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POWER DEPOSITION STUDIES FOR BETATRON HALO LOSSES IN HL-LHC*

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Abstract

The Large Hadron Collider (LHC) is equipped with a betatron halo collimation system designed to prevent magnet quenches during periods of reduced beam lifetime. Protons subject to single diffractive scattering in collimators can nevertheless leak into the adjacent dispersion suppressors (DS). In view of the future high-luminosity (HL) upgrade of the LHC, a better understanding of the quench margin in these DS magnets is needed, considering the increased beam current and the resulting higher beam losses of up to 1 MW of power during a few seconds, which the collimation system is designed to endure without damage. In this contribution, we present FLUKA power deposition simulations for a controlled beam loss experiment at 6.8 TeV, probing the quench level of the superconducting magnets most exposed to collimation losses. The results are compared to the expected power deposition in HL-LHC operation, considering different collimator settings. In particular, we studied the power deposition for relaxed collimator gaps, which are considered for initial operation in Run 4.

INTRODUCTION

In order to ensure the safe and reliable operation of the CERN Large Hadron Collider (LHC), a multi-stage collimation system for both beams was devised and put in place before starting operation in 2008 [1]. It consists of two sub-systems located in different insertion regions (IRs), the betatron cleaning system in IR7 and the momentum cleaning system in IR3. Nowadays, the collimation system comprises a total of more than 100 collimators for both beams [2, 3].

The betatron collimation system was originally designed to prevent magnet quenches in case of a beam lifetime drop to 0.2 hours for a period of up to 10 seconds. For nominal LHC parameters, with a beam intensity of 3.2×10^{14} protons and beam energy of 7 TeV, this corresponds to a particle loss rate of 4.3×10^{11} protons per second, or a power loss of 500 kW. Although the operational beam energy achieved so far (6.8 TeV in 2022) remained slightly below the nominal value, the stored beam energy already exceeded the design value due to a higher-than-nominal beam intensity (3.6×10^{14} protons). To date, no halo-induced quenches were observed in physics operation, demonstrating the excellent efficiency of the betatron cleaning system.

A further increase of the beam intensity to 6.3×10^{14} protons is foreseen in the High-Luminosity (HL) LHC era [4], starting in Run 4 (from 2029). The higher intensity will increase the risk of beam-induced quenches due to collimation losses, since the maximum allowed power loss will almost double to 1 MW for the same beam lifetime assumptions. A potential performance limitation may arise from protons subject to single diffractive interactions in the primary collimators, which can escape from the betatron cleaning system and can be lost on the aperture in the downstream dispersion suppressor (DS). A series of controlled proton beam loss experiments was carried out in previous runs at 4 TeV [5] and 6.5 TeV [6, 7], probing the quench margin of the DS dipole magnets. However, some uncertainty remained as to whether a power loss of 1 MW can be sustained at nominal energy (7 TeV) without quenching main bending dipoles in the DS.

In order to improve the understanding of the quench margin, another controlled beam loss test at 6.8 TeV was performed in 2022 [8], with the goal to replicate as much as possible the power load conditions expected in the HL-LHC era. Although no quench was observed, the test improved the understanding of the allowed power loss. This paper provides the results of FLUKA [9–11] simulations to quantify the amount of power deposited in magnet coils during the test, along with a quantitative benchmark using the beam loss monitor (BLM) signals observed during the test. The results are then compared against the expected power deposition levels in the coils during HL-LHC operation while taking into account different collimator settings. Specifically, for the initial operation during Run 4, relaxed collimator gaps are envisaged, which are studied in this paper.

SIMULATION WORKFLOW

To estimate the cleaning efficiency of the LHC collimation system and the power deposition inside magnet coils and other equipment, a multi-step simulation chain was adopted at CERN [12]. Firstly, collimation losses are obtained from multi-turn tracking simulations performed with SixTrack [13, 14], coupled with FLUKA for realistic interaction with collimators [15]. Primary particles are considered to be lost when they impact on the machine aperture or have an inelastic nuclear collision in the collimator jaws. In the second step, a detailed FLUKA model of the IR7 region is used to perform beam shower simulations and estimate the peak power densities in the magnet coils and BLM signals for the benchmark. The second step starts from the impact dis-

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Table 1: Collimator half-gaps in IR7, expressed as the number of beam σ for a normalized transverse proton emittance of 2.5 μm rad of HL-LHC.

	Quench test 2022		**HL-LHC settings**	
	Nominal	**Relaxed**	**Baseline**	**Relaxed**
TCP	6	6	6.7	8.5
TCSG	7.8	10.2	9.1	10.1
TCLA	12	12	12.7	14.0

tribution on collimators determined in the first step. The geometry of all components is modelled with sufficient accuracy to allow for a quantitative comparison with measured BLM signals.

