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Collimation quench test with 6.5 TeV proton beams

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Summary

We show here the analysis of the MD test that aimed to quench the superconducting magnets in the dispersion suppressor region downstream of the betatron collimation system. In Run I there were several attempts to quench the magnets in the same region. This was done by exciting the Beam 2 in a controlled way using the transverse damper and generating losses leaking from the collimation cleaning. No quench was achieved in 2013 with a maximum of 1 MW of beam power loss absorbed by the collimation system at 4 TeV beam energy. In 2015 a new collimation quench test was done at 6.5 TeV aiming at similar power loss over a longer period, 5-10 s. The main outcome of this test is reviewed.

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 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. This implies that the maximum intensity reach limit is set by the performance of the collimation system.

The first test was done the 5th of September in 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 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. A peak loss of 336 W was observed at the dispersion suppressor region (DS) scaled from the total losses using the cleaning inefficiency at IR7 Q8 DS of 6.6×10^{-4} being the cleaning inefficiency the noise-subtracted BLM signal, normalized. 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 assumed quench limit for the BLMs 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]. This result was used to estimate the performance reach at 7 TeV by taking the achieved loss rate as a pessimistic limit before quench [2].

The second test was done on 15th February 2013, at beam energy of 4 TeV. The procedure was, as for the 2011 test, to induce high losses with the collimation system in place and observe whether any IR7 DS magnet quenches due to the leakage from the collimators. 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 were created by exciting the beam with the transverse damper (ADT) [3]. During the 2013 test the achieve maximum loss rate was 1050 kW with a slow rising time of more than 10 s. The magnets did not quench. The details of the test are described in [4]. Numerical simulations carried out with Sixtrack and FLUKA [5] show that the maximum energy deposition was in the first dipole of cell 9, with a value between $20 - 70$ mW/cm^3. The uncertainty comes from the comparison with the BLM data in the IR7 DS during the test. Table 1 shows a summary of the results from previous tests. The scaled loss to the DS is just cleaning inefficiency multiplied by the total intensity lost. This is not really representative of the energy deposition in a particular quadrupole but could be used to compare within the different tests assuming that the energy will be distributed similarly.

Table 1: Summary of previous quench tests.

Year	**Energy (TeV)**	η_c	**Loss at TCP (kW)**	**Scaled loss at DS (W)**	**Factor to 2013**
2011	3.5	6.6×10^{-4}	215	142	0.14
2011	3.5	6.6×10^{-4}	510	337	0.33
2013	4.0	9.5×10^{-4}	504	479	0.5
2013	4.0	9.5×10^{-4}	640	608	0.6
2013	4.0	9.5×10^{-4}	1050	998	1.0

2 Preparation

The procedure of the test is the same as in 2013, details in a Machine Protection document, see [6]. Initially two set of collimator settings were prepared, i.e. the nominal settings used in 2015 and more relaxed ones. Due to the limited time during the MD (see Sec. 3) only the nominal settings could be used. Table 2 shows the nominal collimator settings for 2015 and the ones used in the previous tests.

The test was performed with Beam 2, the cleaning inefficiency for the nominal settings in 2015 is 6.6×10^{-4} in Q8 at left of IP7. The hierarchy is shown in Figure 1.

Table 2: Collimator settings used in the proton quench tests. Beam size is calculated assuming normilized emittance of 3.5 μmrad.

	2011 - 3.5 TeV (σ)	**2013 - 4 TeV** (σ)	**2015 - 6.5 TeV** (σ)
IP7 TCP/TCSG/TCLA	5.7/9.5/17.7	6.1/10.1/18.9	5.5/8.0/14
IP3 TCP/TCSG/TCLA	nominal	12/15.6/17.6	15/18/20
IP6 TCSP/TCDQ	nominal	10.9/11.5	9.1/9.1

