Status of the Large Hadron Collider

M Lamont
CERN, Geneva, Switzerland
E-mail: Mike.Lamont@cern.ch

Abstract.
The key LHC operating parameters and their impact on potential performance are recalled and a brief summary of the 2010 beam commissioning program is presented. Progress in 2011 has been good and the present performance is discussed. The short and medium term plans and their potential are outlined.

1. Introduction
2010 was the first full year of LHC commissioning and it saw a number of important operational milestones. These included: first collisions at 3.5 TeV; commissioning of the squeeze; the move to physics with nominal bunch intensity; the move to bunch trains followed by a phased increase in intensity. A peak luminosity of $2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ was achieved with an integrated luminosity of 6 pb$^{-1}$ per day delivered in the final week of proton operations. The year culminated in a successful ion run.

2011 has seen a rapid re-commissioning of the machine after the Christmas stop with the main milestones listed below.

- 19th February: circulating beams re-established.
- 3rd March: first collisions at 3.5 TeV, $\beta^* = 1.5$ m with pilot beams.
- 5th March: nominal bunches at 3.5 TeV, start of collimator set-up program.
- 13th March: first stable beams, 3 bunches per beam, initial luminosity $1.6 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}$

By 21st March 2011, the LHC was back up to a peak luminosity of $1 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ and by the end of June had achieved $1.26 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$ and already achieved the year’s modest integrated luminosity target of 1 fb$^{-1}$ in time for the summer conferences.

2. Overview of 2010
The clear priority of 2010 was to lay the foundations for 2011 and the delivery of 1 fb$^{-1}$. The peak luminosity target was $1 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$. Solid operational experience of injecting, ramping, squeezing and establishing stable beams was gained and a large number of issues were addressed along the way. A period of steady running at or around 1 MJ for an extended period was used to fully verify machine protection and operational procedures before performing a safe, phased increase in intensity with validation and a running period after each step-up in intensity.

The luminosity delivery in 2010 can be divided into three main periods: the initial luminosity run with low bunch currents; nominal bunch operation with up to 48 bunches; and the performance ramp up period after the commissioning of bunch trains. The main milestones...
of 2010 commissioning are outlined in Table 1. Some notable achievements of the year’s commissioning are shown in Table 2.

### Table 1. Main phases of 2010 commissioning.

| Date      | Commissioning phase                                           |
|-----------|----------------------------------------------------------------|
| 28th February | Injection of both beams, rough RF capture                   |
| 30th March  | First colliding beams at 3.5 TeV                             |
| March      | Initial commissioning leading to first collisions            |
| April      | Squeeze commissioning                                        |
| May        | Physics 13 on 13 bunches with $2 \times 10^{10}$ protons per bunch |
| June       | Commissioning of nominal bunch intensity                     |
| July       | Physics 25 on 25 bunches with $9 \times 10^{10}$ protons per bunch |
| August     | 3 weeks running with a stored beam energy of 1 to 2 MJ        |
| September  | Bunch train commissioning                                    |
| Oct - Nov  | Phased increase in total beam intensity                      |

### Table 2. 2010 commissioning: some notable records. Data courtesy of ATLAS.

|                                |                                                |
|--------------------------------|------------------------------------------------|
| Peak stable luminosity         | $2.07 \times 10^{32}$ cm$^{-2}$s$^{-1}$         |
| Maximum luminosity delivered in one fill | 6.3 pb$^{-1}$                               |
| Maximum luminosity delivered in one day | 6.0 pb$^{-1}$                               |
| Maximum luminosity delivered in 7 days | 24.6 pb$^{-1}$                               |
| Maximum colliding bunches      | 348                                            |
| Maximum average events/bunch crossing | 3.8                                        |
| Longest time in Stable Beams – one fill | 30.3 hours                                |
| Longest time in Stable Beams – one day | 22.8 hours (94.9%)                            |
| Longest time in Stable Beams – 7 days | 69.9 hours (41.6%)                           |
| Faster turnaround (protons)    | 3.7 hours                                     |
| Maximum stored beam energy at 3.5 TeV | 28 MJ                                      |
| Maximum stored beam energy in physics | 24 MJ                                      |

3. **Machine status at the end of 2010**

2010 was a intense year of commissioning with many issues and problems addressed [1]. When the dust had settled the following key features related to beam based operation may be noted.

