Beam Energy in 2012

- Preamble
- What changed since Chamonix 2011 that allows us to change the beam energy?
- What did not change and what are the constraints?
- What is the envisaged maximum beam energy for 2012 run?

Andrzej Siemko

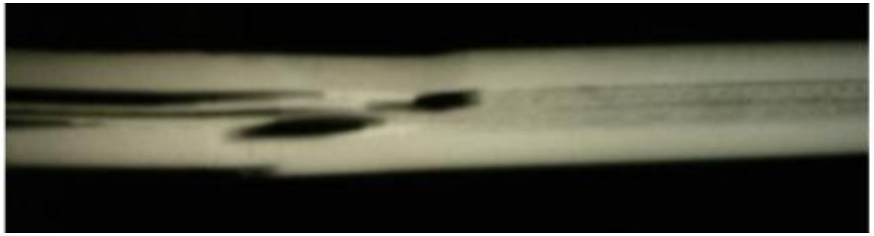
With inputs from:

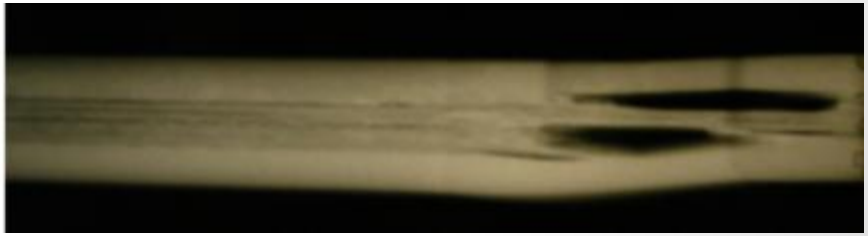
Z. Charifoulline, K. Dahlerup-Pedersen, R. Denz, F. Savary, Ch. Giloux, M. Koratzinos, E. Ravaioli, R. Schmidt, J. Steckert, H. Thiesen, A. Verweij and F. Bordry

Brief recall of copper stabilizer issue

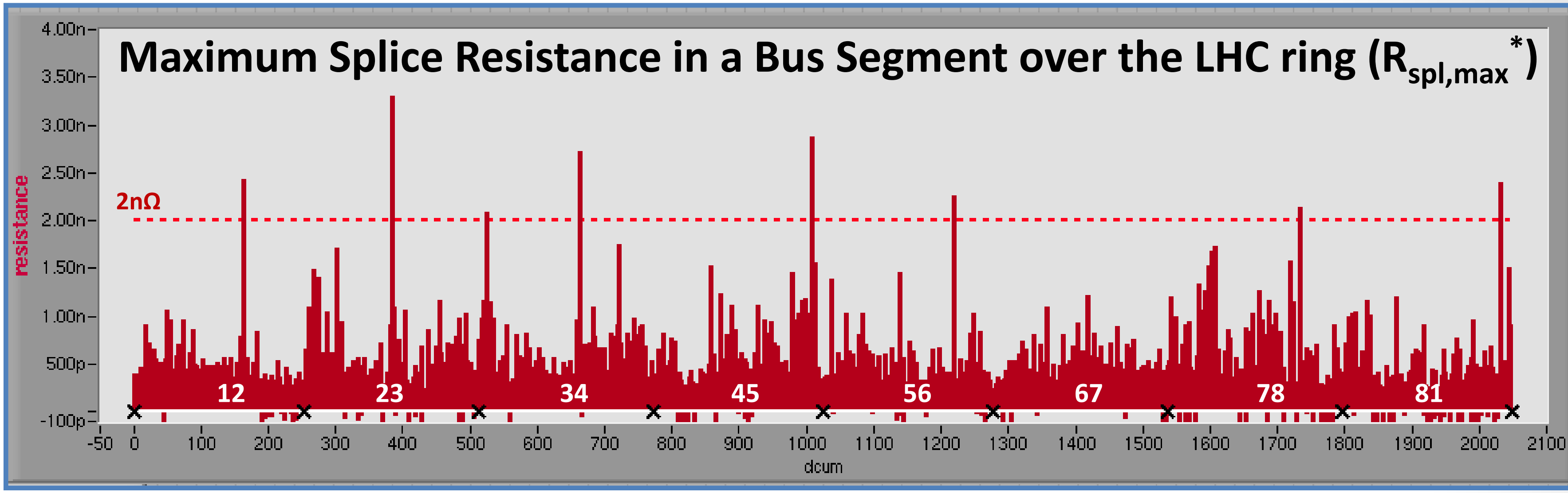
- Despite correct splice resistance between SC cables, a 13 kA joint can burn-out **in case of a quench**, if there would be a bad bonding between the SC cable and the copper bus, coinciding with a discontinuity in the copper stabilizer

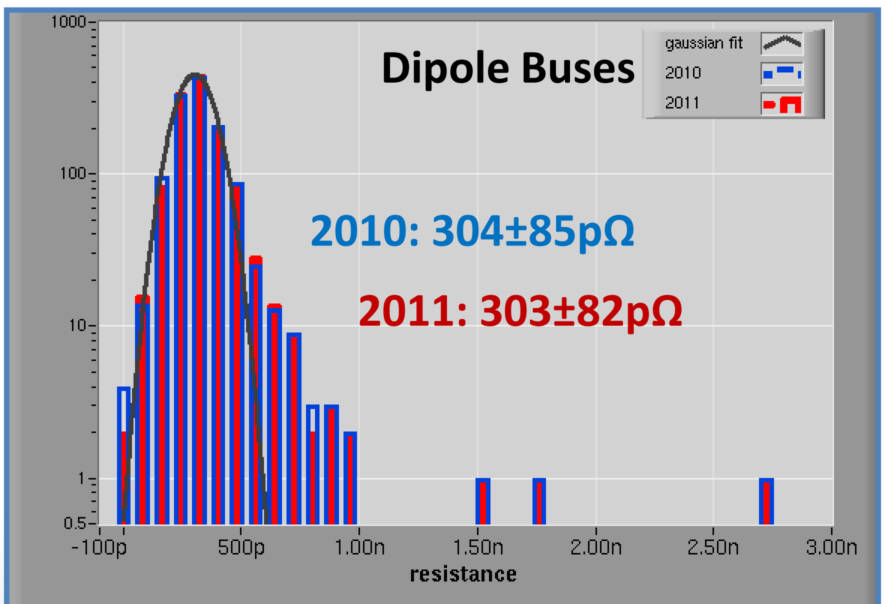
- Resistance measurements and ?-ray pictures have shown the presence of many of such defective joints in the machine, limiting the safe operating current

