Status of the LHC

Frédérick BORDRY
On behalf of the CERN staff, the outside collaborators and industries
CERN
Last Status of the LHC before beam

Frédéric BORDRY
On behalf of the CERN staff, the outside collaborators and industries
CERN
Is it necessary to introduce *the lord of the rings*?

Advanced Technology Issues in the LHC Project  
L.R. Evans, **EPAC 1994**, London, UK

ACCELERATOR PHYSICS ISSUES OF THE LHC  
Jacques Gareyte, **EPAC 1996**, Sitges, Spain

LHC ACCELERATOR PHYSICS AND TECHNOLOGY CHALLENGES  
L.R. Evans, **EPAC 1998**, Stockholm, Sweden

THE CHALLENGE OF FUTURE ACCELERATORS (1st part)  
K. Hübner, **EPAC 2000**, Vienna, Austria

STATUS OF THE LHC  
R. Schmidt, **EPAC 2002**, Paris, France

Experience with LHC Magnets from Prototyping to Large-scale Industrial Production and Integration  
L. Rossi, **EPAC 2004**, Lucerne, Switzerland

LHC PROGRESS AND COMMISSIONING PLANS  
Oliver Brüning, **EPAC 2006**, Edinburgh, Scotland

LHC: Construction and Commissioning Status  
L. R. Evans, **PAC 2007**, Albuquerque, USA
Menu of the day

Amuse bouche
Introduction: LHC and its general parameters

Starter
LHC main milestones from 2002

Main
Last two years events and “where are we?”:
- Completion of the installation and interconnects
- Inner triplet challenges
- Plug-in modules
- Cool-down of the sectors
- Hardware commissioning

Dessert
Beam Plans for 2008 and 2009

Pousse-Café

Conclusions
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 ("missing" magnet strategy)
1996: Final decision to start the LHC construction (7TeV machine)
2004: Start of the LHC installation
2006: Start of hardware commissioning
2007: End of installation and start of cooldown
2008: End of hardware commissioning and beam commissioning

Beams of LEAD nuclei will be also accelerated, smashing together with a collision energy of 1150 TeV
The machine of superlatives

- 7 TeV per beam in LEP tunnel \( \Rightarrow 8.33 \, T \)
- Luminosity goal \( 10^{34} \, \text{cm}^{-2} \, \text{s}^{-1} \)
  - Excludes proton – antiproton
  - Hence proton – proton machine
    - Separate magnetic fields and vacuum chambers in the arcs
    - Common sections in the interaction regions
Two-in-one dipole magnet

Tunnel cross section excludes 2 separate rings of magnets:

- Hence twin aperture magnets in the arcs: 8.33 T (ultimate 9 T)
- **Superconducting magnets with high current density**
  
  *Trade-off between magnet and cryogenic complexity*

  => NbTi at 1.8K (Superfluid Helium)

Field reproducibility/precision $\sim 10^{-3}$

Field homogeneity $\sim 10^{-4}$
Detectors installed and powered... will be ready for beam beginning of August 2008
Detectors installed and powered... will be ready for beam beginning of August 2008
LHC progress 2002-2008

Tunnel activity determined by

<table>
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<tr>
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Dismantling
LHC progress 2002-2008

Tunnel activity determined by

QRL installation and repair
(geometry, weld quality, procedures, leaks, support tables,...)

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![Image of LHC tunnel with people and equipment]
LHC progress 2002-2008

Tunnel activity determined by

- LEP
- QRL (geometry, weld quality, procedures, leaks, support tables, ...)

