CERN-ACC-NOTE-2014-0036

15 August 2014
Belen.Salvachua@cern.ch

Collimation quench test with 4 TeV proton beams

B.Salvachua, R.Bruce, M.Cauchi, D.Deboy, W.Hofle, E.B.Holzer, D.Jacquet, L.Lari, E.Nebot, D.Mirarchi, E.Quaranta, S.Redaelli, M.Sapinski, R.Schmidt, G.Valentino, D.Valuch, J.Wenniger, D.Wollmann, M.Zerlauth, CERN, Geneva, Switzerland

Keywords: LHC, collimation, quench, protons, 4TeV

Summary

In 2013, at the end of the LHC physics run I, several quench tests took place with the aim to measure the quench limit of the LHC superconducting magnets. The LHC superconducting magnets in the dispersion suppressor of IR7 are the most exposed to beam losses leaking from the betatron collimation system and represent the main limitation for the halo cleaning. A collimation quench test was performed with 4 TeV proton beams to improve the quench limit estimates, which determine the maximum allowed beam loss rate for a given collimation cleaning. The main goal of the collimation quench test was to try to quench the magnets by increasing losses at the collimators. This note describes the procedure during the test and the first results with the data. Losses of up to 1 MW over a few seconds were generated by blowing up the beam, achieving total losses of about 5.8 MJ. These controlled losses exceeded by a factor 2 the collimation design value, and the magnets did not quench.

1 Introduction

The LHC superconducting magnets are cooled down to 1.9 K to keep superconducting properties. High energy protons impacting on the magnets can deposit enough energy in the magnet coils to break the superconductivity and make the magnet quench. During regular operation, there are continuos losses at the dispersion suppressor of IR7 after the main collimation betatron cleaning area. In case of low beam lifetime these losses set an upper limit on the maximum number of protons that can be stored in the LHC, the maximum intensity reach.

On the 5th of September 2011, a quench test was performed at 3.5 TeV to address the limitations of the LHC collimation system. The main goal was to achieve the designed loss rate of the collimation system of 500 kW losses at the primary collimators and address the magnet behavior in the these conditions. This was achieved for Beam 2. The 3.5 TeV proton beam was blown-up by crossing the horizontal third order tune resonance. Peak losses of up to 510 kW (9.1×10^{11} proton/s) during 1 s were achieved at the primary collimator in IR7 and a peak of 336 W was observed at the dispersion suppressor region (DS) with the relaxed settings used during 2011, with maximum cleaning inefficiency at IR7 Q8 DS of 6.6×10^{-4} being the cleaning inefficiency the noise-subtracted BLM signal, normalized to the maximum loss (typically in IR7). The maximum loss rate achieved for Beam 1 was 235 kJ over 1 s. No quench was observed in either case. The loss rates achieved in cold magnets for the maximum losses in Beam 2 did not reach the theoretical quench limit of the Q8 quadrupole in the dispersion suppressors: a maximum of 64% of the quench limit assumed for Beam Loss Monitors (BLM) thresholds was reached (measured with running sum of 1.3 s, RS09). The fact that no quench was observed is compatible with the BLM thresholds but is not sufficient to calculate the real quench margin [1].

On the other hand, this import result was used to estimate the performance reach at 7 TeV by taking the achieved loss rate as a pessimistic limit before quench [2]. To refine further the performance reach estimates, a new collimation quench test was prepared for 2013, which is the main topic of this note. The procedure is, as for the 2011 test, to induce high losses with the collimation system in place and observe the whether any magnet quenches due to the leakage from the collimators to the IR7 DS. The goal was to increase the loss levels in steps above what was achieved in 2011, if possible up to the real quench limit, or otherwise to provide a new lower limit of the quench level. Slow losses of the order of 500 kW up to 1 MW over $5 - 10$ s are creating by exciting the beam with the transverse damper (ADT) [3].

Basic scaling of the 2011 results showed that in order to approach further the quench limit at 4 TeV, losses on collimators had to be increased too much for the given collimation cleaning with the present 2012 tight collimator settings. Therefore, during this test we use a special configuration of collimator settings that is described in the following section. These very relaxed settings provide worse cleaning at the DS in IR7 than the present tight settings, which allows generating the same amount of losses at the DS with less intensity in the machine.

2 Preparation

The machine protection aspects of the test as well as the machine settings are described in [4].

2.1 Selection of collimator settings

In order to allow more losses at the DS of IR7 with the same beam intensity it was decided to try a different collimator hierarchy in IR7, with more retraction between the primaries and the secondaries. Tests were done at flat-top before beams are squeeze, with this configuration we get the same cleaning in IR7 without risk for the colliding IRs.

The collimator settings proposed and used for the machine study were prepared and tested in advanced. The 2nd of February 2013, after one of the scheduled collimator alignments, we were able to test 3 different configurations of collimator settings, see LHC Operation e-logbook [5]. We modify IR7 and IR6 collimation hierarchy settings in the following way:

- **Case 1:** IR7 corresponds to the so-called relaxed settings used in 2011 in mm (see Table 1) with an additional $1\,\sigma$ retraction on the secondaries of IR7 (TCSG IR7) and in IR6 (TCSG and TCDQ).
- **Case 2:** IR7 corresponds to case 1 with an opening of $1\,\sigma$ of the primary collimators (TCP IR7).
- **Case 3:** IR7 corresponds to case 2 with an extra retraction of $1\,\sigma$ of the secondaries and of IR6 collimators.

Table 2 shows a summary the three different collimator settings tested expressed in beam sigma size assuming normalized transverse emittance of 3.5 μm rad. Notice that the hierarchy at IR3 was not changed during the tests, which means that IR3 collimation hierarchy was: $12\,\sigma, 15.6\,\sigma$ and $17.6\,\sigma$ at 4 TeV flat top optics. Tertiary collimators in the colliding IRs were set above $20\,\sigma$ at injection optics.

Table 1: Relaxed collimator settings used in 2011 expressed in beam sigma size for 3.5 TeV ($\varepsilon_{\mathrm{norm}} = 3.5$ μm rad).

TCP IR7	**TCSG IR7**	**TCLA IR7**	**TCSG IR6**	**TCDQ IR6**
5.7	8.5	17.7	9.3	9.8

Table 2: Collimator settings tested before the quench test expressed in beam sigma size assuming normalized emittance of 3.5 μm rad. The star in the case number indicates the settings finally selected for the test.

Collimator family	**Case 1***	**Case 2**	**Case 3**
TCP IR7	**6.1**	7.1	7.1
TCSG IR7	**10.1**	10.1	11.1
TCLA IR7	**18.9**	18.9	18.9
TCSG IR6	**10.9**	10.9	11.9
TCDQ IR6	**11.5**	11.5	12.5
TCT	**26**	26	26
Loss map timestamp [2013/02/02]	**08:01:15**	8:07:14	8:17:00
η_{Q8} DS IR7	$\mathbf{9.5 \times 10^{-4}}$	9.3×10^{-4}	10^{-3}

Betatron loss maps were produced to measure the cleaning in the DS left of IR7. This was done with the ADT by blowing up horizontally one selected bunch on Beam 2. The timestamp of the loss maps as well as the measured cleaning inefficiency are also included in Table 2. In particular, we checked that the collimation cleaning hierarchy was still respected and that the difference in collimator settings was only affecting the DS left of IR7. Figures 1, 2 and 3 show the loss maps taken. Since the cleaning was not changing dramatically by opening more the collimators it was decided to use case 1, the relaxed settings used in 2011 (in mm) with an additional sigma retraction in the secondaries of IR7 and IR6. The BLM that measures the highest leakage to the cold magnets in the DS of IR7 is found to be in the three cases BLMQI.08L7.B2I10_MQ and the cleaning inefficiency $\eta_{Q8} \approx 10^{-3}$. In order to complete the validation of the collimator settings used during the quench test, an asynchronous dump test had to be done before injecting higher intensity. This was done (as explained later) with the first fill (low intensity) used in the quench test machine study. Off-momentum loss maps were not requested by machine protection for this test.

