

OPERATIONAL EXPERIENCE DURING INITIAL BEAM COMMISSIONING OF THE LHC

K. Fuchsberger, R. Alemany-Fernandez, G. Arduini, R. Assmann, R. Bailey, O. Brüning, B. Goddard, V. Kain, M. Lamont, A. MacPherson, M. Meddahi, G. Papotti, M. Pojer, L. Ponce, S. Redaelli, M. Solfaroli Camillocci, W. Venturini Delsolaro, J. Wenninger, CERN, Geneva, Switzerland

Abstract

After the incident on the 19th September 2008 and more than one year without beam the commissioning of the LHC started again on November 20, 2009. Progress was rapid and collisions under stable beam conditions were established at 1.2 TeV within 3 weeks. In 2010 after qualification of the new quench protection system the way to 3.5 TeV was open and collisions were delivered at this energy after a month of additional commissioning. This paper describes the experiences and issues encountered during these first periods of commissioning with beam.

INTRODUCTION

After an intense recovery program following the incident on 19th September 2008, LHC beam commissioning restarted on November 20, 2009. It saw a remarkably rapid progress in the three and a half weeks available before the Christmas break. All main commissioning goals were achieved [1]. All key systems went through at least their initial commissioning phases.

After the Christmas break, starting on December 16 and a one month hardware-commissioning phase, beam commissioning started again on February 27, 2010. The subsequent period of commissioning was clearly focused on establishing operational conditions to enable first collisions at 3.5 TeV, which took place on March 30, 2010.

After this rather public event the commissioning team started to focus on establishing operational procedures, commissioning the machine protection systems, in particular the collimation and beam dump systems, and laying out a path to a step by step intensity increase.

PREPARATION

The initial commissioning phase benefited enormously from the meticulous preparation. This included a full series of injection tests [2], 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 runs.

MILESTONES

The main milestones achieved during the beam commissioning in 2009 to 2010 are listed in Table 1. The commis-

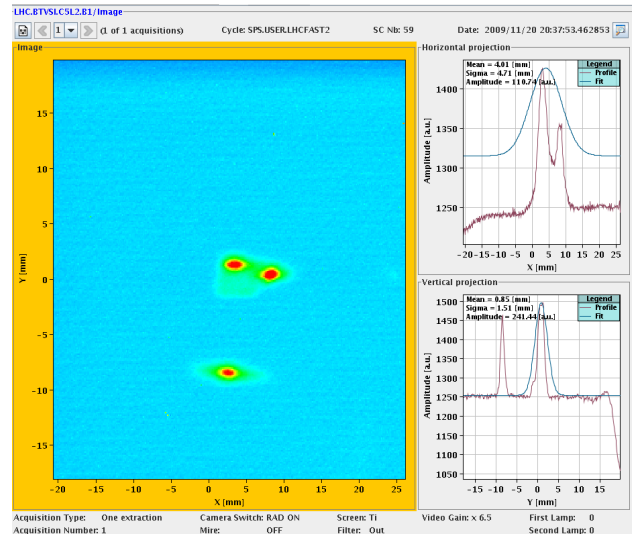


Figure 1: Beam back in LHC (screen in injection region): The lower dot is the injected beam, the upper two dots are the beam after passing the ring once/twice.

sioning process in 2009 can be briefly summarized:

- 3 days for first observed collisions at 450 GeV;
- 9 days to first ramp to 1.18 TeV;
- 16 days to establish stable beams at 450 GeV;
- 18 days to take two beams to 1.18 TeV and observe first collisions at this record energy.

In early 2010 the program continued:

- ~3 weeks for the first ramp to 3.5 TeV
- ~4 weeks to establish first collisions at 3.5 TeV
- ~6 weeks to squeeze all 4 IPs to $\beta^* = 2$ m

Injection

The transfer and injection process from the SPS into the LHC is delicate and complex but operation was well established.

- 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.
- Injection sequencing dealt with requirements of multiple injection schemes that covered multi-bunch injection, two beams and collision scheduling.

Table 1: LHC Main Beam Commissioning Milestones

Date	Milestone
<i>2009</i>	
20 th Nov.	Injection of both beams, rough RF capture
21 st Nov.	Circulating beam 1
22 nd Nov.	Circulating beam 2
23 rd Nov.	First pilot collisions at 450 GeV, first trial ramp
29 th Nov.	Ramp to 1.08, later to 1.18 TeV.
6 th Dec.	Stable beams at 450 GeV
8 th Dec.	Ramped 2 beams to 1.18 TeV, first collisions at 1.18 TeV
14 th Dec.	Ramp 2 on 2 bunches to 1.18 TeV, collisions in all four experiments.
16 th Dec.	Ramped 4 on 4 to 1.18 TeV, squeezed IP5 to 7m, collisions in all 4 experiments End of run 2009
<i>2010</i>	
27 th Feb.	Restart with beam
19 th Mar.	Ramp to 3.5 TeV
30 th Mar.	First collisions at 3.5 TeV,
24 th Apr.	Stable squeezed beams ($\beta^* = 2\text{m}$ in all IPs)

- The injection quality check (IQC) process was deployed and became operational.
- The abort gap keeper, which prevents injecting beam into the abort gap, was commissioned.

A full program of beam-based checks was performed including: positioning of the injection protection devices with respect to the beam, positioning of transfer line collimators, aperture checks and kicker waveform checks.

First Turns and RF Capture

First attempts to thread the beam around the machine were started around 18:45 on 20 November 2009. With the experience gained in 2008 the threading of the two beams around the ring was quickly accomplished. Although interrupted by a quench due to a steering error, both beams were circulating around midnight and captured soon afterwards. Figure 1 shows the first two turns in the LHC as visible on a screen in the injection region.

