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Updated parameters for HL-LHC aperture calculations for proton beams

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Abstract

During the accelerator design, it is important to have a reliable way of estimating the available aperture, in order to ensure a sufficient beam clearing and avoid potentially limiting beam losses on the aperture. Such calculations can be performed using MAD-X, taking as input the beam parameters and the tolerances of, e.g., orbit and optics. Realistic tolerances and an accurate criterion for qualifying the aperture are crucial during the design stage, in order to ensure that all machine apertures are sufficiently protected from harmful beam losses. Previous studies have provided such parameter sets for aperture calculations for both LHC and HL-LHC. This report provides an update to the previous HL-LHC parameters at top energy. First we study the protected aperture that can be tolerated in arbitrary locations without local protection. Furthermore, we investigate also how the protected aperture can be improved using a specially matched phase advance between dump kickers and the tertiary collimators, as was done for the LHC in 2016.

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1 Introduction

The aperture available for the beam is a critical design input for any accelerator. For example, when β^* is squeezed to smaller values in the LHC, the beam size in the inner triplet increases so that the mechanical aperture risks to be exposed to unwanted beam losses, which limits the overall reach in β^*. A 2D calculation model, the so-called n_1 model which is implemented in the MAD-X aperture module, was used to estimate apertures during the design stage [1, 2, 3]. Based on assumptions on orbit and optics errors, as well as mechanical tolerances and an assumed beam halo shape, it gives the minimum opening of the primary collimator, n_1, that can still protect any local aperture.

During Run 1 of the LHC (2010–2013), several of the error tolerances have been found smaller than the design assumptions. Furthermore, the aperture has been measured with beam several times [4, 5, 6, 7, 8, 9, 10] and the results are compatible with a very well aligned machine, with results close to the design values. In a previous report [11], the assumptions on the input parameters for the n_1-model at top energy, or other bottlenecks with local protection, were revised and an updated set of input parameters for aperture calculations was proposed for top energy in HL-LHC. A similar study has also been carried out at injection energy [12]. For example, it was proposed to study the local aperture in units of the RMS beam size instead of the n_1.

The calculated local aperture from MAD-X should be compared to a criterion for the allowed aperture to judge if this aperture is acceptable. This criterion should be chosen in order to ensure that any aperture in σ, which is larger than the criterion, is protected by the collimation system from harmful beam losses, while at the same time not being overly pessimistic and introduce unnecessary constraints on the optics and hardware. In Ref. [11], this criterion for qualifying an aperture was reviewed for the case of aperture bottlenecks with local protection at 7 TeV, in particular the triplets in front of the experiments, which are protected by tertiary collimators (TCTs). Corresponding calculations for injection can be found in Ref. [12].

This report provides an update to Ref. [11], where the protected aperture at 7 TeV is studied for the case of arbitrary locations in the LHC ring without local protection. We study also how the protected aperture with local protection can be improved if the phase advance from the dump kickers is favourable, as was done in the LHC in 2016 [13]. Furthermore, we update the numbers in the previous report to account for a new standardised reference value of the normalised emittance, used to calculate all apertures and collimator settings. This has been updated from ϵ_n =3.5 μm to ϵ_n =2.5 μm for consistency with the reference value used for other HL-LHC studies [14]. The parameters for aperture calculation at injection are also recalled.

It should be noted that we do not treat heavy ion beams in this report, which should be studied separately in the future. However, it is not expected that stricter requirements would apply for heavy ions.

Table 1: Settings of different collimator families for 7 TeV operation in HL-LHC with squeezed beams. In the left column, a normalised emittance $\epsilon_n = 3.5$ μm is assumed for converting to settings in mm for comparison with LHC, while $\epsilon_n = 2.5\,\mu$m is assumed for HL-LHC in the right column (in bold).

