LHC machine
Status and future plans

Dr. Frédérick BORDRY
CERN – Head of Technology Department

Friday 10th December 2010
- LHC machine recap and main challenges
- LHC repair and restart in 2009
- Proton and ion runs in 2010
- Plan for 2011
- 2012- 2030 scenarii
- Conclusion
What is LHC (Large Hadron Collider)?

7 TeV proton-proton accelerator-collider built in the LEP tunnel

1982: First studies for the LHC project
1994: Approval of the LHC by the CERN Council
1996: Final decision to start the LHC construction
2004: Start of the LHC installation
2006: Start of hardware commissioning
2008: End of hardware commissioning and start of commissioning with beam
2009-2030: physics operation

Beams of LEAD nuclei will be also accelerated, smashing together with a collision energy of 1150 TeV
What is special with LHC?

- The highest field accelerator magnets: 8.3 T (ultimate: 9 T)
- Proton-Proton machine: Twin-aperture main magnets
- The largest superconducting magnet system (~8000 magnets)
- The largest 1.9 K cryogenics installation (superfluid helium)
- The highest currents controlled with high precision (up to 13 kA)
- The highest precision ever demanded from the power converters, a few ppm
- A sophisticated and ultra-reliable magnet quench protection system
Final assembly of cryomagnets at CERN

One main dipole magnet:
- 35 tons, 15m
- 108 mH

1232 main dipoles
400 main quadrupoles
100% cold tests at CERN (up to ultimate field)

1232 dipoles and 400 quadrupoles

Cold magnetic performance measured on 20% of the magnets (correlation between warm and cold measurements)
Cryomagnet interconnects challenge

123 000 helium-tight *in situ* welds
LHC accelerator magnet stored energy

$$1232 \times 108 \text{ mH} = 133 \text{ H} ; \frac{1}{2} L \cdot I^2 \approx 10 \text{ GJ}$$

- Energy stored in the magnet system: 10 GJoule
- Energy stored in one (of 8) dipole circuit: 1.3 GJoule

10 GJoule $\approx$ flying 700 km/h

The energy stored in the LHC magnets corresponds approximately to 8 such trains running at 300 km/h
LHC beam stored energy

Momentum at collision 7 TeV (1 eV = 1.6 × 10^{-19} Joule)
Number of bunches 2808
Protons per bunch 1.15 × 10^{11}
Total number of protons (2 beams) 6.5 × 10^{14} (1 ng of H^+)

Energy stored in the two beams: 724 MJoule
Energy to heat and melt one ton of copper: 700 MJoule

700 MJ melt one ton of copper

700 MJoule dissipated in 88 μs
700 \cdot 10^6 / 88 \cdot 10^6 \approx 8 \text{ TW}

World Electrical Installed Capacity \approx 3.8 \text{ TW}

90 kg of TNT per beam
Beam Dump

beam absorber (graphite)

about 8 m

Temperature of beam dump block at 80 cm inside

up to 800 °C
10th September 2008...

First turn!
The Sector 3-4 incident  (just before the 1st ramp)

19th September 2008 at 11:18.36
last test of the last circuit of the last sector: 7kA (4TeV) towards 9.3 kA (5TeV)

Electrical arc between two magnets at 8.7 kA
The start ...

From L. Rossi, CERN Courier September 2010
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

½ machine done
All the work done since November 2008 makes certain that a repeat of September 19th 2008 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 2.7nΩ for dipole busbars and 3.3nΩ for dipole busbars.
LHC main splices today: busbars SC

Main Dipoles&Quads Bus, sorted by position, **2048** segments
All HWC pyramids and plus ~150 ramps to 3.5TeV analyzed

Top 10 Splice Resistances

<table>
<thead>
<tr>
<th>Dipole Buses</th>
<th>Quad Buses</th>
</tr>
</thead>
<tbody>
<tr>
<td>301 ± 85pΩ</td>
<td>306** ± 313pΩ</td>
</tr>
<tr>
<td>R_max = 2.7nΩ</td>
<td>R_max = 3.3nΩ</td>
</tr>
</tbody>
</table>

(**) number of splices in the quads segments corrected, 1.3 added
Main Dipoles

\[ 3.1 \pm 1.2 \Omega \]
8 splices
(but not all the same type)

Main Quads

\[ 1.4 \pm 1.3 \Omega \]
Why do we limit the beam energy to 3.5TeV in 2010-2011?

