Linac Modulator Performance and Upgrades

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TEAM:

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High Voltage Converter Modulator (HVCM) Talk Overview

- Introduction
- System Overview
- Operational Statistics
- Historical Perspective
- Recent Fire Discussion/Root Cause
- IGBT Reliability Improvements
- SCL Modulator Enhancements
- Future Areas of Development
- Conclusion

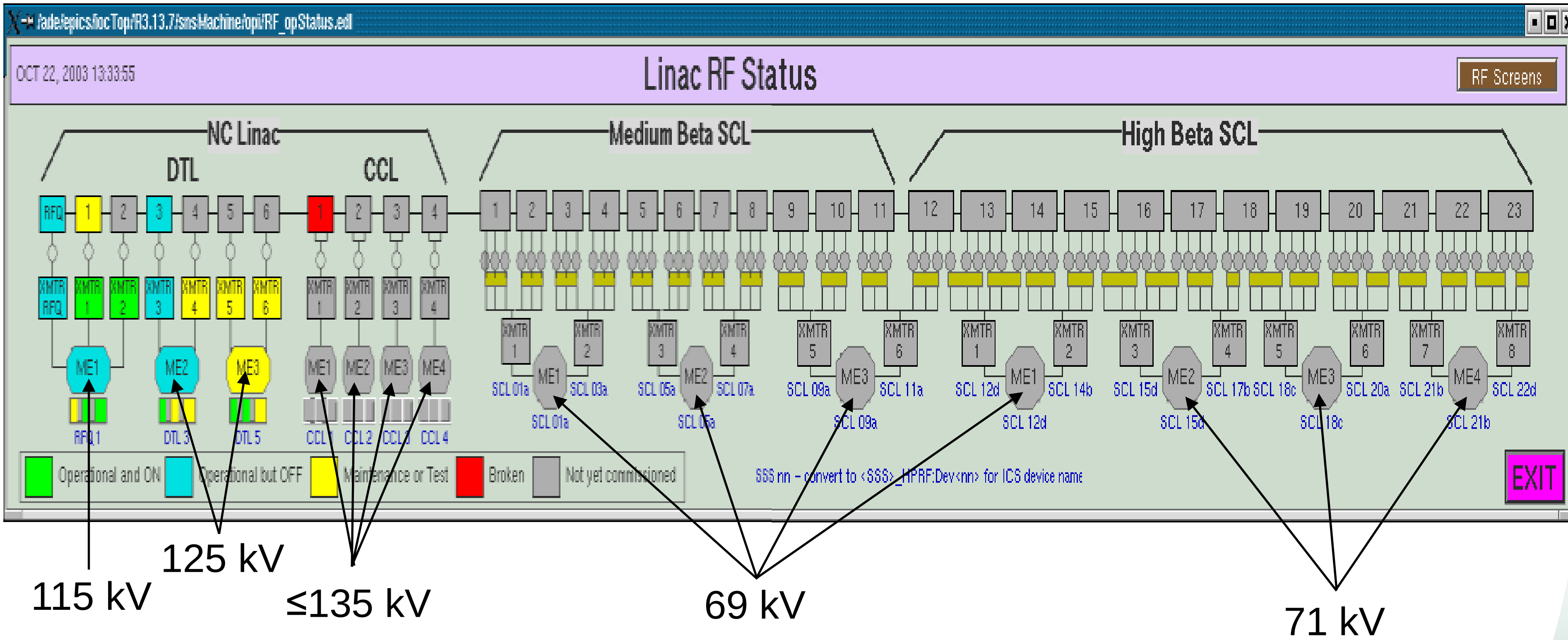
Why this technology?

- Compact topology, competing technologies require more volume and building $$
- High efficiency design should lead to higher reliability (less thermal stress)
- Variable pulse width and rep rate capable
- Active compensation of pulse possible (droop, etc.)
- Crowbar not required
- Drives multiple klystrons, minimizing # of units
- Modular
- Low cost

Development and Manufacturing Challenges and Limitations (in retrospect)

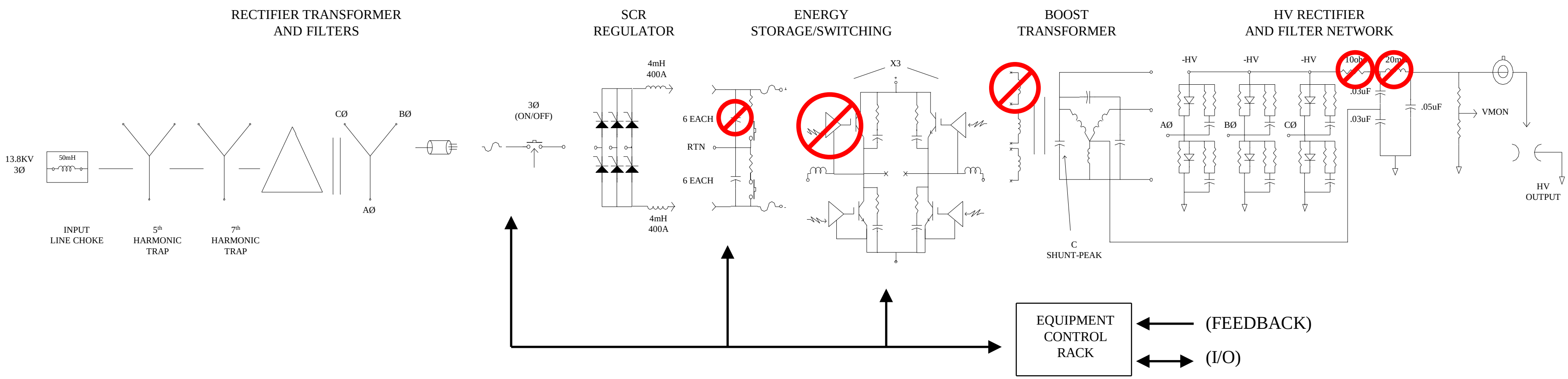
- Exceed capabilities of circa-2000 power devices
  - Insufficient engineering design margins
  - MTBF analysis based on ideal component lifetimes, actual lifetimes fell short of assumptions
- Manufacturing challenges
  - Magnetics design deficiencies
  - Workmanship/quality concerns
- Expedited schedule 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
  - Materials choice
  - Catastrophic capacitor failures not contained