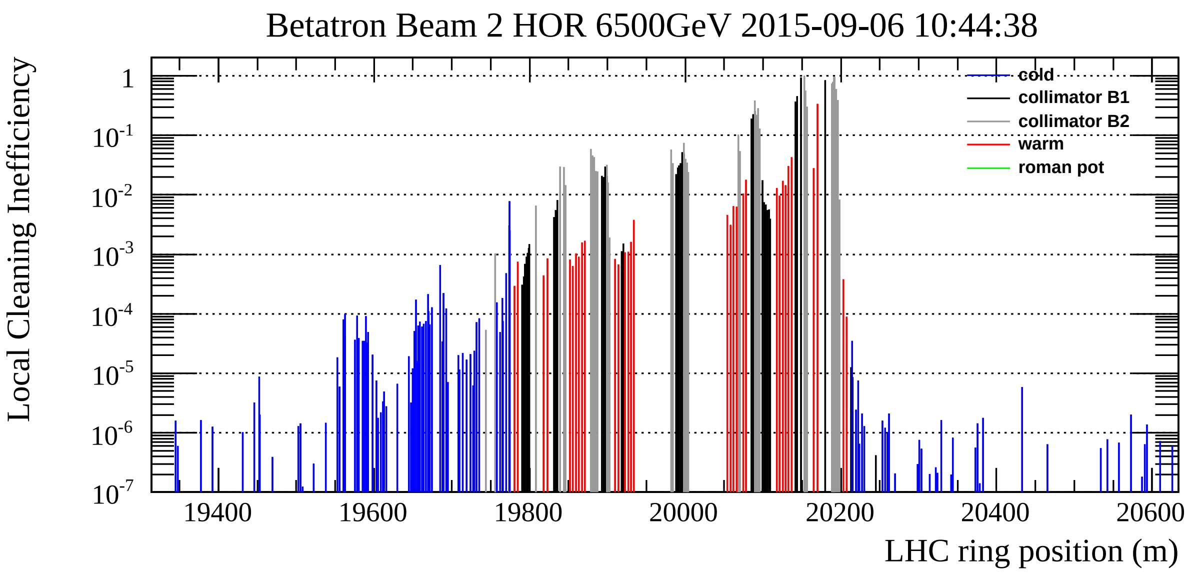

Figure 1: Validation lossmap for nominal collimation settings at 6.5 TeV.

2.1 Modification of BLM thresholds

BLM thresholds in the long straight section of IR7, where the betatron collimation system is located, and in the DS immediately downstream had to be changed, in order to avoid any beam dump which would have prevented to reach 1MW beam losses over few seconds (see Sec. 3) and the desired high power leakage into the DS. In fact, the applied thresholds of the BLMs at IR7 collimators are meant to allow 200kW beam losses in the time window of interest for the test, and those in the IR7 DS are meant to prevent any magnet quench. Moreover, BLM thresholds at warm magnets in IR7 had to be increased as well. In the past tests, the BLM thresholds required for the test were obtained extrapolating qualification loss maps to the desired power loss. Loss maps obtained with the beam/plane of interest with the collimation system at the same settings as for the test were taken, and the beam power loss recorded, to be used as normalization of the scaling of the BLM signals to the desired power loss. Then, thresholds were defined in such a way that minimizes the number of modifications. Therefore, for a given BLM, either the master table (MT) or the monitor factor (MF) was modified but never both. Moreover, modifications to the MTs affected the integration windows of 1.3 s (RS09) and above, with a flat top correction and flattening out the value for RS09 to the longer RSs; thus, shorter running sums were not changed. Conversely, a modification of monitor factors (MF) affected all integration windows and all energies. For the present MD, a similar approach was followed. The description of all the changes can be found in the dedicated ECR [7].

2.2 Setting up of the transverse damper

The filters of the Loop C for Beam 2 Horizontal excitation were updated to 10 MHz settings. This was done by running pre-prepared scripts. The excitation window length of the ADT had also to be changed. The repetition was set such that the noise is played during the whole duration of the gain function.

The gain function was in the Beam Process QUENCH-TEST-ADT, created for this particular test. The procedure was:

- Send the first point of the gain functions to the FGC, so the gain becomes zero.
- With this it is safe to prepare the excitation in the loss maps control application.
- Load the full gain function with Equip State application. The functions has first few seconds with zeros. With this the settings are load to the ADT but not yet played.
- Start the excitation by pressing a button on the loss map application.
- Start the function with Equip State.

The excitation was tested with individual bunches and trains. The final function used is shown in Figure 2.

