SUPERCONDUCTING ELECTRICAL CIRCUITS

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Abstract

During the almost 18 months of hardware commissioning nearly all superconducting circuits of the LHC were tested with success and many of them are/were ready for operation. However a number of unexpected observations were made, which may either limit the performance of the accelerator, have an impact on the operation, require additional hardware and software, or were simply a challenging puzzle without further impact.

INTRODUCTION

The hardware commissioning was an amazing combined effort of various groups and individuals. The teams from ELQA, QPS, OP, PO, Cryogenics, and MPP worked successfully together under the guidance of the hardware commissioning coordination team and were not perturbed by the various ongoing restructurings. Colleagues from all over the world were collecting and interpreting the data, some of which will be explained below. I would like to thank all the team; it was a pleasure to participate. I apologize that not all the other teams, which made LHC possible, can be properly mentioned.

The incident in September has changed our focus, concentrating the attention even more towards the main magnets in sector 3-4. But, first of all, the vast majority of the 1572 superconducting circuits worked according to the procedures published by MPP. It did not come without effort, however. Many cabling mistakes, some failing heaters and occasional high voltage problems had to be fixed. A number of other shortcomings, surprises and even faults attracted even more attention. Some of these, euphemistically called "non-conformities", were known or discovered before the hardware commissioning. They are not subject of this report. Nor will this report give a complete list of the not properly working superconducting circuits. In total 49 circuits are marked as "(still) to be commissioned" in the reports [1-7] of the hardware commissioning coordination team for all sectors except sector 3-4. Evidently, in this sector all cold circuits will have to be re-commissioned.

This report concentrates on the interesting puzzles encountered during the commissioning. In some cases we will even encounter surprises with circuits, which are considered "already commissioned".

One can distinguish four classes of puzzles, as specified below in Table 1.

The list of examples below is not complete. I may have missed some and we may have not discovered all of them. Likewise, I may have sorted some of them into the wrong category; the problem may not exist any more.

Type of puzzle	Affected circuits
harmless	IT…Q10, RU, dump resistors, helium level
potentially inconvenient for operation	D2…Q10, RB, 120 A, 600 A
potentially dangerous	RB, 600 A EE, splices 600 A
unsolved	RCBX, RCBY, RB

Table 1: List of topics

HARMLESS

The Q6.R4 (and similar) puzzle

An example of a simple puzzle, which took nevertheless a lively discussion to solve, is shown in figure 1. The two apertures of the Q6 are fed with 3 cables and 3 current leads.

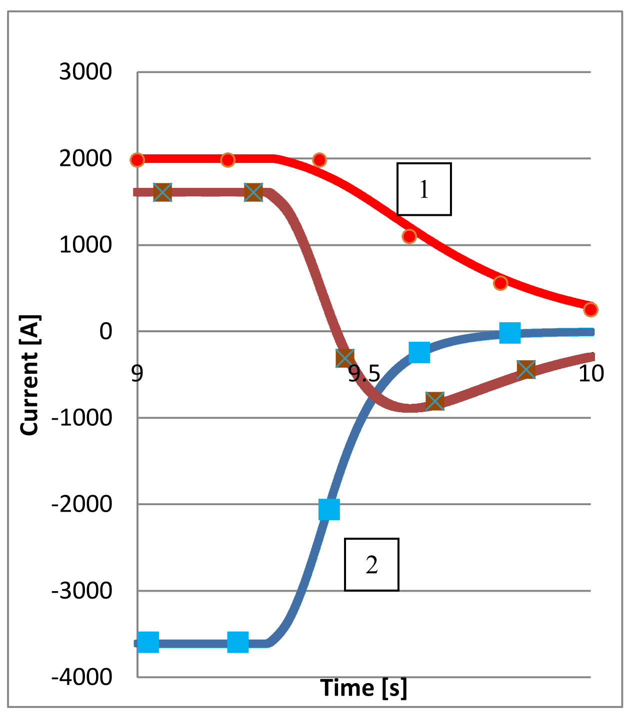

Fig 1: Current distribution between the three current leads feeding the Q6.R4

The plot shows in the upper curve (1) the current through the beam1 aperture of the Q6.R4 during a quench while powering asymmetrically. The lower curve (2) is the current through the aperture of beam 2. The symbols are measurements of the voltage drop over the warm part of the respective current leads, scaled by the resistance of 7μΩ and adjusted in time within one time bin.

The measurement of the voltage drop on the common current lead raised some discussion, until it was discovered that it matches the current measurements very well. Incidentally, the good agreement proves that the voltage measurements over the warm part of a current lead can serve as a current measurement.

During the quench the current through the centre tap of the two magnets reverses the sign. This should never happen in a completely symmetric case. However, the difference in excitation caused a difference of resistance of the quenching apertures and different current decay times. The centre tap current had to change the sign once the current through the B2 aperture (lower) could not compensate or over-compensate the B1 current any more. Needless to say, this observation was completely harmless, but it paves the way for the next puzzle.

The inner triplet current distribution puzzle

Figure 2 shows a similar case [8] for the inner triplet. Here two power converters (plus a trim converter) feed 3 magnetic circuits. The magnetic fields have to be calculated from the measured currents using the full information.

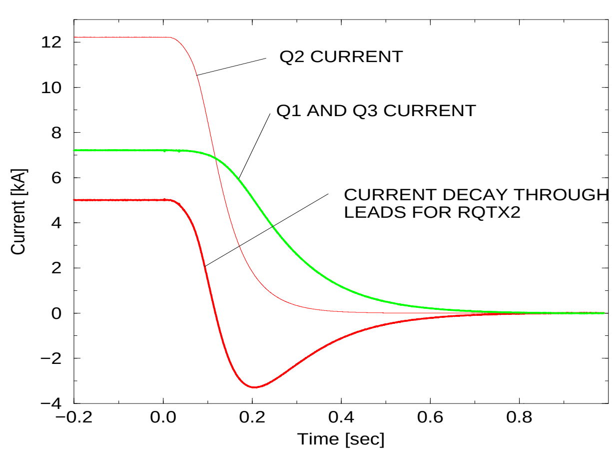

Fig 2: Current distribution of the inner triplet during a quench

In conclusion, most "surprises" have a very simple explanation.

The undulator puzzle

The two undulators are needed for beam diagnostics. As reference [9] defines the requirements for the operation:

"The two synchrotron light sources are the undulator and the D3 magnet physically they are in the same cryostat, with a 40cm gap between them. The D3 magnet provides sufficient light when the beam energy is above 1.5TeV, so the Undulator was added to cover the injection and low energy regime.

Having the Undulator powered at higher energies does not aid the operation of the Synchrotron light monitors, as the spectrum of light that is produced shifts rapidly to the UV. …… However, it is not sufficient to attenuate this unwanted UV light as it will impact on the UHV window, and UV photons with wavelengths of less than 200nm are known to cause fluorescence in the glass. The detectors will see this extra light as an increase in the background "noise", limiting the precision of our measurements.

The best operating scenario is to have the undulator ramped up before injection (pre-pulses etc.) and then when the beam passes the 2TeV level, start reducing the current. The Undulator has been designed and tested to be magnetically "neutral", so the ramp down should not be affect the beam. The nominal current in the undulator is 450A, the maximum allowed dI/dt is 1A/s so the ramp down will take some time." [9]

The undulators consist of 8 superconducting coils, which are pair-wise magnetically coupled. The coils are bridged by resistors, as shown in figure 3. The picture is taken from reference [10].

The internal resistors have a value of 0.15 Ω, the extraction resistor has 0.8 Ω. The undulator RU.R4 was very difficult for the power converter and the quench protection.

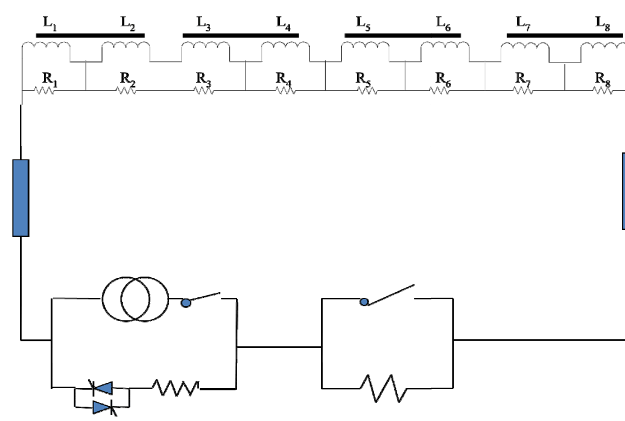

Fig 3: Sketch of an undulator [10]

The reason was found in the saturation of the poles, which leads to the strong current dependence of the inductance, as shown in fig. 4 (from Reference [10]). Moreover, the undulator does not have a voltage tap in the centre (in fact, none at all). Hence the quench protection has to calculate from current measurements the first and second derivative of the current with respect to time in order to make a prediction about the expected inductive voltage. This process relies on current measurements and works only for low current changes. Consequently, only a dI/dt of 0.5 A/s was reached.

