EXTRAPOLATED OPTICS MEASUREMENT FROM BPM TO INSTRUMENTATION IN LHC COMMISSIONING

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Abstract

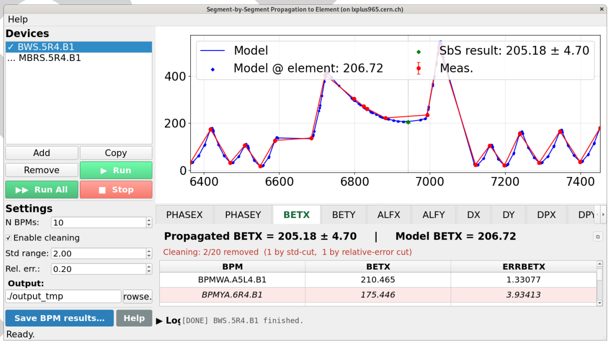
The Segment-by-Segment (SbS) analysis is a technique employed in particle accelerators to identify lattice errors and determine corrections, by identifying deviations between optics functions propagated through a modeled lattice segment and measured values. At the Large Hadron Collider (LHC), this method is routinely applied during optics commissioning to compensate for strong local errors arising in the experimental insertions and arcs. Beyond error correction, the SbS approach is also of interest for propagating optics functions measured at the BPMs to key instrumentation in other locations in the ring, for example to improve emittance measurements by providing more accurate estimates of the optics functions at relevant devices. In this paper, the analysis methods and results from the recent LHC commissioning are presented.

INTRODUCTION

The segment-by-segment (SbS) technique was developed at the CERN LHC to identify and correct local lattice errors [1, 2]. Since 2008, it has been successfully employed during LHC commissioning and operation [3]. The underlying principle is to split the machine into a series of segments, each treated as a transfer line [2]. The measured optics parameters at the Beam Position Monitors (BPMs) are used as initial conditions and are propagated through the corresponding segment of the machine model. The propagated optics are then compared with the measured data over the selected segment; discrepancies between the two can reveal the presence of local lattice errors. Beyond error identification, the SbS method can also be used to propagate optics measurements from the BPMs to other instrumentation in the ring. The goal of this work is to simplify the application of the technique to estimate optics functions at key instrumentation, enabling its routine use.

METHODS

A GUI has been developed to run the SbS-to-element propagation; an example is shown in Fig. 1. The user selects the target element from the model, then provides a nominal optics model and the corresponding measurement. A range of BPMs on either side of the target instrument must be chosen; the propagation is then performed over a collection of segments defined between the selected BPMs. The number of BPMs included around the target device is a crucial parameter for the reliability of the method. Including more BPMs increases the statistical significance of the result, whereas extending the propagation over longer segments may increase the error on the result due to the accumulated lattice errors along the path. Currently, several optics parameters have been included as propagable quantities: vertical and horizontal phase advance, alpha functions, beta functions, dispersions, momentum dispersions, and the coupling Resonance Driving Terms (RDTs), f_{1001}, f_{1010} (amplitude, phase, real part and imaginary part). The measured quantities at the BPMs are propagated through the segments in both directions — forwards from upstream BPMs and backwards from downstream BPMs. The optics parameters are evaluated at the device location for each segment, together with the propagated uncertainty. A cleaning step removes outliers using two criteria: a standard range filter to remove statistical outliers, and a filter on large relative errors. However, this type of analysis is highly case-specific, and experience has shown that it is preferable for the user to inspect the raw results and make their own selection. The final estimate and its corresponding error are obtained through a weighted average of the filtered results, using the propagated uncertainty at the target device as the weighting factor.



Settings
N BPMs: 10
☑ Enable cleaning
Std range: 2.00
Rel. err.: 0.20
Output: ./output_tmp

Propagated BETX = 205.18 ± 4.70 | Model BETX = 206.72

Cleaning: 2/20 removed (1 by std-cut, 1 by relative-error cut)

BPM	BETX	ERRBETX
BPMWA.A5L4.B1	210.465	1.33077
BPMYA.6R4.B1	*175.446*	*3.93413*

```
[DONE] BWS.5R4.B1 finished.
```

Ready.