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Magnet tests (SM18)

Completion of magnet cryostating & tests, 1 March 2007
LHC progress 2002-2008

Tunnel activity determined by

LEP → QRL (geometry, weld quality, procedures, leaks, support tables, ...) → Triplet → Cool-down

2002 2003 2004 2005 2006 2007 2008

Magnet tests (SM18) → Magnet installation

Fr. Bordry, Status of the LHC - 23rd June 2008
LHC progress 2002-2008

Tunnel activity determined by

LEP → QRL (geometry, weld quality, procedures, leaks, support tables, ...) → Triplet → Cool-down

2002  2003  2004  2005  2006  2007  2008

Magnet tests (SM18) → Magnet installation

Required magnet storage 😞
### LHC progress 2002-2008

Tunnel activity determined by:

- **LEP**
- **QRL** (geometry, weld quality, procedures, leaks, support tables, ...)
- **Triplet**
- **Cooldown**

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- **Magnet tests (SM18)**
- **Magnet installation**

- **Required magnet storage 😞**
- **Allowed magnet sorting 😊**

---

![Graph showing the progress of cold masses delivered, cryodipoles assembled, cryodipoles assigned to position in ring, cryodipoles prepared for installation, and cryodipoles installed from 2001 to 2008.](image-url)
LHC progress 2002-2008

Tunnel activity determined by

LEP

QRL (geometry, weld quality, procedures, leaks, support tables, ...)

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Magnet tests SM18

Magnet installation

Magnet interconnects

Descent of the last magnet 26-04-2007
Interconnections: giant work (QA)

Interconnections the superconducting magnets of LHC means:

- 1695 magnet-to-magnet interconnects
- 224 magnet to QRL interconnects

Each magnet to magnet interconnect consists of:

- 18 assembly actions divided in 9 interventions
- 5 leak tightness check
- 5 electrical tests
- 1 RF test

For each sector this is:
- 1964 assembly interventions
- 226 electrical tests on sub-assemblies
- 70 vacuum tests on sub-assemblies
- 14 RF test on sub-assemblies
7th November 2007
last interconnection

30th of April 2008
All the LHC interconnections are closed at the same time for the first time!

Courtesy J-P Tock
LHC progress 2002-2008

Tunnel activity determined by

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Magnet tests SM18

Magnet installation

Magnet interconnects
Pressure test failed in Sector 7-8 (Nov 2006). The heat exchanger did not withstand the differential pressure of 9 bar.

After the repair of the first heat exchanger, pressure test failed in Sector 4-5 (March 2007). Axial movement of the Q1 cold mass due to the thrust force (12 t at 20 bar), which led to the breaking of the support system and rupture of the bellows between the first two quadrupoles.

Courtesy R. Ostojic
Redesign of the heat exchanger: new Cu tubes with larger buckling pressure, and new bi-metallic transitions in the ends.

Redesign of the support system based on four invar/StSt cartridges that react the longitudinal forces and retain the fixed point of the cold mass in its original position. The consolidation of all inner triplets was completed by September 2007.
Don’t worry. Problem solved

Solutions: Inner Triplet

CERN
Fermilab
KEK

based on four Invar/StSt cartridges that react the longitudinal forces and retain the fixed point of the cold mass in its original position. The consolidation of all inner triplets was completed by September 2007.
Low-β triplet in CMS ready for powering
Low-β triplet in CMS ready for powering
Low-\(\beta\) triplet in CMS ready for powering
LHC progress 2002-2008

Tunnel activity determined by

- LEP
- QRL (geometry, weld quality, procedures, leaks, support tables, ...)
- Triplet
- Cool-down

2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008

- Magnet tests SM18
- PC SC tests
- Magnet installation
- Magnet interconnects
- Sector 78 commissioning
LHC progress 2002-2008

Tunnel activity determined by

- LEP
- QRL (geometry, weld quality, procedures, leaks, support tables, ...)
- PIMs
- Cool-down

2002 2003 2004 2005 2006 2007 2008

- Magnet tests SM18
- PC SC tests
- Magnet installation
- Magnet interconnects

PIM : Plug-in Module

Sector 78 commissioning
RF bellows in the 1700 interconnections

LHC cell - length about 108 meters

Interconnection
Interface box
Interconnection
Voltage tap
Interconnection

SSS  MB  MB  MB  SSS  MB  MB  MB

Line-N

Arc plug-in module at working temperature

Arc plug-in module at warm temperature
Failure Simulation on Test Bench

Cold

Warm

Non-conforming contacts, simulating warm-up from cold
Failure Simulation on Test Bench

Not optimal conditions for the beam!

