LHC Commissioning and First Operation

The LHC hardware and beam commissioning and initial operation will be reviewed both in terms of beam and hardware performance. The implemented machine protection measures and their impact on LHC operation will be presented.

IPAC10, May 2010, Kyoto, Japan

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Director for Accelerators and Technology,
CERN Geneva
(On behalf of the LHC team and international collaborators)
Topics

- The LHC
- The Accident
- The Repair and consolidation
- Initial Commissioning
- Present status and plans
Superconducting Proton Accelerator and Collider
installed in a 27km circumference underground tunnel (tunnel cross-section diameter 4m) at CERN
Tunnel was built for LEP collider in 1985
## LHC: Some Technical Challenges

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Circumference (km)</strong></td>
<td>26.7</td>
<td>100-150m underground</td>
</tr>
<tr>
<td><strong>Number of superconducting twin-bore Dipoles</strong></td>
<td>1232</td>
<td>Cable Nb-Ti, cold mass 37million kg</td>
</tr>
<tr>
<td><strong>Length of Dipole (m)</strong></td>
<td>14.3</td>
<td></td>
</tr>
<tr>
<td><strong>Dipole Field Strength (Tesla)</strong></td>
<td>8.4</td>
<td>Results from the high beam energy needed</td>
</tr>
<tr>
<td><strong>Operating Temperature (K) (cryogenics system)</strong></td>
<td>1.9</td>
<td>Superconducting magnets needed for the high magnetic field</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Super-fluid helium</td>
</tr>
<tr>
<td><strong>Current in dipole sc coils (A)</strong></td>
<td>13000</td>
<td>Results from the high magnetic field</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1ppm resolution</td>
</tr>
<tr>
<td><strong>Beam Intensity (A)</strong></td>
<td>0.5</td>
<td>2.2.10^-6 loss causes quench</td>
</tr>
<tr>
<td><strong>Beam Stored Energy (MJoules)</strong></td>
<td>362</td>
<td>Results from high beam energy and high beam current</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1MJ melts 1.5kg Cu</td>
</tr>
<tr>
<td><strong>Magnet Stored Energy (MJoules)/octant</strong></td>
<td>1100</td>
<td>Results from the high magnetic field</td>
</tr>
<tr>
<td><strong>Sector Powering Circuit</strong></td>
<td>8</td>
<td>1612 different electrical circuits</td>
</tr>
</tbody>
</table>
LHC dipoles (1232 of them) operating at 1.9K

Contracts by 4.7cm during cool-down
Helium distribution line (THXRA01 Serge Claudet)

A temperature of around -271°C
or
1.9 degrees above absolute zero
Magnets
During cool-down of the LHC the machine contracts by **80 metres, 10m per octant**

- Vacuum continuity
- Electrical connections
The LHC

The Accident

The Repair and consolidation

Initial Commissioning

Present status and plans
Accident of September 19th 2008

- Following a very impressive start-up with beam on September 10, 2008
  - During a few days period without beam
  - Making the last step of dipole circuit in sector 34, to 9.3kA
  - At 8.7kA, development of resistive zone in the dipole bus bar splice between Q24 R3 and the neighbouring dipole
  - Electrical arc developed which punctured the helium enclosure
Absence of soldering

Resistance 220 nOhm

Bad contact with stabilizer

No sensitive detection on bus bar

Electro-thermal model

Thermal runaway

Meltdown, open circuit

Electrical arc

Power converter fast discharge

Observed on magnet
Fault tree [2/3]

- Electrical arc
  - He vessel perforation
  - Beam pipe perforation
  - Soot
    - He discharge in insulation vacuum
      - Inadequate sizing of relief devices (MCI)
        - Pressurization of vacuum enclosures
      - Loss of beam vacuum
        - Loss of beam vacuum
        - Contamination by soot
      - Blast
        - Trip AUG
        - ODH in tunnel
          - Mechanical damage to MLI
            - Contamination by MLI
      - Contamination by soot
        - Break vent door
          - Contamination by MLI
Fault tree [3/3]

Pressurization of vacuum enclosures

- Pressure forces on vacuum barriers
- Plastic deformation of shells
- Buckling of bellows

Rupture of supports and ground anchors

- Displacement of magnets
- Damage to tunnel floor
- Secondary electrical arcs

Mechanical damage to interconnects

*Used to estimate max pressure reached*
Consequences
Electrical arc between C24 and Q24
Collateral damage: secondary arcs

QBBI.B31R3 M3 line

QQBI.27R3 M3 line
The LHC

Initial turn on in September 2008

The Accident

The Repair and consolidation

Initial Commissioning

Present status and plans

This was NOT a good time for us!!
The LHC repairs in detail

1. 14 quadrupole magnets replaced
2. 39 dipole magnets replaced
3. 54 electrical interconnections fully repaired. 150 more needing only partial repairs
4. Over 4 km of vacuum beam tube cleaned
5. A new longitudinal restraining system is being fitted to 50 quadrupole magnets
6. Nearly 900 new helium pressure release ports are being installed around the machine
7. 6500 new detectors are being added to the magnet protection system, requiring 250 km of cables to be laid

