STUDY OF THE PERFORMANCE AND BEAM LOSS LIMITATIONS DURING INJECTION OF HIGH-INTENSITY LHC PROTON BEAMS

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Abstract

The LHC Injectors Upgrade project at CERN optimized the injection accelerator chain to deliver proton intensities per bunch of 2.3×10^{11} ppb. Throughout 2023, the LHC was filled with up to 2 464 bunches per beam using a hybrid injection scheme, involving up to 236 bunches per injection, with a maximum intensity per bunch of 1.6×10^{11} ppb. These beam parameters already revealed significant beam losses at the primary collimators in Point 7 during injection, with large fluctuations from fill to fill, limiting in several cases the machine performance. This contribution analyses the performance of the LHC during injection and discusses possible improvements.

INTRODUCTION

The CERN Large Hadron Collider (LHC) [1] is providing proton-proton collisions with 6.8 TeV beam energy at four different interaction points (IP1, IP2, IP5 and IP8). The beam injection is done in two dedicated insertion regions, IR2 for Beam 1 and IR8 for Beam 2. Local protection elements are installed in both IRs to protect the machine against injection losses and kicker failures [2]. A multi-stage collimation system [3, 4] protects the superconductive magnets from quenches due to beam losses of the circulating beam by concentrating beam halo cleaning in warm straight sections. The main beam halo cleaning occurs in two regions, IR3 for particle off-momentum cleaning and IR7 for betatron cleaning. In IR7, 3 primary collimators oriented in the vertical, horizontal and skew plane are the first collimation stage of cleaning, with an aperture at injection of 5.7 σ, σ being the measured standard deviation assuming a Gaussian's beam transverse profile with normalized beam emittance of 3.5 µm. Secondary collimators intercept the secondary showers; there are 14 collimators per beam in IR7 and they are set to an aperture at injection of 6.7 σ and 7.2 σ. The remaining particle showers are captured by additional absorbers, 5 per beam set at 10 σ [5].

SPS beams at 450 GeV are injected into the LHC via 2 transfer lines, TI2 and TI8 [6]. These transfer lines are equipped with 6 collimators each (3 on the vertical plane and 3 on the horizontal), the TCDIs. Beam is horizontally deflected by a septum magnet and then injected to the LHC via a vertical kick. In the ring, a double-sided absorber, TDIS, protects against injection failures and can capture vertical losses [7].

During 2023 LHC proton run, losses from Beam 1 in IR7 were triggering beam dumps during the injection of high intensity trains (with up to 236 bunches). These were very fast losses, less than 1 LHC turn, measured by the beam loss monitor (BLM) system. These losses reached the saturation limits of the BLM standard ionisation chambers located downstream the primary collimators in IR7. The analysis of the beam losses in IR7 during beam injection is presented here and mitigation to the saturation of the BLM system is discussed.

FILLING SCHEME 2023

A hybrid injection scheme was chosen to mitigate the e-cloud effect and keep heat-load on the cryogenic system under control. Maximum heat-load per half-cell in 2023 was below 150 W, while in 2022 it reached up to 185 W [8, 9]. This filling scheme is a combination of 7 batches of 8 consecutive bunches and 4 empty 25 ns empty slots (8b4e) up to 5 batches of 36 bunches with the standard 25 ns bunch spacing. This provides a train with a maximum of 236 bunches injected from SPS to LHC.

The full beam in 2023 had a maximum of 2 464 bunches distributed in 12 injections formed as following:

- 1 train of 12 bunches used for the transfer lines steering and orbit verification,
- 2 trains of 164 bunches (7 × 8b4e + 3 × 36 b) and
- 9 trains of 236 bunches (7 × 8b4e + 5 × 36 b).

LHC BEAM INJECTION

The 2023 LHC proton run took place from 21 April, with the first declaration of Stable Beams, until 18 July. The period included in this study is slightly shorter, from 9 May until 18 July, but considers most of the high intensity run. During that period, there were more than 3 000 injection attempts for Beam 1, and similarly for Beam 2.

Figure 1 shows an overview of the beam injections; as function of time, the number of injected bunches (top), the average bunch intensity (middle) and total injected intensity (bottom) for 128 b, 164 b and 236 b (the injections with 12 b trains have been excluded). The figure shows that the maximum intensity per bunch reached was about 1.6×10^{11} ppb and the total injected intensity was just below 4×10^{13} protons, corresponding to the 236 b trains.

