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Collimator losses in the DS of IR7 and quench test at 3.5 TeV

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Summary

Beam studies to address the limitations of the Phase I collimation system were performed. The primary goal was to achieve the design loss rates of the collimation system of 500 kW, and to study the behaviour of the system and of the machine in these conditions. The beam-based determination of the quench limits of the cold magnets with highest losses, can also be addresses in this study. Beam tests consisted in increasing the loss rates at 3.5 TeV with nominal machine configuration and collimator settings in order maximise the losses in the dispersion suppressors of IR7, notably in the Q8 quadrupoles that represent the limiting location with highest leakage from IR7. The cleaning performance of IR7 is very good, with a leakage of a few 10^{-4} in the Q8. Therefore, the test had to be performed with stored energies well above the safe limit.

Contents

1 Introduction

Quench tests with beam performed so far at the LHC were done in conditions that are not necessarily the same as in standard high-intensity operation. Local orbit bumps for circulating or injected beams were used to increase the local losses in selected magnets, which is not a typical case for daily operation with high stored energy. The limiting locations in standard operation are instead localized in the dispersion suppressors (DSs) at either side of the betatron cleaning insertion (IP7), where the leakage of halo particles from the warm collimation insertion is maximum. The highest leakage from the collimation system occurs in the Q8 quadrupole in the DS and the loss distribution follows the dispersion functions. The driving mechanism for losses in the DS is the single-diffractive of primary beam halo that interacts with the primary collimators.

It is important to understand the real limits of the collimation system in realistic beam conditions. In particular, this topics if of primary importance in view of the Phase II collimation system upgrade that aims at addressing the assumed system limitation in the dispersion suppressor.

The collimation cleaning at 3.5 TeV is good. The leakage to the Q8 quadrupoles at either side of IR7 are of a few 10^{-4} of the primary losses at the primary collimators. The system limitations in conditions representative of the standard operation for physics, can only be addressed satisfactorily by maximizing the loss rates on the primary collimators until the design loss rates of 500 kW are reached, or the quench in the dispersion suppressor is triggered. Due to the good cleaning, these extreme conditions are only possibly with stored energies well above the safe limits. Thus, special care must be taken to prepared this test.

On the other hand, such a controlled quench test would be very useful to extrapolate the system performance to higher energies. Presently, quench estimated with realistic beam distributions in the dispersion suppressor rely only on simulations. Therefore, these tests must be followed up with high priority.

In this paper, the results of the first MD on collimator DS losses at 3.5 TeV are discussed. After having presented the special set-up of beam loss monitor (BLM) threhsolds required for the test, the beam set-up and the staged approach to reach safely high loss rates are presented. The beam test results are then presented.

2 Set-up of beam loss monitor thresholds

A possible limitation to achieve loss rates close to the quench limit in the dispersion suppressors of IR7, is that with the operational settings of BLM thresholds, the beams are likely to be dumped by losses in other locations before reaching significant loss rates in the DSs. In particular, it is well known from the long experience on loss maps that various warm and cold elements are closer to the BLM dump limit than the DSs with the present cleaning efficiency (leakage to Q8 is of a few 10^{-4} of primary beam losses):

- Collimators: thresholds for “slow” losses above 0.5 s are set well above the collimator damage limits. Collimators are the primary loss locations and their BLM thresholds are set lower than the damage limit to identify abnormal loss rates (thresholds are set to protect the machine with some margins for the collimator protection);

- cold Q6 magnets in IP7 and cold Q4/Q5 magnets IP6: they see losses from hadronic showers generated in near-by collimators but are protected by local masks/collimators. The masks were designed to exclude the risk of quench but the signals measured by the BLMs are affected by cross-talk and could potentially reach dump levels well before the magnets quench.

Table 1: BLM signal to dump threshold ratios for the cold and warm elements closest to dump limit. This was measured for the 1.3 s loss integration time sum and were measured during a B2 loss map performed on March 9th at 3.5 TeV with un-squeeze beams. Peak loss rate were up to 5×10^{10} p/s. Only one occurrence per element is listed (the BLM with the highest signal is considered). Collimators around the ring reached up to 70 % of the dump thresholds and are not listed here [1].

BLM names	BLM signal	Monitor Factor
Cold magnets		
`BLMEI.11L7.B2I25_MBB`	0.004	0.1
`BLMEI.08L7.B2I22_MBB`	0.005	0.1
`BLMEI.09L7.B2I25_MBA`	0.006	0.1
`BLMQI.07L7.B2I10_MQ`	0.009	0.1
`BLMQI.11L7.B2I10_MQ`	0.010	0.1
`BLMQI.07L7.B1E30_MQ`	0.011	0.1
`BLMQI.09L7.B2I10_MQ`	0.018	0.1
`BLMQI.05L6.B2I20_MQY`	0.020	0.3
`BLMQI.04L6.B2I20_MQY`	0.029	0.4
`BLMQI.06L7.B2I20_MQTL`	0.029	1.0
`BLMQI.08L7.B2I10_MQ`	0.103	0.1
Warm magnets		
`BLMEI.06R7.B2I10_MBW.B6R7`	0.005	1.0
`BLMQI.05L7.B1E10_MQWA.A5L7`	0.006	1.0
`BLMQI.04L7.B1E10_MQWA.A4L7`	0.014	1.0
`BLMQI.04R7.B1E30_MQWA.E4R7`	0.068	1.0
`BLMQI.05R7.B1E30_MQWA.E5R7`	0.135	1.0

- warm dipoles and quadrupoles in IP7: the dump thresholds for slow integration times are set to exclude high steady loads that might damage the epoxy insulator of the coils.

The cases above are assumed not to be hard limitations for pushing the high intensity performance at the LHC but this assumption needs beam validation (e.g., can we guarantee that the Q6 in IP7 will not quench before the DS magnets).

The risk to dump at undesired locations before reaching maximum loss rates at the DS must be avoided in order to make the test meaningful. This can only be done by increasing the BLM thresholds in a way that makes sure that the DSs become the real limiting factor, as expected from simulations. The BLM thresholds configuration used during beam tests is described in detail in the note [1] that was approved by the machine protection panel as a prerequisite for the execution of the tests.

