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MD2191 – β^*–Reach: 2017 IR7 Collimation Hierarchy Limit and Impedance

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Summary

This report summarises the results of MD2191 about the hierarchy limit of the LHC collimation system in IR7 at 6.5 TeV and its impedance. The activity was carried out during MD block 3 of 2017, on the night between 17$^{\text{th}}$ and 18$^{\text{th}}$ September. Measurements were performed mainly on B1, as B2 was dedicated to the follow–up of the impedance measurements of the TCSPM.D4R7.B2 of MD2193 (hence they are not reported here). The hierarchy breakage seen in B1V loss maps in similar activities in 2015 and 2016 when deploying 1 σ–retractions between TCSG and TCP collimators was confirmed. The source, i.e. a possible tank misalignment angle of the TCSG.D4L7.B1 collimator, and its cure, i.e. to compensate the misalignment angle with a suitable tilt of the jaws of the same collimator, was confirmed as well, though not as clearly as it happened in the past; tune shift measurements were mainly devoted to measuring the impact on impedance by applying the compensation angle. The MD activity included a re–alignment of all the IR7 collimators of B1 to the beam. A further verification of the B1V hierarchy breakage and its mitigation was carried out at the end of MD block 4 of 2017, on the night between the 1$^{\text{st}}$ and 2$^{\text{nd}}$ December, after MD2733. The check is reported here as well for completeness, also because it shows the stability of the origin of the hierarchy breakage and, most importantly, of its solution, confirming the possibility of performing only one angular alignment per year in case of pushing the hierarchy. The MD activity is important for understanding the limitations from impedance and from operational margins; these limitations have direct impact on the choice of the collimation configuration kept during operation, especially in the case of a pushed performance (e.g. when deploying TCSG–TCP retractions in IR7 smaller than those used in operation).

Table 1: Collimator settings in IR7 deployed during operation in 2015, 2016 and 2017 at flat top (i.e. 6.5 TeV, in black), along with those tested in MDs (in blue) during MD314, MD1447 and in the present MD. Settings of the IR3 and IR6 collimators and of the TCTs are reported as well, for the sake of completeness. All settings take into account a normalised emittance of 3.5 μm.

	family	2015 [σ]	2016 [σ]	2017 [σ]
IR7	TCP	5.5		5
	TCSG	8 (7.5,6.5)	7.5 (6.5)	6.5 (6,5.5)
	TCLA	14 (10)	11	10
IR1/2/5/8	TCT	37	23/37/23/23	15/37/15/15
IR3	TCP / TCSG / TCLA	15 / 18 / 20		
IR6	TCDQ / TCSG	9.1 / 9.1	8.3 / 8.3	7.4 / 7.4

1 Introduction

The LHC collimation system installed in IR7 is responsible for cleaning betatron tails. It is composed by a large number of two–sided collimators, organised in hierarchical families with very well defined roles. Respecting the hierarchy is key to guarantee the optimal performance of the system.

In order to push performance while accommodating the β^*-reach of the LHC in Run 2 and beyond, it is necessary to tighten the collimator settings. Immediate consequences are the reduction of the operational margins, that are at the basis of the respect of the hierarchy, and the increase of the contribution of the collimation system to the LHC impedance budget [1].

Therefore, it is essential to characterise the tightest settings that can be safely deployed without breaking the IR7 collimator hierarchy. MD activities like that reported here are very important also for Run 2 and Run 3 performance, since they allow to establish the minimum hierarchy that can be achieved with only one alignment per year, and to define the operational configuration of the machine.

In addition, the HL–LHC project [2] foresees to almost double the bunch intensity. This requires an improved performance of the collimation system in terms of cleaning inefficiency and implies an increased contribution to the LHC impedance budget if the present system is deployed. Hence, an intense R&D program has been launched [3, 4, 5, 6], to identify jaw materials with low impedance capable of standing the higher damage potential of HL–LHC beams, to replace the existing primary and secondary collimator families.

During Run 2, MD activities on hierarchy limit and impedance have been carried out regularly, e.g. MD314 (2015) [7] and MD1447 (2016) [8], and the one presented here is their follow–up. In particular, past measurements showed that the collimation hierarchy in IR7 is broken on only B1V when deploying 1 σ–retractions between primary (TCP) and secondary (TCSG) collimators. The origin of the breakage has been traced back to a possible misalignment angle of the tank of the TCSG.D4L7.B1, which propagates also to the collimator jaws; the regular hierarchy can be restored compensating the misalignment angle with an appropriate tilt of the jaws of the concerned collimator. The order of magnitude of the misalignment angle of the concerned collimator is comparable to that of other collimators, but the small beam size locally found implies a sizeable deeper cut into the beam, at the point that the collimator becomes the primary bottleneck.

Impedance–wise, it is necessary to benchmark the impedance model against precise mea-

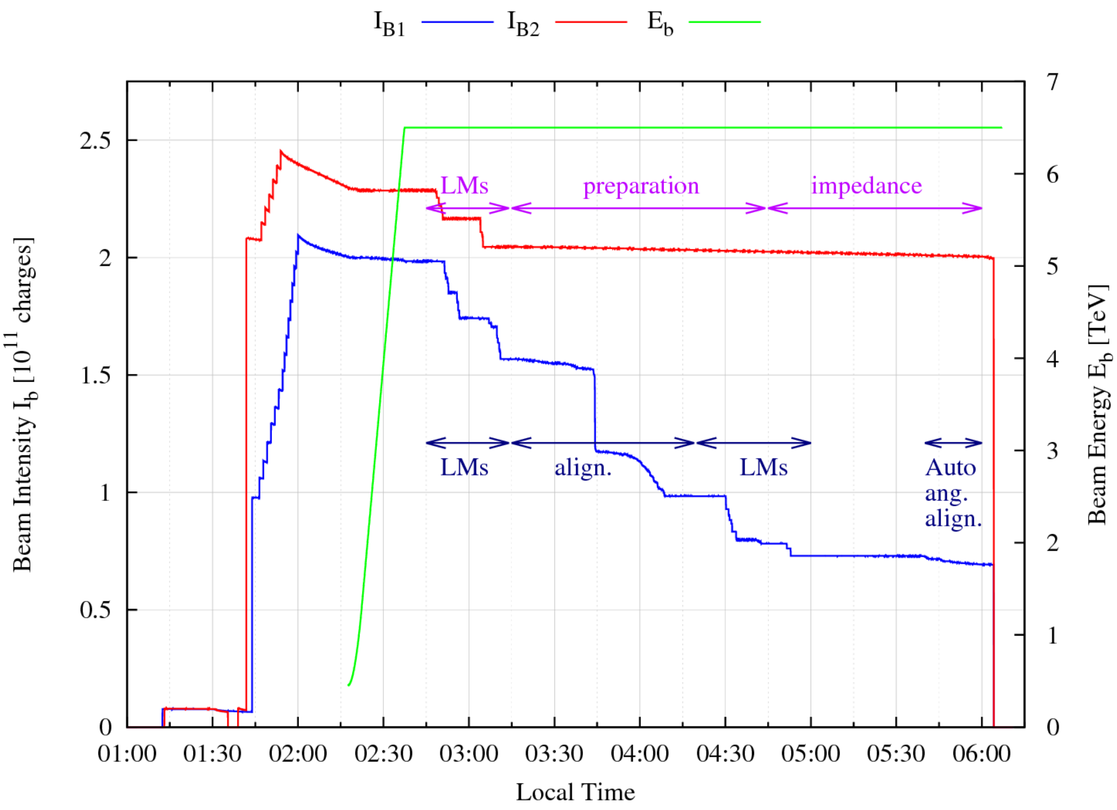

Figure 1: Intensity of B1 (blue curve) and B2 (red curve) as read by the fast beam current transformer (BCTFR), and beam energy (green curve) during the presented MD activity. The time periods of the main activities carried out are highlighted for each beam; for B1: loss maps ("LMs"), IR7 collimator alignment ("align."), automatic angular alignment of selected collimators ("Auto ang. align."); for B2: loss maps ("LMs"), preparation to impedance measurements with the TCSPM prototype collimator ("preparation"), and actual impedance measurements ("impedance"). Details and results about the activity on the TCSPM prototype are reported in Ref. [11], whereas those about the automatic angular alignment of selected collimators are reported in Ref. [14].

surements, either involving entire families of collimators or single devices. MD314 and MD1447 explored the implications of tightening the collimation hierarchy not only in terms of stability of alignment and of performance of the system, but also in terms of impedance; the focus was mainly on the entire family of IR7 TCSGs. Table 1 compares the settings deployed during operation at flat top (FT, i.e. 6.5 TeV) in 2015, 2016 and 2017, along with those tested in the hierarchy limit MD activities carried out in the same years. Another set of MD activities were carried out in recent years, specifically measuring single collimator impedances, e.g. MD1446 [9], dedicated to TCPs, MD1875 [10], dedicated to IR7 TCSGs, and MD2193 [11], dedicated to the prototype of low–impedance collimator TCSPM.D4R7.B2 [12].

