Large Hadron Collider commissioning and first operation

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A history of the commissioning and the very successful early operation of the Large Hadron Collider (LHC) is described. The accident that interrupted the first commissioning, its repair and the enhanced protection system put in place are fully described. The LHC beam commissioning and operational performance are reviewed for the period from 2010 to mid-2011. Preliminary plans for operation and future upgrades for the LHC are given for the short and medium term.

Keywords: particle accelerators; commissioning; Large Hadron Collider

1. Introduction: Large Hadron Collider technical challenges

The design of the Large Hadron Collider (LHC) [1] involved many technical challenges and innovations. Table 1 gives a short list of some of the most notable challenges with some comments.

The magnetic system provides the highest superconducting field (8.4 T) ever used for an accelerator and in addition employs ‘double-barrel’ magnets where the apertures of both beams are within the same cold mass. The cryogenic system [2] is the largest ever built and operates at 1.9 K, and the power converters [3] have a resolution of less than 1 ppm, and use a powering circuit for each octant of the machine.

Of constant major concern is the stored energy in the magnets and in the beam. For this reason, the protection systems [4], including the collimation system [5], are crucial in the operation of the collider.

2. Accident of 19 September 2008

The scheduled start-up with beam on 10 September 2008 could not have gone better. Both beams made a full machine turn within hours and one beam was captured by the radio frequency (RF) system. Following this impressive beginning, a technical problem arose with an electrical transformer that necessitated stopping commissioning for several days. During this stop, it was

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†On behalf of the LHC team and international collaborators.

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Table 1. Technical challenges of the LHC.

<table>
<thead>
<tr>
<th></th>
<th>26.7</th>
<th>100–150 m underground</th>
</tr>
</thead>
<tbody>
<tr>
<td>circumference (km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of superconducting dipoles</td>
<td>1232</td>
<td>cable Nb-Ti, cold mass 37 million kg</td>
</tr>
<tr>
<td>length of dipole (m)</td>
<td>14.3</td>
<td></td>
</tr>
<tr>
<td>dipole field strength (T)</td>
<td>8.4</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>current in dipole SC coils (A)</td>
<td>13000</td>
<td>results from the high magnetic field</td>
</tr>
<tr>
<td>beam intensity (A)</td>
<td>0.5</td>
<td>$2.2 \times 10^{-6}$ loss causes quench</td>
</tr>
<tr>
<td>beam stored energy (MJ)</td>
<td>362</td>
<td>results from high beam energy and high beam current</td>
</tr>
<tr>
<td>magnet stored energy (MJ)/octant</td>
<td>1100</td>
<td>1 MJ melts 1.5 kg Cu</td>
</tr>
<tr>
<td>sector powering circuit</td>
<td>8</td>
<td>1612 different electrical circuits</td>
</tr>
</tbody>
</table>

decided to test the last octant (sector 3–4) up to 9.3 kA, the dipole current required for operation at 5 TeV per beam. At 8.7 kA, a resistive zone developed in the dipole busbar magnet interconnects. This led to thermal runaway in the interconnect, followed by the development of an electrical arc, initially across the interconnect, later puncturing the helium enclosure, and finally puncturing the beam pipes. The release of the helium caused a pressure wave over a region of more than 400 m, resulting in damage to magnets and interconnects and pollution of the ultra-high-vacuum system.

An inquiry by CERN specialists [6] indicated several causes of the substantial damage to the machine:

— there was an absence of solder on the offending magnet interconnect, giving a contact resistance of $220 \, \text{n\Omega}$ (design approx. $1 \, \text{n\Omega}$);
— there was poor electrical contact between the superconducting cable and the copper stabilizing busbar;
— the fault detection of the interconnect was not sensitive enough;
— the pressure relief ports were under-dimensioned for an accident of this magnitude; and
— the anchorage of the magnets to the tunnel floor was inadequate.

