OPERATIONAL EXPERIENCE WITH FIRST CIRCULATING BEAM IN THE LHC

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Abstract

Following a series of injection tests, the first attempts to pass beam around both directions of the LHC were successful and led rapidly to circulating beam in the counter clockwise direction (beam 2) and many turns of beam 1. Unfortunately the beam commissioning was curtailed by the incident in sector 34. However, measurements performed during this first commissioning period showed that the magnet model of the machine had delivered optics close to nominal and also very good performance of beam instrumentation and supporting software. Details of the machine set-up and the commissioning procedures are given. The measurements performed and the key results from this period are described.

INTRODUCTION

The experience with LHC circulating beam in 2008 was limited to about three days of operation, from Sep. 10th to 12th. The effective beam time was about 40 hours; this time was used to close the first turn for both beams and to commission circulating, captured beam 2 with reasonable lifetime. This was done under the light of the cameras that brought additional stress to the operation crews but that provided CERN with a worldwide visibility. During the three days of beam commissioning, the initial beam tests of most of the critical LHC accelerator systems such as RF, beam dump, beam instrumentation, magnetic model, controls, machine protection and collimators were carried out. In addition, first measurements of orbit, linear optics, momentum, aperture, beta-beating, longitudinal dynamics, magnet polarities were also performed, providing first hints of the overall machine performance. These measurements were made for beam 2 (B2). The operational experience of beam 1 (B1) was limited to the beam threading and to the first turn. Clearly the meticulous preparation of the injection tests that took place before Sep. 10th [1] played a key role in the overall success of this initial commissioning.

In this paper, the operational experience with LHC circulating beam is discussed. After reviewing the commissioning strategy, the achieved milestones and the list of performed activities, the operation of the various systems tested during the beam commissioning period are presented.

COMMISSIONING MILESTONES

The beam commissioning was carried out with single pilot bunches of 2 to 4 × 10^9 protons. This ensured safe operation throughout the commissioning of circulating beam. Sectors 23, 34 and 45 for B1 and sectors 78 and 67 for B2 had been tested with beam during previous injection tests [1]. The rest of the machine was explored for the first time starting on the morning of Sep. 10th. Interleaved extractions from the SPS were possible and worked reliably throughout the beam tests. The beam threading started with B1 and continued with B2 after having established the first turn for B1.

Within one shift, the first turn was achieved for both beams. Commissioning then proceeded with B2. Operation was interrupted on Sep. 12th due to a number of unrelated hardware failures. On Sep. 19th came the sector 34 incident which put an end to the 2008 beam commissioning.

The main milestones can be summarized as it follows:

- Threading and first turn closure for both beams during the morning shift on Sep. 10th.
- Circulating, un-captured beam (300+ turns) in the evening of Sep. 10th.
- Captured beam with good lifetime (first beam circulated for more than 10 minutes) on Sep. 11th.
- Establishment of closed-orbit almost within tolerance in the afternoon of Sep. 12th.

The following activities were performed as integral part of the beam tests that led to the aforementioned milestones:

- measurements of optics response matrix with single turn acquisitions (starting on the night of Sep. 10th);
- detailed optics and beta-beat measurements;
- commissioning of asynchronous BPM acquisitions and tune measurements with base band tune system (BBQ) (without and with chirp excitation);
- beam commissioning of various RF measurements and of the hardware needed for the beam capture;
- initial commissioning of beam dump system [2];
- initial commissioning of beam instrumentation (slow and fast beam current measurements, wire scanners);
- beam tests with the collimators around the ring.

Clearly, all the above imply that the required controls layers for settings, measurements and analysis were correspondingly deployed successfully. The importance of the sector tests to ensure this is apparent.

OPERATIONAL EXPERIENCE

The BTV screen images of the first turns achieved for B1 (left) and B2 (right) are shown in Fig. 1. These acquisitions were taken at 10:26 and 15:00 of Sep. 10th, respectively. The aluminium screens of the injection region were left into the beam during the beam threading and, after all the collimators were opened, they recorded the image of the injected beam and of the same beam after 1 turn, i.e. after 89 μs. It was possible to record up to 4 turns on these screens. The screens were then removed from the beam path to proceed with the establishment of circulating beam, which relied of the measurements from the BPM and BLM systems.

