TI 8 transfer line optics studies

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Summary

The note summarises some of the optics studies which have been performed in the TI 8 transfer line during August - September 2008. Dispersion, trajectory excursion and coupling were analysed and compared with expectations. The observed differences between model and measurement were investigated and possible corrective actions are proposed.

1 Nominal TI 8 transfer line optics

The TI 8 transfer line has been matched to fulfill the geometrical and optical constraints from the SPS extraction point to the LHC injection point. The nominal beta functions are plotted in Fig. 1 and the dispersion functions in Fig. 2. They are given for the 2007 version of the optics, from the SPS extraction point at the location of the quadrupole QDA419 to the injection point into the LHC at the entrance of Q4.L8.

2 Dispersion measurements with the 2007 nominal optics

Previous injection tests into the LHC allowed to perform extensive optics studies [1], [2], [3]. During the August 2008 transfer line tests with beam, dispersion measurements were performed for the first time beyond the last beam dump of the transfer line (TED87765). These first measurements revealed a larger dispersion at the end of the transfer line than anticipated. A dispersion beating was as well propagating into the LHC (Fig. 3 and Fig. 4). As can be seen while comparing the expected values (continuous line in Fig. 3) and the
Figure 1: Horizontal and vertical beta functions along TI 8, from the SPS extraction point at QDA419 to the injection point into the LHC at the entrance of Q4.L8.

Figure 2: Horizontal and vertical dispersion functions along TI 8, from the SPS extraction point at QDA419 to the injection point into the LHC at the entrance of Q4.L8.
measurement performed (crosses), the dispersion towards the end of the line differs from the model and the largest discrepancy is observed at the end of the TI 8 matching section into the LHC (at MQIF876), where measurements give about 3 m dispersion compared to the 1 m expected.

Checking the settings of the magnet current in the control system and comparing them with the theoretical requested values revealed that the main defocusing quadrupole magnets (MQID) had been trimmed in the control system by -0.65%. This trim had previously been introduced following analysis of kick response matrix measurements which were hinting at an error in the vertical phase advance of the TI 8 arc. The estimated fit suggested to apply -0.65% on the MQID. The source of the effect is still under investigation.

The TI 8 beam tests performed in May 2008 allowed as well to re-evaluate the initial twiss functions at the SPS extraction point into the TI 8 line. The new values were estimated to $dx = -0.253$, $dp_x = 0.003$, instead of $dx = -0.329$, $dp_x = 0.0123$. The other parameters remained unchanged: $\beta_x = 17.062$, $\alpha_x = 0.459$, $\beta_y = 124.822$, $\alpha_y = -3.444$.

Applying these changes (new initial injection values and trim on main MQID) to the model, without rematching the optics, confirmed that the dispersion was very sensitive to the entrance twiss values at the TI 8 start. The comparison between the distorted model (from the both unmatched initial conditions and decreased main MQID strength) with the measurements is shown in Fig. 5 and Fig. 6.

It is noted that the model matches better the dispersion measurements, including the beating in the LHC, but the measured amplitude is still larger than expected. It should be
Figure 4: Vertical dispersion measurements with 2007 optics, no rematching

Figure 5: Horizontal dispersion measurements with 2007 mismatched optics (new initial conditions, MQID strength reduced by -0.65%)
Figure 6: Vertical dispersion measurements with 2007 mismatched optics (new initial conditions, MQID strength reduced by -0.65%)

noted that the model of the LHC, after the injection point, does not contain the overall errors of the LHC magnets, so the comparison between the expectation and the measurement downstream of IP8 is only indicative.

3 Dispersion measurements with the first rematched 2008 optics

In order to be consistent with the new initial parameters and findings on the MQID in the TI 8 arc, a new version of the TI 8 optics was rematched. It includes the reduced MQID strength (by 0.65%) and the initial conditions as estimated during the TI 8 injection tests in May 2008.

With this updated version of the TI 8 optics, the dispersion was re-measured along the beam line and into the LHC. The measurements gave a better agreement with the model but still indicated a larger dispersion amplitude at the end of the TI 8 line (about 1.5 m measured as 0.9 m expected), with a beating propagation into the LHC (Fig. 7 and Fig. 8).

