THE LHC FROM COMMISSIONING TO OPERATION

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Abstract

In 2011 the LHC moved from commissioning into the physics production phase with the aim of accumulating 1 fb^{-1} by the end of the year. The progress from commissioning to operation is described. Emphasis is put on the beam performance, but also on the performance of the different hardware systems. The role of collimation and machine protection is discussed, in view of the very high stored beam and magnet energy.

MAIN TIMELINE

Although brutally interrupted by the 19th September 2008 incident, the LHC's commissioning with beam has been an intense and fruitful period. The passage from commissioning to operations was relatively smooth following a rigorous validation of operations procedures and machine protection in 2010.

Beam was first introduced into the LHC during a series of injection tests in August and September 2008 [1]. The tests were encouraging and allowed for some serious debugging of controls software, the injection process, magnet polarities and so on. It appeared that the magnetic machine was in good shape, the aperture was clear and that key beam instrumentation was functional. First measurements of the optics were performed.

On 10th September 2008, in a very public display, beams were threaded around the full ring. Beams were captured shortly after. Initial progress was good but commissioning with beam was cut brutally short by the incident on the 19th September [2].

The majority of 2009 was spent in the extensive repair of sector 34. Importantly a more robust and sensitive quench protection system (nQPS) system was deployed. A splice measurements campaign on both warm and cold sectors established a good understanding of the issues. The splices in the interconnects remain a concern and still limit the beam energy to 3.5 TeV for the moment.

Beam was circulated again on 29th November 2009. Once beam was back there was rapid progress in the three and half weeks available in November to December. All key systems went through at least their initial commissioning phases. Collisions with stable beam conditions were established at 450 GeV, and the ramp to the maximum energy at the time of 1.18 TeV was successfully attempted. Most beam-based systems became operational and LHC operations managed to start to master the control of a hugely complex system.

After the 2009 Christmas technical stop first beam was taken again on the 19th February. Colliding beams at 3.5 TeV were established for the first time under the watchful eye of the media on 30th March 2010.

2010 maybe regarded as the LHC commissioning year 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. The year culminated in a successful ion run. A more detailed breakdown of the year is provided below.

2011 saw a rapid re-commissioning of the machine after the 2010 Christmas stop. Circulating beams were re-established on 19th February. By 21st March 2011, the LHC was back up to a peak luminosity of 1×10^{32} $\mathrm{cm^{-2}s^{-1}}$ and by the end of June had achieved 1.26×10^{33} $\mathrm{cm^{-2}s^{-1}}$ and had already achieved the year's modest integrated luminosity target of 1 fb^{-1} in time for the summer conferences.

PREPARATION

The initial commissioning phase in 2008 and 2009 benefited from meticulous preparation. Near term preparation for beam during the periods outlined above saw a three major thrusts: a series of transfer line and injection tests with beam; a comprehensive program of hardware commissioning; and a full program of dry runs leading into a thorough machine checkout phase.

The beam tests started in 2003 with the first extraction into TT40. Although modest, the test saw the operational use of the LSA software for the first time and experience with LHC type beam instrumentation. This was to set the pattern for the coming years, which saw beam successively down TI8, TI2 and in 2008 in the LHC itself for the first time [1].

The hardware commissioning program was a major inter-departmental effort which saw systematic testing of all cold circuits and associated systems. The resultant performance of the magnetic circuits and associated protection systems is testament to the diligence that was brought to bear. Lesson had to be learnt following the 2008 incident and tests were duly extended in tandem with the deployment of the new quench protection system.

The dry runs and machine checkout program saw a full run through and tests of: extraction; transfer lines; injection; synchronization; injection sequencing; timing; beam interlocks; collimators; high level vacuum control; software interlocks; beam instrumentation; beam dumps; cold circuits as available; magnet model; sequencer; alarms; controls infrastructure; logging; databases; high level software; optics; orbit software and so on.

A CLOSER LOOK AT 2010

2010 was the commissioning year. The clear priority was to lay the foundations for 2011 and the delivery of at last 1 fb^{-1}. The peak luminosity target was $1 \times 10^{32}\ \text{cm}^{-2}\text{s}^{-1}$.

