

## LHC TRANSFER LINES AND INJECTION TESTS FOR RUN 2

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### Abstract

The Transfer Lines for both rings of the LHC were successfully recommissioned with beam in preparation for the start-up of Run 2. This paper presents an overview of the Transfer Line and Sector Tests performed to bring the LHC back into operation after a two-year period of shut-down for consolidation and upgrade. The tests enabled debugging of critical software and hardware systems and validated changes made to the transfer and injection systems. The beam-based measurements carried out to validate the optics and machine configuration are summarised along with the hardware systems.

### INTRODUCTION

A combination of bumpers, fast kickers (MKE) and DC electromagnetic septa (MST and MSE) is installed in two SPS Long Straight Sections (LSS6 for Beam 1 and LSS4 for Beam 2) to extract the 450 GeV proton and ion beams towards the LHC [1]. The beams are then transported along two ~3 km long Transfer Lines (TL: TI 2 and TI 8) to the LHC. A system of collimators (TCDIs) is installed at the end of each TL to protect the LHC aperture from large amplitude oscillations due to failures occurring upstream in the line or during SPS extraction.

The injection into the LHC [2] is performed in two Insertion Regions (IR2 and IR8) towards a series of five Lambertson type septum magnets (MSI). Four kicker magnets (MKI) deflect the beam onto the LHC orbit.

The LHC injection system is particularly critical due to the use of high voltage fast (900 ns rise time) kickers and the relative likelihood of failure scenarios (i.e. erratic firing, flashovers, etc). A passive absorber (TDI) is installed at 90° phase advance from the injection kicker to protect the LHC aperture in case of kicker misfiring. The TDI is also used to stop the beam during injection setup.

Accurate hardware checks are performed during the machine check-out period following long shutdowns and/or relevant modifications. Tests with beam are also required to fully validate the systems and insure the correct functionality of each equipment. For this purpose TL and Sector Tests were carried out before the startup of the second LHC Run (in November 2014 and March 2015 respectively). A summary of the performed checks and of the most relevant outcomes are presented.

### LS1 ACTIVITIES

The CERN accelerator complex underwent a long period of consolidation works in view of the second LHC run and operation at 6.5 TeV. Among others, upgrades were

performed on the SPS extraction, TL and LHC injection systems. In the following only the activities directly related to the TL and Sector Test measurements are mentioned.

The quadrupole magnets of the SPS ring, TI 2 and TI 8 were re-aligned.

A clean and steady injection into the LHC strongly depends on the stability of the beam trajectory in the TLs. A reference trajectory, which allows to minimise the injection oscillations into the LHC, has to be defined. A periodic re-steering of the lines is then necessary to compensate for the long term drifts which are induced by variations of the SPS orbit. Current ripples at the MSE Power Converter (PC) were identified as the major source of shot-to-shot variations in the horizontal trajectory of both TLs [3]. Already during Run 1 several mitigation measures were put in place (re-cabling and new configuration of the PC output filters) and the ripple was reduced from 20 A (2011) down to 4 A (2012). Further upgrades were applied during LS1.

On top of the shot-to-shot variations, a bunch-by-bunch pattern could be observed which sampled the MKE waveform. During LS1 the last unserigraphed MKE in LSS4 was replaced with a serigraphed magnet to lower the impedance. Moreover, adjustments were applied to two of the Pulse Forming Networks (PFNs) to try to flatten the MKE waveform.

A number of consolidations were applied to the MKIs in order to reduced the ferrite yoke heating and the flashover rate [4]. The ceramic chambers were equipped with a full complement of screen conductors and a modified external metal cylinder at the capacitively coupled end. This required a full validation of the high voltage performance of the MKI magnets.

### TL TEST

The TL test consisted in extracting both Beam 1 and Beam 2 from the SPS and transporting them until the absorber blocks (TED) located at the end of TI2 and TI8 respectively. This exercise was performed using pilot bunches of  $\sim 5 \times 10^9$  protons.

#### SPS Extraction

In preparation for the TL test, SPS extraction setup and aperture measurements were carried out on October 21<sup>st</sup> 2014. The defined settings for the bumpers, kickers and septa were compared with the theoretical values and those used in 2012; they were well consistent and the beam could be successfully extracted.

A scan of the aperture at the septa was accomplished by scaling the amplitude of the extraction bump with the MKE on (extraction channel) and off (circulating beam aperture).

**1: Circular and Linear Colliders**

**T12 - Beam Injection/Extraction and Transport**

This allowed to define the height of the extraction bump (40 mm for Beam 1 and 35.2 mm for Beam 2) needed to center the beam in the extraction channel and minimise the losses at the septum. No aperture bottleneck was measured in October for either beam. The MSE4 aperture measurements were used as a reference and allowed to identify an aperture restriction in the SPS which appeared at the LHC startup (Fig. 1). The movable chamber of the Cold Bore Experiment (COLDEX) [5] was found blocked at an intermediate position and intercepted the beam when the extraction bump was at its nominal value (35.2 mm). Before replacing the chamber, the obstacle could be bypassed by reducing the bump to 29 mm.

