INJECTION TESTS

V. Kain on behalf of the Injection Test Team, CERN, Geneva, Switzerland

Abstract

The success of the start-up of the LHC on 10th of September was in part due to the preparation without beam and injection tests in 2008. The injection tests allowed debugging and improvement in appropriate portions to allow safe, efficient and state-of-the-art commissioning later on. The usefulness of such an approach for a successful start-up becomes obvious when looking at the problems we encountered before and during the injection tests and could solve during this period. The outline of the preparation and highlights of the different injection tests will be presented and the excellent performance of many tools discussed.

INTRODUCTION- INJECTION TESTS 2008

Sector tests have been on and off the schedule for many years. A full session was dedicated to the discussion and preparation of a Sector Test at the Chamonix LHC workshop in 2006 [1]. The baseline then was to inject beam 2 into sector 78 and stop it at point 7. The tight installation and hardware commissioning schedule, however, did not leave any room for sector tests until very close to the actual start-up of the LHC in 2008. And then the sector tests, or injection tests as they are called now, turned out differently than what was originally planned.

The 2006 proposal foresaw 2 weeks with beam for one sector test. It was scheduled in the midst of installation and a temporary transfer line beam stopper, TED, was meant to go into the LHC at point 7 because of radiation concerns.

Towards the second half of 2008 installation was finished and injection tests only had to co-exist with periods of hardware commissioning. The powering and cooling of the LHC is entirely sectorized and collimators which are installed in almost every long straight section in the LHC serve as perfect beam stoppers for pilot intensity – the maximum intensity which is used during injection tests. In this state of the project injection tests have minimum impact. It was decided not to only have one injection test but three, exploring more and more of the LHC before the actual start-up. For each test a weekend with beam was reserved and even in this much reduced time compared to the originally planned 2 weeks from the 2006 proposal, essentially the same program could be carried out.

The first injection test took place on the weekend of the 8^{th} of August – one month before the LHC start-up. Beam 1 was injected into sector 23 and stopped by the momentum cleaning collimators in point 3, Fig. 1.

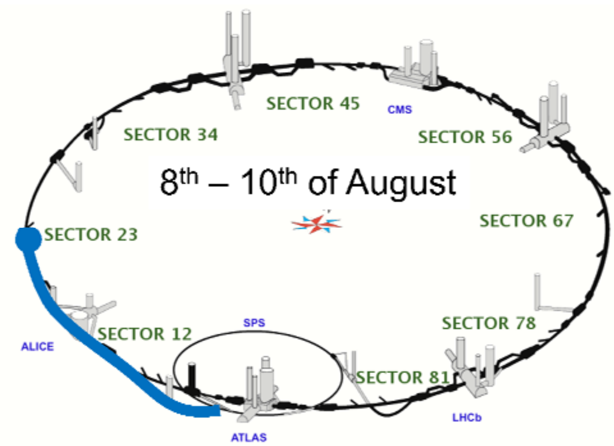

Figure 1: Injection test #1. Beam 1 was injected into sector 23.

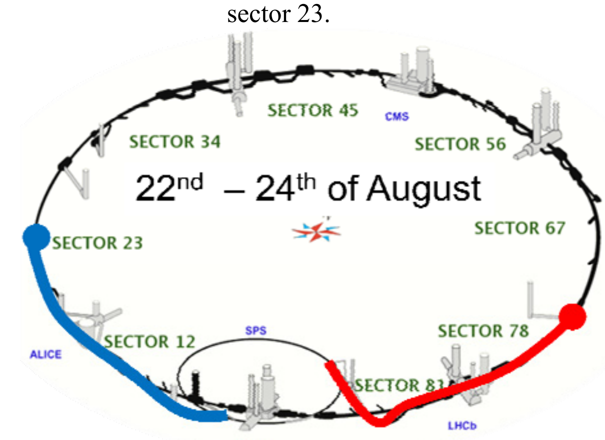

Figure 2: Injection test #2. Beam 1 was injected into sector 23 and beam 2 was injected into sector 78.

