LOCAL OPTICS CORRECTIONS IN THE HL-LHC IR*

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Abstract

For the high luminosity upgrade of the LHC optics correction in the interaction regions is expected to be challenged by the very low β^* and the sizable expected quadrupolar errors in the triplet. This paper addresses the performance and limitations of the segment-by-segment technique to correct quadrupolar and skew quadrupolar errors in the HL-LHC IR via computer simulations. Required improvements to this technique and possible combinations with other correction approaches are also presented including experimental tests in the current LHC IR.

HL-LHC TRIPLET

The High Luminosity upgrade of the LHC targets to increase by a factor 10 the integrated luminosity with respect to the current LHC. The main upgrade from the linear optics point of view will be a β^* of down to 15 cm, an ambitious optics that features the following challenges:

- The peak β-function in the triplet will reach more than 20 km, around 4 times over the current LHC value, increasing by the same factor the effects from gradient and tilt errors in those quadrupoles.
- The new triplet will be actually made of 6 individual quadrupoles each one being an individual sources of errors, but the powering scheme (Figure 1) allows only 4 individual trims, leaving less degrees of freedom to correct than in the LHC.

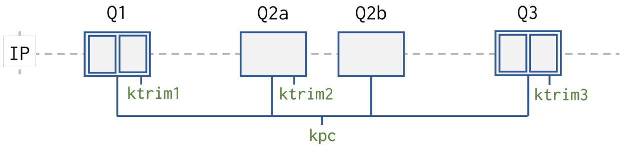

Figure 1: Proposed powering scheme for the HL-LHC triplet. Each group Q1, Q2 and Q3 are composed of 2 individual quadrupoles and the k's represent the different powering circuits

LOCAL β-FUNCTION CORRECTION

Segment-by-segment

The segment-by-segment technique has been used with good success [1–5] to correct strong and localized sources of errors in the machine, like those produced by the triplets. It takes into account only a small part of the machine where strong localized errors are expected to appears, treating these segments as individual beam lines. Measured initial conditions are propagated through the segment and the measured deviations are manually or automatically fitted using the model with errors. The errors found are input then in the machine with the sign flipped to act as correctors.

Phase Measurement Limitations

During past LHC operations the phase advance between BPMs has been used to control the local optics errors of the machine as it gathers the best known properties regarding model and BPM calibration independence [5]. The large β-function around the triplet causes the phase advance in the region to be very small. The size of the phase advance can be smaller than our measurement precision.
This problem will only become worse for the HL-LHC interaction regions. Simulations have shown that using our current methods we will not be able to control locals errors in the HL-LHC by only correcting the measured phase advance (Figure 2). This forces us to search for new methods for accurate corrections in the HL-LHC. Currently there are two options being explored: K-modulation and β from amplitude.

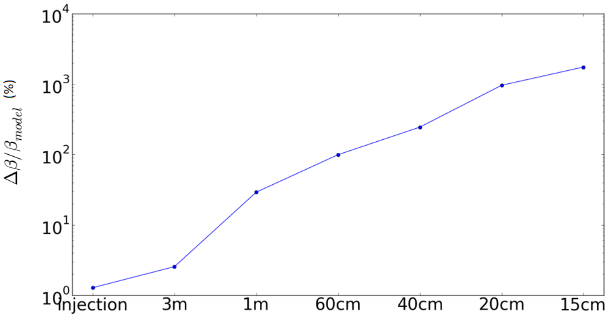

Figure 2: Remaining β-function deviation from the model at the interaction point 1 from triplet field errors in several points during the squeeze, after local correction of the phase advance. Below 1 meter the errors become intolerable for the machine operation.

K-modulation

K-modulation is able to give precise β-function measurement in certain points of the accelerator where we can control the focusing strength of an individual quadrupole. The average β-function at the quadrupole we are modulating is approximately proportional to the change of tune produced

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* Research supported by the High Luminosity LHC project.

by a change on its strength [6].

By modulating the closest quadrupoles of the triplet to the interaction point the β measurement can be propagated to any element in the drift space between them. By feeding the segment-by-segment technique with this information one can precisely control the errors in the surroundings of the interaction point and harmful waist shifts (displacement of the minimum β-function from the interaction point) can be removed (Figure 3).