Figure 1 shows the first page of a three-page fault tree describing in detail the evolution of events immediately following the thermal runaway.

3. The repair

Following the initial investigation of the resulting damage, a crash programme was set up to deal with the repair and consolidation of the LHC. The teams included many CERN partners, collaborators, detector people as well as the accelerator sector. The task was enormous and required not only repairing the damaged components but equally importantly re-engineering many elements so that such an accident would never recur in the future.
internal fact-finding group (P. Lebrun)

fault tree (1/3)

absence of soldering  
no sensitive detection on busbar

resistance 200 nΩ  
bad contact with stabilizer

current runaway

meltdown, open circuit  
power converter fast discharge

electrical arc

Figure 1. Fault tree.

Figure 2 shows a schematic of the main elements of the repair in the damaged part of the tunnel. A total of 39 dipole magnets (marked 2 in the diagram) were required to be replaced. This of course used up all available spares. In addition, 14 quadrupole magnets needed to be replaced (1) and a total of 54 damaged magnet
Figure 3. Measurements of the resistance of the superconducting inter-magnet splice resistances (white lines are the calculated resistances of the splices). (a) Quadrupoles and (b) dipoles.

interconnects needed full repair (3) with around 150 extra (3) needing partial repair. More than 4 km of ultra-high-vacuum beam tube (4) required removal of pieces of super-insulation and black soot followed by careful cleaning [7]. A new longitudinal restraining system (5) was designed and installed on 50 quadrupole magnets. All existing flanges on the magnets were equipped with additional pressure relief ports (typically 10 cm diameter) and 20 cm flanges were cut on dipoles and equipped with double size pressure relief ports. In total, 900 helium pressure relief ports were added (6).

A major task was the upgrade [8] of the magnet protection system, which had proved too insensitive to protect the interconnect splices. The new design is now 3000 times more sensitive than the older system and involves 6500 new detectors (7) and the installation of more than 250 km of cable. A major added advantage of the new magnet protection system is that it gives the possibility of measuring, to sub-nΩ precision, the resistance of all inter-magnet splices in the machine (see figure 3 for results) [9].
4. The copper stabilizer busbars

The completed inter-magnet busbar splice is designed, as shown in figure 4, for two separate functions. First, at superconducting temperatures, it provides perfect electrical contact between the joined superconducting cable braids, and, second, at non-superconducting temperatures (in the event of a quench for example), it ensures electrical continuity across the copper sheath. Hence, in the event of a quench when the superconducting cable has a finite resistance, the copper sheath ‘shunts’ the current away from the superconducting cable while the stored energy is being extracted from the magnet. In this way, the superconducting cable is protected in the case of a quench by the large cross section of the copper stabilizer. If there is no electrical continuity across the copper stabilizer, then the decaying current following a quench will flow through the superconducting cable (which is no longer superconducting) and possibly cause thermal runaway. The quality of a splice is therefore determined by the resistance across the splice measured both at superconducting temperatures and at non-superconducting temperatures. Figure 5 shows a completed busbar as installed in the LHC.

The enhanced quality assurance introduced during the repair of sector 3–4 revealed new concerns about the copper busbar in which the superconductor is embedded. Tests demonstrated that the soldering process can cause discontinuities in the copper part of the busbars and produce voids that prevent contact between the superconducting cable and the copper stabilizer. Consequently, in 2009, a campaign was started to measure the splice resistance [9] at room temperature. The in situ measurement technique had a limited

Figure 4. Exploded diagram of an inter-magnet busbar.
precision corresponding to approximately a factor of 3 higher than the resistance of a perfect splice. Consequently, this technique could only be used to identify ‘outliers’ that had a significantly increased resistance. On identification of outliers, a much more precise measurement (which involved the overhead of opening the interconnect) could be performed. In this way, all significant outliers were identified and repaired. However, the limited precision of the in situ measurement implied that some splices may have resistances significantly above the design value. Calculations, simulations and experimentation revealed that the maximum current that can flow in the interconnects without causing thermal runaway was less than the currents needed for maximum beam energy. It was therefore decided to operate the LHC (for a limited period) at a safe energy compatible with the existing situation of the already installed splices. The decision was taken to operate for data collected at 3.5 TeV per beam until the end of 2012 and then in a shut-down in 2013 to repair and consolidate the splices [10] in such a way that they would be safe for maximum LHC energy and for the lifetime of the machine.

