

DEVELOPMENTS OF THE SEGMENT-BY-SEGMENT TECHNIQUE FOR OPTICS CORRECTIONS IN THE LHC

A. Langner^{*1,2}, J. Coello de Portugal², P. Skowronski², R. Tomás²
¹University of Hamburg, Germany, ²CERN, Geneva, Switzerland

Abstract

Optics correction algorithms will become even more critical for the operation of the LHC at 6.5 TeV. For the computation of local corrections the segment-by-segment technique is used. We present improvements to this technique and an advanced error analysis, which increase the sensitivity for finding local corrections. Furthermore, we will investigate limitations of this method for lower β^* optics as they will be used in the high-luminosity LHC (HL-LHC) upgrade.

INTRODUCTION

The segment-by-segment technique (SbS) was developed at the LHC for the computation of optics corrections for local, strong error sources [1]. The concept is to run MAD-X [2] in a part of the accelerator in between two beam position monitor (BPM) locations. The optical functions which were derived from measured turn-by-turn data of the BPMs are the start parameters for this simulation. For optics corrections the simulated phase advances between BPMs are compared to the measured ones, as they are more directly observable than e.g. the β -function. Possible correction settings aim at eliminating the deviations in the phase advance. This method has been very successful at finding local optics corrections for the LHC, where it was once even able to identify a cable swap between the two beam apertures in a quadrupole which caused an unexpectedly large β -beating [3, 4]. SbS was also successfully tested at RHIC and is fully implemented there [5].

Another purpose of SbS is the propagation of optical functions from the BPM positions to other lattice elements. This allows for example to derive the β -function at the interaction points (β^*). It has also been used to propagate the optical functions to beam wire scanners for an emittance study [6] and to collimators for a comparison to beam sizes as they are measured in beam-based collimator alignment [7]. These studies require very precisely measured β -functions and improvements to SbS were required to comply with these demands. Recent improvements related to SbS include an improved measurement of the β -function from BPM turn-by-turn data [8] which results in significantly more precise start parameters for the SbS simulation.

Furthermore, an automatic routine has been developed to match the measured and simulated phase advances for finding optics corrections [9, 10]. In the following sections we will show improvements in the error analysis for SbS and also present a comparison of simulated local optics corrections for LHC and HL-LHC, which shows a possible limitation of SbS for lower β^* optics.

* andy.langner@cern.ch

IMPROVED ERROR ANALYSIS

Phase Advance

The β -beating propagation can be described by an oscillation with constant amplitude A which propagates with twice the betatron oscillation frequency

$$\frac{\Delta\beta}{\beta}(s) = A \cdot \sin(2 \cdot \phi(s) + \phi_0). \quad (1)$$

$\phi(s) + \phi_0$ is the phase of the betatron oscillation at the position s and ϕ_0 the initial phase for $s = 0$. Using Eq. (1) one can approximate the deviation of the phase $\Delta\phi$ due to the β -beating at the start of the segment. Error propagation on $\Delta\phi$ using the uncertainties σ_{β_0} and σ_{α_0} of the optical functions at the start of the segment leads to the uncertainty of the propagated phase

$$\sigma_{\phi(s)}^2 = \left(\frac{1}{2}(\cos(2\phi(s)) - 1) \frac{\alpha_0}{\beta_0} + \frac{1}{2} \sin(2\phi(s)) \frac{1}{\beta_0} \right)^2 \sigma_{\beta_0}^2 + \left(\frac{1}{2}(\cos(2\phi(s)) - 1) \right)^2 \sigma_{\alpha_0}^2, \quad (2)$$

where α_0 and β_0 are the initial α - and β -function at the start of the segment. The computation of uncertainties for the phase advance in the simulation, which were not regarded before, allow for a better calculation of optics corrections, since the uncertainties can be considered as weights when matching the measured and simulated phase advances. This feature is part of the automatic matching routine [10].