Figure 1: GUI for the SbS-to-element.

Error Propagation

The error propagation for β and α functions and RDTs follows the formalism described in Ref. [4]. For the phase uncertainty, the following expression is used,

$$\sigma^2_{\phi_s} = \left\{\frac{1}{2}\left([\cos(2\phi)-1]\frac{\alpha_0}{\beta_0} - \sin(2\phi)\frac{1}{\beta_0}\right)\right\}^2 \sigma^2_{\beta_0} + \left\{\frac{1}{2}[\cos(2\phi)-1]\right\}^2 \sigma^2_{\alpha_0} , \qquad (1)$$

which introduces a sign correction with respect to Ref. [4]. The corrected formula was derived analytically and validated through a series of MAD-X simulations, as described in Ref. [5]. Here, ϕ denotes the phase advance from the initial position to the observation point, in units of radian.

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It gives the uncertainty on the phase at a position s arising from uncertainties on α and β at $s = 0$, assuming that these uncertainties are independent. For the dispersion, the uncertainty is obtained by applying the transfer matrix to the initial value's uncertainty,

$$\sigma^2_{D(s)} = \sigma^2_{D_0} \frac{\beta(s)}{\beta_0} \left(\cos\phi(s) + \alpha_0 \sin\phi(s)\right)^2 + \sigma^2_{D'_0}\, \beta(s)\beta_0\, \sin^2\phi(s)\ . \tag{2}$$

RESULTS

Propagation to Emittance Measurement Devices

The SbS-to-element tool was first applied to propagate the beta and dispersion functions to the devices used for beam size measurement at the LHC. These include the Beam Wire Scanners (BWS), the Beam Radiation Monitors (MBRS), and the undulator magnets (MU), which serve as synchrotron radiation sources for the MBRS monitors. Emittance reconstruction depends directly on the beta and dispersion functions at these devices, and unaccounted local optics errors can degrade the measurement accuracy. In this study, four optics configurations were investigated during 2025 LHC commissioning: injection optics, flat-top optics with β^* at IP1/IP5 equal to 2 m and 18 cm, and the Van der Meer (VdM) optics used for luminosity calibration. The analysis was repeated for 2026 commissioning, covering additional squeeze steps from 120 cm down to 15 cm, as well as the injection and VdM configurations. An example of the propagation using the 10 closest BPMs on either side of the BWS of Beam 1 for the 2025 injection optics is shown in Fig. 2, where the propagated β_x at the device is plotted as a function of the phase advance between the starting BPM and the target device. This example illustrates how, despite the automated cleaning, spread results can persist across propagation from different starting BPMs. In this particular case, propagation from the left side shows several BPMs with consistent values, whereas propagation from the right side produces a more scattered distribution with larger uncertainties. Such points may therefore be manually discarded by the user. The model, measured, and propagated horizontal (in blue) and vertical (in red) beta functions for both beams are presented for the sample cases of 2025 injection optics in Fig. 3 and for the 18 cm β^* optics in Fig. 4.

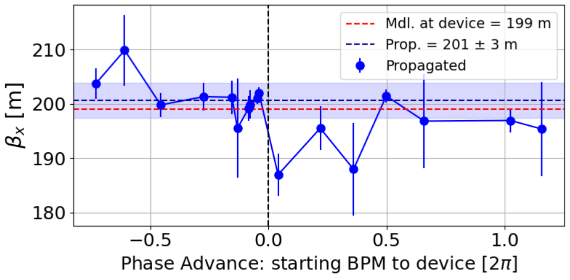

Figure 2: Propagated β_x at BWS.5R4.B1.

