LHC β^*-reach in 2012

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Abstract

The available aperture in the LHC imposes a lower limit on the achievable β^*. The aperture must be protected by the collimation system, and the collimator families have to be ordered in a strict hierarchy for optimal performance, with large enough margins so that the hierarchy is not violated by machine imperfections such as closed orbit distortions or β-beating. The achievable β^* is thus a function of both the aperture and the collimator settings. An overview of the run in 2011 is presented, as well as a review of the necessary margins between collimator families and the aperture. Finally an outlook towards possible scenarios for β^* in 2012 and at higher energies is given.

INTRODUCTION

The luminosity of the LHC [1] is inversely proportional to the optical β-function, called β^*, at the interaction point (IP) [2]. 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 made smaller, the beam size becomes larger in the inner triplets, so that the margin to the aperture there decreases. In a squeezed optics, the triplets are the limiting aperture bottleneck of the ring, which must always be protected by the LHC collimation system [1, 3, 4, 5]. Otherwise, quenches induced by high beam losses could occur or, in the unlikely case of an asynchronous dump, even damage to the triplets. Therefore, a value of β^* has to be found that is as low as possible without compromising machine protection.

The LHC uses a multi-stage collimation system, where the different collimator families have to be ordered in a strict hierarchy for optimal cleaning performance and machine protection [1]. Closest to the beam, in the IR7 betatron cleaning insertion, are primary collimators (TCP), followed by secondary collimators (TCS7), both robust and made of graphite. Further out are tungsten absorbers (TCLA). In IR6, at the beam extraction, are special dump protection collimators (TCS6 and TCDQ). They should be outside the TCS7, since it is not desirable to have the losses from the tertiary halo in the IR6 dispersion suppressor - the efficiency in IR7, where the TCLAs are present, is much higher. Furthermore, in the experimental IRs, tertiary collimators (TCTs) made of tungsten are installed in order to provide local protection of the triplets. The TCTs are not robust and should be positioned outside the dump protection in IR6, since they otherwise might be hit and damaged in case of a dump failure [1]. The hierarchy in the betatron cleaning is schematically shown in Fig. 1, where the settings used in 2010, 2011 and in the nominal design are also shown. All values are given in units of nominal σ, that is, the betatronic beam standard deviation assuming a transverse normalized emittance of 3.5 μm. Unless something else is explicitly stated, we assume this definition of σ throughout this paper.

In order for the collimation hierarchy to be respected, also when there are machine drifts such as β-beat and orbit variations, margins are needed between the collimator families. These margins can be calculated using the models outlined previously [6, 7] as a function of the observed machine stability. Thus, starting from the setting of the TCP, and adding the necessary margin to each family, the required setting of the TCTs can be calcualted 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].

This minimum aperture can then be compared with the expected aperture needed from different running scenarios (β^* and crossing angle given by the required beam-beam separation), which then gives the minimum β^* possible for a given beam-beam separation. The key components for the decision on β^* limits from machine protection are thus

- The setting of the primary collimator.
- The required margins between the different collimator families
- The size of the triplet aperture.

This article discusses these points as input for the 2012 run, based on operational data in 2011. In the following sections, we give first an overview of the relevant aspects of the 2011 run. Based on this, we move on to possible improvements in 2012, considering both 3.5 TeV and 4 TeV. For reference, some results for 7 TeV are also presented.

We discuss only the β^*-limitations caused by aperture margins, since they previously imposed the most severe limitations.

RECAPITULATION OF THE 2011 RUN

β^* *in 2011*

In the 2010 Evian workshop, we showed the possibility of decreasing $\beta^* = 3.5$ m, used in 2010, to $\beta^* = 1.5$ m [6]. This decision was subsequently taken by the CERN management in early 2011. These calculations were based on a TCP setting of 5.7 σ and relaxed margins in IR7 and IR6, called intermediate settings [8, 9], which were defined for the first part of the LHC run to provide more room

