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β^*-Reach – IR7 Collimation Hierarchy Limit and Impedance

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Summary

This report summarises the results of the MD314 about the hierarchy limit of the IR7 collimation system and its impedance. While the activity, the procedures and the results concerning the collimator hierarchy limit are detailed here, the main outcomes from the impedance studies are only briefly reported, as a detailed MD report has been prepared. The MD was carried out during MD block II of 2015, on 29^{th} August, at 6.5 TeV. Different retractions of the IR7 secondary collimators (TCSGs) from the primary collimators (TCPs) were qualified in terms of cleaning inefficiency and impedance. For each retraction, settings of the IR7 movable shower absorbers (TCLAs) tighter than those operationally deployed were qualified as well. Afterwards, the alignment of all IR7 collimators was performed and the beam-based centres compared to those from the alignment done in May 2015, to verify stability. Selected configurations were qualified with loss maps, to spot possible improvements in the cleaning inefficiency due to the alignment. The outcomes are relevant for the potential operation of the LHC at a reduced β^* in the high luminosity experiments below the nominal value.

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1 Introduction and Motivation

During MD block II of 2015 a series of MD activities has been carried out to verify from the point of view of collimation the feasibility of β^* values in the high luminosity insertion regions of the LHC smaller than the nominal one. In fact, decreasing the value of β^* at the collision points implies a smaller normalised triplet aperture, with the consequent need of smaller gaps at the tertiary collimators (TCTs), for maintaining adequate local protection. This requires tightening the whole β^* hierarchy. In order not to reduce too much the retraction between the tertiary and the secondary collimators (TCSGs) in IR7, the opening of the latter is also decreased, to keep a distinct hierarchy of the collimator families [1, 2]. As a reference, Tab. 1

Table 1: Collimator settings in IR7 along with retractions between families. Settings of the IR3 collimators and of the TCTs are reported as well, for the sake of completeness.

	family	settings [σ]	retractions [σ]	
IR7	TCP	5.5	N/A	
	TCSG	8	2.5	(TCSG-TCP)
	TCLA	14	6	(TCLA-TCSG)
IR1/2/5/8	TCT	37	29	(TCT-TCSG$_{\mathrm{IR7}}$)
IR3	TCP	15	N/A	
	TCSG	18	3	(TCSG-TCP)
	TCLA	20	2	(TCLA-TCSG)

reports the operational settings[1] of the IR7 collimators at top energy; those of the TCTs in the interaction regions and of the IR3 collimators are reported for the sake of completeness. Retractions, i.e. how more open settings of a given family are with respect to those of the family in the upper rank in the hierarchy, are indicated as well.

Settings of collimators for betatron cleaning tighter around the beam core imply an increased contribution from collimators to the LHC impedance budget, since jaws are closer to the beam. In particular, TCSGs have the largest contribution, since they are the largest family and they are all made of a carbon-fibre-carbon composite (CFC), characterised by a relatively small electrical conductivity (0.14 MS/m [3])[2]. Moreover, smaller operational margins between families would be deployed, with the risk of jeopardising the hierarchy if they were reduced too much, since orbit variations can make effective settings of collimators smaller. In fact, drifts in orbit and optics over time change the effective settings of each collimator, and the smaller the margin, the easier is to violate the hierarchy. Smaller margins could be compensated by re-aligning the collimators to the beam more often, although it would be more optimal to have very few alignments per year – presently, IR7 collimators are aligned once per year.

The aim of the MD activity reported here (MD314) is to characterise the betatron collimation system when operated with reduced retractions. In particular, since the settings of the TCTs in case of smaller β^* have been characterised by two other dedicated MD activities [4, 5], the focus of the present one is on the retraction between the primary collimators (TCPs) and the secondary ones in the betatron cleaning insertion (IR7); specifically, the focus is:

1. on the identification of the limit retraction, beyond which the hierarchy between the two families is broken;
2. on the impact of the new retractions on the LHC impedance;
3. on the stability of collimator alignment. In fact, a proper alignment of the IR7 collimators could help in fully exploiting the operational margins, especially when they are reduced.

It should be noted that the impedance measurements have been carried out in collaboration with colleagues from BE-ABP-HSC; a dedicated report is in preparation [6], containing the detailed description of the activity and results. The main outcomes are only briefly reported here, for the sake of completeness.

[1] Throughout the text, collimator settings are expressed in units of the local transverse beam size σ, which is calculated using the nominal (i.e. perfect machine) β-function at each collimator and the nominal normalised emittance of 3.5 μm, unless explicitly indicated.

[2] For comparison, the electrical conductivity of copper is $\sim$60 MS/m.