β - and α -function

The same approach as for the phase advance uncertainty can also be used for other optical function. The uncertainties of the propagated α - and β -function at the position s (α_s and β_s) are shown in Eqs. (3-4).

$$\sigma_{\beta_s}^2 = \left[\beta_s \sin(2\phi(s)) \frac{\alpha_0}{\beta_0} + \beta_s \cos(2\phi(s)) \frac{1}{\beta_0} \right]^2 \sigma_{\beta_0}^2 + \left[\beta_s \sin(2\phi(s)) \right]^2 \sigma_{\alpha_0}^2. \quad (3)$$

$$\sigma_{\alpha_s}^2 = \left[\alpha_s \sin(2\phi(s)) \frac{\alpha_0}{\beta_0} + \alpha_s \cos(2\phi(s)) \frac{1}{\beta_0} - \cos(2\phi(s)) \frac{\alpha_0}{\beta_0} + \sin(2\phi(s)) \frac{1}{\beta_0} \right]^2 \sigma_{\beta_0}^2 + \left[\cos(2\phi(s)) - \alpha_s \sin(2\phi(s)) \right]^2 \sigma_{\alpha_0}^2. \quad (4)$$

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$$\sigma_{Re(f_{1001}(s))}^2 = [\sigma_{f_{1001}(s_0)} \cos(\phi_{1001}(s_0) - \phi_x(s) + \phi_y(s))]^2 + [\sigma_{\phi_{1001}(s_0)} f_{1001}(s_0) \sin(\phi_{1001}(s_0) - \phi_x(s) + \phi_y(s))]^2 \quad (5)$$

$$\sigma_{Im(f_{1001}(s))}^2 = [\sigma_{f_{1001}(s_0)} \sin(\phi_{1001}(s_0) - \phi_x(s) + \phi_y(s))]^2 + [\sigma_{\phi_{1001}(s_0)} f_{1001}(s_0) \cos(\phi_{1001}(s_0) - \phi_x(s) + \phi_y(s))]^2 \quad (6)$$

$$\sigma_{Re(f_{1010}(s))}^2 = [\sigma_{f_{1010}(s_0)} \cos(\phi_{1010}(s_0) + \phi_x(s) + \phi_y(s))]^2 + [\sigma_{\phi_{1010}(s_0)} f_{1010}(s_0) \sin(\phi_{1010}(s_0) + \phi_x(s) + \phi_y(s))]^2 \quad (7)$$

$$\sigma_{Im(f_{1010}(s))}^2 = [\sigma_{f_{1010}(s_0)} \sin(\phi_{1010}(s_0) + \phi_x(s) + \phi_y(s))]^2 + [\sigma_{\phi_{1010}(s_0)} f_{1010}(s_0) \cos(\phi_{1010}(s_0) + \phi_x(s) + \phi_y(s))]^2 \quad (8)$$

Previously the uncertainties in SbS were only roughly estimated by running two MAD-X simulations where the start parameters were changed once by adding their uncertainty and once by subtracting it. This is also more time consuming than the evaluation of analytic equations, since more MAD-X runs are necessary. For a tool which is used online during optics measurements, time efficiency is very important to ensure an efficient use of the beam time.

Coupling

The control of the betatron coupling is of great importance in the operation of the LHC and significant progress has been done for its precise measurement and control [11]. Using the SbS technique, strong sources of betatron coupling can be detected and easily corrected. The propagation of the uncertainty of the relevant driving terms (f_{1001} and f_{1010}) for the betatron coupling were computed in the past like those of the β - and α - functions by evaluating additional MAD-X simulations where the start parameters have been varied by their uncertainties.

Analytic formulas have been derived to improve the estimation of the uncertainty in the betatron coupling. As the measured driving terms are given in polar form and the values have to be input to MAD-X using the R-matrix formalism, the transformation given in [12] is needed.

Once the values are input to MAD-X the uncertainty for real and imaginary part of the propagated f_{1001} and f_{1010} can be computed using Eqs. (5-8), with s_0 being the longitudinal position of the first BPM in the segment and $\phi_{x,y}$ the phase advance from s_0 to s and assuming small errors in the measured phase of the driving terms [13].

