COLLIMATOR HIERARCHY LIMITS: ASSUMPTIONS AND IMPACT ON MACHINE PROTECTION AND PERFORMANCE

R. Bruce*, R.W. Assmann, L. Lari, S. Redaelli
CERN, Geneva, Switzerland

Abstract

Collimator settings are key parameters for the LHC performance. This paper summarizes first the evolution of the collimator settings, tightly connected to β^*, during the runs 2010–2012, followed by an overview of how the margins between collimator families are calculated. Ongoing work on improving the models of margins between collimator families for optics imperfections is presented. Finally we give an outlook towards the LHC performance after the long shutdown of the LHC and the possible gains from new collimators with integrated beam position monitors (BPMs).

INTRODUCTION

The LHC collimation system [1, 2, 3, 4] should provide both cleaning—the removal of unavoidable continuous beam losses during routine operation—and machine protection in case of failures and abnormal operation. The collimation system is based on a multi-stage cleaning hierarchy, where the different collimator families have to be ordered strictly with different distances to the beam for optimal cleaning performance and machine protection [1]. Closest to the beam, in the IR7 betatron cleaning insertion, are primary collimators (TCP7), followed by secondary collimators (TCS7). Further out are absorbers (TCLA). In IR6, at the beam extraction, are special dump protection collimators (TCS6 and TCDQ). They should be positioned outside of the TCS7 aperture. Furthermore, in the experimental IRs, tertiary collimators (TCTs) made of tungsten are installed in order to provide local protection of the triplets. We call the horizontal TCTs TCTH and the vertical ones TCTV. The TCTs are not robust themselves and should be positioned outside the aperture of the dump protection in IR6 in order to avoid the risk of being damaged during a dump failure [1]. The hierarchy is schematically illustrated in Fig. 1.

LHC collimation is directly related to the performance of the LHC as it limits the achievable β^*. When $\beta^*$is decreased to gain in luminosity, the beam size increases in the inner triplets, so that the margin to the aperture there decreases. In a squeezed optics, the triplets are the limiting aperture bottlenecks of the ring, which must always be protected by the LHC collimation system. Therefore, β^*should be as low as possible without compromising machine protection.

* roderik.bruce@cern.ch

The cleaning and protection are qualified with provoked losses with safe beams after aligning all collimators [5] and, in subsequent high-intensity fills, the collimators are driven back to the previously qualified settings relying on the machine reproducibility. However, the reproducibility is not perfect and drifts may occur, e.g. in the optics or orbit. Therefore, sufficient margins are needed between the collimator families in order for the collimation hierarchy to be respected for all realistic drifts. These margins are calculated using the models outlined in Refs. [6, 7, 8] as a function of the observed machine stability—we give a review of how this is done later.

Thus, starting from the setting of the TCP7, and adding the necessary margin to each family, the required setting of the TCTs can be calculated and, by calculating the necessary margin between TCT and aperture according to the same principles, the minimum aperture that can be protected is defined [6, 7, 8, 9]. By comparing with the required aperture in different configurations of $\beta^*$and crossing angle, the minimum β^*can be calculated.

EVOLUTION OF COLLIMATOR SETTINGS AND β^*2010–2012

The collimator settings used during the previous years for physics operation at top energy, together with the resulting β^*, are shown in Fig. 1. All settings are shown in units of σ_n, which is the nominal standard deviation of the beam, calculated using the local β-functions at the collimators and a normalized emittance of 3.5 μm. Instead we call the real standard deviation of the beam, accounting for the actual emittance, σ_r, which may vary between fills.

In 2010, a safe and conservative approach was taken. A TCT setting of 15 σ_n made sure that even in extremely pessimistic running conditions, the TCTs would never be exposed. In 2011, the margins between IR6, TCTs, and aperture were evaluated quantitatively using new models [6] and it was found that they could be significantly reduced without compromising machine protection. As a consequence, β^*could be decreased from 3.5 m in 2010 to 1.5 m in 2011. Later in 2011, aperture measurements at 3.5 TeV with squeezed beams [10] showed evidence of a well-aligned machine with smaller errors than foreseen during the design phase. The measured triplet apertures, close to the mechanical design value, were used to refine the experimental basis of the calculation models for the reach in β^* [11] and allowed $\beta^*$to be reduced to 1 m keeping the relaxed collimator settings. The results of all the aperture measurements in 2011 are summarized in Ref. [12]. This

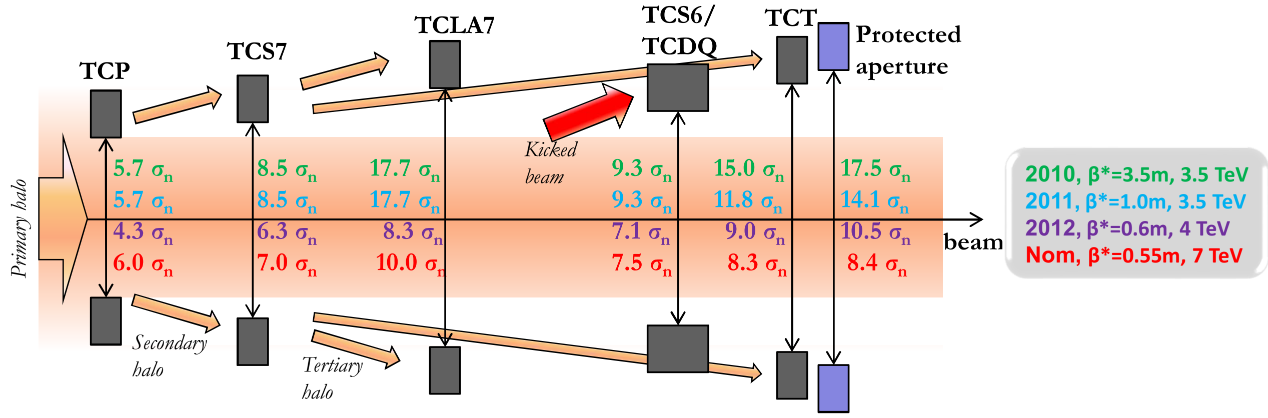

Figure 1: (color) Schematic illustration (not to scale) of the collimator settings and the minimum aperture that can be protected during the physics runs in 2010 (3.5 TeV), 2011 (3.5 TeV), and 2012 (4 TeV), together with the nominal settings (7 TeV).

reduction in $\beta^*$was made possible also by using some margins in the beam-beam separation, which allowed the crossing angle during the $\beta^* = 1$ m operation to be kept at the same value as in the previous operation at $\beta^* = 1$ m.

