THE LHC INJECTION TESTS

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Abstract

A series of LHC injection tests was performed in August and September 2008. The first saw beam injected into sector 23; the second into sectors 78 and 23; the third into sectors 78-67 and sectors 23-34-45. The fourth, into sectors 23-34-45, was performed the evening before the extended injection test on the 10th September which saw both beams brought around the full circumference of the LHC. The tests enabled the testing and debugging of a number of critical control and hardware systems; testing and validation of instrumentation with beam for the first time; deployment, and validation of a number of measurement procedures. Beam based measurements revealed a number of machine configuration issues that were rapidly resolved. The tests were undoubtedly an essential precursor to the successful start of LHC beam commissioning. This paper provides an outline of preparation for the tests, the machine configuration and summarizes the measurements made and individual system performance.

INTRODUCTION

The motivations for an LHC injection test were discussed at length [1, 2]. The tests performed at the LHC in August and September 2008 were unusual in that they were performed only a short time before the start of full beam commissioning. Despite the short lead time, the tests were undoubtedly invaluable and fully met the original goals. They resolved numerous problems, testing as they did controls infrastructure, beam instrumentation, timing and synchronization, software, measurement procedures, and allowing detailed optics and aperture checks. In addition they provided a set of clearly defined milestones for beam commissioning which allowed a targeted and structured preparation to be developed in the preceding months.

Schedule

The hardware commissioning schedule and ongoing system commissioning of the cold machine demanded flexibility and the first test found itself dependent on the successful deployment of the LHC access system and subsequent acceptance tests. Only after the latter had been completed could beam be put in the LHC for the first time.

The success of the first test motivated the rapid scheduling of subsequent tests, see Table 1, mainly at the weekend to minimize the inconvenience to the experiments and hardware commissioning. The eventual goal was the public attempt to pass the two beams around the whole machine. The injection tests were fully vindicated with the success of September 10th [3], accompanied as it was by good machine availability on the day.

Table 1: LHC Injection Test Schedule

Date	Test goal
8-11 August	Beam 1 through sector 23
22-25 August	Beam 2 though sector 78, beam 1 through sector 23
5-8 September	Beam 2 through sectors 78,67, beam 1 through sectors 23, 34, 45
9 September	Preparation for 10th September – beam 1 through sectors 23, 34, 45
10 September	Beam 1 and beam 2 around the whole circumference of the LHC

Beam

The nominal LHC Pilot beam - a single bunch with an intensity of around 5e9 protons - was used at start of the first test. Following the beam induced quench described below and after measurements showed that the beam position monitors (BPMs) would trigger reliably on 2e9, the single bunch intensity used was lowered to this value. This helped to reduce ambient radiation levels thus minimizing the impact on the post-test tunnel activities.

Measurement and Tests with Beam

The planned measurements with beam and the essential pre-requisites were established well before the actual tests and were documented at length; see, for example, [4]. The measurements and checks performed are enumerated in Table 2. In essence an attempt to commission all available functionality and perform the full suite of measurements was made for each new sector within the time constraints given by machine availability.

Stopping the Beam

A pre-requisite for all injection tests was the ability to safely and reliably stop the beam at the end of the sector or sectors being tested. The LHC collimators and other beam absorbers around the machine were used, when appropriate, as beam dumps to safely intercept the injected beam – see Table 3.

For the attempt to perform first turn of both beams on the 10th September, all the above options were used. In addition the tertiary collimators on the left of IP8 and IP1 and the beam dump channel were used for beam 1; the tertiary collimators on the right of IP5, IP2 and IP1 were used for beam 2. The locations where the beam was stopped are shown in Fig. 1.

Table 2: Summary of Tests and Measurements Performed

Transfer line optics checks	Matching between transfer lines and the LHC
Injection	Kicker timing and control RF synchronization, pre-pulses, interaction with timing system, injection requests
Injection region	Dedicated aperture checks
BPM system	Response and acquisition.
Threading	BPM response, trajectory correction, application software tests
Kick response	Checks of BPM and orbit corrector polarities. Linear optics checks
Polarity checks	Powering of corrector circuits coupled with kick-response
Aperture checks	In the arcs using the free oscillation technique
BLM system response	In parallel to other tests, primary measurement in some tests, system response in some specific areas
Collimators	BLM response, validation of control systems with beam, first deployment of interlocking functionality, test of positioning accuracy during beam operational conditions
Magnetic reproducibility	Cycling and magnetic reproducibility
Quench level	Controlled beam loss at given location and intensity. BLM response.

