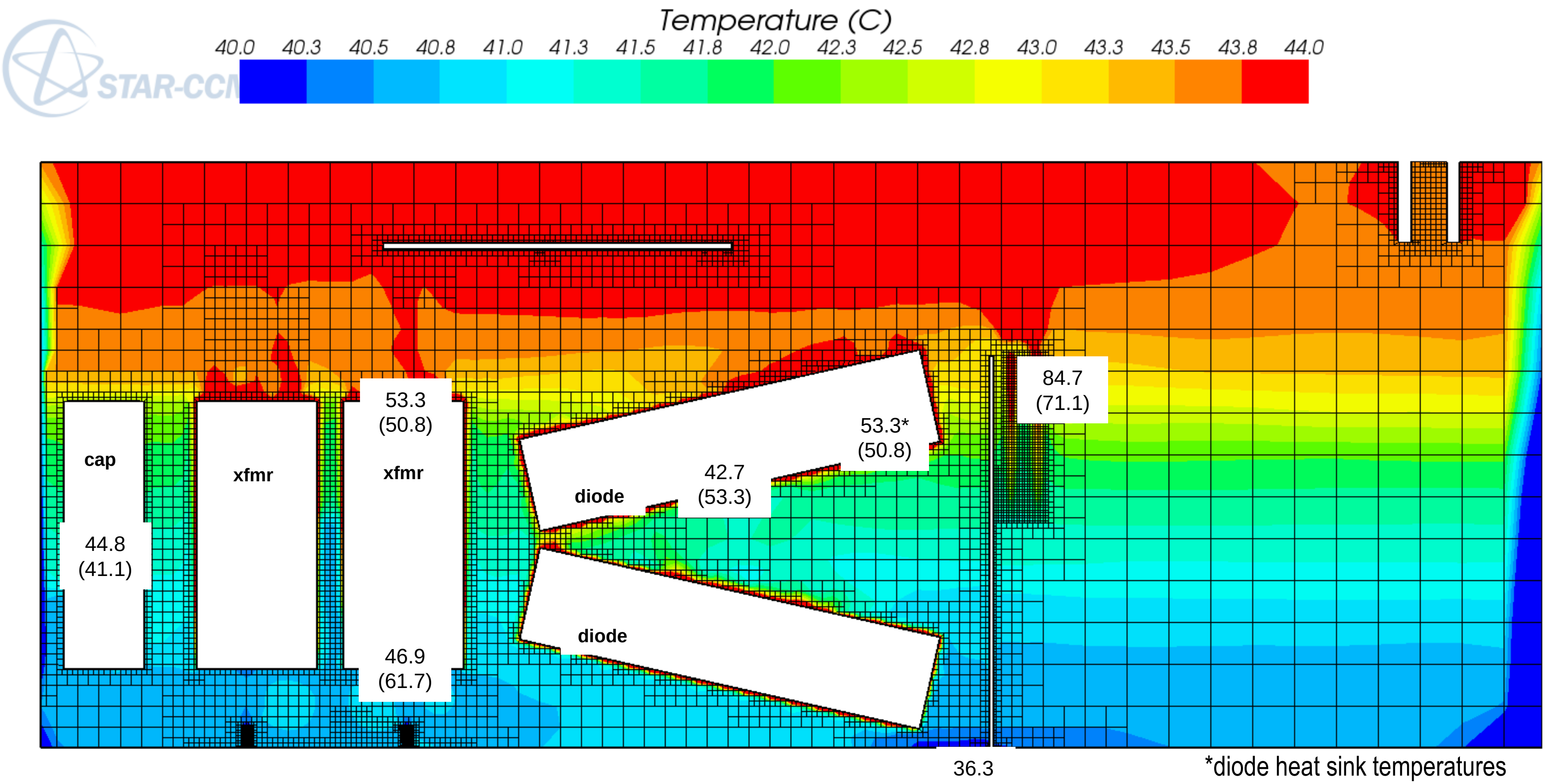
- IGBT shoot-through monitoring & warnings
- IGBT turn on & turn off monitoring, compensation & warnings

Enhanced reliability and reduced MTTR can be achieved by replacing existing oil cooling system

- 1st Article HVCM cooling skid is being built In parallel with this a Computer Flow/Heat Model is being built to simulate the cooling effects on the individual components within the tank
- The cooling system design will provide enhanced flow and heat removal capacity, remove the heat exchanger and filters from within the tank, and allow for quick and easy maintenance of the filter and pump
- Testing scheduled to begin mid-April and single unit installation during the summer outage 2015
- Combined with new controller, offers enhanced oil monitoring



Simulations of temperature profiles and flow rates with current system reveal system shortcomings



