QUENCH TESTS AT THE LARGE HADRON COLLIDER WITH COLLIMATION LOSSES AT 3.5 Z TeV

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Abstract

The Large Hadron Collider (LHC) has been operating since 2010 at 3.5 TeV and 4.0 TeV without experiencing quenches induced by losses from circulating beams. This situation might change at 7 TeV where the quench margins in the super-conducting magnets are reduced. The critical locations are the dispersion suppressors (DSs) at either side of the cleaning and experimental insertions, where dispersive losses are maximum. It is therefore crucial to understand the quench limits with beam loss distributions alike those occurring in standard operation. In order to address this aspect, quench tests were performed by inducing large beam losses on the primary collimators of the betatron cleaning insertion, for proton and lead ion beams of 3.5 Z TeV, to probe the quench limits of the DS magnets. Losses up to 500 kW were achieved without quenches. The measurement technique and the results obtained are presented, with observations of heat loads in the cryogenics system.

INTRODUCTION

At the time of this workshop, the LHC has accumulated more than 5 fb^{-1} at 3.5 TeV and more than 14 fb^{-1} at 4 TeV, with peak luminosities up to $8\times10^{33}\text{cm}^{-2}\text{s}^{-1}$ (80 % of the design luminosity for 7 TeV) and stored beam energies up to 150 MJ. There has been so far no quench induced by losses of the circulating beams. This is an important achievement indicating an excellent performance of the machine protection systems, which catch promptly abnormal loss conditions, and of the collimation system [1], which ensures in all conditions small losses into superconducting magnets. It remains nevertheless crucial to understand the quench limits to predict the LHC performance at the energy of 7 TeV that will be within reach in 2015.

In this paper, the results of quench tests performed with ion and proton beams at 3.5 TeV are presented [2, 3]. These tests are done by maximizing the beam losses on the primary collimators of the betatron cleaning insertion (IR7) to try and reach the quench limits at the limiting locations where the leakage is maximum. We refer to this type of experiments as "collimation quench tests". The present limits of the LHC collimation system are located at the dispersion suppressors (DSs) of the cleaning insertions. Similar losses occur at the DSs of the experimental insertions from luminosity debris. In parallel to this type of tests, other complementary quench tests are being pursued [4, 5, 6] in order to achieve a more complete understanding of the limits in different loss conditions. The machine configuration and the collimator cleaning are presented and the detail procedure established for these tests is introduced. The achieved results in term of peak loss rates for proton and ion beams are discussed. Finally, some conclusions are drawn.

Table 1: Flat-top Collimator Settings for 2011 Quench Tests

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

MACHINE CONFIGURATIONS AND COLLIMATOR CLEANING

Quench tests at 3.5 TeV were performed at top energy before the start of the betatron squeeze ("flat-top"). Collimator settings in IR3 and IR7 reach their final physics settings. Only tertiary collimators in the experimental regions move during squeeze and collision processes, with little effect on the local cleaning in the DSs of IR7. Performing the tests at flat-top has the advantage to avoid additional loss locations in the experimental regions that appear after squeeze, which would require more preparatory work to set thresholds of the Beam Loss Monitors (BLM) system (see next section). The overall turn–around is also shorter than going through the full operational cycle.

The flat-top settings of the different collimators around the ring are listed in Table 1. The same settings were used for proton and ion beams. The cleaning efficiency of the system is shown in Figs. 1 and 2 for the case of proton and ion beams [1]. The ratio between BLM signals measured around the ring and the one measured at the primary collimators of IR7 during dedicated loss maps is given. Loss maps are performed as a part of the system commissioning [7]: the beam lifetime is artificially reduced to maximize the losses at the primary collimators by crossing the third order resonance in either the horizontal or vertical plane,