Table 3: Stopping the Beam During the Tests

Injection – beam 1 & 2	The dump at the bottom of the transfer line and the injection dump (TDI) in the LHC ring were routinely used to verify the transfer line steering and the functioning of the injection kickers before attempting to inject beam through either Alice or LHCb.
Sector 23 - beam 1	Momentum cleaning collimators in point 3. Most intensity was placed on the secondary graphite collimators (TCSGs). To allow some beam to be taken through the warm insertion, some beam was also incident on the tungsten absorbers (TCLAs) on the right hand side of IP3.
Sector 78 – beam 2	Beam taken on to the betatron cleaning collimators in point 7. Again the graphite secondary collimators were used for the most part. Some beam was taken through IR7 onto the tungsten absorbers
Sectors 67,78 – beam 2	Beam was taken into the beam dump channel and onto the dump block (TDE). Initially this was assured with orbit correctors and subsequently with the “inject and dump” mode wherein the injected beam is dumped on the same turn using the LHC beam dumping system.
Sectors 23,34,45 – beam 1	To allow the testing of these sectors, a limited number of shots were put on to the tertiary collimators (TCT) to the left of IP5.

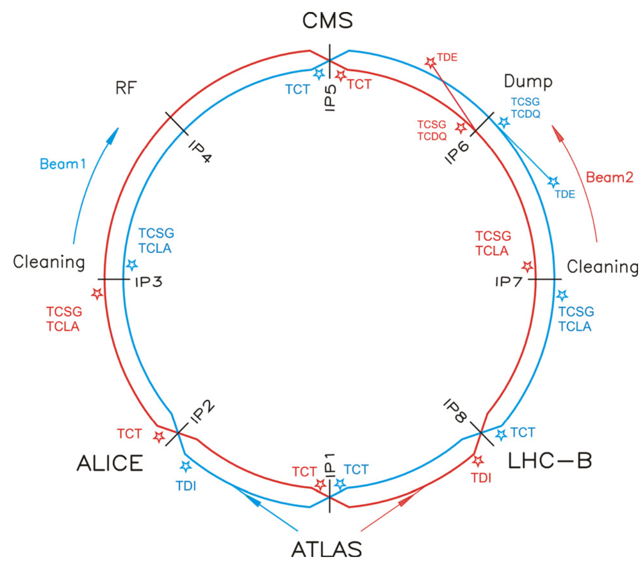

Figure 1: Location of beam stops during injection tests.

PREPARATION

In order to fully exercise all requisite systems and to thoroughly debug their integration, a long series of dry runs took place. These started in earnest in December 2007 and continued throughout 2008 with attention focused on:

- **Injection system**: synchronization of the whole injection process including the delivery of pre-pulses by the RF system, tests of new re-phasing system in the SPS, operational tests of the injection kickers, support software and services, soft-start, timing etc.
- **Beam dump system**: tests of timing, control, Beam Energy Tracking (BETS), post operational checks (XPOC), reliability [5], synchronization, interface to Beam Interlock system (BIS), and full system integration.
- **Beam Interlock system**: staged deployment and integration of the many user inputs.
- **Powering Group of Circuits**: as part of Hardware Commissioning of the cold circuits. This allowed rigorous checks of operational settings generation including injection, ramp and squeeze, interfaces to the power converters.
- **Deployment the magnet model** (FIDEL [6]): to provide transfer functions for all magnet types, and harmonic errors, both static and dynamic, for the main magnets. This required a major offline effort to analyze

the measurement data for all magnet types. Analysis results were fed into the on-line implementation of FiDeL under LSA.

• **Deployment of LSA**: (LHC Software Architecture [7]) for distributed beam instrumentation acquisition and concentration, settings management and so forth.