*diode heat sink temperatures

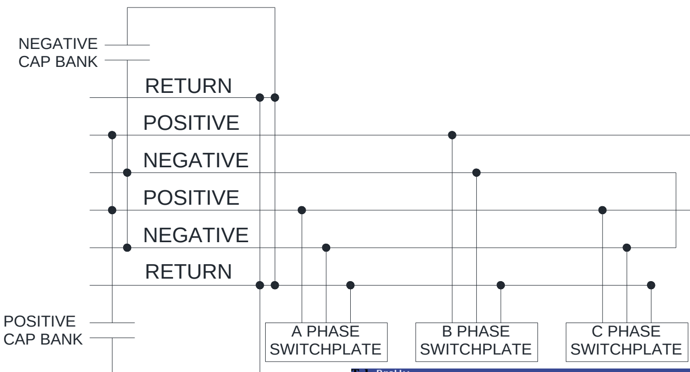
- Actual measured temperatures at rated power shown in °C in white boxes
    - Temperature after testing with prototype shown in parenthesis
- Model based on calculated power losses and estimated flow rate only
- Temperatures acceptable but oil stagnation indicates heat not being removed efficiently

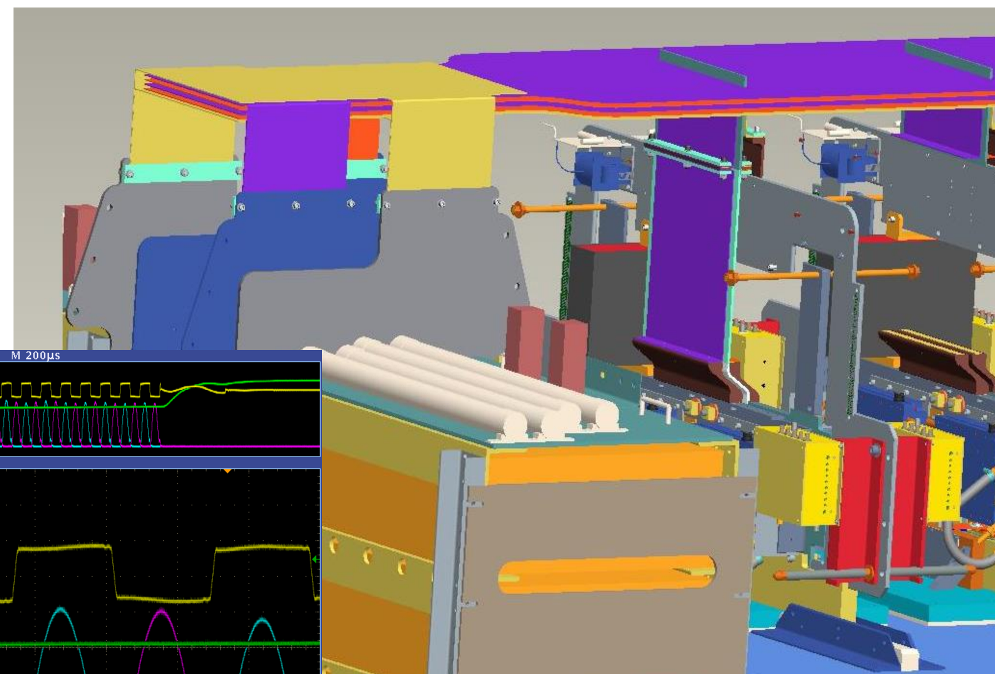
Laminated Bus

- Inductance of header cables, modulator capacitor bank and bypass capacitors form a high Q resonant circuit, which superimposes substantial ripple on the switch plate DC bus. The ~20kHz resonant frequency is not attenuated by the output filter components in the oil tank and appears on the output pulse delivered to the klystron load.

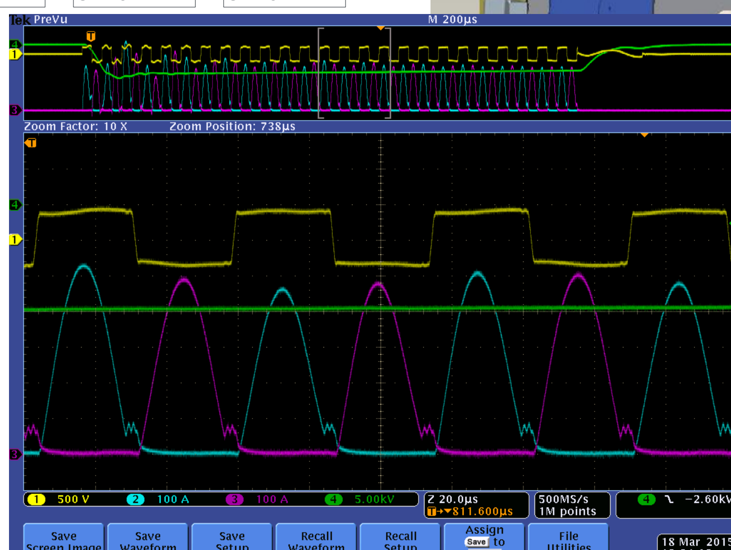
Proposed Solution

- Create a lower impedance (higher bandwidth) bus between main capacitor bank and each switch plate so energy is supplied directly from the bank. Match each phase loop inductance.