The choice of BLM thresholds was based on the analysis of the loss maps performed to validate the cleaning system at flat-top. In Tab. 1, the ratio of BLM signal to dump thresholds is listed for the most critical cold and warm elements. This give the margin that we have for total loss rates before dump. These figures are calculated from a loss maps performed at the beginning of March 2011. Total losses up to 8×10^{10} p in 3 seconds were achieved, with peak losses of about 5×10^{10} p/s. The new thresholds used for the MD were up to a factor 100 higher than the ones used in standard operation for physics fills. The improvement factors are different for the various BLM integration times [1]. Two examples for the running sums RS04 (640 μs) and RS09 (1.3 s) are given in Fig. 1. It is seen that changes of thresholds only occurred in IP6 and IP7. In total, 74 monitors were affected.

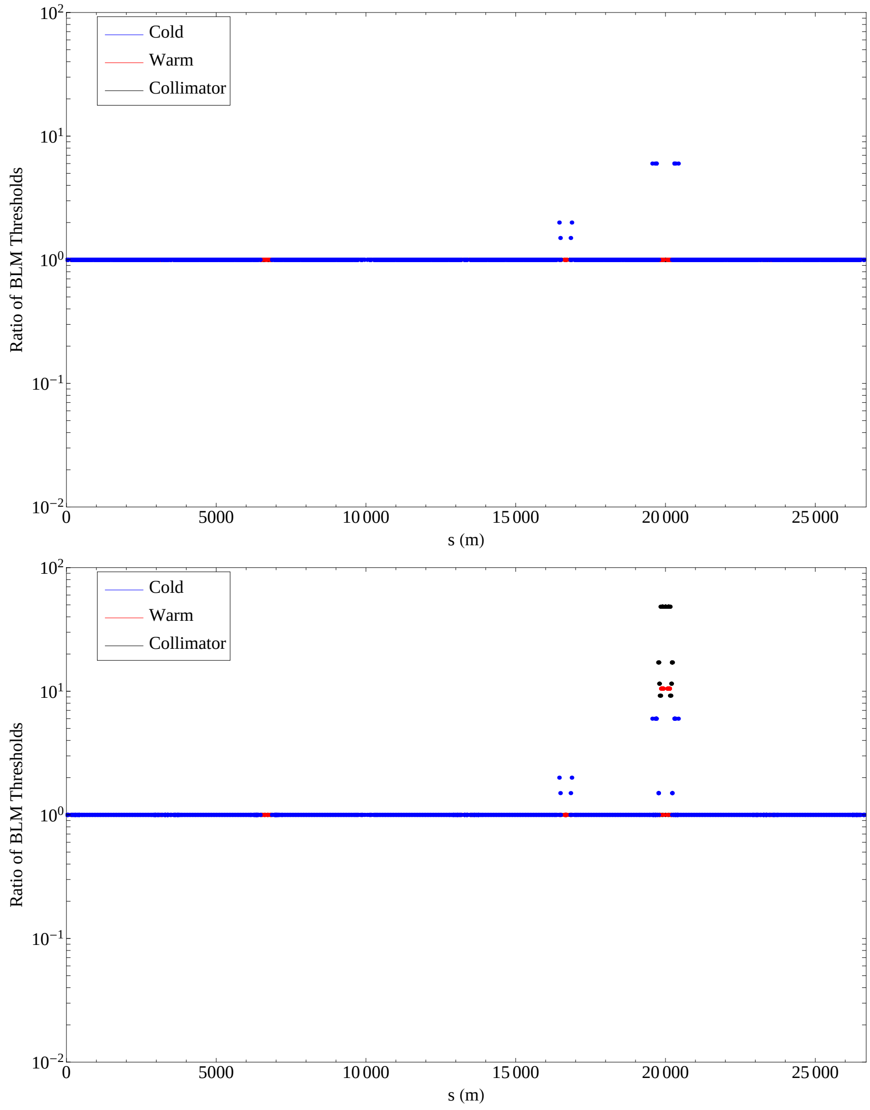

Figure 1: Change of BLM thresholds implemented for the MD. The ratio with respect to the thresholds in the standard operation is given for the running sum of 640 μ (top) and of 1.3 s (bottom).

3 Experimental Setup

3.1 Machine configuration and collimator settings

The DS quench test was performed at 3.5 TeV with un-squeezed beam ("flat-top"). This configuration eases and speeds up the test preparation in two ways:

(1) beam losses outside the collimation insertions are minimum, in particular the experimental regions remain clean: tertiary collimator gaps and triplet aperture are maximum;

(2) the duration of the test preparation is kept to a minimum because there is no need to setup squeeze and collisions.

The item (1) is particularly important because it ensures that the number of BLMs requiring threshold changes is kept to a minimum. This simplifies the handling of critical thresholds and the procedure to recover nominal conditions after the MD. In the present configuration, the data of Tab. 1 and the additional modifications for collimators affected 74 BLMs (Fig. 1).

Table 2: Collimator settings at 3.5 TeV.

Parameter	Unit	Plane	Name	Value
Primary cut IR7	[σ]	H,V,S	TCP	5.7
Secondary cut IR7	[σ]	H,V,S	TCSG	8.5
Quartiary cut IR7	[σ]	H,V	TCLA	17.7
Primary cut IR3	[σ]	H	TCP	12.0
Secondary cut IR3	[σ]	H	TCSG	15.6
Quartiary cut IR3	[σ]	H,V	TCLA	17.6
Tertiary cut experiments	[σ]	H,V	TCT	26.0
Physics debris collimators	[σ]	H	TCL	out
Primary protection IR6	[σ]	H	TCSG	9.3
Secondary protection IR6	[σ]	H	TCDQ	10.6

