ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPL086

BEAM LIFETIME MONITORING USING BEAM LOSS MONITORS DURING LHC RUN 3

S. Morales*[1,2], B. Salvachua[1], P. Hermes[1], S. Redaelli[1], C. Zamantzas[1], C.P. Welsch[2], J. Wolfenden[2]
[1]CERN, Geneva, Switzerland
[2]Cockcroft Institute, Warrington, Cheshire, United Kingdom

Abstract

The Beam Loss Monitoring (BLM) system of the Large Hadron Collider (LHC) at CERN is essential for the protection of machine elements against energy deposition from beam losses. Employing around 4000 detectors placed around the 27 km LHC ring, the BLM system measures secondary particles continuously and can trigger beam extraction in less than 3 turns, in case the signals exceed certain predetermined thresholds. Thanks to its high dynamic range and sensitivity, a signal-to-lost-particle calibration of this system is suited to provide accurate information about the LHC beam loss patterns. This includes online monitoring of the beam lifetime and even the identification of the plane of losses, making it an asset to follow up the performance of the accelerator. In this contribution the principle of the monitor calibration is explained, as well as a description of the machine tests used to acquire the calibration data. Finally, an analysis of the beam lifetime during the first year of the LHC Run 3 is presented together with examples of selected LHC fills.

INTRODUCTION

The LHC at CERN resumed its operation in 2022 after more than 3 years of shutdown, reaching an unprecedented beam energy of 6.8 TeV, with up to 2462 proton bunches per beam and 1.5×10^{11} protons per bunch [1]. In order to keep these highly energetic beams inside the LHC pipes, superconducting dipole and quadrupole magnets operate at cryogenic temperatures. Under these conditions, a transient beam loss of only 4×10^7 protons, equivalent to only around 0.03% of a single proton bunch, could provoke a quench of the superconducting magnets, which would lead to a downtime in the order of hours [2].

In order to actively protect the LHC elements against energy deposition from beam losses, a BLM system is put in place employing around 4000 detectors which are installed all around the machine downstream the most probable loss locations. These detectors measure secondary shower particles continuously and trigger beam extraction in case the signals are above certain predetermined thresholds [3].

The LHC BLM system is considered mainly a machine protection system, but in addition to that its high sensitivity and dynamic range of more than 10^8 (10 pA - 1 mA) make it a powerful diagnostic tool to assess the performance of the LHC by providing an accurate number of the lost beam particles. Other devices such as the LHC Beam Current Transformers (BCT) are very precise in the measurement of high beam intensities, but it is needed to average their signals over several seconds to reach the level of accuracy that the BLM system can provide for measuring beam losses second by second [4]. However, since the BLM detectors signals are saved in Gy/s, a signal-to-lost-particle calibration of the system is required.

The LHC BLM calibration presented in this work is based on the analysis of the BLM detectors signals for the main LHC regular beam loss scenarios, excluding luminosity losses and focusing on the losses occurring at the collimators. These well-defined beam loss scenarios can be reproduced in a controlled way during dedicated LHC beam tests. Similar calibrations of the LHC BLM system have already been performed for past LHC Runs considering only horizontal and vertical beam loss scenarios [5, 6].

From the total number of lost beam protons it is possible to obtain other quantities such as the beam lifetime or the deposited power loss in the collimation system. These need to be followed up continuously to make sure they stay within the LHC specifications and can be helpful to spot potential anomalies in the operation of the machine.

This work explains the principle of the LHC BLM system signal-to-lost-particle calibration, as well as the tests run in the machine in order to obtain the required calibration data. Following this, a summary of the analysis of the beam lifetime across the 2022 LHC cycle is presented.