The real surprise was, however the performance of the RU.L4. It turned out, after days of speculation in the control room, that one of the internal resistors is/was missing, changing the transfer function very profoundly. Details can be found in reference [11].

At present it is being discussed whetherto replace the magnet with a proper spare unit with centre tap. That should solve the speed limitation. Alternatively, a second external dump resistor could be added to ramp down the magnet fast enough, if the speed is really required.

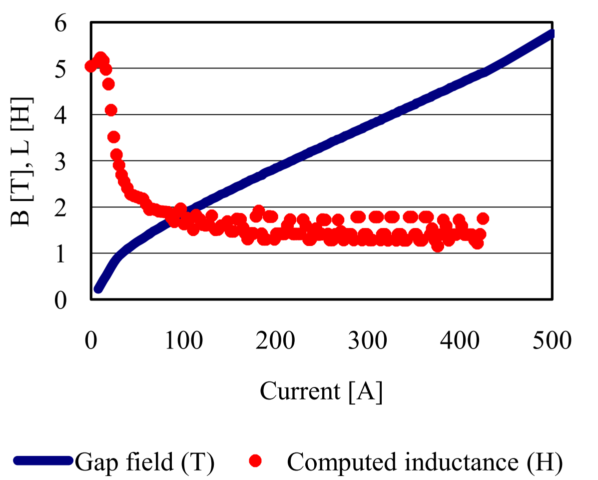

Fig 4 Nonlinear inductance of the RU.R4 as a function of current [10]

Lost and found (QF45)

Sometimes a small failure can cause surprises. Right after the Christmas holydays in January 2008 the dump resistor for the QF45 failed. It failed after extensive testing in Protvino. Figure 6 shows the voltage over the dump resistors of the QF and, for comparison, the QD circuit in sector 45. The measurements describe very well exponential decays with different decay times. Clearly, the QF current (lower curve) decays much slower, indicating a much lower resistance.

The resistor was replaced and inspected. A fixation was broken during transport bringing parts of the resistor into contact with each other.

A different kind of problem occurred in the QD.A56 resistor around the April 24th 2008. This time a short to ground developed during an energy extraction from 7 kA, 50 sec after opening of the switches. This was detected by the active earth current detection system of the power converter. The fault could be reproduced, after disconnecting the resistor, by applying a voltage with respect to ground.

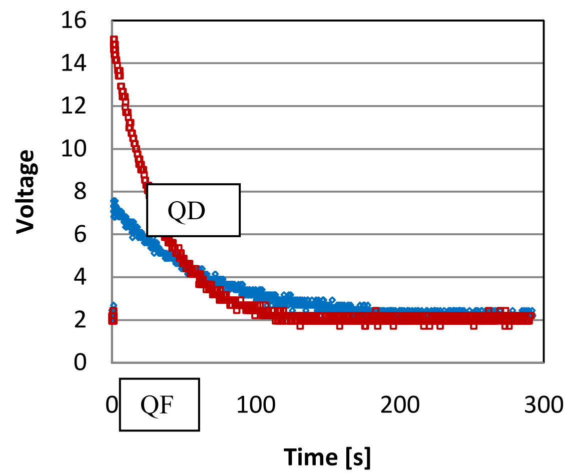

Figure 5: The voltage drop over the dump resistors during a 2 kA fast power abort of the RQ circuits

A breakdown at 550 VDC was observed during a high-pot test. The fault became permanent. It was necessary to open the unit on the surface (in building SD6). A tiny piece of steel wire, presumably of a steel brush, was found. It shorted plates in the resistor against the cover! It was squeezed against an insulator board by the panel at one end. The other end was able to move and, under influence of the air flow of the forced air cooling, to touch occasionally a resistor plate. In addition a few other metal chips were found and removed. They all originated probably from the production site. The resistor unit was remounted and reinstalled without difficulties.

There are 15 other resistors of the same type in the LHC.

The RQT12.R3 etc. puzzle, the RQM5.L8 bus problem

In a number of cases, like the one mentioned in the title, the circuits showed a resistive behavior above a certain current level. In most cases the circuit was switched off, before a quench appeared. However, in some cases, a quench happened minutes after the appearance of the resistance. All these cases could be traced back to not properly wetted and cooled busses. In the case of the RQT12.R3, which showed the same behavior as all other correctors fed via strands in the outer layer of the bus cable, it was the routing and bending of the superconducting link. In the case of the MQM5.L8 the positioning of the DFBM was wrong by 2 cm. These cases have been treated and should be fixed now. The last example demonstrates, however, that a properly working LHC depends very critically on the proper filling of the cryostats and similar events may be expected for the future.

INCONVENIENT

The D2, Q4 puzzle, part I

The historically first puzzle, the D3, Q4, Q5 problem caused a lot of discussions at that time. The D2.L8 was the first magnet to reach its design current in the LHC. The neighboring Q4 and Q5 quadrupoles did also very well, until they were powered simultaneously. Figure 6 shows the currents of the D2, the Q5 and the Q4. The symbols show the voltages, as seen by the quench protection (right scale). The dipole current and the Q5 current were rising, while the Q4 current was stable. Then the D2 quenched (green crosses), followed after 50 ms by the Q5 (light red dots). The Q4 followed about 500 ms later (light blue). One can also see that the resistance over Q4 actually started to rise around 100 ms after the Q5 quench, to calm down again and to take off suddenly. As this was the first incident of this kind and little was known about the stability of the equipment in general, discussions and additional tests went on for a while. It turned out that single magnets were always stable and it needed current changes in at least one magnet to

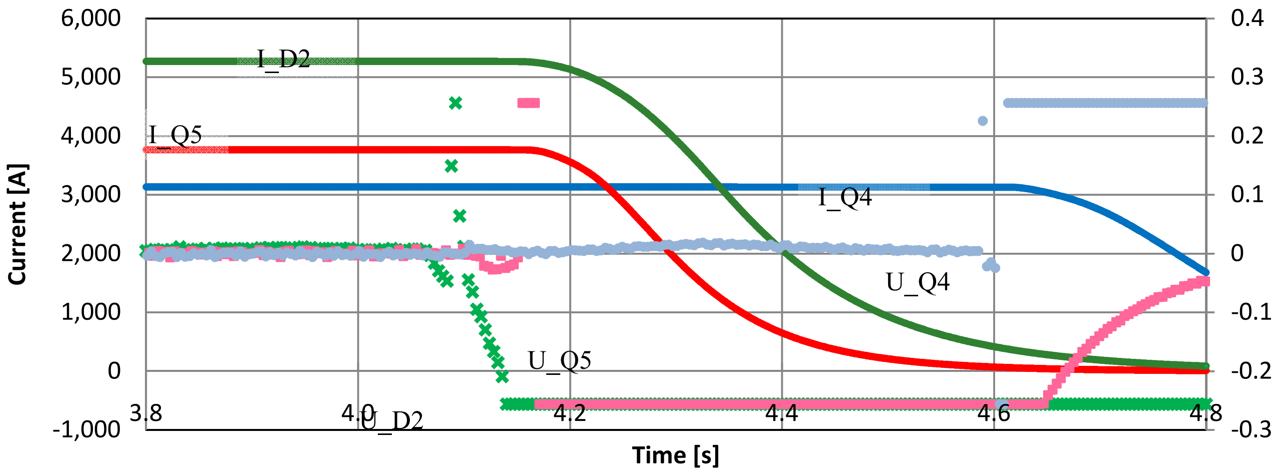

Figure 6: The coupling between D2, Q5 and Q4

reproduce the phenomenon. Then “shaking” was tried by varying the current in one magnet (Q4), while everything was still stable. This did the trick. The apparent coupling disappeared.