Cavity/Klystron/Modulator Layout



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

HVCM Simplified Block Diagram



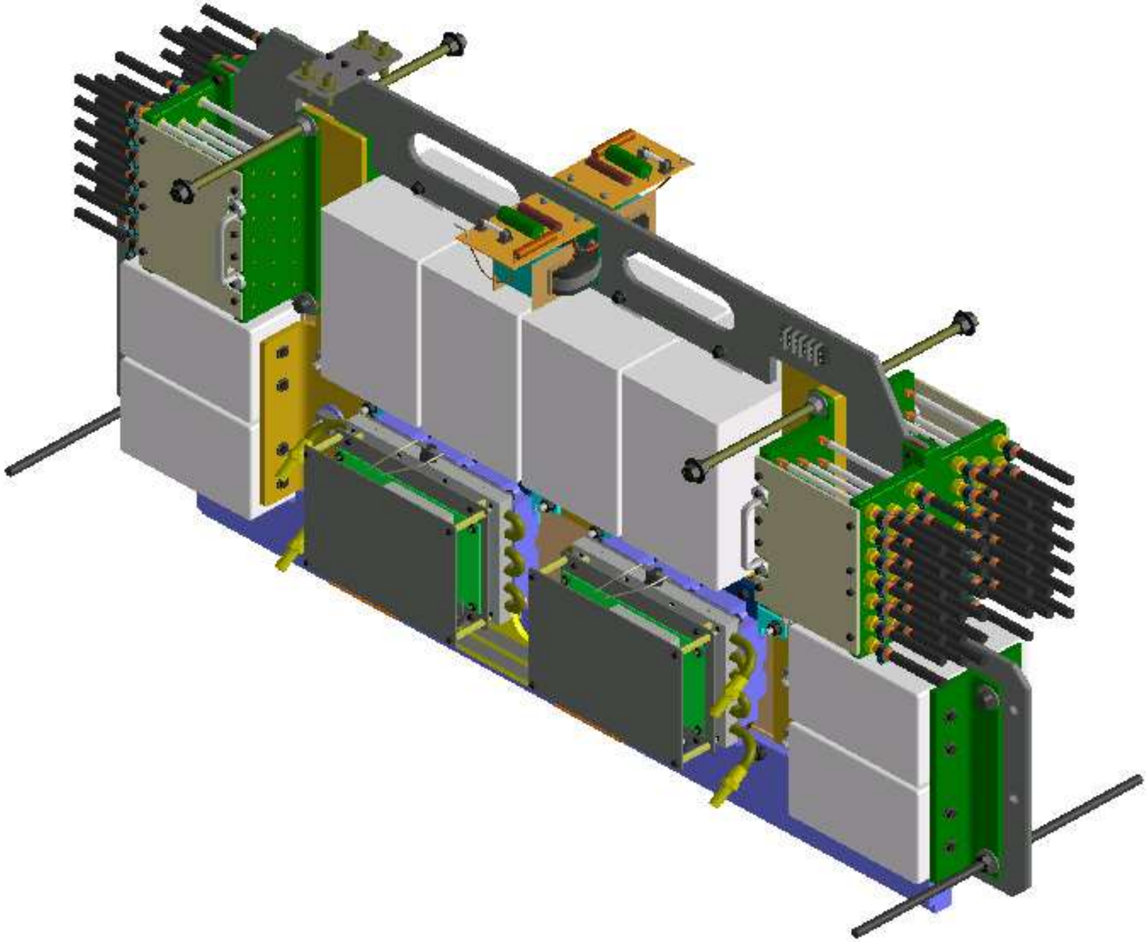
RECTIFIER TRANSFORMER
AND FILTERS

SCR
REGULATOR

HIGH VOLTAGE
CONVERTER/MODULATOR

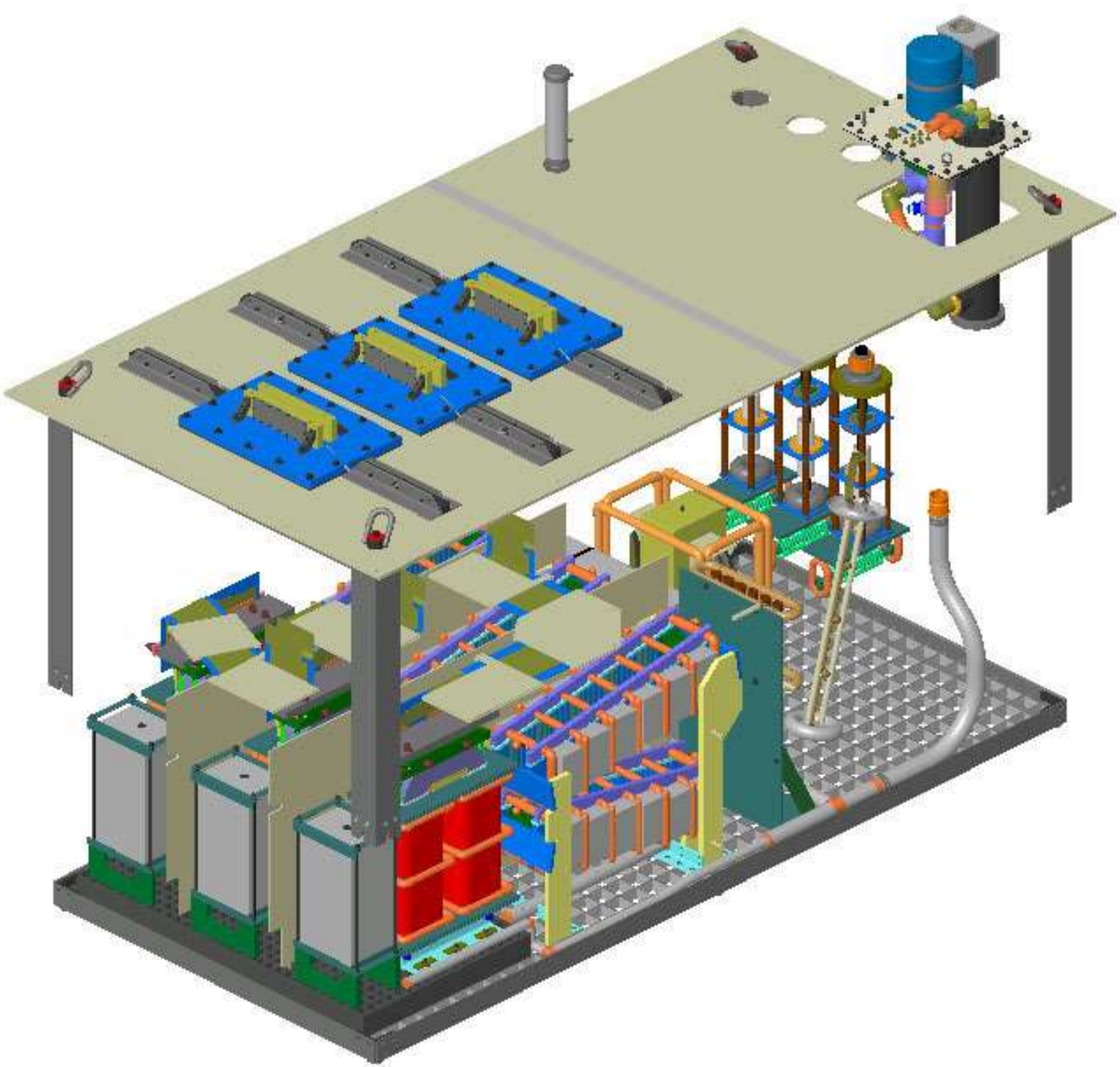
EQUIPMENT
CONTROL RACK

HVCM IGBT Switch Plate Assembly



- 20 kHz switching at ±1200 V
- Eupec FZ1200R33KL2C or Mitsubishi CM1200HC-66H

HVCM Basket Assembly



HVCM Known Problem Areas

•System reliability not meeting requirements
•IGBT drive parameters optimized for speed, not fault tolerance
•Combustible materials on IGBT switches
•Insufficient voltage (presently) on SCL modulators to provide adequate RF control margin, reduce cavity fill time
•Pulse too short on SCL modulators to achieve 1 ms beam due to fill time limitations
•Modulator droop further limits SCL modulator performance

