LHC Performance Note 1

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The LHC Injection Tests

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Summary

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.

LHC-Performance-Note-001

1. Introduction

1.1 Motivation

The motivations for an injection test have been 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. After their initial success, they increased rapidly in scope, and led seamlessly to the commissioning with beam of the whole machine.

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.

1.2 Test schedule

The hardware commissioning schedule and ongoing system commissioning demanded flexibility and the first test found itself dependent on the successful deployment of the LHC access system and subsequent Departmental Safety Officer (DSO) 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, largely at the weekends 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, accompanied as it was by good machine availability on the day.

Table 1: Injection tests - schedule

Date	*Test Outline*
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

1.3 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 in section 3 and after measurements showed that the BPMs would trigger reliably on 2e9, the single bunch intensity was lowered to this value. This helped to reduce ambient radiation levels thus minimizing the impact on the post-test tunnel activities.

1.4 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, [3]. 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.

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, acquisition, concentration
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.

1.5 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 possible as beam dumps to safely intercept the injected beam – see table 3.

Table 3: Stopping the beam during the tests.

Injection – beam 1 & 2	The TED at the bottom of the transfer line and the 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. These checks will be incorporated into the operational sequence for nominal running.
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 (Q4-L3 to Q5-R3) 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. In both cases the TCDQ absorber and TCSG collimator were in to prevent the passage of beam beyond IP6 into sector 56.
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 to the left of IP5.

For the attempt to perform first turn of both beams on the 10^{th} 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 illustrated in figure 1.

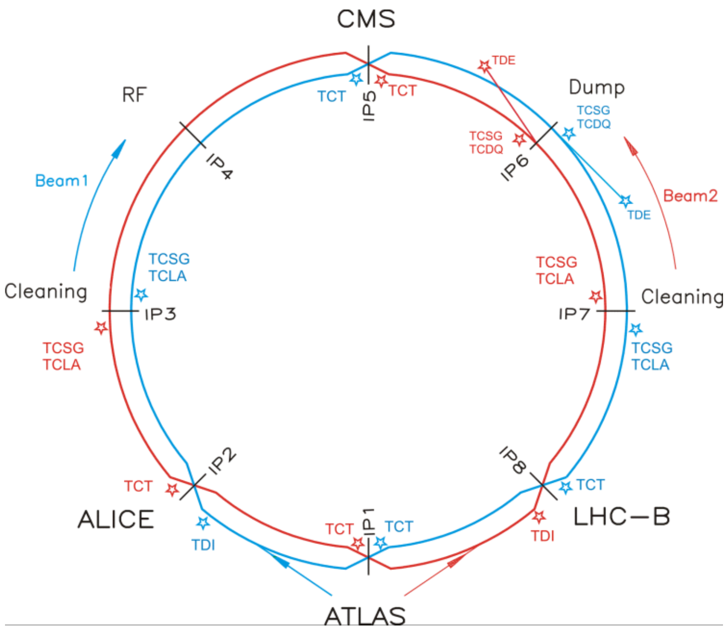

Figure 1: Location of beam stops during injection tests

1.6 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**: timing, control, Beam Energy Tracking (BETS), post operational checks (XPOC), reliability [4], synchronization, interface to Beam Interlock system (BIS), full system integration.
- **Beam Interlock system:** staged deployment and integration of the many user inputs.
- **Powering Group of Circuits (PGC):** as part of Hardware Commissioning. This allowed rigourous checks of operational settings generation including injection, ramp and squeeze, interfaces to the power converters.
- **Deployment the magnet model (FIDEL** [5,6]**):** 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 [7,8]) for distributed beam instrumentation acquisition and concentration, settings management and so forth – see section 9.4 below.
- **Beam instrumentation tests:** full scale tests of distributed systems including acquisition, concentration, logging, and settings management – see section 8.1.
- **Controls:** a series of meetings in a forum called ABCIS was started during 2007. This forum discussed controls issues linked to sequencing the LHC with respect to the injector chain and the fine synchronization between AB-RF and other equipment groups. The different discussions led amongst other to the creation of 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 [9]. All this was tested progressively in the lead up to the tests.

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

2. Summary of Injection Test One (8th to 11th August)

Following a Herculean effort, the LHC access system passed into a DSO certified “Beam On” for the first time at 15:00 Friday 8th August. At 17:30 the single bunch low emittance probe beam was taken on to the TI 2 TED (dump block) at the end of the TI 2 transfer line. In the LHC the injection septum magnets were pulsed and the cold magnets cycled. The LHC injection kickers were timed in with beam; synchronization of the RF and timing control system were verified.

At 18:54 with the kickers off, the TED was taken out, and after correction of the end of TI 2, beam one was seen in the LHC for the first time (see figure 2) with the beam loss monitors (BLM), beam position monitors (BPM), vacuum gauges and screens as witness. At this point the injection absorber (TDI) just after the injection point was in the closed position. There was much excitement in the control room.

At 21:42 the TDI was taken out; beam passed through Alice and to the end of sector 23 at the first attempt. Beam was observed on the screen at Q6.L3. The first trajectory from the BPM systems was observed shortly after. By 23:30 the trajectory to IR3 was corrected with a peak in the arc of less than 3 mm (see figure 3).

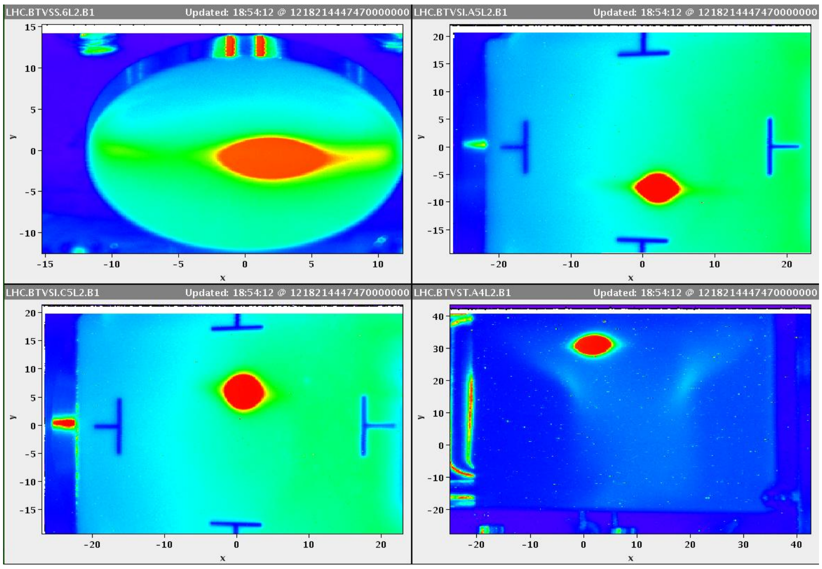

Figure 2: first BTV images of beam 1 in the LSS2 injection region

Figure 3: corrected trajectory sector 23 shortly after injection of first beam and adjustment of SPS momentum

Kick-response measurements revealed a phase error in the arcs (figure 4). This was tracked down to erroneous application of the b2 harmonic compensation. Measurements also revealed one BPM polarity error in the arc of sector 23. All corrector polarities were correct.

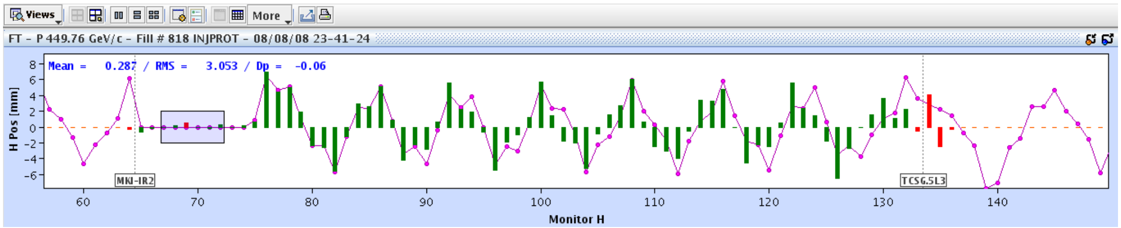

Figure 4: kick-response measurement showing design and measured response following kick to the right of IP. Note phase error.

At 02:35 on Saturday a preliminary attempt to probe the aperture managed to quench a dipole with 3.8e9 protons. The quench occurred in MB.A8.L3 with an oscillation amplitude of ~12 mm caused by 80 μrad kick on MCBV.9R2.B1. At the same time a large number of corrector circuits tripped off. The quench proved to be a gentle one but set a provisional lower quench limit for prompt loss to be around 3.8e9 protons - in almost exact agreement with earlier predictions [10] wherein it notes "*The intensity of the bunch shall therefore not be much larger than 3 10^9 protons.*"

After recovering from the quench and access, beam was back to IR3 after re-cycling at around 15:00 Saturday without any problems. It was noted already at this stage that the machine was magnetically reproducible. Some time was spent checking RF and beam instrumentation timing before starting aperture measurements in the injection region.

The aperture measurement at the injection septa looked as expected with losses starting at about +/- 6 nominal σ in vertical plane, and no losses seen up to 7 nominal σ in the horizontal plane. However, the scan revealed an aperture limitation in the vertical plane at the Q5 entrance. This proved to be, on examination after the test, a displaced section of vacuum pipe and associated valve assembly (see section 7.2).

It was also clear at this point that the injection kickers were sensitive to beam loss. Scattered particles seemed to have caused a flash-over in the injection kickers and there was a period of time with beam off while kickers were reconditioned.

At 22:30 Saturday the collimators left of IP3 were taken out and beam was taken into the warm section of IR3 with the BPMs giving data on the first shot. Beam loss maps in the collimation section of IR3 were obtained and a problem with the handling of geometrical BPM factors was discovered for large beam excursions.

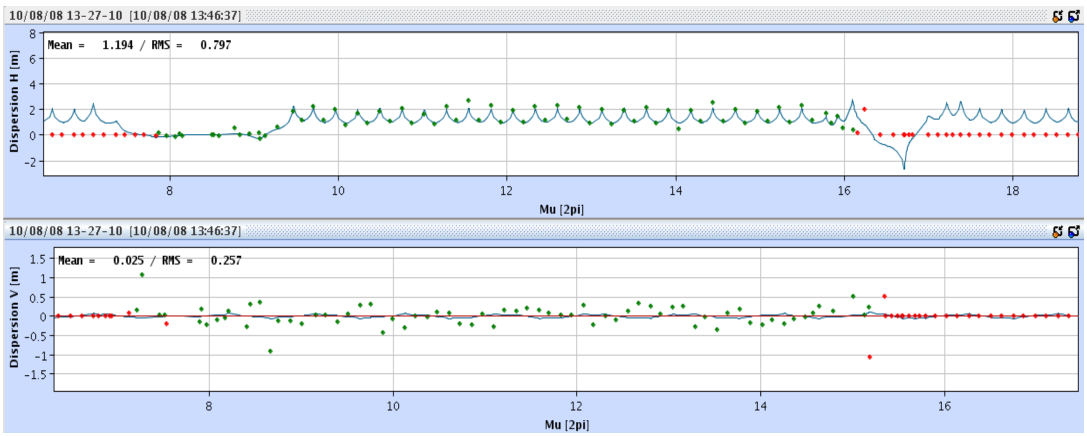

Figure 5: dispersion measurement sector 23 – note problem in IR3 on the right of the figure.