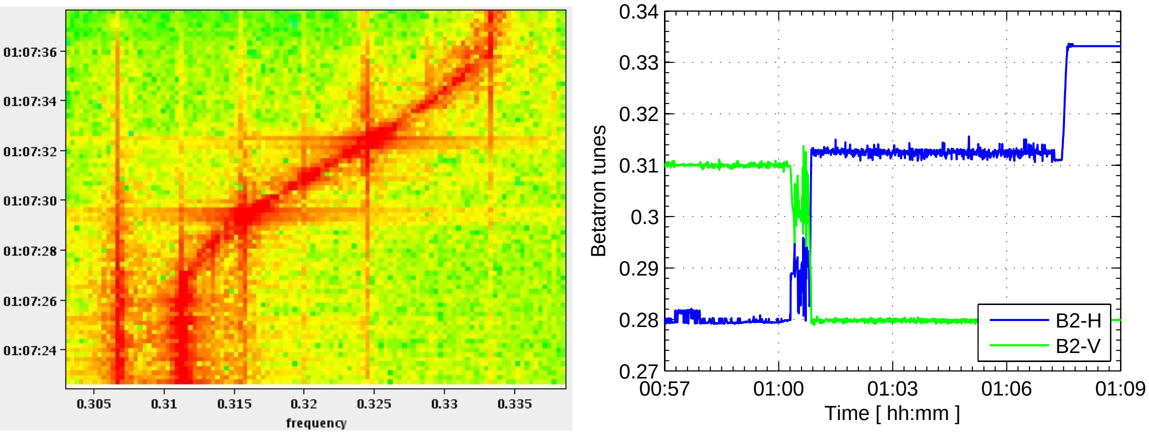

Figure 2: Typical pattern of the horizontal tune versus time during loss maps. The horizontal and vertical tunes are initially swapped to have the Q_h closer to the third order resonance. The Q_h is then moved across resonance to generate loss maps.

The beam tests were performed with individual nominal bunches or trains of 12 nominal bunches with 50 ns spacing. This ensured that the reference orbit used for high-intensity fills could be restored. The machine configuration was the nominal one used for physics fills. In particular, crossing angles (-120 μrad / 80 μrad / 120μrad / -250 μrad in IP1/IP2/IP5/IP8) and beam separation (0.7 mm in all IPs) as well as collimator settings were not modified. The flat-top collimator settings in units of the betatron beam size in the collimator plane, σ, listed in Tab. 2.

High beam losses were achieved by crossing the third-order resonance with the horizontal tune, as it is done in standard loss maps. In order to maximise loss rates, the transverse damper was switched OFF while the tunes were changes. Before starting the loss maps, the horizontal, Q_h, and vertical, Q_v, tunes are inverted to bring Q_h close to the third order resonance. An example of this procedure is shown in Fig. 2.

3.2 Beam test strategy

As a staged approach before producing high losses with unsafe beams, it was proposed to start the test with a first pilot ramp with low intensity, just below the limit of 4×10^{11} p that allows masking interlocks at 3.5 TeV. This first fill had two main purposes:

1. Confirm by beam measurements the limiting locations outside the dispersion suppressor (see Tab. 1); in particular, identify precisely the margins dump thresholds for all the critical BLM signals;
2. Establish a well defined procedure for maximising beam loss rates while crossing the third order resonance.

Based on the results of this first test, additional ramps with higher intensities were then to be performed with a total intensity scaled to achieve the desired peak loss rates in the DS while remaining below dump limits elsewhere. In case of unexpected issues with the beam losses, e.g. unforeseen loss locations close to dump levels, additional adjustment of thresholds could still be performed during the pre-cycle without beam after the first ramp. This additional modification of thresholds was actually not required.

This staged approach proved to be successful. During the MD, a total of three ramps were performed with maximum stored beam energies up to 1.3 MJ at 3.5 TeV.

4 Results of beam tests

4.1 Summary of achieved parameters

The summary of achieved parameters in the three ramps performed during the MD, is given in Tab. 3. The number of bunches (without taking into account the first probe bunch for injection setup), the total injected intensity, the measured leakage in the dispersion suppressor and the peak loss rate on the TCP collimators in kJ/s are listed. The peak loss rates are calculated from the beam current measurements, taking the highest loss over 1 s (see next sections). The leakage in the DS and the loss maps are also calculated by using the BLM signals in the 1 s bins with highest losses.

For each ramp, loss maps were only possible with one beam at a time because the one of the 2 beams was dumped prematurely for different reasons:

- First ramp: B1 was loss at the beginning of the energy ramp due to a glitch of the energy limits of the TCDQ collimator in IP6, affecting only one beam.
- Second ramp: after a successful loss maps for B2, a global beam dump was triggered due to beam losses. This happened when the transverse damper was switched back ON after being switched OFF for the loss maps. Likely, it caused a B2 instability because the tunes were not nominal (see Fig. 2).
- Third ramp: loss maps were performed successfully with B1. The high signal caused a software interlock due to wrong voltage in the BLM electronics, which dumped both beams.

4.2 First ramp (Fill 1776)

The first ramp was performed with three nominal bunches per beam, for a total intensity below the limit for “very relaxed” safe beam limit. BLM interlocks could be masked for the maskable monitors in all IPs. The beam loss was done by moving the horizontal tune to 0.35, i.e. slightly above the third order resonance, with transverse feedback OFF. In these conditions, about 60 % of the total beam intensity was lost in about 1 s. This is shown in Fig. 3, were the beam current measured by the fast beam current monitor (BCT) is shown.

The loss maps produced in these conditions, was used to check the margins to BLM dump thresholds. The intensity for the second ramp was calculated based on the following observations (see Fig. 4):

Table 3: Main parameters achieved in the three ramps of the MD. The leakage in the Q8 is calculate as ratio of the local BLM signal to the BLM of highest signal at the primary collimator (Q8 is thelmiting location for cleaning efficiency).

