Commissioning of the LHC superconducting magnets systems:

Why an LHC Hardware Commissioning?

Specificity and complexity of this machine

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The prototype test String 2
**1. After the qualification for operation of the individual systems** of a sector (vacuum, cryogenics, quench protection, interlocks, powering, etc.), system owners define and carry-out what tests and how they are performed. This includes:

- The procedures and the sequence
- What conditions are required to start
- What conditions determine it is finished
- What conditions are required during the tests

Hardware Commissioning Coordination ensures that the conditions required exist.

**2. Each sector will be commissioned as a whole up to the powering to nominal current of all the circuits.** System Owners define and carry-out what tests and how they are performed. This includes:

- The procedures and the sequence
- What conditions are required to start
- What conditions determine it is finished
- What conditions are required during the tests

Hardware Commissioning Coordination with System Owners define and carry-out and ensures that the conditions required exist.

**3. Validation and specific studies will be carried-out on the first commissioned sector.**
commissioning the superconducting circuits
The LHC is composed of:
- eight cryogenically independent sectors
- fed from four feed points
The LHC is composed of:
- eight electrically independent sectors
- each fed from an UA, an RR, a UJ, and sometimes a USC
the circuits of a sector of LHC

POWERING PROEDURE AND ACCEPTANCE CRITERIA FOR THE 13 KA DIPOLE CIRCUITS

Abstract

This document describes the test procedure and the acceptance parameters applicable for the 13 KA dipole circuits. All of the parameters are required during the state & given as well as the required documents to validate each test.

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Philippe Lebrun
Karl Herbert Hess

157 circuits
6 circuits
Totalling 190 circuits
the electrical subsectors of an LHC sector
the superconducting magnets

<table>
<thead>
<tr>
<th>X</th>
<th>R5</th>
<th>L</th>
<th>R5</th>
<th>A</th>
<th>S</th>
<th>6</th>
<th>M</th>
<th>L</th>
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<tbody>
<tr>
<td>IT</td>
<td>600A</td>
<td>600A</td>
<td>IPQ</td>
<td>IPD</td>
<td>120A</td>
<td>120A</td>
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<td>1</td>
<td>14</td>
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The arc: Most of a sector is composed of 154 dipoles and 40 quadrupoles which are in series: dipoles in series & quads in series operate at 1.9 K the dipoles have a huge inductance 16H contain families of correctors in series dipole correctors

The matching sections: small subsectors operating at 4.5K often standalone magnets very special - often unique - magnets

The inner triplet: composed of very high gradient quadrupoles and a dipole which operate at 1.9K contains a complex electrical circuit with nested converters

All coupled via the headers in the cryogenic distribution line

Any repair or exchange of a component has an impact on the whole sector
The dipole circuit

154 dipoles
Circuit inductance 16 H
Energy stored at nominal current (11.850 A) is 1.12 GJ per sector

The large magnetic energy (1.12 GJ) stored in the magnets of one sector (2.5 x Hera) requires extremely reliable systems to detect failures and safely dump the energy in a controlled way.
The quench detection system

Magnets

\[ U_{\text{res}} = U_1 + U_2 \]

Threshold is 100 mV during 10 ms

\[ U_{\text{mag}_A} + U_{\text{mag}_B} \]

The current leads

Typical resistance 7 \( \mu\Omega \)

Threshold is 3 mV during 1 s

\[ U = R \times I \]

Bus

\[ U_{\text{res}} = U_{\text{bb}_1} + U_{\text{bb}_2} - \frac{N}{2} (U_{\text{mag}_A} + U_{\text{mag}_B})/2 \]

Threshold is 1 V during 1 s

Quench detectors

Current leads

Local on each dipole

Global detectors on the bus bars
what needs to be tested for the cryogenic system

Cryogenic plants of unprecedented capacity (18 kW at 4.5 K) and including main components at the frontier of today’s technology (cold compressors for the 1.8 K refrigeration unit)

- Full scale validation of cooling scheme (cool down and warm ups, quench recovery, redundancy)
- Cryogenic circuit integrity
- DFB & CL
- Instrumentation
- Leak tightness
- Insulation vacuum
- Commissioning of the complete cryogenic system
the cooling scheme

saturated He II, flowing

pressurized He II, static

heat exchanger tube

magnet

sc bus bar connection

vacuum vessel

helium vessel
Helium II in the LHC

![Graph showing the phase diagram of helium](image)