2 Procedure and Beam Conditions

The MD activity was carried out on the night between 16th and 17th September [13], at 6.5 TeV. The optics at flat top was used, at the end of the "combined ramp and squeeze" beam process, i.e. with no tune change and without squeezing beams down to a β^* of 40 cm or 30 cm but remaining at 1 m, or collapsing the bumps for parallel separation at the interaction points (IPs), since the settings of the IR7 collimators do not change throughout these machine configurations. Figure 1 shows the time evolution of beam energy and current, with labels indicating the main activities during the MD.

The MD activity started two hours after the planned time, letting other collimation studies carried out just before to come to a conclusion (namely: MD2504 [14], on automatic angular alignment at injection energy, and MD2167 [15], on resonant excitation); hence, only 5 h out of the 7 originally planned were used. Moreover, since the hierarchy breakage seen in the past was only on B1V, it was agreed to dedicate B2 to continue the impedance measurements on the TCSPM.D4R7.B2, i.e. the prototype of low-impedance collimator (please see ref. [11] for the collected results); anyway, prior to the impedance measurements, betatron loss maps were performed, to verify that no new hierarchy breakage, not seen in the past, appeared on B2. In addition, the last ∼20 minutes were dedicated to automatic angular alignment; since these measurements complement those carried out at injection during MD2504, results are reported in the respective note (see Ref. [14]). Therefore, in the following, only the activity carried out on B1 will be described, with the exception of B2 loss maps prior to the TCSPM.D4R7.B2 impedance measurements.

The filling scheme named as "30 Bunches for MUFO spaced" was used. B1 was filled with a nominal bunch and a train of single pilot bunches, so as to respect the limit set by the "set up beam flag" (i.e. 3×10^{11} at flat top energy), in order to be able to mask interlocks unnecessary to the activity carried out, like collimator movements, beam loss monitors (BLMs), etc... The nominal bunch was required for a more reliable readout of the closed orbit and for clean tune shift measurements, whereas the train of pilots was required to face the potentially large number of loss maps. The drop down in B1 current visible at ∼03:45 was due to a B1H instability, taking place during the alignment of the IR7 collimation system of B1. Similarly to B1, B2 was filled with a nominal bunch but with high intensity ($\sim 1.9 \times 10^{11}$ protons), and few pilot bunches for the loss maps.

The MD activity was divided in two parts, i.e. IR7 collimator hierarchy limit and alignment as first, and impedance measurements as second. The latter is focused only on the tune shift measurements of the TCSG.D4L7.B1 with and without the tilt angle applied to its jaws (to compensate for the tank misalignment angle), and hence appreciate its consequences on impedance.

3 Overview of IR7 Collimator Hierarchy Limit and Alignment

As done in past MD activities of the same kind, betatron loss maps for increasingly pushed collimator settings were performed before and after the re–alignment to the beam of the IR7 collimators. The aim is not only to assess any possible benefit on performance of pushed collimator settings from re–alignment, but also to verify the stability of the performance of the collimation system and trap any possible degradation with time.

A first set of betatron loss maps was carried out with the 2017 operational gaps of the IR7 TCSGs (see Tab. 1), as reference (see Figs. A.1 and A.2). In this configuration, the TCSGs are retracted by 1.5 σ from the TCPs. Patterns are similar to those found during the initial commissioning with beam in 2017 [16], and values of cleaning inefficiency agree within 10–20 %.

Afterwards, the gaps were reduced to the configuration that in past activities was showing the hierarchy breakage, i.e. 1 σ–retraction, with TCSGs at 6 σ (see Figs. A.3 and A.4). Very weak signs of a hierarchy breakage are visible on B1V, not as clear as in the past [7, 8]. The hierarchy breakage was convincingly found on B1V when the TCSG–TCP retraction was pushed to 0.5 σ (see Fig. A.5), even though such small retractions are unlikely to be deployed.

Figure 2 shows the overview of the maximum local cleaning inefficiency in the dispersion suppressor (DS) downstream of the IR7 collimation system as a function of TCSG settings,

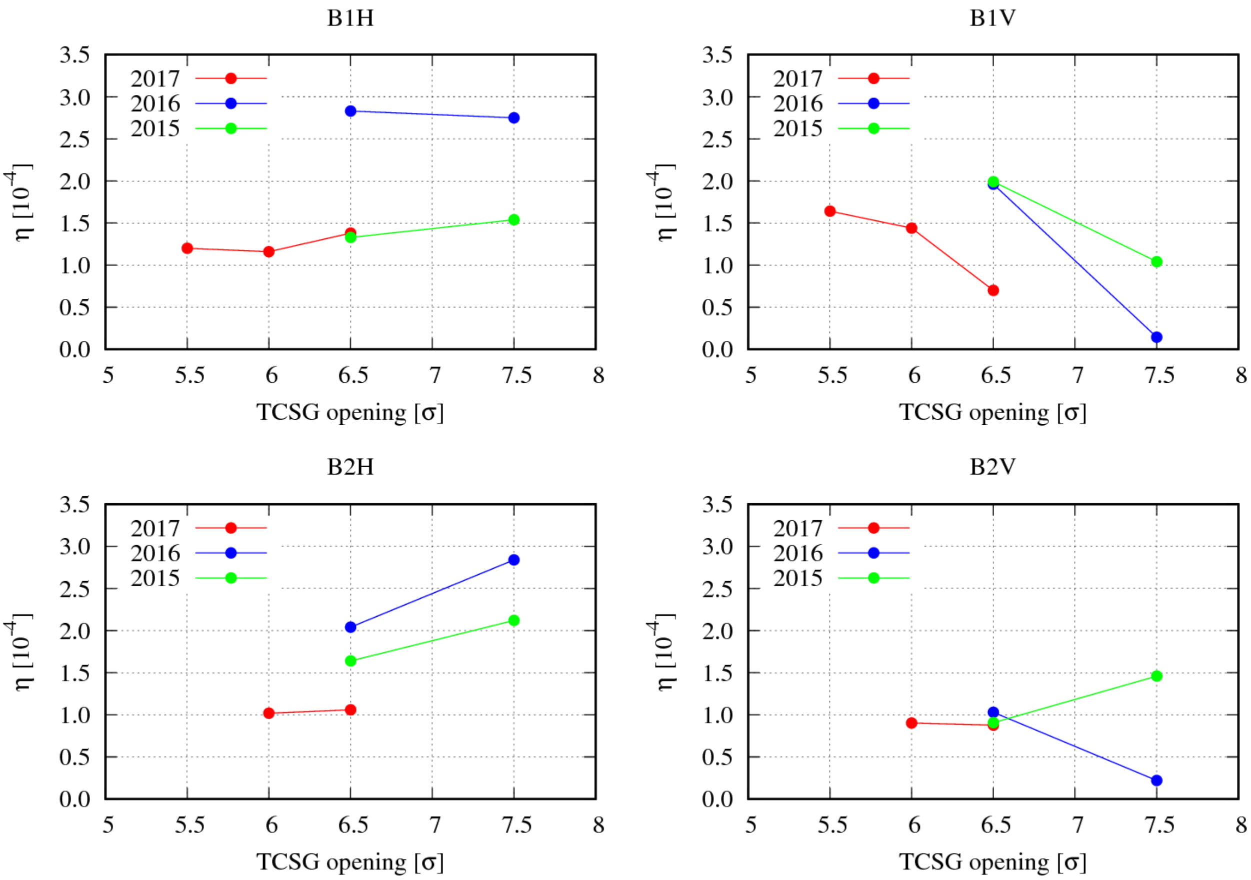

Figure 2: Overview of maximum local cleaning inefficiency in the DS downstream of the IR7 collimation system as a function of TCSG settings, for selected configurations explored in MDs in the last three years of Run 2. The shown configurations of 2015 and 2017 foresee TCLA collimators at 10 σ, whereas that of 2016 foresees TCLA collimators at 11 σ (see Tab. 1). The shown data have been taken before re–aligning the collimators to the beam.

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[1]This hypothesis is enforced by the fact that there is ~90° phase advance between the central part of the TCSGs and Q7; moreover, almost all the planes are affected by this behavior when the TCSG–TCP retractions are pushed. Moreover, BPM readouts show some degradation of the closed orbit, but at most by ~100 μm and not affecting B1 and B2 the same way at the same time.

