ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB001

POWER DEPOSITION IN SUPERCONDUCTING DISPERSION SUPPRESSOR MAGNETS DOWNSTREAM OF THE BETATRON CLEANING INSERTION FOR HL-LHC*

A. Waets†, C. Bahamonde Castro, E. Belli, R. Bruce, N. Fuster-Martínez, A. Lechner, A. Mereghetti, S. Redaelli, M. Sabaté-Gilarte, E. Skordis, CERN, Geneva, Switzerland

Abstract

The power deposited in dispersion suppressor magnets downstream of the Large Hadron Collider (LHC) betatron cleaning insertion is governed by off-momentum particles scattered out of the primary collimators. In order to mitigate the risk of magnet quenches during periods of short beam lifetime in future High-Luminosity (HL-LHC) operation, new dispersion suppressor (DS) collimators are being installed (one per beam). In this paper, we present FLUKA simulations for both protons and Pb ions at 7 Z TeV, predicting the power deposition in the DS magnets, including the new higher-field dipoles (11 T) which are needed to integrate the collimator in the cold DS region. The simulated power deposition levels for the adopted HL-LHC collimator configuration and settings are used to assess the quench margin by comparison with the present estimated quench levels.

INTRODUCTION

The CERN Large Hadron Collider (LHC) [1] is designed to collide proton beams with a center-of-mass energy of 14 TeV and $^{208}Pb^{82+}$ ions with a center-of-mass energy per colliding nucleon pair of 5.52 TeV. The HL-LHC upgrade aims to reach an integrated luminosity of 3 000 fb^{-1} for protons ten years after the upgrade, a factor ten beyond the expected LHC data set, and 13 nb^{-1} for Pb ions up to the end of Run 4 [2]. To achieve this, higher intensity, low emittance beams will be used nearly doubling the amount of stored beam energy currently achieved in the accelerator for protons (up to 700 MJ) and reach roughly five times the LHC design intensity for ions (up to 20.5 MJ). The current collimation system [1, 3] will be upgraded to provide adequate protection for the superconducting magnets in all design beam loss scenarios for the HL-LHC beam parameters [4]. This paper focuses on the potential performance limitation set by collimation debris leaking out of the IR7 betatron cleaning insertion and getting lost in the neighbouring dispersion supressor (DS), potentially causing magnet quenches. During proton and ion operation, the main culprits are single-diffractive (SD) protons and ion fragments respectively which predominantly originate from inelastic collisions in the primary collimators. First, the baseline upgrades of the collimation system in IR7 and the DS relevant for this study are briefly summarized, serving as a basis for the power deposition simulations performed with a multi-step simulation approach, involving SixTrack [5, 6] and the Monte Carlo tool FLUKA [7–9]. Next, the assumed HL-LHC beam loss scenario is detailed, along with a concise overview of the simulation workflow. The power deposition simulation results for proton and ion beams are discussed.

COLLIMATION SYSTEM UPGRADES IN THE BETATRON CLEANING INSERTION

The present collimation system installed in the LHC has performed very well over the course of Run 1 (2009 - 2013) [10] and Run 2 (2015 - 2018) [11] with no halo-induced magnet quenches for nominal operation with both proton and ion beams. It features a dedicated momentum cleaning insertion located in IR3, a betatron cleaning insertion in IR7 and local protection collimators in other IRs [12]. The highest losses in cold magnets in Runs 1 and 2 were located in the DS next to IR7 [10, 13]. This location poses the biggest challenge for HL-LHC in terms of avoiding superconducting magnet quenches. The betatron cleaning insertion IR7 is organised as follows: CFC (carbon-fibre-carbon) primary collimators (TCP) intercept beam halo particles in three planes (vertical, horizontal and skew), a series of CFC secondary collimators (TCSG) intercept beam particles scattered out by the TCPs and secondary particle showers, and tungsten shower absorbers (TCLA) intercept shower products further downstream [4]. Only the HL-LHC modifications expected to directly affect the localized cold losses in the IR7 DS magnets are listed here.

Low-Impedance Collimator Material

For HL-LHC the beam intensity will be doubled to meet the physics needs, requiring a reduction of the machine's impedance to ensure the coherent stability of the beams. The LHC impedance budget at top energy is dominated by the contribution of the collimators [14]. Of the current CFC collimators, 2 out of 3 primary (TCP) and 9 out of 11 secondary (TCSG) collimators will be replaced by low-impedance Molybdenum-Graphite (MoGR) primary (TCPPM) and Molybdenum-coated MoGR (TCSPM) secondary collimators.

