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RISK OF HALO-INDUCED MAGNET QUENCHES IN THE HL-LHC BEAM DUMP INSERTION*

J. B. Potoine[1], A. Apollonio, E. Belli, C. Bracco, R. Bruce, M. D'Andrea, R. Garcia Alia, A. Lechner, G. Lerner, S. Morales Vigo, S. Redaelli, V. Rizzoglio, E. Skordis, A. Waets
CERN, Geneva, Switzerland
F. Wrobel, University of Montpellier, Montpellier, France
[1]also at University of Montpellier, Montpellier, France

Abstract

After the High Luminosity (HL-LHC) upgrade, the LHC will be exposed to a higher risk of magnet quenches during periods of short beam lifetime. Collimators in the extraction region (IR6) assure the protection of magnets against asynchronous beam dumps, but they also intercept a fraction of the beam halo leaking from the betatron cleaning insertion. In this paper, we assess the risk of quenching nearby quadrupoles during beam lifetime drops. In particular, we present an empirical analysis of halo losses in IR6 using LHC Run 2 (2015-2018) beam loss monitor measurements. Based on these results, the halo-induced power density in magnet coils expected in HL-LHC is estimated using FLUKA Monte Carlo shower simulations.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN accommodates a multi-stage collimation system for safely disposing of beam particles with high betatron amplitudes [1]. The collimation system is pivotal for preventing beam-induced quenches of superconducting magnets in case of short beam lifetimes. Beam-induced quenches would adversely affect the machine efficiency due to the lengthy recovery process. At top energy, it can take eight hours or more to restore the nominal operating temperature of quenched magnets. The LHC collimation system exhibited an excellent beam cleaning efficiency in the first two physics runs. No halo-induced quenches occurred in regular physics fills. The operating conditions will, however, become more challenging in the High-Luminosity (HL)-LHC era after Long Shutdown 3 when the stored beam energy will be twice as high (~700 MJ) than in Run 2 (2015-2018) [2].

A small fraction of halo protons intercepted by collimators in the betatron cleaning insertion (IR7) escapes from the cleaning system and can be lost at different locations in the ring. A potential performance limitation arises from off-momentum protons impacting on the aperture in the adjacent dispersion suppressor (DS). The HL-LHC upgrade program foresees the substitution of two regular DS dipoles (one on each side of IR7) with an additional collimator and a pair of shorter, but higher-field magnets (11 T) [3]. This collimator will mitigate the risk of quenches in the dispersion suppressor in case of lifetime drops [4]. Halo protons scattered out of IR7 can, however, also be lost at more distant locations in other insertion regions. In particular, some of these protons are intercepted by absorbers in the extraction region (IR6). These absorbers assure the protection of magnets and the rest of the machine in case of extraction kicker failures or timing errors during the extraction process. The absorbers in IR6 are outside of the global aperture bottleneck created by primary and secondary collimators in IR7, but they still need to be closely positioned to the beam to sufficiently protect the machine in case of accidental beam losses. The tight settings make them particularly susceptible for intercepting secondary halo particles.

In this paper, we present an empirical study of the halo leakage from the betatron cleaning insertion to absorbers in IR6. The study is based on beam loss monitor (BLM) measurements recorded during 6.5 TeV proton operation in Run 2 (2015-2018). Using the reconstructed halo leakage, we assess if particle showers escaping from these absorbers could potentially pose a risk of quenching superconducting magnets in the HL-LHC operation. By design, the HL-LHC collimation system must sustain a beam lifetime of 0.2 hours over a period of ten seconds, which translates into a maximum allowed halo loss rate of $\dot{N}_{max} = 8.8 \times 10^{11}$ protons/s [3]. The results are extrapolated to this loss rate.

