

# STUDIES ON PRE-COMPUTATION OF SPS-to-LHC TRANSFER LINE CORRECTIONS

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## Abstract

The injection process in the LHC gives a non-negligible contribution to the turnaround time between two consecutive physics fills. Mainly due to orbit drifts in the SPS, the steering of the SPS-to-LHC transfer lines has to be regularly performed in view of minimising injection oscillations and losses, which otherwise would trigger beam dumps. Moreover, for machine protection purposes, a maximum of twelve bunches has to be injected after any TL steering to validate the actual applied corrections. This implied at several occasions the need to interrupt a fill to steer the lines and introduced a further delay between fills. Studies are performed to evaluate the option of pre-calculating the required TL corrections based on SPS orbit measurements during the LHC magnet ramp down and the reconstruction of the beam position and angle at the SPS extraction point.

## INTRODUCTION

The transfer of 450 GeV proton beams from the Super Proton Synchrotron (SPS) to the Large Hadron Collider (LHC) occurs through two  $\sim 3$  km long transfer lines (TI2 for Beam 1 and TI8 for Beam 2, Fig. 1). Two conventional fast extraction systems [1] are installed in Long Straight Sections 6 (LSS6) and 4 (LSS4) of the SPS [2] to convey the beams respectively to TI2 and TI8. The circulating beam is extracted towards the lines by means of horizontal closed orbit bumpers, fast pulsed kickers (MKE) and DC magnetic septa (MSE and MST). Similarly, the injection in the LHC [3] is obtained by deflecting the beams from the transfer lines onto the closed orbit, with fast kickers (MKI) and septa (MSI), which are installed in straight section 2 (IR2) for Beam 1 and 8 (IR8) for Beam 2.

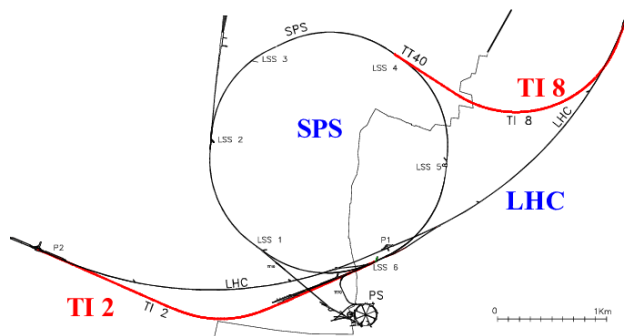


Figure 1: Layout of the transfer lines connecting the SPS extraction to the LHC injection points.

The LHC filling process consists in transferring up to 288 bunches of at least  $1.2 \cdot 10^{11}$  protons each, corresponding to

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a stored energy of 2.5 MJ and, after the injectors upgrade [4], up to 4.8 MJ per injection can be achieved. A system of six collimators (TCDI) [5], placed at a relative phase advance of  $60^\circ$ , is installed towards the end of each transfer line to protect the LHC aperture from particles injected with dangerously large amplitudes ( $>5 \sigma$ ). These collimators consist of two carbon-based jaws which are centered with respect to a reference trajectory that allows to minimize the injection oscillations into the LHC and is defined during the commissioning period.

## TRANSFER LINE STEERING

A good control of the parameters at the LHC injection points, in terms of optics, position and angle, is crucial for luminosity performance and machine protection reasons. A periodic steering of the transfer lines, onto the pre-defined references, has to be carried out to keep the injection oscillations below 1 mm (peak-to-peak) and minimise the losses at the TCDIs. Small losses at these collimators create showers which can trigger the sensitive beam loss monitors (BLM) installed at the nearby LHC magnets and cause beam aborts during the fill [6]. Despite several mitigation measures (shielding, electronic filters and temporary BLM inhibition) were put in place to avoid these unnecessary dumps, a regular correction of the lines has to be performed to compensate for unavoidable trajectory drifts and keep them below  $0.5 \sigma$  at the TCDIs ( $350 \mu\text{m}$  in average). An r.m.s. trajectory of  $350 \mu\text{m}$  is considered as the target for the studies presented in the following. Each trajectory steering has to be validated by injecting maximum 12 bunches of  $1.2 \cdot 10^{11}$  protons, which is considered as a safe beam, to verify that the correction algorithm worked properly and the correctors pulse at the right current. This procedure might require more iterations and thus several low intensity injections while the nominal LHC filling schemes foresee only one 12-bunch train. A dedicated steering time has to be accounted for and this can delay the turnaround [7] between two consecutive physics fills and thus impact the integrated luminosity. The drift of the SPS orbit is considered as the main source of the observed trajectory deviations [8]. The possibility of pre-computing the needed transfer line corrections, based on the orbit measured in the SPS during the ramp-down of the LHC magnets, is analysed in this paper. This would allow to use the only 12-bunch train to validate the applied corrections and continue filling the machine with a non negligible gain in physics time.