5. First beam in November 2009

Following the repair and the hardware commissioning in 2009, there was a time slot of 26 days remaining before the end of the year. It was decided to use this time to operate with beam at a maximum dipole current of 2000 A, which is equivalent to 1.18 TeV per beam.

During this short test period, beams were injected in both rings, stable beam collisions were performed at 450 GeV and beams were accelerated to 1.18 TeV per beam, where a limited amount of physics data collection was performed (see table 2, which gives the highlights of this period).

6. First collisions at 7 TeV in March 2010

The day of the first collisions at 7 TeV centre-of-mass energy was planned for 30 March 2010. The first two attempts at collisions resulted in beam losses

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Table 2. Highlights of first 26 days of LHC operation with beam in 2009.

<table>
<thead>
<tr>
<th>date</th>
<th>day</th>
<th>achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 Nov</td>
<td>1</td>
<td>each beam circulating; key beam instrumentation working</td>
</tr>
<tr>
<td>23 Nov</td>
<td>4</td>
<td>first collisions at 450 GeV; first ramp (reached 560 GeV)</td>
</tr>
<tr>
<td>26 Nov</td>
<td>7</td>
<td>magnetic cycling established (reproducibility)</td>
</tr>
<tr>
<td>27 Nov</td>
<td>8</td>
<td>energy matching</td>
</tr>
<tr>
<td>29 Nov</td>
<td>10</td>
<td>ramp to 1.18 TeV</td>
</tr>
<tr>
<td>30 Nov</td>
<td>11</td>
<td>experiment solenoids on</td>
</tr>
<tr>
<td>04 Dec</td>
<td>15</td>
<td>aperture measurement campaign finished; LHCb and ALICE dipoles on</td>
</tr>
<tr>
<td>05 Dec</td>
<td>16</td>
<td>machine protection (injection, beam dump, collimators)</td>
</tr>
<tr>
<td>06 Dec</td>
<td>17</td>
<td>first collisions with STABLE BEAMS, 4 on 4 pilots at 450 GeV, rates around 1 Hz</td>
</tr>
<tr>
<td>08 Dec</td>
<td>19</td>
<td>ramp colliding bunches to 1.18 TeV</td>
</tr>
<tr>
<td>11 Dec</td>
<td>22</td>
<td>collisions with STABLE BEAMS, 4 on 4 at 450 GeV, &gt; 10^{10} per bunch, rates around 10 Hz</td>
</tr>
<tr>
<td>13 Dec</td>
<td>24</td>
<td>collisions with STABLE BEAMS, 16 on 16 at 450 GeV, &gt; 10^{10} per bunch, rates around 50 Hz</td>
</tr>
<tr>
<td>16 Dec</td>
<td>27</td>
<td>ramp 4 on 4 to 1.18 TeV; squeeze to 7 m</td>
</tr>
</tbody>
</table>

for minor technical reasons. On the third attempt, the beams were successfully brought into collision [11]; a very joyous moment.

The very first events with collisions at 7 TeV are shown for the four detectors in figure 6, and the first two physics runs at this energy are depicted in figure 7.

7. Progress in 2010

During 2010, the LHC operation was divided between machine studies to increase the luminosity and physics data collection. The luminosity increase concentrated on increasing the current per bunch, the number of bunches and reducing the $\beta^*$ in the collision points. The rate of progress was impressive; nevertheless, before each step was taken in increasing the intensity and hence the stored beam energy, all machine protection systems were validated up to the necessary level.