	Fill number	Number of bunches		Total beam intensity [10^{11}p]		Leakage in the DS (Q8) [10^{-4}]		Peak loss rate on TCPs over 1 s [kJ/s]	
		B1	B2	B1	B2	B1	B2	B1	B2
Ramp 1	1776	3	3	3.1	3.1	–	6.2	–	87
Ramp 2	1777	16	16	19.7	19.1	–	6.6	–	510
Ramp 3	1778	16	21	19.1	24.2	3.3	–	235	–

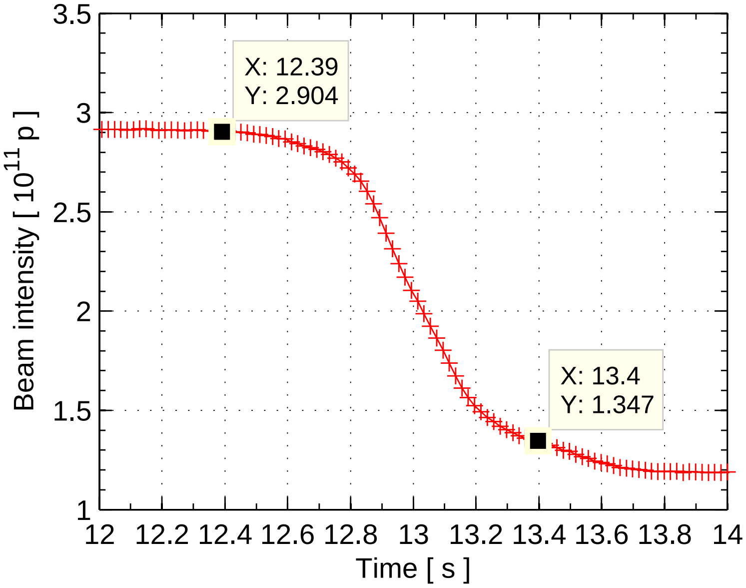

Figure 3: Beam current as a function of time during B2 beam losses in the first ramp.

- The expected limiting locations for BLM were confirmed. High losses were measured at collimators, at the warm magnets in IP7 and at the cold Q6 in IP7 and Q4 and Q5 in IP6.
- The choice of new BLM thresholds was confirmed in the sense that it would make possible to achieve high losses in the dispersion suppressor. Overall, the maximum losses were below 6 % of the dump limits. In particular, for BLM integration times above 1.3 s:
  – The losses at Q6 in IP7 were at about 5 % of the BLM dump limit;
  – The losses at Q4 and Q5 in IP6 were at about 5 % of the BLM dump limit;
  – The losses at the Q8 in the DS (limiting location of collimation cleaning) was also about 5 %. Note that the thresholds are set a factor 2 above the assumed quench limit;
  – The BLM for the TCP.A6L7.B2 layout slot reached 40 % of the dump threshold but this monitor is disabled and cannot dump the beams.
- Faster losses below 1 s reached up to 10 % of the dump thresholds.

The peak loss rate on the primary collimator was 87 kJ over 1 s. In order to achieve the design loss rate of 500 kW, a factor 5.7 of stored beam is needed for the same loss rate. It was therefore decided to perform the second ramp with 16 nominal bunches and repeat the loss maps in the same conditions.

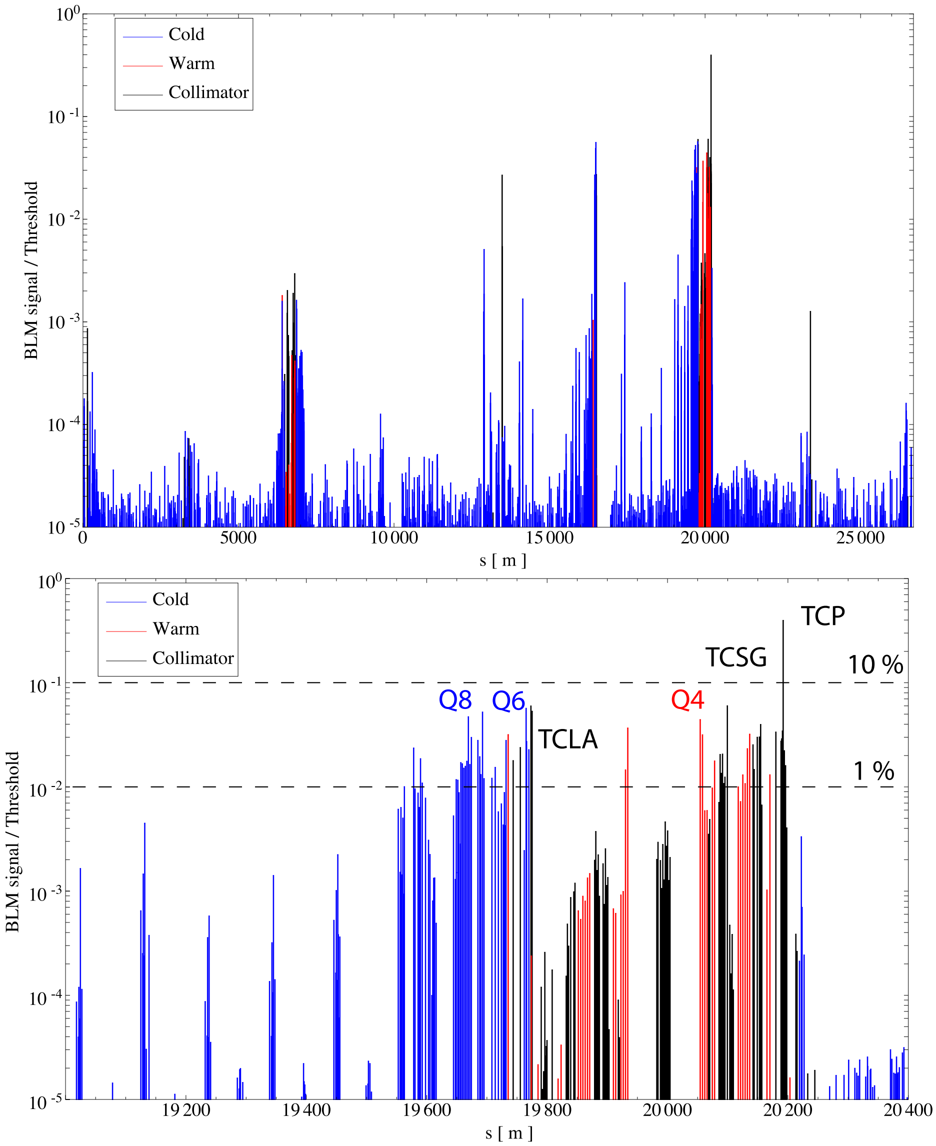

Figure 4: Ratio of BLM signal to dump threshold measured at the peak loss rate during the first ramp with 3 nominal bunches. The BLM integration time of 1.3 s is considered. The full ring (top) and the region around IR7 (bottom) are given.

