COLLIMATION QUENCH TEST AT THE LHC WITH A 6.8 TEV PROTON BEAM*

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Abstract

The High Luminosity upgrade of the CERN Large Hadron Collider (HL-LHC) aims at achieving stored beam energies of 680 MJ. A possible limit on the achievable intensity is the quench limit of the superconducting magnets downstream of the betatron collimation insertion. At HL-LHC beam intensities, even a tiny fraction of particles scattered out of the collimation system may be sufficient to quench them. The quench limit of these magnets, when exposed to proton loss, depends on a variety of parameters. The amount of beam losses needed to cause a quench can be quantified through beam tests under realistic operating conditions. In this paper, we present the design and execution of a quench experiment with proton beams at 6.8 TeV carried out at the LHC in 2022. We describe the experimental approach, the result, and the analysis of the test that aims to probe the collimation cleaning performance while deliberately inducing high beam losses. The result of these tests is crucial to determine the need for future collimation upgrades.

INTRODUCTION

The CERN Large Hadron Collider (LHC) superconducting main dipole magnets (MB) operate in liquid helium at a temperature of 1.9 K [1]. To protect the machine hardware from uncontrolled beam losses, the LHC is equipped with a multi-stage collimation system, mainly located in the betatron collimation insertion region IR7 [2–4]. A small residual proton flux can propagate from the collimation system into the IR7 dispersion suppressor (DS) magnets and could deposit enough power to cause a magnet quench. With the significant increase of stored beam energy after the High Luminosity upgrade (HL-LHC), this risk is further increased. A mitigating measure, based on a hardware upgrade with local DS collimators (TCLD) was proposed to be integrated during LHC Long Shutdown 2 (2018-2022), but was eventually postponed [5]. It is therefore crucial to gather a good knowledge of the quench limit and how it relates to DS loss rates expected in HL-LHC, as input to decide on necessary future upgrade scenarios.

For operation at 7 TeV, the quench limit for LHC MB magnets is currently estimated to be between 20 mW/cm^3 and 30 mW/cm^3 for slow losses of a duration of about 1 s and longer [6]. The peak power deposition (PPD) in the DS dipoles of HL-LHC without TCLD upgrade was simulated to be 15 mW/cm^3 to 20 mW/cm^3 [7, 8] at the loss rate corresponding to the HL-LHC design specification of 946 kW at 7 TeV [9]. Thus, the theoretical quench limit and the expected PPD are close. The uncertainties in these estimates are, however, difficult to quantify. Therefore, it was concluded that an experimental assessment of the actual quench limit under operating conditions is needed to assess whether the HL-LHC target intensities can be reached.

In this paper, we describe a quench test machine development (MD) study carried out at the LHC at 6.8 TeV in 2022. We present the experimental setup, a computation of the achieved loss rate and IR7 DS magnet power deposition. We conclude by summarizing the outstanding uncertainties and provide an outlook on possible future tests.

THE EXPERIMENT

Collimation quench tests aim to deliberately generate high beam losses to probe the response of the collimation system in case of extreme loss conditions and, in particular, if the DS magnets quench under the influence of particles scattered out of the collimators. Previous tests with proton beams were performed at lower energies, from 3.5 TeV to 6.5 TeV, and never resulted in a quench [10–13] (see Table 1). With heavy-ion beams, for which the collimation system is less efficient, a quench was achieved at 6.37 Z TeV at a loss rate of 13.7 kW [13].

Table 1: Collimation Quench Tests Carried Out in the LHC

Year	Species	Energy [Z TeV]	Power [kW]	Quench	Ref.
2011	p	3.5	510	No	[10]
2013	p	4.0	1050	No	[11]
2015	p	6.5	585	No	[12]
2015	Pb^{208}	6.37	13.7	Yes	[13]
2022	p	6.8	666 ± 37	No	

Choice of Beam Parameters

According to the design specification of the HL-LHC collimation system, a loss rate of 946 kW with a 7 TeV proton beam must be sustained over 10 s without magnet quench [5]. We chose 1 MW as a target loss rate for the test with the 6.8 TeV proton beams available in the LHC in 2022. Significantly higher loss rates would have required dedicated stud-

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ies to ensure there is no risk of collimator damage. For the protection of the collimators, and to reduce the risk of triggering a beam dump by the beam loss monitors (BLMs) [14], a slow ramp of the loss rate from zero to 1 MW over roughly 15 s was envisaged.

Three separate energy ramps were performed. For each ramp, two batches of 180 bunches, each with 5 trains of 36 bunches (1.4×10^{11} protons per bunch), were injected for Beam 2, allowing for two quench attempts (QAs) per ramp. Each batch carries an energy of 27.5 MJ, enough to achieve the intended beam loss rate time profile with some margin. Additional trains of 36 bunches were injected to probe and optimise the excitation scheme before each QA. The test was carried out with the optics configuration after the energy ramp in the nominal 2022 LHC cycle.