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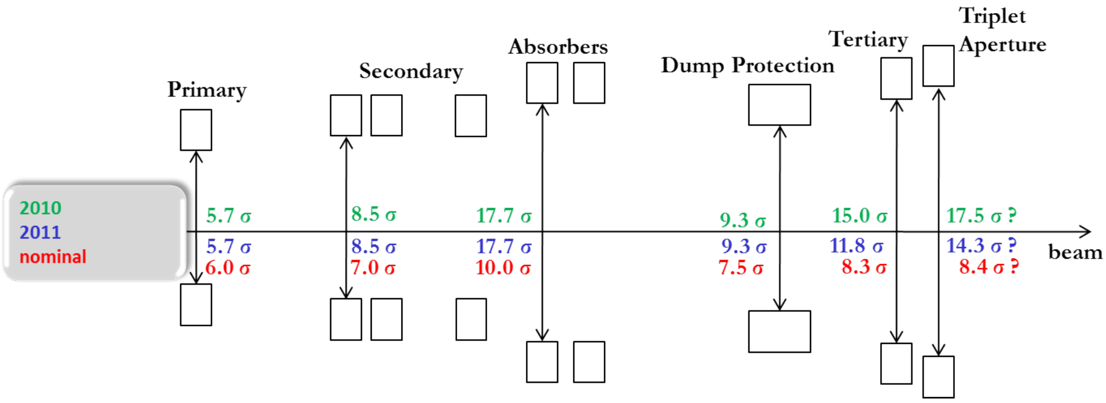

Figure 1: Schematic illustration (not to scale) of the collimator settings used during the runs in 2010 with $\beta^* = 3.5$ m (green), the 2011 run with $\beta^* = 1.5$ m and $\beta^* = 1.0$ m (blue), and the nominal settings (red).

for machine imperfections. Furthermore, the triplet aperture was calculated based on extrapolations from measurements performed by the LHC aperture team at injection energy [10, 11]. The measured aperture was scaled, using the thoretically predicted change in β-function and orbit from the crossing angle, as calculated using MAD-X, taking into account also the change in beam size from the changing energy. Margins for changing β-beat (10%) and orbit drifts (2.3 mm) were also included.

The squeezed optics $\beta^* = 1.5$ m was put into operation and used successfully in physics runs during the first part of the 2011 run. In May, machine development (MD) studies were done on the so-called tight collimator settings [12], where the feasibility of a collimation scheme with the TCPs closer to the beam was investigated; more details on this are given later. Such a scheme allows the full collimation system to be moved closer to the beam, meaning that also the minimum aperture that can be protected becomes smaller. Based on this scheme, the possibility of going to $\beta^* = 1$ m was mentioned in the Mini-Chamonix workshop [13], which motivated a push from the CERN management for further MDs and a commissioning effort by the operational crew in late August 2011 to make $\beta^* = 1$ m operational [14].

However, during the high-intensity commissioning, an instability was observed [15, 16] causing beam losses at the end of the squeeze. Shortly after, another MD was performed by the aperture team [17, 18, 19], where the triplet aperture in IR1 and IR5 was measured at top energy and squeezed optics. The results showed that the measured aperture was very close to the mechanical design aperture and therefore larger than calculated in Ref. [6]; in fact, it could be possible to operate with $\beta^* = 1$ m using the same collimator settings as used in the first half of 2011. The reason for the discrepancy was found to be the use of error margins for β-beat and orbit drifts was too pessimistic—if no additional error margins are used, the raw aperture scaling shown in Ref. [6] produces a result consistent with the measured top-energy aperture in the crossing plane. In the separation plane the model in Ref. [6] was too pessimistic also due to the lack of local aperture measurements at injection energy.

With these new experimental facts at hand, it was decided by the management to operate during the rest of 2011 with intermediate collimator settings, a crossing angle of 120 μrad, and $\beta^* = 1$ m, which thanks to an effort by the operational team was successfully commissioned [14].

Orbit stability in 2011

The margins assigned for orbit in 2011 were 1.6 σ between the TCTs and triplet apertures, and 1.1 σ between the TCSG in IR6 and the TCTs. These are the most critical locations, since a violation of the margins here could, in worst case, lead to sensitive elements being hit directly by beam in case of an asynchronous dump.

The margins between the IR7 collimators (TCP-TCS7-TCLA) and between IR7 and IR6 are less critical, since their main function is to ensure proper cleaning performance. If they are violated, lifetime dips could cause high beam losses in the dispersion suppressor regions that trigger spurious dumps, but machine safety is not at risk. During the 2011 run, these margins were kept at their 2010 values, which were calculated within the framework of the intermediate settings (retraction in mm between steps in the hierarchy kept constant during the energy ramp). The settings used in 2011 for the different families are shown in Fig. 1.