## THE MODEL

The studies presented in the following are purely theoretical and focus on the steering in the horizontal plane for

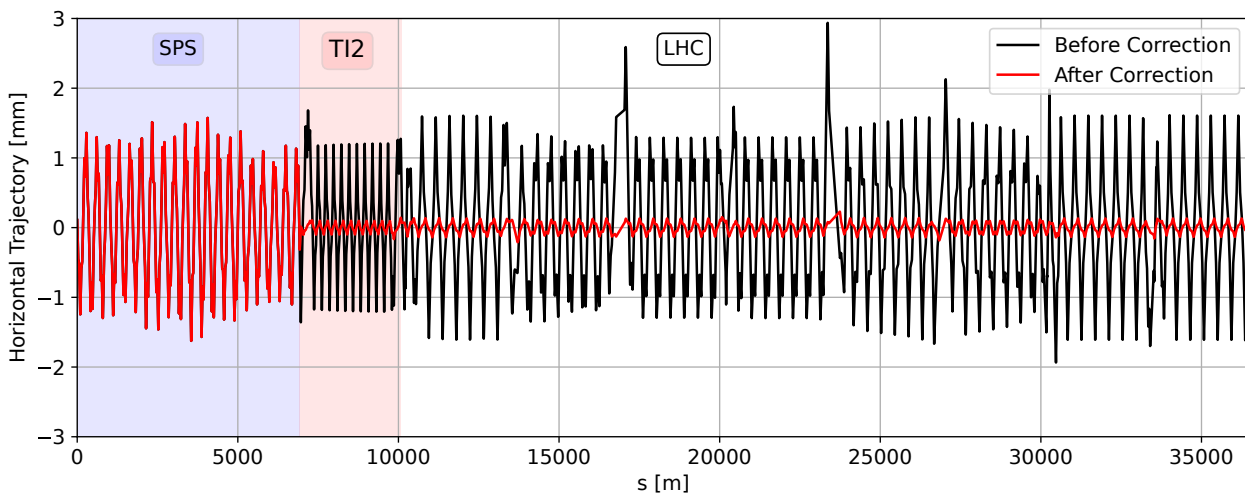


Figure 2: Example of orbit drift in the SPS and consequent effect on the beam trajectory in TI2 and the first-turn orbit in the LHC (Beam 1, horizontal plane). Three correctors at the beginning of TI2 are used to flatten the trajectory in the line and minimise the injection oscillations in the LHC.

Beam 1; equivalent considerations hold for both planes and beams.

A stitched model of the SPS ring, the TI2 line and the full LHC was built with MAD-X [9]. A drift of the SPS orbit, corresponding to a  $\sim 1.5$  mm peak-to-peak variation of the trajectory in the line and the first-turn orbit in the LHC, was obtained by slightly mis-aligning all the SPS quadrupoles (black line in Fig. 2). Three TI2 horizontal correctors (MCIAH =  $2.653 \mu\text{rad}$ , MCIAH =  $-11.939 \mu\text{rad}$  and MCIAH =  $0.004 \mu\text{rad}$ ) allow to flatten the r.m.s. trajectory, both in the line and the LHC, from  $\sim 800 \mu\text{m}$  to  $\sim 70 \mu\text{m}$  (red line in Fig. 2), which is well below the previously mentioned targets. In principle, the knowledge of the pointing vector (i.e. position  $x$  and angle  $x'$ ) at the SPS extraction should be sufficient to determine the expected variation of the downstream horizontal trajectory with respect to the reference and thus the required corrections. For these studies, 200 different SPS orbits were built, by randomly misaligning quadrupoles, corresponding to an average r.m.s. of  $770 \pm 360 \mu\text{m}$ . The feasibility of pre-computing the transfer line steering is assessed.