The LHC machine protection system [4] is probably one of the most intricate accelerator systems ever operated. It relies on very stringent control of the optics of the machine, both locally and globally. For all protection devices, there are closed orbit constraints as well as $\beta$ value constraints. Hence, any effects that are intensity dependent (e.g. closed orbit measurement and $\beta^*$ measurement) complicate the procedure for finalizing the protection.

The collimation system [5] is part of the machine protection system and the collimators must intercept almost the totality of any beam losses if they are to protect the rest of the machine. The hierarchy of the collimation system (primary, secondary and tertiary) must be respected. This implies a stringent control of the $\beta$ functions and the closed orbits at the collimators at all beam energies and throughout the ‘squeeze’ of the low-$\beta$ insertions. The $\beta$ functions are
Figure 6. First events at 7 TeV in the four LHC detectors.

Figure 7. First physics runs at 7 TeV (lower plots are intensity of beam 1/2, respectively; uppermost plot is the beam energy).
measured and corrected [12], and the orbits are subjected to a feedback control with threshold limits. There is a watchdog monitoring the orbit deviations at the locations of the collimators and, if the limits are violated, the beam is dumped. A similar system is employed at the location of the beam dump extraction kicker. The tolerances set on the \( \beta \) ‘beating’ are around 20 per cent and figure 8 shows the first measurements made at beam energies between 1.5 and 3.5 TeV. In recent months (2011), the \( \beta \) ‘beating’ has been corrected to around 10 per cent, a factor of 2 better than the specifications.

In order to measure the cleaning efficiency of the collimation system, ‘loss maps’ are made by provoking beam losses around the circumference. When the collimators are well set up and the hierarchy of losses is correct, the vast majority of all losses should be localized at the collimator. Figure 9 shows one of the early measurements, in which it can be seen that the ratio between the losses at the collimators and the worst cold location is about a factor of 10,000. It has been found that the settings of the collimators remain constant for periods of at least weeks.

From a technical point of view, the very fast initial progress made in commissioning the LHC is due to many factors. To mention just a few:

— the dedication and expertise of the LHC staff;
— the excellent performance of the diagnostics and feedback systems [13];
— the quality of the optics settings stemming from the quality of the magnetic fields, the magnetic modelling and the optics modelling [14–16]; this has allowed fast changes to new conditions with high degrees of confidence;
— the robust applications software that has been well tested in the other CERN accelerators; and
— the reliability of all the technical components (e.g. the RF system [17]) of the LHC as well as the injectors.
There are numerous examples of the high quality of the diagnostics and its implementation into the controls applications. Figure 10 shows one such example. In order to measure the chromaticity during the energy ramp, the beam momentum is modulated by varying the RF and the transverse tunes are measured by a phase lock loop.

Another early example is given in figure 11, which shows the operation of orbit feedback during the energy ramp. The three plots show the mean, r.m.s. orbit distortion and the momentum deviation. The maximum r.m.s. orbit change during the ramp is 0.08 mm.
8. Operational performance in 2010

(a) Protons in 2010

As previously stated, LHC has been operating in shared mode between beam commissioning and physics data collection during 2010. The equation for the luminosity is

$$ L = \frac{n_b \cdot N_{\text{bunch},1} \cdot N_{\text{bunch},2} \cdot f_{\text{rev}}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot R(\phi, \beta^*, \varepsilon_n, \sigma_s), $$

where $n_b$ is the number of bunches per beam; $N$ represents the number of protons in a single bunch; $\beta^*$ is the insertion region focusing parameter; $\varepsilon_n$ is the normalized emittance (related to the cross-sectional dimension of the beam) and $R$ is the interaction region geometric factor.

