LHC Progress and Commissioning Plans

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(for the LHC commissioning team)
Contents

- LHC layout overview and main parameters
- Project status
- Main challenges for the commissioning
- Commissioning plan
LHC Layout and Main Parameters

- 2-in-1 magnet design
  - p-p & Pb-Pb collisions

- 7 TeV p-beam energy
  - > 1 TeV CM energy
  - Higgs discovery

- 2 high L experiments with
  - $L = 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$
  - 2808 bunches / beam
    - with $1.15 \times 10^{11}$ ppb

- 2 low L experiments:
  - ALICE (Pb-Pb) & LHCb
LHC Layout and Main Parameters

- built in old LEP tunnel
  - 8.4 T dipole magnets
  - 10 GJ EM energy
  - powering in 8 sectors
- 2808 bunches per beam with 1.15 \(10^{11}\) ppb
  - 360 MJ / beam
  - crossing angle & long range beam-beam
- Combined experiment/injection regions

[A. Koschik et al, TUPLS014] [A. Koschik et al, WEPCH043]
2-in-1 dipole magnet design
8.4 T, 15 m long, 30 Ton
Project Status

Main dipole (MB) production and installation (1232)
- almost all MB have been delivered to CERN (November 2006)
- all MB will have passed cold test by end of 2006
- 3/4 have been prepared for installation and slot assigned
- almost 50% have been installed in the tunnel
  installation is expected to progress at rate of 18 MB / week

Main quadrupole (MQ) production and installation (392)
- almost all MQ have been delivered to CERN
- 1/3 of the assemblies have been installed in the tunnel
- 2/3 have been slot assigned
  installation is expected to progress at rate of 6 assemblies / week

closure of machine in March 2007, interconnect and pressure test August 2007
Cryodipole overview

Updated 31 May 2006

Data provided by D. Tommasini AT-MAS, L. Bottura AT-MTM
LHC Installation

Q6 with cryogenic connection in IR8

superconducting link
cryogenic distribution in 12
electrical distribution in IR8
LHC Installation
Main Challenges for the Operation

- Mechanical aperture
- Polarity errors
- Global magnet field quality & corrector circuit powering
- Collimation efficiency
- Beam power and machine protection
- Collective effects and impedance
- Triplet aperture and beam-beam
- Electron cloud effect
Mechanical Aperture

- all magnets are geometrically measured

- classification & slot compatibility for installation at critical locations

- microwave reflectrometer:
  - detection of obstacles

[T. Kroyer et al, WEPLS141]
Polarity Errors

the LHC features 112 circuits / beam (+ orbit correctors)

all magnet circuits are tested before and during installation

[D. Bozzini et al, WEPLS099]

adjustments during operation

→ non-destructive beam instrumentation

[P. Cameron et al, THPCH105]
Global Magnetic Field Quality

Field quality measurement before installation:
- All magnets are measured warm at industry ➔ monitoring
- All magnets are cold tested ➔ electrical integrity & quench
- A subset undergoes cold measurements ➔ warm-cold correlation

➔ ‘Sorting’ during installation
  Sector 78 V1
  [S. Fartoukh, EPAC 2004]

- A smaller subset is subject to ‘extended’ measurements
  ➔ field quality modeling during operation ➔ corrector powering!

[N. Sammut et al, WEPLS104] [G. Rijk, WEPLS100]
Collimation Efficiency

Machine operation requires high collimation efficiency:

Collimation inefficiency := \#p above 10 \(\sigma\) / \# p on primary

\(\Rightarrow\) design value of 2 \(10^{-3}\) \(\Rightarrow\) below 0.2 h / 2 h are acceptable

\(\Rightarrow\) 2 stage collimation system with ca 100 collimators!

Effect of machine imperfections:

\(\Rightarrow\) requires good optic and orbit control! \(\Rightarrow\) feedback loops

[R. Assmann, TUODFI01] [C. Bracco et al, TUPLS018] [G Robert-Demolaize TUPLS019]
[S. Redaelli, TUPLS130 and TUPLS131]
Unprecedented beam power:

- potential equipment damage in case of failures during operation
- in case of failure the beam must never reach sensitive equipment!

