Linac Modulator Operations and Performance

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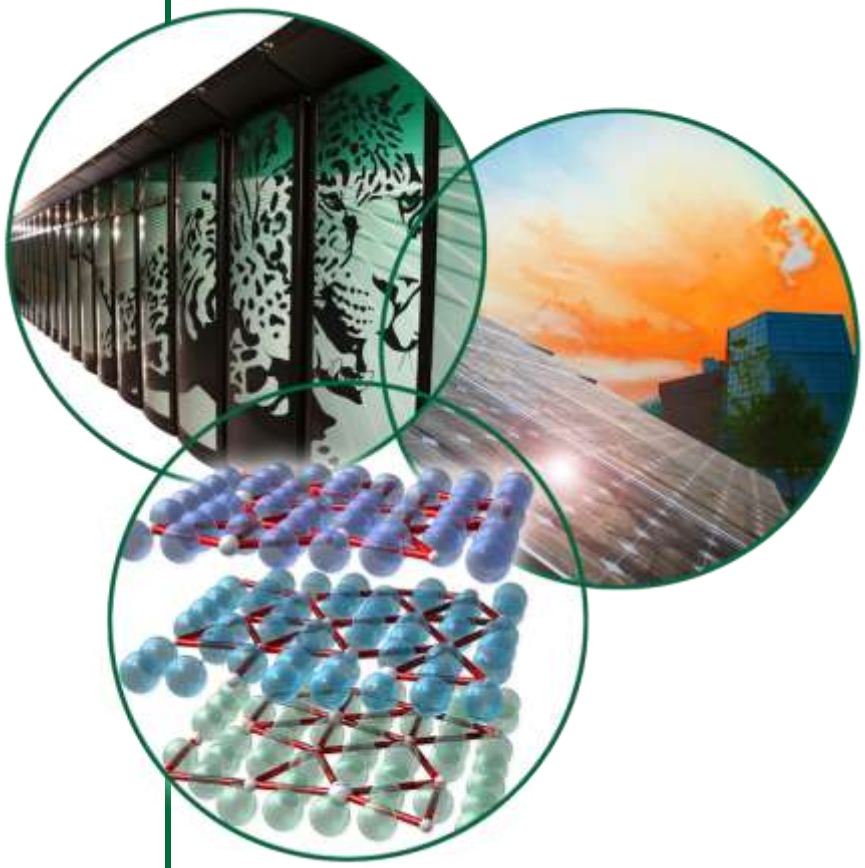
Feb. 2010



U.S. DEPARTMENT OF ENERGY

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

HVCM Breakdown Time

1. 3 runs considered:
   - September – December 2008;
   - March – July 2009;
   - September – December 2009
2. Analysis of downtime:
   - trips interrupted beam delivery only;
   - by sort of failures;
   - by modulators;
   - by runs/months
3. Statistical data:
   - from SNS operators;
   - from e-log;
   - root causes of some events not obvious

Downtime Statistical Data

(Sept. 2008 – Dec.2009)

Hours By Months

Month	Hours	% of total downtime
Sep. 08	80	14.4
Oct. 08	61	10.9
Nov. 08	73	13.0
Dec. 08	7	1.2
Jan. 09	0	0.0
Feb. 09	0	0.0
Mar. 09	39	7.1
Apr. 09	29	5.3
May 09	67	12.0
Jun. 09	15	2.7
Jul. 09	9	1.7
Aug. 09	0	0.0
Sep. 09	10	1.7
Oct. 09	47	8.5
Nov. 09	115	20.7
Dec. 09	4	0.8
Σ	556	100.0

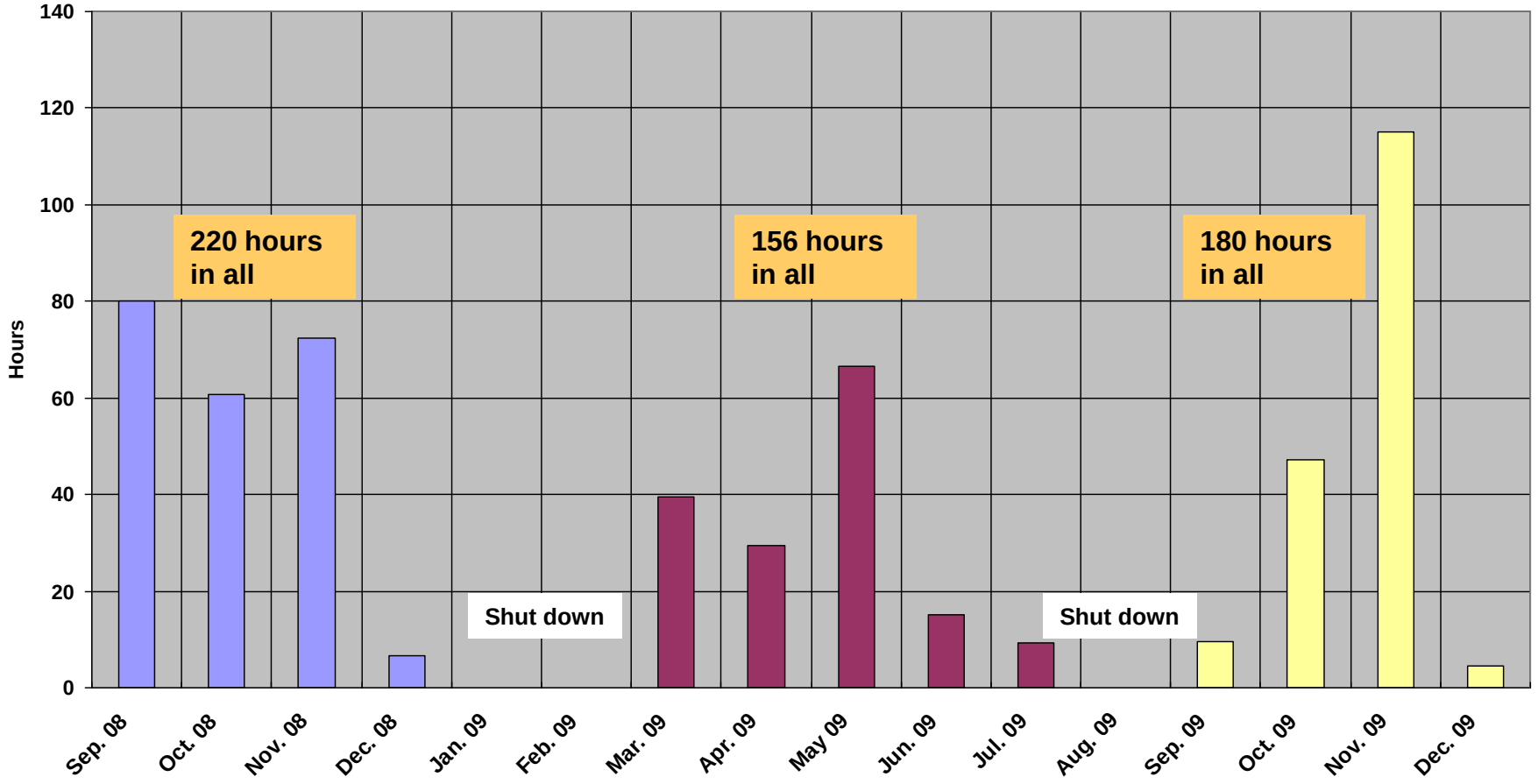
Notice: Beam breakdown hours shown (rounded)