	Setting in σ, $\epsilon_n = 3.5\,\mu$m	Setting in σ, $\epsilon_n = 2.5\,\mu$m
TCP7	5.7	**6.7**
TCS7	7.7	**9.1**
TCSP6	8.5	**10.1**
TCDQ6	9.0	**10.6**
TCT	10.9	**12.9**
aperture	12.3	**14.6**

2 Protected aperture without local protection

We show in Table 1 the baseline collimator settings for HL-LHC v1.2. As in Ref. [11], the protected aperture forms the last stage in the hierarchy. Using the new standardised reference emittance ϵ_n =2.5 μm for HL-LHC, it becomes 14.6 σ. This value was calculated based on the likelihood of the aperture getting exposed to critical beam losses, if it is no longer shadowed by tertiary collimators (TCTs) due to imperfections in orbit and optics. Any element which is not protected locally by a TCT must rely only on global protection. For these apertures, we apply the same methodology as in Ref. [12] to derive a more conservative criterion.

The beam loss mechanism that has so far limited the allowed aperture in the LHC is asynchronous beam dumps [15, 16, 17, 18], which we therefore study in detail here. Regular cleaning losses are expected to be significantly less severe. During a beam dump failure, the horizontal extraction kickers (MKDs) trigger asynchronously with the abort gap, so that bunches experience intermediate kick strengths if they pass during the kicker rise time. These kicks could be too small to reach the extraction line and instead induce an oscillating trajectory, so that the affected bunches could directly impact and damage sensitive elements [16, 17, 18, 19]. The most critical failure mode of this type is called single module pre-fire (SMPF), where only one MKD fires. A re-triggering system then makes the remaining MKDs fire, but this happens after a delay of about 650 ns. With an SMPF, it takes more time to reach the kick strength needed for extraction, meaning that more bunches risk to receive intermediate kicks. Therefore, the SMPF is the most serious accident scenario. The most critical type of SMPF, with the slowest rise, is called type 2 [20]. In the following, we therefore study a criterion for the allowed aperture to stay safe from damaging losses during a type 2 SMPF.

Dedicated dump protection collimators (called TCSP and TCDQ) are installed in the horizontal plane in IR6 to protect against beam dump failures. As in Ref. [12], we use SixTrack with collimation [15, 21, 22, 23, 24, 25] to simulate an SMPF and estimate the distribution of particles that either bypass the dump protection collimators or are scattered out from them. We can then determine a criterion for the allowed aperture by comparing the distribution of escaping protons with the estimated intensity that can cause damage.

Simulations were performed at 7 TeV, using the HL-LHC optics V1.2 collision optics with β^* =15 cm, and with the full collimation system in place with settings as in Tab. 1. As in Ref. [12], we use a 25 ns bunch structure and perform a separate simulation for each bunch, since they receive different kicks from the MKDs. We consider the most pessimistic case where the misfire happens while a PS batch is passing the MKDs, so that every 25 ns slot contains a bunch.

In Fig. 1 we show an example of histograms of the total betatron amplitudes (including the contributions from both position and angle) of the surviving particles that leak out of IR6 during an SMPF, in units of σ, given by the simulations for each bunch. For lower (earlier) indices of the 25 ns bunch slot, the total MKD kick is smaller and most protons survive and escape at small amplitudes. Bunches at larger indices are kicked to larger amplitudes and impact more on the dump protection collimators, and smaller fractions of these bunches survive. Some of the surviving particles have not hit these collimators due to their initial phase and amplitude. Their abundance decreases rapidly with amplitude. We refer to these particles as primary beam. Other surviving particles have hit the TCSP or the TCDQ but scattered out again, which we refer to as secondary beam. They can escape IR6 at rather large amplitudes, since they also may get additional kicks in the scattering. After a certain time, i.e. above a certain bunch index, the kicks are so large that all protons hit deeply into the TCDQ, meaning that practically none of them survives.

