



IR aperture measurement at $\beta^*=40$ cm

R. Bruce, P. D. Hermes, A. Mereghetti, D. Mirarchi, S. Redaelli, B. Salvachua, P. Skowronski, G. Valentino, A. Valloni, CERN, Geneva, Switzerland

H. Garcia, R. Kwee-Hinzmann, Royal Holloway University of London, Egham, Surrey, UK

Keywords: LHC, aperture, collimation

Summary

This note summarizes MD 307, performed on August 27 2015, during which we measured with beam the global apertures at 6.5 TeV with IR1 and IR5 squeezed to $\beta^*=40$ cm and a half crossing angle of $205 \mu\text{rad}$. The measurement technique involved opening collimators in steps, while inducing beam losses at each step, until the main loss location moved from the collimators to the global bottleneck in one of the triplets. Measurements were performed in both beams and planes, and each measurement gave the minimum triplet aperture over IR1 and IR5. The results are in very good agreement with theoretical predictions based on the nominal mechanical aperture. At the end of the MD, an asynchronous beam dump test was performed with all collimators moved in to so-called $2\text{-}\sigma$ retraction settings. This MD is one in a series meant to address various open points for the reach in β^* in Run II.

1 Introduction

As β^* is pushed to smaller values to achieve higher luminosity in the LHC, the normalized aperture in the triplet decreases, but it can only be decreased down to the level which can be protected by the collimation system [1]. The triplets are locally protected by the tertiary collimators (TCTs), which are also not robust against high intensity beam impacts that risk to happen during an asynchronous beam dump. Therefore, in Run I, margins were introduced between collimator families to keep the risk of damaging the triplets and the TCTs very low. This practically constrained β^* and the achievable luminosity.

The margins introduced in Run I accounted for the most pessimistic phase advance of $\pi/2$ between the dump kickers and the TCTs. For Run II, one way of pushing the reach in β^* could be to account for the phase advance between the dump kickers (MKDs) and the TCTs and triplets when determining the margins [2]. Since the phase advance with nominal optics

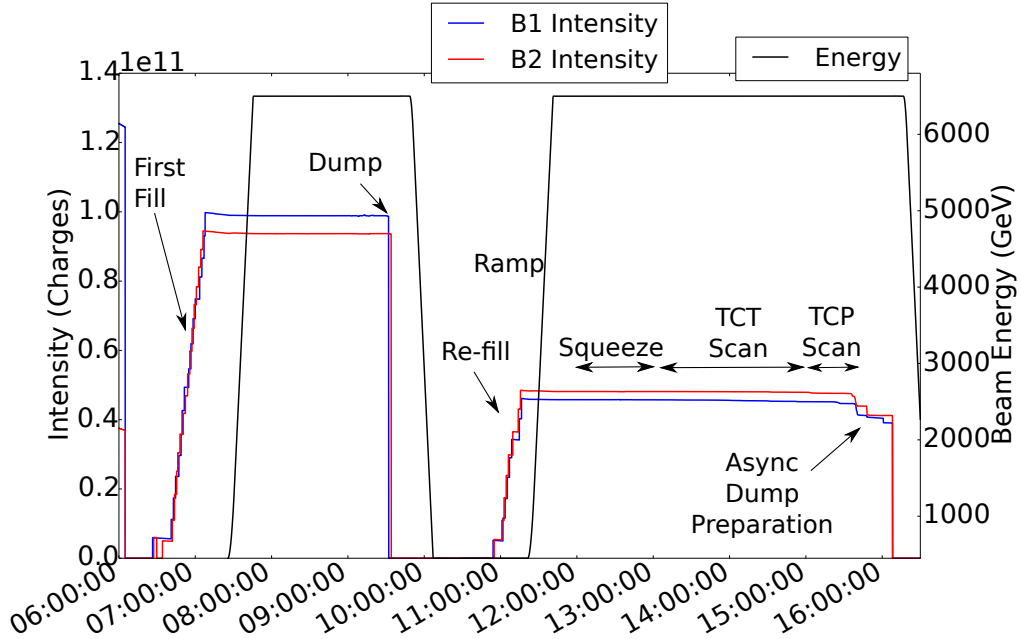


Figure 1: The evolution of beam intensity and energy during the MD.

at $\beta^*=40$ cm and below turns out to be much more favorable than at the higher β^* -values used so far in operation, the TCTs could potentially be moved in significantly without risk, allowing thus a smaller aperture and smaller β^* . In this scenario, the TCT settings could be constrained rather by halo cleaning and experimental background. We present here one in a series of MDs proposed to investigate with beam the feasibility of the needed tighter collimation hierarchy, and ultimately of $\beta^*=40$ cm or below as an operational scenario in Run II. This MD addressed in particular the evaluation of the IR aperture at $\beta^*=40$ cm.

Because of chromatic effects and an optics correction that is potentially not as good as at $\beta^*=80$ cm, the normalized aperture could possibly be worse at very low β^* than the expected aperture extrapolated from measurements at higher β^* . This MD aimed therefore at measuring with beam the aperture of the triplets in IR1 and IR5 at $\beta^*=40$ cm. Furthermore, in a pushed $\beta^*=40$ cm scenario, there is not much margin and it is therefore necessary to know the aperture with best possible precision. The MD serves also as an additional benchmark for the aperture calculation models that have been used to estimate the aperture in any running scenario [1, 3, 4].