Machine Protection System

- Beam Loss Monitors
- Quench protection system
- Beam Interlock System
- reliable Beam Dump system (15)
- dedicated absorbers in case of asynchronous dump

[R. Filippini et al, WEPLS140] [B. Goddard et al, MOPLS008] [B. Goddard et al, TUPLS013]
Unprecedented beam power:

- all absorbers and the collimation system must be designed to survive an asynchronous beam dump!
  (total of up to 136 collimators & absorbers)

Robust collimator jaw design

- fiber reinforced graphite jaws are more robust than Cu jaws
- fiber reinforced graphite has a higher impedance and electrical resistivity

[R. Assmann, TUODFI01] [F. Zimmermann et al, THPCH061]
Collective Effects & Impedance

- resistive wall impedance:
  - image charges trail behind due to resistivity of surrounding materials
  - Wake fields drive beam instabilities
  - effect increases with decreasing gap opening of the collimator jaws

- impedance of Graphite jaws either limits the minimum collimator opening ➔ limit for $\beta^*$ or the maximum beam current

[F. Zimmermann et al, THPCH061]

phased collimation system for the LHC:

- Phase 1: graphite jaws for robustness during commissioning
- Phase 2: nominal performance (low impedance, non-linear or feedback)

[R. Assmann, TUODFI01][J. Resta MOPCH091][A. Faus-Golfe WEXFI03]
long range beam-beam:

Operation with 2808 bunches features approximately 30 unwanted collision points per Interaction Region (IR).

⇒ Operation requires crossing angle

non-linear fields and additional focusing due to beam-beam

efficient operation requires large beam separation at unwanted collision points ⇒ separation of 9 σ is at the limit of the triplet aperture for nominal β* values! ⇒ margins can be introduced by operating with fewer bunches, lower bunch intensities, larger β* values (or larger triplet apertures ⇒ upgrade studies)
Electron Cloud Effect

Synchrotron light releases electrons from beam screen:

- electrons get accelerated by p-beam ➔ impact on beam screen
- generation of secondary electrons ➔ e-cloud
- heating, instabilities and emittance growth

- effect disappears for low bunch currents or large bunch spacing
- secondary emission yield decreases during operation (beam scrubbing)

[E. Benedetto, THPCH018]

[F. Zimmermann]
## Staged Commissioning Plan for Protons

<table>
<thead>
<tr>
<th>Stage I</th>
<th>Stage II</th>
<th>Stage III</th>
<th>Stage IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardware commissioning</td>
<td>Machine checkout</td>
<td>Beam commissioning</td>
<td>43 bunch operation</td>
</tr>
<tr>
<td>No beam</td>
<td>Beam</td>
<td>Beam</td>
<td>Beam</td>
</tr>
</tbody>
</table>

### I. Pilot physics run
- First collisions
- 43 bunches, no crossing angle, no squeeze, moderate intensities
- Push performance (156 bunches, partial squeeze in 1 and 5, push intensity)

### II. 75ns operation
- Establish multi-bunch operation, moderate intensities
- Relaxed machine parameters (squeeze and crossing angle)
- Push squeeze and crossing angle

### III. 25ns operation I
- Nominal crossing angle
- Push squeeze
- Increase intensity to 50% nominal

### IV. 25ns operation II
- Push towards nominal performance

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[R. Bailey et al, MOPLS005]
Staged Commissioning: Tolerances at 7 TeV

0.8 mm at a typical collimator

0.2 mm at a typical collimator

[R. Assmann]
Summary

- Mechanical aperture
- Polarity errors
- Global magnet field quality & corrector circuit powering
- Collimation efficiency
- Beam power and machine protection
- Collective effects and impedance
- Triplet aperture and beam-beam
- Electron cloud effect

- careful analysis and definition of procedures during installation
  - optimization in Stage I
- from Stage I to Stage II
- only at Stage III
- only > Stage III
- only at Stage IV
Stage I physics run

- Start as simple as possible
- Change 1 parameter \((k_b N \beta^*_1, 5)\) at a time

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

Protons/beam \(\lesssim 10^{13}\)
(LEP beam currents)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Beam levels</th>
<th>Rates in 1 and 5</th>
<th>Rates in 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(k_b)</td>
<td>(N)</td>
<td>(\beta^*)</td>
<td>(I_{\text{beam}})</td>
</tr>
<tr>
<td>1</td>
<td>(10^{10})</td>
<td>18</td>
<td>(1 \times 10^{10})</td>
</tr>
<tr>
<td>43</td>
<td>(10^{10})</td>
<td>18</td>
<td>(4.3 \times 10^{11})</td>
</tr>
<tr>
<td>43</td>
<td>(4 \times 10^{10})</td>
<td>18</td>
<td>(1.7 \times 10^{12})</td>
</tr>
<tr>
<td>43</td>
<td>(4 \times 10^{10})</td>
<td>2</td>
<td>(1.7 \times 10^{12})</td>
</tr>
<tr>
<td>15/6</td>
<td>(4 \times 10^{10})</td>
<td>2</td>
<td>(6.2 \times 10^{12})</td>
</tr>
<tr>
<td>15/6</td>
<td>(9 \times 10^{10})</td>
<td>2</td>
<td>(1.4 \times 10^{13})</td>
</tr>
</tbody>
</table>