Hours By Faults

	Sept.-Dec. 2008	March-July 2009	Sept.-Dec. 2009	Σ Hours
Scheduled Beam Run Hours	3218	2873	2475	8567
Fault Type				
IGBT	82	43	4	129
4kV Caps	66	33	25	124
DFDC/Flux	17	26	12	55
Mod. Tank	5	0	40	45
SCR	0	24	8	32
Cable Arcing	19	0	5	24
IGBT Driver	11	5	0	16
Dif. Voltage	2	5	5	12
Water	0	9	2	11
Timing	3	3	3	9
Oil Pump	0	0	7	7
Fiber	3	1	0	4
Mod. OI	0	3	1	4
Misc./Unknown	12	3	69	84
Σ	220	156	180	556
Percent of scheduled Beam Time	6.8 %	5.4 %	7.2 %	6.6 %

HVCM Downtime by Months

(Sept. 2008 - Dec. 2009)



Downtime Statistical Data

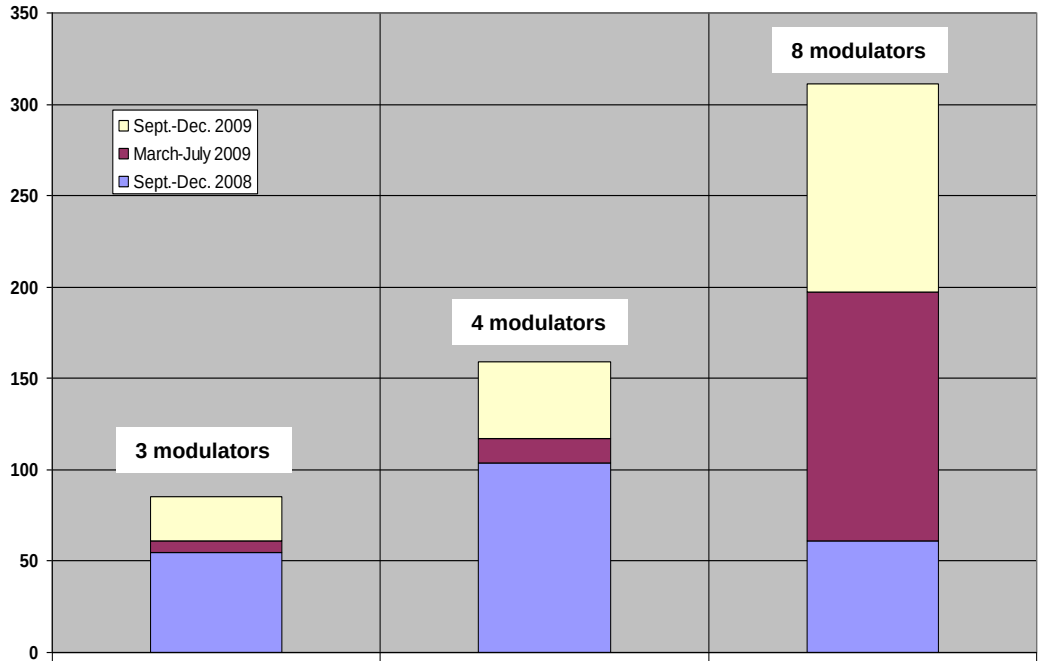
(Sept. 2008 – Dec.2009)

Hours By Modulators

	Sept.-Dec. 2008	March-July 2009	Sept.-Dec. 2009	Σ	% of all
DTL-1	18	4	18	40	7.2
DTL-3	6	1	6	13	2.3
DTL-5	31	2	2	35	6.3
CCL-1	25	4	35	64	11.5
CCL-2	26	0.5	6	32	5.8
CCL-3	26	7	1	34	6.1
CCL-4	26	3	0	29	5.2
SCL-1	2	1	13	16	2.9
SCL-5	0.5	4	0	5	0.9
SCL-9	23	6	0	29	5.2
SCL-12	11	19	38	68	12.2
SCL-14	0	56	21	77	13.8
SCL-15	0	27	16	43	7.7
SCL-18	26	23	28	77	13.8
SCL-21	0	0.5	0.5	0.5	0.1
Σ				556	100

