CERN Large Hadron Collider optics model, measurements, and corrections

R. Tomás,* O. Brüning, M. Giovannozzi, P. Hagen, M. Lamont, F. Schmidt, and G. Vanbavinckhove
CERN, CH 1211 Geneva 23, Switzerland

M. Aiba
PSI, CH 5232 Villigen, Switzerland

R. Calaga and R. Miyamoto
BNL, Upton, New York 11973, USA
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Optics stability during all phases of operation is crucial for the LHC. Tools and procedures have been developed for rapid checks of beta beating, dispersion, and linear coupling, as well as for prompt optics corrections. Important optics errors during the different phases of the beam commissioning were observed and locally corrected using the segment-by-segment technique. The most relevant corrections at injection have been corroborated with dedicated magnetic measurements.

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I. INTRODUCTION

The CERN LHC is the first hadron collider with tight design tolerances on optics errors to guarantee the machine protection during operation with beam. This called for a quest of the most convenient optics measurement techniques [1–4] and instruments [5–7]. Several measurement and correction algorithms were tested in SPS [8–10], RHIC [11], and SOLEIL [12]. The first optics measurement of the LHC [13] revealed an unexpectedly large β beating. The leading source of this error was identified as a cable swap between the two-beam apertures of a trim quadrupole (MQT). This finding was only possible with the aid of a new approach for optics correction, the segment-by-segment technique (SBST). This technique has evolved to include the full set of linear optics parameters in the general case of a coupled lattice, see Sec. II. Figure 1 shows the peak β beating (top) and the rms orbit (bottom) of the LHC beam 2 at injection energy versus the number of days in commissioning with circulating beam. In about 60 days of operation with circulating beam, the dominant optics errors were identified and corrected at injection, considerably reducing the β beating to values close to design targets. The evolution of the rms orbit shows a clear correlation with the β beating since the orbit correction uses the orbit response matrix from the ideal model. Figure 1 also shows the relevant events that affected the optics quality. “LSA tuning” refers to adjustments in the polynomials used to model some magnets. “New cycle” refers to a modification of the energy evolution versus time during the ramp. A good stability of the optics is observed in periods over 10 days when the machine was unchanged.

During the energy ramp the optics errors are considerably reduced due to the lower persistent current effects in the superconducting magnets and the lower remnant magnetization in the normal conducting magnets. Consequently, the optics corrections are zeroed already at 700 GeV. At 3.5 TeV the β^* s at the interaction points (IPs) are squeezed to 2 m to increase the luminosity [14]. The commissioning of the four IPs β^* squeeze is summarized in Fig. 2 showing the peak β beat and the four β^* s versus time. About 15 days were used to achieve 2 m at all IPs. Large optics errors became evident in the interaction regions (IRs) as β^* was being reduced. Local optics

FIG. 1. Measured peak β beating (top) and rms orbit (bottom) at injection for beam 2 versus the number of days of LHC operation after circulating beam was established in 2008. Relevant events affecting the LHC optics are also displayed. LSA stands for LHC Software Architecture [38].

*rogelio.tomas@cern.ch

FIG. 2. Measured β beating (top) and IPs β^* (bottom) versus the number of days of LHC operation during the β^* squeeze commissioning at 3.5 TeV.

corrections were computed on-line and fully implemented in the squeeze procedures. After the squeeze a rather poor reproducibility of the β beating in beam 2 has been observed.

The next sections describe the theory concerning the extensions to the SBST (Sec. II), the implications of using AC dipoles (Sec. III), the experimental measurements and corrections at injection (Sec. IV), and during the β^* squeeze (Sec. V) as well as for coupling compensation (Sec. VI).