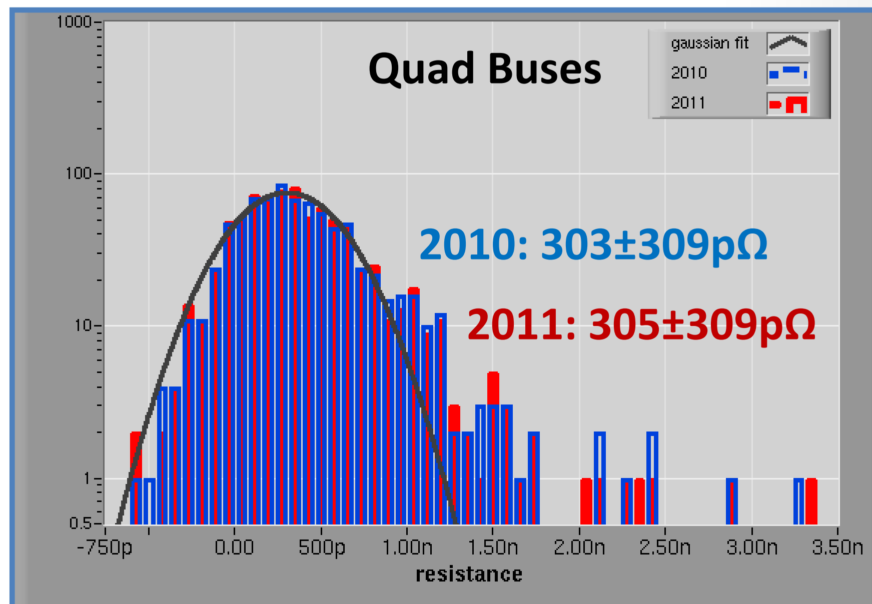




Status of SC cable splice resistances in LHC

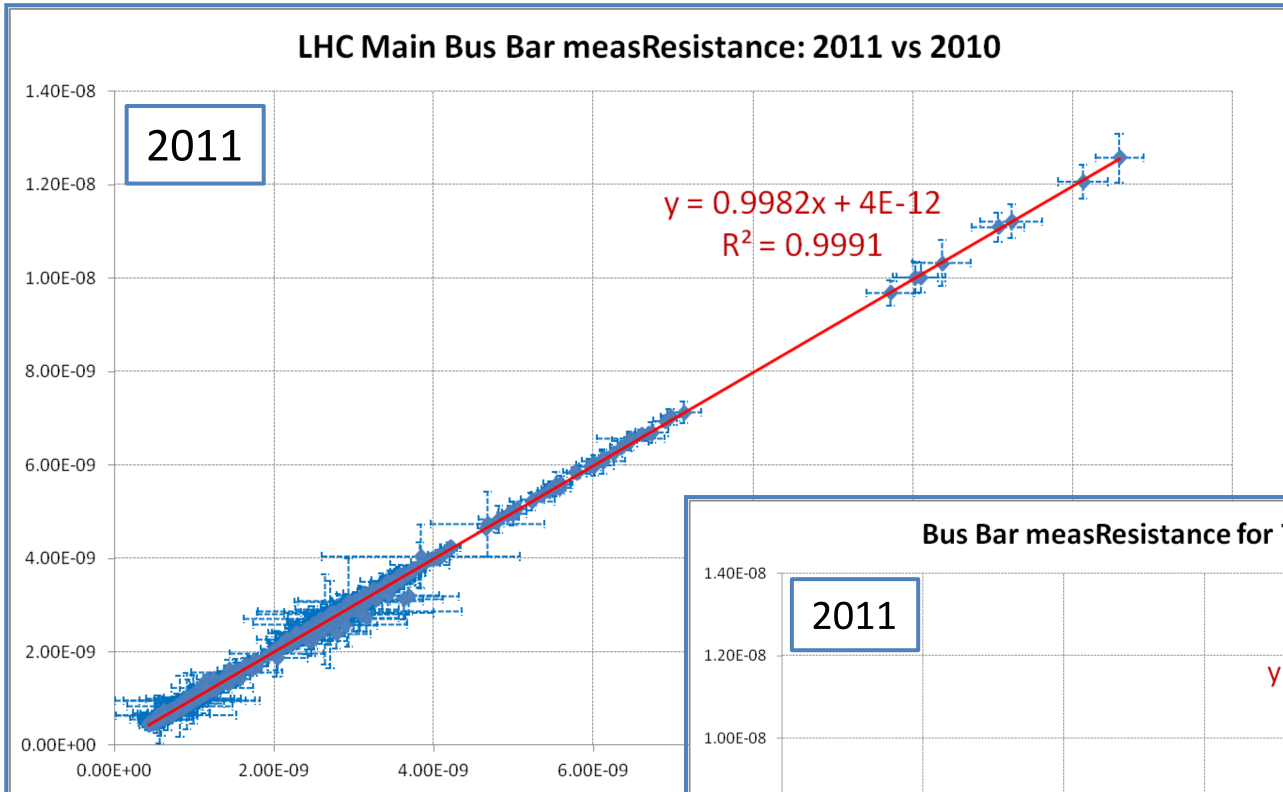


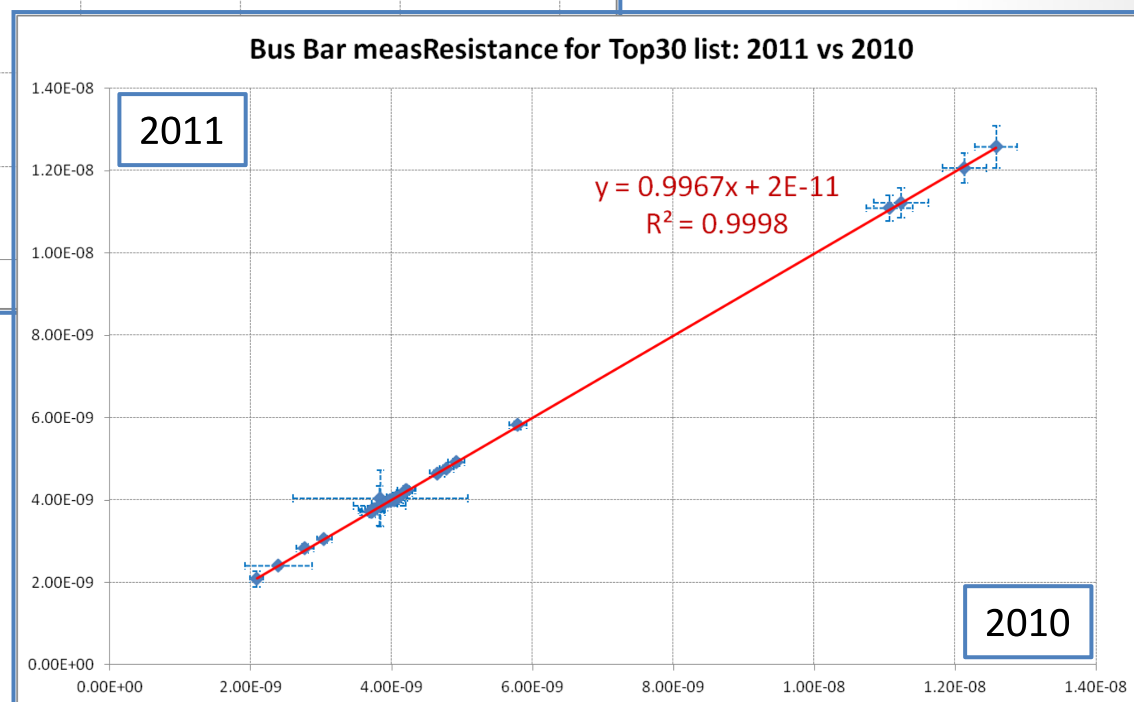




(*) $R_{spl,max} = R_{segment} - (n-1) \cdot R_{spl,average}$

SC splice resistances - long term stability





NO CHANGES OBSERVED! ☺

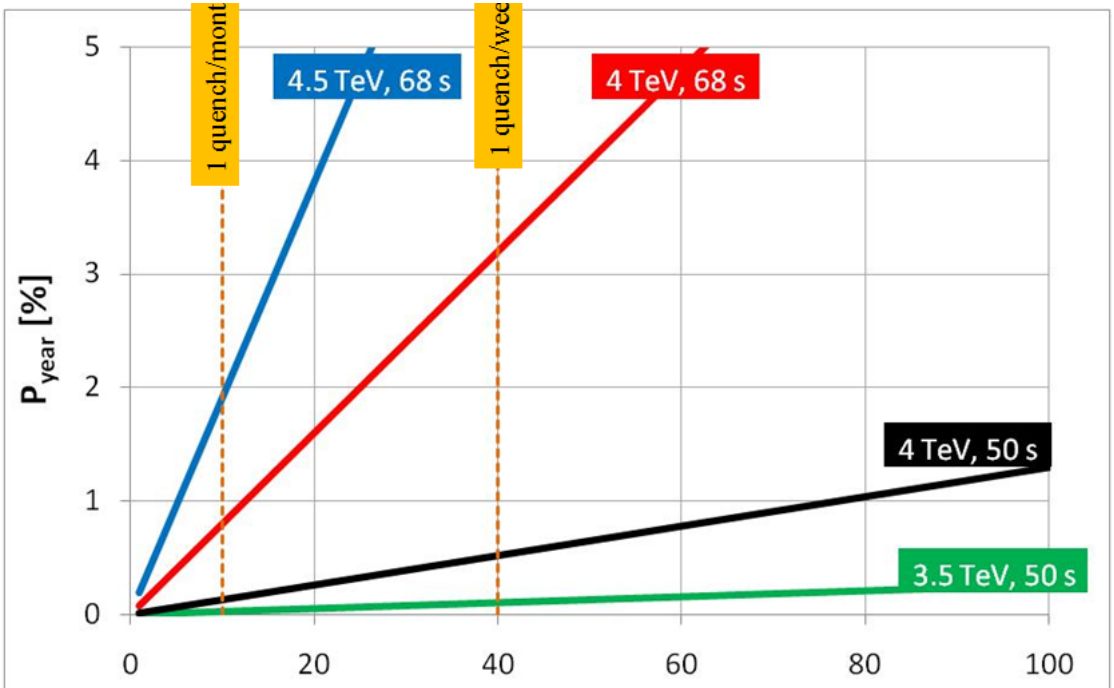
Top 30 list: $R_{spl,max} > 1.2 n\Omega$

$R_{spl,max} = R_{segment} - (n-1) \cdot R_{spl,average}$

No deviations are visible.

Brief recall of Chamonix 2011…

- Chamonix 2011 conclusions regarding the beam energy (Steve Myers):
  - Stay at 3.5TeV for 2011.
  - We should operate in 2011 with the "snubber" capacitors to reduce further the possible number of quenches.
  - "Thermal amplifier" to be developed during 2011 to allow measurements during Christmas shutdown for a deterministic decision on a possible energy increase for 2012.



A. Verweij Chamonix 2011

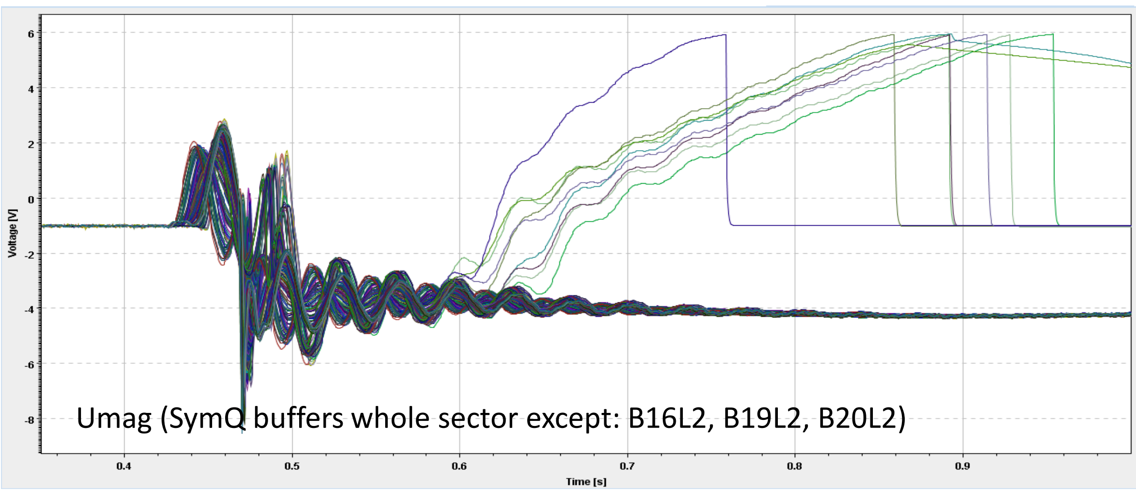
Main arguments against running above 3.5 TeV

