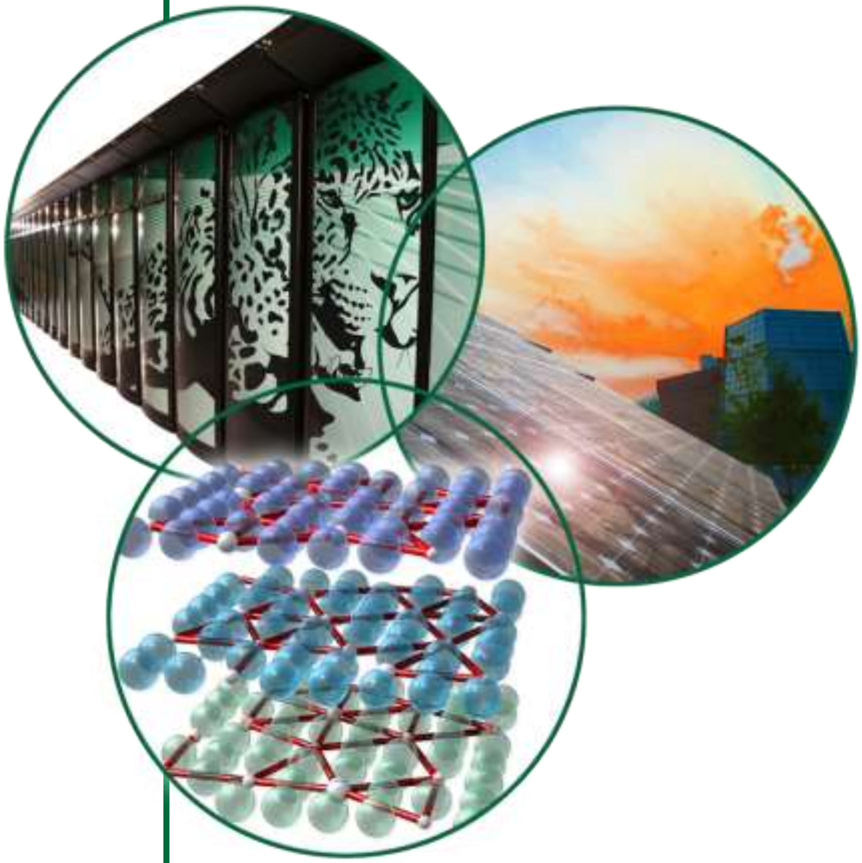
SNS Linac Modulator Operations and Performance



V. Peplov

January, 2012

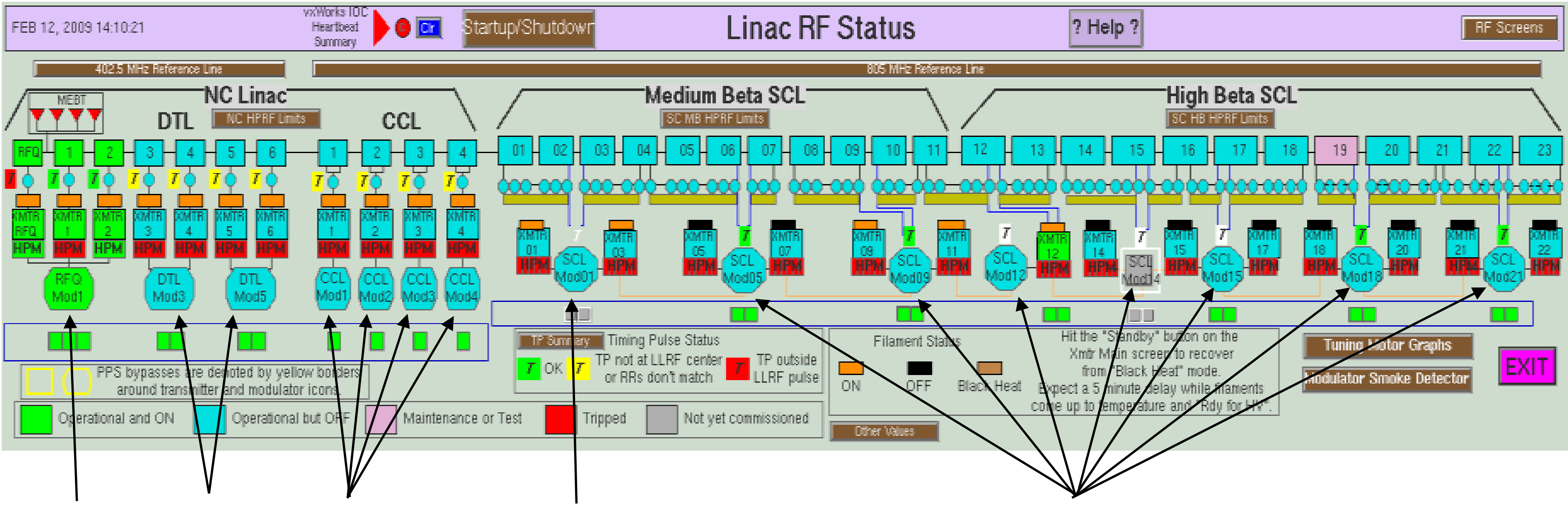
U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Outline

- SNS HVCM configuration
- HVCM downtime statistics
- Failure mode analysis
- Upgrades
- Plans
- Conclusion

Cavity/Klystron/Modulator Layout



115 kV 125 kV ≤135 kV 71 kV 75 kV

DTL CCL SCL

- 15 modulators: 3 - DTL, 4 - CCL, 8 - SCL
- Multiple HVCM/Klystron Configurations

Operational Parameters

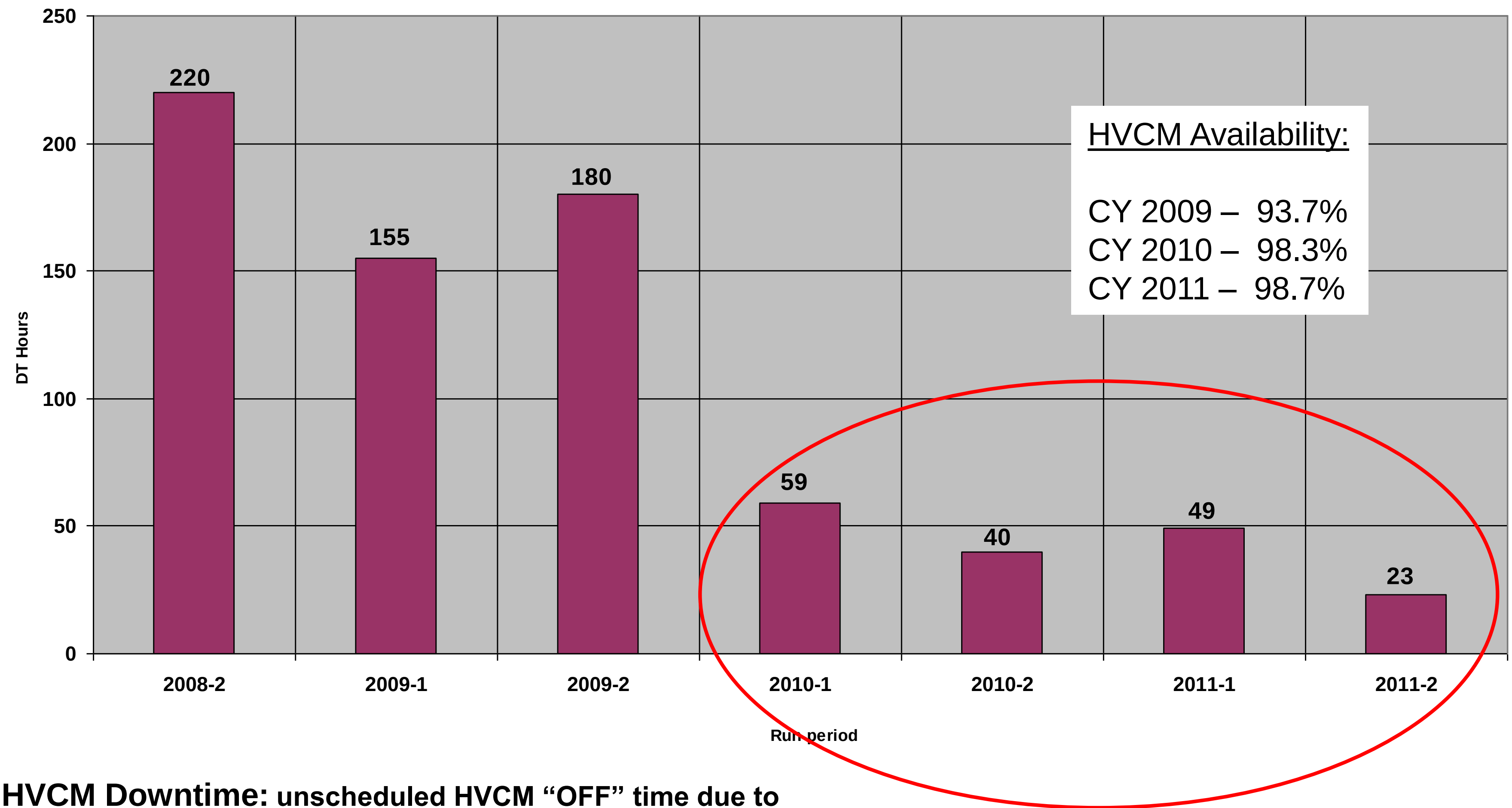
Modulator	Operation hours (as on 12.22.2011)	Load: # of klystrons	V mod, (kV)	I mod, (A)	P peak, (MW)
DTL-1 (RFQ)	43,091	3	115	92	10.6
DTL-3	40,279	2	125	72	9.0
DTL-5	40,231	2	125	68	8.5
CCL-1	38,953	1	128	68	8.7
CCL-2	36,354	1	131	64	8.4
CCL-3	38,203	1	135	67	9.0
CCL-4	36,223	1	126	72	9.1
SCL-1	37,974	11	71	124	8.8
SCL-5	38,044	10	75	109	8.2
SCL-9	36,461	10	75	106	8.0
SCL-12	37,685	10	75	109	8.2
SCL-14	18,871	10	75	109	8.2
SCL-15	36,652	10	75	114	8.5
SCL-18	36,954	10	73	112	8.2
SCL-21	33,248	10	75	108	8.1

