HANDLING 1 MW LOSSES WITH THE LHC COLLIMATION SYSTEM*

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Abstract

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. In 2013, quench tests were performed at 4 TeV 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. 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.

INTRODUCTION

The LHC superconducting (SC) magnets are operated at 1.9 K. High energy protons impacting the magnets can deposit sufficient energy in the SC coils to quench them. A hierarchical collimation system [1] absorbs particles before they reach the magnets. The LHC collimation system comprises 43 ring collimators per beam. The primary collimators (TCP) are closest to the beam, followed by the secondary (TCSG) and tertiary (TCT) collimators, and absorbers (TCLA). They are mainly installed in insertion regions (IR) 3 and 7 to clean particles with large momentum and betatron offsets respectively. During regular operation, there are continuous losses in the dispersion suppressor (DS) of IR7, located downstream of the betatron cleaning area. These losses set an upper limit on the maximum number of protons that can be stored in the LHC.

A quench test was performed in 2011 [2] to address the limitations of the LHC collimation system. The procedure was to induce high beam losses with the collimation in place while observing the magnets at the locations where the energy leakage is the largest, i.e. at the dispersion suppressors (DSs) of IR7. The maximum design loss rate of 500 kW was reached without quenching any SC magnet. A similar collimation quench test was performed in 2013 [3] to probe the magnet behaviour with larger losses. A special machine configuration was setup to achieve losses of about 1 MW, in order to improve the quench limit estimates. This also allowed to test the collimation system beyond its design beam loss conditions. In this paper, the main achievements of these beam tests are presented.

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EXPERIMENTAL SETUP

Selection of Collimator Settings

To allow higher losses in the DS of IR7, "relaxed settings" in mm in IR7 were used as in the 2011 run [4] with an additional 1 σ retraction for the IR7 TCSGs and the IR6 TCSG and TCDQ. The IR6 and IR7 collimator settings were therefore as follows: IR7 TCP 6.1 σ; IR7 TCSG 10.1 σ; IR7 TCLA 18.9 σ; IR6 TCSG 10.9 σ; IR6 TCDQ 11.5 σ. The IR3 collimator settings were not changed from the usual settings. Betatron loss maps were produced by horizontally blowing up B2 with the transverse damper (ADT) [5], to measure the cleaning in the DS left of IR7. This collimation setup for beam tests was carefully chosen to maximize the DS losses while ensuring (1) a safe operation with high losses and (2) a DS loss distribution equivalent to the ones from operational settings [3].

Setup of Beam Loss Monitor Thresholds

The BLM dump thresholds needed to be raised to allow losses in the SC magnets above the assumed quench limits. From loss maps, an estimate of the new thresholds was obtained by measuring and scaling the power loss to allow up to 1 MW of power loss. 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. A full list of the threshold changes for the BLMs measuring losses at the cold magnets, warm magnets and collimators is available in [3].

LHC Fills For Quench Tests

The quench test was performed at 4 TeV with unsqueezed beams to avoid losses in the experimental regions. Following a test ramp, three fills were performed:

- **First ramp (fill No. 3567):** B2 was filled with 144 bunches and a total intensity of $\sim 2.1 \times 10^{13}$ p.
- **Second ramp (fill No. 3568):** B2 was filled with 144 bunches with 2.1×10^{13} p injected.
- **Third ramp (fill No. 3569):** B2 filled with 216 bunches (144 + 72) with total intensity 3×10^{13} p.

In order to have a better control of the loss rate compared to the 2011 tests when losses were achieved by crossing the 3rd order tune resonance in the horizontal plane, the transverse damper (ADT) was used to excite a selected bunch train. The final settings of the ADT were tuned during the test ramp of the MD using a safe intensity of $< 3 \times 10^{11}$ p. Particular care was taken to control the time profile of losses

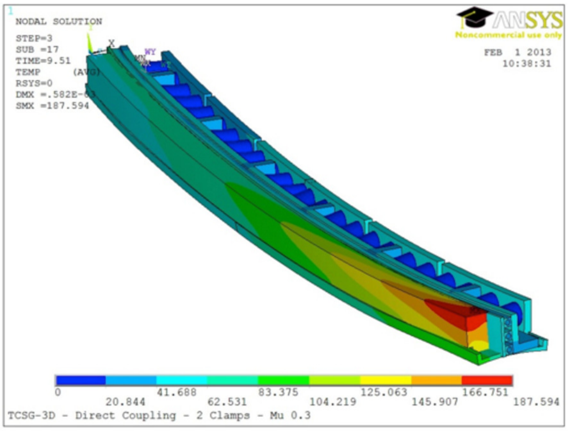

Figure 1: Collimator temperature at the end of the analysis.

