Advances in High Voltage Converter Modulator and Performance

Presented at the

Accelerator Advisory Committee Review

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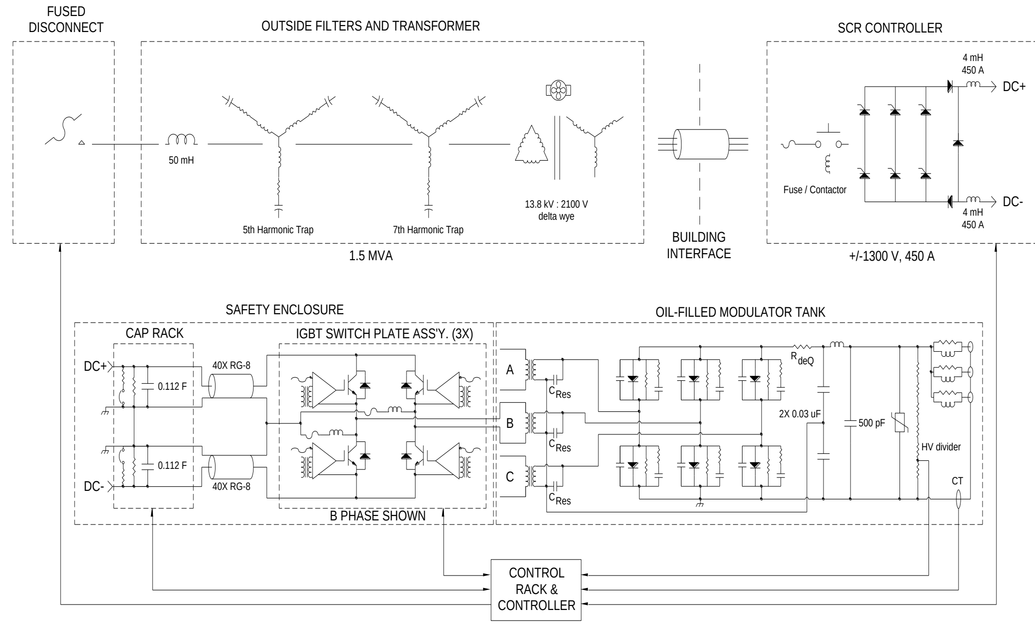
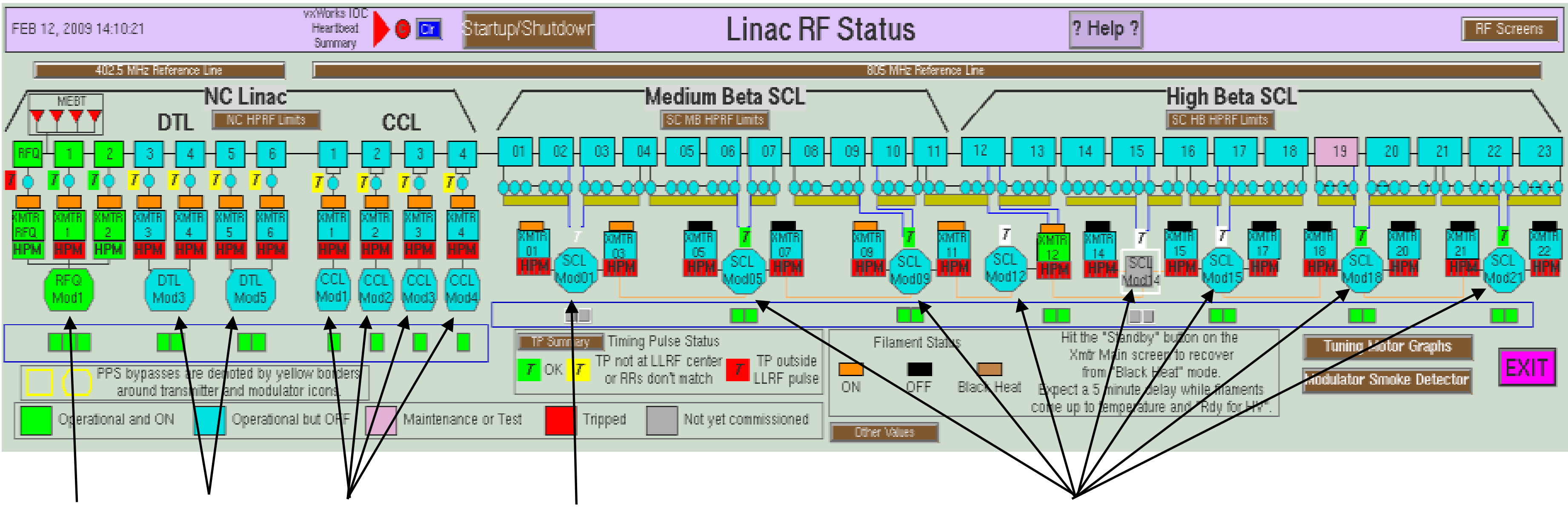
Modulators provide pulsed power to high power RF klystrons using 20 kHz switching with IGBTs

- 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



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



115 kV 125 kV ≤135 kV 71 kV 75 kV

DTL (8.5-10.6 MW peak)

SCL (8.0-8.8 MW peak)

CCL (8.4-9.1 MW peak)

- 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 in both configurations are available to support modulator development and testing activities

RFTF HVCM

- NCL variant of HVCM
- Primary mission is to support RF- and cryomodule-related testing
- Secondary mission is HVCM work
    - Extended run testing and MTBF characterization
    - NCL HVCM-specific issues

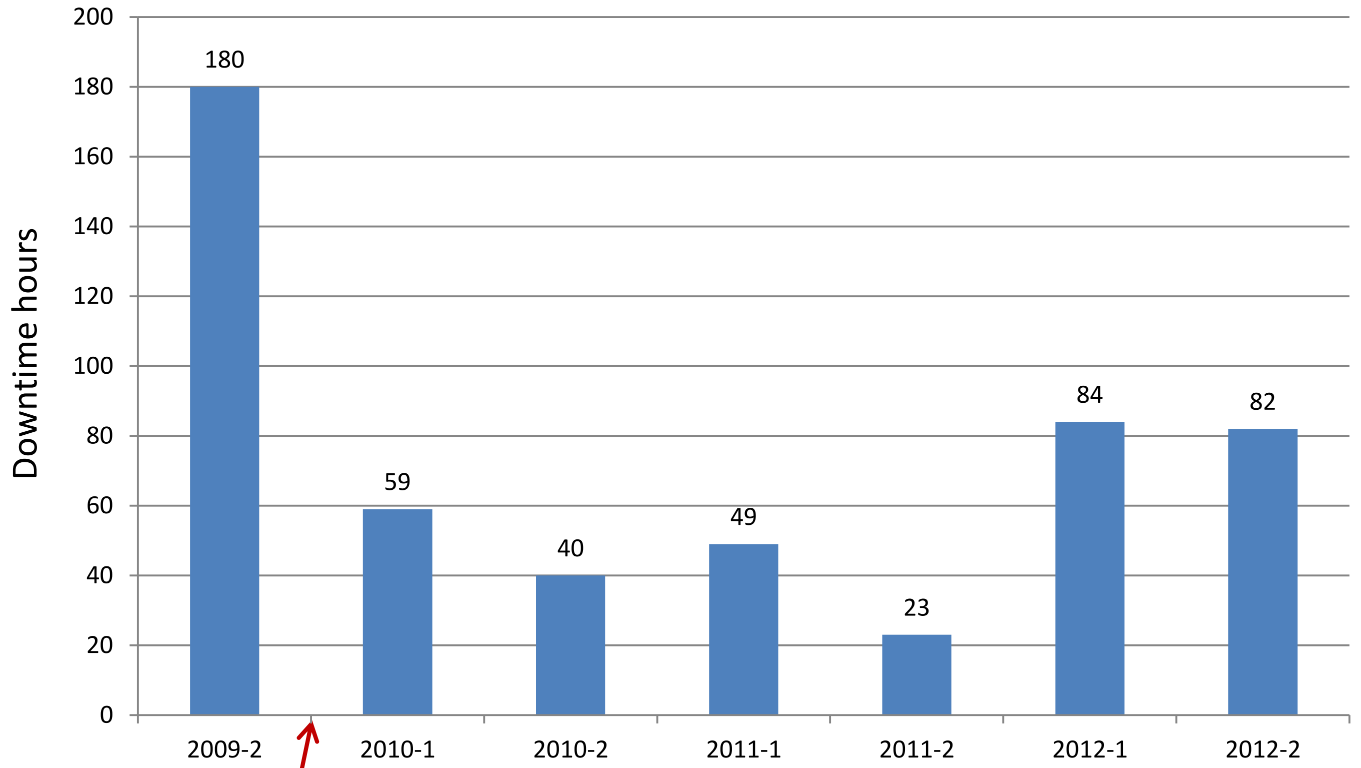
HEBT HVCM

- 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 available to support modulator development and pre-qualifying HVCM assemblies