- The machine is magnetically and optically well understood with excellent agreement between the magnetic and optics models and measured beam parameters.
- Given a rigorous cycling strategy the LHC is magnetically reproducible. This has proved important because set-up remains valid from fill to fill, and indeed from month to month.
- The aperture has been measured carefully and is as expected.
- The operational sequence, after a lot of hard work, allows the beams to be taken through the ramp, squeeze and into collision essentially without loss.
- Better than nominal beam intensity and beam emittance was delivered by the injectors resulting in excellent luminosity performance.
• It was possible to collide nominal bunch currents with smaller that nominal emittances with no serious problems from head-on beam-beam. This important result is another key reason behind the impressive luminosity performance.

• There was excellent cleaning by the collimator system and good control of beam losses at all stages of operation. There were no accidental beam induced quenches above injection energy.

The key machine parameters used in towards the end of the 2010 proton run are shown in Table 3.

Table 3. Main machine parameters in use in 2010 compared with the nominal 7 TeV values.

| Parameter                        | 2010          | Nominal          |
|----------------------------------|---------------|------------------|
| Energy [TeV]                     | 3.5           | 7.0              |
| β* [m]                           | 3.5, 3.5, 3.5, 3.5 | 0.55, 10, 0.55, 10 |
| Normalized emittance [µm]        | 2.0 - 3.5     | 3.75             |
| (start of fill)                  |               |                  |
| Bunch current                    | 1.2×10¹¹      | 1.15×10¹¹        |
| Maximum number of bunches        | 368           | 2808             |
| Maximum stored energy [MJ]       | 28            | 360              |
| Peak luminosity [cm⁻²s⁻¹]        | 2×10³⁴        | 1×10³⁴           |

The LHC has excellent single beam lifetime at 3.5 TeV before collisions of over 300 hours. At the start of a fill the luminosity lifetime is initially in the range 15 to 20 hours lengthening to 25 to 30 hours later. The luminosity lifetime is reasonably well given by the observed emittance growth and the intensity decay. There is minimal drifts in beam overlap during physics and the beams are generally very stable.

The 2010 run was driven mainly by commissioning, and not operations for physics. In this regard, any analysis of operational efficiency should be regarded with some latitude. However for a first year the signs are very encouraging. Some very extensive equipment systems performed above expectations (considering mean time between failures etc.), and the equipment groups are aware of the weak points and are working to improve them. Technical stops certainly caused problems initially but things got better during the course the year and overall there was impressive availability for a first full year of operations with the final number for machine availability being around 65% of the scheduled time [2].

4. 2010: the heavy ion run
The 2010 run finished with a switch from protons to lead ions. The operations team successfully leveraged the experience gained with protons to rapidly push through the ion commissioning program, relying on the fact that the magnetic machine for ions is near identical to that used for protons. The early ion parameters applicable to the 2010 run are shown in table 4 [5].

The first injection of beam took place on 4 November 2010. Stable beams were declared for physics on 7 November. In the following days, the number of bunches per beam was increased through 2, 5, 17, 69, 121 bunches, injecting single bunches or batches of 4 from the SPS in variants of the “Early” filling scheme (see Table 4). In the last few days of the run, injection of batches of 8 bunches gave a total of 137 bunches. The SPS supplied around 1.2×10⁸ ions per bunch which gave a peak luminosity of just over 3×10²⁵ cm⁻²s⁻¹. An integrated luminosity of 9.7 µb⁻¹ was delivered to ALICE, ATLAS and CMS with some interesting results.
Table 4. Parameter list for early (2010/2011) and nominal ion running.

