PHASE-DEPENDANT COUPLING AT INJECTION FROM TILT MISMATCH BETWEEN THE LHC AND ITS TRANSFER LINES

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Abstract

The tilt mismatch between the LHC and its transfer lines arises from the use of combined horizontal and vertical bends. The mismatch gives rise to several subtle optical effects, including a coupling at injection into the LHC which depends on the phase of the oscillation amplitude at the injection point. This coupling was observed for the first time in 2008, and in 2010 dedicated measurements were made. The results are described and compared with the expectations, and the operational implications detailed.

INTRODUCTION

The LHC rings are filled by the SPS via two transfer lines, TI 2 and TI 8, both about 3 km long. The transfer lines contain inclined dipoles which introduce a tilt angle (Ψ) into the beam [1]. At the injection point this tilt is not matched to the local tilt of the LHC, which results in cross-plane coupling. For TI 8 the tilt mismatch is 52 mrad and for TI 2 20 mrad. In 2008 initial measurements showed stronger than expected coupling at injection from TI 8, which was dependent on the phase of the measurement excitation. The source of these features is the tilt mismatch between the transfer lines and the LHC, and was believed to be understood after investigations and analyses of the few measurement points for TI 8 [2]. In 2009 measurements were made for TI 2 and TI 8, and after a brief reminder of the underlying physics, the results are presented with conclusions.

SOURCE OF COUPLING

In response measurements along TI 2 and TI 8 the coupling was determined by checking the out-of-plane response to a dipole kick from orbit correctors at the beginning of the transfer line, using the BPM systems. The main features of the measurement were:

- No coupling observed along the transfer lines proper, which demonstrates that the choice of alignment with the beam plane of the quadrupoles, pickups and correctors was correct;
- Coupling in LHC with an onset around the injection as expected from the reference frame rotation;
- Stronger than expected out-of-plane coupling amplitude in the LHC, reaching ~23% for TI 8;
- An unexpected dependence of the coupling amplitude on the location (phase) of the measurement corrector.

The relatively large phase-dependent coupling was unexpected, as the online models which were used for the measurement did not predict it, and the naïve assumptions about the coupling from the tilt mismatch were over-simplified. The change of frame of reference due to rotation angle between the transfer line and the LHC reference plane was confirmed as the source. A full MADX treatment agreed with the analytical one, below.

Theoretical Considerations

A full description of the effect can be found in [2]. The angle between the reference planes of the transfer lines and the LHC can be described as a so-called s-rotation at (or close to) the injection point in accelerator modelling codes. An s-rotation is a simple rotation of XY and X'Y' by the tilt angle δ. At the entrance to the LHC the phase space coordinates are rotated and transform to:

$$\begin{pmatrix} x \\ x' \\ y \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & 0 & \sin\delta & 0 \\ 0 & \cos\delta & 0 & \sin\delta \\ -\sin\delta & 0 & \cos\delta & 0 \\ 0 & -\sin\delta & 0 & \cos\delta \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \\ y_0 \\ y'_0 \end{pmatrix} \quad (1)$$

Oscillations in e.g. the horizontal plane with any phase can be easily generated by the superposition of two corrector excitations with some phase advance in between. For simplicity the phase advance is assumed to be 90° and correctors are at locations with $\beta_1 = \beta_2$. The required excitation of the correctors for an oscillation of phase θ from the observation point is therefore

$$k_1 = k\cos\theta \qquad k_2 = k\sin\theta \quad (2)$$

The oscillation at a location downstream is then

$$x_0 = k\cdot\left(\cos\theta\sqrt{\beta_{1x}\beta_x}\,\sin\mu_1 + \sin\theta\sqrt{\beta_{2x}\beta_x}\,\sin\mu_2\right) \quad (3)$$

$$= k\cdot\sqrt{\beta_{1x}\beta_x}\,\sin\omega$$

where $\omega = \theta + \mu_1$. The angle x'_0 can be similarly expressed. Equating the invariants of motion

