CERN–ACC–NOTE–2020–0021 MD

April 17, 2020

alessio.mereghetti@cern.ch

MD1447 – β^*–Reach: 2016 IR7 Collimation Hierarchy Limit and Impedance

A. Mereghetti / CERN, BE-ABP, D. Amorim / Université Grenoble Alpes (FR), ex CERN, BE-ABP, N. Biancacci / CERN, BE-ABP, E. Bonanno / Università degli studi di Palermo (IT), ex CERN, BE-ABP, L. R. Carver / University of Liverpool (UK), ex CERN, BE-ABP, D. Ferrazza / Università e INFN Roma I (IT), ex CERN, BE-ABP, T. Lefevre / CERN, BE-BI, T. Levens / CERN, BE-BI, E. Métral / CERN, BE-ABP, E. Quaranta / ex CERN, BE-ABP, S. Redaelli / CERN, BE-ABP, B. Salvant / CERN, BE-ABP, G. Valentino / University of Malta (MT), ex BE-ABP, D. Valuch / CERN, BE-RF, M. Wendt / CERN, BE-BI

Keywords: LHC, collimator settings, cleaning inefficiency, loss maps, impedance

Summary

This report summarizes the results of MD1447 about the hierarchy limit of the LHC collimation system in IR7 at 6.5 TeV and its impedance, performed during MD block 1 of 2016. The hierarchy breakage seen in a similar activity in 2015 when deploying 1 σ-retractions between TCSG and TCP collimators was confirmed, and a viable solution demonstrated with beam. In addition, measurements of tune shifts induced by changes in collimator gaps were performed when moving the IR7 TCSG collimators all together, or when moving only those with the largest contribution to impedance. The MD activity included a re-alignment of all the IR7 collimators to the beam, prior to the investigations on the hierarchy breakage, and an instability threshold measurement, at the end. The MD activity is important for understanding the limitations from impedance; these limitations have direct impact on the choice of the machine configuration kept during operation (e.g. for deploying TCP-TCSG retractions in IR7 smaller than the present ones), or for optimising the design of future devices (e.g. as presently foreseen by the HL-LHC project, since outcomes are important ingredients for finalizing the baseline configuration of the upgraded collimation system).

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 transverse hierarchy is key to guarantee the optimal

This is an internal CERN publication and does not necessarily reflect the views of the CERN management

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 put in place to ensure the collimator hierarchy, and the increase of the contribution of the collimation system to the LHC impedance budget [1].

Therefore, it is essential to characterize 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. Impedance–wise, it is necessary to benchmark the impedance model against precise measurements, either involving entire families of collimators or single devices.

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.

Together with other proposed MD activities [7, 8], the one reported here is the follow-up of a similar one carried out in 2015, i.e. MD314 [9].

1.1 Recap of 2015 Measurements

In 2015, retractions between IR7 TCP and TCSG collimators smaller than those operationally deployed in the same year (i.e. 2.5 σ) were qualified in terms of local cleaning inefficiency in the DS immediately downstream of IR7, and in terms of impedance. Main outcomes are:

1. the feasibility of 2 σ-retractions was proved. These retractions have been operationally deployed in 2016;

2. the hierarchy of the IR7 collimators was found to be broken on B1V when deploying 1 σ-retractions. From the loss map it was possible to determine that the TCSG.D4L7.B1 collimator was at the origin of the breakage, but there was no time to specifically verify this hypothesis;

3. deploying measured beam sizes instead of the nominal ones (i.e. those computed from linear optics) in setting collimator gaps re-established the regular IR7 hierarchy. On the other hand, the beam sizes at collimators measured during alignment were ~ 20 % larger than those from optics; such high discrepancies are not compatible with a β-beating of 5–10 % (peak to peak), pointing to possible misalignments of the tank;

4. the tune shift induced by moving TCSG collimators between 20 σ and 6.5 σ (the latter corresponding to 1 σ-retraction) is about 2×10^{-4}, in good agreement with numerical simulations;

5. the octupole current thresholds for single bunch stability with IR7 TCPs/TCSGs at 5.5/6.5 σ (i.e. with 1 σ retractions) was found at 150 A, not in accordance with predictions from numerical simulations.

Table 1: Collimator settings in IR7 deployed during operation in 2015 and 2016 at flat top (end of the energy ramp, in black), along with those tested during MD314 and MD1447 (marked in blue). Settings of the IR3 collimators and of the TCTs are reported as well, for the sake of completeness.

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

1.2 Scope of the MD

The aim of the present MD activity was to complete the picture gotten in 2015:

1. to identify the origin of the hierarchy breakage already seen on B1V last year. This is a key step towards the possible deployment of these retractions during operation, to accommodate future quests for improving the LHC performance;

2. to verify the stability of the alignment with 2016 machine settings, and to test algorithms for faster alignments;

3. to assess with beam the impact on impedance by deploying IR7 carbon collimators with 1 σ TCP–TCSG retractions;

4. to develop a method of measuring with beam the contribution to the LHC impedance budget from a single TCSG collimator and compare it with expectations.

Table 1 compares the settings deployed during operation in 2015 and 2016, along with those tested in this year and last year MD activities.

The measurement of the contribution from a single TCSG collimator to impedance is an important missing point from last year MD activity, since it is relevant to quantify the effect of the low-impedance collimators foreseen by the HL-LHC project. This kind of measurements are challenging, since numerical simulations predict a tune shift in the order of few 10^{-5} for typical TCSG collimator gaps, close to the limit in sensitivity of the method used in the past, i.e. turn–by–turn BBQ data.

During the 2016 extended year end technical stop (EYETS), a prototype of low-impedance collimator was installed in the slot D4R7 on beam 2 (B2) [10], to appreciate its benefit on beam impedance. The choice of the slot was driven by impedance considerations. In fact, since they have the smallest beam size on the cleaning plane (vertical, in the specific case), the TCSG.D4L7.B1 and the TCSG.D4R7.B2 are the secondary collimators with the largest impact on impedance for the same normalised settings. For the same reason, the sensitivity of the measurements is maximised at this location. Therefore, in preparation for tests of the TCSPM collimator foreseen for 2017, a big effort has been put in understanding the tune shift from the corresponding collimator in graphite.

In the attempt to push the resolution of the measurements, new methods of measuring the tune shift have been proposed for this MD activity:

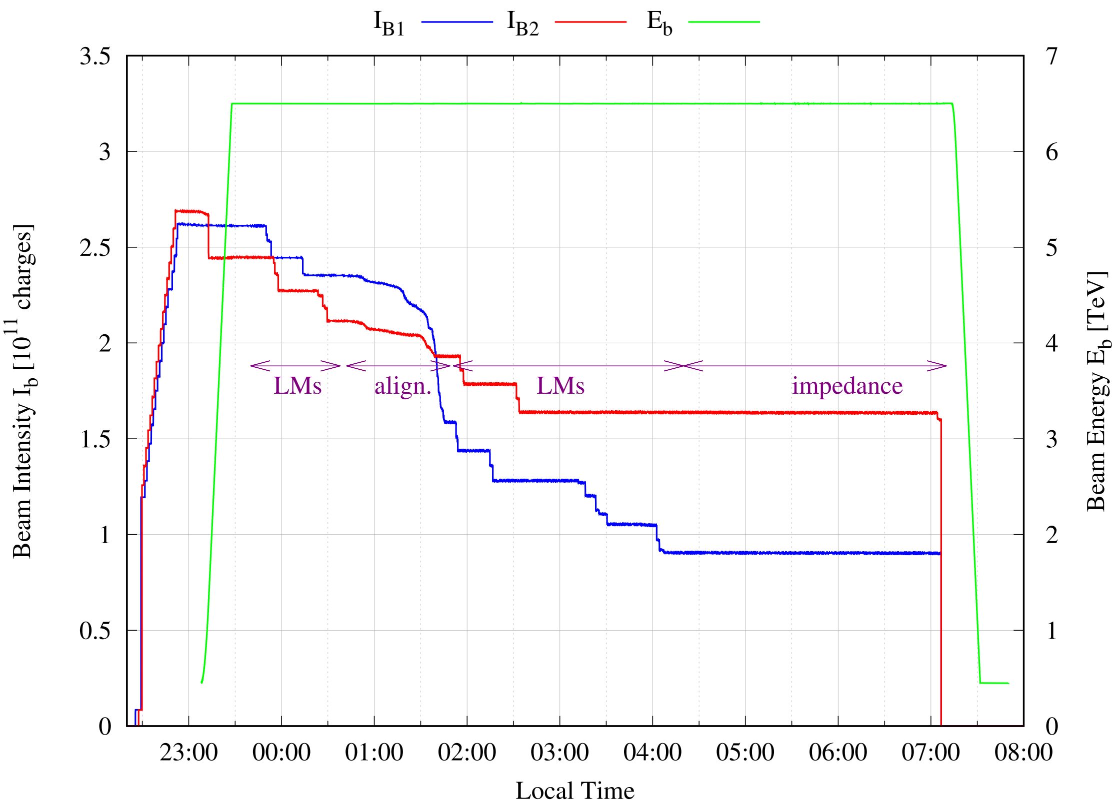

Figure 1: Intensity of B1 (blue curve) and B2 (red curve) as read by the fast beam current transformer (BCTFR), and beam energy (green curve) during the presented MD activity. The time periods of the main activities carried out are highlighted, namely: loss maps ("LMs"), IR7 collimator alignment ("align."),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

1. BBQ signals were collected with reduced chromaticity and octupole current. Chirping was also applied;
2. ADT ObsBox [11] signals were collected when coherent betatron oscillations were induced by means of the tune kicker (MKQA);
3. Schottky measurements.

The second method proved to give the most reliable results.

2 Procedure and Beam Conditions

The MD activity was carried out on the night between the 28^{th} and the 29^{th} July [12, 13, 14], 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 but remaining at 3 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.

Each beam was composed by a nominal bunch followed by a series of 17 pilots (so as to respect the limit set by the "set up beam flag", i.e. 3 10^{11} protons at flat top, which allows to mask interlocks). 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 by the potentially large number of loss maps necessary to adequately spot the source of the hierarchy breakage. The filling scheme named as "30 Bunches for MUFO spaced" was partially filled. The initial drop down in B2 current taking place at 23:10 was due to a trip of a module of RF cavities.

The MD activity was divided in two parts, i.e. IR7 collimator hierarchy limit and alignment as first, and impedance measurements as second.

3 Results

3.1 IR7 Collimator Hierarchy Limit and Alignment

A first set of betatron loss maps was carried out with the operational gaps of the IR7 secondary collimators (i.e. 7.5 σ) prior to any activity, as reference (see Figs. A.1 and A.2). In this configuration, secondary collimators are retracted by 2 σ from the primary collimators. Patterns are similar to those found during the initial commissioning with beam in 2016 [15], and values of cleaning inefficiency agree within 10-20 %.

Afterwards, the gaps were reduced to the configuration of interest, i.e. to the 1 σ-retraction from primary collimators (i.e. at 6.5 σ), still using the operational values of the collimator centres, and loss maps were performed to spot any hierarchy breakage. As shown in Figs. A.3 and A.4, there is indeed a problem of transverse hierarchy when 1 σ-retractions are deployed, confirming the observations from 2015 [9].

All IR7 collimators were then re-aligned to the beam, to verify alignment stability and try faster alignments. Harder scraping conditions were found on B1, especially during the alignment of the skew collimators (i.e. the last ones in the alignment procedure), which caused a visible fraction of beam scraped away (see Fig. 1, at ∼01:30). It took longer to accomplish the alignment of the entire IR7 collimation system with respect to last year, i.e. 1h:10m instead of 50m. Figure 2 shows the comparison between collimator centres as measured during the MD activity and the initial commissioning with beam; values agree within 100 μm, and this level of reproducibility can be regarded as satisfactory.

Betatron loss maps with 1 σ-retractions between TCPs and TCSGs were carried out deploying the beam-beased centres just found during the alignment, to rule out the possible degradation of the collimator alignment over some months as possible source of the hierarchy breakage. Nominal (i.e. as from linear optics) and measured (i.e. as reconstructed by the alignment procedure) beam σ were tried, to verify with beam any mitigation offered by deploying the latter, as found last year. No apparent issue with the hierarchy was found, in contradiction with the observations from 2015.