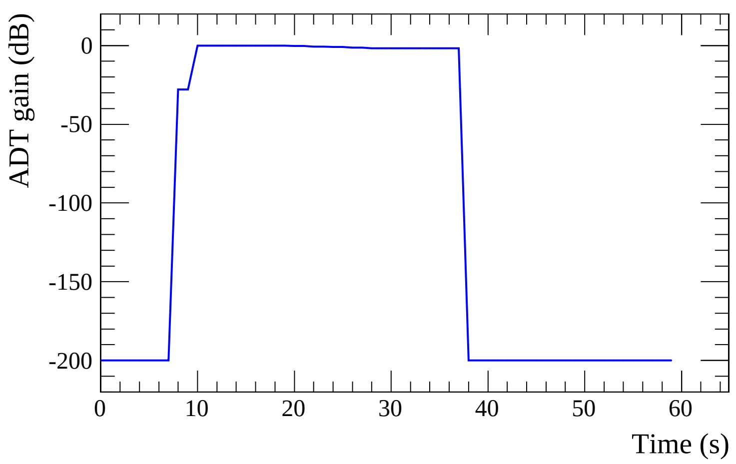

Figure 2: ADT gain function for Loop C.

2.3 Change of QPS symmetric thresholds

MP3 approved the test under the condition that the symmetric quench thresholds will be lowered for the Q4L6 and Q5L6 respectively R6 to 250mV. This was done before the test, however after the test when the ramp down started the Q4L6 and Q5L6 magnets tripped (at -4A/s), due to this change on the symmetric quench protection threshold.

2.4 Online monitoring

Before the MD we prepared an application that displays in real time the beam power loss. The estimated power loss is calculated from the fast BCT signal as the derivative and from the BLMs, see Figure 3. This application used the new calibration factors for the BLMs for 6.5 TeV that are used in the BLM lifetime application, see Figure 4. Both applications were very useful during the test to asses right after the beam excitation the total power loss and the time evolution of the losses for the setting up of the ADT.

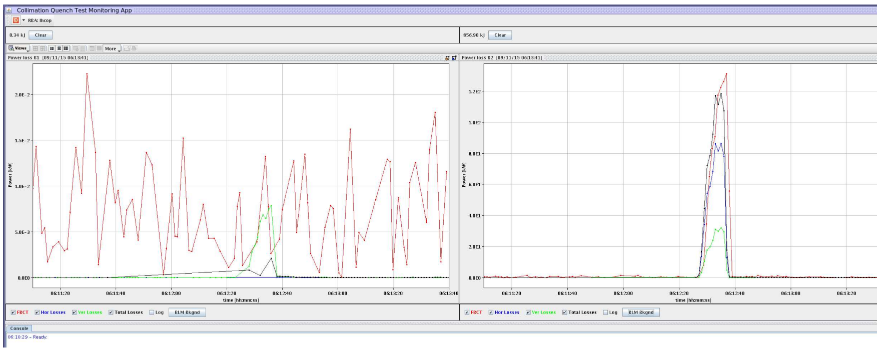

Figure 3: Online display for the Collimation Quench test. Left: power loss for Beam 1. Right: power loss for Beam 2.

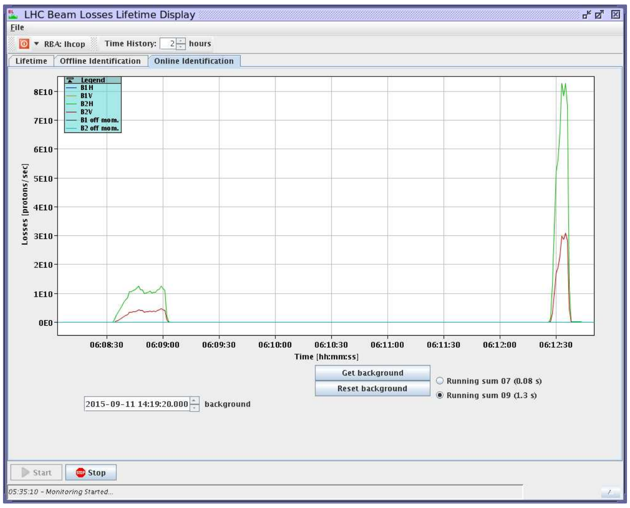

Figure 4: Online display for the Collimation Quench test, BLM lifetime application.

3 MD plan and filling scheme

The initial plan of the MD was to have 3 energy ramps.

- Ramp 1: to setup of the ADT at top energy.
- Ramp 2: with nominal collimator settings to achieve 1000 kW loss rate during 10 seconds.
- Ramp 3: with relaxed collimator settings to achieve 1000 kW loss rate during 10 seconds.

