

REVIEW OF LHC RUN 2 MACHINE CONFIGURATIONS

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Abstract

During LHC Run 2, the LHC machine configuration evolved significantly. Starting from a very careful approach in 2015, with the priority on stability and ease of commissioning, where the limits of operation at the higher energy of 6.5 TeV were not well known, the machine settings were pushed further during the run, which ended with an optimized 2018 scenario with excellent performance. In this contribution, an overview is given of the evolution of different machine parameters, in particular the collimation settings, aperture and β^* , which are tightly linked to the peak luminosity performance of the machine. The key changes and the reasons behind are reviewed, as well as lessons learned for the future.

INTRODUCTION

During Run 2, in the period 2015–2018, the LHC machine configuration evolved significantly and played a major role for the luminosity performance. Several types of beams were used: standard 50 ns, standard 25 ns, BCMS, 8b4e, and 8b4e-BCS [1]. Furthermore, several new operational features were implemented [2]: combined ramp and squeeze, separation leveling in IR1 and IR5, crossing angle anti-leveling [3], β^* -leveling, full RF detuning [4], and the use of the new ATS optics [5]. The peak luminosity was ramped up to about twice the design luminosity, close to the limit acceptable for the heat load on the triplets due to the collision debris [6], and a total of about 160 fb^{-1} were collected by the high-luminosity experiments, as illustrated in the top plot of Fig. 1.

Keys to achieving this excellent peak performance can be seen from Table 1, in which the main parameters determining the LHC luminosity are shown for the LHC design configuration [7] as well as for the configuration achieved in 2018. Most of the 2018 parameters are slightly inferior or about equal to the design parameters, however, two parameters stick out and show a very large improvement compared to the design—both the emittance given by the injector complex and β^* are about half of the design value, which together approximately make up for a factor 2 peak luminosity gain. The emittance is discussed in detail in other contributions [1, 8], while β^* is one of the main topics of this article.

The decrease of β^* over the years is shown in the middle plot of Fig. 1, starting from $\beta^*=80 \text{ cm}$ in 2015 and going down to $\beta^*=25 \text{ cm}$ at the end of the leveling process in 2018, resulting in a strong gain in peak luminosity. The same figure shows also the variation in the crossing angle, while the bottom plot shows the evolution of the bunch intensity and the number of bunches. As can be seen, there has not

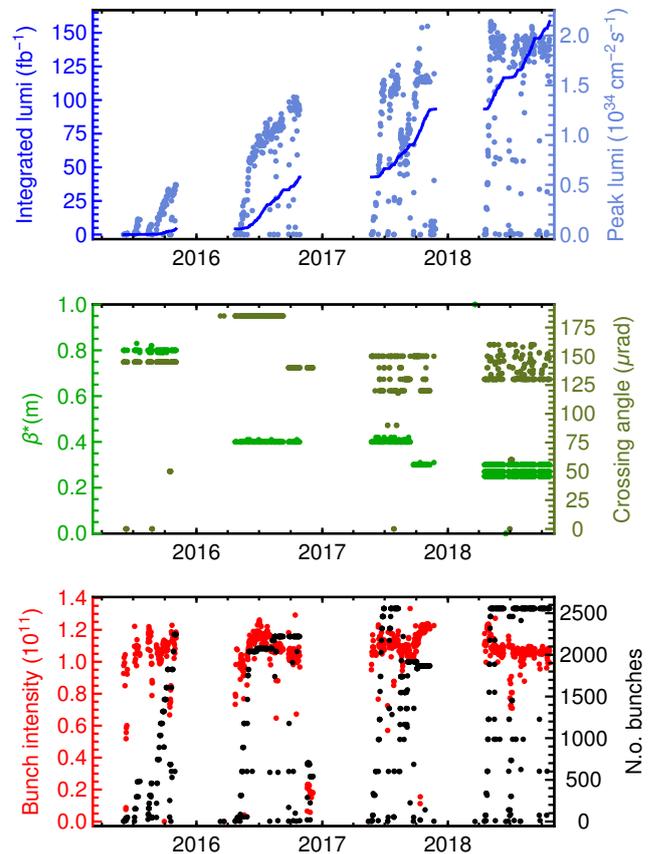


Figure 1: The integrated and peak luminosity (top), the β^* and the crossing angle (middle), and the bunch intensity and the number of bunches (bottom) over the years in LHC Run 2. The dots show the values at the start of stable beams for all Run 2 standard physics fills. Special runs have been excluded.

been any major intensity step, and hence intensity-driven increase in peak luminosity, after the first intensity ramp-up in 2015.

The main limitation on β^* in the LHC has so far not been given by constraints on optics and magnetic strengths, but rather by the available aperture and by machine protection considerations. The stored beam energy in the LHC has routinely been around 300 MJ in Run 2, which means that a local loss of even a very small fraction of the beam inside a superconducting magnet is enough to cause a quench or even permanent damage. The cold aperture is protected against direct losses by the LHC collimation system [9–14]. However, as β^* is squeezed to smaller values, the β -function in the inner triplets increases, so that the available aperture in units of beam σ decreases. The collimation system must

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Table 1: Key parameters for the LHC luminosity in the configuration of the LHC design report [7] and in the achieved 2018 configuration.