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HVCM Operational Hours

SYSTEM	SCR Failure*	Mod. Failure*	Hours
DTL-Mod1	3/2	2/6/🕯	17,920
DTL-Mod3	2	4	16,370
DTL-Mod5		1/🕯	16,340
CCL-Mod1		2/1	15,390
CCL-Mod2	1	4/🕯	15,400
CCL-Mod3	1/1	4	14,800
CCL-Mod4		1	14,420
SCL-Mod1	1	1/3	14,370
SCL-Mod5		1	14,470
SCL-Mod9		3/🕯	12,850
SCL-Mod12	1	2	14,130
SCL-Mod15	1	1	13,880
SCL-Mod18		1/1	13,420
SCL-Mod21		2/5	13,540
RFTF Mod	2	1/🕯	2,890
TOTAL	11	11/33	208,100

*failure >1 hour downtime

- Current as of January 7, 2008
- Mostly 30 Hz operation
- All recent modulator failures* in last since April 06 shown in RED, 🕯=fire event
- Mod failure rate increasing
- SCR previous failure rate MTBF=21,000 hours, 33,200 hours since April 06
- Including LANL unit's operation, ~210,000 hours total
- MTBF averages 4000 hours, up from 3000 hours previously

HVCM Failure Statistics since 4/06

- 20 IGBT Switch Plate failures
  - 5 Fire events, more info to follow
  - 2 due to failed driver cards
  - Remainder due to IGBT shoot-thrus and insulation degradation
- 7 Water leaks, 4 of which attributable to zinc leaching of fittings
- 4 SCR failures
- 2 Control Chassis failures
- 1 choke and 1 boost transformer failure (none since replacement w/ Stangenes units)
- 1 miscellaneous failure

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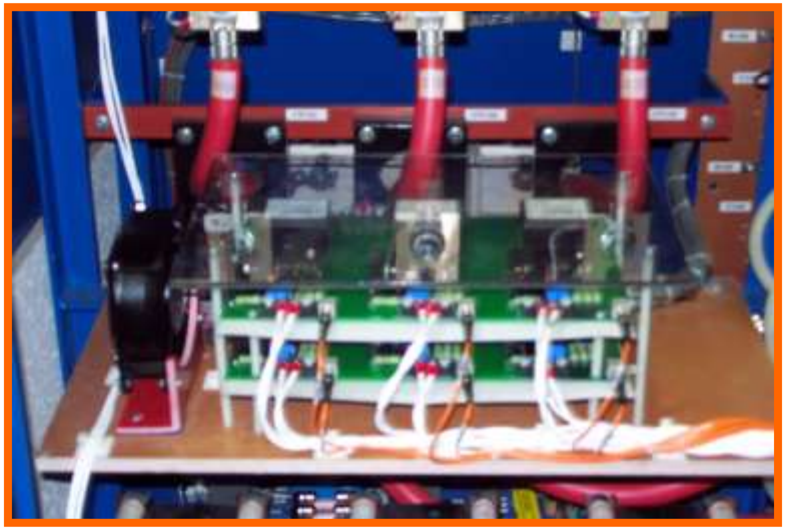
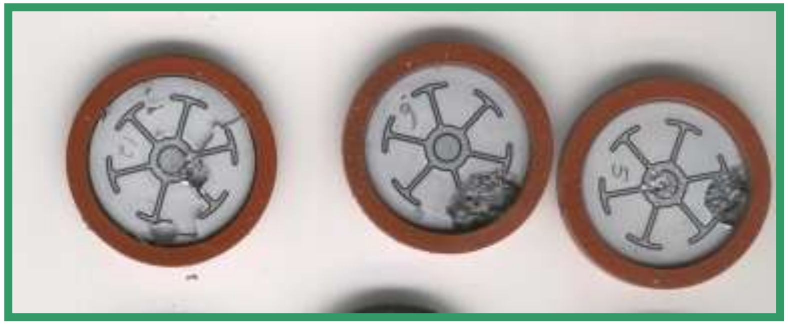
HVCM History – SCR Issues

- **Early Operations revealed SCR reliability problems**
  - Replaced hard-fire cards to provide more robust gate signal
  - Replaced snubbers w/ non-inductive resistors
  - Installed fast overcurrent protection
  - Insulated gate leads (corona-induced failures)
  - Installed SOLA line conditioners
  - Other misc. upgrades
- **Completed FY05**
- **Significant MTBF increase (order of magnitude) since upgrades**





HVCM History – Modulator Upgrades (AIP02)

- **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**
- **Real time signal monitoring**
- **Completed FY07**

HVCM History – AIP02 Remaining

- Complete installation of HEBT Modulator
  - Beamstick loads for full average power operation
  - Characterize components, new IGBTs, etc. off-line
- New gate drive development
  - Active/Passive anti-saturation
  - Improve MTTR and reliability
  - Improve noise immunity
  - More later…