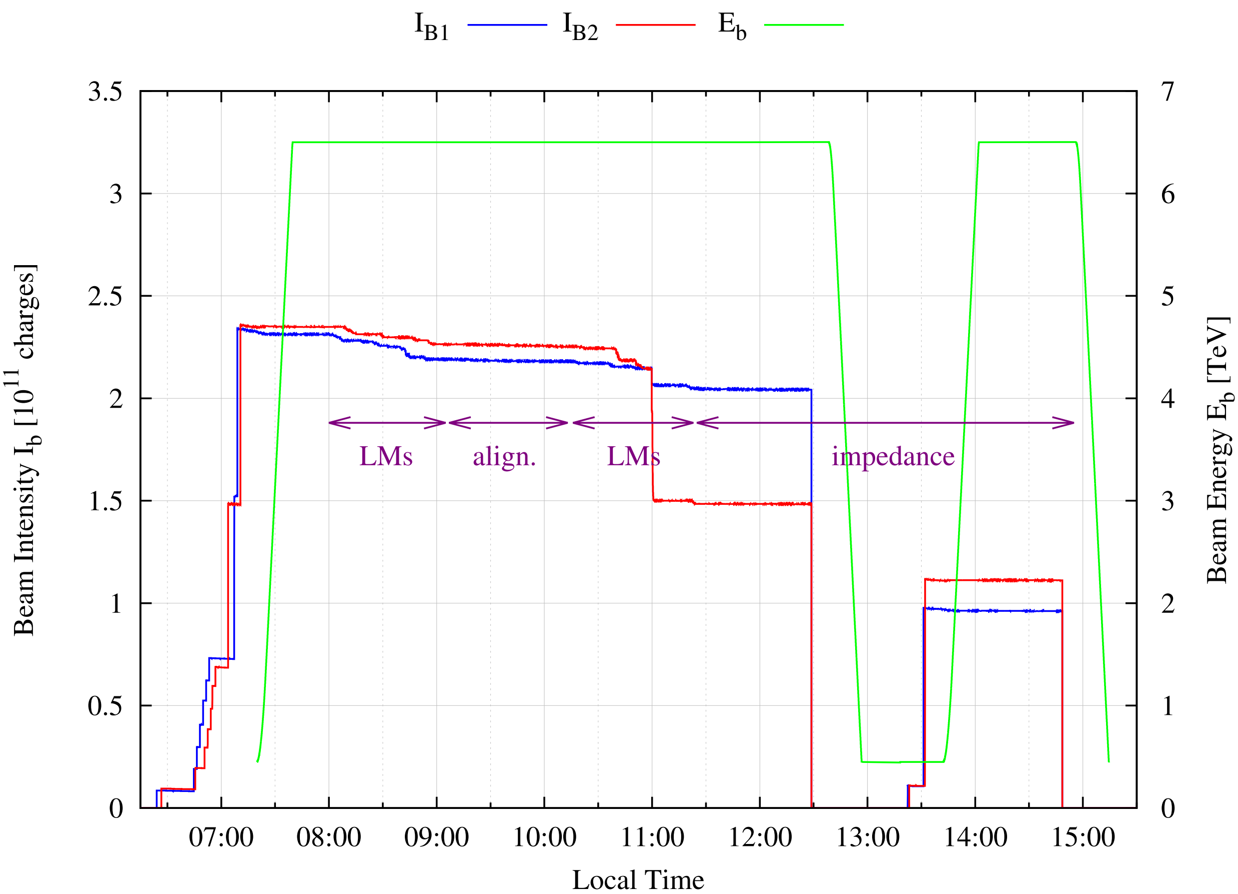

Figure 1: Intensity of B1 (blue curve) and B2 (red curve) as read by the fast beam current transformer (FBCT), and beam energy (green curve) during the presented MD activity. The time periods of the main activities carried out are highlighted, namely: loss maps ("LMs"), IR7 collimator alignment ("align."), and impedance measurements.

2 Procedure and Beam Conditions

The MD activity was carried out on 29^{th} August 2015 [7], at 6.5 TeV. The optics at flat top was used, i.e. without squeezing beams 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 time spent for various activities during the MD. Two energy ramps were required [6]:

1. During the first ramp, the qualification of reduced retractions was carried out, together with the IR7 collimator alignment and a first set of impedance measurements [6]. Two nominal bunches were required per beam, for a reliable monitoring of the beam orbit and for the impedance measurements, whereas a series of seven pilot bunches was used for loss maps to qualify the collimator settings under test. The loss of beam intensity at 11:00 was due to an error while importing measured beam sizes in the TRIM editor and an OP correction taking place immediately afterwards, when collimators still had wrong settings [8]. The loss of intensity rendered B2 unsuitable for use in the forthcoming threshold study.

2. During the second ramp, a second set of impedance measurements was carried out [6].

Table 2: Detailed time-line of the MD activity, along with the tested settings of the IR7 collimators. The primary collimators in IR7 are always kept at 5.5 σ. Collimator settings are given in units of the local transverse beam size, with the exception of the configuration in bold, for which the measured beam σ has been used. The last configuration corresponds to the collimator settings currently deployed during the LHC operation (see Tab. 1). The configurations tested *before* the IR7 collimator alignment make use of the operational collimator centres, whereas those tested *after* the alignment make use of the new collimator centres (i.e. as from the alignment). All the configurations are labelled for reference throughout the text.

time [hh:mm]	**configuration** **TCSG** [σ]	**TCLA** [σ]	**TCP-TCSG retraction** [σ]	**case**
08:00 - 08:15	7.5	14	2	A
08:25 - 08:30	7.5	10	2	B
08:32:42	moving TCSGs to 6.5 σ			
08:40 - 08:50	6.5	10	1	C
08:53 - 08:56	6.5	14	1	D
09:07 - 10:08	alignment			
10:16 - 10:21	**6.5**	**14**	**1**	E
10:36 - 10:42	6.5	14	1	F
10:49 - 10:55	7.5	14	2	G
11:19 - 11:23	8.0	14	2.5	H

Only a pilot and a nominal bunch per beam were used.

Different retractions between TCPs and TCSGs were tested, always keeping the TCPs at their operational opening (i.e. 5.5 σ – see Tab. 1). In particular, 2 σ– and 1 σ–retractions were explored. Table 2 gives the detailed list of the settings tested and the time when their performance was characterised through loss maps. It should be noted that all the other collimators around the LHC ring were kept at their operational settings at flat top, since:

- the largest leakage from the LHC collimation system is found in the dispersion suppressor (DS) immediately downstream of IR7, and collimators in other positions around the LHC cannot offer any mitigation action[3];
- one of the goals of this MD activity is to check the relative impact of a setting change in IR7 on impedance.

Before the alignment, settings of the movable shower absorbers in IR7 (TCLAs) tighter than those operationally deployed were qualified as well – i.e. 10 σ, to be compared to 14 σ, regularly used for operation (see Tab. 1). After the alignment, only a selection of configurations was qualified again, to spot possible improvements in the cleaning inefficiency due to the new beam-based centres from the alignment. The last configuration reported in Tab. 2 corresponds to the collimator settings currently deployed during the LHC operation.

When moving the TCSGs to 1 σ–retraction, a hierarchy breakage was detected, confirmed by the loss map campaign carried out immediately afterwards. For this reason, it was decided

[3]This location is the one which most likely quenches if betatron collimation losses are too high, and it is subject to single diffractive protons lost directly after having interacted in the jaws of the TCP collimators [9].

to test also IR7 collimator settings based on measured beam sizes (settings in bold in Tab. 2), as a possible cure to the breakage. It turned out to be the case.

The collimation performance was characterised by means of betatron loss maps, as regularly done for qualification. The procedure foresees to separately excite each beam on each plane (horizontal and vertical) by means of the transverse damper (ADT) and record signals at beam loss monitors (BLMs) located all around the machine. Their pattern along the ring, and in particular in IR7, allows to identify loss locations and compute the cleaning of the collimation system, judging on its performance.

The beam-based alignment [10] of the IR7 collimators was carried out, as done during commissioning. The overall process took less than 1 h. The procedure foresees that for each collimator the jaws are slowly moved towards each other until the beam envelope is touched, and a small local loss spike is thus detected at the closest BLM; the average between the positions of the two jaws is the centre of the beam envelope. Before and after the alignment of each collimator the TCP on the relevant plane is re-aligned to the beam; consequently, it is possible to express the opening of the collimator being aligned in terms of normalised jaw opening at the TCP, and an effective beam σ at the collimator (measured beam size) can be derived.

Impedance measurements have been carried out [6] with two methods, in order to characterise both its real and the imaginary parts:

1. the jaw opening of the TCSGs was set to 6.5 σ (i.e. 1 σ–retraction), to maximise their contribution to impedance, and the current in the octupoles was decreased in steps, until instabilities started to slowly arise;

2. the jaws of the TCSGs were moved back and forth between 6.5 σ and 20 σ, and variations of the tune signals were recorded.

