2016 LHC CONFIGURATION: CAN WE GET TO β^*=40 CM?

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Abstract

In 2015, the LHC was restarted after a long shutdown. Because of the numerous changes compared to the Run I configuration, most notably a higher beam energy and shorter bunch spacing, we considered 2015 a commissioning year and therefore started with a relaxed parameter set. For 2016, the machine parameters can be pushed to increase luminosity production, based on the MDs and operational experience in 2015. This paper discusses how this can be done, with focus on the feasibility of a decrease in β^* and the margins in the collimation hierarchy.

INTRODUCTION

The first proton run of the LHC (2010-2013), carried out at beam energies of 3.5 TeV and 4 TeV, was very successful and resulted in important physics discoveries [1, 2]. It was followed by a long shutdown (LS1), where a large number of improvements were carried out. The most important upgrades made it possible to increase the LHC beam energy to 6.5 TeV at the restart in 2015, where the bunch spacing was also reduced from 50 ns to 25 ns. Because of the different configuration and the large number of changes carried out in LS1, 2015 was considered as a commissioning year, and the highest priority was to establish smooth running at the new energy and bunch spacing.

In order to provide an easier commissioning, a relaxed set of machine parameters were chosen for the 2015 operation [3, 4]. This concerned in particular β^*, which was chosen to be 80 cm. This value, which is larger than the β^*=60 cm used in 2012, in spite of the higher energy and thus smaller beam size, allowed to have a beam-beam separation of 11 σ, which gave room for a larger dynamic aperture than in 2012 [5]. Furthermore, the collimator settings used in 2015 were the 2012 settings kept in mm, in spite of the higher energy, and with an additional 2 σ margin for protection of the TCTs and triplets. By relaxing these parameters, the risk that the operation would be perturbed by beam instabilities and sudden lifetime drops was kept small.

The 2015 run resulted in an integrated luminosity of about 4 fb^{-1} per high-luminosity experiment and valuable operational experience, where various limitations were encountered and overcome. Furthermore, a number of MDs were carried out to explore various ways of increased performance [6–10]. We consider therefore that the LHC is now ready to put the focus back on physics production in 2016. In order to significantly increase the luminosity, a less relaxed parameter set should be used, while still staying within the limits set by machine safety and availability.

Several ways of increasing the luminosity are possible: increasing the number of bunches, increasing the bunch intensity, decreasing the emittance and bunch length, decreasing the crossing angle, and decreasing β^*. At the end of 2015, 2232 colliding bunches were achieved in the LHC, while the maximum number with the standard 25 ns filling scheme is 2736. There is good hope to reach this number and finalize the intensity rampup after continued scrubbing [11]. Because of electron cloud considerations [11] and longitudinal stability issues [12] it is also recommended to finish scrubbing and intensity rampup with the 10 cm bunch length used in 2015, however, it can be considered later in the run to gradually decrease the bunch length.

The bunch intensity and emittance are given by what the injectors can deliver [13] and the preservation throughout the LHC cycle [14]. Possibly the bunch intensity could be pushed up to 1.3×10^{11} protons per bunch at injection at the expense of a slightly larger emittance. The BCMS option [15, 16] would provide much smaller emittances, however, this might also cause stability issues [17, 18]. It should be noted also that during Run II, the BCMS scheme is limited to 144 bunches per injection into the LHC [19, 20].

These various possibilities of increasing the luminosity in the LHC are discussed in more detail in Ref. [21] and in this paper we discuss mainly how β^* can be decreased. This is a way to increase performance that is largely independent on other parameters such as the intensity. One important contribution to a smaller β^* can come from the beam-beam separation, for which MD studies were carried out in 2015 [10]. The studies have shown that the normalized beam-beam separation that was used in the 2015 physics run (11 σ for a normalized emittance ϵ_n=3.75 μm, corresponding to a half crossing angle of 145 μrad at β^*=80 cm) can be decreased 10 σ [5]. Further gains in β^* can come from making the collimation hierarchy tighter, thus protecting a smaller normalized aperture. This is the main focus of the rest of this paper.

