# PROSPECT OF OPERATING WITH LIMITED SKEW QUADRUPOLE CORRECTOR AVAILABILITY IN THE LHC INTERACTION REGIONS *

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## *Abstract*

In the Large Hadron Collider (LHC), corrections of local Interaction Region (IR) linear coupling are of importance to keep a good control of beam sizes at Interaction Points (IPs) and hence the luminosity performance, as well as to prevent a significant impact on the beam dynamics. During the LHC Run 3, the skew quadrupole corrector magnets used on either side of IPs are expected to exceed their radiation dose limit. In this contribution, studies on the impact of operating with limited availability of these magnets are presented, should one or more become inoperable. Mitigation strategies for different scenarios are discussed.

## INTRODUCTION

The Large Hadron Collider (LHC) has resumed operations and entered Run 3 in 2022. After Run 2 has uncovered challenges in IR local linear coupling correction [1–3], a new method was developed to optimize the use of skew quadrupole correctors around the IPs [4–7], the MQSX magnets. The Interaction Region (IR) around point 5 is shown in Fig. 1, where the position of the dedicated correctors is highlighted in green.

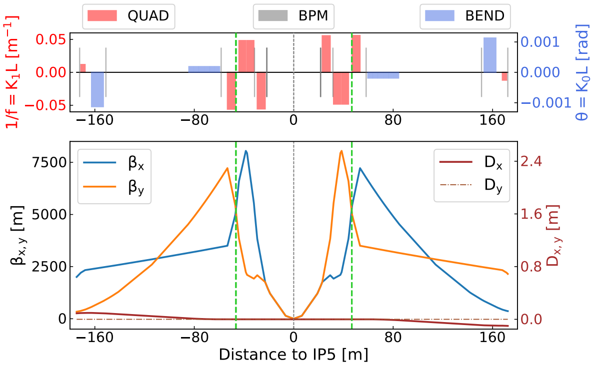

Figure 1: Simplified elements layout and $\beta$-functions around IP5 at $\beta^* = 30$ cm collision optics, without crossing angles.

During commissioning, the initial settings for these magnets are found using the Segment-by-Segment technique [8] in order to compensate for the global coupling originating at the IRs, which are the main contributors in the machine. This first correction is essential in order to reach low $\beta^*$ with good optics control: at $\beta^* = 30$ cm the local errors compensated in Run 2 [2] would contribute to the $|C^-|$ by the amount of 0.33, too high for the arc correctors to handle.

In the second stage, using a Rigid Waist Shift an adjustment to these corrections is determined that would optimize the luminosity by minimizing the coupling at the IP. This adjustment acts through the *colinearity knob*, a powering setting convention that acts anti-symmetrically on the left and right corrector magnets and does not impact the global coupling while inducing a closed coupling bump around the IP [9]. Table 1 provides a definition of the colinearity knob.

Table 1: Definition of one unit of the colinearity knob, a powering setting of the IR skew quadrupole correctors.

| Magnet | $K_{1S}$ [m$^{-2}$] |
|---|---|
| MQSX.3R[IP] → $K_{1S}$ | $+10^{-4}$ |
| MQSX.3L[IP] → $K_{1S}$ | $-10^{-4}$ |

The MQSX magnets' powering settings in the main IRs (IR1 and IR5) are shown in Table 2, as optimized in the 2022 commissioning and used during the year [7].

Table 2: Powering of the MQSX magnets in IR1 and IR5 after optimizations, as used in operation in 2022.

| IR | Circuit | $K_{1S}$ [$10^{-4}$m$^{-2}$] |
|---|---|---|
| IR1 | RQSX.3L1 | 11.5 |
| | RQSX.3R1 | 3.5 |
| IR5 | RQSX.3L5 | 8 |
| | RQSX.3R5 | 4 |

Heat load deposition studies done during LS2 have projected that some magnets in the main IRs will reach their radiation dose limit during Run 3 [10], including the MQSX magnets used for local coupling correction. Table 3 shows the expected total received dose for different magnets in the main IRs, for various scenarios. One can notice that the MQSXs at both IR1 and IR5 are expected to surpass their dose limit during Run 3 regardless of the considered scenario, and it is realistic to expect failures during Run 3.

It is therefore necessary to investigate the operational impact of losing one or more MQSX magnets in the main IRs, specifically in terms of machine safety and luminosity production.

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Table 3: Expected total received dose of the MQSXs in the main IRs [10]. Their radiation dose limit is 7 MGy.

| **Magnets** | **Peak Dose [MGy]** | |
|---|---|---|
| | After 395 $\text{fb}^{-1}$ | After 480 $\text{fb}^{-1}$ |
| MQSX (IR1) | 7.5 | 9 |
| MQSX (IR5) | 8 | 9.5 |

## OPERATING WITH A MISSING MQSX

Should an MQSX stop functioning the priority is to ensure safe machine operation. The following presents the impact of a single corrector failure and investigated mitigation options.

