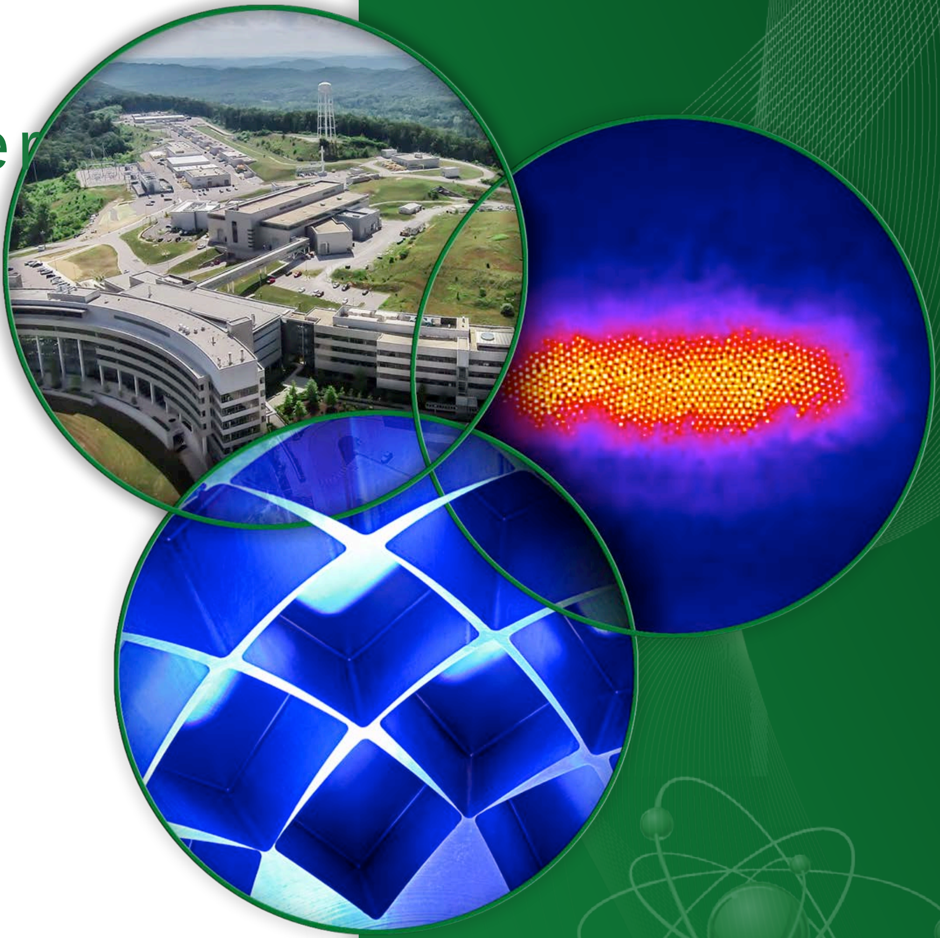
Availability Challenges and Solutions Associated with the High Voltage Converter Modulator at the Spallation Neutron Source



Presented at the

Accelerator Reliability Workshop

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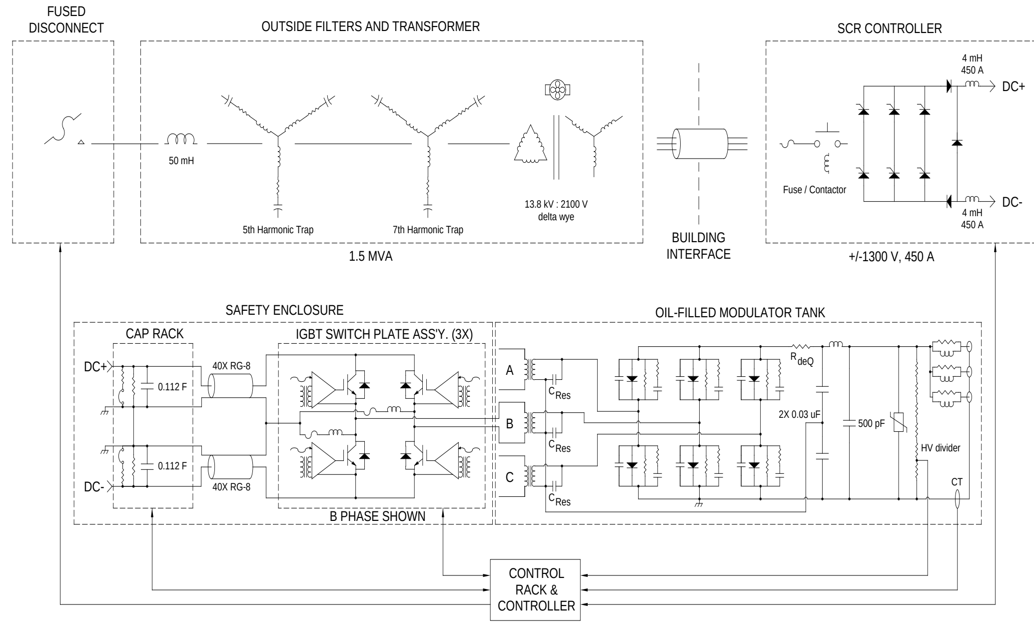
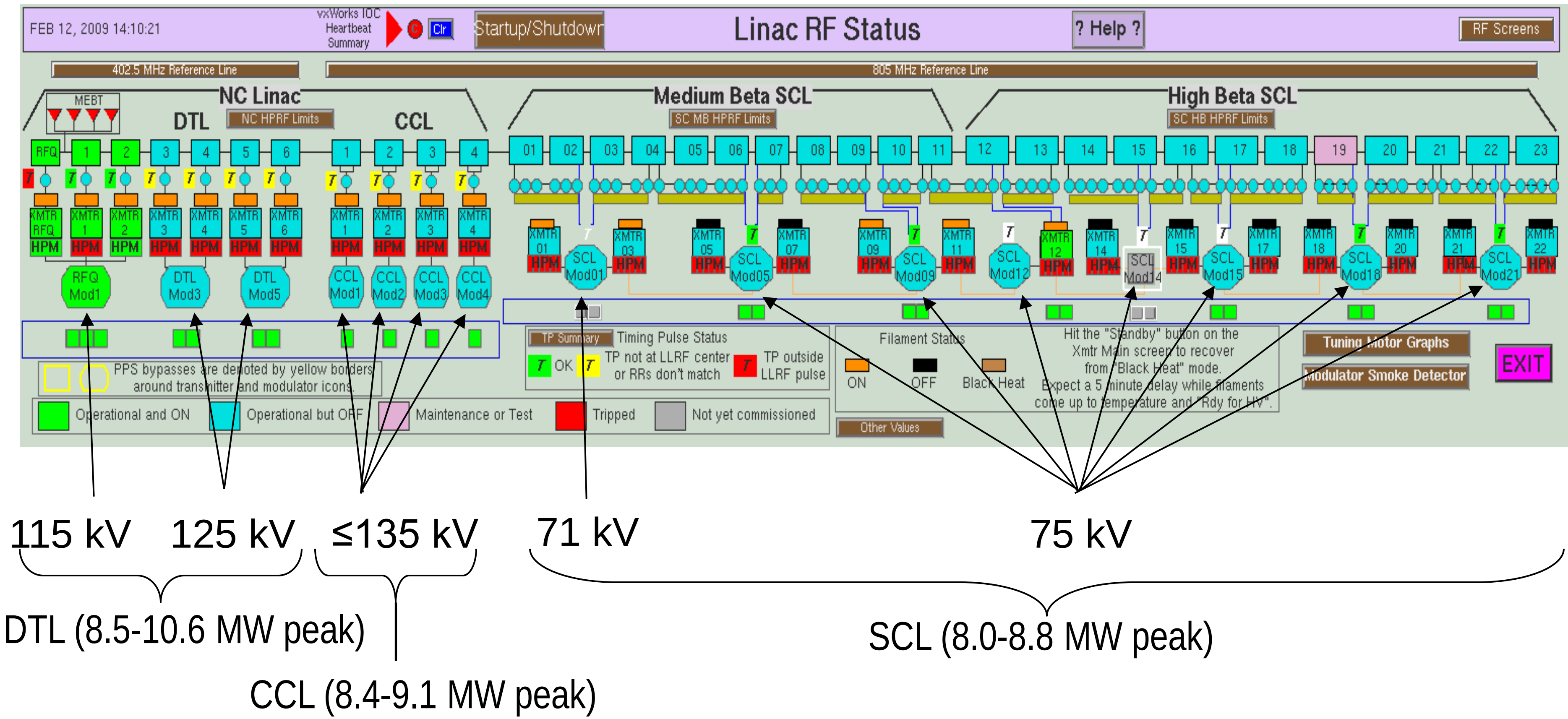
- System overview and history
- Modulator performance during life of the facility
- Early solutions to address system shortcomings
- Other techniques employed
- Prioritization and motivation of current and future upgrades
- Overview of current and future upgrades
- Conclusion