3 Results

The present section summarises the results about the hierarchy limit and the alignment campaign. Results about impedance are only briefly recalled, since they are more widely presented in [6].

3.1 Qualification of Reduced Retractions Between TCPs and TCSGs

All the configurations listed in Tab. 2 have been qualified with loss maps, showing similar patterns for the same beam/plane. For instance, Figs. 2 through 5 compare the loss maps obtained with the tightest settings of the IR7 collimators before the alignment (i.e. case "C" in Tab. 2) with those obtained with the settings presently deployed during operation, after the alignment (i.e. case "H" in Tab. 2 – collimator centres are those from the alignment carried out during this MD activity). In each comparison, trends are very similar between the two cases, with the exception of few local variations. These two cases have been chosen since they give an idea of the largest variations observed in the patterns (the alignment campaign showed a very good stability of the collimator alignment, with very limited impact on the loss maps - see later). As expected, local cleaning inefficiencies in the dispersion suppressors downstream of the IR7 collimators get better when tighter settings are used, by a factor 3 to 4.

In general, a break of the collimator hierarchy is visible as an abnormal BLM pattern, as this qualitatively reflects the pattern of proton losses on collimators, made anomalous by the broken hierarchy. A first sign of hierarchy breakage was observed while moving TCSGs from 7.5 σ to 6.5 σ (i.e. when setting the retraction between TCPs and TCSGs to 1 σ), but in that

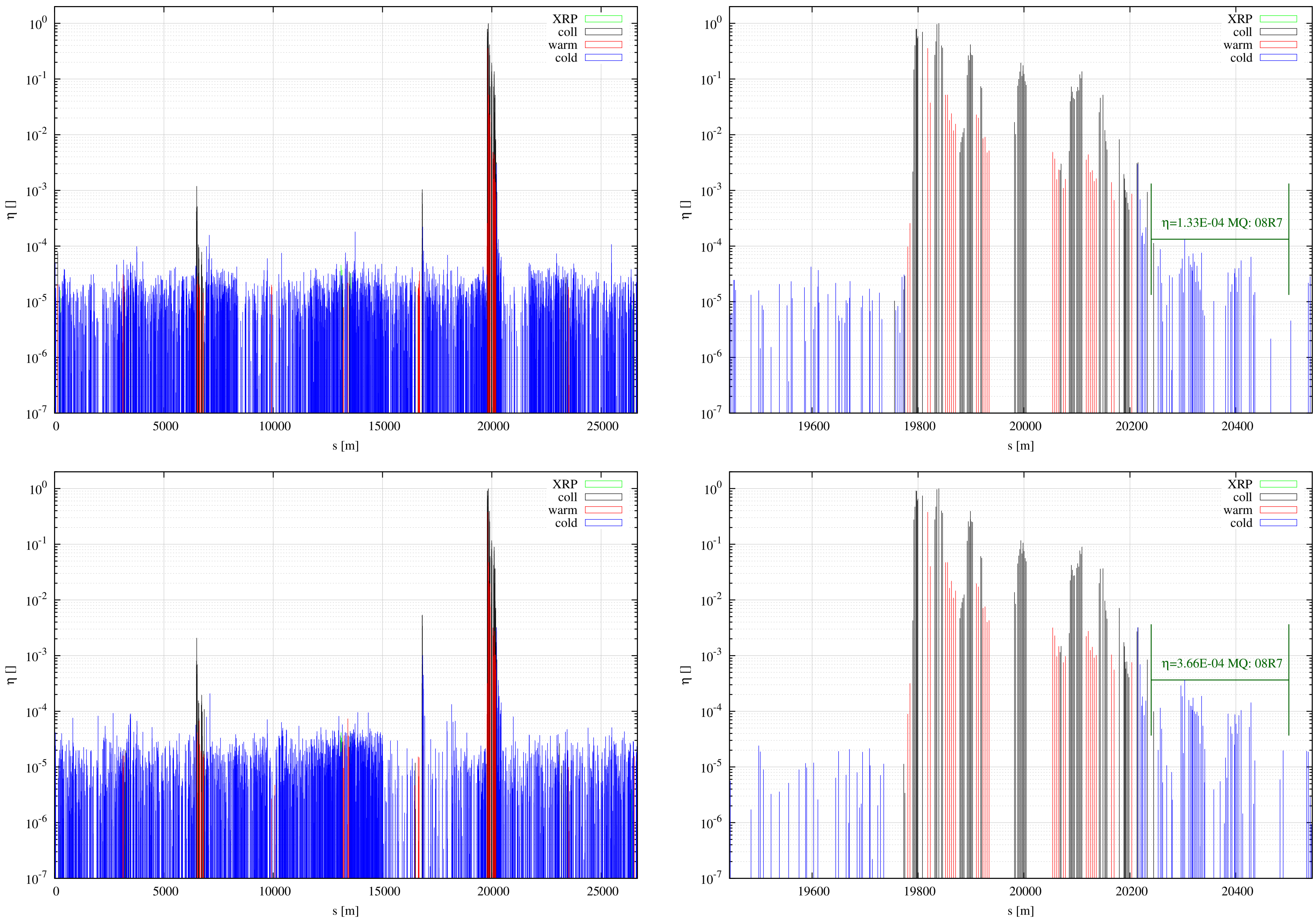

Figure 2: B1H qualification loss maps for case "C" (i.e. with TCSGs/TCLAs at 6.5/10 σ before alignment, see Tab. 2 – upper frames) and for case "H" (i.e. with TCSGs/TCLAs at 8/14 σ after alignment, see Tab. 2 – lower frames). The overview on the entire LHC is shown by the frames on the left, whereas the zoom on IR7 is shown by the frames on the right.

