β^*-REACH IN 2017

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Abstract

In this paper, we review the strategy deployed for decreasing β^* in the past and summarize tests done during 2016 in order to further push down β^* in the future. Improvements are presented in particular for the collimator settings. The tests, combined with detailed aperture knowledge and input on the 2017 run conditions, such as a smaller beam-beam separation or the prospect of adding an orbit bump to shift the CMS IP, are used to conclude on a range of feasible β^*-values for 2017.

INTRODUCTION

One way of increasing luminosity in the LHC, which is independent of the beam brightness, is to decrease β^*. The reach in β^* in the LHC is limited by several factors. On one hand, it becomes harder with decreasing β^* to develop an optics that satisfies constraints on e.g. magnetic strengths. On the other hand the β-functions in the inner triplets in front of the interaction points (IPs) increases as β^* goes down, which means that the normalized aperture[1] becomes smaller so that it risks to no longer be protected by the collimation system. This limit on aperture has been the driving constraint for allowed β^* in the LHC so far [1]. The β^*-reach from this limit can be improved mainly by tightening the collimators, in order to protect a smaller normalized aperture, or decreasing the crossing angle, so that the normalized aperture at a given β^* increases. A better knowledge of the aperture through detailed measurements can also help through reduced margins for imperfections.

In Run 1, an initially conservative approach was taken with rather open collimator settings [2]. Later on, a statistical approach was developed in order to reduce the margins, while still keeping the risk of exposing sensitive elements very low [1], which allowed tighter collimators and a significantly reduced β^* in steps down to 60 cm at 4 TeV in 2012 [3, 4]. In Run 2, 2015 was be considered to be a commissioning year, when operation at 6.5 TeV and 25 ns was established, and rather relaxed machine parameters were used. The Run 1 approach to calculate collimator settings and β^* was used, with a relaxed β^*=80 cm and an additional 2 σ safety margin.

For 2016, a goal was set produce more than 25 fb^{-1}, and more than 100 fb^{-1} of data should be collected in Run 2 up to the end of 2018. To meet these targets, the luminosity had to be increased significantly, and various possibilities of decreasing β^* were studied in detail in MDs [5–9]. One of the largest limitations for tightening collimators and hence the protected aperture up to then was the risk of hitting and damaging a tertiary collimator (TCT), made of tungsten and not robust against high-intensity impacts, or the triplets behind them, with miskicked beams during asynchronous beam dumps. This risk could be effectively alleviated using a new optics, with a specially matched phase advance between the dump kickers (MKDs) and the TCTs close to 0° or 180° [10]. This allowed to reduce the margin between the dump protection (TCDQ) and TCTs by 3.9 σ compared to 2015, which together with a 0.5 σ tighter collimation hierarchy in IR7 and a reduction of the normalized beam-beam separation from 11 σ to 10 σ allowed to reach β^*=40 cm [10, 11]. This gave an important increase in luminosity and is significantly below the nominal design value of β^*=55 cm.

For 2017, luminosity production is again the highest priority, and during the year 2016, a rich MD program connected to the β^*-reach has continued [12–17], in case a further reduction in β^* would be desired. In particular, studies have been carried out to assess whether it is possible to further tighten the collimators. A more detailed knowledge of the aperture has also been gained, and as input we use also the conclusion from the studies on the feasibility of a reduced beam-beam separation. In the following, we summarize these results and use them to conclude on the reach in β^*.

STUDIES ON COLLIMATION HIERARCHY

The LHC collimation system has shown an excellent performance in 2016 [18, 19]. It could therefore be envisaged to further tighten the settings and several options were studied. The retraction between TCP and TCSG was investigated in a dedicated MD, where loss maps were performed at different collimator settings [12]. It was discovered that the limitation found in previous MDs [7], where a breakage of the cleaning hierarchy appeared at 1 σ, was caused by an angular misalignment of the tank of one particular collimator (TCSG.D4L7.B1). Compensating for this through a beam-based alignment of the jaw corners separately to introduce a compensating tilt, a correct cleaning hierarchy was achieved also for the nominal 1 σ TCP-TCSG retraction. The loss map with a 1 σ retraction and compensated tilt is shown in Fig. 1.

