Transfer lines and Injection: results from machine studies during beam commissioning

M. Meddahi, CERN, Geneva, Switzerland

Abstract

Beam commissioning of the SPS to LHC transfer lines performed during the summer 2008 is reported. The emphasis is put on the optical checks measured for the first time in the last part of the lines and into the LHC. In particular, extensive trajectory studies, dispersion measurements and coupling analysis are discussed. These studies were conducted in parallel with hardware checks and the outcome is summarised.

SENDING THE FIRST BATCH ALONG TI 8 INTO THE LHC

Previous injection tests into the LHC allowed to perform extensive optics studies [1], [2], [3] and to conclude that the beam lines were performing 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 [4].

In TI 8, the first batch sent along the beam line into the LHC indicated that the beam was horizontally mis-positioned at the entrance of the first septum magnet by about $2 - 3$ mm. The series of horizontal dipole magnets MBIAH878 were suspected and investigation quickly revealed a false calibration setting of these magnets in the control system (893 A requested in theory versus the delivered 891.5 A, leading to a difference of 5 μrad for each of the 7 magnets in series).

In the vertical plane, the first batch pointed to a reversed polarity of the 3 vertical dipole correctors MCIAV881. This error was traced back to a different sign convention between corrector magnets and dipole magnets, leading to this polarity confusion.

Having corrected these two errors, the first batch was injected into the LHC towards IP 8 and allowed to perform optics measurements, as discussed in this note. It should be added that TI 2 measurements were also performed and showed good agreement with expectation.

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 [5]. The first measurements with beam of the injection into the LHC revealed that the coupling is much larger than was 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 [6]. 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, although 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. An overall correction of the tilt mismatch at the injection point would be possible by skewing several quadrupoles in the transfer line, but is presently not considered worthwhile in view of the extra complexity introduced for the collimation section, the alignment, the layout and for the instrumentation.

DISPERSION STUDIES

Dispersion measurements have been taken in the TI 8 beam line and compared with expectation. In Fig. 1, 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 two sets of measured dispersion values.

As can be seen while comparing the expected values (continuous line in Fig. 1) and the 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), with a dispersion beating propagating into the LHC.

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 quadrupoles of the end of the line were 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 [8].

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, the elements at the end of the line have moved radially, and some of them by up to $1 - 2$ mm [9], which is not too surprising for a new tunnel.