All the work done since November 2008 makes certain that a repeat of September 19th 2008 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 2.7nΩ for dipole busbars and 3.3nΩ for dipole busbars.

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.
Sample pictures

Sample 1 (61 µΩ)

Sample 2A left (32 µΩ)

Sample 2A right (43 µΩ)

Sample 2A right (43 µΩ)

Sample 2B (42 µΩ)

Sample 3A left (26 µΩ)

Sample 3A right (43 µΩ)

Sample 3B (21 µΩ)

Pictures by J.-M. Dalin
Summary of LHC Commissioning in 2009

• November 20\textsuperscript{th} 2009
  – First beams around again

• November 29\textsuperscript{th} 2009
  – Both beams accelerated to 1.18 TeV simultaneously

• December 8\textsuperscript{th} 2009
  – 2x2 accelerated to 1.18 TeV
  – First collisions at 2.36 TeV cm! \textcolor{red}{LHC - highest energy collider}

• December 14th 2009
  – Stable 2x2 at 1.18 TeV
  – Collisions in all four experiments

\textcolor{yellow}{Limited to 2 kA in main circuits (1.18 TeV) during deployment and testing of new Quench Protection System}
Following the technical discussions in Chamonix workshop (Jan 2010) the CERN management and the LHC experiments decided

- Run at 3.5 TeV/beam with a goal of an integrated luminosity of around 1 fb\(^{-1}\) by end 2011
  - Implies reaching a peak luminosity of \(10^{32}\) in 2010

- Then consolidate the whole machine for 6.5 – 7 TeV/beam (during a shutdown in 2012)

- From 2013 onwards LHC will be capable of maximum energies and luminosities
30th March 2010: first collisions at 7 TeV (2 x 3.5 TeV)
First Running Period (low bunch intensity)

<table>
<thead>
<tr>
<th>Event</th>
<th>TeV</th>
<th>OEF</th>
<th>β*</th>
<th>Nb</th>
<th>Ib</th>
<th>Itot</th>
<th>MJ</th>
<th>Nc</th>
<th>Peak luminosity</th>
<th>Date</th>
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<td>0.0113</td>
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> Seven Orders of magnitude below design
Second Running Period (High bunch Intensity)

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<th>$\beta^*$</th>
<th>Nb</th>
<th>$l_b$</th>
<th>$l_{tot}$</th>
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<th>Nc</th>
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</tbody>
</table>

Maximum reached is $10.7 \times 10^{30}$ cm$^{-2}$s$^{-1}$
Approaching 4pb-1 (move to bunch trains)

ATLAS Online Luminosity $\sqrt{s} = 7$ TeV

- LHC Delivered All
- LHC Delivered Stable
- ATLAS Ready Recorded

Total Integrated Luminosity [pb$^{-1}$]

Day in 2010
### Running with Bunch Trains (Parameters)

<table>
<thead>
<tr>
<th>Nb</th>
<th>Ib</th>
<th>MJ</th>
<th>Nc</th>
<th>Peak luminosity (design parameters)</th>
<th>Maximum luminosity (measured)</th>
<th>Pile up (from measured Lumi)</th>
<th>Date</th>
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<td>9.737E+31</td>
<td>2.050E+32</td>
<td>2.9721</td>
<td>25/10/2010</td>
</tr>
</tbody>
</table>

**24MJ stored beam energy and 2.05x10^{32} cm^{-2}s^{-1}**
Luminosity evolution 2010 (proton)

5 orders of magnitude in ~200 days

~50 pb\(^{-1}\) delivered, half of it in the last week!

- \(10^{30}\) cm\(^{-2}\) s\(^{-1}\)

Roger Bailey
Did we reach the intensity limit for 150ns?

