OPERATIONAL EXPERIENCE WITH CIRCULATING BEAM

S. Redaelli on behalf of the LHC beam commissioning team
CERN, Geneva, Switzerland

Abstract

Following various injection tests, the full LHC beam commissioning started on September 10th. Within three days of beam operation, we established stable and captured circulating beam 2 and achieved circulating beam 1 for several turns. This was made possible by a thorough preparation of all the required accelerator systems, beam instrumentation and control software, which all achieved a remarkable performance during this initial phase with pilot beams. First beam measurements of the linear machine optics were carried out and showed that the machine is well under control. The operational experience with circulating beam, the performance of the various systems and the first detailed measurement results are reviewed.

INTRODUCTION

The experience with LHC circulating beam was limited to about three days of operation, from Sep. 10th to Sep. 12th. The effective beam time was about 40 hours that were efficiently used to close the first turn for both beams and to commission circulating, captured beam 2 with decent 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 only possible for beam 2 (B2) because 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. A first look at the overall machine performance is given and some conclusions are drawn. Focus is put on the aspects that were not treated in detail in companion contributions of these proceedings [2, 3, 4, 6, 5].

MILESTONES OF CIRCULATING BEAM COMMISSIONING

Commissioning strategy

The beam commissioning was carried out with single pilot bunches of $2-4\times10^9$ protons. This ensured a safe operation throughout the commissioning of circulating beam. Contrary to what happened during the sector tests, no quench was induced during this phase. Sectors 23, 34 and 45 for B1 and sectors 78 and 67 for B2 were 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 con-

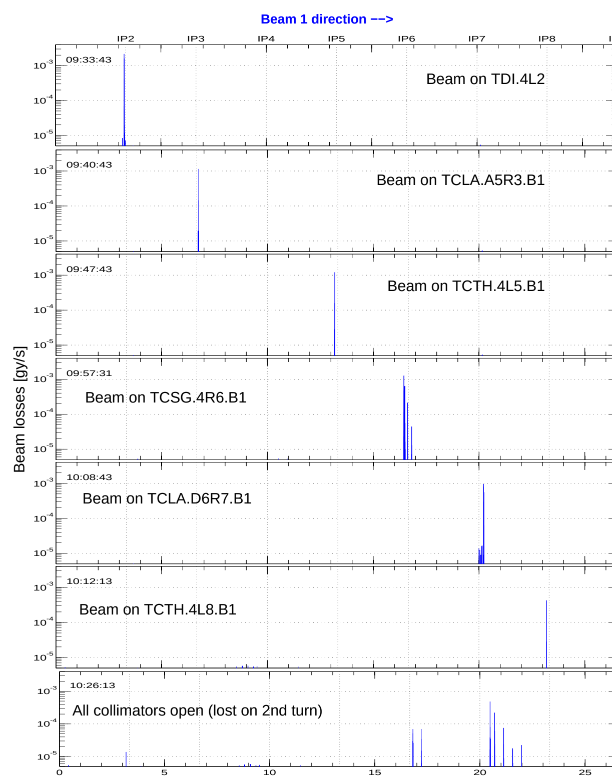

Figure 1: Beam loss patterns along the ring during the various stages of the B1 commissioning. The injected beam was stopped in all the IP's where collimators are installed, and its tajectory was optimized before exploring the subsequent sector. Vertical dashed lines show the IP positions. The full system of about 4000 monitors is shown.