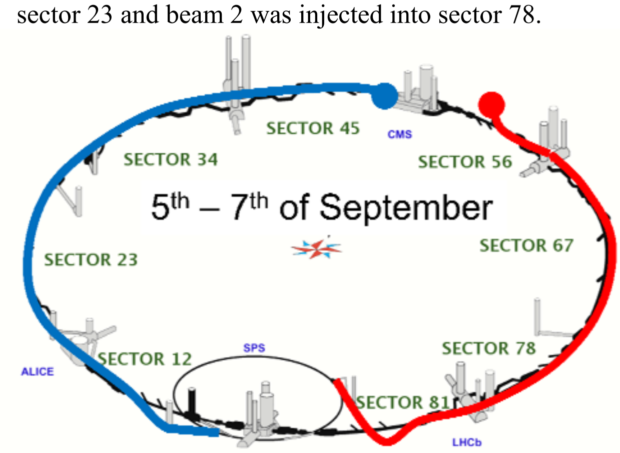

Figure 3: Injection test #3. Beam 1 was injected into sector 23, 34 and 45. Beam 2 was injected into sector 78 and 67.

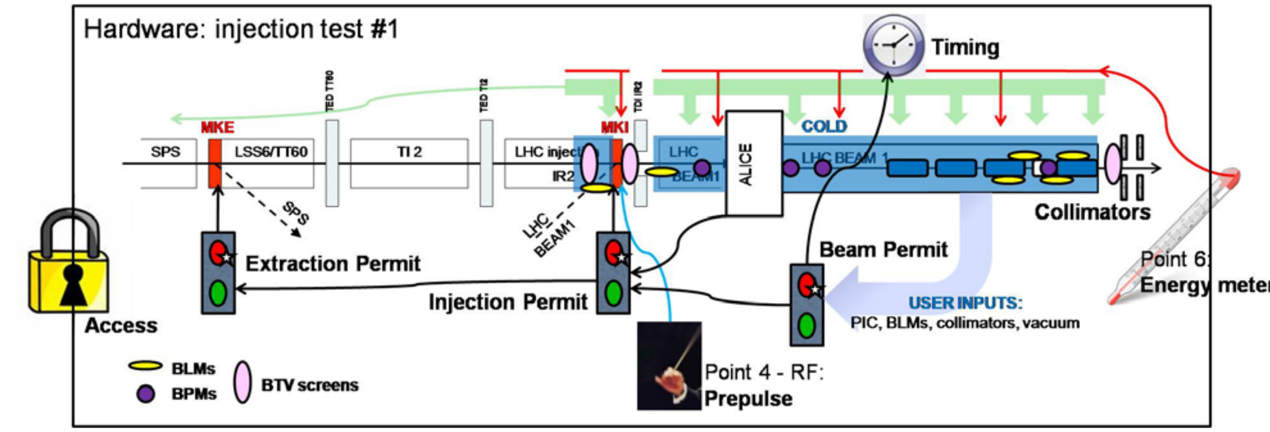

Figure 2: Simplified picture of required hardware systems for injection test #1.

The second injection test was carried out two weeks afterwards, on the weekend of the 22nd of August. Beam 2 was injected into sector 78 and stopped by the betatron cleaning collimators in point 7, Fig. 2. On the weekend before the 10th of September, the official LHC start-up date, another injection test took place, Fig. 3. This time beam 1 was injected all the way to point 5, passing through three sectors – 23, 34 and 45. Beam 2 was injected into 2 sectors, sector 78 and 67, and was extracted in point 6 by the LHC beam dumping system. A comprehensive summary of the achievements during the injection tests and preparations is given in [2].

PREPARATION

One of the reasons of scheduling eventually three injection tests so very close to the start-up of the machine was the apparent usefulness and the big success of the first one. To make it a success a lot of systems - in terms of types almost all system types - had to be already fully operational a month before the start-up date. Fig. 2 indicates which hardware systems had to be available for the first injection test:

The SPS LHC extractions and transfer lines must be commissioned with beam. Parts of sector 12 and sector 23 must be cold and at least commissioned for 450 GeV operation. All the beam instrumentation in the sector - BTV screens in the injection region, beam position monitors and beam loss monitors - must be hardware tested and fully functional. The different systems should be connected to the LHC beam interlock system as user inputs and the LHC interlock systems (beam permit loop via the injection permit) to the SPS extraction interlock system. The LHC timing must be fully operational and be distributed to all the different equipment to trigger acquisitions and to synchronise the LHC with the SPS. Several equipment systems need the Safe Machine Parameter energy for energy tracking systems (injection kickers) or threshold management (beam loss monitors). This information is generated by the beam energy tracking system (BETS) of the LHC beam dump system (LBDS) in point 6. It takes as a reference the adjacent main bend circuit currents and converts it into energy. For the first injection test, the LBDS BETS was already connected to sector 56. So, not only sector 23 had to be at 450 GeV, but also sector 56 to provide the correct energy for the injection kickers. And still the injection kickers will not pulse without the RF pre-pulse created by the RF system in LHC point 4. By the time of the injection test the LHC access system also must be DSO verified.

