HOW LOW CAN WE GO? GETTING BELOW $\beta^* = 3.5$ m

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Abstract

The LHC has made remarkable progress during 2010, fulfilling its demanding goal for the year in terms of integrated luminosity. For 2011, even higher performance goals are set. One way of increasing luminosity is to reduce the beam size at the interaction points (IPs), which is determined by the optical function β^*. However, when β^* is decreased, so is the margin to the triplet aperture in terms of beam σ. This aperture has to protected from beam losses by the tertiary collimators (TCTs), which in turn have to be shadowed by other upstream collimators and protection devices. This imposes a limit on the minimum achievable β^*.

In this article, we discuss estimates of the available triplet aperture as well as the margins in the cleaning hierarchy required to guarantee protection. All estimates of margins are based on assumptions on variations in central orbit and optical functions and we conclude on the achievable β^* for different running scenarios. We also discuss briefly the available margins during luminosity scans.

INTRODUCTION

The luminosity in any collider with round beams is inversely proportional to the optical β-function, called β^*, at the interaction point (IP) [1]. It is therefore, from the point of view of maximizing the accumulated statistics in the experiments, desirable to operate with β^* as low as possible. However, when β^* is squeezed to small values in the LHC, operation becomes increasingly difficult since the beam size in the quadrupole triplets in the interaction regions (IRs) increases [2], which leads to a decreased margin between the aperture and the collimation system that should protect it. In the 2010 LHC optics [3], the triplets become the limiting aperture of the LHC when $\beta^* < 7$ m during the squeeze at top energy. Furthermore, other effects such as the maximum achievable gradient in the quadrupoles and the beam-beam limit introduce additional constraints. In this article we discuss only the β^*-limitations caused by aperture margins, since they imposed the most severe limitations during the 2010 run.

The LHC uses a multi-stage cleaning system to intercept unavoidable beam losses and provide passive machine protection [2, 4, 5]. Tertiary collimators (TCTs) are installed in all experimental IRs. They are the third step in the cleaning hierarchy in the nominal collimation scheme. During the first run in 2010 intermediate collimator settings were used, which provide more margin [6, 7]. Later in 2010 even more relaxed margins were introduced between triplet aperture, TCTs and dump protection. The different collimator settings are presented in Fig. 1.

The TCTs must protect the triplets, and they in turn must thus be positioned outside the primary (TCP) and secondary (TCS) collimators. They must also be protected by the collimators installed in IR6 [2] in the case of a machine failure (asynchronous beam dump), where high-amplitude particles may not pass through the dedicated cleaning insertions before reaching the TCTs. In order to investigate possible values of β^*, we therefore have to review the value of the aperture itself, the required margins between the aperture and the TCTs, and the margin between the TCTs and the rest of the collimation system.

TRIPLET APERTURE

The normalized apertures in LHC were previously calculated [8] using the MAD-X program [9] from the so-called *n1* quantity. It is defined as the maximum acceptable primary collimator opening, in units of beam σ, that still provides a protection of the mechanical aperture against losses from the secondary beam halo. Uncertainties of the closed orbit, mechanical imperfections and tolerances, and possible perturbations of the optical functions are taken into account to find the worst-case aperture. Therefore, the results may be pessimistic. Based on *n1* calculations, the TCTs were placed at 15 σ from the beam center during the 2010 run with the $\beta^* = 3.5$ m optics.

During 2010, measurements of the global aperture have been performed. As an alternative method, we use these measurements to extrapolate the aperture to top energy with a method we call *aperture scaling*. In the following sections we describe first the method then we present results from both calculation methods.

Aperture scaling

Several aperture measurements have been performed in the LHC [10, 11, 12]. Apertures can be measured locally, with a variable orbit bump, or globally [13], for example by opening the collimators and then provoking beam losses by crossing a tune resonance. The beam loss monitors (BLMs) are then used to locate the global aperture limitation. In order to determine the limitation in units of σ, the TCPs are closed in steps, until the beam losses and therefore the limitation moves to the collimator. Both methods can be used independently in the horizontal and vertical planes.

The local aperture can not be estimated from a global measurement but any local aperture can not be smaller than the global one. Therefore, we can use the global measured aperture as a pessimistic estimate of the local one.

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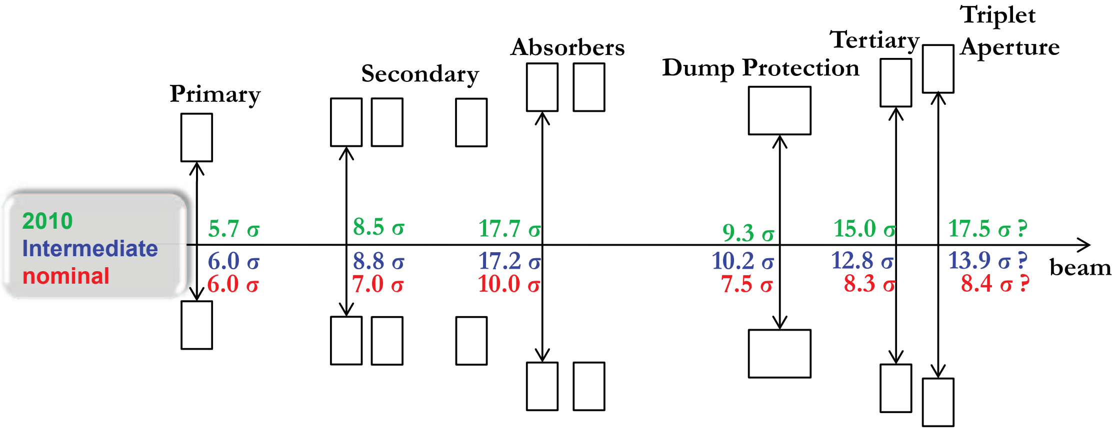

Figure 1: Schematic illustration (not to scale) of the collimator settings used during the 2010 run run with $\beta^* = 3.5$ m (green), the intermediate settings used during the 2010 run with $\beta^* = 2$ m (blue), and the nominal settings (red). These settings imply relaxed margins compared to the nominal case. We also show earlier estimates of the triplet aperture, done with the *n1*-method.

