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PROGRESS ON ACTION PHASE JUMP FOR LHC LOCAL OPTICS CORRECTION

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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. This is even more important for the future LHC upgrade, HL-LHC, where the optics is more sensitive to magnetic errors. For that reason, it is important to explore alternative techniques for local corrections. In this paper we evaluate the performance of Action Phase Jump method for optics correction in the LHC and the HL-LHC and explore ways to integrate this technique in regular operations.

INTRODUCTION

The quality of the beam in high luminosity experiments is highly dependent on the correction of linear magnetic errors at the Interaction Regions (IRs) where these experiments are located. In the past, Action and Phase Jump (APJ) analysis [1] has been used to estimate such corrections with results that are comparable to results provided by other techniques such as Segment by Segment (SbS) analysis [2]. For the first time at the LHC, corrections directly estimated with APJ have been used during the last Run (Run 3, 2022) showing very positive results, particularly for the IR where the ATLAS experiment is located. The first part of this paper describes the operational experience with APJ corrections and compares them to the corresponding SbS corrections.

The HL-LHC optics presents special challenges due to the small β functions at the Interaction Point (IP), expected to reach values as small as 15 cm. In the APJ technique, variables such as action and phase in the inter-triplet space depend on the β functions at the IP and therefore the accuracy with which these latter values are measured affect the performance of the APJ technique. Performance studies of the APJ technique applied to the HL-LHC are presented in the second part of this paper.

OPERATIONAL EXPERIENCE WITH APJ DURING RUN 3 OF THE LHC

The measurements used to estimate the corrections with APJ were taken when the beams were circulating with an energy of 6.8 TeV, all the linear corrections in the IRs were off, and the nominal values of β^* at IP1 and IP5 were 30 cm. To apply the APJ technique, TBT data is required. This data was generated by exciting both beams with the AC dipole and recording 6600 turns at all BPMs. This TBT data was preprocessed with averaging techniques [1, 3] and the action and phase plots were obtained around IR5 and IR1 as can be seen in Fig. 1. Average actions and phases in the arcs found in these plots are used to estimate the corrections in IRs. The actions and phases in the inter-triplet spaces are also necessary and they are estimated with the help of K-modulation data [4, 5]. During the measurements, K-modulation data was generated by changing the strengths of the quadrupoles closest to the IPs (Q1s) in IR1 and IR5 and recording the corresponding tunes changes. Once all the required data was available, corrections for IR1 and IR5 were estimated and applied in the machine a couple of days later. Significant reductions in the β-beating around the ring (from 150% to 20% [6]) and in the IPs were obtained as it can be seen in Table 1.

Corrections based on SbS were also estimated, applied, and their corresponding β^* measured as shown in Table 1. According to this Table, the values of β^* obtained from APJ corrections are close to the nominal values for IP1 while the values β^* corresponding to SbS corrections are closer to the nominal values for IP5. Therefore, a combination of both corrections is currently used for regular operations at the LHC.

APJ FOR THE HL-LHC

The effectiveness of the APJ correction for the HL-LHC and whether these corrections lead to a residual β-beating below the specified tolerances (less than 2% peak β beating in the IPs [7]) can be evaluated through simulated TBT data generated with different IR error distributions. Histograms of the residual peak β-beating after applying APJ corrections to 200 IR error distributions for the HL-LHC optics with β^* = 15 cm can be seen in Fig. 2 (simulations for HL-LHC optics with β^* = 30 cm can be found in [8]). The first histogram (red) is obtained assuming the β^* is known without any uncertainty. For that case, it can be seen that the peak β-beating is very low and only a couple of outliers exceed 2%. The β^* is expected to be one of the most critical measurement in the HL-LHC and it has been found that its accuracy will be around 4%. When this error is added to the previous simulations, there is a visible increase in the peak β-beating (green histogram) but still the number of outliers above 2% are moderate. At this point is should be mentioned that correction estimates done with APJ depend on w and β_w, the waist shift and the β function at the waist rather than the β^*. Therefore, to introduce the 4% error in β^*, a shift in w is added to reproduce this error for all 200 different magnetic error distributions.

