RESULTS OF 2009 OPTICS STUDIES OF THE SPS TO LHC TRANSFER LINES

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Abstract

In 2008, the SPS-to-LHC transfer line operation allowed for the first time to perform beam measurements in the last part of the lines and into the LHC. Beam parameters were measured and compared with expectation. Discrepancies were observed in the dispersion matching into the LHC, and also in the vertical phase advance along the line. In 2009, extensive theoretical and simulation work was performed in order to understand the possible sources of these discrepancies. This allowed establishing an updated model of the beam line, taking into account the importance of the full magnetic model, the limited dipole corrector strengths and the precise alignment of beam elements. During 2009, beam time was allocated in order to perform further measurements, checking and refining the optical model of the transfer line and LHC injection region and validating the different assumptions. Results of the 2009 optics measurements and comparison with the beam specification and model are presented.

INTRODUCTION

During the 2009 LHC beam commissioning, a series of SPS-to-LHC transfer line measurements have been performed. These data taking campaigns and analyses were a logical continuation of the beam studies made in 2008 and described in [1-5]. Investigation on the beam trajectories, kick response and dispersion measurements have been carried out in parallel, in order to arrive to a consistent model of the SPS-to-LHC transfer lines (thereafter TI 2 and TI 8).

FIRST GENERAL OUTCOMES FROM THE DATA TAKING ANALYSIS

The extensive campaign of TI 2 and TI 8 data taking and careful analysis -kick response, trajectory, and dispersion measurements- allowed performing major progress in the consolidation of the beam line operation. First data analyses pointed to possible discrepancies in the Beam Position Monitor reading (thereafter BPM) [6]. Therefore, the calibration of the BPM system was performed and the required corrections, very well in agreement with the simulation results, were included in all beam position readings.

Furthermore, detailed trajectory analyses suggested a large beam excursion at the entrance of TI 2, in a 200 m long region lacking vertical beam position monitors. This area is a critical location in terms of aperture, as it hosts the vacuum chamber transition from the SPS to the TI standards – the latter being much reduced in physical aperture. During the beam-based aperture measurements, it was deduced -without any means to directly measure it- that a π bump had been created at this location, reducing drastically the aperture. The bump was removed and the aperture indeed restored. Finally, during the 2008-2009 LHC shutdown, all TI 8 BPMs were upgraded into dual plane readings, allowing more robust dispersion measurements and facilitating their analysis. The same BPM improvements will be performed in TI 2 for the 2011 start-up.

TRANSFER LINE BEAM TRAJECTORY

Both the TI 2 and TI 8 trajectories were measured prior to any beam excursion corrections –the so called bare trajectory. The trajectory excursion was about 2 mm r.m.s. in both planes, for both lines and the maximum deviation was within the design value of ±4 mm, indicating that there were no evident alignment or powering errors affecting the beam line equipments. Correcting the trajectory with 2 to 3 correctors allowed reducing the excursion to about 1 mm r.m.s. These results were the outcome of careful trajectory studies, using the bare trajectory and comparing it to the model, before adding on correctors one by one and performing the same checks again. It allowed finding errors in the affectation of the calibration curves to some of the recuperated dipole magnets, in particular in the vertical plane, leading to an immediate improvement of the vertical bare trajectory.

INVESTIGATION ON THE TRANSFER LINE MAGNETIC MODEL

As previously mentioned, during the first 2008 SPS-to-LHC injection test, a strong dispersion mismatch was observed between TI 8 and the ring. It is worth mentioning that the number of dipole magnets in the TI 8 transfer line is about twice that of TI 2.

A series of tests and measurements (survey, electrical tests) were then performed to investigate a possible source, but despite all the efforts made, it did not lead to a clear explanation of the problem.

In addition, the analyses of the TI 2 and TI 8 kick response measurement data indicate a dissymmetry between the focusing and defocusing main quadrupole families (thereafter MQIF/D), when trying to fine tune their transfer function in order to best fit the measured data [6]. A redundant feature was for instance that the MQID seemed to be 0.7% stronger than expected while the best fit obtained for the MQIF transfer function corresponded more or less to the values measured on the magnetic bench in the laboratory. Therefore, the beam measurements showed the presence of an unexpected source of quadrupole errors along the line, certainly systematic because not building up any dispersion mismatch in the ~π/2 FODO cells of the line itself and which, surprisingly, left unchanged the horizontal betatron phase of the line with respect to the model, while substantially increasing it in the vertical plane.