As input for the 2012 run, we have analyzed the orbits drifts during physics in 2011 in a similar way. The following BPM signals at critical locations, sampled every 10 s, were analyzed for both beams and planes: TCTs in IR1 and IR5 (BPMWB in cell 4 on incoming beam), triplets close to the theoretical aperture bottleneck (BPMS in cell 2 left and right of the IRs), and the IR6 dump protection (BPMSB in cell 4, right or left of IR6 depending on beam). The raw BPM signals were used to calculate the change in margin at every time instant with respect to the reference orbit that was used during the collimation setup and the qualification

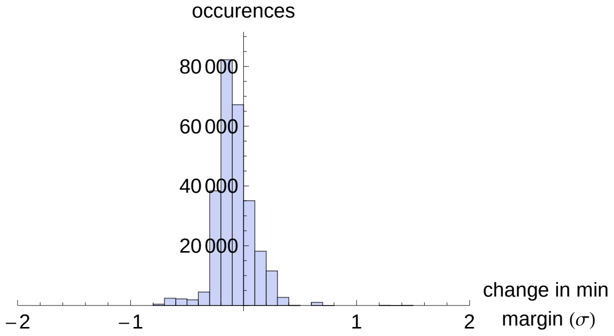

Figure 2: Reduction of margin between the vertical TCT in IR1 B1 and the aperture bottleneck in triplet. All data points from the run in fall 2011 in stable beams and $\beta^* = 1$ m, except where large luminosity scans were performed, were accounted for.

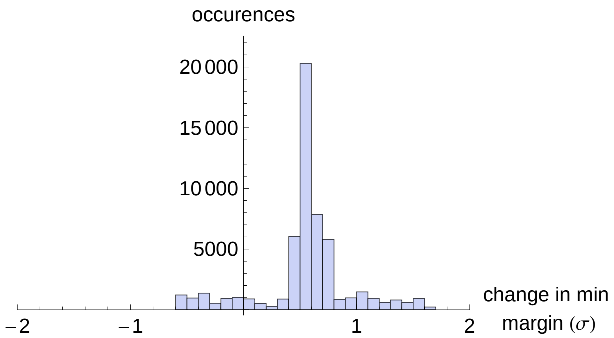

Figure 3: Reduction of margin between the horizontal TCT in IR5 B1 and the aperture bottleneck in triplet. All data points from the run in fall 2011 in stable beams and $\beta^* = 1$ m, except where large luminosity scans were performed, were accounted for.

of the cleaning performance, as shown in Ref. [7]:

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

For the case of the margin between TCTs and triplet, x_{r2} is the reference orbit at the triplet, Δx_2 and Δx_1 are the orbit drifts at the triplet and the TCTs respectively, all given in units of beam σ. The sign depends on the phase advance between the two locations. For the margin between two collimators, $x_{r2} = 0$ and Δx_i are the orbit drifts at the two locations.

Some results of the analysis can be seen in Figs 2–4, where histograms are shown of the reduction in margin. Following the statistical approach outlined in Refs. [6, 7], assuming that the margins should not be violated during more than 1% of the times in stable beams, the margins needed for orbit are 1.1 σ both between TCTs and triplets, and IR6 and TCTs. This is an improvement by 0.5 σ in the IRs compared to 2010.

It should be noted that IR1 was found to have consistently better orbit stability than IR5; the cause of this is not well understood. The analysis was also complicated by

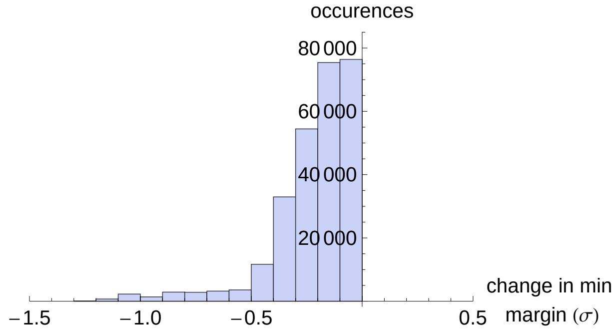

Figure 4: Reduction of margin between the dump protection in IR6 and the horizontal TCT in IR5 B1. All data points from the run in fall 2011 in stable beams and $\beta^* = 1$ m, except where large luminosity scans were performed, were accounted for.

the fact that BPMS.2L5.B1 in most fills had an error flag and was showing an unrealistic orbit. Therefore, this BPM had to be excluded. Furthermore, both BPMs in the IR5 triplets had error flags during the collimation setup, which introduces an uncertainty on the reference orbit. Instead, for these BPMs the reference orbit was extracted from the feedback catalog.