PROTON HALO LOSSES

The LHC BLM system is composed of almost 4000 ionization chambers, which record particle showers induced by beam losses around the rings. Figure 1 shows the time evolution of BLM signals in the betatron cleaning insertion IR7 and the extraction region IR6, respectively. The mea-

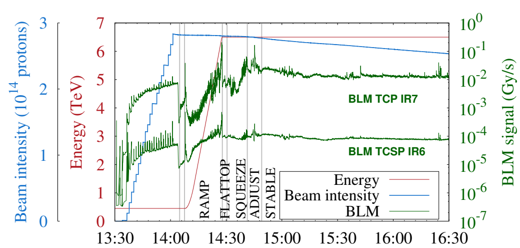

Figure 1: Time profile of BLM signals in IR6 and IR7 during a representative proton fill (19/10/2018). The different operational phases are indicated by the vertical grey lines. For both insertion regions, a BLM located near a collimator was chosen.

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surements were recorded in a representative proton physics fill in 2018. The figure shows different phases of the operational cycle, including injection, energy ramp, squeeze of the β-functions in the interaction points, setup of proton-proton collisions (adjust phase), and eventually stable collisions for physics data taking (stable beam phase). Only the first 1.5 hours of the latter phase are shown.

In regular physics fills, lifetime drops at top energy occur in particular at the end of the ramp and during dynamical changes of the machine configuration until stable collisions have been established. During these periods, high loss rates lasting often more than a few seconds are regularly observed. These lifetime drops manifest themselves as peaks in the time profiles of BLM signals, as can be seen Fig. 1. Once in stable collision mode, the beams are usually stored for many hours. Loss spikes in IR7, where most of the primary beam losses are concentrated, are less frequent, but can still occur, for example during crossing angle adjustments.

As illustrated in the figure, the time profiles in the two insertion regions resemble each other, although they are not fully identical. The figure nonetheless supports the hypothesis that beam losses in IR6 are mainly composed of betatron halo protons scattered out of the IR7 cleaning system. We therefore assume that the proton loss rate in IR6 at a given time t can be expressed as a fraction of the total betatron halo loss rate $\dot{N}$,

$$\dot{N}_{IR6} = f_{IR6} \times \dot{N}, \qquad (1)$$

where $\dot{N}$ accounts for all protons which first impinge on collimators in IR7. In the following, we derive an empirical estimate of f_{IR6}. In particular, we study the dependence of f_{IR6} on $\dot{N}$ since the leakage could vary for dynamical changes of orbit or optics at the two locations.

RECONSTRUCTION OF HALO LOSS RATES FROM BLM MEASUREMENTS

In order to estimate f_{IR6}, the proton loss rate in IR6 as well as the total halo loss rate need to be reconstructed from BLM measurements. Since a large majority of halo particles intercepted by the betatron collimation system is eventually lost in IR7 itself, we only reconstruct losses in IR6 and IR7. The total loss rate $\dot{N}$ is then defined as the sum of the two.

The loss rates in the two insertion regions can be deduced by means of particle shower simulations. In this study, we use the FLUKA Monte Carlo code [5–7] for calculating the BLM response along the beam line in IR6 and IR7, respectively. The FLUKA geometry model of IR7 includes a detailed description of primary and secondary collimators (called TCPs and TCSGs), shower absorbers (TCLAs) and magnets. The IR6 model consists of three about 3 m long extraction protection absorbers (TCDQ), a secondary collimator (TCSP), shower masks and adjacent superconducting quadrupoles (Q4, Q5). As source term for the shower simulations, we used the spatial distribution of proton impacts on collimators and absorbers obtained with the SixTrack-FLUKA coupling code [8–11]. The loss rate in the two insertion regions was then determined by scaling independently the calculated BLM signal pattern in IR6 and IR7 until it matched the measurements (least square method). A similar method has been used previously to determine cumulative proton losses in Run 2 [12].