Table 3 shows the evolution of the beam performance from the first collisions in March 2010 until the middle of August (the machine status is in the row event number, and at each event there were several days of operation under these conditions). During the first period (events 1–6), the total number of bunches (column marked Nb) was increased from the initial value of 2–13 and the interaction region focusing parameter $\beta^*$ was reduced to 2 m for most of the events. This progression in parameters produced an increase in the peak luminosity of around a factor of 250 during this first data collection period.

For the second period (events 7–12), the intensity per bunch ‘$i_b$’ was increased to near the design value of $1.15 \times 10^{11}$, the $\beta^*$ was set to 3.5 m and the number of bunches was progressively increased from 3 to 48. This progression resulted in peak luminosities reaching close to $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$. The stored energy (in mega-joules) in each beam (‘$\text{MJ}$’) reached above 1 MJ in event 11. From experience in previous accelerators, it is known that this amount of stored energy is sufficient to puncture and melt fairly large sections of the vacuum chamber. Increases in the mega-joules from this point onwards was only authorized after a rigorous protocol in the validation of the machine protection system.

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Table 3. Initial performance evolution.

<table>
<thead>
<tr>
<th>event</th>
<th>TeV</th>
<th>OEF</th>
<th>$\beta^*$</th>
<th>Nb</th>
<th>ib</th>
<th>itot</th>
<th>MJ</th>
<th>Nc</th>
<th>peak luminosity</th>
<th>date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.5</td>
<td>0.2</td>
<td>10</td>
<td>2</td>
<td>2</td>
<td>1.00e + 10</td>
<td>2.0e + 10</td>
<td>0.0113</td>
<td>1</td>
<td>8.9e + 26</td>
</tr>
<tr>
<td>2</td>
<td>3.5</td>
<td>0.2</td>
<td>10</td>
<td>2</td>
<td>4</td>
<td>2.00e + 10</td>
<td>4.0e + 10</td>
<td>0.0226</td>
<td>1</td>
<td>3.6e + 27</td>
</tr>
<tr>
<td>3</td>
<td>3.5</td>
<td>0.2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2.00e + 10</td>
<td>4.0e + 10</td>
<td>0.0226</td>
<td>1</td>
<td>1.8e + 28</td>
</tr>
<tr>
<td>4</td>
<td>3.5</td>
<td>0.2</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>2.00e + 10</td>
<td>8.0e + 10</td>
<td>0.0452</td>
<td>2</td>
<td>3.6e + 28</td>
</tr>
<tr>
<td>5</td>
<td>3.5</td>
<td>0.2</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>2.00e + 10</td>
<td>1.2e + 11</td>
<td>0.0678</td>
<td>4</td>
<td>7.1e + 28</td>
</tr>
<tr>
<td>6</td>
<td>3.5</td>
<td>0.2</td>
<td>2</td>
<td>13</td>
<td>2</td>
<td>2.60e + 10</td>
<td>3.4e + 11</td>
<td>0.1910</td>
<td>8</td>
<td>2.4e + 29</td>
</tr>
<tr>
<td>7</td>
<td>3.5</td>
<td>0.2</td>
<td>3.5</td>
<td>3</td>
<td>3</td>
<td>1.10e + 11</td>
<td>3.3e + 11</td>
<td>0.1865</td>
<td>2</td>
<td>6.1e + 29</td>
</tr>
<tr>
<td>8</td>
<td>3.5</td>
<td>0.2</td>
<td>3.5</td>
<td>6</td>
<td>1</td>
<td>1.00e + 11</td>
<td>6.0e + 11</td>
<td>0.3391</td>
<td>4</td>
<td>1.0e + 30</td>
</tr>
<tr>
<td>9</td>
<td>3.5</td>
<td>0.2</td>
<td>3.5</td>
<td>8</td>
<td>2</td>
<td>9.00e ± 10</td>
<td>7.2e + 11</td>
<td>0.4069</td>
<td>6</td>
<td>1.2e + 30</td>
</tr>
<tr>
<td>10</td>
<td>3.5</td>
<td>0.2</td>
<td>3.5</td>
<td>13</td>
<td>2</td>
<td>9.00e + 10</td>
<td>1.2e + 12</td>
<td>0.6612</td>
<td>8</td>
<td>1.6e + 30</td>
</tr>
<tr>
<td>11</td>
<td>3.5</td>
<td>0.2</td>
<td>3.5</td>
<td>25</td>
<td>2</td>
<td>1.00e + 11</td>
<td>2.5e + 12</td>
<td>1.4129</td>
<td>16</td>
<td>4.1e + 30</td>
</tr>
<tr>
<td>12</td>
<td>3.5</td>
<td>0.2</td>
<td>3.5</td>
<td>48</td>
<td>2</td>
<td>1.00e + 11</td>
<td>4.8e + 12</td>
<td>2.7127</td>
<td>36</td>
<td>9.1e + 30</td>
</tr>
</tbody>
</table>

