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Collimator settings and performance in 2011 and 2012

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Abstract

Collimator settings and performance are key parameters for deciding the reach in intensity and β^*. In order to conclude on possible limits for the 2012 run, a summary is first given of the relevant running experience in 2011 and the collimation-related MDs. These include among others tight collimator settings, a quench test, and aperture measurements. Based on the 2011 experience, we conclude on possible running scenarios for 2012 in terms of collimator settings, intensity and $\beta^*$from the collimation point of view.

INTRODUCTION

This article discusses some highlights from 2011 related to collimation and machine performance and uses these points as input for the 2012 run. Only performance limits related to collimation are discussed.

The LHC collimation system [1, 2, 3, 4] 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 (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 leakage rate from the collimators to the cold magnets in IR7, where the TCLAs are present, is much lower. 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 in order to avoid the risk of being hit and damaged in the case of a dump failure [1].

LHC collimation is directly related to the performance and luminosity of the LHC in several ways. The instantaneous luminosity for round beams can be written as [5]

$$L = \frac{N_1 N_2 f_{rev} k_B}{4\pi\beta^*\epsilon_{xy}} \times F, \qquad (1)$$

where N_i is the intensity in beam i, f_{rev} the revolution frequency, k_B the number of bunches per beam, $\beta^*$the optical β-function in the collision point, ϵ_{xy} the geometrical emittance and F the geometric reduction factor.

As can be seen in Eq. (1), the luminosity is inversely proportional to β^*, meaning that it is desirable to operate with β^* as low as possible. However, when β^* is decreased, 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 bottleneck of the ring, which must always be protected by the LHC collimation system. Otherwise, quenches induced by high beam losses or, in the unlikely case of an asynchronous dump, even damage to the triplets could occur. Therefore, β^*should be as low as possible without compromising machine protection.

Margins are needed between the different collimator families in order for the collimation hierarchy to be respected, also when there are machine drifts such as β-beat and orbit variations. These margins can be calculated using the models outlined previously [6, 7, 8] 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 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]. By comparing with the required aperture in different configurations of $\beta^*$and crossing angle, the minimum β^*can be calculated.

The collimation performance has also a direct influence on the intensities N_i in Eq. (1). If both N_1 and N_2 in Eq. (1) can be increased by a certain factor a, the luminosity increases by a^2. The maximum allowed intensity N_{max} that can be stored per beam is limited by [9, 10, 11]

$$N_{max} = \tau_{min} \times R_{max}, \qquad (2)$$

where τ_{min} is the minimum beam lifetime and R_{max} is the maximum tolerable loss rate on the primary collimators without the leakage out of the cleaning insertion causing a quench. The smaller the cleaning inefficiency (the leakage ratio of particles out of the collimation system and into the the cold magnets), the larger R_{max} can be achieved. Furthermore, the intensity is also limited by the impedance from the collimators, which might cause fast losses and instabilities [12].

HIGHLIGHTS IN 2011

Tight collimator settings

One way of decreasing the limit on the aperture that can be protected is to move all collimators closer to the beam. This was tested in several MDs in 2011. In May, an MD was performed where the collimators were set to the nominal 7 TeV settings in mm, keeping the centres from the

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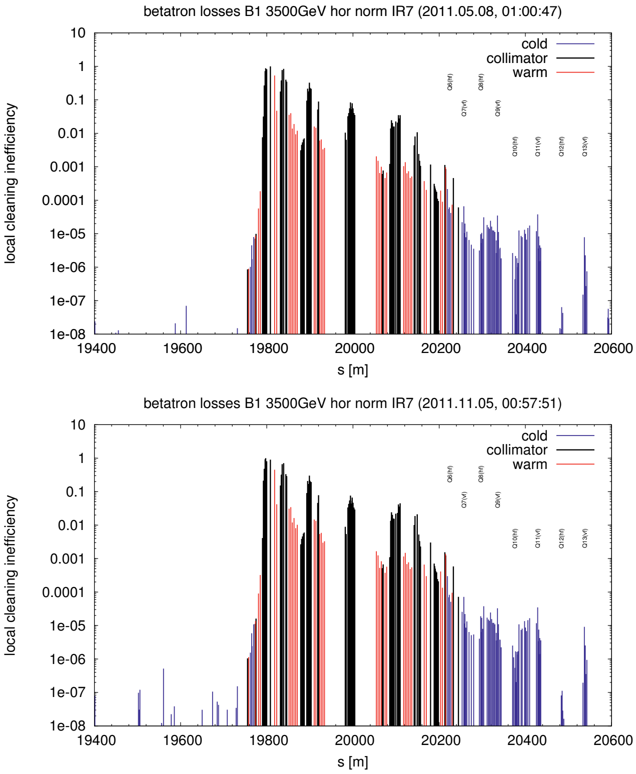