The difference between the measured data and the model is plotted in Fig. 9. This difference is also normalised to the $\sqrt{\beta}$ and plotted in Fig. 10. The measurements indicate that the oscillation seems to originate around Q5.L8. The beating amplitude increases after Q5.

The measurements were analysed using the MAD-X online model [4], and it was checked whether a magnetic error could reproduce the discrepancies with respect to expectations. The model pointed to two possible candidates, MQIF874 and MQIF876, which could be
Figure 7: Horizontal dispersion measurements with first rematched optics (new initial conditions, MQID strength reduced by -0.65%)

Figure 8: Vertical dispersion measurements with first rematched optics
Figure 9: Horizontal dispersion difference between the measurements and the model, with the first rematched optics (new initial conditions, MQID strength reduced by -0.65%)

Figure 10: Horizontal dispersion difference between the measurements and the model normalised to $\sqrt{\beta}$, with the first rematched optics
Figure 11: Horizontal dispersion measurements with first rematched optics and MQIF874 varied by +4% in the model only

potentially exited by too much current, as illustrated in Fig. 11 and Fig. 12.

The trim of −9% on MQIF876 was applied in the control system and the dispersion remeasured. The result is shown in Fig. 13 and Fig. 14.

The dispersion beating in the LHC was nicely reproduced in the vertical plane. In the horizontal plane, the dispersion measurements were slightly out of phase and of still different amplitude. These trials seemed to indicate that the magnets used toward the end of the line to correct for the dispersion values were indeed acting on the dispersion, but were being used as a knob to correct for an error which was originating at another, still unknown, location.

4 Investigation on coupling observations

In the initial response measurements, the coupling was determined by checking the out-of-plane response to a dipole kick from an orbit corrector at the beginning of the transfer line. It was immediately apparent that the amplitude of the coupling measured with this technique was larger than the 6% which had been expected from the 52 mrad rotation of the reference frames between the TI 8 line and the LHC machine [5]. In addition, the amplitude of the coupling was observed to vary with the location of the exciting kick. The observations did not agree with the initial response matrix model, which generated its own transfer matrix elements from the MAD-X output Twiss file data.

The possible source of such a coupling was investigated [6]: unsurprisingly tilted quadrupoles at the end of the transfer line were postulated as candidates, since the focusing magnets in the line are aligned with tilts of up to 66 mrad in the XY plane, to follow the rotation of
Figure 12: Horizontal dispersion measurements with first rematched optics and MQIF876 varied by +9% in the model only

Figure 13: Horizontal dispersion measurements with first rematched optics and MQIF876 varied by −9% in the control system
the beam reference plane introduced by the inclined dipole magnets. All the quadrupole alignments were found to be of the correct sign and magnitude. Many investigations and checks were also made to verify the treatment of the tilted and rotated magnets in MAD-X, with no evident errors uncovered.

5 Investigation on possible magnetic errors linked to magnetic properties or misalignment

A campaign of magnet checks was performed to verify all magnet currents and fields. Calibration curves were checked, magnetic field of matching quadrupole of the end of the line were measured in the tunnel. No significant errors were found, in particular all quad tilts were of the correct magnitude and sign [7].

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 tilted dipoles by 19 degrees. It was found that since the last alignment campaign done in 2007, the elements at the end of the line have moved radially, and some of them by up to $1 - 2\text{ mm}$ [8], which is not too surprising for a new tunnel.

These investigations and measurements allowed to establish a MAD-X list of errors for all the magnets of the line. Adding these errors to the line model, together with the corrector strengths used along the beam line to establish the trajectory indicated:

- the field and alignment errors were indeed acting on the dispersion, but not to the
amplitude observed;

- the trajectory correctors were, by themselves, reproducing the large dispersion amplitude and oscillation propagation through the LHC, see Fig. 15.

While the dispersion pattern was reproduced by the addition of the beam line corrector strength into the model, the resulting simulated trajectory was checked and was not in agreement with what was measured in the beam line. Constructing a model using all the beam line errors (field and alignment) has always been a very delicate task and it was very quickly realised that measuring a bare trajectory for both planes would ease the process considerably.