Warm

Non-conforming contacts, simulating warm-up from cold
Out of tolerances bending angles of the RF fingers

Widespread non-conformities of this type have been seen in non-installed PIMs

Wrong

Easy to repair but how to detect?
Problems: plug-in modules – the solution

16 PIM with buckled fingers of which 9 were unexpected. In total 28 PIM were replaced. The interconnects of the whole sector were X-rayed.

A ball is sucked in at one end of the sector:
- 34mm exterior, 30mm interior
- Total weight ~15 g (ball 8g)

RF characteristics
- 40MHz resonant circuit
- Generates 20V between copper electrodes
- Battery powered Over 2hr lifetime

-BPM trigger threshold at ~3mV

Good opportunity to test BPM with a large particle!
Sputnik and The Dawn of the Space Age

History changed on October 4, 1957, when the Soviet Union successfully launched Sputnik I. The world’s first artificial satellite was about the size of a beach ball (58 cm or in diameter), weighed only 83.6 kg and took about 98 minutes to orbit the Earth on its elliptical path.

The satellite travelled at 29,000 kilometres per hour and emitted radio signals at **40.002 MHz** which were monitored by amateur radio operators throughout the world.
LHC progress 2002-2008

Tunnel activity determined by

LEP → QRL (geometry, weld quality, procedures, leaks, support tables, ...) → Triplet PIMs → Cool-down & HWC

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- Magnet tests SM18
- PC SC tests
- Magnet installation
- Magnet interconnects

Sector 78 commissioning
Sector 45 commissioning
LHC progress 2002-2008

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Magnet tests SM18 → Magnet installation → Magnet interconnects → PC SC tests

Sector 78 commissioning  
Sector 45 commissioning
LHC progress 2002-2008

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- Magnet tests SM18
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- Magnet installation
- Magnet interconnects
- Definitive cooldown and commissioning
- Sector 78 commissioning
- Sector 45 commissioning

Fr. Bordry, Status of the LHC – 23rd June 2008
LHC progress 2002-2008

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- PC SC tests
- Magnet installation
- Magnet interconnects
- Definitive cooldown and commissioning
- Sector 78 commissioning
- Sector 45 commissioning
LHC progress 2002-2008

Tunnel activities

LEP → QRL (geometry, weld quality, process controls)

LHC is not all plain sailing
Think BEAM !!!

<table>
<thead>
<tr>
<th>2006</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC SC tests</td>
<td>Installation</td>
<td>Definitive cooldown and commissioning</td>
</tr>
<tr>
<td>Interconnects</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

LHC project leader

Fk. Bordry, Status of the LHC – 23th-June 2008
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

Huge number of PID control loops per sector!
Cryogenics: the learning curve

- Time for getting nominal conditions:
  - Presently 10 to 6 weeks for getting nominal conditions,
  - In routine operation, about 1 month is foreseen,

<table>
<thead>
<tr>
<th>CW1</th>
<th>CW2</th>
<th>CW3</th>
<th>CW4</th>
<th>CW5</th>
<th>CW6</th>
<th>CW7</th>
<th>CW8</th>
<th>CW9</th>
<th>CW10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Today for HWC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Filling, CD 1.9 K &amp; cryo-tuning</td>
<td></td>
</tr>
<tr>
<td>Purge &amp; leak test</td>
<td>Purging</td>
<td>Flushing</td>
<td>Cool-down 300-5 K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal after a routine shutdown</td>
<td></td>
<td>Purging</td>
<td>Cool-down 300-5 K</td>
<td>Filling, CD 1.9 K &amp; cryo-tuning</td>
<td></td>
<td></td>
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</table>

- LHC cryogenics is the largest, the longest and the most complex cryogenic system worldwide.
- Operation for the needs of Sector HWC is now demonstrated.
- Based on experience, together with procedures and tools being put in place, availability must be improved for the next phase: *The Beam Commissioning.*
Where are we today?

