COLLIMATION AND β^* REACH

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Abstract

The reach in β^* of the LHC depends on a number of different parameters, including both the collimation hierarchy and the available aperture, but also on impedance and the needed crossing angle. We investigate different options and make a proposal for the starting configuration of Run II in 2015. The focus is more on feasibility than on performance, and the proposal is based on what is believed can be achieved based on the Run I experience. Furthermore, we discussed different options on how to push the performance later in the run by squeezing β^* to smaller values.

INTRODUCTION

The LHC collimation system [1, 2, 3, 4] influences directly the peak luminosity performance in two ways. Firstly, the cleaning inefficiency (the local losses in a cold element normalized by the total losses on collimators), together with the beam lifetime and the quench limit, defines the maximum acceptable intensity. Secondly, when pushing the β^* to smaller values, the β-function in the inner triplets increases, meaning that the normalized aperture margin between the central orbit and the mechanical aperture decreases. If this margin becomes too small, the aperture can no longer be fully protected by the collimation system. At what aperture this occurs depends on the collimator settings. The loss in aperture is further enhanced by the fact that a larger crossing angle is needed at smaller β^* in order to keep the same normalized beam-beam separation.

The collimation performance has to be evaluated both in terms of cleaning (the removal of unavoidable beam losses during routine operation) and machine protection, in case of failures and abnormal operation. It is based on a multi-stage cleaning hierarchy, where the different collimator families have to be ordered with different distances to the beam [1]. Closest to the beam, in the IR7 betatron cleaning insertion, are primary collimators (TCP7), followed by secondary collimators (TCS7). Further out are absorbers (TCLA). In IR6, at the beam extraction, are special dump protection collimators (TCS6 and TCDQ). They should be positioned outside of the TCS7 aperture. Furthermore, in the experimental IRs, tertiary collimators (TCTs) made of tungsten are installed in order to provide local protection of the triplets and to reduce background. We call the horizontal TCTs TCTH and the vertical ones TCTV. The TCTs are not robust themselves in case of high-intensity impacts of primary beam and should be positioned outside the aperture of the dump protection in IR6 with adequate margins to avoid the risk of being damaged during a dump failure [1]. The hierarchy is schematically illustrated in Fig. 1.

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RUN I EXPERIENCE

The collimator settings used during Run I (2010–2013) for physics operation at top energy, together with the resulting β^*, are shown in Fig. 1. All settings are shown in units of σ, which is the nominal standard deviation of the beam, calculated using the local β-functions at the collimators and a normalized emittance of 3.5 μm.

After the start-up in 2010, a safe and conservative approach was taken. A TCT setting of 15 σ made sure that even in extremely pessimistic running conditions, the TCTs would never be exposed. In 2011, the margins between IR6, TCTs, and aperture were evaluated quantitatively using new models [5] and it was found that they could be significantly reduced without compromising machine protection. As a consequence, β^* could be decreased from 3.5 m in 2010 to 1.5 m in 2011. Later in 2011, aperture measurements at 3.5 TeV with squeezed beams [6] showed evidence of a well-aligned machine with smaller errors than foreseen during the design phase. The measured triplet apertures, close to the mechanical design value, were used to refine the experimental basis of the calculation models for the reach in β^* [7] and allowed β^* to be reduced to 1 m keeping the relaxed collimator settings. The results of the aperture measurements in Run I are summarized in Red. [8] and the full details can be found in Refs. [6, 9, 10, 11, 12, 13, 14]. This reduction in β^* was made possible also by using some margins in the beam-beam separation, which allowed the crossing angle during the $\beta^* = 1$ m operation to be kept at the same value as in the previous operation at $\beta^* = 1.5$ m.

For the 2012 run, the margins between IR7 collimators were reduced based on experimental studies on the limits of the long-term stability of the collimation hierarchy under drifts of the beam optics and orbit [15, 16, 17, 18]. The same studies showed also that a closer IR7 settings were possible without detrimental effects on beam stability, resulting in the so-called tight collimator settings being put into operation. With these settings, the TCP7 achieved a gap in mm similar to the nominal opening foreseen at 7 TeV. Furthermore, the calculation of margins between IR6, TCTs, and aperture was updated and based on a statistical approach, where the different errors were added in square instead of linearly, in order to have a more realis-