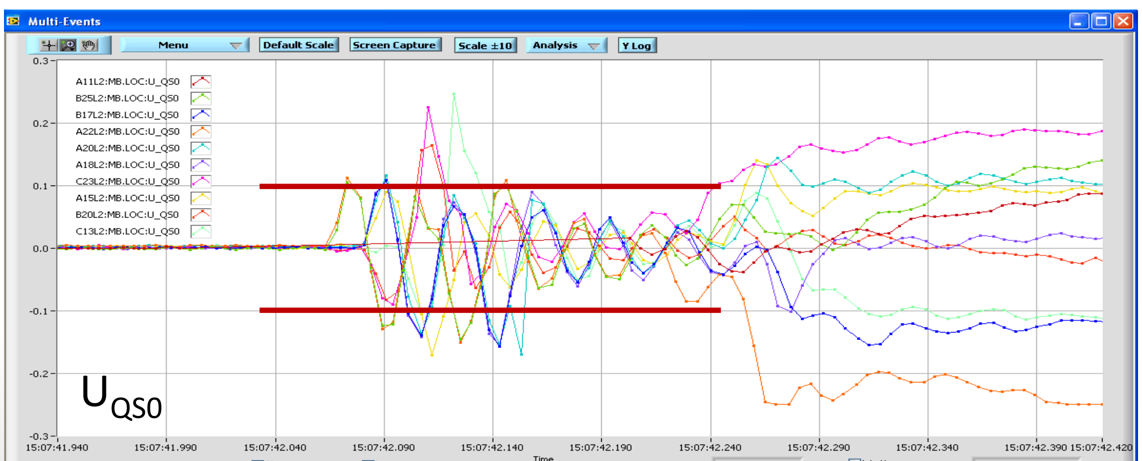
Risk of multiple magnet quench events

Unknown number of quenches to be expected in 2011

Multiple magnet quench events

- Due to the quench detection system vulnerability to withstand the effects of a hostile environment and various transient signals produced by circuit elements, a number of multiple magnet quench events was experienced in 2010





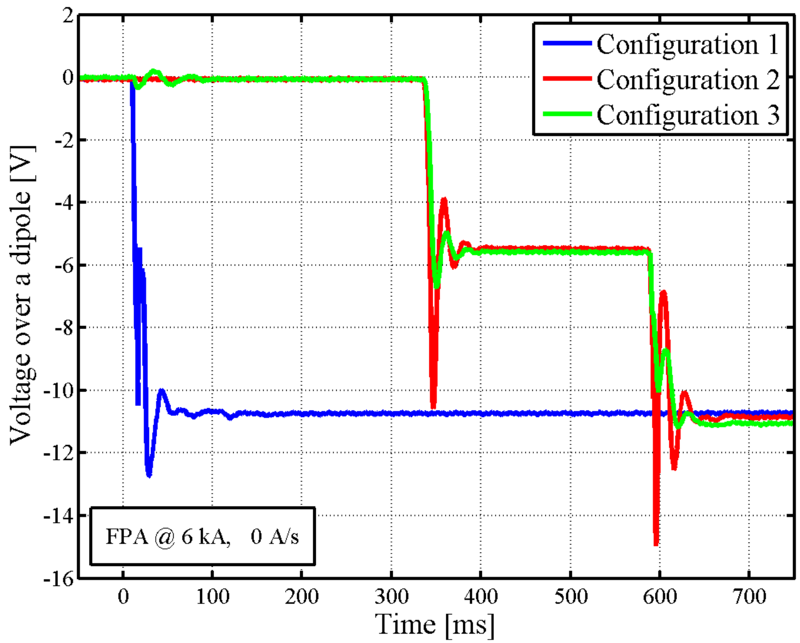
- Example of multiple magnet quench
  - **11.3.2010**,
  - sector 12, 15:07:42
  - 10 quenched magnets by oQPS FPA during -10A/s ramp @ ~2kA

Multiple magnet quench ranking in 2010

# of magnets quenched	Date	Sector	Condition	Cause
50	24.02.2010, 19:08:23	78	~3.2kA coasting	SymQ → adaptive filter triggered during PC trip. During manual abort 20min later filter was not active → big $dUmag_{max}$
25+5	17.03.2010, 02:23:15	56	~2kA, 10A/s ramp	oQPS → EM transients caused by FPA during ramp beyond common mode rejection of DQQDL SymQ → 5 magnets fired due to loss of references (fired by oQPS) in comparison cell
10	11.03.2010, 15:07:42	12	~2kA -10A/s ramp	oQPS → EM transients caused by FPA during ramp beyond common mode rejection of DQQDL
10	13.02.2010, 15:44:52	12	~5.5kA 10A/s ramp	oQPS → EM transients caused by FPA during ramp beyond common mode rejection of DQQDL
7+2	17.02.2010, 19:49:29	34	~3.5kA, 10A/s ramp	oQPS → EM transients caused by FPA during ramp beyond common mode rejection of DQQDL SymQ → 2 magnets fired due to loss of references (fired by oQPS) in comparison cell

QPS consolidation work all over the year

- Main improvements:
  - Snubber capacitors installed in RB circuits during 2010/2011 Xmas break
  - Delay between the power converter switching-off and the opening of the extraction switches
  - Modification of the resistance in the filter at the output of the RB power converter



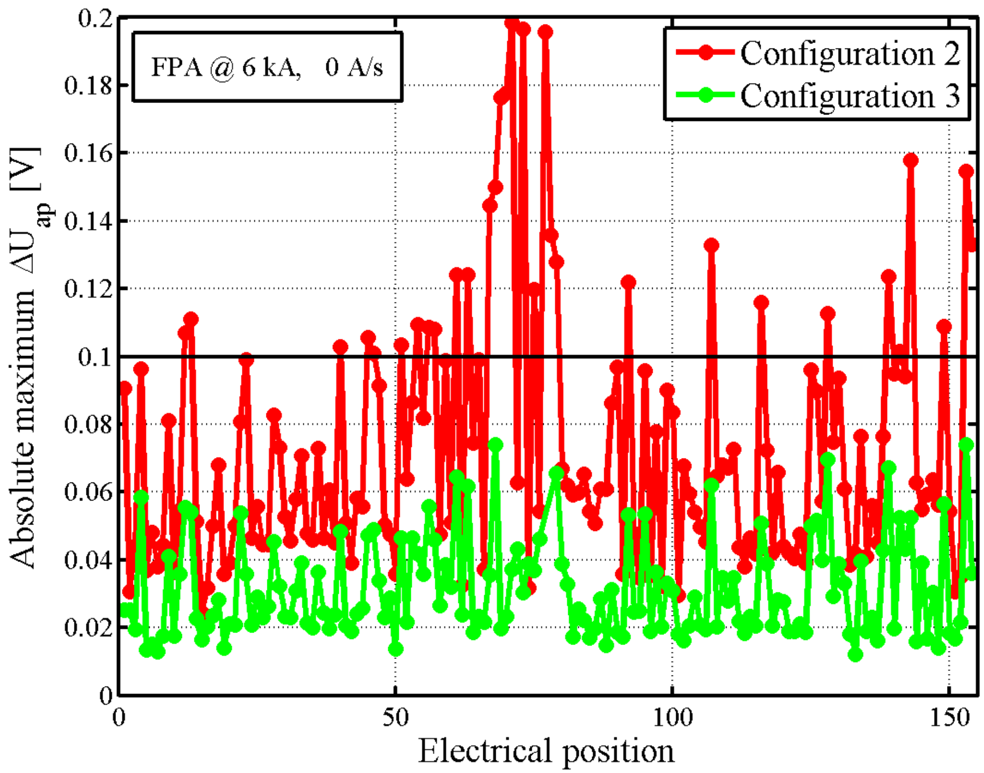
Configuration 1
Before March 2011

Configuration 2
- Delay between the power-converter switching-off and the opening of the extraction switches

Configuration 3
- Delay between the power-converter switching-off and the opening of the extraction switches
- Snubber capacitor in parallel to the extraction switches
- Additional resistance in the filter at the output of the power-converter

Results of the consolidation efforts

- Simulations have demonstrated that the amplitudes of the voltage oscillations seen by the quench detectors were reduced well below the threshold limits