Ripple @ 1kv/div 400Vbus



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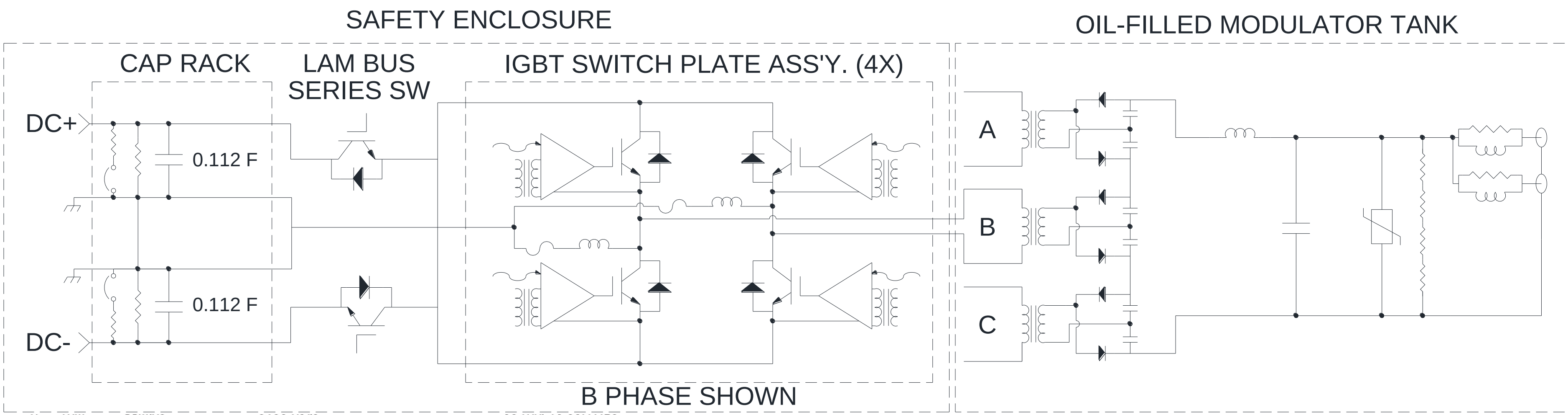
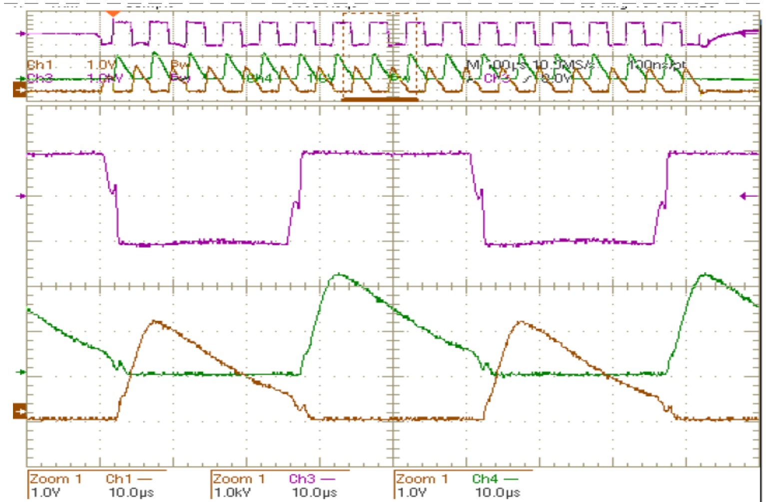
An alternate topology is under investigation for the higher reliability with applications to other long pulse facilities