HVCM Down Time by Area

(Sept. 2008 - Dec. 2009)



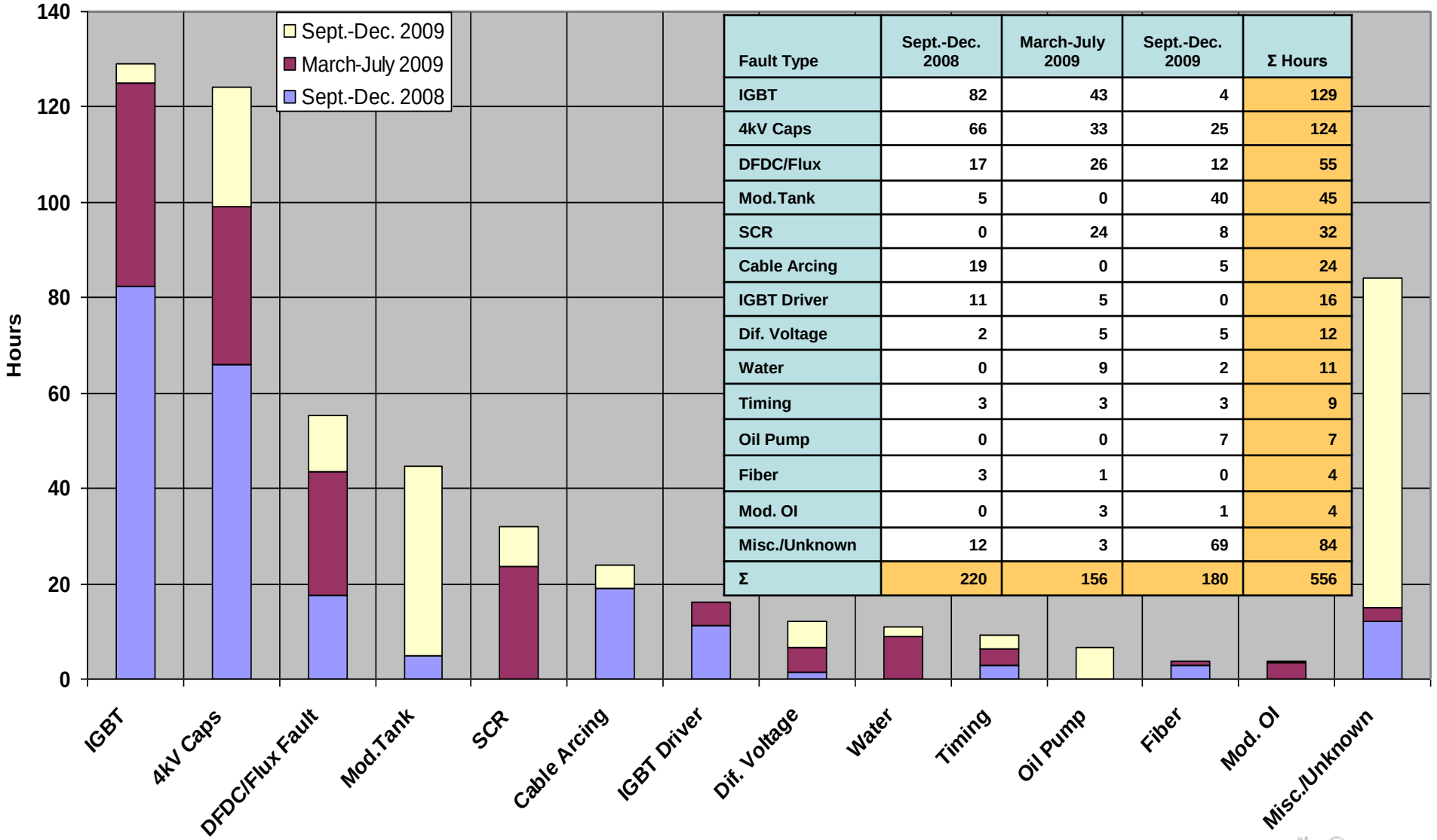
	DTL	CCL	SCL
Sept.-Dec. 2009	24	42	114
March-July 2009	6	13	136
Sept.-Dec. 2008	55	104	61

Typical HVCM Faults

IGBT	**IGBT explosion (smoke alarm); IGBT internal damage**
4 kV Caps	**4kV/10uF capacitor explosion (smoke alarm); Capacitor crack and leak**
DFDC/Flux	**Dynamic fault; Boost transformer magnetic flux**
SCR	**SCR failure; SCR firing circuit failure; Snubber board failure**
Cable arcing	**HV header cables arcing; HV output cable arcing**
IGBT driver	**IGBT driver card failure**
Timing	**Pulse repetition interval; Duty cycle; Gate input pulse width; Interpulse**
Tank	**120 kV boost capacitor failure; Arcing inside tank**
Fiber	**Fiber optic IGBT control/read-back cables failure**
Diff. voltage	**Storage capacitor voltage imbalance; Balance bleeding resistors failure**
Mod OI	**Modulator output over current**
Oil pump	**Oil pump; Oil pump motor**
Water leak	**Water leakage**
Misc./Unknown	**Miscellaneous trips (caused by bad contacts, noise, voltage drops/spikes, control chassis, control head, load, etc.)**

HVCM Downtime by Fault Types

(Sept. 2008 - Dec. 2009)



Fault Type	Sept.-Dec. 2008	March-July 2009	Sept.-Dec. 2009	Σ Hours
IGBT	82	43	4	129
4kV Caps	66	33	25	124
DFDC/Flux	17	26	12	55
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IGBT Driver	11	5	0	16
Dif. Voltage	2	5	5	12
Water	0	9	2	11
Timing	3	3	3	9
Oil Pump	0	0	7	7
Fiber	3	1	0	4
Mod. OI	0	3	1	4
Misc./Unknown	12	3	69	84
Σ	220	156	180	556