Configuration 2

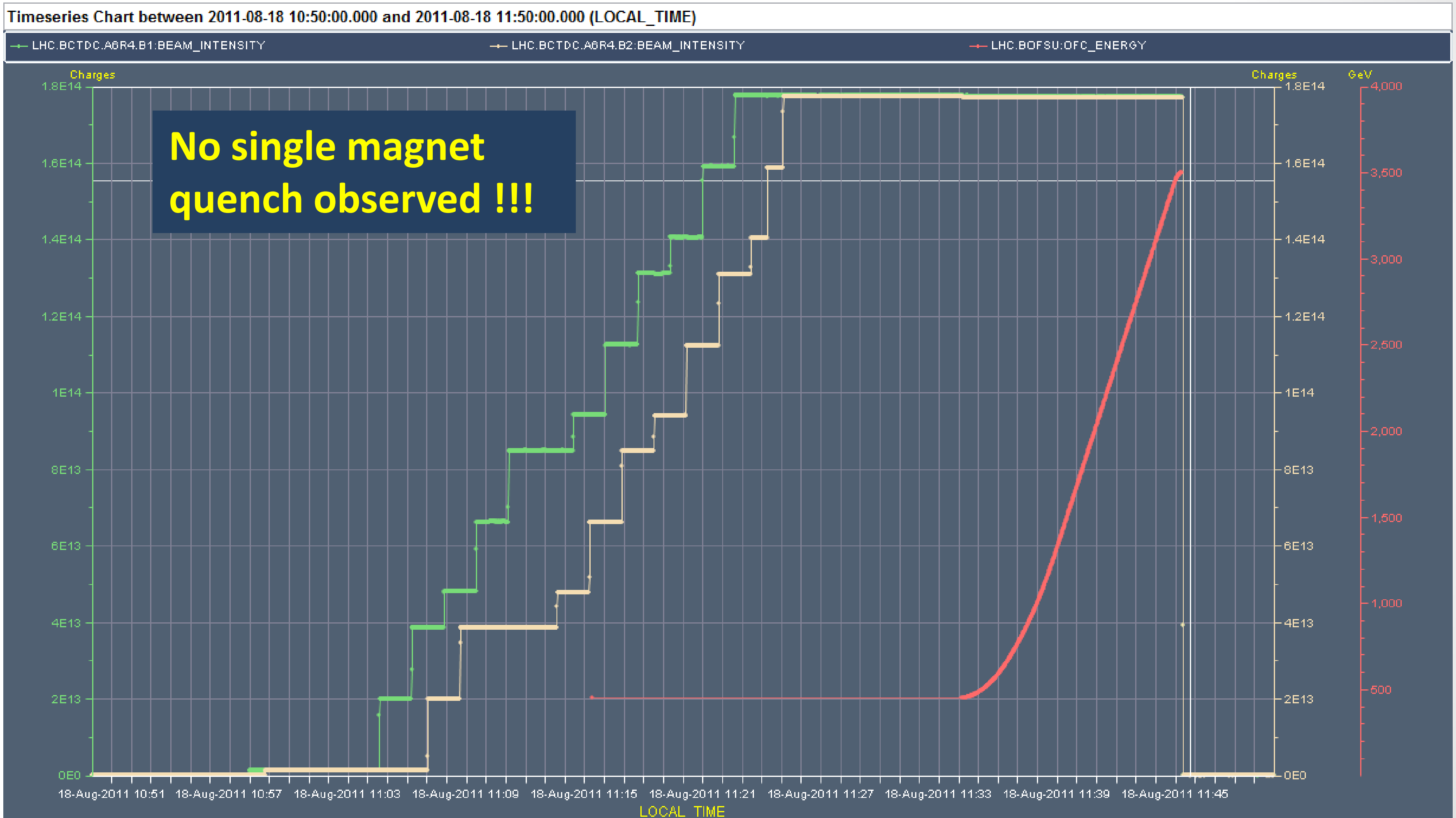
- Delay between the power-converter switching-off and the opening of the extraction switches

Configuration 3

- Delay between the power-converter switching-off and the opening of the extraction switches
- Snubber capacitor in parallel to the extraction switches
- Additional resistance in the filter at the output of the power-converter

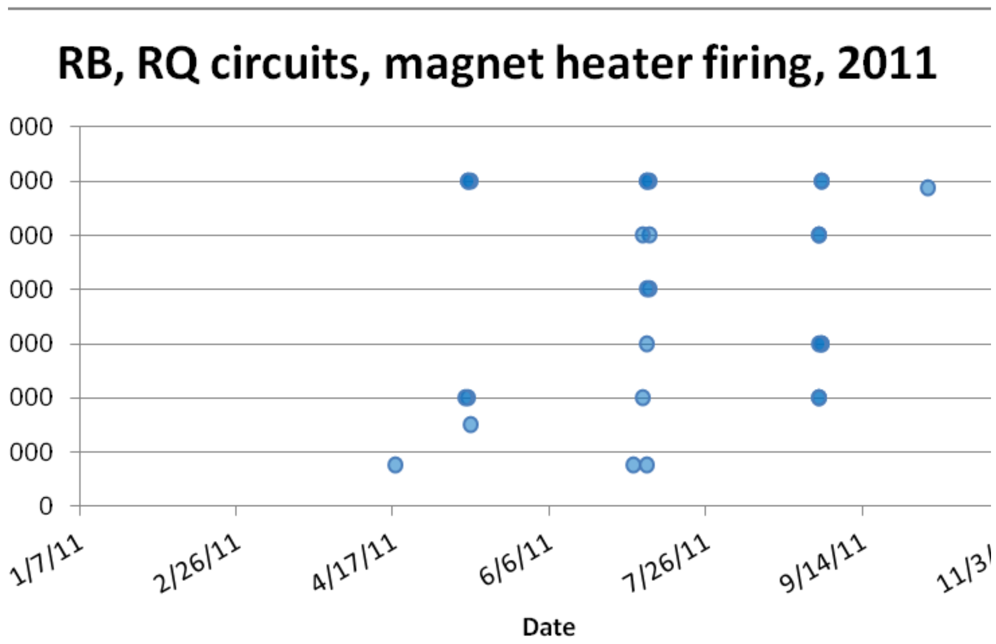
…ultimate test of QPS vulnerability to transient effects

QPS vulnerability to transient effect was unintentionally tested during total power cut on 18 August 2011, close to the most critical moment: maximum current and still ramping



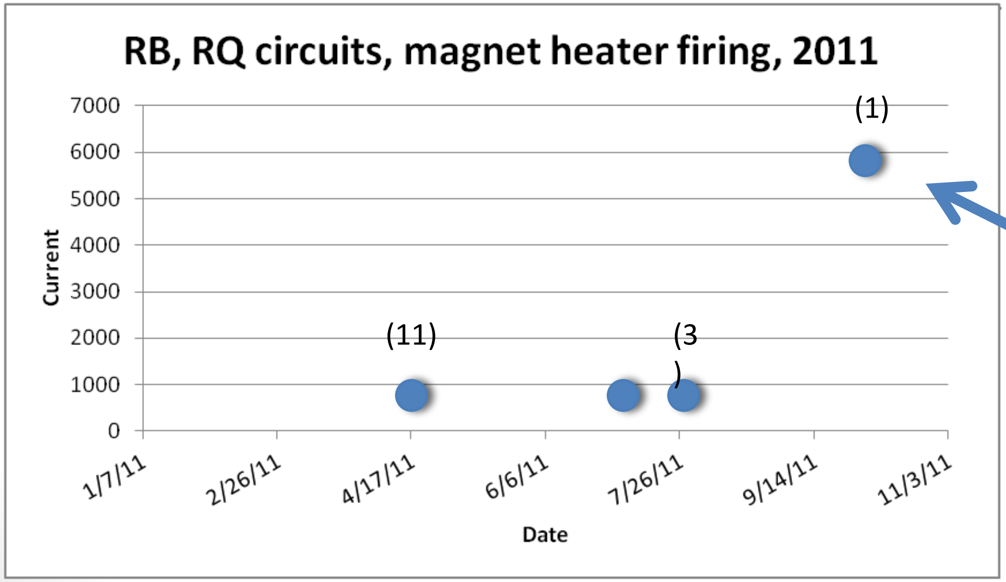
If such event occurred in 2010, massive QPS trips would became apparent around the ring

RB, RQD/F: quench statistics during 2011



Intentional and unintentional quenches in 2011

Most quenches during the quench propagation tests

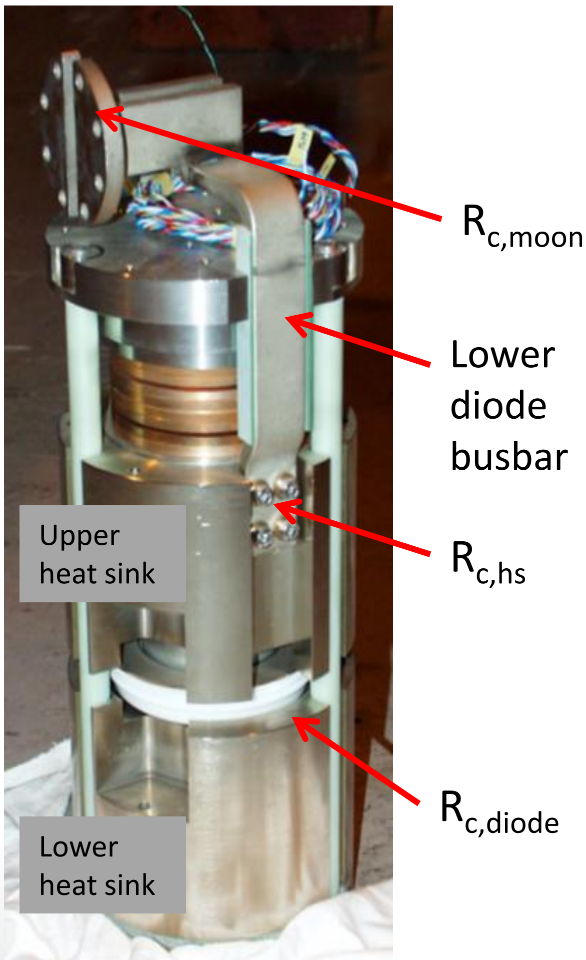


Unintentional quenches only

Only one unintentional quench in 2011 at top energy

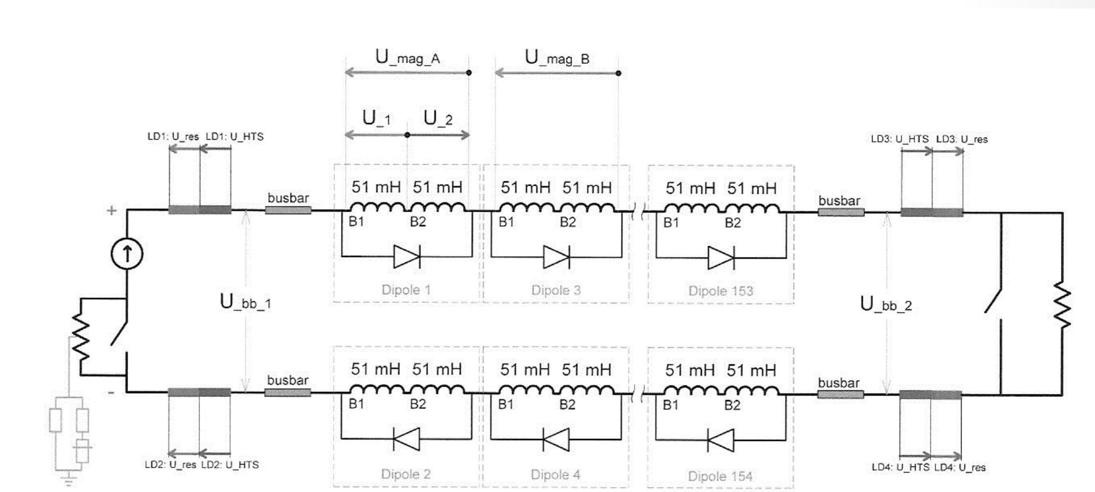
Quench propagation tests in 2011

- Positive quench propagation test results, but…
- Abnormally high resistances observed in the diode circuits that may be an issue, in particular if located in the "half-moon" joints