II. EXTENDED SBST

In [13] the SBST was introduced to identify the dominant optics error in the LHC in 2008. This error was responsible for approximately 50% of the β beating in the vertical plane of beam 2, see Fig. 1. Since then the SBST was extended to localize and correct linear optics errors, both normal and skew. The basic concept of the SBST relies on splitting the machine into various sections and therefore treat them as independent beam lines. The measured optics parameters at the beginning of each section are used as initial optics conditions. This was first applied to β and α functions, which are inferred from the phase measurements between three beam position monitors (BPMs) [15]. The phase advance within the segment proved to be a more precise and local observable. The horizontal and vertical dispersions can also be incorporated in the SBST by computing the angular dispersion ($D'_{x,y}$) at the start of the section. The dispersion measurement at the first two BPMs is used to infer $D'_{x,y}$ by assuming the ideal model between them. A more subtle and innovative addition to SBST is the transverse coupling. All the coupling parameters need to be measured at the start of the segment and translated into the MADX [16] formalism for propagation through each section. The real and imaginary parts of the difference (f_{1001}) and sum (f_{1010}) resonance terms are

extracted from the measured spectrum of the normalized complex signal [17,18], $h_x = \hat{x} - i\hat{p}_x$, which is parametrized to the first order as

$$h_x(N) = \sqrt{2I_x}e^{i\phi_x(N)} - i2f_{1001}\sqrt{2I_y}e^{i\phi_y(N)} - i2f_{1010}\sqrt{2I_y}e^{-i\phi_y(N)} \quad (1)$$

$$h_y(N) = \sqrt{2I_y}e^{i\phi_y(N)} - i2f_{1001}^*\sqrt{2I_x}e^{i\phi_x(N)} - i2f_{1010}\sqrt{2I_x}e^{-i\phi_x(N)},$$

where $I_{x,y}$ are the action invariants and $\phi_{x,y}(N) = 2\pi NQ_{x,y} + \phi_{x0,y0}$ describe the turn-by-turn phase evolution. The LHC double plane BPMs allow the measurement of $\phi_{x0,y0}$ from the horizontal and vertical tune spectral lines. With the measured phases the real and the imaginary parts of f_{1001} and f_{1010} can be calculated from both the horizontal and vertical spectra as shown by Eq. (1). In order to achieve a measurement independent of BPM calibration and beam decoherence, the values obtained from the horizontal and vertical planes are geometrically averaged as described in [19]. The measured f terms unambiguously determine the coupling matrix $\bar{\mathbf{C}}$ using the following relations [20]:

$$f_{1001} = \frac{1}{4\gamma}(\bar{\mathbf{C}}_{12} - \bar{\mathbf{C}}_{21} + i\bar{\mathbf{C}}_{11} + i\bar{\mathbf{C}}_{22}), \quad (2)$$

$$f_{1010} = \frac{1}{4\gamma}(-\bar{\mathbf{C}}_{12} - \bar{\mathbf{C}}_{21} + i\bar{\mathbf{C}}_{11} - i\bar{\mathbf{C}}_{22}),$$

where $|\bar{\mathbf{C}}| + \gamma^2 = 1$. These equations are fundamental to translate the measured coupling terms f_{1001} and f_{1010} into the initial optics conditions in the MADX formalism. An

FIG. 3. Example of the extended SBST applied to the correction of the IR5 normal and skew optics errors for beam 1 at 3.5 TeV. The IR quadrupoles (top), the vertical phase advance error (middle plot), and the difference resonance term f_{1001} (bottom) are shown. The lines represent the matched model with normal and skew errors located in the triplets.

illustration of the extended SBST applied to the correction of IR5 normal and skew gradient errors in the triplet is shown in Fig. 3. The lines represent the propagated model matched to the measurement. The normal gradient errors generate the vertical phase beating. The skew gradient errors cause the jumps of $|f_{1001}|$, which would stay constant in the absence of coupling sources. The matching of f_{1001} uses the inner triplet skew quadrupole correctors as coupling sources for convenience. There is one skew corrector located between the second and the third quadrupole of each triplet. Consequently, only two jumps of $|f_{1001}|$ are observed in Fig. 3.