Based on these encouraging results, we conclude that it is feasible in terms of stability of the cleaning hierarchy to reduce the retraction between TCP and TCSG in operation to 1.5 σ. This should not require more frequent collimator alignments than previously. Further studies in 2017 could show if the 1 σ retraction, with the tilt compensation, can be used to obtain a correct hierarchy throughout the year, in which case it could be envisaged to use that retraction in 2018 if no other limitations are found.

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[1] The normalized aperture is defined as the distance between the beam centre and the mechanical aperture normalized by the local beam size.

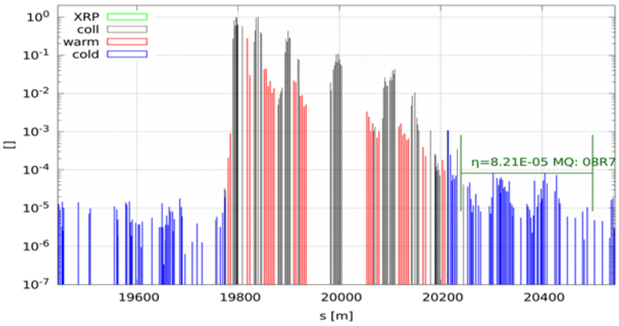

Figure 1: A loss map from MD 1447 [12] in B1, vertical plane, zoomed in IR7. The retraction between TCP and TCSG is 1 σ and an angular alignment of TCSG.D4L7.B1 has been performed.

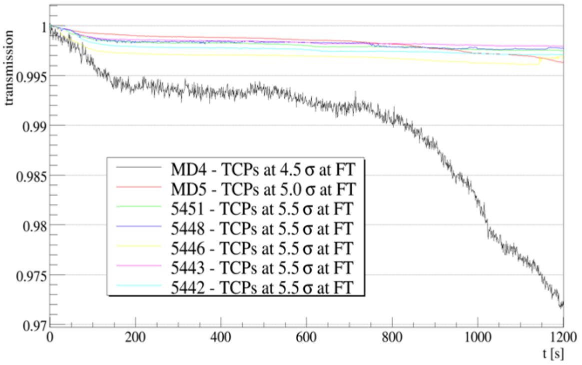

Figure 2: The intensity transmission through the ramp in two fills in MD 1878 [13], where the TCPs were closed to 4.5 σ and 5 σ respectively, shown together with the intensity transmission in a few standard physics fills in 2016.

Furthermore, another MD was carried out to investigate the effect of operating with a tighter TCP setting [13], which would allow all other collimators to follow. Two full cycles were carried out, where the TCPs were closed during the ramp to half gaps of 4.5 σ and 5.0 σ respectively[2], which should be compared to the operational setting in 2015–2016 of 5.5 σ.

Figure 2 shows the intensity transmission in the ramp for the test fills, as well as a few standard physics fills in 2016. During the MD fill where a 5.0 σ TCP setting was reached at flat top, which was carried out with trains and the standard crossing angle to have the full beam-beam long-range effects, the beam transmission and lifetime through the cycle were observed to be very similar to standard 2016 physics fills. A 5.0 σ TCP setting seems therefore feasible considering the losses and beam lifetime, and could be used in operation in 2017, however, we stress that this was tested only in one fill.

With a 4.5 σ TCP setting, the minimum lifetime in the ramp dropped by about a factor 10, and a significant reduction of the beam intensity was observed. It is, however, unclear if these effects were really caused by the tighter TCP cut, since instabilities were observed in that fill already at injection, before closing the TCP. This is not understood in detail and could be investigated in further tests in 2017.

The described studies show that the IR7 collimators can be tightened without jeopardizing the cleaning hierarchy and beam transmission. However, tighter collimators can only be used in operation if the impedance is low enough to avoid beam instabilities. The collimator impedance was therefore studied in detail in several MDs in 2016 [13,16,17]. Based on these results, it is concluded that a TCP setting of 5 σ and a TCSG setting of 6.5 σ is still tolerable for the LHC impedance budget with the envisaged configuration of octupoles and chromaticity [20].

