Operating the

LHC Superconducting Circuits

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Content

- LHC Circuit Overview
- Organisation & systems
- A look at the main dipoles
- Specifics of the other circuits
- New arrivals
Intro

• For an LHC at 7TeV and beyond
  • Requires a dipole magnetic field >8T
  • Impossible with normal conducting magnets

• Some inconveniences
  • Using NbTi requires 1.9K cryogenics
  • Huge amount of stored energy
  • Must protect the magnet if superconductivity no longer present

• Hence
  • Superconducting Magnets = Quench Protection System
## LHC superconducting circuits

<table>
<thead>
<tr>
<th>Description</th>
<th>Name</th>
<th>Circuit Qty*</th>
<th>QPS?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Dipole</td>
<td>RB</td>
<td>8</td>
<td>Y</td>
</tr>
<tr>
<td>Main Quadrupole</td>
<td>RQD, RQF</td>
<td>16</td>
<td>Y</td>
</tr>
<tr>
<td>Individually Powered Quadrupoles</td>
<td>IPQ</td>
<td>156</td>
<td>Y</td>
</tr>
<tr>
<td>Individually Powered Dipoles</td>
<td>IPD</td>
<td>16</td>
<td>Y</td>
</tr>
<tr>
<td>Inner Triplet</td>
<td>RQX</td>
<td>8+8+8 *</td>
<td>Y</td>
</tr>
<tr>
<td>Optical correctors, 600A</td>
<td>RQT.., RS.., RC.., RQS.., RO..</td>
<td>363</td>
<td>Y</td>
</tr>
<tr>
<td>IP correctors</td>
<td>RCBX..</td>
<td>48</td>
<td>Y</td>
</tr>
<tr>
<td>Orbit correctors</td>
<td>RCBH, RCBV</td>
<td>750</td>
<td></td>
</tr>
<tr>
<td>Matching Sector correctors</td>
<td>RCBC, RCBY</td>
<td>234</td>
<td></td>
</tr>
<tr>
<td>Optical correctors, 120A</td>
<td>RCO, RCSX, RCSX, RCTX</td>
<td>52</td>
<td>Y (RCO)</td>
</tr>
<tr>
<td>Undulator</td>
<td>RU</td>
<td>2</td>
<td>Y</td>
</tr>
<tr>
<td>Experiments</td>
<td>ATLAS, CMS</td>
<td>3</td>
<td>Y*</td>
</tr>
</tbody>
</table>

| 1672                               | 652        |
Powering Subsectors

- The powering subsectors are as follows:
  - Cryostat -> PIC
  - 60A circuits (Orbit Correctors) -> virtual PIC
  - Warm circuits -> WIC

LHC Powering Subsectors [https://edms.cern.ch/document/361532/1.0](https://edms.cern.ch/document/361532/1.0)
Main Dipoles

Useful links:
https://wikis.cern.ch/display/MPEEP/QPS_Main_Dipoles
https://edms.cern.ch/file/874713/5.1/LHC-MPP-HCP-0001-5-1.pdf
Main Dipoles
Main Quadrupoles

Useful links:
https://wikis.cern.ch/display/MPEEP/QPS_Main_Quadrupoles
https://edms.cern.ch/file/874714/5.1/LHC-MPP-HCP-0002-5-1.pdf
Individually Powered Dipoles

Useful links:
http://te-epc-lpc.web.cern.ch/te-epc-lpc/converters/lhc4-6-8ka-08v/general.stm
https://wikis.cern.ch/display/MPEEP/QPS_Individual_Dipol_Quadrupol
Individually Powered Quadrupoles

- Up to 6kA
- Small magnet chains

Useful links:
http://te-epc-lpc.web.cern.ch/te-epc-lpc/converters/lhc4-6-8ka-08v/general.stm
https://wikis.cern.ch/display/MPEEP/QPS_Individual_Dipol_Quadrupol
https://edms.cern.ch/edmsui/file/874884/3.0/LHC-MPP-HCP-0009-3-0.pdf
Inner Triplet

Triplet at IP1 and 5 (IP2 and 8 are similar)