In order to run the hardware systems from the control room, the CERN middleware with FESA has to be operational. LSA must be up and running providing the settings management, the timing interface, FiDel, etc. The software interlock system must be configured for the LHC injection permits. The logging system must be available along with the concentrators for the BPMs and the BLMs and generic applications to drive the hardware. Even Role Based Access Control (RBAC) should already be partly used at this stage.

Analysis tools, e.g. the YASP steering application, the screen matching application or MADX-online, have to be ready for use in the CCC. Optics and settings for the combined sequence of the transfer line connected to the LHC have to be loaded. The first sequences for softstarting the injection kickers or arming the beam interlock system also need to be operational together with the injection sequences.

All in all a large number of different systems and software components were required for a successful and useful injection test. With only a weekend available per injection test, testing and preparation beforehand was essential.

Integration Tests and Dry Runs

The success of the LHC injection tests in 2008 is due to the impressive quality of the hardware, due to the hardware commissioning of the powering systems and other systems, but clearly also due to the machine check-out and dry runs where equipment is tested with

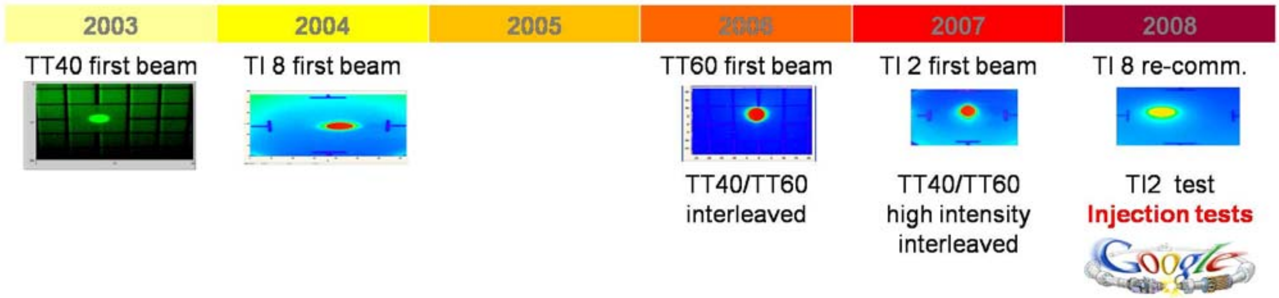

Figure 3: The success of the injections is in part due to the experience gained with the LHC beams during the commissioning of the SPS LHC extractions and transfer lines which started in 2003.

operational parameters, using operational tools and following operational scenarios like injection, inject & dump or circulate & dump.

The first injection dry run took already place in December 2007 [3]. Regular dry runs of different equipment systems were carried out throughout 2008 until the 10th of September, overlapping with an intense phase of machine check-out during the last weeks before the start-up.

A major factor of the success of the injection tests was also the experience and knowledge of the people involved with the tests during these weekends in summer 2008. Experience had been gained with the commissioning of the SPS extractions and transfer lines with LHC beam starting in 2003, Fig. 3.

RESULTS: EXAMPLES

The results will not be discussed in detail as some of them are presented in other contributions to these proceedings or are already described thoroughly in [2]. References will be indicated where possible.

First Beam in the LHC

The first 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, Fig. 4.

The first beam 2 arrived in the LHC on the TDI on the 22nd of August at 20:39:05. And again when the TDI was taken out it went to point 7 without threading.

First Trajectories

The first trajectory in sector 23, see Fig. 5, had a horizontal RMS of 9.9 mm and could be easily corrected to 1.6 mm. In the vertical plane the initial RMS was 1.6 mm which went to 1.1 mm after some correction.

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 went down to 1.1 mm and 1.4 mm after some steering.