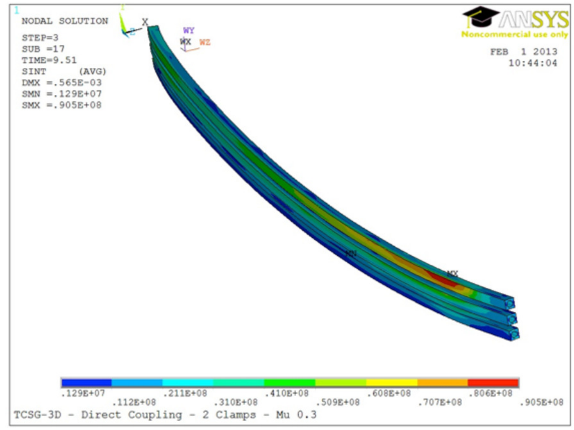

Figure 2: Tresca-Guest equivalent stress on the CuNi 90-10 cooling circuit.

and ensure a rise time below 1 s (see next section). The peak power loss achieved with single bunches in this "pilot" test was 3.5 kW. A scaling from this number shows that 144 bunches would need to be excited to achieve 500 kW with the same excitation strength, which was then used for the first ramp. Larger loss rates were achieved by scaling up accordingly the bunch number.

THERMO-MECHANICAL SIMULATIONS

A thermo-mechanical analysis was performed to verify the collimator response. In the simulation, the collimators were loaded with a power of 1 MW for 10 s, following an initial ramp of 1 s and then a 10 s plateau. The power in this scenario is 2 times higher than the design case for collimators of ~500 kW for 10 s [6]. The energy deposited on collimators was calculated with FLUKA starting from SixTrack simulations of proton loss maps [7]. For 500 kW losses and for the given collimator settings, 241 kW are lost in collimators with a load of 30 kW on the most loaded collimator (TCP.C6L7.B1). For the 1 MW loss case, a peak loss of 60 kW was then assumed.

Since no 3D TCP models were available for the thermo-mechanical analyses, the thermo-mechanical calculations were performed for the TCSG geometry. TCSGs are longer: 1 m active length instead of 0.6 m of the TCPs. An integral power of 100 kW on the TCSG was conservatively assumed to take into account slight differences in the geometry between TCSG and TCP, different settings and beam energy between the 2009 and the 2013 cases and uncertainties in the simulations. A transient thermo-structural analysis was performed with ANSYS to evaluate the temperature and the stresses induced on the TCSG, to avoid any plastic deformation during the quench test. The temperature distribution in the collimator is shown in Fig. 1.

The hottest component is the Carbon-Fibre-Composite (CFC) jaw that reaches 190^oC, while the Glidcop clamp temperature is $<100^o$C. These levels are not problematic for the collimator jaw. From the structural point of view, the equivalent stress on CFC jaw was calculated with the Tresca-Guest criterion. The normal stress estimated in the longitudinal and transverse directions is 15 MPa and 1 MPa, respectively. The CFC is brittle and orthotropic, however these values are not source of concern [8]. The most critical collimator component appears to be the cooling pipes made of CuNi 90-10. In fully-annealed conditions, the material has an elastic limit of 90 MPa. The stress expected during the quench test is shown in Fig. 2. The result is considered acceptable, given the relatively small zone that experiences high stress and the safety factors assumed for the peak load values. However, a constraint on the loss rise time of 1 s was imposed to avoid exceeding the plastic deformation in case of faster losses.

RESULTS FROM THE QUENCH TESTS

After setting up the ADT and validating the collimator settings, three attempts were made to quench the magnets in the DS left of IR7. Sufficient charges were injected to achieve the desired energy loss rate, followed by an excitation with the ADT in the horizontal plane. In the first fill (3567), the maximum peak power loss achieved (as calculated from the BCT signal) was 530 kW. No quench was observed, and the fill was dumped by high losses in the BLMs. After increasing several BLM thresholds [3], the procedure was repeated (fill number 3568) and 640 kW was achieved without quench. On the third attempt (fill number 3569), with about 50% higher intensity, about 1050 kW of beam power loss was measured without any magnet quenches. The beam power loss and intensities are shown in Figure 3 for the three fills. In addition, the plot shows two of the attempts to quench in 2011. Using the ADT, the time profile of losses could be controlled with greater precision, and the power loss could be sustained for a longer time (5 to 10 s).

Figure 4 shows the loss maps taken during the third ramp for the 1.3 s running sum (RS09). Right of IR7, some BLMs were not giving any signal. The leakage to the cold sector (in blue) on the left of IR7 is clearly visible, and expands up to right of IR4. Table 2 summarizes the comparisons of the maximum BLM signal measured during the last ramp (fill number 3569) for RS09 and RS10 (5.2 s). The table shows

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Table 1: Injected intensity and total maximum power loss achieved for quench tests in 2011 and 2013.

Fill (year)	**Intensity [p]**	**Peak Power [kW]**
1777 (2011)	1.8×10^{12}	510
1778 (2011)	1.8×10^{12}	215
3567 (2013)	2.1×10^{13}	530
3568 (2013)	2.1×10^{13}	640
3569 (2013)	3×10^{13}	1050

Table 2: Maximum BLM signal, BLM quench threshold and ratio of both for the peak power loss of 1050 kW.