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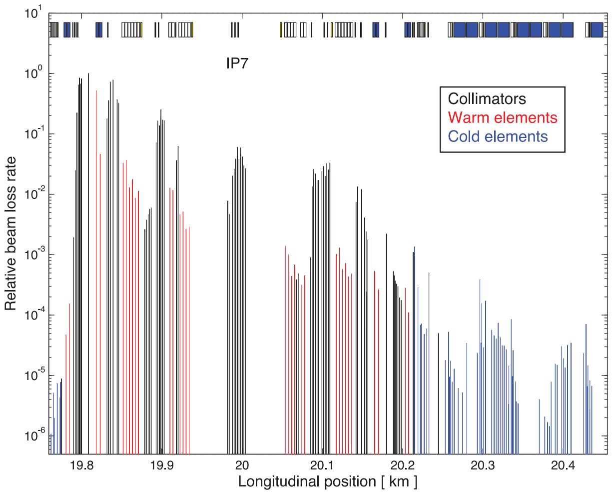

Figure 1: BLM signal normalized to the highest BLM signal at the primary collimators versus longitudinal position, for horizontal losses of beam 1 (proton beams). This is used to estimate the local cleaning inefficiency in IR7 [1]. A zoom in the IR7 region is given.

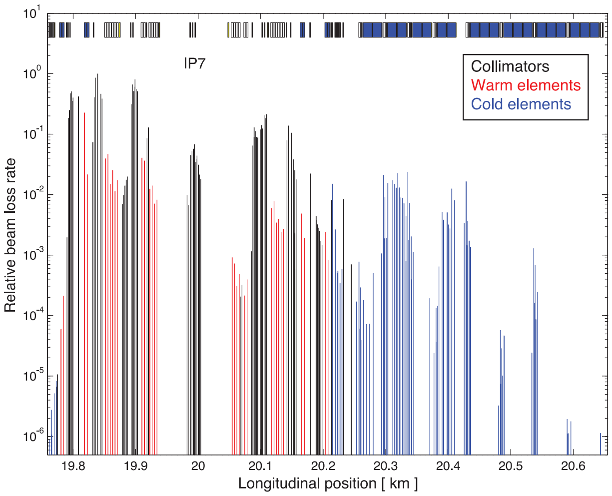

Figure 2: BLM signal normalized to the highest BLM signal at the primary collimators versus longitudinal position, for horizontal losses of beam 1 (Pb ion beams).

as in Fig. 3. The leakage at the limiting locations in the DS of IR7 is summarized in Table 2 for the horizontal case. This case is considered for the quench tests because the collimation cleaning efficiency is lower for horizontal losses (larger leakage in the DS for the same beam loss rate).

Table 2: Leakage from horizontal collimator losses at the limiting locations in the IR7 dispersion suppressors, for ion and proton beams (RS09 corresponding to 1.3 s).

Beam	Particle	Horizontal cleaning
B1	p	3.3×10^{-4} (Q8)
B2	p	6.4×10^{-4} (Q8)
B1	Pb	2.6×10^{-2} (Q11-R7)
B2	Pb	1.6×10^{-2} (Q9-L7)

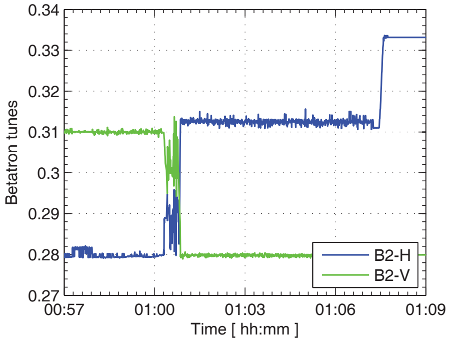

Figure 3: Betatron tunes versus time during a horizontal loss maps. The tunes are swapped from the (0.28, 0.31) working point, then the horizontal is moved above 0.33.