It was also foreseen to perform off-momentum aperture measurements, which could not be carried out due to a delay of several hours caused by a beam dump from an RF software error that was not related to the MD. Such a measurement could possibly be performed during the commissioning in 2016 if needed. In addition to the aperture measurements, an asynchronous dump test was performed at the end of the MD to assess the losses on TCTs with settings close to the IR6 dump protection.

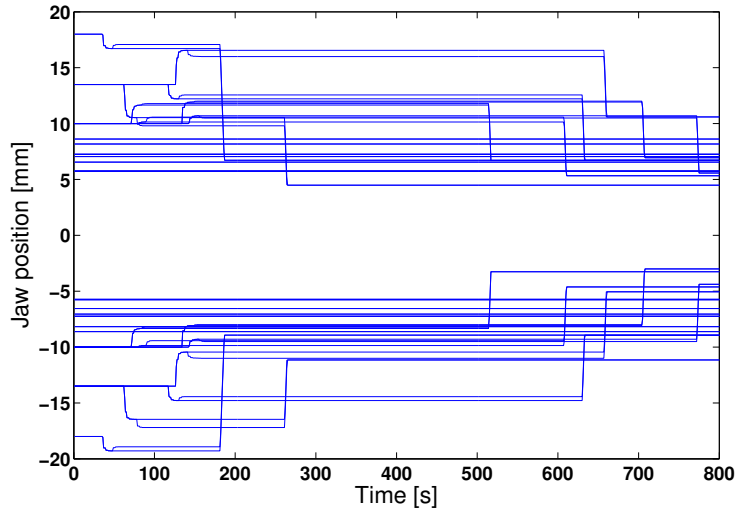


Figure 2: The positions of the TCT jaws as a function of time during the BPM alignment. It should be noted that a BLM-based alignment of all TCTs usually takes around 1 h.

2 Measurement procedure

The evolution of the beam intensity and energy during the MD is shown in Fig. 1. The first fill was dumped due to a software error in the main RF system [5], not connected to the MD, before the measurements could start. The second fill, in which 8 pilot bunches were injected, successfully reached $\beta^*=40$ cm using the standard operational procedure. At flat top, the collimators were driven to coarse settings (TCP7 at $12\sigma^1$, TCSG7 at 13σ , IR6 TCSP at 12σ , TCDQ at 15 mm, and all IR3 collimators at 20σ) and the TCTs symmetrized with respect to the 80 cm orbit. Then all crossing and separation bumps were flattened, followed by a first squeeze to $\beta^*=80$ cm and then second step to $\beta^*=40$ cm, where the optics had previously been corrected [6]. The nominal optics was used all along the MD.

At $\beta^*=40$ cm, a crossing angle of $205\ \mu\text{rad}$ was introduced in IR1 and IR5, which corresponds to a beam-beam separation 11σ using a normalized emittance of $3.75\ \mu\text{m}$, as assumed for long-range beam-beam constraints [7, 2]. as well as the standard separation of 0.55 mm [8]. After that, the TCTs were aligned around the new orbit using the BPM buttons and retracted to an initial setting of 7.8σ . The jaw positions of the TCTs during the alignment are shown in Fig. 2. As can be seen, the full alignment was finished in less than All other collimators were then opened beyond that, in order to make the TCTs the aperture bottleneck of the ring. In this configuration, an ADT white-noise excitation was used to induce transverse losses on individual bunches, in order to probe the aperture. Both beams and planes were probed consecutively with different pilot bunches.

Afterwards, all TCTs in IR1 and IR5 were opened by 0.5 sigma, and new losses were induced in both beams and planes. The procedure of a TCT step outward followed by ADT excitations to create losses was repeated until the main loss location moved from the TCTs to the triplet aperture in one of the IRs. A conservative estimate of the aperture in units of

¹The σ in this note refers always to a $3.5\ \mu\text{m}$ normalized emittance.

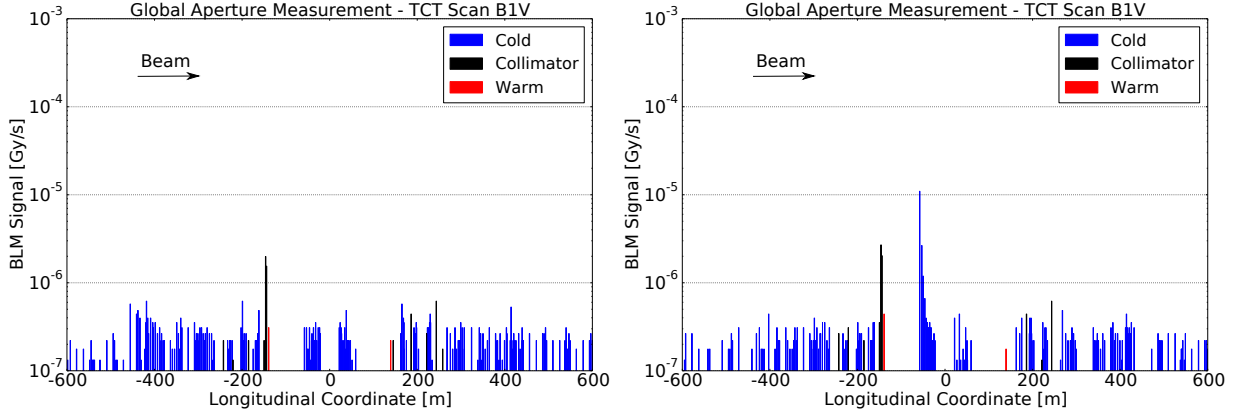


Figure 3: The measured losses in IR1, B1, during a vertical excitation and when the TCT was at 9.5σ (left) and at 10σ (right). It can be seen that between these two steps in TCT opening, the main loss location moves from the TCT (black) to the cold triplet aperture (blue).