- Useful to test IGBT assemblies, assuring timing properly matched on all 4 IGBTs
  - Eliminates need for adjusting after installation reducing MTTR
  - Assures transformer flux doesn't saturate due to different V-s for each switching cycle
- Perform pulsed hipot of transformers prior to installation
- Tool for development of alternate concepts that doesn't require lengthy reconfiguration of HVCM

Transitioning from a prototype modulator directly to production units created challenges for a high availability operational facility



Switch plate cap installation completed here

2012 increase due to:

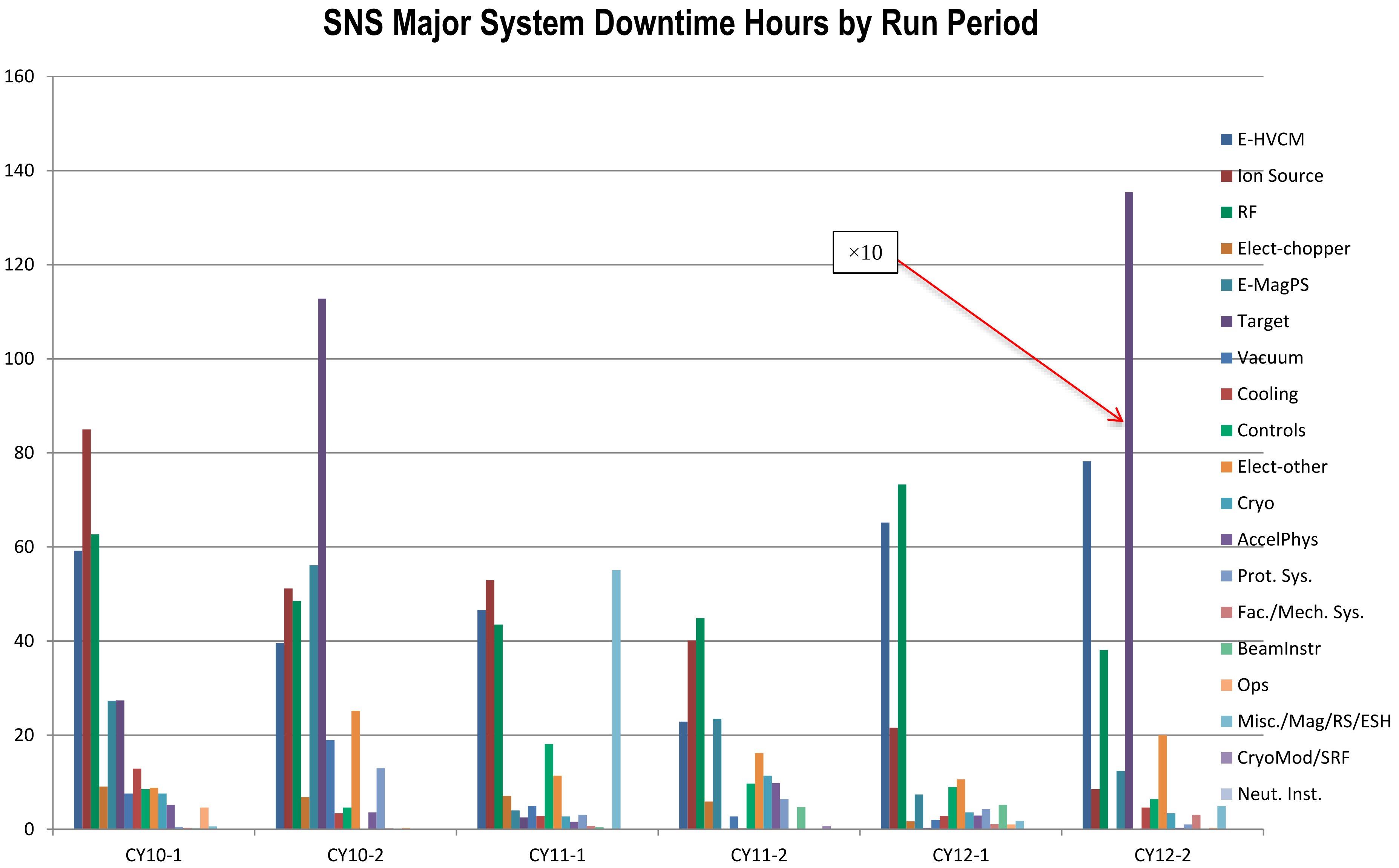
- In-tank component failures recurring
- IGBT shoot-thru (first in 3 years)
- Series of SCR problems (SCRs, drivers, etc.)

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

Downtime Hours	Feb.-July 2010	Sept.-Dec. 2010	Feb.-July 2011	Sept.-Dec. 2011	Jan.-June 2012	Aug.-Dec. 2012	Σ Hours
Scheduled Beam Hours	3131	2985	3099	3353	3040	2846	18,454
Fault Type							
2/4kV Caps	8	-	-	-	-	-	8
IGBT/driver	-	6*	4*	5*	5	24	44
SCR	10	16	9	-	32	3	70
DFDC Trip	-	-	-	6	1	-	7
Mod. Tank	-	5	-	-	37	4	46
Cable Arcing	-	-	20	-	-	-	20
Rectifier	23	-	-	-	-	-	23
Water Panel	-	1	2	-	2	-	5
Timing Faults	-	-	2	-	-	-	2
Oil Pump	-	-	5	3	2	6	16
Fiber	-	-	-	-	2	16	18
Misc./?	18	12	6	15	3	29	83
Σ	59	40	48	29	84	82	337

*IGBT driver only

The HVCM systems are no longer the major contributor to accelerator downtime

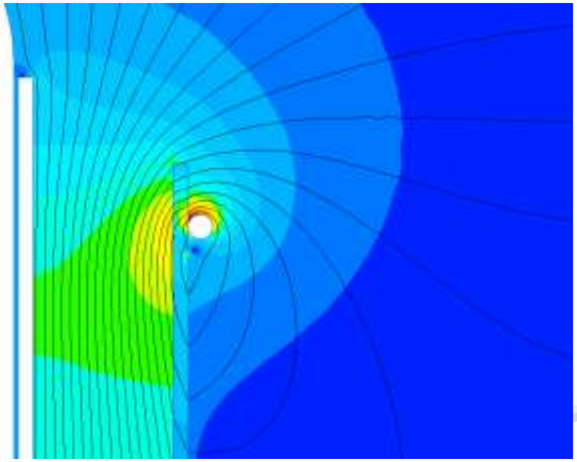


Summary of major HVCM upgrades to-date

- SCR Controller
  - Forced air cooling
- In-tank components (component de-rating)
  - Capacitors
  - De-Qing resistors
  - Transformers
- IGBT Switch Plates
  - Optimize pulse length (discussed later)
  - Replace bypass capacitors w/ metallized film units
  - Gate drivers (partially installed)
  - Thorough pre-installation testing
- Reduced SCL klystron loading with additional modulator
- Better preventative maintenance plans in place

A discovery of transformer failures creates some concern regarding the long-term reliability

- A combination of materials selection, winding placement, corona ring placement & possibly temperature cause the problem
- Significant field enhancement under corona ring
- Mitigation plans
  - Move inner winding layer away from surface of coil form
  - Increase corona ring dimension
  - Eliminate potential trapped air sites
  - Select winding layer material with a better dielectric constant match to oil

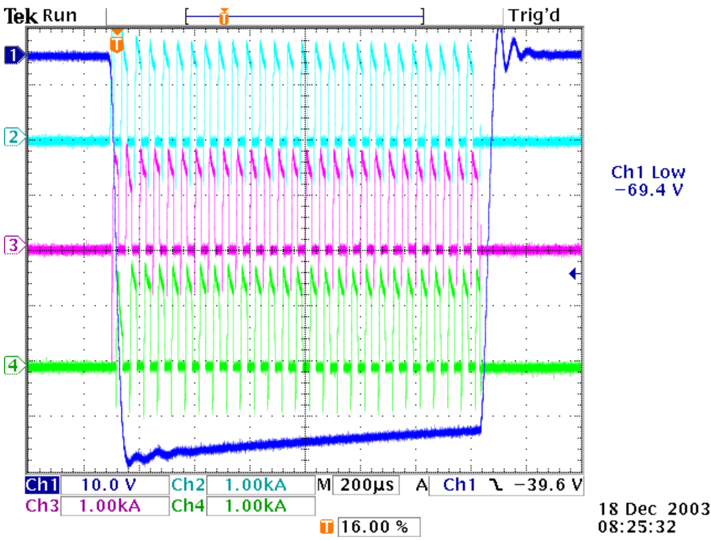


A key vulnerability to continuing reliable operation are the boost capacitors

- Presence of air bubbles inside results in corona inception which leads to catastrophic failure
- The capacitor is now mounted at a 2-3º angle to force any air that may be trapped away from center and terminal no longer near the side of unit
- Newest capacitors incorporate air-free filling technique and integrated shims
- Alternate vendor capacitor tested and appears promising