It was also studied in 2016 if the TCTs could be brought in closer to the beam, thus reducing the margin to the TCDQ and to the IR7 cleaning hierarchy. If it is assumed that an optics with a specially matched phase advance between MKDs and TCTs can be used as in 2016 [10], there is not a strong constraint on the TCT setting from asynchronous beam dumps. In that case, other constraints become limiting, such as the cleaning hierarchy and the potentially increased experimental backgrounds [21], since more protons outscattered from IR7 might impact the TCTs and shower onto the experiments. The TCTs risk also to intercept a larger rate of elastically scattered protons from upstream beam-gas interactions.

The impact on background was studied in an end-of-fill MD, where a physics fill with 2200 bunches per beam was taken over about two hours before it was envisaged to dump [14]. The vertical TCTs were then tightened by 0.5–0.6 σ from their standard physics setting of 9 σ, after going in adjust and still staying within the interlock limits. With these settings, the LHC was brought back in stable beams. Data were accumulated during around 1.5 h, before going back to adjust to open the TCTs again to their standard physics setting.

The analysis of this MD shows no visible change in background in ATLAS and CMS during the period with tighter TCTs, suggesting that at least 0.5 σ tighter TCTs should not cause background issues for the experiments from neither beam-halo nor elastic beam-gas. It should be noted that the beam lifetime was rather good during the test. Therefore, it might be that the beam-halo background component could be higher e.g. during the first hour of collisions, where a lower lifetime has been observed [22].

However, other studies based on recorded background in ATLAS during loss maps [23] support the hypothesis that the machine-induced backgrounds dominated by inelastic interactions close to the detectors and that the beam-halo contribution is negligible (below 1% of the total). In conclusion, it is very unlikely that operation with the TCTs at this smaller retraction to IR7 should cause any background problems. This is also not expected to cause issues in terms of cleaning hierarchy, since during 2016 the TCDQ and TCSP

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[2] Throughout this paper a reference emittance ϵ_n=3.5 μm is assumed for calculating the collimator openings.

Table 1: Collimator settings used in 2016, together with two proposed sets of settings that could be used operationally in 2017. All settings are expressed in units of σ for the nominal β-function and an emittance of ϵ_n=3.5 μm.

Collimator	2016	2017a	2017b
TCP IR7	5.5	5.5	5.0
TCSG IR7	7.5	7.0	6.5
TCLA IR7	11.0	10.5	10.0
TCP IR3	15.0	15.0	15.0
TCSG IR3	18.0	18.0	18.0
TCLA IR3	20.0	20.0	20.0
TCSP IR6	8.3	7.8	7.3
TCDQ IR6	8.3	7.8	7.3
TCT IR2	37.0	37.0	37.0
TCT IR8	15.0	15.0	15.0
TCT IR1/5	9.0	8.0	7.5
Aperture IR1/5	9.9	9.0	8.5

in IR6 were operated at even smaller retractions from IR7 without issues.

Based on the above studies, we present two proposals for operational collimator settings in 2017, called 2017a and 2017b as shown in detail in Table 1. In both cases we use the smaller retraction between TCP and TCSG in IR7, with the rest of the hierarchy following, as well as a smaller retraction between IR7 and the TCTs. In the proposal 2017b, we use in addition the 0.5 σ tighter TCP setting. This is a slightly less proven concept than the other changes, since it was tested only in one fill. Nevertheless, there are no reasons to believe that this should not work in operation in 2017.

It should be noted that both proposals imply that the TCDQ in IR6 is operated at a setting that is 1 σ tighter than in 2016. This is still judged as safe for the robustness of the TCDQ itself in case of an asynchronous dump [24], however, it should be noted that an increase of about 50% in energy density deposited by lost particles can be expected on the Q5 in IR6.