Due to problems with LSA DB the MD was block for many hours and there was time for only one ramp. The strategy was re-discussed during the MD and it was decided to fill both Beam 1 and Beam 2 with 4 nominal bunches and a train of 12 bunches. In addition, in order to have enough beam in the machine to generate 1 MW beam losses over 10 seconds, Beam 2, was filled with:

- 4×36 bunches in the range of the ADT, spaced 3 μs for the final test
- 2×36 bunches for the ADT setup at Flat Top
- 1×36 bunches for the ADT setup at Flat Top

The filling scheme is shown in Figure 5. A limit of 36 bpi trains with some separation between the trains was agreed before starting the test to limit stress on the dump system (due to a leakage of the TDE dump block, under nitrogen overpressure found during the MD period)

4 Excitation at flat top 6.5 TeV

The ADT gain was tuned at flat top first with the nominal bunches before being used on the trains. Figure 6 shows the 3 excitations of the ADT during the test with trains of 36 bunches: 1, 2 and 4 trains. The first two were meant to setup the ADT and the last one to quench. Table 3 shows the times of the 3 excitation, the ADT gain used and the approximate maximum loss rate achieved in each excitation.

- Test on 1 train of 36 bunches: the ADT gain was 0.15, the function for the gain is shown in Figure 7. The maximum loss rate calculated from the 1 Hz BCT signals was 20 kW.
- Test on 2 trains of 36 bunches: the ADT gain was 0.30, the function for the gain is shown in Figure 7. The maximum loss rate calculated from the 1 Hz BCT signals was 130 kW.
- Test on 4 trains of 36 bunches: the ADT gain was 0.40, the function for the gain is shown in Figure 7. The maximum loss rate calculated from the 1 Hz BCT signals was 540 kW.

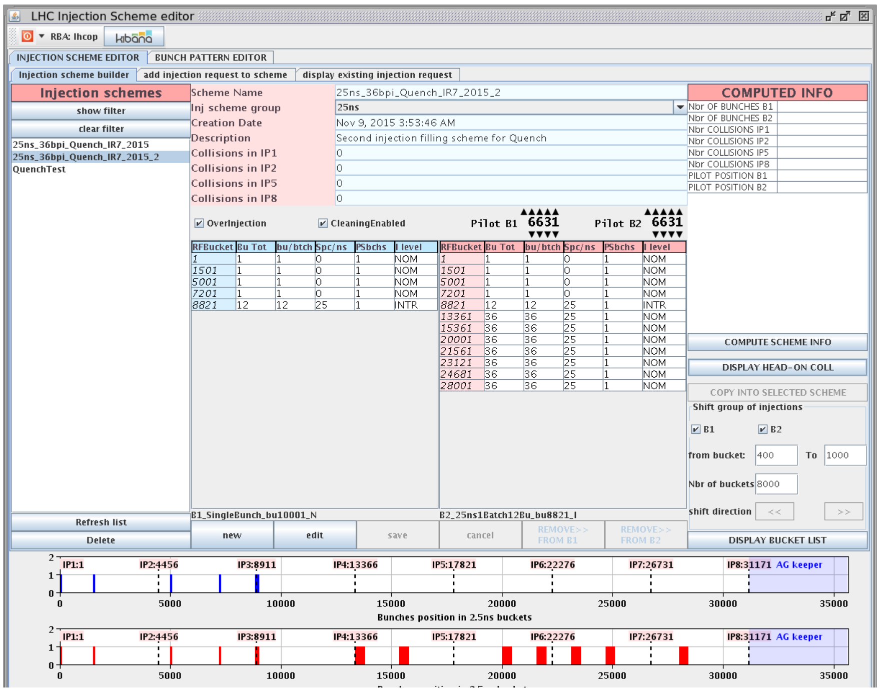

Figure 5: Filling Scheme used during the test.