Collimator Settings

Given the excellent performance of the current collimation system, as well as the higher quench limit at 6.8 TeV compared to 7 TeV, achieving a quench with the operational collimator settings was considered unlikely. One of the main goals of the experiment was to test this hypothesis. Additionally to the nominal betatron collimator settings[1] with primary/secondary collimators (TCP7 / TCSG7) at $5\,\sigma$ / $6.5\,\sigma$, a set of relaxed settings was prepared with the TCSG7 retracted to $8.5\,\sigma$. The latter was selected from a broad set of possible settings, based on the results of simulation campaigns using FLUKA [15], with input from SixTrack [16]. The selected relaxed settings show a similar loss pattern in the critical magnets under scrutiny, but with an increased simulated magnet coil PPD, as shown in Fig. 1.

According to simulations, at a 6.8 TeV proton beam loss rate of 946 kW, a PPD of 14 mW/cm^3 would be reached in the DS MB coils with nominal collimator settings [8]. This is below the expected quench limit at this energy. With relaxed collimator settings, a PPD of 24 mW/cm^3 is simulated for the same loss rate. In both cases, the dipole with the highest PPD is MB.A9L7. Note that the peak on the front face of the magnet, reaching roughly 30 mW/cm^3 for the relaxed settings, does not refer to the power deposited in the magnet coils. The relaxed collimator settings thus allow increasing the PPD in the DS dipoles by roughly 70 %.

Beam Excitation and Instrumentation

The LHC transverse damper (ADT) served the purpose of exciting the beam for QAs [17]. It is a versatile electrostatic kicker that is used as a feedback device to damp beam instabilities. It can also be used to apply white noise and thus induce beam loss by transversely exciting one or multiple bunches. Adjusting the gain of the excitation allows one to tailor the time evolution of the loss rate. A longitudinal window ensures that the excitation acts selectively on a subset of circulating bunches. The number of affected bunches is used to determine the total loss rate. The ADT control tools are flexible and could be used online to adjust and optimise all the relevant parameters.

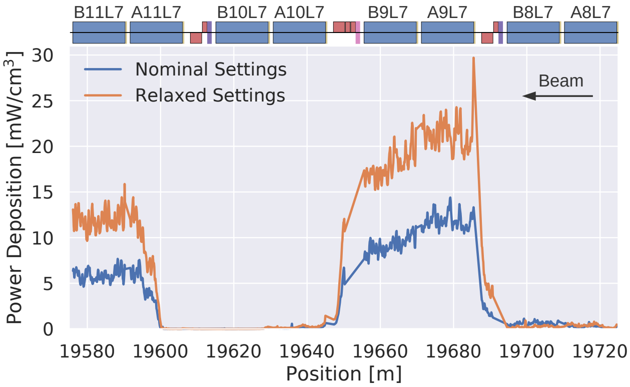

Figure 1: Simulated power deposition in the IR7 DS with nominal and relaxed collimator settings for a beam loss rate of 946 kW (the top labels indicate the MB magnets). The longitudinal position (horizontal axis) refers to the LHC convention, starting at interaction point 1 (ATLAS) in a clockwise direction.

The LHC BLM system required careful preparation for the test. A beam dump is triggered if the signal recorded in any of the ~ 4000 LHC BLMs exceeds any of twelve predefined thresholds. The latter refer to different integration times (called running sums, RS) between half a turn (40 μs) and 82 s duration. In the nominal 2022 operation, the BLM thresholds were set to tolerate beam losses of up to 200 kW on the primary collimators of IR7 without beam dump. For the quench test, increased BLM thresholds were derived, so that the target beam loss rate of 1 MW could be reached without beam dump [18]. Based on reference loss maps (BLM signals recorded while the beam is intentionally excited) for nominal and relaxed settings, scaling factors were derived for each BLM threshold family. The scaling was done such that the test could be done with one single change of the BLM thresholds, independent of the collimator settings.

EXPERIMENTAL OUTCOME

The experiment was carried out in the night from the 22nd to the 23rd of November 2022. In total, five QAs were performed, in three different fills. Each QA consisted of exciting 180 bunches simultaneously with the ADT. Three of the five attempts were made with relaxed collimator settings. None of the attempts resulted in a magnet quench.

The maximum achievable BLM thresholds for the electronics for short integration times imposed an upper limit on the achievable beam loss rate increase without triggering a beam dump. The limiting BLMs were not maskable. A lower limit on the increase in beam loss power was imposed by the collimator temperature interlock of 50 °C that dumps the beams if the jaw temperature exceeds this value. The latter is driven by the total losses on the collimation system.

A compromise with an intermediate loss rate increase had to be found. Despite excellent control of the evolution

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[1] σ: conventional RMS beam size with normalised emittance 3.5 μm rad.