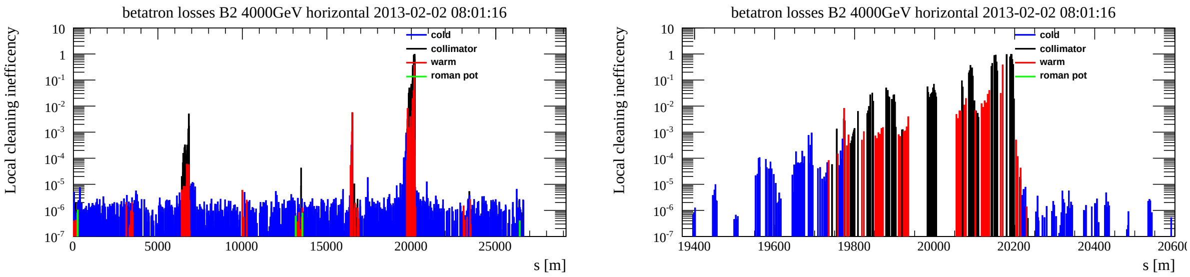


Figure 1: Beam 2 horizontal loss map for case 1. BLM signals are noise-subtracted and normalized to the maximum loss.

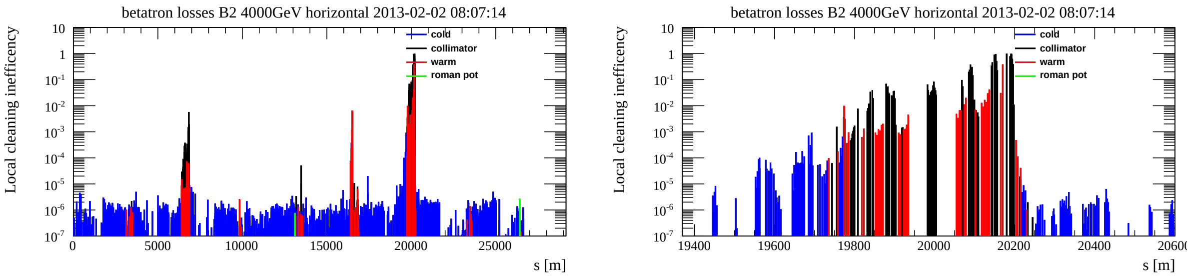


Figure 2: Beam 2 horizontal loss map for case 2. BLM signals are noise-subtracted and normalized to the maximum loss.

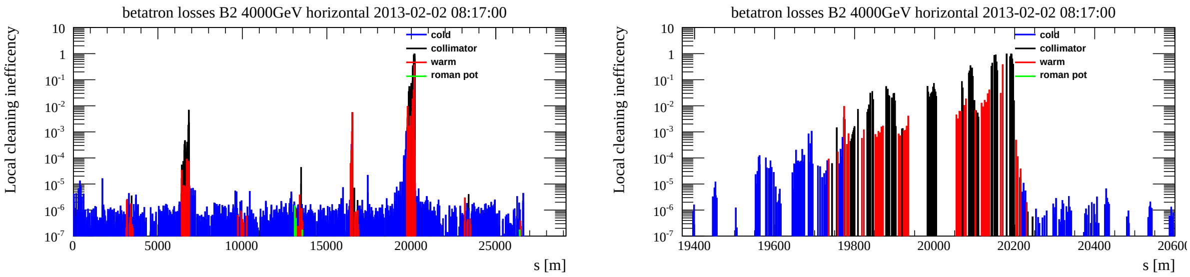


Figure 3: Beam 2 horizontal loss map for case 3. BLM signals are noise-subtracted and normalized to the maximum loss.

2.2 Setup of beam loss monitor thresholds

For the quench test it was needed to raise the BLM dump thresholds in order to allow losses above the assumed quench limit. Using the loss maps taken at *2013-02-02 08:01:16*, see

Figure 1 an estimation of the new thresholds was proposed to allow up to 1 MW of beam power loss. This is done by scaling up the signal at each BLM by the factor 1 MW/P_e, where P_e is the loss achieved during the low intensity loss map. In the analyzed case the power loss measured during the validation loss maps was about 1.71 kW or about 2.68×10^9 proton/s, averaged over 1 second, Figure 4 shows the beam intensity (left) and the beam instantaneous power loss (right) during the loss map. The expected increase of thresholds to allow up to 1 MW beam losses is shown in Figure 5 for running sum of 1.3 s (RS09).

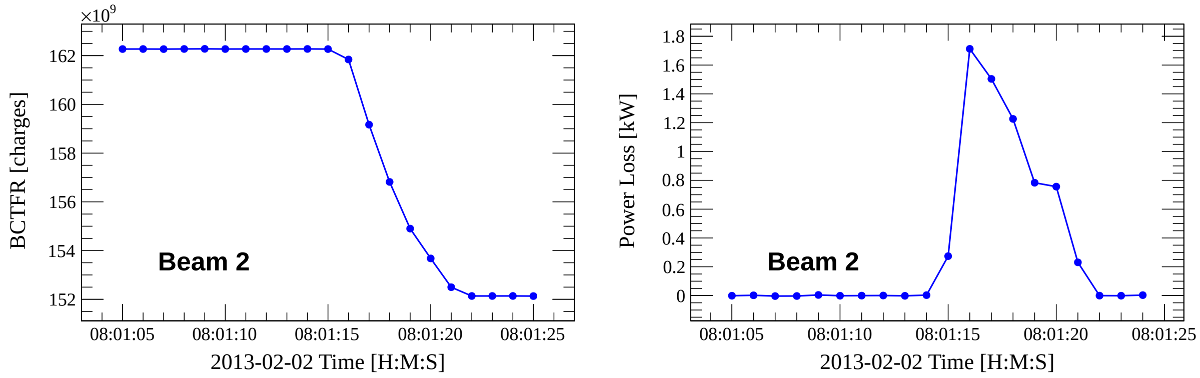


Figure 4: Beam 2 current drop during the loss maps taken on *2013-02-02 08:01:15* (left) and the corresponding power loss (right).

