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Turning on the LHC: Commissioning with beam and the outlook for 2010

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Summary. — After the September 19th 2008 incident and an intense year of recovery, consolidation and testing, LHC beam commissioning started again on the 23rd November 2009 and continued for three and a half weeks before the annual Christmas stop. A summary of the progress made and the performance of the individual accelerator systems is given. The potential performance of 2010 is discussed.

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1. – Introduction

The initial beam commissioning of the LHC saw remarkably rapid progress in the three and half weeks available in November to December 2009. The main commissioning goals were achieved. 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 successful attempted. Most beam-based systems became operational and LHC operations managed to start to master the control of a hugely complex system.

During this period operation was very much in commissioning mode and this initial phase must be seen as part of a necessary learning process with a furious amount of problem resolution and debugging going on. Clearly routine operation will have to be a lot more rigorous and structured.

2. – Preparation

The initial commissioning phase benefited enormously from meticulous preparation. This included a full series of injection tests, extended dry runs of all accelerator systems both separated and combined, and full hardware commissioning of the cold magnet circuits. The curtailed commissioning with beam in 2008 was also very useful in identifying a number of issues that were resolved for the 2009 run.

TABLE I. – *LHC milestones 2009.*

Date	Milestone
20th November	Injection of both beams, rough RF capture
21st November	Circulating beam 1
22nd November	Circulating beam 2
23rd November	First pilot collisions at 450 GeV. First trial ramp
26th November	Pre-cycle established. Energy matching
29th November	Ramp to 1.08 TeV and then 1.18 TeV
14th December	Ramp 2 on 2 to 1.18 TeV—quiet beams—collisions in all four experiments
14th December	16 on 16 at 450 GeV—stable beams
16th December	Ramped 4 on 4 to 1.18 TeV—collisions in all four experiments

3. – Milestones

The main milestones of the 2009 beam commissioning period are outlined in table I. The commissioning process can be briefly summarized: 3 days for first observed collisions at 450 GeV; 9 days for first ramp to 1.18 TeV; 16 days to establish stable beams at 450 GeV; 18 days to take two beams to 1.18 GeV and observe first collisions at this record energy. A more detailed look at the main operational phases follows.

3˙1. *Injection.* – The transfer and injection process from the SPS into the LHC is delicate and complex but operation was well established [1].

- The transfer lines were well optimized after a rigorous measurement campaign.
- Re-phasing of the beam in the SPS, synchronization between the machines and subsequent capture worked well with only some RF controls and procedural issues as negatives.
- Injection sequencing dealt with requirements of multiple injection schemes that covered multi-bunch injection, two beams, and collision scheduling.
- The routine conditioning of the injection kickers (the so-called kicker soft start) is now part of the standard process.
- The injection quality check (IQC) process was deployed, debugged, and became operational.
- The abort gap keeper which prevents injection of beam into the abort gap was commissioned.

A full program of beam-based checks was performed including: positioning of injection protection devices with respect to the beam, positioning of transfer line collimators, aperture checks, and kicker waveform checks [2]. A number of issues were identified, including a general issue with fast losses at injection and the BLM thresholds on shorter timescales. These will be addressed in 2010. Generally the performance at injection was good and clearly benefited from the experience gained during the injection tests. For the moment, however, one would worry about routinely injecting unsafe beam. It is to be noted that the so-called quenchinos (resistive transitions detected by the quench protection system) were again observed with two accidental quenches caused by intensities as low as $2 \cdot 10^9$ protons.

3˙2. 450 GeV. – A full set of instrumentation and associated hardware and software was commissioned and made more-or-less operational. Measurement and control of the key beam parameters (orbit, tune, chromaticity, coupling, dispersion) was routine. Besides this the beam loss monitor (BLM) system performed impeccably. Beam size was measured using the synchrotron light monitors and wire-scanners. Lifetime optimization was 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. A full program of aperture checks was performed covering the arcs and insertions. The experiments solenoids were brought on without fuss and the coupling and orbit perturbations corrected. LHCb and Alices dipoles were brought on at 450 GeV. There are some issues with transfer functions of these dipoles and the associated compensators which are to be resolved.

