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# LHC BEAM COLLIMATION DURING EXTENDED BETA*-LEVELLING IN RUN 3

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*Abstract*

During the third operational Run of the Large Hadron Collider at CERN, starting in 2022, the bunch population will be increased to unprecedented levels requiring to deploy $\beta^*$-levelling of the luminosity over a wide range of values to cope with the limitations imposed by event pile-up at the experiments and heat load on the triplets induced by collision debris. During this levelling, both beam optics and orbit change in various areas of the ring, in particular around the high-luminosity experiments, where several collimators are installed. This requires adapting the collimation system settings adequately, in particular for the tertiary collimators (TCTs) that protect the inner triplet magnets. To this end, two strategies are considered: keeping collimators at fixed physical openings while shifting their centres following the beam orbit, or varying also the collimator openings. The latter strategy is planned when the larger optics range will be deployed. In this paper, we investigate several loss scenarios at the TCTs in different steps of the levelling, and present the proposed collimator settings during Run 3.

## INTRODUCTION

In recent years, the performance of the Large Hadron Collider (LHC) at CERN [1] has been pushed to unprecedented levels [2]. In the present configuration, the maximum instantaneous luminosity is about $2 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$ limited by the cryogenic conditions at the triplet magnets around the high-luminosity experiments and by the number of collisions per beam crossing (pile-up). This limitation requires the use of a levelling scheme [3], where the collider is operated at a constant luminosity with a value below the achievable virtual maximum luminosity of $3.5 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$. Luminosity levelling by changing the colliding $\beta$ function, $\beta^*$, is envisaged. The first successful use of $\beta^*$-levelling at the LHC was done in 2018 after being verified in dedicated tests [4–6]. This was an important milestone for the upcoming high-luminosity upgrade for the LHC [7, 8], where $\beta^*$-levelling is essential.

For the third Run of the LHC (2022-2025), $\beta^*$-levelling will be a part of the operational cycle, with a range from $\beta^* = 60$ cm to 30 cm in the first year, and an extended levelling range from 120 cm to 30 cm in the following years [9]. The optics around the high-luminosity experiments, where the $\beta^*$-levelling is performed, will vary strongly as a function of the $\beta^*$ value. Hence dedicated strategies need to be put in place for the settings of the jaw openings of the tertiary and physics debris collimators in the insertion regions (IRs), which are installed in these areas [10]. The rest of the collimation system is not affected by these local changes.

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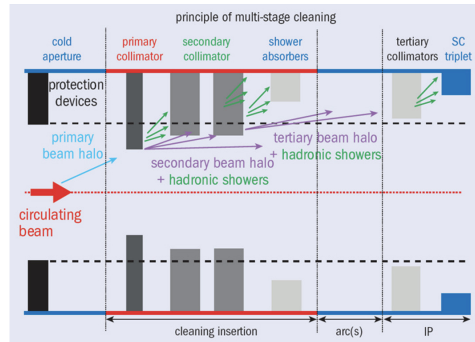


Figure 1: Hierarchy of the LHC collimation system.

## COLLIMATION AROUND EXPERIMENTS

To protect the triplet magnets around the experimental insertions during collisions, the LHC collimation system includes collimators upstream of the interaction point (IP), made of a tungsten alloy and sitting as tertiary stage of the transverse betatron hierarchy, the so-called TCTs (see Fig. 1) [1, 10]. Their half-gap settings are defined at the smallest $\beta^*$, as this is the most constraining case for the triplet aperture. If the TCT settings at smallest $\beta^*$ protect the triplets, they do so for all larger $\beta^*$ in the range considered, so one could keep the same jaw opening in mm for the full $\beta^*$-range. These settings are reported in Table 1. Collimator half-gaps are expressed in RMS beam size units, defined as:

$$\sigma = \sqrt{\beta \epsilon_n / \beta_r \gamma_r}\,, \tag{1}$$

where $\beta$ is the betatron function at the collimator, $\epsilon_n = 3.5\,\mu$m is the nominal normalised emittance, $\beta_r$ is the relativistic speed, and $\gamma_r$ is the relativistic Lorentz factor.