RELATIVE HALO LEAKAGE TO THE EXTRACTION REGION

Representative physics fills with a high number of proton bunches (>1000) were investigated for the different operational years of Run 2. BLM measurements with a time resolution of 1.3 s were used. For each fill, we chose a few selected loss peaks at 6.5 TeV (one per operational phase). For each peak, the maximum proton loss rate in both IR7 and IR6 was reconstructed by comparing FLUKA simulations with the measured BLM signal pattern. This method allowed to obtain f_{IR6} for the different events, covering halo loss rates $\dot{N}$ from 10^7 to almost 10^{11} protons/s. Figure 2 presents the reconstructed f_{IR6} values as a function of $\dot{N}$ for the different operational years. Events on beam 1 (clockwise rotating beam) are shown in blue, while events on beam 2 (anti-clockwise rotating beam) are in red.

A clear trend can be observed for every year, indicating that f_{IR6} decreases with $\dot{N}$. The remaining dispersion of the data for a given loss rate could be due to different machine configurations. For loss rates $\dot{N} > 10^{10}$ protons/s, f_{IR6} generally remains below 10^{-3}, except for 2015. The higher leakage in 2015 can possibly be attributed to different collimator settings. The half-gaps of different IR6 and IR7 collimator families are specified in Table 1 (expressed as multiples of beam σ) [13]. The relative retraction of secondary collimators with respect to the primary collimators in IR7 was reduced over the years. The same applied to the protection absorbers in IR6 (TCDQ and TCSP), which were typically placed one sigma further from the beam than the secondaries in IR7.

Lifetime drops with peak collision rates of $\dot{N} > 10^{10}$ protons/s were generally scarce in Run 2. The highest loss rate occurred during a controlled beam loss experiment probing the quench level of magnets in the DS next to IR7. This quench test, carried out in 2015, was performed on beam 2 with a 585 kW maximum power loss at 6.5 TeV, correspond-

Table 1: Collimators Half-Gaps for Different Operational Years in Run 2 and for HL-LHC. Values are Expressed as Multiples of the Transverse Beam Sigma at the Collimator. Settings are Given for a Normalized Transverse Emittance of ε = 3.5 μm.

[σ]	2015	2016	2017	2018	HL-LHC
TCP7	5.5	5.5	5	5	5.7
TCSG7	8	7.5	6.5	6.5	7.7
TCLA7	14	11	10	10	10.7
TCDQ6/ TCSP6	9.1	8.3	7.3	7.3	8.5

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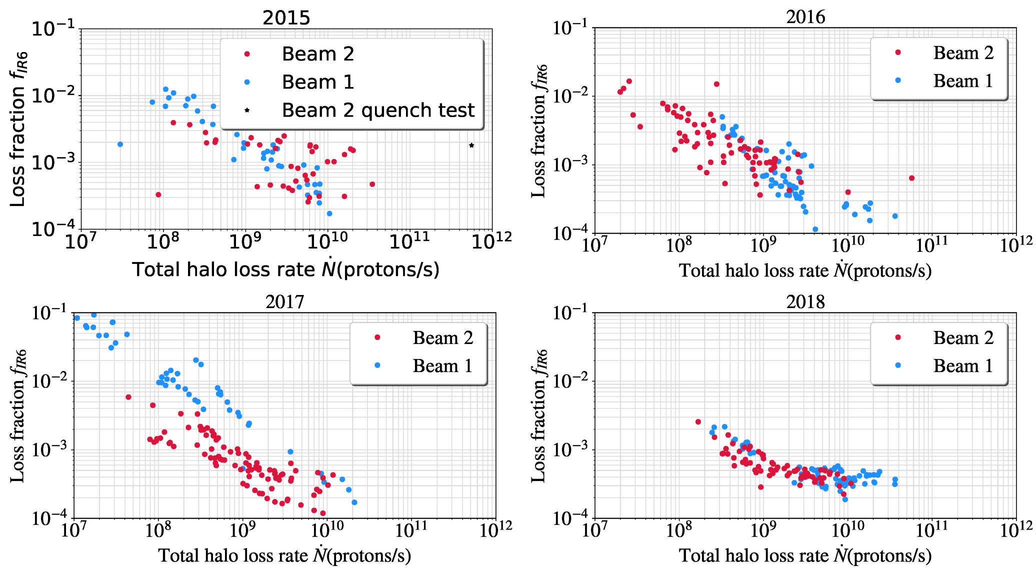