Besides the uncertainties in the β^* already mentioned, the K-modulation technique has shown systematic unreliable

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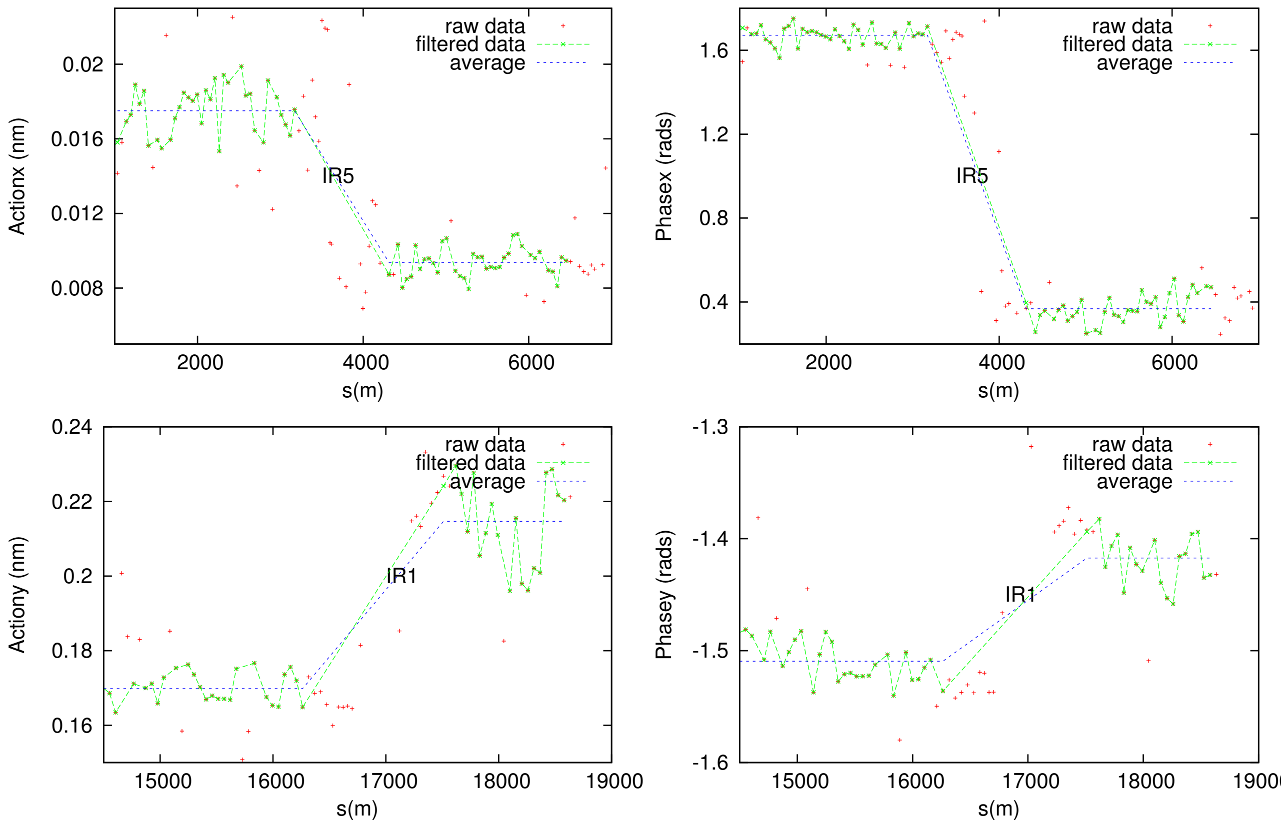

Figure 1: Action and phase plots around IR5 for beam 2 (top) and action and phase plots around IR1 for beam1 (bottom). Average values in the arcs (blue horizontal lines) and in the inter-triplet spaces (no shown) are used to estimate the corrections.