LHC BEAM TESTS FOR BLM CALIBRATION

The BLM calibration factors are obtained by producing well-defined beam loss scenarios in the LHC where losses are created in a controlled way. As the regular beam losses are concentrated in the collimation system during nominal LHC operation, the considered beam loss scenarios include proton impacts on the jaws of the primary Beam 1 (B1) and Beam 2 (B2) collimators in the betatron and off-momentum collimation regions. These measurements are to be repeated if there is a change in beam optics, beam energy or collimation hierarchy, and during beam commissioning after a shutdown or technical stop. The calibration data can be acquired from two different types of tests, the collimation loss maps and the beam scraping tests.

Collimation Loss Maps

The collimation loss maps are machine protection validation beam tests that are usually performed during beam commissioning at different stages of the LHC cycle. Their main

* sara.morales.vigo@cern.ch

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPL086

purpose is to observe the distribution of losses in the machine. During the so-called betatron loss maps, low-intensity bunches are excited either horizontally or vertically with the LHC Transverse Damper. In addition, off-momentum loss maps are done by shifting the RF frequency, causing simultaneous losses of both beams.

With this method it is possible to generate controlled beam losses during only some seconds, and the data can be used to provide a first estimation of the responses of the BLM detectors. The BLM detector responses are defined as the expected signal in each BLM detector per lost proton in the considered beam loss scenarios. As the excitation of the beam is done on selected low-intensity bunches, the BLM detectors signals are cross-calibrated against the Fast BCTs (FBCTs), which measure only bunch-by-bunch beam intensities, but are more accurate for low-intensity beams. The BLM detector responses are then obtained for each beam loss scenario from dividing the integrated BLM detector signals by the total beam losses measured from the FBCTs.

Beam Scraping Tests

During beam scraping tests, well-defined beam loss scenarios can be reproduced during some minutes by closing in small steps one or both jaws of a collimator. In order to improve the calibration results for LHC Run 3, dedicated beam scraping tests were performed for the first time including all the primary collimators in the betatron collimation region, with vertical, horizontal and skew (127.5°) orientations, and in the off-momentum collimation region for B1 and B2. This is the only method that allows to create independent beam loss scenarios for B1 and B2 in the off-momentum collimators and for primary impacts at the skew collimators.

During the beam scraping tests, un-bunched beam can also be intercepted by the collimator jaws. Therefore, the BLM detectors signals are cross-calibrated against the Direct Current BCT (DCBCT), which measures the average current of the circulating beam (including un-bunched beam). In this case, the BLM detector responses are obtained from a linear fit of the BLM detector signals versus the beam losses measured with the DCBCT second by second. High accuracy in the calculation of the BLM detector responses is only reachable with this method. Figure 1 shows the B1 intensity decay measured with the DCBCT and the signals from the BLM detectors located downstream the B1 primary horizontal and vertical collimators during vertical B1 scraping followed by horizontal B1 scraping.

LHC BLM SYSTEM CALIBRATION

Two types of signal-to-particle-loss calibrations were performed taking as a starting point the BLM detector responses calculated for the considered beam loss scenarios. The Global Beam Loss Calibration provides the beam losses in the betatron collimation region and is expected to remain relatively stable during the Run. In contrast, the Beam Loss Plane Decomposition Calibration provides the proton impacts on the primary betatron and off-momentum collimators and needs to be recalculated after every change in collimation settings or beam optics.

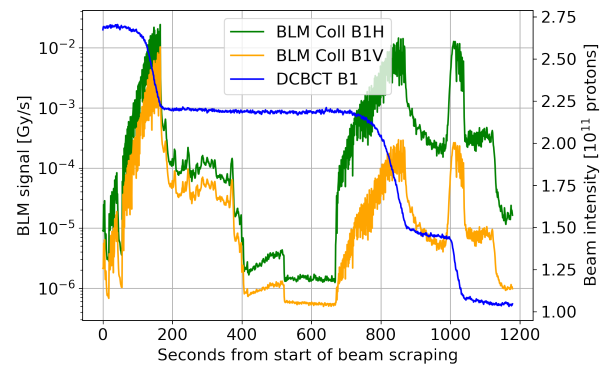

Figure 1: Beam 1 intensity measured with the DCBCT and BLM signals at primary horizontal and vertical B1 collimators during B1 vertical and horizontal beam scraping.