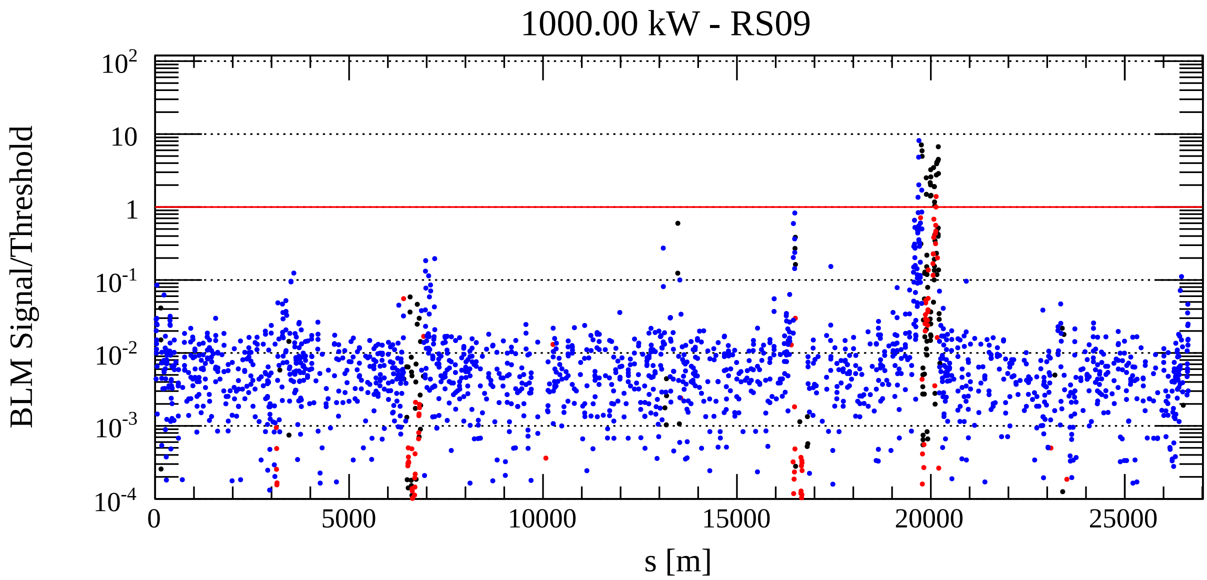


Figure 5: Ratio of the expected BLM signal for beam losses equivalent to 1 1MW to the current thresholds on the machine for running sum of 1.3 s (RS09).

The final procedure to calculate the thresholds is defined in such a way that minimizes the number of modifications. Therefore, for a given BLM, either the master threshold is modified or the monitor factor (MF) but never both:

- The modification of the master thresholds will affect the integration windows of 1.3 s (RS09) and above. As described in [6], the dump thresholds in RS10, RS11 and RS12 (integration windows of 5.3, 20.9 and 83.8 s respectively) will get the same value in Gy/s as the dump thresholds of RS09. The dump thresholds are only modified for 4 TeV. Shorter running sums are not changed.
- Note that the modification of monitor factors (MF) affects all integration windows and all energies.

Table 3 summarizes the threshold changes required for BLMs protecting cold magnets. A threshold increase is required for 5 BLMs and in four of those cases the monitor factor provides the required margin. For simplicity, and given that the maximum required increase is roughly a factor 10, it was chosen to increase the MF for those four BLMs to 1. The fifth BLM (BLMQI.06L7.B2I20_MQTL) currently has MF =1.0 and belongs to family THRI_B2.2_MQTLH. This monitor was moved to a new family (THRI_MQTLH_QT) with thresholds a factor 2 higher (in RS09 as described above) than the original.

Table 3: Summary of threshold changes for BLMs protecting cold elements.

BLM Name	THRES (1 MW)	OLD THRES	MF	MF (new)	Master
BLMQI.08L7.B2I10_MQ	0.011381	0.001396	0.1	1.0	NO
BLMQI.08L7.B2I30_MQ	0.009262	0.001919	0.1	1.0	NO
BLMQI.08L7.B2I20_MQ	0.003863	0.001919	0.1	1.0	NO
BLMQI.06L7.B2I20_MQTL	0.002335	0.001369	1.0	1.0	X 2
BLMEI.09L7.B2I30_MBB	0.002289	0.001682	0.1	1.0	NO

A similar summary for BLMs protecting warm magnets is presented in Table 4. In this case the two BLMs that require an increase of thresholds have MF =1.0 and belong to family THRI_MQW. They will be moved to a new family (THRI_MQW_QT) with the thresholds of the original family increased by a factor 1.5 in RS09. Note that even though the loss map analysis shows that these two BLM would require two different threshold increases, the same one (the largest) is applied to both BLMs.

Table 4: Summary of threshold changes for BLMs protecting warm elements.

BLM Name	THRES (1 MW)	Old THRES	MF	MF (new)	Master
BLMQI.05R7.B1E30_MQWA.E5R7	0.487671	0.350044	1.0	1.0	x 1.50
BLMQI.05R7.B2I10_MQWA.D5R7	0.350148	0.350044	1.0	1.0	x 1.50

Finally, Table 5 summarizes the threshold changes required for BLMs protecting collimators. The approach followed in this case is similar as for warm magnets, i.e, monitors belonging to the same BLM family are moved to a new family (FAMILY_QT) that has the original thresholds increased in RS09 by a factor indicated in the last column of the table. Note that all the monitors showed in this table have MF=0.4 both before and during the quench test. All the thresholds changes described in this document were reverted immediately after the test was finished. Additional modifications had to be done on-the-fly during the tests; they were also reverted afterwards.

Table 5: Summary of threshold changes for BLMs protecting collimators.

BLM Name	THRES (1 MW)	Old THES	Family	Master
BLMEI.07L7.B2I10_TCLA.A7L7.B2	0.01619	0.002277	THRI.07_7_AB_TCLA	x 7.5
BLMEI.06L7.B2I10_TCLA.D6L7.B2	0.03967	0.006723	THRI.06_7_CD_TCLA	x 6
BLMEI.06L7.B2I10_TCLA.C6L7.B2	0.03333	0.006723	THRI.06_7_CD_TCLA	x 6
BLMEI.06R7.B2I10_TCP.B6R7.B2	7.56869	1.680225	THRI_7_TCP	x 4.5
BLMEI.06R7.B1E10_TCLA.B6R7.B1	11.63001	2.712856	THRI.06_7_AB_TCLA	x 4.3
BLMEI.06R7.B2I10_TCSG.A6R7.B2	6.03613	1.470197	THRI_7_TCSG_F5	x 4.1
BLMEI.06R7.B1E10_TCLA.A6R7.B1	10.64474	2.712856	THRI.06_7_AB_TCLA	x 4.3
BLMEI.04R7.B2I10_TCSG.D4R7.B2	0.65651	0.189027	THRI_7_TCSG	x 3.5
BLMEI.04R7.B1E10_TCSG.A4R7.B1	0.61446	0.189027	THRI_7_TCSG	x 3.5
BLMEI.06R7.B2I10_TCP.C6R7.B2	4.83734	1.680225	THRI_7_TCP	x 4.5
BLMEI.06R7.B1E10_TCSG.6R7.B1	4.04297	1.470197	THRI_7_TCSG_F5	x 4.1
BLMEI.04R7.B2I10_TCSG.A4R7.B2	0.48917	0.189027	THRI_7_TCSG	x 3.5
BLMEI.05L7.B2I10_TCSG.E5L7.B2	0.47574	0.189027	THRI_7_TCSG	x 3.5
BLMEI.04L7.B2I10_TCSG.A4L7.B2	0.40789	0.189027	THRI_7_TCSG	x 3.5
BLMEI.04L7.B1E10_TCSG.A4L7.B1	0.38031	0.189027	THRI_7_TCSG	x 3.5
BLMEI.05R7.B1E10_TCSG.B5R7.B1	2.80816	1.470197	THRI_7_TCSG_F5	x 4.1
BLMEI.05R7.B2I10_TCSG.A5R7.B2	2.79542	1.470197	THRI_7_TCSG_F5	x 4.1
BLMEI.05L7.B2I10_TCSG.D5L7.B2	0.28224	0.189027	THRI_7_TCSG	x 3.5
BLMEI.04R7.B2I10_TCSG.B4R7.B2	0.27330	0.189027	THRI_7_TCSG	x 3.5
BLMEI.04L7.B1E10_TCSG.B4L7.B1	0.26771	0.189027	THRI_7_TCSG_F5	x 4.1
BLMEI.05R7.B2I10_TCSG.B5R7.B2	1.72639	1.470197	THRI_7_TCSG_F5	x 4.1
BLMEI.05R7.B1E10_TCSG.C5R7.B1	0.19700	0.189027	THRI_7_TCSG	x 3.5