Table 4. Performance evolution with bunch trains.

<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>
</tr>
</thead>
<tbody>
<tr>
<td>56</td>
<td>1.10e + 11</td>
<td>3.5</td>
<td>47</td>
<td>1.203e + 31</td>
<td>2.000E + 31</td>
<td>1.9054</td>
<td>23 Sep 2010</td>
</tr>
<tr>
<td>104</td>
<td>1.10e + 11</td>
<td>6.5</td>
<td>93</td>
<td>2.381e + 31</td>
<td>3.500E + 31</td>
<td>1.7955</td>
<td>25 Sep 2010</td>
</tr>
<tr>
<td>152</td>
<td>1.10e + 11</td>
<td>9.4</td>
<td>140</td>
<td>3.584e + 51</td>
<td>5.000E + 31</td>
<td>1.7550</td>
<td>29 Sep 2010</td>
</tr>
<tr>
<td>204</td>
<td>1.10e + 11</td>
<td>12.7</td>
<td>186</td>
<td>4.762e + 31</td>
<td>7.000E + 31</td>
<td>1.8307</td>
<td>04 Oct 2010</td>
</tr>
<tr>
<td>248</td>
<td>1.10e + 11</td>
<td>15.4</td>
<td>233</td>
<td>5.965e + 31</td>
<td>1.030E + 32</td>
<td>2.2158</td>
<td>14 Oct 2010</td>
</tr>
<tr>
<td>312</td>
<td>1.10e + 11</td>
<td>19.4</td>
<td>295</td>
<td>7.552e + 31</td>
<td>1.500E + 32</td>
<td>2.5650</td>
<td>16 Oct 2010</td>
</tr>
<tr>
<td>368</td>
<td>1.15e + 11</td>
<td>23.9</td>
<td>348</td>
<td>9.737e + 31</td>
<td>2.050E + 32</td>
<td>2.9721</td>
<td>25 Oct 2010</td>
</tr>
</tbody>
</table>

In the third period of operation in 2010, trains of bunches from the injector were used. This also introduced rigorous control and validation of the machine protection system for injection of bunch trains. As can be seen in table 4, the number of bunches per beam was increased from 56 to 368 from the end of September to the end of October, and the resulting peak luminosity reached $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$.

Figure 12 shows the peak and integrated luminosity evolution during 2010 for proton operation. The initial goal of a peak luminosity of $10^{32}$ was exceeded by more than a factor of 2, and the integrated luminosity delivered to the experiments was 45 pb$^{-1}$. Following the series of fills with 368 bunches per beam, operation was switched to collisions of lead ions.

(b) Lead ions in 2010

The changeover from protons to lead ions went amazingly quickly, taking only 4 days to produce colliding lead ions. Operation of the LHC with lead...
ions was performed for about four weeks and produced luminosities well above expectations. The peak and integrated luminosities are shown as a function of date in figure 13.