Overnight Saturday to Sunday a set of aperture scans using free oscillations were performed - see section 8 below for more details.

On Sunday the LHC to SPS RF frequency control was commissioned. The first dispersion measurements where then made – see figure 5. These revealed an optics problem to the right of IP3. This was tracked down after the test to be caused by powering of some of the trim quadrupoles (QTL/QT) in the dispersion suppressor with the wrong polarity [11].

The BPM intensity threshold was measured to be ~1.5e9 by varying the intensity coming from the PS (extraction intensity raised in steps from 1e9). This redefined the so-call probe beam intensity to 2e9 and this reduced intensity was used systematically in the tests that followed.

On Sunday evening the TDI was put back in and the aperture check of the injection region which had started on the Saturday was finished. After a series of problems, BLM studies in the collimator region took place and commissioning of the polarity check measurement procedure found some interesting results, including more evidence for the QTL polarity errors [11]. This procedure was then used routinely in subsequent tests.

At 06:00 Monday 11th August injection of beam into the LHC was stopped and a radiation survey was performed.

3. Summary of Injection Test Two (22nd – 25th August)

At 14:15 Friday 22nd August the final stages of closure of ring and experiments were in progress. This was followed by access/beam dumping system tests. Although slowed by the need to give access (now routine), by 17:45 the beam was at the end of TI8 and conditions for beam were re-established in the LHC.

At 19:30 the transfer line dump was taken out and after a rather public struggle with timing system, beam was taken into the LHC at point 8. Some steering and the correction the polarity of a set of bends at the end of TI8 beam was required before beam was brought onto the TDI in front of LHCb (see figure 6) at 20:10. At 20:54 TDI was taken out and the beam went to the collimators in point 7 without correction.

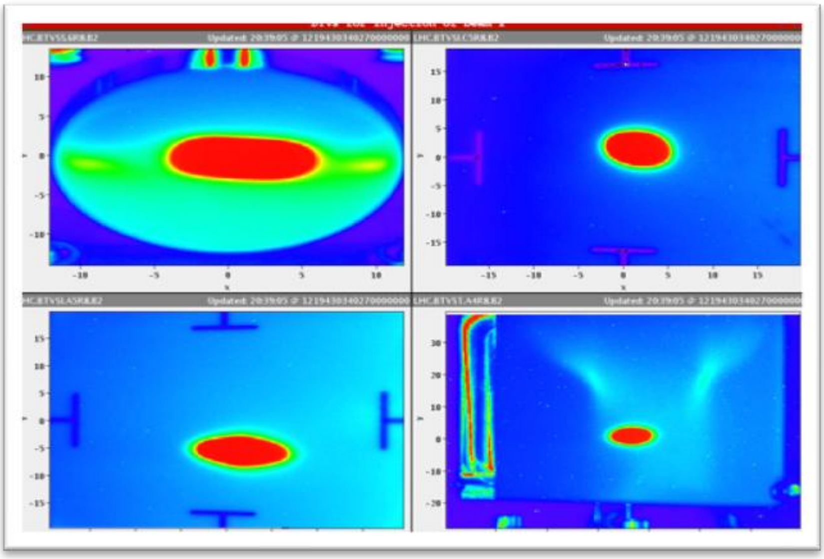

Figure 6: beam on injection region screens right of IP8 – injection kickers on.

Dispersion measurements revealed large beating in the LHC which seemed to hint at a problem near the end of the line (for details see section 7.3). This issue launched a thorough measurement program overnight, a rigourous post-test investigation and checks of magnet positions, tilts, powering etc. A number of BPM polarities problems were identified and fixed.

On the morning of Saturday 23rd the LHC was re-cycled. The TDI gap was repositioned in response to three shots causing showers in LHCb. These were accompanied by LHCb throwing their injection permit.

A variety of problems took out beam for a number of hours. In the meantime, the “inject and dump” mode was commissioned without beam – see figure 7. While the beam was dumped on the

TDI parasitic measurements were performed with the luminosity monitors situated in LSS8R. By 18:45 beam was back to IR7 and follow-up dispersion measurements were performed.

A set of aperture measurements using the free oscillation technique were performed overnight in sector 78 – see section 7.6 below.

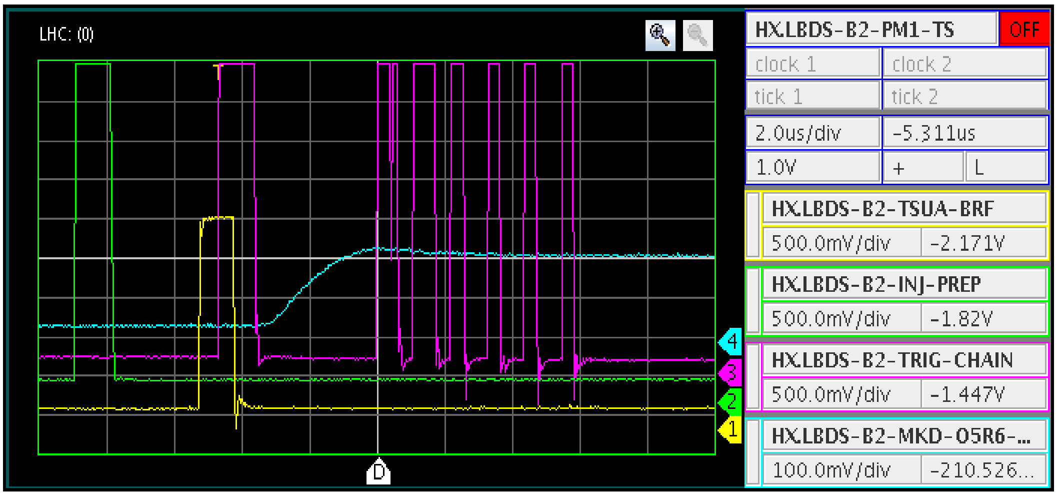

Figure 7: "Injection and Dump" scope snapshot showing injection pre-pulse (green), bunch clock (yellow), beam dump trigger (magenta).

On Sunday morning there were variously accesses and preparation for injection into sector 23. By the start of Sunday afternoon there was beam again on to TDI in front of Alice and by 15:00 beam 1 was back to IR3. As a useful by-product, alternate injection on consecutive SPS cycles into ring one and ring two of the LHC was commissioned and operational by 19:00 Sunday.

Dispersion measurements in sector 23 showed the successful resolution of the trim quadrupole polarity issue (see figure 8). The optics in 23 looked good with the dispersion following well into IR3.

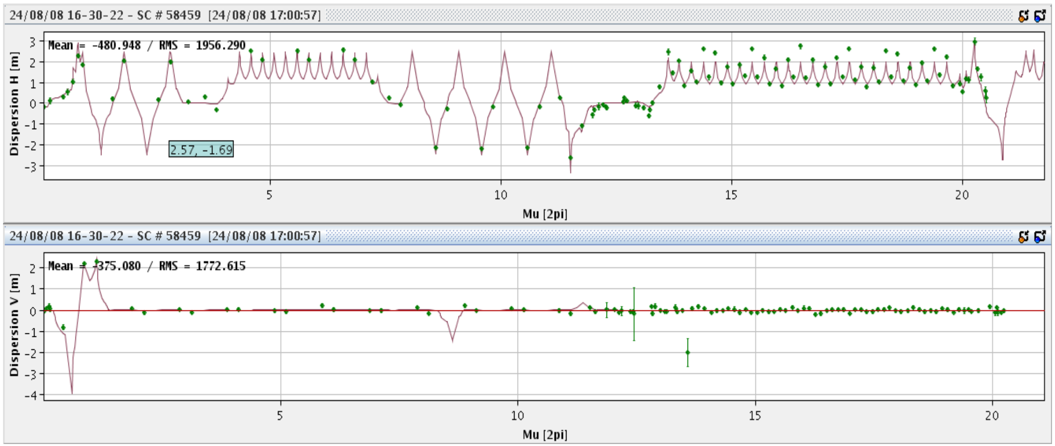

Figure 8: dispersion measurement TI2/Sector 23. Note measured dispersion tracking model through IR3.

A measurement of the BLM response in and around IR3 collimators was performed. Overnight Sunday to Monday there was intermittent beam from SPS; however, the injection region aperture in point 8 was measured and a check of injection aperture in IR2 confirmed the successful correction of the aperture limitation discovered during first injection test (see section 8).

Detailed optics response measurements (TI8 - IP8 - ARC87 - IP7) were performed in parallel. These were followed by polarity checks for various higher-order correctors in sector 78, including the b3 spool pieces, skew sextupoles and focusing octupoles. At 06:00 Monday 25th August beam was stopped and a radiation survey performed.

4. Summary of Injection Test Three (5^{th} – 8^{th} September)

After the resolution of an access system problem, at 03:50 Saturday 6^{th} September beam was first taken to the collimators in point 7 and then, after some steering, to the beam dump in point 6, steering into the beam dump channel with correctors in the first instance. An optics problem around IR7 rapidly became apparent.

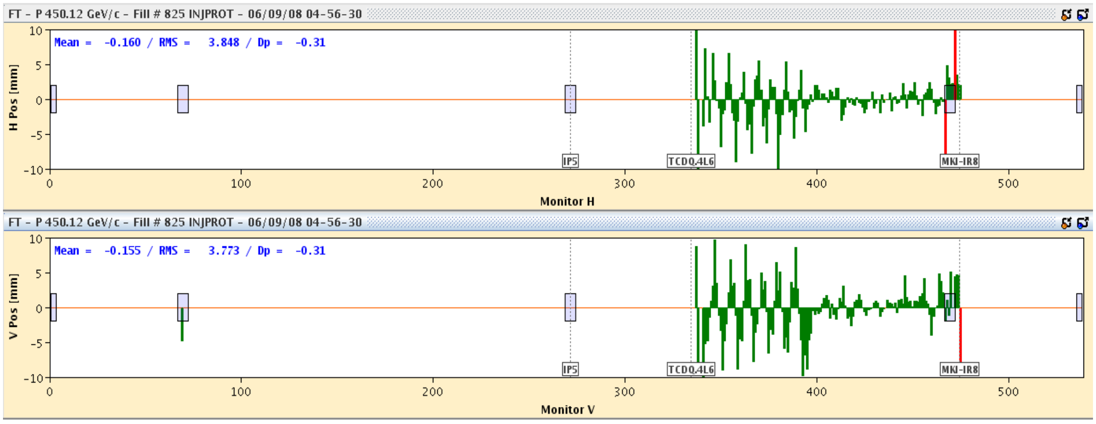

Figure 9: beam 2 travelling from right to left - first beam to point 6 from point 8.

Kick-response comparison of model versus data in the vertical and horizontal plane is shown in figure 10. In IR7 the amplitude in the data (histogram) increases rapidly (note beam comes from right) in the vertical plane. The problem was rapidly tracked down to be the inversion of the polarity of Q6.L7 which is driven by a bipolar power supply.