Figure 1: Losses with tight settings in the cleaning insertion IR7, for the two planes in beam 1, in collimators and cold and warm elements during the crossing of the third order resonance, from MDs in May (top) and November 2011 (bottom). An excellent long-term stability of the cleaning hierarchy with tight settings was observed.

setup in March, followed by loss maps [13]. It was then found that, for the nominal settings, the hierarchy was violated in Beam 1. The smallest retraction between TCP and TCS7 without a hierarchy violation was empirically found to be 2 σ. Consequently, what is called tight collimator settings were defined as having the TCPs at 4 σ, TCS7 at 6 σ and the TCLAs at 8 σ at 3.5 TeV. Thus, the gain in aperture comes both from the TCP being closer to the beam and a smaller margin between TCP in TCS7.

Later in the year, these tight settings were re-qualified in MDs in September [14] and in November [15] and an excellent reproducibility in terms of hierarchy and cleaning efficiency was found. As an example, we show in Fig. 1 the loss maps in IR7 for horizontal losses in beam 1 both in May and November 2011. Both loss maps show a preserved hierarchy with no degradation over time, despite the fact that no intermediate collimator alignment was performed. We can thus expect the tight settings to be stable over longer time scales. A significant reduction of the cleaning inefficiency by a factor 3.3–10 was also found, compared to the relaxed settings, which according to Eq. (2) can be used to gain in intensity reach.

These MDs were carried out with only 1–2 bunches, while an end-of-fill study was done with higher intensity in August 2011 [16]. This study showed promising results but had to be aborted pre-maturely due to an interlock in IR6. Further studies with 84 bunches were done on August 29 [17, 12]. At the end of the squeeze to $\beta^* = 1$ m, high beam losses were observed. In an analysis by the impedance team [12] 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.

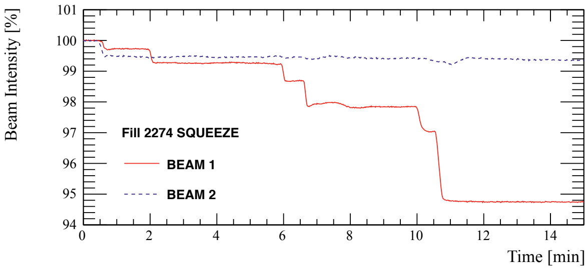

Figure 2: The intensity in both beams as a function of time during the squeeze in the MD with tight settings in November 2011 [15]. About 5% of beam 1 is lost when beam is scraped off at the primary collimators due to orbit oscillations.

Another problem was also observed with the tight collimator settings, which was most clearly seen in the MD in November [15]. 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 as can be seen in Fig. 2. 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 [18].

To conclude, some detrimental effects were observed with tight collimator settings but the problems are understood and solutions underway. The tight settings provide room to squeeze $\beta^*$to smaller values and a better cleaning efficiency, which allows higher intensities to be stored safely, while maintaining full protection of the machine. Furthermore, tight settings provide valuable experience for future 7 TeV operation—in fact, the tight settings (in mm) can be considered as relaxed settings at 7 TeV, since the TCP is at its nominal position while the other collimators are further retracted.

Other important results

Several other aspects of the 2011 operation should be mentioned in the context of collimation-related performance issues. Aperture measurements were performed by the aperture team both at injection energy [19] and top energy [20, 21]. The results show evidence of a well-aligned machine with smaller errors than foreseen during the design phase. The top-energy aperture measurements, which show a triplet aperture close to the mechanical design value, were used to refine the experimental basis of the calculation models for the reach in β^* [22] 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. [23].