At the Run 3 collision energy of 6.8 TeV, the half-gaps of primary and secondary collimators of the betatron system are set to $5\sigma$ and $6.5\sigma$, respectively. In order to respect the hierarchy, the TCT half-gap should hence be larger than this, including operational margins to account for imperfections studied in detail in [11]. The minimum TCT setting is further limited by the requirement to avoid damage in case of fast failures like asynchronous beam dumps: the TCTs should be shadowed by the dump protection collimator (TCDQ). This sets a tolerance on the phase advance between dump kickers and any TCT, which must be lower than 30°off the optimal (0°or 180°) [11, 12]. Accounting for the phase advance in the Run 3 optics and the available triplet magnet aperture, a TCT setting of 8.5 $\sigma$ will be used at $\beta^* = 30$ cm.

The phase advance between the dump kickers (MKD) and the TCDQ can no longer be kept constant for a levelling range with initial $\beta^*$ above 60 cm [13]. This changes the

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Table 1: IR Collimator Settings in Run 3 with XRP In

| $\beta^*$ | $n_{\mathrm{TCT}}[\sigma]$ 2022 | $n_{\mathrm{TCT}}[\sigma]$ 2023 | $n_{\mathrm{TCL4}}[\sigma]$ | $n_{\mathrm{TCL5}}[\sigma]$ | $n_{\mathrm{TCL6}}[\sigma]$ B1 IP1 | B1 IP5 | B2 IP1 | B2 IP5 |
|---|---|---|---|---|---|---|---|---|
| 120.0 | – | 9.35 | 33.7 | 76.7 | 12.0 | 10.2 | 11.3 | 10.2 |
| 60.0 | 12.0 | 8.5 | 24.0 | 58.3 | 16.3 | 14.4 | 15.6 | 14.3 |
| 30.0 | 8.5 | 8.5 | 17.0 | 42.0 | 20.0 | 20.0 | 20.0 | 20.0 |

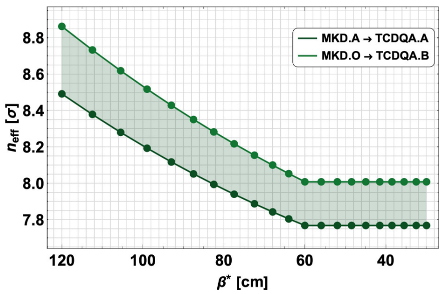


Figure 2: Effective TCDQ gap during $\beta^*$-levelling.

effective gap of the TCDQ:

$$n_{\mathrm{eff}} = \sqrt{n_{\mathrm{TCDQ}}^2 + \left(\frac{n_{\mathrm{TCDQ}}}{|\tan\mu|} + \frac{n_{\mathrm{beam}}}{|\sin\mu|}\right)^2}\,, \tag{2}$$

with $n_{\mathrm{TCDQ}}$ the normalised TCDQ gap, $\mu$ the MKD-TCDQ phase advance, and $n_{\mathrm{beam}}$ an estimate of the relevant beam population (estimated at $\sim 2.5\sigma$). This is illustrated in Fig. 2, where $n_{\mathrm{eff}}$ is shown for the extreme cases among the different LHC dump kickers [1]. As a safe estimate, we take the TCT gap to follow the TCDQ gap (which is nominally $7.3\sigma$), with a margin of $1.2\sigma$ [14], adding the change in effective gap for $\beta^* > 60$cm:

$$n_{\mathrm{TCT}} \geq n_{\mathrm{TCDQ}} + 1.2 + \Delta n_{\mathrm{eff}}(\beta^*)\,. \tag{3}$$

This increases the minimum TCT gap to a maximal value of $9.35\sigma$ at the start of levelling, gradually decreasing towards $8.5\sigma$ at $\beta^* = 60$cm. The TCT settings at all $\beta^*$-steps are reported in [15].