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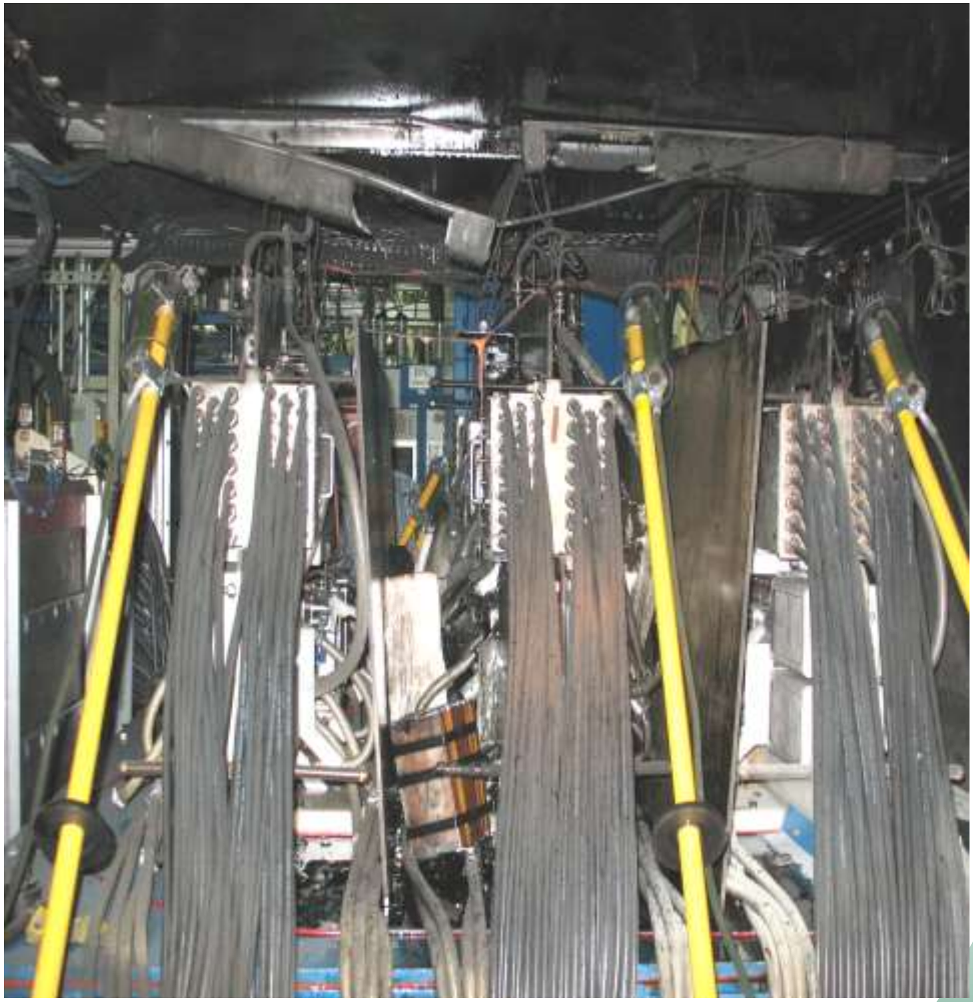
HVCM Recent Fires

- **5 Fires to-date**
- **Collateral damage and long recovery times**
- **3 primary causes**
  - **Open air arcing between different potential surfaces**
  - **Corona degradation of insulation leading to failure**
  - **Capacitor failure**



HVCM Recent Fires – Arcing

- 1st fire, none since, in RFTF
- Workmanship or residual dirt believed responsible
- Repeated arcing acted as ignition source for combustibles
- Corrected with improved training of assemblers, no faults w/ same root cause since (Jan 07)

HVCM Recent Fires – Insulation Degradation

- **Cause of 2 fires and likely many of the IGBT failures**
- **Original design relies on single layer of DMD to insulate cooling tubes from different polarity bus**
- **Interference fit between tube and bus compresses DMD and can cut material if sharp edges present**
- **Corona degrades insulation over time, resulting in arc event**
- **Insulation double, short-term sol'n., cutout long-term**

HVCM Recent Fires – Capacitor Failure

- Cause of 2 fires, other failures due to collateral damage
- Likely internal cap failure and subsequent energy dump
- Cap MTBF 500,000 hours @ 2.4 kV, 168 units
- Path forward
  - Improved lifetime capacitors
  - Non-flammable impregnants (identical cap with rapeseed oil in-house)
  - Reconstituted mica/other technologies?
  - Self-clearing technology?
  - AIP in place to address this concern

HVCM Recent Fires – CO_2 Suppression

- Dedicated CO_2 system installed
- Smoke detector installed
- EPICS screens updated
- Manual discharge from CCR if smoke detector trips
- Prevent or minimize system damage

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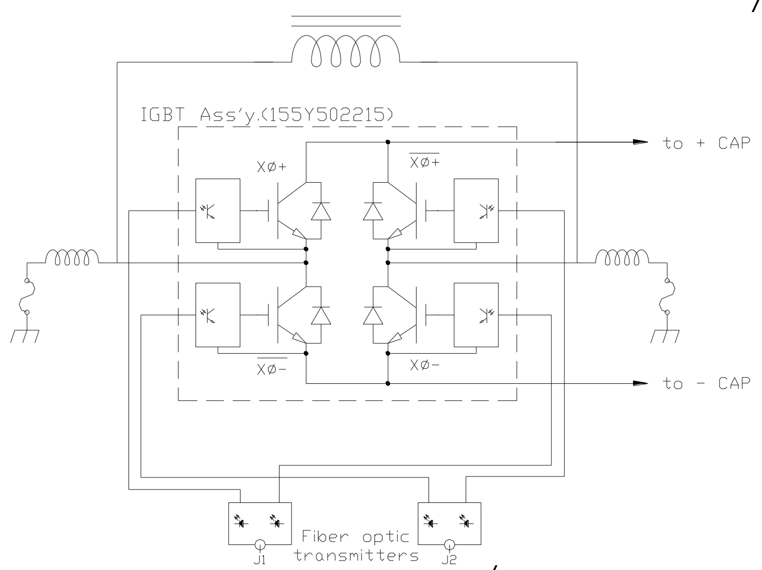
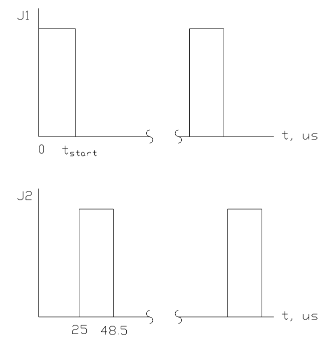
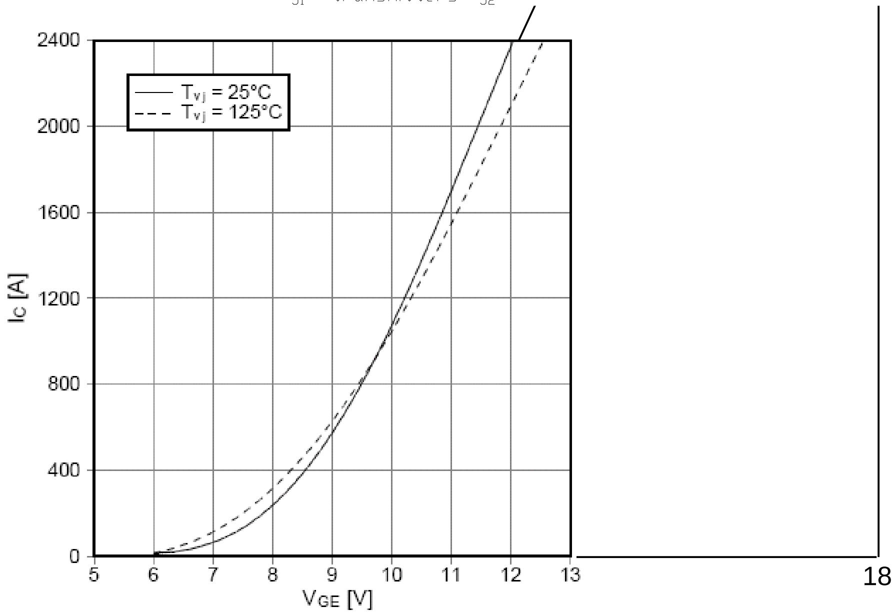
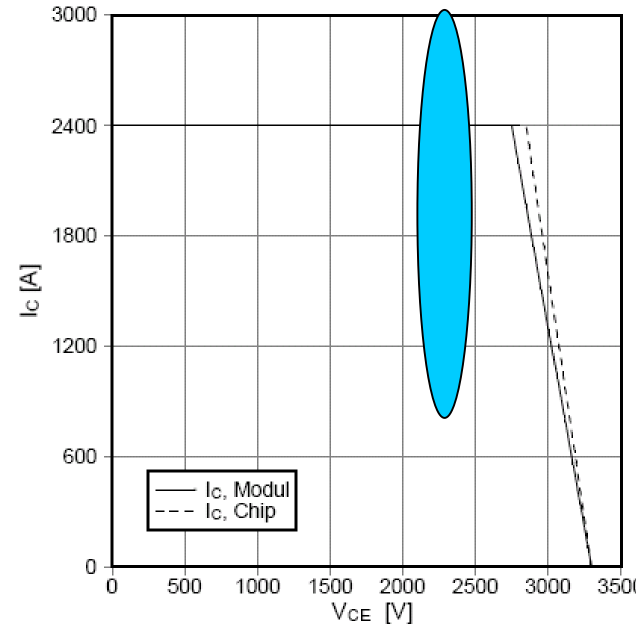
IGBT Gate Drive – Shoot Thru Fault