C=Cathode, A=Anode, Resistances in $\mu\Omega$

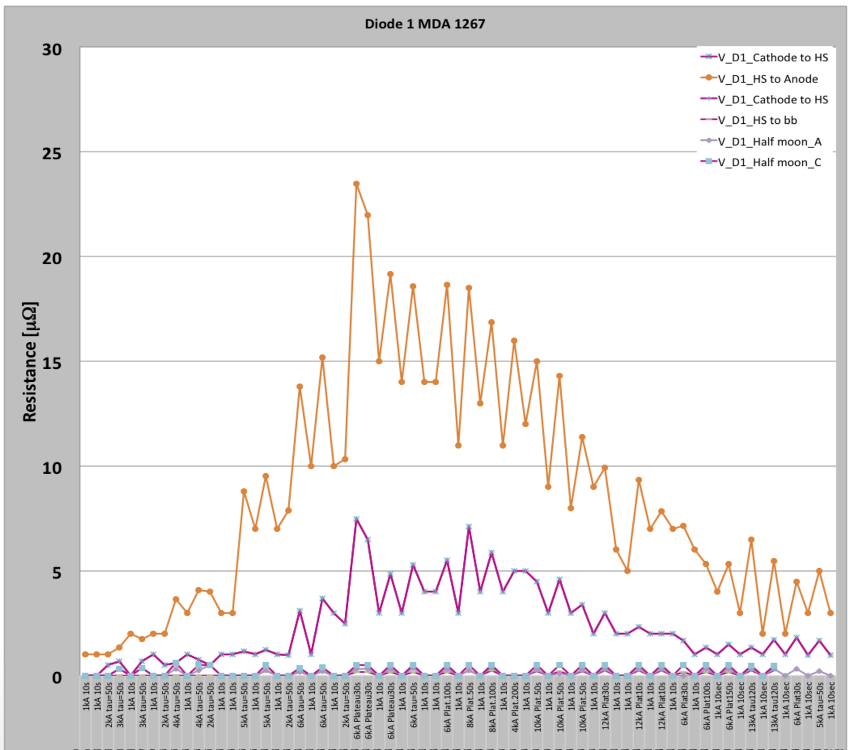
	A15R5		B15R5		C15R5		A16R5		B16R5		C16R5	
	C	A	C	A	C	A	C	A	C	A	C	A
R_{cold}	3	3	2	2.7	3	2.9	3	1.8	3.6	3.2	3.1	2.4
R_{min}	1.5	2.3	2.6	1.8	3.2	1.8	5	2.2	1.6	2.2	1.6	2.2
R_{max}	2.2	9	**24**	**22**	7.9	5.3	**48**	**21**	6	11	4.2	**15**
Prop. in bus	No	10 cm	No	No	11 cm	10 cm	16 cm	9 cm	No	No	No	No

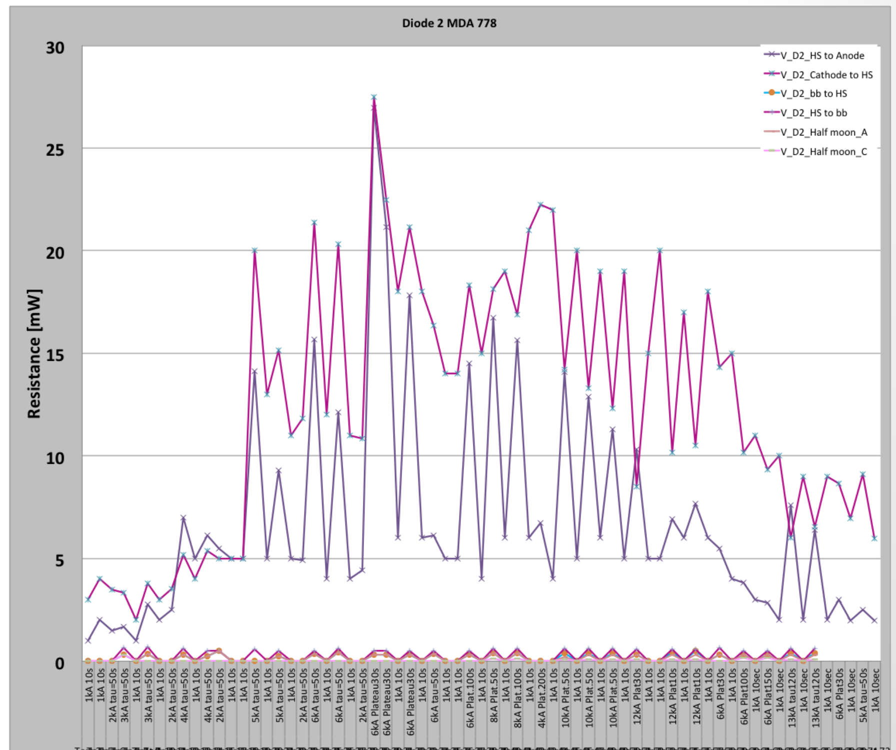


A. Verweij, CMAC, 22 Aug 2011

Resistance of diode contacts – SM18 tests

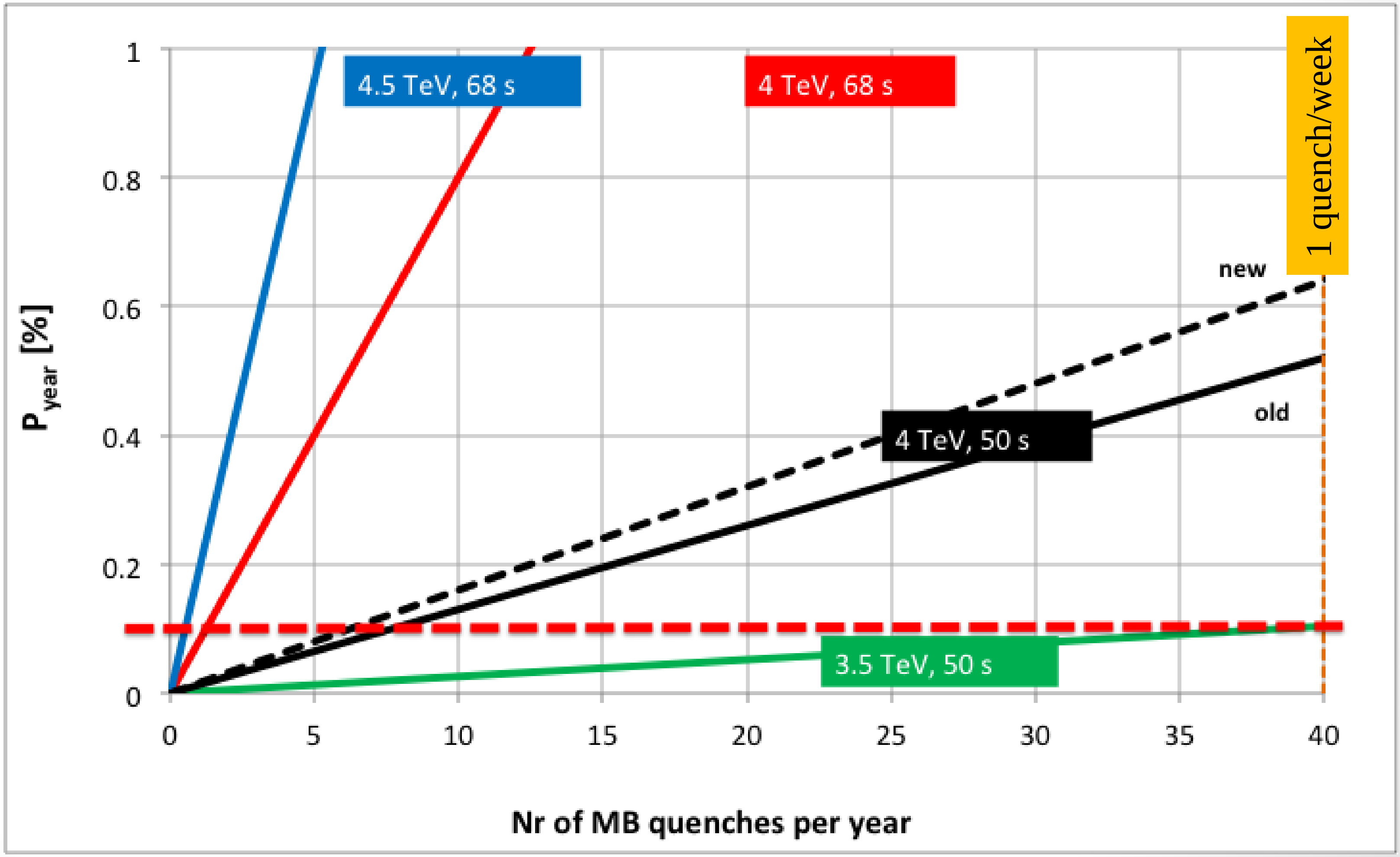
- SM18 test setup allows for measuring resistances of all contacts in diode assembly
- Preliminary results are encouraging:
  - behaviour observed in the tunnel was basically reproduced
  - excess resistance appearing at intermediate currents was localized in contacts between diodes and heat sinks, which are much less critical then half-moon contacts (heat absorbed by heat sink)
  - Resistances of bolted contacts were stable