Two-beam operation was established both with and without separation bumps. Optics checks were performed and the beta beating measured and first attempts at correction made. A full program of polarity checks of correctors and beam position monitors was executed with only a few errors being found [3]. The availability of hardware, instrumentation and software was very impressive reflecting good preparation, very fast problem resolution and the clear benefits of leveraging 21st century technology.

3˙3. *Collisions at* 450 GeV. – Although successful, it is probably worth noting that the LHC was not designed to do collisions at 450 GeV [4]. Nonetheless a full program of machine protection, collimation, aperture and beam dump system checks allowed stable beams to be declared. This permitted the experiments to fully turn on their detectors and start an intense period of commissioning with beam themselves.

Multi-bunch and higher intensities were achieved with a maximum of 16 bunches and a total beam intensity of $1.85 \cdot 10^{11}$ being brought into collision. Luminosity scans were tested gently and successfully [5], and hundreds of thousands of events were collected by the experiments.

3˙4. 8 kHz *and the hump*. – One clear issue at 450 GeV became apparent: the activity in the vertical tune spectrum and associated vertical emittance blow-up. Two main effects were noted: a clear excitation at 8 kHz and a modulated narrow-band excitation that was observed to move slowly around the tune spectrum, particularly in the vertical spectrum of beam two. The latter became known as the hump. The cause of the 8 kHz line was tracked down to the UPS, however the source of the hump is not understood and systematic investigations as to its source will be pursued in 2010 [6].

3˙5. *Aperture*. – A systematic set of aperture measurements was performed in the arcs and insertion regions [7]. 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. However the aperture is out of budget due to beta beating even with the closed orbit reduced to the measured 3.2 mm peak. This implies that correction of beta beating is mandatory at 450 GeV.

3˙6. *Beta beating*. – The availability of measurement and impressive analysis tools should be noted. The uncorrected, measured beating was good although outside the accepted tolerance of $\approx 20\%$ [7]. Several potential sources of error were identified with possible candidates including the warm magnets in IR3 and IR7 (large corrections required). Potential, somewhat large, corrections also pointed to the triplets in IR2 and IR8. The correction strategy will need to be carefully considered.

The pre-cycling strategy of certain classes of magnets will be revisited for 2010 (*e.g.*, Q6 was not pre-cycled and should be) to avoid any potential errors arising from leaving magnets on the wrong branch of their hysteresis curves. In 2010 it will be important to correct the beating early on to avoid having to re-visit collimation and other optimization after any beating corrections.

3˙7. *Ramps*. – 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) 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.

Eight ramp attempts were made with notable success [8]. 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 [6]. Real time acquisition of the closed orbit in the ramp was immediately available. The orbit clearly moves during the ramp but total deviations were small enough to allow good transmission. A feed-forward strategy is to be established. The bare tunes (*i.e.* those that would have been seen had no corrections been applied) were seen to swing considerably. The effect is bigger in the horizontal plane and for beam 2. The origin of the swing is not yet understood.

3˙8. *Squeeze*. – One successful attempt was made to test the squeeze procedure in IR5 [9]. Although not exactly smooth in terms of procedure, the attempt managed the three planned steps: the shift to collision tunes; squeeze from 11 to 9 m.; squeeze from 9 to 7 m. Clearly there is some tidying up to do but to get this far on the first attempt was encouraging. The settings strategy worked and respected the need for smooth round off of power converter functions at the intermediate optics points. Single quadrant power converter limitations were taken into account. The ramp down of some insertion quadrupole in the squeeze defines the length of the process. Beta beating and dispersion measurements showed better agreement with the machine model at the intermediate points of the squeeze than at 450 GeV and the extrapolated values of β^* were closed to nominal.