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 up 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



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



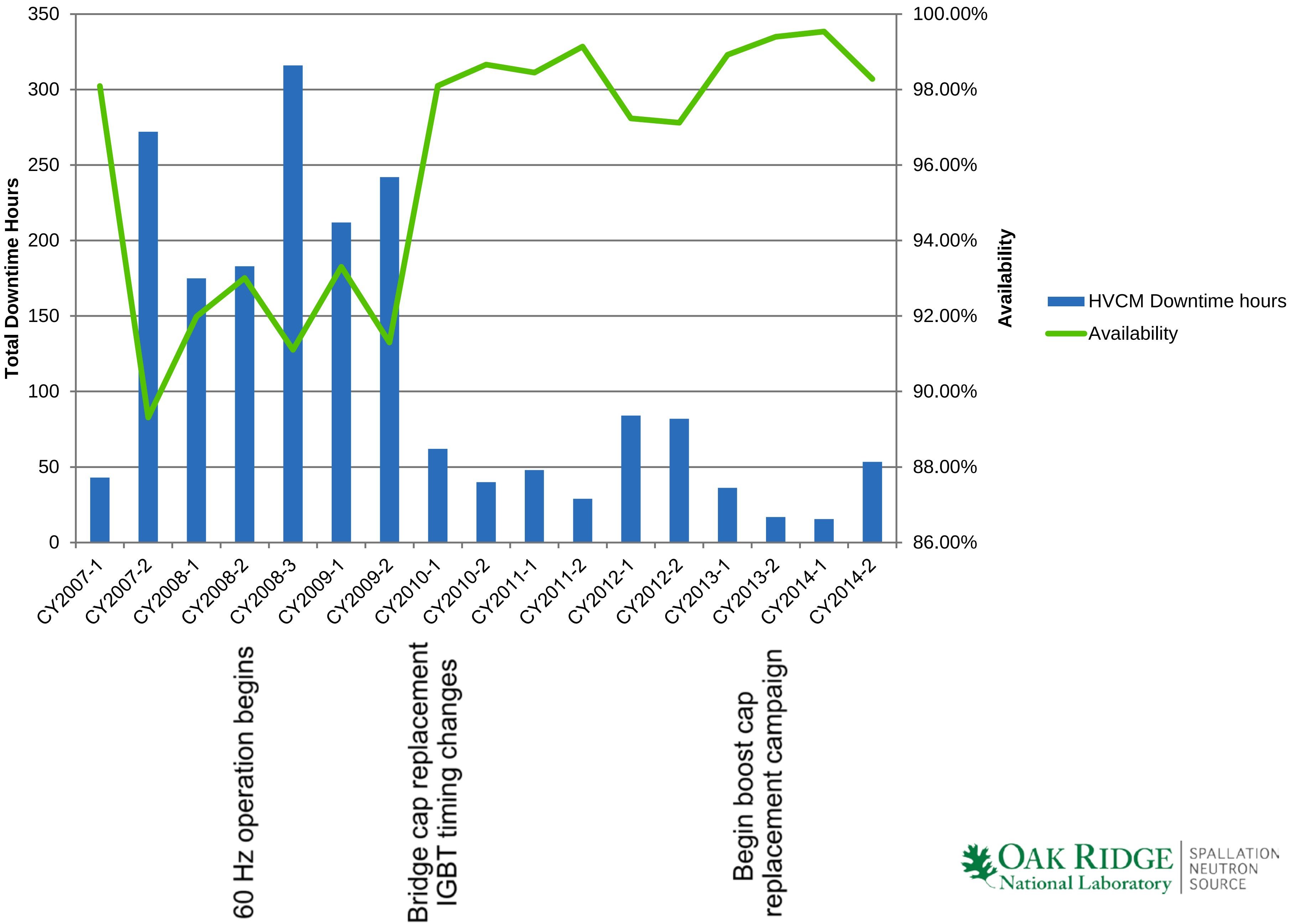
- 15 modulators: 3 - DTL, 4 - CCL, 8 – SCL (1 added 2008)
- Multiple HVCM/Klystron Configurations
- ~750,000 combined operational hours on all modulators

Quick History Lesson important when considering reliability and upgrade priorities

- Designed and procured by LANL
  - Build-to-print on modulator subsystem
  - Other subsystems built to functional specification
  - Subsystems installed, integrated, and tested at ORNL