The information in Fig. 1 can be used to estimate the summed distribution of particles escaping IR6 in the horizontal plane and potentially hitting aperture bottlenecks. We do this in the form of a survival function $S(A)$, which at any given amplitude A returns the integral

$$S(A) = \int_A^\infty f(\tilde{A})\,\mathrm{d}\tilde{A}, \tag{1}$$

where $f(A)$ is the distribution function of the surviving amplitudes, obtained by combining all bunches in Fig. 1. In other words, $S(A)$ shows the total fraction of particles found above amplitude A.

We show in Fig. 2 $S(A)$, normalised to 2.2×10^{11} protons per bunch and summed over all simulated bunches. Using this normalisation, $S(A)$ gives the total number of protons found downstream of the dump protection above amplitude A, which is given in units of betatron σ assuming an emittance of 2.5 μm. Only the bunches that are kicked at dangerous amplitudes are simulated, and it should be noted that if also the other bunches would be included, $S(A)$ would have a much higher value at small A, but not at large A, since the bunches kicked at higher amplitudes are absorbed by the TCDQ or extracted.

It can be seen that the losses increase steeply as A goes down, due to more and more of the primary beam being found at these amplitudes. However, for A outside

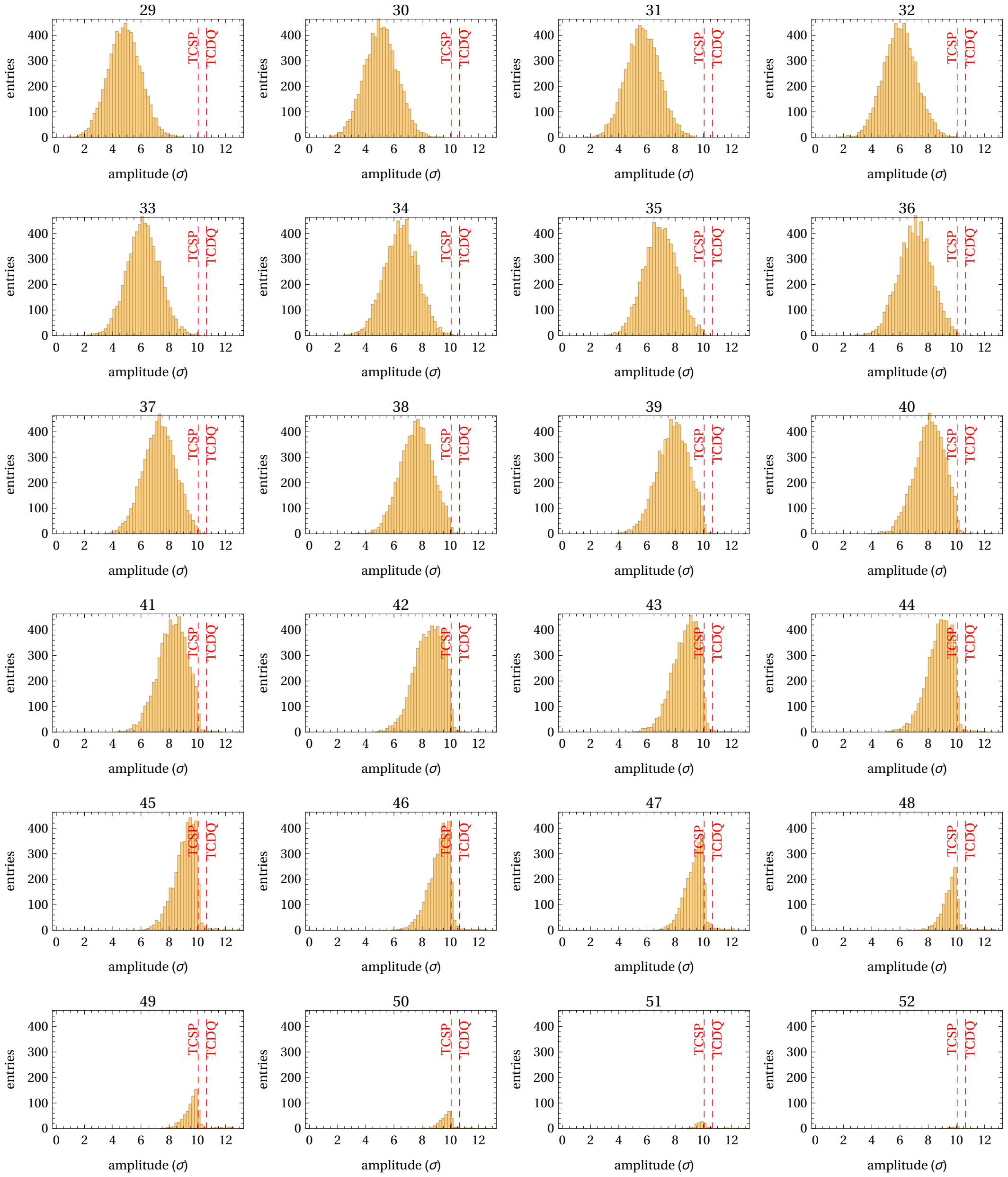

Figure 1: Distribution of macro particles in the SixTrack simulation of a SMPF, which escape the dump protection collimators (TCDQ and TCSP) for a range of simulated bunches that receive increasing kicks from the MKDs. The number on top of each histogram corresponds to the index of the 25 ns slot, starting from the time of the misfire. The beam σ is calculated assuming a normalized emittance of 2.5 μm.

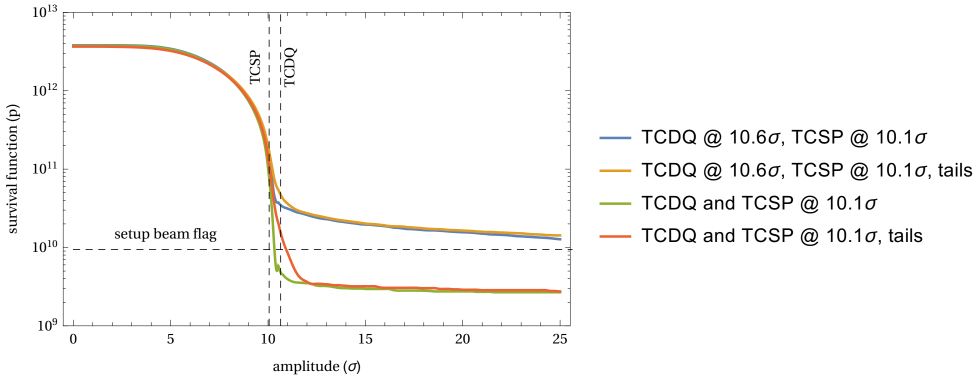

Figure 2: Survival function, normalised to 2.2×10^{11} protons per bunch, for various simulation scenarios, showing the total number of escaping particles from IR6 in the simulated bunches that are above any given amplitude A. The settings of the TCDQ and TCSG in IR6 are indicated, as well as the value of the setup beam flag at top energy in the LHC (9.4×10^9 protons). The simulation is done for B1 of HL-LHC v1.2, using β^* =15 cm collision optics at 7 TeV. The beam σ is calculated assuming a normalized emittance of 2.5 μm.