3 Experimental procedure

The collimation proton quench tests took place between the 14th and 15th February 2013. A special ramp function was used to move the collimators (RAMP_4TeV_2012_Quench). Figure 6 displays the beam intensities for each fill used during the quench test:

- **Tests ramp 1 (fill No. 3565):** Beam 1 and Beam 2 were filled with low intensity (below the setup beam flag). This fill was used to setup the ADT. Beam 1 and Beam 2 filled with 1 pilot bunch and 3 bunches with total intensity below 3×10^{11} protons. This fill finished with an asynchronous dump to complete the collimator settings validation.
- **Failed ramp (fill No. 3566):** This was the first attempt to reach 500 kW. Beam 2 filled with 144 bunches with up to 1.8×10^{13} protons. The fill was dumped due to interlock in collimator settings.
- **First ramp (fill No. 3567):** This is the first fill used for the quench test. Beam 2 was filled with 144 bunches and total intensity of about 2.1×10^{13} protons. The time of the maximum loss taken from the loss maps at 1Hz is *2013-02-14 20:21:15*.
- **Second ramp (fill No. 3568):** Second fill used for the quench tests aiming to get 1000 kW loss rate. Beam 2 filled with 144 bunches with up to 2.1×10^{13} protons injected. The time of the maximum loss taken from the loss maps at 1Hz is *2013-02-15 00:07:25*.
- **Third ramp (fill No. 3569):** Third fill, reaching up to 1000 kW loss rates. Beam 2 filled with 216 bunches (144 + 72) with total intensity up to 3×10^{13} protons. The time of the maximum loss taken from the loss maps at 1Hz is *2013-02-15 03:15:03*.

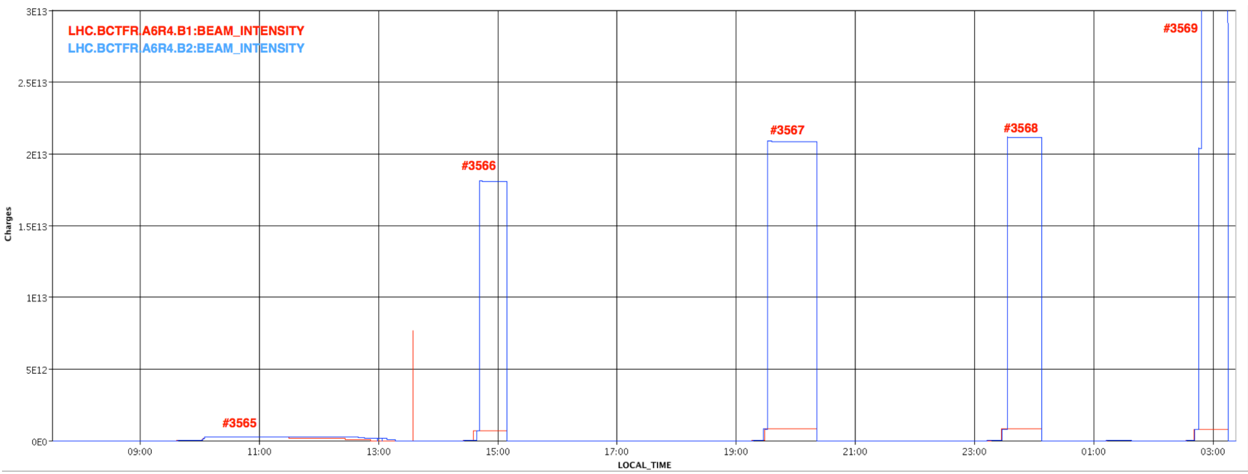


Figure 6: Beam intensity during the duration of the collimation quench test.

4 Results for test ramp (fill 3565)

In order to have controlled loss rates, the beam was excited with the transverse damper (ADT) method. With this method it is possible to excite one single bunch or full batches. The ADT horizontal excitation was used on a selected bunch train. The excitation time as well as the gain can be set up precisely. A special function was trimmed with a similar shape displayed in Figure 7, with the possibility of adding extra points in the middle of the function. The final settings of the ADT were tuned during the first ramp of the MD using low intensity (maximum protons in the machine $< 3 \times 10^{11}$ protons) below the setup beam flag (SBF).

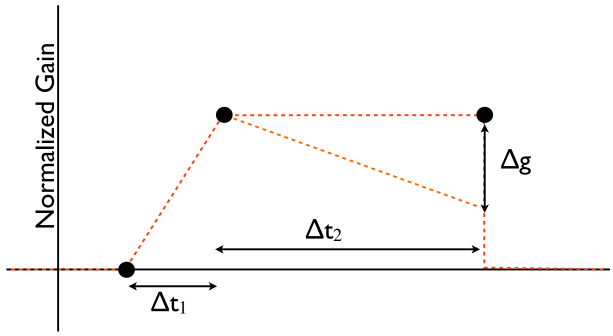


Figure 7: Schematic diagram of the trim functions to control the ADT excitation.

During this low intensity fill we performed 6 excitations of the beam to tune the ADT (3 on Beam 1 and 3 on Beam 2). We used Beam 1 and Beam 2 in order to get more experience with the ADT settings. Figure 8 shows the decrease of beam intensity during the ADT excitation (in blue) and the ADT settings used (in red) for Beam 1 (top) and Beam 2 (bottom).

After finding the ADT settings that on single bunches provide the desired time profile losses, the total intensity was scaled up to achieve the peak loss ratios. For this, Beam 2 collimators were setup with the Case 1 settings shown in Table 2. Figure 9 shows the main collimator settings for Beam 1 (left) and Beam 2 (right). Notice that in this case beam was only injected in Beam 2. The last loss map on Beam 2 was used to decide the desired beam intensity to achieve the desired losses. Figure 10 shows the decrease of beam intensity (left) and the peak power loss over 1 second (right) during the last loss maps on Beam 2. The maximum power loss was 3.5 kW. This was achieved by exciting 1 individual bunch. A scaling from this number shows that we would need to excite 144 bunches to achieve 500 kW with the same excitation strength. This is what we used for the next fill.