QUENCH TEST AT 6.8 TEV IN IR7

The quench experiment in 2022 was performed with the anticlockwise-rotating beam (Beam 2) and induced losses of 2.5×10^{13} protons per attempt. The objective of the test was to produce a high proton loss rate on the IR7 primary collimators (TCPs), in order to approach a power loss of 1 MW. To control the loss rate, white noise excitations were applied to the beam particles using the transverse damper (ADT) [16]. The losses were generated on the horizontal plane, which typically represents the worst type of beam losses for DS magnets. A more detailed description of the experimental setup and quench attempts can be found in Ref. [8].

Two sets of collimator settings were utilized during the test. The first configuration called "*nominal*", consisted of the regular collimator settings adopted in 2022 physics operation for high-intensity proton beams. A second configuration, referred to as "*relaxed*" settings, was designed and optimized based on simulations, with the goal to allow for a higher power deposition in cold magnets per proton impacting the collimators while respecting as much as possible the DS loss distribution for the nominal collimation configuration. The simulations showed that the leakage of diffractive protons to the DS could be enhanced by 50% by increasing the half-gaps of secondary collimators (TCSGs) in IR7 by 2σ while keeping the gaps of the TCPs unchanged. The settings of the shower absorbers (TCLAs), which intercept the shower products further downstream, were the same as for the nominal configuration. Table 1 summarizes the settings used in the test.

Benchmark Analysis of BLM Signals

To assess the accuracy of the simulation setup for the machine configuration in the quench test, simulations were conducted to evaluate the response of BLMs in IR7 and the downstream DS. The measured signals were normalized by the number of protons that were lost on IR7 collimators during the beam excitation. Proton losses on collimators are not measured directly, but have to be estimated from beam current measurements. Since losses in IR7 were by far dominating the overall beam loss rate during the quench test, the normalization factor can be determined with very good accuracy from the stored intensity. A simplification assumed in the simulations is the initial halo distribution hitting the jaws of the horizontal TCPs. As the exact impact distribution on the jaws is not known, the interaction of a pencil beam with an impact distance of 2.5 μm from the jaw surface was tracked for hundreds of turns in the SixTrack-FLUKA coupling to reproduce the expected beam halo.

Figure 1 shows a comparison of simulated and measured BLM signals for relaxed settings obtained during the quench test (attempt QA5 in [8]). The simulation results are divided into two parts: simulation of the long straight section (LSS) of IR7 and simulation of the downstream DS region. Similar to previous benchmark studies [6, 17], our simulation results for the DS region were found to underestimate the measurements by a factor of three and were thus scaled accordingly. This discrepancy is attributed to the absence of imperfec-

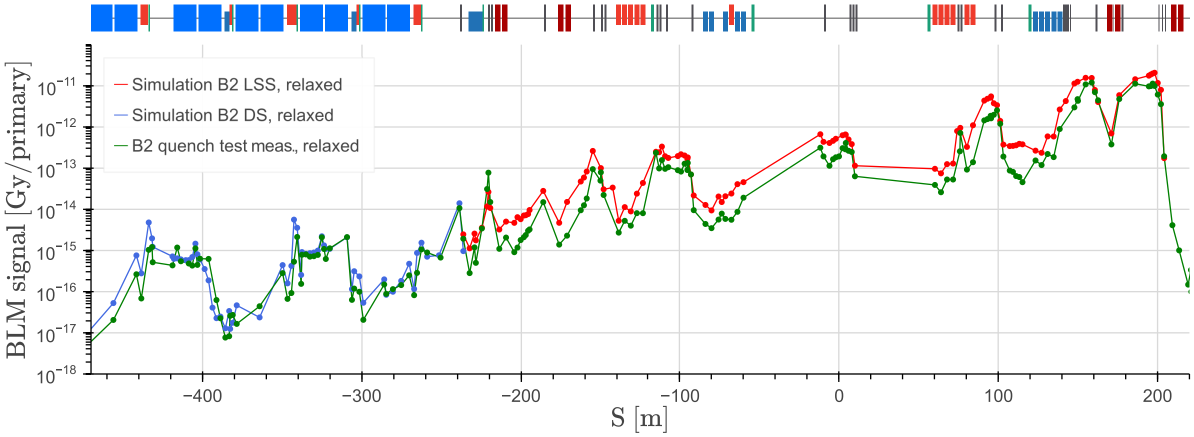

Figure 1: Benchmark of the two-step simulation and BLM signals measured during the quench test in IR7. The coordinate origin corresponds to the center of IR7. Beam 2 direction is from right to left. The measured BLM signals were normalized by the number of protons lost during the test. The simulated signals at cold magnets (blue curve) were normalized by a factor of three to compensate for differences with measurements.

