Superconducting Electrical Circuits
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Hardware Commissioning started seriously in April 2007.

It was interrupted many times for various reasons and lasted until the D-day, in total 18 months.

The organization of the work was constantly improved and reached a very satisfactory level.
(except when I maximized the confusion)

The work was done according to ever improving procedures, prepared and polished by MPP.
Superconducting Electrical Circuits

The work was done by numerous people from many groups.

The results were obtained by the ELQA, QPS, OP, MPP, PO, Cryo, and the HC teams (somebody forgotten? Apologies!)

I’m just reporting other peoples observations, as I recall them. I added the mistakes.

This talk is about surprises and mysteries.
The greatest surprise!

It almost worked!
Other surprises

1. Known Non-Conformities (fixed)
2. Discovered Non-Conformities (now fixed ?)
3. Re-Discoveries
4. Unexpected Discoveries
Other surprises

1. Known Non-Conformities (fixed)
2. Discovered Non-Conformities (now fixed ?)
3. Re-Discoveries
4. Unexpected Discoveries

Not treated here
Other surprises

1. 

2. Discovered Non-Conformities (now fixed?)
   1. The D3, Q4, Q5 puzzle
   2. The RQT12.R3 etc puzzle
   3. The MQM5.L8 bus problem
   4. The Russian #mas present (QF45)
First Indication of Linkage between D2 & Q4

D2 Spontaneously Quenches as it approaches Nominal

50 mS later Q5 Trips due to QPS Imbalance

500 mS later Q4 Quenches but why???
The D2 was quenching when the Q4-B1 was at high value.

The Quench was likely in the part, where the power busses are in the DFBM “side-by-side”.

![Diagram](image)

**Table 2. Distribution of busbars in DFBMAs with NC**

<table>
<thead>
<tr>
<th>DFB</th>
<th>sector</th>
<th>IR</th>
<th>Cable 1</th>
<th>Cable 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFBMA.4L2</td>
<td>1-2</td>
<td>2L</td>
<td>D2A D2B Q4A</td>
<td>Q4B Q4C not used</td>
</tr>
<tr>
<td>DFBMA.4L8</td>
<td>7-8</td>
<td>8L</td>
<td>D2A D2B Q4A</td>
<td>Q4B Q4C not used</td>
</tr>
</tbody>
</table>
Once the cable where shaken into place, no quench occurred any more.

The fault is still in the LHC and may show up again, here and elsewhere.
The RQT12R3.B1 (etc) puzzle

Timeseries Chart between 2008-08-22 10:01:00 and 2008-08-22 14:01:00 (LOCAL_TIME)
Ures (red) continues to rise while the current (green) is constant. A clear sign of a quench. As this was the case for all correctors served by the outer layer of the SCL cable, it was concluded that the link does not work properly. Problem was found in a cold bridge. Fixed (?)
1. Re-Discoveries

- The Q6.R4 (and similar) puzzle
- The inner triplet current distribution puzzle
- The undulator puzzle
- The inner triplet 600A lead problem
- The RB (and similar) re-start problem after a quench
The Q6.R4 puzzle

**Negative Current? Q6.R4 asymmetric quench**

Voltage drop over current lead (~ to current)

- **Corresponds to 2000 A**
- **Centre tap @ 1600 A**
- **Corresponds to 3600 A**

**Time [s]**

DFLCS.P1.Loc.LD1:U_RES
DFLCS.P1.Loc.LD2:U_RES
DFLCS.P1.Loc.LD3:U_RES

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The Q6.R4 puzzle

Negative Current? Q6.R4 asymmetric quench

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Centre tap @ 1600 A

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Voltage drop over current lead (~ to current)

DFLCS.P1.Loc.LD1:U_RES
DFLCS.P1.Loc.LD2:U_RES
DFLCS.P1.Loc.LD3:U_RES

Lead resistance to be included

Similar but more complicated for the inner triplets
The Undulator Puzzle(s)

Circuit diagram

\[ R_{\text{in}} = 0.15 \, \Omega; \quad L(i) \text{ function of current, 1.5 H at 450 A} \]

And the other one is missing a resistor.
Different transfer functions.
Slow ramp rates!

\[ R_{\text{extr}} = 0.8 \, \Omega \]
On Jan. 30th 08 the quench protection trips, while ramping up. It turned out that a “reference magnet” had quenched in the run before. (used as representative for the whole sector to calculate the L di/dt)