### SPS Orbit Reconstruction

No direct measurement of the beam position and angle at SPS extraction exists and, moreover, the Beam Position Monitors (BPM) in the extraction region (BPCE) have a very poor accuracy due to the large aperture required to fit the closed orbit bumps. The signal from all the ring position monitors is used to reconstruct the orbit and calculate the pointing vector at extraction (one example is shown in Fig. 3, blue stars). A random r.m.s. error of  $120 \mu\text{m}$  is applied to all BPMs to account for their accuracy and possible shot-to-shot orbit variations. The beam position and angle at each

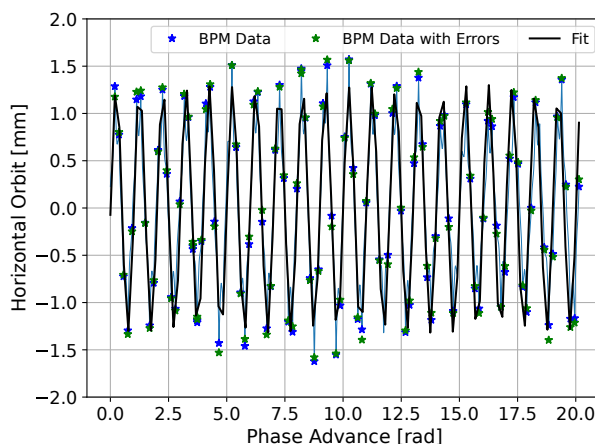


Figure 3: Example of orbit reconstruction starting from the readings of all ring BPMs (blue stars) when applying a random r.m.s error of  $120 \mu\text{m}$  (green stars).

location is calculated using the fitting functions [10]:

$$x = a\sqrt{\beta_x}\cos(\mu_x + \phi_0) + D_x \frac{\Delta p}{p} \quad (1)$$

$$x' = \frac{a}{\sqrt{\beta_x}}[\alpha_x \cos(\mu_x + \phi_0) + \sin(\mu_x + \phi_0)] + D'_x \frac{\Delta p}{p} \quad (2)$$

where  $\beta_x$  and  $\alpha_x$  are the Courant–Snyder parameters,  $\mu_x$  the betatron phase advance,  $D_x$  and  $D'_x$  the dispersion and its derivative while  $a$ ,  $\phi_0$  and  $\Delta p/p$  are the fit free parameters ( $\phi_0$  and  $\Delta p/p$  represent the initial betatron phase and momentum spread, respectively). The computation of  $x$  and  $x'$  at the SPS extraction point is performed by using the nominal optics parameters corresponding to the reference closed orbit. The distribution of the deviations between the actual pointing vectors, as given by the MADX model, and

those obtained with the fitting functions, for all the simulated orbits, is presented in Fig. 4. The standard deviation of the errors on the position and angle are  $210 \mu\text{m}$  and  $7.7 \mu\text{rad}$ , respectively.

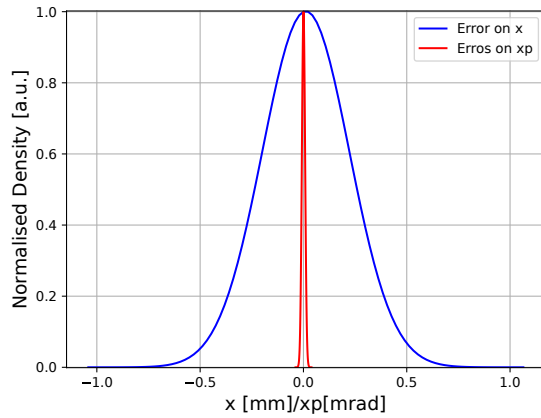


Figure 4: The distribution of the errors on the computed positions (blue curve) and angles (red curve) with respect to the actual values given by MADX is shown.