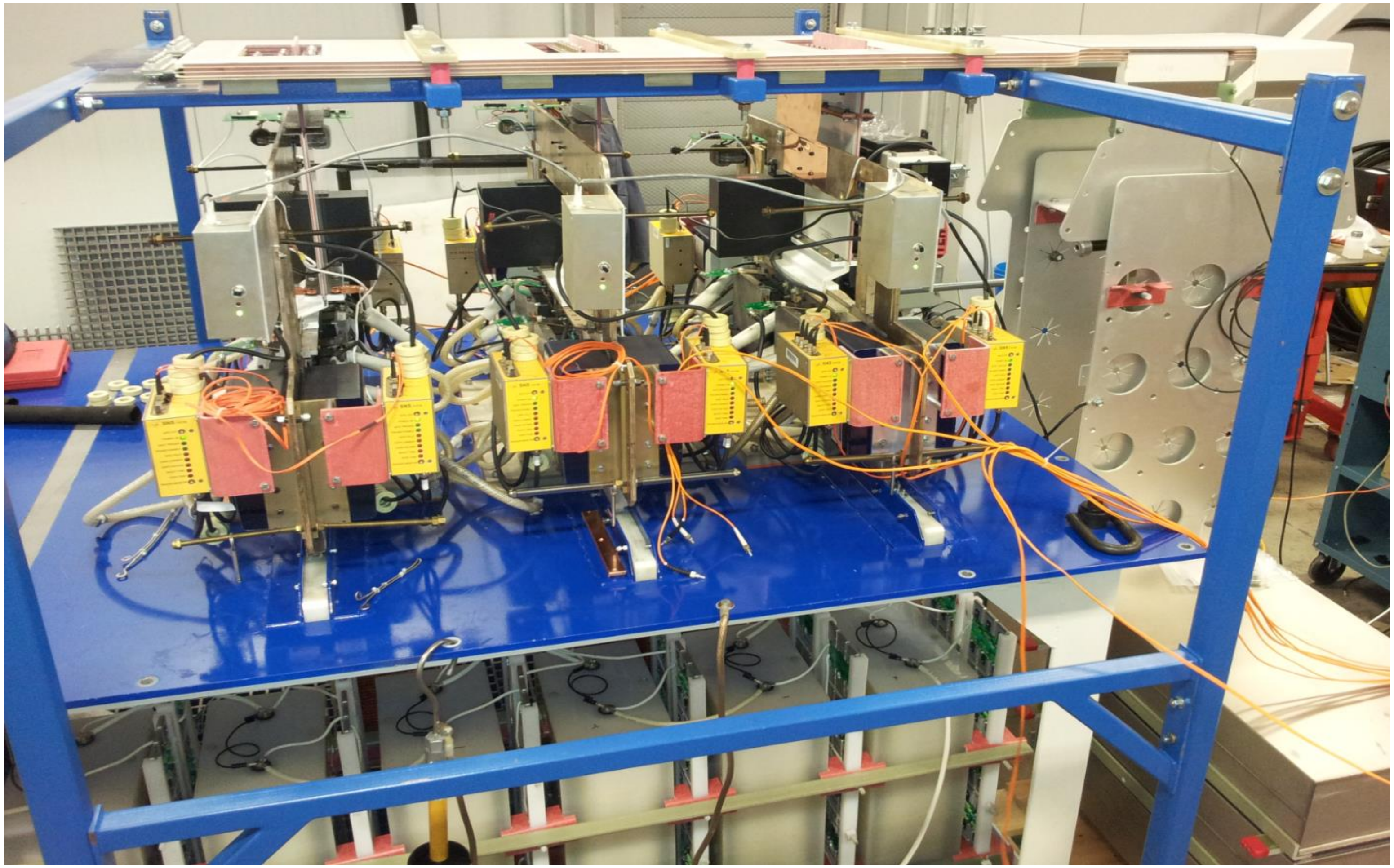




- Present IGBT voltage and current shown
- Not ZVS @ turn-on
- Load sensitive

- Alternate topology IGBT voltage and current shown
- ZVS @ turn-on from magnetizing current
- Load insensitive
- No voltage reversal on caps

Alternate Topology test stand



- New layout optimized by rotating transformers 90^o and by interleaving individual rectifier cards with their equivalent boost capacitor in the stack.

Summary

- **HVCM availability improved substantially and meets facility availability requirements**

- Synergistic solutions in development or installed to address remaining problems with HVCM to further improve reliability, increase available power and flatten pulse

- Capacitor problems continue but multiple options being evaluated

- Implementation of proposed alternate topology allows for future expansion & major subsystem redundancy
  - Supports needs of 2nd Target Station
  - Permits more flexibility with respect to load configuration

- The SNS modulator team and the demonstrated HVCM high availability makes this topology attractive to KAERI and the proposed MaRIE upgrade

- Other modulators (JEMA, DTI) being evaluated internally for future applications.

Backup Material

Recommendations from the last review are addressed throughout and paraphrased below

- Implement replacement of the new tested IGBT gate driver as soon as possible…The new driver design solves these IGBT driver problems.
  - Implemented on 11 of 15 units plus both test stands
  - Multiple configurations exist to address spurious trips from:
    - Higher than average di/dt on the RFQ modulator
    - Runt start pulses on most C phases
  - Current revision of circuit will permit consistency across all HVCMs once implemented
  - Upgraded gate driver PS reduces switching losses and eliminates gate trips under FM
    - Not necessary for current controller operation
    - Currently operating without incident on CCL-Mod1 & CCL-Mod2
- Install as soon as practical the tested snubber networks on the switch plate IGBTs…The installation of the snubber network will assure that there is no overvoltage of the IGBT during any abnormal control condition.
  - Implemented on 5 Of 15 units plus both test stands
  - No failed IGBTs on systems where snubbers are installed
  - Installation performed in conjunction with new IGBT drives
  - Will return and retrofit those without snubbers once all HVCMs have new gate drives