SETTINGS OF BLM THRESHOLDS

The 2011 operational dump thresholds of the BLMs in cold regions were set to 33 % of the assumed quench limits of super-conducting magnets. Thus, it is in principle not possible to approach the quench limit without triggering a beam dump. The verification that quench limits in the DS are not lower the assumed value was confirmed by these tests. Appropriate “relaxed” sets of threshold settings had thus to be prepared for the beam tests.

The choice of updated BLM thresholds was based on loss maps performed at flat-top [2]. For the achieved beam loss rate, the ratio of BLM signal to dump thresholds was calculated for all BLMs to identify the cold and warm elements closest to their respective dump thresholds. The maximum achievable loss rates before dump for a given BLM threshold configuration can then be calculated with a simple scaling and new thresholds calculated accordingly (see next section). Required changes are different for the various integration times: twelve “running sums” (RSs) ranging from 40 μs (RS01) to 80 s (RS12) are available. The focus of these test was on a slow loss regime above 0.5 s. Changes above this range do not affect the machine protection settings for fast beam failures. In practice, only thresholds of magnets around IR7 and in IR6 needed to be changed because at flat-top the losses are well confined in the betatron cleaning region.

QUENCH TEST TECHNIQUE

A staged approach was adopted during the beam tests: the beam intensity for a first fill was chosen such as to achieve losses in the DS comparable to the assumed quench limit. The first fill also served to verify in safe conditions the choice of BLM thresholds and to establish the settings for loss generation (tune trim values, transverse damper settings, etc.). In following fills, the intensity was then scaled up by an appropriate factor calculated to reach or exceed the assumed quench limit by a given amount, i.e. to achieve BLM signals at least a factor 3 above the nominal dump thresholds. The highest leakage was compared to the set BLM dump thresholds and the scaling factor was applied

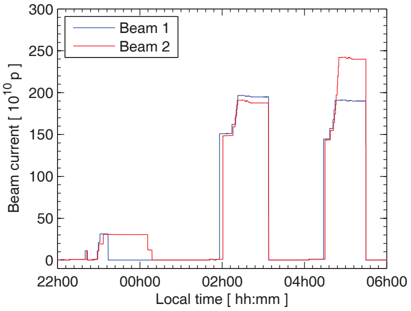

Figure 4: Beam current versus time during the three fills for the proton quench tests done on May 9th, 2011.

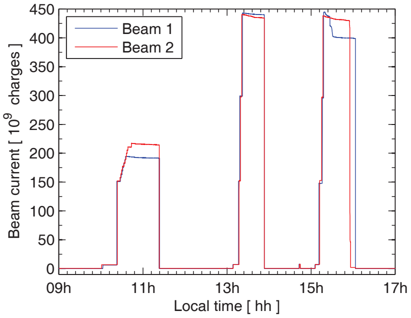

Figure 5: Beam current versus time during the three fills for ion quench test done on December 6th, 2011.

to the initial number of bunches to find the beam intensity that, in the assumption of constant and reproducible beam loss rates, would yield to the desired losses. For both proton and ion quench tests, 3 fills were necessary to complete the test. The beam current as a function of time during the tests is given in Figs. 4 and 5. For protons, no further adjustments of BLM thresholds were required whereas for ion they had to be tuned after each iteration.

RESULTS WITH PROTON BEAMS

The peak loss rates achieved during the three ramps of the proton quench test are summarized in Table 3. The beam loss signals closest to dump limits were always recorded for the 1.3 s running sum (RS09), as expected. For each case, only one beam could be tested at a time because premature beam dumps occurred for reasons not related to the tests [2]. The highest loss rate was achieved in the second ramp for beam 2 and this case is taken as reference. The intensity versus time during the peak loss rates achieved while crossing the 3rd order resonance is shown in Fig. 6. A peak loss rate of 9.1×10^{11} p/s was achieved, corresponding to 510 kW impacting on on the horizontal primary collimator of IR7. The loss map around the ring for this case is shown in Fig. 7. The loss rates in kW around IP7 are shown in Fig. 8. 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 of losses in kW. In this assumption, the peak loss rate at the limiting location Q8-L7 was 336 W.