$$A_x^2 = \gamma_{xr}x^2 + 2\alpha_{xr}xx' + \beta_{xr}x'^2$$
$$A_y^2 = \gamma_y y^2 + 2\alpha_y yy' + \beta_y y'^2 \quad (4)$$

assuming an oscillation (3) rotated into the reference plane of the LHC with (1), the following square of the ratio of invariants results:

$$\left(\frac{A_y}{A_x}\right)^2 = \tan^2\delta\cdot[A_1\sin^2\omega + A_2\cos^2\omega + 2A_3\sin\omega\cos\omega] \quad (5)$$

where $A_2 = \dfrac{\beta_y}{\beta_x}, A_3 = \left(\alpha_y - \alpha_x A_2\right), A_1 = \dfrac{1+A_3^2}{A_2}$

The phase generating the maximum coupling can also be derived, as can the maximum coupling ratio [2].

MEASUREMENTS IN 2009 AND 2010

As part of the commissioning of the LHC in 2009/2010 various aspects of the SPS to the LHC transfer were studied. The effect of the phase dependent coupling was measured for six phases in TI 2, using existing knobs made for aperture measurements, and for a total of 17 phases on two occasions, using two different sets of excitation knobs for TI 8. All excitations were in the horizontal plane only, with response measured in the vertical plane.

Analysis

Trajectory data from single-pass measurements through the transfer line and the first LHC arc (about 6 km total length) was saved from the LHC steering application YASP in raw format for each excitation, and then analysed off-line. Fits were made to determine the amplitude and phase of the normalised oscillation (μ_x, $x/\sqrt{\beta_x}$). The coupling ratio A_y/A_x was determined from the ratio of the vertical to horizontal oscillation amplitude in the LHC. The results were compared with MADX simulations using the applied corrector strengths and the complete optical model, and also with the analytical formula derived above. An example of the MADX simulated data and the measured response data are shown for one measurement phase for TI 8 in Figure 1. The same fitting algorithm is applied to both data sets, to test the routine.