4.3 Second ramp (Fill 1777)

The intensity loss during the second ramp is shown in Fig. 5 for B2. Sixteen bunches of about 1.2×10^{11} p were injected as one train of 12 bunches and 4 individual bunches. The total intensity was about 18×10^{11} p. A peak loss rate of 9.1×10^{11} p/s was achieved, corresponding to 510 kW lost on the primary collimators. This is in good agreement with what was extrapolated from the experience with the first attempt. The loss map around the ring for this case is shown in Fig. 6, where the BLM signal is given as a function of the longitudinal position around the ring. The loss rates in kW around IP7 are shown in Fig. 7. These approximate figures are estimated by assuming that the BLM response is the same for every element, which is clearly too simplistic but gives a reasonable first-order estimate. In this assumption, the peak loss rate at the Q8-L7 (limiting location for B2 collimation cleaning) was 336 W.

The losses in Q8-L7 reached the 32 % of the BLM dump limit. For these beam tests, these thresholds were set a factor 2 higher than the assumed quench limits of super-conducting magnets.

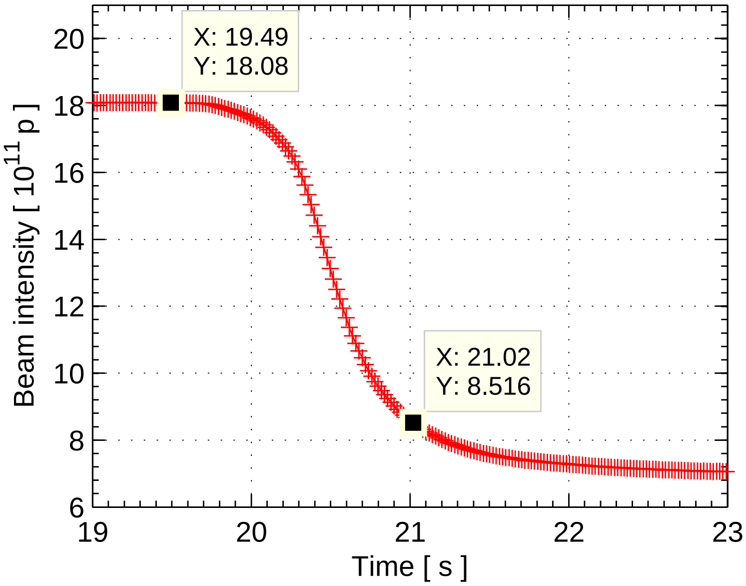

Figure 5: Beam current as a function of time during the B2 beam losses in the second ramp.

The 64 % of the assumed quench limit was therefore reached.

The temperature measured in the Q11L7 magnet of the dispersion suppressor is shown in Fig. 8. A special set-up was prepared to measure heat loads by blocking valves that otherwise would increase the Helium flow into the cryogenics cell [2]. This attempt was not fully successful because the many ramps and pre-cycles performed in the precious MDs did not allow precise calorimetry measurements. An increase of about 36 mK was measured at the moment of the highest loss spike. From this temperature change, it is not straightforward to compute the heat load in the cryogenics system. More analysis is ongoing. The possibilty that the signal is an artifact of radiation effects induced on the temperature sensors seems unlikely but is also under consideration [2].

It is interesting to note that the temperature spike is only seen in correspondance of the missing cryostat, where the cooling capacity from the Helium bath is reduced, even if the higest losses occur at the Q8 quadrupole (see Fig. 7).

4.4 Third ramp (Fill 1778)

As there was not the possibility to have a pilot loss maps for B1 in the first ramp due to premature beam dump, the loss maps with higher intensity were performed with the same settings and intensity used for B2, i.e. with 16 nominal bunches (injected as a train of 12 bunches and 4 individual bunches). Compared to the second ramp, the B2 intensity was increased further by 30 % to approach the assumed quench limit, for a total of 21 bunches (train of 12 bunches and 9 individual bunches). This would allow to approach the assumed quench limit without being limited by other BLMs that reached about 70 % of dump levels for faster integration times.

In the third ramp, the loss map was only performed for B1 with the same conditions as for B2 (Q_h moved to 0.35, damper OFF). In this case, the total loss was however smaller than for B1, see Fig. 9. The peak loss rate was 4.2×10^{11}p/s, corresponding to 235 kW lost on the primary collimators, i.e. less than half than for B2. This is about half the design value of the collimation system. Results in this case are therefore less conclusive than for B2.

The loss map around the ring is given in Fig. 10. The leakage to the dispersion suppressor was 3.3×10^{-4}, i.e. a factor 2 better then for B2 (Tab. 3). This corresponds to a peak 78 kJ lost over 1 s

