ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP49

COLLIMATION OF 400 MJ BEAMS AT THE LHC: THE FIRST STEP TOWARDS THE HL-LHC ERA*

S. Redaelli, A. Abramov, D. Baillard, R. Bruce, M. D'Andrea, R. Cai, F. Carra, M. Di Castro, L. Giacomel, P. Hermes, B. Lindström, N. Mounet, F.-X. Nuiry, D. Mirarchi, A. Perillo Marcone, F. Van der Veken, A. Vella, CERN, Geneva, Switzerland

Abstract

An important upgrade programme is planned for the collimation system of the CERN Large Hadron Collider (LHC) in order to meet the challenges of the upcoming High-Luminosity LHC (HL-LHC) project. The first upgrade stage was already deployed during the last LHC Long Shutdown, offering improvements in the collimation cleaning, a significant reduction of the impedance contribution and better cleaning of collisional losses, in particular for ion-ion collisions. A new crystal collimation system was also deployed to improve the halo cleaning for heavy-ion beams. This upgrade provides the opportunity to explore the intensity limits during the LHC Run 3 and collect crucial feedback to refine upgrade plans and operational scenarios in the HL-LHC era. This paper describes the performance of the LHC Run 3 collimation system that has already enabled record stored beam energies above 400 MJ for protons at 6.8 TeV, and reviews further upgrade plans to reach 700 MJ beams at the HL-LHC.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN is a 27 km-long circular collider for protons and heavy ions [1] designed to accelerate beams up to 7 TeV per charge. The LHC is presently in its third run (Run 3) that will last until 2025, followed by the third Long Shutdown (LS3) that will be dedicated to the deployment of the High-Luminosity LHC (HL-LHC) [2]. One of the key HL-LHC upgrade targets is to increase the beam current by nearly a factor of two, bringing the proton stored beam energy to about 700 MJ to be compared to the LHC design value of 362 MJ. This poses obvious challenges for beam collimation [3]. During LS2 (2019-2021), several important upgrade items were already installed to improve various aspects of the collimation system and to test new technologies planned for HL-LHC. This provides a unique opportunity to push the beam parameters already during Run 3. Presently, the LHC is colliding beams at 6.8 TeV and accelerates up to about 2500 bunches of 1.6×10^{11} protons each. It reached a record stored beam energy of 430 MJ and deployed already complex operational scenarios planned at the HL-LHC, such as luminosity levelling schemes using either β^* and transverse-offset. The rapid deployment of these unprecedented beam parameters is illustrated in Fig. 1, where the stored beam energy achieved in the first commissioning month of 2023 is shown. In this paper, the LS2 collimation upgrades are reviewed and their measured performances during Run 3 are discussed. The next steps of the collimation upgrade for HL-LHC are recalled before drawing some conclusions.

* Work supported by the HL-LHC project.

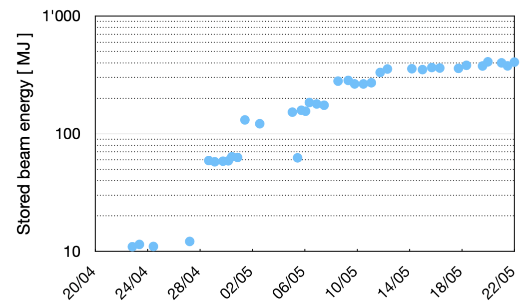

Figure 1: Average stored beam energy of the two LHC beams at the start of collision during the first month of operation in 2023.

LHC COLLIMATION SYSTEM IN RUN 3

The main collimation upgrades in LS2 are summarized [4]: (1) 12 new low-impedance collimators were installed in the insertion region 7 (IR7, betatron collimation): four primary collimators (TCPs) and 8 secondary collimators (TCS). Their jaws are made of the novel molybdenum-graphite (MoGr) material [5]: TCPs use bulk MoGr while TCSs have a 5 µm thick layer of Mo coating (Mo-MoGr); (2) two new collimators (TCLD) were installed in the dispersion suppressor (DS) regions around the ALICE experiment to protect superconducting magnets from heavy-ion collisional losses, to digest the requested luminosity following the ALICE detector upgrade [6]; (3) four new crystal primary collimators (TCPCs) were installed in IR7 and replaced previously used test devices [7, 8] to improve the betatron cleaning of heavy-ion beams for the operational ion runs starting in Run 3; (4) two new passive absorbers (TCAPM) were installed in IR7 to reduce the radiation wear of warm quadrupoles exposed to the loads from TCPs [9]. All new TCP, TCS and TCLD collimators embed in-jaw beam position monitors (BPMs) for fast beam-based alignment and continuous orbit measurements. This design [10, 11] was already successfully deployed for the LHC Run 2 (2015-2018) in the tertiary collimators around each experiment (16 TCT devices) and in 2 dump-protection collimators in IR6.