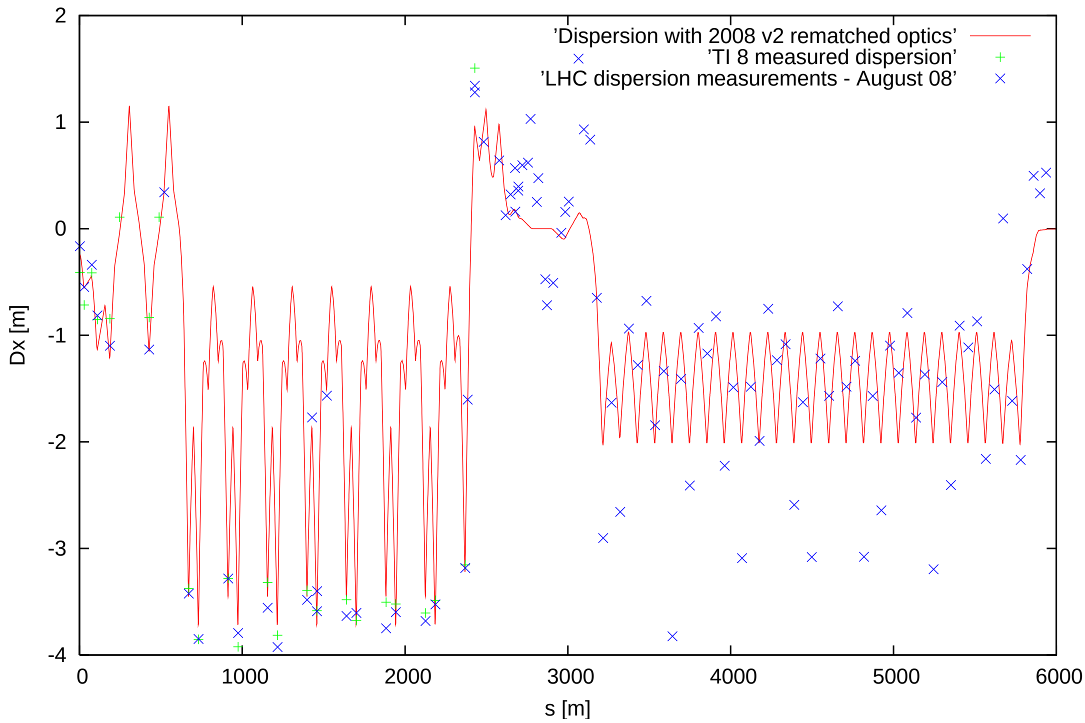

Figure 1: Nominal horizontal dispersion and measured dispersion values

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

TRAJECTORY ANALYSIS

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 only the trims 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 (-10μrad on MBHA400309 and -15μrad on MBIBV877) were removed. It should be noted that the horizontal trims of -10μrad on each MSE and -24.4μrad on the MBHC400107 were left in as they have been optimised in the careful calculation of the injection parameters.
- Applying -10μrad on MDMV400299 and -20μrad 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 -20μrad on MDMV400299 and -50μrad on MDSV400293.
- The bare horizontal trajectory showed excursions within the specification (± 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: MCIAH$853 = 26\mu$rad, MDMV$400097 = -15\mu$rad and MCIAH$845 = 25\mu$rad

The bare horizontal trajectory is shown in Fig. 2. The bare trajectory shows amplitudes within the specification (± 4 mm) along the beam line, at the exception of the MQIF874 and MQIF876 locations, as mentioned above.

The origin of the large trajectory excursion was investigated. A radial displacement of the MQIF872 by dx= 2mm was applied in the model and the bare trajectory computed in the model reproduced the measurements. TI 8 survey measurements indeed confirmed that the entrance of MQIF872 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 63×10^{-6} rad 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. 3, 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. 4. 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 correctors in Fig. 5. 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. 6). 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. 7 and shows a rather good agreement. These results allowed us to build confidence in the beam line model with errors and to therefore exploit this model for further dispersion analysis.

DISPERSION EFFECTS FROM ERRORS AND TRAJECTORY CORRECTOR STRENGTH

Adding all the magnetic errors to the line model, together with the 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. 8. However the dispersion after the injection point still diverges from the revised model, although now to a lesser extent.

A ”dispersion-free” steering algorithm (DFS) was implemented in YASP [10]. 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 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 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 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. Extensive 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 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.