Table 1: The Measured β^* after the Local Corrections Estimated with APJ and SBS were Trimmed in

	IP 1 β^* [cm]				IP 5 β^* [cm]			
	Beam 1		Beam 2		Beam 1		Beam 2	
	H	V	H	V	H	V	H	V
APJ	31.6 ± 0.3	30.9 ± 0.4	29.9 ± 0.1	28.9 ± 0.1	42.6 ± 1.2	35.4 ± 0.6	29.5 ± 0.4	32.2 ± 0.4
SbS	34.5 ± 0.5	31.0 ± 0.3	33.6 ± 0.5	44.0 ± 1.2	39.8 ± 1.0	30.8 ± 0.1	29.3 ± 0.4	30.5 ± 0.1

measurements for low β^* in the LHC with rms uncertainties in the w around 3 cm [9]. The blue histogram shows that these uncertainties lead to corrections with much larger residual peak beta-beating than in the previous case and, hence, they could also be critical for the HL-LHC case.

It also important to identify the dominant sources of uncertainty associated with the APJ technique. This technique uses the actions and the phases in the arcs and in the inter-triplet spaces to estimate the corrections [1, 4]. Previous studies in the LHC showed that the uncertainty contributions from actions and phases in the inter-triplet spaces (J_t and δ_t) are similar to the contributions of actions and phases in the arcs. In the HL-LHC, uncertainties for the actions and phases in the arcs are expected to remain the same. On the other hand, uncertainties in J_t and δ_t are expected to change since they depend on β^*. These uncertainties can be extracted from the above simulations, particularly those simulations performed with a 4% error in the β^*. The corresponding histograms in Figs. 3 and 4 show that the uncertainty of J_t is around 4% and the uncertainty of δ_t is around 0.02 Rads. These values are larger (almost double in the case of J_t) than the values obtained in [4] when other sources of errors were evaluated. This means that the uncertainty in the β^* generates the largest deviations in correction estimates and therefore, it is the dominant source of uncertainty for the APJ technique when used for HL-LHC.

EFFECT OF THE SPLIT QUADRUPOLES ON THE CORRECTIONS

To improve the accuracy of K-modulation measurements in the HL-LHC, the Q1 quadrupoles will be split in two parts, but the number of circuits for correction will remain the same. Concerns are raised about the quality of the corrections because there is an additional source of magnetic errors without compensation. Simulations similar to the one presented in the previous section can be performed to evaluate if the APJ technique is effective for this particular case. A histogram of the peak β-beating was made with no error in

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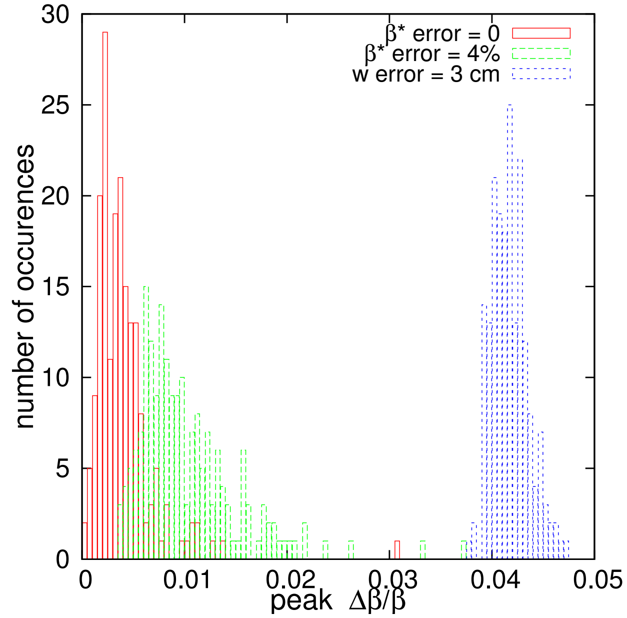

Figure 2: Peak residual β-beating after applying APJ corrections to 200 different IR error distributions. Three different histograms are shown: with no error in β^* (red) , with a 4% error in β^* (green) and, with 3 cm error in w (blue).