6 Trajectory analysis

In order to perform the trajectory measurements with a nominal optics designed with 90 degrees phase advance per cell, a second version of the 2008 optics was rematched, providing these phase advances and also matched to the initial conditions as found in 2008. Beam time was allocated on 17 September 2008 to record the TI 8 bare trajectory. In this process, the following steps and observations were made:

- Removing all the TI 8 horizontal correctors (leaving the trim on all the SPS-type bending magnets in) allowed the beam to still reach the TED at the bottom of the TI 8 line.
• Removing all the vertical correctors led to lose the beam, at MQIF803. This confirmed that the known vertical step of 2 mm in between the SPS and TI 8 reference coordinate system has to be corrected using vertical correctors, in the first 200 meters of the TT40 line.

• The trims on the SPS-type bending magnets ($-10\mu$rad on MBHA400309 and $-15\mu$rad on MBIBV877) were removed. It should be noted that the horizontal trims on the $-10\mu$rad on each MSI and $-24.4\mu$rad on the MBHC400107 were left in as they have been optimised in the careful calculation of the injection parameters.

• Applying $-10\mu$rad on MDMV400299 and $-20\mu$rad on MDSV400293 allowed to restore the beam all the way down to the last TI 8 TED.

• Optimum values for these correctors in terms of trajectory correction was $-20\mu$rad on MDMV400299 and $-50\mu$rad on MDSV400293.

• The bare horizontal trajectory showed excursions within the specification ($\pm 4$ mm) but at MQIF874 and MQIF876 the trajectory excursion was $-8$ mm and $+10$ mm, respectively.

• YASP correction, using MICADO, on the bare horizontal trajectory gave:
  - 1 corrector used: MCIAH872 = 86$\mu$rad
  - 2 correctors used: MCIAH872 = 97$\mu$rad and MCIAH818 = 29$\mu$rad
  - 3 correctors used: MCIAH872 = 80$\mu$rad, MCIAH818 = 80$\mu$rad and MCIAH816 = 17$\mu$rad

• YASP correction, using MICADO, on the vertical trajectory gave:
  - 1 corrector used: MCIAH853 = 43$\mu$rad
  - 2 correctors used: MCIAH853 = 51$\mu$rad and MDMV400097 = $-14\mu$rad
  - 3 correctors used: MCIAH853 = 26$\mu$rad, MDMV400097 = $-15\mu$rad and MCIAH845 = 25$\mu$rad

The bare horizontal trajectory is shown in Fig. 16 and in comparison the nominal TI 8 trajectory used during regular operation in Fig. 17. The bare trajectory shows amplitudes within the specification ($\pm 4$ mm) along the beam line, at the exception of the end where $\approx -8$ mm and $\approx 10$ mm were measured at MQIF874 and MQIF876, respectively.

The origin of the large trajectory excursion was investigated. A radial displacement of the MQIF872 by $dx= 2$ mm was applied in the model and the bare trajectory computed in the model (Fig. 18). The trajectory excursion at the end of the line reproduces the measurements.

As mentioned above, a survey of the end of the TI 8 line (as of MQIF868) was performed in August 2008. The resulting survey at MQIF872 showed that indeed the entrance of the magnet is displaced by 2 mm and the exit by 1.4 mm. Adding this error in the beam line model and applying the trajectory correction module of MAD-X showed that $63 \times 10^{-6}$ rad
Figure 16: Horizontal bare trajectory

Figure 17: Horizontal trajectory during regular beam line operation
Figure 18: Effect of a horizontal displacement of 2 mm of MQIF872 on the trajectory

on MCIAH872 corrects the large trajectory excursion, as predicted by YASP on the measured bare trajectory.
If the horizontal bare trajectory is corrected by applying this corrector strength, the resulting simulated trajectory is shown in Fig. 19, together with the measured trajectory after a similar correction. The agreement is excellent.
The corrected bare trajectory using 14 correctors (as used in the nominal operational trajectory) was compared to the bare trajectory, Fig. 20. Very good trajectory correction is achieved, well within the specifications.
The strength of the 14 correctors used with MICADO are plotted versus the strength of the operational trajectory in Fig. 21. 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 resulting trajectory is plotted along the beam line, it is interesting to compare the simulated trajectory with the measured bare trajectory (Fig. 22). The two trajectories show good agreement.
When the trajectory is corrected towards the end of the line using MCIAH872, the resulting simulated trajectory and measured one are shown in Fig. 23 and shows a rather good agreement.

