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COMPARISON OF SEGMENT-BY-SEGMENT AND ACTION-PHASE-JUMP TECHNIQUES IN THE CALCULATION OF IR LOCAL CORRECTIONS IN LHC

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Abstract

The correction of the local optics at the Interaction Regions of the LHC is crucial to ensure a good performance of the machine. In this paper, we compare two different techniques for local optics correction: Action-Phase Jump and Segment-by-Segment techniques. The comparison is made in view of future machine configurations such as Run 3 LHC optics and HL-LHC optics.

INTRODUCTION

Local corrections of magnetic errors in the interaction regions (IRs) of the LHC are essential to achieve the maximum possible luminosity for the experiments located in these regions and to improve the overall performance of the accelerator. Several techniques have been applied in the past to correct both linear and non-linear optics [1]. However, the demands for LHC Run 3 and its future upgrade HL-LHC require new techniques to provide accurate optics corrections in order to meet the design performance of the machine not only in terms of integrated luminosity but also in terms of luminosity imbalance between the two main experiments: ATLAS and CMS, which must remain below 5%.

Before being used in commissioning or regular operations, new optics correction techniques performance must be tested in simulations and compared to current correction techniques. In this paper we consider the Action and Phase Jump technique [2] as a promising alternative to the current technique based on Segment-by-Segment [3,4] correction in the LHC optics configuration and the performance of both techniques under the same machine conditions is compared.

IR LOCAL CORRECTION TECHNIQUES

In the IR, linear optics is usually corrected locally using the Segment-by-Segment (SbS) technique. However, other alternative methods are considered. In this section the Action and Phase Jump technique is compared to SbS.

Segment-by-Segment Technique

The Segment-by-Segment technique was developed at the LHC for the computation of optics corrections for local, strong error sources. The idea is to run the MAD-X code in a section of the accelerator in between two beam position monitors (BPMs). The optical functions derived from the measured turn-by-turn data are the start parameters of the simulation. For the correction of the optics, the simulated phase advance between BPMs is compared to the measured one. Any deviation between the two values can be, in principle, corrected with quadrupoles inside the segment. This technique has proven to work very well for correcting local optics in the LHC during Run 1 and Run 2. However, for the HL-LHC upgrade, new correction techniques are being explored.

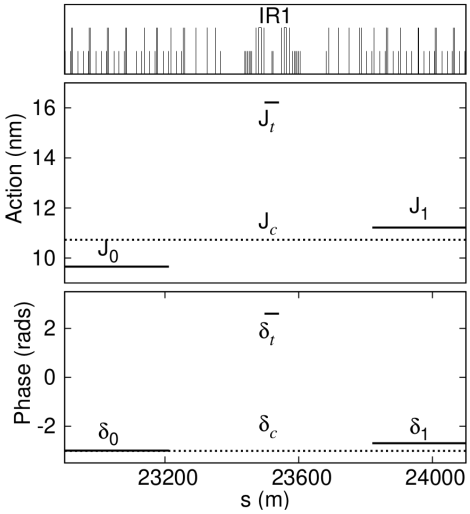

Figure 1: Sketch of the Action and Phase jump technique principle.

Action-Phase Jump Technique

Action and Phase Jump (APJ) technique is one of the available methods to perform magnetic error correction. This method is based in the principle of preservation of Action and Phase variables in the absence of magnetic errors. In Fig. 1 the principle of the Action Phase Jump technique is shown. Before entering the IR, the action is equal to J_0 and changes to J_t due to the magnetic errors present in the left triplet of the IR. Similarly for the phase: it changes from δ_0 before entering the IR to δ_1 after exiting it and at the IP takes the value δ_t. The idea is to use the action and phase jumps to find the magnetic errors or, at least, the corrections that suppress those jumps. A more detailed description of this technique can be found in [2].