Other margins, not related to orbit, have not changed during the year. The β-beat was found to be at a level of 10% as previously, and the errors related to positioning, setup, and lumi-scans can be assumed unchanged.

MDs in 2011

The 2011 MDs relevant for possible reductions in β^* in 2012 are the measurements of the triplet aperture and the tests of tight collimator settings. As already explained in the overview of 2011, the triplet aperture at top-energy and squeeze was found to be close to ideal in measurements done by the aperture team [17, 18, 19]. Some uncertainties are however still present in these results, since both methods used for analyzing the data—reading the BPMs locally at the triplet and using the gap of the upstream TCT as a reference—have intrinsic uncertainties related to the BPM errors at low intensity and large amplitude and the specific shape of the orbit bump. As an extra safety measure, the cleaning performance was therefore qualified with loss maps with the TCTs retracted to 14 σ, where in worst case the aperture was supposed to be. These loss maps still showed losses at the TCTs but negligible losses in the triplets, meaning that in this configuration the TCTs were shadowing the triplets. In order to be on the safe side, we therefore assume a triplet aperture of 14 σ at $\beta^* = 1$ m and a half crossing angle of 120 μrad as a baseline when later calculating the apertures in other configurations. This assumption could be pessimistic.

Several tests with the tight collimator settings were done by the collimation team during 2011. In May, an MD was performed where the collimators were set to the nominal 7 TeV settings, keeping the centers from the setup in March, followed by loss maps [12]. It was then found that, for the nominal settings, the hierarchy was violated in Beam 1. Empirically the smallest retraction between TCP and TCS7 without a hierarchy violation was found to be 2 σ. Consequently, the tight settings were defined as keeping the TCPs at 4 σ, TCS7 at 6 σ and the TCLAs at 8 σ at 3.5 TeV.

The tight settings were re-qualified by the collimation team in MDs in September [20] and in November [21] and an excellent reproducibility in terms of hierarchy and cleaning efficiency was found. We can thus expect the tight settings to be stable over longer time scales.

The above mentioned MDs were performed with low intensities (1–2 bunches), while an end-of-fill study was done with higher intensity in August 2011 [22]. This study showed promising results but had to be aborted prematurely due to an interlock in IR6. Further studies with 84 bunches were done on August 29 [15, 16]. At the end of the squeeze to $\beta^* = 1$ m, high beam losses were observed. In an analysis by others [16] it was concluded that the likely cause was a combination of beam-beam and impedance effects, and that such events could likely be avoided in the future by raising the octupole currents to 450 A, a well-controlled chromaticity close to zero or even negative, and by not reducing the beam-beam separation below what was used in the 2011 run.

Another problem was also observed with the tight collimator settings, which was most clearly seen in the MD in November [21]. During the ramp and squeeze, the orbit was drifting, which caused a significant amount of beam to be scraped off by the TCPs—the worst case showed a 5% loss of the total intensity during the squeeze. This is not acceptable for physics operation but a solution for improved orbit correction, developed by the operation team, is underway at the time of writing [23].

OUTLOOK FOR 2012

Collimator margins and settings for 2012

From the operational observations described in the previous section, we conclude that most error sources that make up the margins IR6-TCT-aperture are unchanged, except the orbit in the IRs, where a 0.5 σ improvement is found compared to 2010. This improvement was already visible in the fist part of 2011 and reported in Mini-Chamonix [13]. However, a significant gain of 2.5 σ is possible by using the tight collimator settings - moving in the TCP and the TCS7.

When calculating the collimator settings, we keep in mind that some of the margins in σ change with the β-function, the beam energy, or with the collimator gap:

- Orbit margins in σ scale inversely with the local beam size, since they are assumed to stay constant in mm. Therefore they are proportional to $\sqrt{\gamma/\beta}$ and should thus decrease when β^* is squeezed. However, based on observations when β^* was reduced from 1.5 m to 1 m, this scaling did not hold in IR5. Therefore, we pessimistically assume that the orbit margins only scale with $\sqrt{\gamma}$.
- Margins for β-beat are calculated as $n_\sigma(\sqrt{\beta_{\mathrm{real}}/\beta_{\mathrm{model}}} - 1)$ [6]. The settings n_σ therefore have to be calculated iteratively.
- Positioning errors and setup errors are assumed to be constant in mm and therefore scale with inversely with the beam size.