Implementation in SbS

To test the implementation of the analytic equations a Monte-Carlo simulation was used where the start values of the β - and α -functions are varied randomly following a Gaussian distribution within their uncertainty. From the variation of the β - and α -functions at the propagated locations, the error bars can be derived. Figure 1 compares the error bars in a specific segment computed by the analytic equation and the Monte-Carlo simulation. The values computed by analytic equations are clearly agreeing well to the error bars as they are derived in the Monte-Carlo simulations. Furthermore, the previously used error bars, which were estimated with two MAD-X runs, are not agreeing well with the real uncertainties and in many cases overestimate the error bars significantly. A similar check has been done

for the uncertainties which are calculated for the real and imaginary part of the propagated f_{1001} and f_{1010} , cf. Fig.2. Also in this case the error bars from Eqs. (5-8) are agreeing well to the Monte-Carlo simulation.

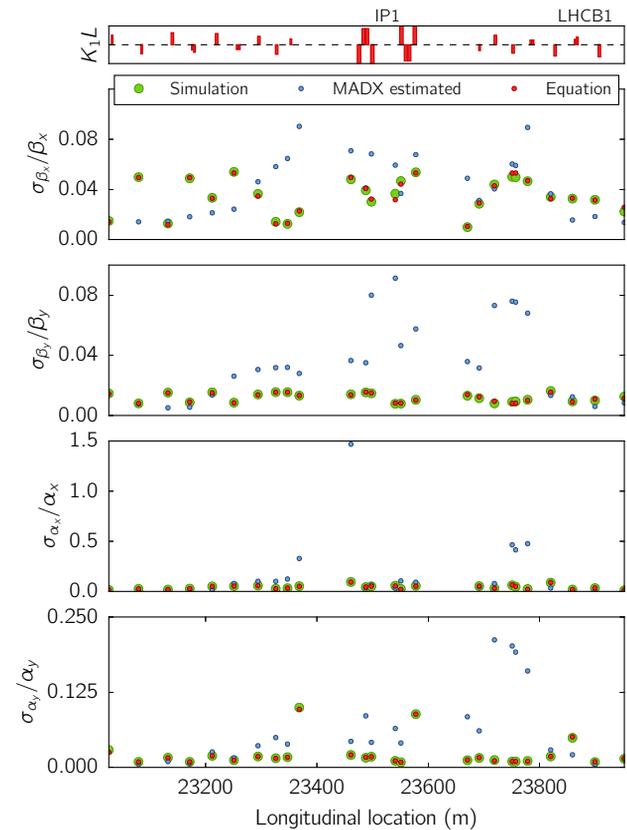


Figure 1: Error bars for propagation in a segment around the ATLAS interaction point (IP1). The Monte-Carlo simulation (green) provides the reference values to which the values from new analytic equations (red) agree very well. MAD-X estimate (blue) shows the values as they were computed in the past before the analytic equations were implemented.

HL-LHC

Recently, studies have been done to investigate how SbS corrections perform in case of strongly squeezed optics, i.e. very small β^* , as those at which the HL-LHC is designed to operate. The effect of gradient errors in the final focusing quadrupoles (MQX) both for LHC and HL-LHC is shown in