9. Proton operation up to mid-2011

Contrary to the mode of operation in 2010, the strategy for operation in 2011 was to separate operations for physics data collection from the machine studies. The goal set for 2011 was to produce an integrated luminosity of at least 1 fb$^{-1}$, more than 20 times that achieved in 2010. Towards the end of 2010, while injecting large numbers of bunches, clear signs of beam and vacuum instabilities appeared, produced by the electron cloud effect. This effect had been predicted for the LHC and the mitigation foreseen was to perform ‘beam cleaning’ or ‘scrubbing’. Beam cleaning required large numbers of high-intensity bunches circulating for extended periods so as to extract the electrons from the vacuum chamber and eventually reduce the secondary electron yield.

The global strategy for operation in 2011 was firstly to re-establish the good performance of 2010 with up to several hundred bunches, followed by beam cleaning and then to increase the number of bunches towards 900 (maximum achievable with a bunch spacing of 75 ns). The beam cleaning was done with
Figure 14. Integrated luminosity (a) and peak luminosity (b) per fill in 2011. (a) Dark circles, ATLAS; triangles, CMS; diamonds, LHCb; light circles, ALICE preliminary.

Table 5. Evolution of the peak performance in 2011.

<table>
<thead>
<tr>
<th>fill number</th>
<th>date</th>
<th>bunch spacing</th>
<th>number of bunches</th>
<th>peak luminosity ((10^{33} \text{ cm}^{-2} \text{ s}^{-1}))</th>
<th>total number of protons per beam ((10^{14}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1635</td>
<td>18 Mar 2011</td>
<td>75</td>
<td>32</td>
<td>0.030</td>
<td>0.038</td>
</tr>
<tr>
<td>1637</td>
<td>19 Mar 2011</td>
<td>75</td>
<td>64</td>
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</tr>
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<td>75</td>
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<td>75</td>
<td>200</td>
<td>0.252</td>
<td>0.243</td>
</tr>
<tr>
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<td>15 Apr 2011</td>
<td>50</td>
<td>228</td>
<td>0.237</td>
<td>0.285</td>
</tr>
<tr>
<td>1716</td>
<td>16 Apr 2011</td>
<td>50</td>
<td>336</td>
<td>0.353</td>
<td>0.423</td>
</tr>
<tr>
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<td>50</td>
<td>480</td>
<td>0.514</td>
<td>0.579</td>
</tr>
<tr>
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<td>30 Apr 2011</td>
<td>50</td>
<td>624</td>
<td>0.716</td>
<td>0.756</td>
</tr>
<tr>
<td>1755</td>
<td>02 May 2011</td>
<td>50</td>
<td>768</td>
<td>0.826</td>
<td>0.925</td>
</tr>
<tr>
<td>1809</td>
<td>27 May 2011</td>
<td>50</td>
<td>912</td>
<td>1.099</td>
<td>1.150</td>
</tr>
<tr>
<td>1815</td>
<td>29 May 2011</td>
<td>50</td>
<td>1092</td>
<td>1.268</td>
<td>1.330</td>
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</table>

a bunch spacing of 50 ns in order to increase the effectiveness of the cleaning. Following the successful beam cleaning runs with 50 ns spacing, it was decided that physics operation could continue with 50 ns, thereby increasing the potential maximum number of bunches to close to 1400. In order to allow the accumulation of such large numbers of bunches, the number of bunches in the bunch trains coming from the injectors had to be increased. In the first half of the year, the trains of bunches were increased progressively from 12 to 144, each step carefully validated by the machine protection panel.

Table 5 shows the evolution of the number of bunches per beam in the LHC during the period from mid-March until the end of May. The maximum number of bunches reached to this date is 1092, with a total number of protons exceeding \(1.3 \times 10^{14}\) and a peak luminosity of \(1.27 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}\). The energy stored in this high-intensity beam is around 80 MJ.
Figure 15. Peak (a) and integrated (b) luminosity during the best fill to date and the weekly integrated luminosity in 2011 (c). White, LHC delivered all; light grey, LHC delivered stable; dark grey, ATLAS ready recorded.