Table 1: Measured apertures of the LHC in units of beam σ (energy deviations not accounted for) at injection energy taken from Ref. [12].

	Horizontal	Vertical
Beam 1	12.5	13.5
Beam 2	14	13

In a general case it is not possible to calculate the aperture for a given machine configuration using data acquired in a another one (e.g. different optics, orbit etc.) without being overly pessimistic or applying additional assumptions. However, in special cases we can use simple scaling laws to estimate the aperture a different configuration. It turns out that this is possible in the triplets with good approximation.

Measurements of the global aperture in the LHC ring at injection energy (450 GeV), performed in September 2010, are presented in Ref. [12] and the results are repeated in Table 1. The measurements were done using the standard injection optics [3] with $\beta^* = 11$ m in IP1 and IP5 and $\beta^* = 10$ m in IP2 and IP8, separation bumps around the collision points activated and half crossing angles of 170 μrad in IP1 and IP5. In IP2 and IP8 the spectrometers were on and external angles of 170 μrad were used. We call this configuration *injection*. We use these measurements to estimate the aperture margins at 3.5 TeV energy or higher, squeezed optics [3] with varying crossing angles and $\beta^* \leq 3.5$ m, spectrometers on in IP2 and IP8, but the beam separation at the IPs still activated. We call this configuration *pre-collision*. This is the most critical point at top energy—when the separation bumps are collapsed, the aperture margins increase.

As an example we consider IR1 B1 (beam 1) and the 2010 pre-collision optics with 3.5 TeV energy, $\beta^* = 3.5$ m in all IPs, half crossing angles of 100 μrad in IP1 and IP5, external crossing angle of 110 μrad in IP2 and 100 μrad in IP8, and a 2 mm beam separation. In order to estimate the margins in the triplets at pre-collision, we first determine the s-location with the smallest aperture in this configuration from a *n1*-calculation including measured profiles. We consider the horizontal and vertical planes separately and select the slice inside the element where the minimum is found. Let us now study these s-locations in the two planes at injection. The parameters at each position are presented in Table 2. A transverse cross section of the ideal physical aperture together with the 16 σ beam envelope at injection (in red) is shown in Fig. 2 for both locations.

We use the measured global aperture as a pessimistic estimate of the local one at these s-locations. At pre-collision the beam size and center changes from injection, while the physical aperture is the same (see Table 2 and Fig. 2). It is clear that the aperture limitation stays in the same plane and on the same side of the beam pipe in both cases. Because of the shape of the vacuum chambers, the vertical change of the orbit in the crossing plane, caused by the reduction in crossing angle, does not influence the margin to the aperture in the (horizontal) separation plane. In the (vertical) crossing plane, the situation is more complicated—a horizontal orbit shift does have an influence on the margin because of the elliptic shape of the vacuum chamber and a detailed study should also account for the expected shape of the halo. In our simplified method, we neglect this effect. The introduced error is small since the change in the vacuum chamber is small over the distance that the orbit can be expected to vary horizontally. We thus reduce the 2D aperture calculation to 1D.

If we designate variables with subscript i at injection and with p at pre-collision, it must hold that

