OPERATIONAL LOSS LIMIT IN THE OFF-MOMENTUM COLLIMATION SECTION OF THE LHC

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Abstract

At the Large Hadron Collider (LHC) at CERN, nearly 3 600 ionization chambers composing the Beam Loss Monitoring (BLM) system are distributed along the ring and at each collimator. They are responsible for protecting the machine against energy deposition originated from beam losses by requesting the beam extraction when the measured signals are above certain predetermined thresholds. The setup of these thresholds is complex and requires a combination of simulations and measurements. In preparation for the High Luminosity-LHC (HL-LHC) era, the bunch intensity has been pushed from 1.4×10^{11} to 1.8×10^{11} protons during the LHC Run 3. With this higher intensity, more power is required in the radio-frequency (RF) cavities to capture the beam and reduce beam losses due to off-momentum particles, in particular at the start of the energy ramp. The present limitation on maximum allowed beam losses on the off-momentum collimation region is around 60 kW and comes from the theoretical quench limit of the matching quadrupole magnets in cell 6 (Q6) which is based on the initial LHC magnet quench models. Supported by simulations, a dedicated machine development test took place in 2025 to assess in two steps if 200 kW and 500 kW beam losses from off-momentum particles could be sustained in the off-momentum collimation section without quenching the Q6 magnets. This paper describes the procedure of the test carried out and discusses the main findings in terms of the power loss reached and the recorded loss patterns.

INTRODUCTION

The LHC at CERN will finish its third period of operation, Run 3, at the end of June 2026. This will be followed by a period of shutdown that will extend until 2029 and will be mainly dedicated to the implementation of the upgrades required for the HL-LHC era [1]. In order to reach higher luminosities, one of the LHC parameters that will be pushed is the beam intensity, which has already been increased progressively during Run 3 to gain operational experience.

Higher beam intensities require higher RF power at capture and throughout the injection sequence [2]. Particles that are not captured by the RF fall outside the accelerating bucket and are lost at the start of the beam acceleration. These losses occur mainly in two locations. One is the off-momentum collimation section in the Interaction Region 3 (IR3), where the dispersion reaches a maximum by design. The other is the betatron collimation section in the Interaction Region 7 (IR7), where the dispersion is not null, thus intercepting also a fraction of these particles [3].

Both regions include a multi-stage collimation system for each counter-rotating beam with an arrangement of primary (TCP), secondary (TCS), and absorber (TCLA) collimators [4]. These regions also include warm and superconducting magnets. Each of these elements is equipped with BLM detectors that protect them from beam losses by requesting the immediate extraction of the beams if the signal of any of these detectors is above certain predetermined thresholds [5]. The thresholds depend on the protected element and the position of the detector.

These increasing beam intensities in the LHC have been causing higher losses at the start of the beam acceleration, with several BLM detectors reaching regularly signals above 30 % of their threshold in the IR3 region, even leading to the beam extraction in some cases. As an effort to mitigate this limitation, it was decided to investigate the possibility of increasing the BLM thresholds in the area.

This was followed by a series of studies that concluded in an experimental beam test to probe that the different elements in the IR3 area can sustain up to 500 kW beam losses impacting on the IR3 TCPs.

BEAM POWER LOSS LIMIT AT 450 GeV

The thresholds of the BLM detectors located at the collimators from the IR3 region of the LHC had been last reviewed in the shutdown period after Run 1, between 2013 and 2015 [6]. At the time, the sharing of beam losses between the IR3 and IR7 regions was not well known, so the BLM thresholds were set to a combined beam power loss in both regions of around 500 kW.

Thanks to a dedicated beam loss decomposition algorithm developed to study off-momentum losses using the signals from the BLM detectors at the collimators, today it is possible to obtain an estimate of the number of protons impacting on each TCP, providing a better understanding of the sharing of beam losses between both collimation sections [3].

Figure 1 shows an example of the estimates of second-by-second beam power lost on the beam 1 (B1) on the left, and beam 2 (B2) on the right, in the IR3 and IR7 sections during the first seconds of beam acceleration from a 2025 LHC fill. It is observed that for B1 the main peak of losses occurs mainly in IR7 collimators as opposed to B2, for which it occurs in IR3 collimators. This has been the case for most of the 2025 and 2026 LHC fills, and it appears to be caused by off-momentum particles that hit a resonance line and are lost betatronically.

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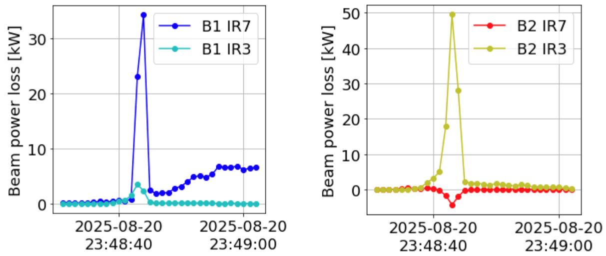

Figure 1: Beam power lost on B1 (left) and B2 (right) in the IR3 and IR7 sections during the start of beam acceleration.