For the 2012 run, the margins between IR7 collimators were reduced based on experimental studies on the limits of the long-term stability of the collimation hierarchy [13, 14, 15, 16]. The same studies showed also that a closer TCP7 setting was possible without detrimental effects on beam stability, resulting in the so-called tight collimator settings being put into operation. With these settings, the TCP7 achieved a gap in mm similar to the nominal opening foreseen at 7 TeV. Furthermore, the calculation of margins between IR6, TCTs, and aperture was updated and based on a statistical approach, where the different errors were added in square instead of linearly, in order to have a more realistic total error [8]. The combination of tight settings and smaller margins made it possible to squeeze $\beta^*$to 60 cm, resulting in a significant gain in luminosity.

CALCULATIONS OF MARGINS IN HIERARCHY

In this section, we summarize the models used presently (2012 and later) to calculate the margins in the collimation hierarchy, both for cleaning and machine protection. More details can be found in Refs. [6, 7, 8, 9].

TCP7 setting

The first ingredient in the calculation of $\beta^*$is the TCP7 setting—moving the TCP7 closer to the beam allows the rest of the hierarchy to follow, thus allowing a smaller aperture margin and β^*. The TCP7s cannot, however, be positioned so far in that they scrape significant fractions of the beam core, which constrains the settings to above 3–4 σ_r.

Furthermore, the impedance of the collimators and the risk of instabilities increase with tighter gaps [17]. Recent calculations indicate that the contribution of the TCPs to the total machine impedance is less than 30% [18].

Another reason for not having too small gaps is that this is more demanding for the orbit correction - if the orbit makes a sudden jump, more beam is scraped off at the TCP7s with a tight setting, possibly resulting in large losses or beam dumps.

Exact theoretical predictions of these limitations are very challenging. Therefore, the tight TCP7 setting used during the 2012 physics run was based on beam tests carried out at different occasions during the 3.5 TeV operation in 2011 [13, 14, 15, 16]. All collimators were moved to tighter gaps and a TCP7 setting of 4 σ_n was qualified at 3.5 TeV (to be compared to the 5.7 σ_n used in physics in 2011).

Margins for cleaning

The margins for cleaning, between TCP7 and TCS and TCS and TCLA in IR7, and between IR7 and IR6, are although important, less critical than the margins for machine protection. If the hierarchy would break and a TCS7 would intercept primary halo, the cleaning efficiency risks to drop, possibly causing beam dumps and the loss of valuable integrated luminosity for the experiments. Although this scenario should evidently be avoided, it does not imply an immediate danger for the LHC and it can be corrected if observed (for example by realigning the collimators or increasing the margins).

During 2010 and 2011 these *non-critical* retractions were kept constant in mm after the injection plateau (so-called relaxed settings [19, 20]). In order to decrease the non-critical margins as much as possible for the 2012 run, the limit for breaking the hierarchy after a long time of operation without re-aligning collimators was explored empirically in 2011 [13, 14, 15, 16]. Based on these studies, the retraction TCS7-TCP7 was reduced from 2.8 σ_n in 2011 to 2.0 σ_n in 2012. Note though that σ_n is not the same in the two cases, as the geometric emittance changes with energy.

The margin between TCS7 and TCS6 in the relaxed scheme was 0.8 σ [20], which was found to be already rather tight and close to the nominal retraction. Therefore, the 0.8 σ_n retraction TCS6-TCS7 has been kept unchanged in 2012.

The cleaning margins in the momentum cleaning in IR3 do not presently impose direct limitations on the machine performance and have been kept at the same relaxed setting in 2012 as in 2010-2011.

Margins for machine protection

The margins between the dump protection and the TCTs, or between the TCTs and the aperture, are needed for machine protection. If an asynchronous beam dump occurs with an incorrect hierarchy, fractions of one or several bunches could possibly impact and damage either the TCTs themselves or the aperture bottlenecks that they should protect [1, 21].

To calculate these *critical* margins between IR6 and the TCTs, and between TCTs and aperture, an in-depth analysis is performed. All factors that change the hierarchy have to be considered and combined. They are: orbit drifts, optics errors, setup error (inaccuracy of the collimator alignment), and positioning error (fill reproducibility of the collimator position). We work in the very conservative simplifying assumption of a 90° phase advance from the dump kickers to all subsequent collimators and aperture bottlenecks. This is approximately true for the dump protection (94° from the central kicker) while TCTs and triplet have phases farther away from 90°. This is clearly a pessimistic assumption, which gives room for the worst possible phase advance errors. A more detailed model, which accounts for the actual phase advance and the areas of the initial phase space that reach downstream apertures, is discussed later.

To assess the orbit margin, we calculate the reduction in margin caused by orbit movements with respect to the orbit that was used during the qualification. This calculation is performed using logged data from the run in the previous year. The change in *minimum* margin ΔM_{min} between a protection device (subscript 1) and a device to be protected (subscript 2) is [7]

$$\Delta M_{min} = |x_{r2}| - |x_{r2} + \Delta x_2 \pm \Delta x_1|. \qquad (1)$$

Here x_{ri} is the offset of the reference orbit at the time of the qualification at device i with respect to the center of the aperture, and Δx_i the change in orbit since then. All quantities are given in units of σ_n. If the device 2 is a collimator, which was centered around the beam at the time of the qualification, we set $x_{r2} = 0$.