Parameter	2018	LHC design
Energy [TeV]	6.5	7.0
No. of bunches	2556	2808
Max. stored energy per beam (MJ)	312	362
β^* IR1/5 [cm]	30 \rightarrow 25	55
Half crossing angle IR1/5 [μ rad]	160 \rightarrow 130	142.5
Normalized beam-beam separation	10.6 \rightarrow 7.9	9.4
p/bunch (typical value) [10^{11}]	1.1	1.15
Typical normalized emittance [μ m]	1.9	3.75
Maximum peak luminosity [10^{34} cm $^{-2}$ s $^{-1}$]	2.1	1.0

therefore protect a smaller normalized aperture at smaller β^* and, to optimize β^* , the tightest possible aperture, which can be protected by the collimation system without compromising safety, must be found. The decrease of β^* over the years is therefore tightly linked to a gradual tightening of the collimators.

The LHC machine configurations used in Run 2 will be reviewed in the following sections, with the focus on the evolution of β^* and the settings of the LHC collimators. Before going into the details of each year, an overview of the performed measurements of the machine aperture and its comparison to expectations is given, which is a crucial prerequisite to the determination of the range of possible machine parameters. Other aspects of the LHC machine configuration are treated in other contributions of these proceedings. The beam characteristics are discussed in Refs. [1, 8], the beam optics and corrections in Ref. [15], the RF settings in Ref. [4], the chromaticity and octupoles in Ref. [16], and the configurations for heavy-ion operation in Ref. [17].

METHODS FOR APERTURE MEASUREMENT AND CALCULATION

In order to calculate the reach in β^* , it is absolutely crucial to have a detailed knowledge of the machine aperture and to be able to predict the available aperture in future, untested, configurations. Otherwise, the aperture risks not being protected. In order to ensure that the aperture is indeed protected by the collimation system, dedicated beam-based aperture measurements have been a mandatory part of the commissioning of each new machine configuration in Run 2, before high-intensity beams are allowed.

Beam-based aperture measurements have thus been performed in the LHC throughout Run 1 [18–24] and Run 2 [25–30]. A few different measurement techniques exist, but they

usually involve scanning the opening of a collimator, in combination with a beam blowup to induce losses measured with the beam loss monitors (BLMs), in order to find the largest collimator opening that still shadows the aperture bottleneck from the losses [27]. Such a measurement gives the global machine bottleneck, which is usually found in the triplet region of IR1 or IR5 in the collision configuration. Local aperture bottlenecks can be probed through orbit bumps, although this method is usually more time-consuming and less precise.

Two main ways of predicting the aperture in future configurations have been used. The first method is based on the MAD-X aperture module [31], where a 2D scan is done in the transverse plane of each longitudinal slice of the studied elements. The method takes as input various error tolerances, e.g. orbit drifts and β -beating, and returns a worst-case aperture. To give realistic results, these parameters have to be tuned to fit the experimental data. A comparison of MAD-X calculations and Run 1 data is presented in Ref. [32].

The other method is to use the measured aperture in a previous run as a starting point, and then scale it to a new configuration by accounting for the change in β -function and orbit at the location of the bottleneck, possibly with additional safety margins. This method is very fast and has shown to give reliable predictions of the global bottleneck as long as the aperture limit lies clearly in one of the two transverse planes, effectively making the calculation 1D, and there are no major optics differences that could shift the location of the aperture bottleneck.

APERTURE MEASUREMENT RESULTS

A summary of all top-energy measurements of the global aperture bottleneck, with squeezed beams (per beam and plane), is shown in Table 2. As can be seen, the bottlenecks are always found in the triplet regions of IR1 or IR5, as expected. It should be noted that when the bottleneck is indicated to be in Q3/D1, the highest loss in the measurement is found at the BLM labeled Q3 that, however, is installed close to the interconnection between Q3 and D1 and likely to be more affected by showers from the upstream D1 than from losses within Q3. From theoretical aperture studies, the bottleneck is also much more likely to be in the D1. Table 2 shows also the predicted aperture, calculated by scaling the measured aperture in the previous year. It can be seen that the predicted aperture was never further away than 0.5σ from the actually measured aperture, which is consistent with that the step size in the collimator scan was for most measurements 0.5σ . We therefore take this as a guide to the uncertainty of the method. We consider this a very good agreement given the collimator step size, unavoidable small differences in orbit and optics corrections between years, and that the magnets could be subject to small movements and realignments.

One striking feature which, however, could not be predicted, was that when the sign of the crossing angle in IR1 was reversed, the available aperture increased locally by

Table 2: Summary of measurements of global aperture bottlenecks per beam and plane in Run 2, as well as the predicted global aperture bottleneck based on aperture scaling from previous measurements. All values are given in units of beam σ , for a normalized emittance of $\epsilon_n=3.5 \mu\text{m}$. Differences between predictions and measurements of up to 0.5σ are expected due to the collimator step size used in the measurement.

	B1H	B1V	B2H	B2V
2015, 80 cm, -145 μrad	18.2 (D1/Q3R5)	15.7 (D1/Q3L1)	16.2 (D1/Q3R1)	15.7 (D1/Q3R1)
Predicted 2015	16.0			
2016, 40 cm, -185 μrad	10.6 (D1/Q3R5)	9.9 (D1/Q3L1)	11.5 (D1/Q3R1)	10.4 (D1/Q3R1)
Predicted 2016	10.2			
2017, 40 cm, +185 μrad	10.9 (D1/Q3R5)	12.0 (D1/Q3L1)	12.9 (Q2R5)	11.4 (D1/Q3R1)
2017, 40 cm, +150 μrad	11.5 (D1/Q3R5)	12.4 (D1/Q3L1)	14.0 (Q2R5)	12.0 (D1/Q3L1)
Predicted 2017, 40 cm, +150 μrad	11.6			
2017, 30 cm, +150 μrad	10.6 (D1/Q3L1 & D1/Q3R5)	11.1 (Q2R5 & Q3/D1 L1)	10.9 (D1/Q3R1)	10.5 (D1/Q3R1)
Predicted 2017, 30 cm, +150 μrad	10.0			
2018, 30 cm, +160 μrad	10.5 (D1/Q3L1)	10.5 (D1/Q3L1)	10.0 (D1/Q3R1)	10.5 (D1/Q3R1)
Predicted 2018, 30 cm, +160 μrad	9.6			
2018, 25 cm, +145 μrad	9.2 (D1/Q3L1)	9.2 (D1/Q3L1)	>12	10.5 (D1/Q3R1)
Predicted 2018, 25 cm, +145 μrad	9.4			