4.35e13 p (?) \rightarrow \text{to be followed...}

Stored energy reached at 3.5 TeV: \quad 28.0 \text{ MJ}

Stored energy at 3.5 TeV in stable beams: \quad 25.2 \text{ MJ}
Initially

- Pressure rise seen in common beam pipe regions
- Particularly unbaked warm-cold transitions
Initially

- Pressure rise seen in common beam pipe regions
- Particularly unbaked warm-cold transitions
- Two effects:
  - electron cloud driven by closely space passage of b1 and b2 bunches
  - synchrotron radiation induced desorption
Initially

- Pressure rise seen in common beam pipe regions
- Particularly unbaked warm-cold transitions
- Two effects:
  - electron cloud driven by closely spaced passage of b1 and b2 bunches
  - synchrotron radiation induced desorption
- Region +/- 58 m of IP1 equipped with solenoids
  - worked well
  - classic cure for electron cloud

Cleaning observed

Initially Vacuum

Solenoid A4L1 ON

Solenoid A4R1 ON

With solenoids on, cloud
Cleaning / Scrubbing with time
[normalised to 1]

Can hope to gain 2 orders of magnitude in ~16h

Valid for a given bunch intensity and filling pattern
Cleaning/Scrubbing ONLY if running with electron cloud!
w/o electron cloud, NO cleaning/scrubbing except by photons (>2 TeV) BUT no pressure rise…
Memory effect will stay (partly/totally) for other schemes

Miguel Jimenez
Long preparation from injector chain

- **ECR ion source (2005)**
  - Provide highest possible intensity of Pb\textsuperscript{29+}

- **RFQ + Linac 3**
  - Adapt to LEIR injection energy
  - Strip to Pb\textsuperscript{54+}

- **LEIR (2005)**
  - Accumulate and cool Linac 3 beam
  - Prepare bunch structure for PS

- **PS (2006)**
  - Define LHC bunch structure
  - Strip to Pb\textsuperscript{82+}

- **SPS (2007)**
  - Define filling scheme
**Ion Commissioning: First 24h from Nov 4th!**

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Fill #</th>
<th>Energy</th>
<th>I(B1)</th>
<th>I(B2)</th>
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<tbody>
<tr>
<td>05-Nov-2010</td>
<td>21:48:18</td>
<td>1473</td>
<td>3500 Z GeV</td>
<td>9.86e+09</td>
<td>1.02e+10</td>
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<table>
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<tr>
<th>Experiment</th>
<th>Status</th>
<th>ATLAS</th>
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<th>CMS</th>
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**LHCb VELO Position:**
- OUT
- Gap: 58.0 mm
- SQUEEZE
- TOTEM: STANDBY

**Performance over the last 24 Hrs**

<table>
<thead>
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<td>1.0E10 Intensity</td>
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**Beam 1:**
- Inj.
- Circ.
- & Capture

**Beam 2:**
- Inj., Circ.
- & Capture

**Optics Checks**
- BI Checks
- Collimation Checks

**First Ramp**
- Collimation Checks
- Squeeze

**Updated:** 21:48:16
First stable beams (2 bunches per beam)

8th Nov. 2010
• Integrated luminosity \( \sim 10 \, \mu \text{b}^{-1} \).
Primary ion beam losses are intercepted at the collimators

Several features contribute to more severe ion loss problems

  – Nuclear physics: Ion dissociation and fragmentation reduce cleaning efficiency by factor ~100 when compared to protons (predicted since years, now confirmed).
    • Collimation upgrade (DS collimators) will solve this.
  – Ion beam lifetimes factor ~3-6 lower than for proton beams
    • Not yet understood

Effects are clearly seen in Radmon monitors
  • And in the equipment!
    – “QPS OK” lost on Q9.L7, communication to quench detector → Single Event Upset (“SEU”). Upgraded firmware in dispersion suppressors of LSS7 on Saturday

    – “QPS OK” lost on Q9.R7 and Q9.L7, FIP communication → SEU?
      No work-around available at the moment
Summary: What did we learn in 2010?