HVCM Downtime

1. 7 runs considered for overview metrics
   – Calendar Year runs: 2008-2 through 2011-2

2. Analysis of Downtime in CY-2011
   – trips interrupted beam delivery only
   – by months
   – by sort of failures

HVCM Downtime Hours by Runs

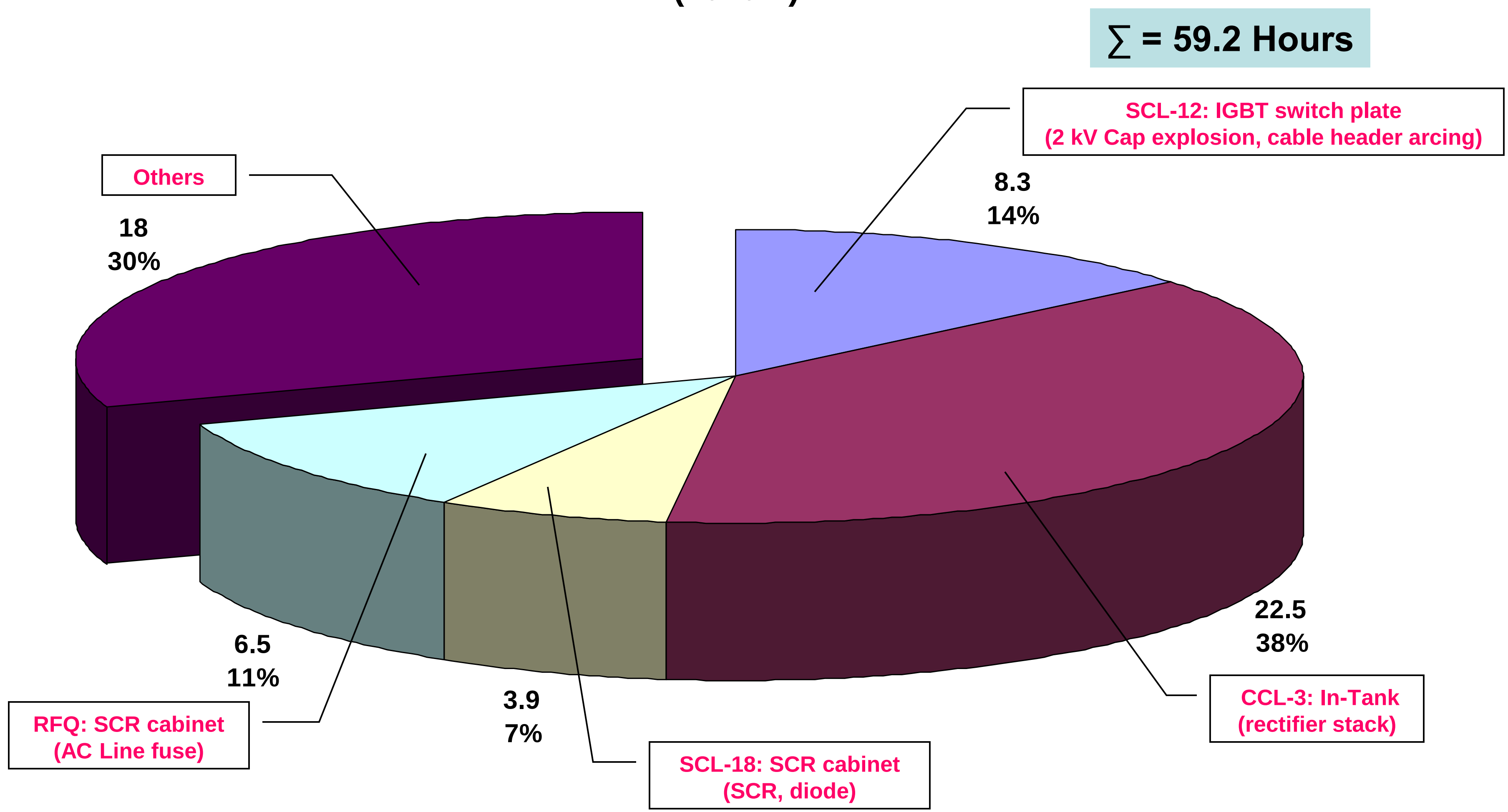


HVCM Downtime: unscheduled HVCM "OFF" time due to any fault in HVCM system during beam delivery

HVCM Availability: a ratio of modulators total running hours to total hours for NP and AP study in each run period

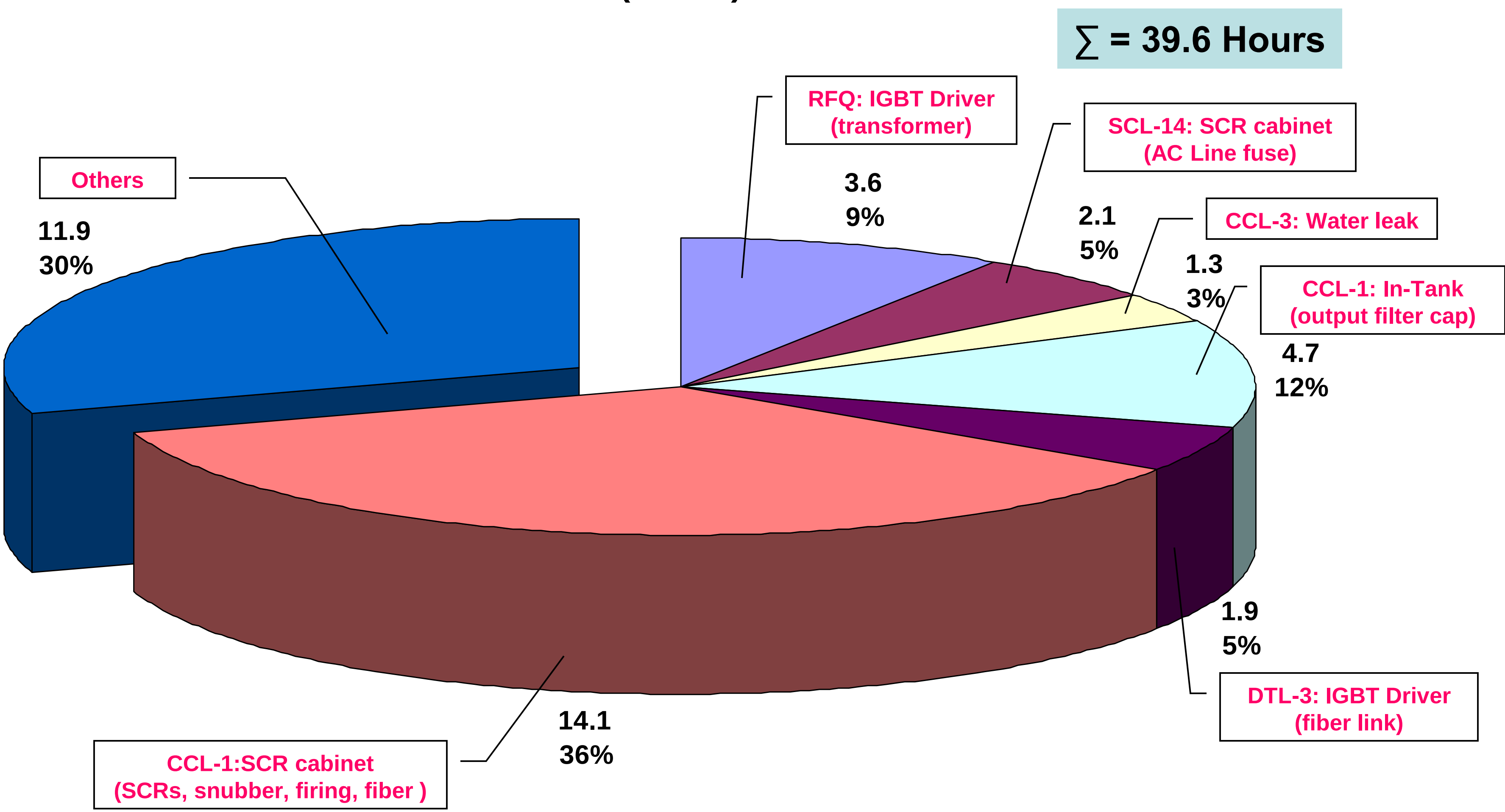
(See following charts)