4. – System commissioning

4˙1. *LHC Beam Dump System (LBDS)*. – There was a rigorous program of measurements and tests to qualify the LBDS with beam [10]. 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 sub-systems 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.

A number of issues were resolved but the performance of the LBDS was in general very good and experience thus far gives confidence in its ability to perform within its very tight specifications.

4˙2. *Collimation system.* – The collimation system saw excellent initial beam based commissioning following careful preparation and tests [11]. 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 setup remained valid over six days, relying on orbit reproducibility and optics stability. TOTEM also saw the first operational tests of their Roman pots with beam.

4˙3. *Machine Protection System.* – The machine protection system (MPS) is mission critical and will clearly be 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) [12]. 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).

Besides this 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 worked as advertised, always pulling a beam abort when called upon to do so. There were some issues with the inputs into the SMP but the system failed safe. The first attempt to establish the LBDS, the orbit, and the collimation as safe for the given aperture and optics was successful at 450 GeV and tests with beam demonstrated that the system setup was effective. Guaranteeing this at all phases of operation has yet to be demonstrated.

4˙4. *Beam instrumentation.* – In general perfomance was excellent. A brief summary of the performance of each system is given in table II.

4˙5. *Magnet model.* – A long and thorough magnet measurement and analysis campaign [13] meant that the deployed settings produced a machine remarkable close to the untrimmed model. In terms of tune and momentum, remarkably small discrepancies between the model and the measure machine were observed. For example, the largest momentum offsets by sector seen were: -0.27 per mil in sector 56 for beam 1 and $+0.32$ per mil in sector 78 for beam 2.

The precycle was fully deployed with precyling prescriptions in place for nearly all circuits with only a handful still missing. The result was very good reproducibility. Some optimization of total length is still possible; it was taking over an hour for the full precycle. There were a number of trips of circuits during the process and its clear that the precycle stressed the Quench Protection System (QPS) and power converters.

4˙6. *Power converters and radio frequency.* – Superb performance of the power converters was observed with excellent tracking between reference and measured and excellent tracking between the converters around the ring.

In general, there was good performance from the key RF systems: power, beam control, low level and diagnostics [14]. 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. There were, however, a number of controls issues with the de-synchronization/re-synchronization process being particularly problem prone. These issues and others are being addressed.

TABLE II. – *Summary of beam instrumentation performance.*

System	Performance overview.
Beam Position Monitors	In general very good, FIFO mode as used as in the injection tests. Capture mode was commissioned enabling multi-turn acquisition and analysis.
Beam Loss Monitors	Excellent performance following full deployment during injection tests delivering a close to fully operational tool. Some issues with the secondary emission monitors; some thresholds to be adjusted.
Bunch Current Transformers	Along with lifetime measurement, the systems were commissioned and operational. Some calibration and controls issues.
Screens	Fully operational.
Wire scanners	Operational, calibrated and giving reasonable numbers.
Abort Gap Monitor	First tests were encouraging.
Synchrotron Light Monitor	Beam 2: undulator commissioned, operational at 450 GeV and 1.2 TeV. Beam 1: undulator not commissioned, operational at 1.2 TeV.
Tune FFT	BBQ used routinely from day one giving tune, coupling, and chromaticity. Used for tune feedback in the ramp. Tune kickers operational.
Tune PLL	Good progress, feedback to be tested, radial modulation tested.
Chromaticity	Measured using: standard delta RF frequency method; semi-automatic BBQ peak analysis; and radial modulation. Some effort required to ensure fast reliable method is available.

5. – 2010—commissioning continued

The main objectives of LHC operation in 2010 are itemized below.

– Beam commissioning continued with the main, final objective of this phase being colliding, safe, stable, squeezed beams.

– This will be followed by consolidation and routine pilot physics at the safe beam limit for an extended period with machine development periods as required.