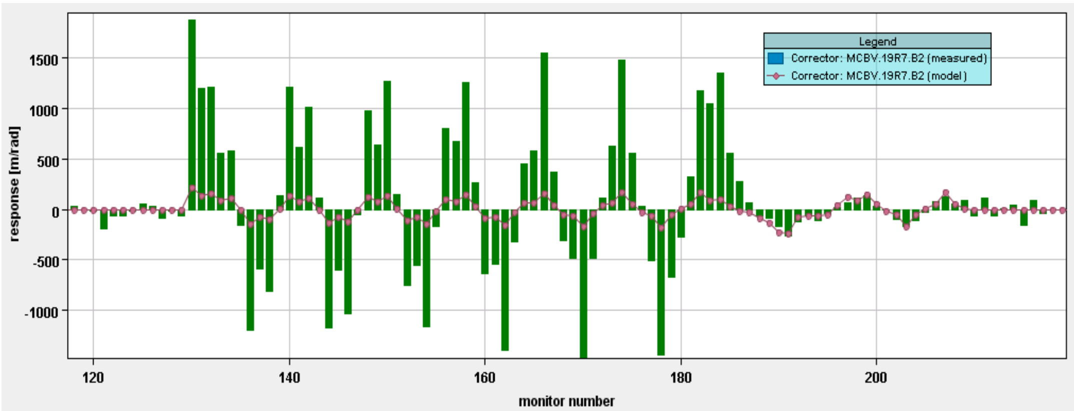

Figure 10: beam 2 – kick-response around point 7. Magenta is the model, green the measurement. Again beam travelling from right to left.

The “inject and dump” mode of beam 2 was commissioned and the beam successfully extracted into the dump line using beam dump kickers timed in with injection.

A fault on an internal temperature sensor on the 3.3kV supply at point 8 caused the loss of the 4.5K refrigerator in S81 and the 1.8K refrigerators in S81 and S78. This precluded further use of beam 2 for the rest of the weekend. Attention was switched rapidly to sectors 23, 34, 45 with the aim to take beam onto the tertiary collimators left of point 5.

After access, the go ahead from the DSO, and the resolution of a number of issues, beam was first taken to point 3. Between 17:00 and 18:00 a quench test was performed and a quench of MB.A10.R2 was induced with 2e9 protons – a new lower limit for a beam induced quench at 450 GeV. This was achieved by steering the beam directly into the magnet concerned – not a typical scenario. Although there appears not to be problem with losing 2e9 while threading, the true lower limit has yet to be established. Recovery time was around 10 minutes and the LHC was then set back to injection plateau without recycling. Reproducibility was again good and beam was taken to the collimators in point 3 without additional corrections.

At 18:30, the collimators at point 3 were retracted. On the next shot, beam passed to the tertiary collimators left of point 5 (see figure 11). The RF group was able to see beam passing through the RF cavities in point 4 for the first time – see figure 12.

Figure 11: beam 1 - first beam to point 5

The beam was also seen by the fast BCT in point 4 – see figure 13. Dispersion and kick-response measurement showed an optics error coming in around IR3. It was noted that some of the QT/QTLs to the right of IP3 had the wrong strength values. These values were introduced by a bug in the settings generation software which was immediately fixed.

To avoid unnecessary activation of the tertiary collimators at point 5 only a limited number of shots were taken. The collimators in point 3 were put back in, some higher intensity shots were taken for Alice and then work on beam 1 stopped late Sunday evening. Work continued in TI8 with dispersion and coupling measurements.

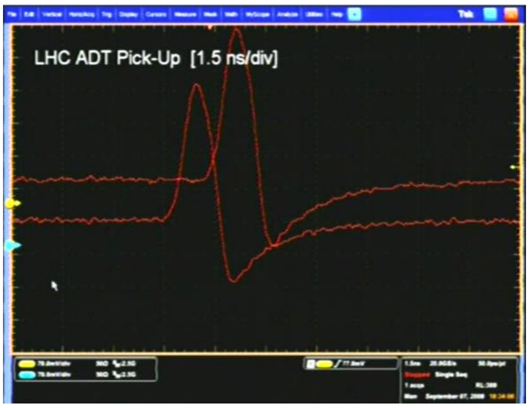

Figure 12: first beam through RF on transverse damper pick-up

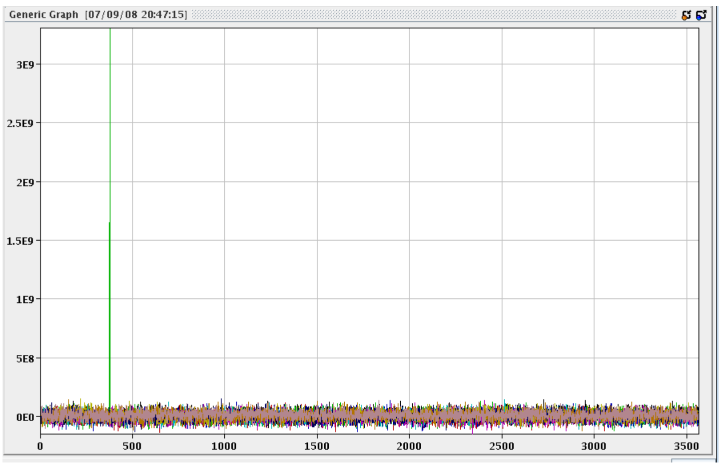

Figure 13: pilot bunch acquired with the Fast BCT transformer in LHC point 4

5. Summary of Injection Test Four (9th September)

A frustrating evening of problem resolution meant limited beam time, with tests restricted to taking beam 1 back to the tertiary collimators left of IP5. A dispersion measurement showing that the optics problem right of IP3 had been cured (see figure 14). The evening, however, successfully set the machine and the stage for the following day.

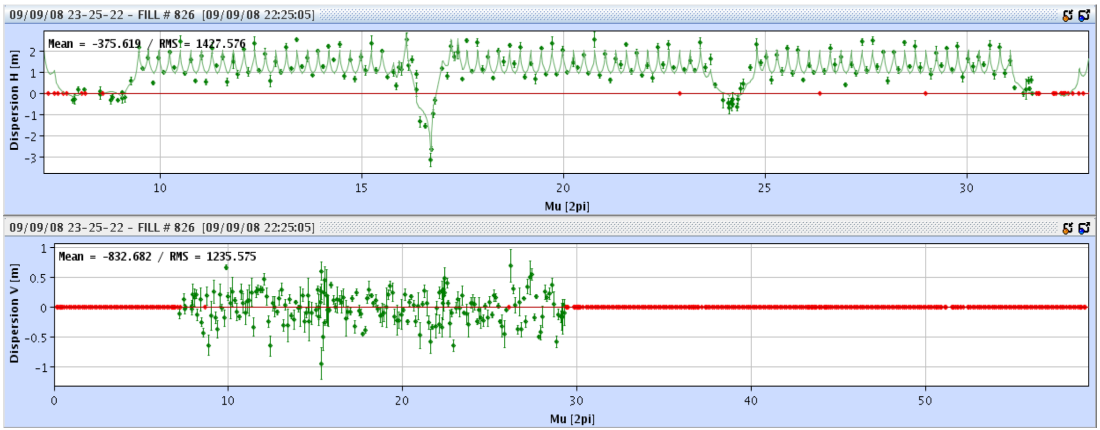

Figure 14: dispersion measurement – sectors 23, 34, 45. (Solid line – model).

6. Summary: First Turn – Beam 1 & 2 – September 10th

Given the preparation and previous tests described above the attempt to perform the first turn of beam 1 and beam 2 went reasonably smoothly.

Beam 1 was injected into IR2 as usual and the TDI was taken out at 09:35 10th September and by 10:26 the first turn had been achieved via:

- the collimators in point 3;
- tertiary collimators left of IP5;
- beam dump at point 6;
- the collimators at point 7;
- the tertiary collimators left of point 1.

At each stage the trajectory was corrected before proceeding to the next section of the ring.

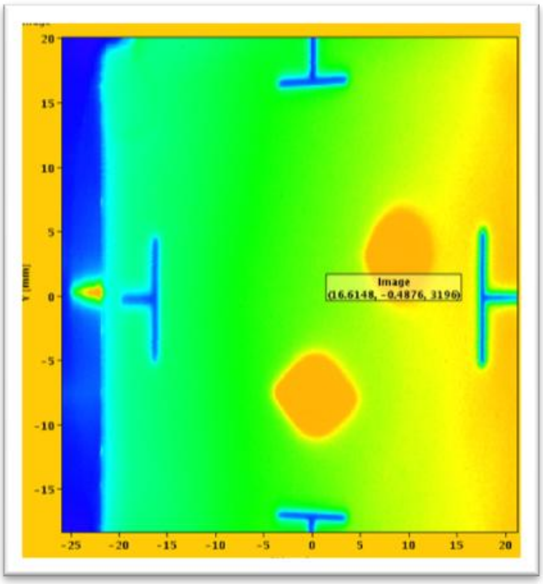

Figure 15: injected beam (lower blob) and beam having made first turn on screen in front of the injection kickers in IP2

Similarly for beam 2. The beam was taken progressively around the ring stopping at:

- the collimators at IP7;
- the beam dump at IP6;
- the tertiary collimators to the right of IP5;
- the collimators at IR3;
- the tertiary collimators right of IR2;
- the tertiary collimators right of IR1.

At each stage the trajectory was corrected as required. At 14:00 beam 2 was taken to point 6 and by 14:59 the beam had completed its first turn (figure 16).

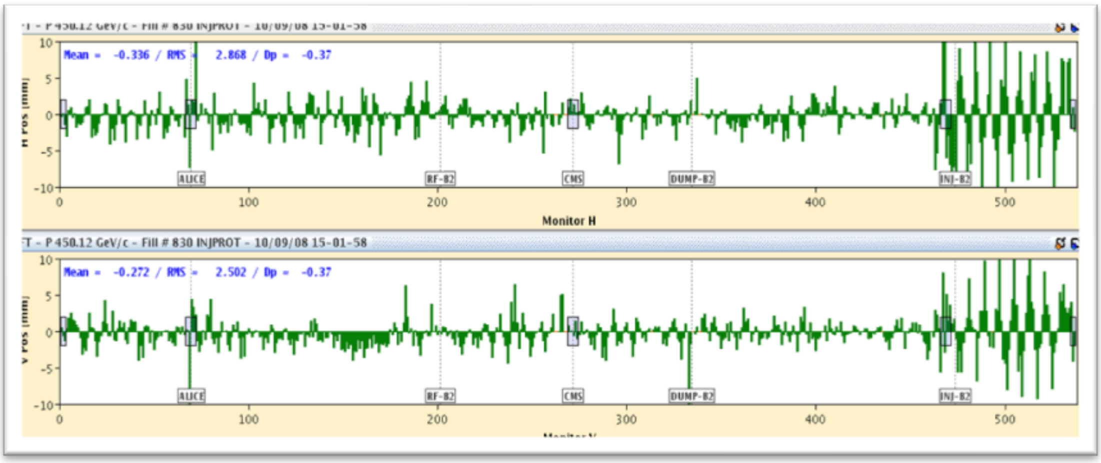

Figure 16: beam 2 - first turn, note beam is travelling right to left from point 8 and then wrapping around through sector 81.

7. Measurements

During the tests summarized above a wide variety of measurements were performed. Some of these will be detailed in upcoming performance notes. A summary of each is presented below.

7.1 Downstream transfer line commissioning and initial steering

The initial threading for the downstream ends of both TI 2 and TI 8 took some time, in both cases due to settings of dipole magnets which needed to be adjusted. In TI 2 the strength of the last horizontal bend family MBIBH293 had to be adjusted by about 1.3% because of a wrong calibration curve which was taken when the momentum of the line was trimmed to match the SPS. In TI 8 the polarity of the vertical MCIAV881 family had to be inverted – this was understood as a simple error during the polarity checks, since MCIAV type magnets are normally correctors, which by convention are cabled with opposite polarity to RBENDs.