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TRIPLET AND MATCHING SECTION QUADRUPOLE ERRORS

In order to accurately reproduce the optics present in the real machine, magnetic errors have been introduced in the triplet quadrupoles and matching section quadrupoles have been included in simulations. In Table 1 the distribution of absolute magnetic errors in the inner triplet and the matching section quadrupoles used in simulations is shown. One can see that the errors assigned to the matching quadrupoles (Q4, Q5, Q6) are particularly high. These values significantly differ from the values reported in dedicated measurements [5]. However, these values are not meant to represent the actual IR magnetic errors and can be interpreted as the effective errors. A more detailed understanding of the nature of these effective errors in the matching section quadrupoles is ongoing.

Table 1: Magnetic Errors Assigned to the Inner Triplet and Matching Section Quadrupoles

Magnet	**Error** $[10^{-5}\text{m}^{-2}]$
Q1L/R	-0.6/0.70
Q2L/R	-1.17/0.74
Q3L/R	-1.31/2.60
Q4L/R.B1	-7.00/5.70
Q4L/R.B2	7.00/-5.70
Q5L/R.B1	-6.86/2.98
Q5L/R.B2	7.01/-3.45
Q6L/R.B1	41.34/-23.71
Q6L/R.B2	-31.51/20.44

SIMULATION METHODOLOGY

The optics used in simulations is the 2016 LHC collision optics with $\beta^* = 40$ cm. This low-β^* optics is particularly sensitive to any non-corrected linear or non-linear errors. These errors are translated into a β-beating and an increase of the β-function at the IP. The errors introduced in previous section have been included in the simulations following a normal distribution centered at 0 with a standard deviation corresponding to the value shown in Table 1 and cut for values beyond 3σ. Tracking data was used to obtain the simulated BPM readings. A transverse displacement in the initial amplitude of the particles was performed. Then, the position at each BPM was recorded for 6600 turns, which is the number of turns usually used during machine measurements. These data were then used as input for both the SbS and APJ algorithms. In addition, data from simulated K-modulation measurements [6,7] was used to obtain a more reliable value for the β-function at the IP. Then, the SbS matching tool used the phase advance between BPMs and the K-modulation data to constrain the algorithm that performs the optimization to find the best correction using the corrector magnets found in the inner triplet region.

CORRECTION COMPARISON

In Fig. 2 and Fig. 3 the residual β-beating is shown for B1 and B2 respectively after applying both methods. When the results obtained using SbS and APJ techniques are compared we can see that the later works better for reducing both the residual β-beating in the ring and for correcting the β-function at the interaction points.

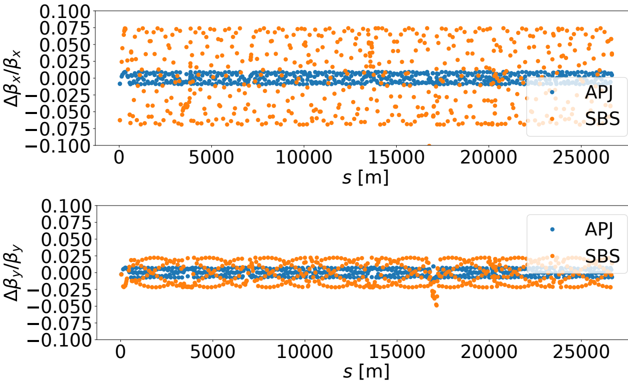

Figure 2: Computed β-beating along the ring for B1 in the horizontal plane (top) and vertical plane (bottom) after adding the errors shown in Table 1.

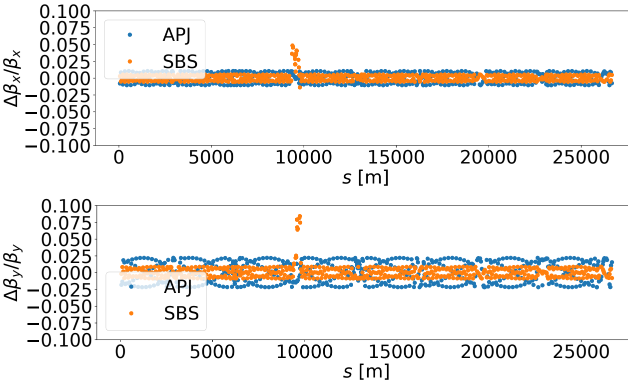

Figure 3: Computed β-beating along the ring for B2 in the horizontal plane (top) and vertical plane (bottom) after adding the errors shown in Table 1.