| Parameter                     | units   | Early          | Nominal         |
|-------------------------------|---------|----------------|-----------------|
| √s per nucleon                | TeV     | 2.76           | 5.5             |
| Initial luminosity            | cm⁻²s⁻¹ | 1.25×10²⁵      | 1×10²⁷          |
| Number of bunches             |         | 62             | 592             |
| Bunch spacing                 | ns      | 1350           | 99.8            |
| β*                           | m       | 2              | 0.5             |
| Pb ions per bunch             |         | 7×10⁷          | 7×10⁷           |
| Transverse norm. emittance    | µm      | 1.5            | 1.5             |
| Luminosity half life (1,2,3 expts.) | hours | 3<τ_{LBS}<70   | 8, 4.5, 3       |

5. Issues

The splices in the interconnects remain a worry and still limit the beam energy to 3.5 TeV for the moment. Among a swathe of issues, two of the main concerns for 2011 are outlined below.

5.1. UFOs

Many sudden local beam losses have been recorded. The rise time of the losses is of the order 1 ms. There is no danger of a quench but preventive dumps are performed if the beam losses go above the threshold of the beam loss monitors implicated.

A potential explanation is dust particles falling into beam creating losses via elastic and inelastic scattering. The showers generated propagate downstream. This explanation has given rise to the moniker ‘Unidentified Falling Object’ or UFO. The UFOs are distributed around the ring and are seen in the arcs, inner triplets, and insertion regions. Most do not generate beam losses severe enough to dump the beam.

There are more UFOs at higher beam intensities and the UFOs observed at 450 GeV have a lower beam loss amplitude than those observed at high energy. The timescale of the losses are shorter with increasing total intensity but it seems that the signal amplitude does not increase with total beam intensity.

Additional quench tests will be used to benchmark the BLM thresholds, perhaps allowing more leeway in the setting of the thresholds. A revision of the BLM thresholds around the ring has been made in an attempt to make the effect of UFOs on operational efficiency acceptable and this has been partially successful.

Given that they tend to dump the beam at high energy, the straightforward cost of above threshold UFOs is machine efficiency and the 2 to 3 hour turnaround from high energy to high energy means that they can have a significant effect if they dump the beam on the order of once per day.

5.2. Electron cloud

Electron cloud effects in particle accelerators are well understood and have been very well studied over the years [3]. In the LHC electron cloud effects are predicted to occur both in the warm and cold regions. The most notable effects are: vacuum pressure rises (potentially causing background in experiments); single-bunch instabilities; multi-bunch instabilities; incoherent emittance growth; heat load in cold arcs (with quenches in the limit); and perturbation of beam diagnostics.

Experience of electron cloud in 2010 showed that it was very much dependent on bunch spacing: 150 ns saw local signs of electron cloud in the common beam pipe; 75 ns showed some first signs around the ring; and 50 ns induced enough vacuum activity to bring the vacuum valves in. Vacuum activity started off in regions with common beam pipe at 450 GeV as the
number of bunches with 150 ns spacing was pushed up. Tests with solenoids wrapped around the beam pipe locally cured the problem, confirming the presence of electron cloud.

When the 50 ns bunch spacing was tried, the effects were very clearly seen. There was high vacuum activity in the warm regions (where the beams travel in separate beam pipes) and significant heat load in cold regions. Instabilities and beam size growth were observed. However, surface conditioning (scrubbing) was also observed with associated gas desorption rates and an implied drop in secondary emission yield (SEY). The time constant for the scrubbing processes was less than a day. The situation was a lot cleaner with 75 ns, however incoherent effects were seen and emittance blow-up was observed when 800 plus bunches in both beams were injected [4].

2010 observations are certainly due to a high SEY between 2 and 2.5, whereas 1.7 was usually the maximum value studied in the past. In 2011 it proved possible to reach 200 to 300 bunches with 75 ns without scrubbing. Thereafter a 5 day scrubbing run with large emittance ($\geq 3.5 \mu m$), 50 ns bunch spacing, and high bunch intensity ($> 1.2 \times 10^{11}$) paved the way for 50 ns operations. In addition solenoids have been installed at many locations during the 2010/11 Christmas technical stop.