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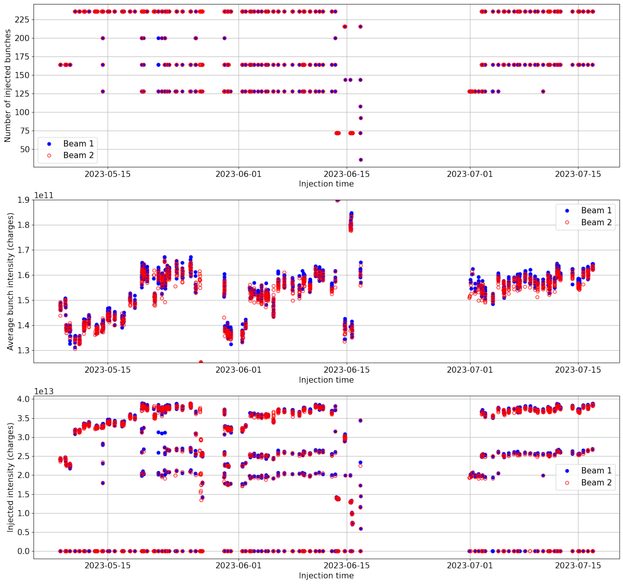

Figure 1: Number of bunches (top), average bunch intensity (middle) and intensity per injection (bottom) all as function of time.

BEAM DUMPS DURING INJECTION

Beam losses are measured in the LHC by a distributed beam loss monitoring system (BLM) consisting of 3 700 ionisation chambers of 0.5 m long located at strategic positions where losses are expected [10, 11]. The BLM system, measures beam losses for beam diagnostics but is also one of the main pillars on the LHC machine protection. It measures continuously beam losses in 12 different running sums, starting at 40 µs up to 83 s. Beam dump limits, so-called also BLM thresholds, are set for each monitor and each running sum as a function of beam energy. If one measurement is above one of this BLM thresholds the beam is extracted within 3 LHC turns.

Each collimator has a BLM detector just downstream, following beam direction, in order to estimate beam impacts at that particular collimator. During 2023, 18 beam dump extractions were triggered in IR7 from saturated signals at the BLM detectors after the primary collimators (TCP.C6L7.B1 and TCP.B6L7.B1 collimators) [12]. The direct impacts into the primary collimators were estimated by calibrating the BLM signal from a BLM located about 40 m away of the monitor saturated. This BLM detector is associated to the secondary collimator TCSG.A6L7.B1, whose signal does not reach saturation levels. Figure 2 shows the estimated protons impacting the primary collimators in IR7 during the LHC beam injections. The signal of the BLM at the TCSG.A6L7.B1 collimator and of the TCP.B6L7.B1 collimator was calibrated to provide the measurement in protons (or charges) instead of Gy [13–16]. Figure 2 shows that saturation was reached at about 6.8×10^8 charges. For single turn losses, the LHC collimation system could handle several orders of magnitude higher beam losses than this, meaning that the BLM system in IR7 is reaching saturation levels too early. Until now, this was never a limitation, as the losses during injection remained always below that limit. However, in preparation of the High Luminosity LHC (HL-LHC) era [17], the beam parameters are being pushed towards higher bunch intensities and smaller emittances in order to increase the instantaneous luminosity during collisions.

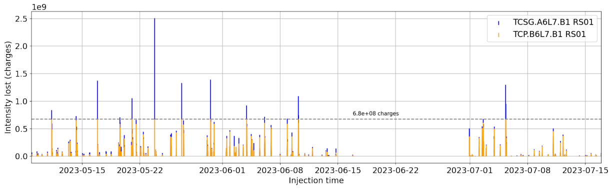

Figure 2: Estimated number of protons impacting the primary collimators in IR7 during injection with the BLM signal at the TCSG.A6L7.B1 secondary collimator and at the TCP.B6L7.B1 primary collimator, where signal shows saturation.

INJECTION LOSSES

For every injection, several quantities have been looked at, such as beam losses at several monitors, SPS beam scraping and SPS energy matching. Figure 3 shows the BLM signals for slow running sums, RS09 with integration time of 1.3 s (on top) and for the LHC half-turn running sum, RS01 (on bottom). It can be observed that Beam 2 losses are systematically lower than Beam 1 beam losses. The black line in the figures indicates the saturation level of the BLM monitor, only reached for fast losses. It seems difficult to observe a trend in the loss pattern, only at the very last part of the proton run the losses seem to be improved but the reason is not well understood.

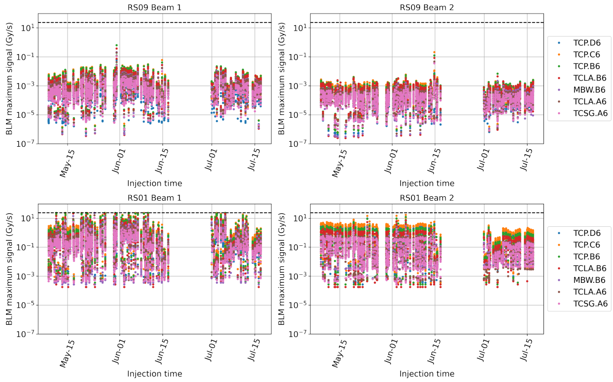

Figure 3: Maximum BLM measurement signal during injection as function of time for Beam 1 (on the left), Beam 2 (on the right) and two different running sums, RS09 (1.3 s, on the top) and RS01 (40 µs on the bottom).