HVCM Downtime
(2010-1)



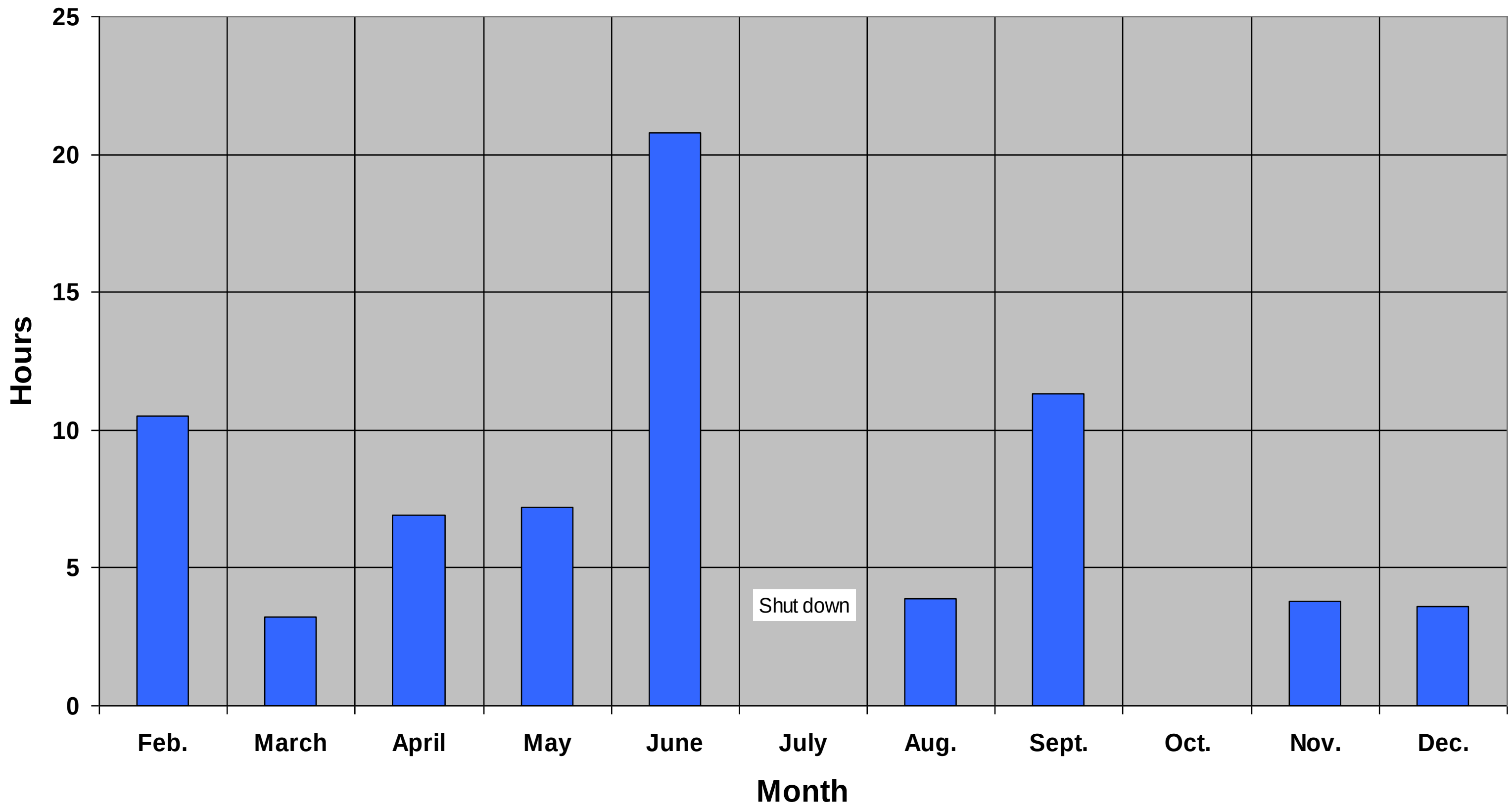
- 4 events – 70% contribution
- More than 1 hour downtime shown separately
- Others: different types of faults; each less than 1 hour

HVCM Downtime (2010-2)



- 2 events – about 50% downtime
- More than 1 hour downtime shown separately
- Others: different types of faults; each - less than 1 hour

HVCM Downtime in CY-2011



Run	Hours
2011-1	
Feb.	10.5
March	3.2
Apr.	6.9
May	7.2
June	20.8
	∑=48.6
2011-2	
Aug.	3.9
Sep.	11.3
Oct.	0
Nov.	3.8
Dec.	3.6
	∑=22.6
Σ	71.2

HVCM Downtime: unscheduled HVCM "OFF" time due to any fault in HVCM system during beam delivery

Downtime Statistical Data (CY-2011)

Hours By Faults

	2011-1 (Feb. – July)		2011-2 (Sept. - Dec.)		
	Number of events	Hours	Number of events	Hours	Σ Hours
Fault Type					
HV Cable	3	20.3	0	0	20.3
SCR Water Leak (CCL-2)	2	9.2	0	0	9.2
Oil Pump	3	5.2	3	3.3	8.5
IGBT Switch/Driver	3	3.5	2	5.0	8.5
Control chassis (SCL-5, SCL-9)	0	0	2	6.7	6.7
Dynamic Fault (Mod RFQ)	0	0	28	6.2	6.2
Timing Faults	12	2.2	0	0	2.2
Water Panel Interlock	1	2.1	0	0	2.1
Voltage Dip (SCL-21)	4	0.5	0	0	0.5
Miscellaneous: Mod. OI, IGBT OI, SCR OI, Flux sat., Dif. V, etc.	Many	~6	Many	~2	~8
Σ		~49		~23	~72