Useful links:
http://te-epc-lpc.web.cern.ch/te-epc-lpc/converters/lhc_inner_triplets/general.stm
https://wikis.cern.ch/display/MPEEP/QPS_Inner_Triplets
https://edms.cern.ch/document/926739/1.0 (inhibit discharge request)
600A circuits

Useful links:
http://te-epc-lpc.web.cern.ch/te-epc-lpc/converters/lhc600a-10v/general.stm
https://wikis.cern.ch/display/MPEEP/QPS_Correctors
120A and 60A circuits

Useful links:
http://te-epc-lpc.web.cern.ch/te-epc-lpc/converters/lhc60a-8v/general.stm
http://te-epc-lpc.web.cern.ch/te-epc-lpc/converters/lhc120a-10v/general.stm
https://wikis.cern.ch/display/MPEEP/QPS_Correctors
What’s important about these circuits anyway?

Fault Duration = Integrated time logged for fault

Machine Downtime = Corrects for parallelism

Root Cause Duration = Corrects for dependencies parent / child / shadow
The magnet interlock system view

Converter states
‘PC Interlock’
‘QPS OK’
...

Circuit OK?
1. Cryo ready
2. No quench
3. No PC fault
4. No AUG

Circuit OK?
1. No PC fault
2. No magnet fault

for each point

for each powering subsector

FMCM @ IR1, 3, 5, 7

Beam Permitted

for each point

BIC

SIS

PIC

WIC

Beam Permitted
A circuit analysis method

- Beams gone
  - Check BIS for culprit
- If PIC
Understanding what’s going on

- ‘Circuit synoptic’ for superconducting circuits
- Organised by powering subsectors
Circuit synoptic: main dipoles

- Quench protection
- Current leads
- Global Detector
- Energy extraction
- PIC status
- Power converter status
- Cryo status
Circuit synoptic: main dipoles

Quench heater charge status
>800V = OK

Prepare/enter/cancel Test Mode
Used during HWC

Select A or B for QPS_OK if stuck
Reset is rarely used (use Macro)
Circuit synoptic: main dipoles

nQPS status
Circuit synoptic: main dipoles

Dump resistor temperature


Fast Abort when quench loop open

Manual switch closing

Reset

Dump resistor temperature <80 degC = OK for powering
Circuit synoptic: main dipoles

All signals are hardwired except QPS_OK
PVSS signal

Typical Sequence
1. Verify no Global interlock is pending
2. Close EE systems (if existing) and re-arm QPS
3. Unlatch Interlocks (SIGNAL Init)
4. Clear PC faults
5. -> Circuit ready for powering
Circuit synoptic: main dipoles

Typical Sequence

6. Verify no Start-up interlock is pending
7. If circuit ‘ready to permit’
8. Give Permit
Additional tools: history buffer

- PIC (and WIC) history buffer can be a useful tool to determine which system triggered first
  - Choose time and filter values as appropriate
Events: main dipoles

- In general covered by [https://twiki.cern.ch/twiki/bin/view/MP3/MP3-OP](https://twiki.cern.ch/twiki/bin/view/MP3/MP3-OP)
- Recovering the circuit after a quench or circuit fault
  - Reset the nQPS when data has been analysed
  - Use QPS Expert Tool to run macro ‘nQPS_Power_reset_xx.java’
  - Run sequence ‘Prepare circuits in SectorXX for powering’

- Special cases that need care:
  - Power converter failure
    - The current will decay very slowly in the Free Wheel Thyristor (many hours)
    - The EPC piquet has detailed instructions how to restart the power converter if the fault can be reset eg here

- Note:
  - The entire subsector will turn off when a main RB/RQ/IPQ circuit trips
  - When a sub-sector is OFF, always good to check for hidden faults in the red sea…
Interlocking

Hardware Interlock Interface  https://edms.cern.ch/document/368927/3.0

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Main Dipoles

Odd points

Even points

Quench loop

Discharge loop

Quench detection

Powering Interlock Controller

Power Converter

CERN

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Main Quadrupoles
Individually Powered Quadrupoles
IPQ and coupling