The errors from all sources are listed in Tables 1–3. The total margins Δ_{tot} needed between the collimator families are shown in Table 4, calculated linearly as

$$\Delta_{\mathrm{tot}} = \sum_i |\Delta_i|, \qquad (2)$$

where Δ_i is the margin needed for each contributing error source as in Ref. [6].

Table 1: Estimated error margins at the TCT, except the orbit, in units of σ, for different energies.

	3.5 TeV	**4 TeV**	**7 TeV**
β-beat	0.44	0.47	0.61
positioning	0.10	0.06	0.03
setup	0.03	0.01	0.01
scans	0.20	0.20	0.20

Table 2: Estimated error margins at the TCSG in IR6, except the orbit, in units of σ, for different energies.

	3.5 TeV	**4 TeV**	**7 TeV**
β-beat	0.33	0.35	0.47
positioning	0.06	0.06	0.08
setup	0.02	0.02	0.02

Table 3: Orbit margins needed between the triplet aperture, TCTs and IR6 for different beam energies, in units of σ. The presumed scaling of these margins with β^* has been neglected based on the operational experience in 2011.

	3.5 TeV	**4 TeV**	**7 TeV**
aperture - TCT	1.1	1.2	1.6
TCT - IR6	1.1	1.2	1.6

There are further gains in margins if we note that it is unlikely that all margins would simultaneously assume their maximum value and add up in the same direction. Another approach for calculating the margins would therefore be to sum them in squares. This assumes that they are statistically independent and builds on the fact that the variances can be added linearly to obtain the variance of the sum of

Table 4: Needed margins in the collimation hierarchy if the errors are added linearly with Eq. (2) between IR6 and the aperture. For IR7, it is assumed that the tight settings qualified in 2011 in MDs are kept constant in mm and therefore scale in σ with the energy.

	3.5 TeV	4 TeV	7 TeV
TCS7 TCP7	2.0	2.1	2.8
TCLA7 TCS7	2.0	2.1	2.8
TCS6 TCS7	0.80	0.86	1.13
TCDQ - TCS6	0.5	0.53	0.71
TCT - TCS6	2.3	2.4	3.0
Aperture - TCT	1.9	1.9	2.4

any uncorrelated stochastic variables. Therefore, if Δ_i is the error margin needed for a 99% confidence level (as previously done for the orbit margins) for each contributing error i, the total error margin needed for 99% confidence is [6]

$$\Delta_{\text{tot}} = \sqrt{\sum_i \Delta_i^2}. \tag{3}$$

The only exception to this is the margins for lumi-scans, which cannot be considered being random. Therefore, we add this margins linearly to Eq. (3). The resulting error margins in the collimation hierarchy with Eq. (3) are shown in Tab 5. One more change has been done compared to Table 4—it has been assumed that the margins in IR7 and between IR7 and IR6 stay constant in σ instead of in mm, which also gains some fractions of σ at higher energies. It can be seen that the gain in minimum aperture that can be protected, compared to when using Eq. (2), is about 1.4 σ.

Table 5: Needed margins in the collimation hierarchy if the errors are added in squares with Eq. (3) between IR6 and the aperture. For IR7, it is assumed that the tight settings qualified in 2011 in MDs are kept constant in σ and therefore scale in mm with the energy.

	3.5 TeV	4 TeV	7 TeV
TCS7 TCP7	2.0	2.0	2.0
TCLA7 TCS7	2.0	2.0	2.0
TCS6 TCS7	0.8	0.8	0.8
TCDQ - TCS6	0.5	0.5	0.5
TCT - TCS6	1.4	1.5	1.9
Aperture - TCT	1.4	1.5	1.9

Aperture calculations

The other important component in the calculation of the reachable β^*-value is the triplet aperture margin as function of β^* and crossing angle. For these calculations we assume that the beam-beam separation from the last part of the 2011 run (with $\beta^* = 1$ m and a 120 μrad half crossing angle) is kept constant. This corresponds to 9.3 σ, if we assume a normalized emittance $\epsilon_n = 2.5$ μm, since the beam-beam separation d is given by [24]

$$d = \phi\sqrt{\frac{\gamma\beta^*}{\epsilon_n}}, \tag{4}$$

with the full crossing angle ϕ and the relativistic factor γ.