• **Beam instrumentation tests**: full scale tests of distributed systems including acquisition, concentration of data from distributed systems, logging, and settings management.

• **Controls**: controls issues linked to sequencing the LHC with respect to the injector chain and the fine synchronization between AB-RF and other equipment groups. LHC central timing events required to trigger acquisitions and the implementation of the Safe-Machine-Parameter hardware and related software with special emphasis on the post-mortem handling.

The dry runs and system tests proved invaluable and narrowed the problem space to an acceptable level when beam finally arrived.

RESULTS

First Beam in the LHC

The first clockwise beam (beam 1) arrived in the LHC on the TDI on 8th of August at 18:54:12. When the TDI was taken out the beam went all the way to point 3 without requiring any threading – a testimony to the excellent alignment of the machine. The first counter-clockwise beam (beam 2) was injected on the TDI in point 8 on the 22nd of August at 20:39:05. Once again when the TDI was taken out the beam went to point 7 without threading.

First Trajectories

The first trajectory measurement seen in sector 23 had a horizontal RMS of 9.9 mm and was easily corrected to 1.6 mm (see Fig. 2). In the vertical plane the initial RMS was 1.6 mm. The first trajectory in sector 78 had an RMS of 4.3 mm in the horizontal plane and 5.2 mm in the vertical plane initially. The numbers were reduced to 1.1 mm and 1.4 m after some steering.

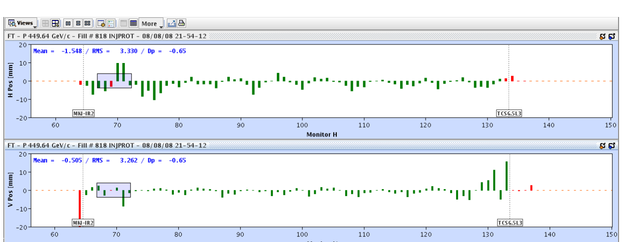

Figure 2: corrected trajectory in sector 23 shortly after injection of first beam and adjustment of SPS momentum.

Aperture Measurements

Aperture measurements in the ring are performed by exciting "free oscillations" of the injected beam trajectory with variable amplitudes and betatron phases. Oscillation scans are done to explore the available beam clearance in the horizontal and vertical planes. The oscillations are induced by exciting two pairs of horizontal and vertical orbit correctors, typically located at a 90º betatron phase advance difference. By changing the ratio of corrector currents, oscillations were generated at betatron phases of 0º, 30º, 90º, 120º, and 150º, which are considered to be sufficient to explore satisfactorily the aperture. A complete scan provides global aperture measurements of the section that is explored. Measurements were performed with 1 µm normalized emittance beams of 2e9 to 5e9 protons.

In Fig. 3 the results of global aperture measurements in sector 7-8 are shown. The horizontal and vertical beam trajectories are given as function of the longitudinal coordinate for all the oscillations induced during the aperture scans. The nominal machine aperture (without alignment errors) is also shown. It is seen that oscillations up to 18 mm (H) and 12 mm (V) were generated without significant beam losses. It is noted that the absolute error of BPM calibration for large oscillations can be up to 15%.

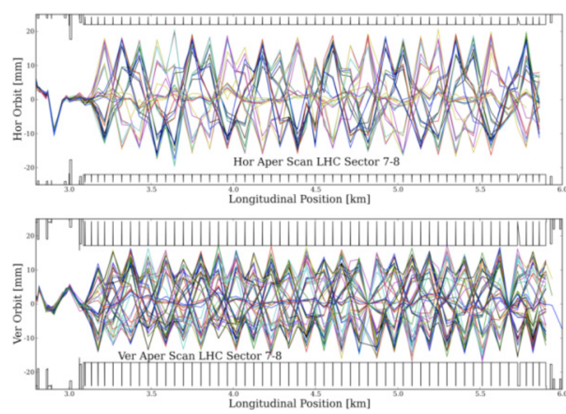

Figure 3: Measured horizontal (top) and vertical (bottom) beam trajectories during the aperture scans of arc 7-8 (Beam 2). The nominal machine aperture is also shown.

