The LHC: Performance and Plans

BLOIS 2010

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Topics

- The LHC (reminder)
- The last 18 months (rapidly)
  - The Accident, Repair and Consolidation
  - Initial Commissioning with Beam
- Plans
  - Near future (2010-2011)
  - Medium future (2012-16) Nominal LHC
  - Far future (2014-2020?) HL-LHC
  - Very far future (2030??) HE-LHC
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>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (km)</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>Length of Dipole (m)</td>
<td>14.3</td>
<td></td>
</tr>
<tr>
<td>Dipole Field Strength (Tesla)</td>
<td>8.3</td>
<td>Results from the high beam energy needed</td>
</tr>
<tr>
<td>Operating Temperature (K) (cryogenics system)</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>Current in dipole sc coils (A)</td>
<td>11850</td>
<td>Results from the high magnetic field</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1ppm resolution</td>
</tr>
<tr>
<td>Beam Intensity (A)</td>
<td>0.5</td>
<td>2.2.10⁻⁶ loss causes quench</td>
</tr>
<tr>
<td>Beam Stored Energy (MJoules)</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>Magnet Stored Energy (MJoules)/octant</td>
<td>1100</td>
<td>Results from the high magnetic field</td>
</tr>
<tr>
<td>Sector Powering Circuit</td>
<td>8</td>
<td>1612 different electrical circuits</td>
</tr>
</tbody>
</table>
During cool-down of the LHC the machine contracts by 80 metres, 10m per octant

- Vacuum continuity
- Electrical connections
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
Bus bar splice

Joint components before soldering

- Superc. cables
- Bus bar from left-side magnet
- U-shaped copper profile
- Flat copper profile
- Sn-Ag foils

Cross section of the joint

- Copper stabilizer
- Superc. cables

Bus bar well reconstituted after soldering

Longitudinal section of the joint, entirely filled with Sn-Ag
Consequences
Electrical arc between C24 and Q24

M3 line

V lines
The cause (bad splice)

No electrical contact between wedge and U-profile with the bus on at least 1 side of the joint

No bonding at joint with the U-profile and the wedge
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!
A78.RB: Normalized Bus Segment Resistance

Every single splice was measured in 2009.
The near future: Decided Scenario 2010-2011

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

The lack of continuity in the stabilizer
A joint between bus bar can quench even if the splice is well done. When a magnet quenches, the warm helium wave makes the SS cable in the joint to quench in about 10-20 s. Since the decay time of the current is 104 s in the bus bar (and so in the joint), cable will become resistive and the stabilizing copper is there just to avoid overheating by diluting the current density. If the current has to pass through the SC cable only, above a certain length it burns. We know we have this situation: then we limit the dipole current to 6 kA (4.2 T → 3.5 TeV/beam)
First Collisions at 7TeV cm
March 30, 2010
11:15 injected again
12:38 : At 3.5 TeV

PROTON PHYSICS: STABLE BEAMS


Comments 30-03-2010 13:22:57 :
Stable beams!

LHC Operation in CCC : 77600, 70480
Soon after the first Collisions
A very good 48 hour period!


<table>
<thead>
<tr>
<th>Experiment Status</th>
<th>ATLAS</th>
<th>ALICE</th>
<th>CMS</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>STANDBY</td>
<td>NOT READY</td>
<td>STANDBY</td>
<td>STANDBY</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Instantaneouse Luminosity</th>
<th>0.000e+00</th>
<th>0.000e+00</th>
<th>0.000e+00</th>
<th>8.989e-04</th>
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</thead>
<tbody>
<tr>
<td>BRAN Count Rate</td>
<td>3.229e-07</td>
<td>4.059e-32</td>
<td>2.086e-11</td>
<td>1.635e-32</td>
</tr>
<tr>
<td>BKGD 1</td>
<td>0.002</td>
<td>0.014</td>
<td>0.002</td>
<td>0.131</td>
</tr>
<tr>
<td>BKGD 2</td>
<td>0.000</td>
<td>0.000</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>BKGD 3</td>
<td>0.000</td>
<td>0.005</td>
<td>0.003</td>
<td>0.037</td>
</tr>
</tbody>
</table>

LHCf: STANDBY  Count(Hz): 0.000  LHCb VELO Position: OUT  Gap: 58.0 mm  TOTEM: CALIBRATION

Performance over the last 12 Hrs:

![Graphs showing intensity and energy over time, with background levels for ATLAS, ALICE, CMS, and LHCb.]
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
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.
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
Second fill with better lifetime conditions for B1 after RF phase loop adjustment.