The reason for keeping 9.3 σ beam-beam separation is that calculations by the impedance team show that this is likely to be sufficient for alleviating the instabilities observed with tight settings [16]. However, this is only true for the 50 ns filling scheme. If a 25 ns scheme is used instead, the beam-beam separation might have to be increased to about 12 σ [25].

In order to estimate the needed aperture in each configuration, we use two methods: i) a scaling with beam size and orbit shift from a measured aperture in a known configuration as described in detail in Ref. [6], and ii) the $n1$-method. With both methods, we assume $\epsilon_n = 3.5$ μm.

As explained above, we use the most pessimistic result from the top-energy aperture measurements at $\beta^* = 1$ m, carried out by the aperture team in August [18, 19]. As a starting point, we therefore assume an aperture of 14 σ in both planes in IR1 and IR5 at separated beams, at $\beta^* = 1$ m and 120 μrad half crossing angle. No extra margins for orbit drifts or β-beat was included, since it was found in 2011 that this gave a very pessimistic aperture. The calculated apertures are for other configurations are shown in Fig. 5.

We have also estimated the aperture using the $n1$-method, but with no error included for the orbit, β-beat and energy offsets. Furthermore, to eliminate the built-in assumptions on the halo, all halo parameters were set to 6. The resulting calculation thus produces the minimum distance from the orbit to the mechanical aperture in units of σ. The results are slightly larger, but consistent,with Fig. 5. Apart from the nominal optics, the ATS

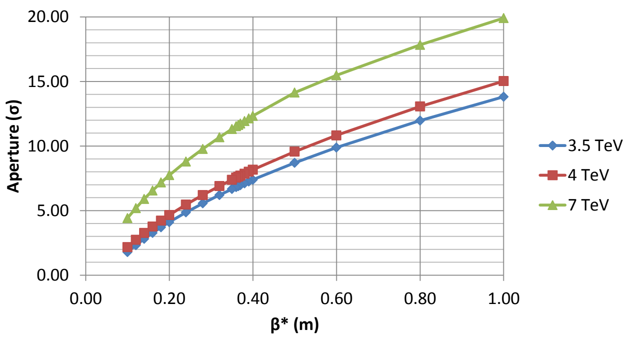

Figure 5: The aperture margin as function of β^* for different energies assuming that the beam-beam separation, Eq. 4, is kept constant from the configuration $\beta^* = 1$ m and a 120 μrad half crossing angle, where the initial aperture assumed for the scaling is 14 σ (3.5 μm emittance assumed). The ATS optics [26, 27] was used for the calculation, but the nominal optics gives the same result within fractions of a σ.

optics [26, 27] was used, in order to get estimates for $\beta^* < 0.55$ m.

It should be stressed that before putting any new configuration into operation, the aperture has to be re-measured, since it cannot be guaranteed that the influence of imperfections stays as small.

Scenarios for β^* for 2012

Base on the minimum aperture that we can protect, and the aperture as function of β^*, we can conclude on the minimum achievable β^*. Two scenarios are presented, using the two sets of margins presented in Tables 4 and 5, based on Eqs. (2) and (3), respectively. The resulting scenarios for 2012, at 3.5 TeV and 4 TeV, as well as at 7 TeV for comparison, are shown in Tables 6 and 7. The 3.5 TeV settings are schematically illustrated in Fig. 6.

It should be noted that the resulting margin between IR6 and the TCTs is only 1.5 σ if Eq. (3) is used and that this value is constrained by other operational considerations [28]. The orbit position at the TCSG6 is interlocked at a deviation of 1.4 σ at 3.5 TeV and 1.5 σ at 4 TeV and the margin should not be too close to this interlock and the expected local fluctuations in IR6. Based on the information in Ref. [28], it is therefore desired that this margin is larger. We therefore assume an additional 0.4 σ that is added in the final setting.