$$|u_i| + n_i\sigma_{ui} = |u_p| + n_p\sigma_{up}, \tag{1}$$

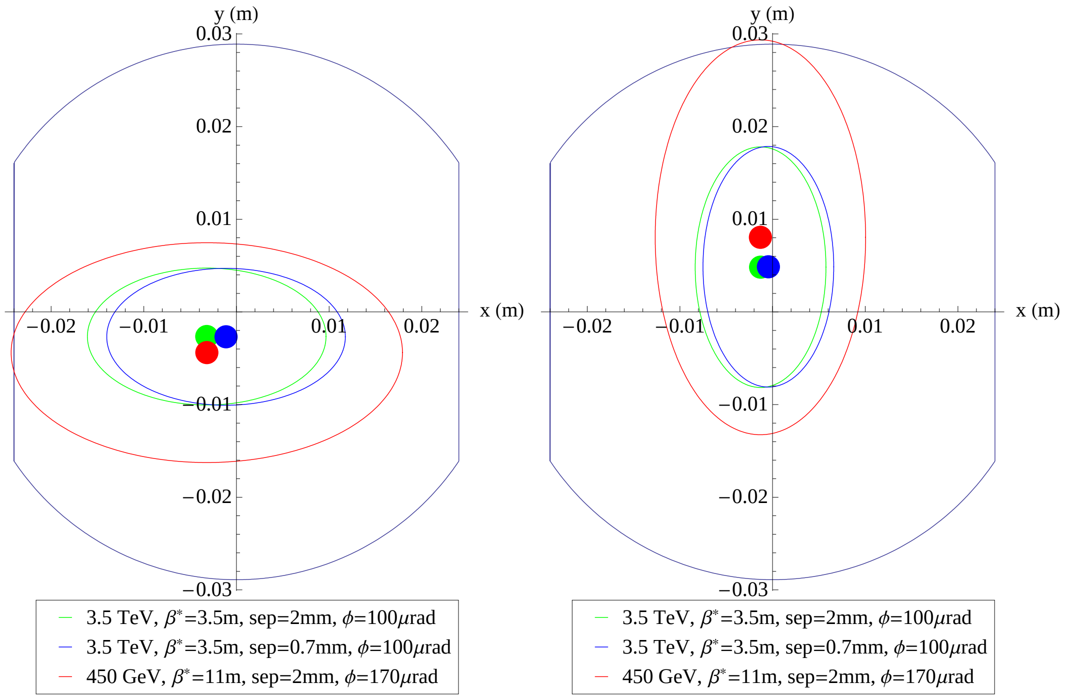

Figure 2: The transverse cross section of the triplet with the found horizontal (left) and vertical (right) aperture limitations in IR1 Beam 1. The 16 σ beam envelopes for injection (red), pre-collision (green) and pre-collision with the separation reduced to 0.7 mm (blue) are included. The dots indicate the central orbits.

where u is the transverse coordinate of the orbit in the limiting plane (we use the absolute value of u in order to account for cases where the orbit is negative), n the distance to the aperture in units of σ_u. Expressing the geometric emittance as $\epsilon_u \approx \epsilon_n/\gamma$, where ϵ_n is the normalized emittance and γ the relativistic factor, we solve Eq. (1) for n_p:

$$n_p = \frac{|u_i| - |u_p| + n_i \sigma_{ui}}{\sigma_{up}} = \frac{|u_i| - |u_p|}{\sigma_{up}} + n_i \sqrt{\frac{\beta_{ui}\gamma_p}{\beta_{up}\gamma_i}} \qquad (2)$$

We can now insert the values in Table 2 in Eq. (2) for $u = x$ or $u = y$, using $n_i = 12.5$ in the horizontal plane and $n_i = 13.5$ in the vertical plane (see Table 1). We use the nominal emittance of $\epsilon_n = 3.75$ μm, since all collimator settings and the measured apertures in Table 1 are expressed in terms of the nominal beam size. With $\gamma_i = 479$ and $\gamma_p = 3730$, we get $n_p = 20.5$ for $u = x$ and $n_p = 26.0$ for $u = y$,. Assuming a 2.5 σ margin between the aperture and the TCT, the maximum settings are 18 and 23.5 σ_u for the horizontal and vertical TCTs.

In this calculation, we assumed that the ratio of the β-functions and the shift in orbit are accurately reproduced by MAD-X. To account for possible variations, we introduce first an additional orbit shift δu. Furthermore, we consider a possibly different β-beat at injection and pre-collision by assuming that the β-function is scaled by λ_i at injection and by λ_p at pre-collision. Eq. (2) then becomes

$$n_p = \frac{|u_i| - |u_p| - \delta u + n_i \sigma_{ui}}{\sigma_{up}} = \frac{|u_i| - |u_p| - \delta u}{\sqrt{\beta_{up}\lambda_p \epsilon_n/\gamma_p}} + n_i \sqrt{\frac{\lambda_i \beta_{ui}\gamma_p}{\lambda_p \beta_{up}\gamma_i}}. \qquad (3)$$

If we assume pessimistically $\lambda_i = 1/1.1$ and $\lambda_p = 1.1$ (this gives an overall β-beat of about 20% between injection and pre-collision) and δu=1 mm, the estimated apertures at pre-collision become instead $n_p = 17.5$ in the horizontal plane and $n_p = 22.7$ in the vertical plane, implying TCT positions of 15 σ_x and 20.2 σ_y.

It should be underlined that the our method does not account the spurious dispersion, both from the crossing angle and from the *a2/b2* errors as pointed out by others [14], while on the other hand the use of the global aperture at injection is pessimistic. A better estimate can be made considering that, when the TCP is moved in during the measurements, the losses move gradually from the global aperture bottleneck to the collimator. The TCP thus first intercepts the secondary halo created by the aperture bottleneck and, once the TCP is the limit, the aperture catches a secondary halo from the collimator. The first losses are seen at a setting about 2 σ outside the point where the limit has moved to the collimator [15]. Thus, if the triplet aperture would be within 2 σ of the global limitation, a beam loss would be observed there as well. Since no losses are seen,

Table 2: The β-functions and transverse coordinates of the central orbit at the horizontal and vertical aperture limitations in IR1 B1 taken from MAD-X. The s-position is given relative to IP1, where a negative value indicates the incoming beam.

		s (m)	β_x (m)	β_y (m)	x (mm)	y (mm)
Hor. limit	injection	-40.8	238	75	-3.2	-4.4
	pre-collision	-40.8	690	227	-3.2	-2.7
Ver. limit	injection	39.6	69	243	-1.3	8.1
	pre-collision	39.6	207	702	-1.3	4.8

we conclude that the triplet aperture is at least 2 σ larger than the values in Table 1, which we used in later calculations.

One way of increasing the aperture is to reduce the separation at pre-collision to the nominal design value of 0.7 mm. Fig. 2 shows in blue the envelope of this configuration. As can be seen, the additional orbit shift increases the margins at the horizontal bottleneck so that the aperture is instead found at $n_p = 19.5$. Since there is no reason known to the authors to keep the larger separation of 2 mm, we recommend to use the nominal value of 0.7 mm. All calculations presented in the remainder of this article uses nominal separation.

Results of aperture calculations

Using both aperture scaling and the *n1*-method, we have estimated the triplet aperture for different values of β^* at an energy of 3.5 TeV. For each considered configuration a beam-beam separation $d = 12\,\sigma$ was assumed (larger than the nominal $d = 9.8\,\sigma$) in order to calculate the half crossing angle α, given by

$$\alpha = d\sqrt{\frac{\epsilon_n}{\beta_u \gamma}}, \tag{4}$$

with ϵ_n being the normalized emittance (we used The nominal $\epsilon_n = 3.75$ μm), β_u the optical beta function in the transverse plane u, and γ the relativistic factor.