APERTURE CALCULATIONS

In order to calculate the required aperture at any given β^*, the corresponding crossing angle must be known, which is determined from the beam-beam separation, treated in detail in Ref. [25]. Based on the results of beam-beam MDs [26], it was concluded in August 2016 that, with the use of the small-emittance BCMS beams, the separation could be decreased from 10 σ for ϵ_n=3.75 μm, which had been used so far in 2016, down to 9.3 σ for ϵ_n=2.5 μm [27], keeping the bunch population constant at 1.15×10^{11} protons/bunch. A reduction of the half crossing angle from 185 μrad to 140 μrad was consequently implemented in the machine, however, still staying at β^*=40 cm and not using the increased aperture margin for a further squeeze.

For 2017, a similar beam-beam separation could be used, however, in order to have comfortable margins in case of an increased bunch population, it has been proposed to have a slightly larger separation of 10 σ for 2.5 μrad [28]. Still, this implies a gain in aperture compared to what was assumed for the 2016 run, which could be used for a potential reduction of β^*. In the following, we study the β^*-reach for different separations: 9 σ for ϵ_n=3.5 μm (assuming that nominal beams are used instead of BCMS), 9 σ and ϵ_n=2.5 μm (as used with BCMS in the second part of 2016), or 10 σ for ϵ_n=2.5 μm, as could be envisaged for an increased bunch intensity in 2017.

In order to calculate the reach in β^* it is also crucial to have a reliable method to estimate the required aperture in any configuration. The aperture was measured on several occasions in 2016, both during the commissioning and in a dedicated MD towards the end of the year [15]. Some of the MD results are shown in Table 2 together with the results from the commissioning. It can be seen that the minimum bottleneck of the ring was consistently found at around 10 σ in B1, vertical plane, on the IP end of D1 on the incoming beam in IR1. It is worth noting that there are some fluctuations between different measurements over the year, and that there is more aperture available with the positive sign of the IR1 crossing angle, than with the negative sign used in 2016.

In order to calculate the aperture at any other β^* and crossing angle than used in the measurements, we scale the worst observed aperture in the crossing plane (9.9 σ for B1 vertical) and in the separation plane (10.6 σ for B1 horizontal) using the method in Ref. [1]. Because of the fluctuations between different measurements over the year, we add on top of the protected aperture in Table 1 an additional safety margin of 0.5 σ, when we judge whether the calculated aperture in any given configuration is acceptable. Conservatively, we also do not use the improved aperture with the positive sign of the IR1 crossing, since it is planned by survey to smoothen the alignment in IR1.

Another important input to the estimates of the aperture is the request from CMS to introduce a vertical shift of the IP, most likely using a magnetic bump of at least -1 mm at the IP [29]. Such a bump could have a significant impact on the available aperture, and MAD-X calculations predict that a vertical bottleneck might be introduced in Q2L5 for B2, where the aperture has not been measured with beam. This introduces a significant uncertainty on the aperture calculations. A local measurement at this location could be envisaged during the commissioning.

To make an estimate of this aperture, we assume conservatively that the vertical aperture measured in Q2L5 for B1 (last line of Table 2) would be symmetric, i.e. that we have 10.8 σ also for B2 in Q2R5, and that MAD-X predicts properly the difference between Q2R5 and Q2L5 to 0.3 σ. This gives an estimated aperture of 11.1 σ in Q2L5 without the CMS bump. With a -1 mm bump to shift the CMS IP, MAD-X predicts a loss of 0.8 σ, so that the aperture would go down to 10.3 σ. This value is then used as an alternative starting point for the scaling of the aperture to other configurations of β^*.

Table 2: Apertures measured with beam, as well as the limiting elements, for β^*=40 cm and a half crossing angle $\phi = \pm 185$ μrad (for $\phi < 0$ unless stated otherwise) at different times in 2016. Apart from in the standard collision configuration, measurements were performed with separated beams at the end of squeeze (e.o.squeeze) and at the end of the TOTEM bump beam process (e.o.TOTEM). The results are expressed in units of σ for the nominal β-function and an emittance of ϵ_n=3.5 μm.