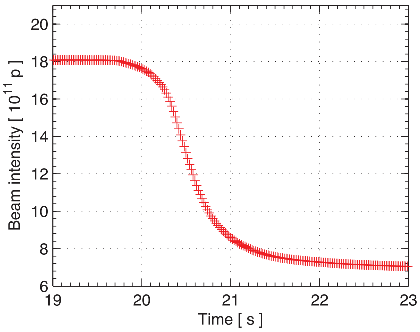

Figure 6: Beam 2 current versus time during the ramp 2 of the proton quench test. A 50 Hz acquisition rate is available within the LHC *post–mortem* system.

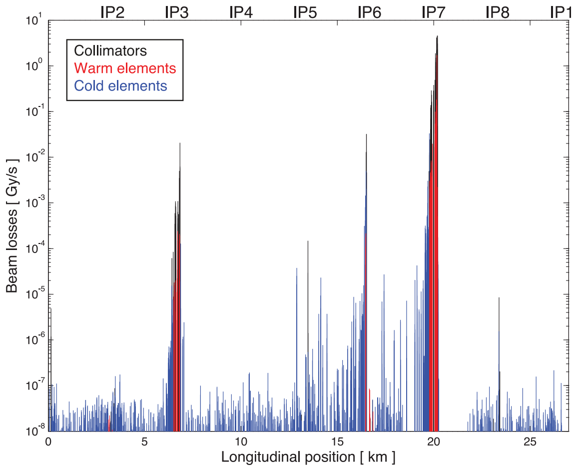

Figure 7: Losses around the ring during the B2 quench test with proton beams. The running sum RS09 corresponding to BLM integration times of 1.3 s is considered.

The losses in Q8-L7 reached 32 % of the BLM dump limit. For these beam tests, these thresholds were set a factor 2 higher than the assumed quench limits of superconducting magnets, i.e. 64 % of the assumed quench limit was therefore reached.

RESULTS WITH ION BEAMS

The summary of achieved parameters in the three ramps performed during the ion quench test is presented in Table 4. For each ramp we give the number of bunches and total intensity per beam, the duration of losses before the beam is dumped, and the amount of losses over 1 s, as well as information on the dump (location and BLM integration times). The first ramp was performed with 20 (24) bunches per beam in Beam1 (Beam2) respectively (for a total intensity of 1.6E11 charges, roughly corresponding to the quench limit in the assumptions made). It is important to note that, unlike for the case of proton beams, the ion beams experienced beam dumps in integration times of losses shorter than 1.3 s. The corresponding limiting locations were also different, reaching magnets further down in the arc. This behaviour required additional adjustments of

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 highest BLM signal at the primary collimator (Q8 is the limiting 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	–

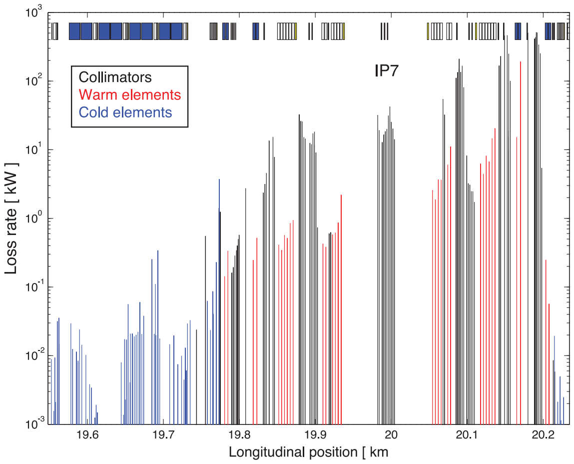

Figure 8: Losses in IR7 achieved during the B2 quench test with proton beams (see Fig. 7) expressed in kW (using RS09). The conversion from Gy to kW is approximated by scaling the measured BLM signal with the peak loss rate of charges/s impacting on the primary collimators of IR7.