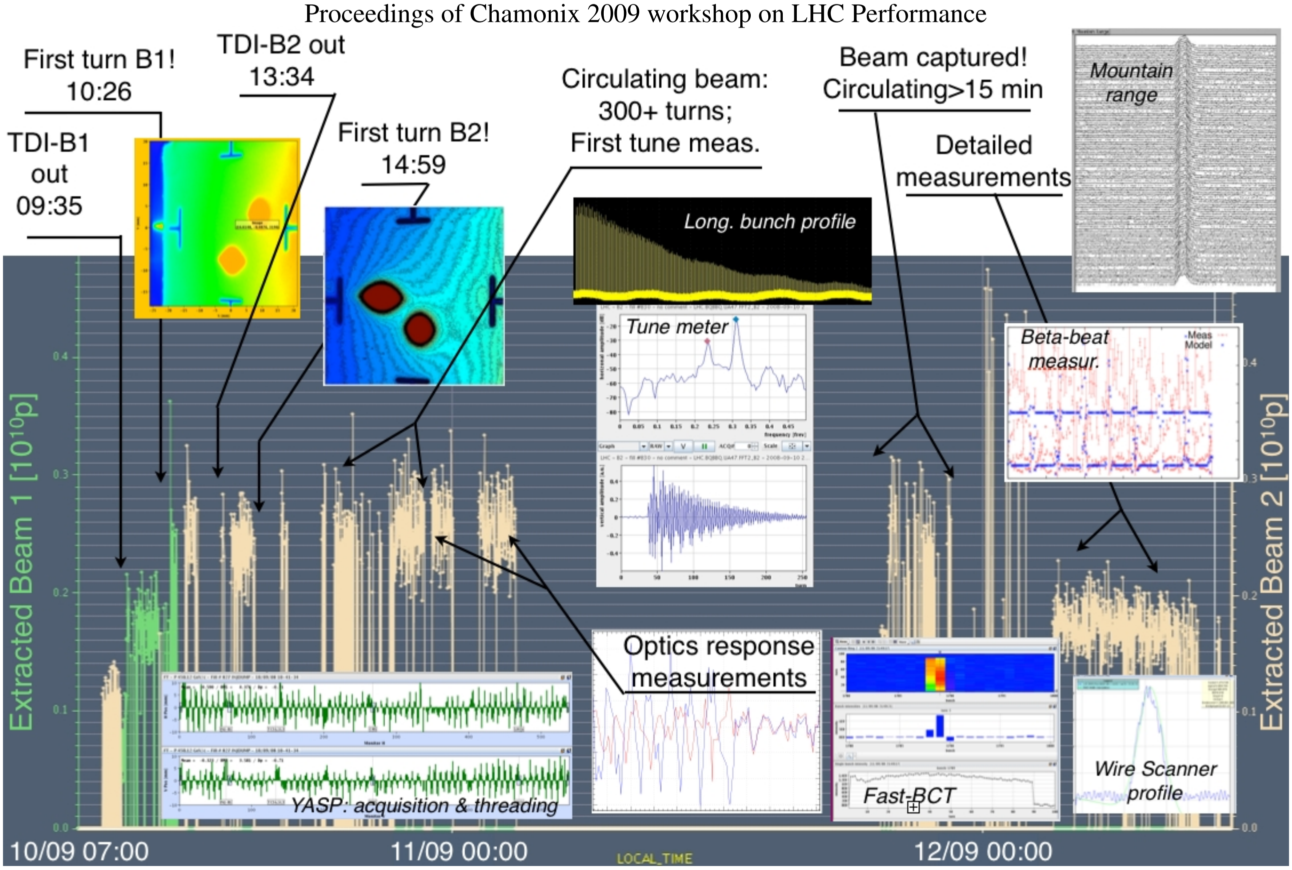

Figure 2: Illustrative view of the milestones of three days of LHC beam operation. The extracted intensity for beam 1 (green) and beam 2 (yellow) as measured in TI2 and Ti8 respectively are given as a function of time. The plots show (1) the BTV screen snapshots of the first turns of B1 and B2, (2) a typical YASP trajectory acquisition, (3) first longitudinal profile and tune measurements, (4) an example of response matrix measurements, (5) the mountain range plot of the first captured beam, (6) the first on-line beta-beat measurement and (7) examples of beam current and wire scanner measurements.

tinued with B2 after having established the first turn for B1. Within one shift, the first turn was achieved for both beams. Then, the commissioning proceeded for B2. The operation was interrupted on Sep. 12th due to a number of unrelated hardware failures that culminated in the Sep. 19th accident, which eventually put an end to the 2008 beam commissioning.