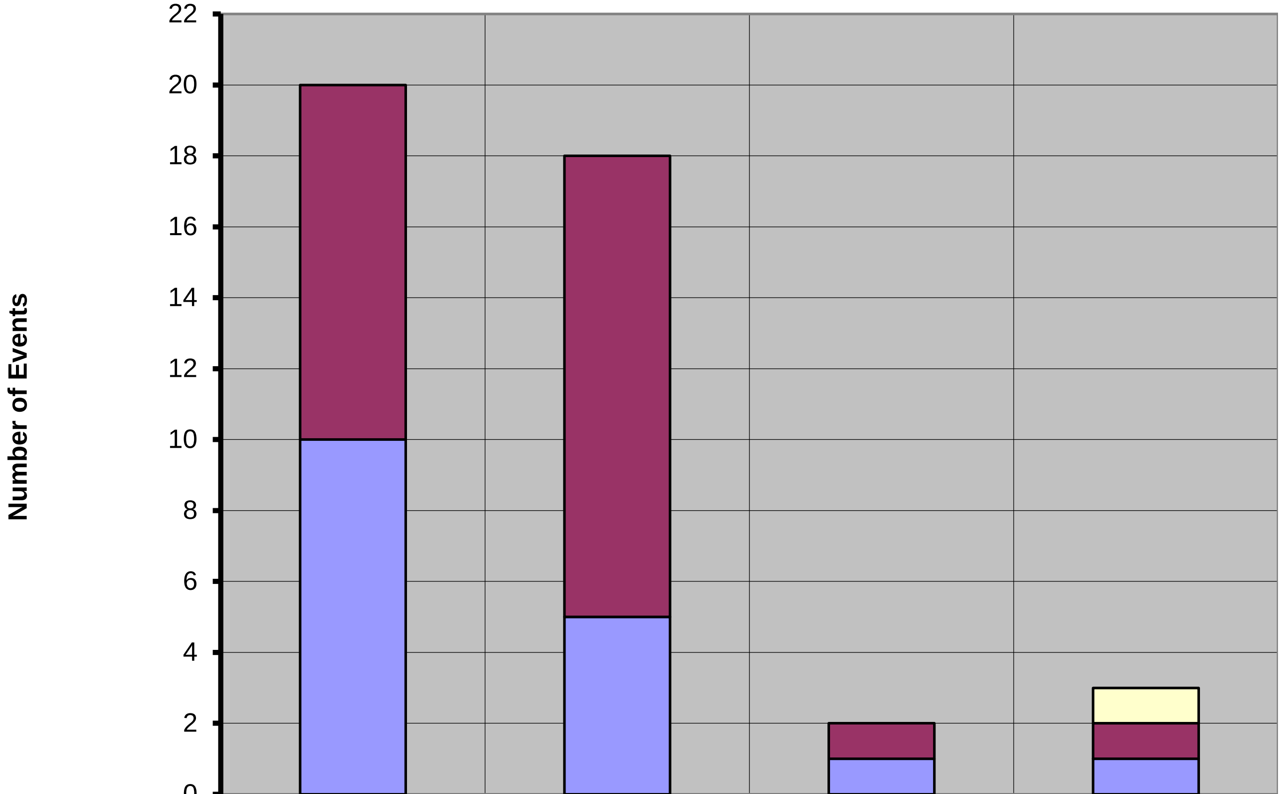
- Installation November 2002 – April 2005
- Initial operation up to 10 Hz w/ select testing to 60 Hz
- Operation currently at 60 Hz (began April 2008 at 200 khours total) with varying duty cycles
- Full 1.4 MW of beam delivery demonstrated with ~2 years of operation at that setpoint

HVCM Downtime Hours over SNS Facility History



HVCM Early History "Smoke Generating" Events identified low reliability components

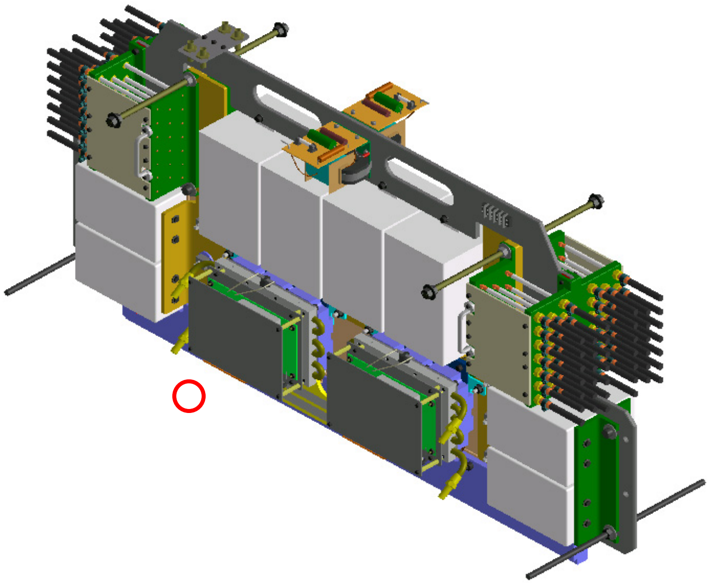
HVCM Smoke Alarm Events by Run and Cause



	Sept. - Dec. 2008	Feb. - July 2009	Sept. - Dec. 2009	Feb. - Apr. 2010
Cable Header				1
IGBT	10	13	1	1
HV Capacitors	10	5	1	1

HVCM Fire Causes – Bus Arcing was an early failure mechanism

- Workmanship or residual dirt believed responsible
- Repeated arcing acted as ignition source for combustibles
- Corrected with improved training of assemblers and full peak power testing, no faults w/ same root cause since (Jan 07)



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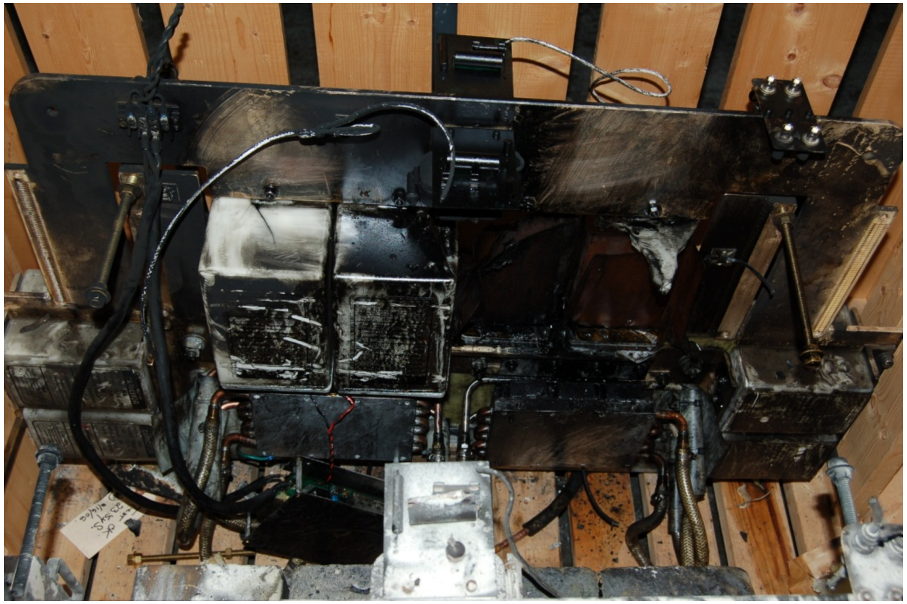
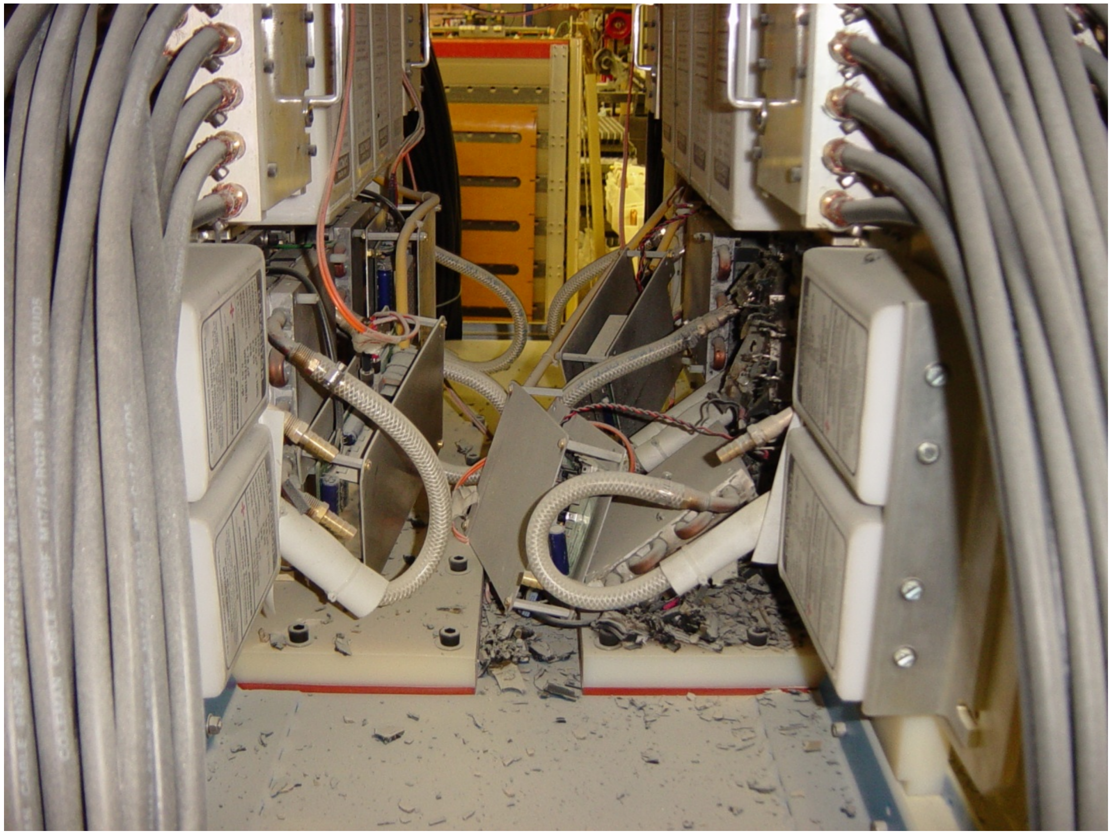
HVCM Fire Causes – Capacitors failures were quite catastrophic and identified low MTBF component