With reasonably broad brush strokes, the year unfolded as follows. Viewed from distance the progress looks reasonably smooth, but the milestones hide an enormous amount of effort and detail.

- The year started with the usual program of measurements and system checks. Among other things there was a concerted program of polarity checks of BPMs and power converters.
- **Ramp commissioning** to 3.5 TeV - limited initially by nQPS system to 2 A/s in the main bends - was smooth.
- **First collisions at 3.5 TeV unsqueezed** took place on the 30th March 2010.
- **Squeeze commissioning** successfully reduced the β^* to 2.0 m in all four experiments. This was a learning process with the need to measure and correct beating, coupling, and sort out the squeeze mechanics (debug software, feedbacks, ensure smoothness of functions).
- After the squeeze was commissioned there was a period of stable beams punctuated with continued system commissioning. At the end of April the LHC was providing collisions with a β^* of 2 m and 3 bunches of around $1{\times}10^{10}$per bunch resulting in a luminosity of the order of $1{\times}10^{28}\text{cm}^{-2}\text{s}^{-1}$. Long fills with a maximum of 30 hours were delivered.
- In June the decision was taken to go for **bunches with nominal intensity**. This involve another extended commissioning period which included the need to stabilize single beam instabilities using octupoles and suppression of coherent beam-beam modes in colliding beams, initially using a tune split and then transverse feedback. The luminosity was up to $2.5{\times}10^{30}\text{cm}^{-2}\text{s}^{-1}$ by the end of July 2010.
- There was a halting push through nominal intensity commissioning to a total stored beam energy of around 1 to 3 MJ. The LHC was held at or around this range for around 3 weeks. This period of steady running was used to fully verify machine protection and operational procedures. It saw the LHC running with 25 bunches per beam (1.6 MJ) until 17$^{\text{th}}$ August and 48 bunches until 1$^{\text{st}}$ September (3.1 MJ).
- **Bunch train commissioning** To increase the number of bunches the crossing angles in the experimental IRs had to be brought on. This necessitated a re-set up of the tertiary collimators and another full set of loss maps. A number of ramps and squeezes were necessary and the exercise was used as an opportunity to fully bed in the operational sequence.
- **Intensity ramp-up** A phased increase in total intensity with validation was performed. Before each step-up in number of bunches, an operational and machine protection validation was performed. Each step-up was followed by a few day running period to check system performance.

An operations review held in June 2010 identified issues with: preparation for beam and operational procedures; injection; collimator settings control; reliability of feedbacks; the sequencer; controls; software and settings management; the post operational checks of the beam dump system (XPOC); post mortem; and orbit stability and control through the nominal cycle.

At the time of the review it was clear that operations was not yet ready to deal with fully unsafe beams. The machine protection systems were working well but the potential to put the machine into an unsafe state was still possible and had been demonstrated on occasions. There was still a lot of room for human error. Following the workshop a lot of effort went into resolving the issues identified and reducing the number of manual actions required when driving the machine through the nominal cycle. Improvements to the sequencer and sequences were rigorously pursued.

The period of steady running at in August was followed by a timeout for bunch train commissioning that lasted around 3 weeks. The importance of this period should be stressed. Besides getting the machine ready for bunch trains this commissioning period saw a lot of ramps and squeezes for the required loss maps. These provided an opportunity to consolidate and marked: the transition to a more rigorous, dependable sequence; the reduction of manual actions in the nominal sequence; and some sense that routine operation was under control.

COMMISSIONING

Nominal Cycle

One of the main commissioning challenges is to bring the beams thourough the nominal sequence and establish stable beams for the experiments. There was major effort in 2010 and by August the operational sequence allowed the beams to be taken through the ramp, squeeze and into collision essentially without loss [3].

The transfer and injection process from the SPS into the LHC is complex process and a lot of effort went into establishing clean and safe injection of the high intensity beams from the SPS [4].

A full program of beam-based checks were performed including: positioning of injection protection devices with respect to the beam, positioning of transfer line collimators, aperture checks, and kicker waveform checks [5]. A number of issues were identified, including a general issue with fast losses at injection and the BLM thresholds on shorter time-scales. Generally the performance at injection was good and clearly benefited from the experience gained during the injection tests.