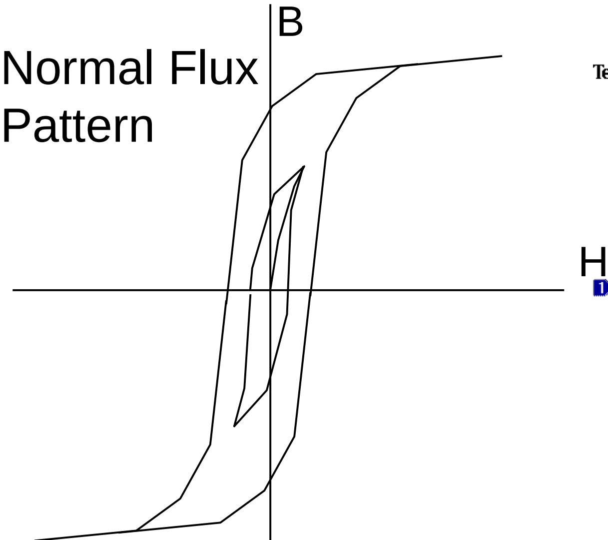


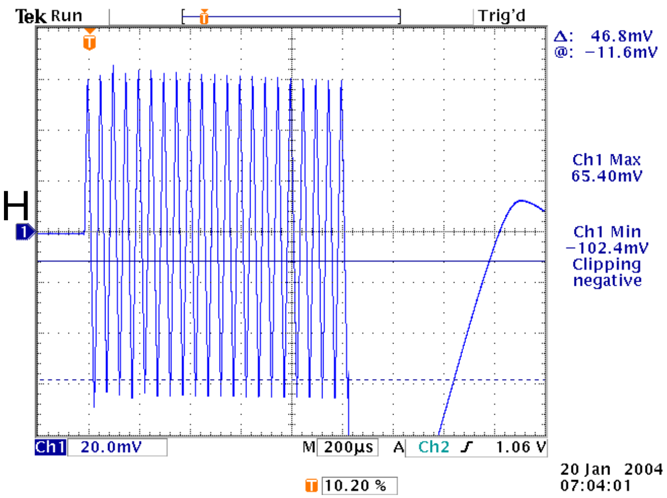
Safe Operating Area (SOA)