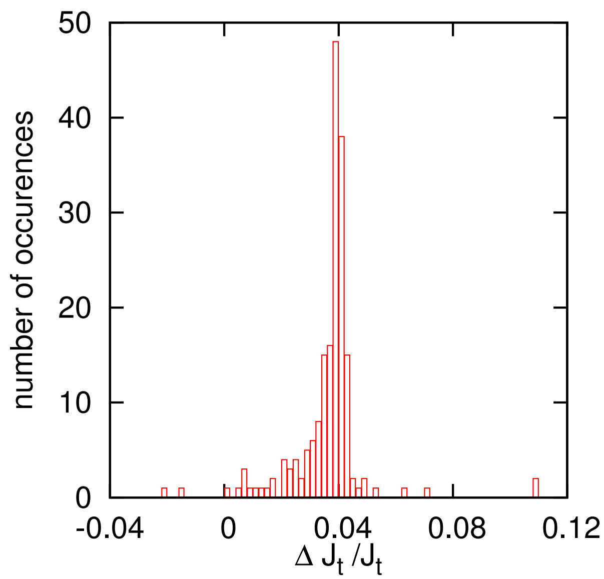

Figure 3: Uncertainty histograms of J_t for 200 IR error distributions in IR1.

β^*, but this time IR error distributions of 8 magnetic errors were used, two more than before to simulate independent errors in each part of the Q1s. The resultant histogram is very similar to the red histogram in Fig. 2 except that there are more outliers. Hence, APJ corrections also work when Q1 is divided but further analysis is required to understand the few additional cases in which the correction is not effective.

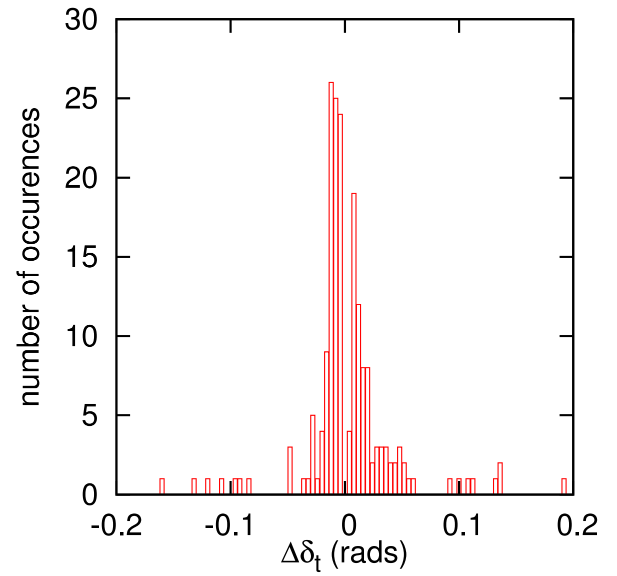

Figure 4: Uncertainty histograms of δ_t for 200 IR error distributions in IR1.

CONCLUSIONS

APJ has been applied in Run 3 of the LHC with very positive results. Corrections based on this method were applied in the IR where the Atlas experiment is located and they are currently used during normal operation of the LHC.

The uncertainty in the value of β^* has been identified as the dominant source of uncertainty in the APJ correction estimates for the HL-LHC.

It has been shown that the APJ method provides effective corrections for the HL-LHC optics with nominal $\beta^* = 15$ cm even considering an error of 4% in the β^*. However, large spreads in the waist shift, such as the one detected during the commissioning of $\beta^* = 30$ cm optics in 2018, may deteriorate the correction leading to a residual peak β-beating beyond 4%.

Finally, simulations show that the APJ method is similarly effective in correcting errors for split quadrupoles using the same number of circuits that are currently used in the LHC triplets except for a few particular IR error distributions.

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