about 2σ . The global bottleneck thus moved to a different location, still giving an overall gain in the smallest aperture of about 1σ . This effect was first observed in tests during the 2016 commissioning and later verified with machine development (MD) studies [26]. The fact that the positive IR1 crossing angle sign was used in operation starting from 2017 thus gave additional aperture margins. It is foreseen to regularly change the polarity of the IR1 crossing in order to better distribute the radiation from the luminosity debris, thus prolonging the triplet lifetime due to radiation damage [33]. So far, about 115 fb^{-1} of data have been collected by the experiments using the positive IR1 polarity, with a larger aperture, and about 75 fb^{-1} have been collected using the negative polarity, out of which about 30 fb^{-1} come from Run 1 where the beam energy was lower. It is therefore likely that the next LHC run will be done with the negative polarity.

The aperture measurements in Table 2 are not trivial to compare directly since they were carried out in different machine configurations. To further examine the variations between the measurements over the years, we show in Fig. 2 the estimated aperture as a function of β^* . Each curve is calculated using the aperture-scaling method, but taking as input a different aperture measurement. All years in Run 2 have been considered, as well as one Run 1 measurement from 2012. For all curves, the beam-beam separation is assumed constant at the 2018 value (10.6σ for a normalized emittance $\epsilon_n=1.9\mu\text{m}$), meaning that the crossing angle varies along the curves.

As can be seen in Fig. 2, all curves based on Run 2 measurements lie within 0.5σ for any given sign of the IR1 crossing angle, which confirms the uncertainty of the method. Based on this experience, a safety margin of 0.5σ has been applied on top of the calculated aperture starting from 2017, in order to ensure that the aperture measured for any new configuration would not turn out to be unacceptable during the beam commissioning. This minimizes the risk of being forced to change the machine configuration after the commissioning has already started, which would cause large delays.

Figure 2 shows also a horizontal line representing the aperture that could be protected by the collimation system, using the 2018 collimator settings, and another line that includes the 0.5σ safety margin. A reach in β^* of about 27.5 cm can be seen directly in the figure by comparing this line with the calculated aperture, in accordance with Ref. [34].

A configuration change that was not possible to assess using the aperture-scaling method was the introduction in 2017 of a vertical orbit bump in IR5 to shift down the CMS IP. This bump reduces the available aperture in the IR5 separation plane, which has not been studied extensively in aperture measurements. Calculations with MAD-X predicted a potential aperture loss of up to several σ [35]. However, measurements of the global aperture bottlenecks during the 2017 commissioning showed that the vertical aperture limitations were still in IR1, even with an IP shift of down to

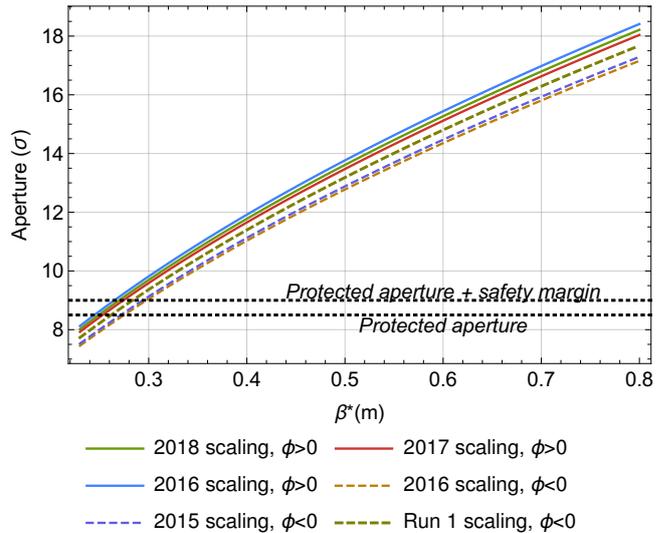


Figure 2: Triplet aperture as a function of β^* , calculated with the aperture-scaling method and using measured apertures for different years as input. These measurements were performed with positive or negative IR1 crossing angle ϕ . All values are given in units of beam σ , for $\epsilon_n=3.5\mu\text{m}$.

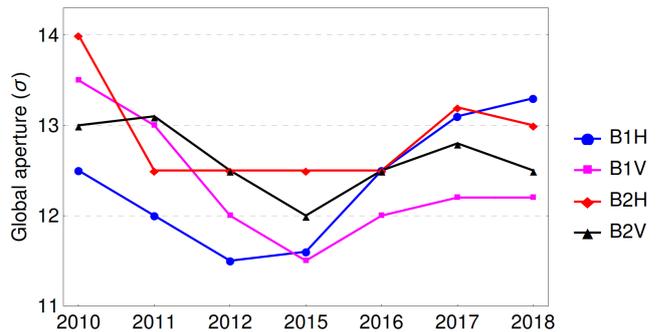


Figure 3: The measured global aperture bottlenecks at injection (per beam and plane) during Run 1 and Run 2. All values are given in units of beam σ , for $\epsilon_n=3.5\mu\text{m}$.