- SOLID
- CRITICAL POINT
- Pressurized He II
- λ line
- Saturated He II
- GAS

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what needs to be tested for the power converters

- Regulation loop
- Free-wheel system at nominal current with high time constant
- Compatibility with QPS at start up
- Tracking
- Inner triplet

Power converters with unprecedented precision (a few ppm) over a very large dynamic range ($10^4$)
### the superconducting circuits: the inventory

<table>
<thead>
<tr>
<th>Circuit Type</th>
<th>Sector 1-2</th>
<th>Sector 2-3</th>
<th>Sector 3-4</th>
<th>Sector 4-5</th>
<th>Sector 5-6</th>
<th>Sector 6-7</th>
<th>Sector 7-8</th>
<th>Sector 8-1</th>
<th>LHC</th>
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<tr>
<td>13 kA</td>
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<td>600A with Energy Extraction</td>
<td>23</td>
<td>27</td>
<td>28</td>
<td>24</td>
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<td>600A Energy Extraction in Converter</td>
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<td>20</td>
<td>20</td>
<td>14</td>
<td>20</td>
<td>20</td>
<td>14</td>
<td></td>
<td>136</td>
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<tr>
<td>600A no Energy Extraction</td>
<td>16</td>
<td>9</td>
<td>2</td>
<td>9</td>
<td>9</td>
<td>2</td>
<td>9</td>
<td>16</td>
<td>72</td>
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<td>80-120A Correctors</td>
<td>50</td>
<td>37</td>
<td>22</td>
<td>33</td>
<td>33</td>
<td>22</td>
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<td>50</td>
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<td><strong>TOTAL</strong></td>
<td><strong>123</strong></td>
<td><strong>105</strong></td>
<td><strong>83</strong></td>
<td><strong>99</strong></td>
<td><strong>95</strong></td>
<td><strong>79</strong></td>
<td><strong>105</strong></td>
<td><strong>123</strong></td>
<td><strong>812</strong></td>
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</table>

**Circuit Type**

<table>
<thead>
<tr>
<th>60A Closed Orbit Correctors</th>
<th>Sector 1-2</th>
<th>Sector 2-3</th>
<th>Sector 3-4</th>
<th>Sector 4-5</th>
<th>Sector 5-6</th>
<th>Sector 6-7</th>
<th>Sector 7-8</th>
<th>Sector 8-1</th>
<th>LHC</th>
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<td>94</td>
<td>94</td>
<td>94</td>
<td>94</td>
<td>752</td>
</tr>
</tbody>
</table>
the methodology

- Test of power converters connected to the DC cables in short circuit, including controls for powering, ramp, monitoring
- Interlock tests of a powering subsector prior and after connection of the power cables to the DFB leads
- Commissioning of the electrical circuits one by one or in groups at low, intermediate and nominal currents
- Commissioning of all the electrical circuits of the sector powered in unison to nominal current with nominal ramp rates
- Individual System Tests of Powering Interlock Control
- Individual System Tests of the Quench Protection and Energy Extraction Systems
- Post-Mortem System tests
- Electrical Quality Assurance

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the methodology for the test procedures & automation of procedures and analysis

The objectives are:

1. the validation of the protection strategies under the different failure scenarios and
2. the evaluation of the behavior and of the performance of
   - the magnet chain,
   - the current leads and
   - the power converters during a normal LHC ramp, in steady state and during a ramp down of the current.
the methodology for the test procedures & automation of procedures and analysis
the methodology for the test procedures & automation of procedures and analysis
automation of procedures

Approved and reproducible test sequences
Assistance to operators
Automatic recording of test results
computer assisted analysis
Automated recording but also manual data entry
Provides data for analysis tools
Ensures perennity of data
real-time follow up of tests