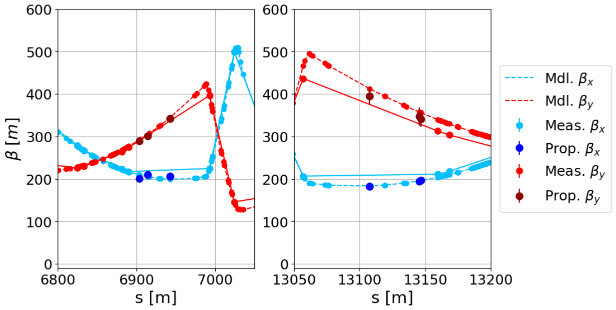

Figure 3: Propagated β for B1 (left) and B2 (right).

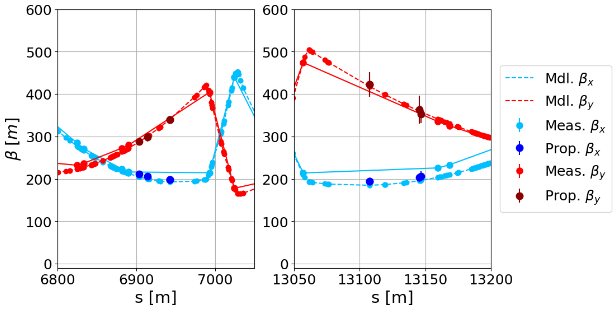

Figure 4: Propagated β for B1 (left) and B2 (right).

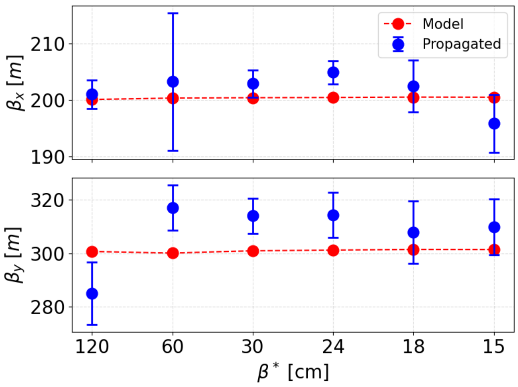

Figure 5: Propagated and model β functions at MBRS.5R4.B1.

For the 2026 optics, Fig. 5 shows the model and propagated beta functions at each squeeze step for the Beam 1 radiation monitor MBRS.5R4.B1, while Fig. 6 shows the corresponding results for the horizontal dispersion. The larger discrepancies observed for the 30 cm and 24 cm cases are due to additional corrections implemented in 2026, which are only compensated at 18 cm. The propagated beta function values are generally consistent with model predictions within the estimated uncertainties, with larger error bars corresponding to greater discrepancies between the model and the measurements. Regarding the horizontal dispersion, the propagated uncertainties appear large relative to the measurement, requiring further dedicated studies. The propagated errors on the optics quantities can be combined with the uncertainty from the beam size measurement to obtain a more robust evaluation of the total emittance uncertainty.

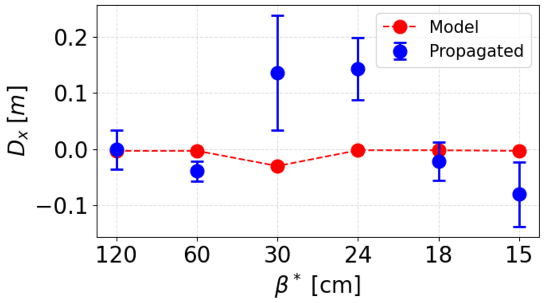

Figure 6: Propagated and model D_x at MBRS.5R4.B1.