In Table 2, the RMS and the maximum β-beating before and after correction using APJ and SbS is shown. In particular, using APJ, the residual RMS is always below 2% while SbS technique results in one case with 3.6% rms value. A peak β-beating of 14% is reached for SbS. However, the local deviations observed around IP1 when using SbS significantly affects the total RMS β-beating since, as we can see in Fig. 2, in this case SbS performs better all around the ring but in IR1.

The residual β-beating at the IP translates into a deviation of β^*. In Table 3, the β^* value in IP1 obtained before and after correction using both methodologies is shown for B1 and B2 respectively. We can see that, in general, APJ performs better in the correction and delivers a β^* closer to the nominal value (40 cm). In addition, in the case where

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Table 2: Computed RMS and Maximum β-beating Along the Ring Before Correction and After Applying APJ and SbS Correction Techniques in B1 and B2

	B1		B2	
$\Delta\beta/\beta$ [%]	H	V	H	V
Uncorrected RMS	8.14	12.8	11.8	6.16
APJ RMS	0.63	0.55	0.73	1.57
SbS RMS	2.56	0.85	1.19	3.57
Uncorrected Max	117	98.6	53.6	79.19
APJ Max	0.92	1.08	1.06	2.21
SbS Max	14.5	6.31	4.62	7.08

Table 3: β^* Values Obtained in IP1 Before Correction and After Applying APJ and SbS Correction Techniques in B1 and B2

	B1		B2	
	β^*_x [cm]	β^*_y [cm]	β^*_x [cm]	β^*_y [cm]
Design	40	40	40	40
Uncorrected	87.0	79.4	61	72
APJ	40.3	40.4	39.96	40.5
SbS	45.8	42.5	38.98	38.7

SbS is used, there is a clear β^* imbalance between B1 and B2.

We can conclude that, for the distribution of errors considered, the APJ technique shows a better performance than SbS and hence it looks as a promising technique for optics correction in the LHC.

SMALLER ERROR DISTRIBUTIONS

When the magnitude of the errors considered in the triplet magnets is reduced (Table 4), then both techniques, SbS and APJ, perform on average equally well as can be seen in Fig. 4 and Table 5. Therefore, in future work, one must understand if the error distribution considered in previous section is representative of a realistic error distribution in the LHC.

CONCLUSION

In this paper we have compared two different techniques for local correction of the LHC optics in the IRs: the Action and Phase Jump technique and the Segment-by-Segment technique. Under the assumption that the magnetic errors in the matching section quadrupoles have a significant contribution to the IR β-beating, we have seen that it is very beneficial to include those magnets in the correction procedure. Under these assumptions, APJ techniques shows a better performance over SbS in the correction of the local optics in the IRs. Due to the promising results obtained in the local correction of the IR optics using the APJ technique, this methodology will be applied to different optics with different sets of errors in the IR magnets. The idea is to test this technique during the commissioning of the LHC at the beginning of Run 3 [8]. If this technique proves to be suitable to correct the LHC optics, the next step will be to test it for HL-LHC optics configurations [9]. In [10], preliminary results on the application of APJ on the HL optics are presented.

Table 4: Magnetic errors assigned to the inner triplet and matching section quadrupoles for the case with small errors in the matching section.