Notice: Beam breakdown events/hours shown

HV output cable damage

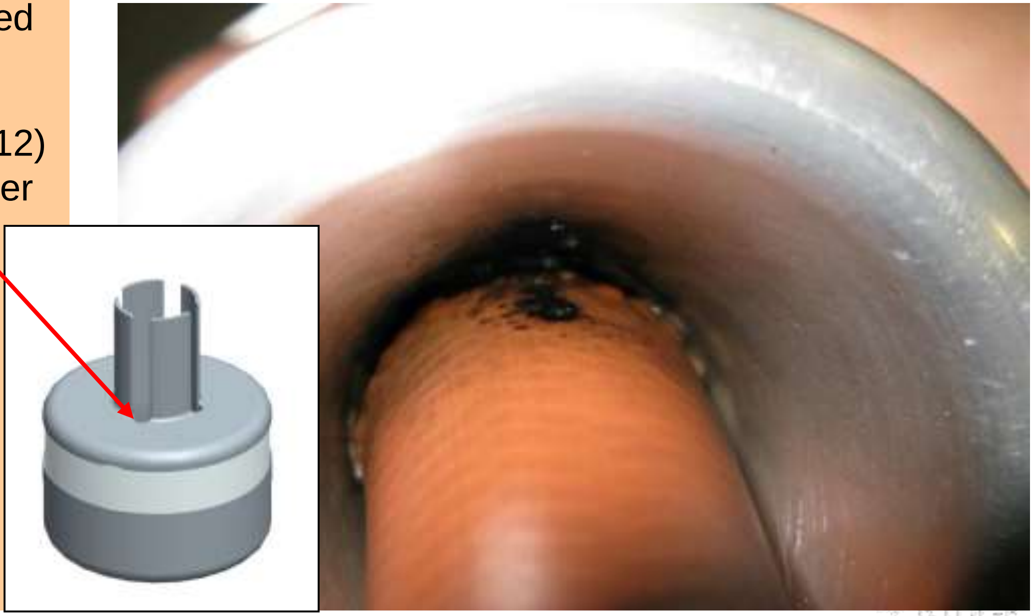
3 events during 2011-1:
- SCL-18, SCL-15 and CCL-2
- Downtime – 20.3 hours total

What happened:
- Long time in service
- Swelling in the oil
- Air bubble possible
- Insulator degradation

Result: Shorted / Arcing Cable

What was done:
- Damaged cables replaced and re-terminated
- New cables in 7 NCL modulators (Summer -2011)
- New cables in 4 SCL modulators (Jan. 2012)
- Improved receptacle return connector (larger radius, no sharp edges) designed and manufactured
- Testing on RFTF

Plans:
- Complete replacement in SCL (Jan. 2012)
- Re-terminate cables with improved receptacle return connector



SCR cooling system: Water leak

What happened:

- Water leakage inside SCR cabinet on HVCM CCL-2 . Two failures in series. 9.2 hours downtime
- This type of failure has not occurred previously

Inspection revealed:

- Failed SCR Cooling Bus - Pinhole Leak with Corrosion
- Rough estimate ~ 0.01” wall thickness between Cooling Water Threads and Wall of Clearance Hole for SCR clamp
- The Clearance Holes for the SCR clamp do not centered in the Bus
- Suspect Repair: the wall of the Clearance Hole has been “soldered” (perhaps to repair a leak at the manufacturer)

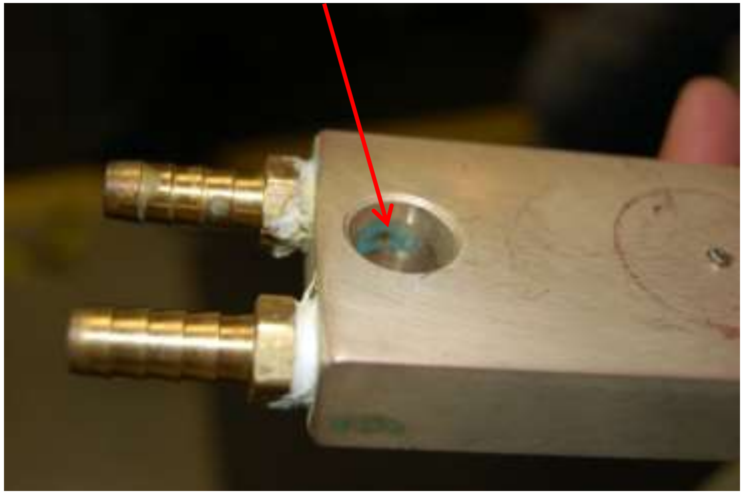
What was done:

- Temporary replaced with other type spare bus
- New bar bus with +0.75” extended length fabricated
- Spare assembly tested and ready for installation

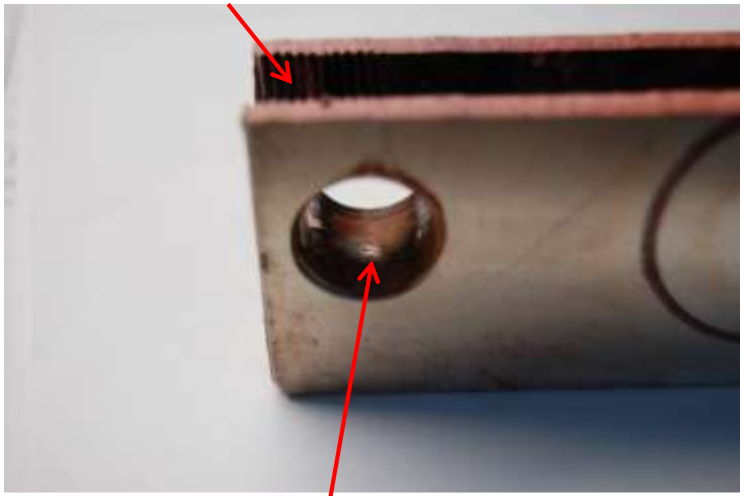
Plans:

- Install spare unit to HVCM CCL-2
- Fabricate improved parts
- Replace in all SCR cabinets according to schedule

Pinhole Leak with Corrosion



Threads for Cooling Water Fittings



The wall of the Clearance Hole “Soldered”

Oil Pump failure

<u>Mechanical issues</u>

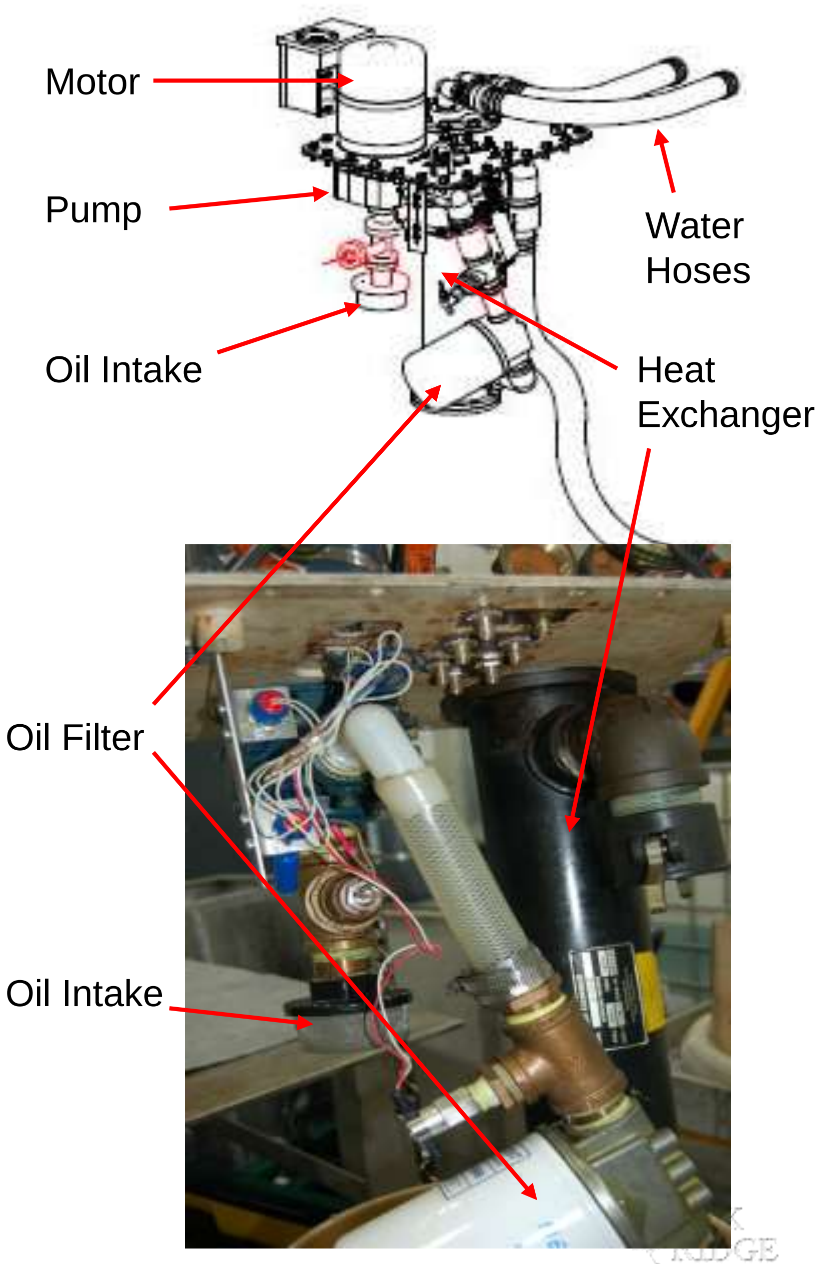
- Long time in service; works 24/7
- Bearing load, vibration: bearing failure is typical
- It takes ~2 hours to replace the assembly
- 6 times & 8.5 hours downtime in 2011