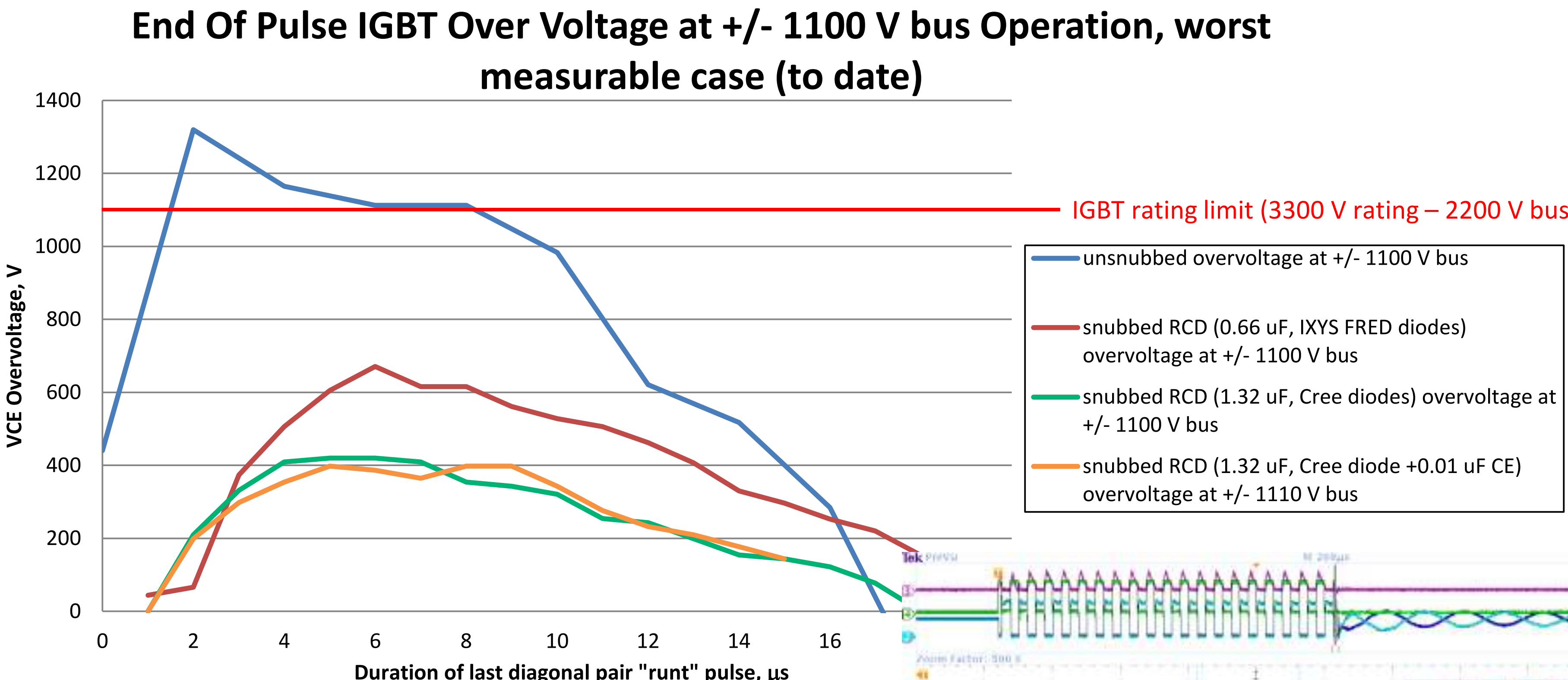
Necessary steps to advance to 1.4 MW operation and ultimately to support 2nd Target Station are under development

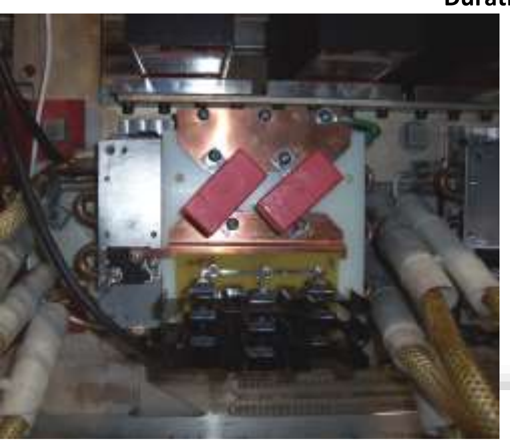
- Currently, klystrons are at saturation at the end of the pulse with no remaining control margin due to cap bank droop in open-loop
- Increasing klystron voltage with no additional changes will significantly degrade HVCM reliability
- Upgrades of cooling system underway
  - Provide higher component reliability
  - Reduce MTTR of key subsystems
  - Improve water chemistry
- Two options exist to permit longer pulse operation
  - Modifying the IGBT circuit to permit higher voltage operation (likely reducing klystron lifetime)
  - Pulse flattening which presents challenges for the HVCM IGBTs (closed-loop operation)

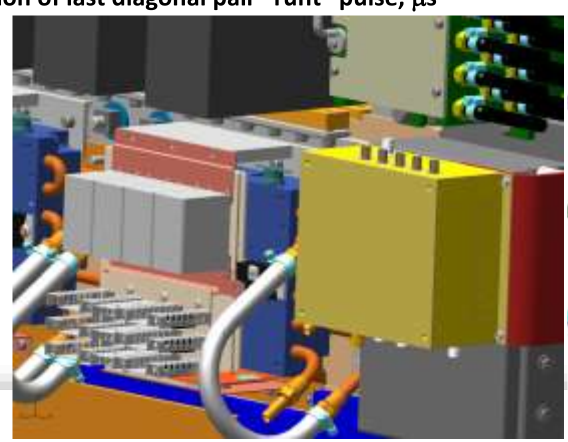


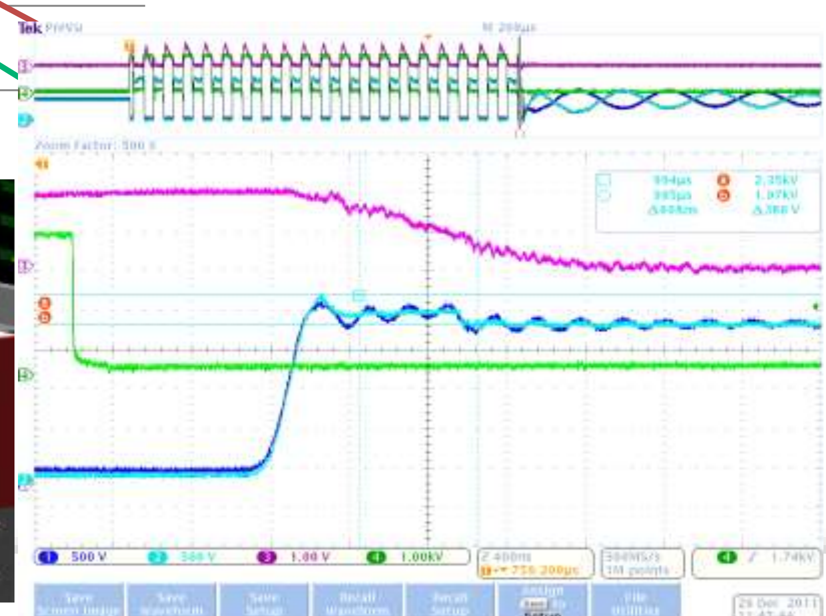
- Transitioning to even higher power presents other unique challenges
  - The current circuit topology creates stresses on components which may be insurmountable with existing technology
  - Switching losses in the IGBTs will significantly degrade their reliability
- N+1 redundancy can be achieved in conjunction with topology changes

Adding IGBT snubbers permits higher voltage operation with comparable reliability & eliminates fault over-voltage problem