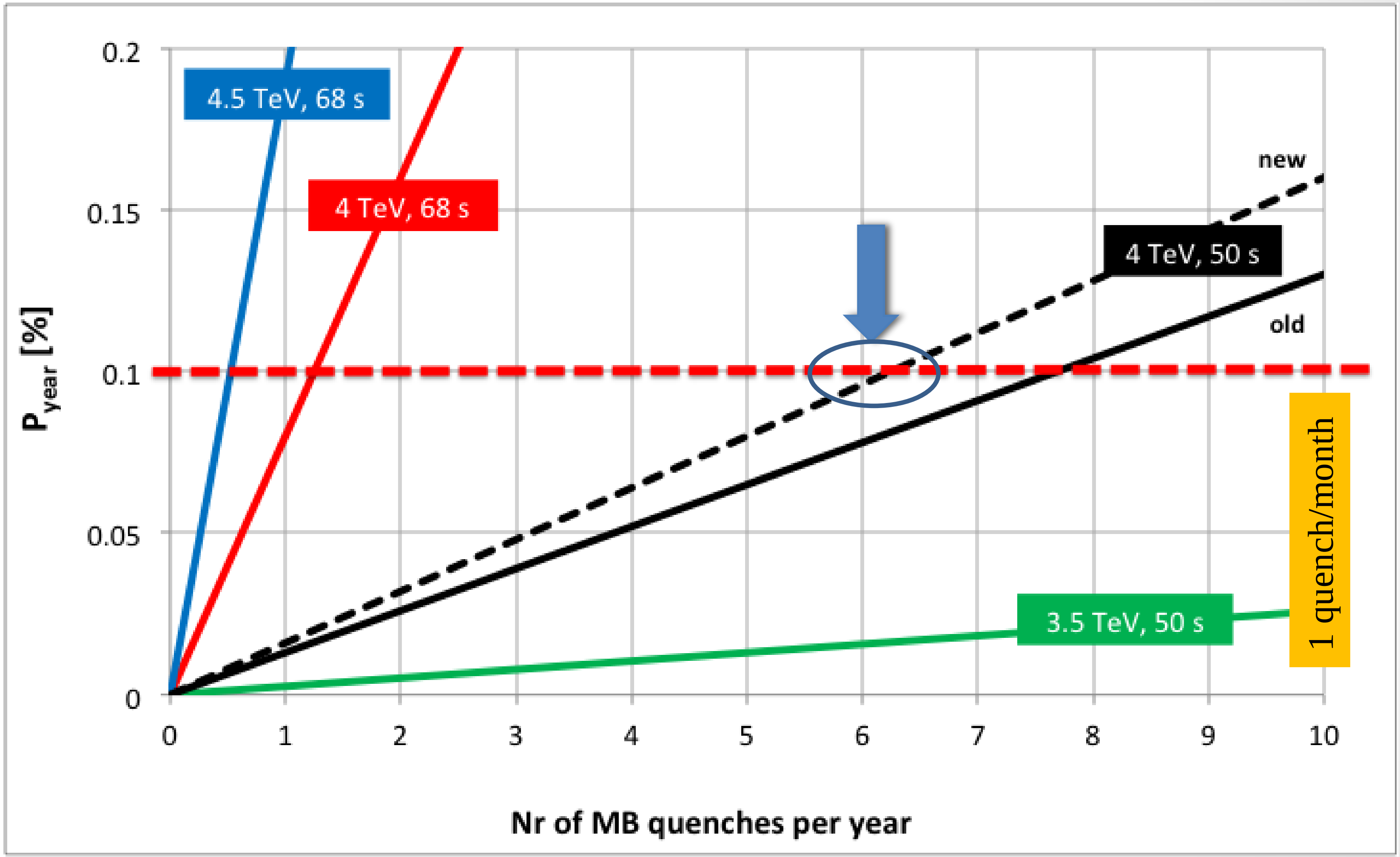


Update on burn out probability calculations

- Additional resistance in by-pass diode stacks (discovered durind 2011 run) needs to be taken into account



What is the envisaged maximum beam energy?



- If during 2012 the number of high current quenches stays below 5-6 then we have the same probability of burn-out as during 3.5 TeV run in 2011 with 40 quench limit

Maximum beam energy for 2012

- Probability of burn-out of the defective 13 kA joints at 4 TeV can now be maintained at the same level as for the 3.5 TeV run in 2011
- Main risk at 3.5 TeV and main risk at 4 TeV are the same: down-time of 8-12 months
- No show-stoppers from equipment point of view to operate LHC at beam energy of up to 4.00 TeV
- 3.9697 TeV might be an interesting option from a precise measurement and precise data analysis point of view (arXiv:submit/0309492 [hep-ph] 31 Aug 2011)

$$\frac{3.9697}{3.5000} \cong \frac{M_Z}{M_W}$$

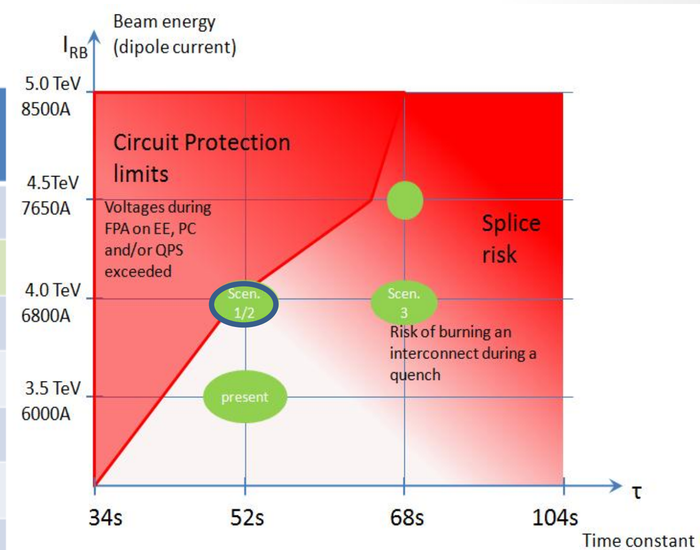
Existing hardware constraints

- At present QPS configuration the energy extraction and quench detection systems are limiting beam energy at 4.00 TeV
- No other hardware constraints up to 4 TeV

For QPS and EE, 3.5TeV/52s is equivalent to nominal settings (7TeV/104s) !

Values for U_{mag} without quenching magnets

	τ [s]	I_{RB} [A]	I_{RBc} [A]	U_{EE} [V]	U_{mag} [V]	di/dt [A/s]	τ [s]	I_{RQc} [A]	U_{EE} [V]	U_{mag} [V]	di/dt [A/s]
Circuit			** RB						RQD/RQF		
3.5TeV	52	5900	6000	882	11.5	116	10	6000	174	2.3	609
OK → 4 TeV	52	6734	6800	999	13*	130	10	6400	187	2.4	655
4 TeV	68	6734	6800	768	10	100	15	6400	120	1.6	421
4.5 TeV	52	7578	7650	1125	14.6	146	10	7200	209	2.7	731
4.5 TeV	68	7578	7650	864	11.2	112	15	7200	135	1.7	747
5 TeV	52	8423	8500	1250	16.2	162	10	8000	232	3	812
5 TeV	68	8423	8500	961	12.5	125	15	8000	150	1.9	527



τ (time constant)

Ref: **J. Steckert**, Chamonix 2011

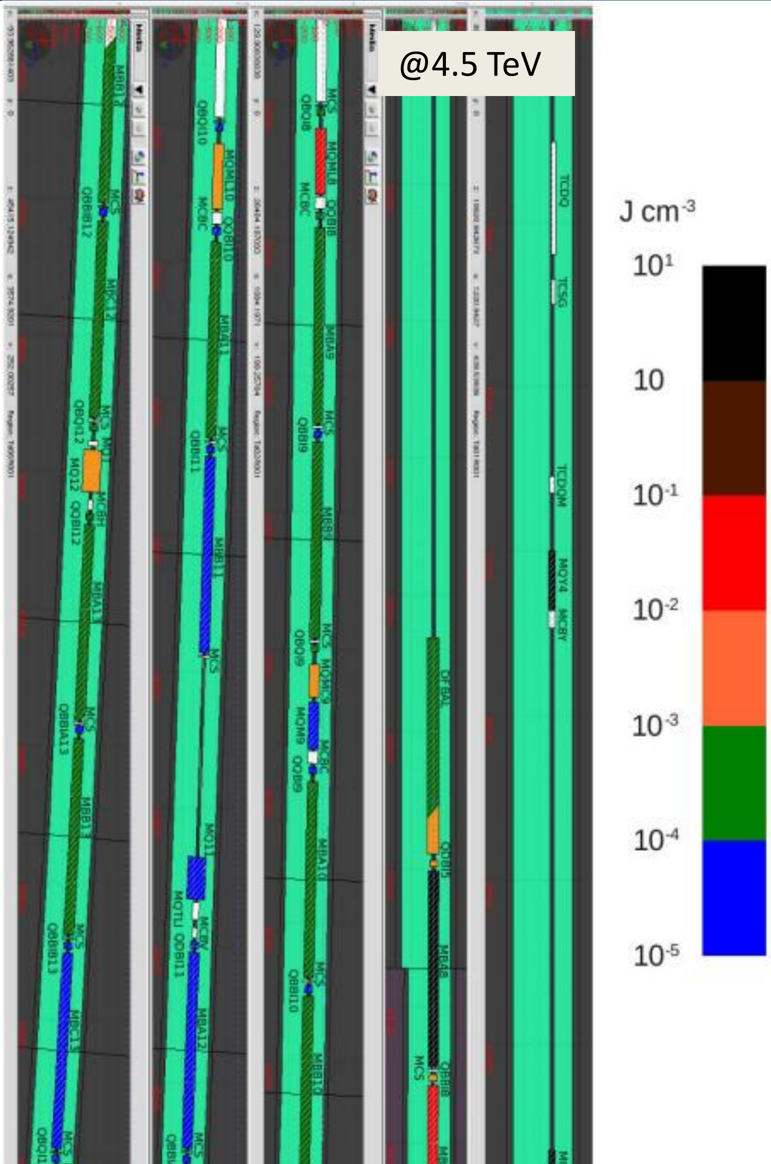
- Beyond 4 TeV the energy extraction time constants for both, RB and RQ circuits must be reconfigured → major operation