<u>Oil/tank overheating</u>

- Cooling efficiency depends on the unit installed
- Mod RFQ: tank temperature changed from ~ 70ºC to ~42ºC after assembly replacement
- Pump impeller, filter, heat exchanger - ? Continue monitoring and inspection
- Larger impeller in the pump: test shows tank temperature drops down by ~3ºC

<u>Future</u>

- Install temperature detectors in the tank (10 probes installed in RFQ tank in Jan. 2012)
- Oil flow measurement
- Vibration analysis
- New system design in progress



IGBT switch plate

4 kV/10 uF solid TPC capacitor

IGBT driver card

2 kV/10 uF solid NWL capacitor

- April 2011: Capacitor replacement completed; no oil-filled capacitors on switch plates
- 5 events & 8.5 downtime hours during CY-2011
- New IGBT drivers installed on RFQ-modulator in Summer 2011; testing continues

Plans:

- Install new intelligent drivers
- Test spare IGBT switch plates on Single Phase Test Stand
- Test IGBTs using Tektronix 371A High Power Curve Tracer
- Use IGBT snubber circuit (development and testing in progress)

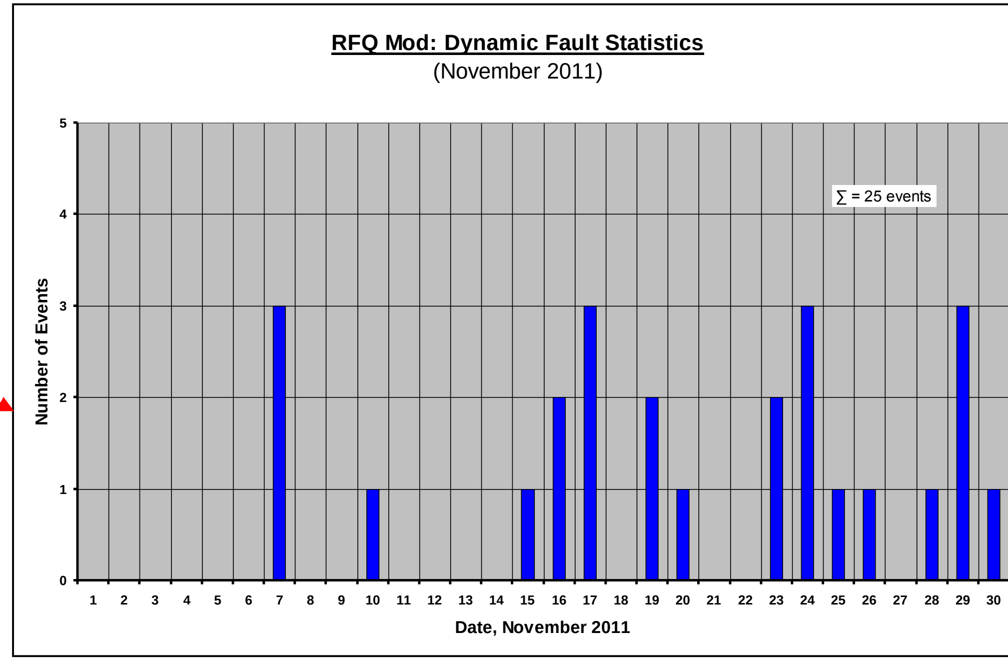
Modulator RFQ: Dynamic Fault

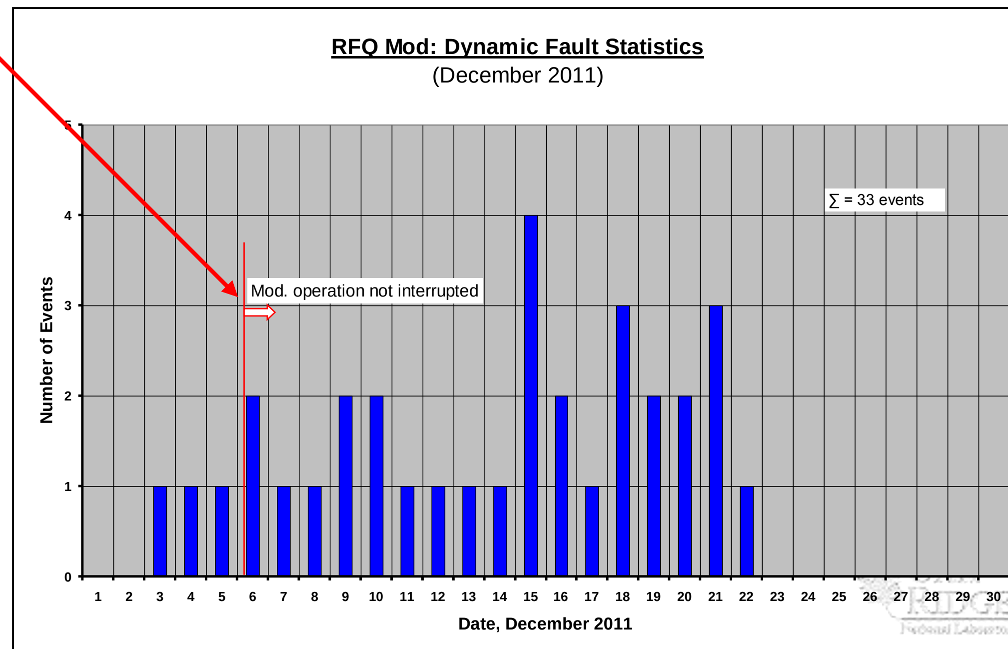
History:

- Dynamic Fault Detector Circuit (DFDC) interrupts modulator running if output voltage changes fast (high dV/dt)
- Trips started in November; statistics shown on the diagrams
- Recovery ~0.2 hours each event
- 28 events & 6.2 downtime hours until Dec.6
- Bypass DFDC out to modulator on Dec. 6, since – no trips, but monitoring continues (+30 events)

Analysis:

- Voltage dips, no modulator current spikes
- Klystron currents follow modulator voltage
- The only tank which has harmonic trap installed





Modulator RFQ: Dynamic Fault (continue)

Tank has been opened and inspected in Dec. 2011:

- Harmonic trap capacitors (1.8 nF & 180 kV)
  - One cap looks good and passed 180 kV hipotting test
  - Two caps - internal breakdown at 100 kV and 120 kV
- Return HV cable – signs of pinch through breakdown
- Two bad capacitors on the rectifier stack
- Boost capacitors : one failed, two have split cases

Done in Jan. 2012:

- 3 new spare boost capacitors installed
- Caps tipped to avoid internal air bubble
- New spare harmonic trap capacitors installed
- Caps on rectifier stack replaced
- HV cable replaced

"In-Tank" boost capacitors (history)

Old 120 kV / 3100 pF GA capacitor (failed); Replaced in Summer 2010

Jan. 2011 inspection: New capacitors failure (brackets removed)

New 150 kV / 3100 pF CSI capacitors with brackets; Installed in Summer 2010

Capacitor's Corner

“In-Tank” boost capacitors (history)

January 2011:
- Upper brackets removed to avoid air traps
- Zip-straps used instead
- DTL and CCL (7 total) modulators upgraded

April 2011:
- CCL-3 tank inspection
- No signs of corona/arcing found

Summer 2011:
- DTL and CCL tanks: inspection - boost caps OK

Winter 2012:
- RFQ tank inspection
- Failed caps found - still remain the problem

Plans:
- 3 caps from RFQ – send to manufactory
- Inspect another tank in Jan. 2012
- 3 new SCL capacitors tested at full power
- Install into SCL tanks (Summer 2012 or regular maintenance days)

Control Issues (SCL-5, SCL-9)

Two events in September 2011:

- SCL-5 modulator Controller (1.6 hours downtime)
  - connections between control chassis and PLC
- SCL-9 SCR rectifier Control Head (5.1 hours downtime)
  - SCR interlock issue
  - long troubleshooting
  - SCR Control Head removed and replaced with a spare unit