III. AC DIPOLE

AC dipoles were initially applied in hadron accelerators to overcome intrinsic spin resonances [21]. AC dipoles force long-lasting betatron oscillation without emittance growth when ramped up and down adiabatically. The long-lasting oscillations are ideal for transverse beam dynamics measurements. The slow increase of the oscillation amplitude guarantees the effective response of the machine protection devices in case of a failure [6]. These properties make the AC dipole an ideal transverse exciter for the LHC. Dedicated measurements were performed in the LHC to verify the safe operation of the AC dipole and to confirm the trajectory predictions in [6]. Figure 4 shows the measured and simulated beam excursion while ramping the AC dipole to 20% of its maximum strength in 2000 turns with a frequency equal to the tune. At the turn 290 the beam was cleanly extracted by the machine protection system after having detected losses in the primary collimators (with a half gap of 6σ). This, together with the good agreement between measurement and simulation, validated the AC dipole as a safe instrument.

However, forced oscillations differ from free oscillations proportionally to the distance between the driving tune and the machine tune [22–25]. In the presence of an AC dipole the measured β functions differ from the machine β functions. This difference is simply modeled as a quadrupole error in the location of the AC dipole [26]. This equivalence allows one to apply exactly the same analysis

FIG. 4. Measured and simulated horizontal beam excursions with the AC dipole ramping up on the tune resonance.

to all experimental data but using a modified reference model which includes the quadrupole error according to the AC dipole settings. The measured difference resonance term $\hat{f}_{1001}$ also differs from the machine f_{1001} as follows [25,27]:

$$\hat{f}_{1001} = \frac{\sin[\pi(Q_x - Q_y)]}{\sin[\pi(Q_{ac} - Q_y)]} f_{1001} [1 + O(\delta)] \quad (3)$$

assuming a horizontal AC dipole with driving tune Q_{ac} and $\delta = Q_x - Q_{ac}$. The fraction on the right-hand side is a global factor easily taken into account. More precise expressions, also for the sum coupling resonance, can be found in [27]. In the LHC it is customary to excite at $|\delta| = 0.005$ without significant emittance blowup, yielding a systematic error of about 3% in f_{1001} .

IV. OPTICS CORRECTIONS AT INJECTION

Optics measurements during 2009 at injection energy allowed one to identify the largest error sources [28]. The sections with the largest error sources are the warm regions IR3 and IR7, which are dedicated to collimation, followed by the triplets in IR2 and IR8 and by the quadrupolar error in the main dipoles (the b_2 component). It is worth mentioning that due to injection constraints the triplets in IR2 and IR8 feature a larger gradient than those in IR1 and IR5 [29]. The error sources in IR3 and IR7 vanish at higher energies [28]. Some quadrupoles in IR3 and IR7 are powered below 1 A at injection. These findings allowed magnet experts to identify a wrong magnetic precycle in the main quadrupoles of IR3, IR7, and the triplets [30]. The quadrupoles in IR3 and IR7 operate at room temperature and they belong to the type of warm quadrupole magnet (MQW). The precycles for the MQW magnets were changed in 2010 in order to improve reproducibility at injection energy where magnetic hysteresis plays an important role, see Fig. 1, improving the horizontal β beating in the

FIG. 5. β beating for beam 1 before and after corrections at injection energy.

FIG. 6. Illustration of the local optics correction in IR3 for beam 2 at injection.

beam 2. Nevertheless optics corrections were still required. Figure 5 shows the β beating before and after correction for beam 1. All the corrections were computed via the SBST to ensure their locality. Figure 6 illustrates the local optics correction in IR3. IR3 and IR7 insertions are particularly constrained for optics correction since the main warm quadrupoles (MQWA) are powered in series on both sides and for both beams, while the trim quadrupoles (MQWB) are powered in series for both beams (but not for both sides) [31]. The size of the required relative corrections is in the 1% level for the MQWA quadrupoles and between 10% and 200% for the MQWB quadrupoles. The MQWB quadrupoles are trim magnets nominally set to a very low field. This explains the larger relative errors in the transfer function of these quadrupoles. These large corrections could only be understood by the fact that the magnetic precycle of the MQW magnets was still not identical to that used during the magnetic measurements. New magnetic measurements of two spare MQW quadrupoles were performed using exactly the same magnetic cycle as in the LHC operation. The results of the magnetic

FIG. 7. Beam 2 β beating at injection before and after updating the MQW magnetic calibrations, showing a comparable performance.

measurements agree to a large extent with the optics corrections applied beforehand in LHC. Table I shows nominal gradients and relative gradient errors for the settings before and after the optics correction using the new magnetic measurements as a reference. The gradient errors after the optics corrections are substantially reduced for all magnets. The locality of the optics corrections based on the SBST proves to reach the magnet level thanks in part to the lack of degeneracy between variables (magnet strengths) and observables (phase advance at the BPMs).

