THE EFFECT OF A PARTIALLY DEPLETED HALO ON THE CRITICALITY AND DETECTABILITY OF FAST FAILURES IN THE HL-LHC*

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Abstract

In the High Luminosity LHC (HL-LHC) era, the bunch intensity will be increased to 2.2×10^{11} protons, which is almost twice the nominal LHC intensity. The stored energy in each of the two beams will increase to 674 MJ. The HL-LHC will feature beams whose transverse halos are partially depleted by means of a hollow electron lens. The reduced stored energy in the beam tails will significantly change the development of losses caused by failures. This paper reports on beam tracking simulations evaluating the effect of a partially depleted halo on the criticality and detection of failures originating from the superconducting magnet protection systems. In addition, the effect of the transverse damper operating as a coherent excitation system leading to orbit excursions on a beam with a partially depleted halo is discussed. The results in terms of time-dependent beam losses are presented. The margins between the failure onset, its detection, and the time to reach critical loss levels, are discussed. The results are extrapolated to failure cases of different origins that induce similar beam loss dynamics.

INTRODUCTION

The levelled luminosity of the CERN Large Hadron Collider (LHC) will be increased to $5 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ [1] following the High Luminosity upgrade. The higher bunch intensity will in turn increase the stored beam energy to 674 MJ for the nominal parameters for each of the two beams, see Table. 1. This will have an important impact on machine protection systems which must safely extract the beams before uncontrolled losses could induce damages to the machine equipment. The HL-LHC project also features an upgrade of the multi-stage collimation system to include a Hollow-Electron Lens (HEL) to reduce the transverse beam halo population [2]. This reduced beam halo density will impact the dynamics of the beam losses induced by fast failure scenarios [3]. Dedicated beam tracking simulations have been carried out to evaluate the criticality and detectability of occurrences of fast failures with depleted transverse beam halos [3, 4].

The following magnet protection system related scenarios are presented: the discharge of quench heater circuits with circulating beams, and the spurious discharge of a Coupling Loss Induced Quench (CLIQ) unit [5]. Next is the impact on the beam of a symmetric quench of one of the triplet magnets on the beam. An occurrence of such an event during Run II with fast propagation of the normal-conducting zone is taken as a typical case for such a failure mode and extrapolated to HL-LHC parameters [6]. Finally, the coherent excitation of the beam with the transverse damper is studied.

For all these cases, the time dynamics of the beam losses for these fast failure cases are simulated in detail to derive specifications for the interlock mechanisms to be developed to protect against such failures and machine protection requirements for the safe operation of HL-LHC with depleted transverse beam halos.

MODELING OF DEPLETED TRANSVERSE HALO

All simulations use the HL-LHC lattice V1.4 configured with the most critical optics settings for round beams, as shown in Tab. 1. The baseline collimation scenario with the primary collimators (TCPs) cut set at 6.7 σ is considered.

Table 1: Machine and Beam Parameters for the Squeezed HL-LHC Optics (as used in the simulations)

Parameter	HL-LHC
Energy	7 TeV
Stored beam energy	674 MJ
Bunch intensity (2736 bunches)	$2.2 \times 10^{11}\ p^+$
Normalized emittance	2.5 µm
β^* at IP1-5	15 cm
Crossing angle at IP1-5	500 µrad
Primary collimator (TCP) cut	6.7 σ
HEL inner radius	4.7 σ

The model of the transverse beam distribution is based on Run II beam scraping measurements performed to characterize the distribution and its halo up to the primary collimators [7]. A fit on the measurement characterizes the transverse distribution as the sum of two weighted Gaussian distributions which have been extended to form the radial distribution over the 4D normalized transverse phase space. To account for the halo depletion induced by the HEL, this distribution function is modified by a decreasing exponential function within the HEL active radii - from the inner radius of the electron beam up to ρ_{TCP}, the radius at which the primary collimators are set - and then re-normalized. The halo depletion factor η represents the relative depletion in the halo. Here $\eta = 0$ implies a non-depleted halo. The resulting density projected on the horizontal displacement axis x is shown in Fig. 1 for different values of η. It should be noted that for a depleted halo the population is decreased at lower

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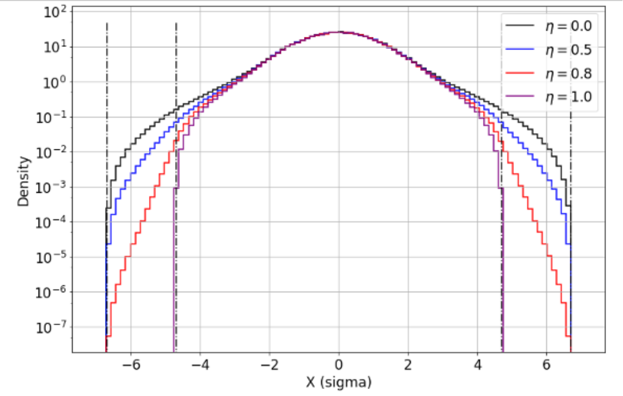

Figure 1: Beam density projected on the horizontal x axis. The halo depletions for different values of the halo depletion parameter η are shown. The inner amplitude of the HEL at 4.7 σ is shown (dotted vertical line). The amplitude of the primary collimators at 6.7 σ is also shown.