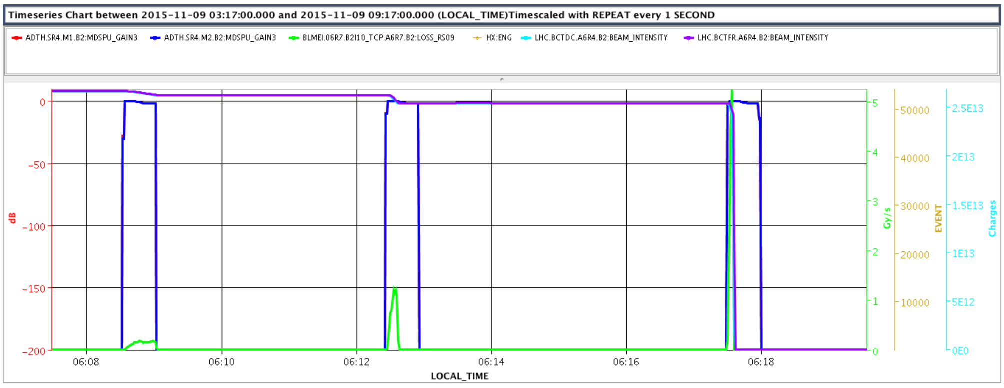

Figure 6: Overview of the beam current, BLM signal at the primary collimators and ADT gain during the test at 6.5 TeV.

Table 3: Timestamps, ADT gain and approximate maximum loss rate of the 3 excitation attempts during the test.

Intensity	Timestamp	ADT gain	Loss Rate (kW)
1×36 bpi	2015-11-09 06:08:24	0.15	20
2×36 bpi	2015-11-09 06:12:18	0.30	130
4×36 bpi	2015-11-09 06:17:22	0.40	540

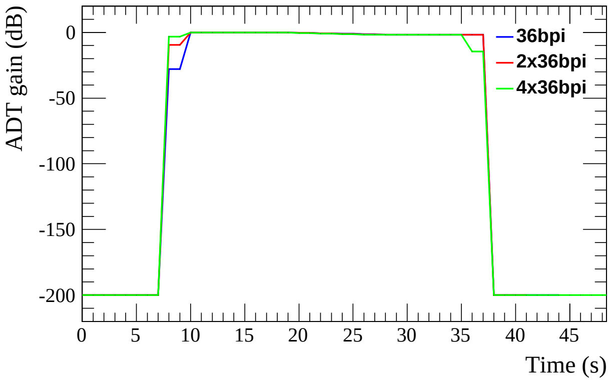

Figure 7: ADT function used during the test to trim the gain of the excitation.

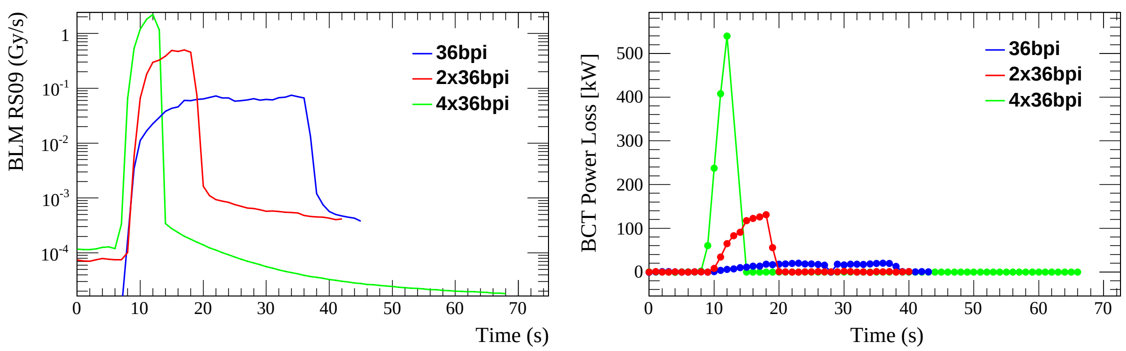

Figure 8: Left: BLM signal at the primary horizontal collimator during the test. Right: power loss calculated from the BCT signal (1 Hz logging).

Figure 8-left shows the BLM signals at the primary collimator recorded during the tests and Figure 8-right shows the power loss calculate from the BCT signal (1 Hz logging). The values in Table 3 are calculated from these figures.