**Quench Protection Reference Magnets**

<table>
<thead>
<tr>
<th>Dipoles</th>
<th>Quadrupoles</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;1-2&quot;</td>
<td>MB.C21R1 MB.C21L2</td>
</tr>
<tr>
<td>&quot;2-3&quot;</td>
<td>MB.C21R2 MB.C18L3</td>
</tr>
<tr>
<td>&quot;3-4&quot;</td>
<td>MB.C21R3 MB.C18L4</td>
</tr>
<tr>
<td>&quot;4-5&quot;</td>
<td>MB.C21R4 MB.C21L5</td>
</tr>
<tr>
<td>&quot;5-6&quot;</td>
<td>MB.C21R5 MB.C21L6</td>
</tr>
<tr>
<td>&quot;6-7&quot;</td>
<td>MB.C21R6 MB.C21L7</td>
</tr>
<tr>
<td>&quot;7-8&quot;</td>
<td>MB.C21R7 MB.C21L8</td>
</tr>
<tr>
<td>&quot;8-1&quot;</td>
<td>MB.C21R8 MB.C21L1</td>
</tr>
</tbody>
</table>

If one of the above magnets has quenched, a special procedure for repowering has to be applied. This costs extra time to recover, of course.
Other surprises

Unexpected Discoveries

• The symmetric quench problem (see Reiners talk)
  • The transient spike problem
  • The coupling Q4-D2.L8 (and similar)
  • The quench back of correctors incl. coupling
  • The RCO.A78B2 splice
• The RQT13.L5B1 splice (or what)
• The RCBCV10.L6B1 threat
• The RD2.L2 and RD3.L4 limitations
• The RCBY mystery
• The extremely fast quench propagation mystery
• ....minor issues....
The transient spike problem

- Quench detected in MB B30 (MB 1007) during fast discharge at 7000A => dI/dt = -70A/s
- There is no real quench. There is a voltage difference between the two apertures which grows with dI/dt and exceeds 100mV.
- Magnetic measurement in SM18 during ramp had also shown a different dynamic behaviour of the aperture with a unusually high sextupole in one aperture. Also no particular asymmetry between upper and lower poles.
- The behaviour in the machine seems therefore identical to the behaviour in SM18, where this magnet was trained to 12KA as usual.
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The behaviour in the machine seems therefore identical to the DG-PRJ-LHU behaviour in SM18, where this magnet was trained to 12KA as usual.
Ua + Ub, Opening EE switch at 3 kA
Ua + Ub calculated from U1, U2, U3, U4

Reconstructed inter-aperture voltage difference
Zinour’s snap-shot tool

Initial Charge [V]: 0 0 0 0
Final Charge [V]: 0 0 0 0
Time [ms]: 0 0 0 0

NQD: 0ms <-> 0ms
MAG NOT_OK: 0ms <-> 0ms

Switch Opening Time = 269ms
U_QSO: 0.097V at 265ms
Peak_res = 0.030V at 275ms

Sampling Rate = 5ms
Threshold = 100mV, Δt=10ms
Zinour’s snapshot tool

Top 10 magnets:
A16L8   3504
B17L8 – 2006
B30R7 – 1007 *
B8R7 – 1031
C28R7 – 2011
B29L8 – 1009
A15R7 – 3020
B29R7 – 1013
A21R7 – 3014
A22R7 – 1023
Zinour’s snap shot tool

Changing the threshold is potentially dangerous!!!!
Zinour’s snap shot tool

The same tool is also used to measure the Difference in resistance in the two apertures of the main magnets to a precision of ~ 10nΩ.
EM Coupling between standalone magnets

The common cabling path induces a signal in the neighbors' quench detector, which is considered as Quench. In this case the D2 was not powered. This phenomenon has been observed in several cases. Mainly a problem for cryogenics and recovery.
In the beginning the current decay is given by the external resistor. After 50 ms the quench back due to the internal bypass resistors sets in. The decay is very fast and is easily picked up on channels, which are “close by”, inducing current changes or quenches.

Basically a nuisance during commissioning but probably also a danger for extended dipole/quadr. Quenches at high excitation. Run away?

Also other transients talk to neighbors, which can lead to sudden, unforeseen current excursions. Danger for beam loss?
The voltage (red, orange) rises with the current (green) and explodes (quench) after ~4 minutes. Bad splice. How to find that one? Out of operation.
<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Time After FT (s)</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>549.9</td>
<td></td>
<td>Quench</td>
</tr>
<tr>
<td>550</td>
<td>28</td>
<td>Quench</td>
</tr>
<tr>
<td>550</td>
<td>90</td>
<td>Trip Reason? (not quench or ground fault)</td>
</tr>
</tbody>
</table>
RQT13.L5B1, RQTF.A45B2, ?