σ is then given by the largest TCT opening where the TCT was still shadowing the triplet. An example of the local loss distribution in the IR is shown in Fig. 3, for both the case when the TCT is still the aperture bottleneck, and the step after in the scan where the bottleneck is found at the triplet.

After the TCT scans, similar scans were performed using the TCP instead, in order to understand some inconclusive results found in the TCP scan. Both the TCT and TCP scans are described in more detail in Sec. 3, while in Sec. 4, a comparison is made to theoretically predicted apertures.

At the end of the MD, all collimators were moved in to the proposed operational settings at $\beta^*=40$ cm. Then an asynchronous dump test was performed, This is discussed more in detail in Sec. 5.

3 Measurement results

The results from the measurements are shown in Fig. 4 in the form of losses at the triplets and TCTs as a function of the TCT opening, for each beam and plane. It should be noted that the raw integrated BLM signals during the loss have been normalized first by the intensity decrease during the excitation (in p) in each step, which is not necessarily the same for each ADT excitation. Furthermore, each data curve has been normalized by the highest intensity-normalized BLM signal, recorded at its respective location. This accounts for the fact that the BLM response (BLM signal per impacting proton) is different at different elements, due to the shower development in the local geometry. With this normalization, which was first introduced in Ref. [9], the losses at each element are given as a fraction of the maximum loss that occurs when the element is the main bottleneck of the ring. The triplet aperture in each case can be estimated as the interpolated cross-over between the TCT losses and the aperture and the results are shown in Table 1, where they are compared to the conservative estimate given by the largest TCT setting where the aperture was still protected in the measurements.

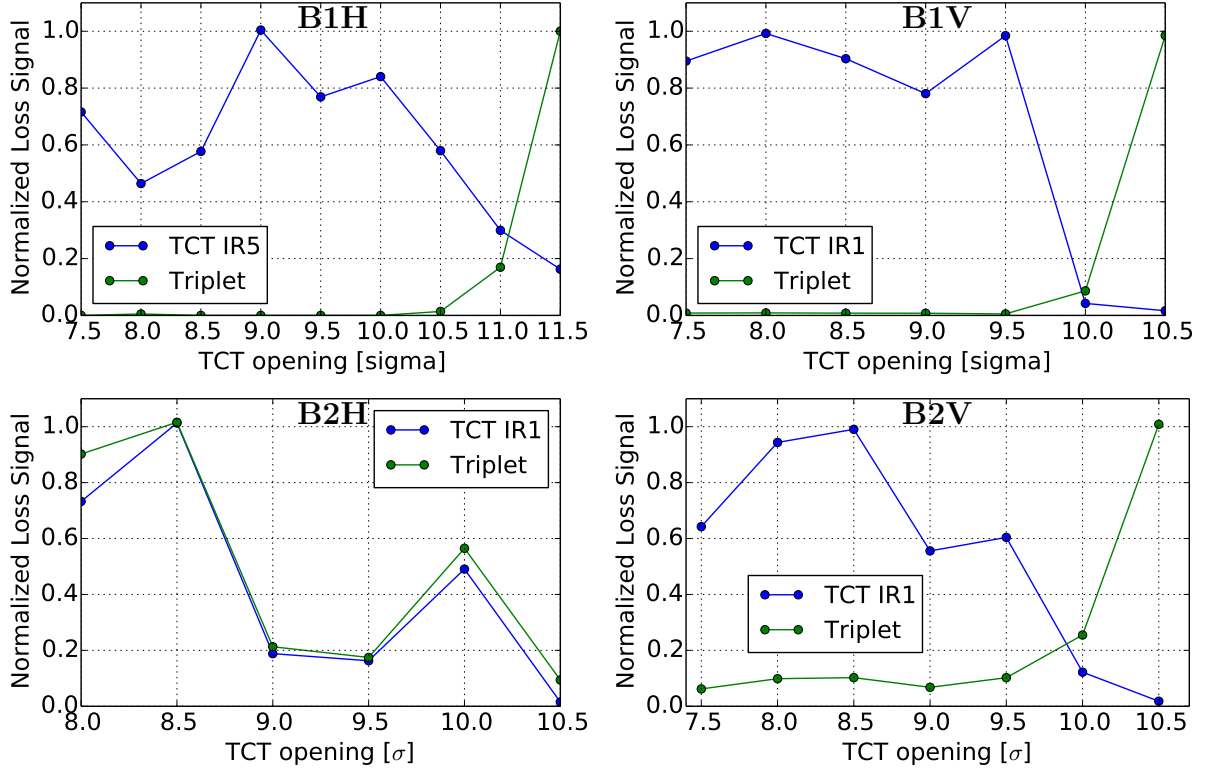


Figure 4: The measured losses at the limiting triplet aperture and the upstream TCT, as a function of TCT setting, and normalized by both the intensity loss at each excitation and the highest loss measured at each element, for each beam and plane.