- Mfgr.'s cap lifetime ratings 100,000 hours @ 3000 V
- Experience indicates MTBF 10-15 khours @ ≤ 2300 V
- Alcohol-based dielectric fluid compounded the problem
- Replaced all caps w/ higher lifetime / metallized film caps (mfgr's MTBF = 150,000 hours)



HVCM Fire Causes – IGBT failures created serious challenges and “false alarms”, revealed over voltage problem and workmanship concerns



- Usually less severe, lower collateral damage
- At transition to 60 Hz operation, incidents increased significantly
- Improved thermal bonding procedures implemented
- Over voltage problem resolved with gate timing changes and snubbers

Other techniques applied to improve system reliability

- Extensive assembly procedures with technician/engineer signoff
- Subsystem testing throughout lifecycle
  - Performance and burn-in testing of new, major subassemblies
  - Performance and burn-in testing of repaired subassemblies
  - New component testing at least equivalent to manufacturers' program
  - Periodic testing of critical components in-situ
- Device characterization for known failure mechanisms
- Quarterly dissolved gas analysis and hipot testing of oil to uncover incipient failures (see D. Brown, this workshop)
- Formal turnover documentation for configuration control
- Key parameters continuously monitored with system shutdown
  - dv/dt for arcing faults
  - Overcurrent for component failure
  - $V_{CE,sat}$ for IGBT lifetime monitoring (pending)

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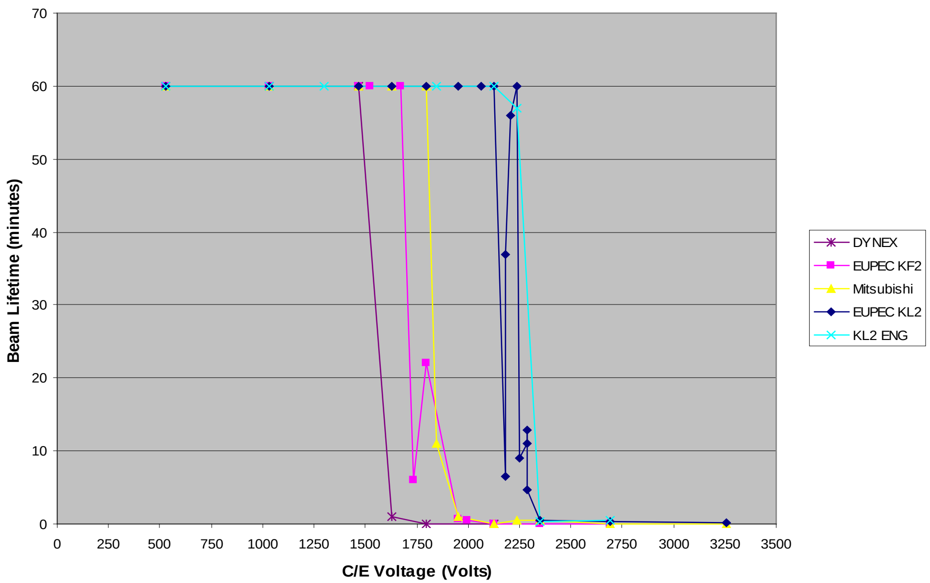
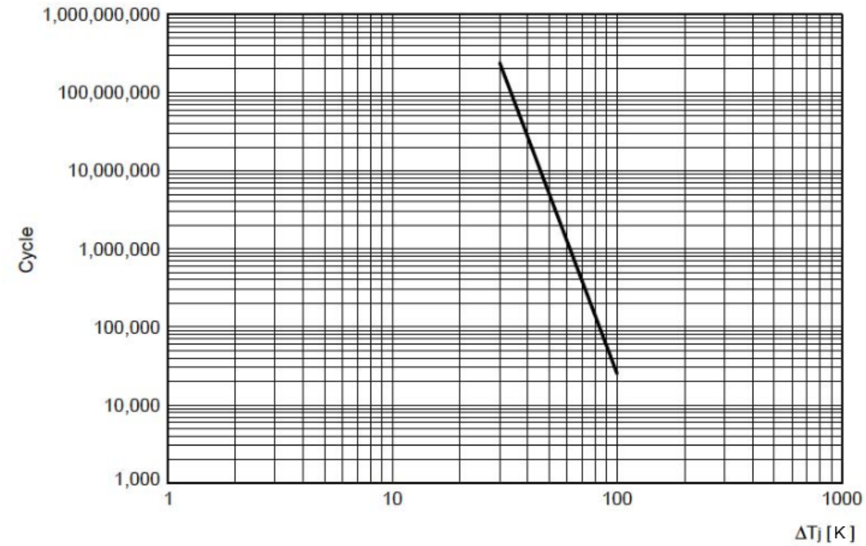
Example of Key Component Characterization – IGBT Failure Rate Comparison for Known Failure Mechanisms

- Cosmic radiation and thermal cycling are the primary failure mechanisms for Si-based devices at high junction voltages
- Characterization of 3300 V, 1200 A devices at Weapons Nuclear Research Center





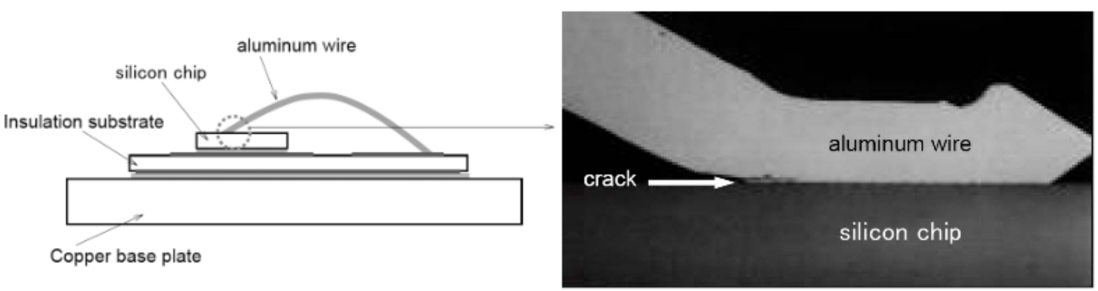


Fig.5 Bonding Surface Fatigue Caused by Power Cycle Testing

$\Delta T_j = \Sigma P_{avg}[\theta_{th}(\tau\text{-}t_n)\text{-}\theta_{th}(\tau\text{-}t_n\text{-}\delta t)] = 17°C$