		B1H		B1V		B2H		B2V	
Date	Config.	ap.	elem.	ap.	elem.	ap.	elem.	ap.	elem.
10/4	Collision	11.3	Q3/D1R5	10.0	D1L1	11.6	D1R1	10.7	D1R1
17/4	Collision	11.0	D1/TAN R5	9.9	D1L1	12.1	D1R1	10.4	D1R1
17/4	Collision IR1 $\phi > 0$			11.8	D1 L1			10.8	D1R1
18/4	e.o.squeeze	11.5	D1/TAN R5	9.9	D1L1	11.5	D1R1	11.0	D1R1
18/4	e.o.TOTEM	>11.0	D1 L1						
10/6	Collision	>11.1	Q3/D1R5	10.0	D1L1	12.0	D1R1	10.0	D1R1
5/10	e.o.TOTEM	10.6	D1 L1	10.0	D1L1	10.8	D1R1	10.6	D1R1
5/10	e.o.TOTEM IR1 $\phi > 0$	10.6	D1 L1	10.8	Q2L5/D1R5	10.8	D1R1	11.5	D1R1

It should be noted that these calculations are performed for the nominal β^*=40 cm optics, assuming the so-called V1 version of the bump as discussed in Ref. [29]. Further checks should be carried out for ATS optics.

β^*-REACH IN VARIOUS CONFIGURATIONS

The previous sections give all ingredients to calculate aperture as a function of β^*, which in turn can be compared with the protected aperture in Table 1, including the 0.5 σ safety margin. The results are shown in Fig. 3 for the crossing plane (solid lines), for different values of the beam-beam separation discussed above, and in the separation plane (dashed lines), with and without the CMS bump. In all cases, the aperture has been scaled from the measurements in Table 2, or from the the estimated using the method in Ref. [1]. From Fig. 3, the achievable β^* for various configurations can be read out directly by comparing the estimated aperture with the protected aperture. Some key values are summarized in Table 3.

As can be seen, a significant gain in β^* is within reach. The line in Fig. 3 corresponding to the smallest beam-beam separation and the one for the separation plane aperture without the CMS bump are both above the 8.5+0.5 σ requirement with 2017b settings at β^*=30 cm, which could thus be a possible running scenario. In this situation, the limit comes from the separation plane. Increasing to 10 σ beam-beam separation, the crossing plane aperture takes over and limits to β^*=31 cm.

If the CMS IP shift of -1 mm is included with the pessimistic assumptions discussed above, the separation plane becomes limiting in all scenarios except if the large nominal emittance is assumed. In that case the crossing plane aperture is marginally worse around the considered β^*. With the bump included, β^* risks to be limited to 32 cm, independently of the crossing angles considered.

These β^*-values are calculated for the 2017b collimator settings. In the scenario where the TCPs are not tightened compared to 2016, the 2017a settings in Table 1 are assumed 0.5 σ is lost on the aperture. The corresponding loss in β^* is 3 cm.

It should be noted that two optics schemes are considered for 2017, called nominal and ATS [30,31]. Nominal optics has been used in the LHC so far, while ATS optics is the baseline for HL-LHC [32]. For the range of β^* considered for 2017, it is possible to produce a suitable optics with both schemes, and our β^*-calculations apply to both, as long as the betatron phase advance between MKDs and TCTs is such that asynchronous beam dumps are not limiting as in 2016. Past studies showed that this is the case for fractional phase advances closer than 30° to 0° or 180°. In the considered β^*-range, the worst phase advance in nominal optics to any TCT in IR1 or IR5 is 4°–6°, while for ATS it is 25°–26 °.

Even though both optics meet the 30°-target, the available safety margins are larger with nominal optics, which in turn translates into a lower probability of critical losses on the TCTs during asynchronous dumps. However, the beams could be dumped before exceeding the safe margin if interlocks are introduced on orbit drifts using the collimator BPMs [33,34]. On the other hand, it should be noted that the better chromatic properties of ATS result in a smaller deterioration of the cleaning hierarchy for off-momentum particles, which however is not judged to be critical in the considered range of β^*. It should also be studied if the impact of the CMS bump in ATS optics is similar to the effect in nominal optics. Other considerations related to the choice of optics, such as compatibility with forward physics or chromatic properties, are not treated in detail in this paper.