7.2 Injection region aperture measurements

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 MSI and the superconducting Q5 in the LHC. This was confirmed by a radiation survey after the first test to be at valve/pump group VMANF.5L2, 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.

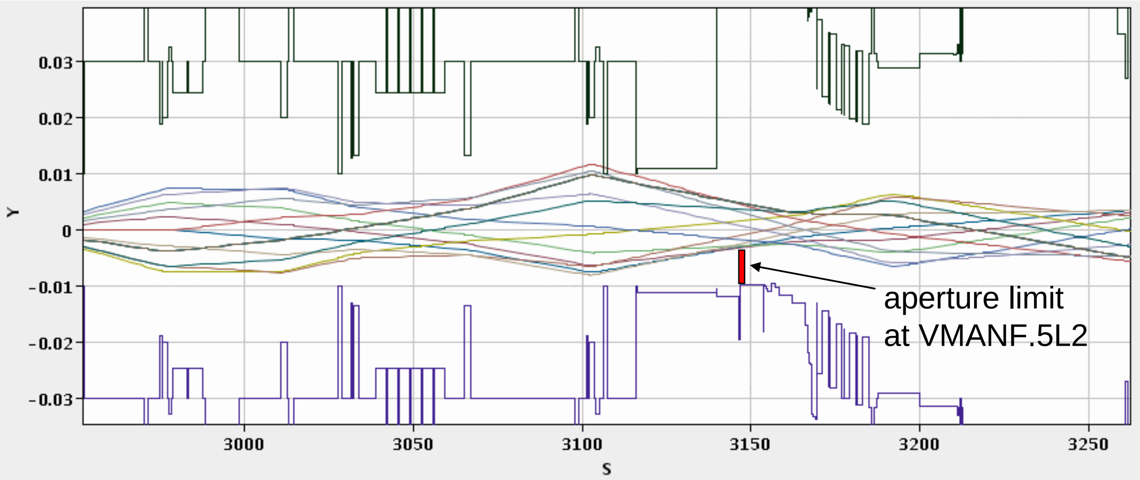

Figure 17: aperture measurement in beam 1 injection region showing location of observed aperture limit found between MSI and Q5 in point 2.

Measurements were also made with the MKI kickers off which in theory allowed the aperture at D1 and the downstream vacuum valve to be checked. No major aperture restrictions were evident but the lack of BLMs between the valve and the TDI meant that no detailed conclusions could be drawn.

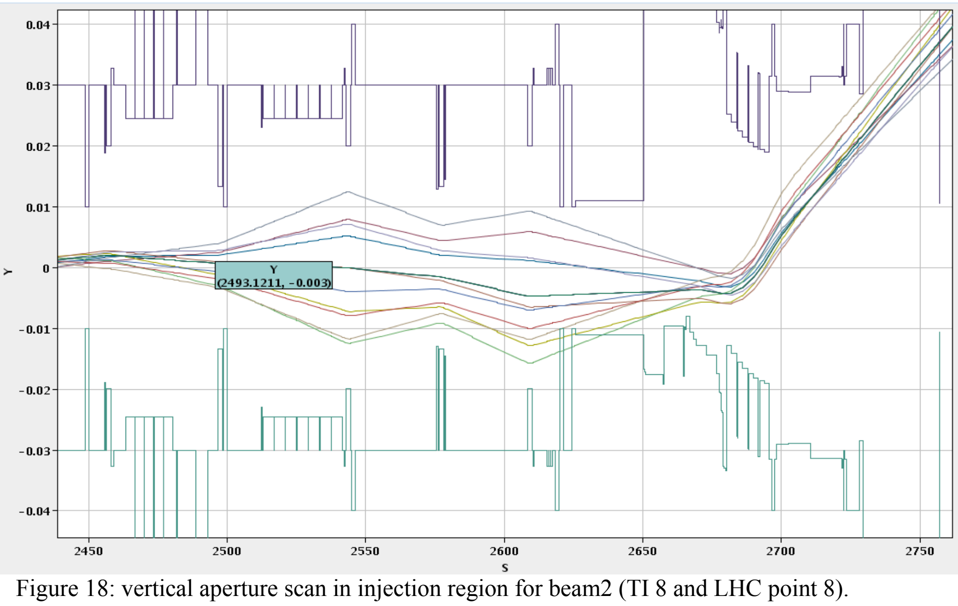

Figure 18: vertical aperture scan in injection region for beam2 (TI 8 and LHC point 8).
The asymmetry is due to the trajectory of the incoming beam

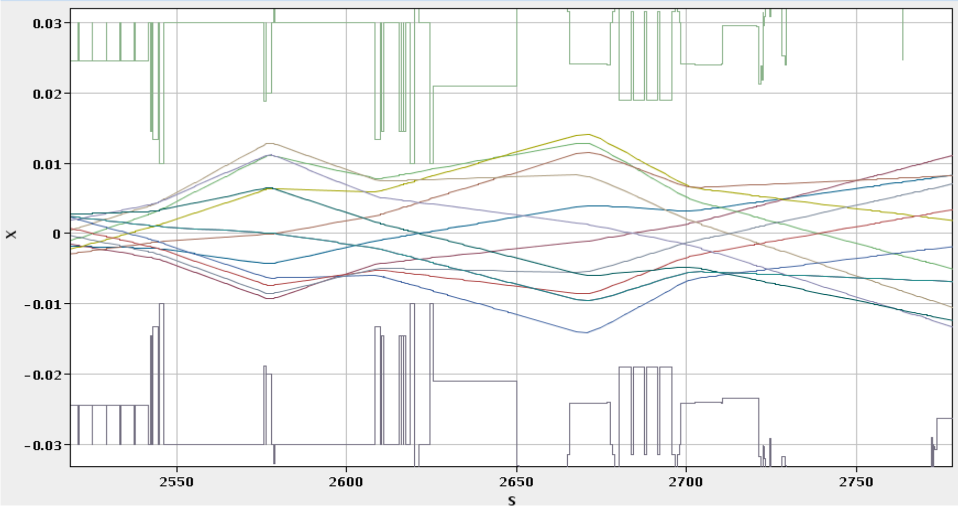

Figure 19: horizontal measured aperture in beam2 injection region (TI 8 and PLC point 8). The measured aperture is about ±8 nominal σ.

7.3 Transfer line optics matching to LHC

A series of measurements was made to determine the quality of the optics matching from the transfer lines to the LHC. The easiest diagnostic was the dispersion measurement, which for TI 2 and beam 1 fitted very well to the model. For TI 8 and beam 2, however, a strong mismatch was immediately visible, with the onset around the junction between TI 8 and the LHC. Many possible sources were postulated and eliminated, with a very large effort from the magnet, power supply and alignment teams to check all of the polarities, strengths and positions of the elements which were suspected. Measurements were taken with bare trajectories to try to confirm the measured alignment and observed corrector settings. The improved knowledge of the alignment and strengths present in the line were introduced into a more detailed optical model which reproduced the observed trajectory, the corrector settings and the perturbation in the dispersion. An algorithm to improve the dispersion matching by steering also for dispersion as well as trajectory was developed but did not have the chance to be tested.

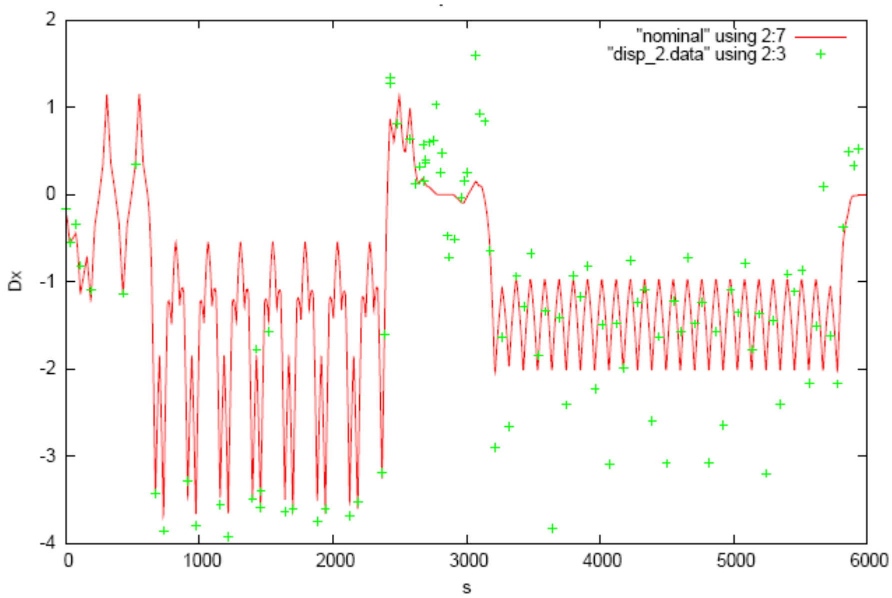

Figure 20: Measured (green) and initial model (red) dispersion in TI 8 and arc 78.

There appears to be no apparent particular problem, but rather an accumulation of various effects, like deviations from the ideal alignment with time (which will be corrected this shutdown), various sizeable corrector kicks, in particular at the beginning and near the end of the line, and a position sampling which was particularly unfavourable for the present case (and which will also be improved during the shutdown).

The response measurements showed a big unexpected cross-plane coupling, up to 20%, which varied with the phase of the measurement oscillation. This was not present in the initial model used for the response measurement. A coupling of about 5% had been expected due to the coordinate frame rotation needed at the end of TI 8, due to the difference in tilt between the line and the LHC machine at the injection. After the measurements were made, a more detailed analysis of the model showed that the coupling produced by this rotation varies significantly with the phase of the betatron oscillation. The full MADX model was used for the response data and could reproduce very well the observed coupling. The effect will not affect the trajectory correction in TI 8 per se, or in the LHC proper. However, the detailed steering of the injection region which uses correctors in both TI 8 and the LHC will need a few more iterations to converge. The emittance growth from the effect was evaluated already and is still expected to be within specification.

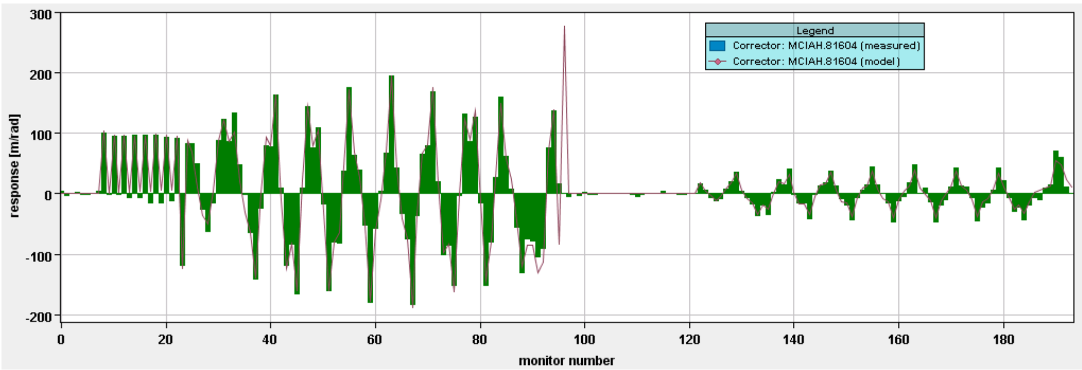

Figure 21: Measured and fitted oscillations in TI8 and LHC – the H plane is on the left up to monitor 95, and the V plane on the right. The coupling into the vertical plane in the LHC of the H oscillation is clearly seen and is explained by the full MADX model with the rotation between the reference frames.