5 Results for quench tests (fills 3567, 3568 and 3569)

After setting up the ADT and validating the collimator settings we had three attempts to quench the magnets in the DS of left of IR7. The procedure was always the same, injecting enough charges to achieve the desired power loss and excite with the ADT settings decided in the test fill. On the first fill, number 3567, we achieved maximum peak power loss calculated

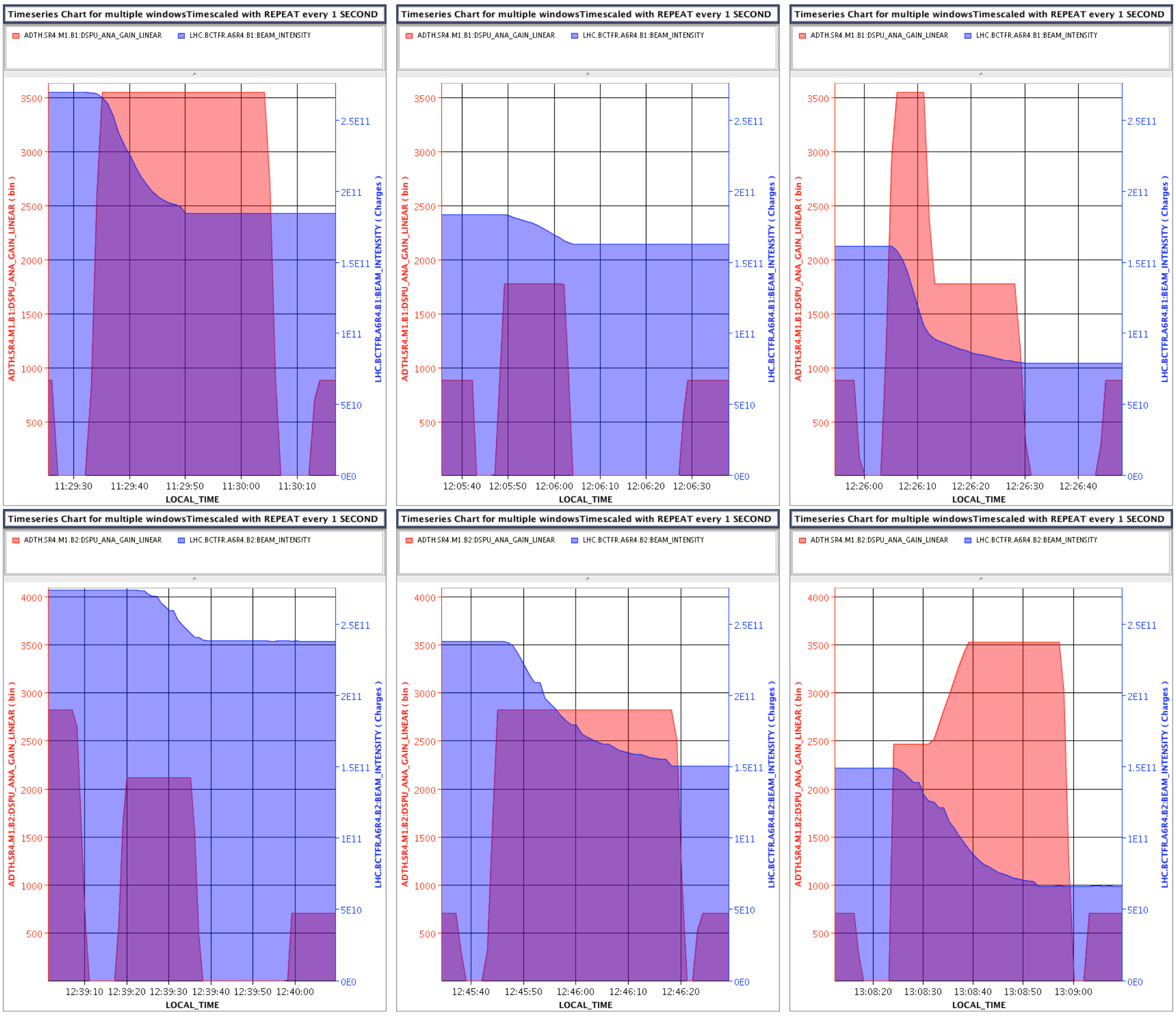


Figure 8: Beam intensity (blue) during the tests in fill 3565 and the ADT gain settings (red) for Beam 1 (top) and Beam 2 (bottom).

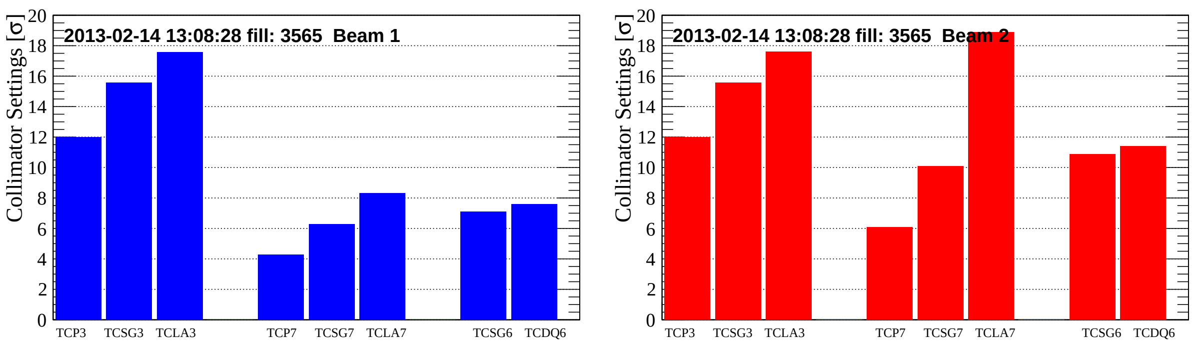


Figure 9: Collimator settings used during the quench test calculated in beam sigma size at 4 TeV for Beam 1 (left) and Beam 2 (right).

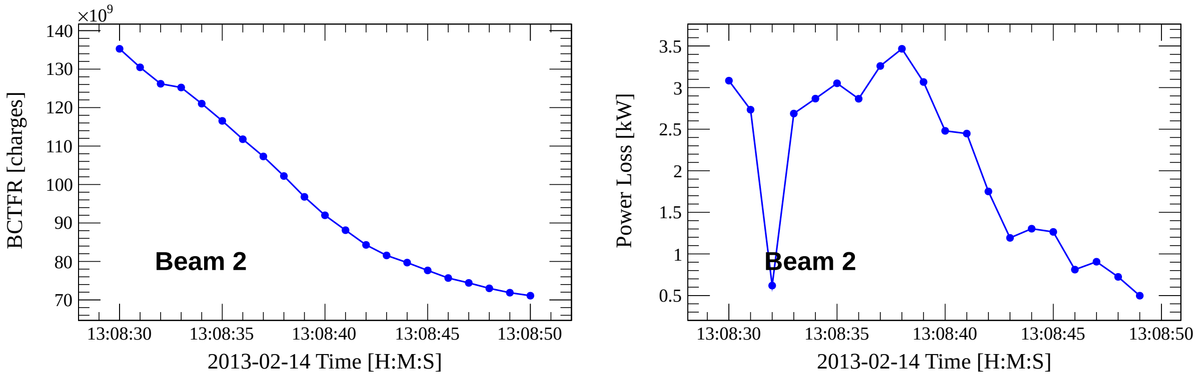


Figure 10: Beam intensity and power loss during the last lost maps on Beam 2 for fill 3565.

from the BCT signal on the post mortem data of 530 kW; no quench was observed, the fill was dumped by the BLMs. After increasing some of the BLM thresholds we tried the same procedure (fill number 3568) and we achieved up to 640 kW, no quench was observed (fill dumped by BLM system). On the third attempt (fill number 3569) the number of injected charges was increased to 216 bunches to achieve the goal of about 1 MW peak power loss; this was indeed the case. About 1050 kW of beam power loss was measured without observing any quench of the magnets; fill dumped by BLM system. Table 6 shows a summary of the achieved peak power loss and the initial beam intensity. The increase of the beam power loss as well as the decrease of the beam intensity is shown in Figure 11 for the three fills injected for the quench tests. In addition, the plot shows two of the attempts to quench in 2011, fill number 1777 and 1778. It is particularly interesting to see that this year, thanks to the use of the ADT we could control smoothly the beam losses, the increase of power loss was longer of the order of 5 to 10 s and in all cases we dump because of the BLM thresholds when the desired maximum power loss was achieved.