6. Operation in 2011

The beam energy remained at 3.5 TeV in 2011. The $\beta^*$s for the run are: 1.5 m in ATLAS and CMS; 3 m in LHCb; and 10 m in ALICE.

The official target for 2011 was 1 fb$^{-1}$ delivered to each of ATLAS, CMS and LHCb at 3.5 TeV. Given the performance in 2010 the 1 fb$^{-1}$ target for ATLAS and CMS was conservative and was indeed reached in June 2011. 1 fb$^{-1}$ is less obvious for LHCb given their maximum acceptable luminosity of between 2 to $3 \times 10^{32}$ cm$^{-2}$s$^{-1}$ and associated pile-up limitations. Luminosity levelling via separation is in use to maximize the delivered luminosity. ALICE’s requirements for the proton run are modest with a demanded luminosity for the proton run of between 5 and $50 \times 10^{29}$ cm$^{-2}$s$^{-1}$ and a “pile-up” of around 0.05.

The baseline operational scenario for 2011 unfolded as more-or-less as planned.

- Re-commissioning with beam after the Christmas technical stop took around 3 weeks. The exit condition from this phase was stable beams with low number of bunches.
- There was a ramp-up to around 200 bunches (75 ns) taking about 2 weeks. Multi-bunch injection commissioning also took place during this phase.
- An 5 day intermediate energy run (beam energy 1.38 TeV) took place towards the end of March. (Here the proton-proton collision energy is equivalent the nuclear-nuclear collision energy in the lead ion run.)
- There was a scrubbing run of 10 days which included 50 ns injection commissioning.
- A staged ramp-up in the number of bunches then took place with 50 ns bunch spacing up to a maximum of 1380 bunches.

6.1. Scrubbing run

The dedicated scrubbing run saw impressive progression in spite of several technical problems not related to the scrubbing. Eventually 5 days of scrubbing took place between 5th and 10th April. All solenoids were switched off (both experiments’ and vacuum solenoids in the warm sections). There was a careful increase in intensity (in steps of 200 bunches) while monitoring cryogenics, vacuum, machine protection and particularly the RF system. The run was limited to 72 bunches/train by injection performance, but managed to reach 1020 bunches per beam at the end of the scrubbing run with a total of more than $10^{14}$ protons per ring. However, there was an impressive reduction of the heat load in the cold sectors of the machine in only a few
hours. The results are consistent with a SEY reduction from 2.5 to less than 1.8. After this encouraging performance the decision was taken to go with 50 ns bunch spacing.

6.2. Operating with higher intensities
Running with higher total beam intensity continues to provoke a number of issues including: UFOs as described above; the effects of radiation to electronics in the tunnel; and increased vacuum activity possibly related to residual electron cloud. The RF team has had to carefully monitor the effects of higher beam intensity and there have been issues with protection of RF Power Couplers and false wave-guide flash-overs (probably linked to beam losses induced by vacuum activity). Beam induced heating of injection kickers, beam screens, and collimators has been observed with a clear dependence on total intensity and bunch length.

6.3. Machine Protection
Machine protection is, as always, a concern. Performance of the machine protection system has been excellent, however some very occasional incidents do give pause for thought. The SPS is now injecting 144 bunches in the LHC and beam quality from injector is very important with over 1 MJ per injection coming down the transfer line. An injection kicker flash-over in April 18th provoked heavy beam loss which was properly caught by the appropriate protection devices. Also in April there was a quench of a high temperature superconducting current lead which revealed a loss of redundancy in the associated protection system. This provoked machine wide check of similar systems.

6.4. Performance 2011
So far in 2011 there has been impressive progress in re-commissioning with beam and following the move to regular operation. Improvements and consolidation across the board took place during the Christmas technical stop. The machine operation is now reasonably well optimized, a faster ramp and squeeze is in place, and the essential mechanics for driving the machine through the nominal cycle well bedded in.