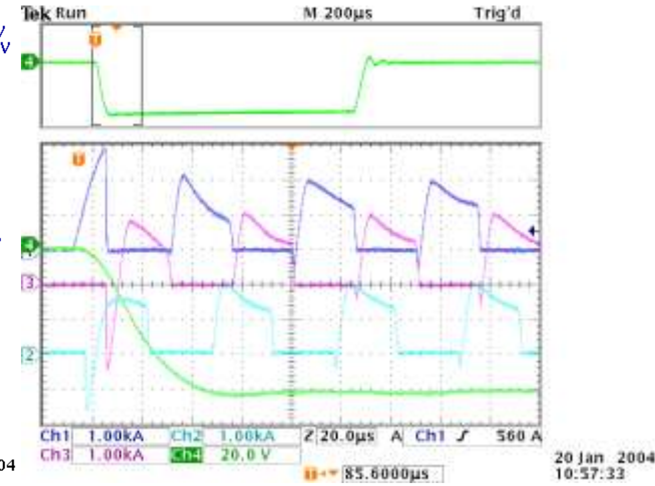


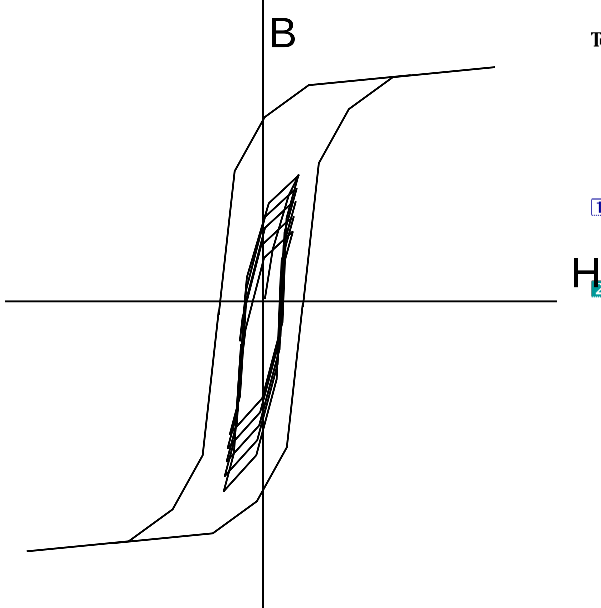
IGBT Flux Saturation

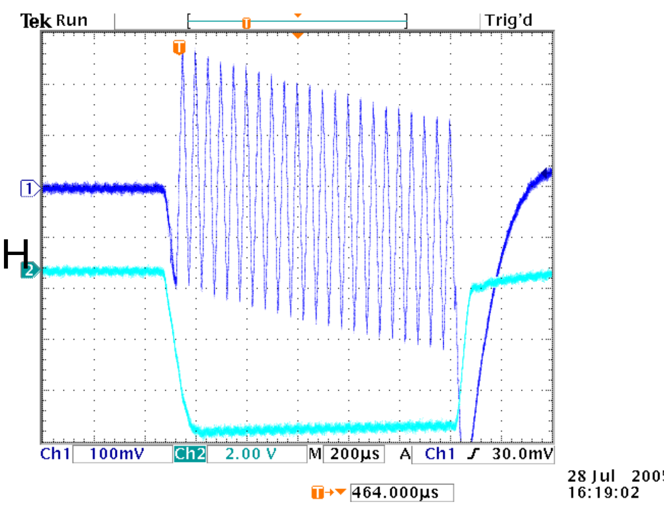
Normal Flux Pattern

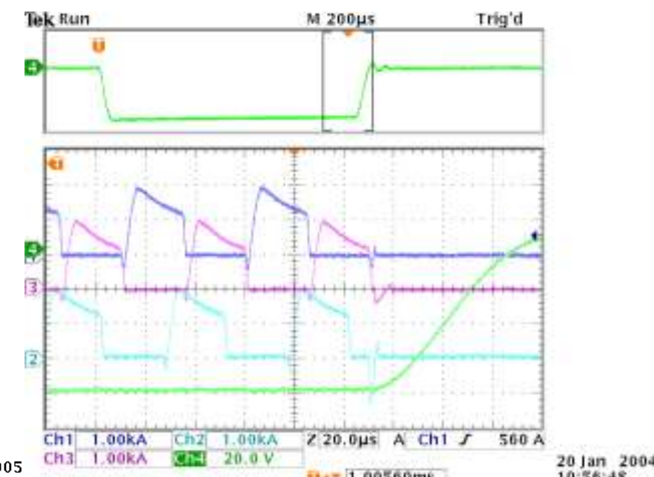










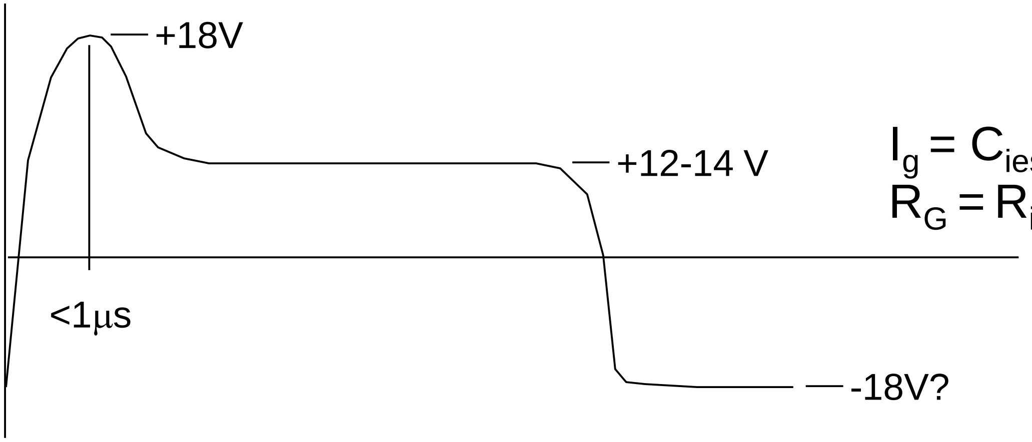


IGBT Gate Drive Prototype 1 Active

- Switch plate module w/ new drives in lab for testing
- Full H-bridge testing complete

IGBT Gate Drive Prototype 2 Passive

- "Picket Fence"-style drive to reduce fault IC
- VCO to pass real-time gate signal over fiber to scope?
- Collaboration pending with SLAC to independently investigate first two bullets, alternatives
- Full installation complete 2009



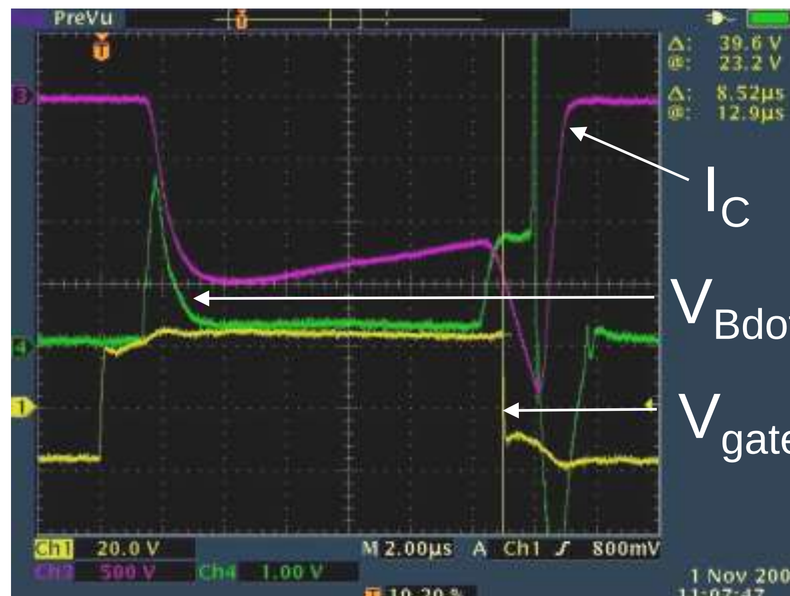
$I_g = C_{ies} dV_g/dt \approx 0.29\ \Delta V_g$

$R_G = R_{int} + R_{ext} \approx 1\ \Omega$

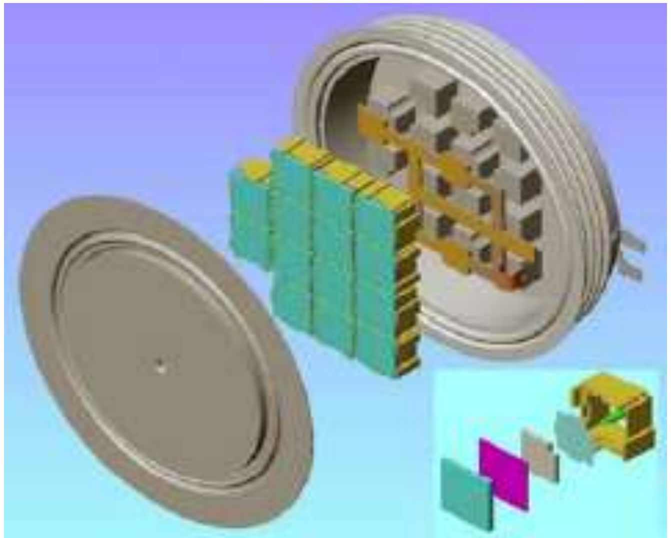
IGBT Gate Drive Proto 1 Progress

- Typical fault current cleared
- Circuit response time 1 μs, dominated by IGBT delays
- Slow V_C falltime due to device doping

- B-dot probe for di/dt detection post-risetime
- Low gated detection threshold on high side drivers
- High ungated detection threshold on low side drivers to protect from interpulse transients



IGBT Next-Generation Development



Next-generation Press-Pac IGBT devices

- Improved current handling, higher commutation current
- Higher voltage rating (4500 vs. 3300 V), higher current rated recently available (2400, 1800 vs. 1200 A)
- External anti-parallel diode required
- Presently developing at SLAC and funded
- Important for MTBF on RFQ HVCM, higher operating voltages on SCL modulators, ultimately PUP
- ~$40k semiconductors per modulator + switch plate mods and development costs