It should be noted that there is still a significant uncertainty on the interpolated values, due to noise in the intensity normalization and shot-by-shot variations in the BLM response. Therefore, in order to be on the safe side, we use instead the conservative estimates for any estimation of the performance reach.

It should be noted that in the case of B2H, the measurement was not conclusive. It can be seen in Fig. 4 that the measured triplet losses were actually slightly higher than the TCT loss already at the starting point, with TCTs at 7.8σ . However, when the TCTs were opened, the ratio of the loss at the TCT to the loss at the triplet remained approximately constant. This hinted that the significant triplet losses were probably not caused by a real aperture bottleneck, but rather by showers starting in the TCT and hitting also the triplet BLM with a higher response there than at the TCT itself. If a primary loss would really have occurred on the triplet, the loss at the TCT should have decreased significantly when this collimator was opened more. Once the TCT setting reached 10.5σ , the ratio changed very significantly, with the TCT losses dropping suddenly to almost zero. This could hint that the real aperture was hit with the primary beam between 10σ and 10.5σ .

In order to verify this assumption, a second measurement was carried out, where the TCTs were opened to 13σ directly at the start, and the the scan was performed with the TCP in IR7, opened in steps of 0.5σ steps, again with a blowup on every step. The initial loss distribution in B2H, with the TCP at 8σ , is shown in Fig. 5. Losses at the triplet can

Table 1: Results of the aperture measurements in units of σ from the TCT and TCP scans, assuming a normalized emittance of $3.5 \mu\text{m}$. We show both the interpolated values, for which the TCT and aperture are estimated to have the same normalized opening from Figs. 4 and 6, and the conservative estimate given by the largest TCT setting where the aperture was not exposed. We show also the IR in which the bottleneck was found.

Plane and beam	Interpolated aperture (σ)		Aperture from coll. setting (σ)		IR
	TCT scan	TCP scan	TCT scan	TCP scan	
B1 H	11.1	–	11.0	–	5
B1 V	10.0	9.8	9.5	9.5	1
B2 H	–	10.1	(10.0?)	10.0	1
B2 V	9.8	–	9.5	–	1

be seen also in this configuration, however, the TCP is the clear bottleneck of the ring with a significantly higher loss peak.

It should be noted that the measurement with the TCP could in principle be expected to be more conservative, as we expect more secondary halo which is outscattered at large amplitudes. A similar leakage of secondary halo to the triplet should not be expected during standard operation, since all other IR7 collimators were open during the MD. This means that IR7 contained a single-stage cleaning, which is much less efficient at absorbing the losses than the standard multi-stage system. Furthermore, the TCTs were retracted in this configuration.

The losses in the triplet and at the TCP, as a function of the TCP setting and using the same normalization procedure as for the TCT scan, are shown in the left part of Fig. 6. It can be seen that the aperture is exposed between 10σ and 10.5σ . This result of the TCP scan thus confirms the suspected aperture in the TCT scan, where the ratio of TCT to triplet losses decreased rapidly above 10σ , and makes it likely that the observed triplet losses at small TCT openings must have been secondary, outscattered particles from the TCT. It is, however, not understood why the BLM at the IR1 triplet records so much higher losses during in B2H excitations than the corresponding BLMs for other planes and beams. Previous studies with FLUKA have shown that the detailed placement of the BLM is very important to the final BLM response [10, 11] and could cause large variations between BLMs placed at similar elements in the ring. For a full understanding, the BLM locations at all triplets and TCTs in IR1 and IR5 should be investigated, as well as possible effects coming from the electronics.

In order to further validate the method with the TCP scan and compare it with the TCT scan, the measurement was repeated for B1V. The resulting losses as function of the TCP setting are shown in the right part of Fig. 6. This measurement agreed also very well with the aperture found in the TCT scan. A TCP scan was attempted also in B2V, however, this measurement was inconclusive as too little intensity was lost in the excitations, which makes the normalization of the data too noisy. The results of the TCP scan are summarized in Table 1.

The aperture measurement data can also be used to extract the ratio of BLM signal, in Gy/s, to lost protons on the TCTs. This can be useful in several applications where it is

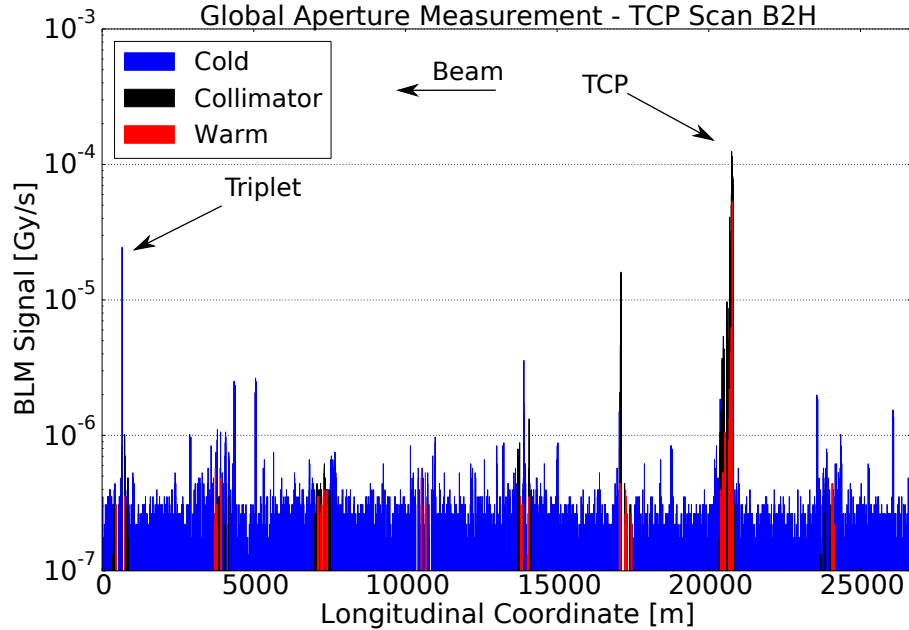


Figure 5: The loss distribution between IR7 and IR1 at the first step of the TCP scan in B2H, with the TCP at 8σ .