+ 8 cryogenics!
Magnet protection and anchoring

- DN200 on dipoles 732/1344 installed
- DN200 on ITs 24/24 installed
- DN160 on SAM 92/96 installed
- SSS anchoring 104/104 installed
The LHC

Initial turn on in September 2008

The Accident

The Repair and consolidation

- Hardware commissioning and preparation for operation

Initial Commissioning

Present status and plans
Pyramid for Splice Mapping

Maya Pyramid

MOPEB044, Koratzinos et al
MOPEB045, Solfaroli et al
MOPEB046, Siemko et al

Current in the Dipoles as function of time
Splice Mapping of Quadrupoles
A78.RB: Normalized Bus Segment Resistance

Every single sc splice were measured in 2009.
<table>
<thead>
<tr>
<th>Date</th>
<th>Day</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 20</td>
<td>1</td>
<td>Each beam circulating. Key beam instrumentation working.</td>
</tr>
<tr>
<td>Nov 23</td>
<td>4</td>
<td>First collisions at 450 GeV. First ramp (reached 560 GeV).</td>
</tr>
<tr>
<td>Nov 26</td>
<td>7</td>
<td>Magnetic cycling established (reproducibility).</td>
</tr>
<tr>
<td>Nov 27</td>
<td>8</td>
<td>Energy matching.</td>
</tr>
<tr>
<td>Nov 29</td>
<td>10</td>
<td>Ramp to 1.18 TeV.</td>
</tr>
<tr>
<td>Nov 30</td>
<td>11</td>
<td>Experiment solenoids on.</td>
</tr>
<tr>
<td>Dec 04</td>
<td>15</td>
<td>Aperture measurement campaign finished. LHCb and ALICE dipoles on.</td>
</tr>
<tr>
<td>Dec 05</td>
<td>16</td>
<td>Machine protection (Injection, Beam dump, Collimators) ready for safe operation with pilots.</td>
</tr>
<tr>
<td>Dec 06</td>
<td>17</td>
<td>First collisions with STABLE BEAMS, 4 on 4 pilots at 450 GeV, rates around 1Hz.</td>
</tr>
<tr>
<td>Dec 08</td>
<td>19</td>
<td>Ramp colliding bunches to 1.18 TeV.</td>
</tr>
<tr>
<td>Dec 11</td>
<td>22</td>
<td>Collisions with STABLE BEAMS, 4 on 4 at 450 GeV, &gt; $10^{10}$ per bunch, rates around 10Hz.</td>
</tr>
<tr>
<td>Dec 13</td>
<td>24</td>
<td>Ramp 2 bunches per beam to 1.18 TeV. Collisions for 90mins.</td>
</tr>
<tr>
<td>Dec 14</td>
<td>25</td>
<td>Collisions with STABLE BEAMS, 16 on 16 at 450 GeV, &gt; $10^{10}$ per bunch, rates around 50Hz.</td>
</tr>
<tr>
<td>Dec 16</td>
<td>27</td>
<td>Ramp 4 on 4 to 1.18 TeV. Squeeze to 7 m.</td>
</tr>
</tbody>
</table>
B2 Measured and Calculated response for 1 Corrector

Red = calculated  Blue = measured

27 kilometers

All systems worked beautifully
Why are we limiting the beam energy to 3.5TeV in 2010-2011?

All the work we have done since November 2008 makes us certain that a repeat of September 19 can NEVER happen.

The offending connector in this incident had an estimated resistance of 220nΩ. We have measured all 10,000 inter-magnet connectors and the maximum resistance we have seen is 2.8nΩ.

BUT in April 2009, we have uncovered a different possible failure scenario which could under certain circumstances produce an electric arc in the “copper stabilizers” of the magnet interconnects.
Decided Scenario 2010-2011

- Run at 3.5 TeV/beam up to a integrated luminosity of around 1 fb⁻¹.
- Then consolidate the whole machine for 7 TeV/beam (during a shutdown in 2012)
- From 2013 onwards LHC will be capable of maximum energies and luminosities
Clamped and shunted

MOPEB042 Bertinelli et al.
First Collisions at 7TeV cm
March 30, 2010

Media foresaw this at 09:17 precise!!
ATLAS IP Separation

H = 4.173 mm : V = 0.035 mm

CMS IP Separation

H = 0.130 mm : V = 3.925 mm

MOPEC003/4 Fuchsberger et al
MOPEC014 White et al

ATLAS Coll Rate Evol

CMS Coll Rate Evol
30/3/2010

11:15 injected again
12:38: At 3.5 TeV
Since the first Collisions
A very good 48 hour period!
Single beam lifetimes:

- Beam 1: 990 hours
- Beam 2: 730 hours
- Very good beam-gas, negligible luminosity burn, negligible diffusion

Luminosity lifetime

- 40 – 50 hours
- Mainly from gentle beam blow-up (tau ~ 40 hours for B2V)
- Beam tune shift ~ 0.0015 (one plane, 2 real collision points, reduced emittances)
The knowledge of the magnetic model of the LHC is remarkable and has been one of the key elements of a very smooth beam commissioning.