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SCL Modulator Test Results 1

Modulator	No. of klystrons	Vo, kV	Io, A	VDC, V	IC comm, kA	IC peak, kA
DTL-Mod1	3	115.0	88.4	±1117	600	2.96
CCL-Mod4	1	136.7*	75.6	±1164	760	2.54
SCL-Mod5	9	69.0	92.7	±1011	<0	2.34
		72.0	98.6	±1061	0	2.44
		75.0[1]	104.2	±1112	100	2.52
SCL-Mod9	10	69.0	96.6	±1015	380	2.24
		72.0	103.2	±1069	450	2.36
		75.0[2]	109.5	±1120	470	2.46

*calculated from klystron perveance and current

[1]77kV calculated [2]75.7 calculated

SCL Modulator Test Results 2

Modulator	No. of klystrons	Vo, kV	Io, A	VDC, V	IC comm, kA	IC peak, kA
SCL-Mod15	11	72.0	122.5	±1106		
SCL-Mod18	11	71.0	114.5	±1087	600	2.32
		76.2*	122.0	±1131		
SCL-Mod21	11	71.0	110.7	±1062	600	2.36
		73.0	115.1	±1096	600	2.40
		74.8*	119.6	±1130	650	2.48
SCL-Mod9	12	72.0[1]	122.8	±1131		
SCL-Mod12	12	72.0[2]	122.1	±1096		

*calculated from klystron perveance and current

[1]73.6kV calculated [2]72.8kV calculated

Results Discussion

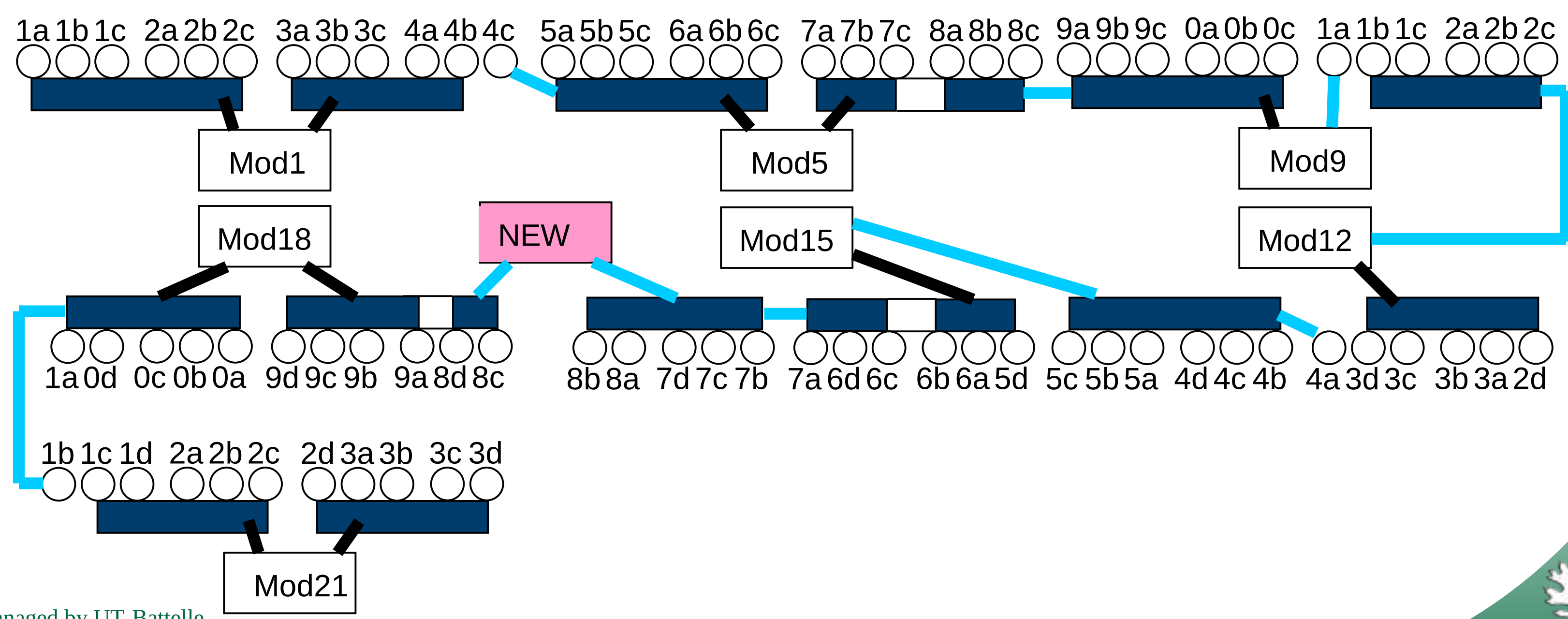
- Running 9-pack is undesirable <75 kV
- Calibration clearly off on many modulators
  - can klystron data be believed?
  - Calibration not yet performed
- 10-pack looks virtually identical to DTL-Mod1 with the existing hardware and should have slightly higher MTBF
- 11-pack can run at 75.0 kV
- 12-pack can run at 72.0 kV, maybe 75.0 kV

Operation Limitations and Penalties

- **11-pack to 75kV**
  - **~90% MTBF of DTL-Mod1**
  - **~125% MTBF of CCL-Mod4 at present setting**
- **12-pack to 75kV**
  - **Est. 58% MTBF of DTL-Mod1**
  - **Est. 80% MTBF of CCL-Mod4**
  - **Danger of frequent spurious trips from protection electronic systems (operating at max. settings)**

Reliable 75kV Operation in SCL

- 10-pack in medium/high beta locations
- 1 11-pack at first medium beta station (SCL-Mod1)
- $L_{cable, total} \leq \sim 200$ feet for $E_{fault} < 20J$
- Additional HVCM, $700k w/ SLAC unit OR $2M for 2 addt'l. HVCM (1 spare+ 1 SLAC unit)