During the attempt to quench (excitation of 4 trains of 36 bunches) the beam was dumped on a BLM un-maskable channel before reaching the target loss rate of 1 MW. The monitor BLMQI.04L6.B2I10_MQY triggered the dump on the integration time of 655 ms. The analysis from the post-mortem data of the BCT shows that the maximum power loss achieved was of 585 kW. Figure 9 shows on the left the intensity for all the collimation proton quench tests done since 2011, in red showing the signal from 2015. The BLM with the maximum signal in the DS area is BLMQI.08L7.B2I30_MQ. Figure 12 shows the ratio of this BLM to the BLM threshold assumed quench level for all the BLM integration times. It should be noted that the quench levels are calculated for different scenarios depending on the integration time. For the 1.3 s running sum the BLM signal was a factor of 1.4 above the assumed BLM quench limit and for the 5.6 s running sum the BLM signal was a factor 1.3 above the assumed BLM quench limit. For all the other running sums the measured loss was below the quench limit.

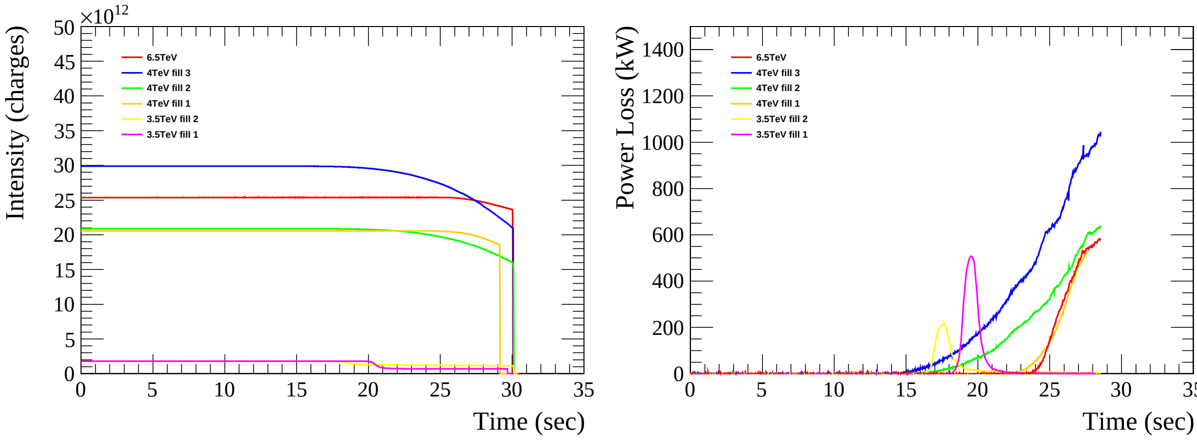

Figure 9: Left: Intensity during the proton quench tests in 2011, 2013 and 2015. Right: Power loss calculated from the BCT on the post mortem logging for the proton quench tests in 2011, 2013 and 2015.

The beam losses measured by the BLMs in all the LHC ring are shown in Figure 10 for integration time of 1.3 s. A zoom into IR7 is shown in Figure 11.

5 Monitoring of collimator temperature

The temperature of the collimators was also monitored during the test. The maximum temperature measured was 30.5 C at the TCSG.A6R7.B2. The collimator is normally at around 27 C. The next collimator heating up was the TCP.B6R7.B2 with a peak at 30 C. Figure 13 shows the measured temperature of of the 4 collimators with highest temperature for the left jaw (left frame) and the right jaw (right frame).