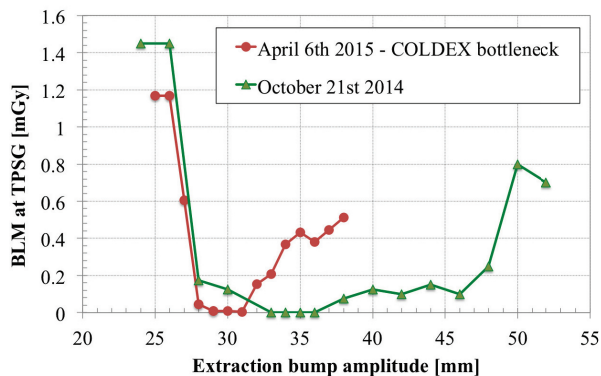


Figure 1: Beam losses as a function of the extraction bump amplitude at the entrance of the septum in LSS4. Measurements during the SPS extraction setup (in green) and at the LHC start up (in red) are compared.

### MKE Waveform and TL Stability

The MKE.4 and MKE.6 waveform scans were part of the TL tests. The measurement consisted in varying the relative delay between the kicker and an extracted bunch and monitoring the position of the beam on a downstream Beam Screen (BTV). A calibration was done beforehand to define the reference beam position on the BTV corresponding to the nominal MKE voltage and the changing position versus PFN voltage. Variations with respect to the previous run were observed only for the MKE.4, which was upgraded during LS1, and are shown in Fig. 2.

The MKE waveform measurement is essential to identify the optimum delay between the beam and the kicker pulse. The aim is to place the injected beam on the flat part of the waveform, in particular the train of 12 bunches used for the TL steering, to minimise the bunch-by-bunch variation. The optimum delay for both beams was defined: 38.5  $\mu\text{s}$  and 48.1  $\mu\text{s}$  for Beam 1 and Beam 2 respectively.

The two beams were continuously extracted for three hours up to the downstream TEDs and the trajectories recorded. The analysis of the data allowed to assess the TL stability and the achieved improvement with the upgrade of the MSE powering system. The current ripples were reduced by a factor of two with respect to 2012; an equivalent

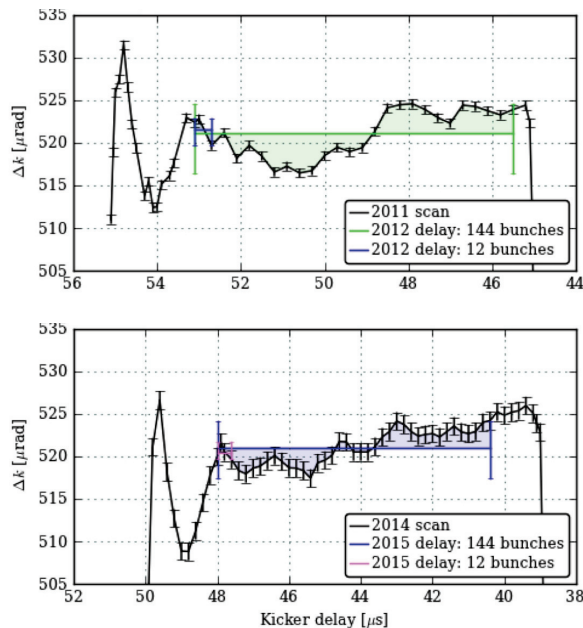


Figure 2: Waveform scan for the MKE.4 performed in 2011 (top) and 2014 (bottom). The optimum delay between the kicker pulse and trains of 12 and 144 extracted bunches (50 ns) is also shown.

attenuation was estimated for the contribution of the MSE to the oscillations in the horizontal plane (Table 1). Taking into account all the different contributions, an r.m.s. variation of  $\sim 70 \mu\text{m}$  was calculated for both beams and both planes.

Table 1: Variation of the horizontal (H) and vertical (V) trajectories in TI2 and TI8 as measured in 2012 and 2014. The MSE current ripples and the relative contribution to the total oscillation in the horizontal plane are included.

		Apr. 2012	Nov. 2014
<b>TI2</b>	r.m.s H [ $\mu\text{m}$ ]	83.0	74.2
	r.m.s V [ $\mu\text{m}$ ]	64.4	63.4
	r.m.s $H_{MSE}$ [ $\mu\text{m}$ ]	54.4	38.9
	$\sigma I_{MSE}$ [A]	3.6	1.8
<b>TI8</b>	r.m.s H [ $\mu\text{m}$ ]	95.6	73.9
	r.m.s V [ $\mu\text{m}$ ]	62.6	63.5
	r.m.s $H_{MSE}$ [ $\mu\text{m}$ ]	72.9	42.2
	$\sigma I_{MSE}$ [A]	4.5	2.1

Drifts of the SPS orbit were also monitored during the test. Big efforts were put in place since Run 1 to understand and correct the sources of the SPS orbit drifts [6] [7]. Studies on the influence of tune variations, momentum offsets and MSE stray fields on the SPS orbit stability are still ongoing and are not presented here.