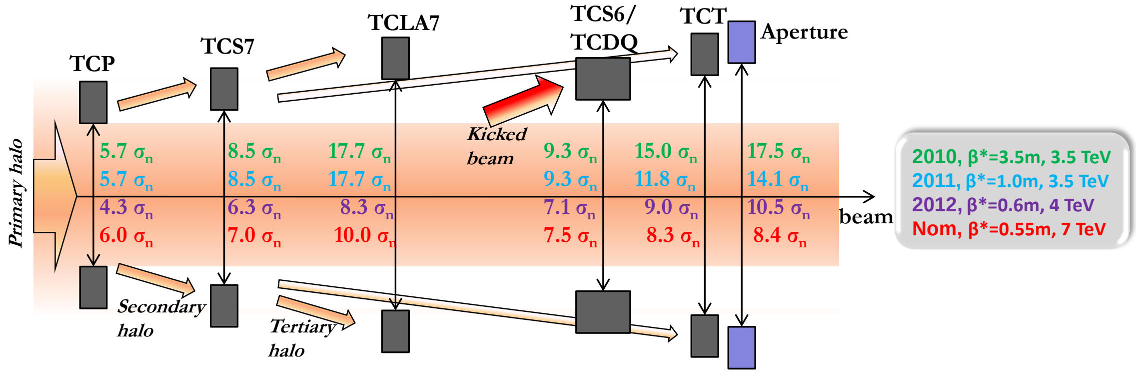

Figure 1: Schematic illustration (not to scale) of the collimator settings and the minimum aperture that can be protected during the physics runs in 2010 (3.5 TeV), 2011 (3.5 TeV), and 2012 (4 TeV), together with the nominal settings (7 TeV).

tic total error [19]. The combination of tight settings and smaller margins made it possible to squeeze β^* to 60 cm, resulting in a significant gain in luminosity.

RUN II ASSUMPTIONS

At the start of Run II in 2015, many things will have changed compared to Run I. Most notably, the beam energy will be increased to about 6.5 TeV and the baseline filling scheme will be 25 ns instead of 50 ns [20], which imply major changes to the mode of operation. The beams will be more dangerous, the quench limit lower, and there are many uncertainties regarding the loss spikes and instabilities observed in Run I. Therefore, the machine behavior is harder to predict in detail than e.g. before the 2012 run. In view of this, it could be considered wise to start carefully in a configuration that provides some margin for the unknowns. Once sufficient beam experience is gathered, however, the performance could be pushed.

Based on these considerations, the authors would like to propose a strategy where, at the start-up, the focus is put more on feasibility, stability, and ease of commissioning, rather than peak luminosity. It should, however, not be overly pessimistic. The operational achievements in Run I are used, where possible, to deduce what is likely to work.

Different collimator settings have been under consideration for the start-up and the three main scenarios are shown in Table 1. In terms of cleaning, the relaxed settings are close to the limit of preventing a beam dump at a beam lifetime of 12 minutes and full nominal intensity, although significant uncertainties exist [21]. The other two settings have better cleaning efficiency and should suffice, unless the beam lifetime drops significantly below the 12 minute specification. Therefore, if the quench limit and beam lifetime are not worse than expected, we do not expect the cleaning inefficiency to be a limiting factor for the total intensity.

In order to be on the safe side for the cleaning, but without going to the tighter gaps with the 2 σ retraction that are more challenging for impedance, we propose to start Run II with the 2012 setting kept in mm (see middle column in Table 1). They also have a well-proven long-term stability in terms of preserving the hierarchy.

The margins in the hierarchy might be reduced even further, using the gain of a better orbit knowledge from the BPM buttons in the newly upgraded TCTs [22, 23], however, before this can be done, more experience is needed in order to understand the limitations. Therefore, we propose to start without using this gain to allow for a learning period, and use it at a later stage to further squeeze β^*.

The impedance and single-beam stability for the different collimator settings are discussed in Ref. [24]. It is shown that for the nominal, large-emittance beam, all proposed collimator settings should provide sufficient stability with both octupole polarities, while stability could be an issue with other beams with smaller emittance. Our assumptions in the rest of this paper is thus a nominal 3.75 μm emittance when considering beam-beam separation and stability[1], which is also compatible with assumptions on electron cloud [25]. The two-beam effects and octupole polarities are discussed in detail in Ref. [26]. Being able to use both octupole polarities introduces more flexibility at the start-up, since there could be a chance to start operation without collide and squeeze, which otherwise requires a significant overhead in terms of commissioning time and complexity [27].

For machine protection, the settings in Tab. 1 fulfill the same demands as used during Run I [19, 28] in terms of the IR6 dump protection shadowing the TCTs and the TCTs shadowing the triplet. However, it is under investigation whether the situation post-LS1 requires additional safety margins because of several factors. Firstly, because of the higher energy, the TCT damage limit in number of protons is also lower. On top of that, the baseline filling scheme is 25 ns instead of 50 ns, which means that there risks to be double the number of bunches within the critical time window during asynchronous dumps when bunches pass the dump kickers and receive intermediate kicks. Now in 2014, more advanced simulation tools are available than during Run I [29, 30, 31], so in order to quantify the im-

[1] 3.5 μm is still used for collimator settings.