HVCM down time

Analysis by faults

1. IGBT failure:
   - **Main contribution in Sept.-Dec. 2008;**
   - **Then number of events and downtime reduced since end-of-pulse stress problem was resolved in March 2009;**
   - **Only one event in Sept.-Dec. 2009 – down time reduced by 20X**
   - **IGBT internal damage caused by previous operational stress;**
   - **Shoot thru condition still may occur due to driver/firing failures;**
   - **Slow change/drift of IGBT internal parameters and electronic delays (drivers)**

2. 4 kV capacitor failure:
   - **Downtime reduced since original small caps were replaced with new large caps;**
   - **Use caps with canola oil impregnant instead of synthetic oil leads to less damage in case of explosion (no fire - reduced repair time);**
   - **Only two events over last run (SCL-1 and SCL-15);**
   - **Dry self-healing caps on CCL-4 - a year without problems - look promising**

Hours By Faults

	Sept.-Dec. 2008	March-July 2009	Sept.-Dec. 2009	Σ hours
IGBT	**82 (22 events)**	**43 (16 events)**	**4 (1 event)**	**129**
4kV Caps	**66 (7 events)**	**33 (4 events)**	**25 (2 events)**	**124**
DFDC/Flux	17	26	12	55
Mod.Tank	5	0	40	45
SCR	0	24	8	32
Cable Arcing	19	0	5	24
IGBT Driver	11	5	0	16
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HVCM down time

Analysis by faults

1. DFDC/Flux:
   - **Flux faults- long adjustment procedure (up to hours);**
   - **Reason - drift of driver/IGBT parameters**
   - **Most of dynamic faults - less than 0.5 hours down time each (RF recovery);**
   - **Arcing in the load, in the tank, voltage spikes may cause this fault;**
   - **Down time reduced over last run**

2. Modulator tank:
   - **Unusual symptoms - long troubleshooting;**
   - **Long repair;**
   - **One case in 2008 run – 120kV resonant capacitor failure; 3 caps and boost transformer were replaced;**
   - **Two events and 40 break hours during last run (22 % of full down time): 120 kV capacitors overheating failure in DTL-1 and CCL-1 (5 years total operation time and 2.5 months with extended pulse width);**
   - **Caps were replaced with the same type caps, but less operation time - have to be replaced with new type caps;**
   - **De-Qing resistors, capacitors and some cables do not satisfy power rating demands – will be replaced in summer 2010**

Hours By Faults

	Sept.-Dec. 2008	March-July 2009	Sept.-Dec. 2009	Σ hours
IGBT	82	43	4	129
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DFDC/Flux	**17**	**26**	**12**	**55**
Mod. Tank	**5**	**0**	**40**	**45**
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HVCM down time

Analysis by faults

1. SCR :
   - **Mostly new modulator SCL-14;**
   - **It has the longest 3-phase input power cable and non-typical location in the gallery;**
   - **Failures of digital and hard firing cards - several times;**
   - **Failure of SCR – repair inside SCR cabinet – difficult access, long process;**
   - **Capacitors on snubber board failed;**
   - **No issues since snubber board replaced**

2. Cable arcing:
   - **Two events in run 2008 - header cable to storage capacitor's plate connection – poor design;**
   - **new design w/ cable replacement;**
   - **One event of arcing in HV output cable terminal (5 down hours in last run);**
   - **Other HV cables inspection – prevent possible arcing (two cables repaired)**

Hours By Faults

	Sept.-Dec. 2008	March-July 2009	Sept.-Dec. 2009	Σ
IGBT	82	43	4	129
4kV Caps	66	33	25	124
DFDC/Flux	17	26	12	55
Mod. Tank	5	0	40	45
SCR	**0**	**24**	**8**	**32**
Cable Arcing	**19**	**0**	**5**	**24**
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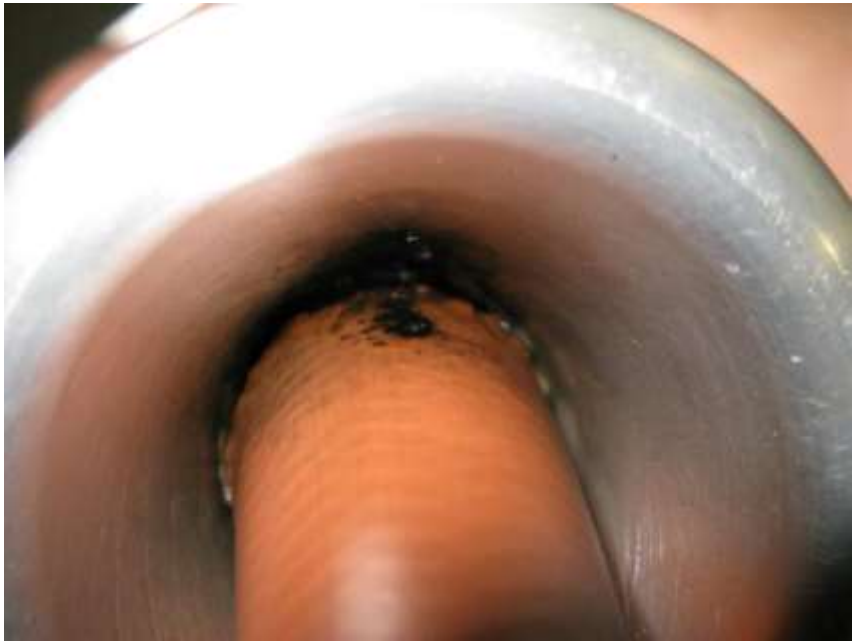
HV output cable damage



- DTL-1 (RFQ) modulator: all three output cables have been re-terminated
- Largest numbers of operation hours
- Insulator degradation during long operation in the oil
- Inspection of all cables in the gallery
- Spare cable ordered