Another important MD in 2011 was the quench test [24]. A very high loss rate of 9×10^{11} p/s was achieved by crossing the third order resonance using a beam consisting of 12 bunches. This corresponds to 0.5 MW of beam power impacting on the primary collimators but with no quench observed. This result can be directly used in Eq. (2). Through a scaling of the measured BLM signals at the TCP and at the highest cold loss location, the achieved beam loss power was estimated to 335 W in the Q8.

It should be noted that the achieved loss rate of 0.5 MW equals the specified design loss at 7 TeV that the collimation system should be able to handle (a 12 minute beam lifetime and an intensity of 3.2×10^{14}). Since no quench was observed, the quench test only establishes a lower limit on the loss rate. However, at 3.5 TeV the quench limit of the magnets are also significantly higher than at 7 TeV due to the lower current and field.

The orbit stability in 2011 has also been analyzed in order to assess the necessary margins between the collimator families [8, 25]. It was shown that a 1.1 σ retraction is needed both between IR6 and the TCTs, and between the TCTs and the triplet aperture, to account for 99% of all observed orbit movements. This is an improvement by 0.5 σ in the IRs compared to 2010. We note that IR1 was found to have better orbit stability than IR5; the cause of this is not well understood. The analysis was also complicated by the fact that one BPM in IR5 was excluded since it had an error flag and showed an unrealistic orbit.

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 are assumed to be unchanged.

COLLIMATION IN 2012

Based on the operational experience in 2011, we propose collimator settings for 2012, which we then use to address the collimation-related performance limits. In all calculations, we assume that the beam energy is increased to 4 TeV, even though some results are shown for other energies for comparison.

Proposed collimator settings in 2012

We have seen 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 [26]. Increasing the energy to 4 TeV does not lead to significantly increased margins, as for example the BPM systematics is not expected to improve [8]. However, a significant gain of 2.5 σ is possible by moving in the TCP and the TCS7 to tight collimator settings.

In addition, further gains can be made by noting 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 the individual errors in squares instead of linearly, relying on the assumption that they are statistically independent. 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 [8]

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

The only exception to this is the margins for lumi-scans, which we add linearly as described in Ref. [8]. Putting all the changes together, a set of proposed collimator settings for 2012 has been calculated [8], as shown in Table 1. The corresponding settings for 3.5 TeV and 7 TeV are shown for comparison. It should be noted that an additional 0.4 σmargin has been added between the TCTs and IR6 in order to make the margin larger than the interlock on the orbit movement [25]. This additional margin could possibly be cut out in the future, thus giving a small improvement in performance. No changes are proposed in IR3.

Table 1: Proposed collimator settings based on individual errors added in square using Eq. (3). IR3 is assumed to stay at the same settings as in 2011.

	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

Apart from the change in settings, the TCL collimators, which are copper absorbers positioned around IR1 and IR5, will be moved in to 10 σ. In previous runs, these collimators were open. It is hoped that they will catch significant fractions of the collisional debris coming out of the IPs, which could improve the radiation to downstream magnets.

Furthermore, a new and faster semi-automatic setup algorithm with a 8 Hz collimator movement will be used to align the collimators around the beam.