-2 mm in IR5. Any possible worsening in IR5 was thus in the shadow of the bottleneck in IR1 and there was no effect on the LHC performance reach. An IP shift bump of -1.5 mm was used in operation in 2017, which was increased to -1.8 mm in 2018 without observed adverse effects.

Although not directly relevant for the LHC β^* -reach, we show in Fig. 3 the measured aperture bottlenecks in the two beams and planes at injection during Run 1 and Run 2. As can be seen, the Run 1 trend of decreasing aperture was broken in Run 2. In 2018 all aperture bottlenecks were measured above 12σ , which is largely sufficient to be protected by the collimation system [36].

2015 CONFIGURATION

The main priority of 2015, which was the first year of Run 2, was to establish operation at 6.5 TeV beam energy and with 25 ns bunch spacing, after the operation in Run 1

at 3.5–4 TeV and with 50 ns spacing. Several uncertainties influenced the choice of machine configuration. One risk considered was beam losses, since the quench limit is lower at higher energy, while at the same time each lost proton deposits more energy. Loss spikes had been observed during the 2012 operation [37], and their scaling to 6.5 TeV carried a significant uncertainty. Furthermore, beam instabilities, the effects of electron cloud, as well as the dynamic-aperture decrease caused by beam-beam interactions, risked to cause beam losses and were not well known at the new energy and bunch spacing.

For the choice of 2015 machine configuration, the focus was put on feasibility, stability, and ease of beam commissioning. The choice was taken to allow comfortable margins rather than to push the performance and to avoid introducing too many untested features at once. Based on these considerations, it was decided to keep the 2012 collimator settings in mm [38]. These settings had sufficient margins in the cleaning hierarchy to provide a well-proven long-term stability and had also shown good cleaning performance in Run 1 [39] and were predicted through simulations to show satisfactory performance also at 6.5 TeV. Refraining from tightening the settings, in spite of the higher beam energy, provided more margins in terms of both beam losses driven by orbit fluctuations and impedance—these limits could then be studied with beam and potentially tightened later. The collimator settings are shown in Table 3, as well as graphically in Fig. 4, together with the settings in the other years of Run 2.

With those settings and assumptions, the limit on β^* was estimated to 65 cm [38]. However, due to the many unknowns and uncertainties and in view of the priorities for the start-up, it was decided not to start at the limiting configuration, but instead at $\beta^*=80$ cm [40]. This gave an additional 2σ margin, which was added to the margin between the dump protection collimators (TCDQ, TCSP) and tertiary collimators (TCTs) in the collimation hierarchy, and hence also to the target aperture. This made the risk negligible that the non-robust TCTs or the triplets behind them would be damaged during an asynchronous beam dump. During such an event, one or several of the extraction kickers (MKDs) misfire and send the passing bunches on oscillating trajectories around the ring, where they risk to hit and damage sensitive equipment [13]. Studies have shown that catastrophic damage would occur if a single nominal bunch of 10^{11} protons would hit a TCT, but even intensities below 10^{10} protons can give rise to plastic deformations [41]. Opening the operational setting of the TCTs and having a larger normalized triplet aperture reduces this risk, which was also not well known due to uncertainties on the frequency of asynchronous dumps as well as in the increase in losses due to the tighter 25 ns spacing.

The resulting machine configuration that was proposed for operation in 2015 had thus $\beta^*=80$ cm and a $150\ \mu\text{rad}$ crossing angle [42]. This configuration, which was based on an allowed beam-beam separation of 11σ for the nominal $\epsilon_n=3.75\ \mu\text{m}$ [43], was successfully commissioned and used

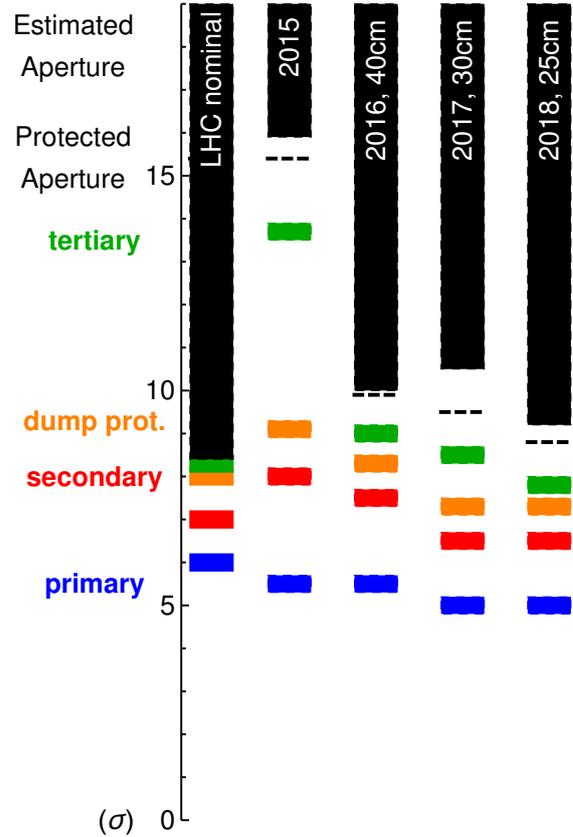


Figure 4: The Run 2 settings of the collimators influencing the reach in β^* , shown together with the measured and protected aperture. The settings from the LHC design report scenario are also shown as comparison [7]. All values are given in units of beam σ , for $\epsilon_n=3.5\ \mu\text{m}$.

in operation throughout 2015. During this commissioning year, a modest $4.3\ \text{fb}^{-1}$ of data were collected by ATLAS and CMS. This rather low amount of data was not surprising for a commissioning year with a long intensity ramp-up extending almost over the full year (see Fig. 1) and a comparably small number of hours spent in stable beams [44].