After detailed checks, it was finally found that the orbit in IR7 had drifted after alignment. In fact, despite being limited in value, the shift in the region at the primary collimators effectively set the TCP back as primary bottleneck, preventing to observe again the hierarchy breakage in any B1V loss map performed after the alignment (see Fig. 3). Since the orbit was distorted also in the other beams/planes (though with less evident effects), none of these loss maps are reported here.

About two hours passed (i.e. from 01:30, corresponding to the end of the alignment campaign, to 03:30, when the closed orbit was corrected back to the reference one) before the problem with the closed orbit was identified and corrected back, and the breakage of the hierarchy was visible again. With the remaining limited time, it was anyway possible to verify that compensating the angular misalignment of the tank with appropriate jaw angles at the collimator responsible of the breakage can restore the proper IR7 hierarchy.

Therefore, once the closed orbit was set back to the reference one, a B1V reference loss map

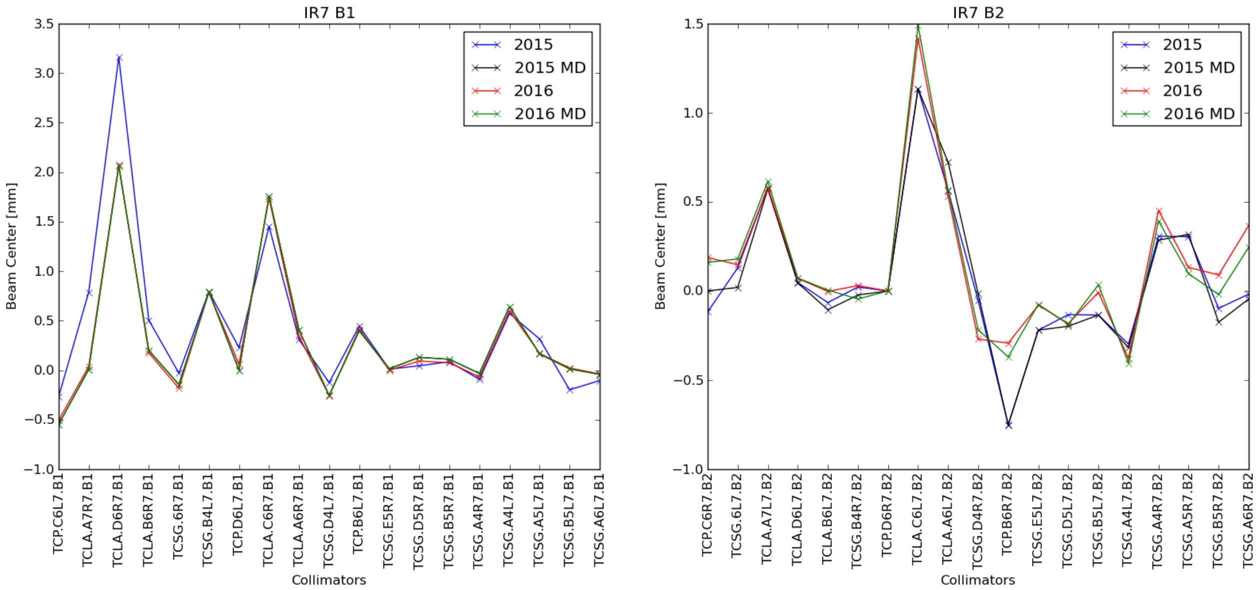

Figure 2: IR7 collimator centres as from the alignment campaign carried out during this MD, compared to past results, i.e. from initial commissioning with beam in 2016 and in 2015, and from last year MD. Left frame: B1 collimators. Right frame: B2 collimators.

Table 2: Collimator names and misalignment angles as from the initial commissioning with beam [16] considered as candidate source of the IR7 hierarchy breakage. The nominal transverse skew angle applied to the collimator and the beam σ on the respective cleaning plane are reported as well.

name	measured misalignment angle [μrad]	skew angle [°]	beam σ [μm]
TCSG.A4L7.B1	500	134.6	255
TCSG.D4L7.B1	-350	90	200
TCSG.A5L7.B1	-300	40.7	290

was taken, confirming the broken hierarchy (see Fig. 4, top-left frame). Afterwards, tilt angles equal to the misalignment ones found during the initial commissioning with beam [16] were applied to the three TCSG collimators with the largest values (see Tab. 2). Another B1V loss map was therefore taken, showing the regular hierarchy restored (see Fig. 4, top-right frame). Then, the tilt angles were removed from the jaw settings, one collimator after the other one, until the collimator at the origin of the hierarchy breakage was spot.

As it can be seen, the collimator at the basis of the collimation hierarchy breakage is TCSG.D4L7.B1. The picture is consistent as:

1. the breakage took place on B1V, and the concerned collimator is the only secondary collimator on the vertical plane;

2. the identified misalignment angle corresponds to a transverse shift of the jaw corners which is of the same order of magnitude of the beam σ at the collimator;

3. having the smallest value of beam σ, any mis-configuration of the jaws leading to mis-centring the jaws has the largest impact in terms of normalised coordinates.

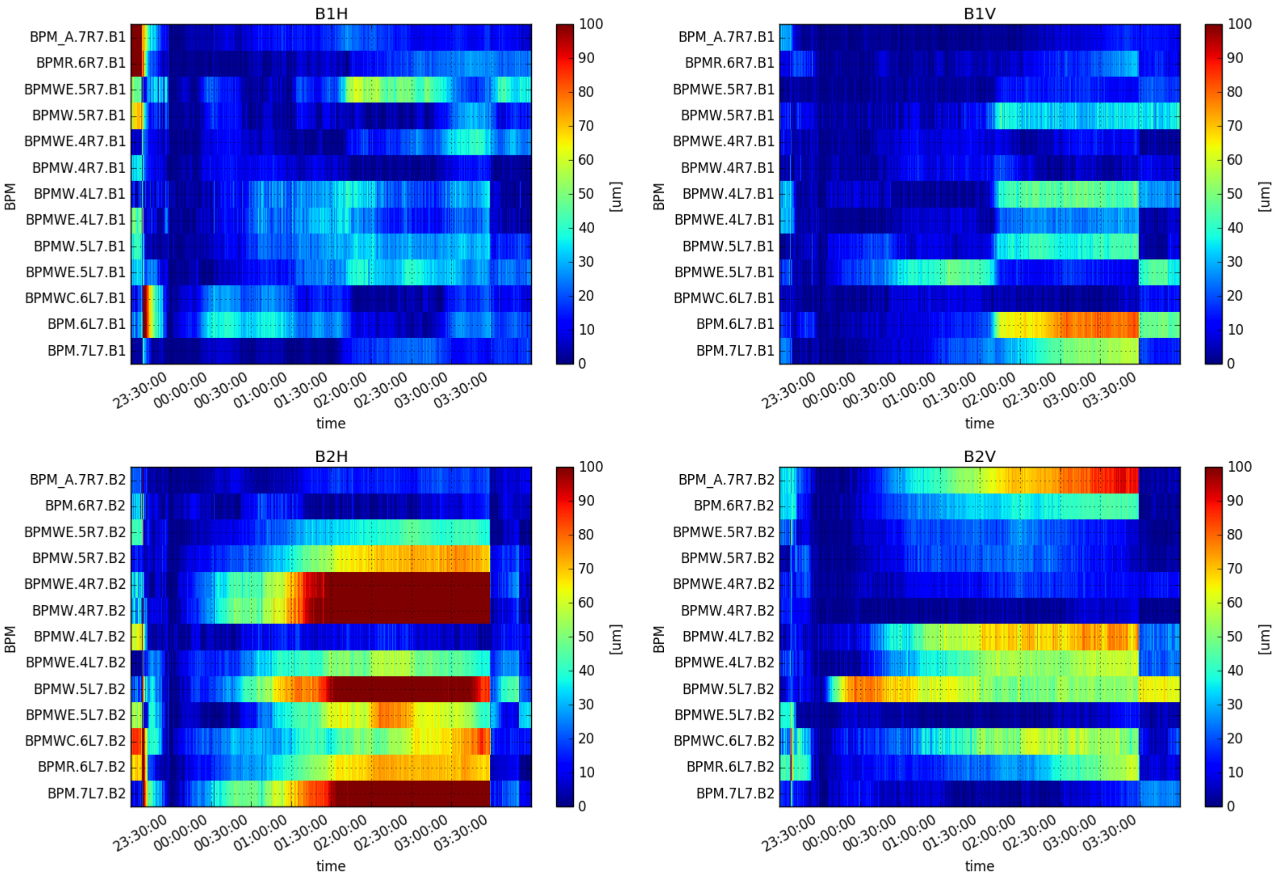

Figure 3: Readouts of IR7 BPMs throughout the MD activity on collimator hierarchy limit; for the sake of clarity, the absolute value of the shift with respect to the readout at the end of the ramp (∼23:30) is actually shown. Upper frames: B1; lower frames: B2. Left frames: horizontal plane; right frames: vertical plane. To be noted the sharp change in the color maps at 03:30, corresponding to the correction of the closed orbit.

Hence, the relatively large misalignment angle of the tank leads the collimator to provide a cut further in than the nominal one, which becomes particularly evident when the TCP-TCSG retraction is pushed.

3.2 Impedance measurements

The impedance measurements were performed mainly measuring the tune shift induced by changing collimator gaps. In order to improve the signal from the tune, it was decided to kick the beam with the MKQA [17], and reconstruct the tune from the damped coherent oscillations.

Few minutes were spent at the beginning of the whole MD activity at injection to set up the tune kicker (see Fig. 5). In particular, the synchronization delays were set to 65.5 μs and 32 μs for B1V and B2V, respectively. These correspond to centering the plateau of the MKQA kick at bucket 1101 and 1001 of B1 and B2, respectively, where the nominal bunches where injected.

An overview of the tune shift versus collimator gap measurements is shown in Fig. 6. As previously mentioned, the measurement of the tune shift was first attempted using the BBQ system to record the tune variation while moving the full set of secondaries in IR7. The chirp excitation was used followed by MKQA kicks. The Schottky was continuously recording data during the MD.