It was decided to update the MQW calibrations in the LHC controls system according to the new magnetic measurements. As expected, the current β beating is comparable to that previously obtained with the optics corrections, see Fig. 7. Further corrections could be applied but the β -beating level is considered to be acceptable for

TABLE I. Gradient errors of IR3 and IR7 quadrupoles at injection energy before and after optics corrections as inferred from the new magnetic measurements performed on the spare MQWA and MQWB magnets. All errors are substantially reduced by factors between 2 and 25 with the exception of MQWA4.LR3.

Magnet	Nominal gradient [T/m]	Estimated error before correction [%]	Estimated error after correction [%]
MQWA5.LR3	1.957	1.1	-0.5
MQWA4.LR3	1.863	1.3	-1.5
MQWA5.LR7	2.005	1.0	-0.1
MQWA4.LR7	1.972	1.1	-0.6
MQWB5.L3	1.459	-11.1	-1.1
MQWB4.L3	1.034	-18.7	-2.5
MQWB4.R3	1.034	-16.6	1.5
MQWB5.R3	1.459	-11.2	-0.6
MQWB5.L7	0.049	-83.4	-8.5
MQWB4.L7	0.498	-32.6	1.9
MQWB4.R7	0.498	-44.1	-15.2
MQWB5.R7	0.049	-81.5	3.8

FIG. 8. Beam 1 horizontal (top) and vertical (bottom) phase beat before and after the dipole b_2 component correction.

the existing aperture (due to a lower than expected rms orbit, see Fig. 1).

The systematic quadrupolar error of the dipoles

The systematic quadrupolar component (b_2) of the LHC dipoles was determined from magnetic measurements [32,33]. This quadrupolar error is corrected arc by arc using the arc MQT magnets to cancel the betatron phase shift [34]. Figure 8 shows the measurements of the horizontal and vertical phase beats before and after implementing the corrections. An excellent correction is achieved removing the systematic phase shift along the arcs. Again, an excellent agreement is found between magnetic and optics measurements at injection.

V. OPTICS DURING β^* SQUEEZE

At 3.5 TeV the IPs were first squeezed sequentially (IP1&IP5, IP8, and IP2) allowing for local optical corrections after each IP reached 2 m, as shown in Fig. 2. All IPs were finally squeezed simultaneously. All measurements at

FIG. 9. Beam 1 horizontal (top) and vertical (bottom) β beating before and after correction with all IPs at $\beta^* = 2$ m at 3.5 TeV.

TABLE II. Magnets used to correct the β beating at 3.5 TeV with the IPs at β^* of 2 m. Design and maximum strengths are shown together with the relative corrections.

Magnet	Design K_1 [m ⁻²]	Maximum K_1 [m ⁻²]	Correction [%]
MQXB2.R5	-0.0087	0.018	-0.15
MQXB2.L5	0.0087	0.018	0.12
MQ5.R8B1	-0.0029	0.013	5
MQ6.L8B2	0.0056	0.013	1.8

3.5 TeV are performed with the AC dipoles. Measurements prior to the local IR corrections at $\beta^* = 2$ m reveal unexpectedly large optics distortions as shown in Fig. 9. Up to 60% β beating is observed in the vertical plane of beam 1. Table II shows the magnets used for this correction. For IR5 it was possible to find a triplet correction that would correct both beams. Figure 10 illustrates the simultaneous two-beam correction showing the local IR5 phase beating before and after correction for the vertical plane of beam 1 and the horizontal plane of beam 2.

The dominant optics error source appears in IR8. In this IR it was not possible to find a local correction for both beams using only the common triplet magnets. A pragmatic approach was to use only independent magnets, resulting in the large relative corrections in Table II. The triplets in IR8 have known relative calibration errors in the order of 13×10^{-4} . After the corrections were applied it was checked that these errors explain about 30% of the vertical phase beating for beam 1, see Fig. 11. Updating the calibration of the IR8 triplets would reduce the required correction from 5% to 3.3%. Figure 9 shows the reduction on the β beating due to all the local corrections together.