<p>| | | | | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>RQ4.R5</td>
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<td>14/15 (93%)</td>
<td>PNO.64</td>
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<tr>
<td>RQ5.L6</td>
<td>FNO.64</td>
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<td>RQ5.R5</td>
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<td>14/15 (93%)</td>
<td>PNO.64</td>
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</tr>
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<td>14/15 (93%)</td>
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<td>14/15 (93%)</td>
<td>PNO.64</td>
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<tr>
<td>RQ8.L6</td>
<td>FNO.64</td>
<td>14/15 (93%)</td>
<td>PNO.64</td>
<td>Y</td>
</tr>
<tr>
<td>RQ8.R5</td>
<td>FNO.64</td>
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<td>PNO.64</td>
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<tr>
<td>RQ9.L6</td>
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<td>14/15 (93%)</td>
<td>PNO.64</td>
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<tr>
<td>RQ9.R5</td>
<td>FNO.64</td>
<td>14/15 (93%)</td>
<td>PNO.64</td>
<td>Y</td>
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<tr>
<td>RXQ.R6</td>
<td>FNO.d11</td>
<td>21/33 (65%)</td>
<td>PNO.d11</td>
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</tr>
<tr>
<td>RBA.56</td>
<td>FNO.b2</td>
<td>21/22 (95%)</td>
<td>PNO.b2</td>
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<tr>
<td>RQD.A6</td>
<td>FNO.b2</td>
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<td>PNO.b3</td>
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<tr>
<td>RQF.A6</td>
<td>FNO.b2</td>
<td>17/19 (89%)</td>
<td>PNO.b3</td>
<td>Y</td>
</tr>
</tbody>
</table>

standard technologies

Normal AC distribution

UPS AC distribution

Demineralized water

Ventilation

Networks

UPS for all converters above 4 kA

UA, UJ, RR, USC

DCCT

Water

Controls equipment

DFB with current leads

Tunnel, UJ

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the short circuit tests

15 underground areas
the short circuit tests

- Ventilation
- Cooling water
- AC distribution
- Power converter
- Energy extraction system
- Powering interlock controller
- DC cables
- Networks
- Fieldbuses
- Gateways
the short circuit tests

Measurement of ambient air temperature close to the electronics racks

UA67

Vacuum Cryogenics Beam diagnostics
Beam dumping system and Power Converters
Electrical Substation
MS Power Converters
Power Cables
Beam dumping system
MS Power Converters

Addition of ventilation ducts and of local ventilation units
the short circuit tests

Measurement of cable temperature during the 24-hour run
support to operation: infrastructure systems

Before global commissioning of complex/large systems can start

- the individual commissioning of the infrastructure systems is carried out
- tuning with the load is carried out
- heat runs are carried out
- performance is measured and recorded
- frequent and multiple adjustments are carried out
- performance is monitored throughout the commissioning
- surprises are often encountered
Access safety and control systems

• The LHC access system was commissioned during the first week of January 2008 by a joint team in collaboration with the supplier’s team.

• From early April access to the LHC is possible with dosimeter and biometric control.

• All the sectors in Hardware Commissioning today make use of the system.

We want to ensure that people who do not need to be there cannot access the sector be sure that nobody is in there during the first cool down and the first warm up as well as when we power a sector learn how to use the system commission the system.
coupling and interdependencies of the systems

- complexity for the diagnostics
  - quantity of signals spread over different systems
  - variety of instrumentation (voltage taps, current sensors, heaters, cryogenic instrumentation, etc.)

- interdependency for safe operation
  - interlocks,
  - QPS,
  - PCs
  - but also cooling, ventilation, AC distribution - normal, UPS, safety network
interdependencies of the systems
Geographical distribution

Odd point

MP Storage

1.8 K Refrigeration Unit
Warm Compressor Station
Cold Box

New 4.5 K Refrigerator
Warm Compressor Station
Cold Box

3'000 m

Surface

Existent 4.5 K Refrigerator
Warm Compressor Station
Upper Cold Box
Lower Cold Box

1.8 K Refrigeration Unit
Warm Compressor Station
Cold Box

Odd point

MP Storage

Even point

MP Storage

Cryogenic Distribution Line (QRL)
Magnet Cryostate, DFB, ACS

Interconnection Box (QUI)

50 m x 50 m
up to 100 m
30 m x 30 m

3'000 m
Software for operation, controls and diagnostics

Using the final software foreseen for operation for the commissioning of the machine systems
- Sequencer
- Logging system
- Post mortem system
- On-line databases
- Industrial supervision systems