2016 CONFIGURATION

During 2015, several MDs were carried out [25, 45–47] in order to pave the way for higher performance in 2016, which was considered a production year. Firstly, tests were done to understand by how much the margins in the collimation hierarchy could be reduced. Loss maps were performed at different collimator settings towards the end of the year, while keeping the collimator settings found through beam-based alignment at the start of the year [46]. It was found that the long-term stability of the cleaning hierarchy, without any hierarchy breakage due to long-term drifts of the orbit or optics, could be maintained with a 2σ retraction between the TCPs and the TCSGs. Reducing the margin to 1σ caused a hierarchy breakage, which was, however, later explained by an isolated issue of the jaw angle of one TCSG. Furthermore,

Table 3: Summary of collimator settings, protected aperture, and β^* in Run 2. All collimator settings and apertures are given in units of beam σ , for $\epsilon_n=3.5 \mu\text{m}$. The configuration called 2017a refers to the first part of the year with $\beta^*=40 \text{ cm}$, while 2017b refers to the second part with $\beta^*=30 \text{ cm}$. The arrows in the 2018 configuration indicate the start and end points of the β^* -leveling.

Collimator	2015	2016	2017a	2017b	2018
TCP IR7	5.5	5.5	5	5	5
TCSG IR7	8	7.5	6.5	6.5	6.5
TCLA IR7	14	11	10	10	10
TCP IR3	15	15	15	15	15
TCSG IR3	18	18	18	18	18
TCLA IR3	20	20	20	20	20
TCSP IR6	9.1	8.3	7.3	7.3	7.3
TCDQ IR6	9.1	8.3	7.3	7.3	7.3
TCT IR1/5	13.7	9	9	8.5	8.5→7.8
Aperture 1/5		9.9	9.9	9.5	9.5→8.8
β^* IR1/5 (cm)	80	40	40	30	30→25
TCT IR2	37	37	37	37	37
TCT IR8	15	15	15	15	15

the impedance was deemed acceptable with these tighter settings [47].

The largest margin in the 2015 collimation hierarchy was between the TCDQ and the TCT. An idea to reduce this margin, without increasing the risk of damage to the TCTs or triplets, was to rematch the optics and adjust the betatron phase advance such that the oscillating trajectory from the mis-kicked beam from an asynchronous dump would be close to a minimum at each sensitive aperture bottleneck [48]. This is illustrated schematically in Fig. 5. Compared to the operational 2015 optics, where the fractional MKD-TCT phase advance was close to 60° , the TCTs could be moved significantly closer to the beam without increased risks with a new optics. This idea triggered significant development work. A large simulation campaign was launched to quantify the risks of damage at different apertures and phase advances [48]. An MD was carried out on an existing optics with a more favorable, although not ideal, phase advance [25], in order to verify the results of the simulations through aperture measurements and asynchronous dump tests. Another MD was carried out to quantify the cleaning and the leakage to the experiments with very tight TCT settings [45]. These studies triggered also a significant development work in the optics team, and a new optics with a 4° MKD-TCT fractional phase advance was implemented [48]. Using the results of all these studies and the new optics, it was found that the TCDQ-TCT margin could be reduced from 4.6σ to in 2015 to only 0.9σ in 2016. [48], as can be

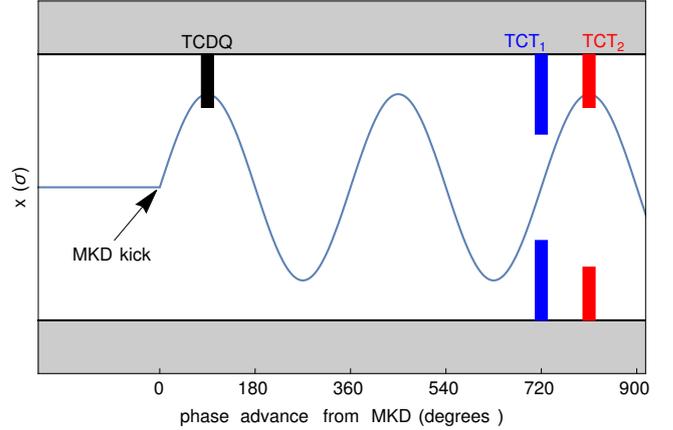


Figure 5: Schematic illustration of the horizontal orbit in normalized phase space resulting from a misfiring dump kicker during an asynchronous beam dump, as it performs betatron oscillations along the machine, shown together with the one-sided TCDQ at 90° phase advance from the kicker, and two different TCT positions at a fractional phase advance of $\Delta\mu_{\text{TCT}}=0^\circ$ or $\Delta\mu_{\text{TCT}}=90^\circ$. Figure taken from Ref. [48].

seen in Fig. 4. Additional verifications, in particular a campaign of asynchronous dump tests at different TCT settings, were carried out during the 2016 beam commissioning, in order to further verify that the TCT losses did not reach dangerous levels even at tight TCT settings in the presence of a favourable MKD-TCT phase advance.