6 sectors with liquid He
1 sector at 10 K (1-2)
1 sector at 100 K (4-5)

http://hcc.web.cern.ch/hcc/field.php
the superconducting circuits
What needs to be tested for the power converters?

~1700 circuits

- Regulation loop (with huge time constant: up to 6h)
- Free-wheel system at nominal current with high time constant
- Compatibility with QPS at start up
- Tracking
- No lagging and no overshoot

Power converters with unprecedented precision (a few ppm) over a very large dynamic range ($10^4$)
What needs to be tested for the power converters?

~1700 circuits

- Regulation loop (with huge time constant: up to 6h)
- Free-wheel system at nominal current with high time constant
- Compatibility with QPS at start up
- Tracking
- No lagging and no overshoot
- Inner triplet
What needs to be tested for the power converters?

- Regulation loop constant: up to 60 A
- Free-wheel switching current with inner triplet
- Compatibility
- Tracking
- No lagging at 0 A
- Inner triplet

---

**Diagram:**

- **RQTX1:** ±600A, ±10V, FWT 7kA
- **RQTX2:** 5kA, 8V

**Q1:**
- Ultimate current: 8960 A
- L = 90.7 mH

**Q2a and Q2b:**
- Ultimate current: 12290 A
- L = 2 x 18.5 mH

**Q1:**
- Ultimate current: 8960 A
- L = 90.7 mH

---

**Graph:**

- Timeseries Chart between 2008-04-24 17:45:00 and 2008-04-24 19:53:00 (UTC_TIME)
Powering Groups of Circuits

176 converters ramped to nominal
Installation and commissioning of …

✓ the warm magnets
✓ the injection systems
✓ the beam dumping system
✓ the collimators
✓ the RF system
✓ the beam instrumentation
✓ the vacuum system
✓ the control system

…

are vital from day 1 for beam operation
SPS- LHC Transfer Lines: T18 and T12

Combined length 5.6 km, over 700 magnets, ~ 2/3 of SPS

Transfer Lines Tests: TI 8 and TI 2

23.10.2004, 13:39 → first beam at end of TI 8

TI 8 beam tests
23./24.10.04
6./7.11.04

Length of beam line: 2941 m
Length of new tunnel: 2631 m
Horizontal deflection: 50.3 m
Vertical deflection: 4.3 m
In view of the first injections into LHC, the beam commissioning of the TI2 and TI 8 lines, was resumed with new successful tests in May and June 2008.
Lead ions: LEIR and the PS commissioning have been performed in 2005 and 2006 and finally the last machine of the injectors, the SPS, in 2007.

The 4 bunch "early" ion beam has been injected and accelerated in the SPS, with quasi-nominal intensity (6E7 ions/bunch), transverse emittances (1.2 microns), and bunch length (1.8ns). Some extraction tests into TT60 have also been successfully performed.

D.Manglunki et al, "Ions for LHC: towards completion of the injection chain" Poster session
The training quenches and 5 TeV strategy

- To meet the summer 2008 deadline for commissioning with beam a reduced beam energy 5 TeV was proposed to the experiments and was accepted.
- The fact that 5 TeV energy level can be easily reached, has been proven in Sector 4-5, Sector 5-6 and Sector 7-8 (commissioned at 5.5 TeV)
- Nevertheless, a quench campaign on the dipoles of Sector 5-6 has been started to find out how much time will be needed to get to 7 TeV.
Beam first stage: 5TeV collisions

\[ L = \frac{N^2 k_b f g}{4 \pi \varepsilon_\gamma \beta^*} F \]