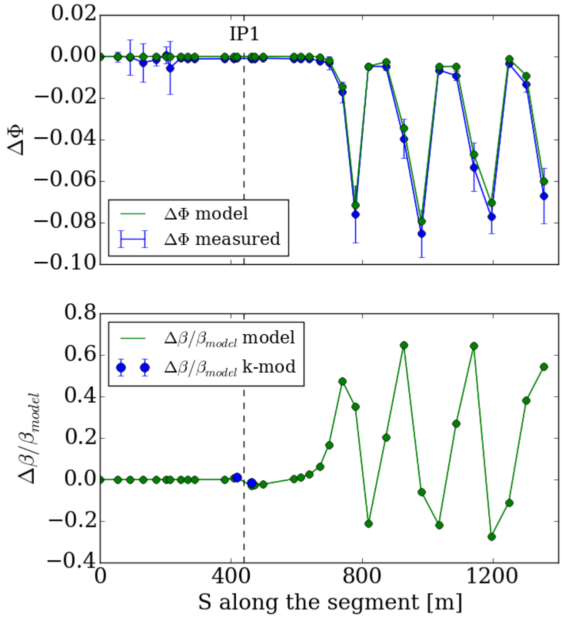

Figure 3: Simultaneous error patter matching of phase and β around IP1, done using the segment-by-segment technique. The upper plot shows in blue the measured error in the phase advance and the corrected model to match the errors in green. The lower plot shows in blue the two points for the beta deviation of the two Q1 magnets measured with k-modulation around the IP and in green the beta deviation of the corrected model to match the k-modulation points.

K-modulation has been successfully used in the current LHC to measure errors in optics with β^* down to 40cm [7–10], it has also been found challenging to use in the HL-LHC [11]

β from Amplitude

The information contained in the amplitude of the oscillation of the particles motion in the accelerator can be used to measure the β-function in the interaction regions without the limitations of the measurements of the phase and to suppress the long time needed to perform k-modulations. The problem here is that the calibration of the beam position monitors (BPMs) is not precise enough to give an accurate measurement of the β-function.

Dedicating some time to perform optics measurements using a special configuration called *ballistic optics* (or *alignment optics*) [12], one can measure precisely the phase in those regions, and use the β-function computed from the phase to find a calibration factor for the BPMs. This calibration is later applied to the β-function computed from amplitude, correcting the BPMs with wrong calibration [13, 14].

LOCAL BETATRON COUPLING CORRECTION

Quadrupole tilts in the triplet can produce very strong and localized sources of betatron coupling. The magnitude of these coupling errors can be measured using resonance driving terms that are given by Eq.(1) [15, 16].

$$f(s)_{\substack{1001\\1010}} = \frac{1}{4[1 - e^{2\pi i (Q_x \mp Q_y)}]} \sum_j k_j \sqrt{\beta_x^j \beta_y^j} e^{i(\Delta\phi_x^j \mp \Delta\phi_y^j)} \tag{1}$$

where $Q_{x,y}$ is the tune and for each tilted quadrupole j, k_j is the effective skew quadrupolar error ($k_j = k \sin(2\delta\Phi)$ with k the strength and $\delta\Phi$ the tilt of the quadrupole), $\beta_{x,y}^j$ the β-function at its location and $\Delta\phi_{x,y}^j$ the phase advance. Having around 20 km β's in some of the triplet quadrupoles, a small tilt will produce a huge coupling.

The two skew quadrupoles correctors in each interaction region are used to counteract these errors and the segment-by-segment technique is used to manually compute corrections. The same strength of the two skew quadrupoles was always used while manually fitting the errors in $f_{1001}(s)$ and $f_{1010}(s)$, as it was easier that way. For lower β^*'s it was found harder to manually fit the error pattern [17] and a new automatic matching tool was developed and tested during 2016 LHC commissioning with success (Figure 4).

Betatron Coupling in the HL-LHC IR

Simulations were performed to study the effect of the HL-LHC IR quadrupoles in the coupling and the efficiency of the corrections in the $\Delta Q_{\min}$ or *closest tune approach* that can be used to quantify the global coupling in the machine [6]:

- The IR1 triplet and matching section quadrupoles (Q4 and Q5) were given a tilt of 0.5 mrad, 1 mrad and 2 mrad r.m.s. Gaussian.
- The behavior of the segment alone was simulated for 100 seeds per tilt angle and the automatic local correction tool applied to it.
- The whole machine was simulated using the errors and their corresponding local corrections and a global correction [18, 19] was applied afterwards to refine the results.
- The remaining $\Delta Q_{\min}$ was computed for each seed, to quantify the success of the correction.