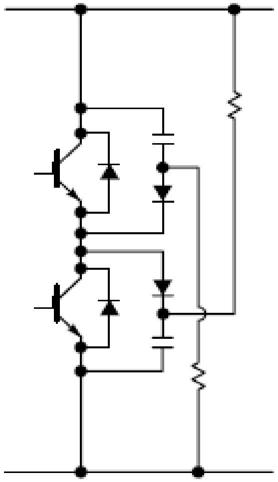


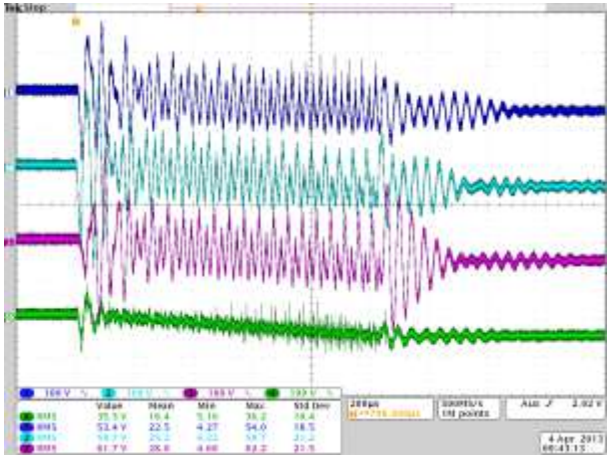




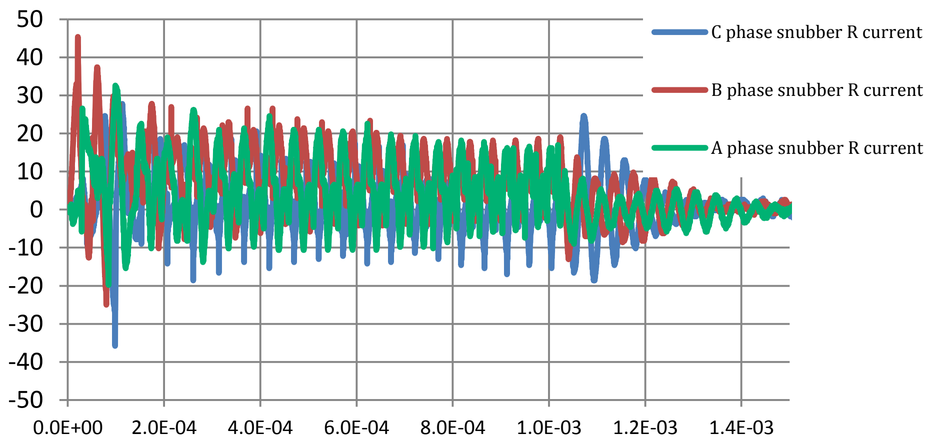
DC bus ripple creates problems for the snubber resistor which tries to track bus fluctuations

- Snubber capacitor tracks bus fluctuations through the bleed resistor – energy exceeds ratings of the water-cooled resistor
- Air-cooled resistor will not tolerate the average power dissipation requirements for the snubber application
- Attempting to resolve by
  - Testing to understand bus ringing to minimize or eliminate it
  - Identifying resistor or resistors that handle both the energy and power dissipation – EBG helpful



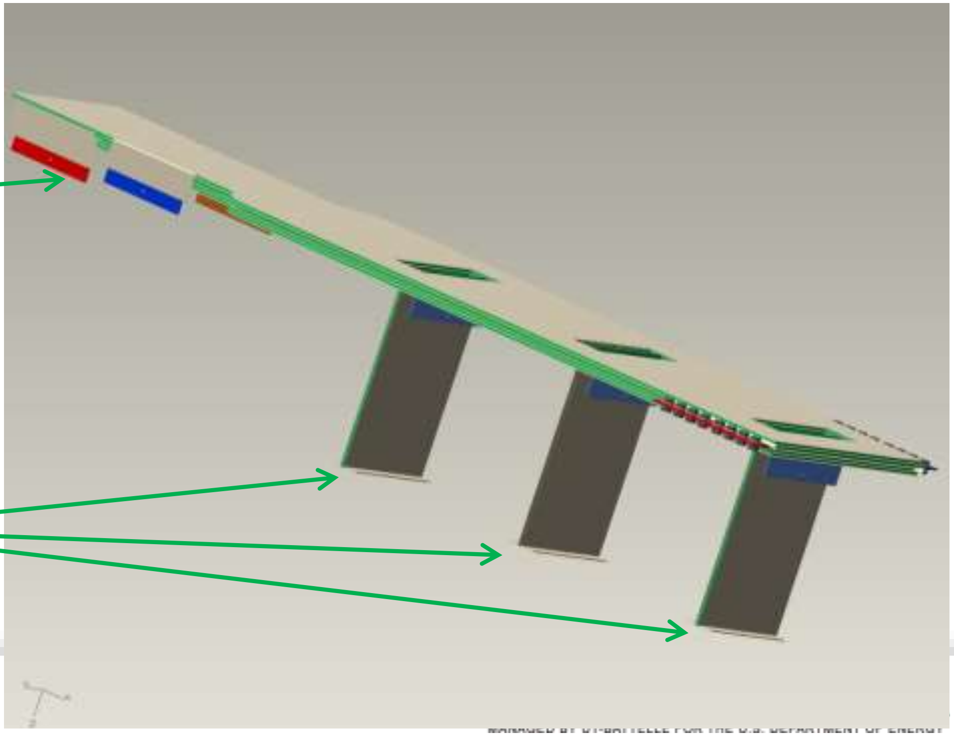


Large cap bank ringing (green) vs. switch plate bus ringing (others)



Additional ripple introduced with pulse flattening can be mitigated by improving bus structure

- Current multiple cables and switch plate bypass capacitors create oscillations on DC bus
- Bypass capacitors cannot be removed without significantly reducing inductance between energy storage capacitors and switch plates in the current design
- Working with Mersen Corp., we are developing a retrofit laminated ring bus structure to address these issues, a standard in traction motor applications
- Thermal and electrical optimization using simulation tools under way



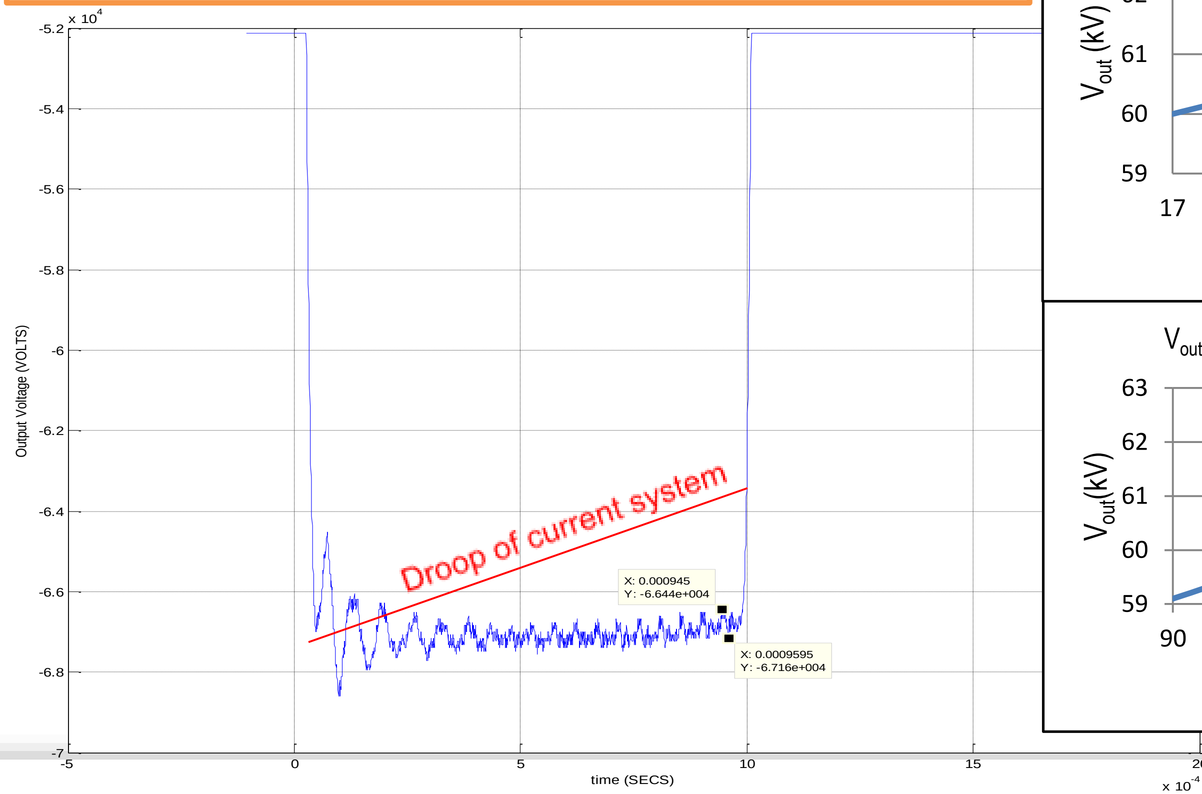
Phase Shift and Frequency Modulation achieves pulse flattening and has been demonstrated at 60 Hz full power