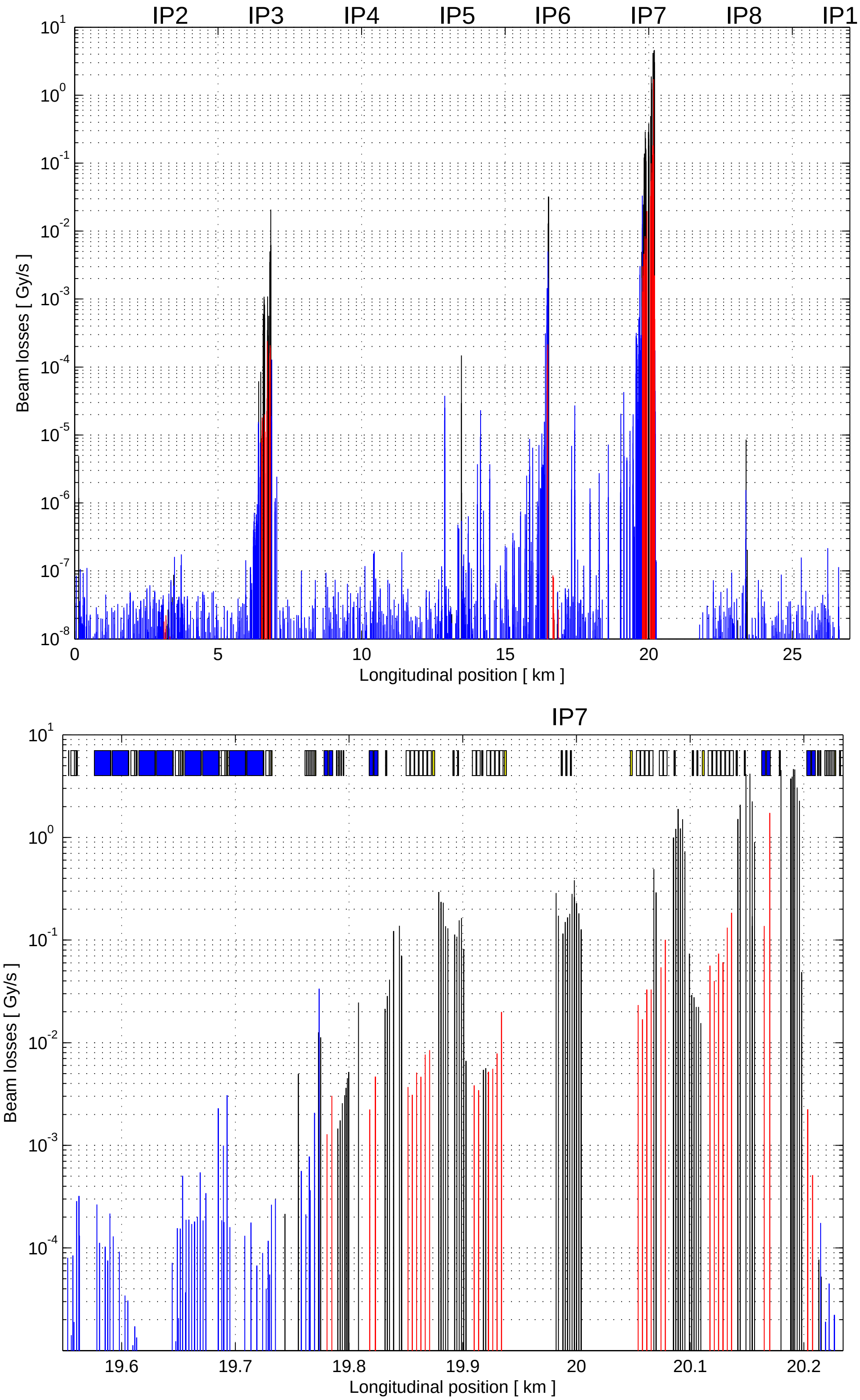

Figure 6: Loss maps around the ring (top) and in IP7 (bottom) for B2 achieved in the second ramp. Black, red and blue bars indicate losses at collimators, warm elements and cold elements, respectively.

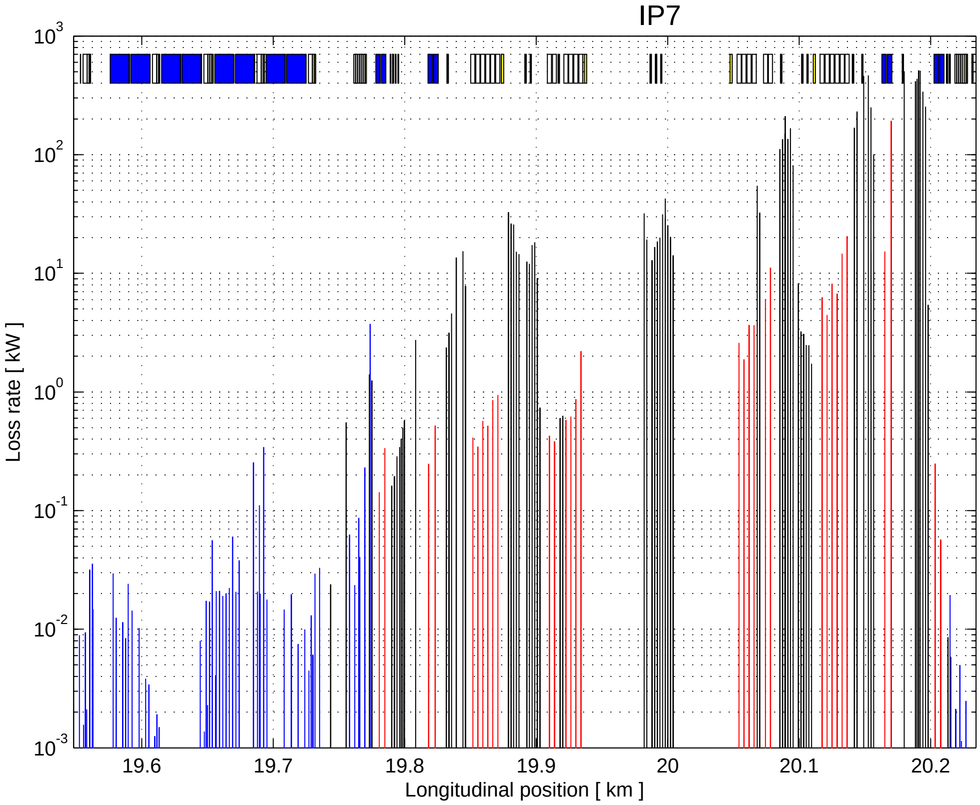

Figure 7: Loss rates in kW in IR7 during the B2 loss maps done in the second ramp. The peak value of 510 kW lost on the primary collimators is scaled for all other elements assuming the same BLM response. Black, red and blue bars indicate losses at collimators, warm elements and cold elements, respectively.