As an example, Fig. 2 (top) shows the distribution of the obtained reduction in margin due to orbit movements between the vertical TCT in IR1 beam 1 (B1) and the triplet aperture during 2012. The orbit was sampled and analyzed every 10 s during stable beams in all physics fills. The observed orbit shifts are dominated by the fill-to-fill variations. Fig. 2 (bottom) shows the corresponding distribution for IR5 B2 in the horizontal plane. Here the distribution is not centered around zero—instead, there is a non-zero average shift in the orbits in stable beams from the reference orbit at the qualification. A shift of the center was observed also for the cases not shown in Fig. 2, although smaller than for IR5 B2.

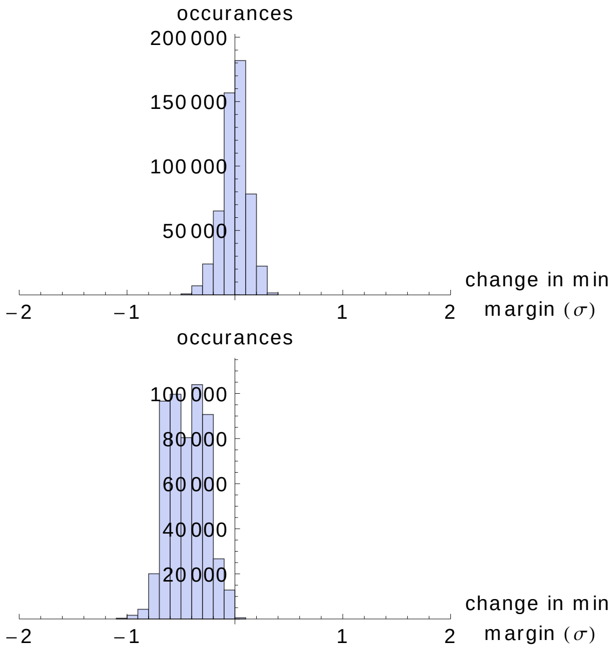

Figure 2: Change in margin due to orbit movements between the IR1 TCTV in B1 and the aperture bottleneck in triplet (top) and the corresponding distribution for the TCTH in IR5 B2 (bottom). All running periods in 2012 with stable beams and $\beta^* = 0.6$ m were accounted for, except where luminosity scans were performed. A negative change corresponds to a reduced margin.

Using the distribution of the reduction in margin, we calculate the final needed margin by demanding that it should be respected during at least 99% of the time spent in stable beams, which results in acceptable risk levels [6, 8].

The needed margin M_β for β-beat is [6]

$$M_\beta = n \left(\sqrt{\frac{\beta_n}{\beta_r}} - 1 \right), \qquad (2)$$

where we assume that the β-function has the value β_r instead of the nominal β_n. It should be noted that M_β depends only on the amount of β-beat and the nominal opening of the collimator—the smaller the opening, the smaller the absolute error in σ_n. We use an upper bound of 10% on the ratio of the β-functions [22, 23, 24].

The remaining margins for setup and positioning are assigned constant values of 10 μm and 50 μm respectively [6]. This typically corresponds to less than 0.1–0.2 σ_n. Furthermore, we assume a margin of 0.2 σ_n for lu-

Table 1: The estimated errors in units of σ_n from various error sources at the dump protection in IR6 and the TCTs.

(σ_n)	IR6	TCT
orbit	1.1	1.1
β-beat	0.35	0.4
Positioning	0.08	0.05
Setup	0.02	0.01
Lumi scans	—	0.2

minosity scans as calculated for the drifts between TCT and triplet at $\beta^* = 3.5$ m in Ref. [6]. This margin has proven to be sufficient also for larger scans to $\pm 3\sigma_n$ at smaller β^*.

To calculate the final margins, all errors at devices 1 and 2 have to be combined. In 2010 and 2011 the maximum possible error, given by the linear sum, was used. This method, although extremely safe, requires rather large margins, which in turn implies a larger β^*. Since it is highly unlikely that all errors would simultaneously assume their maximum values and add up in the same direction, we deploy a more moderate approach and treat the errors as statistically independent by summing them in square. Exception to this rule are the luminosity scans, since they are caused by a deliberate perturbation. In conclusion, we therefore obtain the total margin M_{tot} as

$$M_{\text{tot}} = M_{\text{scan}} + \sqrt{M_\beta^2 + M_{\text{orbit}}^2 + M_{\text{pos}}^2 + M_{\text{setup}}^2}.$$

As an example, obtained numeric values for the different components of the margins used at IR6 and at the TCTs in 2012 are shown in Table 1. As can be seen, the dominating error source is the orbit, followed by the β-beat.

ONGOING IMPROVEMENTS ON MARGINS FOR MACHINE PROTECTION

Although the margin models described in the previous section have allowed a significant reduction in β^*since 2010, they are still based on assumptions that under some circumstances are pessimistic, e.g. the assumed 90° phase advance from the dump kickers. To understand the influence of the phase advance on the needed margins, we consider the normalized betatron phase space (X_0, P_0) of one bunch at an extraction kicker, where it receives a kick θ. Using linear optics, the normalized phase space coordinates are propagated to any later position (X_i, P_i). The condition that a particle is outside the aperture A_i at location i can then be written as:

$$|X_i| \geq A_i \Leftrightarrow |C_{0i}X_0 + S_{0i}P_0 + S_{0i}\theta + D_i\delta| \geq A_i \quad (3)$$

Here (C_{0i}, S_{0i}) are the transfer matrix elements from 0 to i, D_i the periodic dispersion at i and δ the fractional momentum deviation.

The inequality (3) defines a region R_i in the initial phase space at the kick. Analogue to the method used in Ref. [25], the fraction of particles outside the aperture limit A_i is given by integrating the beam distribution ρ over R_i. If there are other aperture restrictions A_j with $j < i$ upstream of A_i, the integration region defining the particles hitting A_i is the phase space area inside all aperture limits A_j (denoted by the complement set R_j^c) but outside the aperture limits A_i.