To estimate δ_u in the aperture scaling calculations, we considered the difference between the orbit at injection and stable beams in the ideal MAD-X model and in measurements from all fills between September 18 and October 31 2010 (data points were sampled every two minutes). We excluded data points from large luminosity scans and we will refer to this as our data set. In total 26 fills were analyzed. The maximum deviations between measurement and MAD-X that were found were smaller than 2 mm, which we used as a pessimistic value of δ_u for all IPs. The two BPMs closest to each aperture bottleneck were considered.

The β-beat parameters λ_i and λ_p were measured in late 2010 [16]. They were interpolated between BPMs and used directly in the aperture scaling calculation. Furthermore, we assume an additional 5% pessimistic error on the β-functions at injection and pre-collision motivated by the observed optics stability [16].

In the *n1*-calculations, we assumed a β-beat of 10%, which is compatible with observed performance in the end of 2010 [17]. An orbit tolerance of 2.3 mm was assumed, which equals the maximum error with respect to the ideal MAD-X orbit seen in the data set on the BPMs in the triplets. Measured profiles were used. Only IR1 and IR5 were treated and the minimum *n1* was taken for each scenario over both IPs, beams and planes.

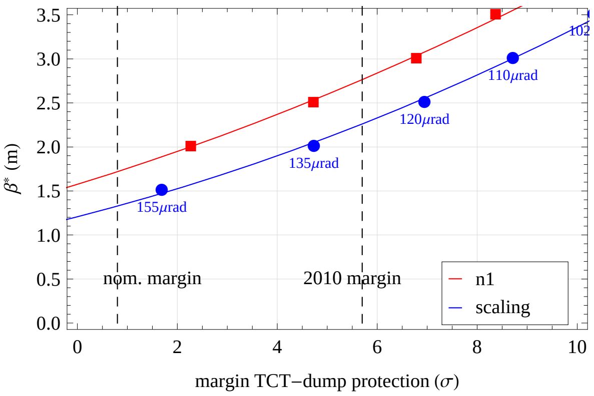

Figure 3: The minimum β^* at 3.5 TeV as a function of the margin between the TCTs and the dump protection, assuming a 2.5 σ margin between the triplet aperture and the TCTs. The crossing angles shown were chosen to keep a 12 σ beam-beam separation. The aperture was evaluated using both aperture scaling and *n1*-calculations. The latter were done for a β-beat of 10%, a closed orbit tolerance of 2.3 mm, and only for IR1 and IR5. The minimum aperture over all IRs, beams and planes was used.

The calculated apertures were used to estimate the minimum achievable β^* as a function of the margins in the collimation system. For each β^*, the minimum aperture was calculated over all IPs, both beams and both planes. Assuming either 2010 margins or nominal margins provides a given setting of the dump protection and the margin between the triplet aperture and the TCTs, which allows the margin between the TCTs and the dump protection to be calculated. The result is shown in Fig. 3, where for convenience we have instead plotted β^* as a function of the margin.

A better result could be obtained using a local measured triplet aperture in both planes at injection. Such a measurement, which we anyway think is necessary to benchmark the scaling model, could be performed with a safe low-intensity beam by first introducing a local orbit bump

Table 3: The margins in units of beam σ needed to compensate for various error sources. Orbit errors are treated separately in the following sections.

Element	β-beat	position	setup	scans	sum
TCT	0.73	0.1	0.025	0.2	1.06
TCSG6	0.45	0.06	0.015		0.53
TCSG7	0.41	0.2	0.05		0.66
TCP7	0.28	0.14	0.035		0.46

of known amplitude in the triplets, to create a global bottleneck, while keeping the collimators retracted. A TCP is then to be moved in stepwise, with provoked losses in each step. The position of the TCP when the global limitation moves from the triplet to the collimator and the amplitude of the orbit in the triplet allows for a more precise aperture estimate. This measurement might even be performed with a squeezed optics, as suggested by others [14].

It is also important to quantitatively understand in detail the discrepancies between the *n1* method and the measurements. This work is underway [18].

MARGINS IN CLEANING HIERARCHY

The margins between the collimator families and collimators and aperture have to be sufficiently large to compensate for errors in such a way that the cleaning hierarchy is not violated. The error sources are:

- Orbit variations can bring the beam closer to collimators. An analysis based on data is done in the following sections.
- β-beat: If the real β-function in the machine deviates from the theoretical model, the aperture at a collimator positioned at n_σ is changed by a factor $n_\sigma\sqrt{\beta_{\mathrm{real}}/\beta_{\mathrm{model}}}$. We use $\beta_{\mathrm{real}}/\beta_{\mathrm{model}} = 1.1$ as an estimate of the achievable β-beating [17].
- Positioning errors are introduced by the non-reproducibility of the end position of the collimators when they are moved in. This is estimated to 40 μm.
- The accuracy of the collimation setup is 10 μm, which is the step size used during the alignment procedure.
- During luminosity scans, an additional orbit shift is introduced at the tertiary collimators, which is less than 0.2 σ [19].

The resulting errors except orbit at key elements are shown in Table 3. Variations in positioning and setup errors caused by the change in beam size during the squeeze were neglected but this is very a small effect.

To estimate the margin between two components, which could be two collimators or a collimator and the aperture, so that one is always in the shadow of the other in units of σ, we add linearly the maximum change in aperture margin at both locations to account for the worst case.