REDUCING MARGINS IN COLLIMATION HIERARCHY

The LHC collimators are ordered in a strict hierarchy as illustrated schematically in Fig. 1, where the leftmost picture shows the 2015 collimator settings in units of σ[1]. Closest to the beam are IR7 primary collimators (TCP), followed by secondary collimators (TCSGs), IR6 dump protection (TCSP and TCDQ), tertiary collimators in front of the experiments (TCT) and finally the aperture bottlenecks of the ring, which during physics operation are in the inner triplets of the experimental IRs. It should be noted Fig. 1 does not show all collimators installed. For example, there are also absorbers (TCLA) in IR7, as well as another similar hierar-

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[1] For the calculation of the beam σ used to position collimators, we use in this paper the nominal β-functions and ϵ_n=3.5 μm unless stated otherwise.

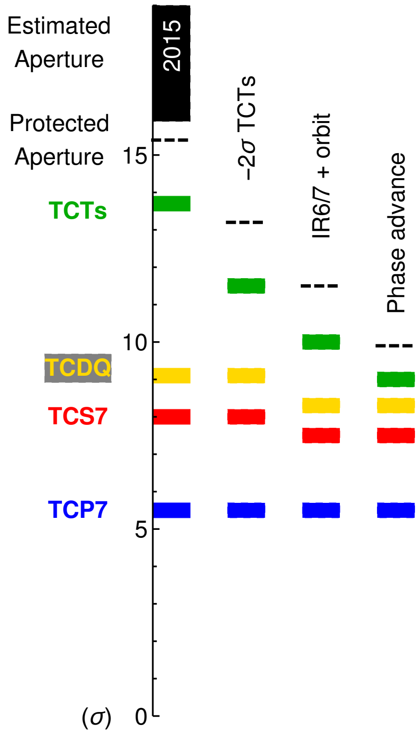

Figure 1: Schematic illustration of the collimation hierarchy in the 2015 physics configuration (leftmost picture) and possibilities for 2016 on the right, under different assumptions on how the margins between collimator families can be reduced. The vertical axis shows the opening of each collimator family in units of nominal σ. It should be noted that the shown TCT settings refer to IR1 and IR5 only.

chy in IR3. However, the settings of these elements do not directly influence the reach in β^*.

The hierarchy in Fig. 1 must be respected at all times during operation with unsafe beams, in order to guarantee sufficient cleaning and protection. Since there are drifts in orbit and optics over time, margins are needed between each collimator family to ensure that the hierarchy is respected. If β^* is decreased, the normalized aperture (in units of σ) in the triplet goes down, and hence also the margin between TCT and the aperture. In this situation, the whole collimation hierarchy has to be moved in, or the margins between the stages decreased, in order to maintain protection. It is thus clear that how much the collimator settings can be tightened, without jeopardizing machine safety, determines how small a value of β^* can be accommodated. We will now discuss the possibilities of reducing the collimation hierarchy margins, based on an extensive MD program [7–9, 22].

With the decision to start relaxed in 2015 at β^*=80 cm, the TCTs were retracted 2 σ from further out from the calculated minimum setting [4, 23]. The easiest way to gain margin would thus be to recuperate these 2 σ. The resulting collimation hierarchy and protected aperture are shown in the second illustration from the left in Fig. 1.

Furthermore, the cleaning hierarchy can be reduced. These are the margins between the TCPs and the TCSGs in IR7, and the margin between the TCSGs and the IR6 dump protection (TCDQ). This hierarchy is in place to optimize the cleaning performance in IR7, as well as to avoid that secondary halo ends up in IR6 where the TCDQ and TCSP are much less efficient in absorbing halo particles than the multitude of IR7 collimators.

MDs were performed during 2015 in order to investigate the cleaning performance with such tighter retractions [9]. The results show that if the 2015 retraction of 2.5 σ between TCP and TCSG is reduced to 2 σ, the cleaning hierarchy is still kept, even over long time periods. This means that it could be possible to carry out only one alignment in IR7 per year without degradation of the hierarchy. Furthermore, the cleaning performance is actually slightly better in this configuration, since more of the secondary halo is captured by the TCSGs. The MD explored also a 1 σ retraction between TCP and TCSG, as foreseen in the design report. This resulted in a hierarchy breakage in one plane [9] and is presently not proposed as operational settings.

The TCSG settings are also limited by impedance, as they make up a significant fraction of the total machine impedance (at some frequencies, more than 50% [24]). Measurements [22] performed during a 2015 MD, in combination with theoretical studies, indicate that a reduction to 2 σ margin between TCP and TCSG [17] should not pose problems of beam stability. Apart from the TCSGs in IR7, we propose also a to move in the dump protection TCDQ/TCSP in IR6 by 0.3 σ, which is considered a minor change.