7.4 Screen matching measurements

Measurements of beam size with the transfer line and injection region screens were used to determine the optics at the screens. The method was mainly performed parasitically and suffered from the lack of stability and in particular from the lack of good measurements of the bunch length. In addition the knowledge of the dispersion in TI 8 was limited by the optics errors; in an ongoing analysis the measured dispersion at the screens is being used to calculate the Twiss parameters more accurately.

The online results showed no major optics surprises – typical mismatch parameters were of the order of 10% in the vertical plane and 20% in the horizontal plane. The method was also used to make quick and accurate measurements of the beam emittance during the aperture tests. The measurement of the optics functions at the injection point required the use of the last 2 screens in the transfer line, due to the small phase advance between the screens.

7.5 Injection stability

The injection stability was measured using the beam position on the four screens in the injection region. The short-term (1 h) stability looks very good – for beam 2 a maximum RMS jitter of 0.27 / 0.13 nominal σ were measured in the horizontal and vertical planes respectively, compared to ±1.5 σ specified. The long-term stability and reproducibility still needs to be evaluated.

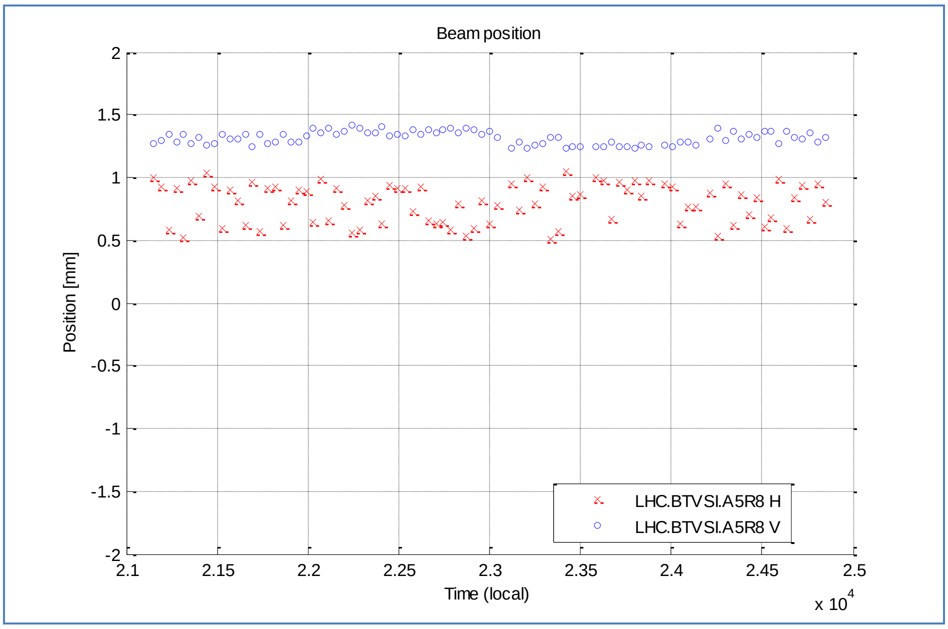

Figure 22: beam position variation on BTVSI.A5R8.

7.6 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 then global aperture measurements of the section that is explored.

Appropriate "knobs" were generated for each oscillations phase and for each plane with the MADX on-line model and were imported into LSA for on-line use. This allowed changing the oscillation within two consecutive injections so to optimize the required time for the aperture scans. The on-line, as-built aperture model was used to identify the possible bottlenecks. Operationally, the procedure was: for each phase, the oscillation amplitude (both signs) was increased gently until the beam touched the aperture. Beam loss monitors were used as expected to determine the loss locations. The resolution for the ionization chamber monitors was estimated to be around 1% of the nominal pilot bunch.

Due to the difference of normalized aperture between the insertions and the arcs, separate sets of knobs for the scans in different LHC sectors were prepared. Knobs for the arcs were generated using pairs of orbit correctors in the dispersion suppressor upstream of the arc itself. Due to time constraints, only scans in the arcs 2-3 (Beam 1) and 7-8 (Beam 2) were performed and not in the insertion regions. Measurements were performed with 1 μm normalized emittance beams of 2e9 to 5e9 protons.

In figures 23 and 24 the results of global aperture measurements in sectors 2-3 and 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%. For the case of sector 2-3 the amplitude of horizontal oscillations was limited by the Q6.L3 stand-alone quadrupole, which is a known aperture limit of the betatron cleaning insertion. The vertical aperture limitation also occurs in this region, which prevented us from exciting vertical oscillations larger than 10 mm in the arc upstream. In figure 25, an example of beam losses in the arc 7-8 recorded on-line during the aperture scan is shown. The elements with larger loss spikes are also listed.

Local aperture measurements can be performed by generating local orbit bumps at the element to be scanned. These local measurements are obviously time-consuming because a complete scan has to be performed at each location. We could only perform such scan at the location of the magnet MQ.7L3 (beam 1), next to the dipole MB.A8L3.B1 that quenched during the first night of beam tests. Figure 26 shows the beam loss monitor signal as a function of the local bump amplitude (the nominal corrector calibration is used to estimate the bump amplitude). One can see that beam clearance before observing beam losses is about ± 11 mm. This is larger than the value that limited our arc scans and therefore the bottleneck is probably located further downstream.

The aperture scan data is ideal to measure and identify coupling errors. In presence of transverse coupling the large free oscillations in one plane induce linearly correlated oscillations in the other plane. During the first injection test in the arc 23 we were able to observe small vertical oscillations while inducing large horizontal free oscillations. To quantify the coupling a linear fit of the vertical excursion at every BPM versus the RMS of all the horizontal BPMs readings has been computed. The slopes of these fits are plotted versus the longitudinal location of the BPM on the bottom plot of the figure 27 for two different scans with almost 180º phase difference. It is clear from the plot that some anti-correlated oscillations originate in the middle of the arc (around 5000m or 31L3.B1) as one expects in the presence of coupling errors. The top plot shows the reference vertical orbit with a negative peak at the same location. This orbit causes coupling through the feed-down effects at lattice sextupoles. However it has been verified with MAD models that this vertical orbit alone cannot explain the observed coupling. For example, three main quadrupole tilts in the order of 3 mrad in the same region should be added to reproduce the observed coupling. The small signal-to-noise ratio forbids a more precise identification of the sources. It is important to mention that no measurable coupling was observed in the second injection test (sector 78) using the same approach.

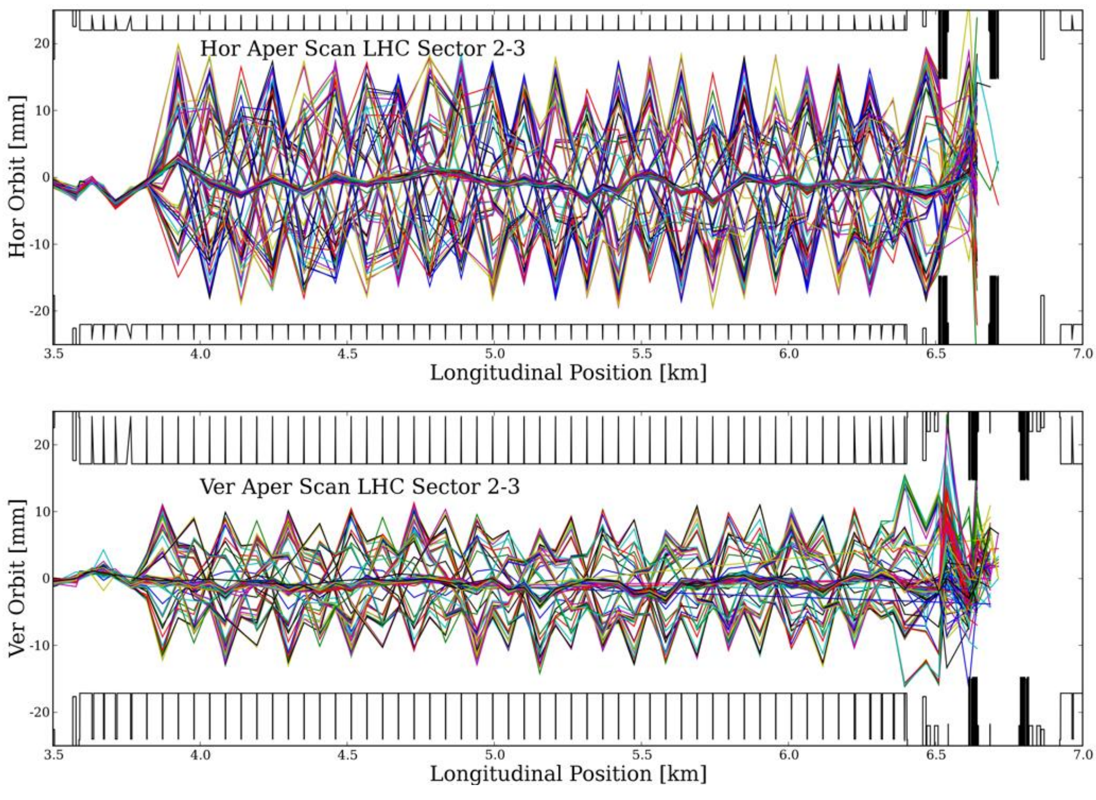

Figure 23: measured horizontal (top) and vertical (bottom) beam trajectories during the aperture scans of arc 2-3 (Beam 1). The nominal machine aperture is also shown.

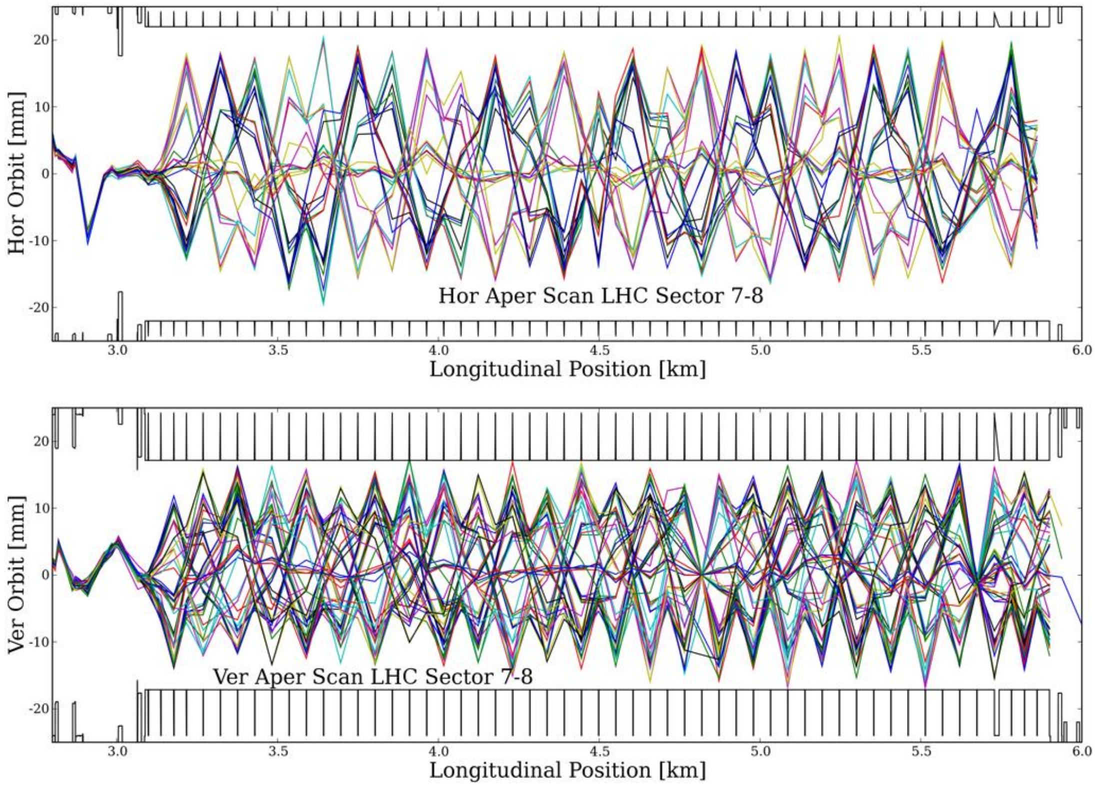

Figure 24: Measured horizontal (top) and vertical (bottom) beam trajectories during the aperture scans of arc 7-8 (Beam 2). The nominal machine aperture is also shown.