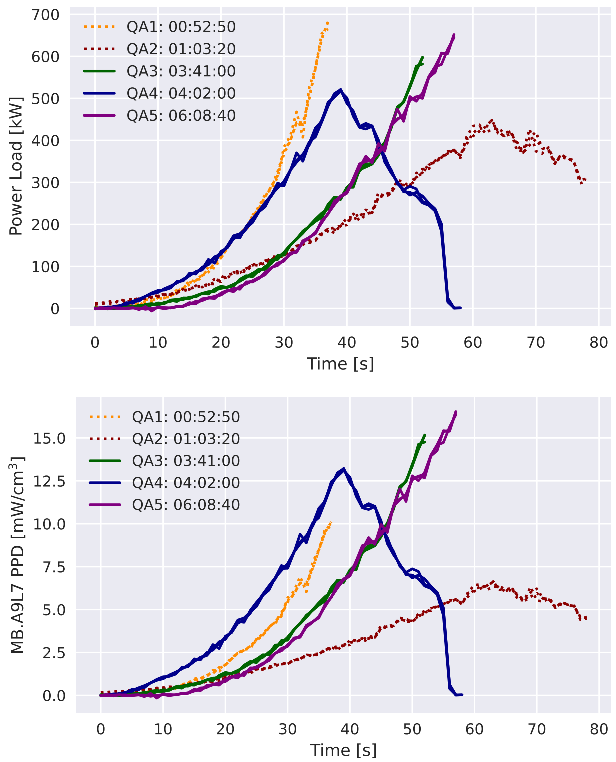

Figure 2: Top: Primary power load for all QAs derived from the BCT signal. The legend shows the time considered as starting time of each excitation. Solid lines show QAs with relaxed collimator settings, and dotted lines show QAs with nominal collimator settings. All considered BCT signals are shown in the same colour and line style. Bottom: PPD estimate based on the primary power load derived by applying a scaling of the FLUKA simulation result. Line styles carry the same information as in the top plot.

of the beam loss rate with the available ADT software, the constraints mentioned above were so tight that the target loss rate of 1 MW was not reached. Two of the three fills were dumped by the collimator temperature interlocks. The last fill was dumped by exceeding the BLM thresholds. From the online monitoring, a maximum loss rate between 600 kW and 700 kW was reported with nominal and relaxed collimator settings. For a more precise offline estimate of the primary power load, we employ two methods. The first method consists of using the derivative of the direct current and fast beam current transformer (BCT) [19] signal: we obtain the number of charges lost per second and multiply it with the energy carried per charge to obtain the power load on the TCP. The result is shown for all the QAs at the top of Fig. 2.

The bottom panel shows the PPD derived by scaling the primary power load with 14 mW/(946 kW cm^3) for QAs with nominal settings and 24 mW/(946 kW cm^3) for those with relaxed settings. From the analysis, we see that the highest beam loss rates were achieved with nominal settings in QA1 (674 kW) and with relaxed settings in QA5 (648 kW).

The maximum PPD reached throughout the test corresponds to 16.3 mW/cm^3 to 16.5 mW/cm^3 in QA5, depending on the BCT signal used for the analysis.

As a second method, we apply a linear regression model to the highest DS BLM signal (independent variable) and the primary power load estimated from all three BCT signals considered before (dependent variable). The BLM with the highest signal in relevant cells 9 and 11 was BLMAI.09L7.B2I30_MBB for all QAs. Using the covariance matrix obtained for the regression parameters, we obtain a sensible figure for the uncertainty on the estimate of the primary power load. For the estimation of the regression parameters, we use all data points recorded for a primary power load greater than 100 kW. In this way, we ensure the best agreement for regimes with high losses. To derive the highest magnet-coil PPD achieved in the test, we only consider the last QA (QA5) with relaxed collimator settings. We considered RS08 (0.3 s integration time) and RS09 (1.3 s). Considering the 95 % confidence level, and using extremes of the prediction intervals obtained from the highest BLM signals recorded for these integration times, we obtain a maximum peak power load of (666 ± 37) kW. Applying the scaling factor from the FLUKA simulation, the following PPD estimate is obtained

$$\mathrm{PPD_{max}} = (16.9 \pm 0.9)\ \mathrm{mW/cm^3}\,. \qquad (1)$$

Note that the uncertainty interval fully encloses the range derived only based on the BCT signals.

CONCLUSIONS AND OUTLOOK

The DS magnet coil peak power deposition during the 2022 collimation quench test at 6.8 TeV reached levels comparable to those simulated for the design loss scenario of HL-LHC at 7 TeV. No quench was observed. Although the two figures are not fully comparable, because the quench limit at 7 TeV is lower due to the higher magnet currents, this result indicates that the current collimation system is likely adequate to fulfil the HL-LHC design specifications.

With the experience gathered in the 2022 quench test, the limitation experienced from BLM thresholds could be mitigated to allow for a faster increase in loss rate in future tests in LHC Run 3. This would enable reaching higher PPDs and provide a firmer conclusion on the quench risk in HL-LHC at 7 TeV. Residual uncertainties due to a possible asymmetric response to beam loss of the dipole magnet in cell 9 left and right of IR7 could also be eliminated, by performing the next quench test using LHC Beam 1, which moves in a clockwise direction.

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