It was then realized [7] that this apparent dissymmetry between focusing and defocusing quadrupoles could be explained by a systematic source of quadrupole error -b2- in the main dipoles of the line (thereafter MBI) which, combined with an inaccurately calibrated transfer function of the MQI, could have a marginal effect in terms of phase shift in one of the two transverse planes, while the effect would be doubled in the other plane. This scenario was indeed motivated by the fact that systematic b2 errors in the MBI would act as a "phase separator" in the two transverse planes (since the beam sees in average the same beta functions in both planes in the MBI) while a systematic calibration error of the MQI (without dissymmetry between MQIF and MQID) would shift by the same amount the betatron phases in the two transverse planes. Then, adding this second knob in the model fitting procedure (in addition to a possible calibration error of the MQI transfer function) allowed excluding a possible MQIF/MQID dissymmetry and then to reconstruct the dispersion mismatch measured in the LHC, as shown below.

The remaining uncertainty was therefore to explain this unexpected systematic b2 in the main dipoles of the line, in particular whether it was an intrinsic harmonic of the MBI (e.g. due to a saturation effect) or coming from feed-down effects from an allowed multipole such as b3.

QUANTIFICATION AND BEAM-BASED VERIFICATION

The kick response measurements were taken and analysed together with the dispersion measurements allowing to fine tune the updated model of TI 2 and TI 8.

The calibration curve of the MQI was decreased by 0.6%. The measurement of the MQI is scheduled in order to confirm this beam-based measurement finding.

Concerning the MBI, a sextupole component of about -4.5e-4 at a radius of 25 mm has been confirmed by 2D calculation [8]. Also, for the MBI, a quadrupole component of about 1.35e-4 at a radius of 25 mm is believed to originate from a feed-down from the systematic horizontal offset performed on the MBI in order to accommodate for the large sagitta of these magnets [9-10].

The optics of the TI 2 and TI 8 were therefore re-matched onto the LHC injection point, taking into account these magnetic errors. Additional kick response measurements were taken with the corresponding rematched optics (rectangular bars) and showed a very good agreement with the model (continuous line), Fig. 1 – 2, for the TI 8 vertical plane.

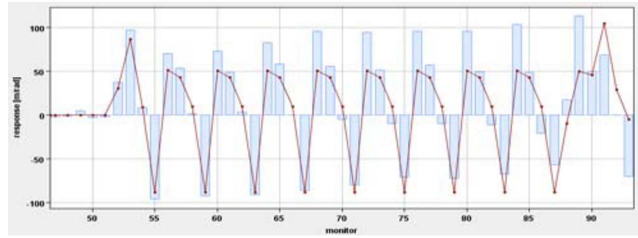

Figure 1: Kick response measurements before the optics rematching.

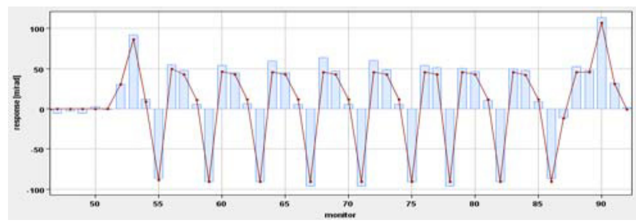

Figure 2: Kick response measurements after the optics rematching.

The same excellent agreement is found for the dispersion measurements (Fig.3) and its derivative (Fig.4).

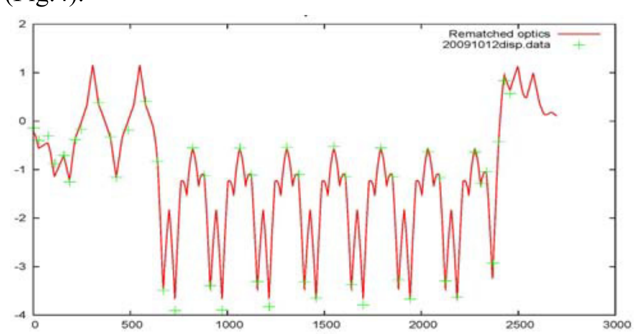

Figure 3: First order dispersion measurements (+) vs. model (continuous line), after the optics rematching.