HVCM down time

Analysis by faults

1. IGBT Driver :
   - **Old type of IGBT driver card used;**
   - **Upgraded for easier access and replacement;**
   - **Preliminary adjustment, testing on the bench helped to achieve more reliable operation;**
   - **New generation of "intellectual" driver – work is ongoing (SLAC and ORNL)**

2. Cap Bank Diff. Voltage:
   - **Most common reason – balance bleeding resistor failure;**
   - **Sometimes this is not a reason of trips, but the result of other type of fault – first fault capture problem**

3. Water:
   - **One event in March 2009 – water leakage into the tank SCL-15;**
   - **Tank opening and oil drying – 9 hours down time;**
   - **Modification was done – seals installed to prevent leak;**
   - **Some small leaks outside tank – repaired quickly**

Hours By Faults

	Sept.-Dec. 2008	March-July 2009	Sept.-Dec. 2009	Σ
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4kV Caps	66	33	25	124
DFDC/Flux	17	26	12	55
Mod. Tank	5	0	40	45
SCR	0	24	8	32
Cable Arcing	19	0	5	24
IGBT Driver	**11**	**5**	**0**	**16**
Dif. Voltage	**2**	**5**	**5**	**12**
Water	**0**	**9**	**2**	**11**
Timing	3	3	3	9
Oil Pump	0	0	7	7
Fiber	3	1	0	4
Mod. OI	0	3	1	4
Misc./Unknown	12	3	69	84
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HVCM down time

Analysis by faults

1. Timing:
   - **Discussed below**

2. Oil pump :
   - **One event during last run – SCL-14 oil pump failure;**
   - **Replacement of broken oil pump assembly – 7 hours down time;**
   - **Upgrade of oil pump assemblies done;**
   - **Spare units prepared and tested;**
   - **Design of new outside heat exchanger - on the way**

3. Fiber:
   - **Most common reason – bad termination (after catastrophic explosion and repair inside enclosure);**
   - **Light intensity should be checked;**
   - **Separate fiber optic cables in enclosure – easy to replace with spare – reduce downtime**

4. Modulator over current:
   - **Rare event, depends on arcing in the load and/or output HV circuits**

Hours By Faults

	Sept.-Dec. 2008	March-July 2009	Sept.-Dec. 2009	Σ
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Water	0	9	2	11
Timing	**3**	**3**	**3**	**9**
Oil Pump	**0**	**0**	**7**	**7**
Fiber	**3**	**1**	**0**	**4**
Mod. OI	**0**	**3**	**1**	**4**
Misc./Unknown	12	3	69	84
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Timing Trips Statistics

Timing Faults:

- - Pulse Repetition Interval;
- - Duty Cycle;
- - Gate Input Pulse Width;
- - Interpulse

Possible reasons:

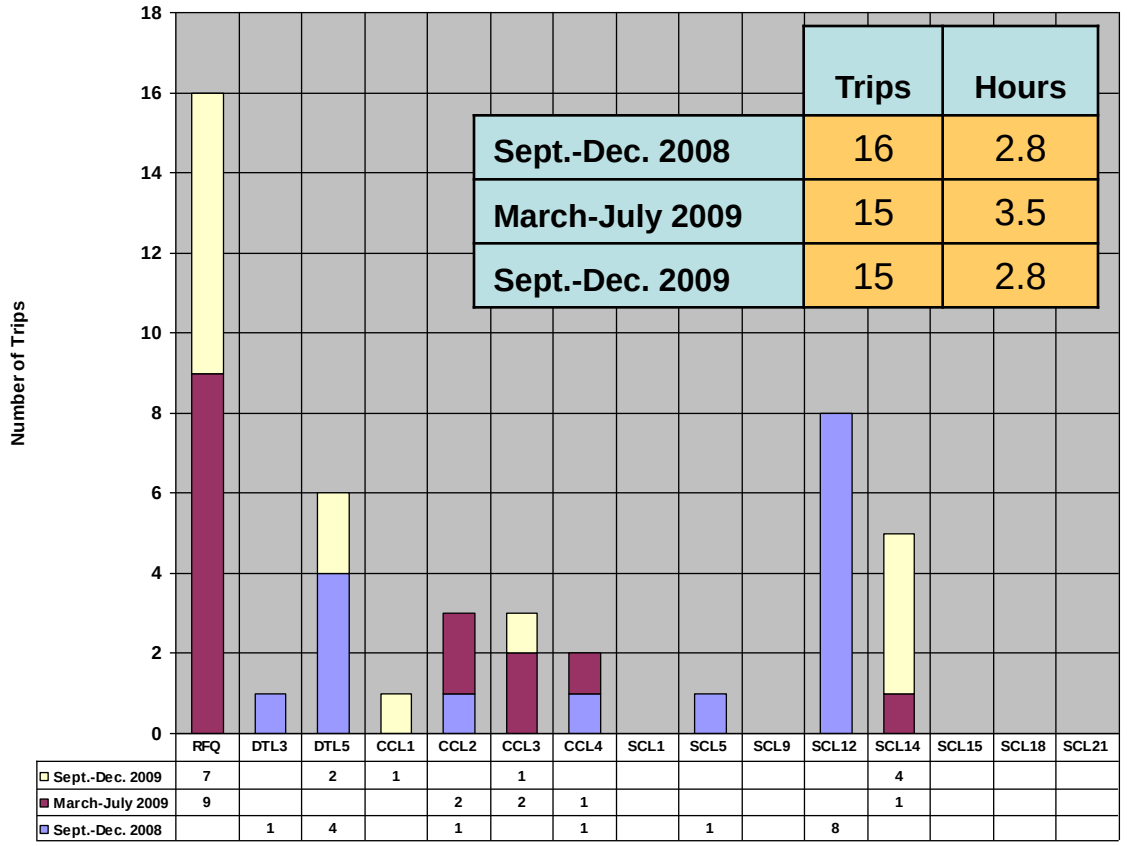
- Optic transceiver/receiver failure;
- Fiber optic damage/dirty fibers;
- Noise;
- Timing system faults

Results:

- Down time – RF cavity recovery time mainly;
- DTL-1 (RFQ) and SCL-14: need to pay attention;
- Additional diagnostics needed;
- Change logic of tripping?
- Some faults unnecessary?