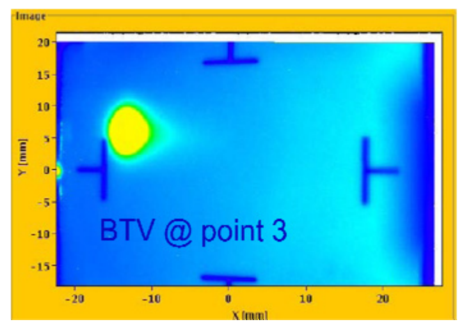

Figure 4: First beam at point 3.

Aperture Measurement

The aperture was measured in the injection regions and the arcs. Details on the results on the aperture measurement in the injection region are given in [4]. The results are as expected.

The aperture in the arcs was measured using free oscillations and beam loss readings. The results are summarised in Table 1. More information is given in [5].

Table 1: Results of arc aperture measurements.

	Horizontal [mm]	Vertical [mm]
S 23	~ 18	~ 10 limit @ Q8/Q7 L3
S 78	~ 18	~15

Dispersion Measurements

The dispersion was measured by injecting off-momentum beam from the SPS. For this sake the LHC frequency was trimmed and the SPS frequency, which is coupled to the LHC at the extraction plateau, followed. Dispersion measurements are a very good means to verify the optics with single-pass data. The measured dispersion in sector 23 followed the nominal dispersion very nicely after the correction of an optics problem due to

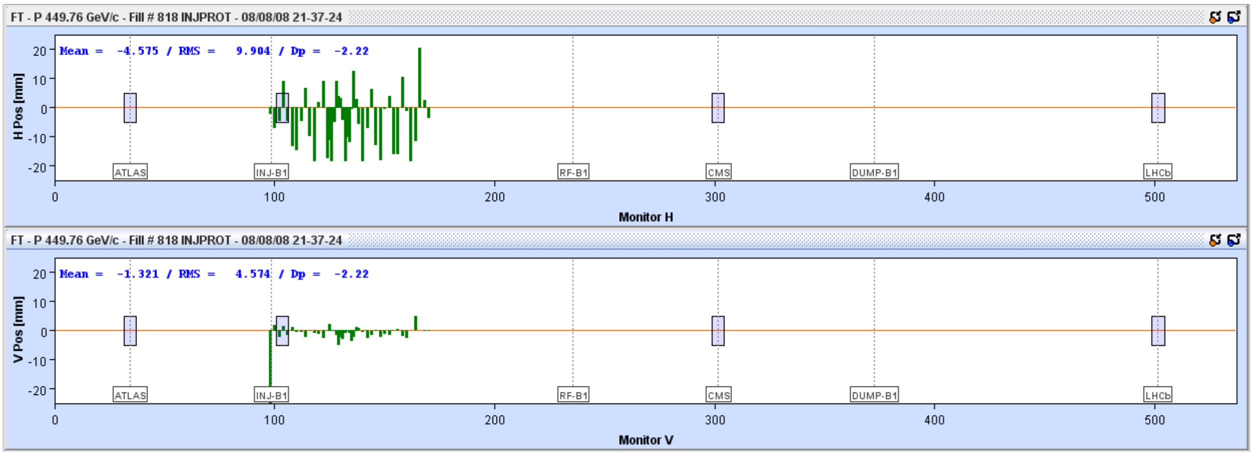

Figure 5: The first trajectory in sector 23. Horizontal RMS was 9.9 mm and vertically 1.6 mm.

