MACHINE STUIES DURING BEAM COMMISSIONING OF THE SPS-TO-LHC TRANSFER LINES

M. Meddahi, I. Agapov, K. Fuchsberger, B. Goddard, W. Herr, V. Kain, V. Mertens,
D. Missiaen, T. Risselada, J. Uythoven, J. Wenninger, CERN, Geneva, Switzerland
E. Gianfelice[*], Fermilab, Batavia, IL, USA

Abstract

Through May to September 2008, further beam commissioning of the SPS-to-LHC transfer lines was performed. For the first time, optics and dispersion measurements were also taken in the last part of the lines, and into the LHC. Extensive trajectory and optics studies were conducted, in parallel with hardware checks. In particular dispersion measurements and their comparison with the beam line model were analysed in detail and led to propose the addition of a dispersion-free steering algorithm in the existing trajectory correction program. Its effectiveness was simulated and is briefly discussed.

INTRODUCTION

Previous injection tests into the LHC allowed to perform extensive optics studies [1], and to conclude that the beam lines were operating as expected up to the last beam dump (thereafter, TED). In August 2008, transfer line tests with beam took place and optics measurements were conducted for the first time beyond the last TED. This paper summarises some of the main findings, while more detailed work can be found in [2].

INVESTIGATION ON COUPLING OBSERVATIONS

The frame rotation between the transfer lines and the LHC, arising from the use of inclined dipoles, produces some subtle beam dynamics effects at injection which have a variety of implications for operation [3]. The first measurements with TI 8 beam of the injection into the LHC revealed that the coupling is much larger than originally anticipated and depends on the phase of the measurement oscillation. This effect is reproduced in the MAD-X model and has been fully described analytically [4]. The initial measurements show that the coupling at injection behaves as the full MAD-X model predicts, although the amplitude is still about 20% larger than expected, which needs further investigation. The effects should not lead to any major operational issues, but the injection steering will be slightly more complicated than foreseen. The emittance growth at injection is still expected to be below 2%, and the issue of tail repopulation needs to be taken into account when the SPS scrapers become operational [3]. An overall correction of the tilt mismatch at the injection point would be possible by skewing several quadrupoles in the transfer line, but this is presently not considered worthwhile in view of the extra complexity introduced for the collimation section, the alignment, the layout and the instrumentation.

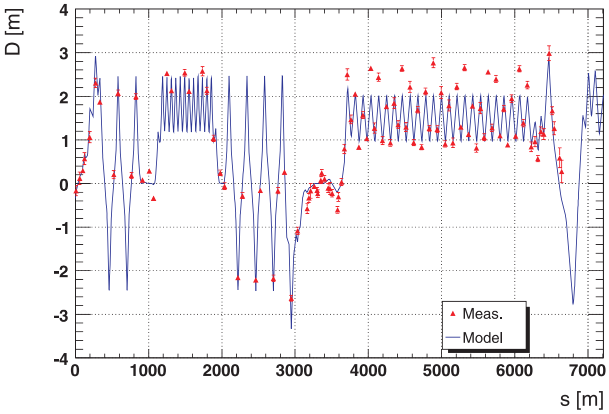

Figure 1: Nominal horizontal dispersion (blue line) and measured dispersion values (red triangles) from the start of TI 2 to the left of IP3 in the LHC.

TI 2 DISPERSION MEASUREMENTS

Dispersion data measured in TI 2 are shown in Fig. 1 and are compared with the model: the dispersion measurements agree very well with the model along TI 2. In the LHC, there is a slight dispersion beating. A fit to the data indicates that almost all the dispersion error in the LHC can be explained by errors in the TI 2 initial conditions.

TI 8 DISPERSION MEASUREMENTS

Dispersion measurements have been taken in the TI 8 beam line and compared with expectation. In Fig. 2, the simulated dispersion of the TI 8 line is plotted along the beam line, down to the left of IP7 in the LHC, together with measured dispersion values. The dispersion towards the end of the line differs from the model; the largest discrepancy is observed at the end of the TI 8 matching section into the LHC (at MQIF876), with a dispersion beating propagating into the LHC. The difference between the measured and nominal dispersion values, normalised to the $\sqrt{\beta_x}$, is plotted in Fig. 3. The measurements indicate that the oscillation seems to originate around Q5.L8, and the beating amplitude increases after Q5.

---

[*] Work partly supported by Fermilab, operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy

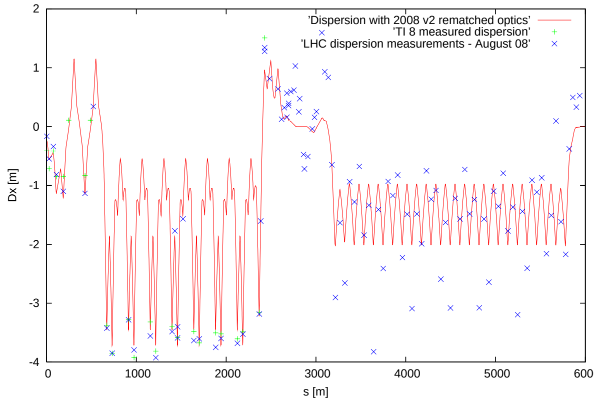

Figure 2: Nominal horizontal dispersion (red line) and measured dispersion values (crosses) from the start of TI 8 to the right of IP7 in the LHC.