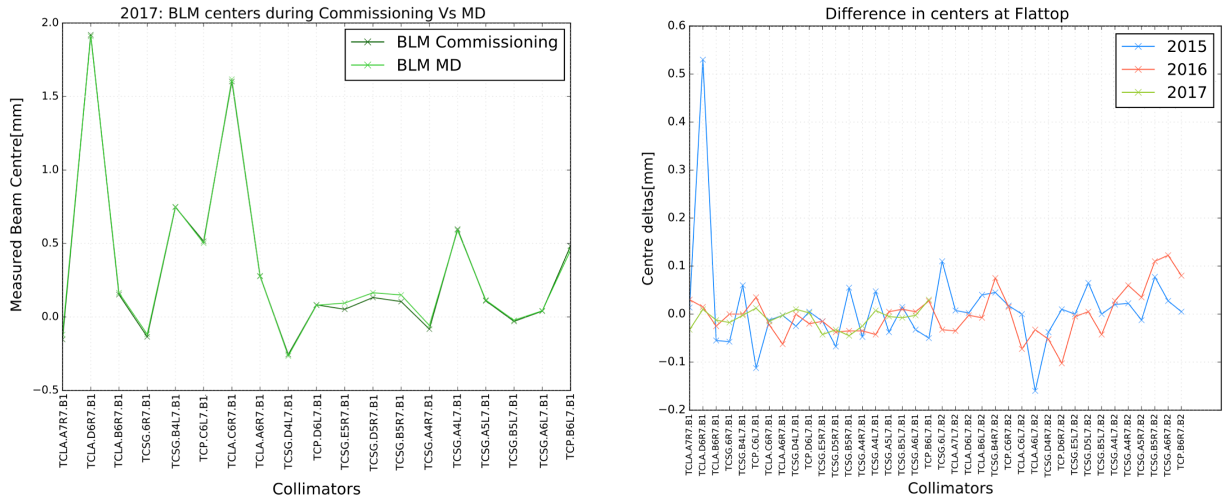

Figure 3: Left frame: IR7 collimator centres as from the alignment campaign carried out during this MD activity and as from initial commissioning with beam in 2017. Right frame: drifts of IR7 collimator centres as measured in MDs and from the initial commissioning with beam of 2015, 2016 and 2017.

in the past.

All IR7 collimators of B1 were then re–aligned to the beam, to verify alignment stability and test more sophisticated alignment procedures [14]. The alignment took 50 minutes, as in 2015, when the IR7 collimator alignment proceeded on each beam, independently and in parallel. Figure 3, left frame, shows the comparison between collimator centres as measured during the MD activity and at the initial commissioning with beam. Figure 3, right frame, shows the drifts of the collimator centres between MD and initial commissioning of 2015, 2016 and 2017; shifts are well below 100 μm for most of the collimators, and this level of reproducibility, the same in the last three years of Run 2, can be regarded as satisfactory. During the alignment, an important instability was observed on B1H only, with a sizeable decrease of the beam intensity, which did not prevent the alignment from being completed.

Betatron loss maps with 1 σ–retractions were carried out deploying the beam–based centres just found during the alignment, to confirm that the hierarchy breakage is not due to a possible degradation of the collimator alignment over the year, as seen in past MD activities. Contrary to expectations, no sign of hierarchy breakage was found in the loss maps (see Fig. A.6); anyway, the tank misalignment angle of the TCSG.DL7.B1, in the past identified to be at the origin of the hierarchy breakage, was measured with the method of angular alignment at maximum angles[2] (see ref. [14]) at -400 μrad. Once applied to the jaws, the pattern of the loss map and the local cleaning inefficiency in the downstream DS got improved (see Fig. A.7).

The reason for the absence of the hierarchy breakage after alignment was not found during the MD activity. Off–line analysis shows that the closed orbit was changing during the MD activity (see Fig. 4); contrary to the MD activity of last year [8], there is no convincing indication from the BPM signals on B1V on the reason why the breakage was no longer visible after alignment.

Nevertheless, the B1H instability took place before aligning the TCSG.D4L7.B1 to the

[2]With this method, the position of the beam at the upstream and downstream corners of the collimator is found aligning the two jaws with a big diverging and converging angle, respectively. The tank misalignment angle is then found by simple trigonometry.

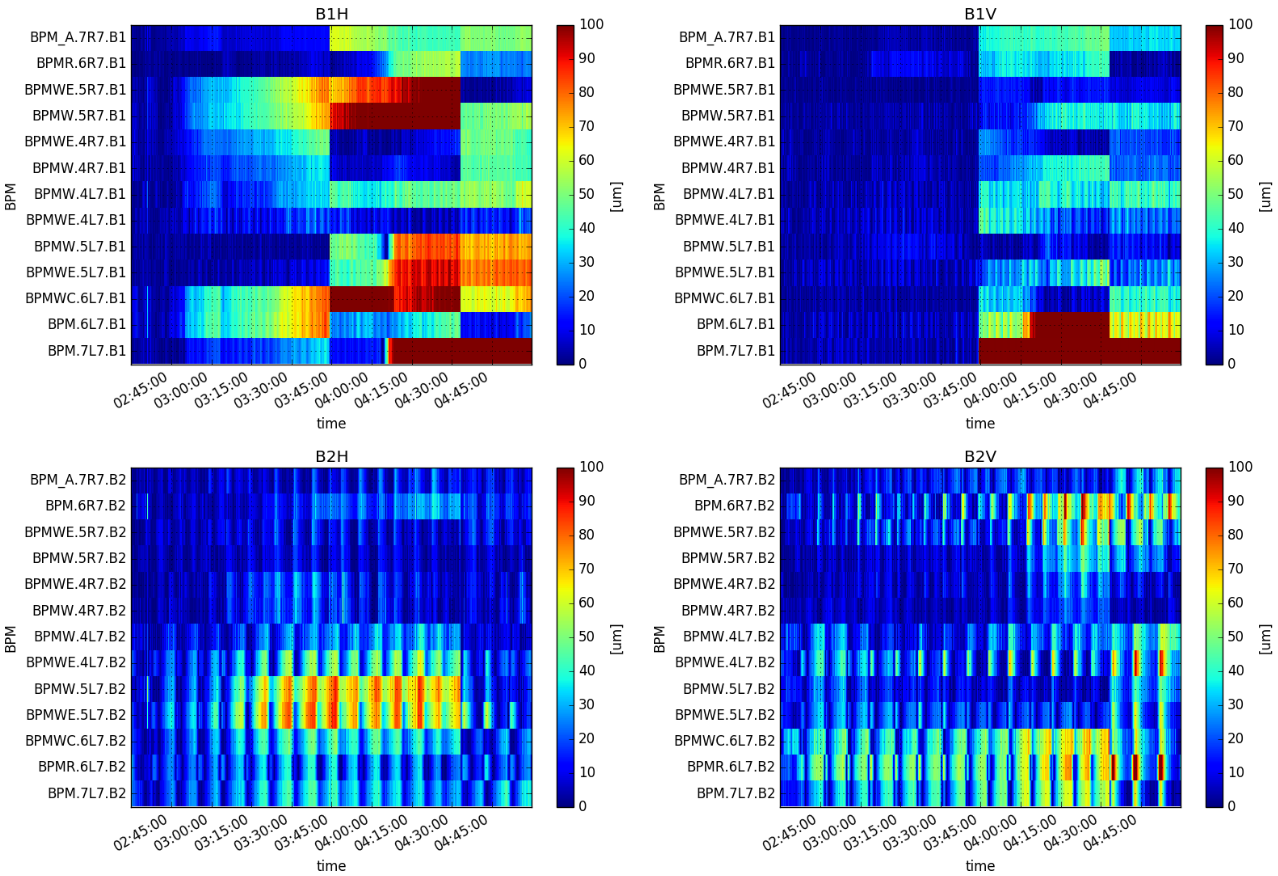

Figure 4: Readouts of IR7 BPMs throughout most of the MD activity; for the sake of clarity, the absolute value of the shift with respect to the readout after the end of the ramp ($\sim$02:45) is actually shown. Upper frames: B1; lower frames: B2. Left frames: horizontal plane; right frames: vertical plane. To be noted the sharp change in the color maps at $\sim$03:45, corresponding to the time when a B1H instability arose.

beam but after the alignment of the TCP.D6L7.B1 (see Fig. 5). Therefore, the vertical shift of the orbit induced by the B1H instability (i.e. 40–50μm, see Fig. 4, BPMWC.C6L7.B1 and BPMWE.5L7.B1 for the TCP, and BPMWE.4L7.B1 and BPMW.4L7.B1 for the TCSG) was taken into account when aligning the TCSG but not the TCP, resulting in a smaller effective cut of the TCP by $\sim$0.25 σ[3], possibly restoring the correct IR7 collimator hierarchy on B1V.