$MTBF_{TC} \geq 10\times10^9/(60\ Hz\times31.5\times10^6) =$ 5.3 years

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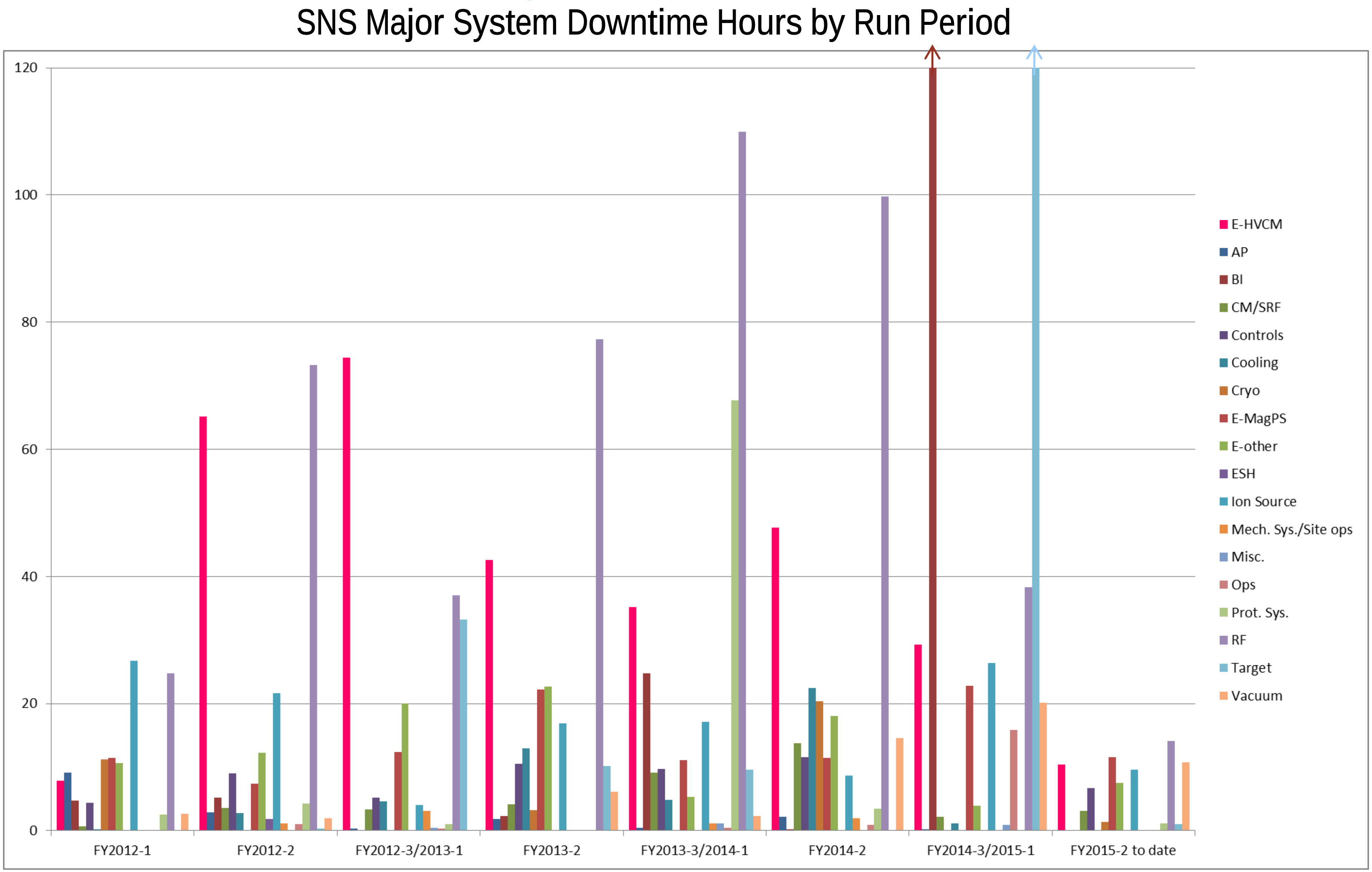
The HVCM systems continue to contribute to accelerator downtime but show improvement



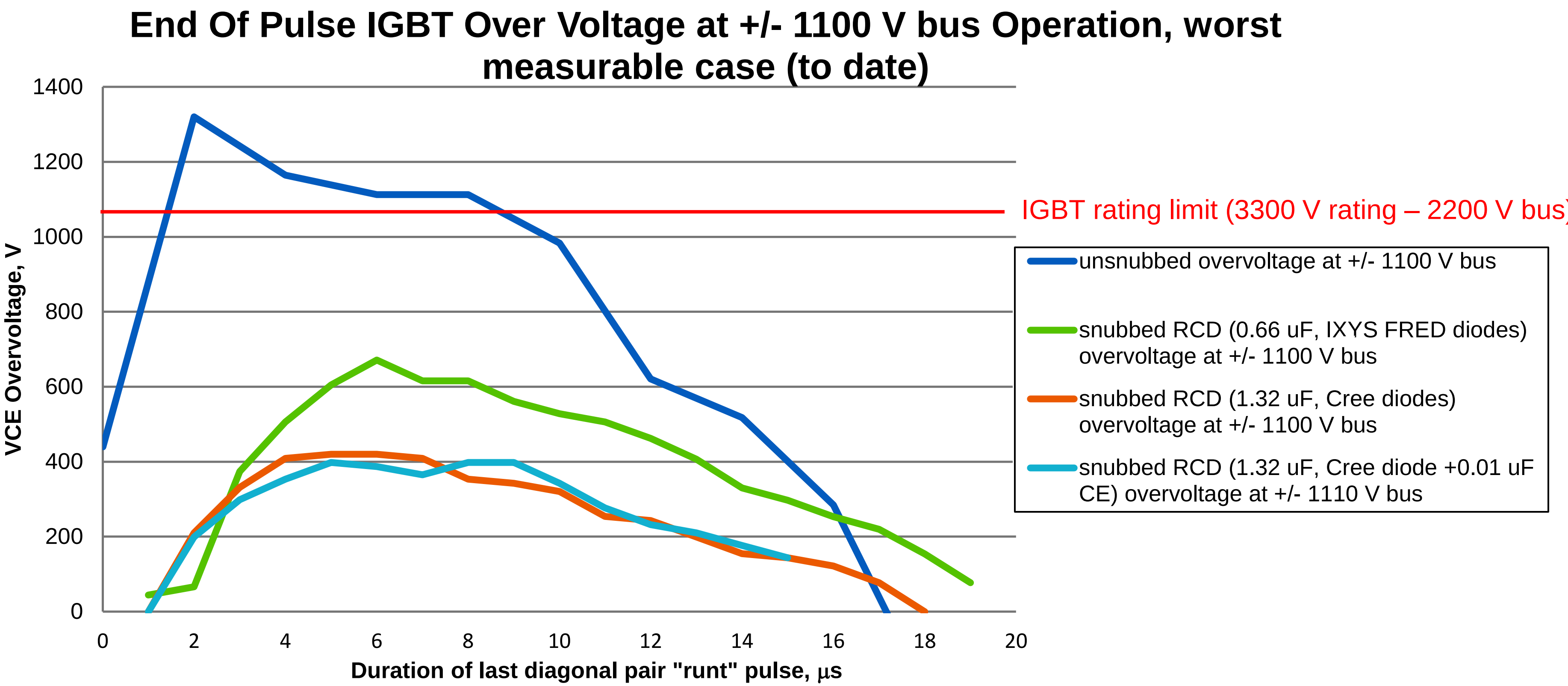
Analysis of major failures by major component & subsystem is critical to identifying areas for improvement