Propagation of β_y to IP1

The second main result concerns the validation of a record-breaking β^* of 7 cm, achieved during one of the final 2025 Machine Development (MD) sessions [6]. The primary goal of the MD was to test additional steps in the LHC β^* squeeze, pushing beyond the operational value of 60/18 cm towards a vertical β^* of 12 cm, and to test dedicated β^*-waist shift knobs designed to correct β^*. Once 12 cm was reached — with beta-beating below 20% for both beams in both planes — the waist knobs were applied. However, the knobs did not perform as expected; instead, they produced an additional squeeze accompanied by beta-beating reaching up to 100% in the arcs. The β^*_y value was assessed from a series of k-modulation measurements performed at IP1, resulting in an unprecedented vertical β^* of approximately 7–8 cm for LHC Beam 2, with a vertical waist $w_y = 3.3 \pm 0.4$cm. Given the unexpected nature of this result, the SbS-to-element tool was used to provide an independent cross-check. During the analysis, propagating directly to the IP produced incoherent results with large uncertainties, most likely due to the high sensitivity to the waist position; the propagation was therefore performed to the devices closest to IP1, separately from the left and right sides, avoiding the ultra-low-beta region in the immediate vicinity of the IP. The vertical beta function β_y and the relative beta-beating $\Delta\beta_y/\beta_y$ were propagated to the inner triplet quadrupole MQXA and to the BPMSW on both sides of IP1. The model, measured, and propagated values at the target locations are shown in Fig. 7 and Fig. 8, and a summary is provided in Table 1. The propagated values at the BPMSWs on both sides of IP1 were subsequently used to interpolate the beta function at the waist. The region between the two BPMs can be approximated as a drift space, in which the beta function follows a parabolic dependence. An optimizer is then run to find the best-fit parabola, minimizing the residuals between the fitted function and the propagated values at the BPMSW locations. The resulting β_y at the waist is shown in Table 1, alongside the value calculated from the k-modulation.

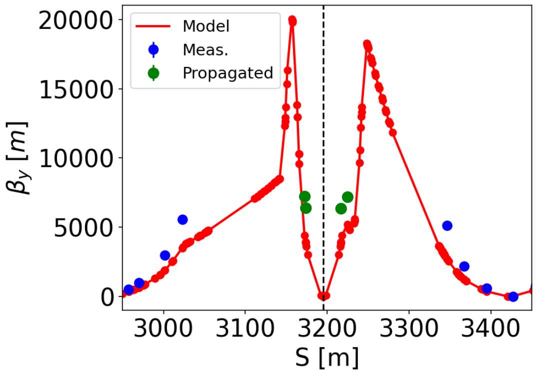

Figure 7: Propagated β_y in the IP1 region.

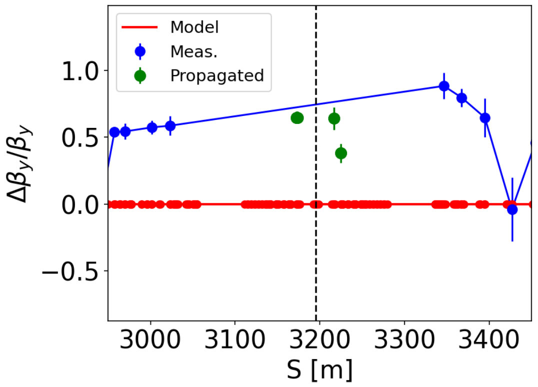

Figure 8: Propagated $\Delta\beta_y/\beta_y$ in the IP1 region.

Table 1: Propagated β_y and β-Waist Estimates

Device	**Prop. β_y [m]**
BPMSW.1L1.B2	6390 ± 170
MQXA.1L1	7240 ± 190
MQXA.1R1	7200 ± 400
BPMSW.1R1.B2	6400 ± 300
β-waist from k-modulation	7.493 ± 0.002 cm
β-waist interpolated from SbS	7.300 ± 0.120 cm

CONCLUSION

The Segment-by-Segment technique has been successfully extended to propagate optics measurements to devices beyond the BPM system, proving to be both versatile and robust across a wide range of LHC commissioning and optics studies. In 2025 and 2026, it was applied to propagate optics parameters to emittance measurement devices, improving the accuracy of emittance estimation. In addition, it provided an independent cross-check of the 2025 MD results, confirming the achievement of a record vertical β-waist of 7 cm at IP1 for Beam 2.

ACKNOWLEDGMENTS

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