The margins between the dump protection and the TCTs, and between the TCTs and the aperture, are more critical in terms of machine protection, since they should ensure that the TCTs and the triplets are never exposed to direct impacts during an asynchronous beam dump [25]. If these margins are violated, there is a risk to damage a TCT or in worst case a magnet, while if the cleaning margins in IR7 are violated, it would only result in beam dumps and possibly a quench.

The margins to the TCTs and the aperture were calculated during Run I using a probabilistic approach [25], accounting for the combined errors of several sources, where the orbit fluctuations were dominating. An example of the loss in margin between TCT and TCDQ in 2015, calculated from the measured orbit variations during stable beams at both elements, is shown in Fig. 2.

Analyzing the achieved orbit stability in 2015, a small improvement can be seen compared to Run I. However, at the same time, the number of expected asynchronous beam dumps per year is now estimated at 3 instead of one as in the past [26]. If this is accounted for, 1.4 σ is needed between TCDQ and TCTs for the orbit contribution. This is still an improvement with respect to the 2012 data, from which 1.7 σ is obtained. Between TCT and aperture, 1.1 σ is needed for orbit, which is identical to what was assumed based on the Run I data. The slightly better orbit is in this case compensated by the expected higher number of asynchronous dumps.

Under the assumption that the orbit stability will not be worse in 2016, so that we can reduce the margin between

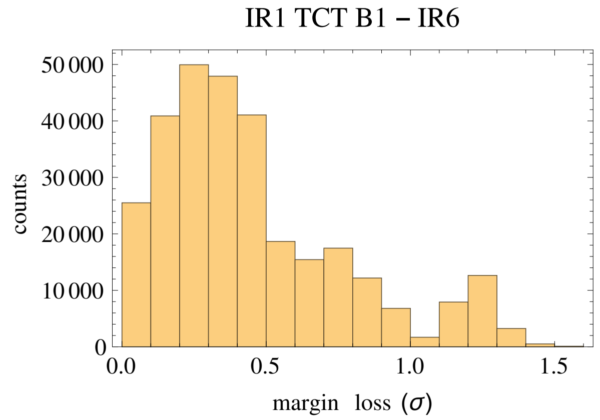

Figure 2: The distribution of combined orbit shifts between the IR1 TCT and the IR6 dump protection during stable beams in 2015 after the second technical stop in 2015.

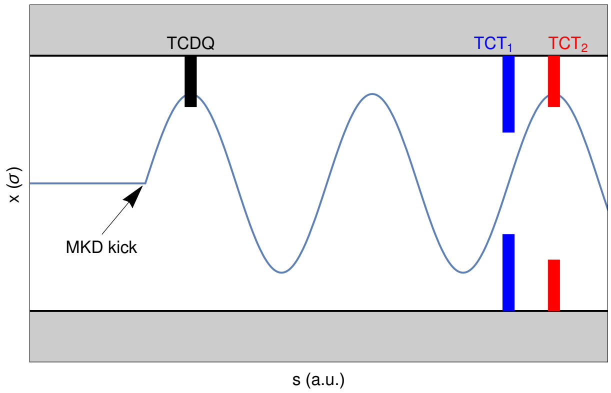

Figure 3: Schematic illustration of the horizontal orbit from a mis-firing MKD during an asynchronous beam dump, as it performs betatron oscillations along the machine, shown together with the one-sided TCDQ at 90° phase advance, and two different TCT positions at $\Delta\mu_{\mathrm{TCT}}$ =0° and $\Delta\mu_{\mathrm{TCT}}$ =90°.

TCTs and TCDQ according to the better orbit, and that we can tighten the cleaning stages as discussed above, we obtain a collimation hierarchy corresponding to the third picture from the left in Fig. 1, with an allowed protected aperture of 11.5 σ. Further reductions of the margin to the TCTs can be done by adjusting the phase advance from the dump kickers (MKDs) to the TCTs. This is further explained in the next section.