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Time after FT</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>549.9</td>
<td></td>
<td>Quench</td>
</tr>
<tr>
<td>550</td>
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</tr>
<tr>
<td>550</td>
<td>90</td>
<td>Trip Reason? (not quench or ground fault)</td>
</tr>
<tr>
<td>525</td>
<td></td>
<td>Quench</td>
</tr>
<tr>
<td>362</td>
<td></td>
<td>Quench</td>
</tr>
<tr>
<td>454A</td>
<td></td>
<td>Quench</td>
</tr>
<tr>
<td>550</td>
<td>32</td>
<td>Quench</td>
</tr>
<tr>
<td>550</td>
<td>2</td>
<td>Quench</td>
</tr>
<tr>
<td>550</td>
<td>24</td>
<td>Quench</td>
</tr>
<tr>
<td>500</td>
<td>26</td>
<td>EE Dump</td>
</tr>
</tbody>
</table>

Is there a bad splice hidden somewhere? Is reducing the nominal current enough???

*) Flat Top
On 11/03/2008, RCBCV10.L6B1 circuit was successfully qualified by ELQA team.

On 14/04/2008, AB/PO can not power this circuit, they have a fault on the PC.

On 16/04/2008, EE811 (cold voltage tap) is found open, directly from the feed through pin coming from the cover flange => NC 908215 opened.

On 05/05/2008:

Intervention to perform a time domain reflectrometry to localize precisely the defect. It is repairable if it is at the level of the cover flange.

Surprise! The voltage tap EE811 is back!
Measurements on the external « sick » orbit dipole:

<table>
<thead>
<tr>
<th>Vtap</th>
<th>Vtap</th>
<th>Resistance [Ω] *:</th>
</tr>
</thead>
<tbody>
<tr>
<td>P25_1 (EE871)</td>
<td>P25_4 (EE872)</td>
<td>0.3</td>
</tr>
<tr>
<td>P25_1 (EE871)</td>
<td>P25_2 (EE811)</td>
<td>1.9</td>
</tr>
<tr>
<td>P25_2 (EE811)</td>
<td>P25_3 (EE812)</td>
<td>0.2</td>
</tr>
<tr>
<td>P25_3 (EE812)</td>
<td>P25_4 (EE872)</td>
<td>0.4</td>
</tr>
</tbody>
</table>

For comparison, measurements on the internal dipole:

<table>
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<tr>
<th>Vtap</th>
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<th>Resistance [Ω] *:</th>
</tr>
</thead>
<tbody>
<tr>
<td>P25_5 (EE971)</td>
<td>P25_8 (EE972)</td>
<td>0.3</td>
</tr>
<tr>
<td>P25_5 (EE971)</td>
<td>P25_6 (EE911)</td>
<td>0.4</td>
</tr>
<tr>
<td>P25_6 (EE911)</td>
<td>P25_7 (EE912)</td>
<td>0.5</td>
</tr>
<tr>
<td>P25_7 (EE912)</td>
<td>P25_4 (EE972)</td>
<td>0.4</td>
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</table>

*: Measurement performed with a portable multimeter.
Measurements on the external « sick » orbit dipole:

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<td>P25_2 (EE811)</td>
<td>P25_3 (EE812)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Avoid the use, it may switch off at any time!

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<th>Resistance [Ω] *:</th>
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</tbody>
</table>

*: Measurement performed with a portable multimeter.
The RD2.L2 and RD3.L4 limitation

Looks like re/de-training. What to do?
The RD2.L2 and RD3.L4 limitation

What to do? Are there more? Quadrupoles?

150 ms !!!
So far, most of what I said is understood, now comes...
So far most of what I said is understood, now come

The Mysteries
Some 120 A magnets quench (?) at a critical di/dt, sometimes very close to nominal, during discharge

- It is ALWAYS when current goes towards 0 A
- Some magnets, which show this strange behavior also have a different transfer function, and have to be specifically trimmed for control
- High inductances (2.84 - 5.27 H)
The RCBY mystery and other strange 120 A magnets

TFM @ cold in Q4 and Q5 R8

Module [Ohm]

100000
10000
1000
100
10
1

Frequency [Hz]

1 10 100 1000

RCBYH4.R8B1
RCBYV4.R8B2 to compare
RCBYHS5.R8B1
RCBYHS5.R8B2 to compare
The RCBY mystery and other strange 120 A magnets

TFM @ cold in Q4 and Q5 R8

Phase [deg] vs Frequency [Hz]

- RCBYH4.R8B1
- RCBYV4.R8B2 to compare
- RCBYHS5.R8B1
- RCBYHS5.R8B2 to compare
The RCBY mystery and other strange 120 A magnets

Why do identical magnets have different transfer functions? What is going on?
The RCBY mystery and other strange 120 A magnets
Transp. prepared by Mirko