A full set of instrumentation and associated hardware and software have been commissioned and made more-or-less operational. Measurement and control of the key beam parameters (orbit, tune, chromaticity, coupling, dispersion) are routine. Besides this the beam loss monitor (BLM) system performs impeccably. Beam sizes are measured using the synchrotron light monitors and wire-scanners. Lifetime optimization is performed via adjustment of tune, chromaticity, and orbit.

Energy matching between the SPS and LHC was performed and revealed only small differences between the two beams. The experiments' solenoids were brought on without fuss and the coupling and orbit perturbations corrected. LHCb and Alice's dipoles were brought on at 450 GeV and in the ramp.

Two beam operation was established both with and without separation bumps. Optics checks were performed and the beta beating measured and corrections made. A full program of polarity checks of correctors and beam position monitors was executed with only a few errors being found [7].

A fully consistent set of machine settings was deployed at injection and for the ramp. These incorporated the output of the LHC magnet model (FIDEL [8]) which consists of all main transfer functions, dipole harmonics etc. For the RF system the necessary parameter space was in place including frequency and voltage control in the ramp.

The ramp was commissioned remarkably easily [9]. Reproducibility in the ramp looked very good enabling tune feed-forward to be deployed successfully. Tune feedback based on the continuous FFT mode of the BBQ tune system worked pretty much first time and was then used systematically during the ramp [10]. Real time acquisition of the closed orbit in the ramp was immediately available.

As of April 2010 the squeeze was commissioned to β^* = 2 m in all four experiments [11]. The squeeze mechanics - settings stitching together matched optics, feedbacks, software, limits - took some sorting out and a phase of furious debugging took place. However, once the problems had been resolved the squeeze proved to be very smooth with excellent reproducibility and only slight lifetime dips. Further optimization means that in 2011 the squeeze inevitable passes without comment.

When going into collisions at the end of the squeeze, the separation bumps are collapsed in all four IPs simultaneously. The process takes about a minute. Lifetimes dips were observed but after some gentle working point optimization the beam lifetimes stay at over 25 hours during the process.

LHC Beam Dump System (LBDS)

There was a rigorous program of measurements and tests to qualify the LHC Beam Dump System (LBDS) with beam [12]. These included: beam based alignment of the protection devices in the vicinity of the beam dump; aperture scans; extraction tests; asynchronous beam dump tests with de-bunched beam. Commissioning of the various subsystems also took place: e.g. the beam energy tracking System (BETS), external post operation checks (XPOC), internal post operation checks (IPOC); interaction with the timing system, synchronization with RF and the abort gap. Inject and dump, and circulate and dump modes were successfully used operationally.

Collimation System

The collimation system saw excellent initial beam based commissioning following careful preparation and tests [13]. The initial phase include a full program of beam based positioning during which the hierarchy was established. Encouragingly this appeared to be respected in planned and unplanned beam loss tests there afterwards, provided the orbit had been corrected to the reference. The collimation set-up remains valid over an extended period, relying on orbit reproducibility and optics stability. There have been no accidental beam induced quenches above injection energy.

Machine Protection System

The machine protection system (MPS) is mission critical and is vitally important for LHC operation over the safe beam limit. In essence it comprises the beam interlock system (BIS) and the safe machine parameter system (SMP) [14]. The BIS relies on inputs from a large multitude of user. The SMP relies on services from other systems (e.g. the timing system and the bunch current transformers). The commissioning period saw a wide range of tests and thorough verification of the system.

The beam drives a subtle interplay of the LBDS, the collimation system and protection devices, which rely on a well-defined aperture, orbit and optics for guaranteed safe operation. The MPS itself has worked as advertised, always pulling a beam abort when called upon to do so. The LBDS, orbit, and collimation have been demonstrated as safe for the given aperture and optics. Guaranteeing this at all phases of operation is vital.

Other Systems

Superb performance of the power converters was observed with excellent tracking between reference and measured and excellent tracking between the converters around the ring.

There was good performance from the key RF systems: power, beam control, low level and diagnostics [15]. Establishing capture was fast and efficient, the frequency and voltage ramps passed on the first attempts. Cogging worked well with the interaction point being re-positioned to the satisfaction of the experiments.