GAIN IN MARGIN FROM PHASE ADVANCE

In Run I, the collimator settings were calculated in the assumption that the dump protection should always be at a smaller normalized opening in σ than the TCTs, which implicitly assumes that the dump protection and the TCTs are at the same phase advance (90°) from the extraction kickers [25]. However, this is a pessimistic assumption in many scenarios. This is schematically illustrated in Fig. 3, which shows the oscillating orbit caused by a mis-firing dump kicker. It can be seen that if a TCT (in blue) is placed at a fractional phase $\Delta\mu_{\mathrm{TCT}}$ from the MKDs close to 0° or 180°, it can be placed much closer to the beam (in units of σ) than a TCT (in red) with $\Delta\mu_{\mathrm{TCT}}$ close to 90° or 270°, without increasing the risk of high-intensity impacts that could lead to damage. The inner limit on the TCT setting, which could potentially be at a smaller normalized opening than the one of the TCDQ, can be estimated through a detailed analysis of the actual expected losses on the TCTs during an asynchronous beam dump, accounting for the actual phase advance.

In particular, the nominal optics with β^*=40 cm has a significantly better phase advance from MKDs to TCTs than the 2015 optics with β^*=80 cm. This led to a first proposal to investigate the feasibility of an operational β^*=40 cm scenario [27] and two MDs were carried out [7, 8]. The MDs confirmed that the TCT losses observed during an asynchronous dump at β^*=40 cm, with a very tight TCT setting, are indeed within the acceptable limits. In most cases, the predicted and measured losses at the TCTs agree within a factor 3, which we consider a very good agreement [8]. However, the IR1 TCT in B2 received higher losses than predicted, which is not yet understood.

In order to be fully safe, it is therefore proposed to further reduce $\Delta\mu_{\mathrm{TCT}}$ from the 37° in the β^*=40 cm nominal optics to be as close as possible to zero. This gives a large increase in safety compared to the present situation, and it has been decided in the optics team to implement these changes in the 2016 optics regardless of the final choice of collimator settings and β^* [28].

Figure 4 shows simulated losses on the most critical TCT in each beam as a function of its normalized opening during a single-module pre-fire, which is believed to be the most critical case of a beam dump failure. The simulations were done with SixTrack, using the setup described in Ref. [25], and were normalized to a bunch population of 1.5×10^{11} protons per bunch in order to stay on the pessimistic side. The MKD kick versus time was modeled using measured waveforms of type 2 for the mis-firing MKDs [29]. We show results for both the 2015 configuration, with β^*=80 cm and the corresponding standard collimator settings (left picture in Fig. 1), and a possible 2016 configuration, with β^*=40 cm, a new rematched optics with $\Delta\mu_{\mathrm{TCT}}$ =0°, and collimator hierarchy as the right picture in Fig. 1.

As can be seen, for the β^*=80 cm case, the losses on the TCTPH.4L1.B1, which has $\Delta\mu_{\mathrm{TCT}}$ =61°, rise steeply when the collimator is moved in (red solid line). These rising losses are caused by primary beam impacts, which we define as particles that have not hit and scattered in any other upstream collimator. Two damage levels for primary impacts are shown for comparison (in black, labeled 1): onset of plastic deformation, where the material is permanently deformed, and the limit where fragments of the collimator material start to detach from the surface and contaminate the surrounding elements [30, 31]. This more critical damage

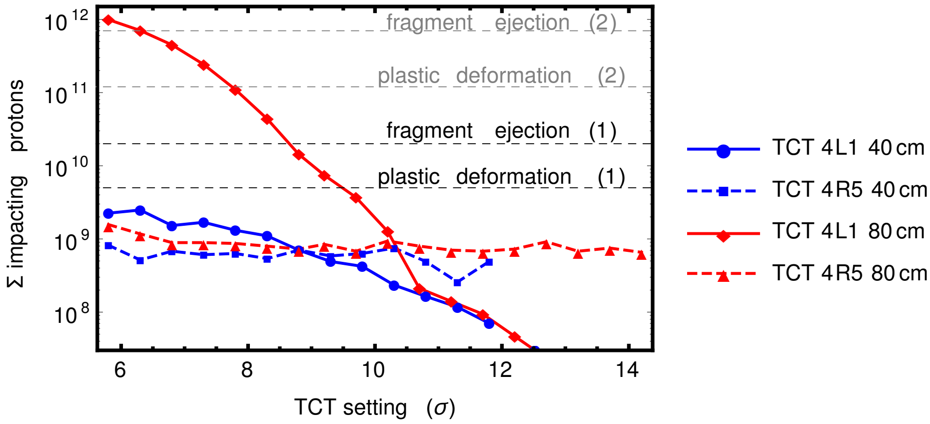

Figure 4: Simulated losses on the TCTs from SixTrack in the 2015 configuration with β^*=80 cm and in a possible 2016 configuration with β^*=40 cm, using a new optics with $\Delta\mu_{\mathrm{TCT}}$ matched to zero. Only the TCTs were varied and all other collimators were kept at their nominal openings for each configuration, except the TCDQ and the TCSP, which were moved out by 2 σ in order to mimic the orbit bump used during asynchronous dump tests. The simulations correspond thus to a pessimistic situation. The simulations were carried out using the methods described in Ref. [27].