Magnet	Error $10^{-5}\mathrm{m}^{-2}$
Q1L/R	-0.6/0.70
Q2L/R	-1.17/0.74
Q3L/R	-1.31/2.60
Q4L/R.B1	0.34/-0.55
Q4L/R.B2	0.23/0.19
Q5L/R.B1	0.25/-0.08
Q5L/R.B2	0.03/0.22
Q6L/R.B1	0.05/-0.009
Q6L/R.B2	-0.12/0.03

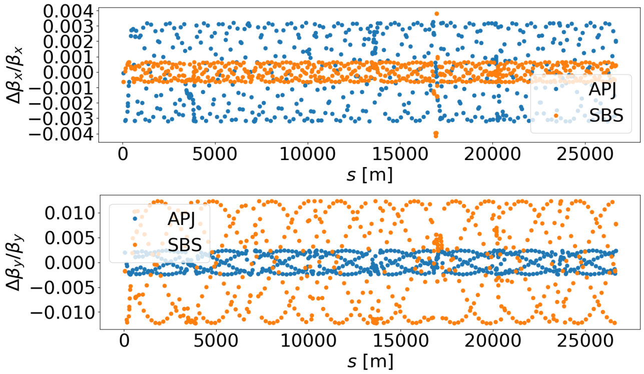

Figure 4: Comparison of the β^* values obtained in IP1 before correction and after applying APJ and SbS correction techniques in B1 and B2 for the case with smaller errors in the matching quadrupoles as shown in Table 4.

Table 5: Computed RMS and maximum β-beating along the ring before correction and after applying APJ and SbS correction techniques in B1 and B2

	B1		B2	
$\Delta\beta/\beta$ [%]	H	V	H	V
Uncorrected RMS	6.10	12.5	13.9	6.22
APJ RMS	0.22	0.17	0.17	0.20
SbS RMS	0.07	0.87	1.48	0.40
Uncorrected Max	102	73.5	79.3	105
APJ Max	0.33	0.26	0.25	0.29
SbS Max	0.41	1.24	2.18	0.59

REFERENCES

[1] T. Persson *et al.*, “LHC optics commissioning: A journey towards 1% optics control”, *Phys. Rev. ST Accel.*

Beams, vol. 20, no. 6, p. 061002, 2017. `doi:10.1103/PhysRevAccelBeams.20.061002`

[2] J. Cardona *et al.*, "Local correction of quadrupole errors at LHC interaction regions using action and phase jump analysis on turn-by-turn beam position data", *Phys. Rev. Accel. Beams*, vol.20, p. 111004, 2017. `doi:10.1103/PhysRevAccelBeams.20.111004`

[3] R. Tomás, M. Aiba, A. Franchi, and U. Iriso, "Review of Linear Optics Measurement and Correction for Charged Particle Accelerators", *Phys. Rev. Accel. Beams*, vol. 20, p. 054801, 2017. `doi:10.1103/PhysRevAccelBeams.20.054801`

[4] R. Tomás *et al.*, "Record low β beating in the LHC", *Phys. Rev. ST Accel. Beams*, vol. 15, p. 091001, Sep. 2012. `doi:10.1103/PhysRevSTAB.15.091001`

[5] J. Coello *et al.*, "MD Tests of a Ballistic Optics", CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2016-0008, Jan. 2016.

[6] F. Carlier and R. Tomás, "Accuracy and feasibility of the β^* measurement for HL-LHC using K-modulation", *Phys. Rev. Accel. Beams*, vol. 20, p. 011005, 2017. `doi:10.1103/PhysRevAccelBeams.20.011005`

[7] M. Hofer, F. S. Carlier, and R. Tomás, "K-Modulation in Future High Energy Colliders", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 476–479. `doi:10.18429/JACoW-IPAC2019-MOPMP022`

[8] T. Persson *et al.*, "Optics Correction Strategy for Run 3 of the LLHC", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper WEPAB027, this conference.

[9] T. Persson *et al.*, "Optics Measurements and Correction Plans for the HL-LHC", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper WEPAB026, this conference.

[10] H. Garcia Morales, R. Tomas, and J. F. Cardona, "HL-LHC Local Linear Correction at the Interaction Regions", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper MOPAB185, this conference.

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