In general the performance of beam instrumentation was excellent. This is discussed in detail elsewhere in these proceedings [16].

Software and controls have benefited from a coherent approach and early deployment on the injectors and transfer lines and have facilitated rather than hampered commissioning. After the inevitable debugging, things have settled down and operations enjoys some excellent facilities and functionality.

Exit 2010

When the dust had settled the following key features related to beam based operation may be noted.

- The machine is optically well understood with excellent agreement between optics models and measured beam parameters. The availability of measurement and impressive analysis tools should be noted. The uncorrected, measured beating was good although outside the accepted tolerance of ≈20% [17] and correction was required.
- The magnetic machine is well understood. The modelling of all magnet types by the FIDEL team has delivered an excellent field description at all energies. This model includes persistent current effects which have been fully corrected throughout the cycle. A long and thorough magnet measurement and analysis campaign [8] meant that the deployed settings produced a machine remarkable close to the untrimmed model.
- 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 pre-cycling strategy of certain classes of magnets was revisited in 2010 to avoid any potential errors arising from leaving magnets on the wrong branch of their hysteresis curves.
- The aperture has been measured carefully and is as expected. A systematic set of aperture measurements was performed in the arcs and insertion regions [17]. The beam clearance in general seems to be OK, and is above or equal to expectations. Some measured bottlenecks agree with model predictions using measured beta functions.
- Better than nominal beam intensity and beam emittance was delivered by the injectors and it proved possible to collide nominal bunch currents with smaller that nominal emittances with no serious problems from head-on beam-beam.
- 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.

By the end of the 2010 proton run the peak luminosity in stable beams was 2.07×10^{32} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with 368 bunches per beam and 348 colliding pairs in Atlas and CMS. Up to 6.0 pb^{-1} was delivered in one day. The longest time in Stable Beams in a 7 days was 69.9 hours (41.6%). The fastest turnaround from physics to physics was 3.7 hours The maximum stored beam energy at 3.5 TeV was 28 MJ.

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 [18].

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 the last few days of the run, injection of batches of 8 bunches gave a total of 137 bunches. The SPS supplied around 1.2×10^8 ions per bunch which gave a peak luminosity of just over 3×10^{25} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. An integrated luminosity of 9.7 $\mu\mathrm{b}^{-1}$ was delivered to each of Alice, Atlas and CMS with some interesting results.

OPERATION IN 2011

The beam energy remained at 3.5 TeV in 2011. The β^*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 3×10^{32} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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 50×10^{29} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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. A 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 nucleon-nucleon collision energy in the lead ion run.)

There was a scrubbing run of 10 days which included 50 ns injection commissioning [19]. After an encouraging performance the decision was taken to go with 50 ns bunch spacing. A staged ramp-up in the number of bunches then took place with 50 ns bunch spacing up to a maximum of 1380 bunches. Luminosity levelling in LHCb via transverse displacement of the beams at the collision point was operational.

Having raised the number of bunches to 1380, performance was further increased by reducing the emittances of the beams delivered by the injectors and by gently increasing the bunch intensity. The result was a peak luminosity of 2.4×10^{33} cm^{-2}s^{-1} and some healthy delivery rates which topped 90 pb^{-1} in 24 hours.

AVAILABILITY AND OTHER ISSUES

Machine availability is dictated by the exposure to the intersecting failure space of a number of complex systems with huge number of components. Some very extensive equipment systems performed above expectations (considering mean time between failures etc.) the final number for machine availability being around 65% of the scheduled time in 2010 , a remarkable number for an immature machine [6]. The failure space has been clearly inflated by high intensity effects. Nonetheless, despite the inherent complexity of the LHC, availability remains acceptable.

Running with higher total beam intensity provokes a number of issues including: UFOs; 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.

CONCLUSIONS

A lot of hard work over the years has enabled a truly impressive period of commissioning with beam. The performance of hardware, instrumentation and software has been very impressive reflecting good preparation, very fast problem resolution and the clear benefits of leveraging 21st century technology.

The LHC is a beautiful machine and a testament to those that conceived, constructed and installed her. A remarkable effort has been repaid with remarkably well behaved machine and excellent progress so far.

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