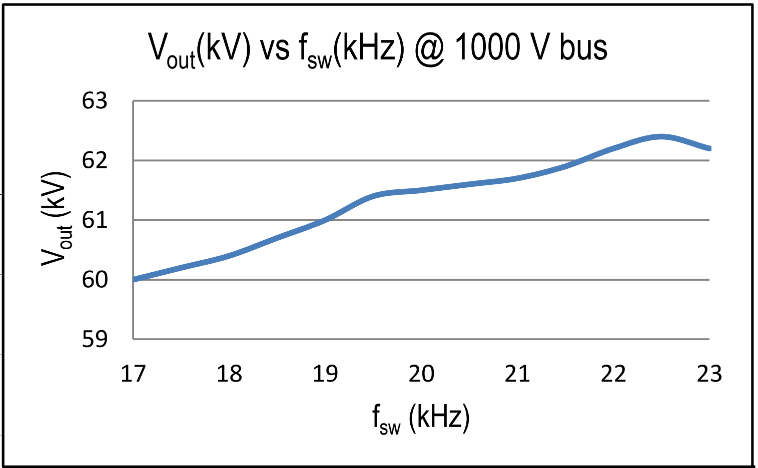
Output Voltage= 61.8 kV
Bus Voltage= +/- 1004 V
FM = 20 kHz to 22 kHz
PSM = 95% to 100%

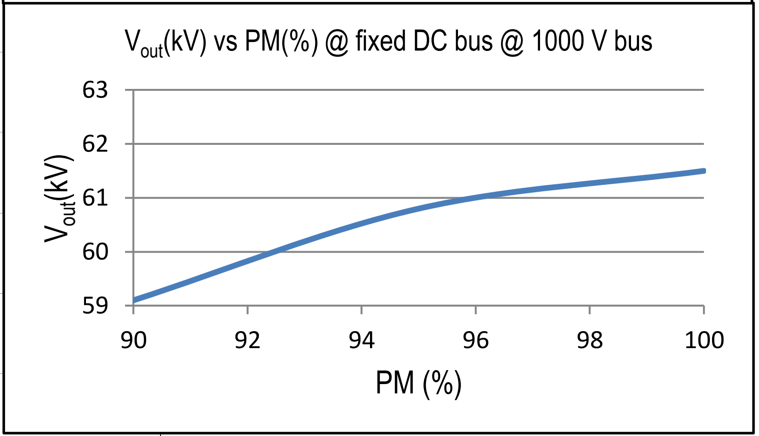
→

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

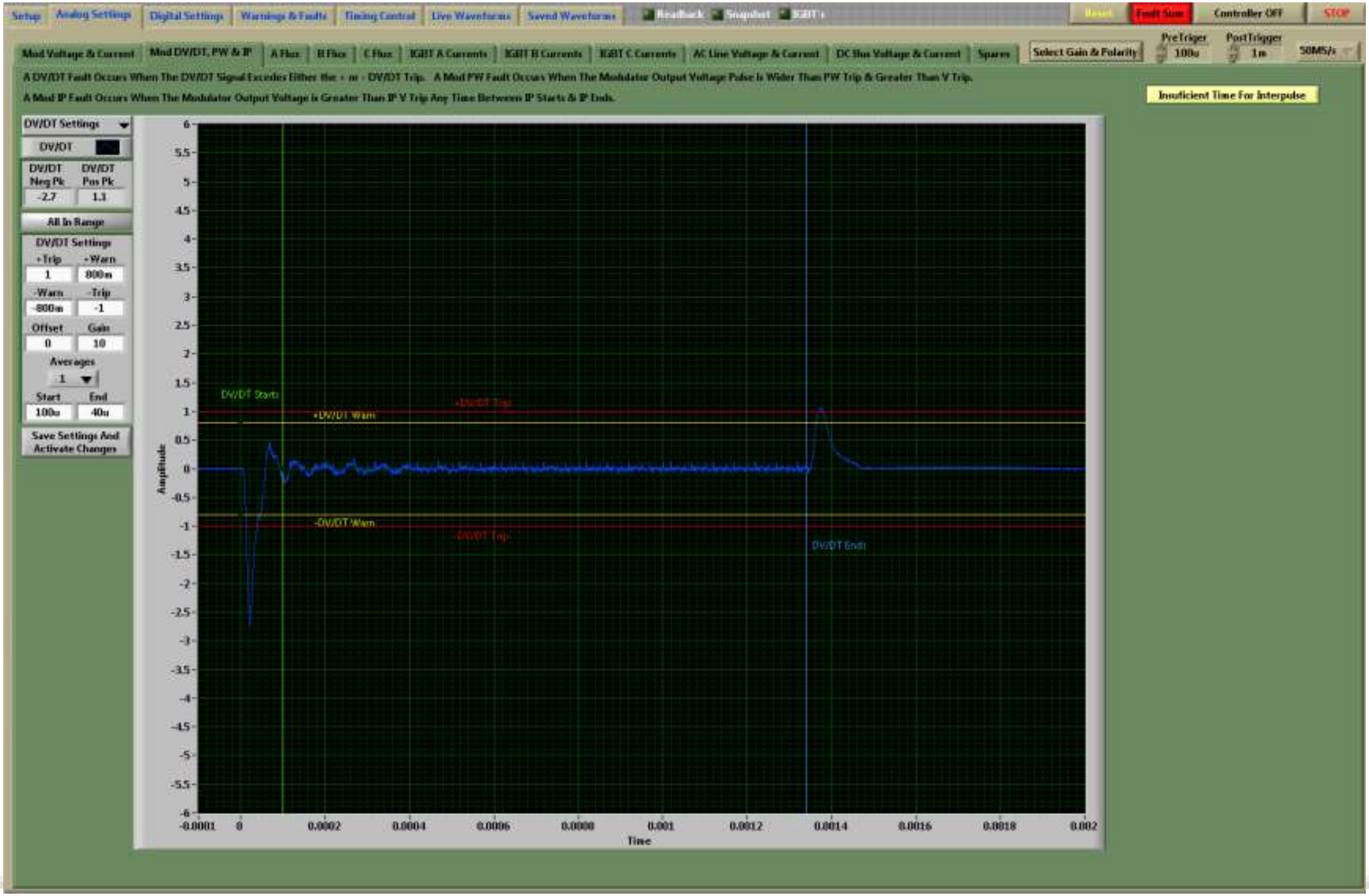
Improved adjustable output filter components on order to reduce ripple and "tune" rise time.