HVCM Trips caused by Timing Faults

(Sept. 2008 - Dec. 2009)



HVCM down time

Analysis by faults

Miscellaneous/Unknown Faults

1. Main contribution to down time during last run
2. Trips caused by different types of faults
3. Possible reasons:
   - **bad contacts,**
   - **electrical noise,**
   - **wiring defects,**
   - **voltage drops/spikes,**
   - **control circuits,**
   - **PPS and MPS interlock,**
   - **feedback reading,**
   - **load,**
   - **etc.**
4. Two modulators - main contributors to down time (see next slide)
5. SCR control head - replaced
6. Causes of trips not obvious – long troubleshooting
7. More diagnostics should be helpful
8. New controller – best solution

Hours By Faults

	Sept.-Dec. 2008	March-July 2009	Sept.-Dec. 2009	Σ
IGBT	82	43	4	129
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Misc./Unknown	**12**	**3**	**69**	**84**
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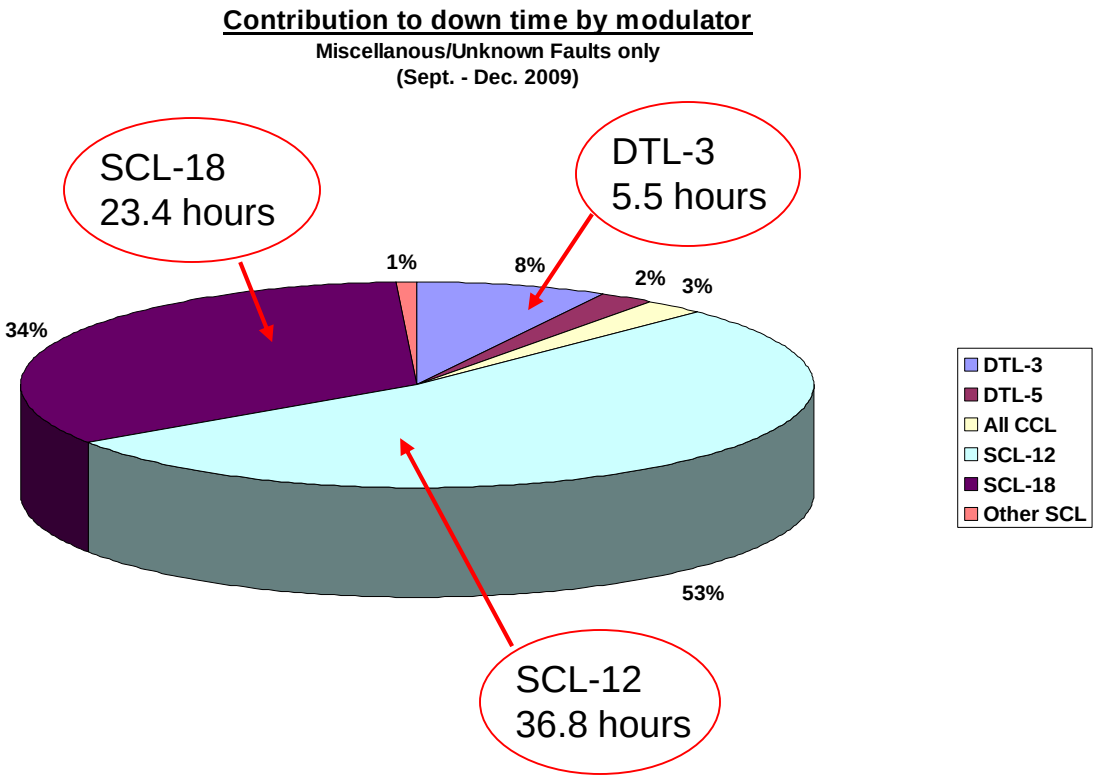
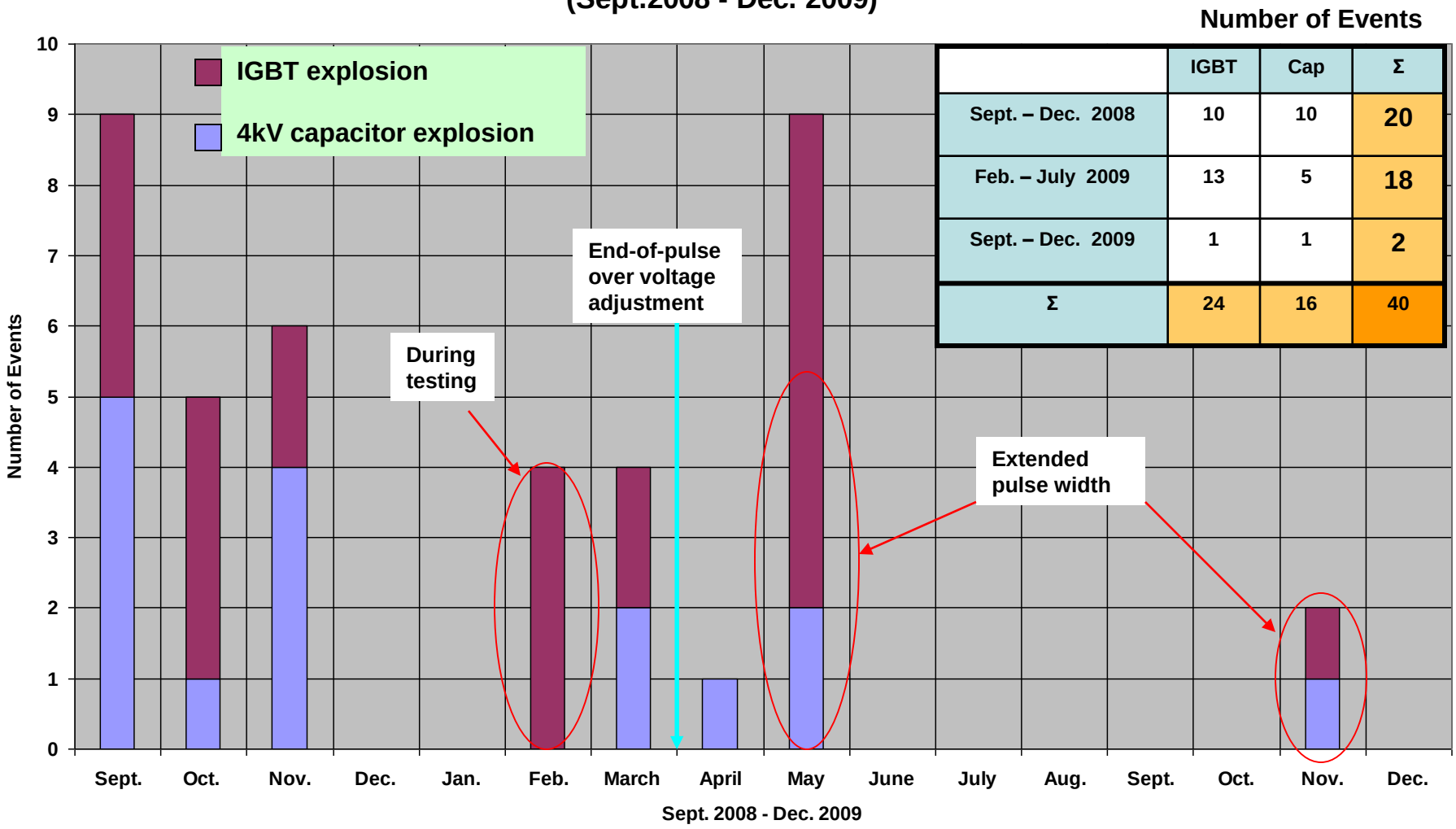
HVCM down time