Dispersion Supressor (DS) Collimation

To better clean the off-momentum collimation products from proton and ion beams, an extra collimator (TCLD) per beam made of tungsten alloy will be placed in the DS next to IR7, where a regular 8.33 T dipole magnet will be replaced by two shorter 11 T dipole magnets (MBH) with the TCLD in between. An iterative study using SixTrack and FLUKA simulations yielded adequate cleaning performance

---

* Research supported by the HL-LHC project.

† andreas.waets@cern.ch

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB001

and minimal load on SC magnets for placing the assembly in Cell 9 [15–17]. A depiction of the upgraded DS configuration with respect to the current LHC layout is shown in Fig. 1.

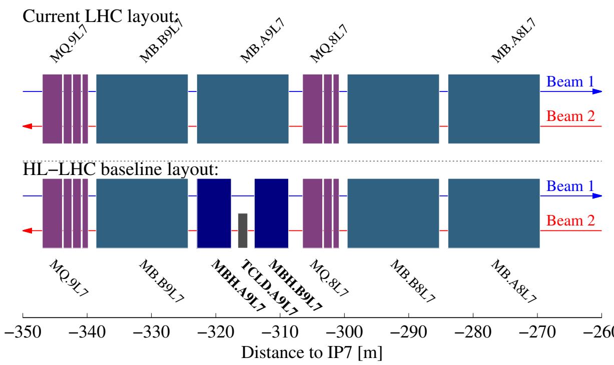

Figure 1: Illustration of the DS layout left of IR7 for the current LHC machine (top) and the HL-LHC baseline (bottom). One dipole (MB) magnet in Cell 9 will be replaced by two shorter 11 T (MBH) dipoles with in between the TCLD collimator on Beam 2 left of IR7. The mirrored configuration is found right of IR7 with the TCLD on Beam 1.

SIMULATION WORKFLOW AND HL-LHC BEAM LOSS SCENARIO

To assess the effect of losses in the DS the following approach is used: First, the spatial distribution of primary halo impacts on collimators is calculated using the SixTrack-FLUKA coupling [18] with HL-LHC optics version 1.2 assuming a nominal 2 σ secondary collimator retraction for protons and 1 σ for ions (Table 1) in IR7. We assume that all primary losses occur on the horizontal TCP, known to be the worst-case for collimation cleaning efficiency [16]. Second, high-energy particles emerging from these impacts or from consecutive showers are tracked in FLUKA until they are lost in the aperture [18]. Finally, a separate high-precision simulation of the DS region calculates the power deposition in the cold magnets. An accurate geometric model is used, including all mentioned updates.

Table 1: Collimator Half-Gap Settings (in Units of σ Wrt the Normalized Emittance ϵ^*) for HL Optics Versions Used

HL optics ϵ^* [µm]	v1.2/v1.3 2.5 protons	v1.2 2.5 ions
TCP	6.7	6
TCS	9.1	7
TCLA	11.9	10
TCLD	16.6	14

The power deposition in the magnets determines whether a magnet will quench when assuming a certain loss scenario. Since the collimation system is required to cope with the full design rates of beam loss during normal operation without quenches, the simulation results are therefore expressed in terms of a worst-case beam lifetime (BLT) of 0.2 h to be sustained for 10 s, the LHC design limit [4]. For HL-LHC beams this corresponds to loss rates of 8.81×10^{11} protons/s (2800 bunches with 2.3×10^{11} particles/bunch) and 3.64×10^{8} ions/s (1250 bunches with 2.1×10^{8} particles/bunch) [17].

POWER DEPOSITION IN DS MAGNETS

The combination of FLUKA power deposition simulations, electro-thermal simulations and several dedicated experiments during LHC Runs 1 and 2 have improved the understanding of magnet quench levels [19]. Assuming steady-state losses at 7 Z TeV for 10 s and a radially averaged power density profile in the magnet coils, these amount to 20 mW/cm^3 for the regular LHC dipole magnets (surpassed without TCLD collimator in HL [17]) and 40 mW/cm^3 for the quadrupoles. The better performance of Nb_3Sn coils compared to the Nb-Ti coils of the regular dipoles for slow losses sets the expected quench limit for the 11 T dipole to 70 mW/cm^3 [20]. FLUKA simulations of power deposition in the IR7 DS have been benchmarked against beam loss monitor (BLM) signals measured during controlled beam loss tests [21, 22]. The simulation results underestimated measurements by a factor of three, attributed to the absence of imperfections in the simulation model leading to a higher leakage of particles to the DS. We hence apply a factor of three on top of all results presented below. All results are summarized in Table 2 and the statistical uncertainties are estimated to be a few mW/cm^3 at maximal values.