Table 4: Overview of Peak Loss Rates and Dump Locations for the Different Ramps Performed. When applicable, the elements that caused a beam dump and the corresponding RS that exceeded the limits are given.

Fill	Beam	$(dI/dt)_{max}$ [charges/s]	Duration [ms]	Dump RS	Magnet
1	B2	2.7×10^{11}	75	RS06	Q9.L7
2	B2	2.5×10^{11}	100	RS07	Q19.L7
3	B2	4.9×10^{10}	1000	-	-
3	B1	1.1×10^{11}	200	RS07	Q11.R7

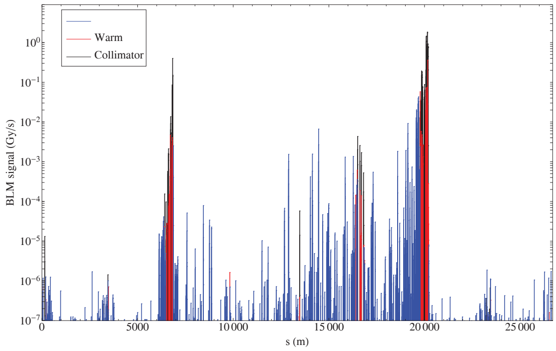

Figure 9: Losses around the ring during the B2 quench test with Pb ion beams. The running sum RS09 corresponding time intervals of 0.086 ms is considered.

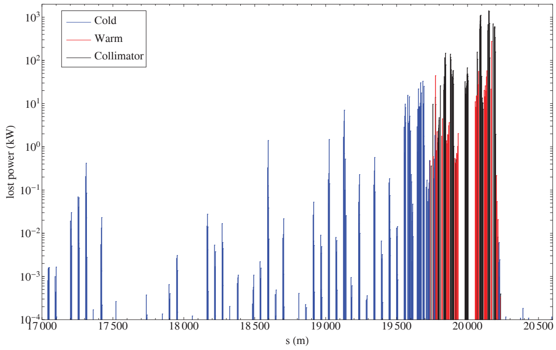

Figure 10: Losses in IR7 achieved during the B2 quench test with PB ion beams expressed in kW (for RS07). The conversion from Gy to kW is approximated by scaling the measured BLM signal with the peak loss rate of charges/s impacting on the primary collimators of IR7.

the thresholds for the subsequent attempts. For example, since the BLM to quench threshold ratio measured on Q8 during the first fill was 0.57 (Table 4), the beam intensity was doubled to 3x12 bunch trains (or 3.4E11 total number of charges per beam) to reach this upper limit. This second attempt was limited by losses in the Q19.L7 that reached a factor two above the quench limit on the 86 ms running sum (RS07). The BLM signals measured around the ring and the losses in kW in IR7 are given in Figs. 9 and 10. A third fill was performed after a further increase of the BLM thresholds for 26 additional monitors.

The tests failed to quench any magnets for the following achieved maximum BLM ratios to the assumed quench limits at 3.5 TeV: factor 2.4 above the quench limit for Q8.L7 for RS07 (86 ms); factor 1.2 for Q11.R7 for RS07; factor 1.7 for Q8.L7 for RS06 (10.6 ms); factor 1.6 for MB9.L7 for RS09 (1.3 s). This test provided a lower limit of losses rates, which can still be tolerated without causing a quench. The BLM thresholds might be adjusted accordingly without compromising the operation efficiency.

CRYOGENICS OBSERVATIONS

Measurements of the cryogenics system were used to estimate the energy deposited in the cold magnets during the

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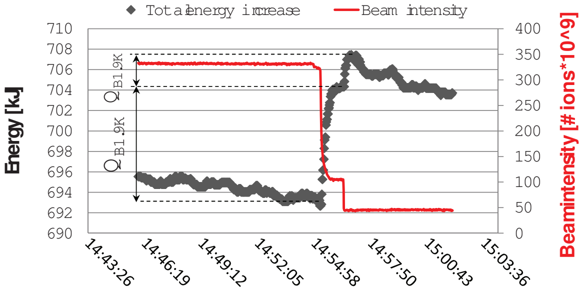

Figure 11: Deposited energy (gray, left axis) and beam intensity (red, right axis) in the cell 11-L7 during the second ramp of the ion test [8].