The fraction f_i of particles outside A_i thus becomes

$$f_i = \iiint\limits_{R_i \cap R_{i-1}^c \cap \ldots \cap R_1^c} \rho(X_0, P_0, \delta)\, \mathrm{d}X_0\, \mathrm{d}P_0\, \mathrm{d}\delta. \quad (4)$$

In order to calculate the leakage fraction, we assume furthermore that ρ is Gaussian:

$$\rho(X_0, P_0, \delta) = \frac{1}{2\pi\sigma_n^2} \exp\left(-\frac{X_0^2 + P_0^2}{2\sigma_n^2}\right) \times \frac{1}{\sqrt{2\pi}\sigma_\delta} \exp\left(-\frac{\delta^2}{2\sigma_\delta^2}\right) \quad (5)$$

As an example, the leakage integral in Eq. (4) and its integration regions, taking into account only the dump protection situated at 7.1 σ_n as in 2012 and all TCTs are illustrated in Fig. 3 for $\beta^* = 60$ cm assuming a perfect machine. Each collimator is represented by a cut in the initial phase space, where earlier cuts shadow later ones. For easier readability, the IR7 collimators are not shown.

The TCT receiving the highest leakage in this case—evaluated numerically with *Mathematica* to 3‰ of the initial bunch at this particular θ, where half of the bunch passes the dump protection—is in IR1 B1 and we therefore focus on this collimator. The total impacts that it will see during a dump failure is Eq. (4) summed over all bunches, each having a different kick angle θ.

In Fig. 4 we show this summed leakage over all bunches, assuming a 50 ns bunch spacing, to the IR1 TCTH as a function of the retraction between the TCS6 and the TCTs. The results were obtained by keeping the TCS6 opening constant and checking the leakage for different TCT openings, using the kick angles for a single module pre-fire (1 of the dump kickers fires and the other follow after short delays). The exact form of $\theta(t)$ provided by Ref. [26] was used. This is considered as the worst dump accident in terms of beam risking to hit sensitive equipment. The results are obtained by considering 1000 random non-perfect optics configurations, with an average resulting β-beat of 10–15%. The point shown for every TCT retraction is the leakage which is larger than 99% of the studied scenarios.

In Fig. 4, we have included also the TCT 7 TeV damage limits as given in Ref. [27], and the same limits scaled by the energy ratio to 4 TeV. These limits were calculated assuming a fixed impact parameter of 0.5 mm for a single bunch and can be improved using our studies where instead fractions of several bunches impact.

We show two limits: both when plastic deformation starts to occur, and when particle detachment occurs. Above the latter limit, a considerable downtime of the LHC has to be envisaged. Between these two thresholds, the TCTs can be moved orthogonally to the collimation plane

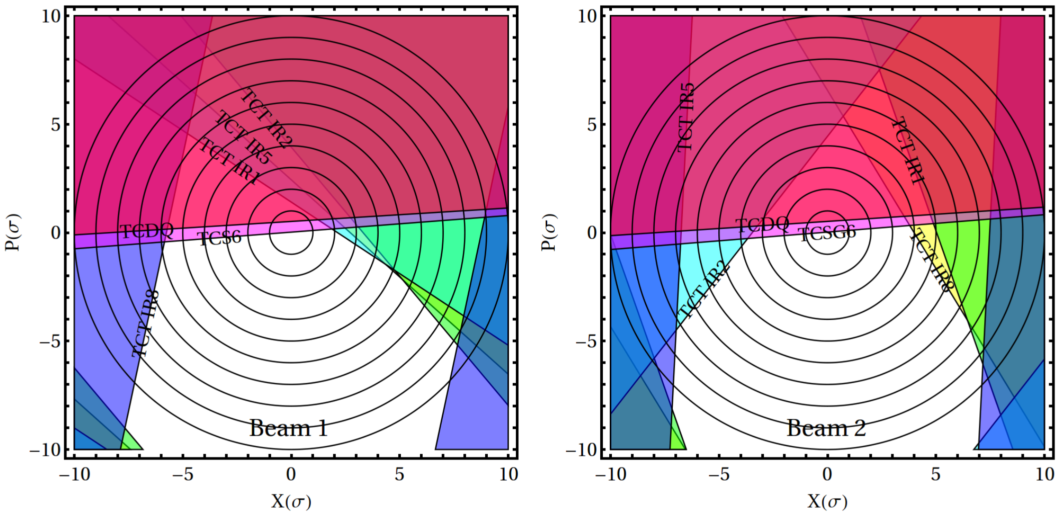

Figure 3: Example of the on-momentum integration regions defined by Eq. (3) for the dump protection collimators (TCS6 and TCDQ) and all TCTs in B1 (left) and B2 (right) for a setting of 7.1 σ_n for the TCS6 and the TCTs, while the TCDQ is positioned at 7.6 σ_n. The kick θ is also at 7.1 σ_n and a perfect machine is assumed. The circles represent lines of constant phase space density at every σ_n. The TCDQ is the first collimator seen by the beam, followed by the TCS6 and the TCTs. A perfect optics and $\beta^* = 60$cm was assumed.

to expose a fresh undamaged surface to the beam. Comparing to the assigned margin used in the 2012 run of 0.55 σ_n, we see that this was sufficient to be below even the 7 TeV limit for plastic deformations. This confirms that the method based on shadowing described in previous sections gives safe results but slightly on the pessimistic side. The protection was thus largely sufficient during the 2012 run.

Furthermore, out of the 1000 studied optics configurations we study the one with the highest leakage in more detail. This case has been simulated with a modified version of SixTrack [28, 29]. This simulation setup is more accurate than the numeric integral in Eq. (4), since non-linearities and out-scattering from the collimators are accounted for, but at the same time significantly slower in terms of CPU time, which makes it impractical to study many configurations.

As an example of the SixTrack result, Fig. 5 shows the simulated losses around the LHC for the most critical bunch. As can be seen, the TCT in IR1 receives a very significant leakage, and, summed over all bunches, the integrated intensity hitting it is about 30% of a bunch. The coordinates of the inelastic interactions on the TCTs are available as starting point for further studies of energy deposition and structural analysis, as was done in Ref. [27]. This could in turn allow updated damage limits.

Our model for integrating the fractions of a bunch hitting a certain aperture bottleneck can also be updated to include random errors for the other sources, which will allow an alternative coherent model to calculate the margins.