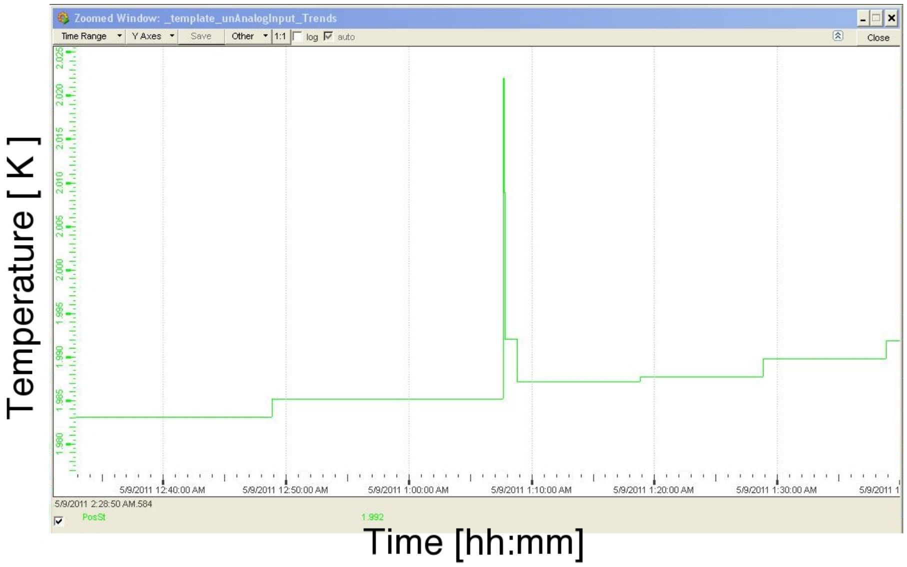

Figure 8: Temperature measured at the Q11-L7 during the loss map test of the second ramp. Courtesy of the cryogenics operation crew.

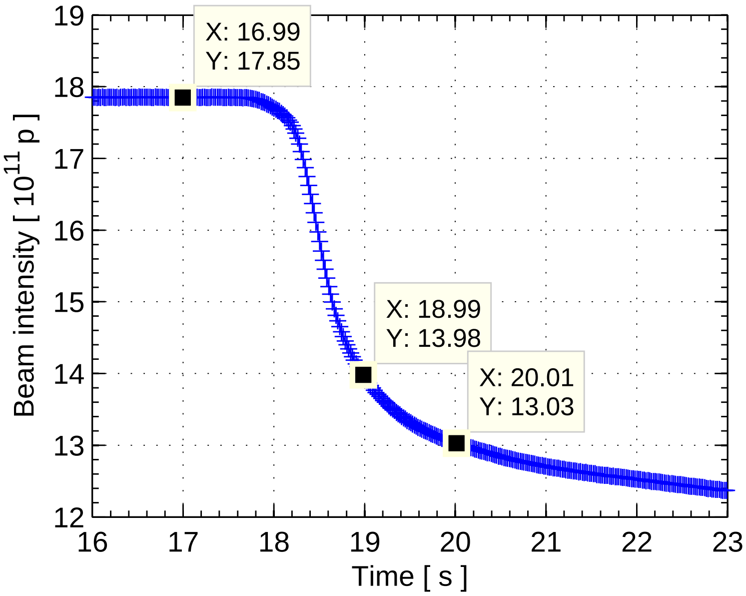

Figure 9: Beam current as a function of time during the B1 beam losses in the third ramp.

in the Q8-R7, assuming the same BLM response as the TCPs, see Fig. 11. No temperature increase was seen on the cryogenics system in the DS cryo cell in this case.

5 Preliminary conclusions

In this MD, the design loss rate of the collimation system of 500 kW was achieved for B2. Losses of up to 9.1×10^{11} p/s were obtained by crossing the horizontal third order resonance at 3.5 TeV. This corresponds to a peak loss on the primary collimators of 510 kJ over 1 s (i.e., peak of 336 J/s in the dispersion suppressor with the present cleaning of 6.6×10^{-4}). In these conditions, the collimation system behaved as expected and did safely handle these high losses. In particular, no quench occurred in the dispersion suppressor magnets on the left side of IR7, which represent the limiting location for cleaning.

The maximum loss rate achieved for B1 with the same total store beam energy, was a factor 2 lower than for B2. The peak loss was 235 kJ over 1 s. No quench was recorded in this case. This is not surprising, also because the B1 cleaning performance in the dispersion suppressor on the right side of IR7 is about a factor 2 better than for B2 (total peak leakage of about 80 J over 1 s).

The loss rates achieved in cold magnets during this experiment did not allow to reach the BLM thresholds of the Q8 quadrupole in the dispersion suppressors. A maximum of 64 % of the quench limit assumed for BLM threshols was reached for B2. The fact that no quench was observed is then consistent with the present threshold settings but clearly this results is not sufficient to calculate the real margin. This result does not allow to revise the BLM thresholds. These figures will be taken into account for detailed calculations of collimation-induced intensity limitations for the LHC.

The authors would like to acknowledge the cryogenics team, the members of the rMPP, and the colleagues from magnet and QPS teams who were available and provided support during the MD (in particular, Z. Charifoulline, K. Dahlerup-Petersen, A. Siemko, J. Steckert).