- LHC is magnetically very reproducible on a month to month time scale
- High precision of the powering system (8 independent sectors!)
- High availability of the cryogenics and hardware system
- Head on beam-beam limit higher than foreseen
- Aperture better than foreseen
- Not a single magnet quench due to beam
- Careful increase of the number of bunches OK

- Electron cloud and vacuum
- Machine protection
  - Set up is long
  - Quench levels for fast and slow losses needs optimized
  - UFOs (Unidentified Falling Object: dust?)
- Radiation to Electronics (R2E)
LHC power converter accuracy

- High accuracy of LHC power converters
  - Drift less than 15ppm/year (50ppm was specified)
  - No tracking issue between the 8 sectors

<table>
<thead>
<tr>
<th>Converter category</th>
<th>Accuracy class</th>
<th>1 year accuracy (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main dipoles, quads, inner triplets</td>
<td>Class 1</td>
<td>50</td>
</tr>
<tr>
<td>Separation dipoles, insertion quadrupoles</td>
<td>Class 2</td>
<td>70</td>
</tr>
</tbody>
</table>

CCC sees the sectors as one!
LHC Cryo global availability

Powering tests
Learning spring
Fantastic since summer!

Results for 2010 above expectations, thanks as well to periodic technical stops
• Beam back around 21\textsuperscript{st} Feb.
• 2 weeks re-commissioning with beam (at least)
• 4 day Technical Stop (TS) every 6 weeks
• Count 1 day to recover from TS (optimistic)
• 2 days machine development every 2 weeks or so
• 4 days ions set-up
• 4 weeks ion run
• End of run – 12\textsuperscript{th} December

\textit{\~200 days proton physics}
plans for 2011

- running conditions in 2011
  (will be discussed at Chamonix Workshop 24\textsuperscript{th}-28\textsuperscript{th} January 2011)
  - maximum beam energy
  - bunch spacing
    - 75 ns (max bunches 936)
    - 50 ns (max bunches 1404)
  - integrated luminosity evaluation

=> goal set is 1fb\textsuperscript{-1}
2011: “reasonable” numbers

- 4 TeV (to be discussed at Chamonix)
- 936 bunches (75 ns)
- 3 micron emittance
- $1.2 \times 10^{11}$ protons/bunch
- $\beta^* = 2.5$ m, nominal crossing angle
- Hubner factor 0.2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak luminosity</td>
<td>$6.4 \times 10^{32}$</td>
</tr>
<tr>
<td>Integrated per day</td>
<td>11 pb$^{-1}$</td>
</tr>
<tr>
<td>200 days</td>
<td>2.2 fb$^{-1}$</td>
</tr>
<tr>
<td>Stored energy</td>
<td>72 MJ</td>
</tr>
</tbody>
</table>

Usual warnings apply – see problems, problems above

Mike Lamont
2012 – 2013 long shutdown

10-15% of interconnections to be opened and to be re-welded
100% (10'000) to be consolidated
Consolidation of LHC Vacuum systems
Pressure relief valves, rupture disks and protective shells

New design of DN200/160/100 valves

PIMs protection

For Beam Vacuum
Connection Cryostats

DS collimators

Arc side

DS center

LSS side

Courtesy: J.Coupard
LHC cryo-collimator upgrade

New cryo collimators in P3: move of DFBAE/F & Q4s: QRL extension studies
Run the LHC between 6.5 TeV and 7 TeV according to magnet training
Upgrades: Foreword

New Studies were launched more than one year ago

• Performance Aim
  – To maximize the useful integrated luminosity over the lifetime of the LHC

• Targets set by the detectors are:
  \(3000 \text{fb}^{-1} \text{ (on tape) by the end of the life of the LHC}\)
  \(\rightarrow 250-300 \text{fb}^{-1} \text{ per year in the second decade of running the LHC}\)

Goals

• Check the coherence of the presently considered upgrades wrt
  • accelerator performance limitations,
  • Detector needs,
  • manpower resources and,
  • shutdown planning including detectors
The CERN accelerator network