- Approx 30 days of beam to establish first collisions
- Approx 2 months elapsed
  - Given optimistic machine availability
  - Un-squeezed
  - Low intensity
- Continue commissioning thereafter
  - Increased intensity
  - Squeeze

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Rates in 1 and 5</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Luminosity (cm(^{-2})s(^{-1}))</td>
</tr>
<tr>
<td>(k_b) 1 (3)</td>
<td>10(^{10})</td>
</tr>
<tr>
<td>4</td>
<td>10(^{10})</td>
</tr>
<tr>
<td>43</td>
<td>10(^{10})</td>
</tr>
<tr>
<td>43</td>
<td>4 \times 10(^{10})</td>
</tr>
<tr>
<td>43</td>
<td>4 \times 10(^{10})</td>
</tr>
<tr>
<td>156</td>
<td>4 \times 10(^{10})</td>
</tr>
<tr>
<td>156</td>
<td>9 \times 10(^{10})</td>
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</table>

Achievable (in 1 and 5)

30 days of physics
Efficiency for physics 40%
Peak luminosity around \(10^{31} \text{ cm}^{-2} \text{ s}^{-1}\)
Integrated luminosity \(\sim 10 \text{ pb}^{-1}\)
<table>
<thead>
<tr>
<th>Hardware commissioning</th>
<th>Machine checkout</th>
<th>Beam commissioning 5TeV</th>
<th>43/156 bunch operation</th>
<th>Train to 7TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>To 5TeV</td>
<td></td>
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</table>

2008

No beam → Beam

Courtesy R. Bailey
Strategy for 2008 and 2009

2008

Hardware commissioning To 5TeV

Machine checkout

Beam commissioning 5TeV

43/156 bunch operation

Train to 7TeV

No beam

Beam

Courtesy R. Bailey
Aims for 2009

- Commission high energy operation
  - Aim for 7TeV (magnets will decide)
  - 43 / 156 bunch running to start (brief)
  - 75ns running
  - 25ns running
  - High $10^{32}$ cm$^{-2}$ s$^{-1}$ is in reach

- Mixture of
  - Operation for physics
  - Machine studies
  - Scheduled stops
  - Access, injection, ramp, squeeze, ...
  - Colliding beams
  - Ion run (to be confirmed)

Realistically (in 1 and 5)

- 150 days of physics
- Efficiency for physics 40%
- Peak luminosity around $10^{33}$ cm$^{-2}$ s$^{-1}$

Integrated luminosity $\sim$ few fb$^{-1}$

$(10^6$ seconds $@ <L>$ of $10^{33}$ cm$^{-2}$ s$^{-1} \rightarrow 1$ fb$^{-1}$)

Courtesy R. Bailey
R. Saban
LHC Hardware Commissioning Summary
Monday 23rd June 15:30 MOZDM01

J.M. Jimenez
LHC: The World's Largest Vacuum Systems being Commissioned at CERN
Wednesday 25th June 12:10 WEOBM04

P. Lebrun
Collaborating with Industry: Lessons from the LHC Megaproject
Wednesday 25th June 14:30 WElM02

R. Garoby
Upgrade Issues for the CERN Accelerator Complex
Friday 27th June at 11:00 FRYAGM01
Conclusion: Schedule for 2008

- One sector (5-6) give to Operation group for dry runs
  (-> powering of ALL circuits in parallel for injection, ramp and squeeze)
- The last sector (4-5) will be at 1.9 K by mid July
- First beam injected early August
- Colliding beams at 10 TeV in 2008

It’s the place where to be this summer!
Conclusion

As any large and complex project, LHC is not all plain sailing but CERN and collaborations have shown an impressive reactive force to overcome the obstacles and continued progressing towards its target of completing the LHC for physics.

The commissioning and the operation of the LHC machine are and will be an absorbing and captivating period

Beam is imminent!