Stored energy/beam \(\lesssim 10\text{MJ}\)
(SPS fixed target beam)
Stage II physics run

- Relaxed crossing angle (250 μrad)
- Start un-squeezed
- Then go to where we were in stage I

### Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Beam levels</th>
<th>Rates in 1 and 5</th>
<th>Rates in 2 and 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_b$</td>
<td>N</td>
<td>I$_{beam}$, proton</td>
<td>E$_{beam}$ (MJ)</td>
</tr>
<tr>
<td>936</td>
<td>$4 \times 10^{10}$</td>
<td>18</td>
<td>$3.7 \times 10^{13}$</td>
</tr>
<tr>
<td>936</td>
<td>$4 \times 10^{10}$</td>
<td>2</td>
<td>$3.7 \times 10^{13}$</td>
</tr>
<tr>
<td>936</td>
<td>$4 \times 10^{10}$</td>
<td>1</td>
<td>$3.7 \times 10^{13}$</td>
</tr>
<tr>
<td>936</td>
<td>$9 \times 10^{10}$</td>
<td>1</td>
<td>$8.4 \times 10^{13}$</td>
</tr>
</tbody>
</table>

Protons/beam ≈ few $10^{13}$

Stored energy/beam ≤ 100MJ

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

Event rate / Cross = \[
\frac{L \sigma_{\text{TOT}}}{k_b f}
\]
Stage III physics run

- Nominal crossing angle (285 μrad)
- Start un-squeezed
- Go to where we were in stage II

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Beam levels</th>
<th>Rates in 1 and 5</th>
<th>Rates in 2 and 8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k_b N β* 1,5 (m) l_{beam} E_{beam} (M) luminosity (cm²s⁻¹) Events/crossing</td>
<td>luminosity (cm²s⁻¹)</td>
<td>Events/crossing</td>
</tr>
<tr>
<td>2808 4 10¹⁰ 18</td>
<td>1.1 10¹⁴ 126</td>
<td>4.4 10³¹ &lt;&lt; 1</td>
<td>7.9 10³¹ 0.15</td>
</tr>
<tr>
<td>2808 4 10¹⁰ 2</td>
<td>1.1 10¹⁴ 126</td>
<td>3.8 10³² 0.72</td>
<td>7.9 10³¹ 0.15</td>
</tr>
<tr>
<td>2808 5 10¹⁰ 2</td>
<td>1.4 10¹⁴ 157</td>
<td>5.9 10³² 1.1</td>
<td>1.2 10³² 0.24</td>
</tr>
<tr>
<td>2808 5 10¹⁰ 1</td>
<td>1.4 10¹⁴ 157</td>
<td>1.1 10³³ 2.1</td>
<td>1.2 10³² 0.24</td>
</tr>
<tr>
<td>2808 5 10¹⁰ 0.55</td>
<td>1.4 10¹⁴ 157</td>
<td>1.9 10³³ 3.6</td>
<td>1.2 10³² 0.24</td>
</tr>
<tr>
<td>Nominal</td>
<td>3.2 10¹⁴ 362</td>
<td>10³⁴ 19</td>
<td>6.5 10³² 1.2</td>
</tr>
</tbody>
</table>

Protons/beam ≈ 10¹⁴
Stored energy/beam ≥ 100MJ
Five geometry sub-classes for the LHC main dipoles and their variants used in the sorting algorithm to preserve aperture

Golden R (GR)

Mid-cell (MC)

Silver L (SL)

Silver R (SR)

Golden L (GL)

\[ S \subseteq SLR = SL \cap SR \subseteq MC \]

\[ G \subseteq GLR = GL \cap GR \subseteq SLR \]

GL \subseteq SL and GR \subseteq SR

but

GL \not\subseteq S and GR \not\subseteq S
Global Magnetic Field Quality

Field quality measurement before installation:

- All magnets are measured warm at industry ▶ monitoring
- All magnets are cold tested ▶ electrical integrity & quench
- A subset undergoes cold measurements ▶ warm-cold correlation ▶ ‘sorting’ during installation
  [S. Fartoukh, EPAC 2004]
- A smaller subset are subject to ‘extended’ measurements ▶ field quality modeling during operation ▶ corrector powering!
  [N. Sammut et al, WEPLS104] [G. Rijk WEPLS100]