### *Mitigation Options and Luminosity Loss*

Since the skew quadrupole correctors left and right of an IP have similar optics conditions, the contribution of one magnet can be replicated by its counterpart with a similar powering setting. For instance, looking at Table 2, if the MQSX.3R5 were to fail the loss of contribution to global coupling would be that of a $K_{1S}$ of $4 \cdot 10^{-4}\,\text{m}^{-2}$ from an MQSX magnet at this location, which could be compensated by modifying the powering setting of MQSX.3L5 by $4 \cdot 10^{-4}\,\text{m}^{-2}$. In a simulation this would correspond to a trim of $-4$ units of the colinearity knob around IP5 (see Table 1). As such, should one MQSX fail its counterpart could still compensate for the IR's contribution to global coupling.

It would therefore be possible to fulfil the first correction stage mentioned previously and to squeeze the beams down to $\beta^* = 30\,\text{cm}$. Minimizing coupling at the IP, however, would not be possible anymore as it requires trimming both magnets simultaneously. The operational impact of losing one of the correctors would then be that of a potentially strong coupling at the IP.

At the LHC IPs with round beams, the betatron coupling's impact manifests as an increase of the beam size [7, 11]. Simulations were done with the MAD-X code [12] to assess the impact of missing a specific corrector magnet and compensating its effect by carrying its correction setting over to its counterpart. The powering settings from Table 2 were used, and beam size increases were determined from Ripken parameters [13–15], according to [16]. From these, the changes in instantaneous luminosity were calculated according to:

$$\mathscr{L} = \frac{N_1 N_2 f_{rev} N_b}{2\pi\sqrt{\left(\sigma_{x,1}^2 + \sigma_{x,2}^2\right)}\sqrt{\left(\sigma_{y,1}^2 + \sigma_{y,2}^2\right)}}, \qquad (1)$$

where $N_n$ is the number of protons per bunch in beam $n$, $f_{rev}$ the revolution frequency of particles, $N_b$ the number of bunches per beam and $\sigma_{z,n}$ is the size at the IP of beam $n$ in the transverse plane $z$. Figure 2 shows the expected luminosity reduction from the nominal case for various trims of the colinearity knob corresponding to different missing MQSX magnets, for different $\beta^*$ optics.

We find that, should the most powered correctors fail, the instantaneous luminosity at the affected IP would drop considerably at $\beta^* = 30\,\text{cm}$: by up to ≈ 60 %. Importantly, as the powering limit of the MQSXs is $K_{1S} = 25 \cdot 10^{-4}\,\text{m}^{-2}$, it would be possible to compensate for any failing one.

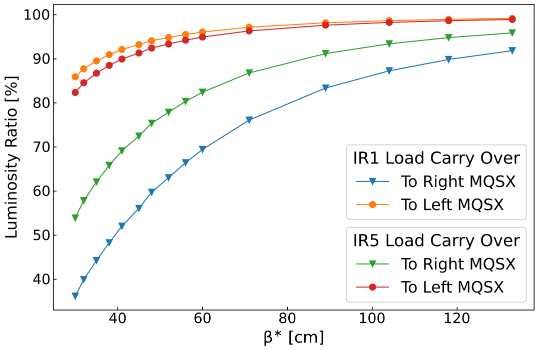

Figure 2: Expected luminosity reduction for various trims of the colinearity knob at IP1/IP5 for different $\beta^*$ optics.

### *Experimental Measurements of Carry-Over*

Measurements were conducted in late 2022 to assess the accuracy of these predictions. A comparison of instantaneous luminosity loss from carrying over the left corrector's powering to the right one at IR1 is shown in Fig. 3, at $\beta^* = 30\,\text{cm}$. Carrying over the correction to the left magnet was not done due to time constraints. Figure 4 shows a similar comparison for IR5, also at $\beta^* = 30\,\text{cm}$. Due to time constraints again, however, the trim could not be fully done when carrying over the correction to the right corrector.

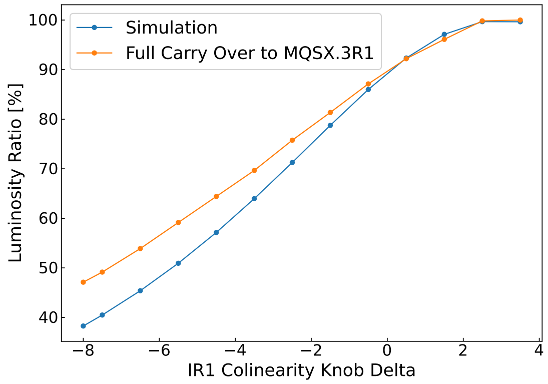

Figure 3: Luminosity drop from correction carry-over to the right MQSX at IR1 at $\beta^* = 30\,\text{cm}$.

Simulations and measurements show a reasonable agreement in both cases. Simulations systematically overestimate the loss of luminosity, but some discrepancy is to be expected as Eq. (1) is a simplified calculation which does not take into account *e.g.* the crossing angles.