Table 2: Radially Averaged Peak Power Deposition Values (Units of mW/cm^3) in the 11 T (MBH), Dipole (MB) and Quadrupole (MQ) SC Coils for the Cases Simulated As Function of Collimator Material and Optics

		Protons (8.81×10^{11} s^{-1})			**Ions (3.64×10^{8} s^{-1})**		
		MBH	**MB**	**MQ**	**MBH**	**MB**	**MQ**
v1.2 (B2)	**CFC**	50	6.5	6.4	32.5	6.5	2
	MoGR	35.5	6	5	33.5	6	3.5
v1.3 (B1)	**MoGR**	31.5	5.8	5	N/A		
	MoGR 2 mm bump	27	7.1	2.9			
	MoGR 2 mm bump, 1 mm tilt	22	5.7	1.5			

Proton Beams

Radially averaged peak power deposition values in the SC magnet coils on beam 2 (left of IR7) are shown in Fig. 2. The highest load is encountered in the MBH.B9 magnet, the 11 T dipole upstream of the TCLD. Studying the effect of the primary collimator material, a reduction of the peak load in the MBH from 50 mW/cm^3 for CFC to 35.5 mW/cm^3 for

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB001

MoGR is observed, mainly attributed to the higher-density of the MoGR, affecting the inelastic nuclear interaction probability. The power deposition in the 11 T dipole coils is dominated by single-diffractive (off-momentum, small angle) protons scattering off the TCPs and lost in the DS due to the elevated dispersion. In general, the power deposition values for the other cold magnets remain well below quench limits.

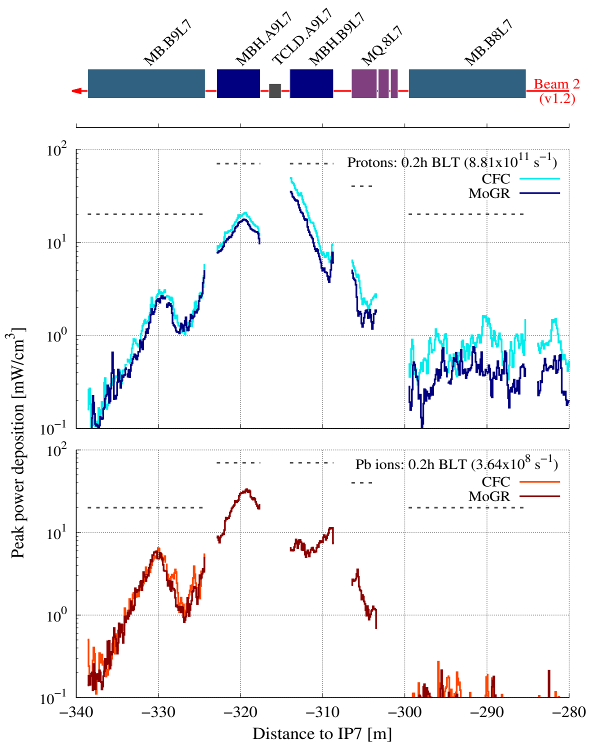

Figure 2: Radially-averaged peak power deposition [mW/cm^3] in the cold DS magnet coils along beam 1 for protons (top) and Pb ions (bottom) with 0.2 h BLT, comparing the use of CFC and MoGR collimators. Dashed lines indicate the respective estimated magnet quench levels.

The simulated peak power deposition is between a factor 1.5 and 2 lower than the magnet quench limit for CFC and MoGR collimators, respectively. Since the 11 T quench level could not be tested experimentally yet in controlled beam loss experiments, an increased margin with respect to the theoretical quench level is still desirable, in particular at the localized loss peak found in the 11 T dipole upstream of the TCLD collimator, caused by SD protons hitting the inner edge on the downstream end. As suggested in [23], a proposed loss mitigation strategy consists of implementing a closed local orbit bump of 2 mm amplitude at the most loaded 11 T dipole by using three corrector magnets. In addition, the TCLD jaws are re-centered over the new orbit and both 11 T magnets are shifted by 1 mm towards the center of the accelerator. Assuming this new configuration and MoGR collimators, peak power deposition values in the SC magnet coils were calculated for 0.2 h BLT of beam 1 (right of IR7) for HL-LHC optics v1.3 (see Table 1), for proton beams only. In the upstream 11 T, a reduction from 31.5 mW/cm^3 to 27 mW/cm^3 is observed when comparing peak values without and with the orbit bump. Applying a 1 mm tilt of the upstream 11 T, shifting the exit aperture away from the nominal beam trajectory, further reduces the peak power to 22 mW/cm^3. All results are shown in Fig. 3 and summarized in Table 2. A good agreement between beam 1 and beam 2 results is observed, given the very similar absolute half-gaps between optics versions 1.2 and 1.3.