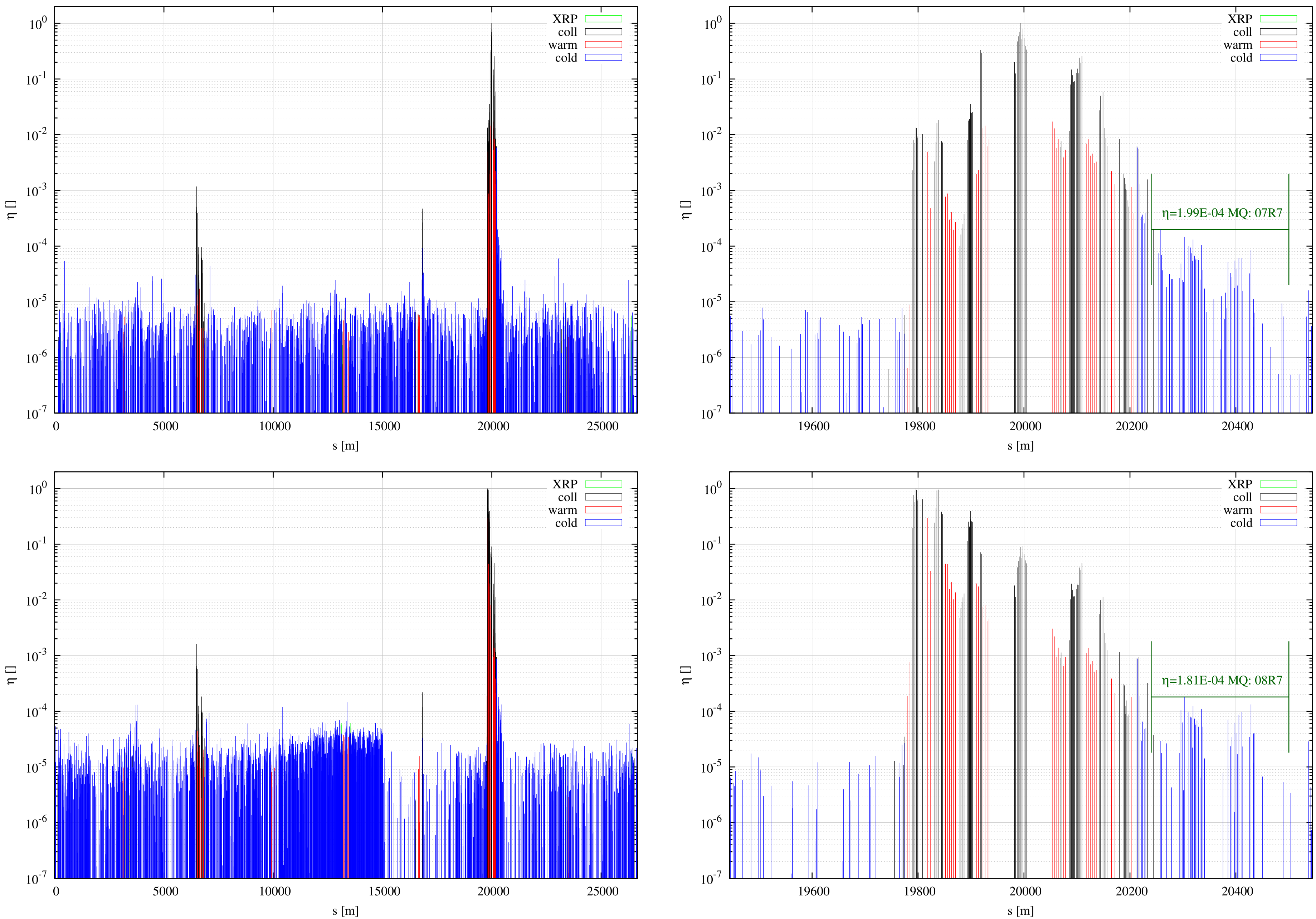

Figure 3: B1V qualification loss maps for case "C" (i.e. with TCSGs/TCLAs at 6.5/10 σ before alignment, see Tab. 2 – upper frames) and for case "H" (i.e. with TCSGs/TCLAs at 8/14 σ after alignment, see Tab. 2 – lower frames). The overview on the entire LHC is shown by the frames on the left, whereas the zoom on IR7 is shown by the frames on the right.

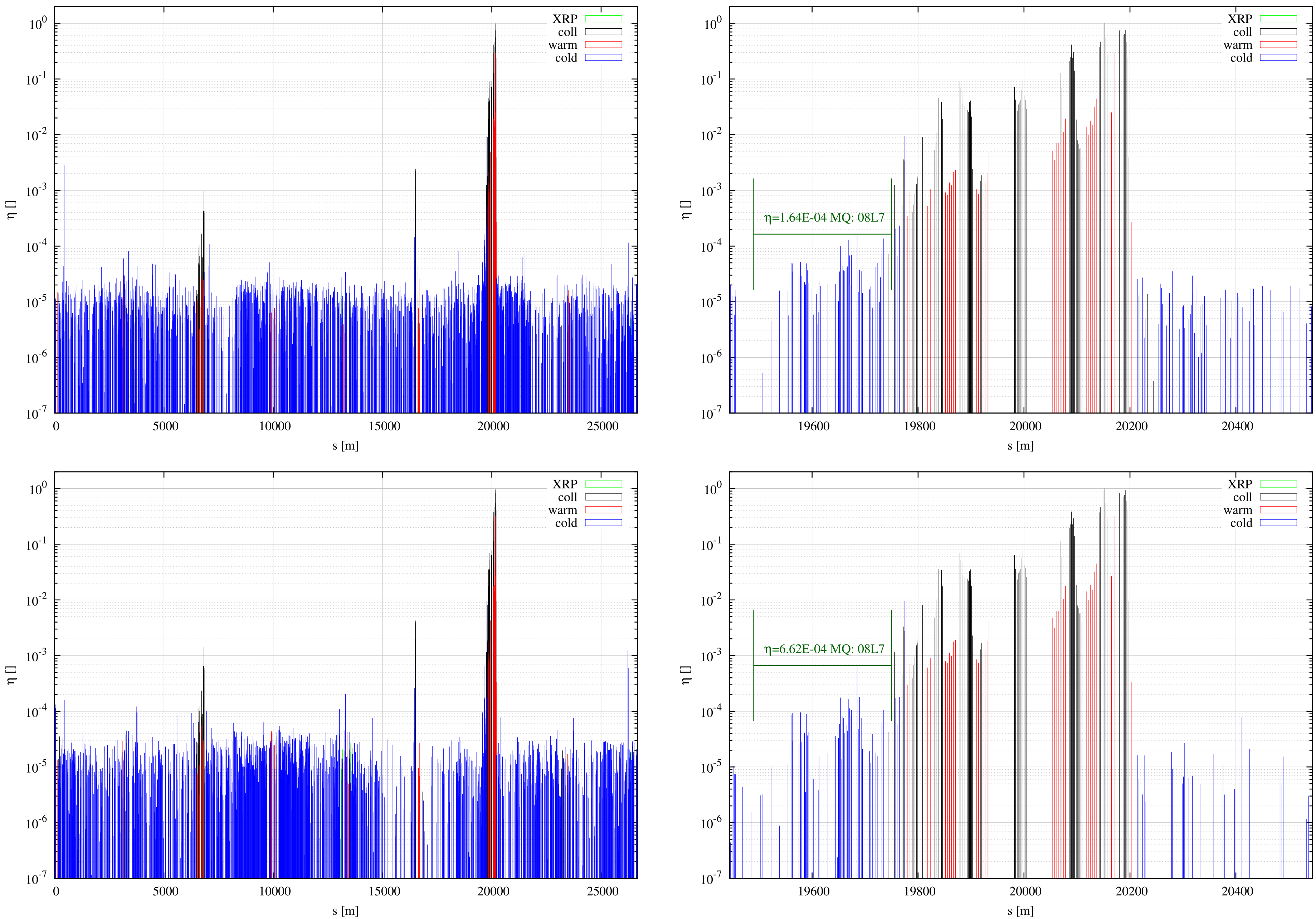

Figure 4: B2H qualification loss maps for case “C” (i.e. with TCSGs/TCLAs at 6.5/10 σ before alignment, see Tab. 2 – upper frames) and for case “H” (i.e. with TCSGs/TCLAs at 8/14 σ after alignment, see Tab. 2 – lower frames). The overview on the entire LHC is shown by the frames on the left, whereas the zoom on IR7 is shown by the frames on the right.