The most likely explanation is a movement of the bus cable inside the DFBM. Alternatively, it could be related to an incomplete filling. However the disappearance of the phenomenon was not correlated with an action of the cryo-control.

The D-Q4 puzzle, part II (and similar)

A year after the first Q4-D2 puzzle (see above) the same set of circuits showed again a peculiarity. During the re-commissioning of the sector 78 the B1 aperture of the Q4 was powered with the B2 aperture already at 3600 A. Around 4 seconds on the scale of figure 7 a quench happened and the current changed with more than 10^4 A/s. This induced a voltage of up to 0.25 V on the D2 dipole, which was not powered. If this would have been the case, again a multiple quench would have shown up.

Note that there are several cases of a similar wiring mistake, as described in reference [12]. Table 2 is copied from this reference. The coupling will remain an issue with these circuits, as long as the problem is not fixed. This is demonstrated in figure 8, showing the same phenomenon in sector 3-4 between the Q9 and the Q10.

DFB	Cable 1			Cable 2			Cable 3			Cable 4		
DFBAO.L8	?	?	?	?	?	?	?	?	?	?	?	?
DFBAA.L1	Q9C	Q9A	Q7B	Q10A	Q10B	Q10C	Q7A	Q7C	Q8B	Q8A	Q8B	Q9B
DFBAP.R8	Q8A	Q8C	Q10C	Q9C	Q9B	Q8C	Q7A	Q7B	Q9A	Q10A	Q10B	Q7C
DFBAH.R4	Q7C	Q10B	Q9B	Q9A	Q8B	Q9C	Q8A	Q7A	Q8C	Q7B	Q10A	Q10C
DFBAI.L5	Q8A	Q8B	Q10B	Q7A	Q7C	Q8C	Q9B	Q9C	Q7B	Q10A	Q10C	Q9A
DFBMA.4L2	D2A	D2B	Q4A	Q4B	Q4C							
DFBMA.4L8	D2A	D2B	Q4A	Q4B	Q4C							
DFBLA.L1	D2A	D2B	Q6A	Q6B	Q6C		Q4A	Q4B	Q4C	Q5A	Q5B	Q5C
DFBLB.R1	D2A	D2B	Q6A	Q6B	Q6C		Q4A	Q4B	Q4C	Q5A	Q5B	Q5C
DFBLD.R5	D2A	D2B	Q6A	Q6B	Q6C		Q4A	Q4B	Q4C	Q5A	Q5B	Q5C

Table 2 : List of couplet circuits

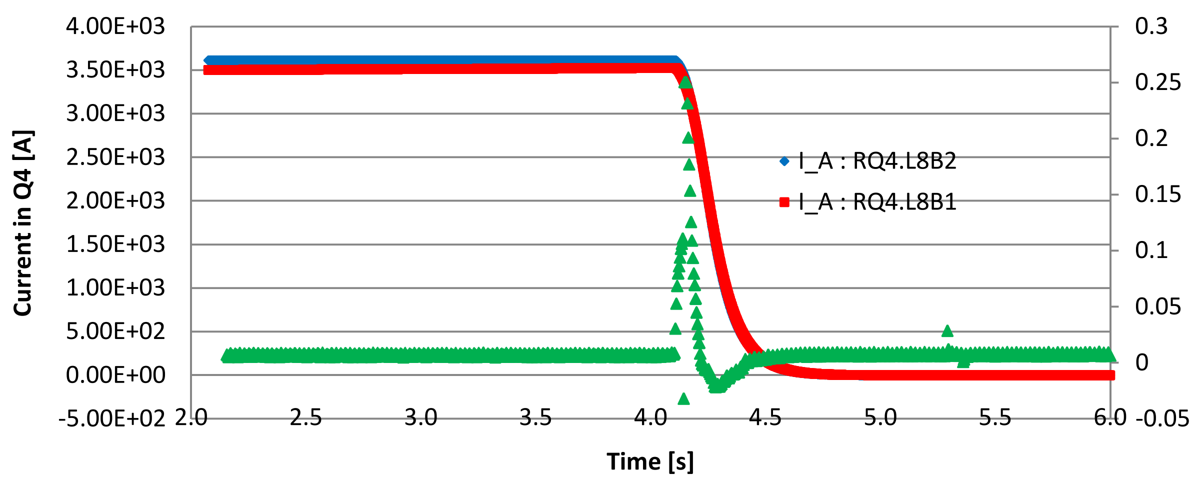

Figure 7: Current of the quenching Q4.L8 and the voltage picked up by the quench protection for the D2 (right scale)

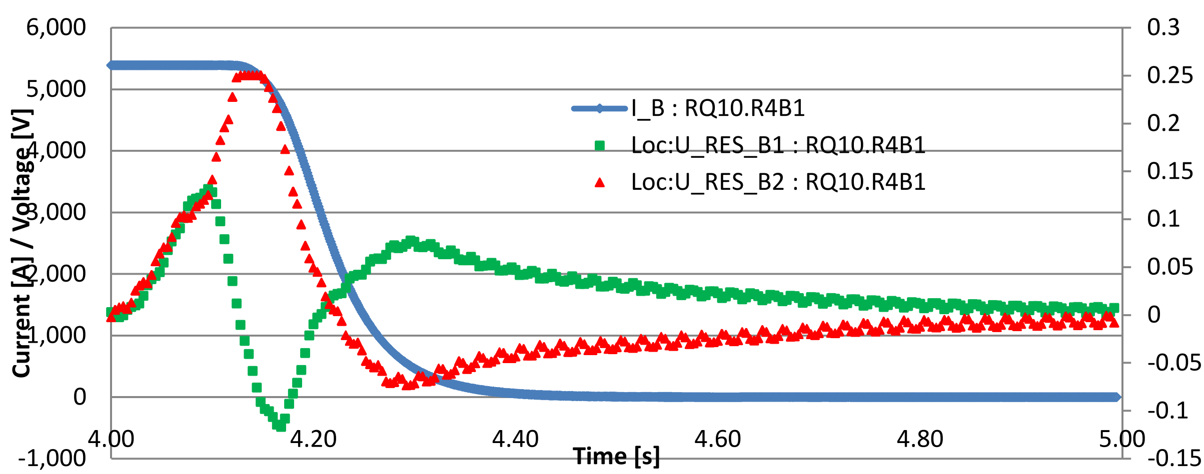

Figure 8: Current of the quenching Q10.R4 and the voltage picked up by the quench protection for the Q9.R4 (right scale)

The RD2.L2 detraining puzzle

Figure 9 Voltages over the "detraining" RD2.L2

Figure 9 shows the voltages over the half-coils of aperture B1 of the D2.L2 during an apparent detraining quench on August 6th 2008. The magnet had been without problems at 6 kA before. Now it quenched at about 5.5 kA. Both half-coils (blue and red) seem to develop a resistance, which is reflected in the difference (blue) going rapidly into saturation. The logbook says "detraining ?". The question mark is well deserved, because the Q4.L2 aperture 2 had been ramped up to nominal the day before, in between this quench and the previous successful 6 kA run. Table 2 reveals that the two magnets share cable 1 in the DFBMA.4L2. So, it is maybe not a mystery at all? The question has to be followed up.

The reference magnet puzzle

On Jan 30th 2008 it was rediscovered that the LHC contains really superconducting magnets.

Superconducting magnets experience a very pronounced hysteresis. In particular, the transfer function of a newly quenched (virgin) magnet differs considerably from the transfer function of a magnet which has just seen a high field and stayed cold. This effect may have a limited impact of the beam because most of it happens way below injection (beam) energy.

The existing bus quench protection for the arc dipoles and quadrupoles works by comparing the total voltage with an expected voltage, calculated as a multiple of the voltage over two "reference" magnets. The inductance of a quenched magnet differs, as said, at low excitation from the expected. Hence, in order to get the ramp started again, one has to make a slow magnetization cycle. This issue has to be included in the acceleration procedures. The table below shows for completeness the list of reference magnets.

Note that a similar problem will arise with the new bus fault detection system. The new system compares electrically adjacent magnets. The new system will signal a "fault" situation after each quench, because the quenched magnet will always be compared with a "healthy" one. It might be a good idea to enforce a magnetization cycle after each and every quench.