**LIU project**
LHC Injectors Upgrade
- Linac 4 (ready 2014, connection in 2016 or 2017)
- PSB (Booster) 2 GeV
- SPS upgrade
- PS review

**Consolidation project**
Injectors must operate hit high reliability up to 2030
Luminosity Upgrade Scenario: HL-LHC

- For LHC high luminosities, the luminosity lifetime becomes comparable with the turn round time ⇒ Low efficiency

- Preliminary estimates show that the useful integrated luminosity is greater with
  - a peak luminosity of \(5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}\) and a longer luminosity lifetime (by luminosity levelling)
  - than with \(10^{35}\) and a luminosity lifetime of a few hours

- Luminosity Levelling by
  - \(\beta^*\), crossing angle, crab cavities, and bunch length

Detector physicists have indicated that their detector upgrades are significantly influenced by the choice between peak luminosities of \(5 \times 10^{34}\) and \(10^{35}\).
  - Pile up events
  - Radiation effects

Steve Myers
HL-LHC: Hardware for the Upgrade

• Upgrade of the intensity in the Injector Chain (LIU)
• New high field insertion quadrupoles
• Upgraded cryo system for IP1 and IP5
• Crab Cavities to take advantage of the small beta*
• Single Event Upsets
  – SC links to allow power converters to be moved to surface
• Misc
  • Upgrade some correctors
  • Re-commissioning DS quads at higher gradient
  • Change of New Q5/Q4 (larger aperture), with new stronger corrector orbit, displacements of few magnets
  • Larger aperture D2
We now have a **good grasp** on the current carrying limits for \( \text{Nb}_3\text{Sn} \) strand and cables.
Design and preliminary test of MgB$_2$ feeder system (up to 120 kA) that could be used to remove the power converters from the proximity of the tunnel (access, radiation issues)

Reached 17 kA w/o quench !!!

Reached 11 kA w/o quench !!!

Cold powering system for the LHC IR Upgrade Phase 1
11T DS Dipole

- Goal: liberate space for collimation phase II upgrade in the DS regions of points 2 & 7.
- Scenarios: replacing MBs by shorter twin-aperture dipoles with higher field (same integrated strength)
  - using Cryo-collimators: 2 HF dipoles / DS
  - using Warm collimators: 4 HF dipoles / DS

Fermilab puts 400 k$ + 5-8 FTE 1m-1bore model by end 2011 !!!!
The 10 year technical Plan

Field progress in accelerator magnets

- **Nb₃Sn**
- **Nb-Ti**
- **LHC**
- **RHIC**
- **HERA**
- **Tevatron**
- **SPS & Main Ring (resistive)**

Timeline:
- **1975**
- **1985**
- **1995**
- **2005**
- **2015**

**5.10^{34} and luminosity levelling**
HIGH ENERGY LHC (HE-LHC): A PRELIMINARY STUDY

• A 20 T operational field dipole for a HE-LHC
  – Preliminary conceptual design [R. Assman, et al., CERN ATS 2010 177]
    • A 80 mm thick coil with
      \(~400 \text{ A/mm}^2\) operational $j$
    • Grading of the material necessary to reduce cost

Coil thickness versus operational field in accelerator magnets

Magnet cross-section [E. Todesco]

Coil lay out
Linear Collider Studies Leader: Steinar Stapnes as from 1 January 2011.
2010 was an absorbing, captivating and successful year for the LHC

As any large and complex project, LHC was not all plain sailing project but CERN and collaborations have shown an impressive reactive force to overcome the obstacles, continue progressing towards the nominal performance and to prepare the next high energy frontier project

Thanks for your attention and for your kind hospitality
Not everything is perfect. The LHC has reached a stage where interesting things are beginning to pop up …

- The smaller bunch spacing with trains can provoke electron clouds
- In warm regions of the machine this can lead to a vacuum pressure rise
- In cold regions of the machine this would create an additional heat load on the cryogenic system.
- In addition all the electrons in the beam pipe can feed back to affect the beam stability
- Can be eliminated by conditioning the surface - scrubbing

schematic of e-cloud build up in LHC arc beam pipe, due to photoemission and secondary emission