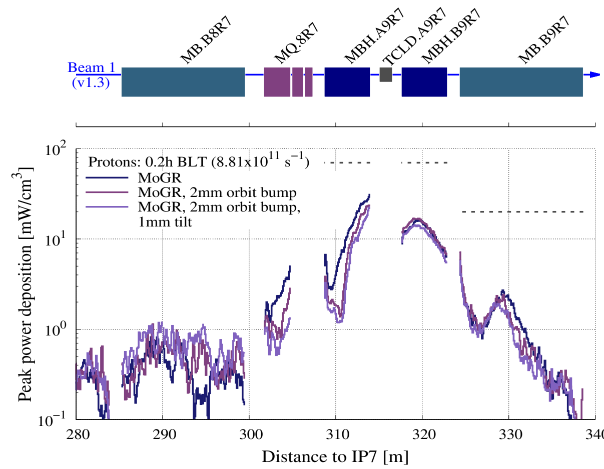

Figure 3: Radially averaged peak power deposition [mW/cm^3] in the cold DS magnet coils along beam 1 for protons with 0.2 h BLT, comparing the cases without an orbit bump and a 2 mm orbit bump with and without an additional 1 mm shift. Dashed lines indicate the respective magnet quench levels.

Ion Beams

Peak power deposition from $^{208}Pb^{82+}$ ion beam losses for the same beam lifetime (0.2 h) are of the same order of magnitude for dipole and quadrupole magnets as for protons, as shown in Fig. 2. As a result of nuclear fragmentation and electromagnetic dissociation of halo ions impacting on the primary collimator, particles reaching the DS have different charge-to-mass ratios with respect to the primary beam particles and hit the aperture [24]. Including the TCLD [17] at the same halfgap as for protons, the highest peak power load is now located downstream of the collimator, caused by secondary ion fragments from the TCLD itself. The peak load on the upstream MBH is reduced by a factor of 2 with respect to proton operation.

CONCLUSION

Power deposition in the superconducting coils of dispersion suppressor magnets downstream of the LHC betatron collimation cleaning insertion were calculated using FLUKA. Taking into account the planned layout configuration for the HL-LHC upgrade and a worst-case beam lifetime scenario, the values remain well below the expected quench limits for nominal proton and Pb ion beams. During proton operation, a local orbit bump combined with an intentional shift of the magnet aperture can further reduce the peak power deposition in the most loaded 11 T magnet, increasing the margin with respect to the estimated quench level.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB001

REFERENCES

[1] L. Evans and P. Bryant, "LHC machine", *Journal of Instrumentation*, vol. 3, no. 08, p. S08001, Aug. 2008. doi:10.1088/1748-0221/3/08/s08001

[2] R. Bruce *et al.*, "HL-LHC operational scenarios for Pb-Pb and p-Pb operation", CERN, Geneva, Switzerland, Rep. CERN-ACC-2020-0011, Jul. 2020.

[3] R. W. Assmann *et al.*, "The Final Collimation System for the LHC", in *Proc. 10th European Particle Accelerator Conf. (EPAC'06)*, Edinburgh, UK, Jun. 2006, paper TUODFI01, pp. 986–988.

[4] S. Redaelli, R. Bruce, A. Lechner, and A. Mereghetti, "Chapter 5: Collimation system", in *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*, Geneva, Switzerland: CERN, 2020, pp. 87–114.

[5] G. Robert-Demolaize, R. W. Assmann, S. Redaelli, and F. Schmidt, "A New Version of SixTrack with Collimation and Aperture Interface", in *Proc. 21st Particle Accelerator Conf. (PAC'05)*, Knoxville, TN, USA, May 2005, paper FPAT081, pp. 4084–4086.

[6] SixTrack – 6D Tracking Code, http://sixtrack.web.cern.ch

[7] FLUKA, https://fluka.cern/.