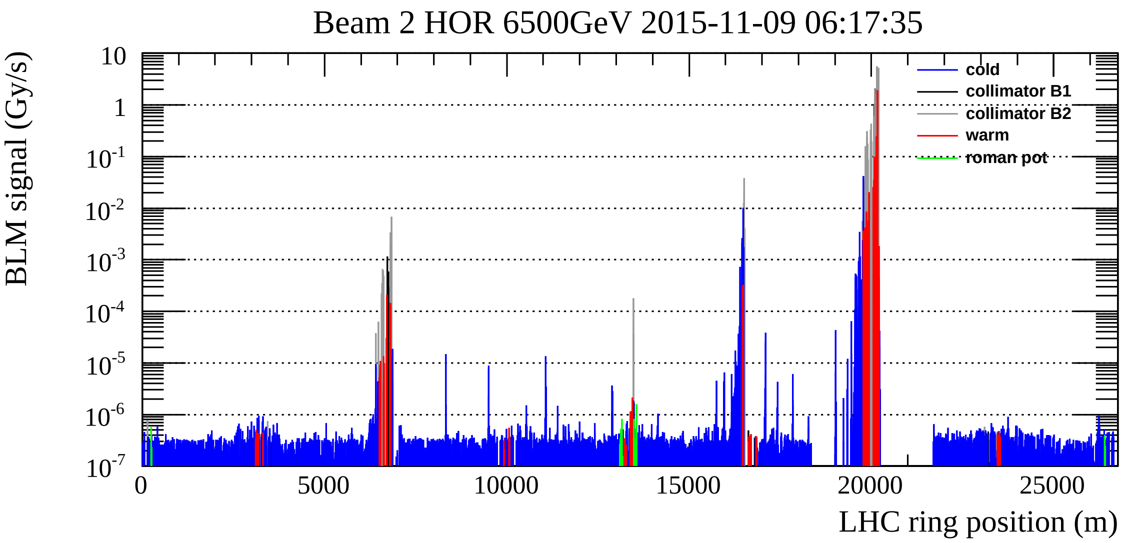

Figure 10: Beam losses in the LHC ring measured by the BLMs at the moment of maximum power loss.

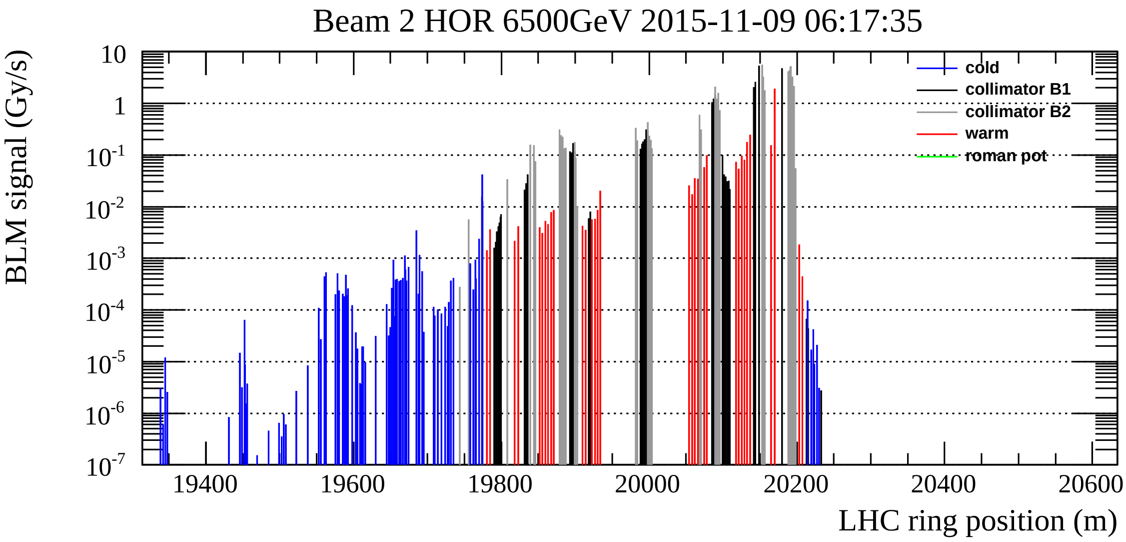

Figure 11: Beam losses in IR7 measured by the BLMs at the moment of maximum power loss.