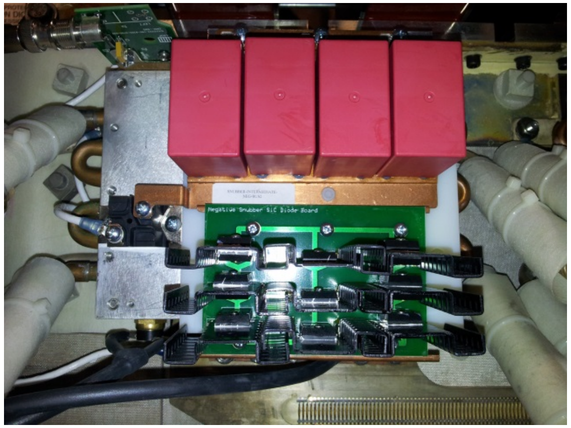
Downtime Hours	FY2012-2		FY2012-3/ FY2013-1		FY2013-2		FY2013-3/ FY2014-1		FY2014-2		FY2014-3/ FY2015-1		Σ Hours
Scheduled Beam Hours	3130		1868		3353		2789		3331		3105		17.576
Fault Type	BT	nBT*	BT	nBT*	BT	nBT*	BT	nBT*	BT	nBT*	BT	nBT*	
Boost Capacitor	29.7	7.2	8.9	3.5	20.2	5.5	10.4	-	-	-	-	-	85.4
IGBT/driver	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

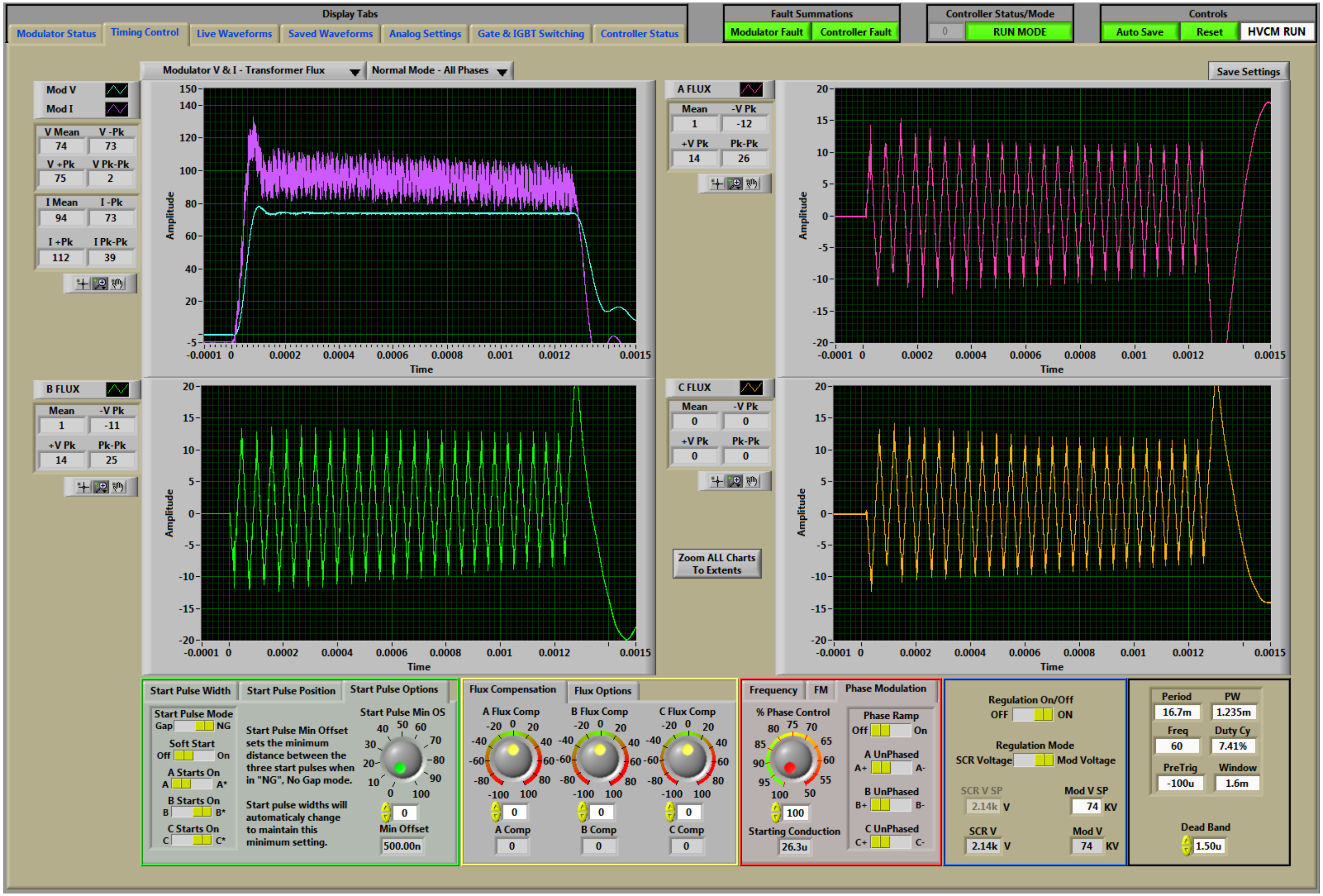
Adding IGBT snubbers permits higher voltage operation, reliable higher current IGBT operation & eliminates fault over-voltage problem





- 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

The new controller enables all types of modulation and provides real-time waveforms for troubleshooting while eliminating obsolescence and improving reliability



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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
- Custom interface modules are simple designs employing buffers and op-amps for signal conditioning and gain control
- Entire system should prove to be much more reliable, more easily maintained and permit more system flexibility