The values provided by the decomposition algorithm can also be used to study the dependence of the signals from the BLM detectors on the beam power loss at the collimators. During Run 3, the BLM detector reaching the highest signal to threshold ratio (and therefore the most limiting one) was found to be the one protecting the B2 Q6, which is the first superconducting magnet downstream the IR3 B2 collimators. The thresholds for this BLM detector are based on the quench level of the Q6, assuming beam losses from an orbit bump moving the beam towards the beam screen. However, the loss scenario is very different at the start of the beam acceleration, as the energy deposition in the Q6 is originated by particle showers initiated several meters upstream at the IR3 collimators from off-momentum particles.

Figure 2 shows the signal to threshold ratio of this BLM detector as a function of the B2 power loss in IR3 during the start of beam acceleration from LHC proton fills in 2024. A linear dependence between both is observed, with the BLM detector reaching its signal threshold at a beam power loss of around 60 kW.

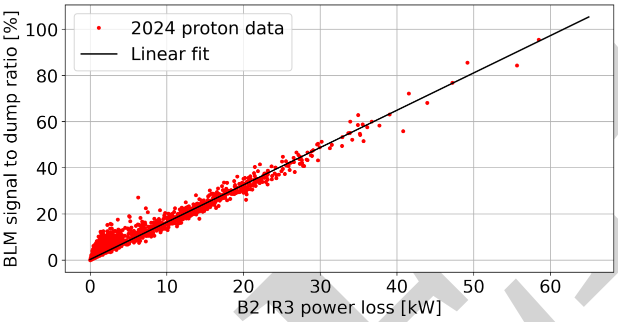

Figure 2: Signal to threshold ratio of the IR3 Q6 B2 BLM detector as a function of the estimated B2 power loss in IR3 during the start of beam acceleration in 2024.

A campaign of particle tracking, energy deposition and thermo-mechanical simulations targetting IR3 magnets and collimators was launched to determine whether it was possible to increase safely the BLM thresholds in the area to allow for higher beam power loss at the TCPs in IR3 at the start of beam acceleration [7–9]. It was agreed by all equipment owners and teams involved in the studies that allowing a beam power loss of up to 500 kW in IR3 at 450 GeV was acceptable. This allows one to increase the limit imposed by the BLM thresholds by a factor of more than 8. It was decided to test this limit experimentally, with the goal of inducing up to 500 kW beam losses at the IR3 TCPs during a beam test to demonstrate explicitly that no other limitation to operation occurs during this high-loss regime.

PREPARATION OF THE BEAM TEST

Several ways of inducing the beam losses in IR3 were considered. The first one by performing collimator scraping of the circulating beam, where the TCP jaws are closed in steps until the required level of losses is reached. However, a comparison of the pattern of BLM signals generated during a beam scraping exercise and the start of beam acceleration showed large differences around the TCSs for both beams, meaning that beam scraping does not reproduce well the desired beam loss pattern towards the end of the collimation section.

Figure 3 shows the signals of BLM detectors around IR3 at the start of beam acceleration (green) and during a beam scraping exercise (blue, scaled up to match the signal at the TCPs). The x axis represents the location of the BLMs in the area with respect to its centre. In the figure, B1 travels from left to right and B2 from right to left. The TCPs and TCSs of each beam are indicated. Note that for this example, a 2024 LHC fill was used, as the signals at the TCPs of both beams are of the same order of magnitude.

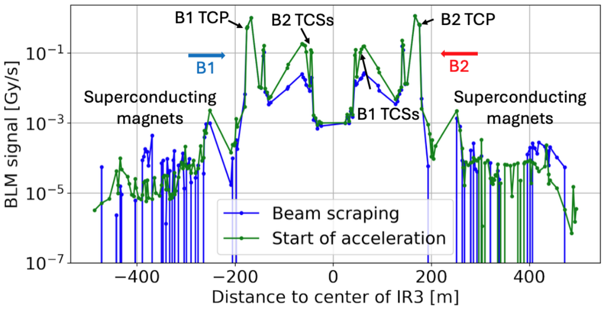

Figure 3: BLM signals around IR3 at the start of beam acceleration (green) and during beam scraping (blue).

Another possibility was to inject high intensity beam and stay at injection energy for some time. Due to the high bunch intensity a large number of particles would debunch before triggering the beam acceleration to obtain high off-momentum losses. This idea was not pursued further as it is not easy to estimate the fraction of the beam that will be lost, and just a few attempts would consume too much time.

Eventually, it was observed that the BLM signal pattern during an off-momentum loss map recreates well the loss pattern at the start of beam acceleration. These are beam tests during which off-momentum losses are generated by changing the RF frequency in small steps to verify that the collimator system is properly set up [10]. Changing the RF frequency naturally brings the beam particles off-momentum, producing an overall beam displacement in IR3 due to the large dispersion. Figure 4 shows the comparison between BLM signals in IR3 at the start of beam acceleration (green) and during an off-momentum loss map where the

RF frequency was reduced (blue). Note that these examples also correspond to 2024 fills.