Quench Protection Reference Magnets				
	Dipoles		Quadrupoles	
"1-2"	C21R1	C21L2	A21R1	A20L2
"2-3"	C21R2	C18L3	A21R2	A17L3
"3-4"	C21R3	C18L4	A20R3	A18L4
"4-5"	C21R4	C21L5	A20R4	A20L5
"5-6"	C21R5	C21L6	A20R5	A20L6
"6-7"	C21R6	C21L7	A20R6	A20L7
"7-8"	C21R7	C21L8	A21R7	A20L8
"8-1"	C21R8	C21L1	A20R8	A20L1
"1-2"	C21R1	C21L2	A21R1	A20L2
"2-3"	C21R2	C18L3	A21R2	A17L3

Table 3: Reference magnets

Too slow?

The list of commissioned circuits [1…7] is impressive. However, not all circuits work and not less than 47 circuits do not reach, or not yet reach, the required rate of current change. This is often caused by excessive noise, which prevents the quench protection to calculate the rate of change and its derivative precise enough for a low threshold. Raising the threshold or lengthening of the time window, used by the quench protection, are clearly increasing the risk and not recommended.

POTENTIALLY DANGEROUS

The symmetric quench problem

In June 2008, during the training campaign of the dipoles the dipole B16.R5 quenched due to the "hot" helium coming from the quenching neighbor. This is so far quite normal. In this case, however, a phenomenon showed up, which had been previously excluded on the basis of the string experience and theoretical assumptions.

The voltage traces of this event are shown in figure 10 [10]. The curves labeled U1 and U2 (green and blue, respectively) show the voltage over the respective aperture. Clearly something develops around 0.5 seconds. The quench grows, however, so symmetric that the difference U_Qs0 (red dots, right scale) stays within 100 mV. This threshold is reached 650 ms later. The total integral over the square of the current (MIITS) increased to 50 MA^2, corresponding to an adiabatic temperature of 600 K [14].

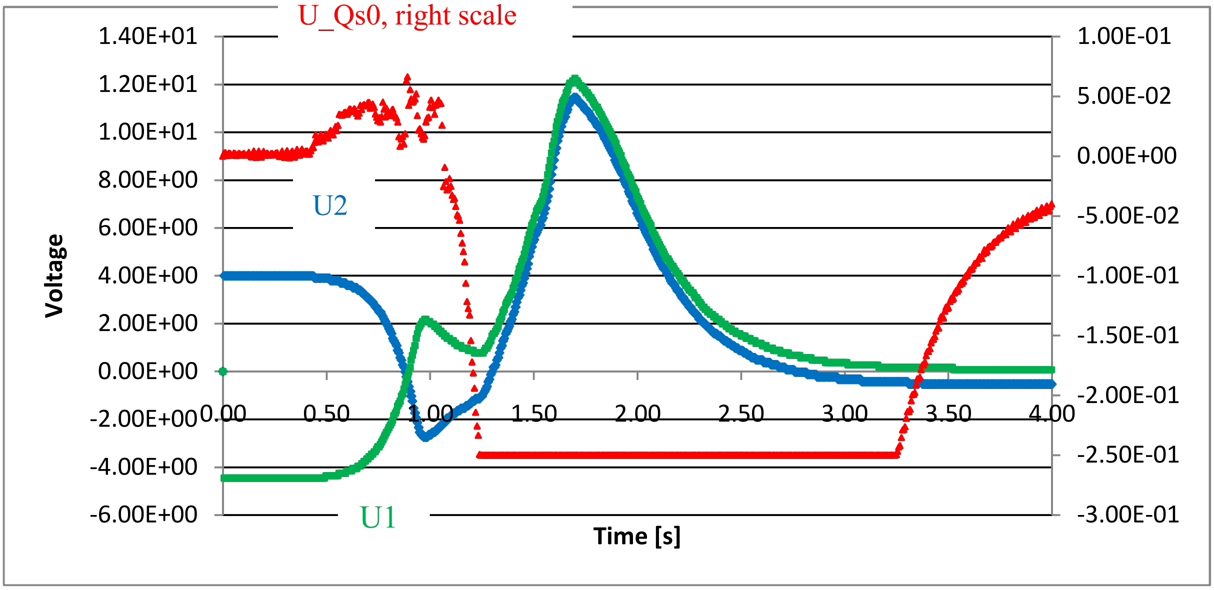

Figure 10 Voltage traces from the B16.R5 (6.6.08). The quench develops very symmetric and is discovered 650ms later [13].

Several similar cases were found by looking back in the data. Consequently the training of the dipoles was temporarily interrupted

The extension of the quench protection, necessary to detect early faults in the main busses makes it also possible to compare two electrically adjacent magnets [15]. This solution is currently being implemented. It requires, however, a large quantity of additional cables, which spread high voltages all around the LHC and which increase the risk of complicated earth faults.

The transient spike problem

A magnet in an electrical circuit behaves always as a transmission line [16]. The series resistance is of course very low; consequently the damping is very poor. The transfer function is dominated by the interplay of the main inductance, the eddy currents and the capacitance. The impedance becomes more and more capacitive at low frequencies.

On the other hand, in order to dump the stored energy the transmission line has to be altered to include the dump resistors. This action results in a global redistribution of the voltage. The transients (from both ends of the sector in case of the dipoles) have a velocity of about 150 µs/dipole.

The effect of the sudden voltage change is not very visible, while looking at the voltage difference over the two coils of one aperture, because the strong coupling between the coils washes out the differences in the response of the single coils. This is different for the difference in voltage between apertures (or, even worse, between magnets; this is probably an issue for the symmetric quench detection).

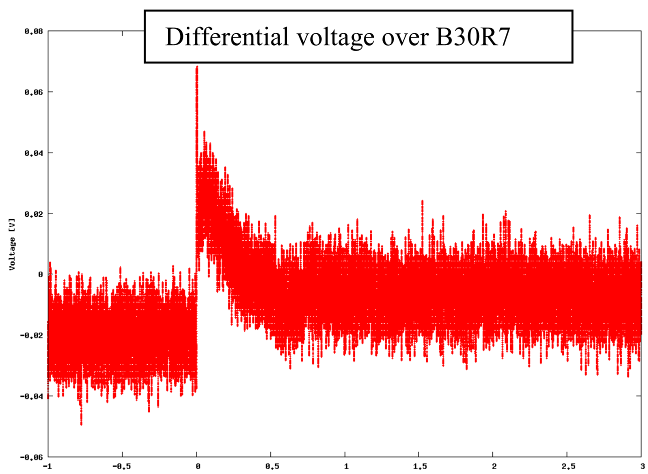

Figure 11: The differential voltage over B30R7 during a 3 kA energy extraction. Vertical scale: 0.02 V/div; Horizontal scale:0.5 s/div

The effect [17] was first observed in MB B30.R7 (MB 1007) during a fast discharge at 7000A => dI/dt =-70A/s. The event is shown in figure 11. The voltage difference between the two apertures is clearly incompatible with a quench. The voltage increased with dI/dt and exceeded 100mV [18]. Figure 12 shows the differential voltages over the two apertures. There was no unbalance between upper and lower poles. Magnetic measurement in SM18 had also shown a different dynamic behaviour of the aperture with an unusually high sextupole in one aperture and no particular asymmetry between upper and lower poles [19]. It was therefore concluded [20] that the contact resistances in the two apertures, and hence the eddy currents, are quite different. However no particular problem for the safety was envisaged and the quench detection threshold was raised to 250 mV. This decision seems discussable and potentially dangerous in view of the symmetric quench issue (see above).

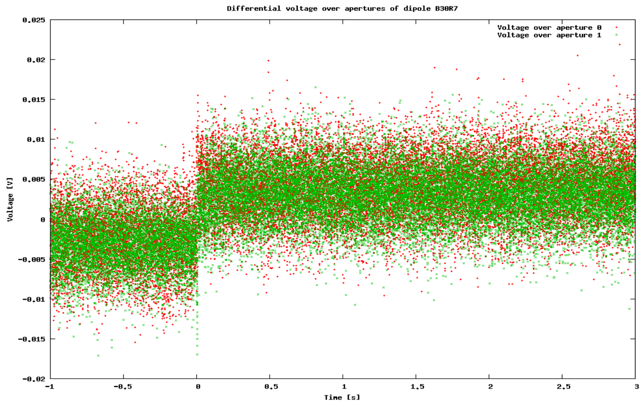

Figure 12: The differential voltages over the two apertures of B30R7. Scales: 0.005 V/div and 0.5 s.