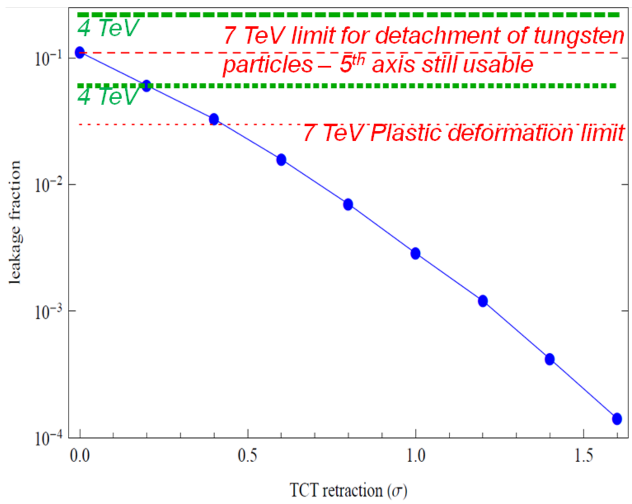

Figure 4: The integrated leakage to the TCTH in IR1, B1, during a single-module pre-fire dump accident, summed over all bunches with 50 ns spacing for an optics with β^*=60 cm, as a function of the retraction between the TCS6 and the TCTs. The leakage fraction is expressed in units of 1 nominal bunch. The point shown for every TCT retraction is the leakage which is larger than 99% of the studied scenarios.

COLLIMATION AND β^*REACH AFTER LS1

Upgrades and maintenance of the collimation system are planned to take place during LS1. One upgrade is of importance for the calculation of the hierarchy margins and β^*: the replacement of all TCTs and TCS6 by new collimators

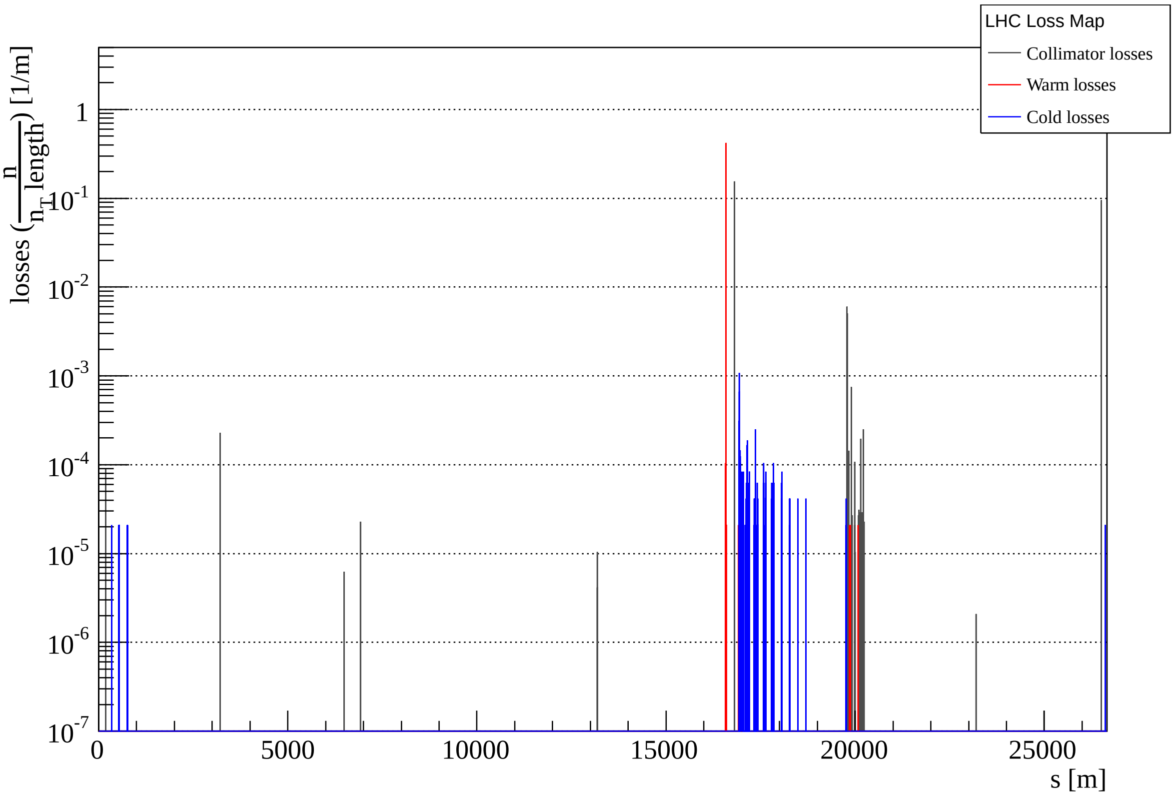

Figure 5: Loss map around the LHC, as simulated with SixTrack, for the bunch in a train causing the highest losses on the TCTs during a single-module pre-fire dump accident.

with integrated beam position monitors (BPMs). Several successful test have been performed previously with a prototype in the SPS [30]. These new BPM collimators can be aligned without touching the beam [31]. Thus, the alignment does not require special low-intensity fills. This drastically reduces the setup time and therefore increases the flexibility of the configurations of the experimental IRs in terms of $\beta^*$and crossing angle.

Furthermore, if the TCTs and TCS6 would always be centered around the real orbit with high precision, the margins for orbit in the collimation hierarchy could be significantly reduced, which would make room to squeeze $\beta^*$to smaller values. As potential gain we assume that the collimator can always be centered around the orbit within 50 μm, which is an upper limit given by the SPS measurements [30]. Such a reduction is, however, non-trivial, since allowing the collimators to move automatically during a high-intensity fill using a feedback algorithm implies in itself a machine-protection risk. Possible solutions could involve interlocking either the collimator movement or the orbit as read out by the collimator. Another option could be to insert the orbit measured by the collimators into the orbit feedback, although the gain is unclear as the default mode of the feedback does not necessarily correct local errors. Furthermore, the strategy required in case of a faulty BPM reading is still to be specified. As the detailed scheme for moving and interlocking the BPM collimators is yet to be decided, the gain in terms of $\beta^*$is likely not to be usable directly after the startup after LS1, but rather after some time of operation and beam experience.