needed to estimate from the BLM signal the number of impacting protons, such as in the analysis of asynchronous beam dump data in MD 310 [12]. The reason is that the TCTs were the limiting bottleneck in the ring, while the beams were excited with the ADT to create losses. Averaging over the points with close TCT settings (to the left in Fig. 4), we extract an average BLM response of 2.1×10^{-11} Gy/p lost on the TCTs, with a standard deviation of about 70%.

4 Comparison with predicted aperture

The measured apertures presented in Table 1 can be compared to the theoretical estimates using either a scaling of previous aperture measurements as in Ref. [1], or using the MAD-X aperture module [13].

For the aperture scaling, we use as a starting point the interpolated apertures measured in collision at $\beta^*=80$ cm during the 2015 commissioning [14] and scale each plane individually by the theoretically expected change in beam size and add the theoretically expected change in orbit expressed in units of σ without any additional tolerances. We then compare with the interpolated values from our measurements at $\beta^*=40$ cm, shown in Table 1.

In MAD-X, we calculate the apertures in the crossing and separation planes with a more realistic set of tolerances than what was used during the LHC design stage, called Run I in Table 2 of Ref. [4]. We assume a 5% β -beat (translating into a 2.5% change of the beam size), 0.5 mm orbit shift, and no off-momentum component. This parameter set reproduced well the smallest measured aperture with $\beta^*=60$ cm in 2012 [4].

The comparison between the two calculation methods and the measurements is shown in Fig. 7. It should be noted that the aperture scaling gives an excellent agreement in

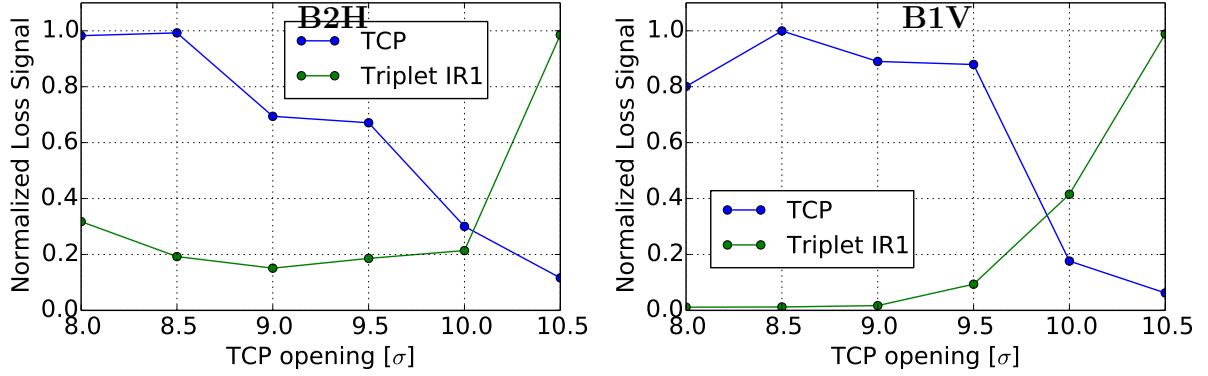


Figure 6: The measured losses at the limiting triplet aperture and the TCP, as a function of TCP setting, and normalized by both the intensity loss at each excitation and the highest loss measured at each element, for each beam and plane.

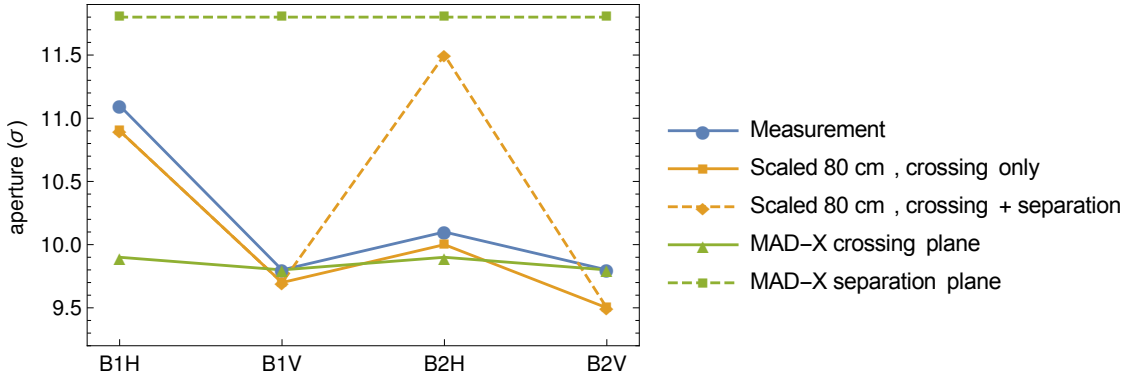


Figure 7: The measured aperture at $\beta^*=40\text{cm}$, from the interpolated values in Table 1, shown together with the scaled apertures from previous measurements at $\beta^*=80\text{ cm}$, as well as calculated values from MAD-X.