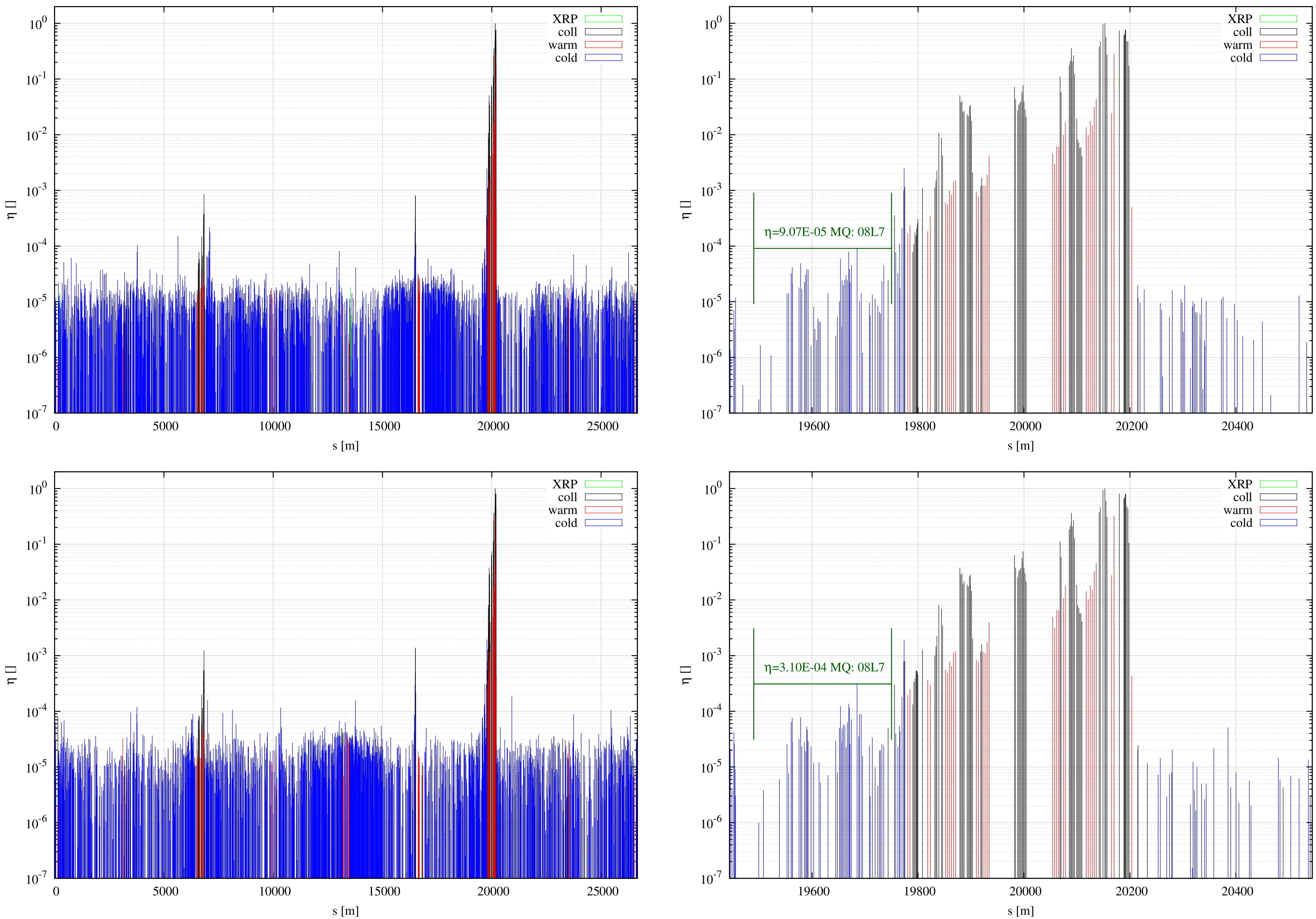

Figure 5: B2V qualification loss maps for case “C” (i.e. with TCSGs/TCLAs at 6.5/10 σ before alignment, see Tab. 2 – upper frames) and for case “H” (i.e. with TCSGs/TCLAs at 8/14 σ after alignment, see Tab. 2 – lower frames). The overview on the entire LHC is shown by the frames on the left, whereas the zoom on IR7 is shown by the frames on the right.

moment it was not possible to disentangle which beam/plane was affected and which collimator was responsible for it, since all the TCSGs were moved at the same time, regardless of beam and plane. Loss maps carried out immediately afterwards on single beam/plane clarified that the collimator hierarchy was broken for B1V, as visible in the top–right frame of Fig. 3, which shows the zoom on the IR7 region. The BLM pattern is qualitatively different from the regular one (the one in the bottom–right frame of the same figure can be taken as example), with the by far highest peaks at the TCSGs in the middle of IR7. The collimator sticking out at $\eta \sim 0.3$ is the TCSG.D4L7.B1, i.e. the vertical TCSG in IR7.

A cure was found by using settings based on measured beam sizes instead of the nominal ones (i.e. from optics), as it can be seen in Fig. 6. In fact, when deploying the nominal beams sizes (case “F” in Tab. 2), the BLM pattern in IR7 (upper–right frame) is similar to the one with the broken collimator hierarchy shown in Fig. 3 for the same TCP-TCSG retraction (upper–right frame), whereas when using the measured beam sizes (case “E” in Tab. 2), the regular BLM pattern is restored (lower–right frame), a sign of the collimation hierarchy being respected. It should be noted that the loss maps shown in Fig. 6 were obtained after the alignment campaign (thus using updated collimator centres), showing that the stability of the machine/alignment is not the source of the problem.