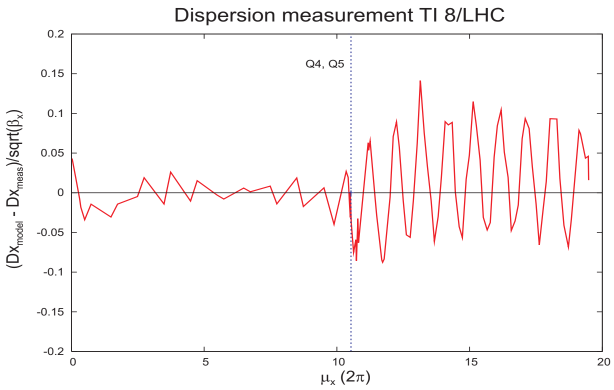

Figure 3: Horizontal dispersion difference between the measurements and the model, normalised to $\sqrt{\beta_x}$.

INVESTIGATION ON POSSIBLE MAGNETIC ERRORS

A campaign of magnet checks was performed to verify all magnet currents and fields. Calibration curves were checked, the magnetic field of matching quadrupoles of the end of the line was measured in the tunnel and alignments were verified. No significant errors were found; in particular all quadrupole tilts were of the correct magnitude and sign. In parallel the survey team remeasured the position of the magnetic elements from MQIF868 to the end of the line, with particular care to the dipoles tilted by 19 degrees. It was found that since the last alignment campaign done in 2007, elements at the end of the line have moved radially, some of them by up to $1-2$ mm, which is not too surprising for a relatively new tunnel.

These investigations and measurements allowed to establish a MAD-X file of errors for all magnets of the line. Simulation showed that the field and alignment errors were indeed acting on the dispersion, but not to the amplitude observed.

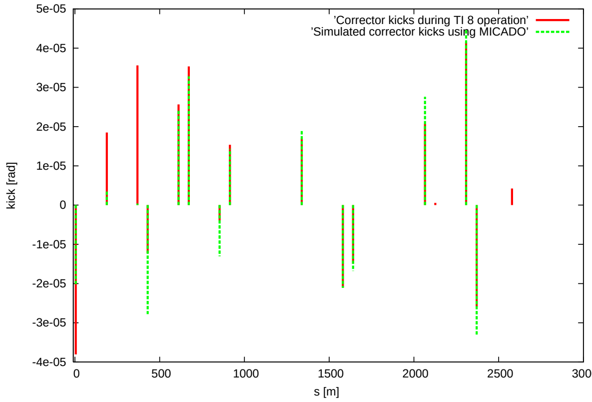

Figure 4: Corrector strengths used to correct the bare trajectory with 14 correctors, and used for the nominal operating trajectory.

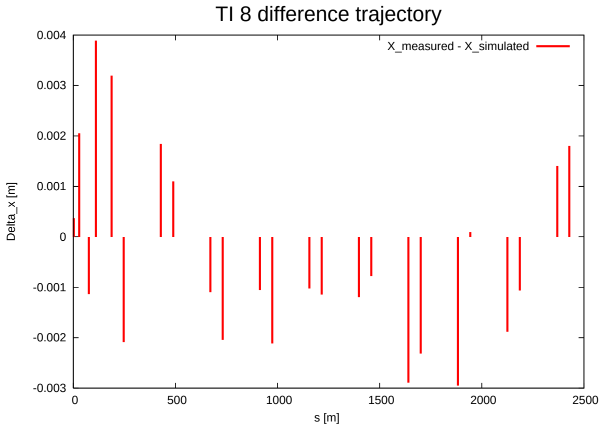

Figure 5: Corrected bare trajectory from the model with all errors in and as measured in the TI 8 line.

TRAJECTORY ANALYSIS

Beam time was allocated on 17 September 2008 to record the TI 8 bare trajectory. The measured trajectory excursion showed amplitudes within the specification (± 4 mm) along the beam line, at the exception of the MQIF874 and MQIF876 locations. The origin of the large trajectory deviation was quickly identified as a radial displacement of the MQIF872 by dx$=$ 2mm. TI 8 survey measurements indeed confirmed that the entrance of MQIF872 was displaced by 2 mm and the exit by 1.4 mm. The strength of the 14 correctors used with MICADO are plotted versus the strength of the operational trajectory correctors in Fig. 4. The strengths show a good agreement between the two cases. When all the measured beam line element errors are added to the model and the bare trajectory is corrected towards the end of the line using MCIAH872, the difference between the resulting simulated bare trajectory and the measured one is plotted in Fig. 5. The beginning of the line shows the largest discrepancies and the model will be improved with the addition of magnetic corrections applied during operation in order to optimise the trajectory at this