It should be noted that at 4 TeV, there is still some margin to the estimated aperture at $\beta^* = 0.6$ m, which is to 10.8 σ(see Fig. 5), and that this aperture estimate is likely to be pessimistic. Therefore, this provides some extra margin

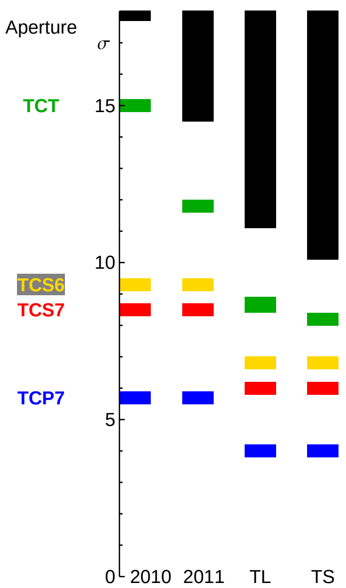

Figure 6: Schematic illustration for 3.5 TeV of the relaxed settings together with the minimum aperture that can be protected, in 2010 and 2011, and the tight settings with linear margins (TL) and with square margins (TS).

Table 6: The collimator settings proposed based on the margins shown in Table 4 with the errors added linearly using Eq. (2). The minimum β^* compatible is also shown together with the corresponding half crossing angle $\phi/2$ for a 9.3 σ beam-beam separation.

	3.5 TeV	**4 TeV**	**7 TeV**
TCP 7 (σ)	4.0	4.3	5.7
TCS 7 (σ)	6.0	6.4	8.5
TCLA 7 (σ)	8.0	8.6	11.3
TCS 6 (σ)	6.8	7.3	9.6
TCDQ 6 (σ)	7.3	7.8	10.3
TCT (σ)	9.1	9.6	12.6
aperture (σ)	10.9	11.5	15.0
β^* (m)	0.7	0.7	0.6
$\phi/2$ (μrad)	143	134	110

Table 7: The collimator settings proposed based on the margins shown in Table 5 with the errors added in square using Eq. (3). The minimum β^* compatible is also shown together with the corresponding half crossing angle $\phi/2$ for a 9.3 σ beam-beam separation.

	3.5 TeV	**4 TeV**	**7 TeV**
TCP 7 (σ)	4.0	4.3	5.7
TCS 7 (σ)	6.0	6.3	7.7
TCLA 7 (σ)	8.0	8.3	9.7
TCS 6 (σ)	6.8	7.1	8.5
TCDQ 6 (σ)	7.3	7.6	9.0
TCT (σ)	8.5	9.0	10.4
aperture (σ)	9.9	10.5	12.3
β^* (m)	0.6	0.6	0.45
$\phi/2$ (μrad)	155	145	126

for comfortable operation. On the other hand, we conclude that in this scenario the nominal $\beta^* = 0.55$ m is not far away and may be reachable—using instead the $n1$-method with no error margins, this is indeed the case (estimated aperture at $\beta^* = 0.55$ m and 4 TeV is then 11 σ).

In case of a 25 ns scheme, the beam-beam separation has to be increased to 12 σ, which would lead to a loss of about 10 cm in β^*. This is shown in Fig. 7. Furthermore, the emittance from the injectors is likely to be larger, which makes the loss even larger—almost 20 cm is lost if the emittance is assumed to be instead 3.5 μm.

Several operational challenges are connected with the proposed scheme: the orbit feedback during the squeeze has to work, and the octupoles and chromaticity must be such that instabilities are suppressed. Both these issues are expected to be solvable, but the solutions are still to be demonstrated experimentally and operationally. Furthermore, a small β^* might require the use of non-linear correctors in the IRs, which has to be studied further.

Therefore, we must also consider the case that the tight

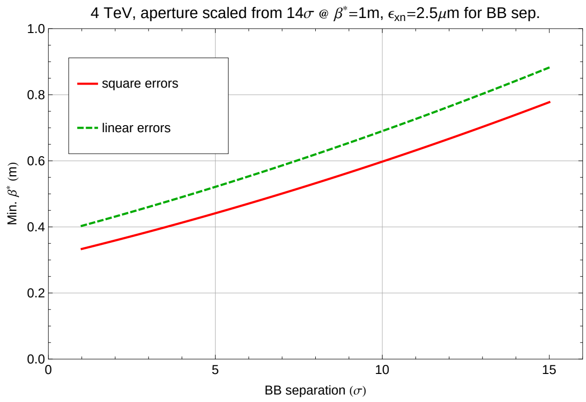

Figure 7: The minimum achievable β^* as function of beam-beam separation, assuming an emittance of $\epsilon_n = 2.5$ μm and 4 TeV. The aperture is scaled from 14 σ at $\beta^* = 1$ m and $\phi/2 = 120$ μrad. The result is shown both for the case of adding the errors linearly [Eq. (2)] and in square [Eq. (3)]