limit, which would likely cause significant downtime of the LHC, is reached around 8.7 σ, which is still far from the operational setting of 13.7 σ.

On the other hand, for the TCTPH.4R5 at β^*=80 cm (red dashed line), the losses are approximately independent of the setting over the considered interval. This is caused by the fact that this collimator has already in the β^*=80 cm optics $\Delta\mu_{\mathrm{TCT}} \approx 190°$, only 10° away from 180°. Therefore, it does not intercept any primary beam impacts. However, it intercepts secondary impacts, defined as particles that have impacted on and scattered out of upstream collimators. In this case, they have primarily scattered in the TCSP in IR6.

These secondary particles have a much larger spread in amplitudes, with a large contribution at high amplitudes, which explains the flat curve [31]. Since secondary particles are more spread out when they hit the TCT than the primary impacts, and are distributed over the two jaws, different damage limits apply, which are more than a factor 20 higher than the limits for primary beam [31]. These limits are indicated in gray with index 2. As can be seen, the TCTPH.4R5.B2 is more than two orders of magnitude below the plastic deformation limit, which provides a comfortable margin.

For the β^*=40 cm case, all TCTs have $\Delta\mu_{\mathrm{TCT}}$ =0° or $\Delta\mu_{\mathrm{TCT}}$ =180°. Therefore, the TCTPH.4R5.B2 (blue dashed line) shows a similar trend as in the β^*=80 cm optics, since the dynamics has not changed much. On the other hand, in this scenario the TCTPH.4L1.B1 (blue solid line) no longer intercepts primary beam, but instead secondary impacts, which means that its losses have a similar flat dependence on the setting as the TCTPH.4R5.B2. It is not as flat though, since the secondary losses in this case originate mainly in IR7 and not in IR6, as for TCTPH.4R5.B2. In this scenario with a phase advance close to zero or 180°, all TCTs are at least a factor 50 below the lowest estimated damage limit in the considered interval of settings.

From the MD [8] and the simulations, we conclude that the scenario with $\Delta\mu_{\mathrm{TCT}}$ close to zero is safe as long as the phase does not drift significantly. Such drifts are expected to be a few degrees over the year and should thus not influence the safety. It should be noted that if phase drifts would occur that are large enough to cause a risk for the TCTs, they would be coupled with such a large β-beat that also the collimator hierarchy margins calculated with the previous 90°-model, which assumes a maximum β-beat of 10%, would likely be violated.

CONFIGURATIONS WITH TIGHT TCTS

In a scenario when $\Delta\mu_{\mathrm{TCT}}$ is close to zero, the TCT setting can thus be considered as decoupled from the setting of the TCDQ in the given interval, which gives a significant gain in the hierarchy margins. However, the TCTs cannot be moved in arbitrarily far. They must be well outside the TCSGs in IR7, as they would otherwise intercept secondary halo, from which outscattered showers risk to increase the power load on the triplet and cause an intolerably high experimental background.

Even if the TCTs are shadowed by the secondaries, the cleaning losses on the TCTs from tertiary halo increase steeply when the setting is reduced. This was predicted in simulations and verified in measurement [8]. This MD was carried out in collaboration with ATLAS and CMS, where the backgrounds were monitored. The measurements showed a similar increase in the beam-halo background at smaller TCT settings [32]. Compared to the 2015 configuration, more than order of magnitude higher beam-halo background could be expected due to the very tight TCT settings. However, it should be noted that Run I studies have shown that the dominating source of machine-induced background comes from beam-gas collisions [33], and that the increased beam-halo contribution should still be in the shadow of beam-gas. Therefore, this increase is probably not a show-stopper.