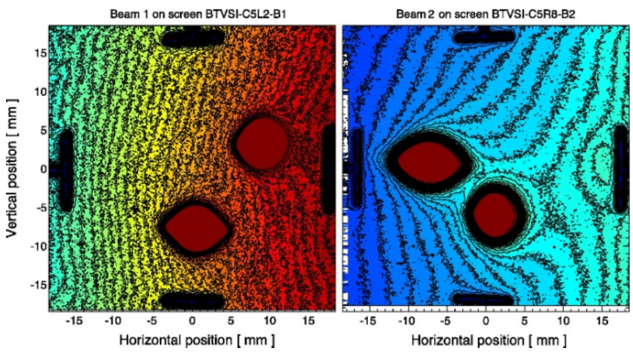

Figure 1: Beam screen (BTV) acquisitions that illustrate the very first turn of B1 (left) and B2 (right).

The BPM system worked remarkably well during this commissioning phase with pilot beam [3]. The system was only available in asynchronous mode, with auto-triggered acquisitions of first turn, injection turns (up to 120) and 1 Hz closed orbit data with circulating beams.

One of the key ingredients for a rapid establishment of circulating B2 was the early commissioning of the BBQ based tune measurement system [3] because it allowed the observation that the tunes were close to a half-integer resonance.

A few tune trims to change the working point were sufficient to achieve several tens of turns and marked the start of beam lifetime optimization. The beam lifetime of the un-captured beam was further improved with additional tune and chromaticity trims. More than 300 turns were established in the night of Sep. 10th. This is illustrated by the measurements of longitudinal beam profile from the wall current monitors in IP4, see Fig. 2. Later on, after beam capture, the BBQ tune measurements with chirp excitations were also successfully commissioned with the circulating beam.

The initial commissioning of the “inject and dump” mode and “circulate and dump” mode of the beam dump system was performed. Beam dumps after up to about 4 seconds after injection were programmed and this operational mode was maintained during the subsequent commissioning phases, until stable circulating beam was established.

After an interruption tests continued in the evening of Sep. 11th with the initial commissioning of the RF system resulting in first beam capture. After switching on the RF, the RF phase and frequency were adjusted and the beam capture was achieved. When the programmed beam dump was removed, the first captured beam circulated in the machine for more than ten minutes without further adjustment of transverse optics parameters. This indicated a very good overall quality of the machine alignment, aperture, magnetic model, setting generation, etc.

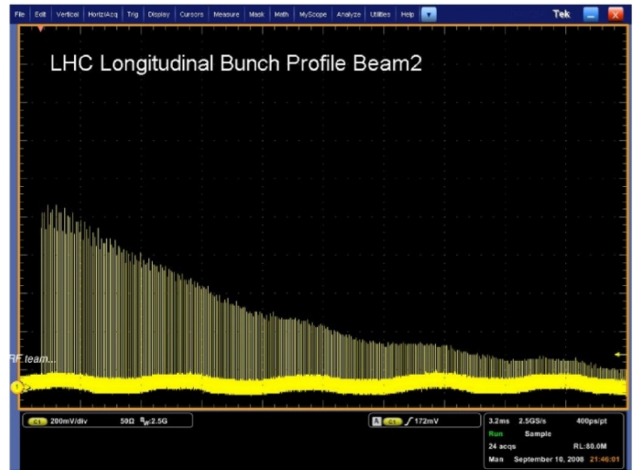

Figure 2: Longitudinal beam profile of the circulating, un-captured B2. Each vertical line represent one turn. Courtesy of RF team.

It is interesting to note that the beam that first circulated in the LHC for several minutes also experienced the first real emergency beam dump, caused by a fault in a main quadrupole circuit at about 22:45 on Sep. 11th. The beam dump worked as expected and the LBDS system successfully executed and passed the external post operation checks (XPOC) [2].

The set-up of circulating beams is a pre-requisite for further detailed beam tests of various systems. On Sep. 12th, the initial commissioning of additional beam instrumentation such as wire scanners and slow and fast beam current monitors was started. By using the 90 turn acquisition of the injection oscillations, it was also possible to have the first on-line measurements of horizontal and vertical beta-beating for B2. The last hours of beam operation were dedicated to the optimization of the closed orbit – see below.

OVERALL MACHINE PERFORMANCE

As noted above, the commissioning of B1 was only limited to the threading around the ring and the closure of the first turn. Beyond what was measured during the various sector tests [1], no detailed measurements were performed.