The margin could potentially have been reduced even further, however, there was a concern that too tight TCT settings would give rise to increased experimental backgrounds [49], since more protons outscattered from IR7 might impact the TCTs and shower onto the experiments. The TCTs would also risk to intercept a larger rate of elastically scattered protons from upstream beam-gas interactions. Initial tests had shown that the 0.9σ margin was acceptable [45], and it was therefore adopted for the 2016 run. Combined with the tighter hierarchy in IR7, the total gain in protected aperture for 2016 was 5.6σ .

Further MDs were carried out on the long-range beam-beam effect [50, 51], which showed that the normalized beam-beam separation could be safely reduced from 11σ to 10σ (for $\epsilon_n=3.75 \mu\text{m}$ [52]).

Combining the gain in aperture due to a smaller crossing angle with the new optics and the very large reduction in collimation hierarchy margins, it was found that a machine configuration with $\beta^*=40 \text{ cm}$, and a half crossing angle of $185 \mu\text{rad}$ was within reach. This configuration was successfully commissioned and used in operation. The 2016 operation marked an important milestone, as it was the first time ever that high-intensity physics operation at the LHC was carried out below the nominal $\beta^*=55 \text{ cm}$.

During 2016, small-emittance BCMS beams were used regularly in operation, and it was shown that they could be used reliably without large emittance blowup or losses. Further beam-beam MDs carried out in 2016 showed that it

was possible to reduce the crossing angle based on the real emittance of the beam and also that a smaller normalized separation was possible [53]. It was therefore concluded in August 2016 that the normalized beam-beam separation could be decreased from 10σ for $\epsilon_n=3.75\mu\text{m}$, which had been used so far in 2016, down to 9.3σ for $\epsilon_n=2.5\mu\text{m}$ [54], keeping the bunch population constant at 1.15×10^{11} protons/bunch. A reduction of the half crossing angle from $185\mu\text{rad}$ to $140\mu\text{rad}$ was consequently implemented, however, still keeping $\beta^*=40\text{cm}$.

In summary, 2016 was the first strong production year in Run 2, and a total of about 40fb^{-1} were accumulated in ATLAS and CMS.

2017 CONFIGURATION

When the crossing angle was reduced to $140\mu\text{rad}$ in 2016, thus moving the orbit away from the triplet aperture, more margin was made available, which could be directly translated into a gain in β^* . For 2017, a similar beam-beam separation could be used as in 2016, however, in order to have margin for an increased bunch population, it was proposed to increase the separation to 10σ for $\epsilon_n=2.5\mu\text{m}$ [55]. Still, this implied a gain in aperture compared to what was assumed initially for the 2016 run.

After the very good collimation performance in 2016 [56, 57], it was investigated whether the settings could be tightened further in 2017. An MD was dedicated to the retraction between TCP and TCSG, where loss maps were performed at different settings [58]. It was discovered that the limitation found in previous MDs [46], where a breakage of the cleaning hierarchy appeared at 1σ , was caused by an angular misalignment of the tank of one particular collimator (TCSG.D4L7.B1). Compensating for this through a tilt in the opposite direction, a correct cleaning hierarchy was restored for the nominal 1σ TCP-TCSG retraction. For operation, a 1σ margin was still considered potentially risky and instead 1.5σ was proposed.

Another MD was carried out to investigate the effect of operating with a tighter TCP cut [59], which would allow all other collimators to be tightened. Two full cycles were carried out, where the TCPs were closed during the ramp to half gaps of 4.5σ and 5.0σ respectively, which should be compared to the operational setting in 2015–2016 of 5.5σ . As illustrated in Fig. 6, it was found that with a 4.5σ TCP setting, the minimum lifetime in the ramp dropped by about a factor 10, and significant losses were observed. This was not fully understood. At 5.0σ no detrimental effect was observed.

A significant effort was also invested in MDs throughout 2016 to quantify the impedance of the tighter settings [59–61]. Through e.g. measurements of the tune shift between configurations with open and closed collimators, the impedance was judged to be acceptable.

Based on these various MD results, it was proposed to use these tighter settings operationally in 2017 with the TCPs at 5σ and TCSGs at 6.5σ .

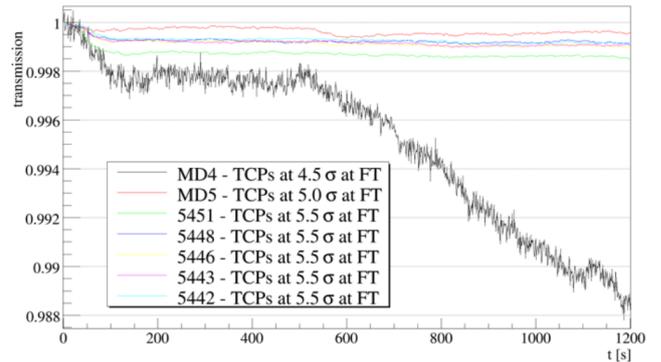


Figure 6: Beam transmission as a function of time during the energy ramp, for different TCP cuts in Beam 2, as measured in MDs and during regular operation (fill numbers are indicated). Figure taken from Ref. [59]

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 the IR7 collimators. Using an optics with a small MKD-TCT phase advance as in 2016 [48], there was no strong constraint on the TCT settings from asynchronous beam dumps, but other constraints were limiting the inner TCT position, such as the potentially higher experimental background. The latter was studied in an end-of-fill MD in 2016, where the TCT settings were tightened by $0.5\text{--}0.6\sigma$ without any observed effect on the background [62]. Other studies based on background in ATLAS during loss maps [63] support the hypothesis that the machine-induced backgrounds are dominated by inelastic beam-gas interactions and that the contribution from the TCTs is negligible. It was therefore decided to allow a TCT setting of 7.5σ , only 0.2σ outside the TCDQ, which allowed a protected aperture of 8.5σ , to which the 0.5σ safety margin should be added. This gave a new β^* -reach of 30cm .