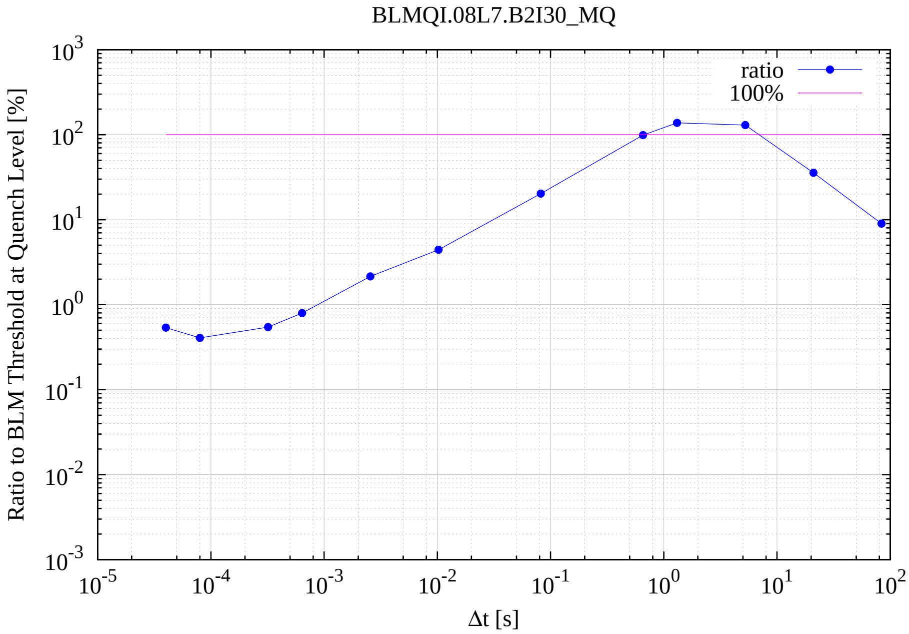

Figure 12: Ratio of BLM signal to BLM Threshold at quench level for the monitor BLMQI.08L7.B2I30_MQ for all the BLM integration times.

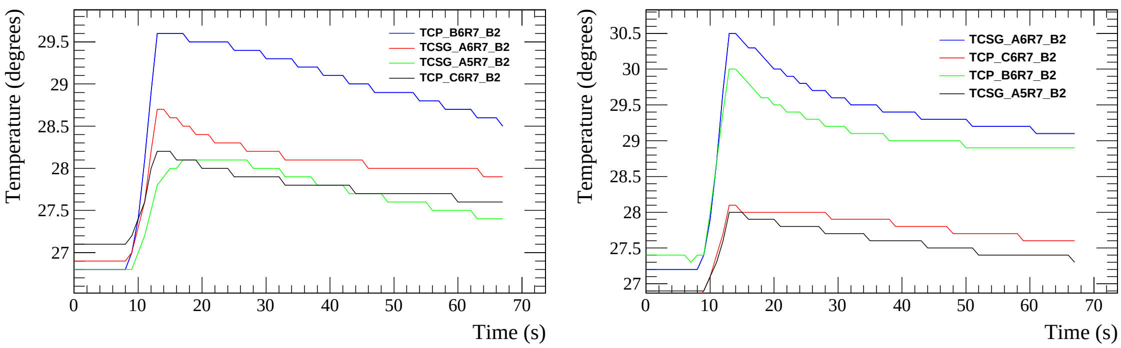

Figure 13: Monitoring of collimator temperature during the last attempt to quench. Left: for the sensor downstream the left collimator jaw. Right: for the sensor downstream right collimator jaw.

6 Conclusions

The quench MD was severely compromised by a controls problem with the BLM threshold settings that became apparent when changing the Beam 2 threshold to the values computed for the tests. This could only be solved some 7h later, which left only less than 3h of beam time. It was decided to squeeze into one single ramp the tests that we planned for 3 ramps.

- ADT excitation tests were done primarily at injection.
- We ramped to 6.5 TeV a combination of single INDIV, 12b trains and 36b trains that allowed - in the same fill - to test the excitation and to try the quench test, keeping a minimum separation of 3 μs between the trains.

Finally, the achieved losses were 585 kW exciting the Beam 2 horizontally with the ADT. The excitation was rising all time, but the rising slope decreased in the last few seconds before the dump. No quench was recorded in any magnet of the dispersion suppressor left of IR7. A premature dump was triggered by a BLM un-maskable channel. The monitor BLMQI.04L6.B2I10_MQY triggered the dump on the integration time of 655 ms.

The Q4L6 and Q5L6 magnets tripped during the ramp down (at -4A/s), due to the symmetric quench protection threshold, which was tightened at the beginning of the MD, to increase the level of protection in case of a beam induced symmetric quench. Thus, no beam induced quench was recorded.

7 Acknowledgments

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References

[1] R.W. Assmann et al. 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. Collimation quench test with 4 tev proton beam. (CERN-ACC-NOTE-2014-0036), 2014.

[5] B. Auchmann et al. Testing beam-induced quench levels of lhc superconducting magnets. (Phys. Rev. StT Accel. Beams 18, 061002).

[6] B. Salvachua et al. Md 340 collimation proton quench test 2015. (EDMS No. 1556166), 2015.

[7] M. Kalliokoski and A. Mereghetti. Blm thresholds for md340 quench test at 6.5 tev. (LHC-BLM-ECR-0042,EMDS 1557789), 2015.