3.1 Additional Measurements on 2nd December 2017

A further verification of the B1V hierarchy breakage and its mitigation was carried out at the end of MD block 4 of 2017, on the night between the 1st and 2nd December [17], after MD2733. On that occasion, a couple of B1V loss maps were taken with 1 σ retractions (i.e. with 5/6/10 σ as TCP/TCSG/TCLA settings, see Tab. 1), one with the IR7 collimation system as it is and another one applying a tilt to the jaws of the TCSG.D4L7.B1 collimator to compensate for the tank misalignment angle (see Figs. A.8); the value of 350 μrad, found back during commissioning activities in 2016 [8, 18], was used. The hierarchy breakage on B1V was confirmed, after a full year from the alignment carried out during the initial commissioning with beam; more importantly, measurements proved the stability of the mitigation strategy, by applying a

[3]It should be noted that σ $\sim$200 μm at 6.5 TeV at the TCP.D6L7.B1, for a normalised emittance of 3.5 μm.

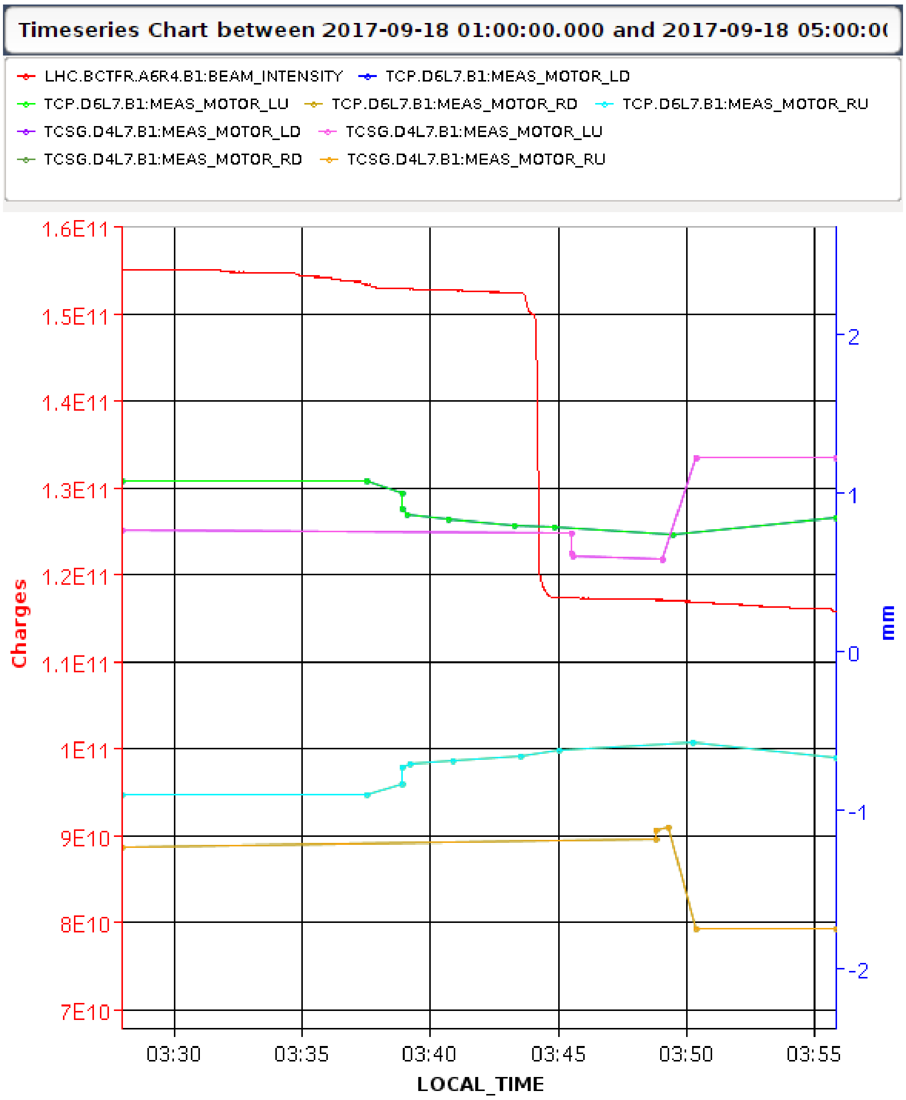

Figure 5: Timing of alignment of the TCP.D6L1.B1 and TCSG.D4L7.B1 collimators (i.e. IR7 vertical TCP and TCSG collimators) along with B1 intensity.

compensation angle as tilt of the jaws, the value of which was found more than 1.5 years before.

4 Impedance Measurements

As done in previous MDs [8, 9, 10, 11], the impedance measurements were performed by coherently kicking the beam with the transverse damper (ADT) in AC-dipole mode [19] while varying the gap of the collimator under measurement. The measurement procedure is described in detail in [11]. In this MD the studies were focused on the effect of collimator alignment of a secondary collimator TCSG.D4L7.B1 on its impedance.

The measurement was performed by exciting a single bunch of 0.5×10^{11} protons in B1 in the vertical plane and measuring the vertical tune shift between two collimator positions: "closed", i.e. with a half gap of 6 σ, and "open", with a half gap of 20 σ. Two collimator alignment configurations were studied: one with the jaws aligned with respect to the machine and the other one with the jaws tilted and aligned with respect to the beam, compensating for the tank misalignment angle of 400 μrad. The data were taken for about three minutes per collimator position per tilt angle, yielding sufficiently large datasets of roughly 100 points

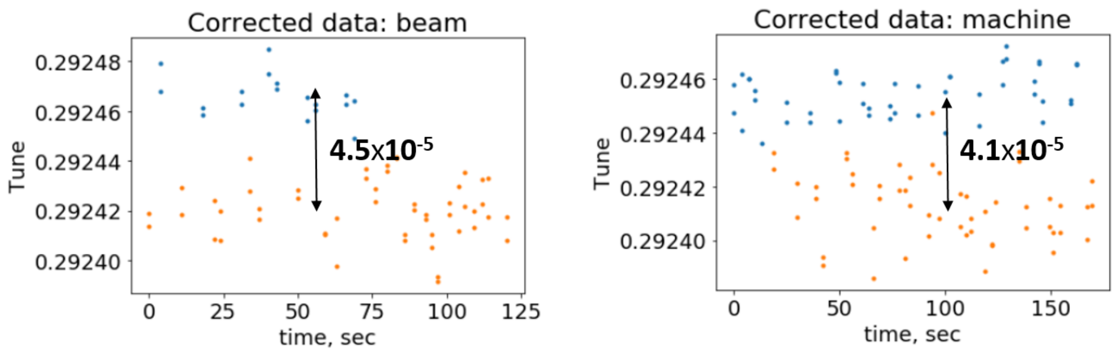

Figure 6: No significant difference can be observed between the collimator aligned with respect to the beam (left) and the machine (right). Vertical tune shift measured for two collimator openings: 6σ (blue dots) and 20σ (yellow dots). $E = 6.5$ TeV, $N_b = 5 \times 10^{10}$ p, $Q' = 15$, $\sigma_z = 8.1$ cm.

per study case; some of the points contained bad data and were later filtered out during the analysis and post–processing. Similar to the previous studies [11], the tune drifted significantly during the measurements. A large number of obtained data points allowed correcting for the tune drift and clearly separating the tunes at the two collimator positions (Fig. 6).

In order to quantify the effect of the misalignment we compared the tune shifts measured for different alignment set–ups with those predicted by the IW2D [20] impedance model, which does not take the tilt into account. The model was computed for the actual beam, optics, and collimator settings used in the MD. The calculation yields a tune shift of 3.7×10^{-5} for both alignment setups. The measured values of $4.5 \pm 1.4 \times 10^{-5}$ for the alignment with the beam and $4.1 \pm 1.5 \times 10^{-5}$ for the alignment with the machine both agree with the model prediction and are basically equal within the uncertainty of the experiment (Fig. 6). Thus, for the operational settings the tilt of the collimator jaws does not lead to a significant change of its impedance.

5 Conclusions

5.1 Hierarchy limit

The IR7 collimation system was qualified in terms of local cleaning inefficiency in the downstream DS with 2017 operational settings, and with 1 and 0.5 σ-retractions between TCP and TCSG collimators, hence smaller than those deployed operationally. Findings of past year measurements were confirmed, i.e. the IR7 hierarchy is broken only on B1V when so small retractions are deployed.

The system was fully aligned in 50 minutes (as in 2015); the alignment proved to be very stable, with re–measured centres off those from the initial commissioning with beam by well within 100 μm and not in a preferential direction.