Plans:

- Replace connectors/cables in SCR Control Head

  or
- New intelligent controller:
  - Remove SCR Control Head
  - Easier diagnostics

Control Issues (SCL-21)

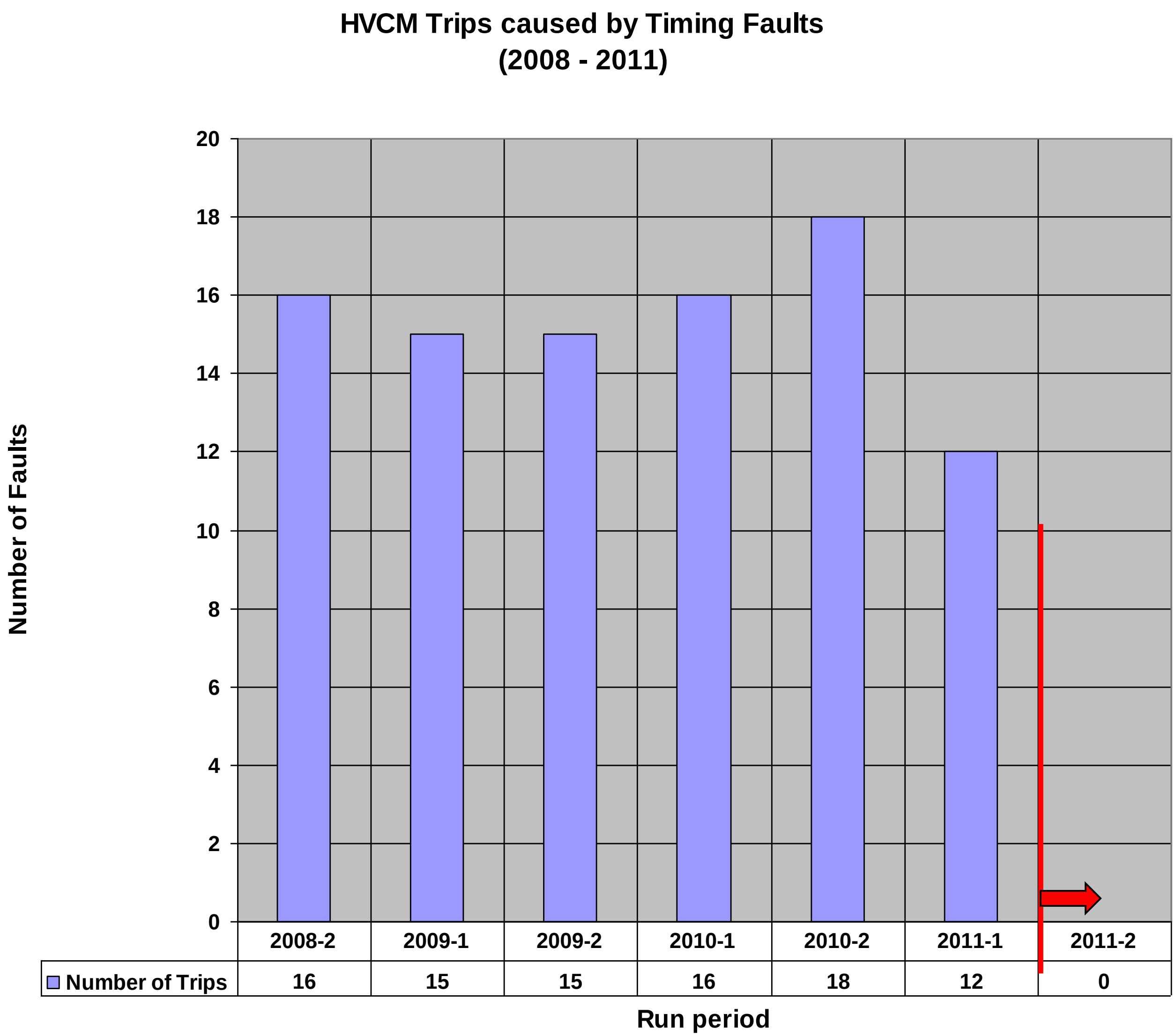
History:

- Modulator Voltage jumps cause Chatter Faults
- A lot of trips beginning October 2010
- 8 Trips in February 2011
- Long recovery
- Origin of faults - ?
  - SCR cabinet
  - Modulator
  - Load
- Instrumented SCR Cabinet, Modulator and Klystron Currents
- Streaming EPICs data

Found:

- SCR regulation feedback signal “Positive Bus Current” drifts and has sudden steps
- SCR feedback signal moved to “Negative Bus Current” sensor for regulation – no Voltage jumps since that time
- Current sensor on Positive Bus replaced

Timing Trips Statistics



Timing Faults:

- Pulse Repetition Interval
- Duty Cycle
- Gate Input Pulse Width
- Inter-Pulse
- ~0.2 hours recovery each time

Upgrade inside controller:

- Input gate noise filtering board installed
- All old coax cables replaced with new
- Loads moved from chassis onto PCB

Result:

- No trips since upgraded in Summer 2011

HVCM Upgrade

Other works during CY 2010-2011 outages:

- Output filter capacitors removed from all NCL modulator tanks
- New De-Qing resistors assembly, new voltage dividers and new cables installed in NCL modulator tanks in Summer 2010
- Forced air cooling system assembled in 8 SCR cabinets (2 - in 2010, 2 - in April 2011, and 4 - in Summer 2011)
  - Air temperature inside SCR cabinet reduced from 180ºF to 90ºF (in RFQ modulator)
- Interlock connector on water panel box replaced (9 of 15 completed to the date)
- New IGBT drivers installed on 3 switch plates on RFQ modulator (Summer 2011)

Maintenance Plans

- Upgrade SCL tanks (boost capacitors, de-Qing resistors, HV divider and HV cables)
- Complete SCR cabinet air cooling system assembling (7 more)
- Complete HV cables replacement in SCL modulators (Jan. 2012)
- Re-terminate HV output cables with improved return conductor
- Complete Interlock connectors replacement on Water panel (6 more)
- Checkout/replacement storage and switch plate capacitors
- Upgrade DC Bus Voltage and Current monitoring circuitry
- Upgrade modulator Output Current monitoring circuitry
- A bunch of miscellaneous items

R&D efforts underway to support future activities:

- New IGBT gate driver implementation
- IGBT snubber circuit
- New intelligent FPGA based controller
- Oil cooling system upgrade (outside heat-exchanger)
- Series opening IGBT switch
- New HVCM topology
- “N+1” redundant H-bridge topology

CONCLUSION

- The HVCM system was a major contributor to the accelerator down time until 2009
- Thorough failure mode analysis done
- A lot of upgrades and modifications during last two years
- HVCM downtime reduced about factor of 10 (!) from 220 hours in 2008-2 running cycle to 23 hours in 2011-2
- Overall HVCM system availability increased from 93.7% in 2009 to 98.7% in 2011