A new software tool [21], which takes "snap shots" using all quench detection channels of a given arc simultaneously, made the search for candidates for this type of unbalance possible on a global scale. Figure 13 shows the result of such a scan.

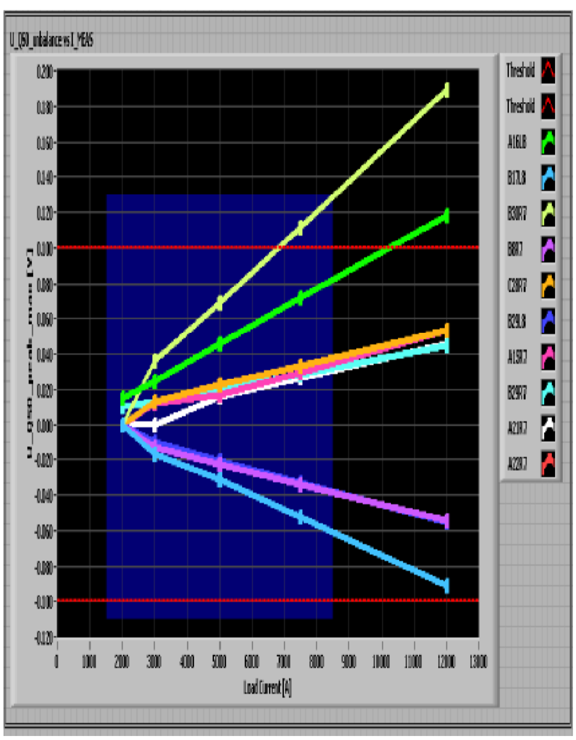

Figure 13: Sensitivity of dipoles in sector 78.

The plot shows the observed peak voltages as a function of current. The red horizontal lines correspond to the quench protection threshold. The yellow line on top belongs to the B30.R7. As useful as this tool is for the original purpose, it turned out even more important for the search of abnormal splices.

The quench back of correctors incl. coupling

As mentioned above, suboptimal cabling can introduce electromagnetic coupling. Not only are the 6 kA circuits affected but also most 600 A circuits. The spool piece bus bars consist of straight wires, closely running in parallel. The so-called line N bus is made of a three layer cable. Again, the two wires, which belong together, are not twisted.

Many cases of coupling have been observed, more or less accidentally, because no procedure was set up to test for this phenomenon. It is highly recommended to systematically include this in the next hardware commissioning procedures!

Figure 14 shows the current in RSD1.A56B1 and RSD2.A56B1 (red and green) respectively. In blue (right scale) the resistive voltage of the RSD2 is plotted. The curves starting from below are the voltages over the external dump resistors. The sextupole correctors, like many others, are protected by internal resistors and by external dump resistors [22].

A quench happens in RSD1, while the current in RSD2 is slowly ramped down. The current in RSD1 drops rapidly by more than 100 A. The mechanism is well explained in reference [23]. The current diverts in part into the local bypass resistor (150 mΩ each, 1.8 Ω total), which are mounted on the magnets. This happens in a very short time. The enormous change in current (amounting to almost 18 kA/s in fig. 14) is "seen" by the adjacent circuit. The blue symbols indicate the (calculated) resistive voltage, which reaches easily the quench detection threshold. The switch of RSD2 is being opened and the current is being redistributed.

Note the acceleration of the current decay in the RSD1 after about 300 ms. The bypass resistors act as quench heaters and quench all magnets of the circuit.

This type of coupling has also been seen between RQTF and RSD1.A56 (dI/dt = 36 kA/s), RSF1 and RDF2.A56 (dI/dt = 30 kA/s) [24] and in other cases. As to be expected, also the nested coils show coupling. Reference [25] reports about an influence of the RSD2.A56B1 ramp on the voltage loop of the ROD.A56B2. The two circuits are on conductors 9 & 10 respectively 39 & 40 in the line N cable. Note that this is in the outer and the innermost layer, which are cabled in the same sense. The conductors run in parallel, about 3 mm apart, over a length of more than 3kilometers.

One might say: if a corrector quenches, who cares if the whole family quenches and a few more as well? The beam is lost anyway! This argument is certainly right; however the correctors are heating the helium in the short straight sections (or the dipoles, in case of the spool pieces) within less than a second. Hence, the main magnets will "see" the temperature increase, while they are still at high current. This may result in massive quenches, with the corresponding recovery time for the cryogenics or, worse, in a wearing of the main magnets, due to the many quenches.