Table 1: Settings, of different collimator families, for different scenarios for 6.5 TeV operation after LS1, where either the 2012 settings are kept in mm, in σ or more open (relaxed).

Settings	Relaxed settings	mm settings kept,	σ settings kept
TCP7 (σ)	6.7	5.5	5.5
TCS7 (σ)	9.9	8.0	7.5
TCLA7 (σ)	12.5	10.6	9.5
TCS6 (σ)	10.7	9.1	8.3
TCDQ6 (σ)	11.2	9.6	8.8
TCT (σ)	13.2	11.5	10.7
protected aperture (σ)	14.8	13.4	12.3

pacts on the TCTs during various accident scenarios, new studies are ongoing to estimate the expected damage risks and if the model to calculate margins are suitable also for Run II.

Furthermore, the collimator margins are calculated based on what was achievedd in 2012. If the stability of the optics or orbit correction for post-LS1 would be worse, larger margins are needed. Therefore, one could consider introducing more margins at the startup, before the machine performance is well known, in order to be sure that the TCTs and aperture are protected. If no extra margins are introduced for the machine stability, these parameters have to be monitored very carefully at the startup.

Finally, it is under consideration whether the LHC optics will be changed to ATS [32]. This optics has a fractional phase advance in Beam 2 between IR6 dump kickers and the TCT in IR5 close to 90°, while the phase advance in the nominal optics is close to 180°. Therefore, the IR5 TCTs are much more prone to being hit by primary beam during asynchronous beam dumps with the ATS optics. The introduction of ATS optics may therefore require larger margins in the hierarchy on top of the possible increase mentioned above. Studies to quantify this are ongoing.

In order to estimate the reach in β^*, the aperture margin in the triplet needs to be calculated for different β^*. For that calculation, we assume that the aperture has not become worse during LS1 and, at this stage, do not include additional safety margin there. In any case, it is very important that the aperture is measured with beam very early on during the commissioning, and if it turns out that it is worse than expected, the time loss when stepping back to a larger β^* is very small.

For the aperture calculation, it is also needed to make an assumption on the crossing angle as function of β^*. For this, we use a beam-beam separation of 11 σ, as recommended in Ref. [26] and an emittance of 3.75 μm, corresponding to a half crossing angle of about 170 μrad for β^* =55 cm. This angle is sufficient even if the real emittance would be smaller. This is considered a safe value for the start-up, but could possibly be pushed to smaller values with beam experience. On the other hand, even larger beam-beam separations could be beneficial in order to suppress the long-range effect during the squeeze [26].

INITIAL PERFORMANCE REACH

We use two methods to calculate the aperture: the MAD-X aperture module with the parameters that gave the best agreement with Run I data (see Table 2 in Ref. [8]) and aperture scaling [28], starting from the most pessimistic aperture measurement in Run I. The results are shown in Fig. 2. The MAD-X calculation can for obvious reasons be carried out only at the matched optics points, presently available with a 5 cm granularity below 1 m, while the scaling provides a continuous function. Most calculations were carried out for the 11 σ beam-beam separation mentioned above and for nominal optics, but we show also a result for 12 σ separation and one point with ATS optics (more points are expected to be available in the future [**?**]). Fig. 2 shows also the minimum aperture that can be protected for the different collimator settings in Table 1.

Several conclusions can be drawn directly from Fig. 2. It is clear that the two aperture calculation methods agree very well, as also demonstrated during Run I [19]. Furthermore, at the β^* value where the ATS optics is available, the achieved aperture with ATS is very similar to the nominal one. In terms of performance, the β^* value compatible with the different collimator settings can be read directly from Fig. 2. Sticking to the matched optics points, β^* =65 cm is the smallest value compatible with the mm kept settings. This is thus our proposed baseline, corresponding to a half crossing angle of 160 μrad.

This leaves also a small aperture margin. One option, if the aperture is well under control and checked with measurements, could be to use this additional margin to increase the beam-beam separation. As can be seen in Fig. 2, the aperture protected by the mm kept settings coincide almost exactly with the predicted required aperture if 12 σ beam-beam separation is used.