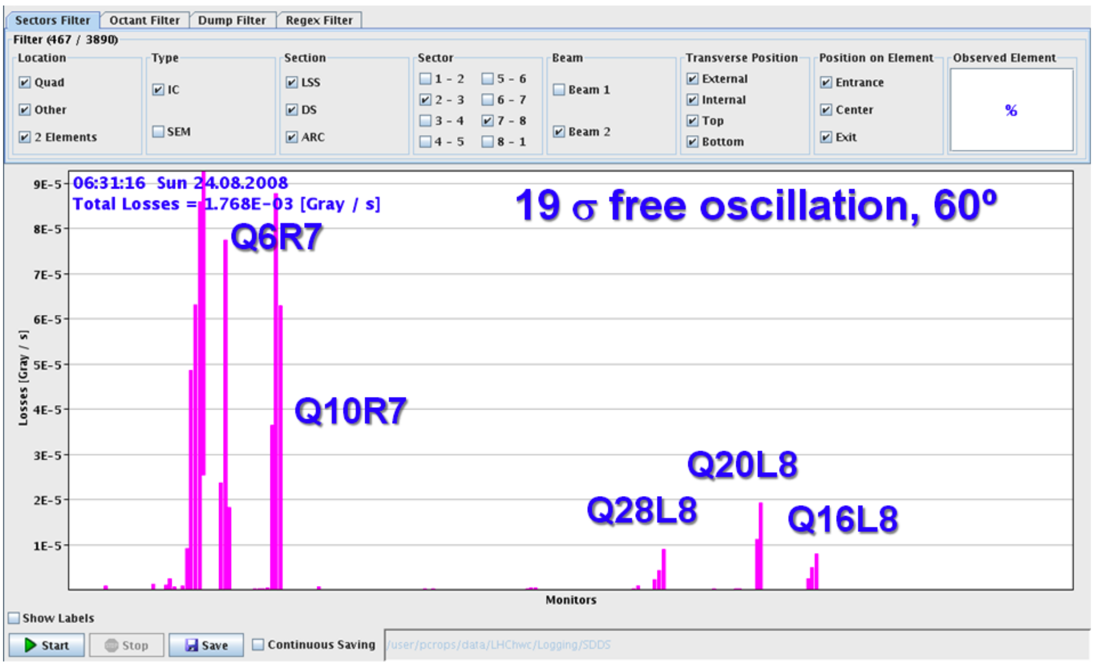

Figure 25: Beam losses recorded during a horizontal aperture scan in arc 7-8 for an oscillation amplitude of 19 nominal beam σ. The horizontal axis shows the monitor number. The locations of larger losses are indicated.

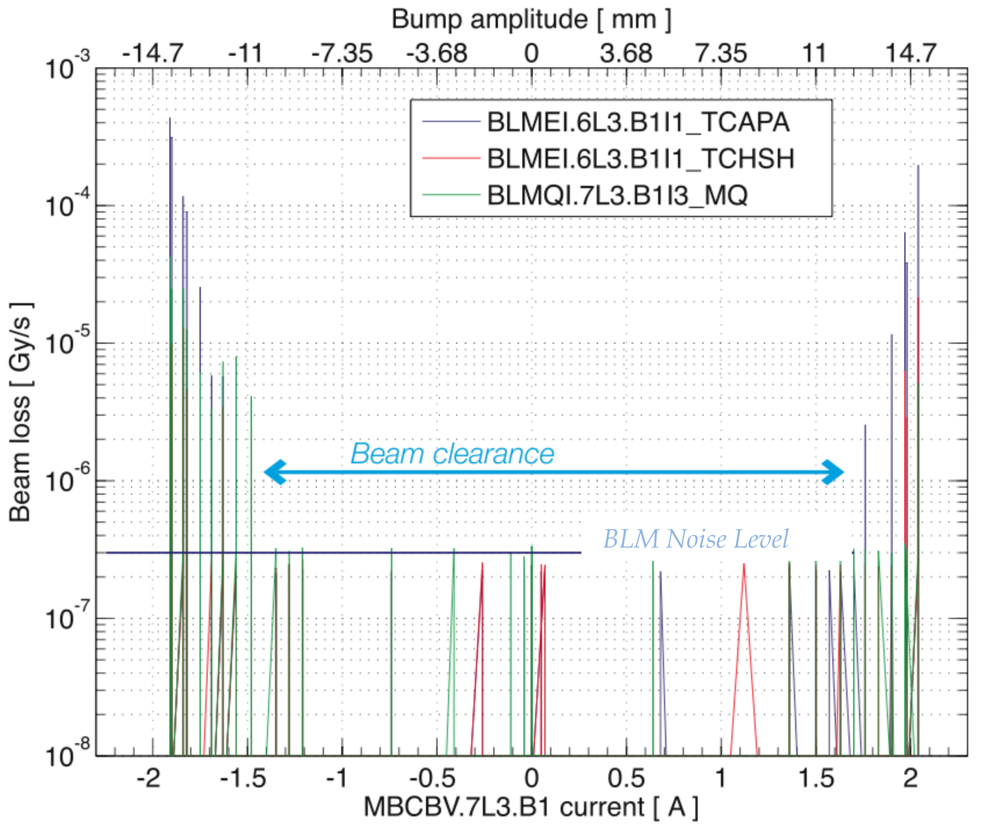

Figure 26: beam losses versus bump amplitude during the aperture scan at the MQ.7L3.B1 magnet. The bump amplitude in millimeters (top axis) is calculated with the nominal current calibration of the correctors used for the bump.

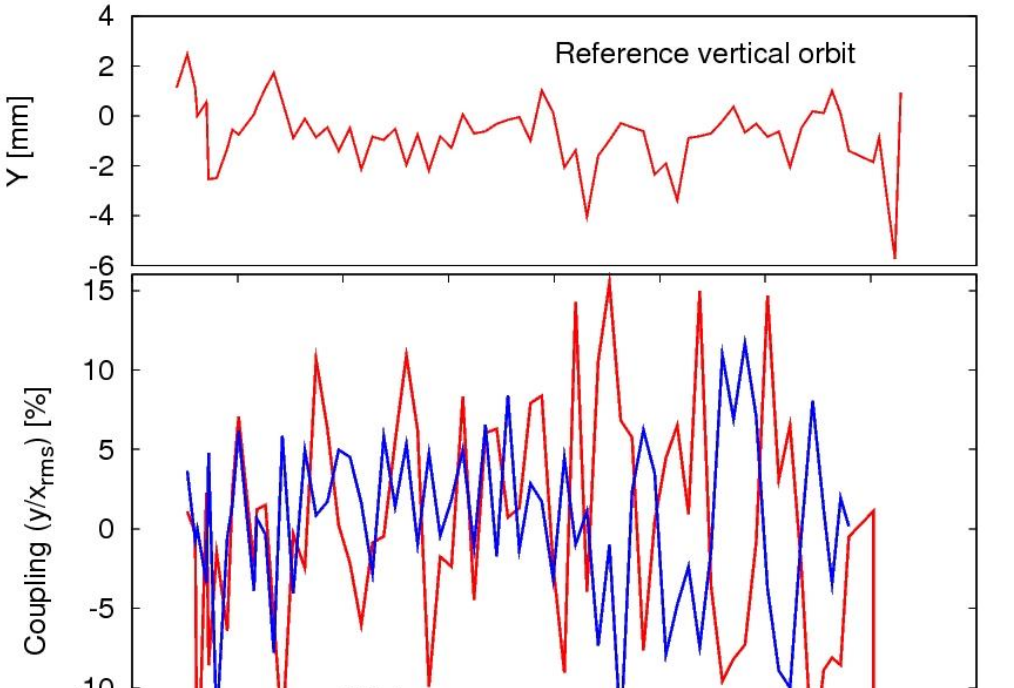

Figure 27: vertical reference orbit (top) and estimate of coupling source (bottom) as a function of the longitudinal position during two horizontal aperture scans performed in the arc 2-3.

7.7 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 (see section 7.8) performed during the same period indicated an inversion of the trim quadrupole QTL11.R2. 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 [11].

Both kick-response measurements and polarity checks were a feature of all tests, and proved to be powerful methods for identifying the sources of optics errors.

7.8 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. For further details see [11].

The technique proved very powerful and was able to identify polarity problems or at least raise suspicions about a wide variety of circuits – see table 4 (NB analysis still in progress!).