B2 - Tune, Coupling, Chromaticity and Beta-beat

The integer tunes in both planes were extracted by analysis of the trajectory data from the injection oscillations. The nominal values were achieved in both planes without need of correction. The summary of the best estimates of linear optics parameters for beam 2 can be summarized as it follows:

- Tunes: Qx = 0.3803−0.3015, Qy = 0.3066−0.2441 (Nominal values: Qx = 0.28, Qy = 0.31).
- Coupling (closest tune approach): |C−| = 0.07−0.06

- Chromaticity |Qx| ≈ |Qy| ≈ 30 units.

The values of Qx and Qy listed above are calculated with the BBQ system on the circulating beam [3] or with Fourier analysis of the injection oscillations [4]. The difference between the tunes in the two planes is consistent with the coupling measurements. Throughout the days of beam tests it has not been possible to consistently reproduce tune measurements – probably due to a lack of operational rigour during this hectic period. The coupling is within the range that can be corrected without requiring special injection optics with widely separated tunes. On the other hand, there was not the possibility to attempt coupling corrections. No dedicated tune measurements were carried out for different beam momenta. The quoted chromaticity estimates were inferred from preliminary measurements of synchrotron side bands around the tune peak [4].

Updated estimates of the beta-beat have been calculated off-line [5]. The horizontal beating is typically below 30% with isolated peaks up to 40%, to be compared with the tolerance of 20%. This indicates that the optics is very well under control. For the vertical plane, errors up to 100% were measured. The analysis carried out in [5] has identified potential polarity errors that could explain this discrepancy. They will be corrected for the 2009 operation.

Closed Orbit and Aperture for Beam 2

The best reference closed-orbit, established after beam capture, is shown in Fig. 3. The horizontal RMS orbit was 1.6 mm and the vertical was 1.3 mm. These were achieved by using a limited number of correctors. The analysis of the residual orbit suggests that by using more correctors one could easily improved the RMS errors by a factor 3-5 [6].

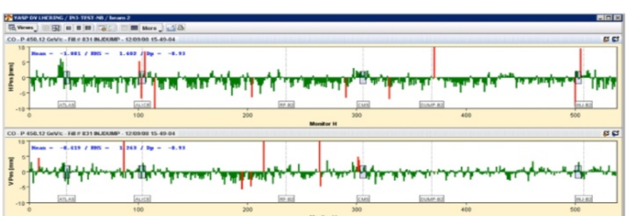

Figure 3: Best B2 closed-orbit as established on Friday 12th. Faulty monitors (red) are disregarded for the RMS calculation.

Note that the horizontal offset for the captured beam has an offset of about -1.2 mm due to the energy mismatch discussed below.

It was not possible to perform dedicated aperture measurements in the LHC ring after establishing the circulating beam. The aperture of only two arcs – 23 for B1 and 78 for B2 – was systematically measured during the sector tests by exciting free oscillations of the injected beam trajectory, with varying oscillation phases and amplitudes [1]. A machine aperture very close to nominal was measured.

Radio-frequency Settings and B2 Momentum

The LHC frequency was set to 400788963 Hz, i.e. 229 Hz higher than the nominal. This is consistent with the observed average energy error of about -10 units of the dipole field component. The synchrotron frequency calculated from a peak detector Schottky spectrum is about 60 Hz to be compared with the expected 66 Hz.

CONCLUSIONS

Given the short period of having the whole ring available to take beam (10th – 12th Sep.) a remarkable amount was achieved. Progress was so rapid in fact, the carefully laid out commissioning plan was not rigourously adhered to. In the circumstances, this was not really a problem: firstly because the beam intensity was safe, and secondly because consolidation was possible during the enforced days without beam that followed

The curtailed but productive beam commissioning period coupled with the results from the injection tests have given us some confidence in numerous aspects of the LHC's potential operation, namely: magnet model, magnet field quality, machine aperture, machine alignment, optics, injection and beam dump systems, collimation, beam instrumentation, controls and software.

It also had to be noted that only limited progress was made into the full beam commissioning program and that a lot remains to be done before we reach the first major milestone of the program – colliding low intensity beams at high energy. Systematic and careful progress will be essential if the potential dangers of even moderate intensity beams are to be dealt with properly.

ACKNOWLEDGEMENTS

The success of the initial LHC beam commissioning was due to an enormous and very professional effort by a large number of teams ranging through magnets, survey, RF, beam instrumentation, cryogenics, hardware commissioning, controls, beam transfer, radiation protection, quench protection and beyond.

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