Global Beam Loss Calibration

This calibration provides an accurate number of the losses in the betatron collimation region independently of their origin. These account for the majority of the total losses in the LHC. The BLM detectors included in this calibration are those with high and similar responses for all the loss scenarios of one of the beams, and low responses for the other beam. Therefore, this calibration is less sensitive to the plane of losses. During normal operation periods, the lost intensity is calculated from a combination of the selected BLM detectors signals as:

$$\frac{dI}{dt} = \alpha \times \sum_i BLM_i \tag{1}$$

Where α is the calibration function, which depends on the beam energy and is obtained empirically from the beam tests data. At injection energy, α is calculated as the sum of the integrated signals of the chosen BLM detectors (which is independent of the plane of losses) divided by the total beam loss measured by the BCTs, averaging the results obtained for each beam test. The same procedure is performed at top energy. For the energy ramp, several calibration factors are computed performing loss maps at different energies. Finally, an interpolation with a monotone function between the calculated points provides the calibration function. A comparison between DCBCT and BLM calibration measurements of beam losses shows a difference of around 30%, which is at the limit of the DCBCT resolution.

This calibration is used for online monitoring of the beam lifetime, which is defined as the total beam intensity (measured with the DCBCT) divided by the instant lost beam intensity (from Eq. (1)). Additionally, it allows to disentangle the machine losses and the luminosity losses during stable beams, which would not be possible with the BCTs alone.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPL086

Beam Loss Plane Decomposition Calibration

This calibration is based on the fact that there are BLM detectors located downstream each one of the primary collimators. As seen in Fig. 1, the ratio between their signals is different depending on the beam loss scenario. Therefore, from their measurements it is possible not only to obtain the total number of lost protons, but also to know the origin of the primary impacts. This calibration is also used for monitoring the beam lifetime at the start of the ramp, as off-momentum losses are predominant at that moment and not included in the Global Beam Loss Calibration.

From the beam tests data, the responses of the BLM detectors located downstream the primary collimators are calculated for each beam loss scenario and a response matrix, $\boldsymbol{M}$, is built at injection and top energy. During nominal LHC periods, the beam intensity lost in each beam loss scenario, $\overrightarrow{dI/dt}$, is obtained from the BLM detectors signals, $\overrightarrow{BLM}$, as $\overrightarrow{dI/dt} = \boldsymbol{M}^{-1} \times \overrightarrow{BLM}$ [6].

LHC BEAM LIFETIME ACROSS THE 2022 CYCLE

The LHC collimation system is designed to handle beam lifetime drops of 0.2 h at top energy, corresponding to a power loss of around 500 kW, for a maximum of 10 s without damage. At injection energy, this value is 0.1 h, corresponding to a power loss of around 60 kW. At the beginning of the energy ramp, due to the un-bunched protons which result in off-momentum losses, acceptable beam lifetimes go down to around 20 s (around 0.006 h) for 1 s. It is assumed that in case of higher proton loss rates the beams will be dumped by the BLM system.

The LHC beam lifetime was analyzed across the 2022 cycle using the LHC BLM calibrations to assess the performance of the machine, detect errors linked to sudden beam lifetime drops and verify that the values of minimum beam lifetime and maximum power loss in the collimation system stayed within the specified limits. This analysis was also useful to verify the need to adjust BLM thresholds.

All fills from July 2022 until the Year End Technical Stop (which started at the end of November 2022) with a minimum of 10^{13} protons (around 100 bunches) per beam were analyzed from the moment in which there was circulating beam in the LHC. The beam lifetime was always above the limits. Table 1 shows the average percentage of beam lost in each beam mode with respect to the initial beam intensity, and the respective average minimum beam lifetime.

Even though as seen in Table 1 most of the initial beam intensity is lost in the STABLE beam mode, it is only because of its longer duration, and in all cases the minimum beam lifetime in STABLE beam mode was well above 0.2 h (including the routine operation of luminosity levelling schemes), while the average beam lifetime was above 10 h.