Continuation of recommendations from the last review

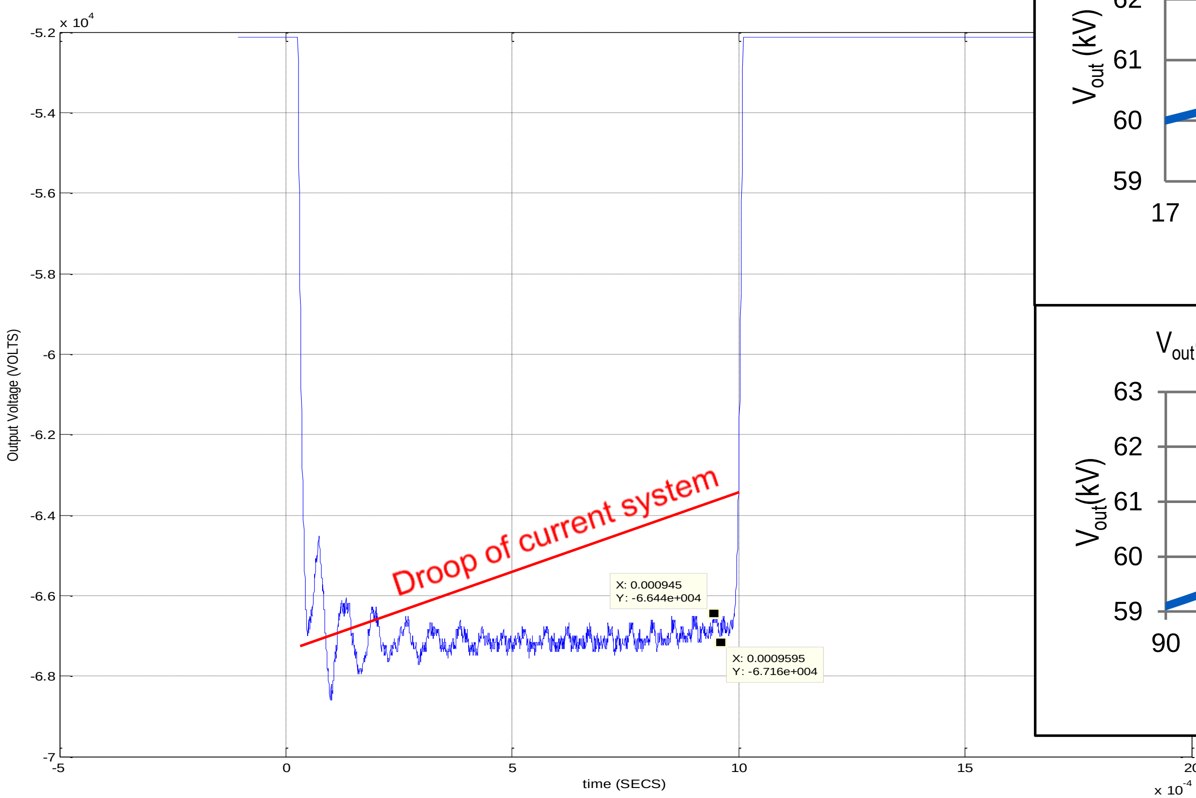
- Proceed with the replacement of the controller with the new flexible controller, which would allow for correct trigger control, droop correction and will provide improve monitoring of the HVCM during operation and faults.
  - Initial plans to install in the winter delayed by shortened outage duration
  - Currently plan to install on SCL-Mod14 in the summer
  - Currently running on HEBT and RFTF test stands
- To make 1.4MW possible the committee recommends that the proposed swappable 3 out of 4 redundant alternate topology be pursued vigorously...In addition to allowing redundancy to failure, it provides for a mechanism for clearing of the IGBT switch plate fault without exploding the IGBT...With a failure of one switch plate, the remaining 3 switch plates could continue to operate until an appropriate maintenance time for replacement.
  - Focus has been on alternate topology and associated discoveries
  - Series switch, a key component to 4 phases, demonstrated previously

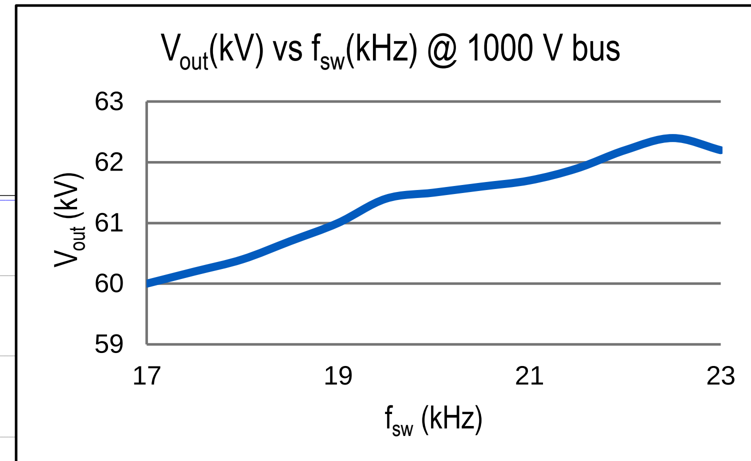
Early attempts utilizing Phase Shift and Frequency Modulation achieve pulse flattening and have been demonstrated at 60 Hz full power on a SCL system