On the other side of the interaction point are the physics debris collimators (TCLs), three per beam and per IP (TCL4, TCL5, and TCL6), and the Roman pots (XRPs), placed between the TCL5 and TCL6, which are movable detectors used for forward physics measurements [16, 17]. The TCLs are at parking until collisions are established. Two configurations are used: if XRPs are not taking data and are out at parking positions, the TCL4 and TCL5 are set at 17 $\sigma$ while the TCL6 remains at parking. When the XRPs are moved in to take data, the TCL5 needs to open to avoid intercepting particles of interest to the XRPs. As a consequence, the TCL6 needs to move in [18, 19].

Taking both the physics requests and protection requirements into consideration, the nominal TCL settings at $\beta^* = 30$ cm are $17\sigma$ for the TCL4, $42\sigma$ for the TCL5, and $20\sigma$ for the TCL6. As the role of these collimators is fulfilled by their jaw openings in mm, their half-gap in beam sigma will change as a result of the changing local betatron function:

$$n(\beta^*) = \frac{\sigma(\beta^* = 30\mathrm{cm})}{\sigma(\beta^*)} n(\beta^* = 30\mathrm{cm})\,, \tag{4}$$

where $n$ is the half-gap expressed in beam sigma, and $\sigma$ is the local RMS beam size calculated at a given $\beta^*$. This is illustrated in Table 1 and Fig. 3, which shows the collimator half-gaps in IP5 for beam 2 as an example. For large $\beta^*$, the TCL6 half-gap would become smaller than the TCT half-gap if the latter stayed at a fixed jaw opening in mm. This would violate the hierarchy. To avoid this scenario, either the TCTs need to be closed more, or the TCL6 needs to be open.

The XRP settings must respect the requirement to have a margin of at least $3\sigma$ and 0.3 mm with respect to the TCT half-gap, i.e,

$$d_{\mathrm{XRP}}[mm] \geq (n_{\mathrm{TCT}} + 3)\sigma_{\mathrm{XRP}} + 0.3\mathrm{mm}\,. \tag{5}$$

The forward physics teams require the smallest XRP settings, with a limit of 1.5 mm defined by the Roman pot design [20].

## STRATEGY IN 2022

In the first year of operation of Run 3, we propose to keep the TCTs and TCLs at a fixed aperture in mm, while shifting their centres following the beam orbit that changes because of variations of the crossing bumps while the local optics varies. This approach has been used in the previous runs, and it is the easiest as it requires no modification to the current hardware interlock implementation. Most of the roman pots can get close enough to their ideal value of 1.5mm, except one which has to remain at 2.3mm. The values at all levelling steps are reported in [15].

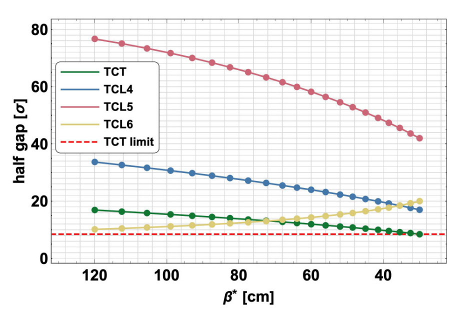


Figure 3: Beam sizes for collimator jaws with settings fixed in mm during extended levelling (IP5 beam 2).

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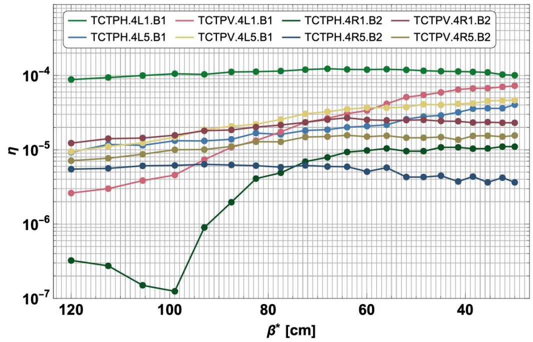


Figure 4: Local inefficiency on the TCT's for different $\beta^*$ values during levelling.