A hierarchy breakage was seen also during the commissioning activities carried out in May 2015 [11], when performing preliminary impedance measurements [12]. While moving TCSGs to 6.4 σ using nominal beam sizes, an abnormal BLM pattern in IR7 was seen, but slightly different from that observed during this MD activity [8]. This difference could be explained by the fact that in May losses were observed during the collimator movement instead of in a dedicated loss maps, as in the present MD. As realised during the present MD activity, the use of measured beam sizes also cured the hierarchy breakage found in May 2015.

A comparison of the cleaning performance before and after alignment is given in Fig. 7, which shows the highest value (“worst”) of the local cleaning inefficiency at the DS immediately downstream of IR7 for all the collimator settings tested (see Tab. 2). In general, values after the alignment (right frames) are lower than those before the alignment (left frames), by $\sim$35% at most for B2H with TCSGs at 7.5 σ, and B2V with TCSGs at 8 σ. This shows the positive (though small) effect of the collimator re-alignment. Moreover, for most of the cases, the closer the TCSGs are to the beam, the better the cleaning inefficiency is, as expected. A better cleaning is also found when the TCLAs are set to 10 σ instead of 14 σ, also as expected.

Before alignment, a factor between 3 and 4 better cleaning is found for B1H when moving TCSGs/TCLAs from 8/14 σ to 6.5/10 σ. On the contrary, B1V is affected by the hierarchy breakage. In fact, the point for B1V with TCSGs/TCLAs at 6.5/10 σ before alignment (light blue curve in the top–left frame) corresponds to the configuration which revealed the broken hierarchy, and it is reported for the sake of completeness; the same point with TCLAs at 14 σ (dark blue curve in the top–left frame) is absent, as this configuration was skipped due to the hierarchy breakage found immediately before. Conversely, the patterns for B2 are smooth and very similar to that of B1H, since no hierarchy breakage was found for this beam.

After alignment, the patterns of the curves are similar to those before the alignment (with B1V still being affected by the hierarchy breakage). While for B2 the use of measured beam sizes with TCSGs at 6.5 σ slightly improves the performance of the collimation system, this is not the case for B1. The reason of this discrepancy is still not clear at the time of writing.

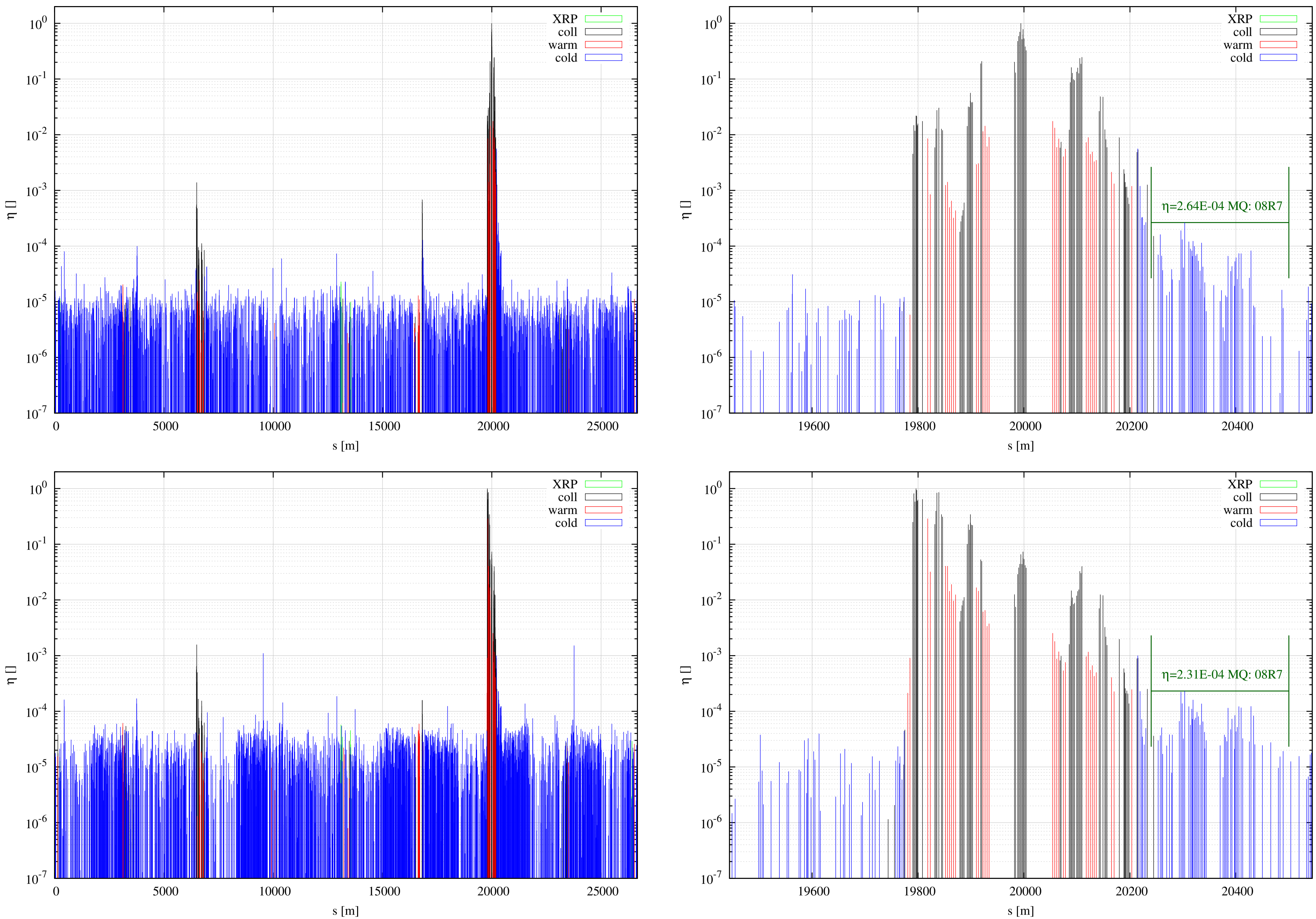

Figure 6: B1V qualification loss maps with TCSGs/TCLAs at 6.5/14 σ with nominal beam sizes (case “F” in Tab. 2 – upper frames) and with measured beam sizes (case “E” in Tab. 2 – lower frames). The overview on the entire LHC is shown by the frames on the left, whereas the zoom on IR7 is shown by the frames on the right.