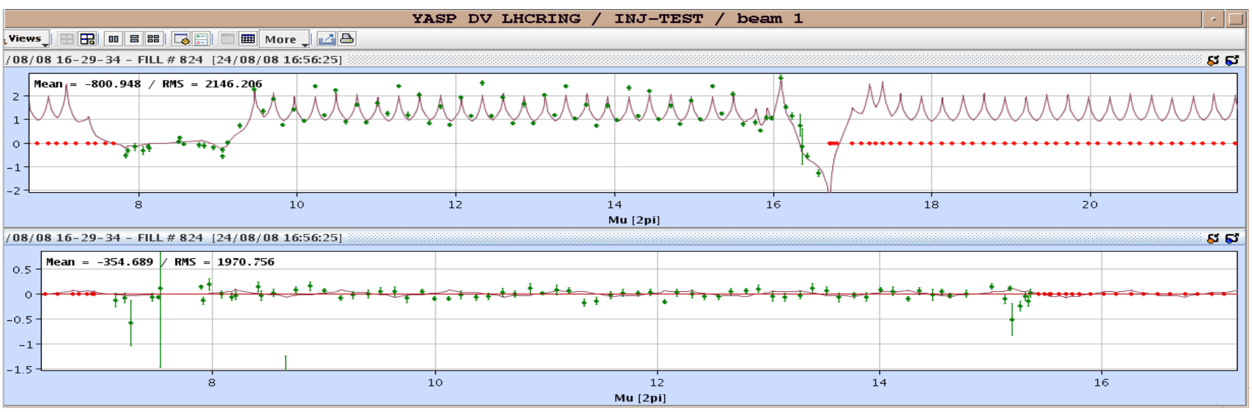

Figure 6: Dispersion measurement in sector 23. The beating in the horizontal plane amounts to about 20 % and follows the dispersion bump well at point 3, the momentum cleaning area.

polarity errors on a number of quadrupole magnets [6]. The beating was measured to about 20 % in the horizontal plane, Fig. 6. The dispersion measurement in sector 78 revealed a major dispersion mismatch between the LHC and the transfer line. The origin of the problem has not been found yet. The dispersion beats by more than 100 % in the horizontal plane. For further discussion of the problem refer to [7].

First Beam induced Quench

During the kick response measurements at the first injection test a 12 mm vertical oscillation caused the first beam induced quench in the LHC. The magnet MB.A8.L3 quenched due to the local loss of $< 4 \times 10^9$ protons. This number is consistent with what had been predicted earlier, [8]. 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 3×10^9 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 be run with an intensity down to about 1.5×10^9 protons per bunch without losing any triggers [9]. 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 2×10^9 protons for the rest of the injection tests.

Kick Response Measurements

Kick response measurements were one of the main points in the measurement programs for injection tests. This type of measurement can be used to find polarity errors of beam position monitors and orbit corrector magnets and also to give some insights about optics problems [9]. Several polarity, gain and mapping errors of beam position monitors have been found using this technique. The results are summarised in Table 2. All the tested correctors - not all of them could be tested - seem to have the correct polarity.

Table 2: List of BPM polarity, calibration or mapping errors found with kick response measurements. *Courtesy R. Steinhagen*

BPM	Comment	Corrected for 09/10
BPMs from Q1-Q7 L8	Wrong mapping, fibres swapped in SR8	yes

BPM.12R7.B2	Unresponsive to beam excitations	yes
BPM.28R7.B2	B1-B2 mismatch of button	yes
BPM.34R7.B2	Hor. plane inverted	yes
BPMIV.88014	H/V flip	yes
BPMWE.5L7B2	Hor. plane inverted	yes
BPMSX.4L8.B2	polarity, gain, optics?	yes
BPMW.5L7.B2	polarity, gain, optics?	yes
BPMSW.1L2.B1	Spurious triggers (EMC?)	no
BPM.6L3.B1	polarity	yes

Operational Scenarios

A number of operational scenarios were tested during the injection tests. Fully automatic interleaved injections driven by the injection sequencer took place at the second injection test on 24th of August.

During the third injection test, when beam 2 was extracted onto the beam dump, the scenario inject & dump was successfully tested. This scenario implies injecting and dumping on the first turn. The kickers in point 6 are triggered by the injection pre-pulse. For more information see [4].

Magnetic Model

The complete static magnetic model from FiDel was used during the injection tests. The effect of cycling was studied during the third injection tests, where beam 1 was exploring already three sectors up to point 5. The exercise consisted of ramping sector 23 to 1 TeV and cycling it back to the injection plateau without going through the pre-injection plateau. The effect of this abnormal cycle was consistent with prediction. The trajectory moved on average by -1.4 mm corresponding to a momentum change by 0.1 %. Further details are given in [10].

Polarity Checks of Higher Order Magnets

Another remarkable result was obtained when studying the effects of higher order magnets with kick response data. Due to the excellent performance of the beam instrumentation, the polarity and strength to the 10 % level could be measured for trim quads, sextupoles, skew sextupoles, b3 spool pieces and Landau octupoles with single-pass data. The results of these measurements are presented in [5].

PROBLEMS AND PUZZLING RESULTS

One main objective of the injection tests was to find problems early enough before the start-up. Several problems were found, most of them minor.