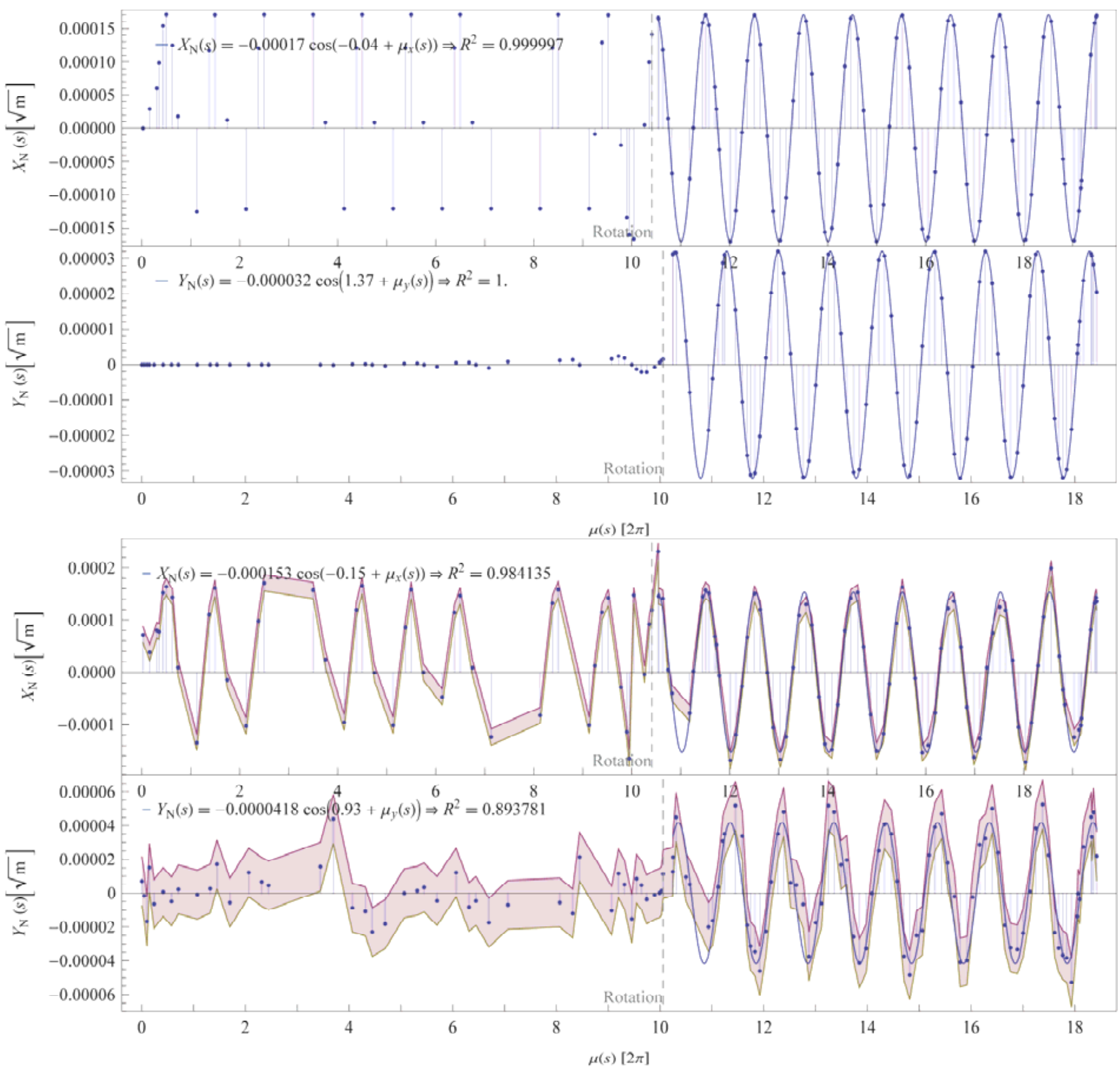

Figure 1: Example for simulation (top) and measurement (bottom): horizontal and vertical BPM measurements in TI 8, normalised. A horizontal betatron oscillation is generated starting at the beginning of the line TI 8. No coupling occurs in the line. In the LHC (after the rotation) coupling appears. The oscillations are normalised and fitted with a cosine in the LHC. The amplitudes of the cos-functions are used to determine the coupling ratio.

Results

Figure 2 compares the measured results of the coupling ratio for one of the TI 8 measurements with the prediction from the MADX code. Whereas the agreement in phase seems very good, the measured coupling is higher than the prediction. The most obvious explanation for the higher amplitude is the betatron mismatch in the order of 10 % at the injection point which enters in the coupling ratio via (5). However, it is also possible that an instability of the transfer line, presently under investigation, might play a role, since differences between shots of about 0.7 σ have been seen in the horizontal plane which originate at a single phase, and which might distort this type of measurement.

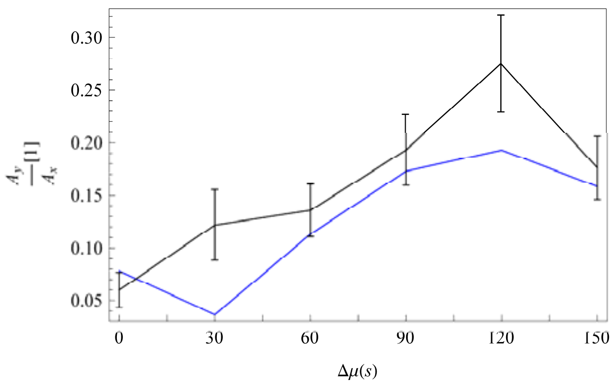

Figure 2: Coupling ratio in TI 8 for different oscillation phases. Black curve: measurement; blue curve: MADX prediction. The measured coupling is systematically higher than the prediction.