Whenever possible, the collimators in each insertion region (IR) were closed to stop the beam and give the possibility of optimizing the trajectory steering before sending the beam into next sector(s). This has been possible for all IRs except for IR4, where no collimator is installed. This sector-by-sector steering proved to be very effective because both beams went through all sectors at the first shot with small losses. This is illustrated in Fig. 1 where the beam losses measured for B1 at the collimators in the various IP's are shown (about 4000 monitors the 27 km). After steering adjustment on the TDI, the beam 1 was then stopped in IP3, on the tertiary collimator left of IP5, on the beam dump collimators in IP6, on the collimators in IP7, on the tertiary collimators left of IP8 and left of IP1 (the latter is not shown in Fig. 1) before finally closing the first turn. Similarly, B2 was stopped in IP7, IP6, IP5, IP3, IP2 and IP1 before closing the first turn. Correspondingly, all the available screens (BTV's) in the various points (injection regions, IP3, IP4, IP6, and IP7) were also inserted in the beam path and used to witness the beam passage. The beam loss monitoring (BLM) and beam position monitoring (BPM) systems were deployed for day-1 and worked reliably in asynchronous mode.

When the beams reached IP1 and IP5, several shots where intentionally lost on the tertiary collimators upstream of the IP in order to provide to ATLAS and CMS the first chance to acquire beam-induced events (ALICE and LHCb had extensively done the same during the sector tests).

The full static magnetic model of the LHC based on FiDeL [5] was used to generate injection currents for all the circuits. A full machine re-cycle was performed after a 20 hour stop caused in the night of Sep. 10th by a failure of the quench protection system of the circuit RB.A34.

Milestones and performed activities

The main milestones and the activities performed during three days of beam operation, from Sep. 10th until Sep. 12th, are graphically illustrated in Fig. 2. The plot of the extracted beam intensities for beam 1 (green) and

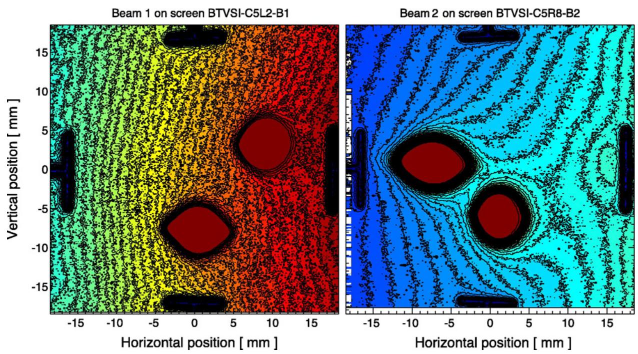

Figure 3: Snapshots of the beam screen (BTV) acquisitions that illustrate the very first turn of B1 (left) and B2 (right). These screens are located in the injection regions of either beam and could record the image of the injected beam as well as the image of the beam after one turn, 89 μs after.

beam 2 (yellow) as a function of time, as measured at the end of TI2 and TI8, is used as a background to show highlights plots of the achievements of the first exciting LHC beam commissioning phase. 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 BBQ system (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 [4];

– 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 achieve this is apparent.

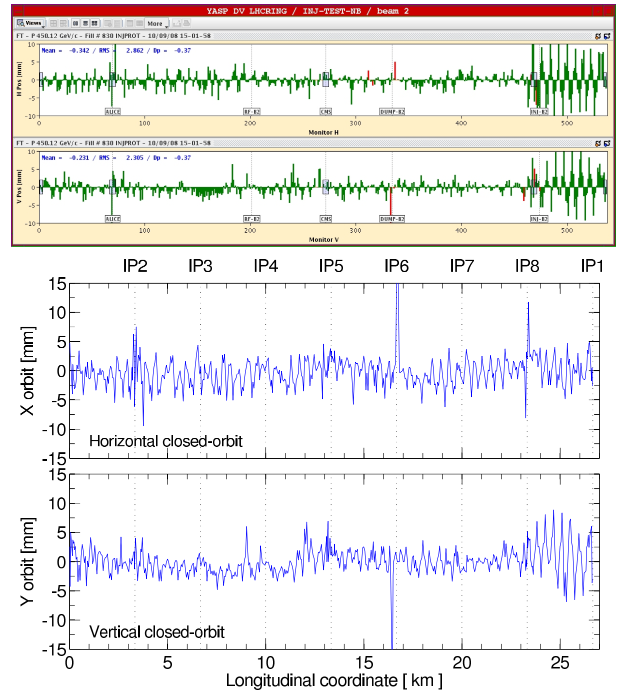

Figure 4: First turn of B2 as measured with YASP (top) and closed-orbit calculated as average of the first 90 turns of B2, on the evening of Sep. 10th (bottom). In both cases, horizontal and vertical planes are given.