Figure 14 shows the evolution of the integrated (figure 14a) and peak (figure 14b) luminosity during the first half of 2011. It can be seen that the 2011 goal of 1 fb\(^{-1}\) has been achieved very early in the year. Figure 15 shows details of the most productive fill to date with an integrated luminosity (47 pb\(^{-1}\)) in 15 h, which exceeded total production in 2010. Also shown is the evolution of the weekly luminosity (figure 15c), which has reached a peak of 230 pb\(^{-1}\). At the time of writing, there remains 16 full weeks of data collection at high luminosity before the changeover to lead ions.

The record performances up to mid-June 2011 are detailed in table 6.

10. Plans for the future

Following the achievement of the initial luminosity goal, the new goal for the LHC is simply to maximize the integrated luminosity by the end of 2011. In addition, there will be operation with colliding lead ions, again for about one
Table 6. Records as of June 2011.

<table>
<thead>
<tr>
<th>Record Description</th>
<th>Value</th>
<th>Fill</th>
<th>Date/Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak stable luminosity delivered</td>
<td>$1.26 \times 10^{33}$</td>
<td></td>
<td>11 May 29, 06.41</td>
</tr>
<tr>
<td>Maximum luminosity delivered in one fill</td>
<td>$46.61 \text{ pb}^{-1}$</td>
<td></td>
<td>11 June 01, 18.49</td>
</tr>
<tr>
<td>Maximum luminosity delivered in 1 day</td>
<td>$46.84 \text{ pb}^{-1}$</td>
<td></td>
<td>Thursday 02 June 2011</td>
</tr>
<tr>
<td>Maximum luminosity delivered in 7 days</td>
<td>$229.64 \text{ pb}^{-1}$</td>
<td></td>
<td>Thursday 02 June 2011 – Wednesday 08 June 2011</td>
</tr>
<tr>
<td>Maximum colliding bunches</td>
<td>1042</td>
<td></td>
<td>11 May 29, 06.41</td>
</tr>
<tr>
<td>Maximum peak events per bunch crossing</td>
<td>14.01</td>
<td></td>
<td>11 Apr 23, 05.47</td>
</tr>
<tr>
<td>Maximum average events per bunch crossing</td>
<td>8.93</td>
<td></td>
<td>11 Mar 22, 02.20</td>
</tr>
<tr>
<td>Longest time in stable beams for one fill</td>
<td>17.9 h</td>
<td></td>
<td>11 Apr 23, 10.25</td>
</tr>
<tr>
<td>Longest time in stable beams for 1 day</td>
<td>19.7 h (82.1%)</td>
<td></td>
<td>Sunday 27 March 2011</td>
</tr>
<tr>
<td>Longest time in stable beams for 7 days</td>
<td>93.0 h (55.4%)</td>
<td></td>
<td>Thursday 21 April 2011 – Wednesday 27 April 2011</td>
</tr>
<tr>
<td>Fastest turnaround to stable beams</td>
<td>2.4 h</td>
<td></td>
<td>11 Apr 16, 22.56</td>
</tr>
</tbody>
</table>

month. In 2012, the LHC will continue operation at or slightly above 3.5 TeV per beam, with the goal of maximizing the integrated luminosity before the machine shuts down for a long period in 2013–2014.

During this long shut-down, the inter-magnet connectors will be repaired and upgraded by an improved design. Several other consolidation programmes are foreseen during this shutdown both for the LHC and for the injectors. Following this shut-down, the goal is to operate close to 7 TeV per beam with high-intensity beams.

This paper summarizes the work carried out by hundreds if not thousands of scientists, engineers and technicians both employed by CERN and, very importantly, by the many institutes that collaborate with CERN. It is a great personal pleasure to acknowledge the incredible contributions and dedication of such a wonderful team.

References


Phil. Trans. R. Soc. A (2012)


Phil. Trans. R. Soc. A (2012)