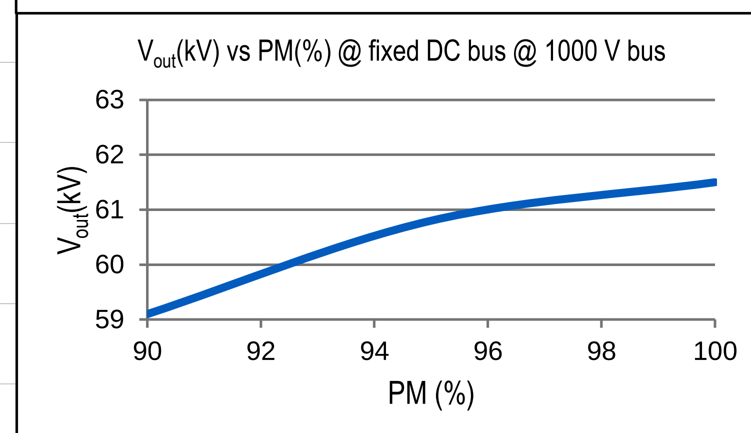
Output Voltage= 61.8 kV
Bus Voltage= +/- 1004 V
FM = 20 kHz to 22 kHz
PSM = 95% to 100%

→

$\Delta Vdroop$ = *304 V/ms (0.5% vs. 3-5% currently*
$\Delta Vripple$ = *664 V*







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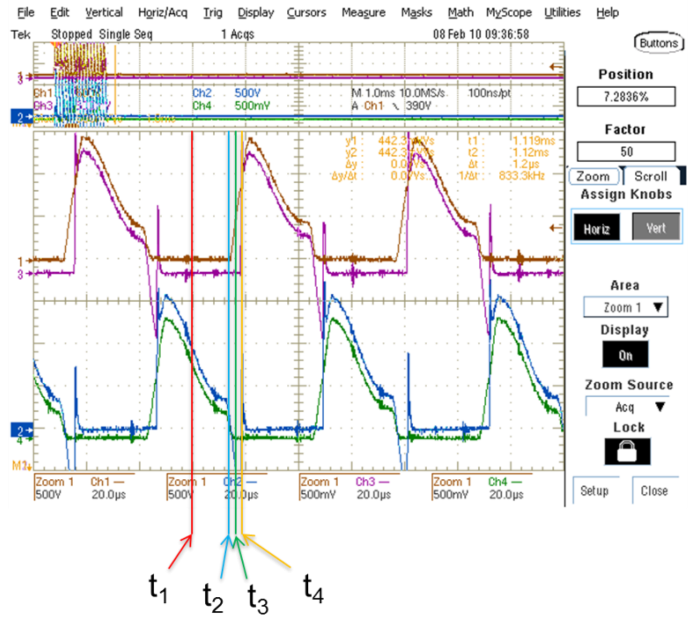
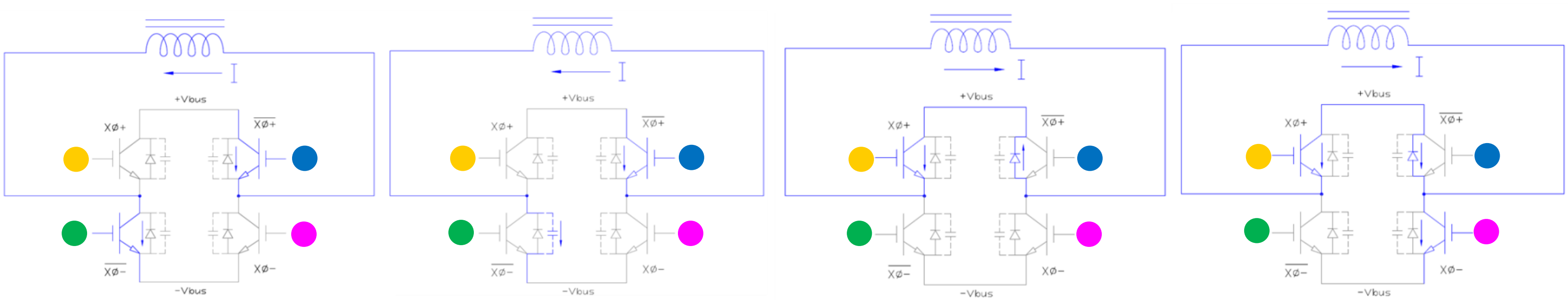
Pulse flattening originally included provisions for Phase Shift Modulation which introduces large switching losses