With these constraints, we tentatively put an ultimate inner limit on the TCT setting at about 8.3 σ, which is 0.8 σ behind the TCSGs in IR7. This is the same setting that we propose for the TCDQ and the TCSP, in order to stay clear of secondary halo. Nevertheless, we propose to start slightly more relaxed with a TCT setting of 9 σ and to keep the aperture larger than 9.9 σ, in order to gain operational experience at this settings before going to the limit. The resulting collimation hierarchy is shown in the rightmost picture of Fig. 1.

As can be seen, the tightened hierarchy for a favorable $\Delta\mu_{\text{TCT}}$ has much smaller margins than the one used in 2015, which at a first glance might lead to worries about the TCT safety. However, it should be noted that the SixTrack simulations, which have been benchmarked with the MD results, indicate that even at $\Delta\mu_{\text{TCT}}$ =20° the margin between the proposed setting at 9 σ and the estimated limit for plastic deformation of the jaws is about 5 σ. This level of safety margin is very similar to the situation in the 2015 configuration, including the extra 2 σ margin that was added when stepping back to β^*=80 cm.

Furthermore, a few simple measures can be taken to enforce safety even further. In order to verify the flat dependence of the TCT losses on the setting, shown in Fig. 4, we propose to do two asynchronous dump tests during the commissioning in 2016 at β^*=40 cm with the new optics. One test should be done at the nominal settings, without any orbit bump in IR6, while the second test should be done in a very pessimistic configuration, with such a large loss in margin that this would realistically never happen during operation, e.g. introduce the 2.4 σ orbit bump in IR6, at the same time as the TCTs are moved in from 9 σ to 8 σ. According to Fig. 4, the TCT losses in these two configurations should be similar. If this is confirmed in measurements, an optional interlock could be introduced on the BPMs in the TCSP and the TCTs, which triggers a beam dump before the margin loss in the qualified configuration is exceeded. If the margin loss is chosen large enough, this interlock should never trigger during normal running conditions. If these measures are implemented, we should be at least as safe as in 2015.

Further ideas under study, to ensure that the tighter hierarchy is indeed safe during asynchronous beam dumps, are an interlock on the phase, implemented by monitoring the quadrupole currents, and the possibility to include a more detailed analysis of the TCT losses in the XPOC, in order to early on spot any anomalies in the dump loss pattern.

POSSIBLE CONFIGURATIONS IN 2016

Starting from the aperture that the collimation system can protect, we can determine the reach in β^* if also the normalized aperture margin at the triplet as a function of β^* is known. This function is shown in Fig. 5. The two uppermost curves, for 10 σ and 11 σ beam-beam separation, are calculated by scaling the aperture measured with protons during the 2015 commissioning [34], using the methods in Ref. [25]. The crossing angle is varied along the curves in order to keep the beam-beam separation constant. It should be noted that with this scaling, the last aperture measurements at β^*=40 cm, which were performed during an MD, are very well reproduced [7].

However, the aperture was measured also during the commissioning for the heavy-ion run in December 2015 [35], and these measurements showed a loss of about 1.5 σ aperture compared to the scaling from the previous results. If instead the obtained heavy-ion measurement is scaled to compute β^* as a function of aperture, the brown dotted line in Fig. 5 is obtained. This loss in aperture has now been largely understood to be caused by a combination of a systematic orbit drift over time, combined with a β-beat in the wrong direction. Therefore, there is good hope that the 2015 proton aperture can be recovered again through corrections.

Figure 5 shows also the protected aperture for the various scenarios of collimator settings in Fig. 1, together with the minimum value of β^* for each configuration, rounded to 5 cm: the 2015 settings (A), if the 2 σ extra margin gained at β^*=80 cm are removed (B), if in addition the cleaning hierarchy is tightened in IR7, IR6 and using slightly better orbit at the TCTs (C) and finally if the phase advance between MKD and TCTs is used to further squeeze the hierarchy (D). As can be seen, the tightened hierarchy (C) is compatible with β^*=50 cm if, in addition, the 10 σ beam-beam separation is implemented. Relying on the phase advance, β^*=40 cm is within reach. However, if the heavy-ion aperture measurement is used for the scaling, we would lose up to 10 cm in β^*.

The different collimator settings, and the resulting values of β^* and half crossing angle, are summarized for the 2016 scenarios B–D in Table 1, assuming that there is no worsening of the aperture compared to the 2015 proton commissioning and MDs.