After alignment, the breakage was no longer visible; the reason is not fully understood, but it is very likely connected to the distortion experienced by the closed orbit as a consequence of a B1H instability which took place when aligning the vertical IR7 collimators. The tank misalignment angle of TCSG.D4L7.B1 was compensated by applying the measured angle as tilt of the jaws, and the B1V loss map got better.

An additional set of B1V loss maps was carried out at the end of MD block 4 of 2017, with 1 σ retractions. The loss maps showed the stability of the issue with the IR7 collimation hierarchy and how important it is to compensate for the misalignment tank angle of the TCSG.D4L7.B1 to restore the correct hierarchy on B1V.

5.2 Impedance Measurements

Challenging measurement of tune shift induced by the single TCSG.D4L7.B1 collimator at flat top were carried out. The impedance measurements were performed by coherently kicking the beam with the ADT in AC–dipole mode while varying the gap of the collimator during the measurement. The studies were focused on the effect on impedance from tilting the jaws of the TCSG.D4L7.B1 collimator of about 400 μrad for compensating the tank misalignment angle. No significant impact of the tilt on the collimator impedance has been observed for the studied operational settings. The measured values of tune shift agree with the impedance model predictions within the uncertainties of the measurement. If needed, the precision of the measurement can be improved if the test is repeated at a higher intensity and a tighter collimator gap.

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A Loss Maps

The present Appendix collects all the LMs quoted but not shown in the main body of the text for the sake of clarity.

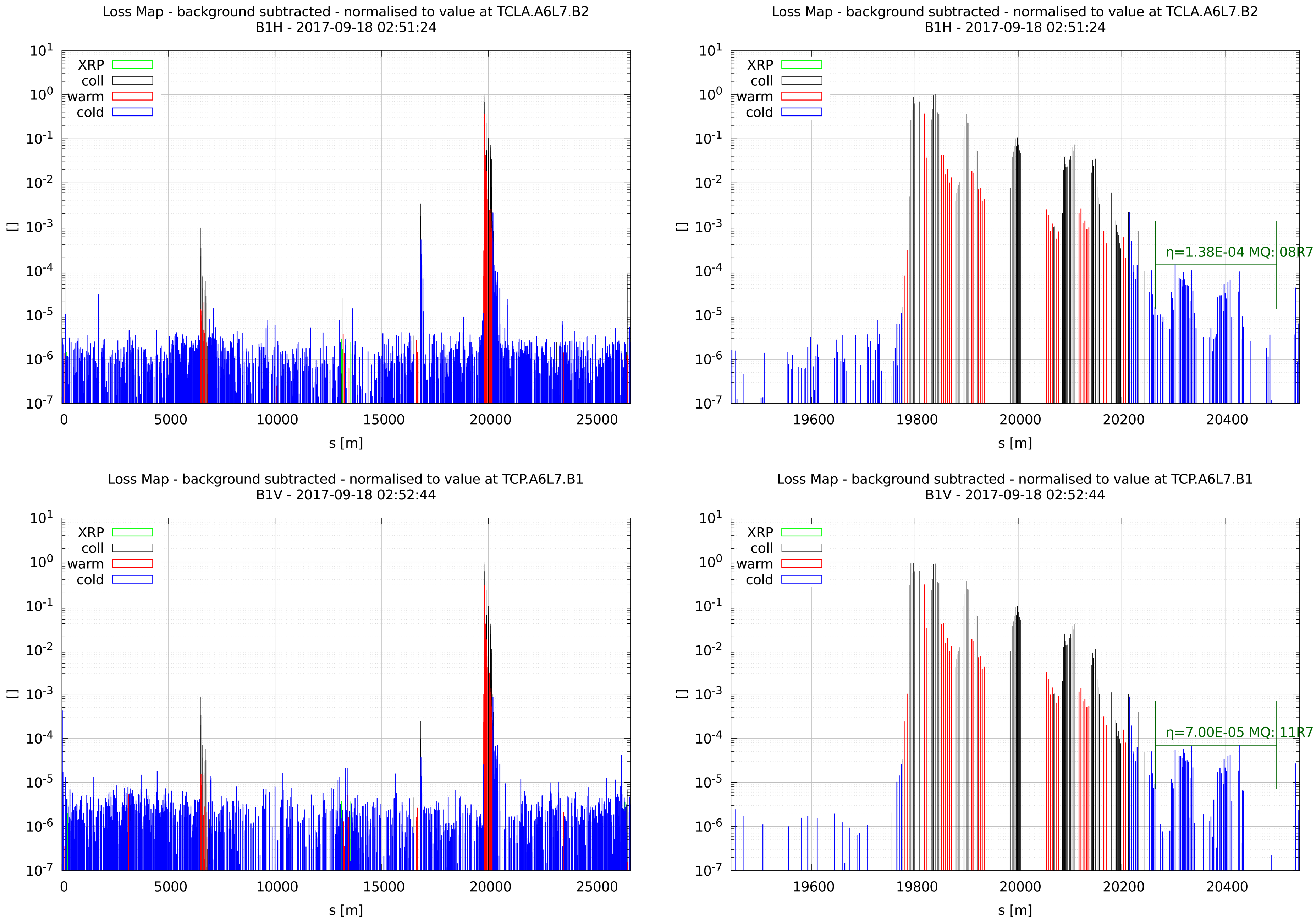


Figure A.1: B1H (upper frames) and B1V (lower frames) qualification loss maps with 1.5 σ–retraction (i.e. TCPs/TCSGs/TCLAs at 5/6.5/10 σ, i.e. the 2017 operational settings, see Tab. 1) before alignment: overview on the entire LHC (left frames) and zoom on IR7 (right frames).

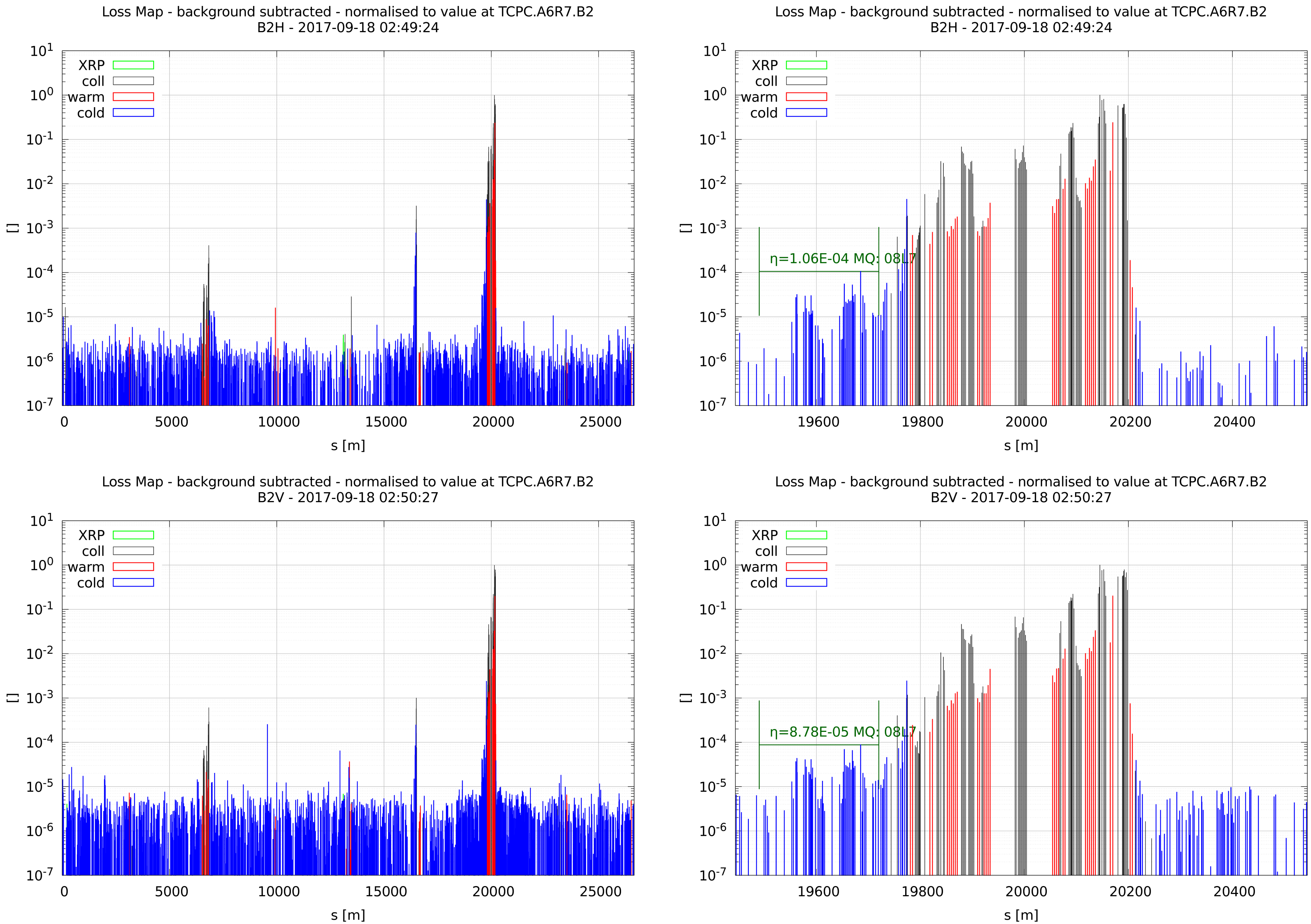


Figure A.2: B2H (upper frames) and B2V (lower frames) qualification loss maps with 1.5 σ–retraction (i.e. TCPs/TCSGs/TCLAs at 5/6.5/10 σ, i.e. the 2017 operational settings, see Tab. 1) before alignment: overview on the entire LHC (left frames) and zoom on IR7 (right frames).