– Increased intensity phase one and associated machine protection qualification. The aim is to establish secure and reproducible operation under these conditions. This phase will move the total beam intensity above the safe beam limit.

– Consolidation and routine physics, again for an extended period.

– Increased intensity phase two and associated machine protection qualification, etc.

TABLE III. – *Breakdown of* 3.5 TeV *beam commissioning plan.*

Phase	Days	Key objectives
Circulating beam	2	Essential checks
450 GeV commissioning	7	Injection, tune, chromaticity, coupling, orbit, collimators, LBDS, beam instrumentation
450 GeV optics checks	3	Beat beating, energy matching tuning
450 GeV two beams	1	Separation bumps as standard
450 GeV collisions	2	Experiments on at 450 GeV, stable beams
Ramp to 3.5 TeV	5	Commission essential machine protection, bring experiments' dipoles on in ramp, commission orbit and tune feedback
Pilot collisions un-squeezed	3	Stable beams
Commission squeeze	4	Orbit and tune, collimation, aperture, bumps, machine protection checks
Collisions squeezed	7	Stable beams up to the safe beam limit

An estimate of the time required for the above phases in shown in table III. Machine protection is clearly hypercritical once the safe beam limit is passed, as is fault-free operations and operational procedures. It could take some time to fully establish the latter.

The pre-requisites and detailed planning for increasing intensity in place will essentially cover: a full verification of aperture, orbit and optics; full verification of beam dum, protection devices, collimation, injection protection; guaranteed beam quality from injectors; a fully tested beam interlock system including transmission of safe machine parameters; fully tested hardware interlock systems; all required feedback systems operational and appropriate interlocks fully tested.

This list is not exhaustive. Resolution of all procedural, operation, controls, MPS, instrumentation, hardware issues must all have been addressed. It is clear that the above will not happen overnight and that a full and careful program of tests and checks is required. An extended operational running period at safe beam limit with all prerequisites in place should be pursued. This will allow confirmation that all operational procedures, controls, and instrumentation are fully and faultlessly functional.

6. – 2010 potential

A proposed staged increase in intensity to a total single beam energy of 2 MJ has recently been approved. The resultant luminosity and estimates for the integrated luminosity are given in [15]. The machine will be moving out of the commissioning phase, treading carefully as experience is gained with potentially dangerous beams. The main aims are to deliver around $100\,\text{pb}^{-1}$ in 2010 and finish the year pushing $1\cdot10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$ in preparaton for 2011's target of $1\,\text{fb}^{-1}$. The first 5 months of operations will hopefully deliver a final luminosity of $1\cdot10^{31}\,\text{cm}^{-2}\,\text{s}^{-1}$—a useful and encouraging first stage deliverable. Given the proposed steps to 2 MJ and a conservative approach to intensity increase it is clear that the final steps to over $1\cdot10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$ may not be realized in 2010 and represent target for a mature, well-optimized, well-tested machine that one might hope to see in 2011.

7. – Conclusions

A lot of hard work over the years has enabled a truly impressive period of initial commissioning with beam. Given initial indications, the LHC is reproducible; is magnetically well understood; is optically in good shape. It is armed with a powerful set of instrumentation, software, and hardware systems. It is also clear there is still considerable detail to sort out before the machine becomes fully operational with unsafe beams. If things go well at the start of 2010, it will take about 4 weeks to establish stable, safe, squeezed beams at 3.5 TeV. Here the demand is for stable beams, allowing the detectors to turn on fully and continued their commissioning at higher energy. This will be followed by an extended running period at or around the safe beam limit to bed in machine protection and operations. Blocked machine development periods will be taken as required.

Intensity increases will be a judicious and stepwise process with the main aims for 2010 being around $100\,\mathrm{pb}^{-1}$ and to be pushing $1 \cdot 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at the end of the year in preparation for a 2011 integrated luminosity target of around $1\,\mathrm{fb}^{-1}$.

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