By June the LHC was running with 1092, 1236, and finally 1380 bunches per beam with a peak luminosity of up to $1.27 \times 10^{33}$ cm$^{-2}$s$^{-1}$.

- The luminosity lifetime remains very acceptable at around 25 to 30 hours.
- Luminosity levelling in LHCb via transverse displace of the beams at the collision point is operational.
- The daily luminosity production rate held at around 30 pb$^{-1}$ through June.
- Machine availability is dictated by the exposure to the intersecting failure space of a number of complex systems with huge number of components. This failure space is clearly inflated by high intensity. Nonetheless, despite the inherent complexity of the LHC, availability remains acceptable.
- Precise measurement of the luminous region (via Van der Meer scans) and beam intensity have given a useful handle on the absolute luminosity for cross section calibration and the obtained accuracy is currently at the 5% level.

The parameters in use at the end of June 2011 are shown in table 5. Performance related records, also at the end of June, are shown in table 6.

Given the a peak luminosity of $1.3 \times 10^{33}$ cm$^{-2}$s$^{-1}$, around 90 days of delivery at or around this level, and reasonable operational efficiency reflected in the Hübner factor of around 0.2, the LHC should be able to deliver at total of 3 to 4 fb$^{-1}$ in 2011. The main known unknowns with the potential to disrupt the delivery of this total are UFOs and radiation to electronics. There is the possibility to gently increase the bunch intensity and lower the emittances delivered by
The LHC performance in 2010 and 2011 has been very encouraging: the magnetic model and optics look excellent; the beam instrumentation is in good shape; beam cleaning and collimation works reliably with predicted efficiency; the machine protection system’s performance has been excellent; and the machine aperture looks good. The performance with beam (losses, lifetimes, luminosity, emittance growth) has been surprisingly forgiving.

2011 has seen an increase in number of bunches to 1380 using 50 ns bunch spacing and a peak luminosity of between around $1.3 \times 10^{33}$ cm$^{-2}$s$^{-1}$. This should allow the LHC to deliver an integrated luminosity of around 3 to 4 fb$^{-1}$ in 2011. Increasing intensity has brought with it a number of issues. Of these, UFOs and SEUs, perhaps, present the biggest threat to operational efficiency and they will both have to be carefully monitored and mitigation anticipated if their effects prove too serious. The destructive power of the stored energy of the beam at high energy is an ever present concern and diligent attention to the machine protection system is mandatory.

7. Conclusions

The LHC performance in 2010 and 2011 has been very encouraging: the magnetic model and optics look excellent; the beam instrumentation is in good shape; beam cleaning and collimation works reliably with predicted efficiency; the machine protection system’s performance has been excellent; and the machine aperture looks good. The performance with beam (losses, lifetimes, luminosity, emittance growth) has been surprisingly forgiving.

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**Table 5.** Performance related parameters for operation in 2011 (as of end June 2011).

| Parameter                        | Value                        |
|----------------------------------|------------------------------|
| Energy                           | 3.5 TeV                      |
| $\beta^*$ in ATLAS and CMS       | 1.5 m                        |
| Bunch spacing                    | 50 ns                        |
| Number of bunches                | 1380                         |
| Maximum intensity in collisions  | $1.6 \times 10^{14}$ protons per beam |
| Bunch intensity                  | $1.2 \times 10^{11}$         |
| Stored beam energy               | $\approx$ 93 MJ             |
| Emittance [mm.mrad]              | $\approx$ 2.5               |

**Table 6.** Operational high points as of end June 2011. Data courtesy of ATLAS.

| Parameter                           | Value                        |
|-------------------------------------|------------------------------|
| Integrated luminosity               | 1.06 fb$^{-1}$ (0.36 fb$^{-1}$ in LHCb) |
| Peak stable luminosity              | $1.26 \times 10^{33}$ cm$^{-2}$s$^{-1}$ |
| Maximum luminosity delivered in one day | 63 pb$^{-1}$               |
| Maximum luminosity delivered in 7 days | 242 pb$^{-1}$              |
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