RS	**BLM Signal Measurement**	**BLM Quench Threshold [Gy/s]**	**Ratio**
RS09	1.08×10^{-2}	4.65×10^{-3}	2.3
RS09	3.81×10^{-3}	6.40×10^{-3}	0.6
RS10	8.42×10^{-3}	1.67×10^{-3}	5.1
RS10	2.87×10^{-3}	2.29×10^{-3}	1.3

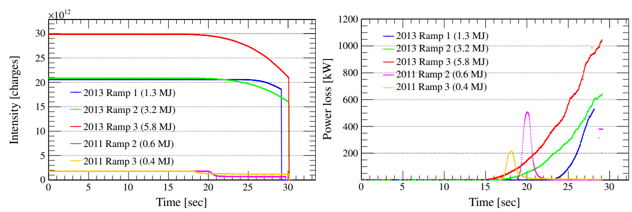

Figure 3: Beam intensity and peak power loss for the quench tests at 3.5 TeV and 4 TeV in 2011 and 2013.

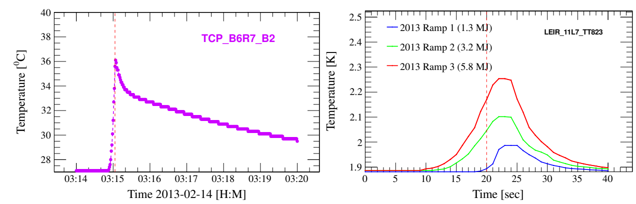

Figure 5: Temperatures in the right-downstream jaw of the skew B2 TCP for the last ramp and the empty cryostats.

also the BLM quench thresholds for the respective sensors and the ratio BLM signal to BLM quench threshold.

Temperature Measurements

The collimator temperatures were monitored throughout. The skew TCP (TCP.B6R7.B2) displayed the highest temperature increase (~ 10 ^{0}C) w.r.t. the start of the fill. This is much lower than the simulated jaw value of 190^{o}C due to a low contact pressure between the thermal probe and the CFC jaw, causing a high thermal resistance between the two. The collimator gap measured with LVDTs remained constant within 5 μm, which is within the sensor precision. Hence, there was no deformation due to the temperature rise. The temperature in the cold sector left of IR7 was also monitored. The highest increase of 0.35 K was observed in an empty cryostat in cell 11, left of IR7. No significant increase of temperature was observed in other cold sectors. Figure 5 shows the temperature spike at the collimators in the last fill and the measured temperatures in the empty cryostat for the three tests. The red line indicates the time when the maximum beam loss was recorded.

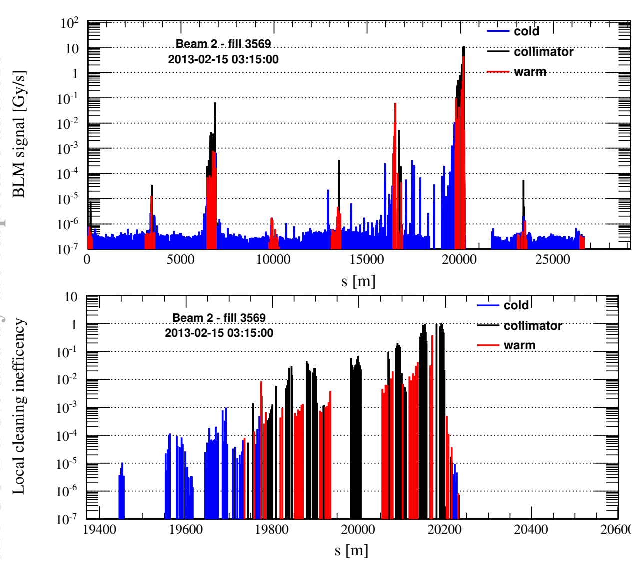

Figure 4: Beam loss map for the whole LHC ring (top) and zoom of the losses in IR7 (bottom) for fill number 3569.

CONCLUSION

At the end of the physics run of the LHC in 2013, several beam tests took place to measure the real quench limit of the LHC superconducting magnets. The beam was blown up, and collimator settings were modified to allow more losses into the cold DS magnets in IR7. Beam losses with 1050 kW peak power loss averaged over 1 second were generated, but the magnets did not quench. The beam losses in the DS were 2.3 times higher than the BLM quench limit threshold for the running sum of 1.3 s. These results are being used to improve operational BLM settings for the 2015 LHC startup. The highest collimator temperature rise was ~ 10 ^{o}C and there were no indications of deformation, while the cold sector temperature did not increase significantly. The collimation system could withstand peak losses a factor 2 above its design specification, for controlled time profiles of losses. This might also be used for the improving the collimator BLM thresholds.

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