It should be pointed out that the proposed configuration relies on several assumptions. For the collimation hierarchy to provide adequate protection of the TCTs and the aperture, the optics and orbit correction has to be at least as good as in Run I. Furthermore, the aperture has to be as close to the ideal one as in the Run I measurements. If any of these prerequisites would not be met, one might have to start at a larger value of β^*. As an example, stepping back from 65 cm to 70 cm would imply a gain of about 0.7 σ

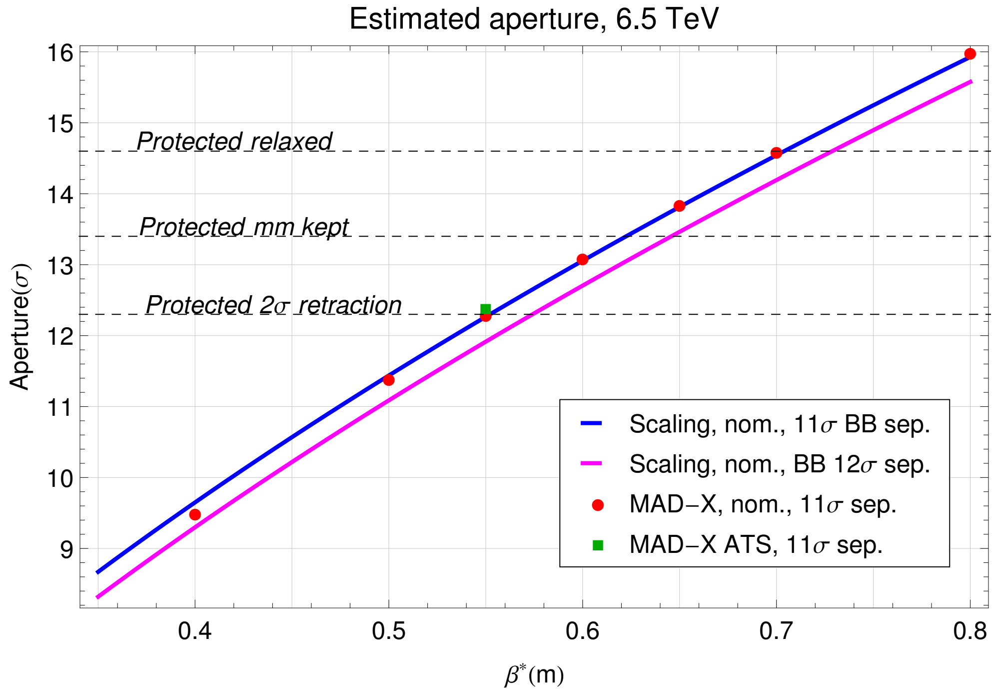

Figure 2: Schematic illustration (not to scale) of the collimator settings and the minimum aperture that can be protected during the physics runs in 2010 (3.5 TeV), 2011 (3.5 TeV), and 2012 (4 TeV), together with the nominal settings (7 TeV).

in aperture, while the gain is about 2.1 σ at 80 cm. The relaxed aperture margin could be used as additional margin between the steps in the collimation hierarchy according to the needs, to retract the whole hierarchy to gain impedance, or to tolerate a larger beam-beam separation and crossing angle if that would be needed.

For completeness, we investigate the reach in β^* also with the other collimator settings. For the 2 σ retraction settings, the protected aperture agrees almost exactly with the required aperture at β^* =55cm. Since there is no margin, it could be that this point does not work, as the aperture can only be predicted with a limited precision. Measurements with beam have to be used to determine if this point is acceptable. With the relaxed settings, β^* =75 cm the smallest compatible value, within 5 cm intervals. Stepping back to this configuration could be an option in order to decrease the impedance, if further studies show that the beam stability is an issue.

POSSIBILITIES TO PUSH β^* LATER IN THE RUN

Once the LHC has been successfully put into operation and a first period of stable beams has been established, the performance limitations and possibilities will be better known [33]. Then, the performance could be increased based on the operational experience and possible MDs. Several machine parameters could be changed to gain in luminosity performance (here we focus on the ones connected to β^*, and mention only briefly the most important other parameters):

- Collimator settings: If the margins in the hierarchy are reduced, e.g. by establishing the 2 σ retraction settings, a smaller aperture can be protected, and thus a smaller β^* tolerated. However, with tighter settings, the impedance increases. Whether this is tolerable has to be evaluated after some first MDs. Based on further operational experience, the margins between the dump protection and the TCTs, as well as the margin between TCTs and triplets, might be decreased if the integrated BPM buttons can be used to reduce the drift of the orbit from the center of the collimators. The less temperature-sensitive BPM electronics could also be used to determine whether some of the large orbit drifts between TCTs and triplets, observed in Run I, are real or an artefact of the measurement.