Operation at 450 GeV

The full set of beam instrumentation hardware and software was commissioned and made operational. Measurements of the key beam parameters (orbit, tune, chromaticity, coupling, dispersion) swiftly became operational and the BLM system performed impeccably. Beam size was

measured using the synchrotron light monitors and wire-scanners. Lifetime optimization via adjustment of tune, chromaticity and orbit became routine.

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 associated coupling and orbit perturbations were corrected. LHCb and Alice dipoles were brought on at 450 GeV. Some issues with transfer functions of these dipoles and the associated compensators were resolved.

Two beam operation was established both with and without separation bumps. A full program of polarity checks of correctors and beam position monitors was executed and the (few) detected errors were fixed soon afterwards.

One clear issue pervaded the whole commissioning: the activity in the vertical tune spectrum and associated vertical emittance blow-up. The source of the excitation is still not completely understood. More systematic investigations are ongoing.

Ramps

Eight ramp attempts to 1.18 TeV were made in 2009 with notable success. Reproducibility of beam parameters in the ramp was very good enabling tune feed-forward to be deployed successfully. Tune feedback based on continuous FFT mode of the BBQ tune system worked almost from the beginning and was then used systematically during the ramps [3].

Real time acquisition of the closed orbit in the ramp was immediately available. The orbit clearly moved during the ramp but total deviations were small enough to allow good transmission. For the ramps to 3.5 TeV the orbit change diminished which allowed a simple correction strategy (few correctors) to be put in place which brought the orbit rms change down to below 300 μm .

Collisions at 3.5 TeV

On 30 March, 2010 the first attempt was made to collide two beams at 3.5 TeV with some attendant media attention. After some delay - the beam was lost during the first ramp attempt due to trips of quadrupole power converters - the top energy was finally reached around lunch time. Finally, at 12:56 the separation bumps were collapsed in all four experiments and the experiments started recording collision events. The collision rates were optimized by performing luminosity scans in all four IPs [4].

Squeeze

A partial squeeze of the beams was made in 2009 and the efforts were continued in 2010. A settings strategy was put in place which respects the round off required for the power converter functions at the intermediate optics points and allows one to stop the squeeze at these intermediate

points. 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 close to nominal.

Squeeze commissioning progressed rapidly after the first-collisions event and on 24 April, 2010 stable beams with squeezed optics to $\beta^* = 2.0$ m in all IPs was declared the first time. Based on the experience gained in these first manual attempts, procedures and automated sequences were put in place to automatize the squeeze process. Mechanisms for automatic optics changes and corresponding interaction strategies with the orbit feedback system are under development.

SYSTEMS - EXAMPLES

Beta Beating and Coupling

Impressive measurement and analysis tools were available [5] and allowed a fast progress in correcting beta beating and coupling. The uncorrected measured beating was good although outside the accepted tolerance of $\sim 20\%$. Several potential sources of the errors were identified quite early and were subsequently corrected close to specification for both beams and both planes. The beta beating was reproducible after cycling of the magnets to within 5%. The beta beating at 3.5 TeV was around 20% [6].

Collimation and Aperture

The collimation system saw excellent initial beam based commissioning following careful preparation and tests [7]. The initial phase included 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 was well corrected to the reference.

A systematic set of aperture measurements was performed in the arcs and insertion regions. The physical aperture was globally probed by launching free betatron oscillations and some doubtful cases were checked by means of local bump scans [8]. The aperture in the arcs at injection is above 9σ (H) and 11σ (V). The availability of sophisticated tools like the LHC online model contributed heavily to the fast progress [9].

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), which both depend on inputs from a multitude of users and other systems. Besides this the beam drives a subtle interplay of the LBDS (LHC beam dump system), the collimation system and protection devices which rely on 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. It has been operational since 2006 and the deployed system has seen 99.996% availability. The system had been internally reviewed and was ready for 2010 operation with only minor changes [10].

Beam Instrumentation and Control Systems

In general all the beam instrumentation systems delivered excellent performance. The same is valid for the vast number of control system components. An overview of the performance of the systems can be found, for example, in [1].

SUMMARY

Good preparation led to an impressive period of initial commissioning with beam. The beams were brought into collisions at 3.5 TeV under stable beam conditions after only 2 months of beam commissioning. The LHC is magnetically well understood and optically in good shape. It is armed with a powerful set of instrumentation, software and hardware systems. Clearly, there are still many issues to sort out. Commissioning for unsafe beam has just started and the increase in intensity will be a judicious and step-wise process. Each step will be followed by an extended running period.

REFERENCES

- [1] M. Lamont, "Summary of the Evian beam commissioning workshop", Proceedings of the Chamonix 2010 Workshop on LHC Performance., CERN-ATS-2010-026
- [2] K. Fuchsberger et al., "Operational experience during the LHC injection tests", these proceedings
- [3] R. Steinhagen et al., "Commissioning and Initial Performance of the LHC Beam Based Feedback Systems", these proceedings
- [4] S. White et al., "First Luminosity Scans in the LHC", these proceedings
- [5] G. Vanbavinckhove et al., "Software Package for Optics Measurement and Correction in the LHC", these proceedings
- [6] R. Tomas, "LHC Optics Model Measurements and Corrections", these proceedings
- [7] D. Wollmann et al., "Beam Based Setup of LHC Collimators in IR3 and IR7: Accuracy and Stability", these proceedings
- [8] R. Redaelli et al., "LHC Aperture Measurements", these proceedings
- [9] G. Müller et al., "The Online Model for the Large Hadron Collider", these proceedings
- [10] R. Schmidt, J. Wenninger, "Initial Experience with the Machine Protection System for LHC", these proceedings