...and worries

- Case of an asynchronous beam dump:
  - Multiple quenches of the magnets in the matching section and at the beginning of the DS can be expected
  - Energy, of the order of 1 Joule per cm^3, would be deposited in MQY.4R6, MQY.5R6, and MB.A8R6
  - Some tenths of Joules per cm^3 would be released in MB.B8R6 and MQML.8R6

- ...fortunately the busbar joints in sectors 56 and 67 are relatively good

Sector	Measured at 1A at:	Max R_excess (uΩ at warm)	Approximate Emax (5 magnet quenches)
12	At warm	39±9	**4.5TeV**
23	At cold	80±40	-
34	At warm	36±8	**4.8TeV**
45	At warm	53±15	**3.6TeV**
56	At warm	20±7	**5.8TeV**
67	At warm	31±9	**4.8TeV**
78	At cold	90±30	-
81	At cold	120±40	-



R. Versaci, et al.
CERN-ATS-Note-2011-081 TECH.

Conclusion

- Main arguments against 4TeV during Chamonix 2011 were:
  - Number of spurious quenches observed over 2010, in particular several events involving large number of dipoles
  - Very small margin for nQPS (symmetric quench detectors) at 4TeV with τ = 52s. In case of simultaneous quench of 15 dipoles the nQPS symmetric quench detectors are saturating and are blind

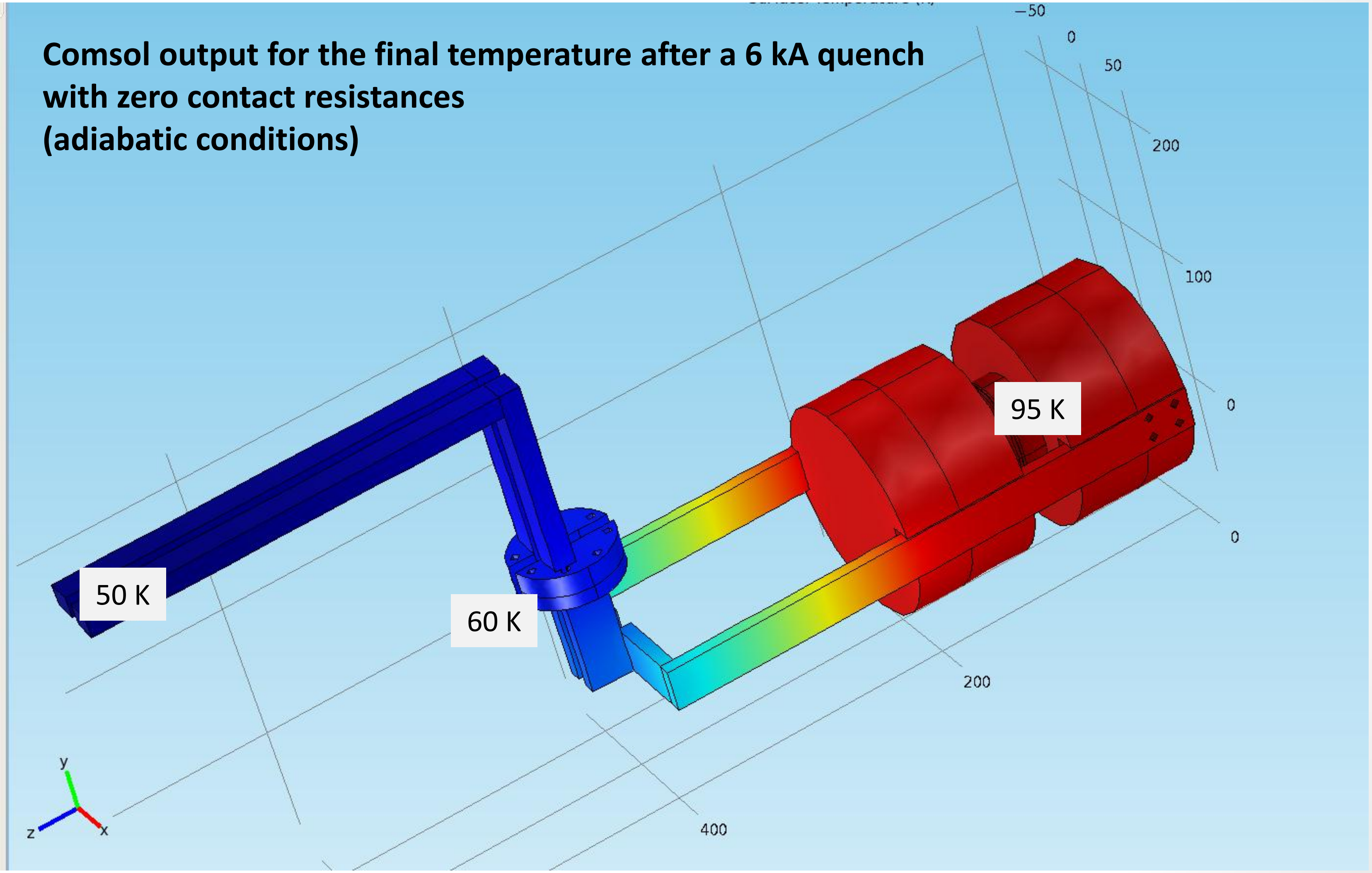
- In 2011 the number of spurious quenches was radically reduced. This was achieved mainly thanks to the snubber capacitors installation and improvements introduced to the power converters and energy extraction delays
- In 2011 no quenches observed during hardware commissioning and only 1 high current, single magnet spurious quench with beams
  - Better operational procedures with beams > 100 MJ
  - Efficient BLM protection

- No show-stoppers from equipment point of view to operate LHC in 2012 at maximum beam energy of up to 4.00 TeV

Annex slides

Simulations – MB diode

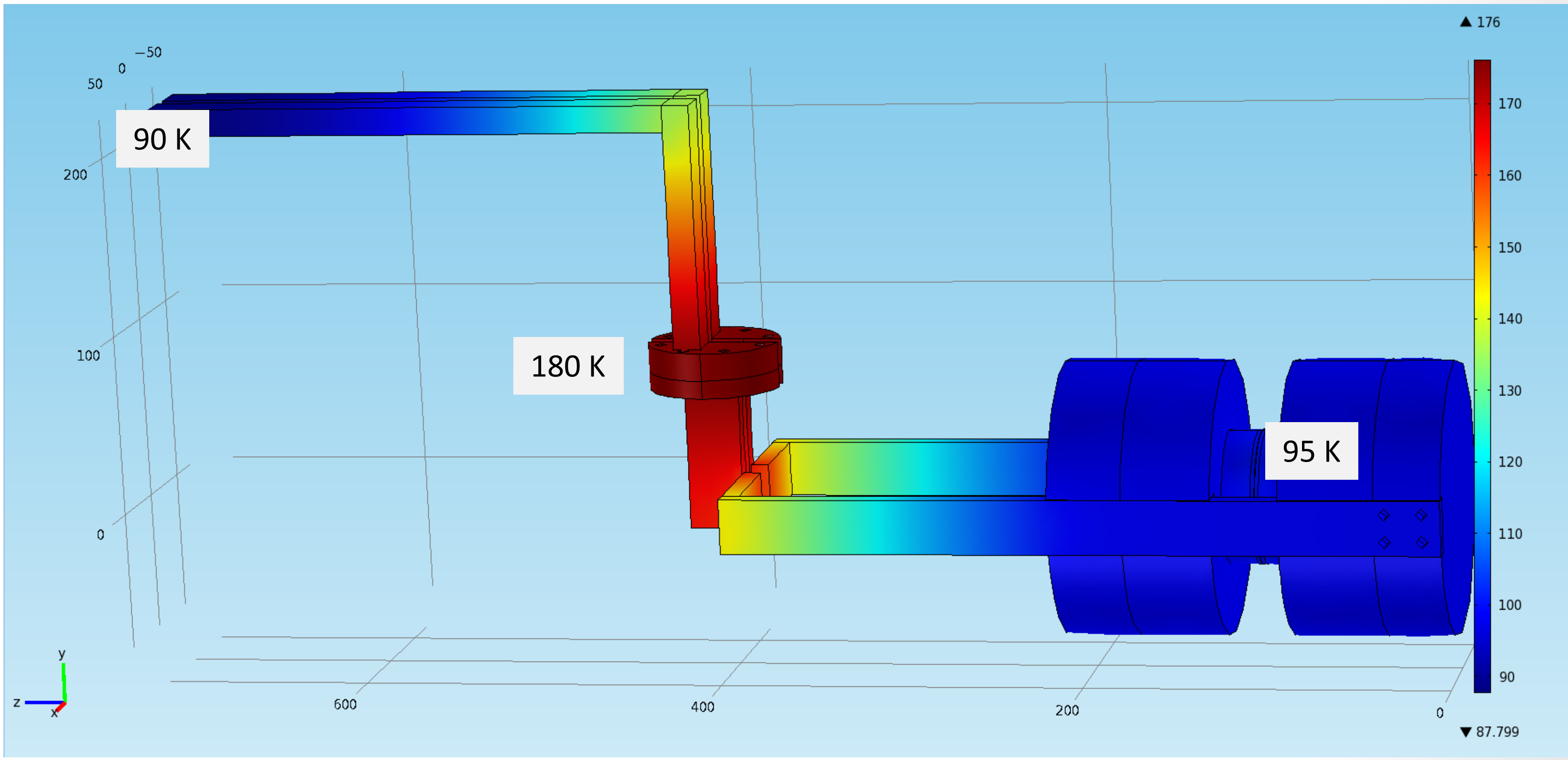
Simulations are performed using the codes **Comsol** and **QP3**, giving very similar results.