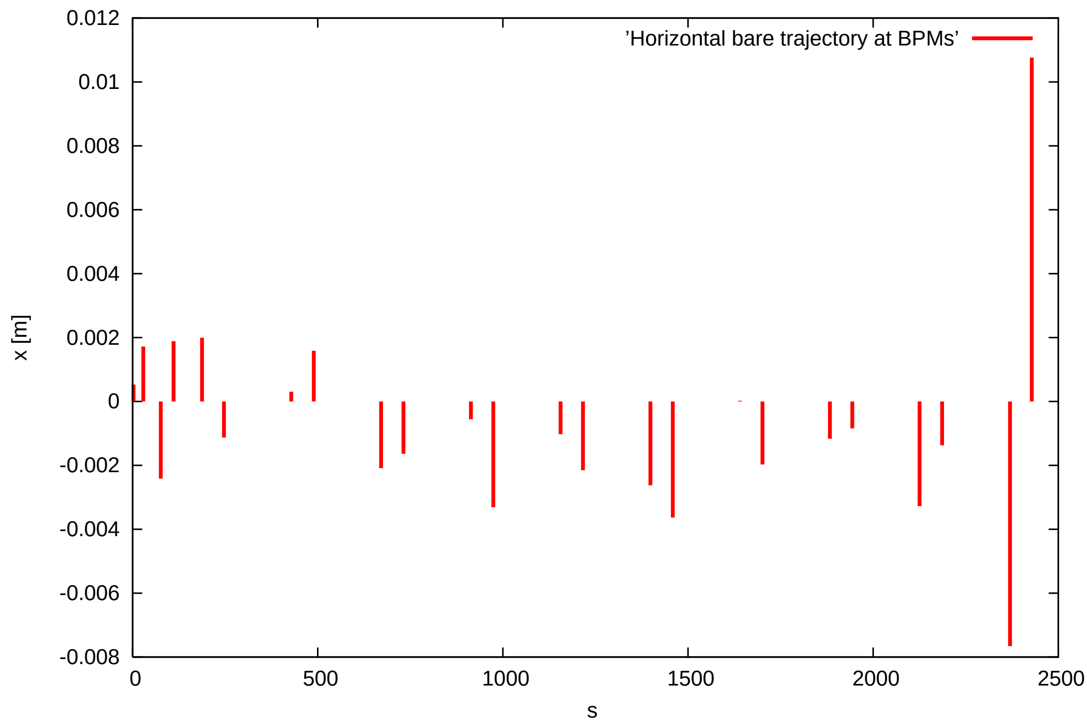

Figure 2: Horizontal bare trajectory

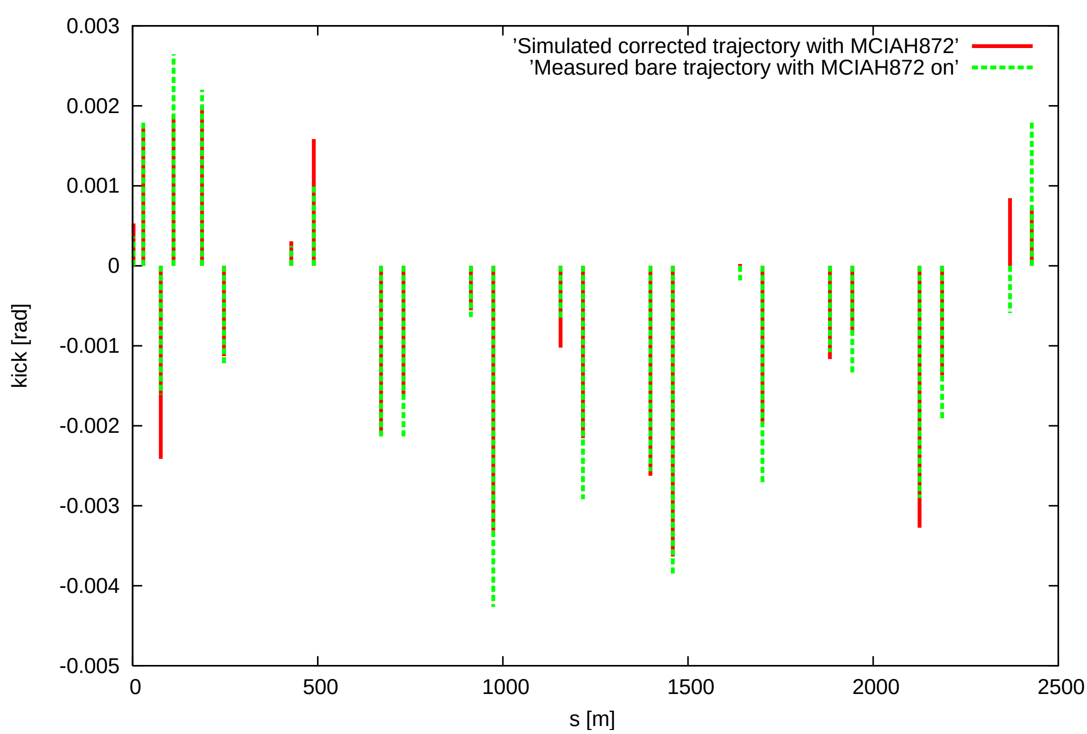

Figure 3: Using MCIAH872 in the model and in the beam line to correct for MQIF872 displacement