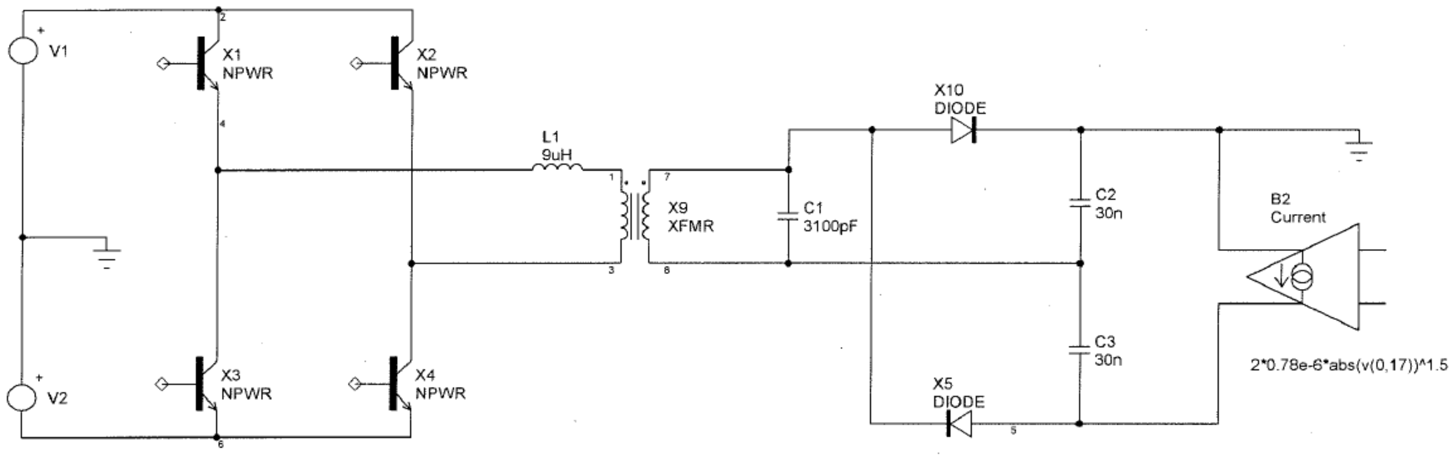


$t=t_1$ $t=t_2$ $t=t_3$ $t=t_4$

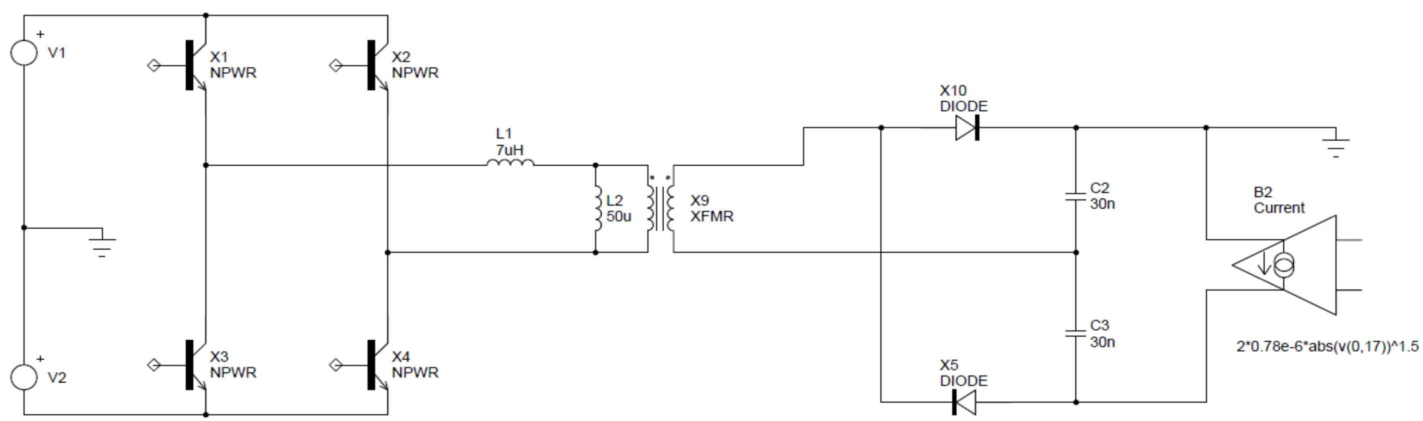
16 kHz, 13% phase shift (8.1 μs) shown. When X- turns on at t_4, current that has built up in X+ PLUS I_{rr} of X+* body diode creates large current spike, increasing switching losses in X- IGBT