[8] G. Battistoni *et al.*, "Overview of the fluka code", *Annals of Nuclear Energy*, vol. 82, pp. 10–18, Aug. 2015. doi:10.1016/j.anucene.2014.11.007

[9] T. Böhlen *et al.*, "The FLUKA Code: Developments and Challenges for High Energy and Medical Applications", *Nuclear Data Sheets*, vol. 120, pp. 211–214, Jun. 2014. doi:10.1016/j.nds.2014.07.049

[10] B. Salvachua *et al.*, "Cleaning Performance of the LHC Collimation System up to 4 TeV", in *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13)*, Shanghai, China, May 2013, paper MOPWO048, pp. 1002-1004.

[11] D. Mirarchi *et al.*, "Collimation: experience and performance", in *Proc. 7th Evian Workshop on LHC beam operation*, Evian Les Bains, France, Dec. 2016, pp. 105-112.

[12] S. Redaelli, "Beam Cleaning and Collimation Systems", in *Proc. 2014 Joint Int. Accelerator School: Beam Loss and Accelerator Protection*, Newport Beach, CA, USA, Nov. 2014, pp. 403–437. doi:10.5170/CERN-2016-002.403

[13] R. Bruce *et al.*, "Beam losses, lifetime and collimator hierarchy", presented at the 8th LHC Operations Evian Workshop, Evian Les Bains, France, Dec. 2017, unpublished.

[14] S. A. Antipov *et al.*, "Low-Impedance Collimators for HL-LHC", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 1794-1797. doi:10.18429/JACoW-IPAC2018-WEYGBE4

[15] R. Bruce, A. Marsili, and S. Redaelli, "Cleaning Performance with 11T Dipoles and Local Dispersion Suppressor Collimation at the LHC", in *Proc. 5th Int. Particle Accelerator Conf. (IPAC'14)*, Dresden, Germany, Jun. 2014, pp. 170-173. doi:10.18429/JACoW-IPAC2014-MOPRO042

[16] A. Lechner *et al.*, "Power Deposition in LHC Magnets With and Without Dispersion Suppressor Collimators Downstream of the Betatron Cleaning Insertion", in *Proc. 5th Int. Particle Accelerator Conf. (IPAC'14)*, Dresden, Germany, Jun. 2014, pp. 112-115. doi:10.18429/JACoW-IPAC2014-MOPRO021

[17] C. Bahamonde Castro, "Energy deposition from collimation losses in the DS region at P7", presented at the 8th HL-LHC Collaboration Meeting, Geneva, Switzerland, Oct. 2018, unpublished.

[18] E. Skordis and V. Vlachoudis, "FLUKA coupling to Sixtrack", in *Proc. ICFA Mini-Workshop on Tracking for Collimation in Particle Accelerators*, Geneva, Switzerland, Oct. 2015, pp. 17–25. doi:10.23732/CYRCP-2018-002.17

[19] B. Auchmann *et al.*, "Testing Beam-Induced Quench Levels of LHC Superconducting Magnets", *Physical Review Special Topics - Accelerators and Beams*, vol. 18, no. 6, p. 061002, Jun. 2015. doi:10.1103/PhysRevSTAB.18.061002

[20] L. Bottura, "Quench performance and assumptions: Magnets and cryogenics", presented at the Int. Review of the HL-LHC Collimation System, Geneva, Switzerland, Feb. 2019, unpublished.

[21] E. Skordis *et al.*, "Study of the 2015 Top Energy LHC Collimation Quench Tests Through an Advanced Simulation Chain", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 100-103. doi:10.18429/JACoW-IPAC2017-MOPAB012

[22] A. Lechner *et al.*, "Validation of energy deposition simulations for proton and heavy ion losses in the cern large hadron collider", *Physical Review Accelerators and Beams*, vol. 22, no. 7, p. 071003, Jul. 2019. doi:10.1103/PhysRevAccelBeams.22.071003

[23] E. Belli, R. Bruce, M. Giovannozzi, A. Mereghetti, D. Mirarchi, and S. Redaelli, "Different approaches for minimising proton beam losses on the 11 T dipole in the IR7 dispersion suppressor", CERN, Geneva, Switzerland, Rep. CERN-ACC-NOTE-2021-0002, Jan. 2021.

[24] N. Fuster-Martínez, R. Bruce, J. M. Jowett, A. Mereghetti, D. Mirarchi, and S. Redaelli, "Performance of the Collimation System During the 2018 Lead Ion Run at the Large Hadron Collider", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 677-680. doi:10.18429/JACoW-IPAC2019-MOPRB050