The results from the earlier TI 8 measurements were also analysed in a similar way, and the coupling ratio dependence on the oscillation phase derived. The results for the two data sets are plotted in Figure 3, together with the analytical expectation from eqn. (5).

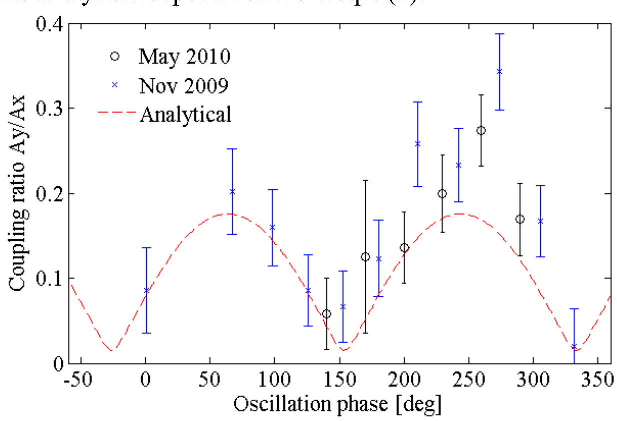

Figure 3: TI 8 to LHC coupling as a function of oscillation phase, and expectation from eqn. (5). As for MADX the agreement in phase is excellent but the amplitude seems to be higher.

For TI 2 the corresponding results are shown in Figure 4. Here the form of the curve looks very good but the analytical phase has had to be adjusted by 60º to fit the measured response, for reasons which are not yet clear - since the oscillations were generated with knobs on RBEND magnets in the early part of the line, it may be that there is simply an error in the attribution of the phases used in the comparison. Again it is noticeable that the amplitude seems higher than expected.

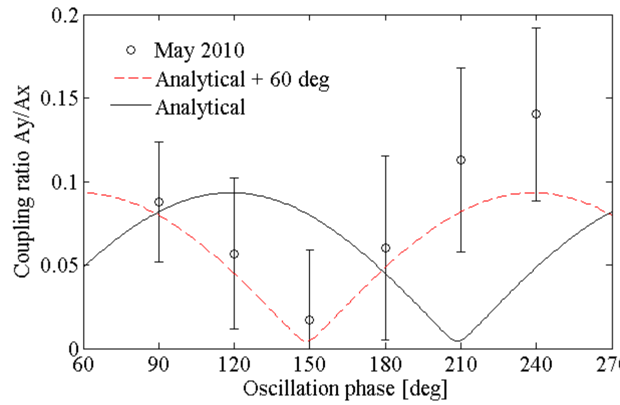

Figure 4: TI 2 to LHC coupling as a function of oscillation phase. The form is reasonable but the agreement in phase is only obtained by a 60º adjustment, for reasons which are not yet clear. Again the amplitude seems to be higher than expected, perhaps by 50%.

CONCLUSIONS

The phase-dependent coupling expected from theoretical considerations associated with the tilt mismatch between the LHC and its transfer lines has been observed and broadly agrees with expectations. So far, in early LHC commissioning, no big problems have been encountered from this effect, neither in the trajectory and injection steering nor in the emittance preservation in the LHC. Concerning the higher than expected coupling it would be interesting to repeat the measurements with higher sensitivity (more averaging and higher bunch current) to determine whether the stability of the lines is in fact an issue, and also to investigate this aspect theoretically. For TI 2 the difference in expected and observed phase response needs to be understood.

If the peak coupling of ~0.3 is confirmed for TI 8 this may necessitate more deterministic measures than at present for the correction of the trajectory at injection, and may also produce larger beam tails. The emittance growth from this effect will still remain small, around 2%.

REFERENCES

[1] B.Goddard et al., CERN LHC Project Report 719, CERN, Geneva, 2004.

[2] B. Goddard et al., CERN LHC Performance Note 003, CERN, Geneva, 2008.