### *Impact Through the Operational Cycle*

In Run 3 a $\beta^*$-levelling was introduced in the LHC operational cycle to limit pile-up at the main IPs [17]. As seen in Fig. 2, the luminosity losses depend on the $\beta^*$, thus in

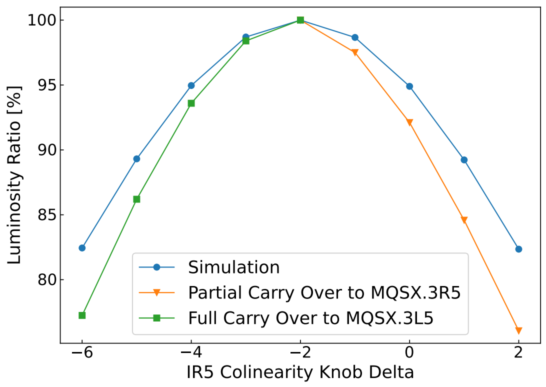

Figure 4: Luminosity drop from correction carry-overs in both directions at IR5 at $\beta^* = 30\,\text{cm}$.

order to keep operating at the pile-up limit one would have to take more frequent steps in the levelling, reducing its overall length, as well as the integrated luminosity over the fill.

For instance, the levelling time would be reduced from 8.2 h to 1.23 h in the worst case, where the MQSX.3L1 were to fail. Studies were done to assess the impact of operating with a single MQSX on the integrated luminosity over a fill, with 2023 settings. The resulting integrated luminosity loss over a day is shown in Fig. 5, for each missing MQSX and for two different baselines of instantaneous luminosity [18].

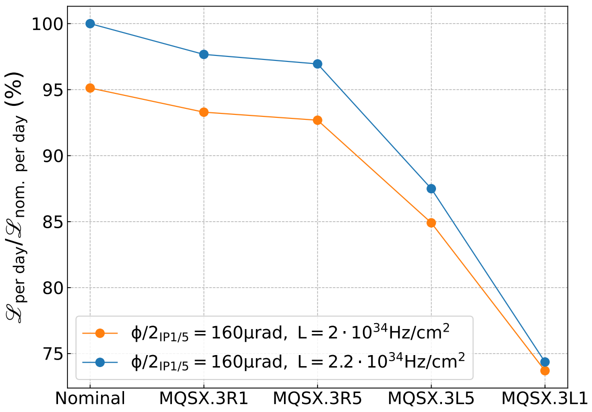

Figure 5: Integrated luminosity loss over a day for each missing MQSX and for two different baselines of instantaneous luminosity.

Over a day the integrated luminosity loss is 25 % for the worst case, failure of MQSX.3L1, relatively to the nominal scenario with an instantaneous luminosity target of $2.2 \cdot 10^{34}\,\text{Hz} \cdot \text{cm}^{-2}$. It was also observed that operating with settings at the Beam-Beam Long Range limit would only improve the loss by a few percents in the worst case.

### *Impact on the Aperture*

The possible impact of this compensation scheme on the aperture was also considered by assessing the relative change in beam size around the IP from such a trim. The checks were performed for the $\beta^* = 30\,\text{cm}$ optics where, due to the high $\beta$-functions, the triplet becomes the aperture bottleneck of the machine. Figure 6 shows the relative change in beam size around IP1 from the most important trim: carrying over the correction of the MQSX left to the one right of IP1.

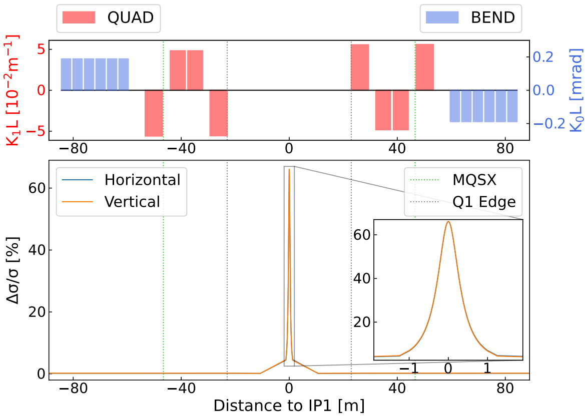

Figure 6: Relative change in beam size from carrying the correction from the left to right corrector around IP1.

In all cases of the most important trim, the beam sizes are significantly affected only in the space between Q1 to Q1, whereas, elsewhere, they are kept close to the nominal ones at less than a 1 % deviation. This specific behavior was also observed in [19] where the coupling RDTs themselves are only significantly affected in the same space for a similar trim. As the drift space right around the IP is not a constraint for aperture limitations, one can conclude that the aperture would not suffer from such a compensation scheme.

## CONCLUSIONS AND OUTLOOK

A good correction of the local linear coupling is essential to ensure operational safety as well as the correct beam size at IPs. Projections suggest that the skew quadrupole correctors used for IR coupling correction could fail in Run 3 due to radiation. Studies were carried on the impact of a single corrector failure both in terms of operational feasibility and impact on the luminosity, and it was shown that collisions could be guaranteed at the price up to 25 % integrated luminosity loss over a day. Should the two correctors at an IP fail, it would not be possible to squeeze the beams to low $\beta^*$ and new solutions would be needed. Preliminary studies are ongoing for such scenarios.

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