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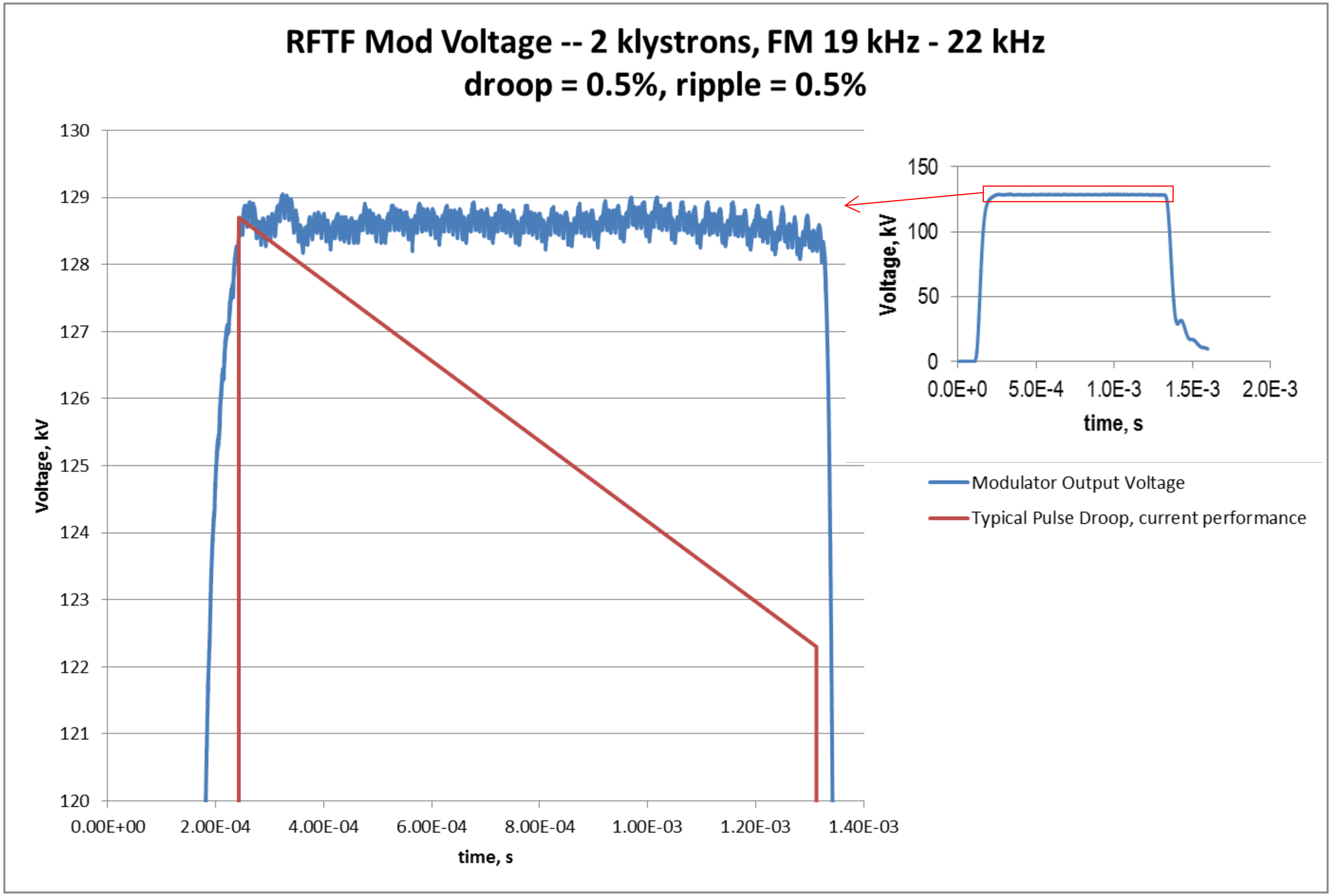
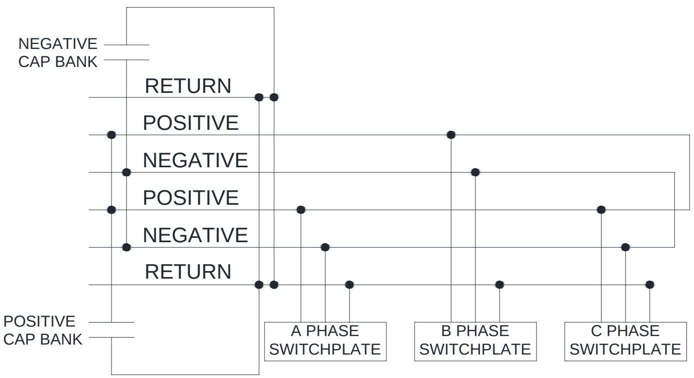
New controller also permits Frequency Modulation to achieve flat top goals with minimal increases in IGBT switching losses

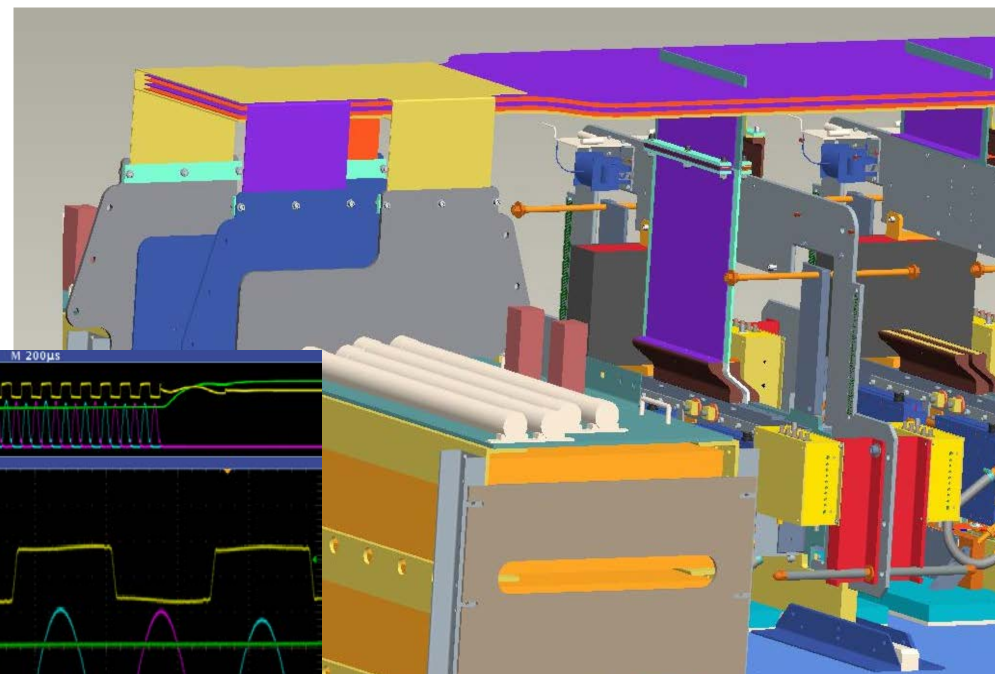


Operational for 100s of hours on NCL HVCMs, 1000s of hours on SCL HVCMs on test stands at full power

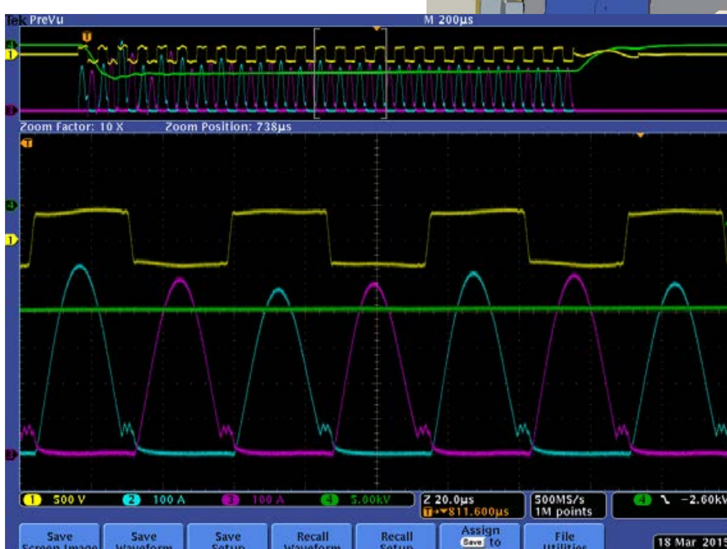
A custom commercial laminated bus appears to eliminate the ripple problem associated with the current HVCM bussing