Using the same models as used for the 2012 run, the margins in the collimation hierarchy can be calculated for the next LHC run scheduled to start in 2015 at 6.5 TeV. For the non-critical margins in IR7 we consider several different scenarios. If constraints from beam losses induced by tighter settings [32, 33] turn out not be limiting, the option where the 2012 settings in mm are retained is a safe and stable choice from the operational point of view—the cleaning hierarchy showed an excellent stability during 2012. Possibly this could be used directly after the restart. A slightly more pushed scenario, which could be introduced later, is to keep the 4 TeV retractions in σ_n, which implies smaller gaps in mm. This scenario might require more frequent collimation setups, but allows a gain in β^*.

At the time of writing, it is not clear how severe possible performance limits related to the collimator gaps will be after LS1 [32, 33]—e.g. there is a risk that octupoles will be needed to stabilize the beam and that the available current will not suffice or that beam losses caused by orbit jitter become critical. If the impedance turns out to be limiting, it is not clear by how much the settings have to be relaxed but, in order to approximately quantify the loss in performance, we study one scenario with relaxed settings, where the openings in mm in IR7 and IR6 are increased

Table 2: Settings, of different collimator families, for different scenarios for 6.5 TeV operation after LS1, where either the 2012 settings are kept in mm, in σ_n or more open (relaxed). We show also the resulting reach in $\beta^*$and the corresponding crossing angles ϕ for two different configurations of filling scheme (25 ns bunch spacing assuming 12 σ beam-beam separation needed, and 50 ns bunch spacing assuming 9.3 σ beam-beam separation) and normalized emittance ϵ_n.

Settings	Relaxed settings without BPM	mm settings kept, without BPM	σ settings kept, without BPM	mm settings kept, with BPM	σ settings kept, with BPM
TCP7 (σ_n)	6.7	5.5	5.5	5.5	5.5
TCS7 (σ_n)	9.9	8.0	7.5	8.0	7.5
TCLA7 (σ_n)	12.5	10.6	9.5	10.6	9.5
TCS6 (σ_n)	10.7	9.1	8.3	9.1	8.3
TCSDQ6 (σ_n)	11.2	9.6	8.8	9.6	8.8
TCT (σ_n)	12.7	11.1	10.3	10.0	9.1
protected aperture (σ_n)	14.3	12.6	11.7	11.2	10.3
25 ns, $\epsilon_n = 3.75$ μm, 12 σ beam-beam separation					
β^*(cm)	72	60	55	52	46
$\phi/2$ (μrad)	165	180	189	194	205
50 ns, $\epsilon_n = 1.6$ μm, 9.3 σ beam-beam separation					
β^*(cm)	52	43	38	35	31
$\phi/2$ (μrad)	98	108	115	119	127

by 23% compared to 2012. This value, which corresponds to a TCP7 setting of 7.1 σ_n at 6.5 TeV, has been obtained as a very rough estimation by assuming that the beam was stable in 2012 with 510 A octupole current at 4 TeV. The needed octupole current has then been scaled with energy and the square root of the gap, which is more pessimistic than the cubic root and is approximately valid at lower frequencies, to obtain a stable beam at 6.5 TeV and with a 550 A octupole current (the maximum allowed with the present hardware). These collimator settings are, evidently, less performing in terms of $\beta^*$and should only be used if the other tighter settings provoke too high beam losses.

Calculated collimator settings, for all these options, as well the aperture that can be protected, are presented in Table 2. Results are shown both with and without the additional gain in margin that the BPM button collimators could bring.

Given the aperture that can be protected, the reach in β^*at the high-luminosity experiments can be calculated, by considering the needed aperture as a function of β^*. This function varies depending on the assumptions that are made on the needed crossing angle, which in turn depends on the real beam emittance and the needed beam-beam separation. Several possibilities are available for the post-LS1 operation: one option uses 25 ns beams, with the envisaged emittance of 3.75 μm or with a new scheme from the injectors possibly delivering 1.9 μm. The other option would be to stay with 50 ns beams either with emittance of 2.5 μm as achieved in 2012, or using the new injector scheme, possibly providing 1.6 μm. The needed aperture as function of $\beta^*$is shown for the crossing plane for all these options in Fig. 6, as well as for the separation plane, where it has been assumed that the parallel separation remains at a value scaled from the previous 4 TeV operation. The shown values have been calculated by scaling the measured 2012 aperture [34] using the models described in Refs. [6, 8, 7].

The possible values in $\beta^*$are shown for the two extreme beam configurations in Table 2. As can be seen, a wide range of β^*values are possible between about 30 cm and 70 cm. The final β^*will be known once the collimator settings and the beam conditions are decided. The choice has to account for the intricate interplay between beam stability, i.e. the increased risk of high beam losses and dumps with tight collimator settings, and the peak luminosity. The choice should be made in order to maximize the delivered integrated luminosity. Before the final decision is taken, it is also necessary to perform new aperture measurements to validate that the aperture has not changed during the shutdown or that other effects decreasing the margins in the experimental IRs, such as spurious dispersion, do not become too important.

SUMMARY AND OUTLOOK

The LHC collimators are ordered in a strict hierarchy and the critical margins between families are calculated using a detailed error model including e.g. orbit movement and optics errors. The resulting aperture that can be protected by the collimation system imposes a limit on the achievable β^*. During the previous LHC run in 2010-2012, the collimator settings were optimized to squeeze β^*as much as possible. Based on theoretical and experimental studies on minimizing the margins in the hierarchy without compromising machine protection, β^* was decreased in steps from 3.5 m in 2010 to 60 cm in 2012. This resulted in a very significant increase of the delivered luminosity.