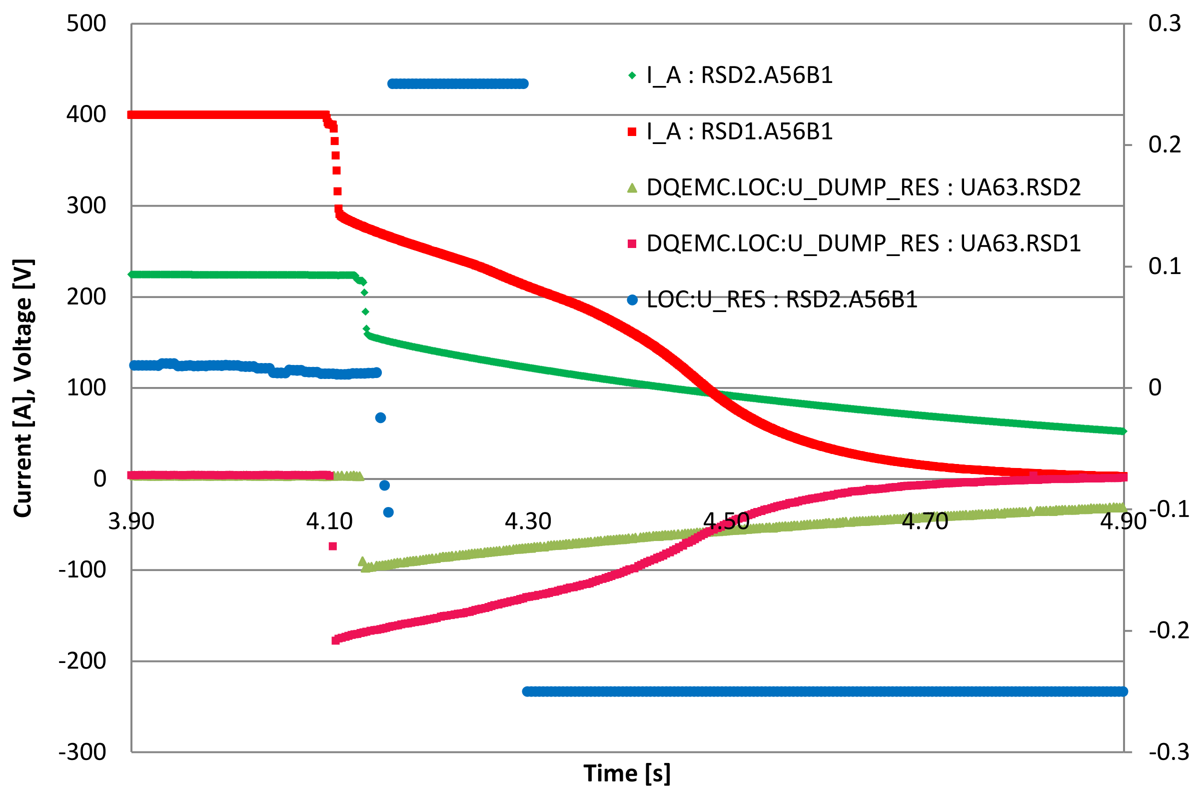

Figure 14: Coupling between RSD1.A56B1 and RSD2.A56B1

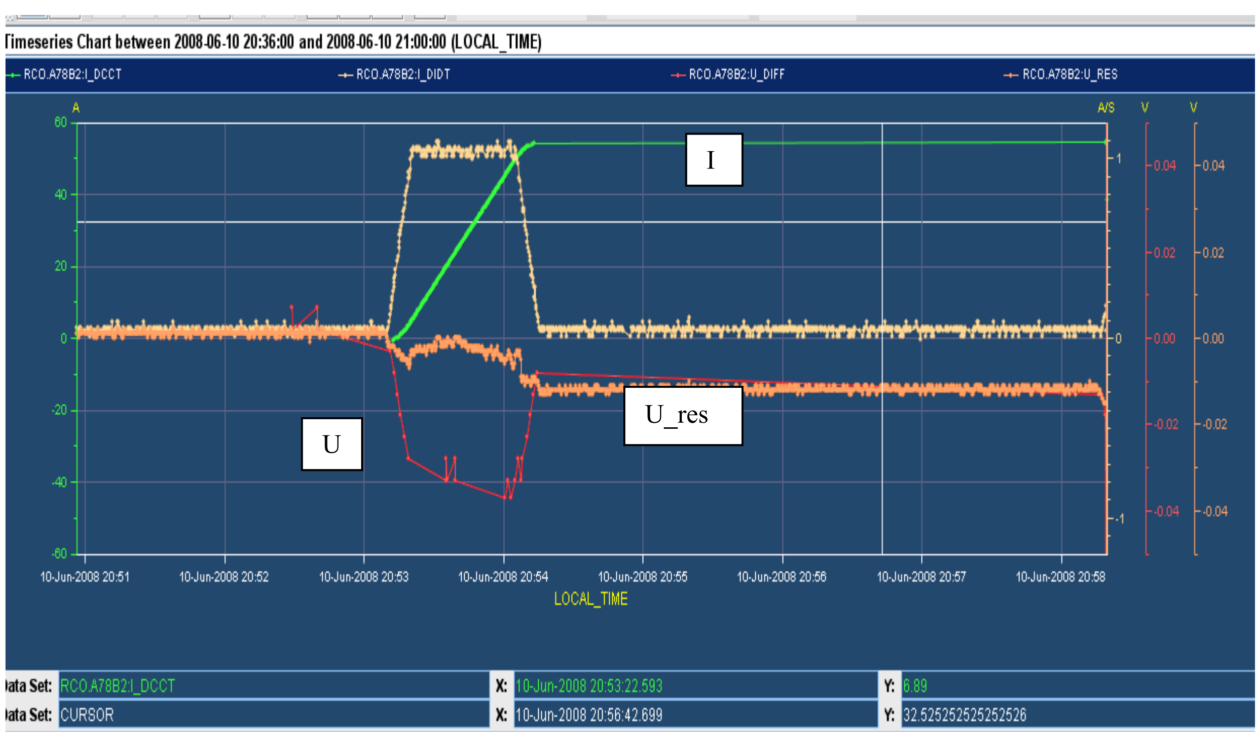

Figure 15:Voltage (red), resistive voltage (orange) and current (green) of the RCO.A78B2. The resistive voltage rises with current and explodes after ~4 m.

The RCO.A78B2 splice

Figure 15 [26] shows in green the current applied to the RCO.A78B2 as a function of time. The red curve, the total voltage, should be reflection of the yellow curve, which indicates the current change. It is however rising, while the current change is constant. Subtracting the inductive part one arrives at the orange curve, which is the resistive voltage. It is clearly rising with current and it explodes after about 4 minutes.

The observation is best explained by the presence of a bad joint. The spool corrector circuit RCO.A78B2 is maybe not really needed for the LHC operation, because the corrector strength of the other 7 sectors should be sufficient.

To find a splice fault in this circuit would be quite challenging. The MCOs are installed in all MBA magnets of the sector. The 77 correctors are connected via the spool bus with 509 welded splices. Inside the magnets and at the magnets connections are another 385 joints [27].

A resistance of 0.3 mΩ can be calculated from figure 15. This corresponds to an average joint resistance of 330 nΩ, or, more likely, a bad splice with 0.27 mΩ.

The RQT13.L5B1 splice (or what)

As to be expected, also the line N cable is holding some surprises. Figure 16 shows the current and resistive voltage of the RQT13.L5B1, as an example. The circuit quenched 28 s after having reached 550 A. The resistive voltage is detected after the current starts to drop. This is very likely a sign for an increasing resistance somewhere outside the coil.

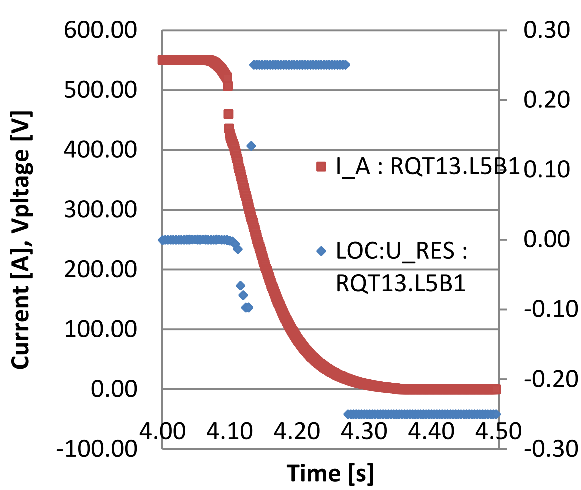

Figure 16: Current and resistive voltage (right scale) for the RQT13.L5B1

Circuit	Current	Delay	Comment
RQT13 L5B1	549.9 A		Quench
	550 A	28 s	Quench
	550 A	90 s	Trip, unknown
RQTF A45B2	525 A		Quench
	362 A		Quench
	454 A		Quench
	550 A	32 s	Quench
	550 A	2 s	Quench
	550 A	24 s	Quench
	550 A	26 s	EE Dump

Table 4 summarizes [28] the behavior of the RQT13.L5B1 and the similarly behaving RQTF.A45B2 .

It was decided to reduce to maximum current for these circuits, in order to progress with the hardware commissioning. This seems to be a quite questionable decision in view of the September experience. The circuits should be declared “out of order” to avoid damage.

The RCBCV10.L6B1 threat

The RCBCV10.L6B1 circuit was tested on March 11th 2008 by the ELQA team [29] and found OK. On April 4th the AB/PO team tried to power the local corrector circuit and failed. The ELQA checked the circuit again and found on April 16th the cold voltage tap EE811 to be unconnected [30]. During the intervention on May 5th, which was aimed to localize the fault by time domain reflectrometry, the voltage tap was back, however with a 4 to 5 time higher resistance (additional 1.5 Ω).

Such a high resistance increase is not normal and likely not stable. There is a permanent risk to “loose” the circuit again. The operation of this steering corrector needs to be avoided! It should be blocked on the software level.

UNSOLVED

The MCBX mystery

The power converter group reported an unexpected problem, while trying to power the RCBXH3.R8 [31].

The model, underlying the regulation of the converter, was wrong. The (green) inductance (see figure 17) is far from the purple constant, which was the expectation. This magnet seems to have either an exceptionally low eddy current resistance or (equivalently) a parallel resistance of ~10 Ω, or.

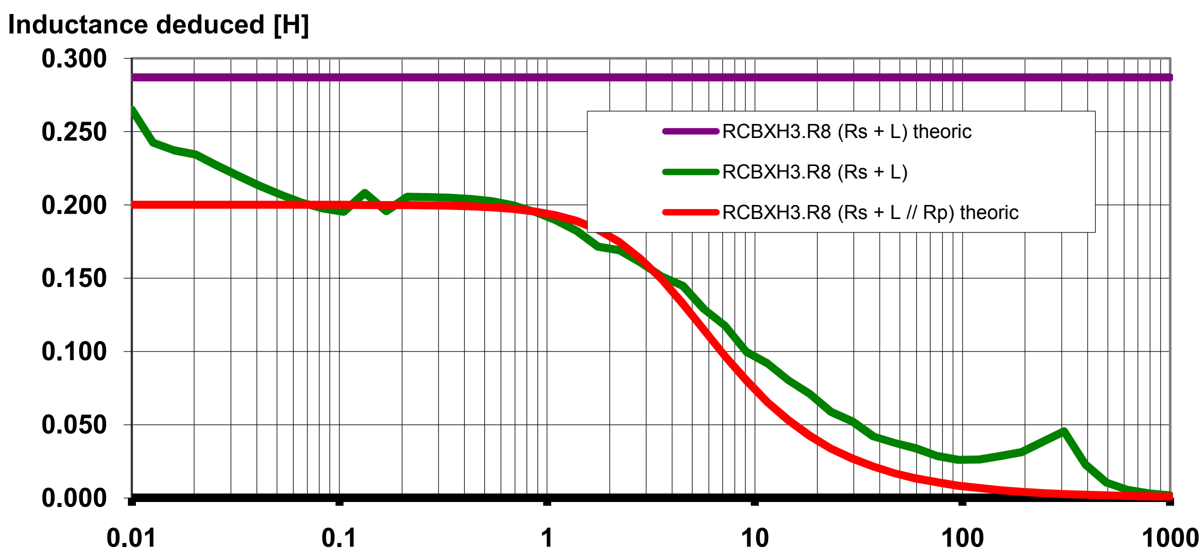

Figure 17: Inductance of the MCBXH3.R8 [31]

It was possible to get the magnet working with this assumption (lowest, red, curve)

At the time being, no information is available over the condition of the other, orthogonal, magnet of the same aperture. It might have been shorted and magnetic coupling could have induced the effect. Clearly, the experiment has to be repeated at the earliest possible occasion.