Stable beams at design current per bunch at 450GeV
Pushing Number of $2 \times 10^7$ Bunches

2 x $2 \times 10^7$ ➔ 4 x $2 \times 10^7$  
6 x $2 \times 10^7$ per beam

Allowed doubling the integrated luminosity for 2010 within 48 hours!
13 bunches: \(3 \times 10^{29}!!\)
Getting to Stable beams at $1.1 \times 10^{11}$.

Instabilities in Collision at 3.5TeV/beam

- **longitudinal emittance control**
  - In the SPS
  - During the ramp in the LHC
- **Transverse damper working**
- **Collimators set up**
- **Injection set up for new high intensity**
- **Beam dump set up for higher intensity**

- **Started physics data taking under these conditions on Saturday 26$^{th}$ June**
Ramps for Operations set up for $10^{11}$ protons/bunch
26th June: $5 \times 10^{29}$ with 3 bunches/beam; $10^{11}$/b
2nd July: Colliding 6 bunches per beam; $10^{11}/b$
6 bunches/beam New Record Lumi > 1e30 cm\(^{-2}\)s\(^{-1}\)

**LHC status 7/18/2010**

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<th>LHCb</th>
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<tr>
<td>Instantaneous Lumi (ub.s(^{-1}))</td>
<td>1.054</td>
<td>0.004</td>
<td>1.172</td>
<td>1.047</td>
</tr>
<tr>
<td>BRAN Count Rate (Hz)</td>
<td>1.098e+04</td>
<td>3.100e+01</td>
<td>1.657e+04</td>
<td>2.124e+04</td>
</tr>
<tr>
<td>BKGD 1</td>
<td>0.028</td>
<td>0.016</td>
<td>2.416</td>
<td>0.169</td>
</tr>
<tr>
<td>BKGD 2</td>
<td>0.000</td>
<td>0.008</td>
<td>0.002</td>
<td>1.974</td>
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<tr>
<td>BKGD 3</td>
<td>0.000</td>
<td>0.005</td>
<td>0.003</td>
<td>0.060</td>
</tr>
</tbody>
</table>

**LHCf MOVING Count(Hz): 0.114**

**LHCb VELO Position OUT Gap: 58.0 mm**

**TOTEM:** STANDBY

**Performance over the last 12 Hrs**

- **Emittances before ramp:**
  - B1 H: 2.5
  - B1 V: 2.5
  - B2 H: 2.5
  - B2 V: 3.0 (measure not so good)

- **Emittances meas during the ramp**
  - B1 H: 4.2
  - B1 V: 5.1
  - B2 H: 2.3
  - B2 V: 2.9
Beam Lifetime

Collisions

ALICE
Better but not perfect stability…

Intensity Luminosity
Integrated Luminosity on 14th July

LHC 2010 RUN (3.5 TeV/beam)

PRELIMINARY (±10% scale)

- ATLAS / LHCf
- ALICE *
- CMS / TOTEM
- LHCb

*ALICE: low pile-up since 01.07.2010
The same vs fill number in log graph

LHC 2010 RUN (3.5 TeV/beam)

PRELIMINARY (±10% scale)

- ATLAS / LHCf
- ALICE *
- CMS / TOTEM
- LHCb

*ALICE: low pile-up since 01.07.2010
Summary of Milestones thus far

- 30 March: first collisions at 3.5TeV/beam
- 19 April: order of magnitude increase in luminosity
  - doubling the number of particles/bunch
  - $\beta^*$ from 11 to 2m (4b/beam) $L \sim 2 \times 10^{28}$
  - Beam lifetimes of $\sim 1000$ hours
- 22 May another order of magnitude:
  - 13 bunches in each beam ($L \sim 3 \times 10^{29}$)
- 26 May: Design intensity bunches were brought into collision at 3.5TeV/beam.
- 2nd July peak luminosity of $10^{30}$cm$^{-2}$s$^{-1}$.
- Half July: 1.4 $10^{30}$cm$^{-2}$s$^{-1}$ consolidated, aiming at more
- By August: bunch train
Presently

- **From experience so far**
  - No fundamental issue for $1 \times 10^{30}$ luminosity
  - Further equalize beam parameters (emittance, intensity, ...) while delivering luminosity. Try to get nominal beam and bunch parameters, including variations.
  - As stability is improved, push up again on luminosity

- **In addition:**
  - Cross calibrate emittance measurement devices.
  - Push transverse damper into full operation in collision, however, possibly needs noise reduction.

