IMPROVED PROTECTION OF THE WARM MAGNETS OF THE LHC BETATRON CLEANING INSERTION*

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Abstract

After the High Luminosity (HL) upgrade in 2024-2026, the LHC is anticipated to increase its integrated luminosity by a factor of 10 beyond its original design value of 300 fb^{-1}. In preparation for this, several improvements to the equipment will already be implemented during the next Long Shutdown (LS2) starting in 2019. In the betatron cleaning insertion, the debris leaking out of several collimators will deposit energy in the downstream warm magnets, causing long-term radiation damage. A new layout has been proposed in which the most exposed magnet of each assembly is removed, reducing the assembly from 6 to 5 magnet units and gaining 2 spare magnets. New absorbers are therefore required to enhance the shielding of the remaining magnet string. In this paper, we present an evaluation of the dose to the warm magnets for post-LS2 operation, and we quantify the achievable reduction of the long-term radiation damage for different absorber configurations. A solution for an improved magnet protection that fulfills the HL-LHC requirements is proposed.

INTRODUCTION

In LHC's Insertion Region 7 (IR7), the betatron cleaning of the beam is done through a multi-stage collimation system [1, 2]. The interaction of the beam with the collimator jaws produces particle showers that can deposit energy in sensitive accelerator components like magnets located downstream in the Long Straight Sections (LSS). Since both beams of the LHC undergo this cleaning, the described losses can be seen on both left and right sides of IR7. Because of this high radiation levels, superconducting magnets could not be installed close to the collimators, as there is a high risk that they would quench. Warm, i.e., non-superconducting dipoles (MBW), quadrupoles (MQW) and correctors are used instead, but their operating lifetime is still tightly related to the amount of radiation they receive. Long-term exposure to the high radiation levels of IR7 could damage the coils and their insulating resin as well as other sensitive parts of the magnets, what highlights the need to quantify the acceptable dose limits they could withstand. This is done through irradiation tests that measure the loss of properties of the magnet materials when exposed to ionizing radiation.

Under the scope of the HL-LHC upgrade, the integrated luminosity of the accelerator is anticipated to increase 10-fold. This requires an assessment of the dose levels that could be expected in IR7 in HL-LHC conditions, in order to ensure the limits determined by the irradiation tests are respected. Passive protection is already installed in this area but will not suffice to withstand HL-LHC conditions according to previous studies [3-5]. From all warm magnets accommodated in IR7, the most exposed ones are the MQWs installed in cell 5 left and right of IR7. In this paper, we present an estimation of the dose received by these MQWs if the current layout and shielding configuration were kept, and we quantify the achievable reduction of this dose if the layout was changed in LS2. Envisioned changes include the removal of one quadrupole per side and the installation of new tungsten masks and inserts in the magnets [6]. In addition, a new shielding design was also included to fulfill the HL-LHC requirements.

DOSE LIMITS AND BEAM LOSSES

The most recent irradiation tests performed in MQW materials show that the coils of the magnets would only present signs of moderate damage after receiving around 50 MGy of dose [7]. Nevertheless, the plastic spacers used to hold the four separate coils of the MQW in place are less radiation resistant and would already have signs of heavy damage when exposed to more than 10 MGy [7]. These dose limits are not to be surpassed over the whole HL-LHC era, in which the expected integrated luminosity is 3000 fb^{-1} [8].

In order to estimate the dose levels in IR7 for pre and post-LS2 layouts and to see if they comply with these experimental limits, FLUKA [9, 10] simulations were performed. Realistic geometry models of the IR7 tunnel, collimators, vacuum chambers and warm magnets were implemented in FLUKA [11] including the most sensitive parts such as the magnet coils and the plastic spacers between them. Figure 1 shows an overview of the IR7 warm section simulated for this study. The particle distribution reproducing the impacts on the jaws of the primary collimator, needed as an input for the FLUKA simulations, was produced using the FLUKA-SixTrack coupling [12-15] assuming a proton energy of 7TeV in collision settings, 40 cm β*, 205 μrad crossing angle and nominal collimator settings [16]. A 1-σ retraction between secondary and primary collimators, tighter than the present HL-LHC baseline [17], is used as a pessimistic scenario for the MQW losses.