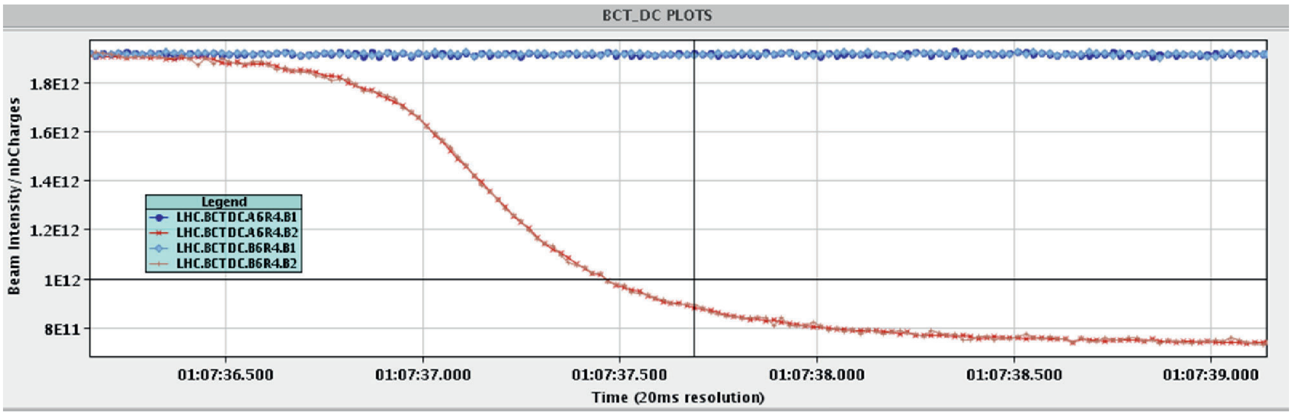

Figure 3: The measured beam current in beam 1 (blue) and beam 2 (red) during the quench test MD [24]. The current decays by about 9×10^{11} protons in beam 2 over 1 s starting at $t = 01:07:36.5$.

Intensity limits

The collimation limit on intensity can be addressed using the result $R_{max} = 9 \times 10^{11}$ p/s from the quench test MD [24] in Eq. (2). Together with an observed minimum lifetime of about 1 h [9], this gives an allowed intensity of 3×10^{15}. If we in addition assume that tight settings are used, a further improvement of the cleaning efficiency by a factor 3.3 can be assumed, which gives a total achievable intensity of 1.1×10^{16}. This is about 30 times nominal intensity at 3.5 TeV. We thus conclude that even if the quench limit is slightly worse at 4 TeV, there is no intensity limit from collimation within reach in 2012, provided the lifetime does not degrade. The rest of our discussion is therefore focused on the limit in β^*.

Limits on β^*

The collimator settings in Table 1 give the minimum aperture that can be protected, which together with the required aperture for different $\beta^*$and crossing angle can be used to calculate the limit on β^*. In this article, we deal only with limits on β^* from collimation and aperture. For other optical limitations, the reader is referred to Ref. [27].

The aperture has been calculated in Ref. [8], using both a scaling of the measured aperture and the $n1$-method. It has been assumed pessimistically that the available aperture at β^*=1 m and 120 μrad half crossing angle is 14 σ. This corresponds to the configuration that was qualified with loss maps (TCTs retracted to 14 σ without leakage). The 14 σ is a smaller value than what was found in the aperture measurements when referring to the gap of the TCTs [21]. This conservative approach is motivated by the uncertainties in the aperture measurements (influence of bump shape on the location of the aperture limit, BPM systematics, and the dependence on the phase advance between these specific orbit correctors and the aperture bottleneck).

Certain assumptions must be made on the beam-beam separation in order to define the crossing angle as function of β^*. Calculations by the impedance team [12] show that a 9.3 σ beam-beam separation is likely to be sufficient for alleviating the instabilities observed with tight settings, corresponding to the running conditions during the last part of the 2011 run ($\beta^* = 1$ m and a 120 μrad half crossing angle for a normalized emittance $\epsilon_n = 2.5$ μm.). Keeping this assumption for 2012, the estimated scaled aperture as function of β^*, taken from Ref. [8], is shown in Fig. 4.

However, this is only true for the 50 ns filling scheme. If a 25 ns scheme is used instead, a 12 σ separation should be envisaged [28]. On top of that, the emittance delivered by the injectors is larger (could be $\epsilon_n = 3.5$ μm) in 25 ns operation. Therefore, the crossing angle has to be significantly increased.

The resulting allowed values of $\beta^*$and crossing angle at 4 TeV, at 25 ns and 50 ns, are shown in Table 2, using the calculated aperture in Fig. 4 and the collimator settings in Table 1. It should be stressed that before putting any new configuration into operation, the aperture has to be remeasured, since it cannot be guaranteed that the influence of imperfections stays as small.

Table 2: Values of β^*at 4 TeV in IR1 and IR5 where the aperture is compatible with the collimator settings shown in Table 1.