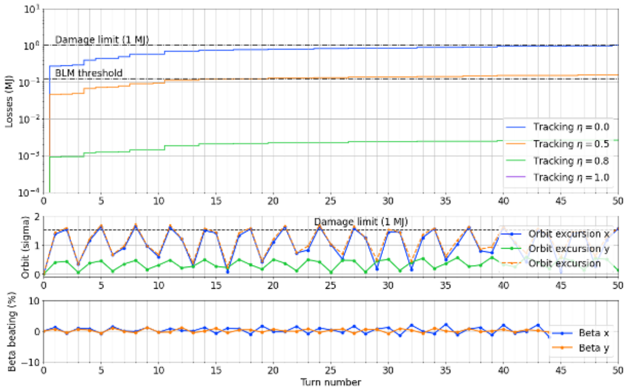

Figure 2: Beam losses (top), orbit excursion (middle) and β-beating (bottom) simulated for the spurious discharge of the most critical quench heater circuit on the D1 magnet. The beam losses are shown for multiple values of the halo depletion parameter η.

radii due to the projection effect from the 4D phase-space, although the HEL only acts at radii larger than 4.7 σ.

In the simulations, the distribution is sampled uniformly inside a 4D hypersphere with a radius equal to ρ_{TCP}. A weight is associated to each particle during the analysis of the tracking data, allowing to reduce the statistical error and the results to be recomputed for different values of η.

BEAM IMPACT OF SUPERCONDUCTING MAGNET PROTECTION SYSTEMS FAILURES

Key components of the quench protection system of the HL-LHC triplet circuits [1, Chapter 3] around the low-β experiments Atlas and CMS are quench heaters and the novel Coupling Loss Induced Quench (CLIQ) system [1, Chapter 7]. Due to the large β-functions and beam offsets in the triplet areas the impact of the triggering of these systems on the circulating beam has to be carefully studied. The quench detection system will nominally fire the quench heaters and trigger the discharge of the CLIQ units only after triggering a beam dump. However, the spurious discharge of either system with circulating beams cannot be excluded and is, thus, considered as a fast failure case. A detailed account of the critical CLIQ fast failure case is provided in [5] and was found to be the fastest and most critical failure scenario for HL-LHC, for all levels of halo depletion. This triggered the development of a dedicated fast detection mechanism of the spurious current discharge.

For the spurious discharge of a single quench heater circuit, all LHC and new HL-LHC circuits have been considered: the main dipoles, the 11 T dipoles, the separation and recombination superconducting dipoles D1 and D2, and the triplet circuits in IP1 and 5. The magnetic field resulting from the specific configuration of the quench heater circuit was computed in static conditions using Biot-Savart. Multiple quench heater circuits protect a given magnet and for each magnet, the discharge of a single circuit was considered. The worst cases, in terms of induced kick on the beams, of each magnet type were identified, then multi-particle tracking simulations were performed to obtained the time-dependent beam losses. Overall, the most critical case, shown in Fig. 2 for the losses as a function time, orbit excursion and β-beating, is the new HL-LHC D1 [8], followed by the triplets and D2 [9]. The field induced by the quench heater discharge is static, leading to a sudden displacement of the closed-orbit and to an oscillation of the orbit excursion. This results in a sudden jump in beam losses, followed by a slow increase. In case of the D1, for non-depleted halo the critical loss level of 1 MJ is reached asymptotically. Negligible β-beating is observed. It should be noted that in case of the D1 and D2, the simultaneous firing of all quench heater circuits would be less critical for the circulating beam due to symmetry effects from the connection schemes, resulting in partial cancellation of the induced magnetic fields. We conclude that this fast failure is not critical even for depleted halos as sufficient margin is available between triggering the BLMs and reaching the critical loss level. The halo depletion is beneficial in this case, as it prevents reaching the critical loss level even for small values of the depletion factor.

SYMMETRIC TRIPLET QUENCH

While superconducting magnet quenches are usually not critical in terms of machine protection due to their fairly slow development (10s of milliseconds), occurrences of quenches with fast normal-zone propagation have been identified and observed already during Run II [6]. The effect is amplified by the very large β-function and crossing angle bump at the location of the triplet magnets, even more so for the HL-LHC parameters. Magnet simulations were adjusted to the HL-LHC triplet magnet with assumptions on the propagation speed of the quench matching the Run II event [10]. To evaluate the criticality and detectability of this failure case