Analysis of misc./unknown trips

- Last run Sept. – Dec. 2009 considered;
- Beam down time - 69 hours;
- HVCMs SCL-12 and SCL-18 are main contributors;
- Many different trips with/without indication - long troubleshooting;
- Fixed by replacing SCR control head (old units tested – OK);
- Control issues: poor connectors, SCR control head, modulator control chassis, wiring – re-termination and connector replacement in plans;
- Reason not clear up to now;
- HVCM DTL-3 – PPS interlock issues (contacts in connectors and switches);
- Problem of diagnostics still exists



HVCM Smoke Alarm Events by Months
(Sept.2008 - Dec. 2009)



	IGBT	Cap	Σ
Sept. – Dec. 2008	10	10	20
Feb. – July 2009	13	5	18
Sept. – Dec. 2009	1	1	2
Σ	24	16	40

Smoke Alarm Events

Analysis

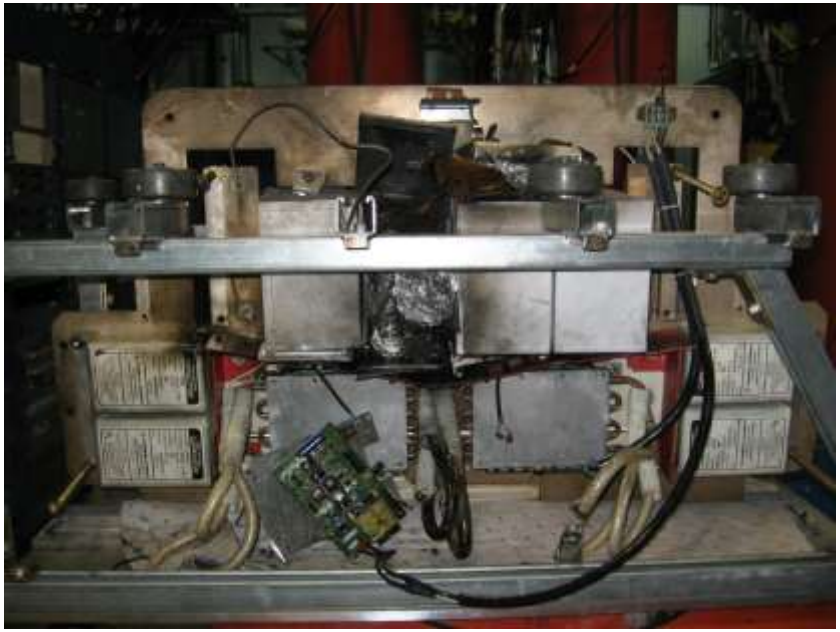
1. Run 2008:
   - Overheating, end of life of original small 4kV flammable oil filled capacitors;
   - IGBT stress/internal damage (end-of-pulse over voltage)

2. Feb. – July 2009:
   - Rest of small 4kV capacitors failure, no one of new caps lost;
   - 4 events due to IGBT during adjustment and testing in February – no contribution to beam downtime;
   - Since April – quantum fixed modulator pulse width; adjustment done to reduce IGBT over voltage stress at the end of the pulse;
   - Half of failures in May - when pulse width was increased by 15%;
   - Sequence of 3 IGBT explosion events on SCL-14 modulator in May – use of old IGBTs, collateral damage inside enclosure may cause the event