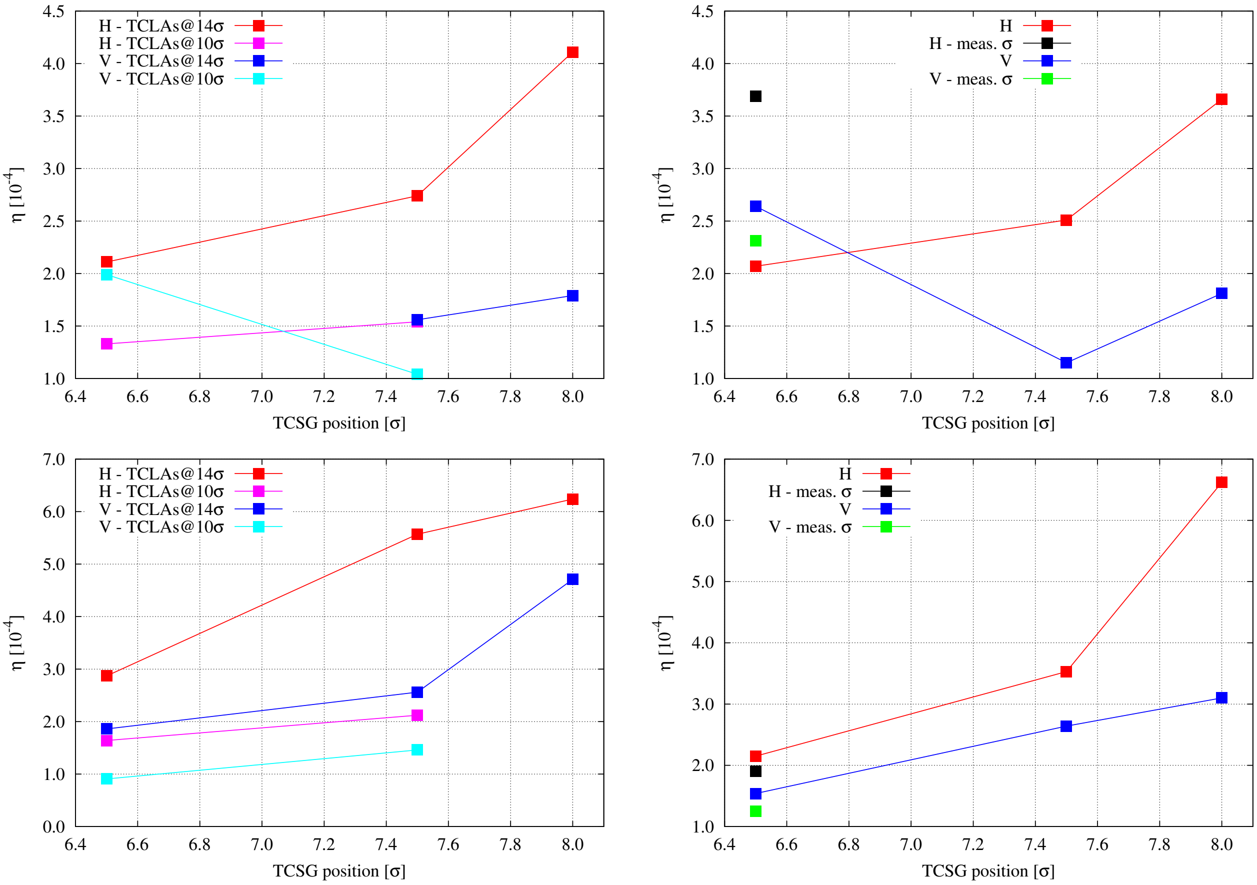

Figure 7: Worst local cleaning inefficiency at the DS immediately downstream of IR7 as a function of the TCSG settings, for all the configuration tested (see Tab. 2). Results for B1/B2 are shown by the upper/lower frames, whereas those obtained before/after the alignment campaign are shown by the left/right frames. The results shown in the right frames have been obtained with TCLAs at 14 σ. It should be noted that no loss map was performed before alignment with the TCSG opening at 8 σ; those points are indeed from the qualification campaign carried out in view of Van der Meer scans [13], few days before this MD activity, and thus are the most up-to-date values available.

3.2 Alignment of IR7 Collimators

Figure 8 shows the results of the alignment campaign carried out during this MD activity, compared to those from the alignment campaign carried out during the LHC commissioning for RunII (May 2015). The stability of both the collimator centres and the measured beam sizes over about four months is good, with the exception of the TCLA.A6L7.B2, for which the measured beam size as from the present MD is clearly different from the one previously found. Collimator centres are almost unchanged (within few tens of μm), giving reasons for the tiny effect of the re-alignment on the cleaning inefficiency and in curing the hierarchy breakage found for B1V[4].

After technical stop 2 (TS2, taking place between 31$^{\text{st}}$ September 2015 and 4$^{\text{th}}$ October 2015), a couple of IR7 collimators were re-aligned to the beam [14], i.e. the TCSG.D4L7.B1 (causing the hierarchy breakage on B1V) and the TCLA.A6L7.B2 (just aforementioned). Re-

[4]In fact, collimators were found to be pretty well aligned; on the contrary, a mis-centring of the jaws translates into smaller normalised collimator openings, and in a reduction of margins between families. If margins are small, as in the case of 1 σ–retraction, mis–alignment may end up in a loss of the correct hierarchy.