Table 6: Injected intensity and total maximum power loss achieved for the three fills of the quench tests in 2012 and two fill of the quench test in 2011.

	Beam Intensity [protons]	**Max. Peak Power [kW]**
Ramp 1: fill 3567	2.1×10^{13}	530
Ramp 2: fill 3568	2.1×10^{13}	640
Ramp 3: fill 3569	3×10^{13}	1050
year 2011: fill 1777	1.8×10^{12}	510
year 2011: fill 1778	1.8×10^{12}	215

Figure 12 shows the loss maps taken during the last fill, when 1050 kW power loss was achieved. Figure 12-left shows the raw signal of all BLMs (ionization chamber) along all the ring for running sum of 1.3 s (RS09). The plot shows the BLM background noise at the level of about 3×10^{-7} Gy/s. It is noticed that on right of IR7 some BLMs were not giving any signal. On left of IR7, it is clearly evident the leakage to the cold sector (in blue) that expands from IR7 up to right of IR4. Figure 12-right shows the cleaning inefficiency.

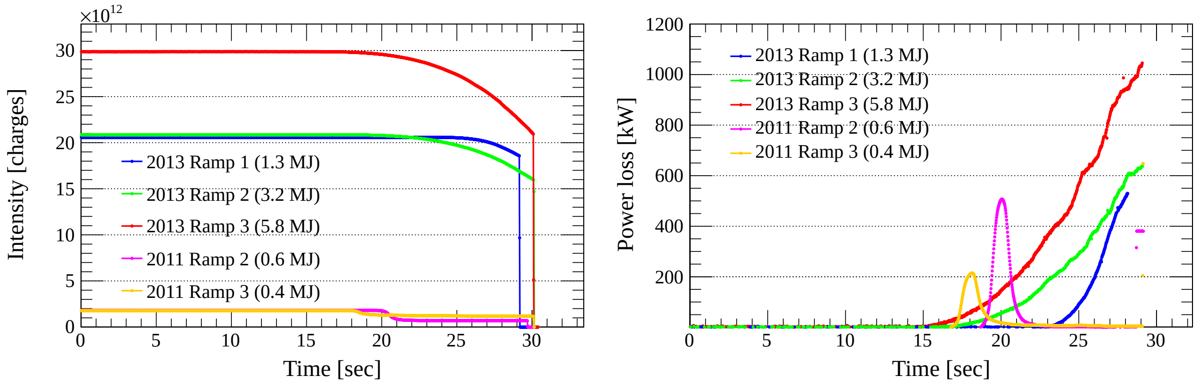


Figure 11: Total beam intensity (left) and peak beam power loss (right) for the three ramps to 4 TeV of the quench test in 2013 and two ramps to 3.5 TeV of a similar test in 2011.

This shows a very good agreement with the loss maps taken on the 2nd February for the preparation of the MD. The loss maps for the other fills are shown in the Appendix.

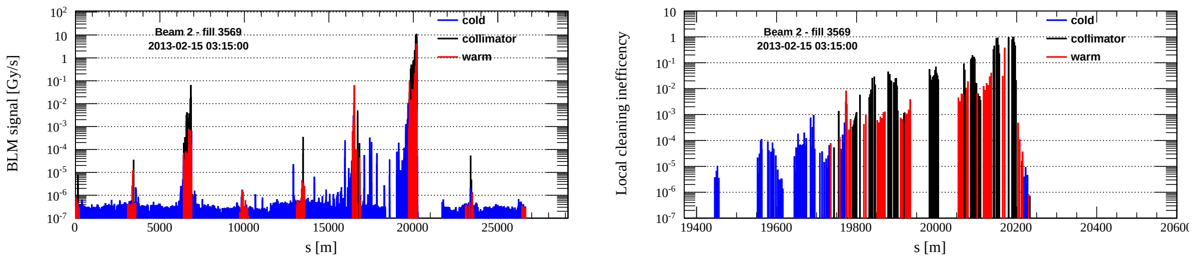


Figure 12: Measured loss map in all the LHC ring during the fill number 3569 (left) and zoom of the losses in IR7 during the fill number 3569. BLM signals are noise-subtracted and normalized to the maximum loss.

During the last fill, the signal from the very high radiation detectors based on secondary electron emission (BLM SEMs) was also monitored. These BLM chambers are located in high radiation areas such as collimation, in all IPs and in the beam dump region. Their sensitivity is lower than the regular BLMI used for the standard loss maps, therefore they can only measure very high signals. Figure 13 shows the measured signal during the last ramp, showing in pink the signal from the BLM SEMs. Figure 13-left displays the losses in the full LHC ring and shows that the BLM SEM signals are sensitive to the losses in IR7, see zoom in Figure 13-right.

Table 7 summarizes the comparisons of the maximum BLM signal measured during the last ramp (fill number 3569) for running sums of 1.3 s (RS09) and 5.2 s (RS10). The table shows also the BLM quench thresholds for the respective sensors and the ratio BLM signal to BLM quench threshold. It has to be noticed that the BLM thresholds were set according to orbit bump loss scenario.

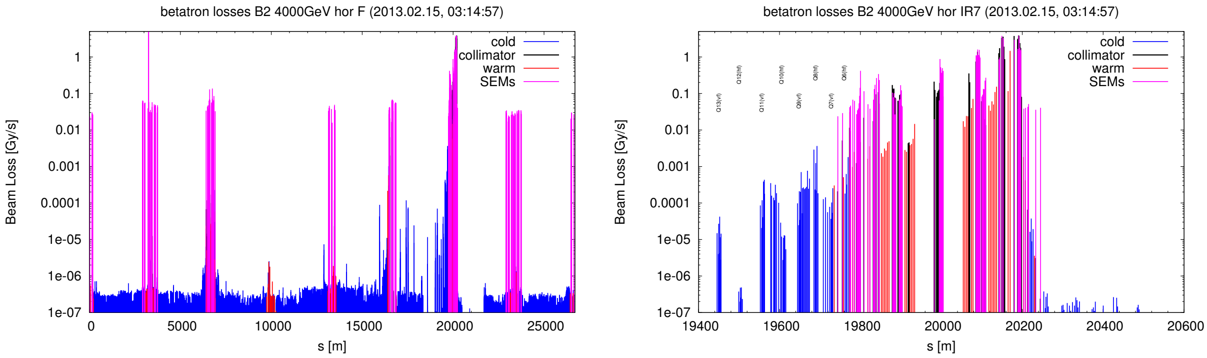


Figure 13: Measured loss map in all the LHC ring during the fill number 3569 (left) and zoom of the losses in IR7 during the fill number 3569. BLM signals from SEMs BLMs.