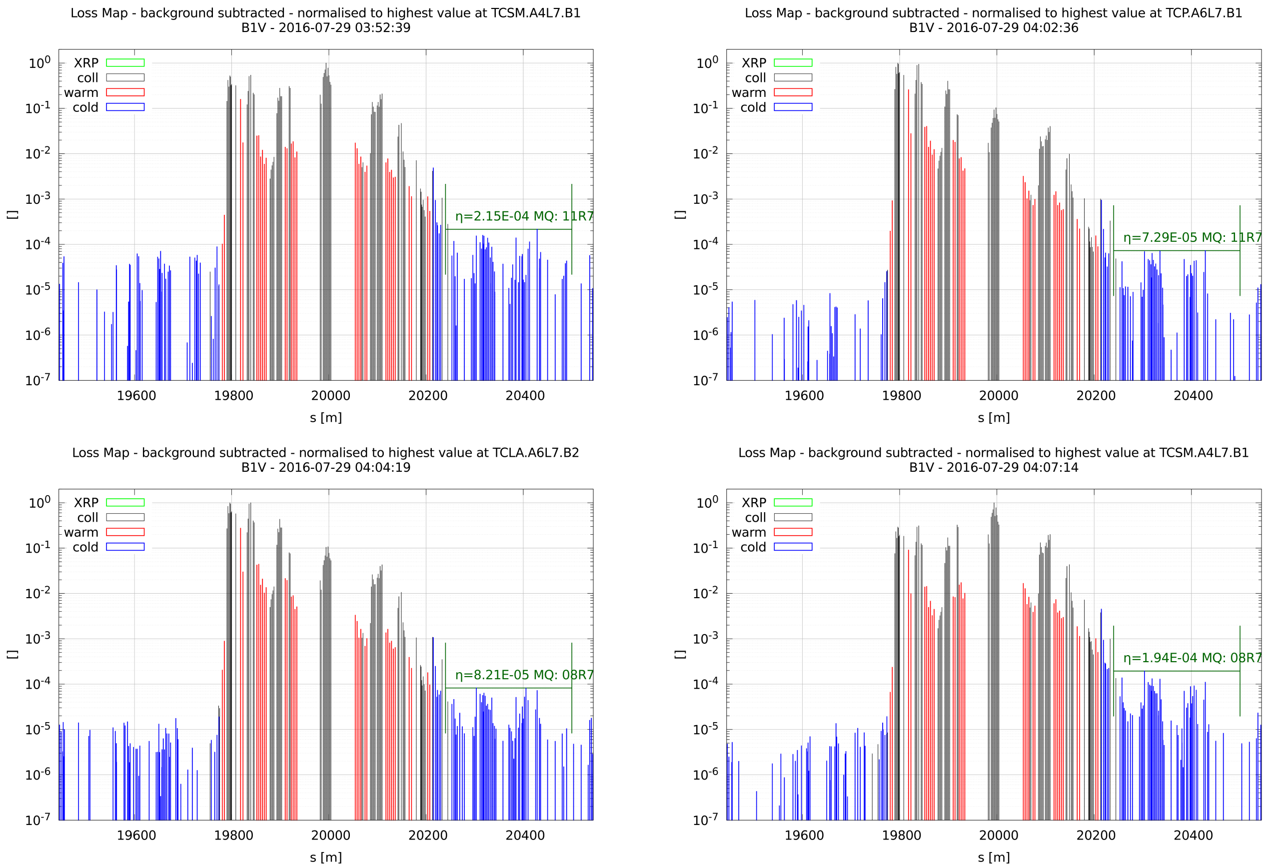

Figure 4: B1V loss maps (actually zooms on IR7) obtained with different configurations of applied tilt angles to TCSG jaws. Top-left frame: no tilt angle applied to any TCSG (i.e. loss map obtained after the reference closed orbit was restored). Top-right frame: all considered tilt angles applied (see Tab. 2). Bottom-left frame: tilt of the TCSG.A4L7.B1 jaws was removed. Bottom-right frame: tilt of the TCSG.D4L7.B1 jaws was removed.

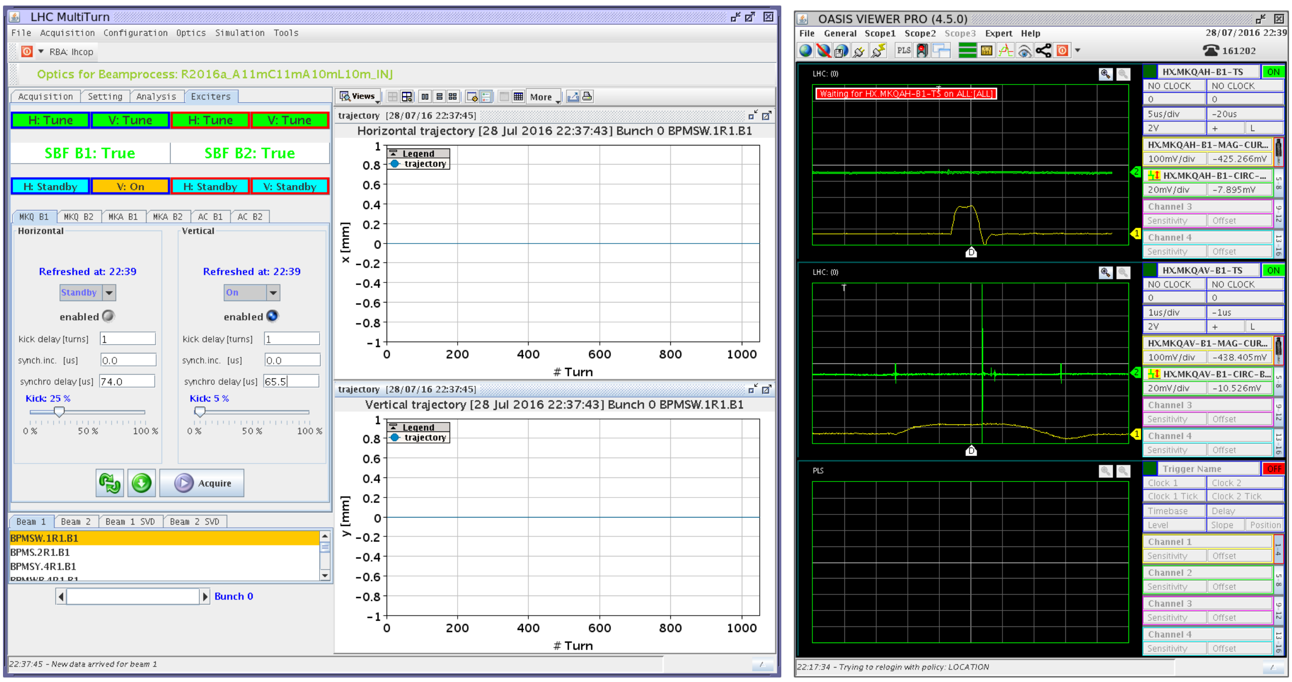

Figure 5: MKQA settings used for the tune shift measurements.

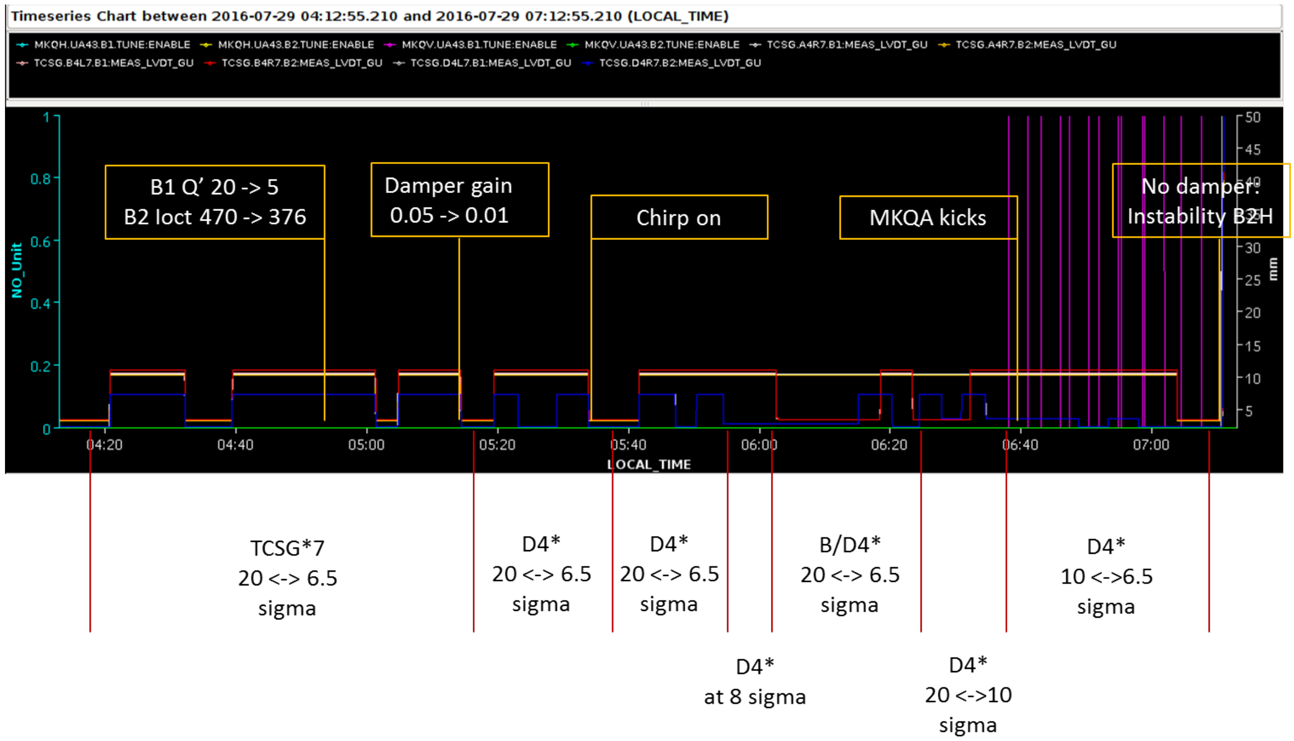

Figure 6: Overview of tune shift measurements.

More details concerning the data analysis can be found in [18].

The MD activity ended with a measurement of instability threshold with the ADT switched off with TCSGs set at 6.5 σ, to verify the need for the ADT to stabilise the LHC beams in case IR7 collimator settings are further pushed.

3.2.1 Measurements with the BBQ system

Table 3 resumes the main outcomes of measurements with the BBQ system. As one can see, the tune shift is only visible when all the TCSGs are moved from 20 σ to 6.5 σ, whereas it is very difficult to draw conclusions when single collimators are moved.

As an example, Fig. 7 shows the BBQ signal recorded during the first scan: the noise lines around the tune are dominating the spectrum, and only a careful analysis with SUSSIX [19] allows to identify a better correlation with the gap movement as one can see in Fig. 8. After averaging the signal and compensating for the tune drift, the tune shift distribution can be inferred, from which mean and standard deviation are calculated, as shown in Figs. 9 and 10.

The entire set of TCSGs in IR7 was moved an the tune shift recorded from the BBQ system.

3.2.2 Measurements with the Chirp excitation

Figure 11 shows the effect of the chirp excitation on the BBQ spectrum. As it can be seen, the tune line is excited together with the adjacent noise lines, making it difficult to disentangle the actual tune line from the noise ones. Therefore, the chirp excitation cannot be of practical use.

Table 3: Summary of tune shifts as a function of collimator gaps as predicted by simulations and measured with beam using the BBQ system. The column "interval" allows the reader to better understand the machine configuration occurring at the specified local time (see Fig. 6).

B1	Beam parameters			Collimator settings				Measured		Simulated	
Scan	Nb [1e11]	b.length [ns]	Qp	Comment	time OUT	time IN	Interval	H	V	H	V
#1a	0.88	0.96	15	TSG*7 20 -> 6.5	4:24	4:19	4:10 -> 4:50	1.0 +/- 0.3	1.9 +/- 0.3	1.5	1.5
#1b	0.88	0.96	5	TSG*7 20 -> 6.5	4:24	4:19	4:59 -> 5:17	N.A.	1.9 +/- 0.8	1.8	1.8
#2	0.88	0.93	5	TCSG.D4L7 20 -> 6.5	5:21	5:26	5:20 -> 5:31	N.A.	0.27 +/- 0.47	~0	0.43
#3	0.88	0.92	5	TCSG.D4L7 20 -> 8.0	5:51	6:04	5:51 -> 6.19	N.A.	N.A.	~0	0.2
#4	0.88	0.92	5	TCSG.B4L7 20 -> 6.5	6:00	6:10	5:56 -> 6:38	N.A.	N.A.	0.34	~0
#5	0.88	0.92	5	TCSG.D4L7 20 -> 10	6:31	6:30	6:25 -> 6:37	N.A.	N.A.	~0	0.12
#6	0.88	0.91	5	TCSG.D4L7 10 -> 6.5	6:56	6:52	6:46 - 6:59	-	0.39 +/- 0.10	~0	0.32

B2	Beam parameters			Collimator settings				Measured		Simulated	
Scan	Nb [1e11]	b.length [ns]	Qp	Comment	time OUT	time IN	Interval	H	V	H	V
#1a	0.97	0.85	15	TSG*7 20 -> 6.5	4:24	4:19	4:10 -> 4:50	0.62 +/- 0.14	1.5 +/- 0.3	1.81	1.81
#1b	0.97	0.85	15	TSG*7 20 -> 6.5	4:24	4:19	4:59 -> 5:17	0.65 +/- 0.44	2.0 +/- 0.7	1.81	1.81
#2	0.97	0.88	15	TCSG.D4R7 20 -> 6.5	5:21	5:26	5:20 -> 5:31	~0	N.A.	~0	0.43
#3	0.97	0.88	15	TCSG.D4R7 20 -> 8.0	5:51	6:04	5:51 -> 6.19	N.A.	N.A.	~0	0.26
#4	0.97	0.87	15	TCSG.B4R7 20 -> 6.5	6:00	6:10	5:56 -> 6:38	N.A.	N.A.	0.32	~0
#5	0.97	0.89	15	TCSG.D4R7 20 -> 10	6:31	6:30	6:25 -> 6:37	N.A.	N.A.	~0	0.11
#6	0.97	0.89	15	TCSG.D4R7 10 -> 6.5	6:56	6:52	6:46 - 6:59	-	-	~0	0.31