Work is ongoing to improve the models for the margins,

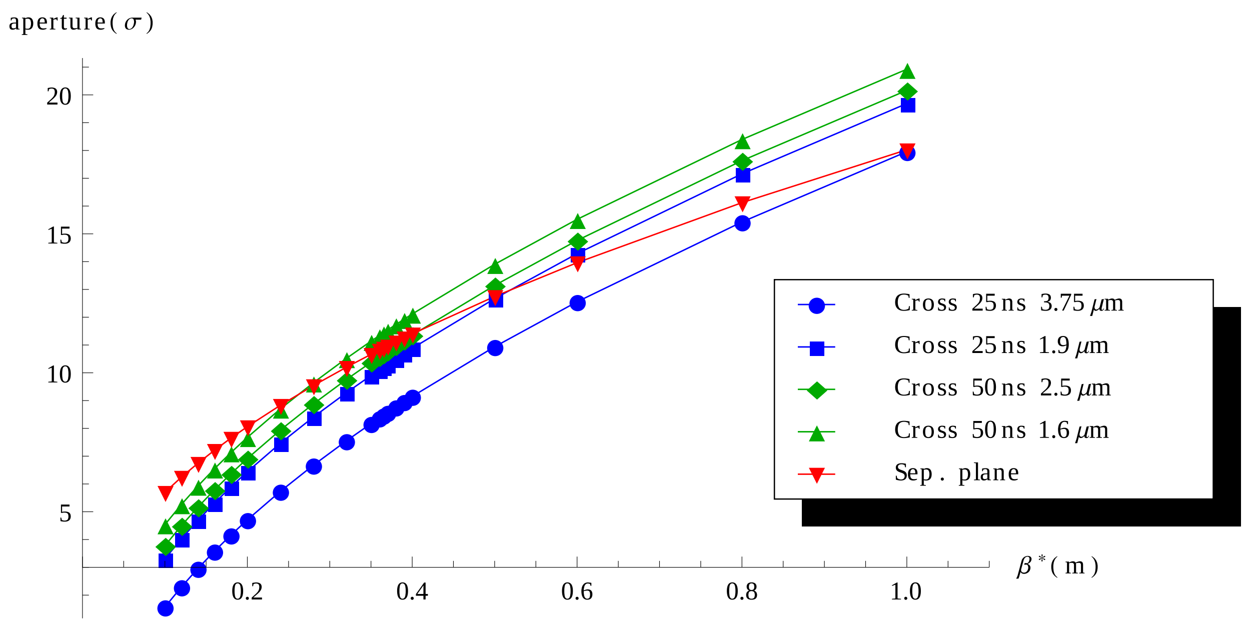

Figure 6: The calculated aperture margin in IR1 and IR5 as function of $\beta^*$for different configurations of bunch spacing (25 ns with an assumed needed beam-beam separation of 12 σ_r or 50 ns with 9.3 σ_r beam-beam separation). The aperture is shown both for both the crossing and separation planes.

where a small number of impacting protons—well below the TCT damage limit—is allowed during asynchronous dumps. We include realistic errors on the phase advance and the β-functions. With this model, the margin for optics errors used in the 2012 run could possibly have been reduced by a few fractions of σ_n without risk. A similar study can be done also for the margins between TCTs and triplets, and, in the future, the model can be expanded to include also the other error sources such as orbit deviations.

During LS1, all TCTs and TCS6 will be replaced by new collimators with integrated BPM buttons. They allow a faster collimation setup and much greater flexibility in the experimental IR configuration and, eventually, the BPMs could be used to ensure that these collimators are always centered around the orbit. This can in turn be used to further reduce the margins in the cleaning hierarchy and squeeze to smaller β^*.

Several options for collimator settings after LS1 have been studied under different assumptions on emittance and bunch spacing. Preliminary performance estimates shows that after LS1, the reach in $\beta^*$is between 30 cm and 60 cm if settings similar to 2012 or tighter can be assumed, unless it will be necessary to open the collimators more than in 2012 in order to avoid drops of the beam lifetime. The final decision on β^*has to be taken after a new aperture measurements and verifications on the beam stability.

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REFERENCES

[1] O. S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, and P. Proudlock (editors). LHC design report v.1 : The LHC main ring. *CERN-2004-003-V1*, 2004.

[2] R.W. Assmann. Collimators and Beam Absorbers for Cleaning and Machine Protection. *LHC Project Workshop - Chamonix XIV*, page 261, 2005.

[3] R.W. Assmann *et al.* The Final Collimation System for the LHC. *Proc. of the European Particle Accelerator Conference 2006, Edinburgh, Scotland*, page 986, 2006.

[4] D. Wollmann *et al.* First cleaning with LHC collimators. *Proceedings of the International Particle Accelerator Conference 2010, Kyoto, Japan*, page 1237, 2010.

[5] Gianluca Valentino, Ralph Aßmann, Roderik Bruce, Stefano Redaelli, Adriana Rossi, Nicholas Sammut, and Daniel Wollmann. Semiautomatic beam-based lhc collimator alignment. *Phys. Rev. ST Accel. Beams*, 15:051002, 2012.

[6] R. Bruce and R.W. Assmann. How low can we go? Getting below β^*=3.5 m. *Proceedings of the 2010 LHC beam operation workshop, Evian, France*, page 133, 2010.

[7] R. Bruce, R.W. Assmann, W. Herr, and D. Wollmann. Calculation method for safe β^* in the LHC. *Proceedings of IPAC11, San Sebastian, Spain*, page 1828, 2011.

[8] R. Bruce and R.W. Assmann. LHC β^*-reach in 2012. *Proceedings of the 2011 LHC beam operation workshop, Evian, France*, 2011.

[9] R. Bruce *et al.* Collimator settings and performance in 2011 and 2012. *Proceedings of the LHC Performance Workshop - Chamonix 2012*, 2012.

[10] C. Alabau Pons, R. Assmann, R. Bruce, M. Giovannozzi, E. MacLean, G. Mueller, S. Redaelli, F. Schmidt, R. Tomas, and J. Wenninger. IR1 and IR5 aperture at 3.5 TeV. *CERN-ATS-Note-2011-110 MD*, 2011.

[11] R. Assmann, R. Bruce, M. Giovannozzi, M. Lamont, E. Maclean, R. Miyamoto, G. Mueller, G. Papotti, L. Ponce, S Redaelli, and J Wenninger. Commissioning of the betatron squeeze to 1 m in IR1 and IR5. *CERN-ATS-Note-2012-005 MD*, 2012.