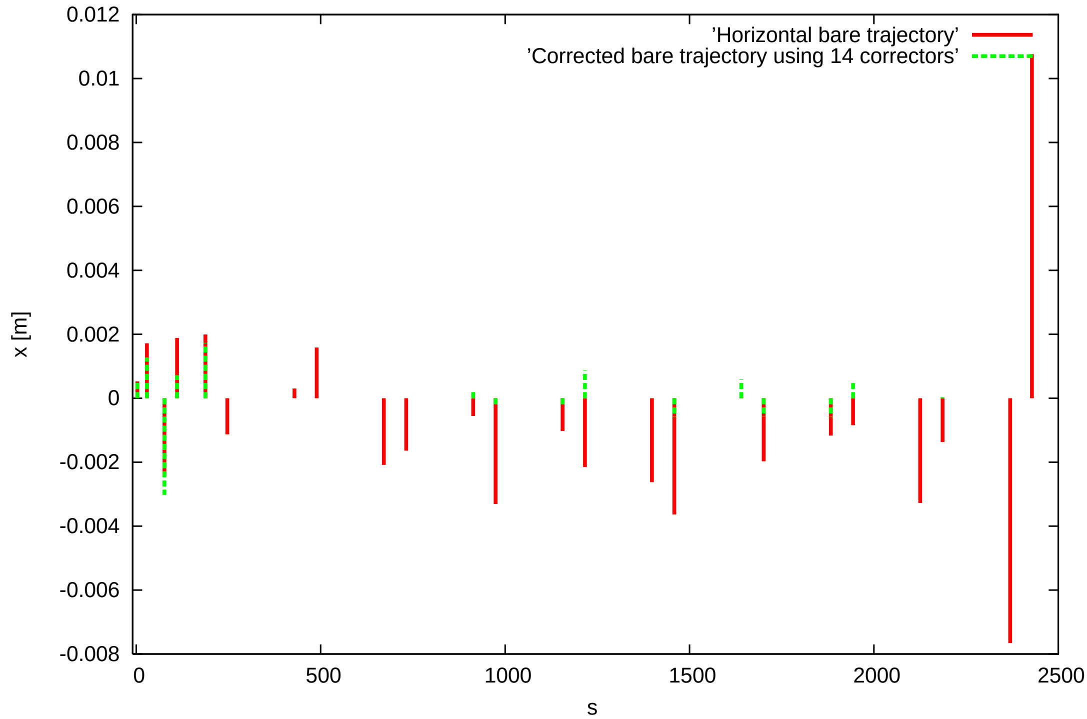

Figure 4: Bare trajectory without and with correctors (MICADO, 14 correctors)