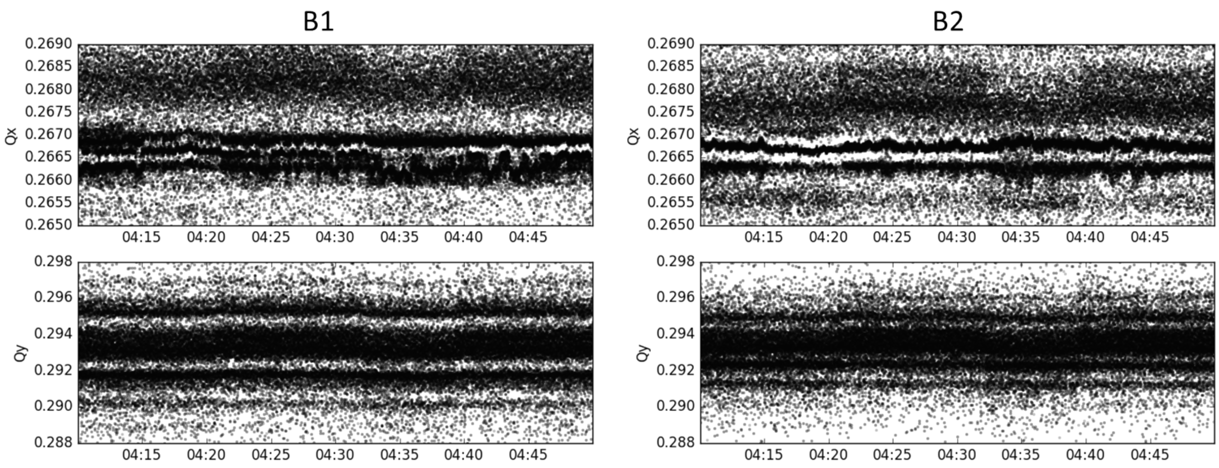

Figure 7: B1 and B2 spectrogram from the BBQ, post-processed with SUSSIX.

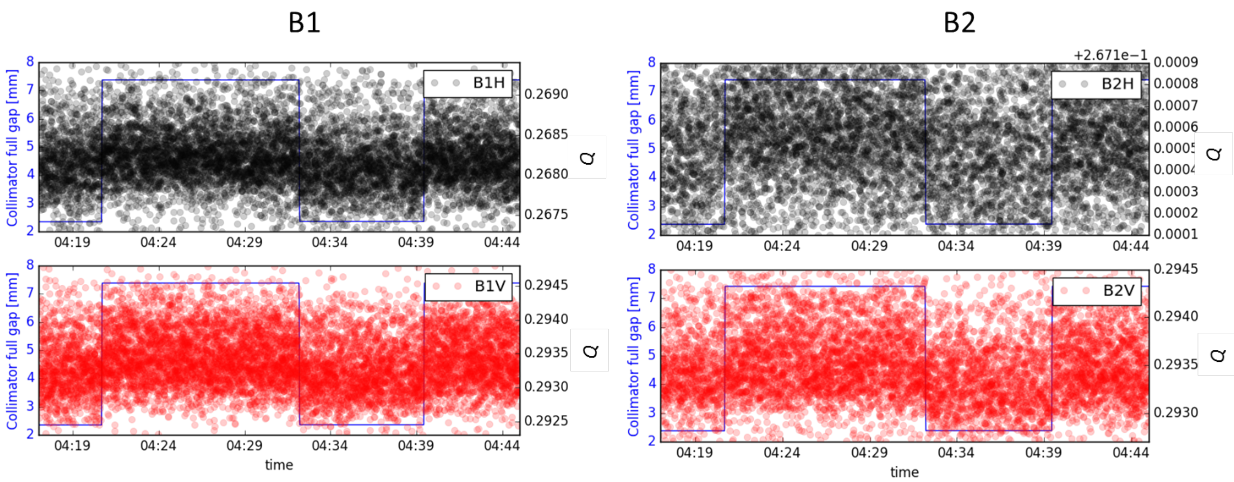

Figure 8: B1 and B2 spectrogram from the BBQ, post-processed with SUSSIX, and filtered around the expected tune value.

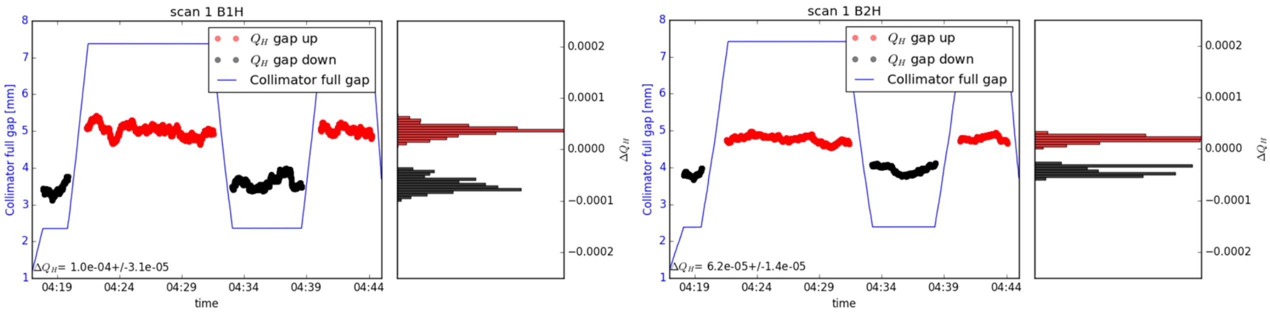

Figure 9: Average horizontal tune shift versus collimator gaps as from measurements when moving all IR7 TCSGs.

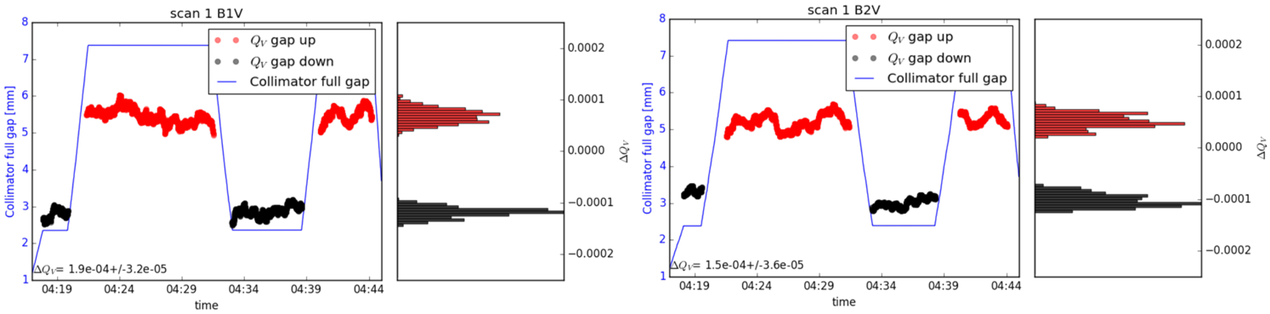

Figure 10: Average vertical tune shift versus collimator gaps as from measurements when moving all IR7 TCSGs.

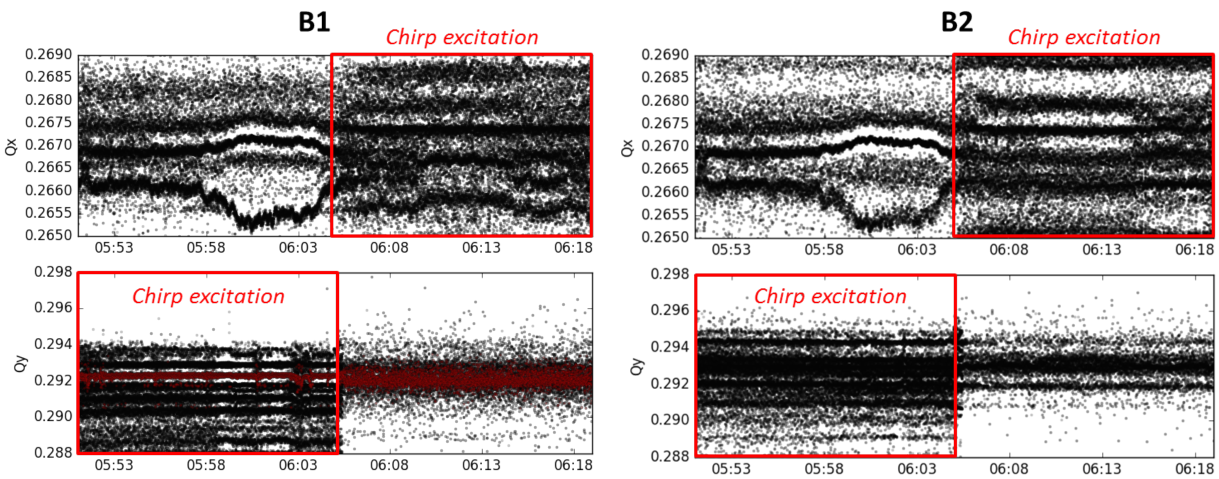

Figure 11: B1 and B2 spectrogram from the BBQ post-processed with SUSSIX. The segments during which the chirp excitation was applied are shown in red.

3.2.3 Measurements with the MKQA excitation

Remarkable results were achieved by using the MKQA excitation. Kicks were sent and data recorded by the BBQ and the ADT systems. The spectrogram of the excitation is shown in Fig. 12 while an example of excitation is shown in Fig. 13, where more than 1000 turns of coherent oscillation could be recorded. The corresponding frequency analysis of the performed series of kicks is also reported and an accuracy of the order of 10^{-5} could be achieved for the

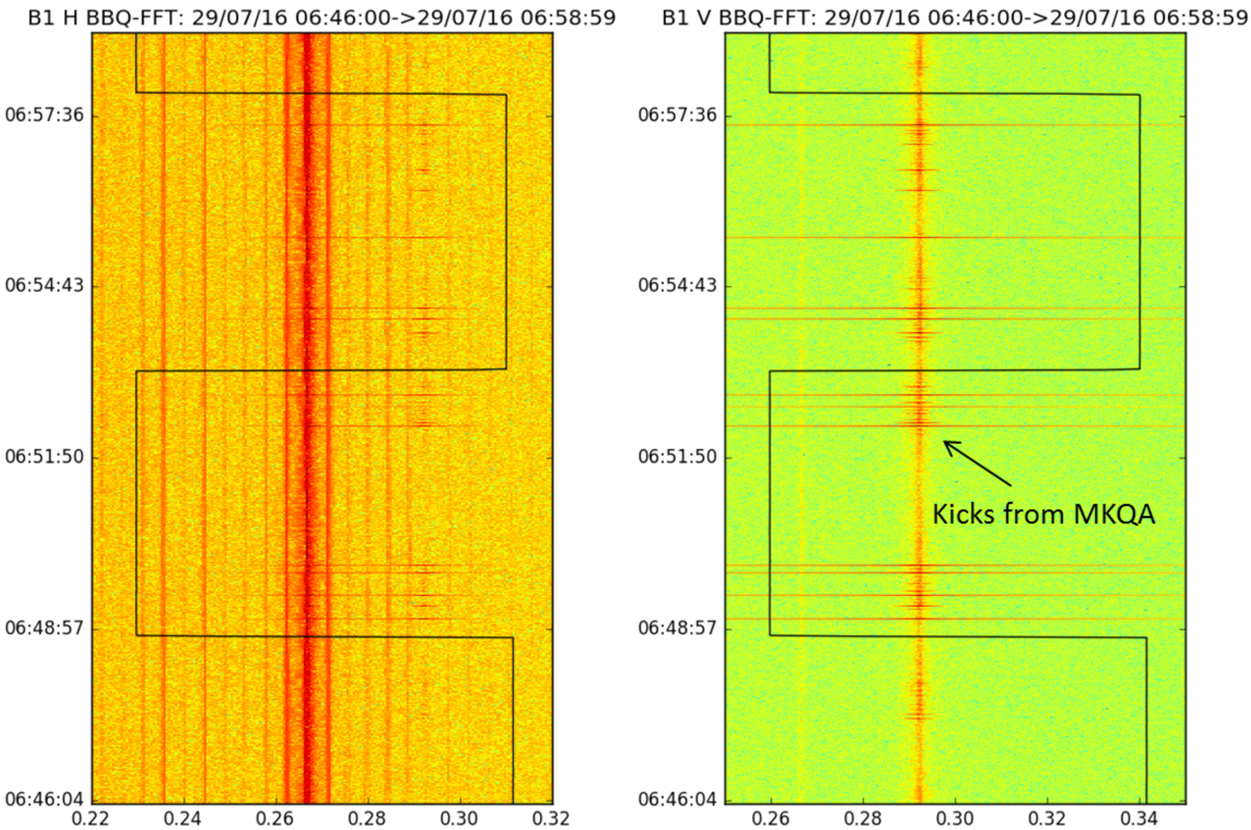

Figure 12: B1 spectrogram during TCSG.D4L7.B1 collimator movement.