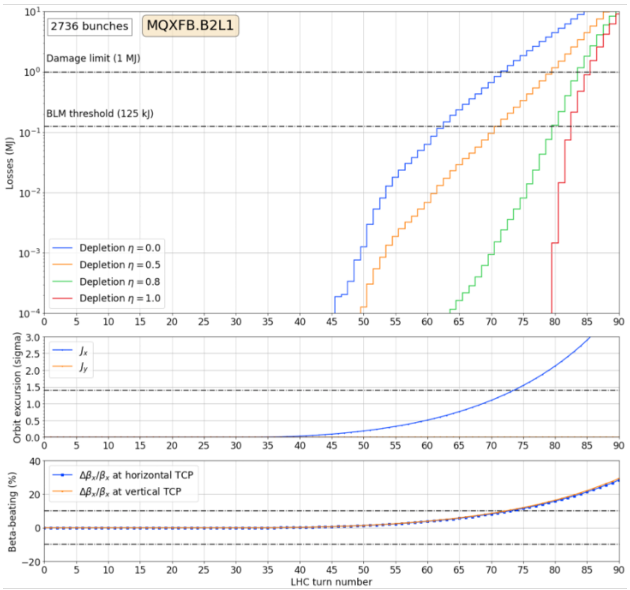

Figure 3: Beam losses (top), orbit excursion (middle) and β-beating (bottom) for the symmetric triplet quench case.

for the HL-LHC era with depleted halos, a new tracking simulation campaign was carried out.

The worst triplet magnet was identified to be MQXFB.B2L1, left of the Atlas experiment with the results shown in Fig. 3. The field change is initially slow and then increases quickly, as seen by the effect on all three sub-figures. The losses are directly correlated with the orbit excursion increase, while no significant β-beating is present before reaching the critical loss level. The critical loss level is reached in 72 turns for non depleted halo and in 85 turns for fully depleted halo. A critical parameter is the margin between reaching the BLM detection level and the critical loss level. For non-depleted halo, the BLM losses provide sufficient margin (10 turns). However, despite the slow growth rate, the case of 80% halo depletion is critical as only a 2-turn margin is available. A halo depletion of 50% restores a 5-turn margin, which is sufficient for the BLM interlock to safely dump the beams. This puts a clear limit on a total halo depletion level which should not exceed 50%, either on a bunch-by-bunch basis with $\eta \leq 0.5$ or keeping a fraction of so-called "witness" bunches with no depletion.

FAST BEAM LOSSES FROM COHERENT BEAM EXCITATION

The transverse damper (ADT) provides an operational mode to coherently excite individual bunches. Given the available voltage and the number of affected bunches, this is a potential fast failure leading to beam losses within few milliseconds. With the coherent excitation switched on and the usual damping mode activated, the orbit excursion will follow a linear increase at small amplitudes, which will flatten out at higher amplitudes. This model is also applicable in case of other sources of coherent beam excitation, with the transverse damper always providing the damping mechanism.

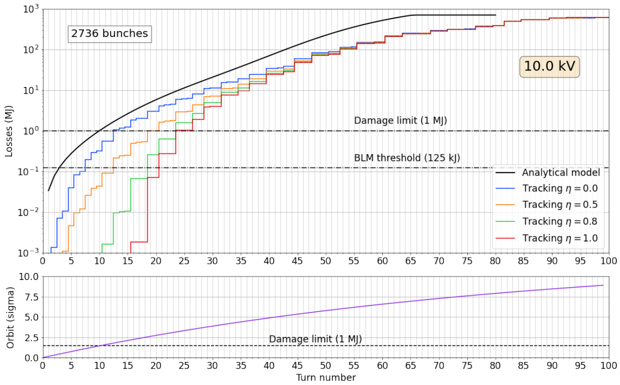

Figure 4: Beam losses (top) and orbit excursion (bottom) for the case of the coherent excitation provided by the ADT. The beam losses match closely the analytical estimate. It is visible that the halo depletion reduces the margin between reaching the BLM threshold and the critical loss level.

The tracking results shown in Fig. 4 are in good agreement with the analytical estimates where the losses are estimated from the orbit excursion using a rigid beam model. For the maximum voltage (10 kV), fast losses are observed and the beneficial impact of the depleted halos is clearly visible. The results are shown for a full machine (2736 bunches). Extending the results to a variable number of bunches with the requirement that there is a sufficient margin between the detection of the beam losses with the BLMs and reaching critical losses, results in the allowed operation of the ADT in coherent excitation mode to be limited to a window of 480 bunches. Additionally, similar results obtained at injection energy (450 GeV) required that the available voltage at injection be limited to 5 kV.

CONCLUSION

A parametric beam model for partially depleted halo has been derived and used extensively in beam tracking simulations to evaluate the criticality and timely detectability of fast failures in the HL-LHC. The effect of magnet protection systems on circulating beams has been quantified in detail. In particular, the spurious CLIQ discharge has been identified as the fastest and most critical failure for HL-LHC and for all levels of halo depletion. The effect of quench heater discharge has been found to be significantly less critical, with the most critical case being the new superconducting separation dipole (D1). In that case the depleted halo provides a beneficial effect. The case of symmetric quench with fast propagation of the normal-conducting zone on the triplet magnets has been analyzed and shown to be critical in case of important halo depletion. Finally, the case of the transverse damper has been studied, leading to a recommendation on the length of the excitation and excitation voltage to be used.

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