3. Sept. – Dec. 2009:
   - Extended pulse width since beginning;
   - Only two events; with minimal fire/smoke

SCL Mod 15: Smoke alarm

An NWL capacitor failed on B phase IGBT switch plate on 11/07/2009



- Downtime – 12.9 hours
- Classic capacitor failure - blast only - no fire (canola oil) - less damage
- Adjacent caps, IGBTs and driver cards destroyed
- Charring of the cables that were above the cap bank - replaced
- Header cable damage - replaced
- Switch plate - replaced
- Re-termination several fiber cables
- Cleaning up the mess

HV Capacitors Failure History

1. Small case size BTDP oil filled GA caps:
   - **Overheating – up to 160ºF,**
   - **End of life,**
   - **Explosion with fire (5 events during Feb.-July 2009),**
   - **Main contribution to downtime,**
   - **All removed**

BTDP = benzyltoluene diphenylethane
RSO = canola oil (vegetable oil)
DRY = self-healing metalized polypropylene (no oil)

2. New large BTDP oil filled GA caps:
   - **Heating – up to 150ºF,**
   - **No catastrophic explosion events,**
   - **More damage inside enclosure in case of fire – more time to repair needed**
   - **All removed**

3. New large RSO oil filled NWL caps:
   - **Overheating – up to 165ºF,**
   - **Only one catastrophic failure during last run,**
   - **Creaked and leaked during last run– poor case design,**
   - **Short life time if duty factor increased**
   - **All removed**

4. **Dry self-healing AVX/TPC caps:**
   - **Case temperature does not exceed 100ºF at full duty cycle,**
   - **No degradation after 1 year usage (were installed on CCL-4 in Dec.2008,**
   - **Tested for 500 fault events (10 years equivalent),**
   - **Installed everywhere during present outage**

5. **120 kV caps inside oil tank:**
   - **Overheating when duty cycle increased,**
   - **Long repair – main contribution to down time during last run,**
   - **Have to be replaced with new design higher rating caps**

HVCM Upgrade

Done in the past:

1. Tank:
   - new boost transformer
   - upgraded oil cooling assembly
   - resonant capacitors replaced, cap value adjusted
   - new design de-Qing resistors and snubber assembly
   - new inductive choke
2. SCR:
   - fiber optic cabling
   - new hard firing cards and wiring inside the cabinet
   - fast response protection circuit
   - upgraded snubber boards
3. Dynamic fault / magnetic flux detection system implementation
4. Implement Alarm Handler for smoke event
5. Water panel box circuitry upgrade
6. Additional diagnostic for IGBT and cap over current installed

HVCM Upgrade

Done during CY 2009:

- New modulator SCL-14: new configuration modulator-klystrons, (SCL modulator output voltages increased up to 75 kV)
- 4kV/10uF capacitors replacement
- IGBT driver cards (easier to replace, more robust connections)
- IGBT switch plate mechanical (gaps increased, additional insulation)
- IGBT switch plate electrical (120 V AC distribution wiring)
- Replacement of header cables (flame-proof cable used)
- “Banana” type termination of header cables replaced with hard bolted
- Replacement feed thru insulating plates on the top of tanks (flame-proof material)
- Oil pumps (seal - to prevent water leak, mechanical assembling modification – easier to access and repair)
- SCR snubber boards (wiring, caps soldering)
- Monitoring logic and screen view modification (helpful for troubleshooting)

- Done on all DTL, CCL and SCL modulators (15 units)

HVCM Maintenance Activities

Works during Jan. 2010:

- New 4 kV self-healing capacitors installed on all modulators
- 120 kV caps replacement inside DTL and CCL tanks
- Tank inspection and repair: DTL, CCL, SCL-1 and SCL-14
- HV output cables checkout/repair – all modulators
- Interlock connector replacement on water panel box
- New higher rating resonant caps ordered for testing
- 2kV/10uF dry type capacitors received and tested in RFTF

Plans for summer 2010 outage:

- Replace parts with low power rating in the tank (caps, resistors, cables) – critical for high duty factor operation
- Mechanical upgrade of safety enclosure doors clamping (fast access inside, robust frame)
- Install additional shield plate inside enclosure
- Fiber optic patch panel installation (short fibers inside enclosure)
- SCR control head connectors replacement/re-termination
- Partial IGBT driver replacement

Conclusion

Results:

- Many of the HVCM subsystems/components have been upgraded in 2009 to improve reliability and resistance to fire events
- Number of smoke/fire catastrophic events reduced
- Down time caused by IGBT faults reduced since end-of-pulse stress problem resolved
- 4 kV capacitors problem hopefully resolved
- Last run operation with increased duty cycle reveals new problems
- Additional efforts needed to understand root causes of failures

Plans:

- Replace low power rated parts in the tank (boost and filter caps, de-Qing resistors, HV cables)
- New higher voltage rating IGBT usage
- New IGBT driver implementation
- Mechanical upgrade of safety enclosure frame and door's clamping
- Oil cooling system upgrade (outside heating exchanger)
- New intelligent FPGA based controller
- IGBT switch plate test stand

R&D efforts underway to support future activities

Smoke Alarm Events

Main results

Number of catastrophic events reduced

1. IGBT:
   - Use new devices when replaced;
   - Improved thermal bonding procedures implemented;
   - Overvoltage problem solved, minimal problems since
2. Capacitors:
   - Original small caps were replaced with new large caps;
   - RSO filled instead of BTDP were used;
   - All oil filled caps replaced with dry self-healing caps during Jan. 2010 maintenance period
3. Implement Alarm Handler for smoke detector events
4. Old style header cables replaced with non-flammable and improved end connections
5. Inside enclosure: replaced combustible materials with flame-proof
6. Emergency Off modified to remove 2100 V primary energy source automatically
7. Installing shrapnel shields around capacitors to minimize collateral damage