Table 1: Settings of different collimator families for the different scenarios for 6.5 TeV operation in 2016 (see Fig. 5). All collimator settings, illustrated also in Fig. 1, are given in units of the local transverse beam size σ, which is calculated using the nominal β-function at each collimator and the nominal emittance of 3.5 μm. On the other hand, for the beam-beam separation, an emittance of 3.75 μm is used.

Scenario	B	C	D
TCP7 setting (σ)	5.5	5.5	5.5
TCS7 setting (σ)	8.0	7.5	7.5
TCS6 setting (σ)	9.1	8.3	8.3
TCDQ6 setting (σ)	9.1	8.3	8.3
TCT setting IR1/5 (σ)	11.5	10.0	9.0
protected aperture (σ)	13.4	11.5	9.9
beam-beam separation (σ)	11	10	10
half crossing angle (μrad)	160	165	185
β^* at IP1/5 (cm)	65	50	40

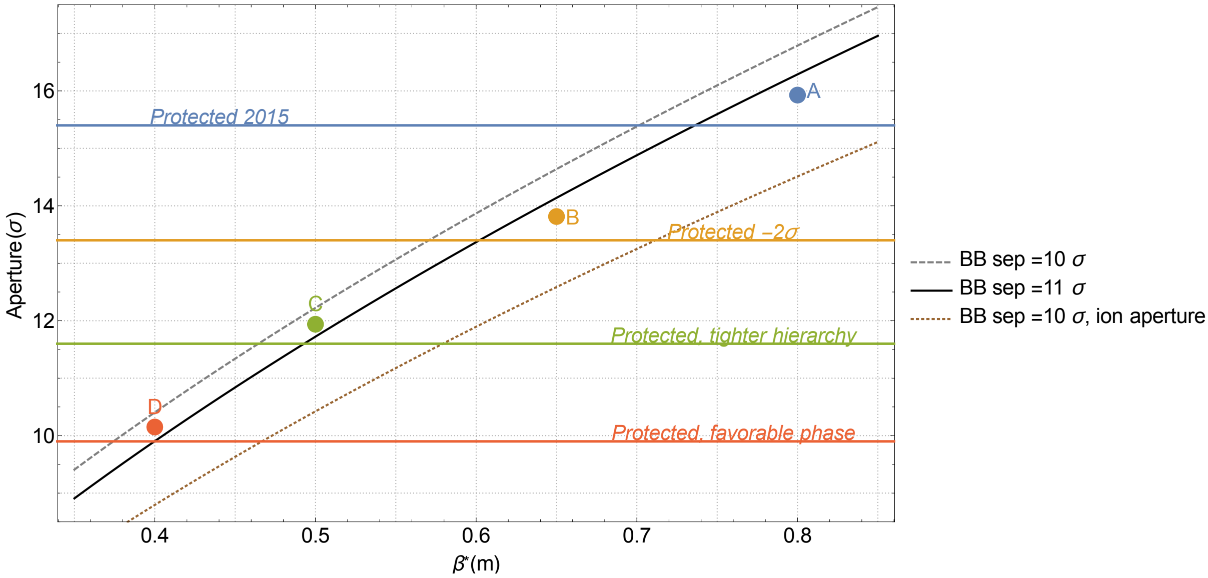

Figure 5: The aperture as a function of β^*.

The peak luminosity performance as a function of β^* is shown in Fig. 6 for different beam-beam separations and bunch lengths. The various options A-D are indicated, assuming for scenario A the achieved 2015 parameters and for the 2016 scenarios B–D that we can reach 2736 bunches, 1.3×10^{11} protons per bunch and ϵ_n=2.7 μm [13] at injection. Using a 98% transmission through the cycle [36] and a 25% emittance blowup [14], this translates into 1.27×10^{11} protons per bunch and ϵ_n=3.4 μm in collision.

It can be seen that, under these assumptions on the intensity and emittance, it could be possible to surpass the nominal design luminosity for both options C and D. The increase in luminosity when going from β^*=50 cm to β^*=40 cm is about 9% for the 10 cm bunch length. On the other hand, if it would be possible to go down to the nominal bunch length of 7.5 cm (light gray curve in Fig. 6), and the potential issues with electron cloud [11] and longitudinal stability [12] are overcome, the difference in peak luminosity is 13% between β^*=50 cm and β^*=40 cm. Furthermore, if at β^*=50 cm, decreasing the bunch length from 10 cm to 7.5 cm would give a gain of 15% in peak luminosity.