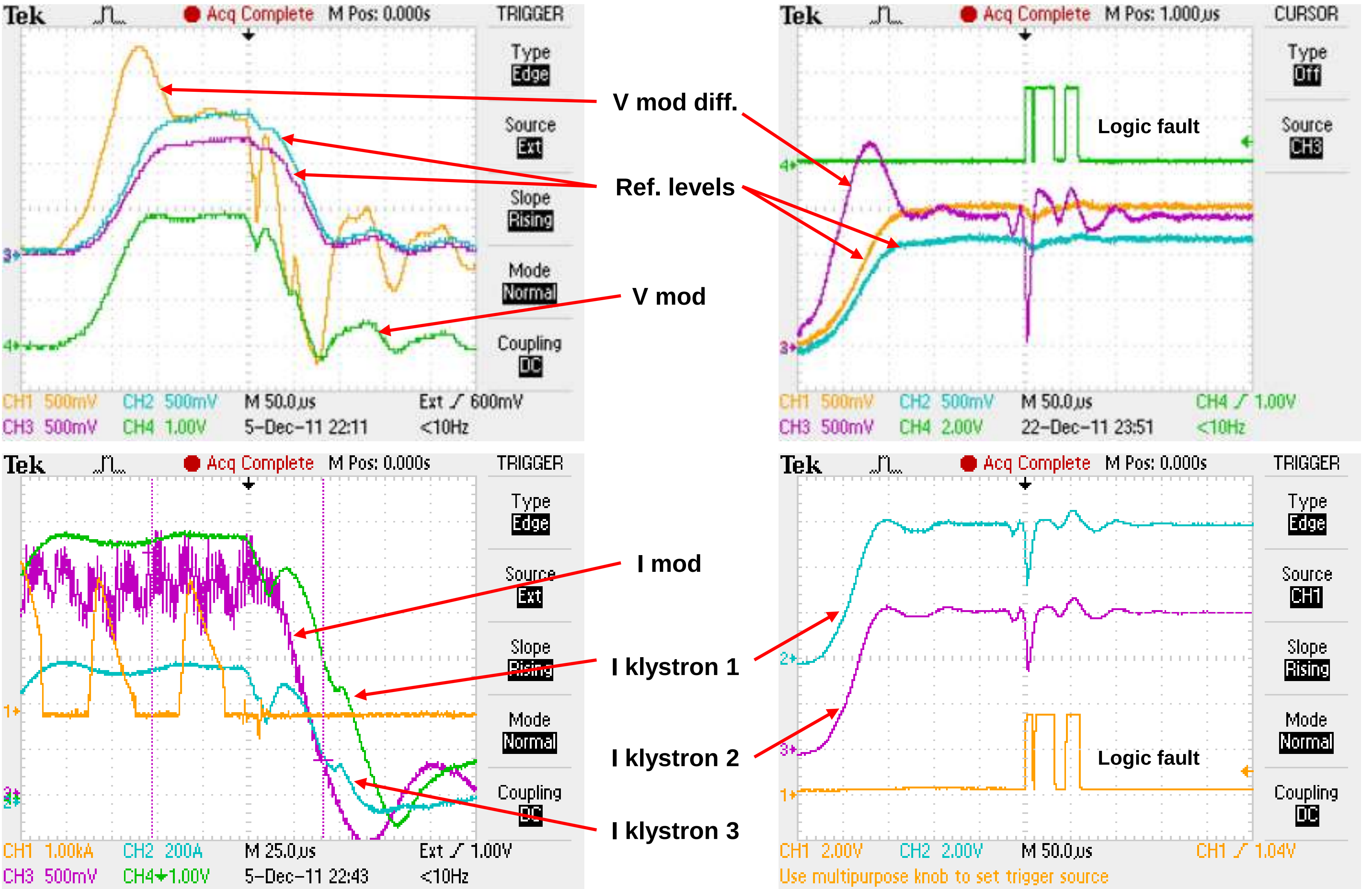
Backup slides

SNS
SPALLATION NEUTRON SOURCE

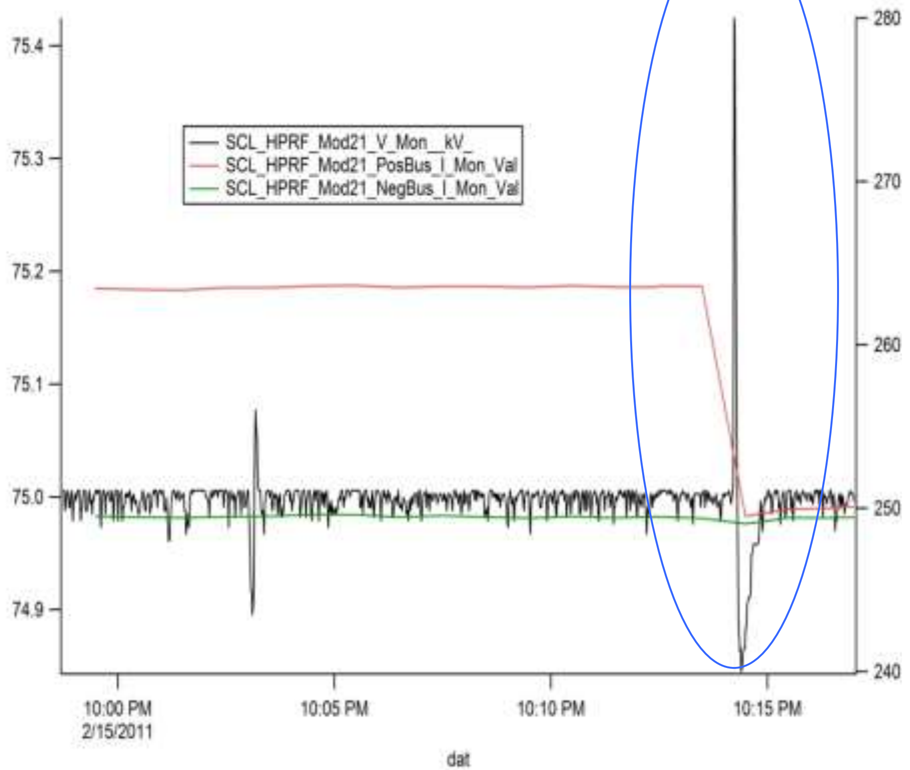
Modulator RFQ: Dynamic Fault

Modulator trips

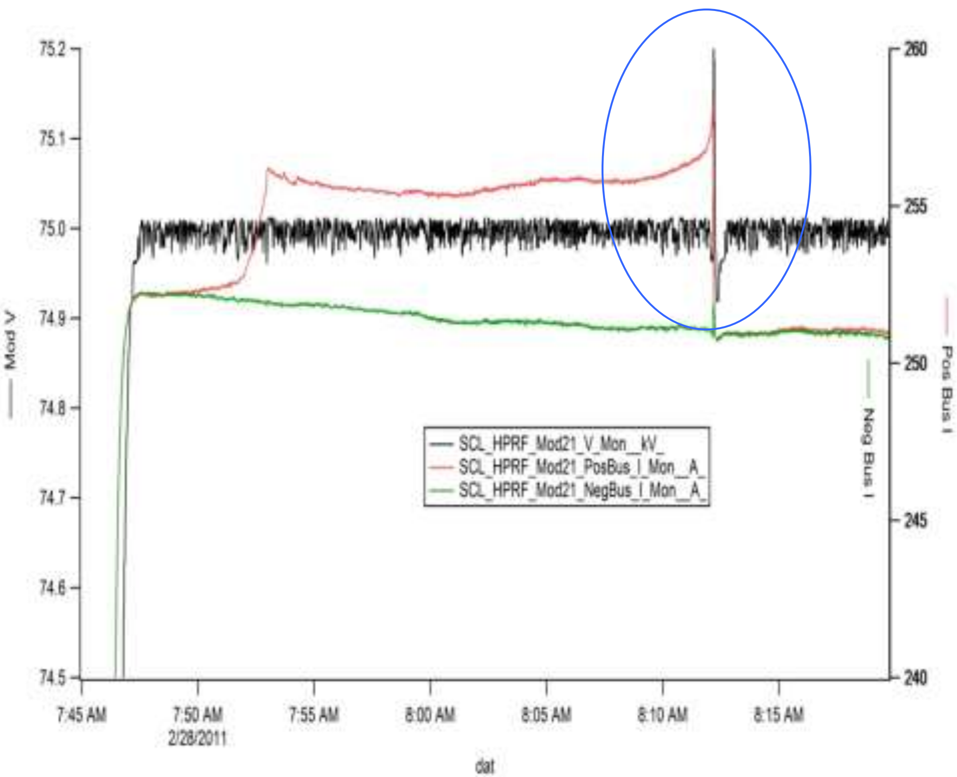
Modulator stays running



Mod Voltage, Pos & Neg Bus Currents at 1 Hz sample rate



Feb. 15, 2011
Chatter Fault
15 Amp Step in Pos Bus Current



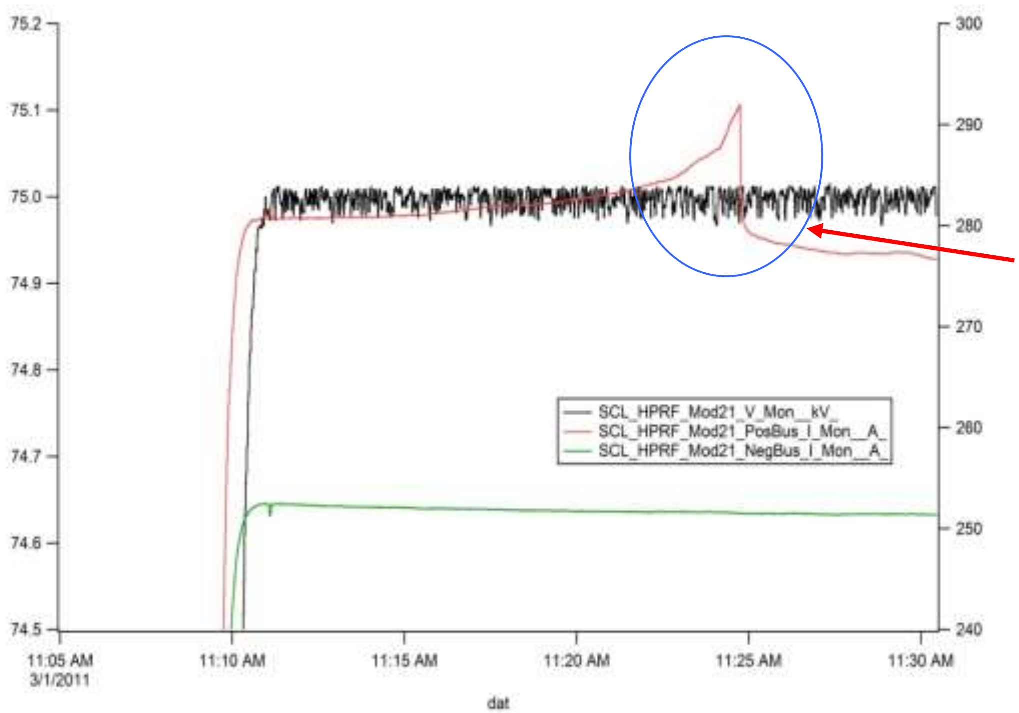
Start up Feb. 28, 2011
7 Amp step in Pos Bus Current
causes 200V jump in Mod V

 Managed by UT-Battelle
for the U.S. Department of Energy

OAK RIDGE National Laboratory

March 1, 2011:

SCR Feedback signal moved from Positive Bus Current sensor to Negative



SCL-21:

- Positive Current feedback signal drifts and has sudden steps
- Changed to Negative Current feedback signal for regulation – no Voltage jumps

- Current sensor on Positive Bus replaced

“In-Tank” boost capacitors

Old 120 kV / 3100 pF GA capacitor (failed)

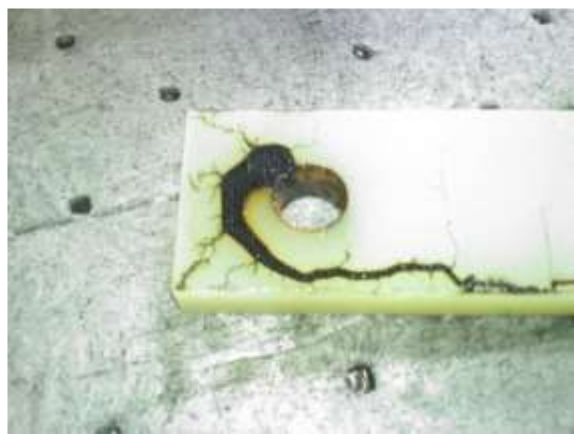
New 150 kV / 3100 pF CSI capacitors with brackets

New capacitors failure (brackets removed)

CCL4, RFQ – Damage on the caps

Cap Corners

RFQ Brackets



Cracks on the case

- **Inspection in Jan. 2011 revealed the problem**
- **Analysis and simulation done (SNS and CSI)**
- **Mounting brackets changed**

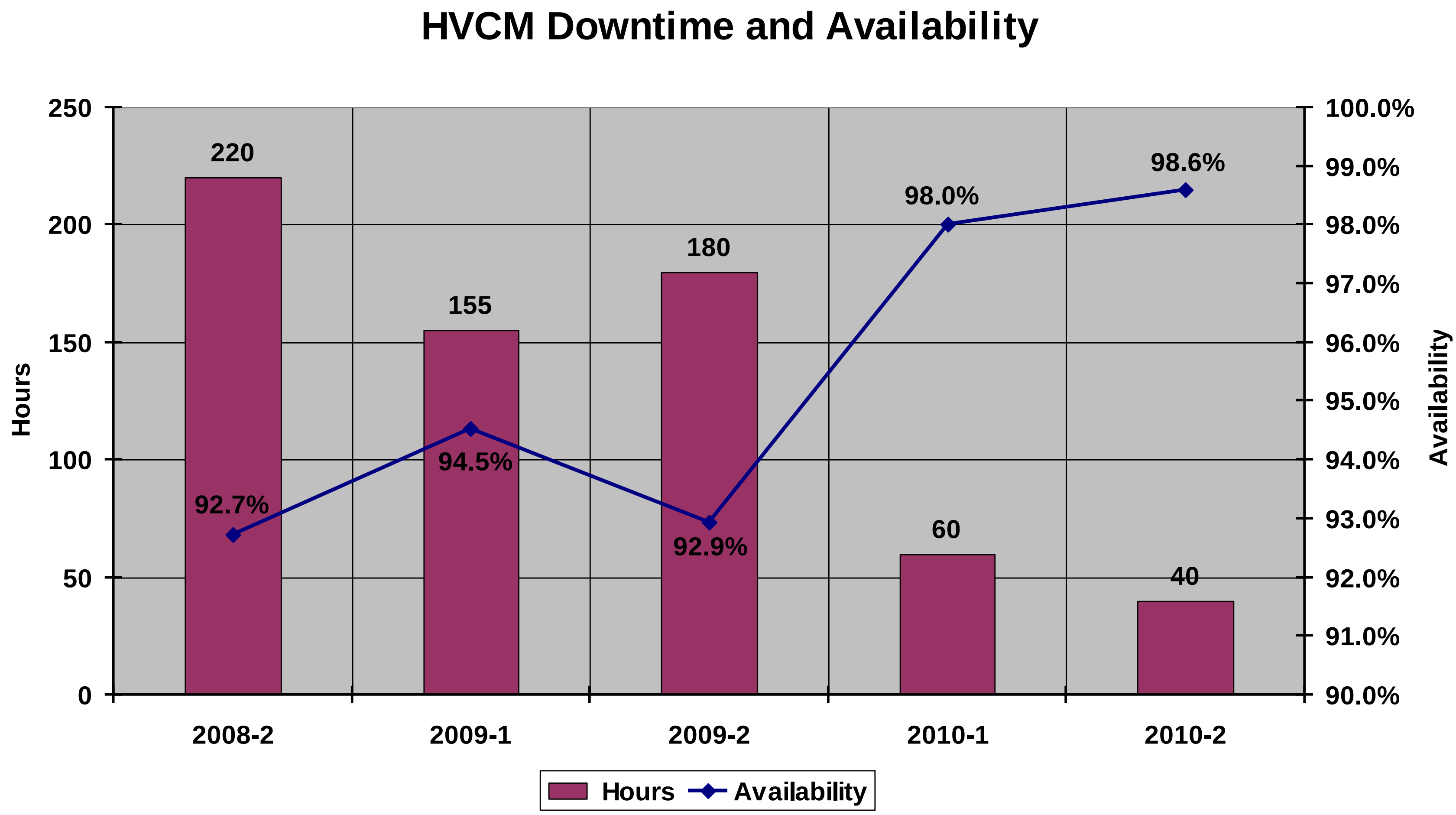
CSI Failure Analysis of RFQ/ CCL4 Caps

- Pictures from CSI
- All 7 capacitors repaired

"In-Tank" boost capacitors Analysis results*

- Presence of air bubbles either inside or external to the capacitor creates a problem where corona inception will eventually cause degradation of the surrounding insulation system and lead to catastrophic failure
- The upper brackets should be replaced with another style of bracket less likely to trap air
- The capacitor should be mounted at a slight angle to force any air that may be trapped internally away from the electrode since the manufacturer cannot guarantee that the unit will be bubble-free
- A follow-on inspection should occur at the next available opportunity to conform the mitigation strategy employed during the recent winter shutdown
- Further testing should continue on the virtually-equivalent SCL boost capacitors in the HEBT modulator for as much time as operational and other developmental demands will permit.

*SNS WARM LINAC HIGH VOLTAGE CONVERTER MODULATOR (HVCM) BOOST CAPACITOR FAILURE ANALYSIS AND CONCLUSIONS
DAVID E. ANDERSON, FEBRUARY 25, 2011



HVCM Downtime: unscheduled HVCM "OFF" time due to any fault in HVCM system during beam delivery

HVCM Availability: a ratio of modulators total running hours to total hours for NP and AP study in each run period

Modulator Tank HV Output Receptacle Return Connector