OPERATIONAL EXPERIENCE OF ACCELERATOR SYSTEMS

The BTV screen images of the first turns achieved for B1 (left) and B2 (right) are shown in Fig. 3. These acquisitions were taken at 10:26 and 15:00 of Sep. 10th, respectively. The Aluminum 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, as it is shown in the next Section for B1. Screen 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.

The BPM system worked remarkably well during this commissioning phase with pilot beam [6]. 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. The YASP program by J. Wenninger was used to handle all these acquisition types. An example of first turn YASP acquisition is given in Fig. 4 (top), where the very first turn of B2 is shown. An example of the average closed-orbit over 90 turns, as established on the evening of Set.10th with uncaptured beam, is also shown.

One of the key ingredients for a rapid establishment of circulating B2 was the early commissioning of the BBQ-based tune measurement system [7] because it allowed the

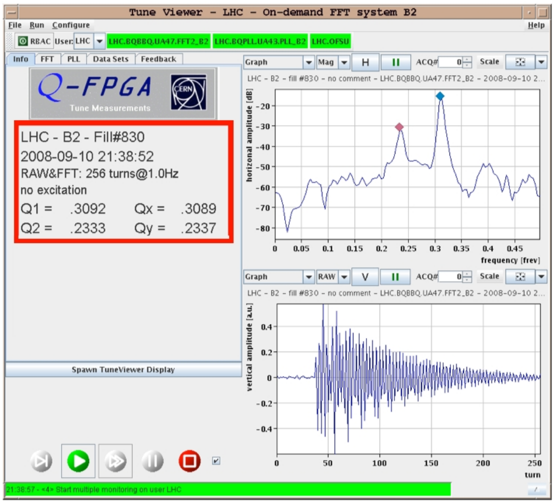

Figure 5: On-line tune application with the first tune measurement performed on the un-captured beam. The commissioning of the BBQ system was done in the early stage and was used to establishing circulating B2 [7].

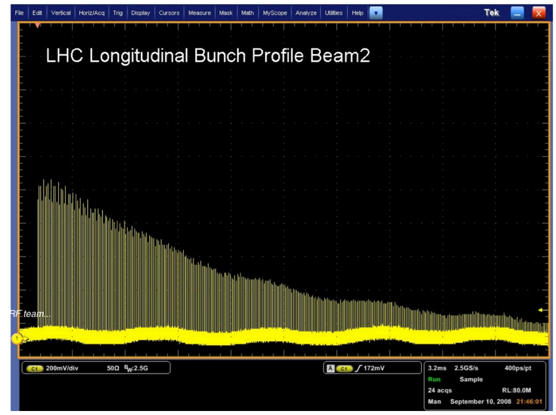

Figure 6: Longitudinal beam profile of the circulating, uncaptured B2. Each vertical line represent one turn. Courtesy of RF team.

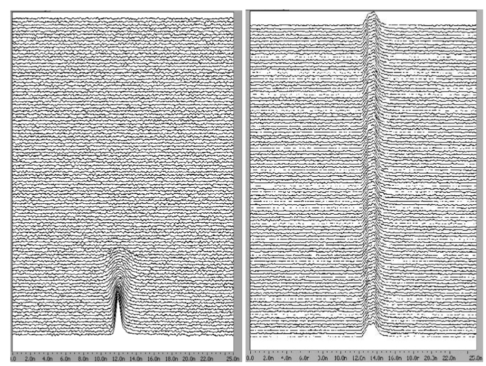

Figure 7: Mountain range graphs of the circulating B2 with RF off (left) and with RF on after adjustment of RF phase and frequency (right). The beam capture was performed on the evening of Sep. 13th. After capture, the circulating beam was kept stably in the machine for 10-15 minutes without special optimization of the transverse optics parameters. Courtesy of RF team.