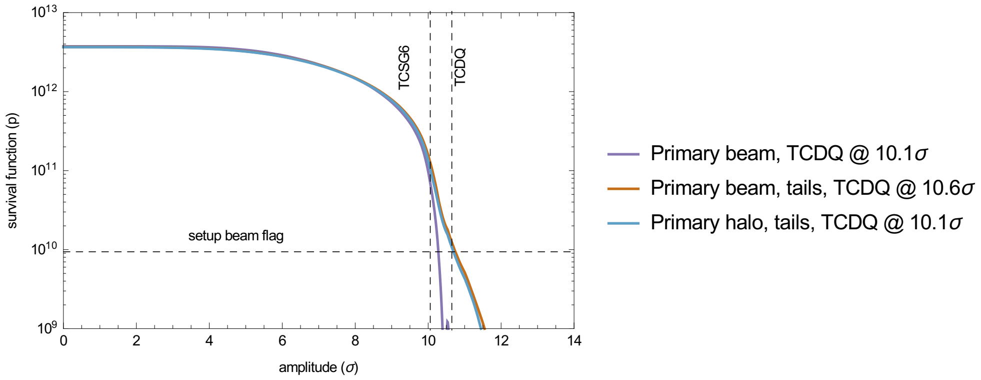

Figure 3: Survival function, normalised to 2.2×10^{11} protons per bunch, shown for primary beam only for three of the cases in Fig. 2. The beam σ is calculated assuming a normalized emittance of 2.5 μm.

the openings of the TCDQ, there is a long and flat tail, which is caused by secondary beam. Results are shown both for Gaussian bunches and bunches with increased tail population. In this latter case, the tail population has been fitted to measurements as in Ref. [12], using the data in Ref. [26]. The tails make the primary beam extend to slightly larger amplitudes, but do not significantly influence the secondary beam. Furthermore, two cases of the TCDQ setting have been simulated; the baseline setting of 10.6 σ and also a tighter setting of 10.1 σ, where the TCDQ is at the same level as the TCSP. This significantly reduces the tail of secondary beam, which is mainly caused by the TCSP. It should, however, be noted that it is not sure that the tighter TCDQ setting can be used in operation, since the TCDQ itself might not be robust to the high-intensity impacts during a beam dump failure [27].

We show also in Fig. 2 the 7 TeV LHC setup beam flag $N_{\mathrm{max}} = 9.4 \times 10^9$ protons [28], which gives the largest intensity that is allowed without all protection systems in place. This limit is based on an experimental damage level of copper with a factor 2 safety margin [29], and it is supposed to reflect a beam intensity that in most conditions will not cause damage to impacted elements. It should be noted that, since the secondary beam is much more diluted due to the scattering, the damage level caused by these impacts is expected to be much higher. Simulation studies on tungsten show that the damage limit is about a factor 20 higher than for the focused primary beam [30]. Although no explicit simulation has been carried out on copper, it is expected that also this case the secondary beam is much less damaging. Therefore, we conclude that the tail of secondary beam is not limiting, and that the aperture criterion should be based on the distribution of primary beam. We show therefore in Fig. 3 the survival function for primary beam only, for three of the cases in Fig. 2.

To calculate the minimum allowed aperture A_{min}, we demand that $S(A_{\mathrm{min}}) \leq N_{\mathrm{max}}$ for primary beam. This criterion would ensure that even if the total integrated intensity at amplitudes above A_{min} would impact the same element, which is a very pessimistic assumption since the losses are likely to be distributed over several bottlenecks, damage is very unlikely to occur. Taking the worst case for $S(A)$ in Fig. 3, it crosses the setup beam flag at around 11 σ, which is just outside the nominal TCDQ setting of 10.6 σ.

In order to estimate the aperture criterion, we must also account for possible errors, since the results presented in Fig. 2 are for a perfect machine. If the effective setting of both the TCSP and the TCDQ would be larger than the nominal ones, all curves would be shifted to the right and hence also the setting at which $S(A)$ crosses the setup beam flag. Without triggering a dump by the interlock BPMs in IR6, the worst-case orbit that is possible is 3.5 mm. This translates into 7.3 σ for the studied optics. In addition to this, we account for β-beat. With a 10% β-beat, we get an additional 0.8 σ offset, using the calculation methods in Ref. [15]. Furthermore, we account for 0.3 σ for alignment errors on the dump protection collimators (corresponding to about 200 μm). Starting from the 11 σ found in the perfect case, and adding the margins for imperfections, we end up at a minimum allowed aperture of 19.4 σ for ϵ_n =2.5 μm, which corresponds to about 16.4 σ for ϵ_n =3.5 μm.

