BEAM COMMISSIONING OF INJECTION INTO THE LHC

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Abstract

The LHC injection tests and first turn beam commissioning took place in late summer 2008, after detailed and thorough preparation. The beam commissioning of the downstream sections of the SPS-to-LHC transfer lines and the LHC injection systems is described. The details of the aperture measurements in the injection regions are presented together with the performance of the injection related equipment. The measured injection stability is compared to the expectations. The operational issues encountered are discussed.

INTRODUCTION

Injection Systems

The LHC injection systems [1] are located left of the experimental insertion 2 (Alice) for Beam 1 and right of the insertion 8 (LHCb) for Beam 2. Beam arriving through the transfer line TI 2 (TI 8) in case of Beam 1 (2), Fig. 1, sees in turn a series of 5 Lambertson type septum magnets MSI (total horizontal deflection 12 mrad), 4 injection kickers MKI (total vertical deflection 0.85 mrad), an injection stopper TDI at 90° phase advance downstream of the MKI, supplemented by a shielding block TCDD to protect the superconducting D1 magnet against particles escaping or scattered by the TDI. Collimators TCLI on the other side of the long straight section complete the protection of the machine. Dedicated instrumentation for beam steering and diagnostics comprises (per beam) 5 beam screens BTV, 1 beam current transformer BCT at the end of the transfer line, and a number of ring beam position and beam loss monitors (BPM, BLM).

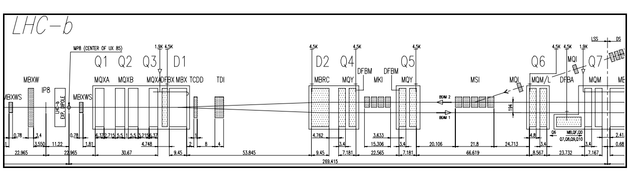

Figure 1: Schematic view of the Beam 2 injection.

Scope and Schedule of Beam Tests

Beam commissioning of the LHC injection began in summer 2008 [2]. During a first injection test (8th-11th August 2008) the end of TI 2 and the Beam 1 injection system were commissioned. In a second test (22th-25th August) the end of TI 8 and the Beam 2 injection were commissioned, and the interleaved injection of Beam 1 and Beam 2 was successfully tested. Further tests were carried out on 5th-8th and 9th September.

Preparation

The injection tests were preceded by many dry runs through 2008 during which the hardware and control systems were thoroughly tested and debugged. Precious experience had also been gained during beam commissioning of the SPS-to-LHC beam transfer systems over the previous years [3,4]. The injection tests allowed in turn to debug and demonstrate the functionality of the main systems and to perform part of the detailed measurement programme, and were thus instrumental for the good progress during the official LHC startup on 10th September.

To ease the injection commissioning, optics sequences with complete aperture information were prepared, comprising for Beam 1 the SPS extraction in LSS6, TT60, TI 2, LHC arc 2-3, and for Beam 2 the SPS extraction in LSS4, TT40, TI 8, LHC arc 7-8 and beyond. The sequences were fed into an online version of MADX [5] to generate bumps and knobs, which allowed dynamic configuration and visualisation of the results. During most of the tests pilot beam of 5×10^9 p+ in a single bunch was used; a number of commissioning steps was also performed with multiple bunches with a total of 1.2×10^{11} p+ per SPS pulse. The total intensity used per test weekend was of the order of $3\text{-}5\times10^{12}$ p+.

This article focuses on the performance of the main injection elements and the aperture results, the lessons learnt and the inferences for 2009/2010. Details of the beam instrumentation and the control system, which both performed excellently and contributed decisively to the good progress, are given elsewhere [6,7], as are details from optics and dispersion studies [8,9].

RESULTS

Initial Steering and Element Strengths

Previous tests of TI 2 and TI 8 had allowed to perform extensive optics studies and to conclude that the beam lines were essentially behaving as expected up to beam dumps about 100 m upstream of the injection points. In both lines already the very first extracted beam had reached the end of the nearly 3 km long lines, without the need for any threading. In contrast the initial threading of the downstream ends of TI 2 and TI 8 took some time, in both cases due to wrong settings of dipole magnets. In TI 2 the strength of the last horizontal group of bends had to be re-adjusted by about 1.3 % as a result of an erroneous setting in a data base. In TI 8 the first beam was horizontally mis-positioned by 2-3 mm at the entrance of the MSI, caused by a false calibration setting of a bending group. In the vertical plane the polarity of a groups of 3 correctors used as bends had to be inverted; this was understood as a simple polarity confusion, since corrector type magnets are by convention cabled with opposite polarity to bends. After ironing this out the beam passed through the injection septa and kickers (which were initially switched off) and was stopped by the TDI, Fig. 2. After some verifications and adjustments the kickers were timed in and switched on, while the beam was still stopped by the TDI, entirely closed for this purpose. After all basic checks were done the beam was allowed to continue into the LHC.