collimator settings could not be used, e.g. if the impedance and beam-beam effects would be stronger than expected or orbit correction would not work out during the squeeze. In this case some improvement is still possible. The secondary collimators can be moved from the 8.5 σ, used in 2011, to a 2 σ retraction behind the TCP, which is left at 5.7 σ. The other collimators could stay at the same retraction as in 2011, which would allow $\beta^* = 0.9$ m. However, it should also be mentioned that the tight settings, in mm, are more relaxed than the nominal settings at 7 TeV. Therefore, it is crucial for later improvements that the LHC can be made operational in these conditions.

Room for further gain

The resulting values of β^* shown in Table 7 are not yet at the ultimate limit for the LHC. A few things can still be done with the present machine to achieve improvements, which all require further theoretical and experimental studies:

- There might be possibilities to further reduce the margins in IR7 and IR6, since a violation of the hierarchy here is not catastrophic—in worst case the cleaning inefficiency will degrade, possibly resulting in spurious dumps but no material damage.
- The primary collimators could be moved even closer to the beam, e.g. keeping 4 σ also at higher energies. This becomes, however, increasingly challenging in terms of impedance and orbit correction.
- The BPMs in the IRs show large drifts, which are not well understood. If parts of the drifts can be shown to be uncorrelated to the beam movements, the orbit margins can be reduced [29].
- It has been proposed [29] that a new optics, with a phase advance of exactly $\pi/2$ between the IR6 dump extraction kicker and the TCDQ could make the necessary margin between TCTs and IR6 smaller.

Furthermore, in the longer scale, several upgrade scenarios exist with much smaller β^*, profiting from new hardware and the ATS optics [26, 27]. Upgrades of the collimators to include BPM buttons [30] are another promising concept. If the collimators can be automatically realigned in every fill, or even during a fill, without touching the beam, the margins for orbit drifts can be drastically reduced. A dream scenario would therefore be to use only about 0.1 σ for orbit and furthermore move in the TCPs to 4 σ also at higher energies. At 7 TeV, this would mean that only 1 σ is needed between IR6 and the TCTs, and 0.6 σ between the TCTs and the aperture. Assuming a 2 σ retraction in IR7 and 0.8 σ to IR6, minimum aperture that can be protected ends up at 8.3 σ, which is very close to the nominal specification. This would mean that $\beta^* \approx 25$ cm might be within reach at 7 TeV. However, it should be stressed that such a scenario is highly demanding in terms of impedance and orbit correction, so the operational feasibility is extremely challenging and still to be proved. The relative gain is also decreased due to the geometric reduction factor.

SUMMARY

We have given an overview of the 2011 run in terms of β^*, orbit stability (slightly better than in 2010), and relevant MDs. In particular, new aperture measurements gave at hand an aperture at top energy that is very close to the design value and MDs on tight collimator settings showed the possibility of moving in the collimation system closer to the beam in order to protect the triplet with a smaller aperture margin.

Further gains can be done by a statistical approach, where the errors are added in square instead of linearly. Combining this with the data and experience from 2011, we defined possible scenarios for 2012: $\beta^* = 60$ cm is feasible at 4 TeV with a beam-beam separation of 9.3 σ. This scheme is only possible to put into operation if firstly the chromaticity and octupoles can be used to alleviate instabilities while keeping the same beam-beam separation as in late 2011, and secondly the orbit correction during the squeeze is improved. Both these points are likely to be solvable although this has not yet been shown experimentally. Furthermore, the proposed scenario assumes also that the aperture stays as good as previously found. To confirm this, the aperture has to be re-measured in the new configuration.

In case of problems, more relaxed running scenarios were discussed, with tight settings but linear addition of the errors ($\beta^* = 70$ cm) or a fall-back solution keeping the intermediate settings ($\beta^* = 90$ cm). The proposed scenarios are not yet at the performance limit of the present machine and several possibilities for improvements, which require further in-depth studies, were discussed.

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