In an attempt to better understand the error sources the SBST was applied to the horizontal and vertical dispersion in IR8, see Fig. 12. However, no significant dispersion error is observed, probably due to the low dispersion values

FIG. 10. Illustration of the two-beam β beating correction using the IR5 triplets.

FIG. 11. Local Beam 1 IR8 correction increasing by 5% the fifth quadrupole to the right of IP8.

FIG. 12. Measured and propagated horizontal and vertical dispersions across the IR8. No significant error is observed from the dispersion functions.

across the IR8 triplet. No crossing angles were used at the time of the measurements.

A lack of reproducibility of the β beat in the 10% level was observed for the first time with the squeezed β^* . Figure 13 shows the difference of the vertical β beat between two measurements separated by five days. One measurement was performed immediately after the squeeze while the second was done at the end of a 30 hours physics fill. The figure shows abrupt jumps at IR8 and IR2. One possible explanation is the decay of the quadrupolar errors in IR superconducting magnets along the fill. Such a decay has been observed in magnetic measurements with the 7 TeV settings [35] but there is no data for the settings at 3.5 TeV. More measurements are needed to better understand the level of reproducibility and the “dynamic” error sources.

FIG. 13. Difference of the beam 1 vertical β beating between two measurements at $\beta^* = 2$ m separated by 5 days.

FIG. 14. Skew quadrupole current along the squeeze. kqsx3.r5 is one of the IR5 triplet skew quadrupole correctors. kqs.a78b2 is one of the skew quadrupole families involved in the global coupling correction.

VI. COUPLING CORRECTION

The transverse coupling is generally compensated online [36] by using two orthogonal global knobs constructed with arc skew quadrupoles to correct the real and imaginary parts of f_{1001} . During the squeeze these global knobs need to be stronger as the β^* decreases in the IPs (β functions increase in the triplets) as shown in Fig. 14. With all IPs at $\beta^* = 2$ m the global knobs were not sufficiently strong to correct the coupling and the IR local coupling correction was mandatory.

The extended SBST was applied to all IRs, as shown in Fig. 3 for IR5. The strengths of the inner triplet skew quadrupoles were computed to reproduce the measured f_{1001} . A considerable reduction of the required strengths of the global knobs was achieved after the local coupling correction.

VII. SUMMARY AND OUTLOOK

Unexpectedly large optics errors have been observed in the LHC at injection energy and at 3.5 TeV after the

FIG. 15. Extrapolation of the 3.5 TeV identified optics errors to 7 TeV with nominal optics.

β^* squeeze down to 2 m. The dominant errors were locally corrected by applying the extended SBST. The results of this new technique at injection have been corroborated by dedicated magnetic measurements of the spare MQW magnets. The new magnetic calibration curves have been implemented in the LHC controls system without requiring further corrections at injection.

At 3.5 TeV and $\beta^* = 2$ m, the error sources are not fully understood. If we assume these errors to remain the same at 7 TeV with the nominal collision optics ($\beta^* = 0.55$ m), a β beating over 120% would arise in the horizontal plane of beam 2, Fig. 15.

The use of the inner triplet skew quadrupoles to correct the local coupling with moderately low strength is mandatory at $\beta^* = 2$ m (3.5 TeV). The required triplet quadrupole tilts to reproduce the observed local coupling range between 0.5 and 2.0 mrad for different error distributions. Recent alignment measurements show a tilt of 0.6 mrad in one of the IR5 quadrupoles [37]. This error explains about 40% of the local coupling error observed in IR5.

A poor reproducibility of the LHC optics after the squeeze was observed. A possible explanation could be the decay of the quadrupolar error of the superconducting magnets during the fill. Improvements in this area combined with further optics corrections, both local and global, could allow reducing the current β beat margins in the aperture and therefore push the machine performance by further reducing the β^* , provided the closed orbit stability is also well within tolerances.

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