observation that the tunes were close to a half-integer resonance. A few tune trims to change the working point were then sufficient to achieve several tens of turns and then start the beam lifetime optimization. A snapshot of the tune measurement application that show the first tune spectrum measured over about 200 turns is given in Fig. 5. The beam lifetime of the un-captured beam was then 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. 6. 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&Dump" and of the "Circulate&Dump" operational modes was also performed. Beam dumps after up to about 4 seconds from the injection were programmed and this operational mode was maintained during the subsequent commissioning phases, until stable circulating beam was established. More details on the beam dump tests were presented in [4].

After an interruption of the commissioning plan due to a failure of the quench protection system of the circuit RB.A34, beam tests continued in the evening of Sep. 11th with the initial commissioning of the RF instrumentation in IP4 and with the beam capture. This phase was driven by the RF team in SR4. After switching ON the RF, the RF phase and frequency were adjusted and the beam capture was achieved. This is illustrated in Fig. 7, where the "mountain range" plot of the longitudinal beam profile is shown with RF OFF (left) and with RF ON after tuning (right). 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. 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 the RQD.81 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).

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 (see an example of acquisition in Fig. 8) and slow and fast beam current monitors [6] was started. By using the 90 turn acquisition of the injection oscillations, it was also possible to have a first on-line measurements of horizontal and vertical beta-beating for B2. A snapshot of the application is given on Fig. 9. Last but not least, the last hours of beam operation were dedicated to the optimization of the closed orbit, which was brought almost within tolerance with a limited number of corrections.

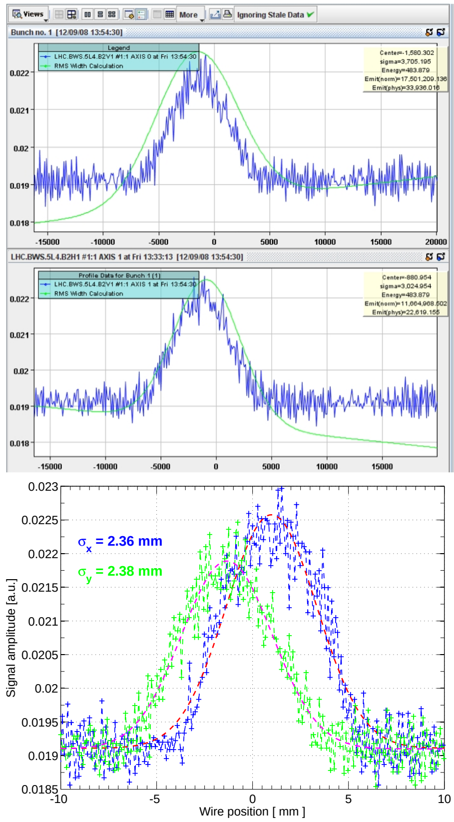

Figure 8: First vertical wire scanner measurement with captured beam (top, ingoing and outgoing scans) and Gaussian fits of the horizontal and vertical profiles (bottom).

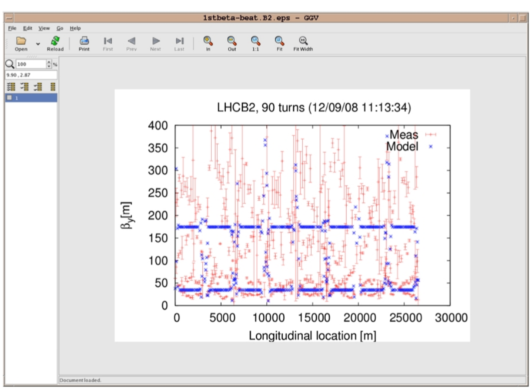

Figure 9: First on-line beta-beat measurement available on Sep. 12th. The 90-turn injection oscillations was sufficient for a estimate. Courtesy of R. Tomàs.