Aperture Limitation in IR2

During the measurement of the aperture in the injection region of IR2 in the course of the first injection test an aperture limitation was found. The problem could be pinned down to a certain region. Radiation measurements after the test indicated an elevated radiation level at a vacuum valve at Q5. It was later confirmed that the vacuum valve had been installed too high, see Fig. 7. The alignment of the valve had been re-visited for the second injection test and the aperture finally turned out to be as expected [4].

Figure 7: Results of aperture measurement of injection region in point 2 during first injection test. An aperture limit - a vacuum valve installed too high - was found with beam.

Issues with Synchronisation

The beginning of the first injection test was marked by problems with synchronisation between the SPS and the LHC. The culprit was a timing event needed to start the RF re-phasing in the SPS which was coming out too late. The result was a substantial jitter of the pre-pulse for injection and extraction of more than 5 μs. A temporary fix was already put in place during the first injection test. The nominal solution was working for the 10th of September. The problem is described in more detail in [11].

Phase dependent Coupling between TI 8 and LHC

During the measurement of kick response oscillations in sector 78 launched with TI8 correctors it was noticed that certain phases result in significant coupling into the other plane in the LHC. About 20 % maximum coupling was measured, see Fig. 8. Investigation off-line showed that the origin of the phase dependent coupling is the tilt angle of 53 mrad between the reference plane of TI 8 and the LHC, see [12].

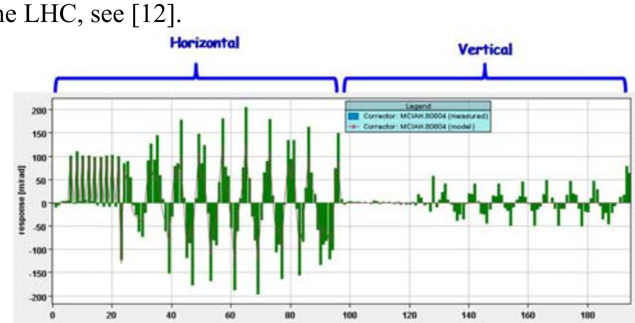

Figure 8: Phase dependent coupling from TI 8 into LHC.

Extraction Septum MSD Calibration Curve

During the first extractions from the LHC into the dump line for beam 2 in point 6, losses occurred each extraction. A large vertical bump of 70 μrad had to be applied to reduce the losses. When reconstructing the trajectory from the beam positions on the screens in the dump line after the test, it was realised that the MSD strength had been wrong by 200 μrad. The problem had been fixed by 10th of September.

Polarity Errors and Settings errors

Circulating beam could be established so quickly on 10th of September partly because of the fact that BPM polarity, calibration and mapping errors as well as setting and polarity errors of magnet circuits found in the injection tests had been removed by then. Dispersion measurements and kick response measurements were used to diagnose strength errors of trim quadrupole magnets in the LHC [5, 6, 13]. The threading through the last 200 m of the transfer lines also revealed bending magnet setting and polarity errors. The infamous group of 3 MCIAV corrector magnets which are used as RBEND had the corrector magnet polarity convention in the database. The family MBIBH293 had the wrong calibration curve loaded.

Unsolved Problems

For most of the issues a quick solution could be found during or right after the injection tests. Some issues persist and will have to be re-investigated during the shutdown or next run.

Unsolved problems are the dispersion mismatch between TI 8 and LHC ring 2, the vertical offset of the trajectory in sectors 23, 34 and 45 and the suspected sensibility of the injection kickers to beam loss. Concerning the beam loss sensitivity of the injection kickers, beam loss monitors were installed on the kickers after a flash-over had occurred following the injection aperture scan in point 2 and hence beam loss at or close to the kickers. Nevertheless, the intensities the aperture studies were carried out with and led to a flash-over were so small that minimal losses during injections of nominal intensities might become an issue.

SUMMARY

The 2008 LHC injection tests were crucial to the rapid commissioning on 10th of September as debugging exercise for hardware, software, settings, measurement procedures, operational procedures and commissioning strategy. Due to the intense preparation of almost one year, the injection tests took a minimum of time, had minimum impact and achieved invaluable results which partly altered the rest of the commissioning plan.

In view of the very late start-up of the LHC in 2009, injection test(s) is (are) recommended again as early as possible. The preparation needs to be started now.

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