[12] S. Redaelli, R. Bruce, X. Buffat, M. Giovannozzi, M. Lamont, G. Mller, R. Tomas, and J. Wenninger. Aperture and optics measurements and conclusions. *Proceedings of the 2011 LHC beam operation workshop, Evian, France*, 2011.

[13] R.W. Assmann, R. Bruce, F. Burkart, M. Cauchi, D. Deboy, L. Lari, E. Metral, N. Mounet, S. Redaelli, A. Rossi, B. Salvant, G. Valentino, and D. Wollmann. Summary of MD on nominal collimator settings. *CERN-ATS-Note-2011-036 MD*, 2011.

[14] R.W. Assmann, R. Bruce, F. Burkart, M. Cauchi, D. Deboy, L. Lari, S. Redaelli, A. Rossi, G. Valentino, and D. Wollmann. Tight collimator settings with $\beta^* = 1.0$ m. *CERN-ATS-Note-2011-079 MD*, 2011.

[15] R.W. Assmann, R. Bruce, F. Burkart, M. Cauchi, D. Deboy, L. Lari, S. Redaelli, A. Rossi, B. Salvachua, G. Valentino, and D. Wollmann. Tests of tight collimator settings in the LHC. *CERN-ATS-Note-2012-022 MD*, 2012.

[16] R.W. Assmann, R. Bruce, F. Burkart, M. Cauchi, D. Deboy, S. Redaelli, R. Schmidt, A. Rossi, G. Valentino, and D. Wollmann. End-of-fill study on collimator tight settings. *CERN-ATS-Note-2011-125 MD*, 2011.

[17] N. Mounet. *The LHC transverse coupled-bunch instability*. PhD thesis, EPFL Lausanne, 2012.

[18] N. Mounet *et al.* Collimator impedance. *Presentation in the LHC collimation review 2013*, 2013.

[19] C. Bracco. *Commissioning Scenarios and Tests for the LHC Collimation System*. PhD thesis, EPFL Lausanne, 2008.

[20] R. Bruce, R.W. Assmann, and S. Redaelli. Principles for generation of time-dependent collimator settings during the LHC cycle. *Proceedings of IPAC11, San Sebastian, Spain*, page 3753, 2011.

[21] R.W. Assmann and B. Goddard and E. Vossenberg and E. Weisse. The consequences of abnormal beam dump actions on the LHC collimation system. *LHC Project Note 293, CERN*, 1996.

[22] M. Aiba, S. Fartoukh, A. Franchi, M. Giovannozzi, V. Kain, M. Lamont, R. Tomás, G. Vanbavinckhove, J. Wenninger, F. Zimmermann, R. Calaga, and A. Morita. First β-beating measurement and optics analysis for the cern large hadron collider. *Phys. Rev. ST Accel. Beams*, 12:081002, 2009.

[23] R. Tomás, O. Brüning, M. Giovannozzi, P. Hagen, M. Lamont, F. Schmidt, G. Vanbavinckhove, M. Aiba, R. Calaga, and R. Miyamoto. Cern large hadron collider optics model, measurements, and corrections. *Phys. Rev. ST Accel. Beams*, 13:121004, 2010.

[24] G. Vanbavinckhove, M. Aiba, R. Calaga, R. Miyamoto, and R. Tomas. Record low β-beat of 10% in the LHC. *Proceedings of IPAC11, San Sebastian, Spain*, page 2061, 2011.

[25] R. Bruce, D. Bocian, S. Gilardoni, and J. M. Jowett. Beam losses from ultraperipheral nuclear collisions between pb ions in the large hadron collider and their alleviation. *Phys. Rev. ST Accel. Beams*, 12(7):071002, Jul 2009.

[26] B. Goddard, private communication.

[27] A. Bertarelli *et al.* Updated robustness limits for collimator materials. *MPP Workshop March 2013, Annecy, France*, 2013.

[28] L. Lari *et al.* Accelerator physics studies on the effects from an asynchronous beam dump onto the LHC experimental region collimators. *Proceedings of IPAC12, New Orleans, Louisiana, USA*, page 547, 2012.

[29] L. Lari, C. Bracco, R. Bruce, B. Goddard, S. Redaelli, B.Salvachua, G. Valentino, and A.Faus-Golfe. Simulation and measurements of beam losses on LHC collimators during beam abort failures. *Proceedings of IPAC13, Shanghai, China*, page 996, 2013.

[30] D. Wollmann., O. Aberle, R. W. Assmann, A. Bertarelli, C. Boccard, R. Bruce, F. Burkart, M. Cauchi, A. Dallocchio, D. Deboy, M. Gasior, R. Jones, S. Redaelli, A. Rossi, and G. Valentino. First beam results for a collimator with in-jaw beam position monitors. *Proceedings of IPAC11, San Sebastian, Spain*, 2011.

[31] G. Valentino *et al.* Successive approximation algorithm for BPM-based LHC collimator alignment. *to be submitted to PRSTAB*, 2013.

[32] N. Mounet, E. Metral, G. Arduini, T. Pieloni, B. Salvant, S. White, X. Buffat, R. Calaga, J. Esteban-Muller, R. Bruce, S. Redaelli, B. Salvachua, and G. Rumolo. beam stability with separated beams at 6.5 TeV. *Proceedings of the 2012 LHC beam operation workshop, Evian, France*, 2012.

[33] T. Pieloni, X. Buffat, S. White, N. Mounet, W. Herr, E. Metral, G. Arduini, and R. Bruce. Beam stability with colliding beams at 6.5 TeV: in the betatron squeeze and collisions. *Proceedings of the 2012 LHC beam operation workshop, Evian, France*, 2012.

[34] S. Redaelli, C. Alabau Pons, R. Assmann, R. Bruce, M. Giovannozzi, G. Muller, M. Pojer, and J. Wenninger. aperture measurements in the LHC interaction regions. *Proceedings of IPAC12, New Orleans, Louisiana, USA*, page 508, 2012.