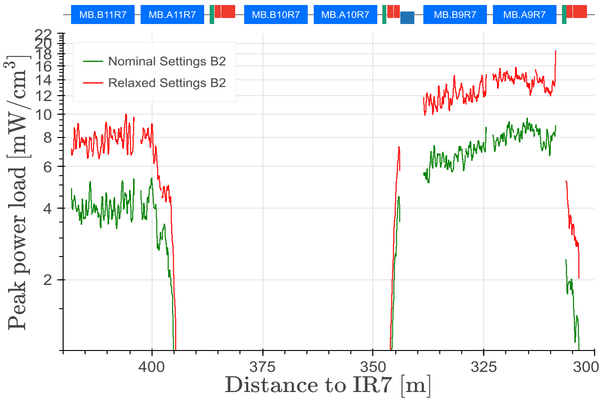

Figure 2: Longitudinal distribution of the peak power density in the inner coils of DS magnets normalized to the particle loss rate during the quench test at 6.8 TeV (650 kW in both cases). The beam direction is from the right to the left.

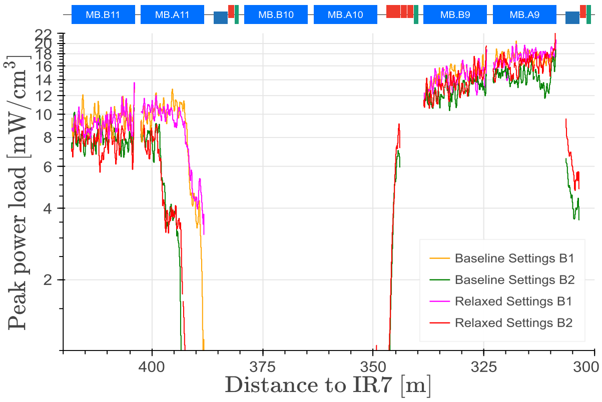

Figure 3: Expected longitudinal distribution of the peak power density in the inner coils of DS magnets in Run 4 (1 MW power loss, 7 TeV beams). Baseline and relaxed collimator settings for Run 4 are compared for both beams. The beam direction is from the right to the left.

tions in the simulation model. The good agreement between the scaled BLM pattern and the measurements provides us confidence in the expected power density distribution in DS magnets. All power deposition results presented in the following were multiplied with a factor of three to compensate for differences found in the benchmark.

Power Deposition in Cold Magnets

Figure 2 shows the longitudinal distribution of the simulated peak power density in magnet coils for both collimator settings. The power densities were averaged radially over the width of the inner coil layer. Both curves were normalized to the maximum proton loss rate in the collimation system achieved during the test (~650 kW in both cases). The highest power deposition was obtained with relaxed settings, with values of about 16 mW/cm^3 delivered to the coils of one of the bending dipoles; the simulation predicts an even higher peak value at the magnet front, but this peak is not considered here since the quench margin is different in the coil end region.

Since no quench was observed in the test, the observed value of 16 mW/cm^3 provides a lower bound for the dipole quench level at 6.8 TeV for slow losses. The quench level depends, however, on the time profile of the heat deposition [5]. In the test, the proton loss rate, and hence the deposited power density, was rising for several tens of seconds before the peak value of 16 mW/cm^3 was reached [8]. It is expected that the quench level for a pure constant time profile differs to some extent from the value found.

POWER DEPOSITION IN RUN 4 (HL-LHC)

Within the scope of HL-LHC, it was foreseen to install additional collimators in the high-dispersion region of the DS downstream of IR7, with the aim of mitigating the risk of quenches by particles leaking from the IR7 collimation system [2]. This upgrade was mainly envisaged for heavy ion operation, but would have also been beneficial for protons [18]. Presently, the installation of these collimators has been deferred due to the unavailability of higher-field dipoles, which are needed to create space for the collimator. Alternative solutions to decrease the delivered power to cold magnets in proton operation are therefore explored, in particular a new beam optics for the betatron collimation insertion [19].

This section provides FLUKA simulation predictions of the expected power deposition during Run 4 with HL-LHC beam parameters (7 TeV). The studies were carried out for HL-LHC optics version 1.5, using again dedicated tracking studies as input [20]. The obtained power density distribution in cold magnet is shown in Figure 3 for both counter-rotating beams. The results were normalized to a power loss of 1 MW, corresponding to a beam lifetime of 0.2 hours. We considered two sets of collimator settings, called "*baseline*" and "*relaxed*", with the half-gaps of each collimator family shown in Table 1. The "*relaxed*" settings shall decrease the impedance budget of collimators. Contrary to the relaxed settings in the quench test, the "*relaxed*" configuration for Run 4 features larger gaps for all collimator families, not only for secondary collimators. The results show that the expected maximum power density is only 25% higher than what was achieved in the 2022 quench test. These results provide confidence about the collimation system performance in the HL-LHC.

CONCLUSIONS

We used FLUKA to calculate the power density deposited in the superconducting coils of dispersion suppressor magnets downstream of the betatron cleaning region in the LHC. The calculations were validated against BLM signals measured during a quench test in IR7, carried out in 2022. The results showed that the peak power deposition expected in case of a lifetime drop to 0.2 hours in Run 4 (HL-LHC) is comparable to power densities reached in the 2022 test. A second quench test on B1 is planned in 2023 to demonstrate the symmetry of the collimation system for both beams.

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