OVERALL MACHINE PERFORMANCE

After having had a look at the various systems available from the LHC control during the first days of beam commissioning, the main machine parameters from detailed measurements are reviewed.

A quick look at beam 1

As already discussed, 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. In Fig.10 the profiles of the first tree turns of B1, as measured with the Titanium screen BTVSI-C5L2-B1 in IP2 are shown. The beam sizes for the projected beam profiles can be calculated with Gaussian fits, as shown for the horizontal plane in the bottom part of Fig.10. The ratio σ_x/σ_y calculated from the nominal optics is 2.7 whereas from the fits one gets 2.5 (taking into account a factor 1.8-2 difference on the emittances, $\epsilon_x \approx 2\epsilon_x$, as indicated by transfer line screen matching).

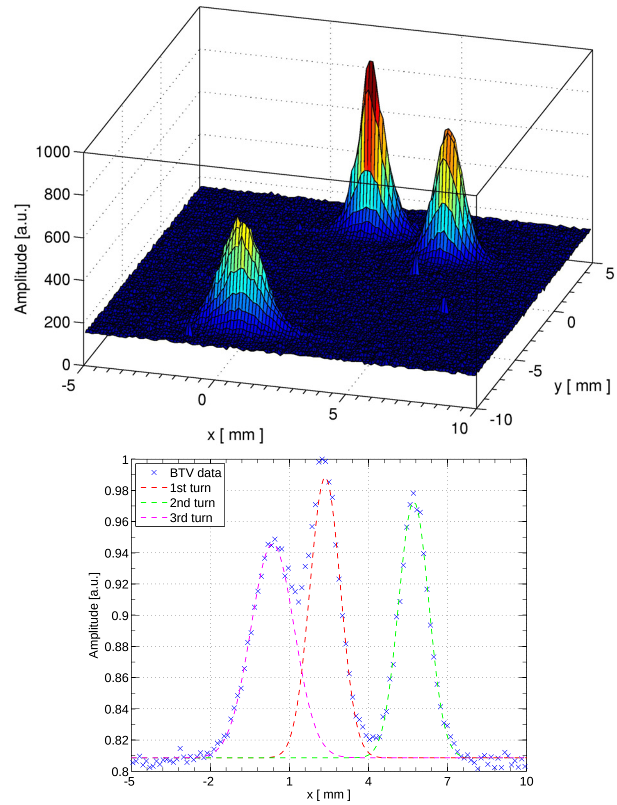

Figure 10: Profiles of the three first turns of B1 recorded on the Ti screen BTVSI-C5L2-B1 (top) and Gaussian fits of the projected horizontal profiles. Similar fits have been performed also for the vertical plane. The estimated beam size are approximately $\sigma_x = 0.58$ mm and $\sigma_y = 0.33$ mm.

Tune, coupling, chromaticity and beta-beat for beam 2

The integer tunes in both planes were measured with the trajectory data from the injection oscillations. The results are illustrated in Fig. 11. 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 (the two values quoted are from references [7] and [8], respectively):

- Tunes: $Q_x = 0.3803 - 0.3015$, $Q_y = 0.3066 - 0.2441$ (Nominal values: $Q_x = 0.28$, $Q_y = 0.31$).

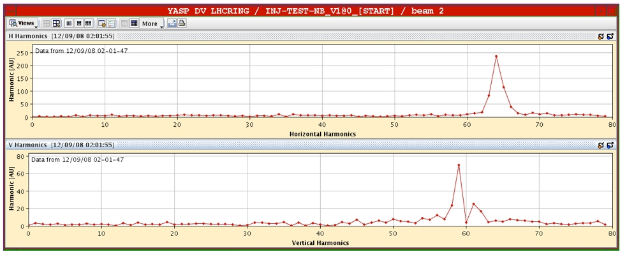

Figure 11: Integer tunes calculated for B2 with YASP. The nominal values $Q_x = 64$ and $Q_y = 59$ were achieved.

- Coupling (closest tune approach): $|C_-| = 0.07 - 0.06$
- Chromaticity $|Q'_x| \approx |Q'_y| \approx 30$ units.