At the triplet, the β-beat is already accounted for in the aperture calculation and should not be counted twice. If, in addition, a biased β-beat correction is done, with the beam size always increasing more at the TCT than at the triplet, only the drifts in β-beat must be accounted for. We assume this to be 5% at the TCTs which give a contribution of 0.35 σ to the margin.

ORBIT ERRORS

The collimators are centered around the reference orbit and a static orbit offset at the triplet is taken into account in the aperture calculation. Thus we only need to account for the orbit drifts from the reference when calculating the margins.

In order to see by how much the margin is reduced by orbit movement we consider two elements A and B somewhere in the ring where A should shadow B. Let the initial mechanical aperture in σ be n_A of device A in the transverse plane u. If the orbit later moves by an amount Δn_A, the new aperture is $n_A - \Delta n_A$ in positive u and $n_A + \Delta n_A$ in negative u. Analogous relations hold at B. If the betatron phase advance μ_{AB} between A and B is such that $\cos\mu_{AB} \geq 0$, the u-coordinate of a particle has the same sign at both A and B. The reduction ΔM of the original margin $M_0 = n_B - n_A$ due to orbit movements Δn_A and Δn_B is then

$$\Delta M_+ = (n_B - \Delta n_B) - (n_A - \Delta n_A) - M_0 = \Delta n_A - \Delta n_B \quad (5)$$

for the aperture at B in positive u and

$$\Delta M_- = (n_B + \Delta n_B) - (n_A + \Delta n_A) - M_0 = \Delta n_B - \Delta n_A \quad (6)$$

for the aperture in negative u. The reduction can thus be summarized as

$$\Delta M = |\Delta n_B - \Delta n_A|. \quad (7)$$

If $\cos\mu_{AB} \leq 0$ on the other hand is negative, the u-coordinate of any larg-amplitude particle changes sign between A and B and the aperture at B with $u < 0$ is shadowed by the aperture at A with $u > 0$. Therefore the reduction in margin on the two sides is

$$\Delta M_+ = (n_B + \Delta n_B) - (n_A - \Delta n_A) - M_0 = \Delta n_A + \Delta n_B \quad (8)$$

and

$$\Delta M_- = (n_B - \Delta n_B) - (n_A + \Delta n_A) - M_0 = -\Delta n_B - \Delta n_A. \quad (9)$$

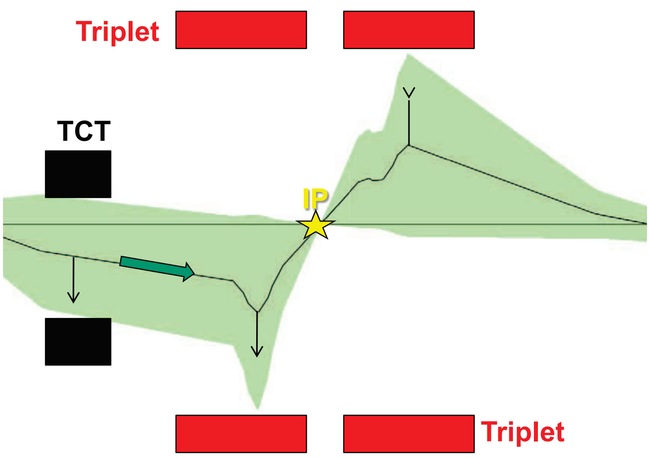

Figure 4: Schematic illustration (not to scale) of the beam envelope (green), the TCTs, and the triplet apertures in the crossing plane in an experimental IR (beam propagating from left to right). The vertical arrows symbolize the amplitude of a particle, which after a betatron phase advance of π is on the opposite side of the central orbit at the second triplet.

So the maximum reduction in margin is

$$\Delta M = |\Delta n_B + \Delta n_A|. \tag{10}$$

As an applied example, Fig. 4 shows schematically a TCT protecting the triplets on the incoming (0 phase advance) and outoing (π phase advance) beams. Because of the phases, Eq. (7) has to be used when calculating the reduction in margin on the incoming beam while Eq. (10) has to be used on the outgoing.

We now select the BPMs closest to A and B and use Eqs. (7) and (10) to calculate the reduction in margin at all data points. The resulting error distribution can then be used to decide the required margin between A and B. It should be noted that even if a margin is selected, such that no data points in the 2010 run violated the shadowing of B, it does not mean that B is guaranteed to always be protected, since the available statistics is limited and we cannot know future data samples. Instead we can use the data to define a confidence level with which B is protected.

We propose to use a margin such that A shadows B at least 99% of the time spent in stable beams. To see what this means in terms of expected rate of dangerous accidents we consider the case of asynchronous beam dumps. Assuming that only orbit errors are taken into account, one asynchronous dump per year, a probability of 0.01 that the TCTs are exposed and that 30% of the time is spent in stable beams, we expect a dangerous event to occur every 300 years. The real risk is however much lower since errors from other sources should be added to the final margin—the probability that all errors add in the pessimistic direction must be folded in.

Work is ongoing to quantify the damage to a TCT for the very unlikely event of a bunch hitting it. If it can be shown that damage is not catastrophic, e.g. downtime of the LHC will be less than a few days, the possibility of moving in the TCTs further could be considered.

The risk of an event in which the triplet is exposed is even smaller. We assume the reduction in margin between aperture and TCTs to be independent of the reduction between the dump protection and TCTs due to the local correction scheme. With a 1% probability of the triplets being exposed, a dangerous event is expected once every 30000 years.

Finally, interlocks can be added to dump the beam before the protection is violated. A less drastic method could be to have displays to monitor the reduction in margin so that the operators can perform corrections if the margins are close to the limits.