All results presented in this paper are normalized assuming $1x10^{18}$ protons of collimation losses over the whole HL-LHC era, consistently with previous studies [5]. This estimate has been established in the first years of LHC operation, however more recent dosimeter measure-

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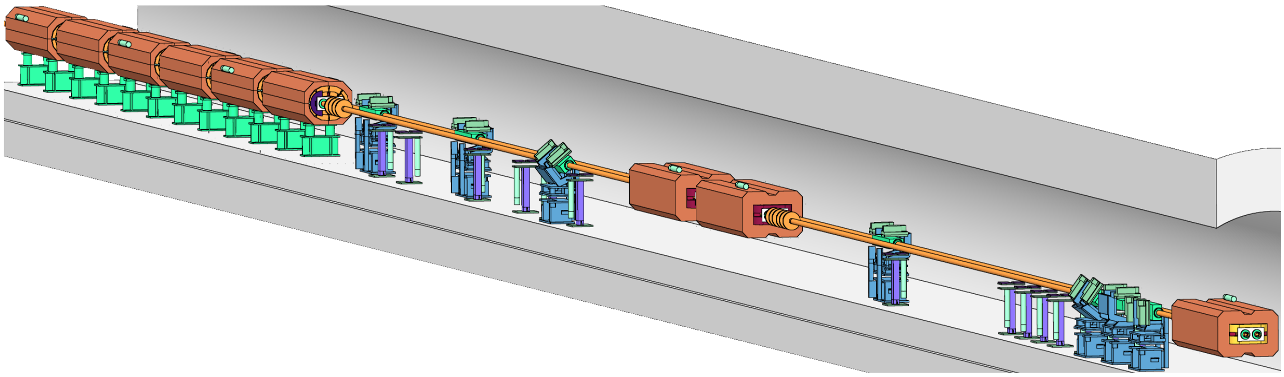

Figure 1: Overview of the FLUKA geometry of LHC's IR7 warm section used for this study.

ments carried out during the 2016 run indicate that this assumption is highly conservative. In the present study, the original value is still kept as the analysis of the measurements is still ongoing, but the simulation estimates will be updated once more accurate predictions of beam losses in the HL era become available.

CURRENT IR7 LAYOUT

The layout of cell 5 as currently installed on both sides of IR7 is shown in Figure 2, and will be maintained up to LS2 [18].

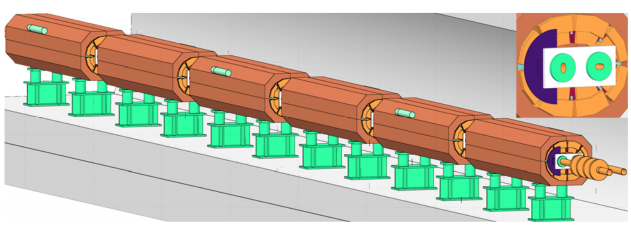

Figure 2: Present layout of the Q5 magnet, with 6 MQW module and a TCAPC passive absorber for the protection of incoming B1 losses.

In front of the string of MQWs there is a passive absorber (TCAPC.6), meant for protecting the magnets from some of the shower debris from the upstream collimators. In addition, the first and most exposed magnet (MQWA.E5) is equipped with a tungsten mask, installed in the front of the magnet, and tungsten inserts placed between the beam pipe and coils. The rest of the magnets in cell 5 do not presently have this protection. A detailed view of this mask can be seen in the top right corner of the figure.

Table 1 shows peak dose estimates in the coils and spacers of the different quadrupoles in cell 5, scaled up to 10^{18} protons lost in the collimation system.

Only the last magnet of the string would comply fully with the aforementioned material dose limits (50 MGy for the coils and 10 MGy for the spacers). Although the dose to the coils in MQWA.B5 would also be acceptable by these standards, the dose to the spacers is excessive, and in the rest of the magnets both the dose to the coils and to the spacers appears concerning for future operation. In order to meet the HL-LHC goals, some changes in the layout will therefore be necessary.

Table 1: Peak Dose Estimates for Present Layout of Cell 5 of LHC's IR7

	COILS (MGy)	SPACERS (MGy)
MQWA.E5	80	60
MQWA.D5	80	20
MQWA.C5	Not available	Not available
MQWB.5	60	20
MQWA.B5	40	20
MQWA.A5	40	10

POST-LS2 LAYOUT

Figure 3 shows the first approach to a possible geometry post-LS2 in cell 5 of IR7. As can be seen, the new layout for HL-LHC involves the removal of the first magnet (MQWA.E5) in order to avoid any further long-term radiation damage and allowing at the same time the recovery of two spare magnets. This removal is planned for LS2 together with the installation of the tungsten masks and inserts, described in the previous section, in all remaining magnets MQWA.D to MQWA.A, what should improve their protection.