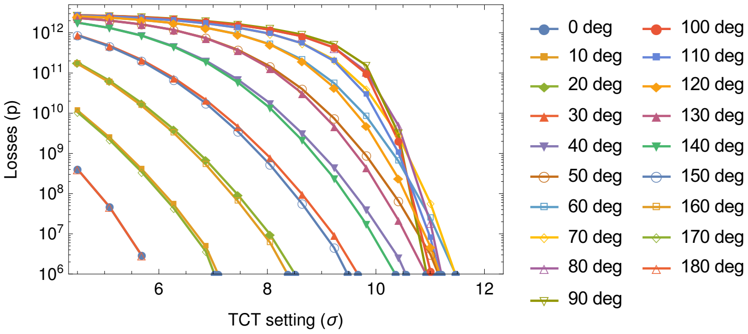

Figure 4: TCT losses, calculated using the phase-space integration method, during a type 2 SMPF event as a function of the TCT setting, for various values of $\Delta\mu$ between the first MKD and the TCT, and assuming a cut on the primary beam by the IR6 dump protection collimators at 10.1 σ (see Table 1). The simulations are normalised to 2.2×10^{11} protons per bunch. The beam σ is calculated assuming a normalized emittance of 2.5 μm.

3 Protected aperture as a function of phase advance

The aperture criterion in Table 1 makes no assumptions on the betatron phase of the element from the MKDs. However, it is clear that if an element has a fractional phase $\Delta\mu$ close to 0° or 180°, it is extremely unlikely to be hit by miskicked beam. This fact was used in LHC operation in 2016. A new optics, with $\Delta\mu$ matched to these constraints, was used to practically eliminate the risk of damage to the TCTs and triplets from asynchronous beam dumps [13]. As a consequence, a smaller normalised aperture could be tolerated. This made it possible to squeeze to a record-low β^* =40 cm, which is significantly below the nominal design value β^* =55 cm. In this section, we apply the same principles to HL-LHC. We do not study new optics, but what aperture could be tolerated for different values of $\Delta\mu$, which can be used as an input to the optics design. We use the same method as in Ref. [13], where full details can be found.

We use the phase-space integration method [13, 15] to calculate the losses during a type 2 SMPF in HL-LHC. This method consists of integrating the particle distribution over the parts of phase space that are outside given aperture cuts. It does not rely on particle tracking or a complete optics, and allows to quickly study a large number of cases. Only impacts of primary beam can be calculated with this method.

We consider first a simplified system of only one tungsten TCT, which risk to be damaged, and one dump protection collimator. The losses on the TCT, as a function of both the TCT setting and the $\Delta\mu$ from the first MKD, are shown in Fig. 4. The result is similar to Fig. 6 in Ref. [13], except that the normalisation is done to a bunch population of $2.2{\times}10^{11}$ protons, that the HL-LHC values for the normalised dispersion and TCDQ phase have been used, and that the setting of the dump protection has been adjusted to 10.1 σ. This corresponds to the TCSP cut in HL-LHC, which limits the