REQUIRED ORBIT MARGINS

Using the method described in the previous section we have calculated the reduction in margin during the 2010 run due to orbit movements between different steps in the cleaning hierarchy.

Margin aperture-TCT

In all experimental IRs we analyzed the orbit movements at the BPMs about 3 m upstream of the horizontal TCTs together with the BPMs in the triplets between Q1 and Q2. Since $\mu_{AB} \approx 0$ between the TCTs and the triplet on the incoming beam, Eq. (7) was used in this case, while at the triplet on the outgoing beam we have $\mu_{AB} \approx \pi$ and therefore used Eq. (10). The calculation was performed in both planes for both triplets and is still pessimistic, since in the crossing plane the protection is essentially one-sided due to the large orbit excursions (see Fig. 4), meaning that only one of ΔM_+ and ΔM_- needs to be considered.

The resulting reduction in margin is summarized in Table 4. The largest reduction was found in IR2 B2 and Fig. 5 shows an example of the orbit evolution during a fill on the three relevant BPMs in IR2 together with their respective reference orbits. Significant variations can be seen during the fill. The reduction of margin in IR2 comes mainly from large systematic offsets but fluctuations, likely to be caused by the luminosity leveling, give a small contribution. The luminosity was adjusted in IR2 by changing the magnitude of the separation bump, which decouples the orbit movements at the TCTs and the triplets

A histogram of the reduction in margin at all data points in the vertical plane in IR1 is shown in Fig. 6. This is the most critical case among the other IRs. Here a large static offsets with respect to the reference orbit was found. One example is shown in Fig. 7.

In our data set we have excluded times when large luminosity scans were performed (discussed in more detail in Ref. [19]). An example of a fill where this was done is shown in Fig. 8. In this case the maximum reduction of the margin was 2.2 σ. These variations can not be accounted

Table 4: The reduction of the margin TCTs-triplets and TCTs-dump protection during the fall of 2010 per IP, plane and beam as calculated with Eqs. (7) and (10). We show both the maximum values and the values below which 99% of the data sample can be found. Each number is the maximum over both triplets and planes.

(σ)		TCT-triplet			TCT-TCSG IR6	
beam	plane	mean	max	99%	max	99%
IR1						
B1	X	0.80	1.39	1.25	0.85	0.73
B1	Y	0.54	1.64	1.60		
B2	X	0.66	1.62	1.55	1.30	0.97
B2	Y	0.50	1.26	1.17		
IR2						
B1	X	0.52	1.17	1.14	1.29	1.10
B1	Y	0.80	1.88	1.78		
B2	X	1.38	2.46	2.37	2.18	2.10
B2	Y	0.41	1.10	1.00		
IR5						
B1	X	0.44	1.19	1.17	0.92	0.78
B1	Y	0.54	1.17	0.93		
B2	X	0.42	0.98	0.92	1.18	1.00
B2	Y	0.67	1.78	1.04		
IR8						
B1	X	0.33	0.77	0.74	0.83	0.50
B1	Y	0.71	1.81	1.63		
B2	X	0.61	1.68	1.58	1.41	1.10
B2	Y	0.17	0.65	0.55		

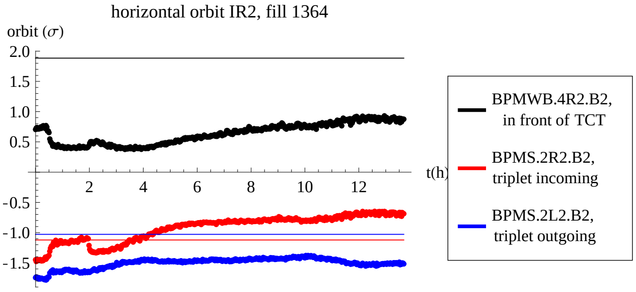

Figure 5: Horizontal orbit in IR2 B2 at BPMs close to the TCTs and the triplets on the incoming and outgoing beams with respect to IP2 during fill 1364. The solid lines are the reference orbit used during the collimation setup. During the fill, a large systematic offset from the reference orbit can be seen, as well as fluctuations likely to be caused by luminosity leveling.

for without a loss in performance so we propose that the TCTs should move with the beam during large scans.

If IR2 does not have to be squeezed to a small β^*, a 1.6 σ margin for orbit between the TCTs and the aperture could be used, covering 99% of the time in the other IPs (see Table 4). If also IR2 should be squeezed, the margin has to be increased to 2.4 σ unless the static offsets are improved.

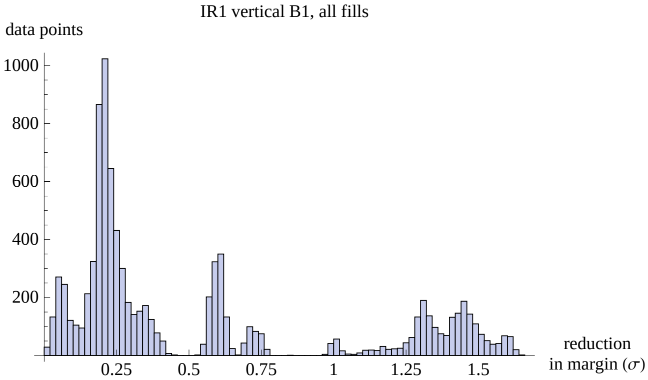

Figure 6: Reduction of margin between the vertical TCT in IR1 B1 and the aperture bottleneck in triplet on the outgoing beam. All data points from the run in fall 2010 in stable beams, except where large luminosity scans were performed, were accounted for.