The values of Q_x and Q_y listed above are calculated with the BBQ system on the circulating beam [7] or with Fourier analysis of the injection oscillations [8]. The difference between the tunes in the two planes are consistent with the coupling measurements. Throughout the days of beam tests it has not been possible to consistently reproduce tune measurements. This aspect is not fully understood. A possible problem with the reproducibility of trim quadrupole field [5] is being investigated. The coupling is within the range that can be corrected without requiring special injection optics with 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 [7].

Updated estimates of the beta-beat have been calculated off-line with a much improved statistic compared from the initial on-line estimates as in Fig. 9 [8, 3]. The horizontal beating is typically below 30% with isolated peaks up to 40%, to be compared with the tolerance of 20% [3]. 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 [3] 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. 12. The horizontal RMS orbit was 1.6 mm and the vertical was 1.3 mm. This levels 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 [9]. Note that red bars in Fig. 12 indicate faulty monitors or monitors with known calibration errors that have been disregarded for the calculation of the RMS. Figure 13 shows the distribution of monitor readings for the first closed-orbit established for un-captured beam (top graphs, corresponding to the data of Fig. 4) as well as for the best orbit of Fig. 12 (bottom graphs). The distribution is

Figure 12: Best B2 closed-orbit as established on Friday 12th. The RMS orbit deviation excluding a few suspicious monitors is about 1.6 mm (horizontal) and 1.3 mm (vertical), compatible with the expected tolerance from beam dynamics. Faulty monitors (red) are disregarded for the RMS calculation.

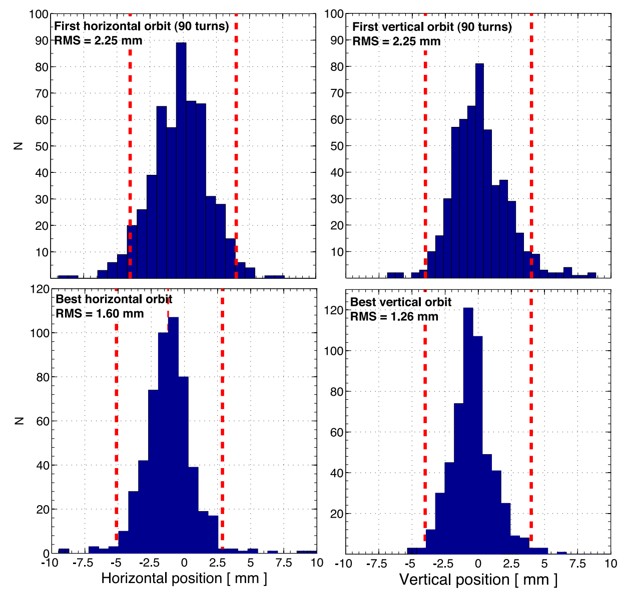

Figure 13: Distribution of horizontal (left graphs) and vertical (right) BPM readings for the first closed-orbit established on the night of Sep. 10th (top) and for the best closed-orbit achieved on Sep. 12th (bottom). The read lines indicate the ± 4 mm LHC tolerance in the arcs. The horizontal orbit shows a negative offset of 1.2 mm, corresponding to an energy error of about 10^{-3}.

compared with the LHC arc tolerance of ± 4 mm. It is seen that after corrections only a limited number of monitors exceeds the tolerances and the distributions are narrower. Note that the orbit in the insertion regions where the two beams share the same vacuum pipe were not optimized. It is also noted that the horizontal offset for the captured beam has an offset of about -1.2 mm due to the energy mismatch discussed in the next Section.

It has not been 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.