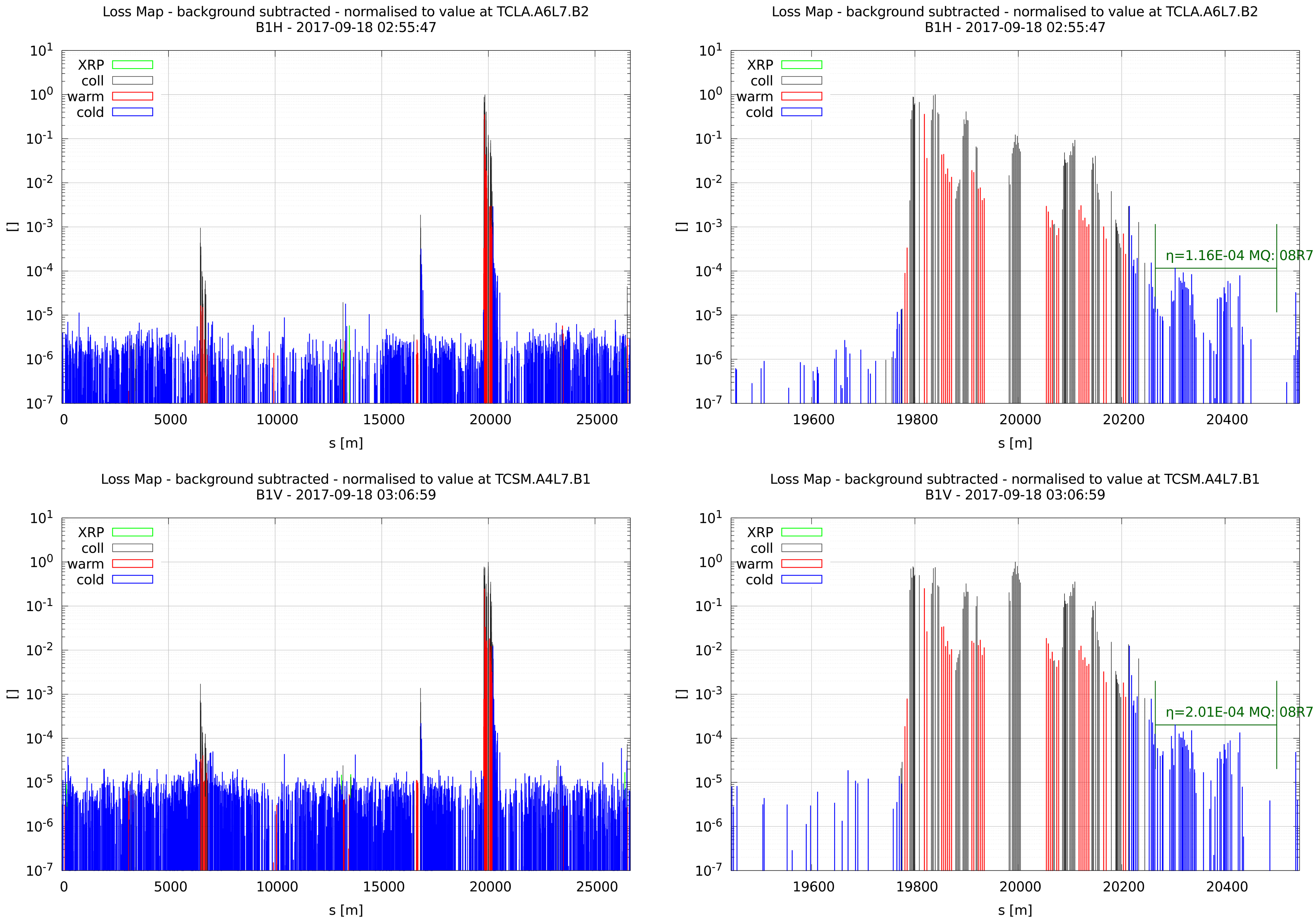


Figure A.3: B1H (upper frames) and B1V (lower frames) qualification loss maps with 1 σ–retraction (i.e. TCPs/TCSGs/TCLAs at 5/6/10 σ, see Tab. 1), before alignment: overview on the entire LHC (left frames) and zoom on IR7 (right frames).

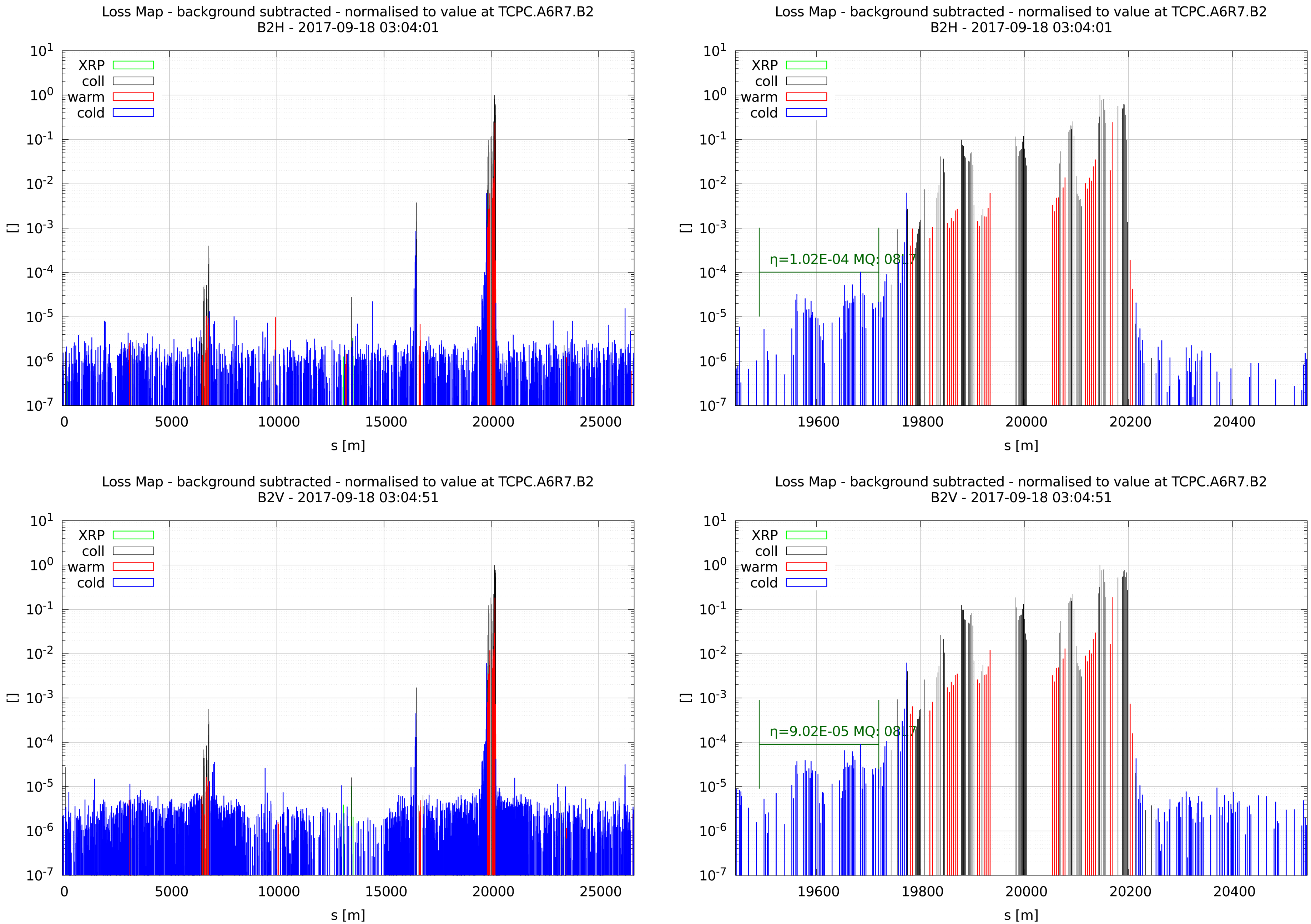


Figure A.4: B2H (upper frames) and B2V (lower frames) qualification loss maps with 1 σ–retraction, (i.e. TCPs/TCSGs/TCLAs at 5/6/10 σ, see Tab. 1) before alignment: overview on the entire LHC (left frames) and zoom on IR7 (right frames).