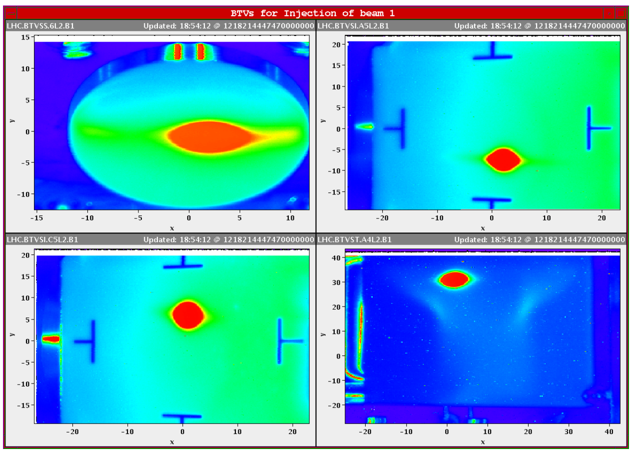

Figure 2: Injected Beam 1 on screens in IR2 on 8 August 2008, top left: after MSI, top right/bottom left: before/after MKI, bottom right: at TDI (MKI off).

The strengths of the injection elements were verified from checking the positions on the injection screens and the injected trajectory. The strengths were correct to the resolution of the measurement (2 % for the MKI; 0.4 % for the MSI). No trims of these elements were applied at this early stage. Later on a periodic displacement of the circulating LHC beam by 0.5 mm was discovered which is probably due to the leakage field of the MSI pulsed with the SPS cycle. In the future the MSI will be powered DC which is feasible from the cooling and powering side, but requires some modifications to the control and interlocking.

Synchronisation

The synchronisation between the SPS extraction and the LHC injection worked well, after some initial problems with the timing system had been sorted out. The rough MKI timing adjustment was straightforward, although somewhat complicated by the kicker noise on the transfer line BCT signal, Fig. 3; this has since then been improved by using tri-axial shielded cables.

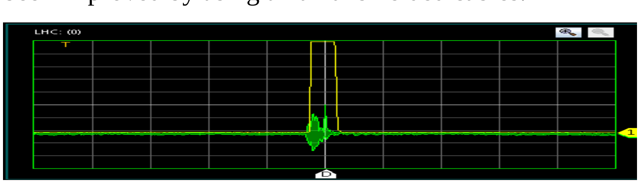

Figure 3: Injection of a pilot bunch; yellow: kicker waveform; green: TI 2 BCT signal (beam signal at centre of plot, after kicker noise).

Aperture Measurements

The apertures in the injection region were measured with a pair of correctors using the single pass technique of unclosed oscillations at phases of 0, 30, …, 330 degrees, with a small emittance pilot beam (ε_n of about 1 µm per plane). The 20 mm aperture of the MSI protection device TCDIM was confirmed, with the beam well-centred in IR2 and displaced vertically by about 2 mm in IR8, Fig. 4. In IR2, however, during the first test it was quickly apparent that the vertical aperture between the MSI and the downstream Q5 quadrupole was about 6 mm smaller than expected. A radiation survey after the test confirmed a hot-spot on a vacuum valve assembly; checks revealed that this element was installed 10 mm too high. After a re-alignment the next check with beam showed that the aperture was as expected.

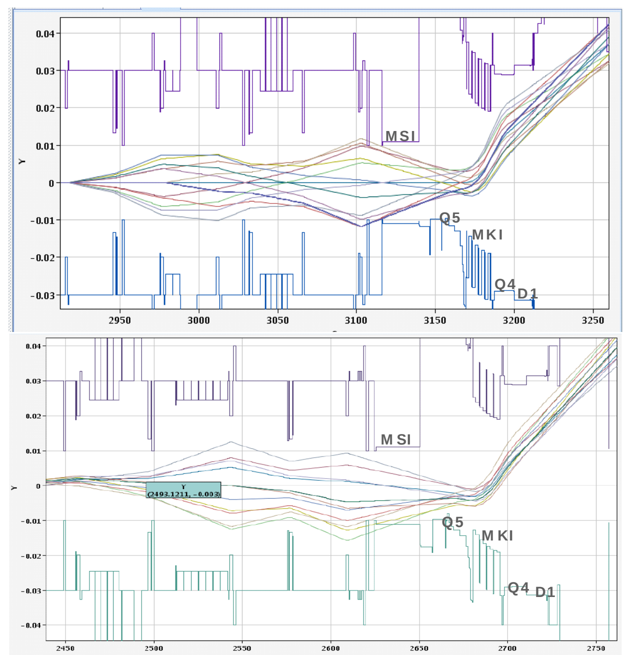

Figure 4: Vertical aperture scans of the injection regions in IR2 (top) and IR8 (bottom). The estimated edge of the beam envelope is plotted, calculated by adding the actual trajectory to the beam size. The MKI are off, and the beam direction is from left to right in both cases.