**Aim** is for $10^{32}$ before the end of 2010 which is needed for an integrated luminosity of **1 fb-1 before end of 2011**

At 7 Tev c.o.m. energy
$10^{32}$ how far we are?

(modulo some possible luminometers down time...)

Fills 1005-1199

~70 days
Medium future: 2012-13 shutdown

- **Splice consolidation for nominal energy 13-14 TeV c.o.m.**
  - All sectors to be warmed up
  - All Interconnects to be opened (about 2000), and 5000 helium enclosure - pipes with flanges and bellow - cut and opened
  - All 10,000 joints inspected, some 15% expected to be repaired and **ALL to be consolidated with a copper shunt**
  - Some 5 magnets to be replaced for electric or vacuum defects and 10-15 for n.c. internal (inside magnets) splice.

- **Completion of collimation system for nominal luminosity**
  - (we think we will be limited at 2-20% of nominal luminosity by lack of complete collimation)
  - This requires to remove to surface 24 main magnets (+ 4 cryostats) and to reinstall in displaced position in order to fit:
  - **NEW 4 cold-warm-cold transitions to place 4 collimators in the DS zone of P3** (in addition to six more normal collimator s still missing)
Sketch of the copper shunt

Superconducting cable

Bus bar (insulated)

Copper shunts 2 per side of each splice

Splice length
Sketch of the restraining box

Cross profile for bus-to-bus insulation

Superconducting cable

Bus bar (insulated)

Interconnection box for ground insulation and for mechanical restraint of the splice
A possible schedule for the next decade ....
A look to a possible – possible!!! – lumi evolution

Courtesy of M. Lamont

Luminosity [cm$^{-2}$s$^{-1}$]

Integrated luminosity [fb$^{-1}$]

S. Myers QUB March 11, 2009
**New Hardware**

- 13 T magnets, 16 high grad low beta quadrupoles for ATLAS & CMS and 4 large aperture dipoles
- New IR magent layout with also new cryo-plants
- New SC crab cavities to rotate the beam and make effective the gain of the low beta quads
- New magnets in the Matching sections with larger apertures
- New Sc links to remove Power Supply on surface (R2E problem)
- Further collimation system in the DS of P7, IP2 (IP1 and IP5?) requiring special 11 T LHC like dipoles
- New collimation system and absorber in the IR to protect magnets.

**What is the time scale?**

- The Study and R&D takes 5 years
- In 2013-14 we are ready for a decision, then 5 year to built and test
- Installation from 2020… some 1500-2000 fb-1 by 2030…
Atre we ready with this new technology? Almost…

US – LARP (DOE program) is developing Nb3Sn SC magnets LQS is a 3.6 m coil length quadrupole with **90 mm aperture**. Its goal is 200 T/m, as LHC @ 70 mm and 1.9 K!
New Hardware

- 17-20 T main dipole magnets!
- Synchrotron radiation also a big issue
- But it looks possible…
- Sketch of a 20 T dual dipole with 40 mm bore with Nb-Ti (LHC), Nb$_3$Sn (HL-LHC) and HTS.
- Working group lead by S. Meyers is – slowing – taking momentum
- Taking profit form HL-LHC R&D

What is the time scale?

- The Study, R&D, industrialization will take 10 years
- Construction further 10 years
- Installation from 2030… or later
Conclusions

- **LHC is finally there!**
  - 1 fb\(^{-1}\) @ 7 TeV c.o.m. by 2011
  - 14 TeV and 50-100 fb\(^{-1}\) by 2016,
  - 200-400 fb\(^{-1}\) by 2020.

- **HL-LHC**
  - Aiming @ 5 \(10^{34}\) cm\(^{-2}\) s\(^{-1}\) average, 1500-2000 fb\(^{-1}\) by 2030
  - Decision in 2014 for installation in 2020
  - Cost: 500 Millions

- **HE-LHC**
  - Aim at 28-33 TeV c.o.m by 2030…
  - Cost: 5000 Millions + …
  - I don’t know if physics requires such accelerator…
  - If we can afford a linear collider, we can certainly afford HE-LHC!