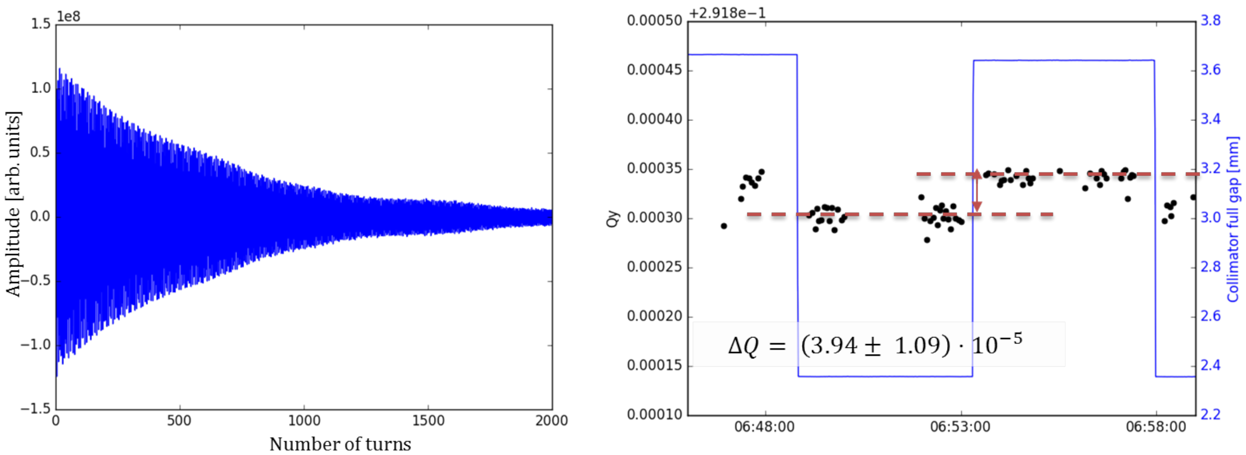

Figure 13: BBQ signal after MKQA excitation (on the left) and corresponding post-processed tunes (on the right).

first time. The tune shift of the TCSG.D4L7.B1 was measured and agrees with the impedance model predictions within 20%, as also reported in Tab.3.

Compatible results were achieved by post-treating the coherent signal recorded by the ADT pickups as shown in Fig. 14. The ADT has potentially higher versatility in comparison to the MKQA, giving the possibility to fine tune the kick amplitude, to easily select bunches, to direct data storage from the high resolution pickups, etc... These characteristics make the use of the system promising in view of future MD studies towards the characterization of the impedance

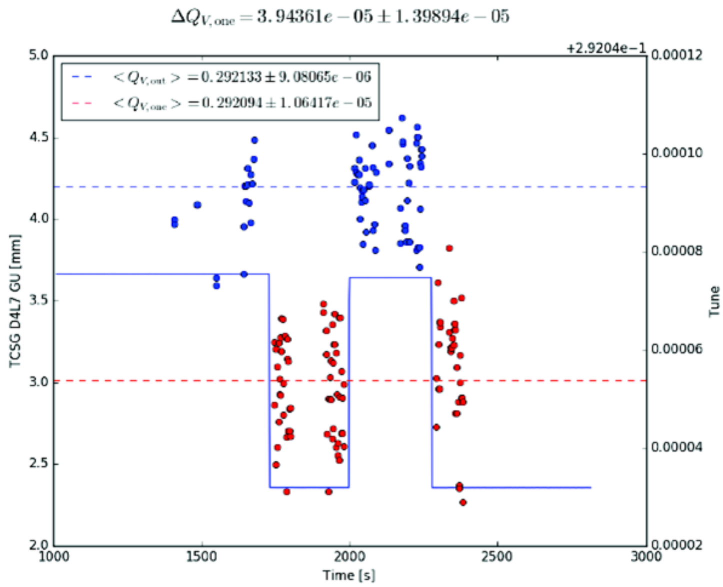

Figure 14: Tune shift as reconstructed by post-processing data from the ADT pickups.

of each single collimator. Details of the ADT analysis have been reported in [20].

3.2.4 Measurements with the Schottky Acquisition

The Schottky signal was continuously acquired during the collimator movements and post-processed. The results for B1H are showed in Fig. 15, compared to the vertical movements of the TCSG.D4L7.B1, and in a zoomed view in Fig. 16, compared also against the movements of the TCSG.B4L7.B1. A correlation between the B1H tune signal and the vertical movement of the TCSG.D4L7.B1 collimator can be noticed: despite this seems unexpected and counter intuitive, there might be an effect of the incoherent tune into the measurement, which is under investigation.

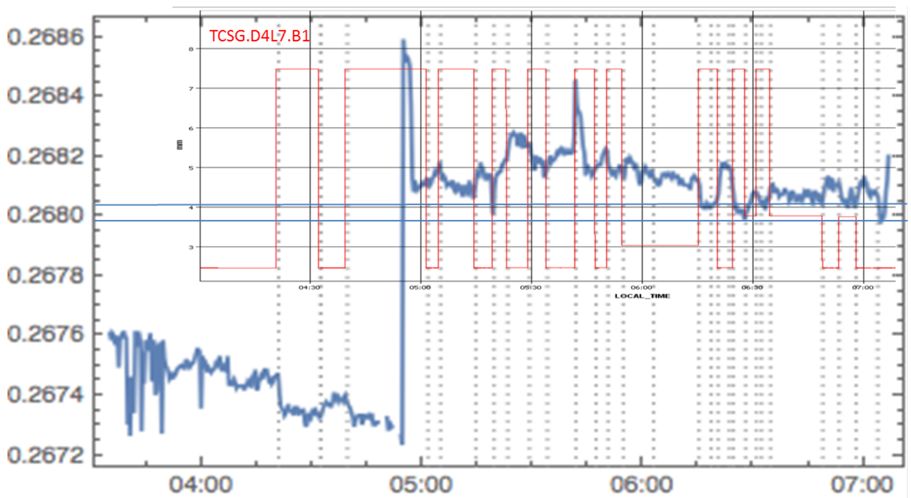

Figure 15: Schottky acquisition for B1H and correlation to the movement of the TCSG.D4L7.B1.

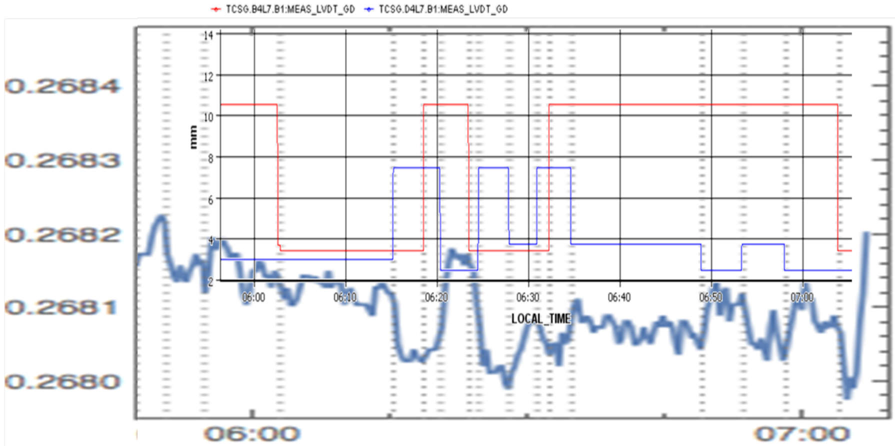

Figure 16: Schottky acquisition for B1H and correlation to the movements of the TCSG.D4L7.B1 and TCSG.B4L7.B1 collimators, zoomed view.

Similar conclusions can be drawn for the measurements on B2H, showed in Fig. 17, where a correlation between the movement of the TCSG.B4R7.B2 collimator and the horizontal tune change is found.

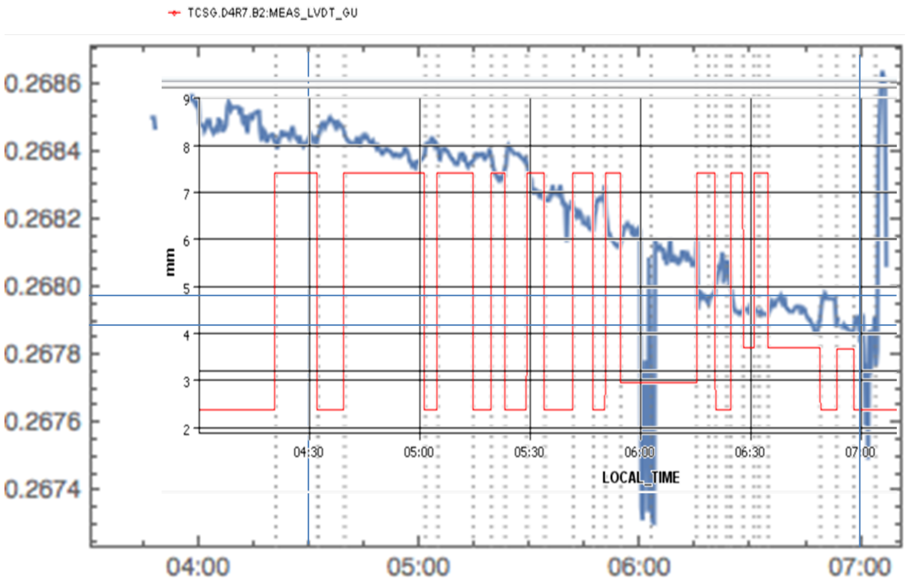

Figure 17: Schottky acquisition for B2H and correlation to the movement of the TCSG.B4R7.B2 collimator.

The measurements on the vertical planes of B1 and B2 did not show any significant tune variation, as shown in Figs. 18 and 19. The measurement on B2, in particular, was largely dominated by the tune drift.

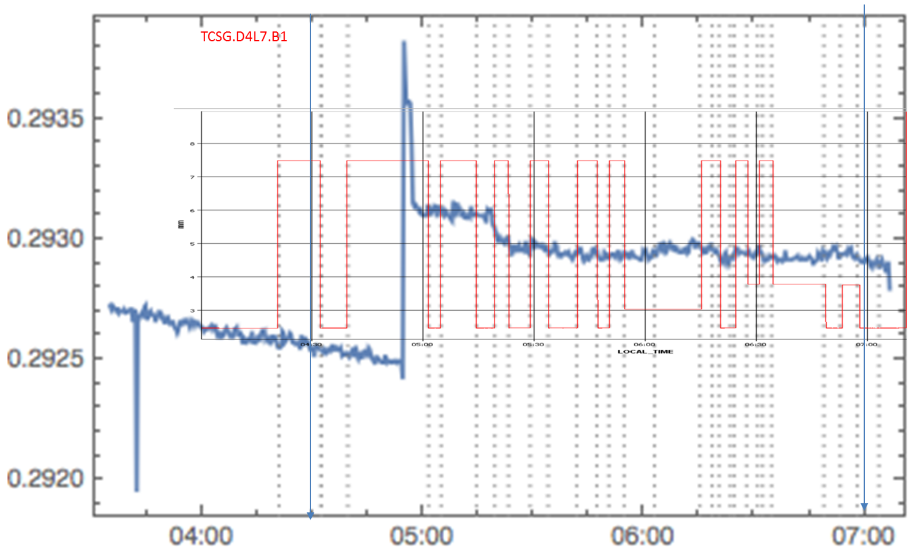

Figure 18: Schottky acquisition for B1V and correlation to the movement of the TCSG.D4L7.B1.