Table 7: Maximum BLM signal, BLM signal expected at quench and ratio of both during the peak power loss of 1050 kW for running sum of 1.3 s (RS09) and 5.2 s (RS10).

	Fill 3569	**BLM Measurement [Gy/s]**	**BLM Quench Threshold [Gy/s]**	**Ratio**
RS09	BLMQI.08L7.B2I10_MQ	1.08×10^{-2}	4.65×10^{-3}	2.3
RS09	BLMQI.08L7.B2I20_MQ	3.81×10^{-3}	6.40×10^{-3}	0.6
RS10	BLMQI.08L7.B2I10_MQ	8.42×10^{-3}	1.67×10^{-3}	5.1
RS10	BLMQI.08L7.B2I20_MQ	2.87×10^{-3}	2.29×10^{-3}	1.3

5.1 Temperature measurements

The temperature of the collimators was monitored during the full duration of the test. The collimator with highest increase of temperature was the skew primary collimator of Beam 2 (TCP.B6R7.B2). During the last ramp the collimator temperature rose up to 36.1 ^{0}C degrees, an increase of about 10 ^{0}C degree with respect to the start of the fill until the test was done. Figure 14 shows the temperature for the TCP.B6R7.B2 during the three main fills for the test. The measurement of the collimator gap with the LVDT sensors was also monitored in order to check if there was any deformation due to the rise of temperature. The gap remained the same within 5 μm, which is within the precision of the sensor.

The temperature in the cold sector left of IR7 was also monitored. The highest increase of 0.35 K degrees was observed in an empty cryostat in cell 11, left of IR7. The temperature rose from 1.9 K to 2.25 K. No significant increase of temperature was observed in any other cold sector.

Figure 15 shows the detailed temperature spike at the collimators during the last tests (left) and the measured temperature in the empty cryostat for the three tests (right). In both cases the red line indicates the time were the maximum loss was recorded.

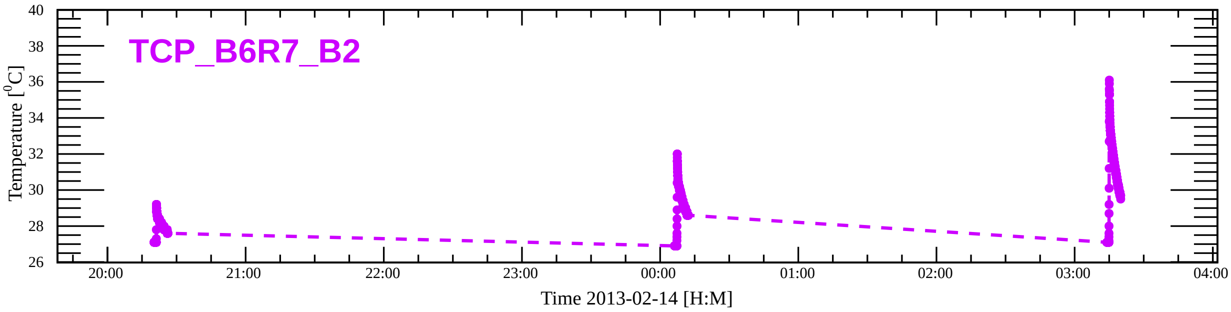
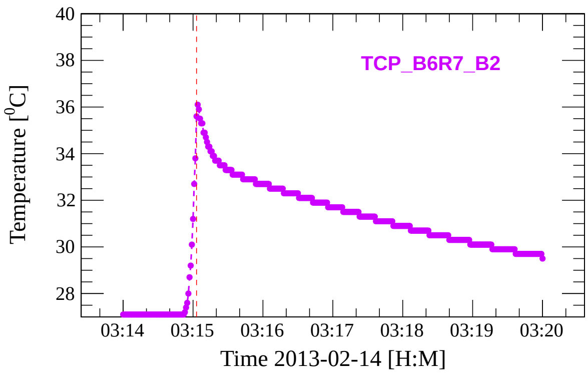


Figure 14: Temperature of the right-downstream jaw of the primary collimator (skew) of Beam 2 for the three main fills of the test.



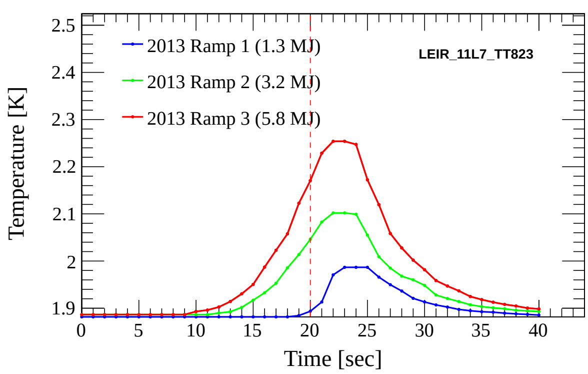


Figure 15: Temperature of the right-downstream jaw of the primary collimator (skew) of Beam 2 for the last test when the maximum power loss was reached.

6 Conclusions

At the end of the physics run of the LHC in 2013, several machine studies took place with the aim to measure the real quench limit of the LHC superconducting magnets. Here we have shown the results from the proton collimation quench test. In this case, Beam 2 was excited by blowing-up the beam with the transverse damper. The settings of the collimators in IR7 and IR6 were modified in order to allow more losses into the cold DS magnets in left of IR7. In the last fill (fill number 3569) we generated beam losses with a peak of 1050 kW peak power loss averaged over 1 second, but the magnets did not quench. The BLM losses measured at BLMQI.08L7.B2I10_MQ were compared to the BLM quench limit thresholds. For this monitor the measured losses were 2.3 times higher for the running sum of 1.3 s and 5.1 times higher for the running sum of 5.1 s. The highest rise of temperature was about $10\,^0$C for the skew primary collimator of Beam 2 in IR7, but no indications of a deformation were observed, since the gap stayed the same within the measurement precision. The temperature of the cold sector did not increase significantly. Detailed simulations on the expected distribution of the losses in the magnets coils should be done to provide a new estimate of the real quench limit.

7 Acknowledgments

The authors would like to thank the LHC operation crews for support during the beam study, F. Cerutti for FLUKA simulations, A.Bertareli and F.Carra from CERN EN-MME group for thermo-mechanical simulations and the cryogenics team for temperature measurements.

References

[1] R.W. Assmann, R. Bruce, F. Burkart, M. Cauchi, D. Deboy, B. Dehning, E.B. Holzer, E. Nebot del Busto, A. Priebe, S. Redaelli, A. Rossi, R. Schmidt, M. Sapinski, G. Valentino, J. Wenninger, D. Wollmann, and M. Zerlauth. Collimator losses in the DS of IR7 and quench test at 3.5 TeV. May 2011.

[2] LHC Collimation Review 2011
http://indico.cern.ch/event/139719/.

[3] W. Hofle, R. Assmann, S. Redaelli, R. Schmidt, D. Valuch, D. Wollmann, and M. Zerlauth. Controlled transverse blow-up of high energy proton beams for aperture measurements and loss maps. *Conf. Proc.*, C1205201(CERN-ATS-2012-128):THPPR039, 3 p, May 2012.