- Crossing angle: reducing the crossing angle at a given β^* implies a gain in the required aperture. This reduction can be accommodated either by reducing the beam-beam separation, or operating at a smaller emittance. However, the needed beam-beam separation also increases slightly with decreasing emittance [26]. If the beam-beam separation is decreased, the long-range effect becomes more critical, in particular during the squeeze [26].

- Aperture: unless additional margins are introduced at the start-up, the gain should be rather small. The aperture in Run I was found in measurements to be very close to the ideal one, and the same assumptions are used for Run II.

- Other parameters independent of β^*: A number of parameters can be used to increase luminosity, most notably the bunch intensity, bunch length, and machine availability. These are not discussed in detail in this paper.

As a realistic example on how to push the performance, we show how the design value of β^* =55 cm can be reached. One way would be to change the collimators to the 2 σ retraction settings. As can be seen in Fig. 2, the required aperture is at the limit of what can be tolerated. If the aperture, after measurements, turns out not to be sufficient, an additional small gain could be obtained by reducing also the margins between IR6 and the TCTs, based on the experience with BPM buttons. Possibly, the change of settings could also be combined with a small reduction of crossing angle.

Alternatively, the main gain could come from the crossing angle. Keeping the mm kept settings, β^* =55 cm and a crossing angle of 130 μrad implies an aperture that fits almost exactly with what can be protected. This configuration corresponds to a beam-beam separation of 8.3 σ for an emittance of 3.75 μm. If the emittance can be reduced to 2.5 μm, the beam-beam separation with this crossing angle is about 10 σ. This configuration is possibly compatible with 6 σ dynamic aperture [26].

In summary, several possibilities are at hand for reaching β^* =55 cm. We consider it rather likely that this should be possible through one, or through a combination, of the mentioned methods.

If we assume that both the collimation hierarchy and the crossing can be pushed to the limits that one can optimistically expect, then β^* could be squeezed significantly below the design value. For this ultimate scenario for Run II we assume the 2 σ retraction settings, with the addition of using the BPM button collimators to their full potential. Furthermore, we assume a beam-beam separation of 10 σ at an emittance of 2.5 μm. These assumptions are considered challenging but possible. They also require significant beam experience and commissioning time.

Using these collimator settings and crossing angle assumption, we obtain β^* =40 cm, together with a half crossing angle of 155 μrad. As an alternative to further increase the integrated luminosity by minimizing the loss from the geometric reduction factor at smaller β^*, flat beams could be considered. A configuration with β^* =40 cm in the separation plane and β^* =50 cm in the crossing plane should be compatible with the same aperture constraints [34]. In this configuration, the present planes for crossing and separation would be switched in order to optimize the usage of the beam screen aperture, which is larger in one plane.

In the future, we still hope to achieve nominal collimator settings in IR7 with a 1 σ retraction between the TCP7 and the TCS7. This would allow to reduce β^* additionally by 5 cm. However, because of the impedance constraints, this is unlikely to be usable during Run II. Installing new TCS7 made of other materials with lower impedance could help to make this possible. Furthermore, integrated BPMs in the TCS7 would help to ensure that the hierarchy is kept in spite of the smaller margin.

CONCLUSIONS AND OUTLOOK

We have given a brief overview of the collimation-driven limits on β^* and the evolution of β^* in Run I. For the 2015 start-up, we propose a configuration with the focus on feasibility and ease of commissioning, rather than peak luminosity, since many important changes have taken place. Based on the Run I experience, the 2012 collimator settings in mm could be used also in 2015. Together with the assumption of 11 σ beam-beam separation [26] and a nominal 3.75 μm emittance, this results in an initial β^* =65 cm and a half crossing angle of 160 μrad. To ensure that all limitations are under control, this could possibly be further relaxed. More aperture margin might be needed e.g. to retract all collimators and reduce impedance, to account for possibly larger drifts in orbit and optics than in 2012, or the higher risk of TCT damage during an asynchronous dump with ATS optics.

Later in the run, based on operational experience and MDs, it is likely that β^* can be squeezed further. The two main methods are to reduce the margins in the collimation hierarchy or reduce the crossing angle by using a smaller beam-beam separation or emittance. It seems realistic to go to the nominal β^* =55 cm, and even smaller β^*-values could be within reach. If we optimistically assume that a 10 σ beam-beam separation is sufficient for a 2.5 μm emittance, that the full theoretical gain in collimation margins from the BPM buttons can be used, and that the 2 σ retraction settings do not cause impedance problems, then β^* =40 cm is within reach. However, it might be that the real limit is higher, and it can be determined only with beam experience.

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