### Other Measurements

Measurements were carried out on both TLs to check the aperture after the magnet re-alignment in LS1. Knobs were used to excite trajectory oscillations in the horizontal

and vertical plane at different phases (from  $0^\circ$  to  $360^\circ$  with  $30^\circ$  steps). The amplitude of the oscillations, in beam size ( $\sigma$ ) units, was increased and the beam current monitored at the beginning and at the end of the line. The aperture for each phase was defined as the amplitude at which half of the beam was lost in the line. A minimum aperture of  $10\sigma$  was calculated, in agreement with past measurements [8]. Dispersion and linear optics in the lines were also measured and found compatible with previous observations. The polarities of Beam Position Monitors (BPMs) and correctors were checked; few non-conformities were found and those were corrected.

## SECTOR TEST

During the Sector Test the beams were injected into the LHC for the first time after two years. Initially both beams were stopped by fully closing the TDIs in IR2 and IR8. BTV screens at the MSI exit (BTVSS) and in front of the TDI (BTVST) were used to check the beam presence. The MKIs were in standby for the first injections. Beam 2 made it through the MSI up to the TDI. Beam 1 was lost at the MSI since the polarity of the magnet was inverted by mistake. After correction, also Beam 1 was successfully injected onto the TDI. The MKIs were switched on and the TDIs opened. Beam 1 was stopped with the collimators in IR3 while Beam 2 could be extracted by the LHC Dump System (LBDS) in IR6 [2].

### MKI Waveform and Injection Aperture Measurements

Waveform scans were performed for the MKIs in IR2 and IR8. The same procedure as for the MKE was used and the results for Beam 1 are shown in Fig. 3. The scans were performed for the nominal pulse length and, in view of operation with longer trains (80 bunches instead of 70), for up to a  $1\mu\text{s}$  longer pulse (maximum allowed by the PFN). The measurements showed a variation at flattop of  $\pm 0.6\%$  around the nominal beam position, while the allowed voltage ripple is  $\pm 0.5\%$ . A significant part of this variation can be ascribed to shot-to-shot fluctuations. Direct measurements of the PFN voltage showed a ten times lower ripple and no correlation with the beam position variations. Measured rise and fall time were found consistent with the design values (900 ns and  $3\mu\text{s}$  respectively) within the measurement accuracy.

The MSI aperture was measured with the knobs used for the TL aperture measurements ( $0^\circ$  phase, combined horizontal and vertical plane) and checking the losses at the septum. A radial scan could be performed and an average aperture of  $\sim 9\sigma$  was found for Beam 1 and Beam 2. Since the MSI vertical aperture represents the main bottleneck in the line, an additional scan was performed moving vertically the beam parallel with respect to the MSI mechanical axis. A clearance of  $9.5\sigma$  was measured for Beam 1 and of

$10.0\sigma$  for Beam 2, which is in agreement with the design requirements.

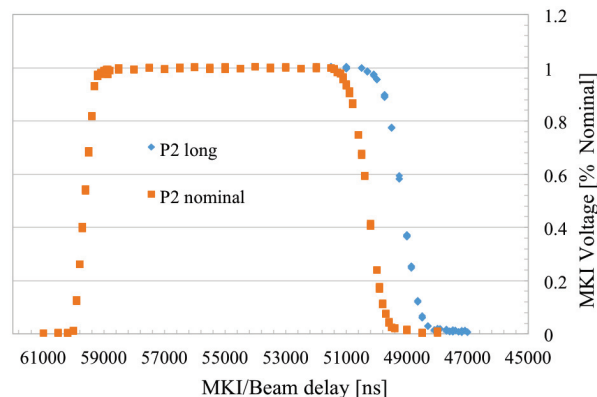


Figure 3: Nominal and long waveform of the MKI in IR2.

### Other Measurements

A preliminary synchronisation between the injection kickers and the LBDS was performed during the Sector Test and allowed operation in inject-and-dump mode for Beam 2. Moreover the global status of the systems could be checked together with the related diagnostics, data logging, etc. Some non-conformities were found and those were followed up in preparation of the LHC startup.

## CONCLUSION

Tests with beam were performed to fully validate the TL and injection systems before the second LHC Run. Both beams were successfully extracted from the SPS, transferred and injected into the LHC. These tests allowed to complete validations, set up references and discover non-conformities which were fixed in view of the LHC startup.

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