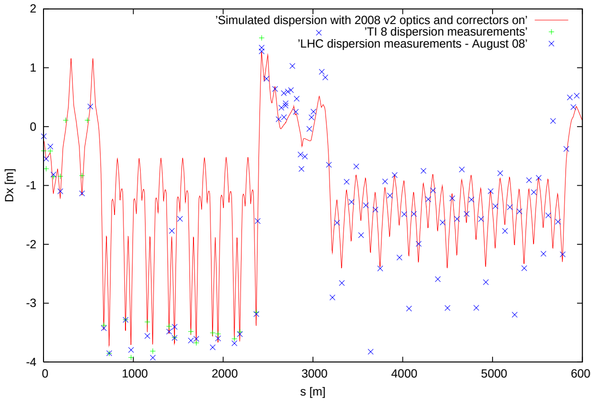

Figure 6: Simulated horizontal dispersion after trajectory correction (14 correctors) and measured dispersion values.

location. Along the beam line, at this stage, the agreement is considered satisfactory. These results allowed us to develop confidence in the beam line model with errors and to therefore exploit this model for further dispersion analysis.

DISPERSION EFFECTS FROM ERRORS AND CORRECTOR STRENGTHS

Adding all magnetic errors to the line model, together with the trajectory corrector strengths used along the beam line to establish the trajectory, indicated that the misalignments and the trajectory correctors were, by themselves, reproducing the larger dispersion measured towards the end of the TI 8 line, Fig. 6. However the dispersion after the injection point still diverges from the revised model, although now to a lesser extent. A ”dispersion-free” steering algorithm (thereafter, DFS) was implemented in the operational steering program [5]. It was applied to the measured TI 8 and LHC sector 87 trajectory and dispersion. The results indicate that the large dispersion error in the LHC cannot be corrected using DFS in TI 8, unless a very large trajectory oscillation of 6-10 mm is launched in TI 8 to produce a ’compensating’ dispersion wave.

SUMMARY

The model of the line has been refined with the addition of all known field and alignment errors, together with the actual corrector settings used for the measurements.

For the trajectory, the measured alignment offsets reproduce fairly well the measured ’bare’ trajectory in the line. Using MICADO to correct the trajectory, the corrector settings found in MAD-X and the actual operational settings also agree well. The beginning of the line shows some unexplained behaviours which need further clarification.

The dispersion behaviour with all the errors included - with the trajectory correctors powered- shows the same amplitude and phase of perturbation that was measured along TI 8. There are still differences in the beating pattern in the LHC, but the magnet errors and corrector strengths in the LHC proper were not included, and these may explain part of the effects.

It may be possible already to improve the beating with the realignment of the TI 8 quadrupoles, especially in the radial plane. In addition, an algorithm for ’dispersion-free’ steering was tested with MAD-X and showed encouraging results. However, DFS alone can only correct a fraction of the dispersion error observed in the LHC.

In conclusion it seems now as if the perturbation to the dispersion at the end of the TI 8 line is caused by the accumulation of these small errors (alignment and steering) along TI 8 which have to be corrected by some strong powering of corrector magnets. The main sources of dispersion at the end of the TI 8 line (MQIF876) seem to be nearer to the start of the line. The same model explains this and reproduces the measured trajectory. The larger amplitude of the dispersion beating in the LHC, downstream of the TI 8 line, remains to be understood. Machine development time has been requested in order to perform detailed measurements in 2009. The misalignment and magnetic errors of the LHC ring elements seen by the injected beam will be added in the model, together with the strength of the LHC correctors.

The limited number of BPMs in the transfer lines made the analysis more difficult, especially when trying to disentangle dispersive and trajectory effects. Therefore, 4 additional BPMs have been installed at the end of TI 8 in order to have beam instruments at each quadrupoles in this region. Also, the acquisition system of all installed TI 8 BPMs has been upgraded to allow dual plane measurements. The same improvements will be performed in TI 2 during the 2010-2011 shutdown. Finally regular alignment checks / re-alignment campaigns will be planned.

ACKNOWLEDGMENT

Many colleagues contributed to these measurements and investigations, in particular O. Brüning, S. Fartoukh, M. Giovannozzi, L. Jensen, M. Jones, R. Jones, M. Lamont from CERN and R. Calaga from the USLARP collaboration. Finally the excellent support from the numerous teams involved in preparing and running the LHC is acknowledged.

REFERENCES

[1] V. Mertens et al., Beam commissioning of injection into the LHC, these proceedings.

[2] I. Agapov et al., TI 8 transfer line optics studies, LHC Performance Note 004.

[3] B. Goddard et al., Geometrical alignment and associated beam optics issues of transfer lines with horizontal and vertical deflection, LHC-Project-Report-719, 2004.

[4] K. Fuchsberger et al., Coupling at injection into the LHC from reference frame rotation, LHC Performance Note 003.

[5] J. Wenninger, Dispersion free steering for YASP and dispersion correction for TI 8, LHC Performance Note 005.