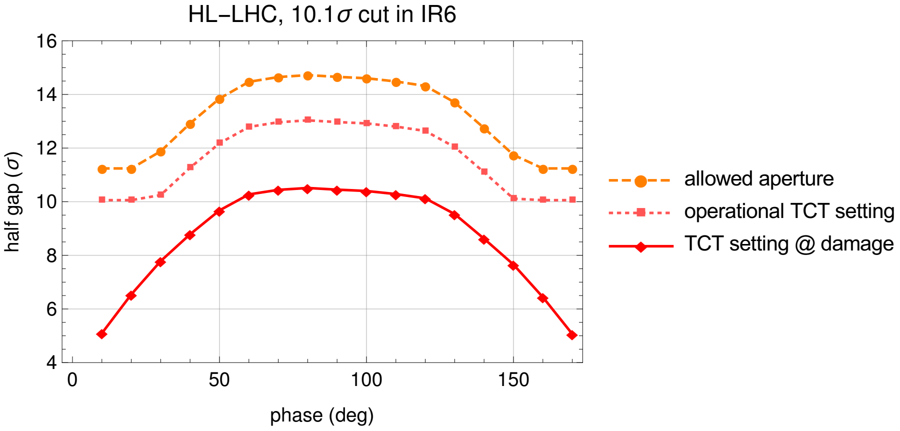

Figure 5: The minimum allowed effective TCT opening for beam dump failures, the minimum allowed operational TCT setting, and the minimum allowed aperture, as a function of the phase advance $\Delta\mu$ from the dump kickers. The aperture is calculated from the operational TCT setting, which in turn is derived from the minimum TCT setting, as in Ref. [15]. The minimum TCT setting is the smallest opening where the losses in Fig. 4 are still a factor 2 below the plastic damage limit [31]. The beam σ is calculated assuming a normalized emittance of 2.5 μm.

primary beam.

As in Ref. [13], we can now calculate the setting at which the TCT risks to be damaged at each $\Delta\mu$, by finding the setting where the curves in Fig. 4 reach losses a factor 2 below the estimated tungsten damage level of 5×10^9 protons [31]. These values, which can be considered as the minimum allowed TCT opening, are shown in Fig. 5, where we show also the operational TCT setting, and the corresponding protected aperture, calculated as in Ref. [15].

An underlying assumption here is that, based on LHC experience, the TCTs can anyway not be operated further in than the cut in IR6 at 10.1 σ due to constraints from the cleaning hierarchy. Therefore, the curves for the TCT setting and protected aperture flatten out close to 0° and 180°. It can be seen that, below 20°, an aperture of 11.2 σ is tolerated. This could potentially be used to squeeze β^* further. The maximum aperture is instead rather flat with a plateau around the 14.6 σ protected aperture calculated previously.

It should also be noted that, as for LHC in Ref. [13], our quoted values of $\Delta\mu$ refer to what can be achieved in the real machine. The optics design has therefore to be done with a stricter target for $\Delta\mu$, including a suitable margin for imperfections. Another caveat is that, before a new machine baseline is designed based on our quoted settings, it has to be verified in simulations that the secondary protons, which could hit the TCTs during asynchronous beam dumps even at $\Delta\mu$ =0°, do indeed not risk to cause damage. We consider it very likely that this is the case, since it has been verified for the nominal TCT position in Ref. [30]. However, the study should in that case nevertheless be repeated with the final settings and accounting for pessimistic imperfections. As

Table 2: The proposed parameters to be used in the n_1 model for HL-LHC studies at top energy (in bold) together with the parameter set used during the LHC design, as well as a parameter set that gives results close to the measured apertures in the LHC in Run 1 and Run 2 [11].

Parameter set	LHC design	**HL-LHC design**	LHC measured
Primary halo extension	6 σ	**6** σ	6 σ
Secondary halo, hor./ver.	7.3 σ	**6** σ	6 σ
Secondary halo, radial	8.3 σ	**6** σ	6 σ
Normalised emittance ϵ_n	3.75 μm	**2.5** μ**m**	3.5 μm
Radial closed orbit excursion x_{co}	3 mm	**2 mm**	0.5 mm
Momentum offset δ_p	8.6×10^{-4}	$\mathbf{2 \times 10^{-4}}$	2×10^{-4}
β-beating fractional beam size change k_β	1.1	**1.1**	1.025
Relative parasitic dispersion f_{arc}	0.27	**0.1**	0.1

discussed in Sec. 2, the amount of secondary beam can be substantially diminished if the TCDQ can be operated 0.5 σ closer than the present baseline in Table 1, at the same setting as the TCSP. This strategy, which was used in the LHC in 2016, would be a good improvement to the HL-LHC baseline collimation settings. However, it has to be studied further whether this is indeed feasible, due to robustness constraints on the TCDQ itself.