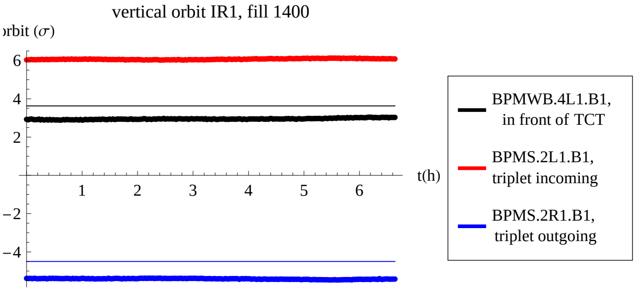

Figure 7: Vertical orbit in IR1 B1 at BPMs close to the TCTs and the triplets on the incoming and outgoing beams with respect to IP1 during fill 1400. The solid lines are the reference orbit used during the collimation setup. During the fill, a systematic offset from the reference orbit can be seen.

Margin TCT-dump protection

A typical example of the orbit on the BPM closest to the secondary collimator in IR6 (TCSG6) and the horizontal TCT in IR5, beam 2, is shown in Fig. 9. The static offsets as well as the drifts during the fill are small. If we consider again a margin for which the hierarchy is preserved over 99% of the times in stable beams, 1.1 σ is enough for all IRs except IR2, where 2.1 σ is needed. Numbers for all IPs are given in Table 4.

We have not taken into account the phase between the BPMs and thus taken the maximum reduction given by Eqs. (7) and (10). Therefore, our calculation is pessimistic.

Margins between other collimators

A similar study has been carried out also in IR7. Here a pessimistic approach was taken in which we study the reduction of margin from orbit movements between the BPM

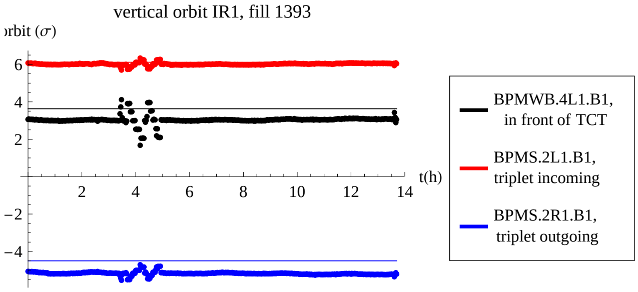

Figure 8: Vertical orbit in IR1 B1 at BPMs close to the TCTs and the triplets on the incoming and outgoing beams with respect to IP1 during fill 1393. The solid lines are the reference orbit used during the collimation setup. During the fill, a large systematic offset from the reference orbit can be seen.

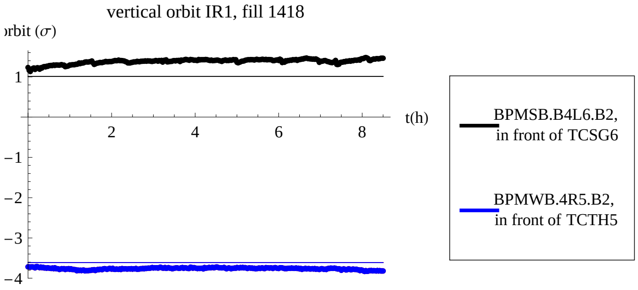

Figure 9: Horizontal orbit in front of the TCSG in IR6 and the TCT in IR5 B2. The solid lines are the reference orbit used during the collimation setup. This TCT is most critical in terms of protection since it is the first collimator downstream of the dump protection.

in front of the TCPs and all other BPMs in IR7 close to a TCS. Again the phase was not considered, so both Eqs. (7) and (10) were used. It was found that a margin of 1.7 σ preserves the hierarchy in both planes and beams on all BPMs more than 99% of the operational time. This value could possibly be reduced if a more detailed analysis is performed where the phases of all collimators is taken into account. This is left as future work.

We studied also the margin between the TCSs in IR7 and IR6. Based on the 2010 data set it can not be reduced without a risk of hierarchy problems.

PROPOSED MARGINS AND SETTINGS

Adding linearly the variations in orbit, shown in previous sections, to other errors in Table 3, we calculate the required margins in the cleaning hierarchy. Starting from a setting of the primary collimator at 5.7 σ we then calculate all settings and finally the minimum aperture that is protected. The result is shown in Table 5.

Table 5: The minimum collimator setting achievable based on the analysis in previous sections and the minimum aperture in units of σ.

TCP IR7	TCS IR7	TCS IR6	TCT	aperture
5.70	8.50	9.30	11.80	14.10

More aperture could be gained by moving in all collimators closer to the beam by the same amount. This could be motivated also because the emittance used in the 2010 runs was significantly smaller than nominal [20, 21]. On the downside, this might cause an increased risk of instabilities induced by impedance. A study of this is left as future work.

It should be underlined that the linear sum of the errors gives a pessimistic estimate—it is very unlikely that they add up in the same direction. An alternative could be to consider the errors as independent random variables and add them in square. A confidence interval then has to be defined and the machine can be interlocked to protect against a violations.

A further gain in margins could be achieved through:

- More detailed aperture measurements, which are anyway needed to validate the scaling method.
- Adding errors in square instead of linearly in the margins.
- Reducing the crossing angle by either using a smaller-than-nominal emittance or going to a smaller beam-beam separation. This gains aperture, but may be possible or not depending on the filling scheme. More details will be given in Ref. [21].
- More margin could be gained if the large static offsets to the reference orbit, seen during stable beams in the experimental IRs, could be better corrected. This is true in particular for IR2.
- A more detailed analysis of the reduction in margin caused by orbit variations, taking into account the phase advance between collimators, could show that the margins can be decreased further.