	β^*	**half crossing angle**
50 ns	0.6 m	145 μrad
25 ns	0.8 m	192 μrad

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

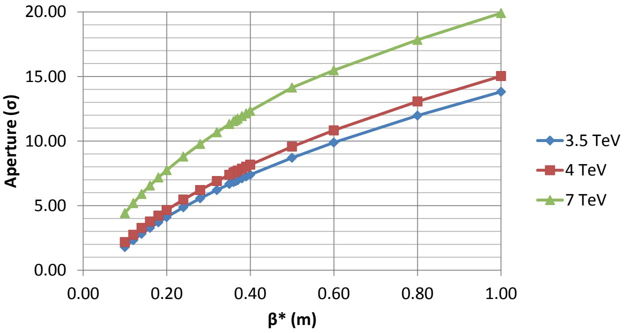

Figure 4: The aperture margin as function of β^* for different energies assuming that the beam-beam separation is kept constant from the configuration $\beta^* = 1$ m and a 120 μrad half crossing angle. The initial aperture assumed for the scaling is 14 σ (3.5 μm emittance assumed). The ATS optics [29, 30] was used for the calculation, but the nominal optics gives the same result within fractions of a σ.

aperture at $\beta^* = 0.55$ m and 4 TeV is then 11 σ).

It should be stressed that 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 set in such a way 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^* causes a large off-momentum β-beat in the experimental insertions [27]. The effect of this on collimation has be examined more closely during the qualification of the cleaning.

In the case of unexpected problems, where the settings in Table 1 could not be used, several fall-back options are possible: $\beta^* = 0.7$ m and margins added linearly as before or $\beta^* = 0.9$ m if relaxed settings must be used. These options are discussed more in detail in Ref. [8].

The proposed configuration is not yet at the final limit of the LHC. Several measures, which require further in-depth studies, can still be taken in the present machine to achieve improvements [8]. Some topics include optimizing further the margins in IR7 and IR6, and better understand what parts of the drifts of the BPMs in the experimental IRs correspond to real beam movements [31].

On a longer time scale, several upgrade scenarios exist with much smaller β^*, profiting from new hardware (such as collimators equipped with BPM buttons [32]) and the ATS optics [29, 30]. A dream scenario would be to use only about 0.1 σ for orbit and furthermore move in the TCPs to 4 σ also at higher energies This would mean that $\beta^* \approx 25$ cm might be within reach at 7 TeV [8]. 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 in luminosity is also decreased due to the geometric reduction factor F in Eq. (1) which is decreased with smaller β^* [33].

SUMMARY

We have summarized some important results from operation and MDs in 2011 in order to define scenarios for collimation in 2012. Based on this, we have examined the resulting machine performance. Tight collimator settings—with primary collimators at 4 σ—showed an excellent long-term stability, improved cleaning performance and more room to squeeze β^*. However, before these settings can be used in physics operation, the orbit correction in ramp and squeeze has to be improved and large beam losses caused by a combination of impedance and beam-beam effects alleviated. Solutions have been proposed but must be demonstrated experimentally.

A quench test established 0.5 MW of beam power as a lower limit on the acceptable loss rate on the primary collimators that does not cause a quench. Together with observed beam lifetimes of about 1 h, this means that 30 times nominal intensity can be tolerated at 3.5 TeV. Consequently, no intensity limit from collimation is within reach at 4 TeV either, if the lifetime does not degrade.

Aperture measurements carried out by the aperture team showed that the inner triplet aperture in IR1 and IR5 is very close to the mechanical design aperture, which has positive consequences on the reach in β^*.

For 2012, several changes of the collimator settings are presented. Apart from the use of TCL collimators and a faster setup, tight settings and the summing of error margins in squares are proposed. This gains room to squeeze β^*further—at 4 TeV, $\beta^* = 60$ cm and a half crossing angle of 145 μrad is compatible with the protection of the aperture. This scheme can be made operational only if the detrimental effects of tight settings, outlined above, can be overcome as expected. 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.

More relaxed running scenarios were discussed as fall-back solutions, with tight settings but linear addition of the errors ($\beta^* = 70$ cm) or keeping the intermediate settings ($\beta^* = 90$ cm). The proposed scenarios are not yet at the performance limit of the LHC and several possibilities for improvements, requiring further in-depth studies, exist.

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