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



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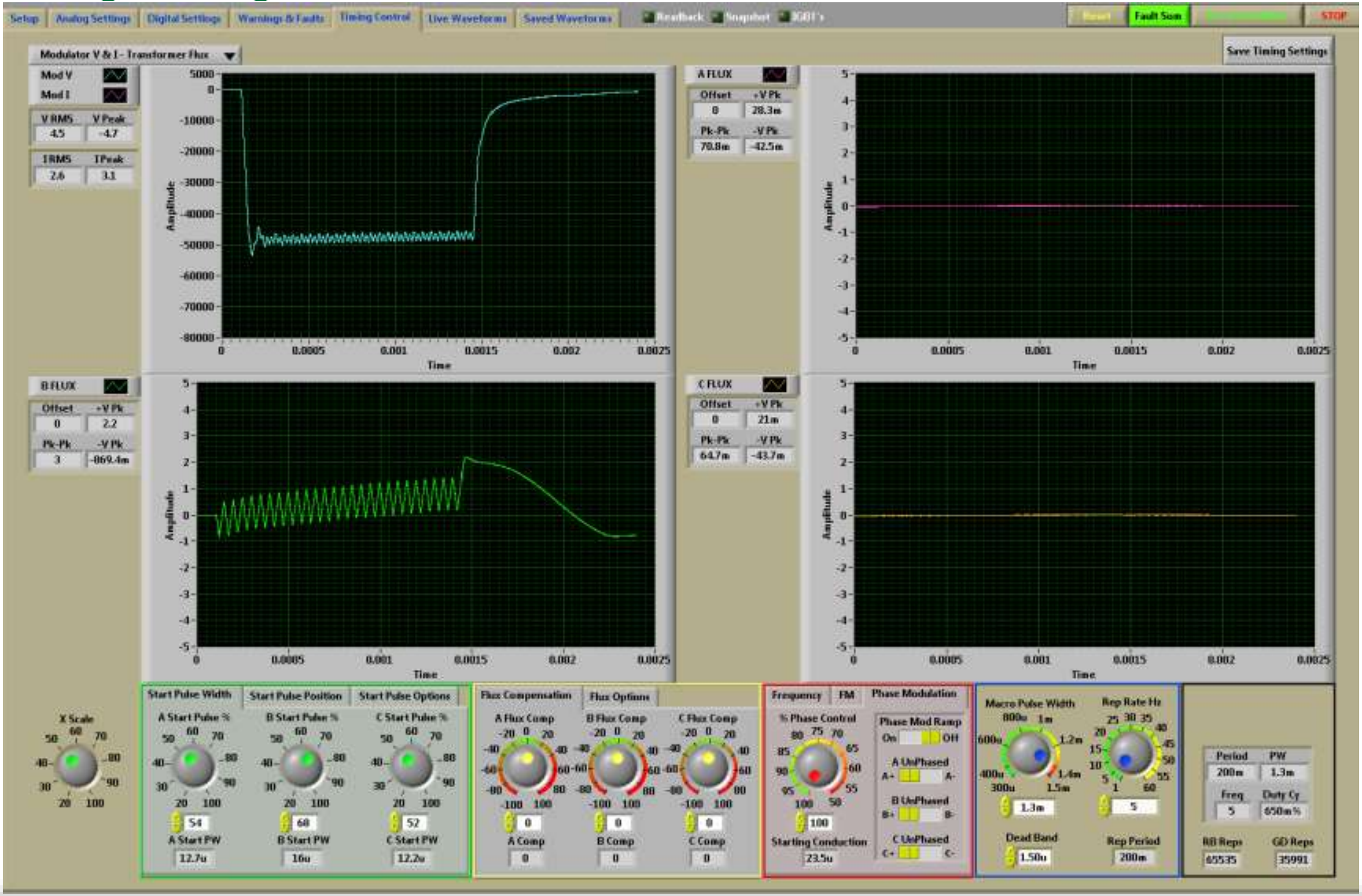
The new controller enables all types of modulation and provides real-time waveforms for immediate assessment of timing changes…



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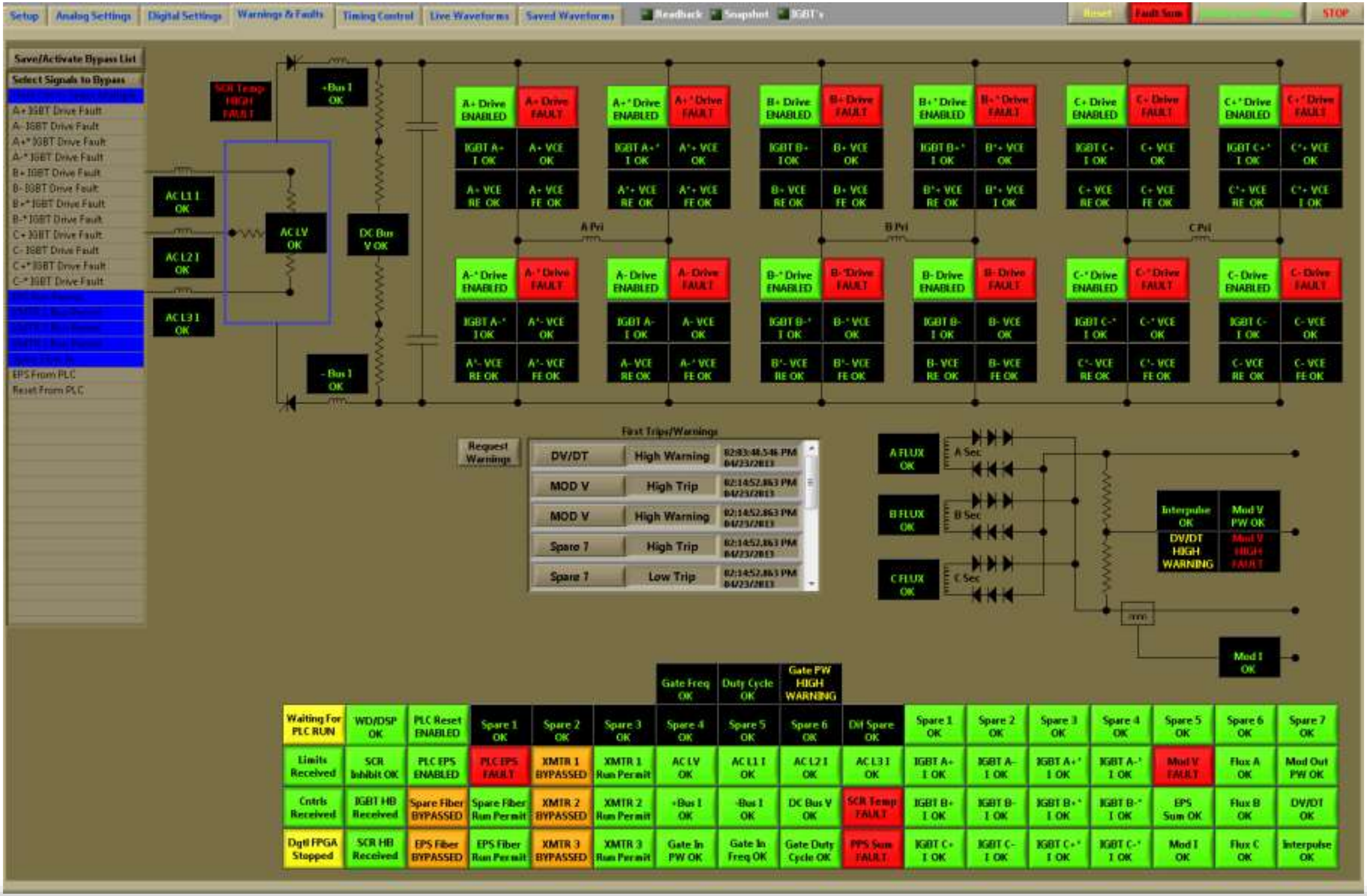
The new controller mimics current user interfaces and enhances them…



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

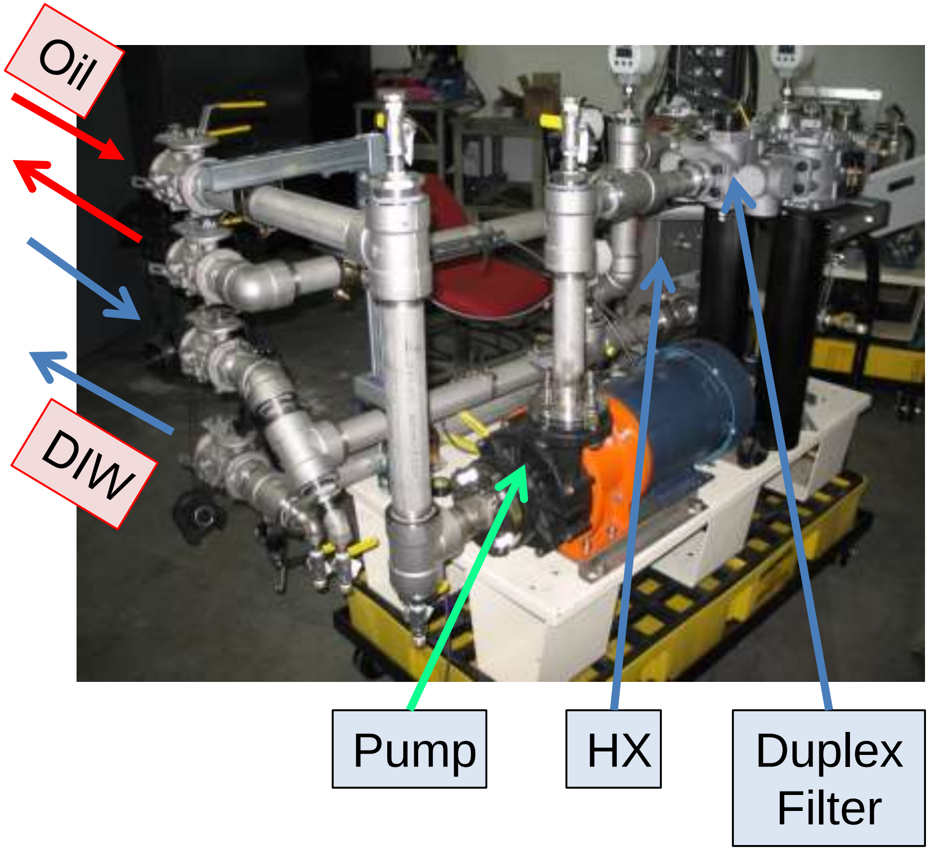
Future versions of the new controller will provide:

- EPICS interface
- Flexible smoke detector logic
- Control of series switches for IGBT fault isolation
- 3 & 4 phase operation with semi automatic IGBT fault recovery
- IGBT shoot-through monitoring & warnings
- IGBT turn on & turn off monitoring, compensation & warnings

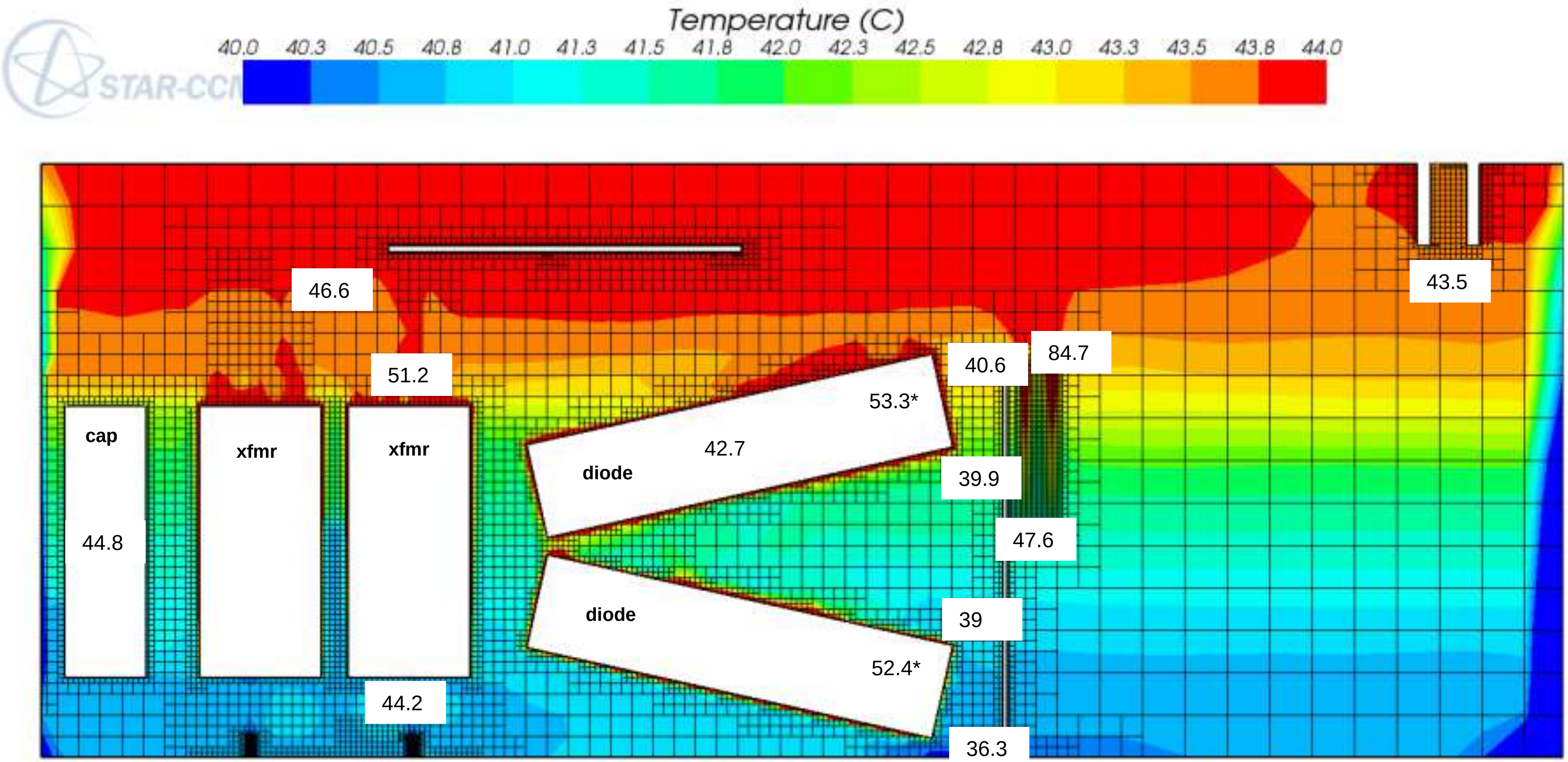
Enhanced reliability and reduced MTTR can be achieved by replacing existing oil cooling system

- Prototype HVCM cooling skids is being built to determine the appropriate flow and oil distribution within the tank – start mid-May
- 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
- Plan to upgrade the Accelerator HVCM cooling systems in FY-2014 & -2015

Prototype Pump Skid



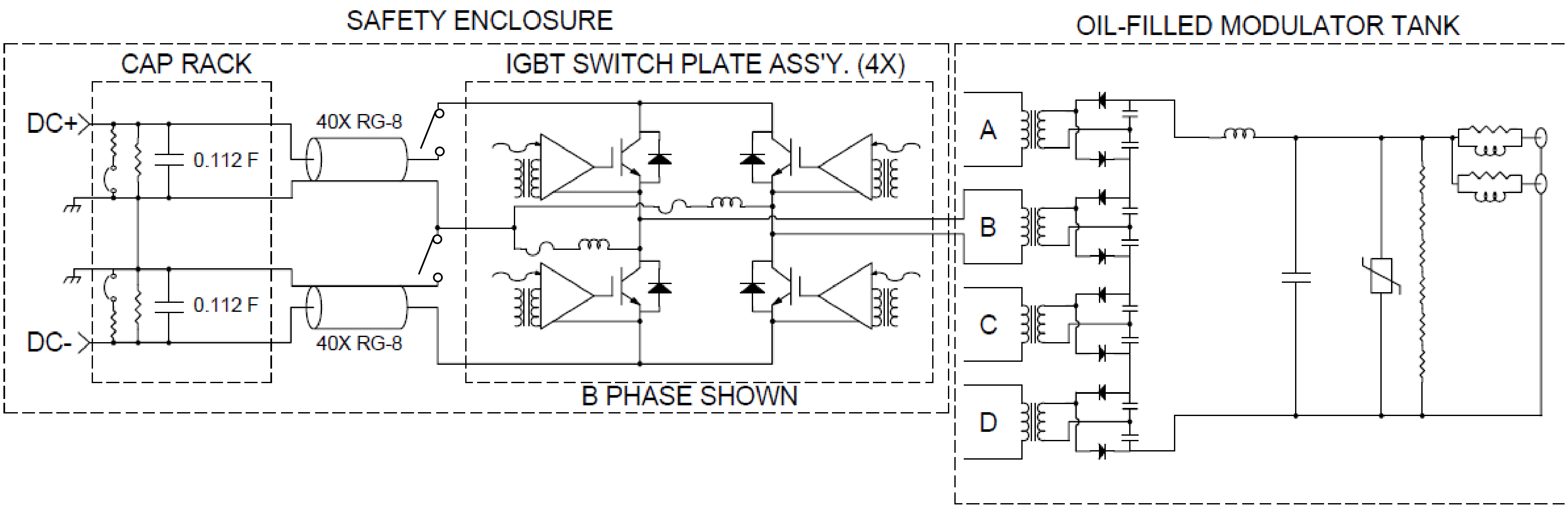
Simulations of temperature profiles and flow rates with current system reveal system shortcomings