A. Verweij, TE-MPE, 26 Aug 2011

Simulations – MB diode

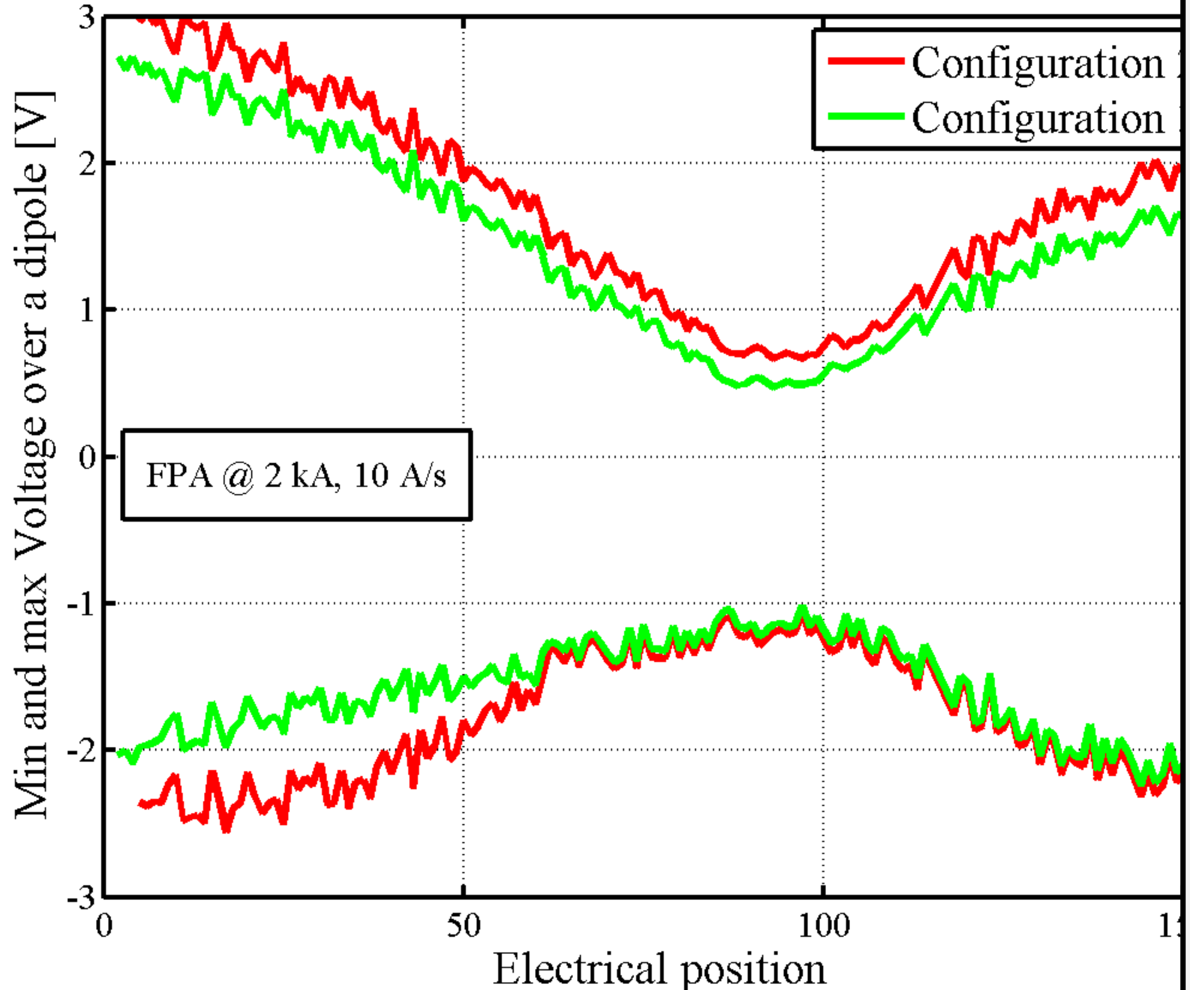
Comsol output for the final temperature after a 6 kA quench with $R_{c,moon}$=40 μΩ (adiabatic conditions)



A. Verweij, TE-MPE, 26 Aug 2011

Maximum and Minimum values of the Voltage across each dipole

Fast Power Abort at 2 kA, 10 A/s



Configuration 2

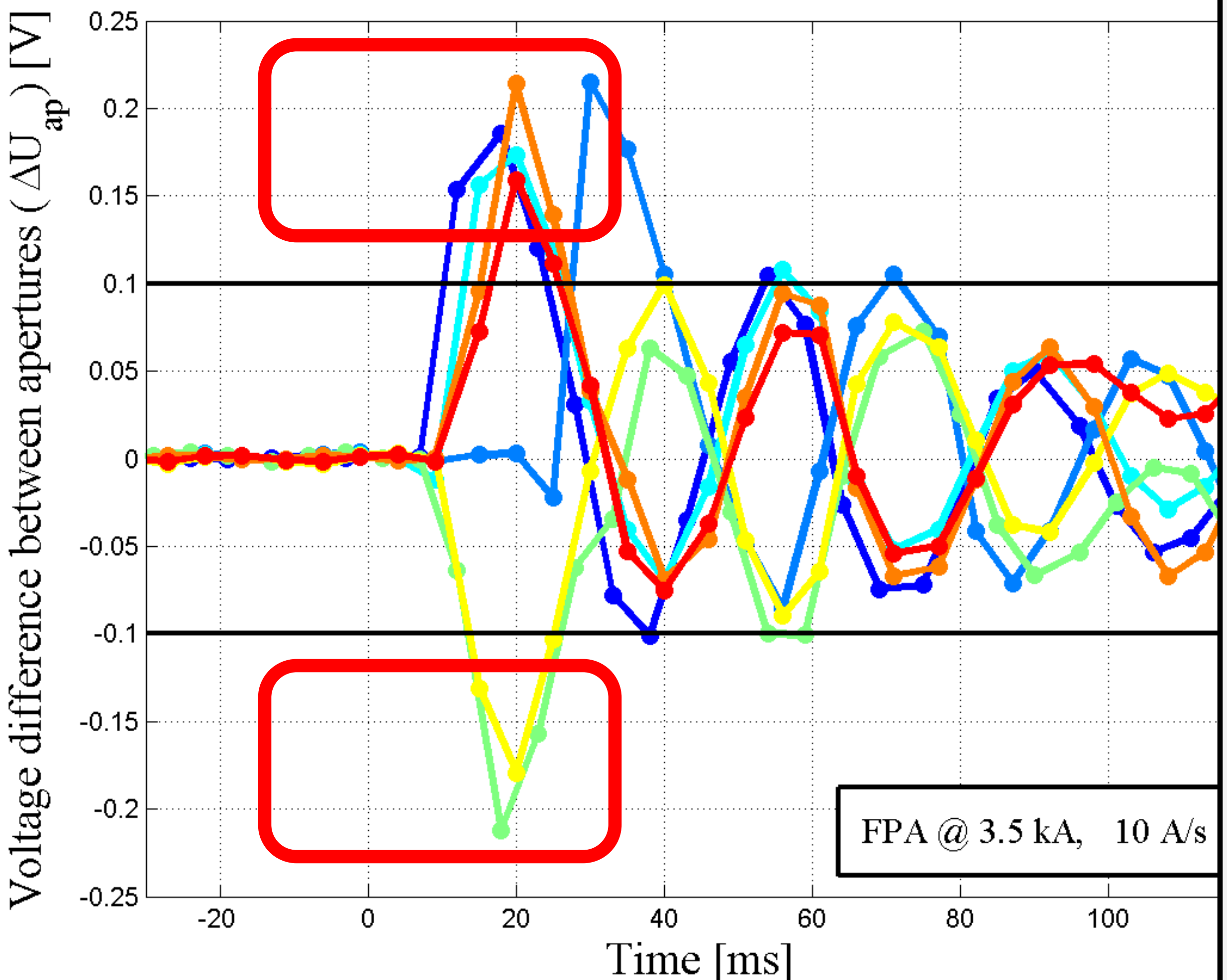
- Delay between the power-converter switching-off and the opening of the extraction switches

Configuration 3

- Delay between the power-converter switching-off and the opening of the extraction switches
- Snubber capacitor in parallel to the extraction switches
- Additional resistance in the filter at the output of the power-converter

Event on 17th February 2010, Sector 34
Voltage difference between the two apertures of a dipole

Fast Power Abort at 3.5 kA, 10 A/s



The Quench Protection System triggered and fired the quench heaters of 11 dipoles.

Cause: The voltage oscillations caused by the switching-off of the power converter and by the opening of the extraction switches travel along the dipole chain, and cause a different voltage drop across the two apertures of the magnets.

Propagation test : diode => interconnect