B1H, B1V, and B2V, where the maximum discrepancy is only 0.3σ . In all these cases, the bottleneck was found in the crossing plane (IR1 for vertical losses, IR5 for horizontal) at both $\beta^*=40\text{ cm}$ and $\beta^*=80\text{ cm}$. In B2H, the aperture bottleneck was instead found in the separation plane in IR1 at both values of β^* . This is not expected theoretically, where the crossing plane is expected to be limiting. If the aperture scaling is performed assuming that the bottleneck is indeed in the separation plane, thus applying the expected change of orbit and beam size in the horizontal plane in IR1, the estimated aperture at $\beta^*=40\text{ cm}$ is 1.5σ larger than what was measured (dashed yellow line in Fig. 1). If, on the other hand, we use the scaling in the crossing plane (solid yellow line), the agreement is again excellent.

The reason for these puzzling results is not well understood. It should be noted that the measurement in B2H was also the one that was showing issues during the TCT scan and thus had to be repeated using a TCP scan (see Sec. 3). One explanation could be the presence of a strong coupling, which would cause particle losses in the vertical or skew plane even though the initial ADT excitation was done in the horizontal plane. Indeed, the optics

Table 2: Collimator half opening, in units of σ with a normalized emittance of $3.5 \mu\text{m}$, at top energy and squeezed optics for the 2015 operational settings at $\beta^*=80$ cm, called “mm kept” and the settings used during the MD for the asynchronous dump test.

Collimators	2015 OP setting (σ)	MD setting (σ)
TCP IR7	5.5	5.5
TCS IR7	8.0	7.5
TCLA IR7	14.0	12.0
TCP IR3	15.0	15.0
TCS IR3	18.0	18.0
TCL IR3	20.0	20.0
TCT IR1,IR5	13.7	9.0
TCSP IR6	9.1	8.6
TCDQ IR6	9.1	8.6

measurements in B2 at $\beta^*=40$ cm showed a significant coupling source in IR1 [6]. This, in combination with the large betatron amplitudes that the particles reach, could cause the losses to have a vertical component. However, detailed quantitative studies are required to understand more in detail if the effect is strong enough.

An alternative explanation for the B2H result would be systematic differences in the BPM sensitivity between $\beta^*=40$ cm, where only pilot bunches were used and the BPMs therefore working at a different gain, and $\beta^*=80$ cm, where nominal bunches were used. Nevertheless, for the three other measurements, this effect seems to be negligible and the variation between the different beams and planes shows an excellent agreement. This could mean that the optics and closed orbit imperfections go in a similar direction in both configurations, or that the variations between planes and beams are driven more by the misalignment of the magnets. In any case, the overall agreement between the scaling method and the measurement is excellent and it successfully predicts the lowest apertures that are potentially limiting the reach in β^* .

The MAD-X results are shown in Fig. 7 both for the crossing and separation planes. No measured element misalignments were included. It is seen that, also for the $\beta^*=40$ cm configuration, the aperture model with the used parameter set gives an excellent estimate of the interpolated aperture without margins. With a momentum offset of 2×10^{-4} , MAD-X reproduces instead the conservative estimate from the TCT setting. Our studies gives another example that both the scaling method and MAD-X can be used to reliably predict the aperture in future configurations.

5 Asynchronous dump test

After the aperture measurements, at the end of the MD, an asynchronous dump test was performed in order to study the losses on the TCTs in a configuration with tight settings. For this test, all collimators that had been taken out for the aperture measurements were moved in again, in order to have the full collimation system in place. The deployed settings

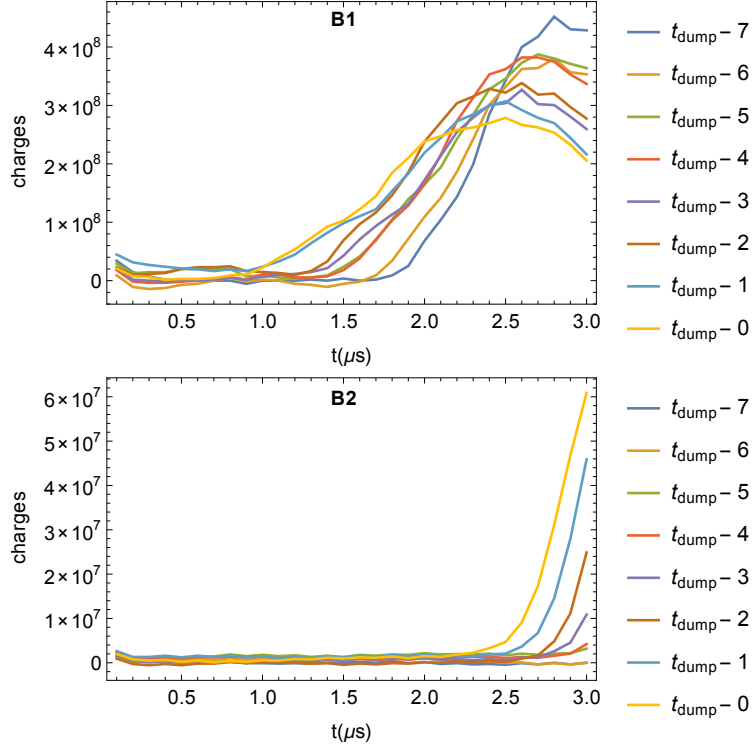


Figure 8: The longitudinal beam profile along the abort gap, as measured by the BSRA, during the seconds preceding the asynchronous dump test for B1 (top) and B2 (bottom). It can be seen that the population in B2 is significantly lower and that the B2 bunch enters the abort gap much later.