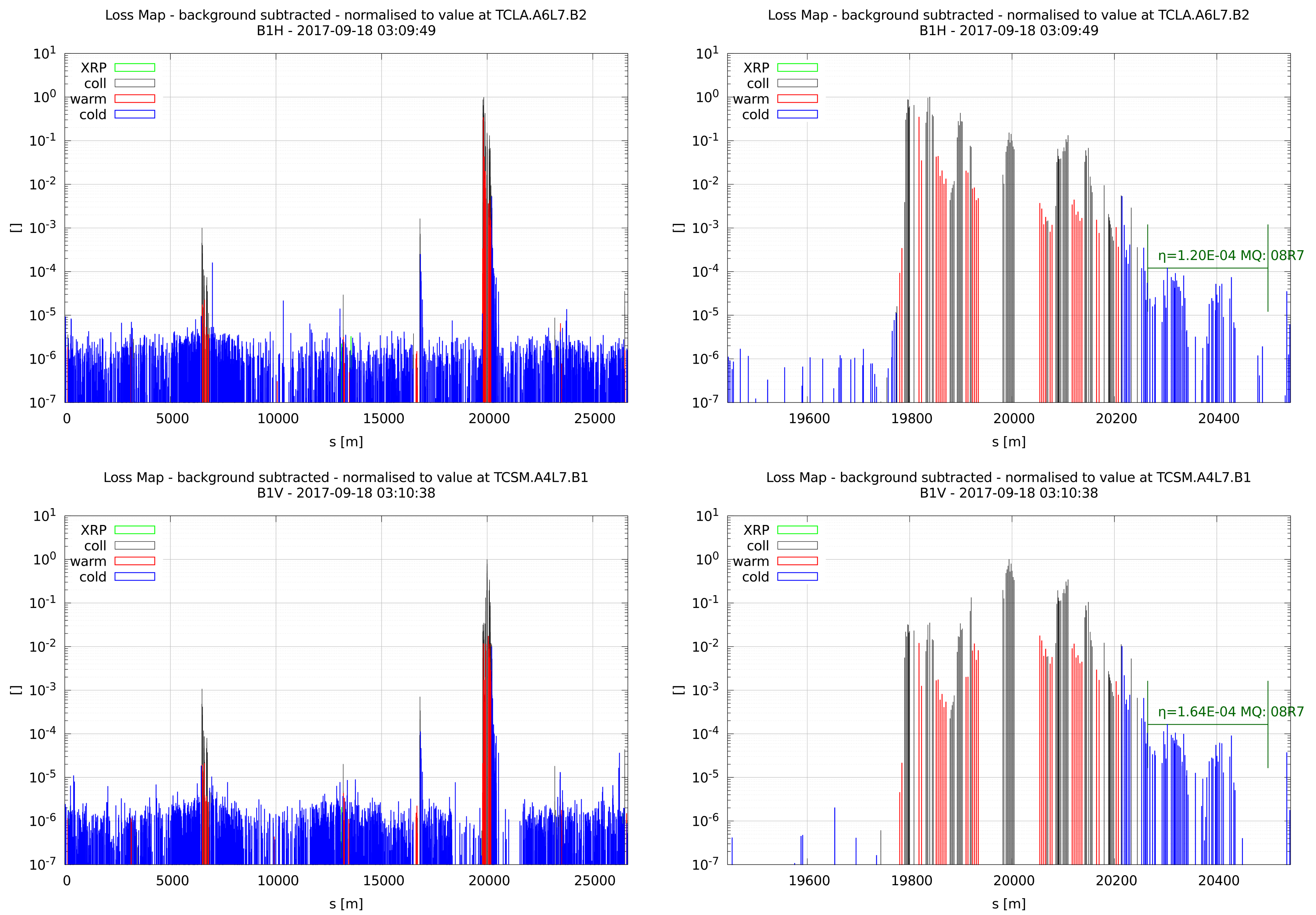


Figure A.5: B1H (upper frames) and B1V (lower frames) qualification loss maps with 0.5 σ–retraction (i.e. TCPs/TCSGs/TCLAs at 5/5.5/10 σ, see Tab. 1), before alignment: overview on the entire LHC (left frames) and zoom on IR7 (right frames).

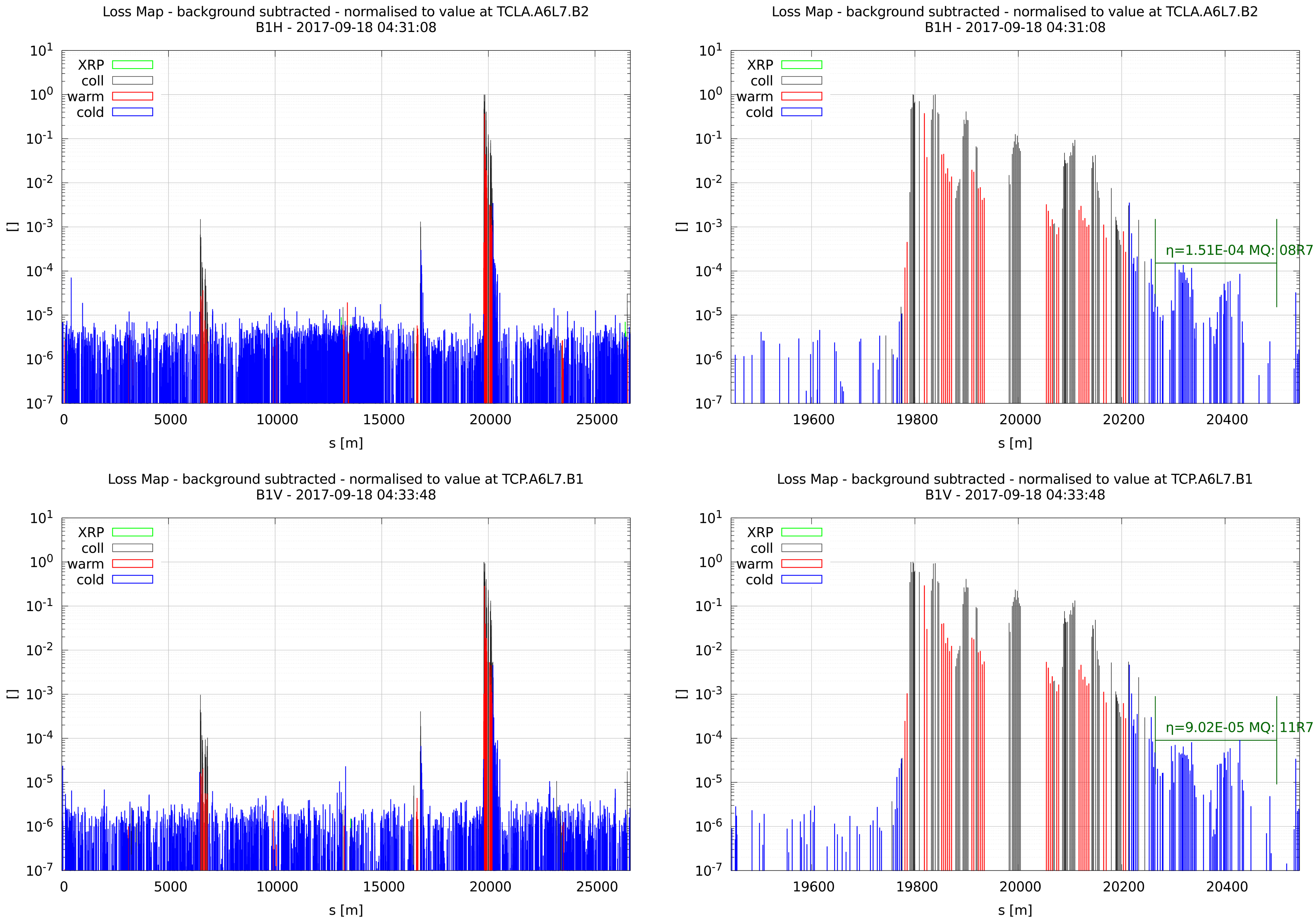
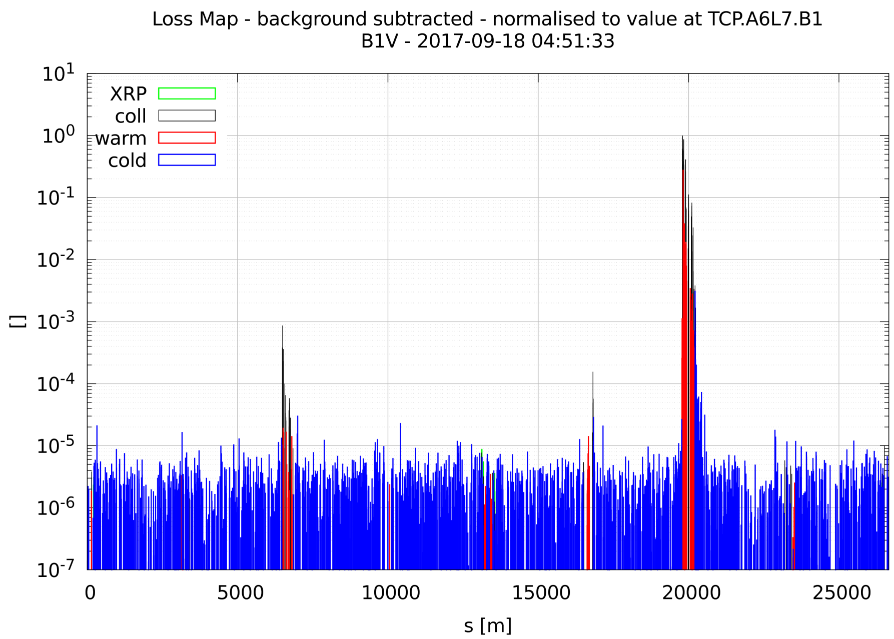