Several uncertainties existed for the 2017 run, in particular the introduction of the bump to shift the CMS IP, initially feared to cause a significant aperture loss. Furthermore, the ATS optics [64] had in the meantime been developed further to include the favorable MKD-TCT phase advance below 30° , which was however further away from zero than the 4° used in 2016. It was therefore decided to start at $\beta^*=40\text{cm}$, but to commission the optics further down to $\beta^*=30\text{cm}$ for a possible step in β^* later in the year.

In the commissioning it was found that the CMS bump did not cause any loss in aperture, since the bottleneck was shadowed by IR1 as explained earlier. Instead, a comfortable aperture margin was available with the positive crossing angle polarity in IR1. In view of this and the successful operation with ATS optics, which did not reveal any unforeseen bottlenecks, it was decided to decrease β^* to 30cm in September 2017. To ensure that the collimation margins were respected at the smaller β^* , an interlock on the orbit at the TCTs and at the TCSP in IR6 was introduced, using the built-in collimator BPMs. When β^* was reduced, the crossing angle of $150\mu\text{rad}$ was not increased, based on

further beam-beam studies [65]. This implied an effective reduction in beam-beam separation from 10σ to 8.6σ (for $\epsilon_n=2.5\mu\text{m}$). Because of the extra margins from the beam-beam separation and the inverted crossing, there was never a need to push the TCTs to the tightest allowed setting, and they were kept at 8.5σ . The final 2017 collimator settings can be seen in Fig. 4.

It should also be noted that in 2017, crossing angle anti-leveling was introduced as a way to further optimize the luminosity, based on promising MD results [3]. As the intensity decays during a fill, the needed beam-beam separation goes down. Therefore, the crossing angle was decreased dynamically during physics operation in steps of $10\mu\text{rad}$ from $150\mu\text{rad}$ to $120\mu\text{rad}$, thus improving the geometric reduction factor and hence the luminosity. During this leveling, the TCTs were kept at a constant gap that was moved automatically to follow the shift in closed orbit.

In summary, despite of problems with beam dumps caused by losses in cell 16L2 [66], 2017 turned out to be another very good production year, where in total about 50fb^{-1} were delivered to ATLAS and CMS. A special filling scheme (8b4e) was used mitigate the dumps and the push in β^* and beam-beam separation gave an appreciable boost in luminosity.

2018 CONFIGURATION

For the 2018 run, no major changes were implemented in the collimation hierarchy, which was already rather tight with the smallest TCP gaps below 1 mm. The 1.5σ retraction in IR7 was not reduced further due to the risk of introducing a hierarchy breakage caused by orbit drifts. Such a breakage had been observed at the requalification after the second MD block in July 2017, but it could be restored by a careful orbit correction [67].

To make higher bunch intensities possible, it was proposed to increase the normalized beam-beam separation to 9.2σ (for $\epsilon_n=2.5\mu\text{m}$) in 2018 [68], which corresponded to $160\mu\text{rad}$ at $\beta^*=30\text{cm}$. This was, however, still smaller than what had been initially considered for operation at $\beta^*=30\text{cm}$ in 2017. Using the margins from the beam-beam separation and the increased aperture with the positive sign of the IR1 crossing angle, which was kept also for 2018, a further squeeze down to $\beta^*=27.5\text{cm}$ was possible at the start of the fill [34], and β^* could possibly be reduced further to $\beta^*=25\text{cm}$ later in the fill at lower intensity. Leveling using β^* , which had been successfully tested in MDs in 2017 [69], was considered important to implement operationally, as it is part of the HL-LHC baseline [70].

Because of the relatively small gain and the additional overhead, it was decided to stay at $\beta^*=30\text{cm}$ as the baseline for 2018 operation, but to also move towards the implementation of β^* -leveling down to 25cm . This leveling, which took place once a crossing angle anti-leveling from $160\mu\text{rad}$ to $130\mu\text{rad}$ had been performed, was successfully commissioned and used in operation throughout 2018. During the β^* -leveling, the TCTs did not move. However, due to the

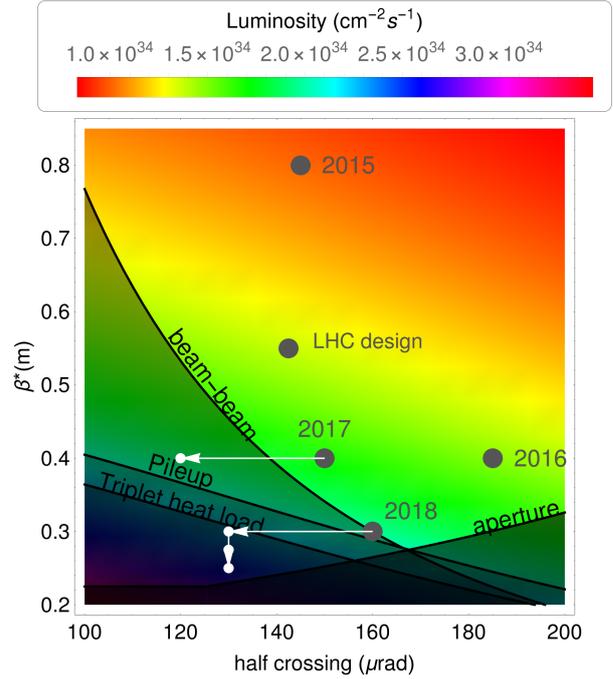


Figure 7: Summary of the configurations of β^* and half crossing angles used at the start of every year in Run 2, shown together with various constraints on the parameter space and the luminosity. The luminosity has been calculated using the 2018 beam parameters in Table 1. The indicated limits, except the one on aperture, are intensity-dependent and calculated for the start of the fill. The white arrows show configurations reached later in the fill using leveling, after the intensity has decayed.