Injection Aperture

The aperture scans through the injection region were made using a set of correctors in the transfer lines excited to produce oscillation peaks at phases of 0 to 330 degrees, at 30 degree intervals. MADX online was used extensively to prepare the bumps, to generate the knobs and to analyze the data. The measurements for beam 1 showed a vertical aperture limit of 5-6 mm in the negative direction between the downstream septa (MSI) and the superconducting Q5 in the LHC. This was confirmed by a radiation survey after the first test to be at a valve/pump group almost exactly halfway between the MSI exit and the Q5 entrance. During these measurements several full bunches of about 5e9 protons were lost on the aperture limit, without quenching Q5.

Between the first and second sector tests the vacuum elements were realigned and the aperture was re-measured and found to be correct. The beam 1 measurements in the horizontal plane and for beam 2 showed the expected aperture.

Dispersion and Kick Response Measurements

As noted in the test summary above, during the first injection test measurements of the horizontal dispersion measured with beam 1 at the end of Sector 23 differed from the model prediction close to point 3. Beam-based polarity checks performed during the same period indicated an inversion of the trim quadrupole QTL11.R2 in the dispersion suppressor right of IP2. Combined with other evidence, like electrical drawings and earlier Hall-probe measurements of warm magnets, this gave rise to the hypothesis of a systematic error. Indeed a model inversion of all trim quadrupoles (QT or QTL) attached to a defocusing main quadrupole (actually the odd-numbered trim quadrupoles in Sector 23) reproduced the dispersion measurement.

An analysis of kick-response measurements independently revealed an optics error left of point 3, and confirmed the inversion of the odd-numbered trim quadrupoles in this sector. After changing the polarity of the suspected set of quadrupoles prior to the second injection test on August 24, the measured dispersion nicely traced the model prediction. Full details are available in [8].

Polarity Checks

The basic procedure is to launch betatron oscillations with a single orbit corrector; to change the strength or polarity of circuit under investigation, and take four trajectories: oscillation with new strength, oscillation with old strength, a reference orbit with new strength (i.e. without the kick), reference orbit with old strength. Data for several different circuit types was taken including lattice sextupoles, skew sextupoles, sextupole spool pieces, skew quadrupoles, octupoles and the trim quadrupoles (QTs, QTLs) used in the dispersion suppressor. For the sextupole circuits measurements were taken with a momentum offset of injected beam in place.

The technique proved very powerful and was able to identify polarity problems or at least raise suspicions about a wide variety of circuits [8].

Beam Induced Quenches

During the kick response measurements at the first injection test a 12 mm vertical oscillation caused the first beam induced quench in the LHC. A dipole magnet quenched due to the local loss of < 4e9 protons. This number is consistent with what had been predicted earlier, [9]. It was stated that if quenches were to be avoided during the initial threading the intensity of the bunch should not be much larger than 3e9 protons. A test of the dependence of the number of beam position monitors triggering versus beam intensity during the first injection test showed that the LHC beam position monitor system can trigger reliably with an intensity down to about 1.5e9 protons per bunch [10]. This result is much better than what has been expected. After the first quench and with this impressive performance of the beam position monitor system it was decided to run with an intensity of 2e9 protons for the rest of the injection tests.

SPECIFIC SYSTEM PERFORMANCE

Beam Instrumentation

The performance of beam instrumentation and the control systems on which its software relies is crucial for the successful outcome of beam commissioning in any new accelerator. Robust and well-tested electronics and related software was therefore put in place for the LHC injection tests. The announcements of clear dead-lines helped to finalize the installation and commissioning of hardware and software in time for the foreseen LHC injection tests. The distributed acquisition systems, BPM and BLM, rely on LSA concentrators to combine the results from many front-end systems. Starting with a subset of systems to be tested during the dry-runs and later with beam in limited sectors allowed several problems to be pinpointed, allowing the time to find and implement solutions. The early performance of the LHC beam instrumentation can be found in dedicated documents [10] so only a few main points will be mentioned here.

For the BPM system a very robust asynchronous FIFO mechanism was put in place for acquiring the position of single bunches. This had no need for fast external timing, instead requiring only two injection timing events sent out shortly before and after the injection into the LHC to open and close the acquisition window. This system worked extremely well from the first shot.