The RCBY mystery

Figure 18 shows the inductances of 4 MCBY apertures [32]. The upper curves belong to "normally" behaving magnets. The lower curves, indicating lower inductance already at low frequencies, behave very strange. Special transfer functions are being employed. Nevertheless, the magnets have other shortcomings, which may or may not be related to the strange inductance.

It is not known, why some transfer functions are completely different. Up to now, no hint was found in the production data [33].

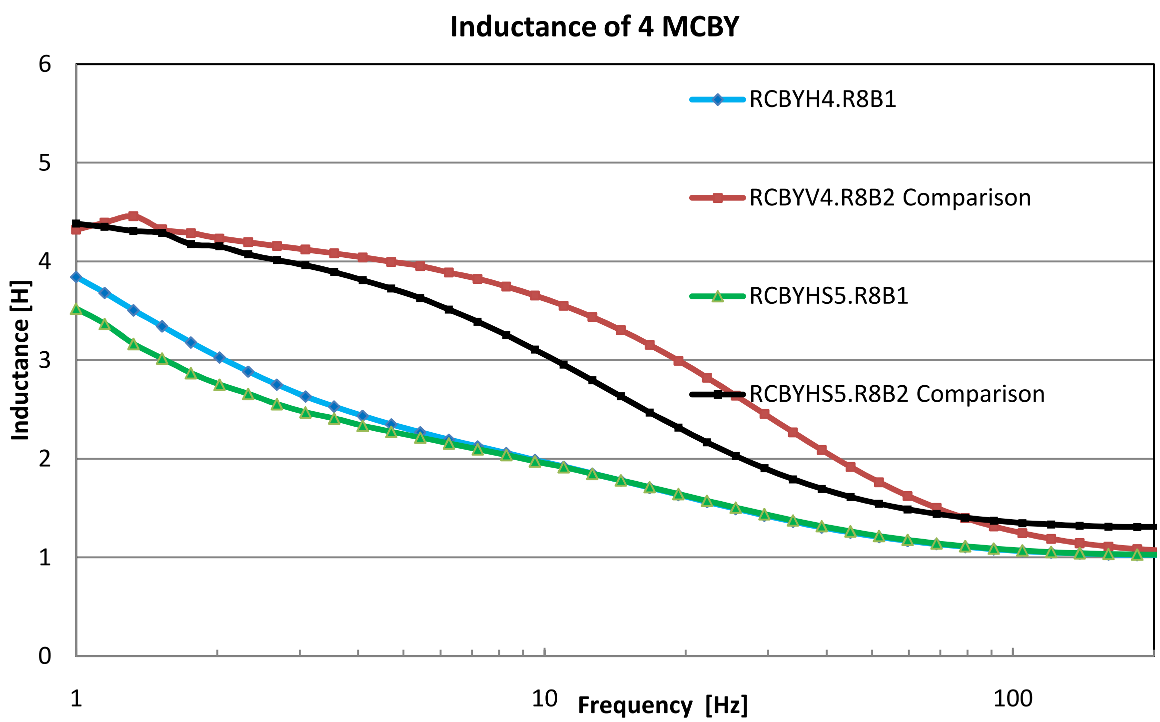

Figure 18: The inductances of 4 MCBY apertures [32]

The "bump" mystery

The hunch mystery may very well be related to the previous mystery. In fact the above mentioned strange magnets and a few others (RCBCV8.L1B2, RCBYHS4.L5B1, and RCBCV5.L4B2, maybe more) show a remarkable behavior. They reach their respective nominal current. However, on the way back to zero they suddenly "quench", the converter stops, and the crowbar fires.

The level at which the "quench" happens depends on the dI/dt, and is for a given dI/dt surprisingly stable. The 72 A MCBY "quench" for a dI/dt of 0.6 A/s precisely at 71.5 A . The level is lower at higher ramp rates. The product of ramp rate * "quench" level seems, within the limited knowledge, to be constant.

The most remarkable feature of this "quench", however, is shown in figure 19 from reference [34].

The sudden bump confuses the power converter and is interpreted as abnormal situation, hence the switch off. But where does the energy to create the current bump come from? The current increases by ~50 mA, i.e. by 0.07%. The Inductance seems to shrink by 0.14%, assuming that the current is being driven up by the magnetic energy.

Has the transfer function been measured in all cases? Is there a correlation? What makes the inductance "jump", if that is the proper explanation? Is this harmless, or will it destroy the magnet (and more)? Is it related to an inwards movement of the scissor laminations by ~40 µm, which would explain the change in inductance? Could the observation that the magnets seem sometimes to work properly for hours be related to friction of the laminations? As already said, no systematic differences during production have been detected so far.

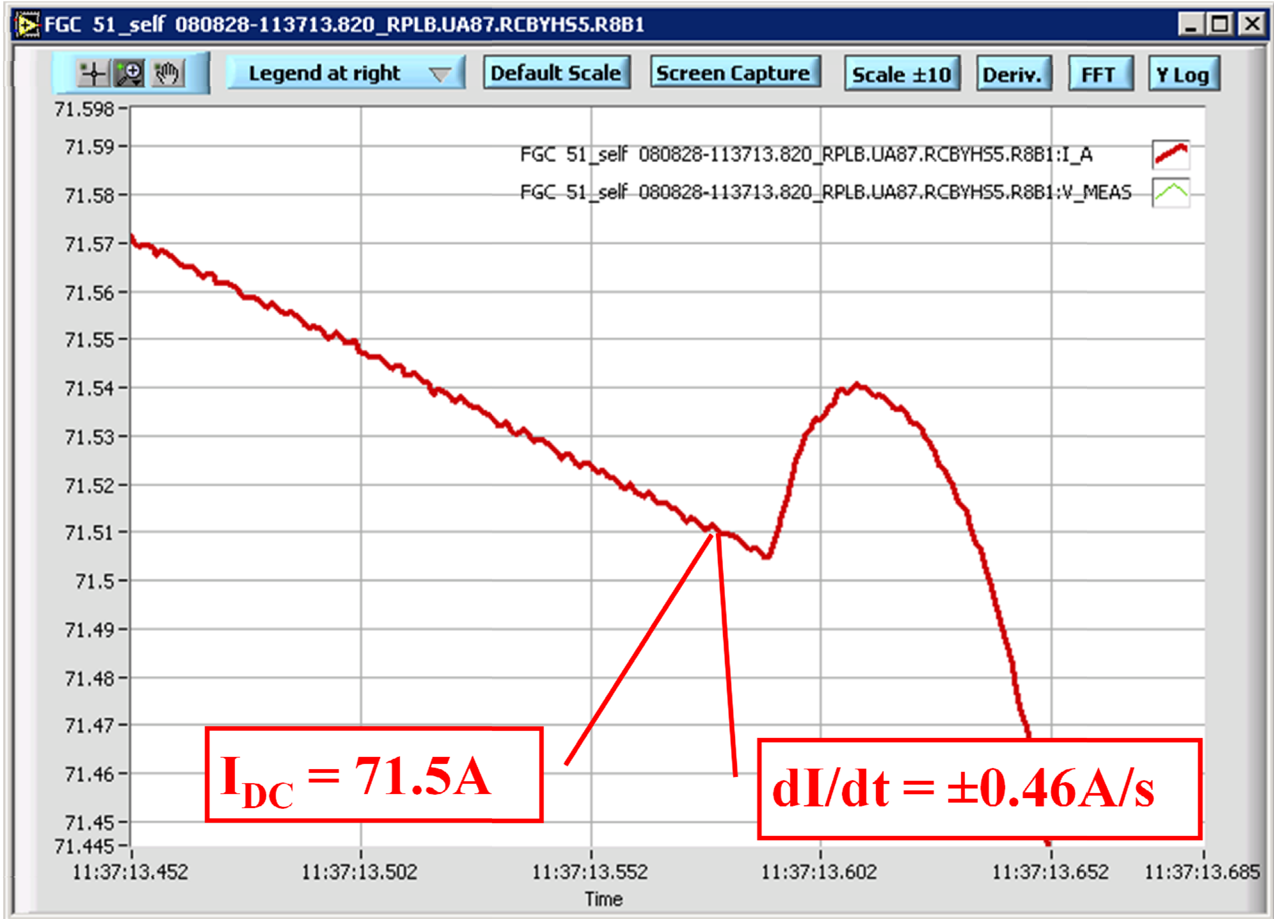

Figure 19: The current hunch

The extremely fast quench propagation mystery

The propagation of quenches has been observed regularly. After some 30 – 40 s usuall the neighboring dipole will quench due to the temperature rise in the helium.