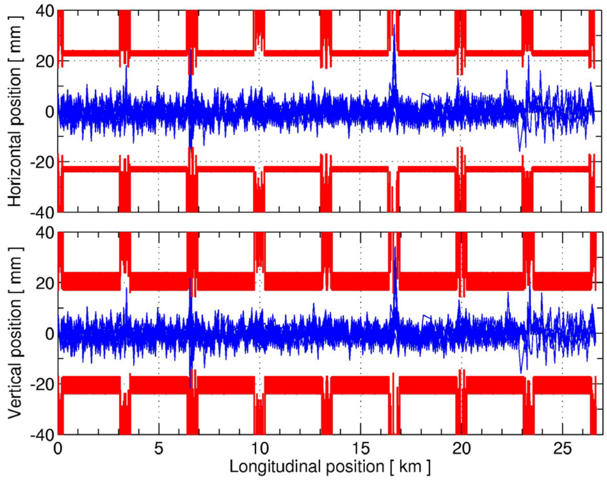

Figure 14: Horizontal (top) and vertical (bottom) trajectories as measured for B2 during matrix response measurements, compared with the nominal mechanical aperture. All monitor readings are shown.

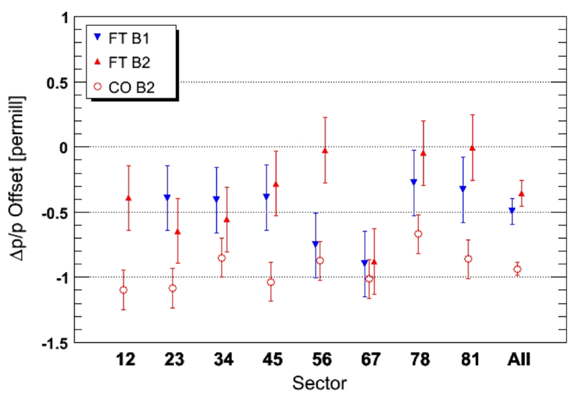

Figure 15: Sector-by-sector momentum error for B1 (blue) and B2 (red) as calculated from the first turn (FT) and from the closed-orbit (CO) measurements. CO estimates for B2 refer to the best achieved orbit as in Fig. 12. Courtesy of J. Wenninger.

For the circulating B2, an attempt was made to estimate the available aperture by looking at all the different beam trajectories measured during the optics response matrix measurements. This is shown in Fig. 14. The phase coverage of these oscillations is not complete and hence these cannot be considered as systematic measurements. On the other hand, oscillations of about ± 10 mm were routinely excited in the full ring without apparent beam loss problems.

Radio-frequency settings and beam 2 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, see Fig.15. The synchrotron frequency calculated from a peak detector Schottky spectrum [10] is about 60 Hz to be compared with the expected 66 Hz.

CONCLUSIONS

In this paper the operational experience with LHC circulating beam has been reviewed. The achieved milestones, the activities performed and of the tools available during three days of LHC beam commissioning have been reviewed. It has been shown that most of the key accelerator systems of the LHC have been deployed and have successfully been used during the Sep. 10th event, which was a great achievement for CERN in many respects.

An impressive amount of useful information could be inferred from the limited beam commissioning experience, thanks to the availability from day-1 of a large number of sophisticated control applications and analysis tools. A selection of results from many beam based measurements have been presented. It is fair to conclude that, even though some localized problems have been identified, the overall machine performance was impressive. This indicates a remarkable good quality of machine alignment, magnetic model, magnets, settings management generation. These achievements were made possible by the great performance of the involved accelerator systems that preformed as expected during the initial tests with pilot beams. On the other hand, it is important to realise that the 2008 beam experience only covered a minor fraction of the commissioning steps required to achieve physics production at the LHC and the work ahead should not be underestimated.

ACKNOWLEDGMENTS

As mentioned in the text, the good results presented here were only possible thanks to the work of many people that worked on the LHC during the last two decades. This contribution has been prepared on behalf of the LHC beam commissioning team. In particular, T. Bohl, M. Lamont, R. Steinhagen, R. Tomàs and J. Wenninger are specially thanked for having provided material for this paper and for the presentation. The many discussions with and inputs from G. Arduini, R. Bailey, E. Bravin, A. Butterworth, E. Ciapala, S. Fartoukh, M. Giovannozzi, R. Jones, W. Venturini and many others are also kindly acknowledged. The colleagues from OP and the shift crews of the LHC injection complex, which delivered reliably the required LHC beams during the beam tests, are also sincerely thanked.

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