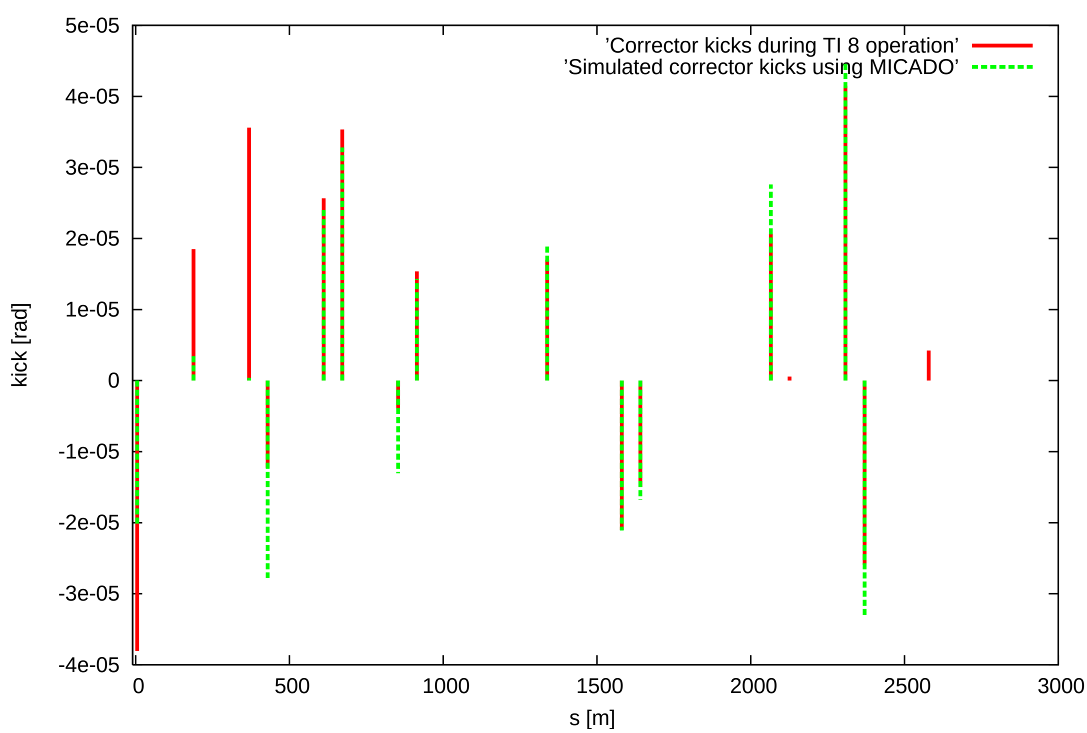

Figure 5: Corrector strength used to correct the bare trajectory with 14 correctors, and used for the nominal operating trajectory

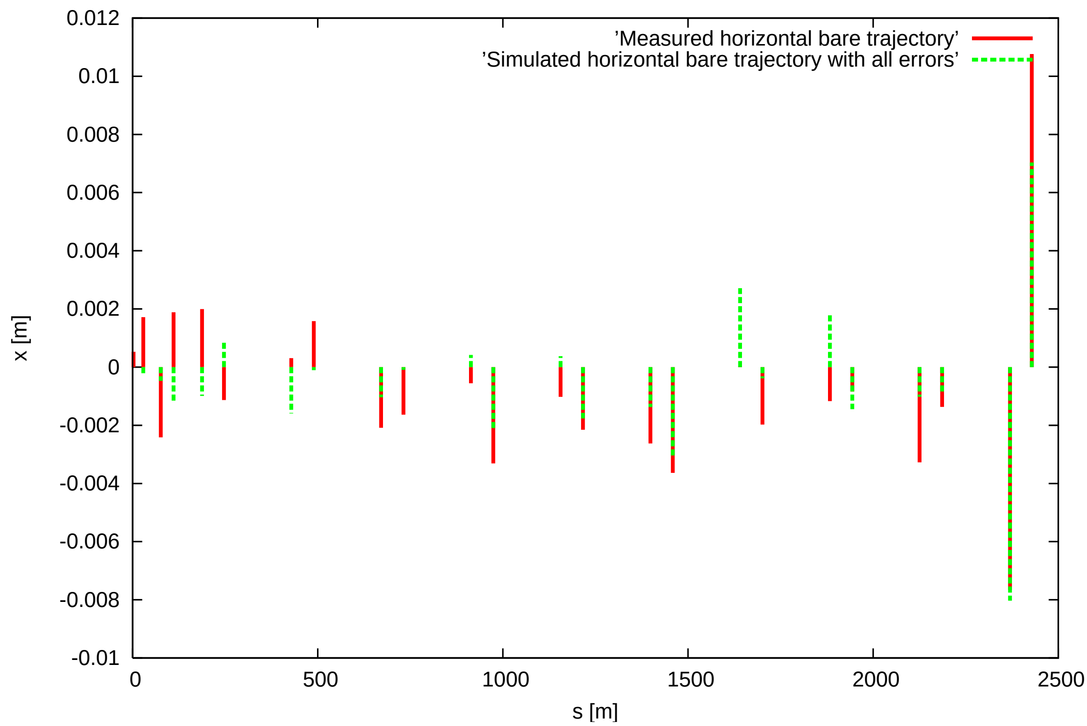

Figure 6: Bare trajectory from the model with all errors in and as measured in the TI 8 line