REACH IN β^*

In addition to the new margins calculated here we consider also two other options, giving in total three different operational scenarios:

- *2010 settings*: Keeping the same margins as during the 2010 run.
- *2011 proposal*: Using the settings presented in Table 5.
- *Nominal*: Going to nominal collimator settings (see Fig. 1). For this to be possible an orbit stability of 0.1–0.2 σ is necessary, so these settings are clearly too tight to guarantee protection. We include calculations anyway for comparison.

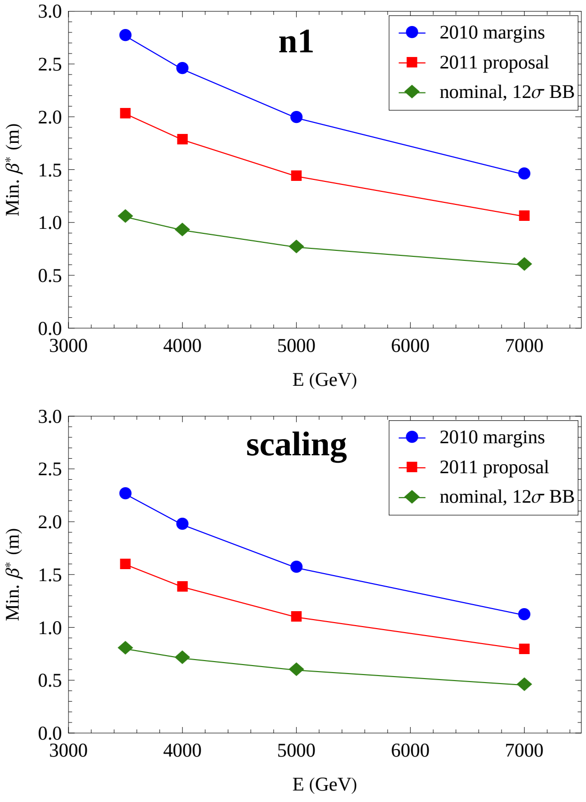

Figure 10: The minimum β^* as a function of beam energy for three different sets of margins between the collimators, with the aperture calculated with the *n1*-method (top) and aperture scaling (bottom).

For each scenario, the minimum aperture that can be protected is defined (see Table 5 and Fig. 1). The aperture was calculated, using aperture scaling and the *n1* method with a 10% β-beat and 2.3 mm orbit tolerance, for a range of β^*-values (with the crossing angle varied to keep a 12 σ beam-beam separation) and interpolated by a second degree polynomial as in Fig. 3. The intersection between the interpolated line and the minimum aperture that can be protected gives an estimate of β^*. The calculations were repeated also at 4 TeV, 5 TeV and 7 TeV. The resulting reach in β^* as a function of beam energy is shown in Fig. 10.

SUMMARY AND CONCLUSION

We have performed an evaluation of the reach in β^* based on data from 2010. Only limits from aperture were considered. We have reviewed first the triplet aperture itself and used scaling laws to extrapolate the measured injection aperture to top energy. We have also performed a detailed revision of the margins between different steps in the cleaning hierarchy.

Our operational proposals are:

- Reduce the separation at the IPs to its nominal value of 0.7 mm to gain aperture.
- Measure the triplet aperture locally.
- β-beating should be corrected to below 10% and with a reproducibility better than 5% with a bias at the TCT and triplets so that the beam size increases more at the TCT than at the triplet.
- The residual risk of magnet damage (estimated to $<$ 1 over 30000 years) or damage to the TCTs can be reduced further by interlocks or warnings when the orbit movements run out of defined margins.
- New settings have to be carefully verified with loss maps and asynchronous dump tests. If problems with the cleaning hierarchy are detected, relevant margins must be increased.
- The cleaning hierarchy has to be verified on a regular basis to monitor possible drifts. Regular beam dumps provide useful data on the leakage to the TCTs if uncaptured beam is present.

Based on data from the 2010 run, we have calculated new margins for 2011 presented in Table 6. The reach in β^*, calculated with aperture scaling, is presented in Table 7. With the *n1*-method, about 0.4 m is lost in β^*.

Table 6: Proposed margins based on data from the 2010 run in units of $\sigma$and mm. The margins in mm were calculated for $\beta^* = 3.5$ m, 3.5 TeV, for the 2010 case and for $\beta^* = 1.5$ m, 4 TeV, for the 2011 case. A range of values is given corresponding to different elements.

	2010		2011	
	(σ)	(mm)	(σ)	(mm)
triplet–TCT	2.5	0.9–2.1	2.3	1.1–2.7
TCT–TCSG IR6	5.7	3.5–4.4	2.5	1.3–1.8
TCSG IR7–TCP	2.8	0.6–1.6	2.8	0.5–1.5

Table 7: Calculated reach in β^* and corresponding half crossing angles when using aperture scaling and the 2010 margins with a 12 σbeam-beam separation. It is assumed that IP2 is not squeezed.

	3.5 TeV		4 TeV	
	β^* (m)	α (μrad)	β^* (m)	α (μrad)
2010 margins	2.3	125	2.0	125
2011 proposal	1.6	150	1.4	150

We propose to start with $\beta^* = 1.5$ m at 4 TeV, which is the closest matched optics point to the 1.4 m calculated with the scaling method. The collimation system has to be qualified before regular operation. In case of problems, the margins and maybe β^* must be increased. This proposal assumes that IP2 remains at a larger β^*.

The final choice of β^* has to be based on both machine protection and experimental requirements on luminosity. Higher luminosity can also be achieved through higher intensity [22] and a smaller emittance.

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