The overall minimum beam lifetime happens at the beginning of the energy ramp, which was still well above the limit in all cases. The lowest beam lifetime recorded in this beam mode was of 0.02 h for B1. A deeper analysis of the beam losses around that specific beam lifetime drop with the Beam Loss Plane Decomposition calibration showed that it was not because of higher capture losses, but due to additional losses in the vertical plane, as it can be seen in Figure 2.

Table 1: Average beam transmission and average minimum beam lifetime at each beam mode from BLM calibration.

Beam mode	Losses (%)	Min. lifetime (h)
INJPHYS	0.1	11
RAMP <500 GeV	2.5	0.5
RAMP >500 GeV	2	2
FLATTOP	0.1	147
SQUEEZE	0.4	25
ADJUST	0.3	5
STABLE	15	6

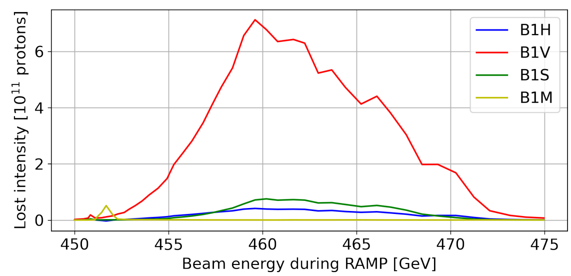

Figure 2: Proton impacts on the B1H (horizontal), B1V (vertical), B1S (skew) and B1M (off-momentum) primary collimators around a beam lifetime drop at the beginning of the energy ramp.

CONCLUSION

Even though the main purpose of the LHC BLM system is machine protection, it can also be used as a powerful diagnostic tool to improve the performance of the machine by providing an accurate number of the lost beam protons when calibrated. The data for the calibration can be acquired via two types of beam tests: the collimation loss maps and the beam scraping tests. Two types of calibration are performed, the Global Beam Loss Calibration, which provides the total number of protons lost in the betatron collimation region, and the Beam Loss Plane Decomposition Calibration, which provides the proton impacts on the primary collimators in the betatron and off-momentum collimation regions. A series of beam tests run during the 2022 LHC operation period provided the data for the calibration, which was then used to analyze the beam lifetime across the 2022 cycle. The minimum beam lifetime remained at all times well above the limits set for the collimators, with the possibility of analyzing further the cases with unexpected beam lifetime drops.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution to these studies to the LHC CERN Beam Instrumentation group and LHC operators for their assistance and guidance during the execution of the tests.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPL086

REFERENCES

[1] M. Lamont, "LHC Chamonix Workshop Summary". `https://indico.cern.ch/event/1262929/`

[2] O. Bruning *et al.* (editors), "LHC Design Report Vol 1: The Main LHC Ring", CERN, Geneva, Switzerland, 2004. `doi:10.5170/CERN-2004-003-V-1`

[3] E. B. Holzer *et al.*, "Beam loss monitoring system for the LHC", in *IEEE Nuclear Science Symposium Conference Record*, Fajardo, PR, USA, Oct. 2005, pp. 1052–1056. `doi:10.1109/NSSMIC.2005.1596433`

[4] B. Salvachua, "Beam Diagnostics for Studying Beam Losses in the LHC", in *Proc. IBIC'19*, Malmö, Sweden, Sep. 2019, pp. 222–228. `doi:10.18429/JACoW-IBIC2019-TUAO01`

[5] B. Salvachua *et al.*, "Decomposition of Beam Losses at LHC", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 88–91. `doi:10.18429/JACoW-IPAC2017-MOPAB009`

[6] S. Morales Vigo *et al.*, "Beam Loss Signal Calibration for the LHC Diamond Detectors During Run 2", in *Proc. IBIC'21*, Pohang, Korea, Sep. 2021, pp. 290–293. `doi:10.18429/JACoW-IBIC2021-TUPP33`