SUMMARY

After the very successful LHC run in 2016, where β^* was reduced by a factor 2 to 40 cm, the luminosity production should continue with high priority in 2017. Various ways

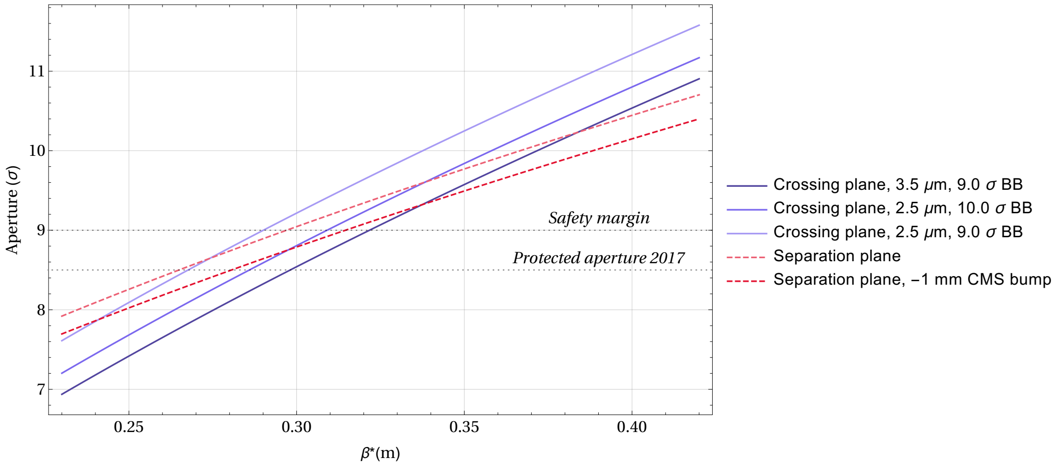

Figure 3: The estimated aperture as a function of β^* in the crossing plane, for two different values of the beam-beam separation, and in the separation plane, with and without a bump for shifting the CMS IP by -1 mm. We show also the smallest protected aperture, using the 2017b collimator settings in Table 1, as well as the protected aperture with an applied 0.5 σ safety margin.

Table 3: Reach in β^* for various collimator settings (2017a or 2017b as defined in Table 1), beam-beam (BB) separations, and assumptions on the bump for shifting the CMS IP.

Configuration	9 σ BB, ϵ_n=3.5 μm	10 σ BB, ϵ_n=2.5 μm	9 σ BB, ϵ_n=2.5 μm
2017a, no CMS bump	35 cm	34 cm	33 cm
2017b, no CMS bump	32 cm	31 cm	30 cm
2017a, -1 mm CMS bump	35 cm	35 cm	35 cm
2017b, -1 mm CMS bump	32 cm	32 cm	32 cm

to further decrease β^* have been explored, in case this is needed. Based on a range of MDs and theoretical studies, it has been concluded that the collimation hierarchy can be tightened to gain 1–1.5 σ margin compared to 2016. The proposed collimator settings are judged to be compatible both with requirements on beam cleaning, impedance, and protection. Furthermore, the beam-beam separation can be reduced compared to the startup configuration in 2016, and a corresponding decrease in crossing angle was already carried out during the year, but without decreasing β^*. Combining the various gains, a β^* as small as 30 cm could be envisaged, depending on parameter choices. However, the picture is complicated by the unknown influence of the IP shift in CMS, which could cause a loss of 3 cm in β^*.

Any intermediate β^*-scenario is also possible, e.g. β^* =35 cm covers all scenarios in Table 3. A smaller β^* <40 cm could be introduced directly at the startup, or in a staged approach, where the 2017 operation starts at β^*=40 cm and β^* is reduced later, as in 2011. This would allow gaining operational experience with any other new operation mode, e.g. if a decision is taken to use ATS optics or the tighter collimation hierarchy, before pushing β^*.

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