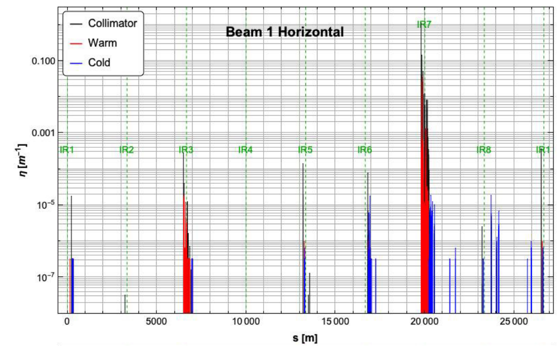


Figure 5: Horizontal loss map for beam 1 at $\beta^* = 30$ cm with moving TCT jaw, simulated using the SixTrack-FLUKA coupling.

## STRATEGY IN FOLLOWING YEARS

There are two motivations to change the strategy in 2023 and onward, where the $\beta^*$ range during levelling will be extended towards larger values. First of all, the situation would not be ideal for the Roman pots, which at larger $\beta^*$ values would be limited to larger settings by Eq. (5). Second, keeping both the TCTs and the TCLs at a fixed opening in mm would result in a hierarchy breaking as illustrated in Fig. 3. One could consider opening the TCL6 to stay behind the TCT, however, this would not alleviate the situation for the XRPs and increase the leakage of collision debris. For this reason, we propose a different scenario, where besides shifting the TCT centres also the half gaps are varied, such that they remain at a fixed half-gap of 8.5 $\sigma$ (and up to 9.3 $\sigma$ for $\beta^* > 60$cm) during levelling.

This strategy is more complex controls-wise since both the TCT jaw positions and gaps are protected by hardware interlocks. The interlock limits are digitally signed Machine Critical Settings (MCS, see [21]) and, as such, must be pre-generated and validated. Once the limits are established and signed, they cannot be altered and only be loaded to the hardware and applied as a whole. Therefore, to change the limits following the $\beta^*$-levelling steps, the limits for the squeeze from 1.2 m to 30 cm must be segmented at the intermediate $\beta^*$ values, each segment must be individually signed, and the segments and their signatures must be stored in the settings database [22].

## COLLIMATION PERFORMANCE

Both aforementioned strategies have been verified in simulations with dedicated loss maps, at every step in $\beta^*$, using the MAD-X [23, 24] model of the LHC and the SixTrack software [25, 26] to track an initial distribution of particles and calculate the resulting losses in the collimation system and the aperture around the ring. This is illustrated in Fig. 4, which shows the losses on the TCTs for the second strategy at the different levelling steps. One can clearly see that the horizontal TCT in beam 1, IP1, which has the largest local inefficiency, is barely influenced by the levelling, while all others remain at acceptable values.

Additional simulations have been performed using the SixTrack-FLUKA coupling software [27–31] at the start- and endpoints of levelling. An example loss map is shown in Fig. 5. No issues have been found in any of the loss maps, and there is very little change between the different loss maps over the different levelling steps.

## CONCLUSION

We explored the impact of the foreseen $\beta^*$-levelling in the baseline Run 3 operation on the LHC collimation system. We defined two different strategies for the settings of the tertiary collimators around the high-luminosity experiments, both adequate from the point of view of the machine and the experiments.

For the first year of operation in 2022, we propose to keep the TCTs at a fixed opening in mm, while shifting their centres following the beam orbit, as successfully done in Run 2. This is the easiest solution that satisfies the hierarchy and machine protection requirements, with tolerable impact on the forward physics settings.

For the following years of operation, 2023 and beyond, we propose to keep the TCTs at the smallest possible normalised half-gap, hence varying their gaps during the levelling process. Their gaps gradually grow for larger values of $\beta^*$. This strategy implies a need to change the current implementation of the collimator limit interlocks, for which a staged commissioning implementation is proposed. It is a more complex strategy, but it provides better performance and flexibility, with an immediate gain for the forward physics experiments that can approach their minimum allowed settings in all phases of the levelling.

Finally, both strategies have been verified in dedicated loss map simulations to be compatible with the projected collimation performance, both using SixTrack and the SixTrack-FLUKA coupling.

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