The LHC BLM system was used extensively during the different tests to measure local aperture restrictions in the injection and extraction areas as well as in the LHC arcs very accurately. The acquisition mode called ‘running-sums’ (used heavily during hardware commissioning) with 12 different integration times was used along with a dedicated operational application and the logging system to do on-line checks. This system performed very well.

During the 3rd injection test, beam 2 was sent through the dump line in point 6, allowing the dedicated dump instrumentation to be tested. Specifically the dump-line BTV monitors were used to acquire beam images on three dedicated screens at the entry of the septum, downstream of the dilution kickers and in front of the dump block. Due to the asynchronous nature of any beam dump, an analogue signal produced by beam dump system on firing of the dump kickers was used to freeze the images. Not enough time was available to fully commission the dump line beam instrumentation and further studies will be needed when the LHC starts up again.

During the same weekend, beam 1 was sent to the tertiary collimators in point 5 allowing tests to be performed with the beam instrumentation in point 4. Specifically the Fast BCT system was used to acquire the low-intensity pilot beam and a beam induced signal was observed on the tune measurement pickup.

Magnet Model

The complete static magnetic model as prescribed by the FiDeL algorithm [6] was implemented in LSA and used throughout the injection tests. The magnet settings for injection were based on the parameterization of the strength of the single circuits. In addition to powering the main magnet circuits (dipoles and optics quadrupoles), appropriate injection corrections were applied to trim quadrupoles, lattice sextupoles, sextupole spool pieces, and decapole spool pieces. All corrections were based on the FiDeL prediction of the static field errors.

The tests provided very constructive feed-back, and in particular on the practical aspects of setting generation and on the requirements to recycle the LHC after any loss of powering condition (e.g. circuit trip, loss of powering permit, loss of cryogenic OK, or similar). On this last issue, simplified recycling policies were defined to facilitate operation:

• for single beam pass, a sufficient pre-cycle was to ramp the circuit in question to minimum current, and back to injection setting;

• for circulating beam, the circuit in question needed to be pre-cycled to a pre-set fraction of the maximum allowable current (about 80%, defined as a result of the hardware commissioning tests), for a time of 1000 s, then ramped to minimum current and a pre-injection plateau, with a waiting time of 800 s or longer. Finally it would be ramped to injection. Injection would take place at least 800 s after reaching the plateau. With this prescription the dynamic effects in dipoles and quadrupoles have stabilized and are known with good accuracy.

Although the LHC proved to be sufficiently robust to variations of pre-cycle, the effect of cycling was clearly visible.

CONCLUSIONS

The injection tests were a remarkable success. Although many controls, instrumentation and configuration issues did arise, the problems encountered were rapidly overcome. The quality and sophistication of the measurements that were performed are unparallel in initial accelerator commissioning. Among the contributing factors might be included:

• three years of preparation during which prerequisites, requirements, measurements, software, controls was re-visited in depth a number of times;

• analysis of operational requirements and development of core software to provide required functionality;

• deployment of software and controls components with enough lead time to allow in-depth pre-testing;

• 8 months of dry runs allowing individual systems and integration tests;

• excellent performance of the key beam instrumentation all the way through the acquisition chain;

• a robust and complete magnet model based on processing and analysis of measurement data;

• a highly motivated and reasonably well organized team;

• excellent support from the numerous teams involved in preparing and running the LHC.

From the start of the distant, original discussions on the need for sector tests, it has always been argued that they are essential precursors, and milestones, in the preparation for full beam commissioning for any accelerator. This has, at last, been proven for the LHC.

ACKNOWLEDGEMENTS

The success of the tests was made possible by the meticulous preparation of the hardware commissioning team. This included magnet commissioning, the power interlock system, power converters and quench protection. The active support of the cryogenics team, the magnet performance panel, and the FiDeL team was essential.

Throughout the injection tests, and indeed during the transfer line tests that preceded them, the Radiation Protection team has provided professional support at all times. Thanks the Access team for a remarkable effort in getting the LHC in a state to safely take beam at the start of August. The CCC was packed for all the tests, apologies to all those who contributed but are not explicitly named in the author list.

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