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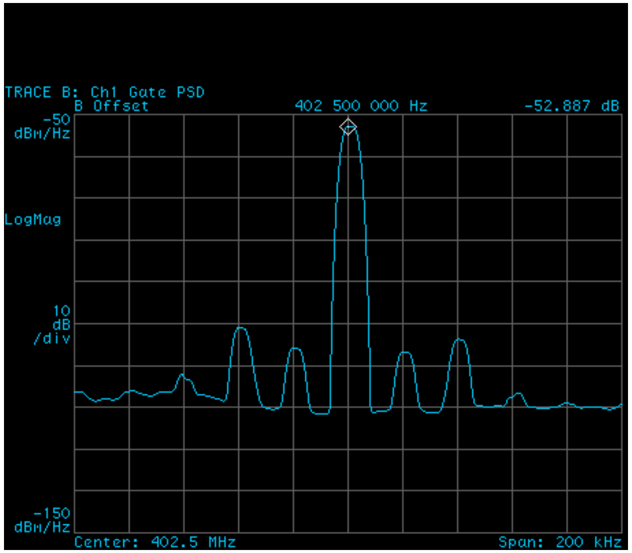
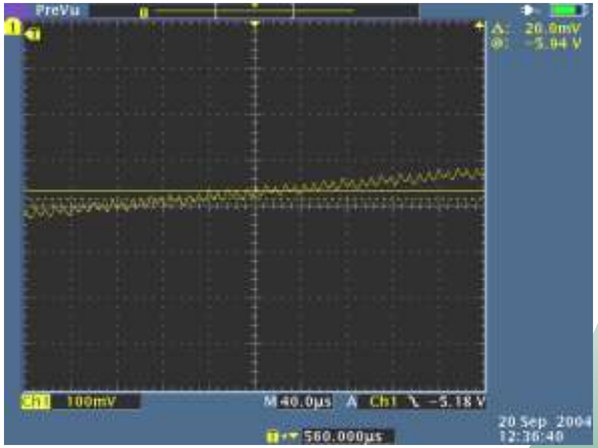
20/40 kHz Harmonic Filter for Ripple Reduction

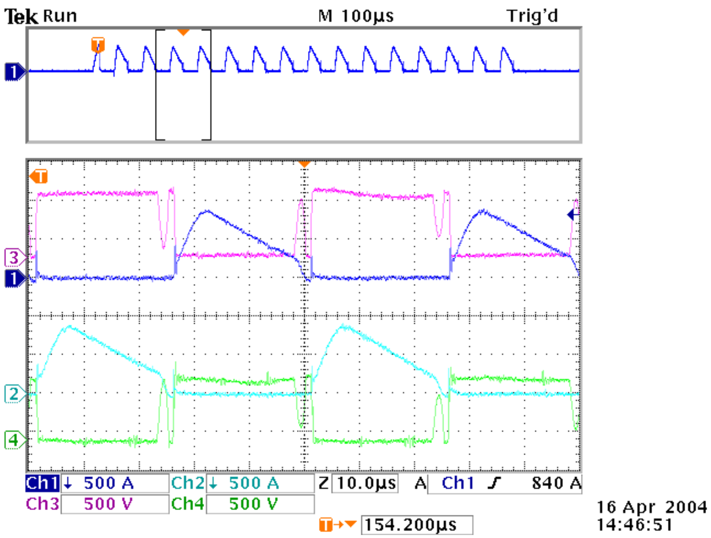


- 20/40 kHz Harmonic Filters on output section to reduce ripple
    - Factor of 2 improvement in ripple (0.33% p-p)
    - Design exists and tested on a CCL modulator

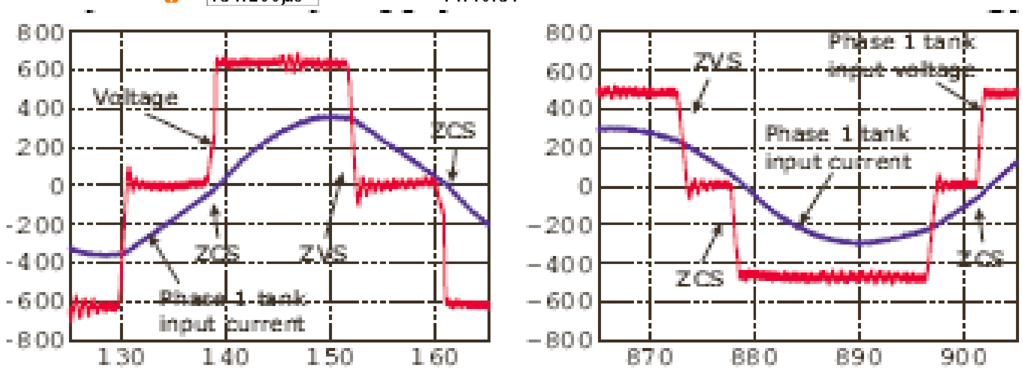


Pulse Droop Correction

69 kV "phased back" – PWM requires more work



- •Switching losses too high in initial tests
- •Alternative droop compensation scheme – frequency modulation, phase shift modulation, both, ???

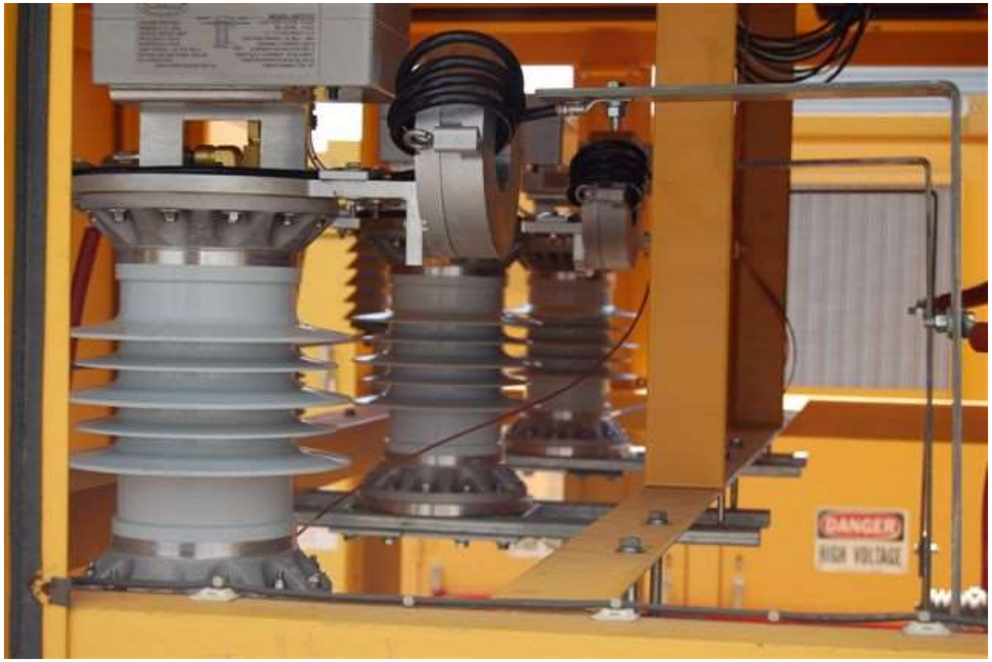


(a) Start of pulse (b) End of pulse

University of Nottingham PSM/FM scheme POP

Line P.F. and Harmonic Characterization

- MetPod by Field Metrics field evaluation unit in SCL-Mod1
- FO-coupled V and I available adjacent to control rack
- Study impact on line parameters



Conclusion

- Many of the HVCM subsystems/components have been or will be upgraded to improve reliability
  - Funded activities completed mid-FY09
- Fire mitigation has been prompt and will be complete mid-FY09 (outage dominated)
- Test stand in place early this calendar year to support additional development
- R&D Efforts underway to support future activities
- Collaborative efforts utilized to extend available resources
- Modulator issue resolution well-received by management