increase in the β -function, the effective setting went down from 8.5σ at $\beta^*=30\text{cm}$ to 7.8σ at $\beta^*=25\text{cm}$. This marked an important milestone, as it was the first time ever that the TCTs were operated at a setting that was tighter than the 8.3σ in the LHC design report. The triplet aperture decreased by the same ratio, meaning that they were always protected by the TCTs.

Throughout 2018, the LHC thus regularly operated with a β^* that was less than half of the nominal $\beta^*=55\text{cm}$ in a highly optimized running scenario that relied on two different leveling techniques. At the end of 2018, about 65fb^{-1} of data were collected, which was the highest value achieved so far in a single year.

RUN 2 PARAMETER SPACE

Figure 7 summarizes the configurations used at the start of every year in Run 2 (intermediate configurations have been left out to enhance visibility). The color scale shows the luminosity as a function of the β^* and the half crossing angle, assuming typical 2018 beam parameters as shown in Table 1. It is assumed that 2544 bunches collide, and that the bunch length is 8 cm.

The darker shaded areas are excluded as working points at the start of the fill due to various constraints, where one is

the criterion that the triplet aperture must stay above 8.5σ , to which 0.5σ safety margin has been added. Along the limiting line at constant aperture, any decrease in β^* must be compensated by a decrease in crossing angle. The aperture has been calculated by scaling the aperture from the 2017 measurement, which is the most pessimistic one with positive crossing angle in IR1 (see Fig. 2). It can be seen that the curve flattens out just below $130\mu\text{rad}$, below which it is independent on the crossing angle. This is due to the fact that the 1D aperture limitation moves to the separation plane instead.

Another constraint is the beam-beam separation that determines the crossing angle at any given β^* . Along the limiting line, which represents a constant beam-beam separation of 9.2σ for $\epsilon_n=2.5\mu\text{m}$, a larger crossing is needed if β^* is decreased. Furthermore, direct luminosity limits are also shown. One limit is given by the maximum pileup of 60 events per crossing tolerated by the experiments [71], and the other limit is given by the maximum acceptable luminosity of $2.2 \times 10^{34}\text{ cm}^{-2}\text{s}^{-1}$, above which the cryogenic system can no longer handle the heat load on the triplets [6].

As can be seen in Fig. 7, the 2015 scenario had a similar crossing angle as the LHC design scenario but was significantly more relaxed in terms of β^* . In 2016, a very large step was done in β^* , for which a much larger crossing angle had to be used. In 2017, the starting configuration included a significant reduction in crossing angle at constant β^* . The white arrow next to the 2017 point shows the crossing angle anti-leveling, which brought the working point outside the initially allowed zone. This was only possible with the lower intensity later in the fill, which effectively relaxed the beam-beam constraint and moved its limiting line further to the left in Fig. 7. Finally, it can be seen that in 2018, the tightest configuration in terms of β^* and crossing angle was used, where the end point at $\beta^*=25\text{ cm}$, after crossing and β^* -leveling, is close to the aperture limit and beyond the limit of what is acceptable at the start of the fill for the other intensity-dependent constraints.

CONCLUSIONS

In conclusion, a large parameter space was explored in LHC Run 2, starting from the prudent commissioning scenario in 2015 and going all the way to the pushed 2018 configuration. The philosophy behind the machine configuration changes in Run 2 was always to perform changes to improve machine performance while staying safe and not reducing machine availability. One significant change was a large reduction of β^* during Run 2, and the operation did not show any indication that the machine availability would be negatively affected by operation at a very small β^* .

One important aspect of ensuring the safety in any chosen scenario has been beam-based measurements of the limiting machine apertures. The results have been consistent over the years within 0.5σ , which was used as error margin on the calculated aperture. One unexpected result was that a larger aperture was found in IR1 with a positive crossing

angle than with a negative angle, which gave more margins in the collimation hierarchy in 2017–2018.

Over these years, the collimator settings have been gradually tightened, based on machine studies, so that a smaller normalized machine aperture could be protected. One key to achieving the tighter collimator settings was the introduction in 2016 of a matched phase advance between the extraction kickers and the sensitive aperture bottlenecks in the experimental insertions. With the new optics, it was possible to operate with the tertiary collimators and the triplet aperture significantly closer to the beam without increased risk of damage during an asynchronous beam dump. This made it possible to squeeze β^* to very small values, with the $\beta^*=25\text{ cm}$ configuration used in 2018 representing a very large gain compared both to the LHC design scenario with $\beta^*=55\text{ cm}$ and the 2015 configuration at $\beta^*=80\text{ cm}$. As was shown in Table 1, the β^* was, together with the injected beam brightness, the major contributors that made it possible to reach an excellent performance at the end of Run 2, with a factor 2 higher peak luminosity than in the LHC design. In Run 2, decreasing β^* has proven to be a very effective way of increasing the peak performance even in the presence of limitations on the beam intensity.

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