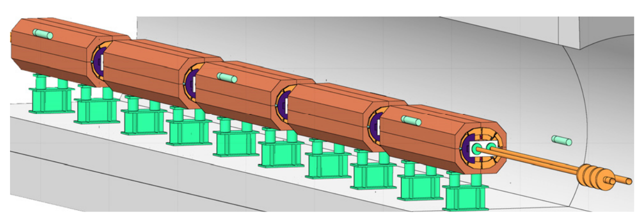

Figure 3: First approach to post-LS2 layout of cell 5 in LHC's IR7.

The corresponding peak dose levels estimated by FLUKA simulations for this layout are shown in Table 2. The tungsten mask installed now in all the magnets greatly helps decreasing the dose received both in the coils and in the spacers, to the point that only the spacers of the first magnet are now over the dose limits determined by the irradiation tests. It is worth noticing the substantial decrease of the dose received in the first magnet of the as-

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sembly (now MQWA.D5) compared that of the previous layout (MQWA.E5) even if in both cases the tungsten mask was installed. This decrease by roughly a factor of 2 in both the coils and the spacers is most likely due to the larger distance between the first magnet and the TCAPC.6. This indicates that showers are not sufficiently contained in the passive absorber and that the larger distance helps in diluting them before their impact on the magnets.

Since the dose received by the spacers of the first magnet is still over the dose limits determined in the irradiation tests, a suitable solution to alleviate this is necessary. After careful study of several strategies that could help diminishing the magnet exposure [19], it was concluded that the main contribution to the dose received by the first magnet comes from particle showers travelling outside the beam pipe, most likely originated in interactions with the TCAP. This lead to the design of a simple shielding surrounding it, suitable to reduce this exposure. Details on this design and the quantification on the reduction on the dose that can be achieved with its installation are detailed in the next section.

Table 2: Peak Dose Estimates for the First Approach to Post-LS2 Layout of Cell 5 of LHC's IR7

	COILS (MGy)	SPACERS (MGy)
MQWA.D5	40	35
MQWA.C5	10	10
MQWB.5	<10	8
MQWA.B5	<10	5
MQWA.A5	<10	<5

POST-LS2 DOSE REDUCTION WITH ADDITIONAL SHIELDING

Figure 4 shows the post-LS2 geometry in cell 5 of IR7 including the shielding designed as part of this study. Its design is very simple, consisting of an iron block of rectangular dimensions 40 cm vertically, 20 cm horizontally and 100 cm longitudinally, enough to cover the area in which the spacers and coils of the MQWA.D5 extend both horizontally and vertically. It is worth pointing out that the block is not in direct contact with the beam pipe.

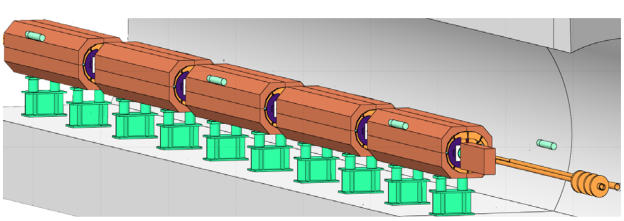

Figure 4: Layout post-LS2 after shielding evaluation.

In addition to the shielding, an elliptical beam pipe matching exactly the dimensions of the beam screen used inside the MQW is installed in the segment between the TCAPC.6 and the MQWA.D5. The dose levels for this layout are shown in Table 3. This proposed layout also minimizes aperture transitions and is beneficial for machine impedance.

The results shown in the table evidence the high efficiency of the iron shielding protecting the first module of the magnet string. A factor of 2 reduction was achieved in the coils of the MQWA.D5 and at least a factor of 3 in the spacers, which now comply with the dose limits set by the irradiation tests. A clear reduction in the dose is also evident in the rest of the magnets, which now fall well below the dose limits, ensuring their correct operation throughout the HL-LHC era.

Table 3: Peak Dose Estimates for Layout Post-LS2 with Additional Shielding in front of the MQWs of Cell 5 of LHC's IR7

	COILS (MGy)	SPACERS (MGy)
MQWA.D5	20	10
MQWA.C5	<10	<5
MQWB.5	<10	<5
MQWA.B5	<10	<5
MQWA.A5	<10	<5

CONCLUSION

The betatron cleaning of the beams taking place in IR7 generates an environment of high radiation levels that puts in danger the correct operation and integrity of the warm magnets in the LSS long-term. In view of the upcoming increase in luminosity in the HL-LHC era, changes in the layout of this region will be needed during LS2. The presented new mitigation strategy consisting on a simple iron block together with a change on the pertinent section of the beam pipe achieves a factor 2 reduction in the dose to the magnets, allowing the dose levels to comply with the irradiation test standards and providing, therefore, a suitable solution to ensure correct magnet operation while fulfilling HL-LHC requirements. Several other solutions have been studied, for example a layout including an additional TCAP upstream from the present one, but the dose reduction achieved with them was not enough to comply with the dose limits.