7 Dispersion studies

Using the second 2008 rematched optics, dispersion measurements were performed in TI 8 all the way to the downstream beam dump. The simulated dispersion of the TI 8 line is plotted along the beam line to the left of IP7 in the LHC in Fig. 24, together with the measured
Figure 19: Using MCIAH872 in the model and in the beam line to correct for MQIF872 displacement

Figure 20: Bare trajectory without and with correctors (MICADO, 14 correctors)
Figure 21: Corrector strength used to correct the bare trajectory with 14 correctors, and used for the nominal operating trajectory.

Figure 22: Bare trajectory from the model with all errors in and as measured in the TI 8 line.
dispersion along TI8. Previous dispersion measurement results are also indicated as they contain the LHC dispersion measurements which were this time not possible to take. In the case of the simulated bare trajectory, corrected with 14 horizontal correctors, one can see that the effect on the dispersion is large and leads to a dispersion beating in the LHC Fig. 25.

If, in the model, the correction of the trajectory is done using only 1 corrector, the dispersion effect is reduced, as shown in Fig. 26.

The additional dispersion coming from the powering of the trajectory correctors seems to be the source of the larger dispersion measured towards the end of the TI 8 line. A "dispersion-free" steering algorithm (DFS) was implemented in YASP. 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. This agrees with the fact that to generate a dispersion wave of the amplitude shown in Fig. 11 and Fig. 12, a local kick of 7 to 10 mrad is required. This is two orders of magnitude larger than the typical corrector kicks.

8 Dispersion studies in TI 2

Dispersion data measured in the TI 2 line are shown in Fig. 27 -horizontal plane- and in Fig. 28 -vertical plane- and are compared with the model.

The difference between the measured and simulated dispersion values, normalised to $\sqrt{\beta}$, are plotted in Fig. 29 -horizontal plane- and Fig. 30 -vertical plane. It is seen that
Figure 24: Nominal horizontal dispersion and measured dispersion values

Figure 25: Simulated horizontal dispersion after trajectory correction using 14 correctors and measured dispersion values
Figure 26: Simulated horizontal dispersion after trajectory correction using 1 corrector and measured dispersion values

Figure 27: Horizontal dispersion measurements from the start of TI 2 to the left of IP3 in the LHC
the dispersion measurements agree very well with the model along TI 2. In the LHC, the amplitude of the dispersion beating is slightly larger than expected -however, the agreement is much better than for the measured LHC dispersion beating of the TI 8 injected beam. A fit to the data indicates that almost all the dispersion error in the LHC can be explained by errors on the TI 2 initial conditions. The same investigation on the effect of injection errors in the TI 8 did not lead to a possible explanation of the source of the large dispersion beating in the LHC.

9 Summary

The model of the line has been refined with the addition of all the known field errors 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 settings also agree well. The beginning of the line, still in TT40, has some unexplained features 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 in the 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 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
Figure 29: Difference between the horizontal dispersion measurements and model, in TI 2 to the LHC left of IP3

Figure 30: Difference between the vertical dispersion measurements and model, normalised to $\sqrt{\beta}$, in TI 2 to the LHC left of IP3
only explain 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 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. An extensive set of machine development time has been requested in order to perform detailed measurements. 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 line makes all the analysis more difficult, especially when trying to untangle dispersive and trajectory effects. Therefore, 4 additional BPMs will be 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 will be upgraded to allow dual plane measurements in TI8. This will be done for TI 8 during the 2008/2009 shutdown. The same improvements will be performed in TI 2 during the 2009-2010 shutdown. Finally regular alignment checks / re-alignment campaigns will be planned.

References


[7] V. Mertens and AT/MCS, investigation of possible sources of errors