4 Summary of aperture parameters and protected aperture

This report provides updates to the previous report (Ref. [11]) for baseline parameters for aperture calculations for HL-LHC at 7 TeV. As a reminder, we show in Table 2 the updated parameters for aperture calculation for HL-LHC at 7 TeV. All values are identical to the values shown in Ref. [11], except that the reference emittance is updated to use ϵ_n =2.5 μm for HL-LHC. For comparison, we show a lso the old parameters used during the LHC design phase, as well as a parameter set that has been adapted empirically to fit well with the LHC aperture measurements.

We have reviewed the criterion with which the apertures, calculated using the parameters in Table 2, should be compared at 7 TeV. Assuming the collimator settings in Table 1 and that no local protection is present, as is the case for most elements outside the experimental insertions, an aperture of 19.4 σ can be tolerated. We have also reviewed the allowed aperture in the experimental IRs, behind the local protection of the TCTs, in case of an optics with a specially matched phase advance from the beam dump kickers, as was used in the LHC in 2016 [13]. It was found that for a fractional phase advance close to 0° or 180°, 2.4 σ aperture can be gained.

Table 3: The allowed aperture at 7 TeV in the experimental insertions for elements protected by the TCTs, as a function of the phase advance from the beam dump kickers that can be achieved in the machine (during the optics design, a suitable margin for imperfections should be taken). We show also the allowed aperture outside the local protection. We show the results both for the HL-LHC baseline emittance ϵ_n =2.5 μm, and for comparison also for the LHC emittance ϵ_n =3.5 μm used for collimation settings.

$\Delta\mu$ MKD-TCT	Protected aperture (σ)	
	LHC, ϵ_n =3.5 μm	**HL-LHC, ϵ_n =2.5 μm**
0°	9.5	**11.2**
10°	9.5	**11.2**
20°	9.5	**11.2**
30°	10.0	**11.9**
40°	10.9	**12.9**
50°	11.7	**13.8**
60°	12.3	**14.5**
70°	12.3	**14.6**
80°	12.3	**14.6**
90°	12.3	**14.6**

Table 4: The proposed parameters to be used in the n_1 model for HL-LHC studies at injection (in bold) [12] together with the parameter set that was used during the LHC design phase.

Parameter set	LHC design	**HL-LHC design**
Primary halo extension	6 σ	**6** σ
Secondary halo, hor./ver.	7.3 σ	**6** σ
Secondary halo, radial	8.3 σ	**6** σ
Normalised emittance ϵ_n	3.75 μm	**2.5** μm
Radial closed orbit excursion x_{co}	4 mm	**2** mm[1]
Momentum offset δ_p	1.5×10^{-3}	$\mathbf{8.6 \times 10^{-4}}$
β-beating fractional beam size change k_β	1.1	**1.05**
Relative parasitic dispersion f_{arc}	0.27	**0.14**
Qualification criterion	$n_1 > 7$	Aperture $> 12.6\ \sigma$

All these values are summarised in Table 3. The quoted apertures rely on the assumption that secondary impacts during asynchronous beam dumps pose no danger to the TCT since they are much more diluted, however, this assumption should be verified in simulations for the final settings. These losses can be improved if the TCDQ is operated 0.5 σ further in than the baseline setting in Table 1, however, it has to be studied if this is possible due to the robustness of the TCDQ itself.

Updated parameters for aperture calculations at injection energy have been described in Ref. [12]. We show a summary of the main results in Table 4, comparing to the LHC design parameters.

We have not treated aperture calculations for heavy ion beams in this report, which should be studied separately in the future. However, based on LHC experience, we do a priori not expect that stricter requirements would apply for heavy ions than for protons.

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