Table 4: Polarity checks - brief summary of circuits tested

Test	Sector	Circuits	Preliminary Conclusion
1	23	RSD1&2, RSF1&2, MCS, MSS (slightly off-momentum)	
1	23	QTL11.R2.B1,QTL11.L3.B1, QT12.R2.B1, QT13.R2.B1	Polarity problems
1	23	MQS.A23.B1 (no reference orbit)	
1	23	OD, OF (only one orbit each due to lack of time)	OD – wrong polarity
2	78	RSD1&2, RSF1&2, MCS, MSS (all off-momentum)	- RSS.A78 – wrong polarity. - SF1 amplitude problem - SD1& SD2 swap
2	78	QTL11L8.B2, QT12L8.B2, QT13L8.B2	QT13 - ambiguous
2	78	MQS.A78.B2	Polarity problem
2	78	OD, OF (on and off-momentum)	KOD - ambiguous
3	23	QTL11R2.B1, QT13R2.B1, QT12R2.B1	QTL11 – wrong polarity
3	23	MQS.A23.B1	Wrong polarity
3	23	SF1, SF1&SF2, SF2 (off-momentum)	
3	23	OD.A23.B1(off-momentum)	Ambiguous

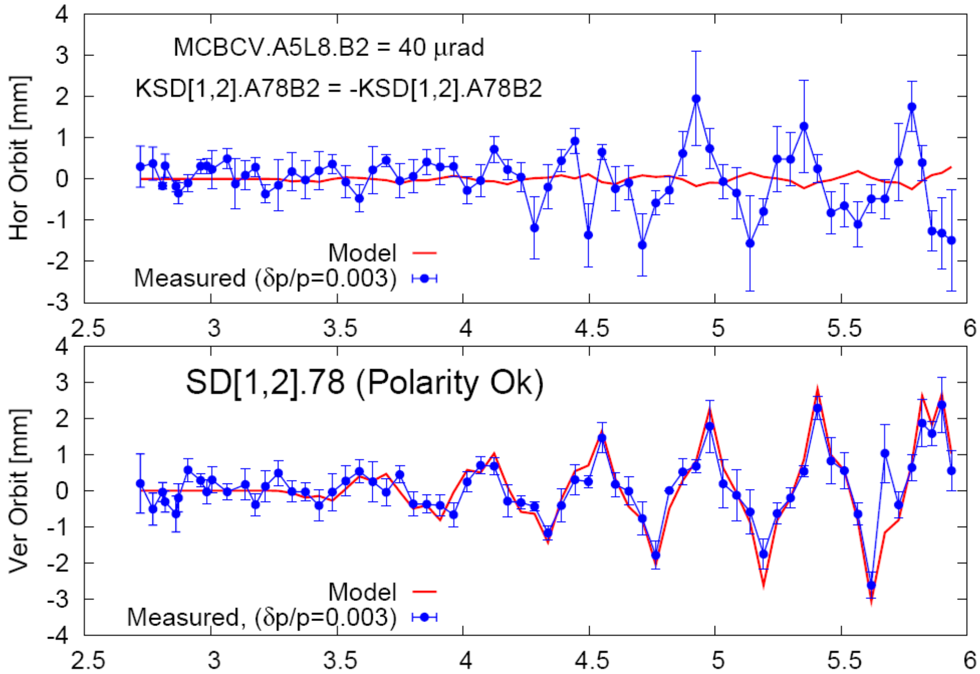

Figure 28: example polarity check measurement - SD1.A78 & SD2.A78, polarity OK

The polarity check measurements demonstrated that it is possible to verify the polarity and strength (at the 10% level) of trim quadrupoles, sextupoles, skew sextupoles, b3 spool pieces, and Landau octupoles using trajectory data for a few single passes of a bunch of 2e9 protons, thanks to an excellent BPM performance bettering the specification.

7.9 Magnetic model

The complete static magnetic model as prescribed by the FiDeL algorithm [5,6] was active 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. This is demonstrated in figure 29 where the BPM readings for an injection of beam 1 in point 2 through point 5 are shown. The first reading was taken with orbit corrected, in stable conditions. The main dipole circuit in sector 23 was then recycled, but injection settings were approached from higher currents, inverting the contribution of persistent currents to the main field. The effect of this anomalous cycle is to displace the orbit in sector 23 radially by 1.4

mm, which is consistent with a field increase of the order of 0.1 %, as expected from magnetic measurements.

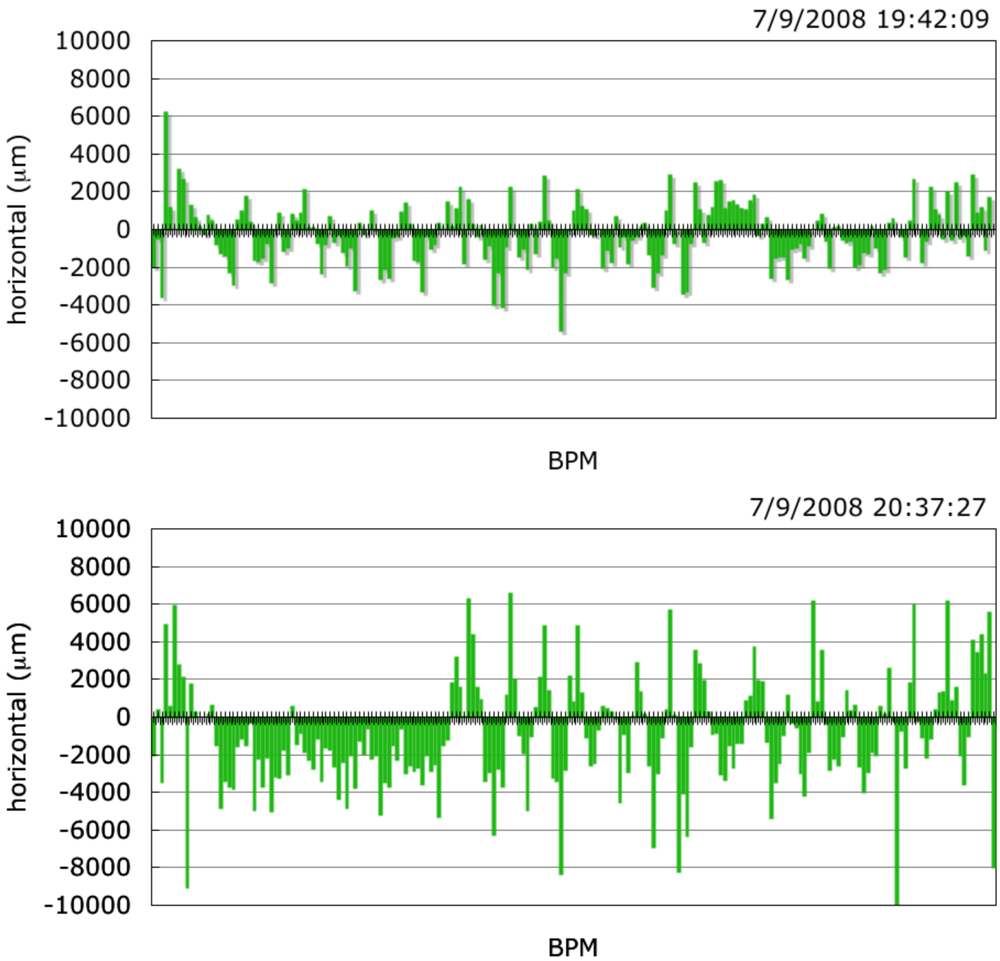

Figure 29: Shift of the horizontal BPM reading produced by an anomalous cycle performed on the dipoles of sector 23. The beam travels from left to right through three sectors, up to point 5.

Thanks to the striking performance of beam instrumentation, it was possible to give accuracy bounds for a number of settings, and in particular on main dipoles, main quadrupoles and sextupole correctors:

- the energy of the LHC was consistent with the SPS calibration to better than 10 units;
- the matching of the dipoles setting from sector to sector is within a RMS of 3 units of B1. The RMS cycle-to-cycle reproducibility of the setting is around 1 unit of B1;
- the settings of the main quadrupole are accurate to much better than 50 units of B2. Taking the best running conditions, which required a tune correction of 0.1 units of Q, a realistic estimate for the accuracy of the quadrupole setting is 15 units of B2;
- chromaticity was corrected to better than 30 units, which corresponds to an accuracy of 0.7 units of b3 in the main dipoles. Based on the long lifetime of the captured beam 2 (September 11th), the actual accuracy of the setting may be much better than this upper bound.

The numbers quoted above are provisional, and will need further analysis and more beam time to be confirmed. They are nonetheless consistent with the expected.

7.10 Quench - BLM thresholds

The beam induced quench of the dipole magnet in cell 8L3 allowed the very first cross-check of the BLM thresholds. The highest loss observed at the quadrupole magnet in figure 30 (red curve) is a factor 2 below the expected quench level while the losses observed at the bending magnet MBB (blue curve) is a factor 2 above the threshold values.

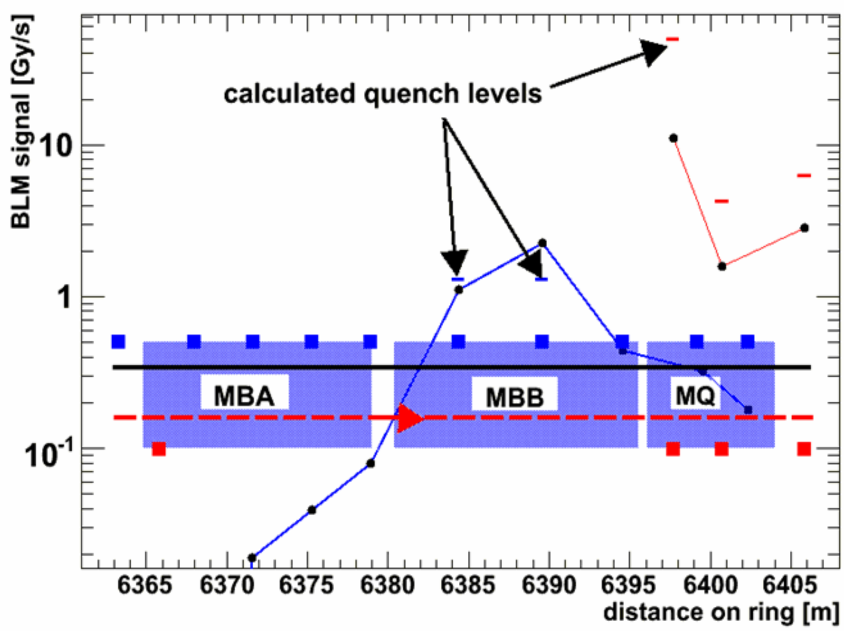

Figure 30: BLM response at location of first quench

8. System Performance

8.1 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 [13] 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. Very promising measurements with the parallel acquisition mode called the “synchronous capture” were also performed. This mode will become necessary for acquiring the injection oscillations on a newly injected beam into an LHC ring which is not empty. Using LHC injection pre-pulses produced by AB-RF and transmitted over the LHC BST system, it was possible to trigger and acquire the beam induced signals with a shot-by-shot jitter of less than ~2 nsec. The BPM capture mode requires a phasing-in and alignment of data due to the time-of-flight between pick-ups and the differing cable lengths to the acquisition electronics in the surface buildings. A semi-automatic software implementation which would set-up the ~2000 BPM channels is presently being developed.

During the first injection tests, when no intensity measurement was available in the LHC tunnel due to the absence of ring BCTs in the neighbouring sectors, investigations using the BPM intensity modules allowed much useful experience to be gained for later use. Problems were experienced in calibrating the signals for the very low intensity pilot bunches used (2e9 charges) as the non-linear behaviour is very pronounced in this region. Investigations are on-going to try and solve this problem.

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 AB-BT on firing of the dump kickers was used to freeze the images. Not enough time was available to fully commission the LBDS 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.

Due to the limited time available it was not possible to properly commission the post-mortem features of the main BI systems (BPM, BLM and BCT). This system will become important as soon as the intensity and energy increases. Much of the testing and debugging of this system can be continued during the present shutdown, but a full test will be required during the early phases of the next LHC run.

8.2 MKI kicker performance

The MKI kicker strengths were as expected and no adjustment was required. The MKI C magnet in point 2 experienced a flashover after about 5e10 protons were lost on the aperture limit upstream of Q5 during the aperture scans. This was clearly beam-induced since abnormal signals on the MKI vacuum were seen indicating some ionization in the gauge feed-throughs, correlated with the beam losses. To help avoid this in the future BLMs were added on the MKIs in both P2 and P8.

A flashover was also seen during the 3rd sector test, again in point 2 on the D magnet (the first seen by the injected beam). In this case there were no beam losses or beam-related causes found, and the flashover was a spontaneous one. Interestingly, the trajectory of the injected beam was captured and an oscillation of about 5-6 sigma was produced. This is consistent with a flashover about 60% of the way along the magnet. The need for injection protection with the TDI and auxiliary collimators is clearly evident for higher intensity beams.