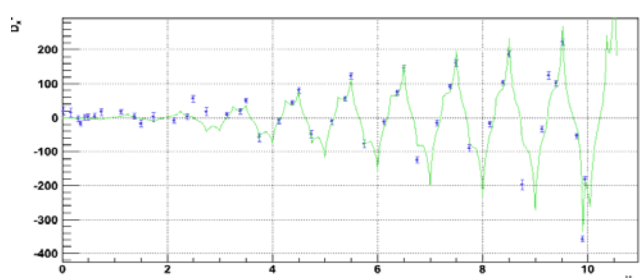

Figure 4: Second order dispersion measurements (+) vs. model (continuous line), after the optics rematching.

Further kick response measurements were performed as well, this time taking also into account the response into the LHC ring. The agreement between the measurements and the model (continuous line with dots) was again in very good agreement (Fig. 5 and Fig. 6).

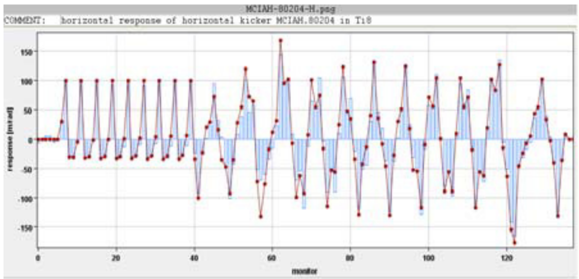

Figure 5: Horizontal response from horizontal kick at the TI 8 start. Beam from the left.

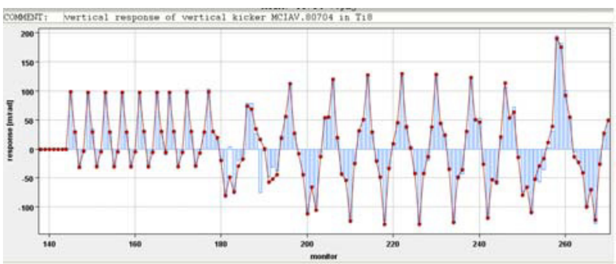

Figure 6: Vertical response from vertical kick at the TI 8 start. Beam from the left.

INJECTION STEERING STUDIES

The beam steering of the TI 2 and TI 8 transfer lines into the LHC is of high importance as any deviation from the tight constraints would lead to injection oscillations and in turns to emittance growth. The transfer line and LHC steering application has been much improved [11]. It now uses by default the transfer line and the first adjacent LHC sector, as illustrated in Fig. 7. It will display the trajectory in the transfer line and the ring first turn to which the ring closed orbit has been deducted (thereafter, FT-CO), providing a direct measurement of the injection oscillation.

Figure 7: Steering application display showing the trajectory in the transfer line and the "first turn-closed orbit" in the LHC adjacent sector.

The improvement allows using the injection "autopilot" which performs automatic correction of the injection oscillations. This feature is manually activated and the present algorithm performs a fit of the betatron oscillation to the ring "FT-CO", taking into account the $\delta p/p$ error in the horizontal plane, then interpolate the fit to a virtual start point (position and angle) and finally, if the position and angle are out of tolerance, a trajectory correction will be applied, using 2 correctors at the end of the line. First 2010 experience with the beam operation now confirms that manual steering of the injection oscillation is still required, sometime involving correctors at the start of the transfer line, and should be done with care in order to make sure the correction is done on the FT-CO. In particular, as the transfer line collimators are now setup, the trajectory at their location must be monitored carefully and should not be changed through automated steering, after the collimator setting-up.

OUTLOOK

The transfer line and injection systems were thoroughly checked during 2009. The dedicated beam time allocated to the studies of the injection systems before the LHC re-start was essential to update the transfer line model and build confidence into it. The robustness of the model has been established, the TI 2 and TI 8 beam line optics rematched and is now used in regular operation. This updated model was crucial in order to continue the setting up of the LHC injection systems, provide the required beam parameters and prepare for higher intensities.

ACKNOWLEDGEMENT

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