- Tunes, energy matching, optics remarkably close to the model already
- Bodes very well for the future.
Tuesday 13.4.

Q' measurement during energy ramp: Beam2 Vertical

WEPEB041 R. Steinhagen et al
Tuesday 13.4.

- $\beta^*$ during squeeze to $\beta^* = 2m$ in IR8:
IP1&5 lumi vs squeeze

- Raw (online) lumi plots on 10 apr 2010, during the squeeze to 2m in IP1 and IP5
- Factor gained (raw numbers):
  - ~4.5 in Pt5 (after min scan)
  - ~4 in Pt1
- Not corrected for lumi decay over the ~5h of squeeze and mini scans
Low intensity beam test.

Trajectory evolution after OFF send to RD1.LR1, with FMCM masked.

Beam dumped by BLMs in IR7.

- Trajectory over 1000 turns at a BPM.
- Position change of ~1.5 mm over last 250 turns.

Online PM!
FMCM beam tests

- Low intensity beam test.
- Trajectory evolution after OFF send to RD1.LR1, with FMCM active.
- Beam dumped by FMCM.

- Trajectory over 1000 turns at the same BPM.
- No position change visible within resolution.

>>> The redundant protection is working
Higher intensity

Over-injection working well

Over-injected 1.1E11, with collimators at nominal 4.5 sigma settings.

Emittance at 1E11: 2.5 um H, 2.3 um V.
Qualification: Off-momentum collimation

Loss map for off-momentum error. All OK. See expected low leakage to experimental IR's. OK for stable beams from coll.

TUOAMH01 (Wollmann, Assmann et al)
Squeeze to 2 m: Fast and Smooth

10 m to 2 m

45 min

| Beta* IP1 [m] | 2.000 |
| Beta* IP5 [m] | 2.000 |
| Beta* IP2 [m] | 2.000 |
| Beta* IP8 [m] | 2.000 |
Ramp & Squeeze Start to Work Smoothly

~ 48 hours

Ramp & squeeze @ 3.5 TeV qualification: ...
...last 2 fills w/o problem, lost on purpose...
Transverse damper commissioning @ 450 GeV

Ramp & squeeze for physics @ 3.5 TeV with higher intensity

LHC UPS repair
SPS problem
Saturday 24/4/2010

PROTON PHYSICS: STABLE BEAMS

Energy: 3500 GeV  I(B1): 2.75e+10  I(B2): 3.22e+10

Comments 24-04-2010 03:04:01:

injection scheme 3x3 bunches:
B1 buckets: 1, 8941, 17851
B2 buckets: 1, 8911, 17851
All IPs to 2m!!! Preparing stable beams

LHC Operation in CCC: 77600, 70480

BIS status and SMP flags

PM Status B1  ENABLED  PM Status B2  ENABLED
All experiments: \( L > 1.1 \times 10^{28} \text{ cm}^{-2} \text{ s}^{-1} \)
factor \( \sim 10 \) achieved, as predicted
New Record Fill

Fill length:
- First time: 30 h with unsafe beam.
- Luminosity: > 1.1e28 Hz/cm^2
- First time: 3 bunch scheme
- First time: end of fill studies and dump.

One order of magnitude increase in luminosity

Just 4 more to go before the long shutdown!!!
Maximum orbit change during energy ramp: 0.08 mm

Ralph Steinhagen et al
Transverse Damper: Damping Beam Excitations

Crucial device to keep emittance growth under control!

Wolfgang Hoefle et al

Transverse Damper will stabilize against the Hump
Collisions with design current at 450GeV
Sunday 02/05/2010 Stable beams at design current per bunch at 450GeV

02:04 Stable beams for the second time after LHCb polarity switch and some troubles at injection
Second fill with better lifetime conditions for B1 after RF phase loop adjustment.
Peak and Integrated Luminosity
Ramps for Beta Beat: 1.5 TeV $\rightarrow$ 3.5 TeV

MOPE062 R. Steinhagen et al.
Closing Collimators During Ramp

R. Assmann
Orbit and Tune Feedback in Operation

WEPEB041 R. Steinhagen et al

LHC status 5/23/2010
Pushing Number of $2 \times 10^{10}$ Bunches

$2 \times 10^{10} \rightarrow 4 \times 10^{10}$  
$6 \times 10^{10}$ per beam

48 hours

Allowed doubling the integrated luminosity for 2010 within 48 hours!
Integrated Luminosity versus Time

LHC 2010 RUN (3.5 TeV/beam)

PRELIMINARY (±10% scale)
The work summarized here is the result of work carried out by hundreds if not thousands of scientists, engineers and technicians both employed by CERN and very importantly by the many institutes which collaborate with CERN.

It is a great personal pleasure to acknowledge the incredible contributions and dedication of such a wonderful team.
Thank you for your attention

and please wish us good luck for the future