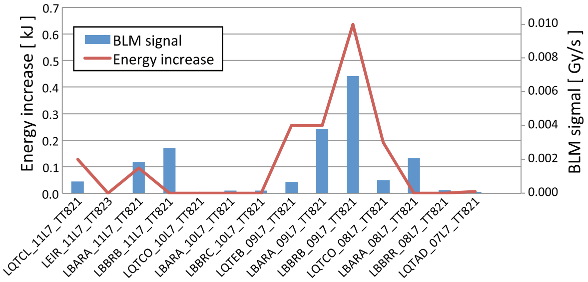

Figure 12: BLM signal and estimated deposited energy from cryogenics measurements in the DS-L7 during the second ramp of the ion quench test [8].

quench tests. The whole magnet cold masses are in a superfluid Helium bath that is maintained at about 1.9 K with an active low pressure helium circuit hydraulically independent from the bath. For a standard LHC arc cell, one bath contains 4 quadrupoles and 12 dipoles corresponding to a length of about 214 m. Each quadruple and dipole are equipped with temperature sensors (TT) and the bath with one pressure transducer (PT). When some energy is deposited in the Helium bath, e.g. from hadronic showers caused by beam losses, bath pressure and temperature vary. It is possible to calculate from these measurements the internal energy of the Helium [8].

Correspondingly, the energy deposited in the bath can be quantified for a given mass of Helium. An example of the calculated energy in cell 11-L7 is given in Fig. 11. The energy increase caused by ion beam losses was about 14.5 kJ. The step in the energy curve is correlated in time with the steps in intensity loss (red line). The longitudinal distribution calculated for different magnets in the DS L7 for the same ion loss case is given in Fig. 12. The measured BLM signal at the same locations is also given. There is a clear correlation between the two signals. Detailed comparisons between the results of this model and the approximated estimates from the sole BLM reading (Fig. 10) are ongoing. The method based on cryogenics measurements will be explored in more details in future quench tests.

CONCLUSIONS

The results of collimator quench tests done with 3.5 Z TeV proton and ion beams were presented. The motivation of these studies is to understand the quench limits of the LHC super-conducting magnets at the limiting locations observed in standard operational conditions. Results of these tests provide insight of the performance reach from collimation limitations at highest beam energies.

For proton beams, the design loss rate of the collimation system of 500 kW was achieved for beam 2. Losses of up to 9.1×10^{11} p/s were obtained at 3.5 TeV, for a peak loss on the primary collimators of 510 kJ over 1 s. In these conditions, the collimation system behaved as expected and safely handled these losses. No quench occurred in the dispersion suppressor magnets. A maximum of 64 % of the assumed quench limit was reached (1.3 s). This provides a lower limit for achievable loss rates below the quench. The real limit can only be established if quenches are achieved. The BLM thresholds were kept at their present values.

For the case of ion beams, it was found that the time distribution of losses is different as limitations occurred over much shorter time scales, down to below 0.01 s, even if the same loss mechanism was used. These fast losses were observed for the first time during these tests. The extrapolation of the measured losses to the target “slow” loss regime above 0.5 s is not trivial. On the other hand, the assumed quench limits were exceeded for different integration times, up to a factor 2.4 larger, without inducing quenches.

These results provide a solid base to understand the performance of the LHC collimation system and of the quench limits in the DS magnets in all LHC IRs, e.g. the one affected by similar dispersive losses from luminosity debris. It is planned to repeat similar quench tests at 4 TeV at the end of the 2012 run in order to understand better the limits.

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