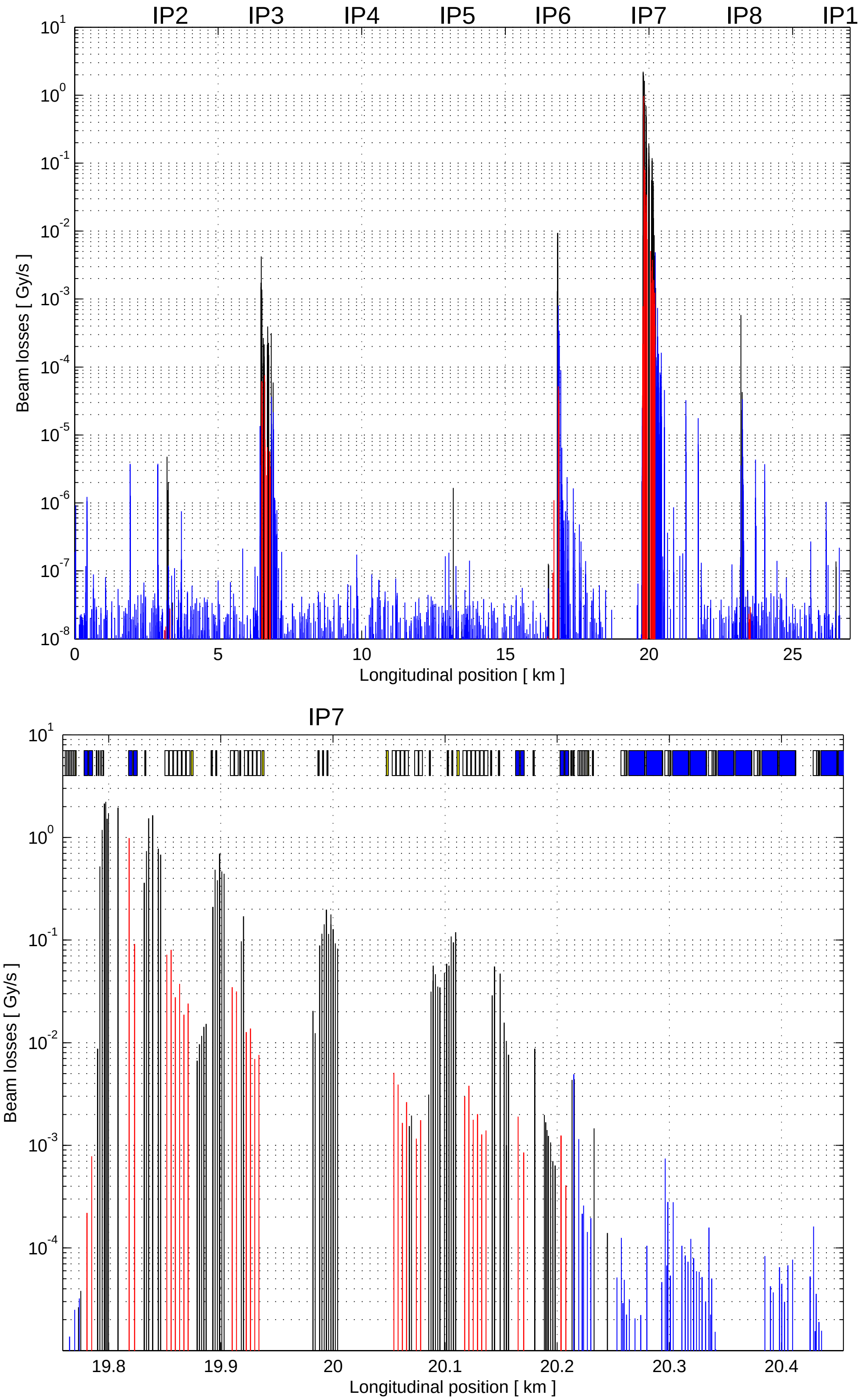

Figure 10: Loss maps around the ring (top) and in IP7 (bottom) for B1 achieved in the third ramp. Black, red and blue bars indicate losses at collimators, warm elements and cold elements, respectively.

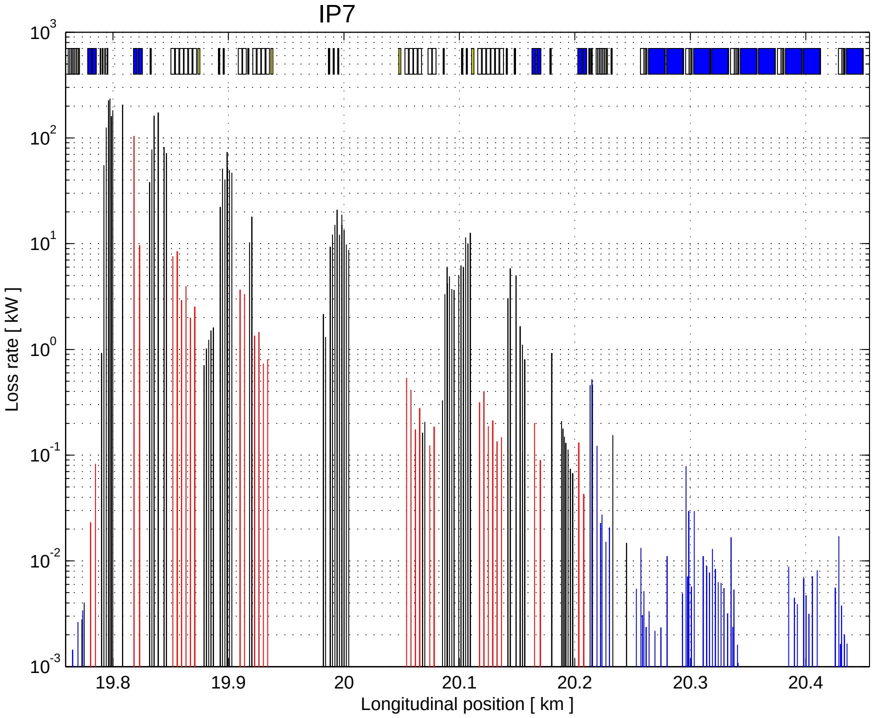

Figure 11: Loss rates in kW in IR7 during the B1 loss maps done in the third ramp. The peak value of 235 kW lost on the primary collimators is scaled for all other elements assuming the same BLM response. Black, red and blue bars indicate losses at collimators, warm elements and cold elements, respectively.

6 Next steps

The design loss rates could not be achieved for B1 and therefore measurements should be repeated for this case. It addition, it is important to address with high priority the quench limit of the dispersion suppressor magnets that could not be identified in the first beam tests (a lower limit was established).

The strategy of this first tests was based on achieving maximum loss rates for short times of 1–2 s with moderate total stored intensities. With this approach, it is not possible to address loss rates that last for several seconds. This is however important for understanding the performance reach of the collimation system. Future tests should therefore be focused on slower losses with higher total stored energy in order to achieve design loss rates for several consecutive seconds. The feasibility of achieving controlled losses by approaching in small steps to the third order resonance shall be addressed in dedicated beam tests, e.g. a end-of-fill studies.

It is also important to stress that these first tests done with un-squeeze beams did not allow to investigate possible limitations in the experimental regions. Even if there are indeed no limitations expected (the tertiary collimators efficiently absorb the local losses at the triplets), a solid beam-based verification of the limits in the IRs in case of high beam loss, would be important to improve the system performance estimates. These future tests would also profit from a more optimized set-up of the cryogenics in IP7 for calorimetry measurements.

References

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[2] S. Claudet, U. Wagner, private communication.