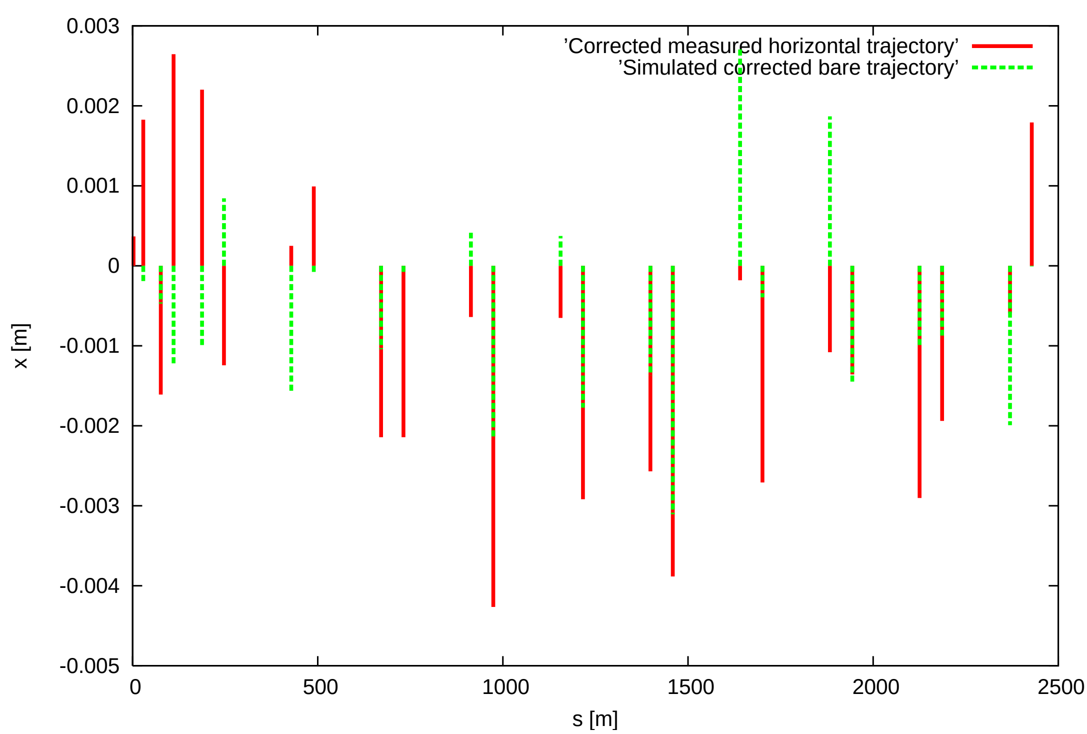

Figure 7: Corrected bare trajectory from the model with all errors in and as measured in the TI 8 line