The simulation showed an almost total suppression of the $\Delta Q_{\min}$ (Figure 5), if the strengths of each side corrector is

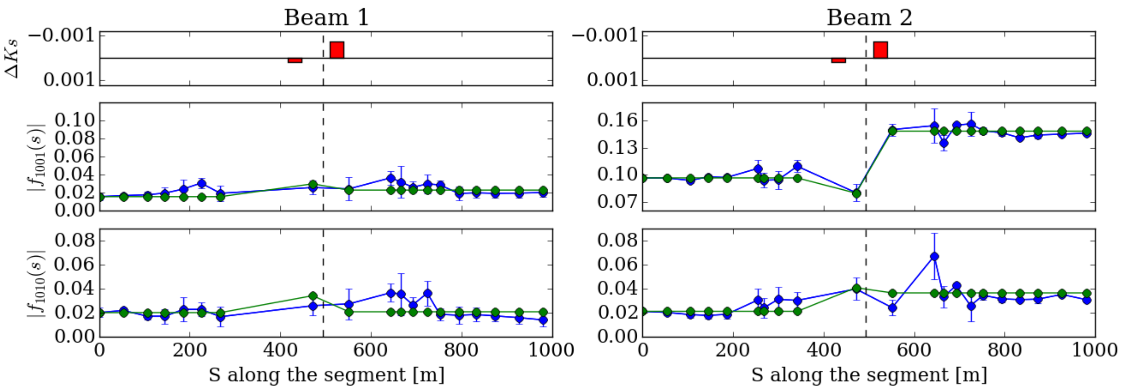

Figure 4: Correction for the betatron coupling of IP1 at a β^* of 40 cm computed using the automatic tool during 2016 commissioning. In blue is shown the measurement of the observables $|f_{1001}(s)|$ and $|f_{1010}(s)|$ and in green the corrected model automatically computed to fit them. The red bars represent the computed trim of the skew quadrupoles. The correction was manually trimmed before being put in the machine.

let to change independently (Figure 6). Around 1% of the simulation seeds had to be removed from the strong coupling. This could be a hint of actual unstable seeds.

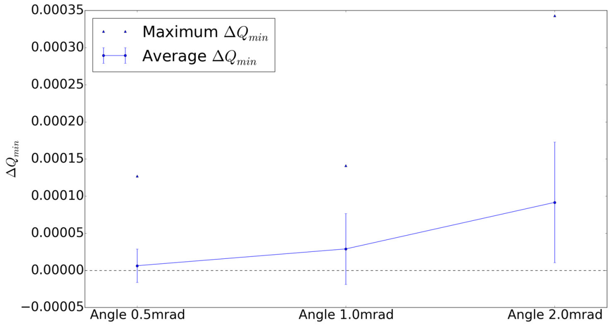

Figure 5: Simulated ΔQ_{min} for different tilt errors in the triplet, Q4 and Q5 of the HL-LHC IR1, after automatic local and global corrections of the betatron coupling, showing and almost complete correction in every case.

SUMMARY AND OUTLOOK

During 2016 commissioning both k-modulation and β from amplitude have been tested successfully in the current LHC, showing that we can use them to control the β-function in the interaction region with β^* down to 40cm.

As we now have those other data sources apart from the phase advance to take into account in the local corrections, the automatic local correction tool [20] can be improved to take advantage of this new information. This will also make it suitable to perform simulations and obtain statistics for the HL-LHC, to test the performance of the new methods for local corrections.

Regarding the coupling correction, the rejected seeds should be carefully reconsidered to avoid a bias in the data shown in Fig. 5. New simulations should be performed under the influence of the expected noise in the relevant resonance driving terms.

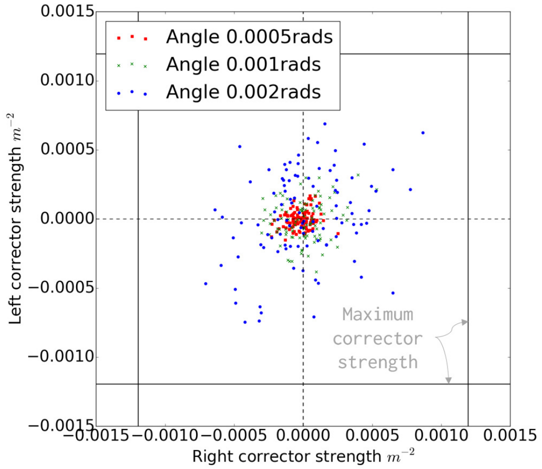

Figure 6: Skew-quadrupole correctors strength in IR1 for the HL-LHC for 100 seeds and different values in the Gaussian tilt angle error of the magnets (triplet + Q4 + Q5). It can be seen that the optimal correctors strength lays far away from the diagonal for a significant amount of seeds.

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