RCBYHS4.L5B1

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The RCBY mystery and other strange 120 A magnets
Transp. prepared by Mirko

IDC = 72A
Converter Stops, firing crowbar, then developing 7V across Magnet, then dI/dt > 1.3A/s
=> Quench

I_{DC} = -68A
dI/dt = ±1.25A/s
<table>
<thead>
<tr>
<th>Electrical circuit</th>
<th>Fault</th>
<th>Critical ramp rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPLB.RR53.RCBYHS4.L5B1</td>
<td>Cannot handle LHC di/dt</td>
<td>0.6 A/s (LHC: 0.66A/s)</td>
</tr>
<tr>
<td>RPLB.UA87.RCBYHS5.R8B1</td>
<td>Cannot handle LHC di/dt</td>
<td>0.46 A/s (LHC: 0.66A/s)</td>
</tr>
<tr>
<td>RPLB.UA87.RCBYH4.R8B1</td>
<td>Cannot handle LHC di/dt</td>
<td>0.6 A/s (LHC: 0.66A/s)</td>
</tr>
<tr>
<td>RPLB.UJ83.RCBCH7.L8B1</td>
<td>Quench @ discharge</td>
<td>&gt; 2.5 A/s (LHC: 1A/s)</td>
</tr>
<tr>
<td>RPLB.UA23.RCBYH4.L2B2</td>
<td>Quench @ discharge</td>
<td>&gt; 1.25 A/s (LHC: 0.66A/s)</td>
</tr>
<tr>
<td>RPLB.RR13.RCBCV8.L1B2</td>
<td>Quench @ discharge</td>
<td>1.2 A/s (LHC: 1A/s)</td>
</tr>
<tr>
<td>RPLB.UJ23.RCBCV7.L2B2</td>
<td>Quench @ discharge</td>
<td>&gt; 2.5A/s (LHC: 1A/s)</td>
</tr>
<tr>
<td>RPLB.UA43.RCBYV5.L4B2</td>
<td>Cannot reach nominal current</td>
<td>Rated 72 A, it cannot go higher than 65 A</td>
</tr>
</tbody>
</table>
Observations:

We have em transmission $\sim 150$ $\mu$s/dipole. This includes the spike problems. We have 30 … 40 s heat wave transmission.

We observed in a few cases times of $\sim 100$ … 200 ms.
The next mystery: very fast quench propagation

Observations:

We have transmission ~ 150 μs/dipole. This includes the spike problems.

We have observed in a few cases times of some 100 ms.

Superconducting 100 ms scale

Induced quench @ 7500 A
The next mystery: very fast quench propagation

Observations:

We have em transmission ~ 150 μs/dipole. This includes the spike problems. We have 30 … 40 s heat wave transmission

We [12] observed in 4 cases times of some 100 ms.

![Fast Quench Propagation Graph]

- 4 cases found

- Difference to Neighbour Quench Start [mS]
- Difference to Neighbour Heater Fire [mS]
The next mystery: very fast quench propagation

Observations:

- We have transmission $\sim 150 \mu s/dipole$. This includes the spike problems.

- We have $30 \ldots 40 \mathrm{ms}$ heat wave transmission.

- We observed in 4 cases times of some 100 ms.

The observed current dependence is, at least partially, due to the current & field dependence of the critical current & temperature. The data are compatible with a constant time delay between magnets + a current dependent quench development/detection.

Note that also in the event of the 19. a similar (not the same) behavior can be found. [13]

The observation was unexpected and may contain physics.

If the phenomenon is more likely at higher peak temperatures, we may expect spectacular fast quench propagation at high magnet currents.

Interesting times ahead!
• We rediscovered Ohms law.

• We rediscovered that superconductivity happens at low temperatures.

• We rediscovered Faraday’s law.

• We rediscovered Kirchhoff’s law.

• We discovered shortcomings & operational complications.

• We discovered that we have not understood everything.

  *There are more things in heaven and earth, Horatio,*
  *Than are dreamt of in your philosophy.*

• The re-commissioning will be very exciting!
Summary

• We rediscovered Ohm's law.

• We rediscovered that superconductivity happens at low temperatures.

• We rediscovered Faraday's law.

• We rediscovered Kirchhoff's law.

• We discovered shortcomings & operational complications.

• We discovered that we have not understood everything.

• The re-commissioning will be very exciting!

• A challenge again! Good luck!
References

[1] G. Kirby, Commissioning Review of Q4 D2 & Q5
[2] W. Venturini Deisolara
[3] Rob Wolf, MPP Minutes 18.6.08
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[8] S.LeNour, private communication
[10] G. d’Angelo, private communication