During beam operation, beam scraping at the SPS had a large impact on the losses at the LHC. Figure 4 shows the percentage of beam that was scraped at the SPS before the LHC injection versus the BLM signal measured at a secondary collimators in IR7 (TCSG.A6L7.B1 and TCSG.A6R7.B2, for Beam 1 and Beam 2, respectively). The data above 3 Gy/s corresponds to unsuccessful injections (where saturation of the BLMs at the primary collimators was happening). This indicated that scraping above 6 – 7% was needed for Beam 1 in order to reduce the risk to have high losses. Figure 5 shows that the scraping for Beam 1 and Beam 2 was very similar, however the impact on beam losses in the LHC was different.

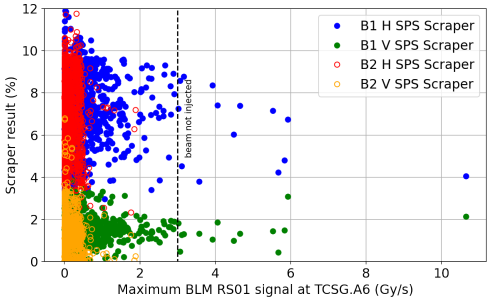

Figure 4: Percentage of injected beam scraped at the SPS as function of the measured BLM signal in IR7.

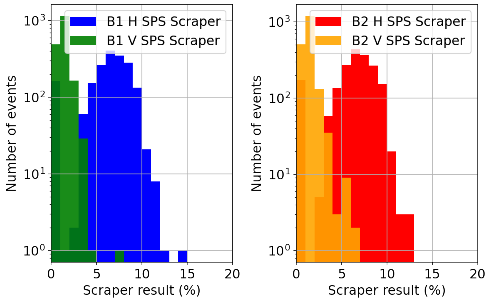

Figure 5: Histogram of the percentage of injected beam scraped at the SPS for Beam 1 (left) and Beam 2 (right).

The maximum losses in IR7 were also analysed as function of the injected intensity and the number of bunches in the injected beam, see Figs. 6 and 7 respectively. BLM signals above 3 Gy/s indicates that the beam was extracted. Higher losses are observed for higher injected beam intensity, as expected. However, the outliers that will trigger the beam extraction do not have a strong dependence on the injected beam intensity.

Figure 8 shows the energy error of the injected SPS beams, as function of time. Periodically the LHC energy is rematched to the SPS using the horizontal orbit correctors to adjust the mean dipole field. It is observed that towards the end of the run the correction was smaller, meaning that the energy matching was improved, this correlates on time with an improvement of beam losses but there is no evidence of a direct correlation.

CONCLUSION

During 2023, beam losses in the betatron collimation region (IR7) were triggering the beam extraction during injection of high intensity trains. The reason was the saturation of

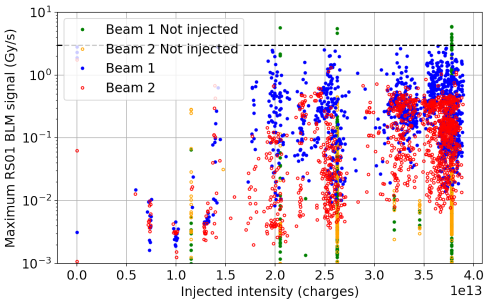

Figure 6: Maximum BLM signal in RS01 at the monitor downstream the TCSG.A6L7.B1 collimator as function of the injected intensity.

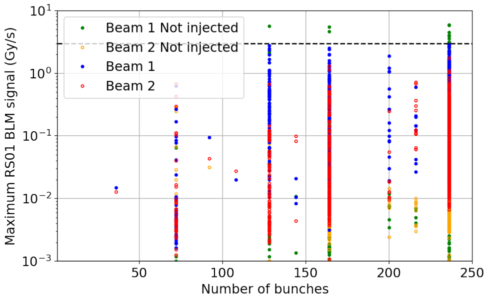

Figure 7: Maximum BLM signal in RS01 at the monitor downstream the TCSG.A6L7.B1 collimator as function of the injected number of bunches.

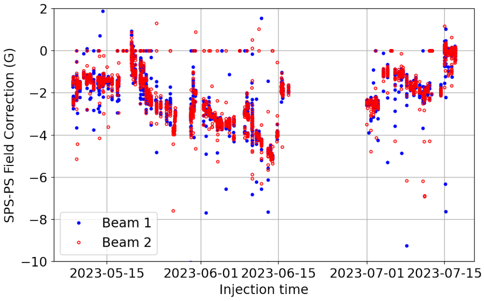

Figure 8: Energy offset of the beams injected from the SPS.

BLM signals at the primary collimators. This limitation was not observed in the previous runs as injection losses in IR7 have been always below those levels. Several quantities that indicated improvements during the run were analysed but none of them fully explains this effect of beam loss increase. In view of the 2024 LHC run some mitigation measures are being proposed. The BLM monitors that showed higher signal during these injections have been displaced to a new nearby location where their signal will be lower per proton impacting the collimator. Beam losses at these monitors will continue to be monitored during the 2024 run and further improvements on the BLM system will be proposed.

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