This following graph shown the operating area when:

\[
\frac{dI}{dt} < 0 \quad \frac{dI}{dt} = 0 \quad \frac{dI}{dt} > 0
\]

https://edms.cern.ch/document/1231467/1
Individually Powered Dipoles

30 March 2017

OP Lectures: LHC Circuits
600A circuits
Events: 600A circuits

- In the event of a 600A QPS controller crashing
  - Use the QPS ‘swisstool’ and select desired circuits
  - Note that a controller is common for up to four circuits
  - Make sure they are all OFF!
  - Then power cycle crate
Inner Triplet

\[ I_{Q1} = I_{RQX} + I_{RTQX1} \]
\[ I_{Q2} = I_{RQX} + I_{RTQX2} \]
\[ I_{Q3} = I_{RQX} \]
For the future…

- Include feedback and 2017 HWC experience
- Circuits and access
  - EIS
  - Threshold currents and sectors
- Circuits and SIS
## LHC warm circuits

<table>
<thead>
<tr>
<th>Description</th>
<th>Name</th>
<th>Circuit Qty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Septa</td>
<td>RMSI</td>
<td>2</td>
</tr>
<tr>
<td>Dump septum</td>
<td>RMSD</td>
<td>2</td>
</tr>
<tr>
<td>Warm Quads</td>
<td>RQ4.LR3 (LR7), RQ5.LR3 (LR7)</td>
<td>4</td>
</tr>
<tr>
<td>Separation Dipole</td>
<td>RD1.LR1, RD1.LR5, RD34.LR3, RD34.LR7</td>
<td>4</td>
</tr>
<tr>
<td>Warm Circuits 600A</td>
<td>RQT4.L(R)3(7), RQT5.L(R)3(7), RCBW</td>
<td>24</td>
</tr>
<tr>
<td>Experiments</td>
<td>ALICE (RBAWV, RXSOL), LHCb (RBXWH)</td>
<td>3</td>
</tr>
<tr>
<td>LHCb compensators</td>
<td>RBXWSH, RBLWH</td>
<td>3</td>
</tr>
<tr>
<td>ALICE compensators</td>
<td>RBWMDV, RBXWTV</td>
<td>3</td>
</tr>
<tr>
<td>Gas monitoring in IR4</td>
<td>RGMW</td>
<td>4</td>
</tr>
<tr>
<td>Collimator Wire @ IR5</td>
<td>RBBCW</td>
<td>2</td>
</tr>
</tbody>
</table>

**Total Circuits:** 51
New arrivals: RD1 and RD34

Integration (front side)

- Should lead to reduced FMCM events
- Parameters same as for previous power converter
- New electronics control (FGC Class 61)
- Injector technology is coming to the LHC 😊
New arrivals: FGClite

https://indico.cern.ch/event/543104/
https://edms.cern.ch/document/1739691
The SVC

- Static Var Compensator
  - Present at points 2, 4, 6, 8
  - If one SVC trip occurs, generally not critical to restart immediately
  - All interventions are coordinated by TI-OP
  - Involves EN-EL and TE-EPC
  - Must not be beam in the machine
  - Discussion ongoing whether circuits should be OFF or at low current/injection
Links

- MPE wiki https://wikis.cern.ch/display/MPEEP/Home
- MP3 https://twiki.cern.ch/twiki/bin/view/MP3/WebHome
- MP3 OP: https://twiki.cern.ch/twiki/bin/view/MP3/MP3-OP


- Power converters: EPC piquet
- QPS, PIC, WIC : MPE piquet
- Magnet analysis: MP3 best-effort
Conclusion

• The LHC has a large and complex magnet powering system
  • Some background and reminders provided for understanding and operation
  • Intention is to update this presentation based on 2017 commissioning experience
  • Comments and feedback welcome to make the information pertinent to all
Powering categories

Magnet current operation

Power converter type

1-Quadrant mode

2-Quadrant mode

4-Quadrant mode

In quadrant 2 and 4, the magnet stored energy returns to the power converter.