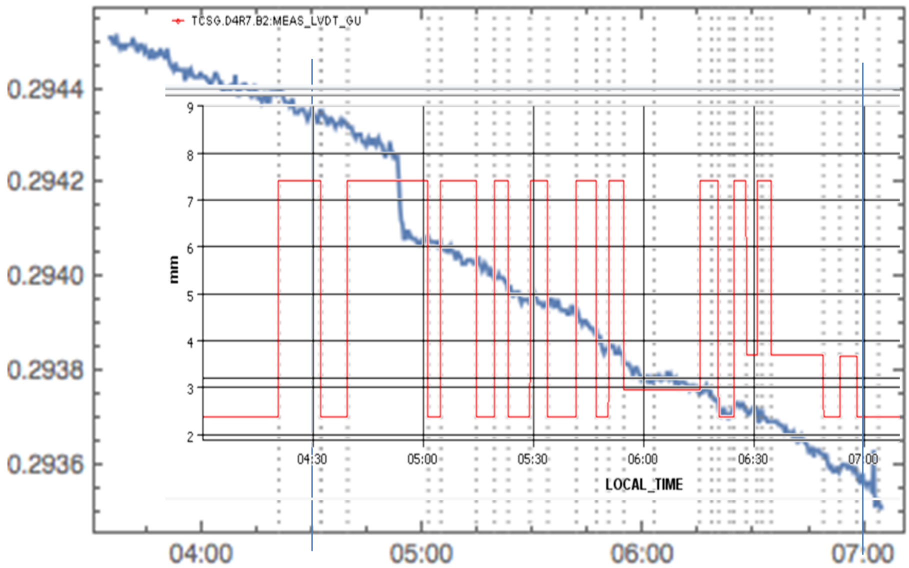

Figure 19: Schottky acquisition for B2V and correlation to the movement of the TCSG.B4R7.B2 collimator.

3.2.5 Instability observations

In order to benchmark the present transverse impedance model, at the end of the MD, all the TCSGs in IR7 were set to 6.5σ and the transverse damper was switched off, leaving the octupoles at 370 A as the only stabilizing mechanism. As shown in Fig. 20, an instability started in B2H. The main beam and machine parameters are summarized in Tab. 4. The instability exhibited a head-tail azimuthal mode $m = -1$ (see spectrogram in Fig. 21) and a rise time of $\tau = 1.2$ s. The comparisons to the expected octupole current threshold and unstable mode are shown in Figs. 22 and 23, and are in reasonably good agreement respectively with NHTVS [21] and DELPHI [22] simulations for $Q' = 15$.

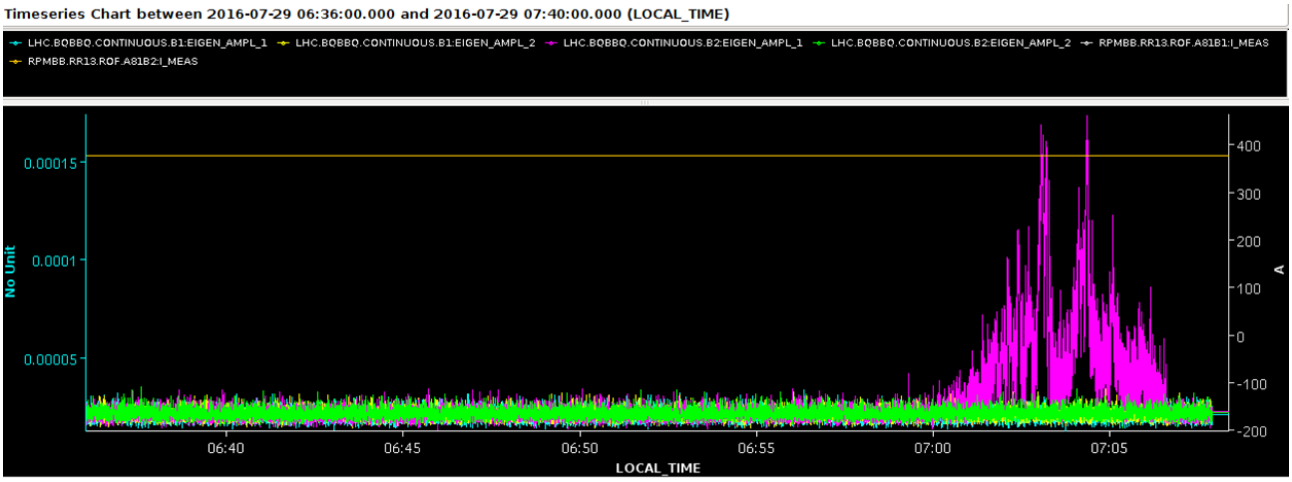

Figure 20: Amplitude signal versus time for both B1 and B2 and current in the octupoles. The instability arises only in B2.

Fill	Time	Beam/Plane	N_b [10^{11}]	Q'	$\varepsilon_{n,x/y}$ [μm]	m []	l []	τ [s]	Gain	I_{oct} [A]	σ_b^{rms} [m]
5130	7:04	B2H	0.97	15	2.7/2.1	-1	?	1.2	Inf	376	0.067

Table 4: Summary of beam and machine parameters during the observed B2H instability.

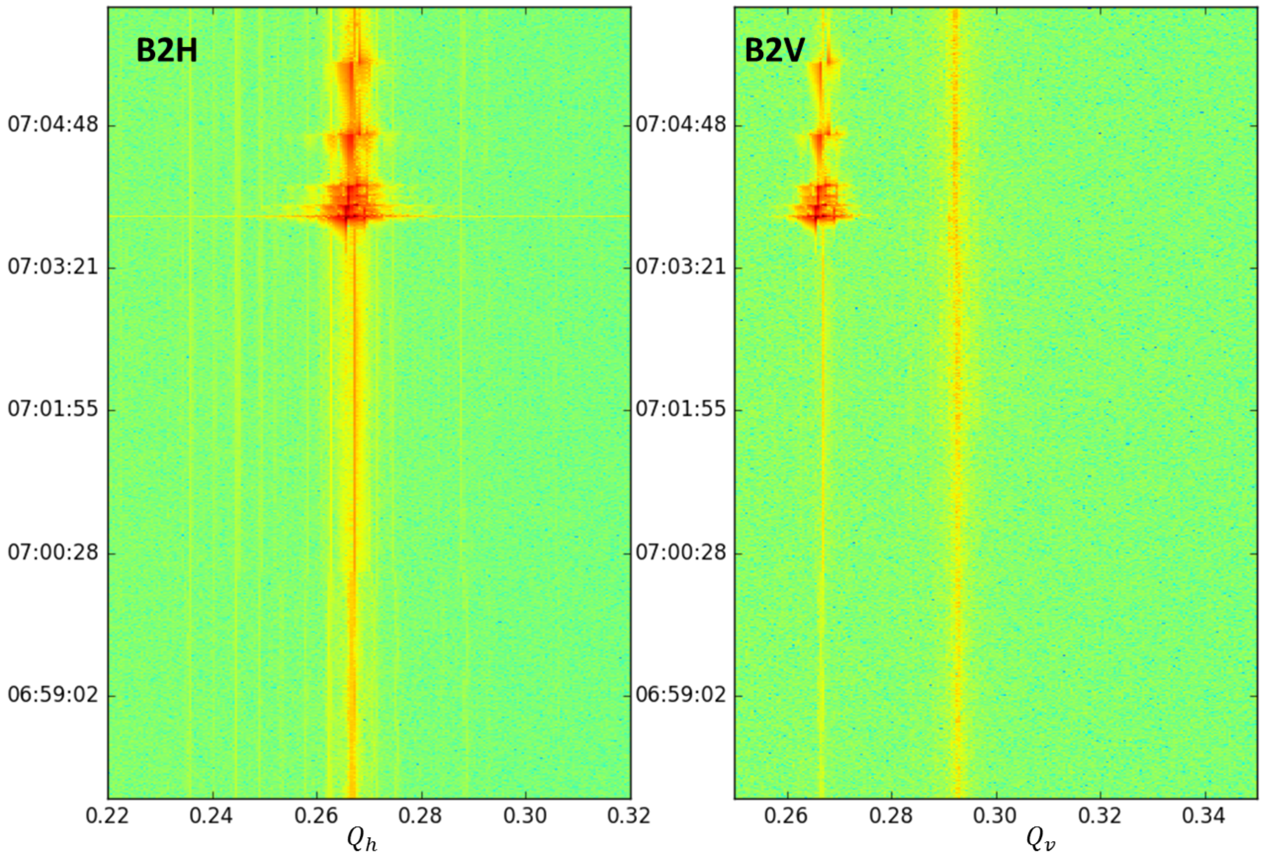

Figure 21: Spectrogram of the BBQ signal of B2. After 07:03, the instability starts in the horizontal plane and it is visible, through coupling, also in the vertical plane.

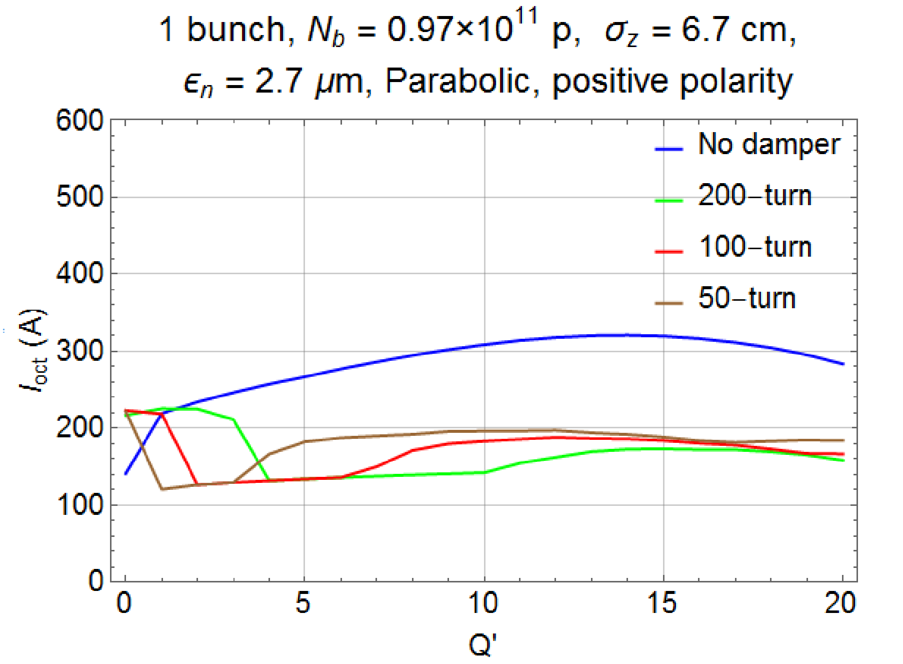

Figure 22: Octupole current threshold expected from NHTVS simulations versus Q' and damper gain, for a single bunch of 6.7 cm rms bunch length, 2.7 μm emittance and 0.97 10^{11} p^+.

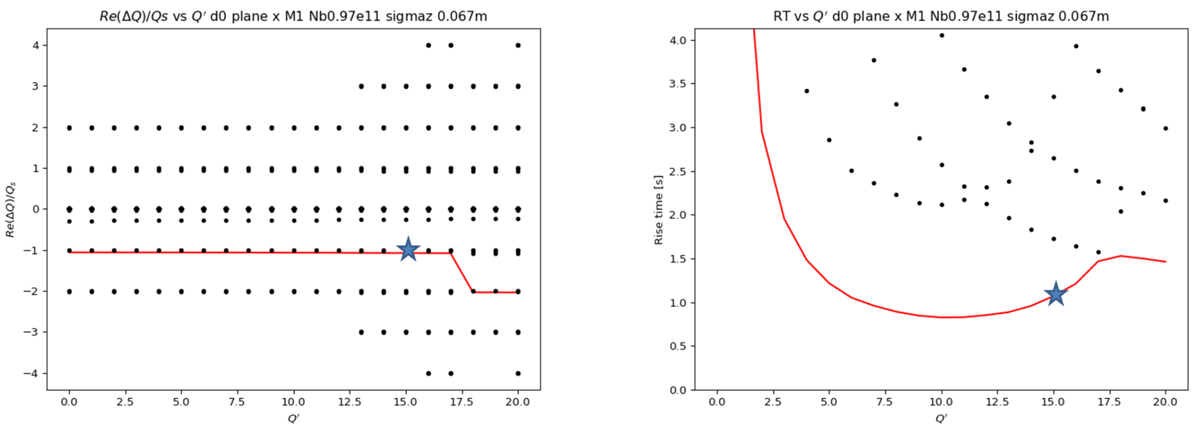

Figure 23: Head-tail azimuthal mode number (left) and rise time without octupoles (right) expected from DELPHI simulations versus Q' and damper gain, for a single bunch of 6.7 cm rms bunch length and 1.2 10^{11} p^+. The observed instability is marked by the blue star, whereas the red line represents the most unstable mode.