[4] B. Salvachua et al. Quench test 2013: Quench margin at 4 TeV. (EDMS No. 1264646), Jan 2013.

[5] LHC operation e-logbook (2013/02/02 7:00am)
http://elogbook.cern.ch/eLogbook/eLogbook.jsp?shiftId=1051647.

[6] E. B. Holzer et al. DS Quench Tests. (MD1-2011 DS Quench Tests, EDMS No. 1151015.).

Appendix A

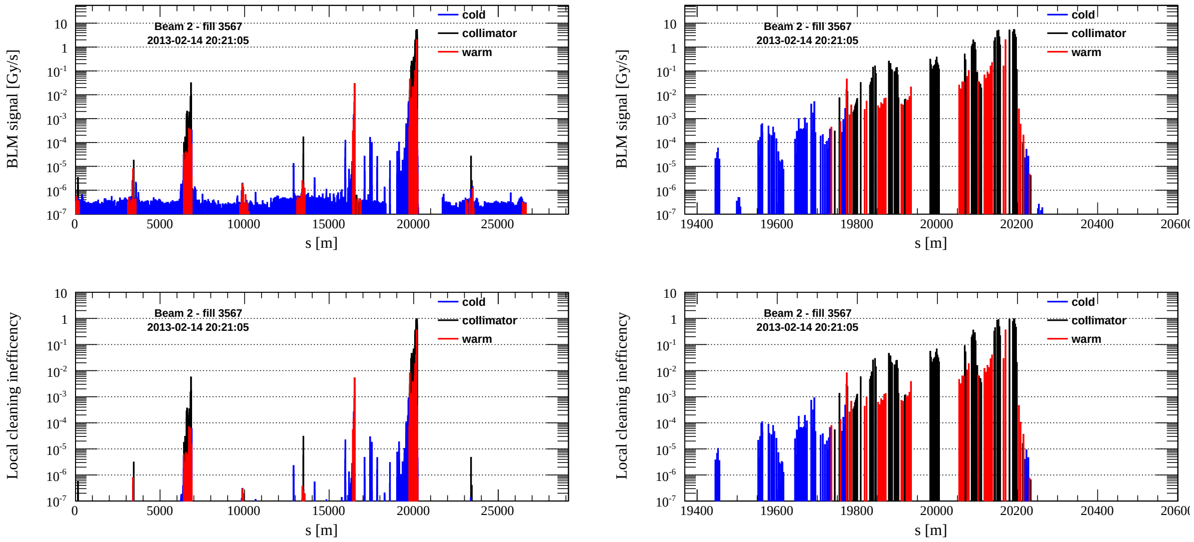


Figure 16: Loss maps distributions during fill number 3568. BLM signals are noise-subtracted and normalized to the maximum loss.

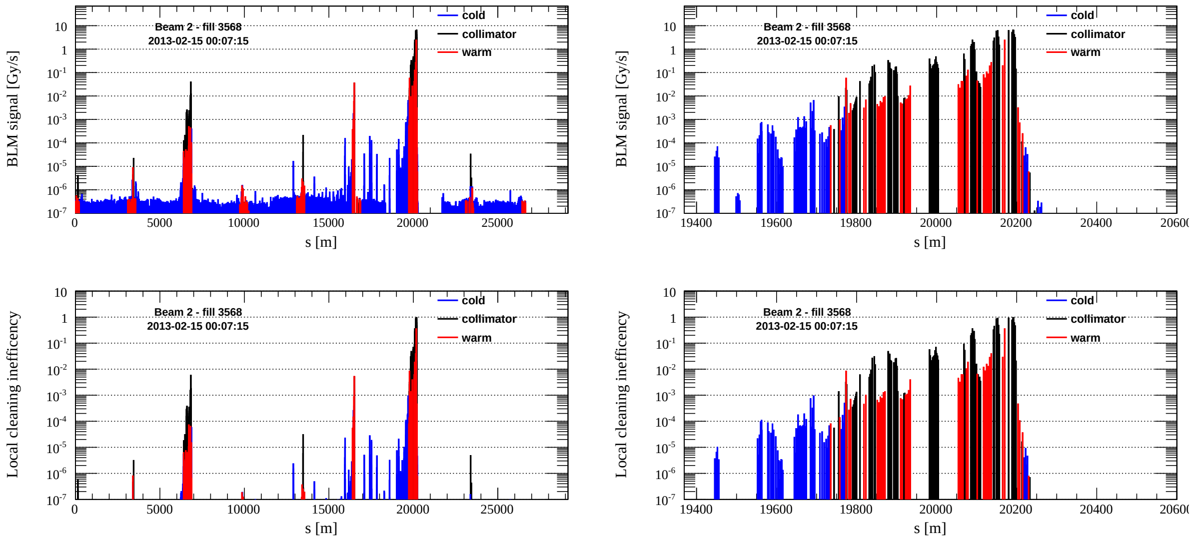


Figure 17: Loss maps distributions during fill number 3568. BLM signals are noise-subtracted and normalized to the maximum loss.

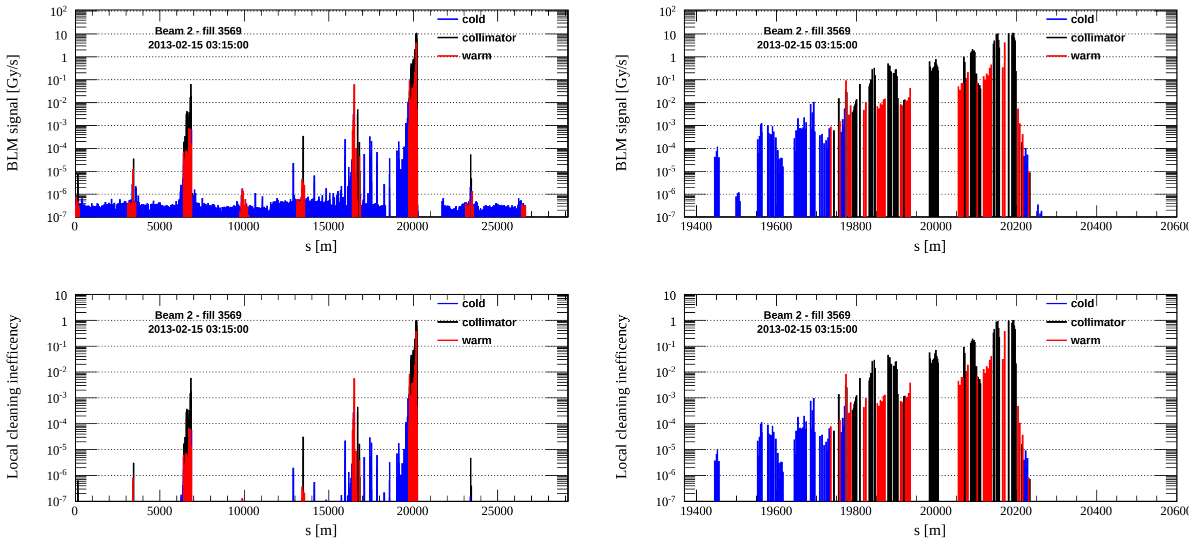


Figure 18: Loss maps distributions during fill number 3569. BLM signals are noise-subtracted and normalized to the maximum loss.