REFERENCES

[1] S. Redaelli, "Beam Cleaning and Collimation Systems", in *Proc. Joint Int. Accelerator School*, Newport Beach, CA, USA, 5 - 14 Nov 2014, pp.403-437 (CERN-2016-002).

[2] R. Assmann, M. Magistris, O. Aberle, M. Mayer, F. Ruggiero, J.Jimenez, S.Calatroni, A.Ferrari, G.Bellodi, I. Kurochkin *et al.*, "The final collimation system for the LHC", in *Proc. EPAC2006*, Edinburgh, Scotland, 2006, paper TUODFI01,pp.986-988.

[3] P. Fessia, N. Mairani, F. Cerutti, E. Gallay, M. Guinchard, E. Skordis, D. Tommasini, "LHC Normal Conducting Magnets Toward HL-LHC and Beyond: Life Span Evaluations, Corrective Actions, and Future Upgrades", *IEEE Trans. Appl. Supercond.* 26 ,2016, 4004005.

[4] B. Salvachua, R. Bruce, M. Brugger, F. Cerutti, S. Redaelli, "Estimate of Warm Magnets Lifetime in the Betatron and

Momentum Cleaning Insertions of the LHC", in *Proc. 4th Int. Particle Accelerator Conf. (IPAC'13)*, 12–17 May 2013, Shanghai, China, pp.1011.

[5] E. Skordis *et al.,* "Impact of Beam Losses in the LHC Collimation Regions", in *Proc. IPAC'15*, Richmond, USA, paper TUPTY046.

[6] P. Fessia, "Present baseline of HL-LHC integration", in 3rd Joint HL-LHC-LRP Annual Meeting, 11-15th November, Daresbury Laboratory , 2013.

[7] P. Fessia, "Radiation levels of MBW and MQW", 14th HL-LHC TCC, CERN, 2016.

[8] O. Brüning, "The High Luminosity LHC Project", in Proc. 6th Int. Particle Accelerator Conf. (IPAC'15), 3–8 May 2015, Richmond, VA, USA, paper FRXC2.

[9] T.T. Böhlen, F. Cerutti, M.P.W. Chin, A. Fassò, A. Ferrari, P.G. Ortega, A. Mairani, P.R. Sala, G. Smirnov and V. Vlachoudis, "The FLUKA Code: Developments and Challenges for High Energy and Medical Applications", Nuclear Data Sheets 120, 211-214 , 2014.

[10] A. Ferrari, P.R. Sala, A. Fasso, and J. Ranft, "FLUKA: a multi-particle transport code", CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.

[11] A. Mereghetti *et al.,* "The FLUKA LineBuilder and Element Database: Tools for Building Complex Models of Accelerator Beam Lines", in *Proc.IPAC'12*, New Orleans, Louisiana, USA, paper WEPPD071, pp.2687-2689.

[12] F. Schmidt, "SixTrackVersion 4.2.16 Single Particle Tracking Code Treating Transverse Motion with Synchrotron Oscillations in a Symplectic Manner", CERN, Geneva, Switzerland, Rep. CERN/SL/9456, 2012.

[13] G. Ripken and F. Schmidt, "A symplectic six-dimensional thin-lens formalism for tracking", CERN, Geneva, Switzerland, Rep. CERN/SL/95–12(AP), 1995.

[14] R. De Maria *et al.,* "Recent developments and future plans for SixTrack", in *Proc. IPAC'13*, Shanghai, China, 2013, pp. 948–950.

[15] A. Mereghetti, "SixTrack-FLUKA Active Coupling for the Upgrade of the SPS Scrapers", in Proc. 4th Int. Particle Accelerator Conf., 12–17 May 2013, Shanghai, China, paper WEPEA064.

[16] C. Bracco *et al.,* "Scenarios for beam commissioning of the LHC collimation system". In *Proc.PAC'07*, paper YUPAN087, pp. 1577-1579.

[17] D. Mirarchi *et al.,* "Cleaning performance of the collimation system of the high luminosity Larger Hadron Collider", in *Proc. IPAC'16*, paper WEPMW030.

[18] LHC design report, Vol. 1. The LHC main ring, CERN-2004-003-V-1 ,CERN, Geneva, 2004.

[19] C. Bahamonde Castro, "Simulations of new passive absorbers in IR7", "Update on new TCAP collimators", "Update on TCAP simulation", "Update TCAPs and final design", ColUSM 76th, 77th, 81st, 83rd , CERN, Geneva, 2016-2017.

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