Figure 2: Analysis of proton leakage from IR7 to IR6 during high loss events in Run 2.

ing to a loss rate of 5.6×10^{11} protons/s [14]. The collimator settings were the same as in regular 2015 operation. The estimated fraction f_{IR6} of protons leaking to IR6 was about 2×10^{-3} in this case (see Fig. 2).

POWER DEPOSITION IN IR6 MAGNETS

In order to estimate the risk of quenching superconducting quadrupoles downstream of the protection absorbers in IR6, FLUKA simulations of the halo-induced secondary showers were performed. The spatial impact distribution on the absorbers was obtained with coupled Sixtrack-FLUKA simulations (for HL-LHC optics version 1.3). Figure 3 presents the longitudinal peak power density profile in the inner coils of the first magnet (Q4) downstream of the absorbers. Since the heat deposited by showers can spread across the coils, the power density has been averaged over the radial cable thickness (8.5 mm). The results shown in the figure correspond to different fractions f_{IR6} of the HL-LHC design loss rate of $\dot{N}_{max}$ = 8.8 × 10^{11} protons/s. For comparison, the figure also includes the estimated quench level derived by means of electro-thermal simulations [15].

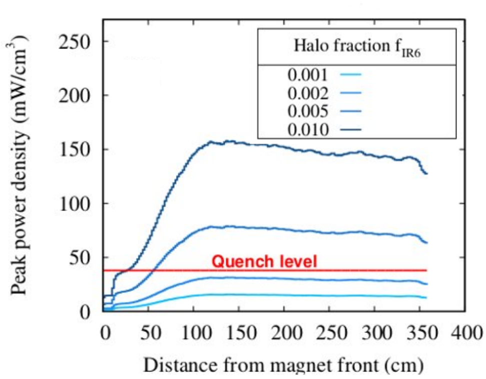

Figure 3: Peak power density in the coils of the Q4 magnet (IR6) for a 0.2 h beam lifetime in HL-LHC. Results were normalized to different halo fractions f_{IR6}.

The simulations indicate that the Q4 quench level would be exceeded for $f_{IR6} > 2 \times 10^{-3} - 3 \times 10^{-3}$. Similarly for the Q5 magnet, located 30 m away from the Q4, the quench level would be reached for $f_{IR6} > 10^{-3}$. Contrary to the Q4 magnet, the Q5 magnet is not protected by shower-absorbing masks. The global trend observed in Fig. 2 for the different years of Run 2 seems to indicate that f_{IR6} might not reach 10^{-3} for a halo loss rate $\dot{N}$ of 8.8 × 10^{11} protons/s. The only exception is 2015, when the collimator settings were less tight. We thus conclude that in case of a 0.2 h beam lifetime in HL-LHC operation, the risk of quenches in IR6 might be manageable through appropriate collimator settings.

CONCLUSIONS

This empirical study indicates that the fraction of beam protons leaking from the LHC betatron cleaning insertion to other locations depends on the absolute loss rate $\dot{N}$. This phenomenon has been studied in detail for halo particles intercepted by protection absorbers in the beam dumping insertion. Preliminary investigations for other regions, such as the dispersion suppressor next to IR7 (not presented in this paper), resulted in similar findings. These observations could potentially be explained by an enhanced absorption in the betatron cleaning system due to a larger impact parameter on primary collimators resulting from an increased diffusion speed in high loss events. Tracking studies and beam loss experiments are needed to further investigate this phenomenon. Nevertheless, this study indicates the risk of quench in IR6 seems acceptable in case of a 0.2 h beam lifetime for HL-LHC since collimator settings can be used as a mitigation measure.

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