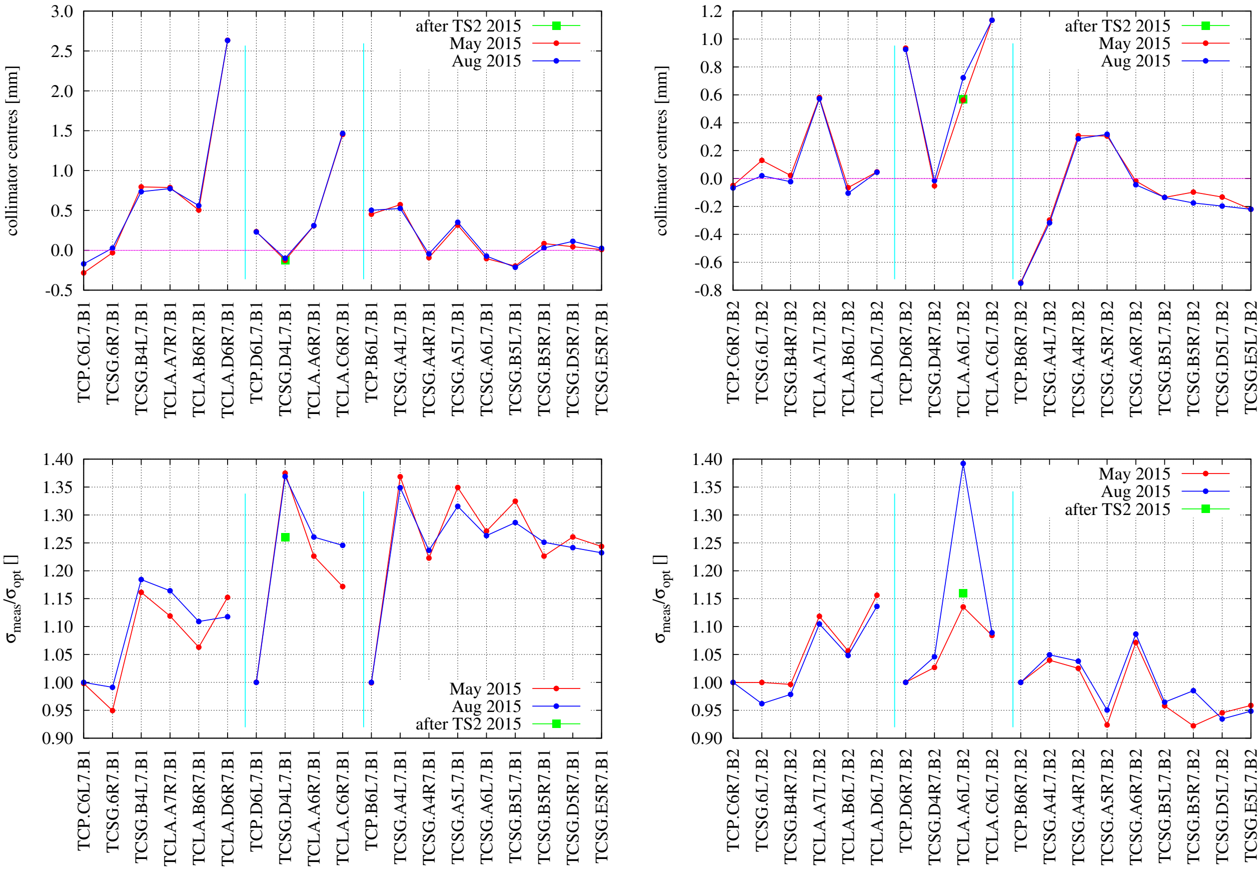

Figure 8: Beam-based centres of all IR7 collimators from the alignment campaign carried out during the present MD activity and the one carried out during the LHC commissioning with beam (May 2015). Results for B1/B2 are shown by the frames on the left/right. Collimator centres are shown by the upper frames, whereas measured beam sizes are shown by the lower ones, expressed as ratio to the nominal values. Later results from the re-alignment to the beam [14] of the TCSG.D4L7.B1 and of the TCLA.A6L7.B2 are shown as well.

sults are reported as well in Fig. 8. For the latter, the collimator centre and the measured beam size were found to be close to past values; for the former, a smaller measured beam size was found. More importantly, a jaw tilt of $\sim$200 μrad was found at this collimator (by means of an alignment of the individual jaw corners), consistent with a tilt of the collimator tank. It should be noted that the beam σ at this location is of the order of 200 μm, comparable to the error induced by the possible tilt of the tank[5] and would thus explain the hierarchy breakage.

3.3 Impedance Measurements

The impedance measurements have been carried out in collaboration with colleagues from BE-ABP-HSC; a dedicated report is in preparation [6], containing the detailed description of the activity and results. The main outcomes are here only briefly reported, for the sake of completeness.

The instability threshold was measured in terms of octupole current required to stabilise beams with the tightest IR7 TCSG settings tested in this MD (i.e. 6.5 σ). Measurements did not agree with predictions, according to which an octupole current double the one necessary

[5]It should be kept in mind that the length of the jaws of this collimator is 1 m.

with operational TCSG settings (i.e. 8 σ) was needed. Moreover, ignoring the bunches that lost heavily on the collimators during the first ramp, the horizontal plane was always found to become unstable before the vertical one, despite having a higher emittance than in the vertical plane. Possible causes are not clear at the time of writing, but some truncation of the transverse profile, which affects the stability diagram, might be at the basis of this behaviour. However, this typically should only have an impact on modes that are in the tails of the stability diagram, and it isn't enough alone to explain the level of discrepancy seen. These measurements need to be repeated to clarify the open points.

The tune shift induced by moving all the IR7 TCSGs back and forth between 6.5 σ and 20 σ was found to be of the order of 2×10^{-4}, compatible with expectations. Only measurements for the vertical planes could be used, since those obtained for the horizontal planes were too noisy.

4 Conclusions

The results of the MD314 have been presented. The activity of the MD mainly consisted in qualifying settings of the IR7 collimators with reduced retractions between TCPs and TCSGs, since these are relevant for operating the LHC with values of β^* in the high luminosity experiments below the nominal one. Moreover, a fast alignment of the IR7 collimators has been tried out, verifying that a relatively short time is needed for a complete re-alignment. In addition, the long term stability of the collimator alignment has been evaluated.

The performance of the IR7 collimation system with tighter settings has been characterised by measuring the local cleaning inefficiency at the DSs immediately downstream of IR7 through loss maps. The tested retractions between TCPs and TCSGs were 2– and 1–σ, with the TCLAs at both their operational settings, i.e. 14 σ, and with tighter ones, i.e. 10 σ. An overall improvement in the local cleaning inefficiencies at the DSs by a factor 3 to 4 has been found between the two extreme collimator configurations, i.e. 5.5/8/14 σ (TCP/TCSG/TCLA) and 5.5/6.5/10 σ, confirming the positive effect of the tighter settings on the local cleaning inefficiency.

The loss map campaign carried out during this MD activity helped to identify the present hierarchy limit of the IR7 collimation system. In fact, a breakage in the IR7 collimation hierarchy was found for B1V, when TCSGs were set to 6.5 σ. The deployment of measured beam sizes instead of the nominal ones proved to be a viable cure. This does not necessarily imply a deterioration of the quality of the reproducibility of the optics, but it could be related to little hardware modifications, e.g. a tilt of the tank.

All the IR7 collimators were re-aligned to the beam within only ∼1 h, a record time achieved thanks to the new software implementation for 2015. New centres and measured beam sizes are very close to past values (obtained during the LHC commissioning with beam in May 2015), showing a very good stability of the beam orbit in the machine and the collimator alignment over about four months. Thus, it can be concluded that 7.5 σ settings for TCSGs should be fine and safe in terms of cleaning, while more studies are needed to deploy 1 σ retraction settings.

Smaller retractions between TCPs and TCSGs have been characterised also in terms of impedance [6]. While tune shift measurements are compatible with numerical predictions, this is not the case for instability threshold measurements, requiring further investigations to be carried out before drawing conclusions.

This MD is part of a series of MDs intended to explore the LHC β^*–reach in RunII. Combining the results of all MDs, we hope to conclude on the the feasibility of β^*=40 cm or below.

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[14] LHC elogbook of 5$^{\text{th}}$ Sep 2015, afternoon and night shifts: `http://elogbook.cern.ch/eLogbook/eLogbook.jsp?shiftId=1068485` and `http://elogbook.cern.ch/eLogbook/eLogbook.jsp?shiftId=1068492`.