are shown in Table 2. IR7 was moved to the 2σ retraction settings. The TCTs were moved to 9σ , which is 0.5σ inside found aperture and close to the 8.8σ tentatively proposed earlier [2]. The standard orbit bump for asynchronous dump tests was introduced in IR6. It brings the beam 1.2 mm further away from the TCDQ and the relevant TCSP jaw. This corresponds to a loss of 2.4σ margin in IR6, which is larger than expected from optics correction and studies of orbit variations [15, 16].

In this configuration, the RF was turned off to make the beam debunch and drift longitudinally and the BSRA was used to monitor the abort gap population. A dump was triggered when a maximum abort gap population was estimated online. The integrated abort gap population was, at the moment of the dump, 4×10^9 protons in B1 and 3×10^8 protons in B2. The reason for this large asymmetry was the filling pattern, which had a bunch in bucket 1, next to the abort gap, in B1 but not in B2.

Fig. 8 shows the measured bunch profiles in the abort gap at different times up to the dump. It can be seen how the bunch enters the abort gap from the right (bucket 1) and moves to the left at the same time as it spreads out. Unfortunately, at the time of the dump, the core of the bunch was still in the right part of the window. This means that very few particles entered the region where losses on the TCTs could be expected, which is in the left part of the window.

This is illustrated in more detail in Fig. 9, which shows the abort gap population at the

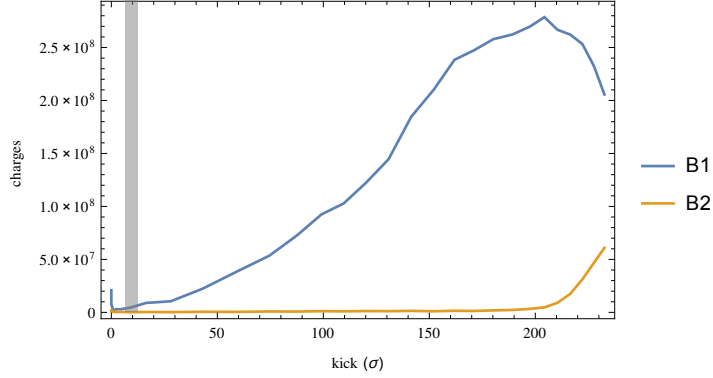


Figure 9: The longitudinal beam profiles along the abort gap, as measured by the BSRA, at the second of the asynchronous dump test for both beams. The abort gap population is given as a function of total kick in σ , summed over all MKDs, and assuming that all kickers fire at the same time with the ideal waveform. The gray band indicates the region where particles could end up at the TCTs.

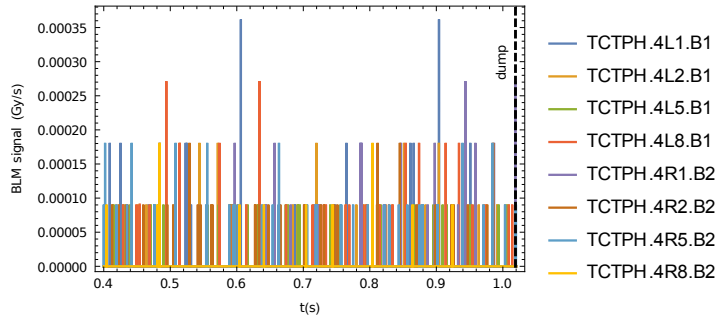


Figure 10: The BLM signals at all TCTs, as a function of time, up to the asynchronous beam dump test. As can be seen, all BLMs are dominated by noise and no particular signal above the noise is noticed at the time of the dump.

time of the dump in B1 and B2. In this figure, the horizontal axis has been scaled by the expected normalized kick in σ as a function of time in the abort gap, assuming the ideal MKD kicker waveform and that all kickers fire simultaneously. The gray band indicates the range 6–12 σ that could potentially cause impacts on the TCTs. As can be seen, it is only a small fraction of the abort gap. Figs. 8 and 9 show that if we had waited a bit longer, the particles would have drifted more to the left and we would have had a higher population in the gray band and thus better resolution of the losses on the TCTs.

Unfortunately, the BLM data at the TCTs from the asynchronous beam dump test were within the noise of the monitors, which can be understood from the fact that only pilot bunches were used, and the abort gap population in Fig. 9. One example of this is shown in Fig. 10, which shows the BLM signals at the TCTs as function of time up to the dump. As can be seen, no spike above noise level is observed at the TCT at the time of the dump. Therefore, these data cannot be used to extrapolate whether a beam dump with a full machine is safe in the same configuration.

6 Conclusions and outlook

We have shown the results of MD 307, where the global aperture was measured with IR1 and IR5 squeezed to $\beta^*=40$ cm and with a half crossing angle of $205 \mu\text{rad}$. The smallest measured aperture is about 9.5σ and was found in the vertical plane. This agrees well with predictions. Slightly larger apertures were found in the horizontal plane. In general, the results confirm the theoretical models and do not pose any showstopper for operation at $\beta^*=40$ cm, provided that the general philosophy for collimation margins outlined in Ref. [2] is adopted and assuming that the same optics and orbit control can be achieved.