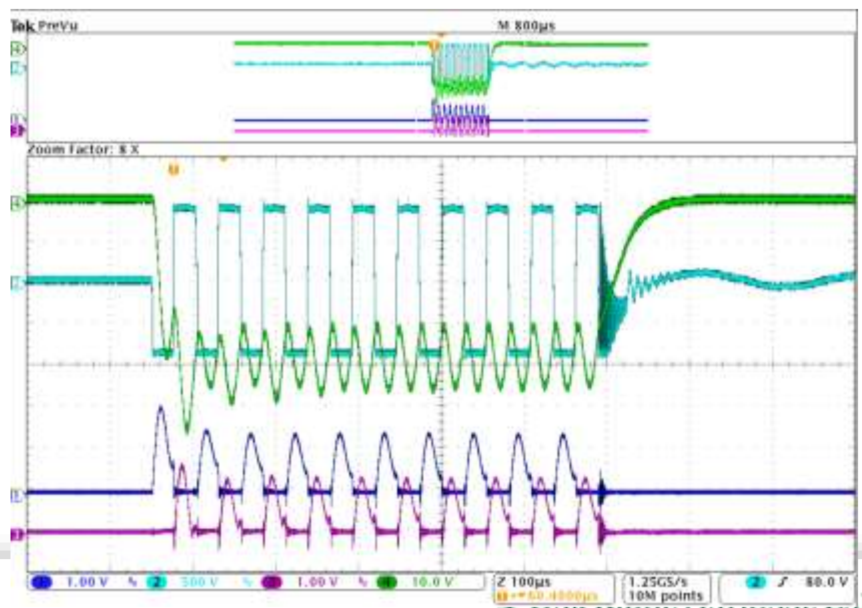
*diode heat sink temperatures

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

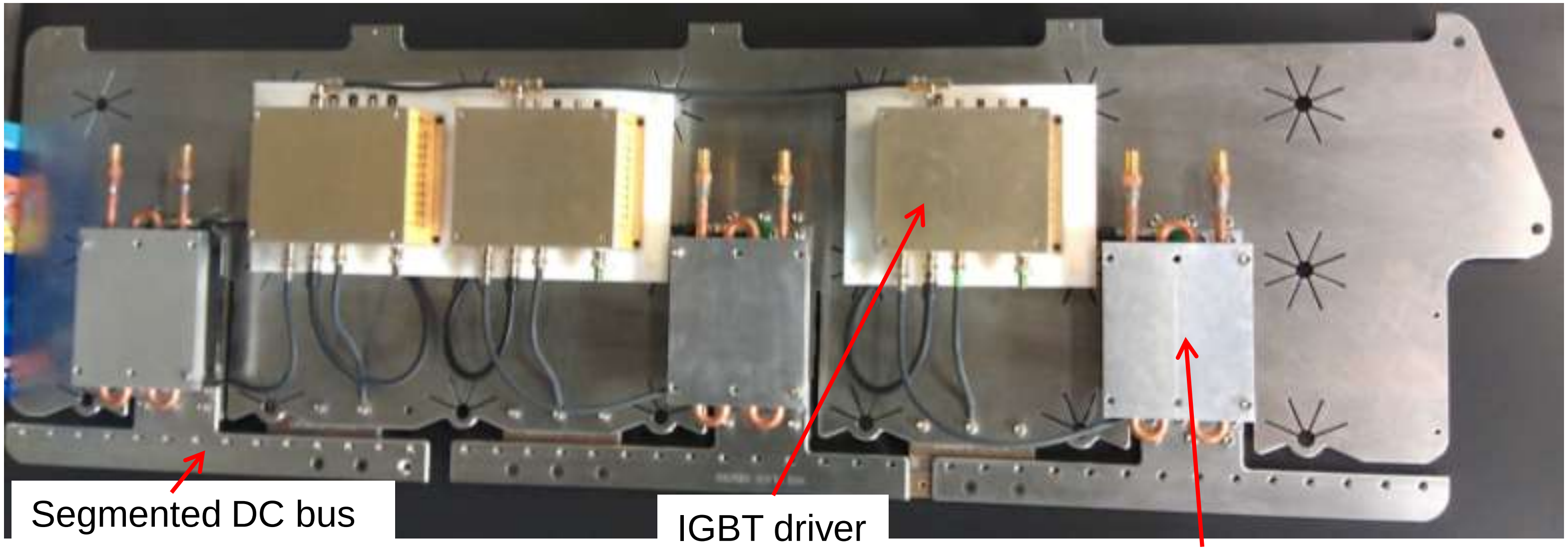
An alternate topology is under investigation for the 2nd Target Station with applications to other long pulse facilities



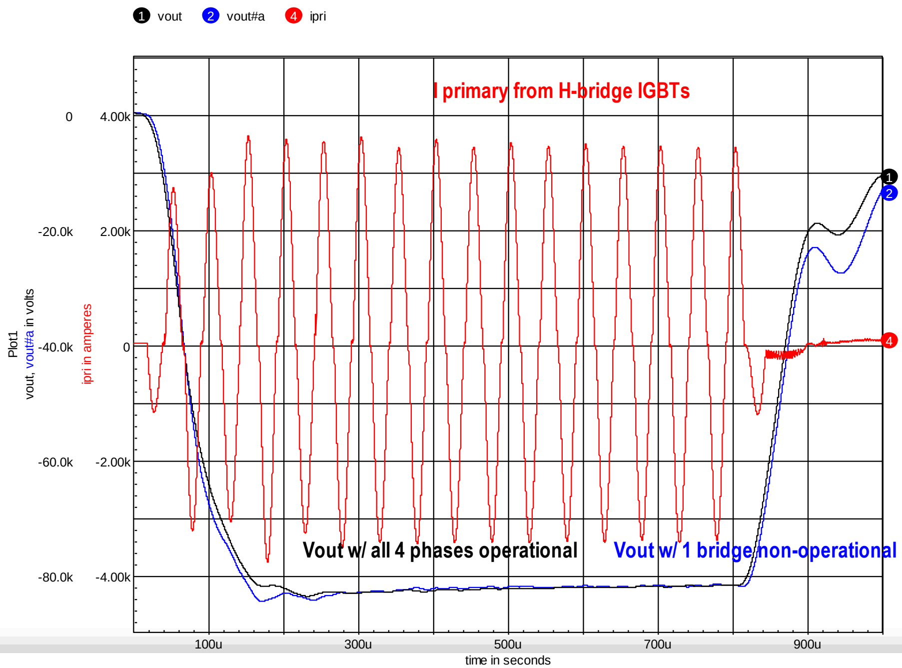
- Single phase waveforms shown
- Reduced stress on capacitors
- Single phase tested, parts for full system under procurement
- Less sensitive to load variations
- Improved soft switching using magnetizing inductance of transformer
- Better efficiency



Opportunities for redundancy with the alternate topology have been explored and are promising



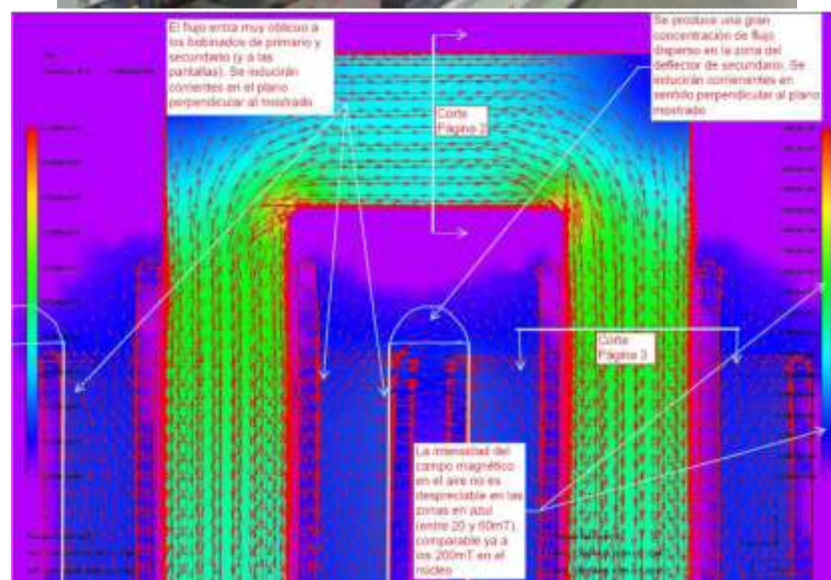
IGBT and cold plate



- 4 phase → ±750 V DC
- 3 phase → ±990 V DC
- Controller reconfigures system for 3 phase operation
- Series switch built and tested for ½ HVCM, incl. severe fault testing
- Would be used in conjunction with alternate topology

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

- Pad poured at ORNL and awaiting delivery
- Discovery June 2012 that induced eddy current losses in secondary shields and field-grading structures high at full average power operation
- Subsequent discovery that secondary conductor losses too high led to replacement with Litz wire
- 2013 discovery that excessive losses in primary led to design of cooling plenums for primary
- Factory acceptance testing scheduled for mid-May through June, delivery early August
- Specified to meet STS requirement to drive 12× 700 kW CPI klystrons (85 kV, 160 A)



The following comments are added in Spanish to this figure:

- Flux crosses sidewise the primary and secondary windings (and also the screens) at several areas . Stray currents will be induced
- High B is found in the secondary deflector area
- B corresponding to the stray field is not negligible (between 20 and 60mT, comparable to the 200mT in the core)

Summary

- **HVCM availability improved substantially**

- 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 the ESS, KAERI and others