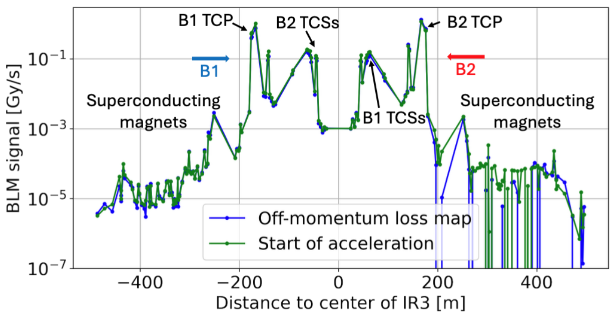

Figure 4: BLM signals around IR3 at the start of beam acceleration (green) and during an off-momentum loss map (blue).

Therefore, it was decided to generate the beam losses during the test by reducing the RF frequency as it is done during off-momentum loss maps. Similarly as to what was observed at the start of beam acceleration, B1 losses occur mostly in IR7 collimators during off-momentum loss maps in 2025 and 2026. For this reason, it was decided to perform the test only with B2 in the machine.

Before starting the test, the BLM thresholds in IR3 were increased to allow up to 500 kW beam losses. These thresholds were calculated by scaling the BLM signals recorded during the start of beam acceleration. Similarly, an RF interlock was modified to allow for large RF frequency changes.

BEAM TEST PROCEDURE AND RESULTS

The beam test was performed in two stages which took place during two different days. The goal of the first stage was to reach up to 200 kW beam losses in IR3, while the ultimate goal was reaching 500 kW beam losses.

In both cases, a gradual approach was taken, starting with low beam intensity to tune the speed and value of the RF frequency change to obtain the expected loss rate. This led to just a few kW beam losses in the beginning, with the beam intensity being progressively increased after each attempt.

On the first stage of the beam test, a peak beam power loss of around 350 kW was achieved, and no superconducting magnets were quenched. The collimator temperature was also monitored, showing significant operational margins. No issues linked to the beam test were observed in the warm magnets either. The losses around the ring remained low, with no other BLM reaching threshold values. However, the ultimate goal could not be achieved during this test as the BLM signals generated downstream of the TCSs were higher than it was anticipated, exceeding the BLM thresholds.

Nevertheless, the final goal of reaching 500 kW beam losses was achieved several times during the second stage of the beam test, demonstrating that this level of losses can be safely sustained operationally without the risk of quenching any superconducting magnet in IR3. Figure 5 illustrates this achievement by showing a comparison between the B2 power loss measured by the Beam Current Transformer (BCT) and the BLM algorithm during one of the attempts.

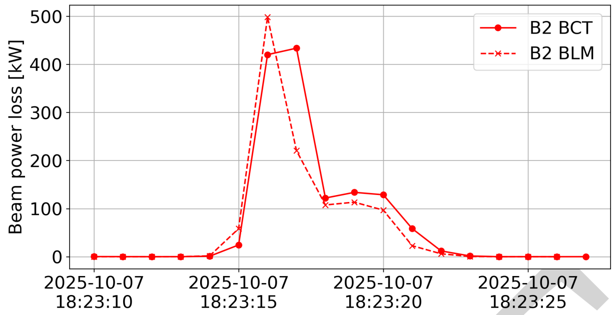

Figure 5: B2 power loss during one of the attempts of the beam test as measured by the BCT and the BLM algorithm.

Figure 6 shows the comparison between BLM signals in IR3 at the start of beam acceleration (green), and during one of the attempts of the beam test (blue). Note that in this case, both loss patterns are taken from 2025 fills. For the case of the start of beam acceleration, the signal at the B1 TCP is much lower than that of the B2 TCP, as most B1 losses occur in IR7. The signal at the B1 TCP during the test is even lower as B1 was not present during it.

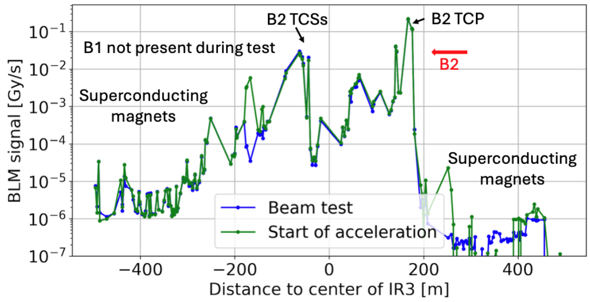

Figure 6: BLM signals around IR3 at the start of beam acceleration (green) and during the beam test (blue).

CONCLUSION

Higher beam intensities in the LHC risk reaching BLM thresholds in IR3 at the start of beam acceleration due to off-momentum particles that are lost. A series of studies was conducted to investigate the possibility of increasing the BLM thresholds in the area. These studies led to a final experimental verification showing that up to 500 kW beam losses can be sustained in IR3 at 450 GeV without risking to quench any superconducting magnets. This result represented an important milestone that led to an increase of BLM thresholds in IR3 implemented already in 2026, giving more flexibility and margins for high-intensity beam tests organized as a preparation for the HL-LHC era.

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