Likewise, signals can be transported along the transmission line of magnets at a speed of about 150 µs/dipole.

The plot in figure 20 shows an example of a quench propagation time of the order of 100 ms between the three magnets each. R. H. Flora found two other cases, involving only 2 magnets. The result is plotted in figure 21. No explanation has been found so far. It is also unclear, whether this phenomenon has anything to do with the exceptionally high quench propagation, observed during the incident/accident on September 19^{th} [36, 37].

The phenomenon, which seems to happen with a ~1% probability above 7000 A (based on the observed training quenches), will also show up at high excitation. Is the propagation rate maybe even higher? Does the probability increase with excitation? An extraordinary load may wait for the cryogenics, if this is the case.

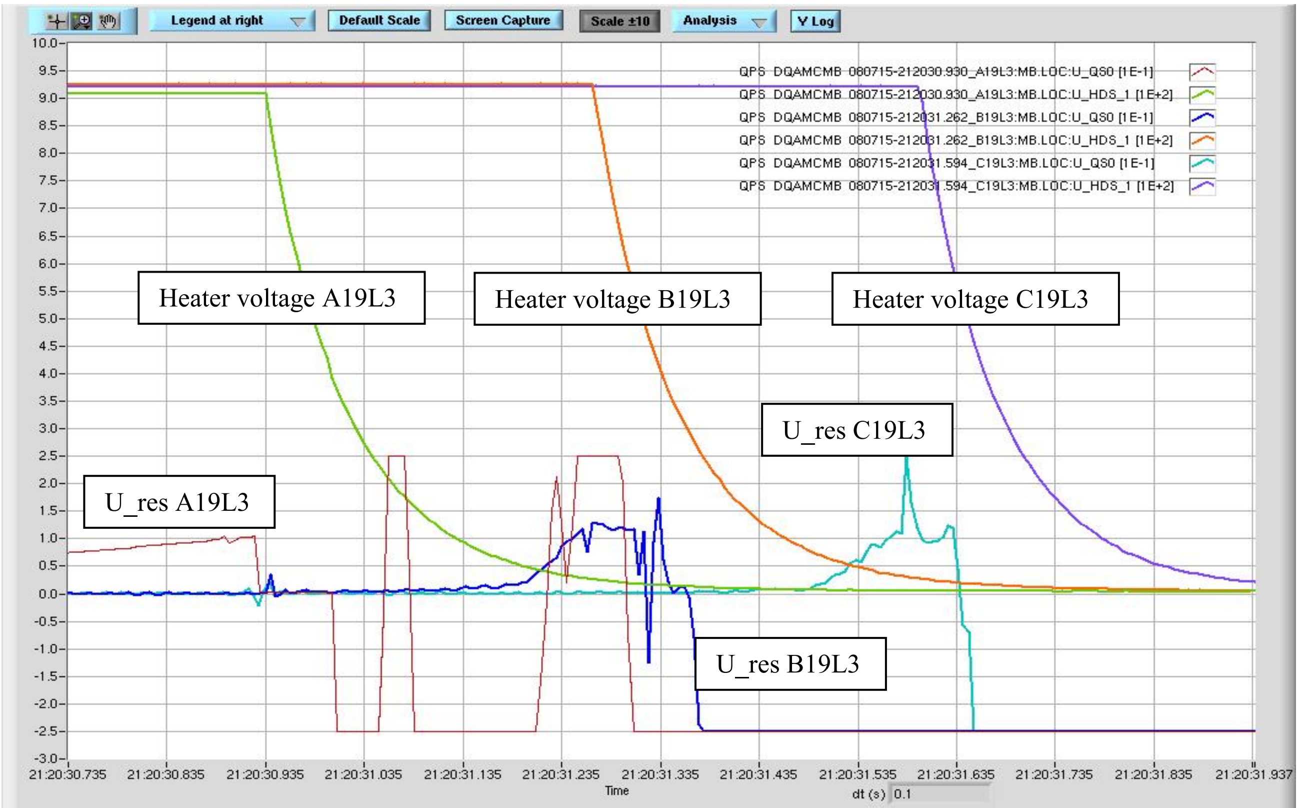

Figure 20: Three dipoles quenching at a very fast rate [35]

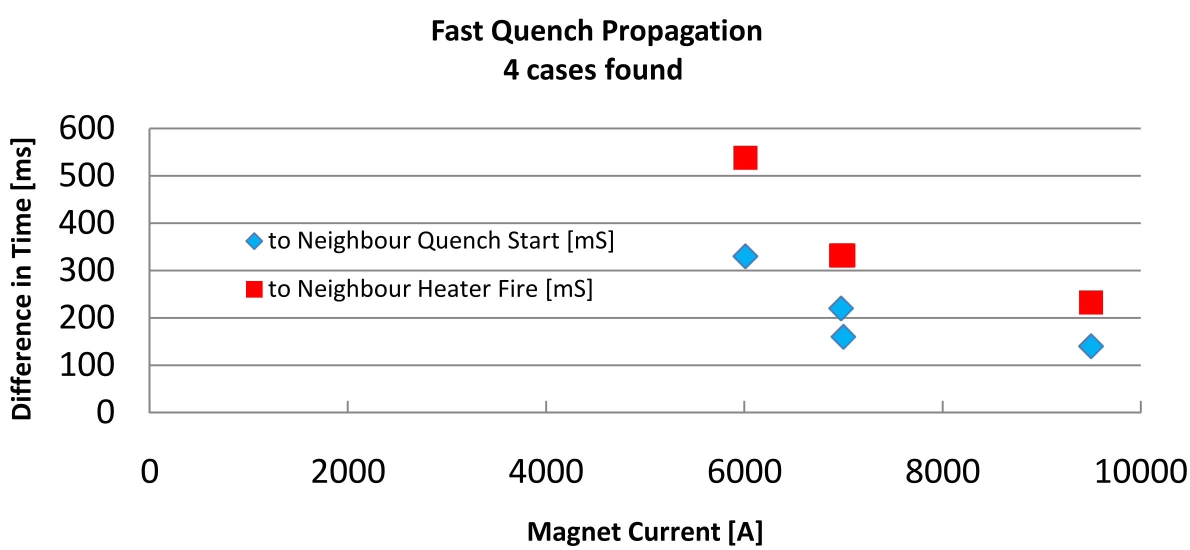

Figure 21: All fast quench propagation cases [35]

CONCLUSION AND ACKNOWLEDGEMENTS

Much has been achieved during the hardware commissioning and a lot of data has been collected by the many participants. Interesting observations have been made and in cases, where it was deemed necessary, corresponding actions have been initiated.

Nevertheless, many new discoveries are waiting for those that endeavor to sail this ocean of data. Unfortunately, there is little help for navigation. One has to prepare for a long journey, unless one remembers the exact name of the circuit and the day when a phenomenon happened. It is a pleasure to apply the well developed tools once the day and minute is found.

I have pointed out a few areas, where more data are needed to understand better, whether the observations have a harmless explanation or if something has to be improved. The next hardware commissioning should give the time for it. I also pointed at shortcomings, like the limited current change rate, which may have an impact on operation. One needs to prepare procedures.

I would like to thank all my pilots, those which are referred to in the references, and those, which contributed by refreshing the memory and discussing the issues.

I would like to thank the operation team and the hardware commissioning coordination team for the kind hospitality, the power converter crew for their precise analysis, and the quench protection team for the “homelike” atmosphere. The greatest thanks go to our American friends, with whom I had so many excited (and loud) discussions in the control room. I am sure; this will be remembered, not only by me.

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