Dry runs

1. Injection kickers system
2. LHC Beam dumping system (kickers, energy tracking, diagnostics,)
3. Beam instrumentation (loss monitors, position monitors, current transformers, screens)
4. Power converters in simulation mode
5. Collimators
6. Timing system
7. Communication with experiments (handshakes, modes, fill number, beam based measurements, etc.)
8. Post mortem data acquisition system
9. Squeeze
... in summary

- Technologies at or beyond the start of the art
  - Superconducting magnets operating close to the limit of the load line
  - Cryogenic plants of unprecedented capacity (18kW at 4.5K) and including main components at the frontier of today’s technology (cold compressors at 1.8K)
  - Power converters with unprecedented precision (a few ppm) over a very large dynamic range ($10^4$)
  - Each sector stores a large magnetic energy (1.2 GJoule) in the magnets (2.5 x Hera) and therefore requires extremely reliable systems to detect quenches and safely dump the energy in a controlled way
- High tech components in industrial quantities (1800 circuits, large circuits 154 dipoles, 16 H, 12kA) which justifies
  - methodology for test procedures,
  - automation of procedures and analysis
  - quality control
... in summary

• **Standard technologies**
  – in infrastructure systems (electrical, ventilation, water cooling, networks, fieldbuses, control infrastructures, etc.)
  – in large quantities,
  – various types and
  – stretching over large distances

• **Coupling and interdependencies of the systems**
  – complexity for the diagnostics (quantity of signals, spread over different systems) & instrumentation (voltage taps, current sensors, heaters, flow meters, cryogenic instrumentation, etc.)
  – interdependency for safe operation (interlocks, QPS, PCs but also cooling, ventilation, AC distribution - normal, UPS, safety network)

• **Geographical distribution which**
  – extends the size of the installation (e.g. cryogenics: surface buildings 50 x 50 m, shafts 100 m deep, tunnel 2 x 3 km long)
the superconducting circuits but also all the other systems
… where are we today
cool down status
... where are we today

cool down status

<table>
<thead>
<tr>
<th>Sector</th>
<th>Average $T$ [K]</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>300</td>
<td>Flushing</td>
</tr>
<tr>
<td>23</td>
<td>22</td>
<td>Cool down</td>
</tr>
<tr>
<td>34</td>
<td>177</td>
<td>Cool down</td>
</tr>
<tr>
<td>45</td>
<td>300</td>
<td>Commissioned to 5 TeV except for the triplet&lt;br&gt;Inner triplet now connected&lt;br&gt;Consolidation complete&lt;br&gt;Cool down starts in two weeks</td>
</tr>
<tr>
<td>56</td>
<td>2</td>
<td>Fully commissioned to 5 TeV&lt;br&gt;Dipoles and quadrupoles being trained to 7 TeV</td>
</tr>
<tr>
<td>67</td>
<td>25</td>
<td>Cool down</td>
</tr>
<tr>
<td>78</td>
<td>2</td>
<td>Partially tested in June 2007&lt;br&gt;Inner triplet connected&lt;br&gt;Powering tests start tomorrow</td>
</tr>
<tr>
<td>81</td>
<td>2</td>
<td>Powering tests start in one week</td>
</tr>
</tbody>
</table>
... where are we today
powering tests of sector 56

Training campaign on the dipoles starts
Powering Groups of Circuits

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A strategy, where the initial beam energy is at least 5 TeV, is proposed to gain time with the training of magnets and meet the summer deadline.

The fact that we can easily reach that energy level has been proven both in Sector 45 and Sector 56.

Nevertheless, we have started a quench campaign on the dipoles of Sector 56 to find out how much time we will need to get to 7 TeV.

<table>
<thead>
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<tbody>
<tr>
<td>10004</td>
<td>5.91</td>
<td>3362 (A28L6) - 2245 (B29R5)</td>
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<td>6.12</td>
<td>3372 (A23L6)</td>
<td>29/04/08</td>
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<td>6.23</td>
<td>3188 (A15R5)</td>
<td>30/04/08</td>
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<td>3368 (C32R5)</td>
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