Creates 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

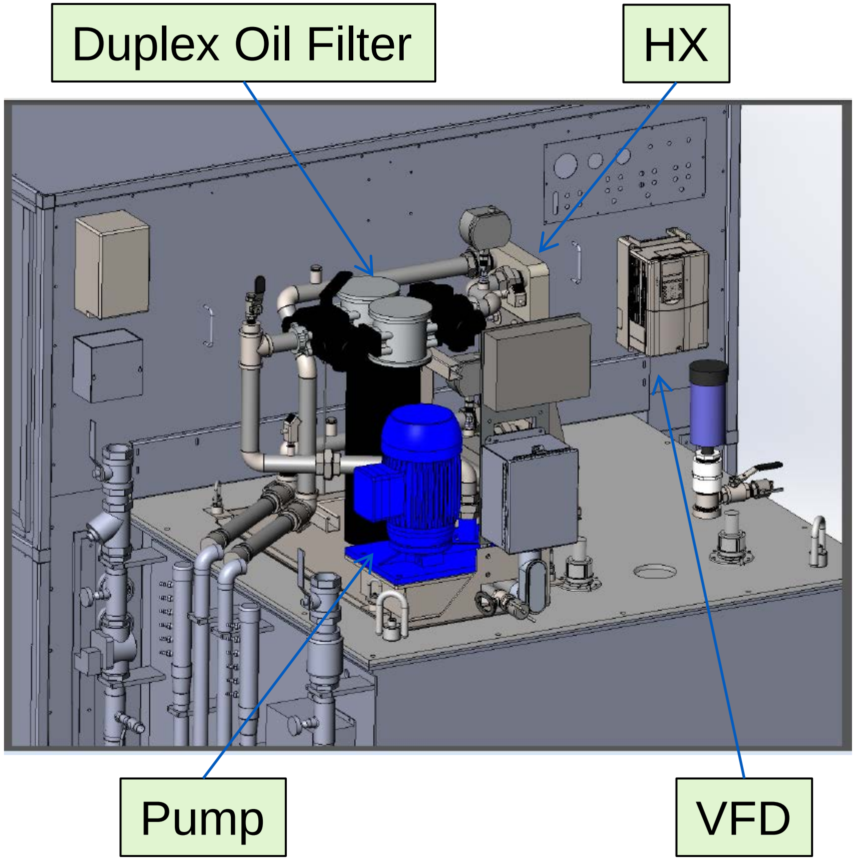


Combined effects of the recent aforementioned upgrades permits better LLRF performance and enhanced RF reliability

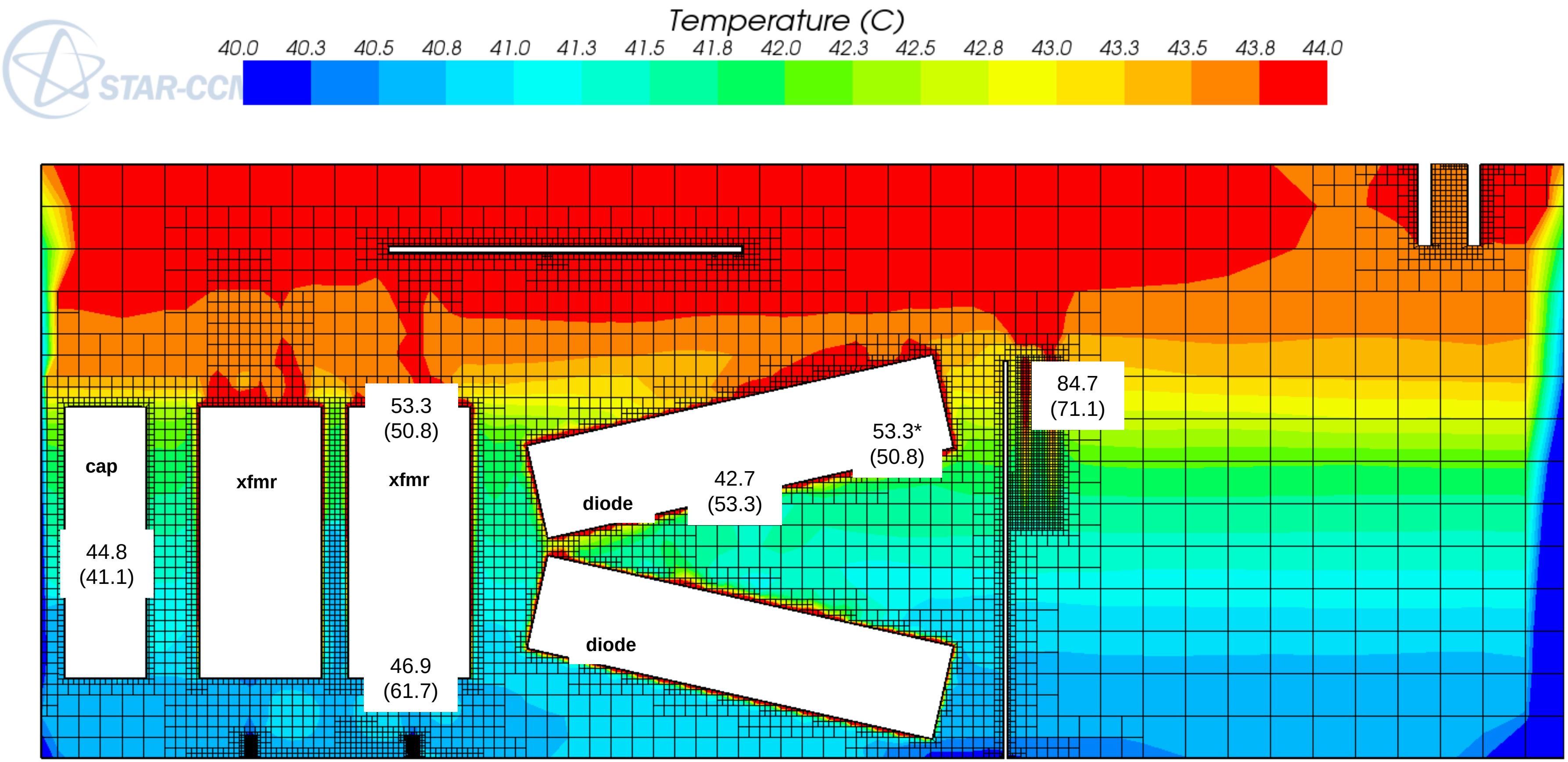
- No longer necessary to over-drive the klystrons at the beginning of the pulse
  - Reduced voltage stresses
  - Longer life for the klystron, filament transformers, other RF HV components
- LLRF control margin will be restored at the end-of-pulse
  - Improved field fidelity
  - Better utilization of modulator pulse widths and possible reduction of system average power
- Lower ripple may reduce LLRF complexity for next-generation design
- Minimal impact on modulator operating parameters

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

- Current system is submerged in the oil tank, creating long MTTR for oil circulation / heat exchanger system
- 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 end of May 2015 and single unit installation during the winter outage 2015
- Combined with new controller, offers enhanced oil monitoring



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



- Actual measured temperatures at rated power shown in °C in white boxes
  - Temperature after testing with prototype shown in parenthesis
- Even lower temperatures can be achieved with improved oil circulation
- Should permit a factor of 2 or better increase in component MTBF

Summary

- HVCM availability improved substantially and meets facility availability requirements
- Previous upgrades resulted in an order of magnitude improvement in HVCM reliability
- Synergistic solutions in development or installed to address remaining problems with HVCM to further improve reliability, increase available power and flatten pulse
- The SNS modulator team and the demonstrated HVCM high availability makes this topology attractive to KAERI and the proposed MaRIE upgrade
- Tools and personnel exist to address future upgrades and to further enhance HVCM performance