The potential limits in the vertical aperture at D1 (with MKI off) were planned to be checked but not done due to lack of time. No systematic circulating beam aperture checks were made, in particular at the MSI and TDI; the TDI for Beam 1 was however moved in to the "protect" position while Beam 2 was circulating, with no beam losses detected.

Steering and Stability

Some early injection steering was done for Beam 2, which was initially several mm off in the vertical plane (see Fig. 4). The algorithm converged correctly; there was no time however to re-measure the aperture and also to revisit the MSI and MKI strengths.

The short-term (~1 h) stability was measured for Beam 2 at the injection point using the screens in LHC point 8, from which very accurate position data were obtained on a shot-by-shot basis. The measured RMS jitter was 0.27 (0.13) nominal beam σ in the horizontal (vertical) plane, compared to the specification of ±1.5 nominal σ RMS error in both planes. From this data an upper limit on the MKI kicker instability from the charging voltage was made, of about 1.7×10^{-3}, compared to 5×10^{-4} specified.

MKI Kicker Flashovers

Flashovers of the IR2 injection kickers were seen on two occasions. The first occurred on 9th August 2008 after the aperture measurements described above, during which the pilot beam was lost several times on an aperture limit upstream of Q5, with a total loss of about 5×10^{10} p+. The flashover happened some 30 minutes later when the kicker was switched on again and the voltage increased to nominal. A later analysis showed that the beam losses were visible on the measured vacuum signal, as physically impossible dips in the pressure reading, probably resulting from ionisation in the HT feedthroughs. This sensitivity to beam loss is worrying; to provide more exact data additional BLMs were installed for 2009 on the MKI kickers themselves, and the beam loss signal from these monitors will be interlocked or alarmed to try to avoid this.

A second flashover occurred on a different magnet in IR2 on 7th September, during the kicker pulse, while doing a polarity measurement of magnets in the LHC arc. This event was not preceded by an apparent beam loss. The injected trajectory, Fig. 5, showed a clear overkick of one magnet by about 40 μrad (20 % of the nominal kick) and corresponds to a 5 σ oscillation which indicates that the magnet broke down some 60 % along its length. This failure demonstrates clearly the need for the TDI protection to prevent damage to the downstream arc. The magnet was suspected to have been weakened on the test bench due to a calibration error and has meanwhile been replaced by the spare.

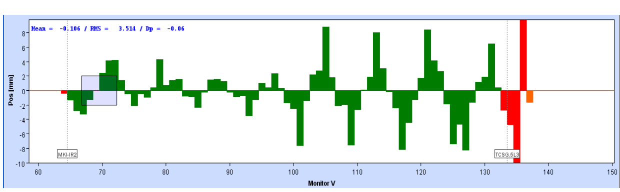

Figure 5: Injected beam trajectory during MKI flashover. The oscillation starts at the MKI and shows an overkick of about 5-6 σ (the larger oscillations further downstream in the LHC are due to the measurements taking place at that time).

SUMMARY

The LHC injection systems for both rings were successfully and efficiently commissioned with pilot beam, during the tests and the short period of ring operation in 2008. Although not all planned measurements could be carried out due to the limited beam time, the correct functioning of the main components has been demonstrated. No major issues have been found, although there is some concern about MKI flashovers with beam, for which an operational strategy needs to be defined. Operator handling of the injection related tools and systems, with their complicated dependencies to and from other systems, will be further improved and automated where feasible to reduce the workload and to increase the overall efficiency. In addition, a first version of injection quality checks should be ready in 2009 to monitor kicker pulses, BLMs and the filling pattern. All hard- and software improvements undertaken since September 2008 need thorough validation to fully re-qualify the LHC injection systems for operation with beam. A new series of dry runs, transfer line and injection tests are organised to be able to focus on the main ring once the LHC becomes again fully operational. The main tasks for 2009 include measurement of the circulating beam apertures, injection steering, kicker waveform measurement, detailed optics matching to the LHC, injection into the crossing/separation bumps, checks that no beam is injected into the beam abort gap, and setting-up of the protection systems before increasing the intensity.

ACKNOWLEDGEMENTS

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