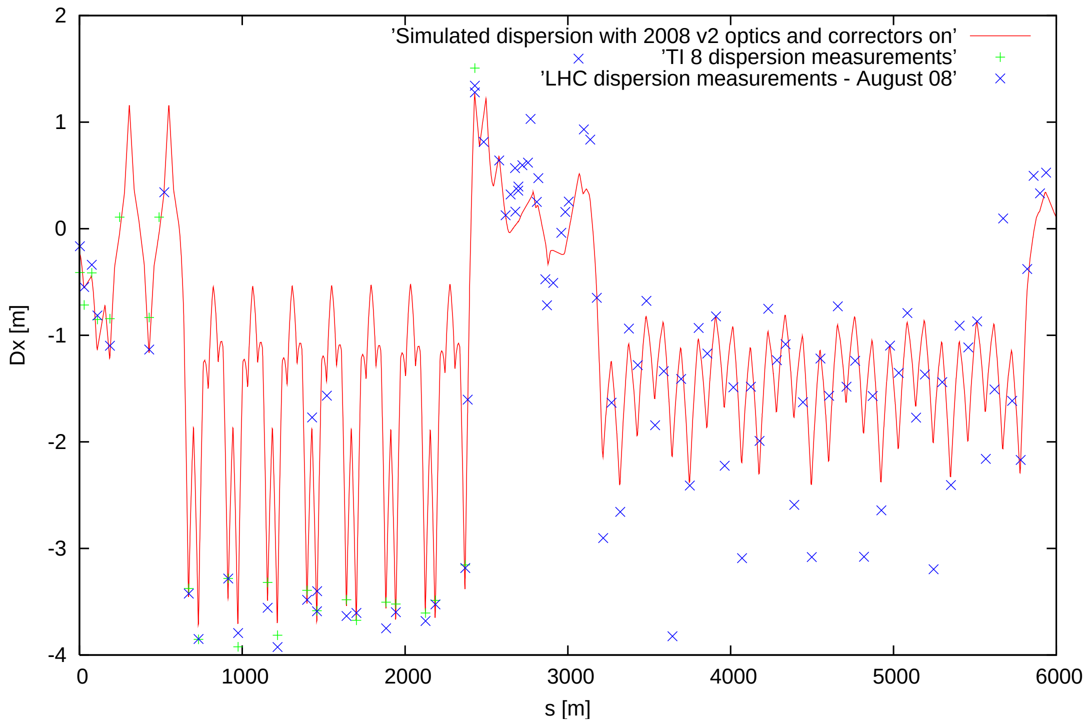

Figure 8: Simulated horizontal dispersion after trajectory correction using 14 correctors and measured dispersion values

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REFERENCES

[1] G. Arduini, Y.C. Chao, B. Goddard, D. Jacquet, V. Kain, M. Lamont, V. Mertens, J. Uythoven, J. Wenninger; Optics Studies of the LHC Beam Transfer Line TI 8; LHC-Project-Report-827; CERN, 2005

[2] J. Uythoven, G. Arduini, Y.C. Chao, B. Goddard, D. Jacquet, V. Kain, M. Lamont, V. Mertens, A. Spinks, J. Wenninger; Commissioning of the LHC Beam Transfer Line TI 8; LHC-Project-Report-816; CERN, 2005

[3] B. Goddard, V. Mertens, T. Risselada; Status and Plans for the SPS to LHC Beam Transfer Lines TI 2 and TI 8; LHC-Project-Report-751; CERN, 2004

[4] I. Agapov, K. Fuchsberger, W. Herr, V. Kain, B. Goddard, E. Gianfelice, M. Meddahi, D. Missiaen, V. Mertens, T. Risselada, J. Uythoven, J. Wenninger; TI 8 transfer line optics studies; LHC Performance Note 004

[5] B.Goddard, M.Gyr, V.Kain, T.Risselada, Geometrical alignment and associated beam optics issues of transfer lines with horizontal and vertical deflection, LHC-Project-Report-719, 2004.

[6] K.Fuchsberger, B.Goddard. V.Kain, M.Meddahi, T.Risselada, J.Wenninger, Coupling at injection into the LHC from reference frame rotation, LHC Performance Note 003

[7] I. Agapov; The LHC Online Model: Design and Implementation; CERN-AB-Note-2008-053

[8] V. Mertens and AT/MCS, private communication on the investigations of possible sources of errors

[9] http://proj-lti.web.cern.ch/proj-lti/LTIcoordination/Archive/2008/250908/250908.htm

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