## COMPUTED CORRECTIONS

The  $x$  and  $x'$  values calculated with the fit can be used to assess the corrections needed to steer the line. Typically, with the MICADO automatic algorithm of MADX, the optimum correction is achieved by using 3-5 correctors and up to  $10\text{-}15 \mu\text{rad}$ . The error on the calculated angles is equivalent to the proposed correction and this could translate in a noticeable amplification instead of the damping of the original oscillation. For this reason, the computation of the steering was performed using 13 out of the 25 available

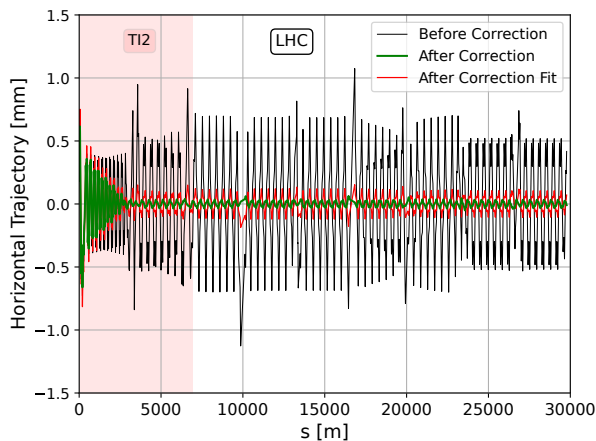


Figure 5: Transfer line trajectory and LHC injection oscillations induced by an orbit drift in the SPS (black line). The results of the steering performed based on the actual  $x$  and  $x'$  values at extraction (green line) and those obtained with the fitting curves are also plotted.

correctors and limiting the maximum kick to  $\pm 5 \mu\text{rad}$  to eliminate single sources of large amplitude oscillations.

Figure 5 shows an example of a successful pre-computed steering where the peak-to-peak oscillation, induced by an SPS orbit drift (black line), is reduced from  $\pm 700 \mu\text{m}$  to below  $\pm 120 \mu\text{m}$  (red line). The correction calculated using the actual pointing vector would further reduce the final amplitude by a factor of four (green line).

The proposed method strongly depends on the quality of the fit and the relative uncertainty on  $x$  and  $x'$  at the extraction point; not all the calculated corrections were as effective as the previous one. In total, 76.5% of the applied steering reduced the amplitude of the original oscillation but only 52.2% allowed to stay below the target r.m.s. trajectory of  $350 \mu\text{m}$  (Fig. 6). Wrong corrections increased the oscillation in average by a factor of 2.3 and up to a factor of 4.4.

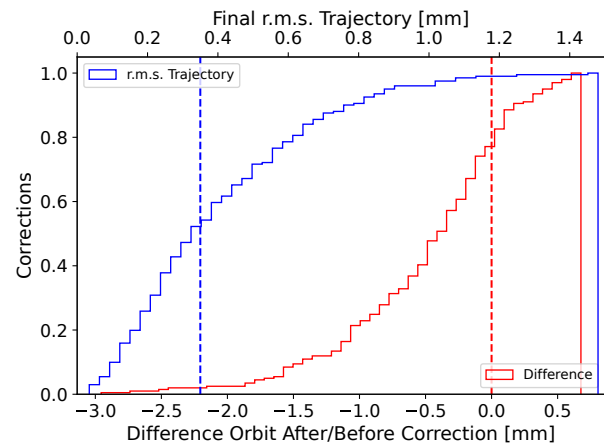


Figure 6: The effectiveness of the computed steering for the 200 scenarios analysed is presented. A smaller orbit, after correction (negative values of red line), implies that the amplitude of the original oscillation was indeed damped. In about half of the cases the correction brought the final r.m.s trajectory below the target of  $350 \mu\text{m}$  (blue lines).

## CONCLUSIONS

The possibility of performing the steering of the LHC transfer lines, based on the calculation of the position and angle at the SPS extraction point by fitting all the ring BPMs, has been studied. The effectiveness of the correction is highly dependent on the quality of the fit and, in  $\sim 25\%$  of the analysed cases, larger amplitude oscillations were excited instead of being damped. About half of the steerings brought the r.m.s. trajectories below the  $350 \mu\text{m}$  target. The benchmark with real measurements and corrections will be performed. As a general remark, it looks evident that this method is not sufficient to prevent dedicated time for steering. Moreover, the drift of the elements in the transfer lines is not taken into account. Parallel studies are ongoing to develop a machine-learning-based optimiser which will allow an on-line check and correction of the lines during each fill.

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