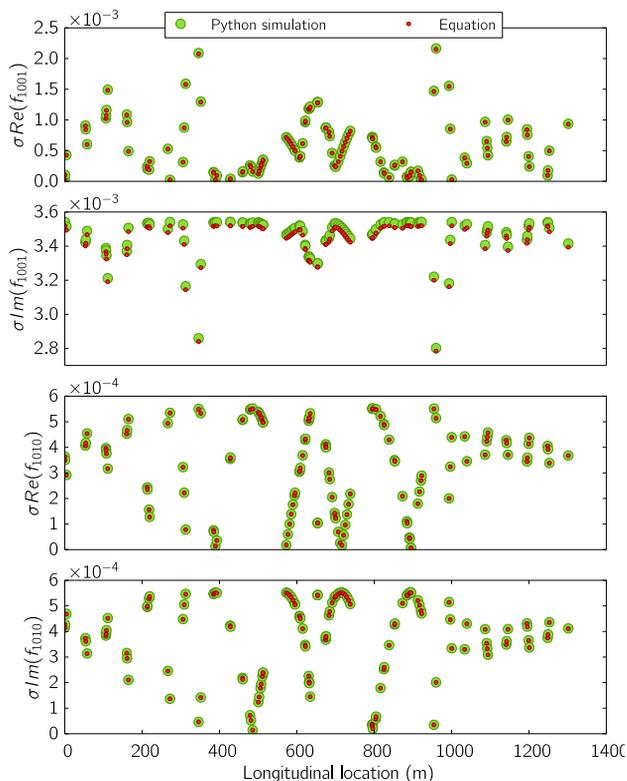


Figure 2: Error bars for propagation of the coupling driving terms (f_{1001} and f_{1010}) in a segment around IP1. The green dots represent the reference Monte-Carlo simulations in Python. In red, the error computed using the analytic equation is displayed.

Fig. 3. The gradient uncertainty for the LHC MQX is $4 \cdot 10^{-4}$ in relative units with respect to their main field, whereas for the HL-LHC MQX even larger uncertainties might be possible. Figure 4 shows how the β^* values deviate from the nominal value, after corrections have been computed and applied using SbS..

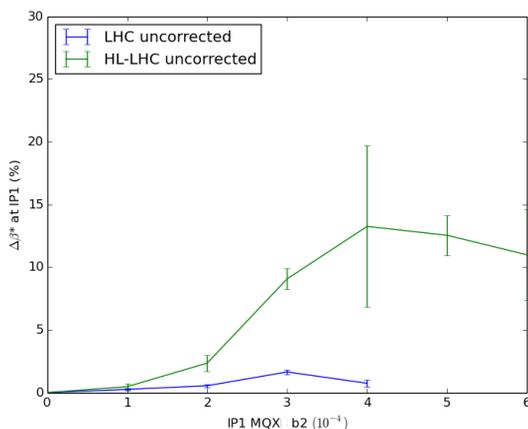


Figure 3: β -beating at IP1 for different gradient errors in the final focusing quadrupole magnets (b_2). The errors are in relative units with respect to the main field.

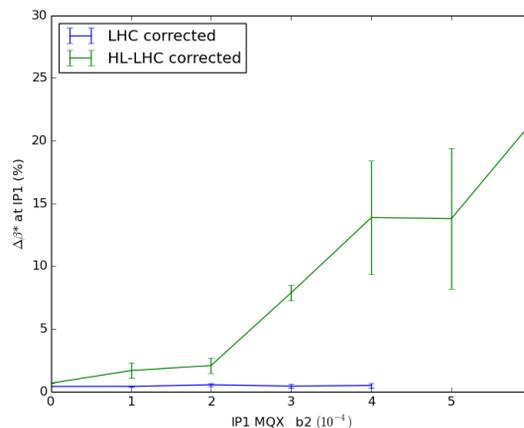


Figure 4: β -beating in IP1 for different gradient errors in the final focusing quadrupole magnets after corrections have been applied. The gradient errors (b_2) are in relative units with respect to the main field. Corrections were computed with the automatic matching routine.

Not only do the magnetics errors for the LHC have a much smaller effect on the β^* , but also the correction improves the β^* -beating. On the other hand, for the HL-LHC, this uncertainty is more destructive and the correction algorithm seems to have large difficulties to improve it, even making it worse for high gradient uncertainties of the triplet magnets. These results show that the SbS technique in its currents state will not be able to provide the desired results for the future and an effort has to be made in understanding and improving this behavior.

CONCLUSION

The SbS technique which started as a tool for local optics corrections of strong error sources, has evolved since then due to e.g. including more optical parameters like coupling and dispersion or the propagation of measured β -functions to other lattice elements. Demands for precisely measured optical functions at various lattice elements triggered the error analysis which was presented here. Using the presented analytic equations for the uncertainty of the propagated optical functions is not only more accurate but also faster than the previously used additional MAD-X simulations. Furthermore, the uncertainty for the phase advance which is also derived now in the propagation, can be considered as a weight when optics corrections are computed which will increase the sensitivity for finding optics corrections. A remaining challenge is the correction of local errors for very small β^* optics since the automatic matching routine fails to find suitable corrections. One improvement which is foreseen for SbS would be to include the effect of systematic error sources from lattice uncertainties. This could further increase the sensitivity for finding optics corrections.

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