Figure A.6: B1H (upper frames) and B1V (lower frames) qualification loss maps with 1 σ–retraction (i.e. TCPs/TCSGs/TCLAs at 5/6/10 σ, see Tab. 1), after alignment: overview on the entire LHC (left frames) and zoom on IR7 (right frames).



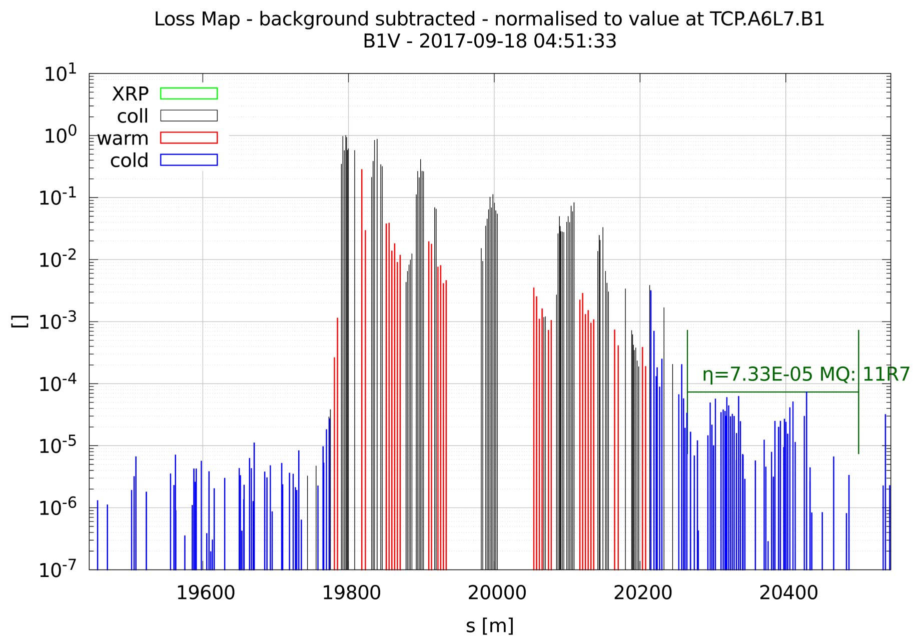


Figure A.7: B1V qualification loss maps with 1 σ–retraction (i.e. TCPs/TCSGs/TCLAs at 5/6/10 σ, see Tab. 1), after alignment, including the tilt angle to the TCSG.D4L7.B1 collimator: overview on the entire LHC (left frame) and zoom on IR7 (right frame).

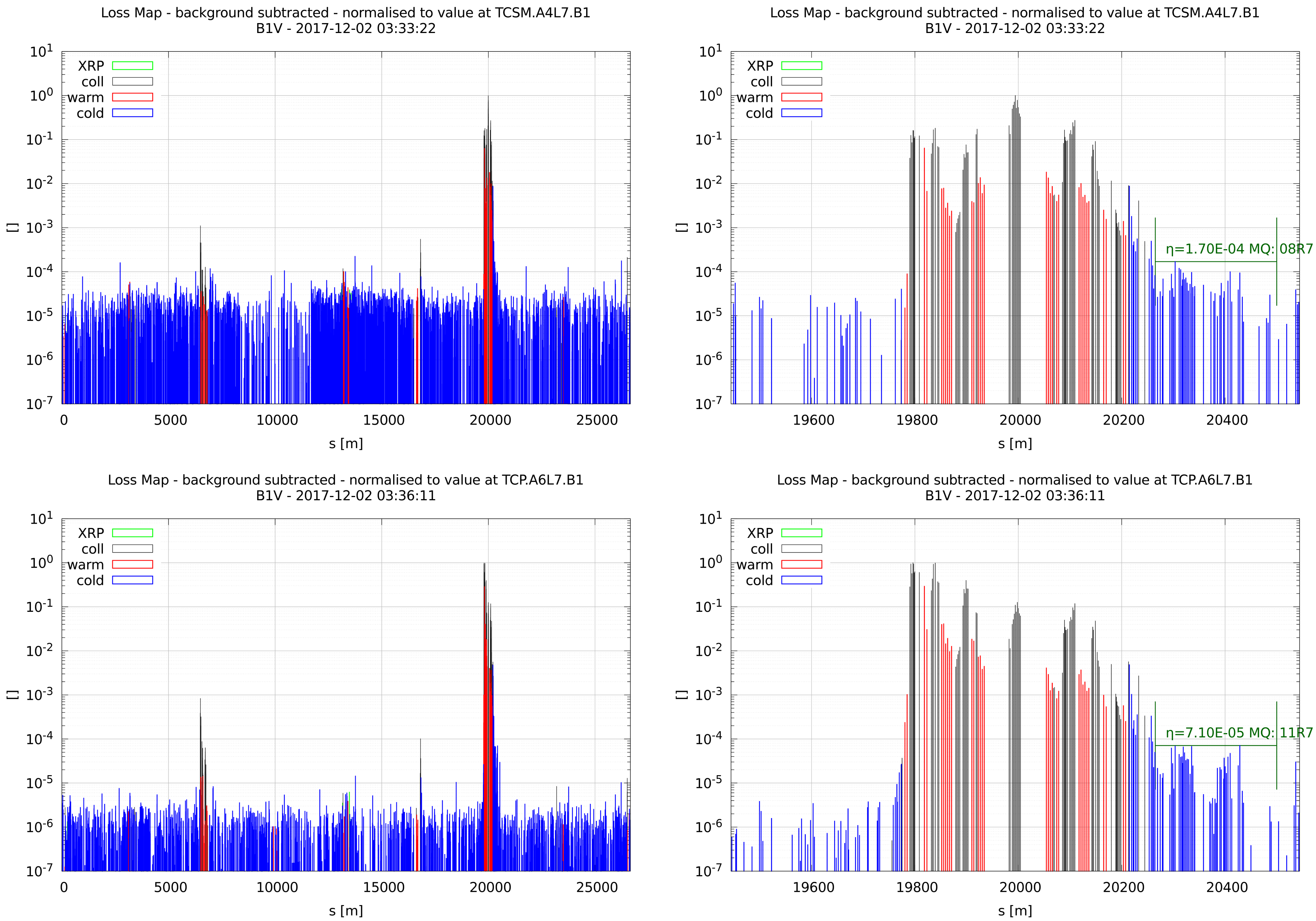


Figure A.8: B1V loss maps with 1 σ–retraction (i.e. TCPs/TCSGs/TCLAs at 5/6/10 σ, see Tab. 1) with the IR7 collimation system as is (upper frames) and applying a tilt angle of 350 μrad to the jaws of the TCSG.D4L7.B1 collimator (lower frames): overview on the entire LHC (left frames) and zoom on IR7 (right frames).