4 Conclusions

The first part of the MD activity was devoted to IR7 hierarchy limit measurements, whereas the second one was devoted to impedance measurements.

4.1 Hierarchy limit

The IR7 collimation system was qualified in terms of local cleaning inefficiency in the downstream DS with 2016 operational settings and with 1 σ-retractions between TCP and TCSG collimators, smaller than those deployed operationally. Findings of past year measurements were confirmed, i.e. the IR7 hierarchy is broken on B1V when such retractions are deployed.

The system was fully re-aligned to the beam in 1h:10m (i.e. 20 minutes more than the 2015 record). The alignment proved to be very stable, with modified centres within 100 μm, not in a preferential direction.

The TCSG.D4L7.B1 was found to be at the origin of the hierarchy breakage on B1V. The relatively large misalignment angle of the tank leads the collimator to provide a cut further in than the nominal one, which becomes particularly evident when the TCP-TCSG retraction is pushed.

4.2 Impedance Measurements

Challenging measurements of tune shift induced by single collimator at flat top were carried out. In terms of methodology, several different methods were compared, with the coherently kicking of beams via MKQA being the most promising one. The accuracy on single collimator tune shift reached the order of 10^{-5}. Schottky signals were also analyzed, showing a good potential for continuous non-destructive measurement of the beam tune, even though the interpretation of data is still on-going.

The impedance of the TCSGs in IR7 was measured with the BBQ and compared to expectations. The vertical impedance was found within $\simeq$ 20%, in agreement to the model, while the horizontal impedance was found much lower than expected. The discrepancy may arise from an incomplete knowledge of the beam and machine parameters (e.g. chromaticity, bunch longitudinal profile, etc. . .). On the other hand, the measurement on the single collimator tune shift TCSG.D4L7.B1 performed with the advanced techniques involving MKQA and ADT is in excellent agreement with the model.

The MD activity ended with a measurement of instability threshold with the ADT switched off, showing the need for it when TCSGs are set at openings as tight as 6.5 σ. The instability was observed in B2H, in good agreement with the expectation from the LHC transverse impedance model.

Acknowledgements

We would like to thank the OP crew, and in particular M. Albert, R. Alemany Fernandez, G. Crockford, K. Fuchsberger, G. H. Hemelsoet, and M. Pojer, for their assistance during the MD activity.

References

[1] N. Mounet *et al.*, in *Proc. IPAC'13*, pp. 1817–1819.

[2] G. Apollinari *et al.* (eds.), "High Luminosity Large Hadron Collider (HL-LHC) Technical Design Report V.01", CERN, Geneva, Switzerland, Rep. CERN–2017–007–M, Sep. 2017. `https://cds.cern.ch/record/2284929?ln=en`

[3] A. Bertarelli *et al.*, "2014 Development and testing of novel advanced materials with very high thermal shock resistance", in *Proc. Tungsten, Refractory and Hardmetals Conference*, Orlando, Florida, USA, May 2014.

[4] N. Mariani, "Development of Novel, Advanced Molybdenum–based Composites for High Energy Physics Applications", PhD. thesis, Politecnico di Milano, 2014.

[5] J. Guardia-Valenzuela *et al.*, "Development and properties of high thermal conductivity molybdenum carbide - graphite composites", in *Carbon*, vol. 135, 2018. doi: 10.1016/j.carbon.2018.04.010

[6] D. Amorim *et al.*, "HL-LHC impedance and related effects", CERN, Geneva, Switzerland, Rep. CERN–ACC–NOTE–2018–0087, Dec. 2018. https://cds.cern.ch/record/2652401

[7] A. Mereghetti *et al.*, "MD1875 – Impedance Contribution of Single IR7 Secondary Collimators", Rep. CERN–ACC–NOTE–2020–0022 (2020), CERN, Geneva, Switzerland, https://cds.cern.ch/record/2715362

[8] S. Redaelli *et al.*, "MD1446 – β^*–Reach: Impedance Contribution of Primary Collimators", Rep. CERN–ACC–NOTE–2020–0020 (2020), CERN, Geneva, Switzerland, https://cds.cern.ch/record/2715360

[9] A. Mereghetti *et al.*, "β^*–Reach – IR7 Collimation Hierarchy Limit and Impedance", Rep. CERN-ACC-NOTE-2016-0007 (2016), CERN, Geneva, Switzerland, https://cds.cern.ch/record/2120132

[10] R. Bruce and S. Redaelli, "Installation of a low-impedance secondary collimator (TCSPM) in IR7", EDMS. doc. 1705738, https://edms.cern.ch/document/1705738/1.0

[11] M. Soderen, D. Valuch, "ADT ObsBox Data Acquisition", presentation at the LHC Beam Operation Committee, 13th June 2017, CERN, Geneva, Switzerland, https://indico.cern.ch/event/645898

[12] LHC OP elogbook, afternoon shift of 28th June 2016, https://ab-dep-op-elogbook.web.cern.ch/ab-dep-op-elogbook/elogbook/secure/eLogbook.php?shiftId=1077699

[13] LHC OP elogbook, night shift of 28th June 2016, https://ab-dep-op-elogbook.web.cern.ch/ab-dep-op-elogbook/elogbook/secure/eLogbook.php?shiftId=1077708

[14] LHC OP elogbook, morning shift of 29th June 2016, https://ab-dep-op-elogbook.web.cern.ch/ab-dep-op-elogbook/elogbook/secure/eLogbook.php?shiftId=1077712

[15] D. Mirarchi, "Status of Loss Maps Validation", presentation at the LHC Collimation Working Group Meeting, 25th April 2016, CERN, Geneva, Switzerland, https://indico.cern.ch/event/522874/

[16] G. Valentino, "Collimation System Commissioning in 2016", presentation at the LHC Collimation Working Group Meeting, 25th April 2016, CERN, Geneva, Switzerland, https://indico.cern.ch/event/522874/

[17] R. Barlow *et al.*, "Control of the MKQA tuning and aperture kickers of the LHC", Rep. TE–Note–2010–002 (2010), CERN, Geneva, Switzerland, https://cds.cern.ch/record/1232062

[18] N. Biancacci *et al.*, "Outcome of TCSG single collimator impedance and instability measurements", LHC Collimation Working Group n. 207, 22nd August 2016, CERN, Geneva, Switzerland, https://indico.cern.ch/event/564394

[19] R. Bartolini, F. Schmidt, “A Computer Code for Frequency Analysis of Non-Linear Betatron Motion”, Rep. SL–Note–98–017–AP (1998), CERN, Geneva, Switzerland, https://cds.cern.ch/record/702438

[20] D. Valuch *et al.*, “Update on single-collimator impedance measurements” presentation at ColUSM n. 76, 19th August 2016, CERN, Geneva, Switzerland, http://indico.cern.ch/event/562580

[21] A. Burov, “Nested head-tail Vlasov solver”, *Phys. Rev. Special Topics Accel. Beams* 17.021007, Feb 2014.

[22] N. Mounet, “DELPHI: an analytic Vlasov solver for impedance-driven modes”, HSC meeting, 9th April 2014, CERN, Geneva, Switzerland, https://espace.cern.ch/be-dep-workspace/abp/HSC/Meetings/DELPHI-expanded.pdf.

A Loss Maps

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

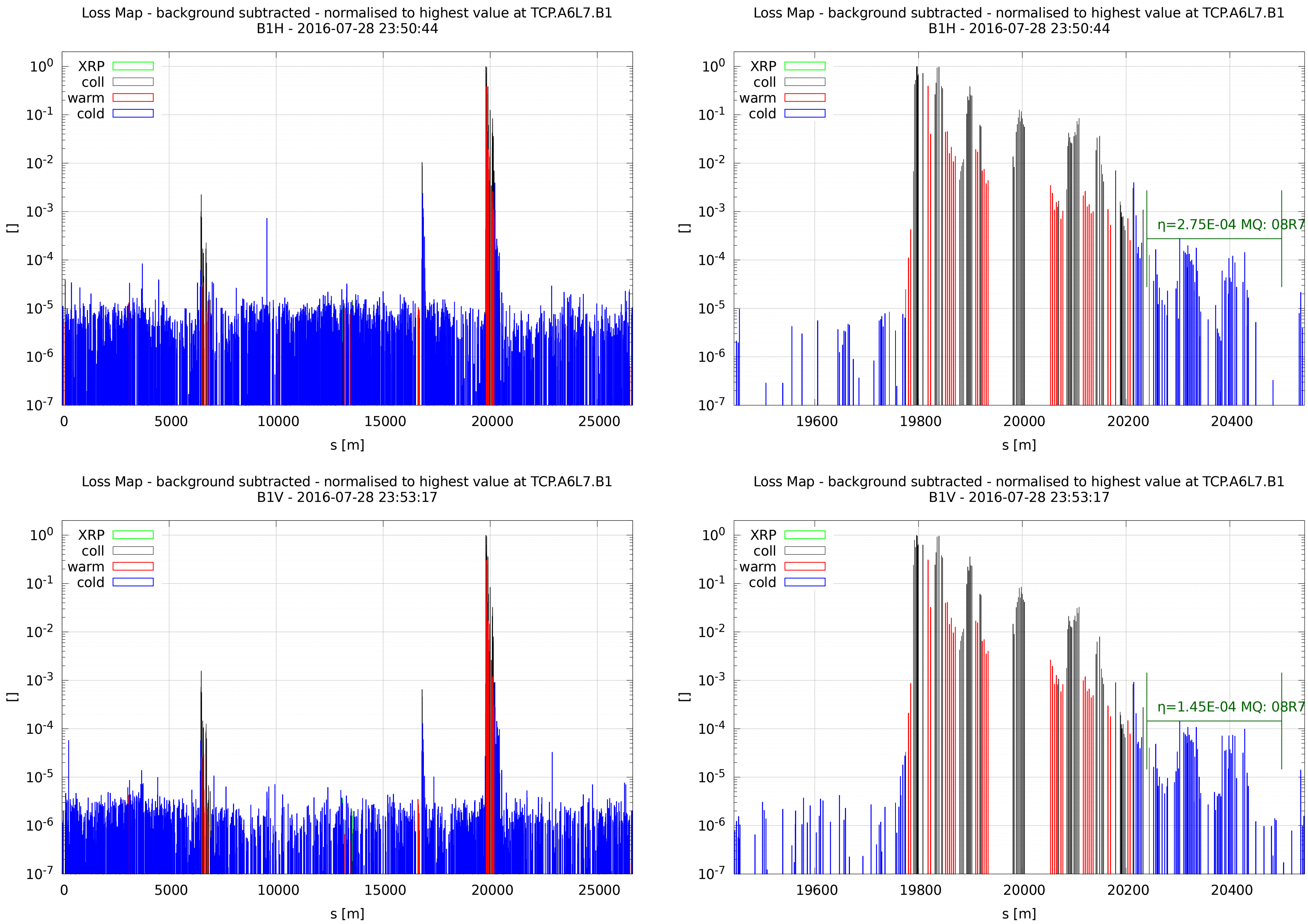

Figure A.1: B1H (upper frames) and B1V (lower frames) loss maps with 2 σ-retraction, i.e. with 2016 operational settings (i.e. TCPs at 5.5 σ and TCSGs at 7.5 σ) before alignment. The overview on the entire LHC is shown by the frames on the left, whereas the zoom on IR7 is shown by the frames on the right.