HVCM Topologies

Present design: three phases are interleaved and connected in parallel

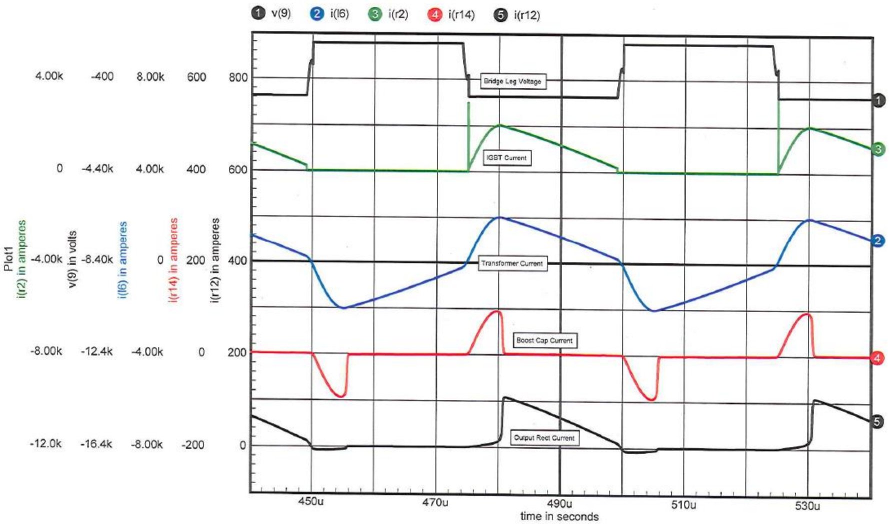


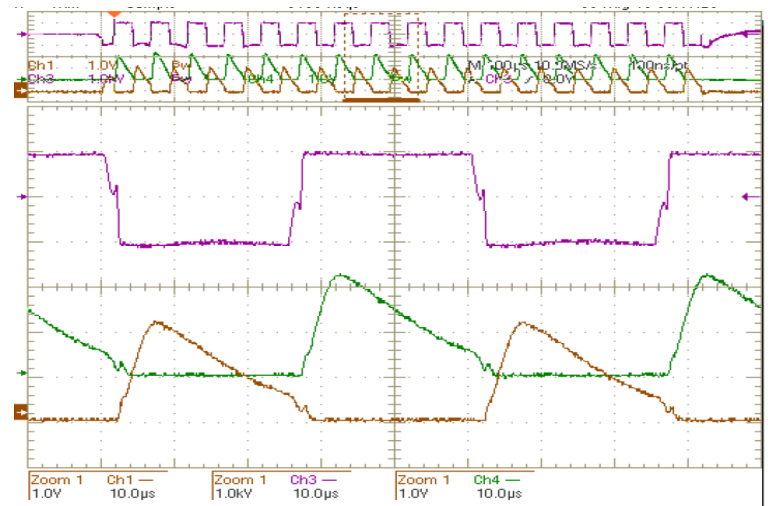
New design: three phases interleaved and connected in series.



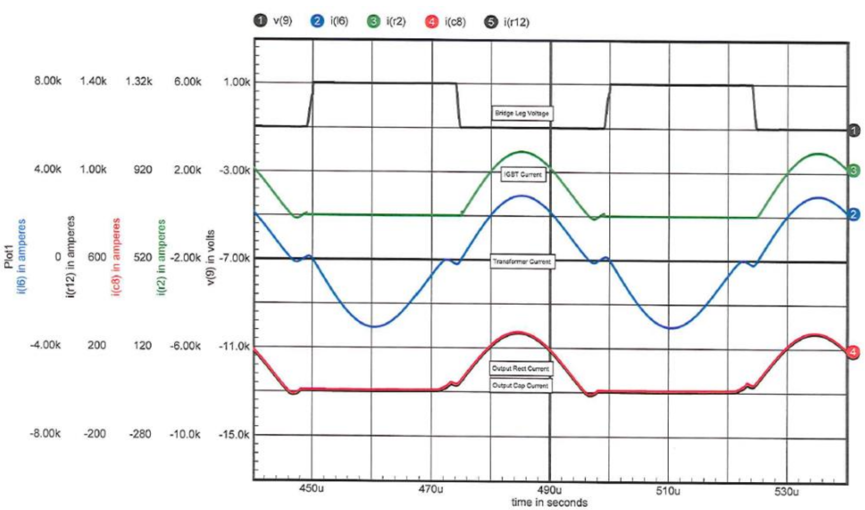
SPICE waveforms for 2 DTL 2.5 MW klystron load

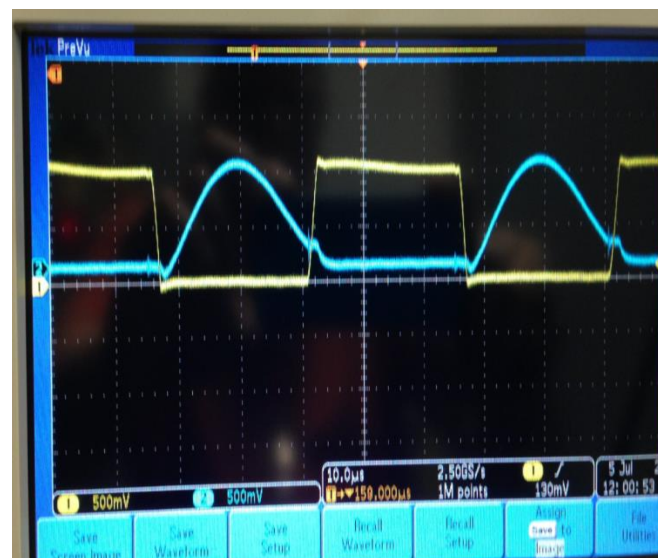
Existing HVCM design





Alternate topology





Challenges remain on HVCM systems which are still judged to be potential vulnerabilities, particularly for the future of the facility

- Boost capacitors
- Obsolescence
- Aging electromechanical components
  - Relays
  - Fans
  - Pumps
  - Flow/temperature/pressure transducers
  - PLCs (relay outputs)
- As-builts and update documentation
- Configuration management
- Spares and inventory management
- Work control
- Train personnel on new subsystems

An alternate STS solution, the hybrid inverter – Marx modulator from JEMA, is awaiting testing at ORNL

- On-site with preliminary checkout performed
- Awaiting installation of infrastructure to support preliminary testing
- Required significant improvement of safety systems to meet DOE Electrical Safety requirements
- Specified to drive 12× 700 kW CPI klystrons (85 kV, 160 A)