In B2H, the first measurement with a TCT scan was inconclusive, since the triplet gave the highest BLM signal already at the smallest TCT setting. This was suspected to be caused by showers, since the BLM ratio between TCT and triplet did not change until the TCT reached 10.5σ . This measurement was repeated with a TCP scan, which confirmed an aperture between 10σ and 10.5σ .

Scaling the aperture found in each plane at $\beta^*=80$ cm to the used machine configuration, an excellent agreement within 0.3σ is found in three cases out of four. In B2H, the bottleneck was found in the separation plane in IR1. In this assumption, the scaling yields a discrepancy of 1.5σ , however, an agreement of 0.2σ is found if the scaling of the crossing plane is used. This is not well understood, but it could be that the significant coupling source found in Ref. [6] at IR1, B2, causes skew losses, or that the orbit was not as well corrected for this beam and plane.

The asynchronous beam dump test at the end of the MD did not show any unexpectedly high losses, however, only minor losses were intercepted by the TCTs, so that their BLMs did not exceed the noise level. Therefore, we cannot conclude on the overall safety for the TCTs at $\beta^*=40$ cm from these measurements. It should be noted that the asynchronous beam dump test in MD 307 [12], where nominal bunches were used, produced TCT BLM signals well above the noise level.

7 Acknowledgments

We would like to thank J. Uythoven, M. Fraser and C. Bracco for discussions of the asynchronous dump and the OP shift crew for their assistance during the MD.

References

- [1] R. Bruce, R. W. Assmann, and S. Redaelli. Calculations of safe collimator settings and β^* at the CERN Large Hadron Collider. *Phys. Rev. ST Accel. Beams*, 18:061001, Jun 2015.
- [2] R. Bruce. Update on possibilities to reach $\beta^*=40\text{cm}$. *presentation in the LHC Collimation Working Group, 2015.01.19*, 2015.
- [3] R. Bruce and R.W. Assmann. LHC β^* -reach in 2012. *Proceedings of the 2011 LHC beam operation workshop, Evian, France*, 2011.

- [4] R. Bruce, R. de Maria, S. Fartoukh, M. Giovannozzi, S. Redaelli, R. Tomas, and J. Wenninger. Parameters for HL-LHC aperture calculations. *CERN Report CERN-ACC-2014-0044*, 2014.
- [5] LHC morning meeting, August 28, 2015. https://indico.cern.ch/event/437959/contribution/4/attachments/1145995/1643030/LHCmorning_meeting_20150828.pdf, 2015.
- [6] A. Langner, F. Carlier, J. Coello de Portugal, A. Garcia-Tabares Valdivieso, E.H. Maclean, L. Malina, T.H.B. Persson, S. Mönig, B. Salvachua Ferrando, P. Skowronski, R. Tomas, and J. Wenninger. LHC optics commissioning with $\beta^* = 40$ cm and 60 cm. *CERN-MD-Note-2015-?*, 2015.
- [7] T. Pieloni, X. Buffat, D Banfi, J. Barranco, G. Arduini, E. Metral, N. Mounet, S. M. White, and J. Qiang. Two beam effects. *Proceedings of the 5th Evian Workshop, Evian, France*, 2014.
- [8] R. Bruce, G. Arduini, S. Fartoukh, M. Giovannozzi, M. Lamont, E. Metral, T. Pieloni, S. Redaelli, and J. Wenninger. Baseline LHC machine parameters and configuration of the 2015 proton run. *Proceedings of the LHC Performance Workshop (Chamonix 2014), Chamonix, France*, 2014.
- [9] R.W. Assmann, R. Bruce, M. del Carmen Alabau, M. Giovannozzi, G.J. Mueller, S. Redaelli, F. Schmidt, R. Tomas, J. Wenninger, and D. Wollmann. Aperture Determination in the LHC Based on an Emittance Blowup Technique with Collimator Position Scan. *Proceedings of IPAC'11, San Sebastian, Spain*, page 1810, 2011.
- [10] R. Bruce and E. Skordis. Predictive power of SixTrack+FLUKA: Comparison between simulated and measured loss maps. *presentation in the LHC Collimation Working Group, 2013.05.06*, 2013.
- [11] E. Skordis *et al.* Updates on FLUKA simulations of the 4 TeV quench test. *presentation in the LHC Collimation Working Group, 2014.10.06*, 2014.
- [12] R. Bruce, H. Garcia, P. Hermes, R. Kwee-Hinzmann, A. Mereghetti, D. Mirarchi, E. Quaranta, S. Redaelli, and A. Valloni. Collimation with tighter TCTs at $\beta^*=40$ cm. *CERN-ACC-NOTE-2015-0036*, 2015.
- [13] MAD-X program. <http://cern.ch/mad/>.
- [14] P. Hermes *et al.* Status of aperture measurements. *presentation in the LHC Collimation Working Group, 2015.06.08*, 2015.
- [15] R. Bruce. Status of collimation analysis for $\beta^*=40$ cm. *presentation in the LHC Collimation Working Group, 2015.10.05*, 2015.
- [16] G. Valentino and A. Valloni. Analysis of collimator BPMs during the machine cycle. *presentation in the LHC Collimation Working Group, 2015.10.05*, 2015.