Among the possible scenarios B–D for 2016, the one with the highest performance should be chosen, as long as there are no negative consequences in terms of safety or availability of the machine. Before the operational value of β^* can be concluded, it should be decided whether the method of using the phase advance to squeeze the collimation hierarchy can be used in standard operation. Furthermore, it is crucial to remeasure the aperture early on in the 2016 commissioning, in order to verify if the aperture assumptions used for the calculations are still valid. If this is not the case, the β^* has to be adjusted accordingly.

SUMMARY

The LHC should in 2016 go into a production phase after the 2015 commissioning year. We have discussed ways to improve the performance, with the focus on how the β^* can be reduced using the collimation hierarchy. Three different scenarios for collimator settings are presented, using different assumptions based on the MDs and operational experience in 2015, which allow β^*-values of 65 cm, 50 cm or 40 cm respectively. In the 40 cm scenario, it is assumed that the phase advance between MKDs and TCTs can be matched in such a way that the TCTs should not be hit by damaging primary impacts during an asynchronous beam dump, and that this can be used to allow a tighter TCT setting. Furthermore, the beam-beam separation is in this scenario reduced to 10 σ (for a 3.75 μm emittance) and the secondary collimators in IR7 are moved in by 0.5 σ compared to the 2015 setting. This scenario relies also on that aperture will not be worse than in the proton MDs and operation in 2015. To verify this, it is essential to remeasure the aperture early on in the commissioning.

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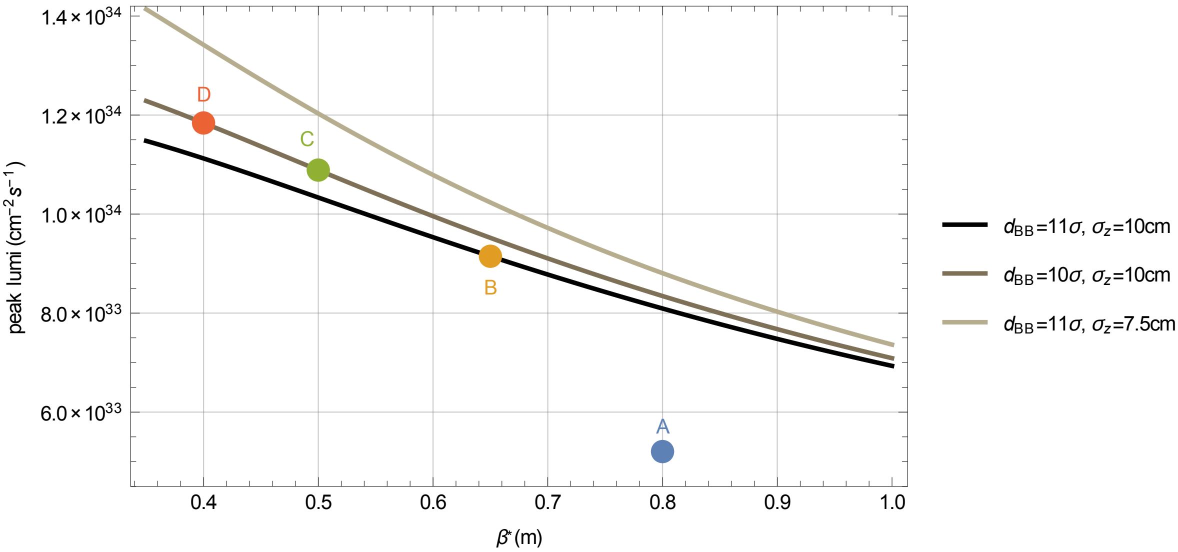

Figure 6: The peak luminosity for round beams at IP1/5 as a function of β^* for the scenarios A–D shown in Fig. 5 and Table 1, including the geometric reduction factor and the hourglass factor. For scenario A, which approximately represents what was achieved in 2015, it was assumed to have 2232 colliding bunches, 1.17×10^{11} protons per bunch, 10 cm bunch length, ϵ_n=3.75 μm normalized emittance and a half crossing angle of 145 μrad. For solid lines and the scenarios B–D, under consideration for 2016, we assume 2736 colliding bunches, 1.27×10^{11} protons per bunch, and ϵ_n=3.4 μm [21].

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