8.3 Beam dump systems

In the 3rd sector test the beam was extracted first without the MKD kickers, using the two upstream horizontal orbit correctors in the LHC to provide the 0.35 mrad and 50 mm required at the MSD septum entrance. The beam trajectory in TD62 was seen to be well off in the vertical plane, with large beam losses along the TD line, and vertical correctors were used to steer through, with an angle of over 100 μrad required to reduce the losses. Later analysis of the strengths showed a simple 200 μrad error in the MSD strength, which was set at a total of 2.6 mrad for the 15 septa.

The extraction kickers were switched on and the beam was extracted correctly, with the MKD strengths observed to be in the correct range. No optimization or detailed measurement took place.

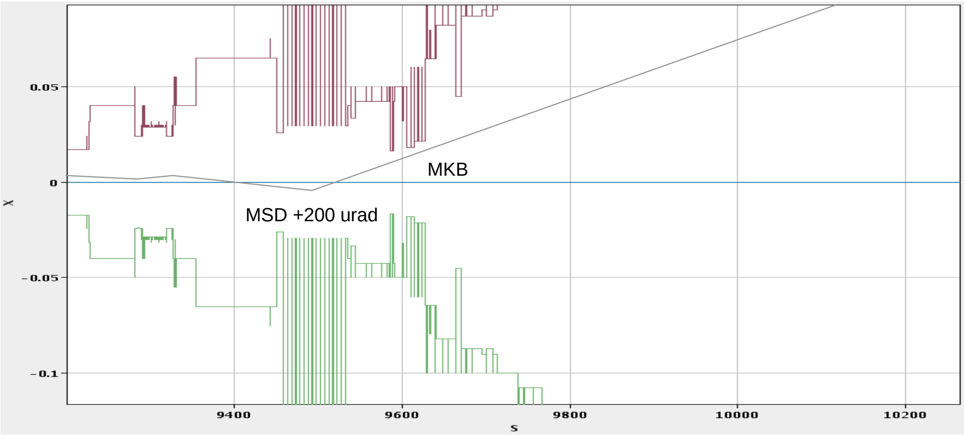

Figure 31: Reconstruction from BTV screen measurements of first trajectory extracted

The dump arming and triggering worked as designed, and the "inject and dump" mode was switched on and used, driven by the sequencer. No detailed kicker synchronization was made.

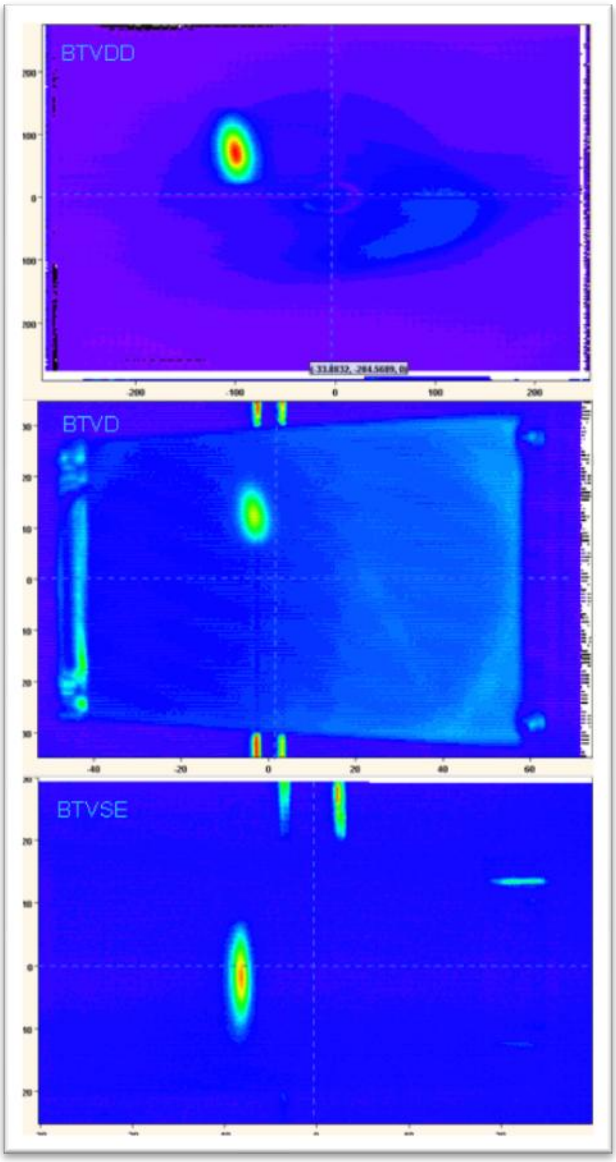

Figure 32: TD62 beam dump line screenshots from the first beam 2 extraction with beam dump kickers

9. Controls

9.1 Controls Infrastructure

A large number of components of the LHC controls infrastructure have been intensively exercised during several dry runs in 2008 and have been commissioned to near their full functionality. The systems involved include: fixed displays, the sequencer, OASIS, the alarm system (LASER), cryogenics control, the quench protection system, and the underlying infrastructure.

One of the objectives of the five injection tests was to further commission controls components, which had only been tested locally, but which never had been used in full deployment.

During these tests, emphasis was given on the commissioning of two major controls components, the timing system software and the logging system.

The timing system initially demonstrated problems with RF synchronization sending the information about the next injected bucket and ring too late in the SPS cycle. The source of the problem was identified by the system expert and appropriate solutions were put in place to allow for the continuation of the tests.

For the logging system some problems appeared at the moment of high data rates and large data volumes especially for the clients like the BLM, BPM and Power Converters. A new API was developed which offered massive parallelization guarding, in addition, against lost of database connection by persisting the data in local store. This new API successfully allowed for full LHC logging of all required equipment parameters without any data loss.

The Beam and Software interlock systems being part of the machine protection systems protected the LHC machine by surveying and analyzing the state of various key parameters and devices and dumping or inhibiting the beam if a potentially dangerous situation occurred.

During the injection tests we took the opportunity to commission for the first time the Role Based Access Control (RBAC) system. The commissioning was prepared via several dry runs and RBAC was put in effect from the second injection test onwards protecting successfully the access to the BI, PO and BT equipment and critical settings with the appropriate rules and roles defined in the access database.

Support was also given to the diagnostics and monitoring system (DIAMON), which was fully deployed during the tests to monitor the LHC controls infrastructure.

The LHC Controls evolved progressively during the injection tests to a stable and well functioning infrastructure, which supported well the successful LHC start-up. All the prior tests were extremely useful to identify areas of weakness and to prepare the LHC controls infrastructure for beam commissioning. The controls commissioning work will continue well after the first months of LHC beam operation as new applications will be deployed, which have been developed specifically for the next phases of LHC as it moved towards first collisions.

9.2 Database Performance during the tests

The accelerator on-line database services (LSA, Controls Configuration, Measurement and Logging) were all deployed in a high-availability setup called Oracle Real Application Clusters (RAC) in March 2008. This was a major and crucial upgrade in order to ensure a maximum of reliability for these mission-critical services. The technology relies on transparent fail-over to redundant components in a clustered architecture, both in the software as in the hardware. To illustrate this: the first incident appeared during the weekend of the first injection test in August whereby a 146GB fiber channel disk on the Measurement database (ACCMEAS) broke down. The incident passed unnoticed: the Measurement Service continued as if nothing had happened. The faulty disk was replaced by the provider after the weekend.

Early September, just a few days before D-day (10^{th} September), the Measurement Service welcomed many more clients, all concerning beam related data: BLM, RadMon, BCT, Wire Scanners, Tune measurements. The major clients that were already in place --Power Converters, Collimators-- were also upsized to capture equipment data from the full LHC. This brings the load close to the expected nominal value, whereby most of the clients provide 1Hz data. It has to be noted that BLM data was reduced by a factor of 4 (2 Hz, half of the running sum values). The implementation of a more intelligent data loading API with a recording-on-change functionality reduced significantly the data input volumes, peaking at 76GB/day (26-Aug-2008) and currently averaging around 60GB/day for a total of 200'000 variables.

At 09:00 on 10th September, the CPU usage of one of the two nodes in the ACCMEAS database cluster increased from 80% to 95% due to a vast number of people suddenly interested in reading the data. Nevertheless, the service maintained all data loading, data filtering and data reading activities seamlessly. Roughly 10% of the Measurement data gets pushed to the Logging database (ACCLOG). In the future, this figure can be reduced by optimizing the filtering criteria and avoiding recording signal noise in the long-term logging.

During the beam injection tests the Logging service did not suffer, as 90% of the data rates were already present during the Hardware Commissioning period. All data from the industrial systems, captured and pushed via SCADA has stabilized since mid-2008. The current average for ACCLOG is 30GB/day for some 100'000 variables. The total recorded data since mid-2003 is more than 8TB. The interactive access to all of this data is ensured by the widely used TIMBER interface. In addition, a dedicated API serves several applications to retrieve and visualize the logged data.

The third RAC serves the most critical data: the LSA repository and the Controls Configuration. With respect to the other two, this service is very relaxed in terms of load and throughput. The essential requirement is the immediate response of any action issued via a console application deployed in the control room. With a close collaboration between the application developers and the database team, this objective has been achieved.

In-depth investigations continue in order to improve the performance and the efficiency of the database services, namely in the areas of instrumentation, auditing, table statistics gathering (essential for automatic feedback on the Oracle engine), backup strategy, load distribution, disk storage utilization and standby service.

9.3 Software

The primary suite of software used to controls the LHC was delivered by LSA [7, 8]. The injection tests represented the culmination of an intense deployment and test program for the LSA. A summary of the key components and functionality provided is shown in table 4.

Table 4: LSA – main components provided for injection tests

Settings	Full machines settings at physics parameter, strength and current level for all magnets, power converters, collimators, kickers, RF etc.
Optics	Optics (parameters and strengths), Twiss imported from MAD. On-line retrieval, display, API for client applications (e.g. YASP).
Trim	Ability to modify high level parameters (e.g. extraction bump amplitude, corrector strengths, tune etc.) was provided along with full trim functionality: history, rollback, incorporation etc.
Equipment control	Appropriate software/APIs for control of power converters, RF, collimators, beam instrumentation, injection kickers etc.
Equipment monitoring	Power converters, RADMON, collimators, LBDS, kickers etc.
Measurement acquisition	Acquisition and concentration of distributed systems (BPMs, BLMs) Acquisition and applications for BCTs, screens etc.
YASP	Trajectory correction facilities were provided by YASP beam steering program [14], which uses the LSA trim, drive, and configuration services.
Measurement history	Shot-by-shot acquisition, storage and retrieval of measurements.
Magnet model	Full deployment of FIDEL to provide transfer functions, prediction and

	correction of harmonic errors, decay, snap-back.
High level process control	Interface to timing system, injection sequencing
LSA database	Full machine settings, optics, trims, machine configuration, equipment parameters, parameter hierarchy, equipment data, instrumentation data, critical settings etc. etc.

Given the deployment on other accelerators, the dry runs and debugging induced by the injection tests, the LSA software and the all-important database contents was in remarkably good shape by the 10th September. Everything worked remarkably well on the day and in the subsequent, although regrettably foreshortened, beam commissioning. The software facilitated the process rather than hampering it.

10. 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.

11. 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, despite very short notice at times.

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