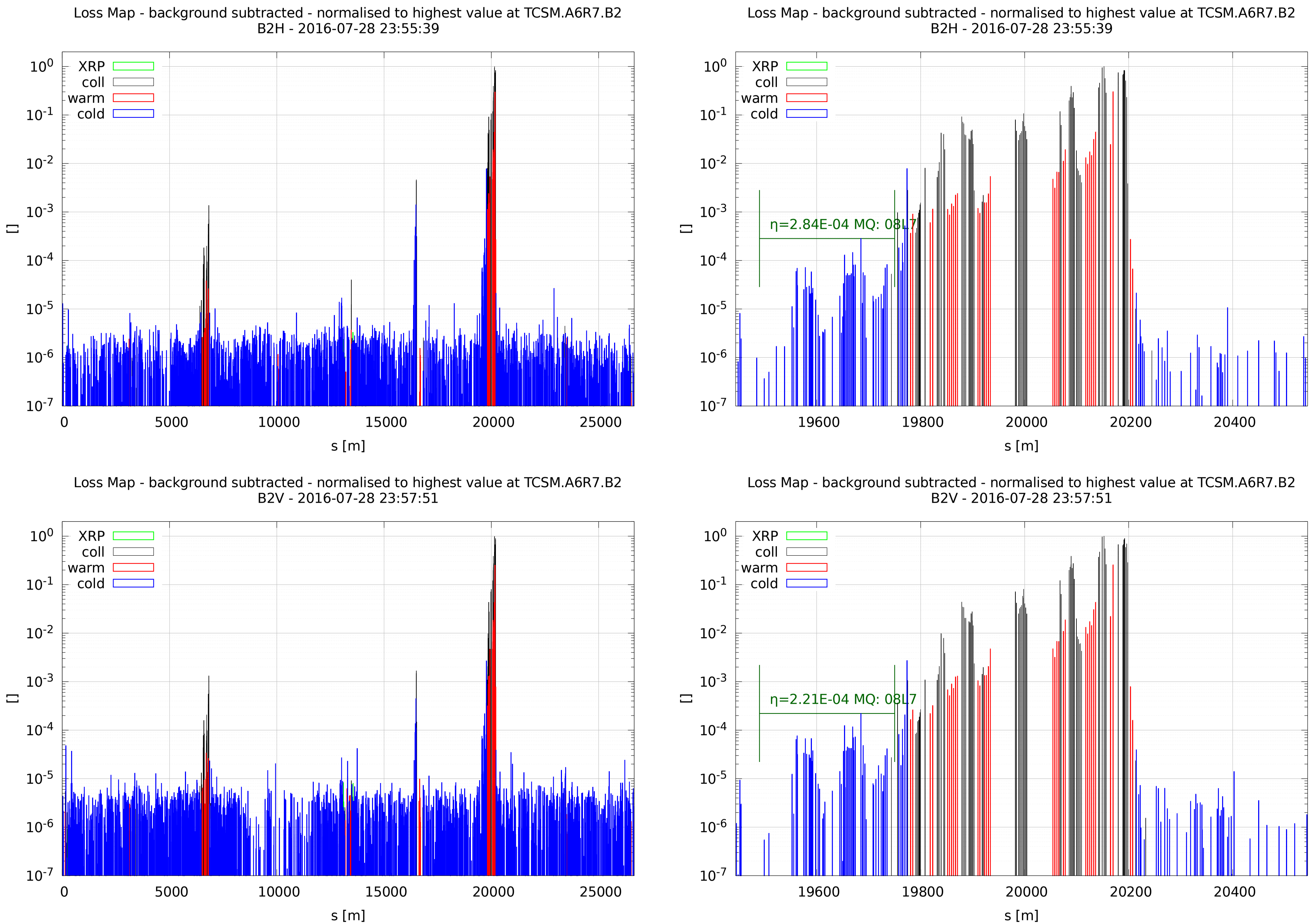

Figure A.2: B2H (upper frames) and B2V (lower frames) loss maps with 2 σ-retraction, i.e. with 2016 operational settings (i.e. TCPs at 5.5 σ and TCSGs at 7.5 σ) before alignment. The overview on the entire LHC is shown by the frames on the left, whereas the zoom on IR7 is shown by the frames on the right.

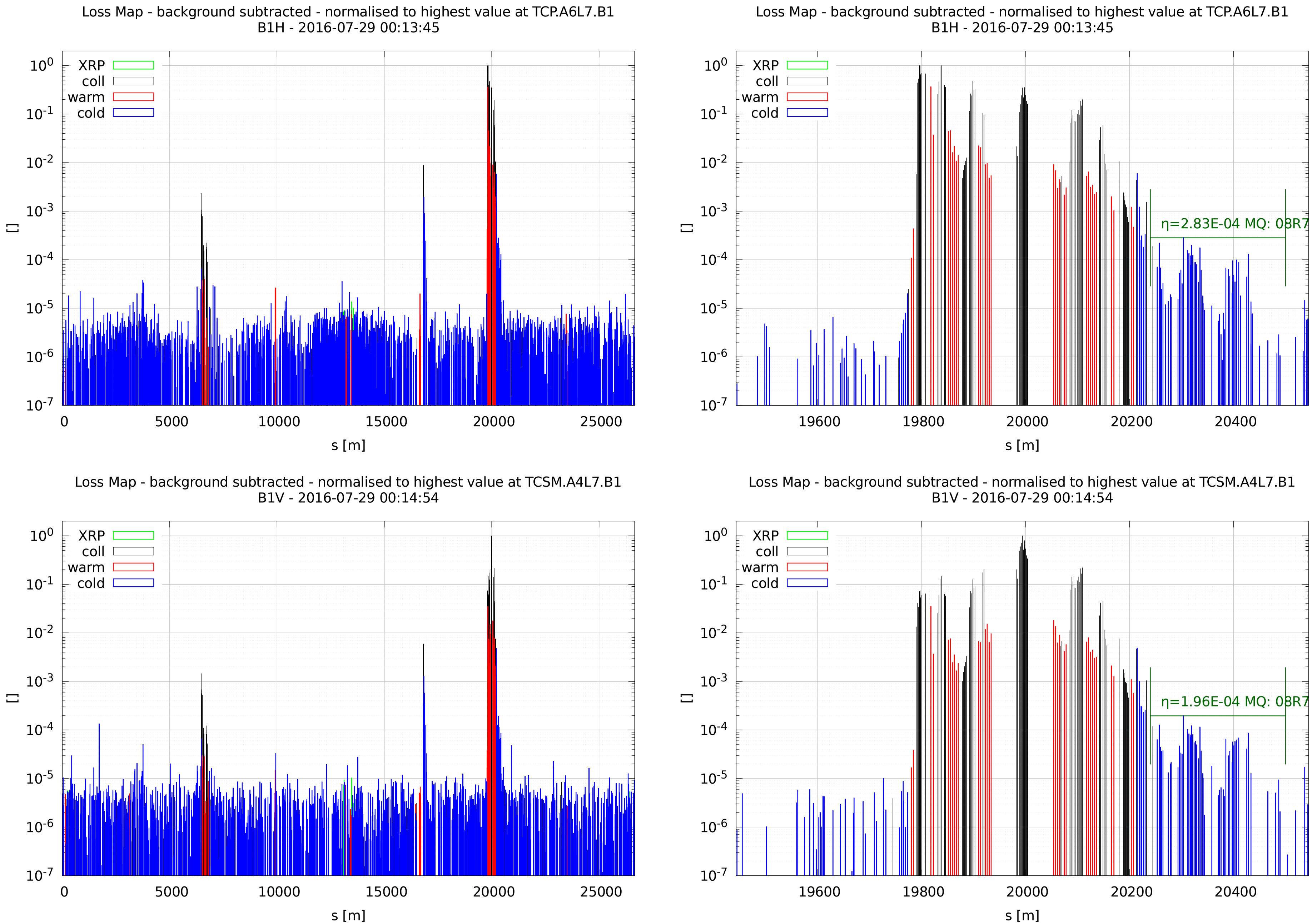

Figure A.3: B1H (upper frames) and B1V (lower frames) loss maps with 1 σ-retraction (i.e. TCPs at 5.5 σ and TCSGs at 6.5 σ) before alignment. The overview on the entire LHC is shown by the frames on the left, whereas the zoom on IR7 is shown by the frames on the right.

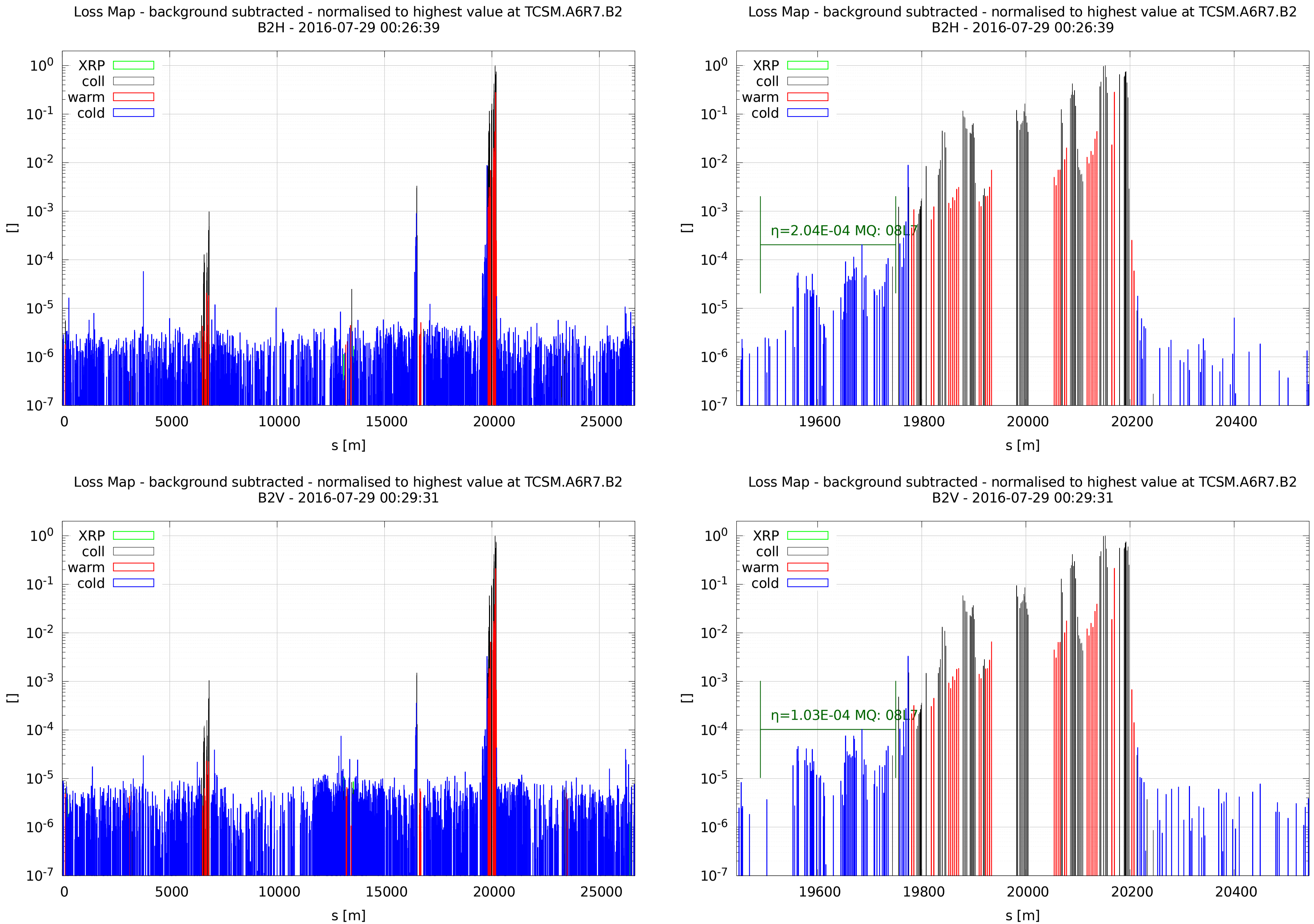

Figure A.4: B2H (upper frames) and B2V (lower frames) loss maps with 1 σ-retraction (i.e. TCPs at 5.5 σ and TCSGs at 6.5 σ) before alignment. The overview on the entire LHC is shown by the frames on the left, whereas the zoom on IR7 is shown by the frames on the right.