All new collimators were integrated into the LHC system and are available for Run 3 operation [12]. The upgrade items (2) and (3) target improvements to the heavy-ion beam operation. They have also been successfully commissioned with proton beams [13] and in a heavy-ion test in 2022 [14].

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP49

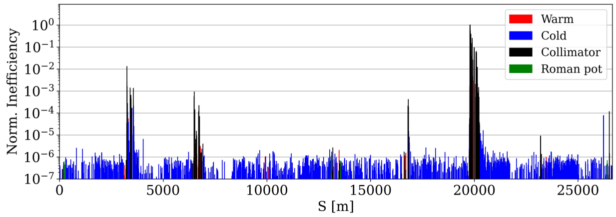

Figure 2: Betatron collimation loss map at 450 GeV for horizontal B1 losses, as measured in 2023. Losses around full ring are shown. The largest loss cluster occurs in IR7 (region at around 20000 m in the abscissa). Losses in IR2 (around 4000 m) occur at the injection protection devices that are closed in this configuration at 450 GeV.

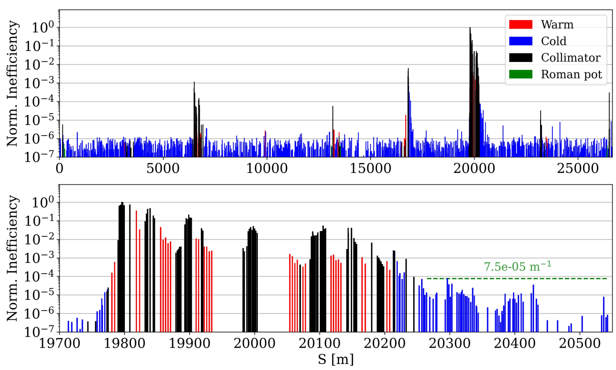

Figure 3: Collimation loss map at 6.8 TeV for horizontal B1 losses as measured in 2023, with a zoom of IR7 (bottom). Cleaning inefficiencies below 10^{-4} are achieved in this case.

Their detailed performance will be established in the 2023 Pb-Pb run that is about to start at the time of writing. The remainder of this paper is therefore focused on the proton runs.

The collimation cleaning for protons at 450 GeV and 6.8 TeV, measured for horizontal Beam 1 losses using the technique in [15], is shown in Figs. 2 and 3, respectively. The losses in the most exposed cold magnets downstream of IR7 are below 10^{-4}, highlighting an excellent collimation performance. In simulations, the new TCP material improved the DS losses by up to 15% thanks to the effective higher Z and density of MoGr [3, 16]. The main motivation for the deployment of new materials remains the collimation impedance reduction. The gains achieved with respect to the first-generation collimators made of a carbon fibre-reinforced composite (CFC) are illustrated in Fig. 4: the single-collimator tune shift, measured with the procedure described in [17], shows a reduction by about a factor of five for the TCSPM.D4L7.B1 (the largest TCS contributor in IR7). Additional detailed considerations on beam stability can be found in a compani0on paper [18].

The in-jaw BPMs make the LHC operation more flexible: different configurations can be set up more efficiently and continuous orbit measurements guarantee safe conditions during luminosity levelling, while the β^* is reduced at the high-luminosity experiments [19, 20]. The example in Fig. 5 shows BPM measurements during a typical fill, with orbit shifts below 200 µm throughout the cycle for a selection of collimators around the experiments (top graph) and readings well below 1 σ in IR7 during the collision process (bottom). These analyses are used to define interlocks on jaw positions to ensure safe execution of the β^*-levelling [21], by making sure that the beams are safely dumped before dangerous errors arise (e.g. exposing metallic TCT or even apertures close to the experiments to high beam losses).

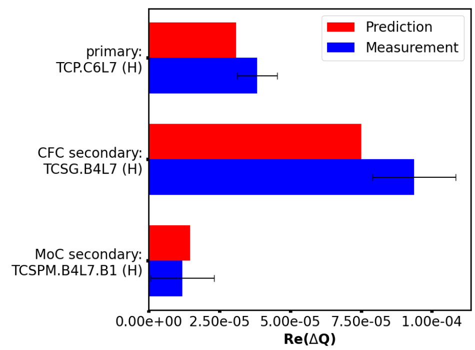

Figure 4: Simulated (red bar) and measured tune shift at some MoGr (TCP, top), CFC (TCSG, middle) and Mo-MoGr (TCSPM, bottom) collimators.

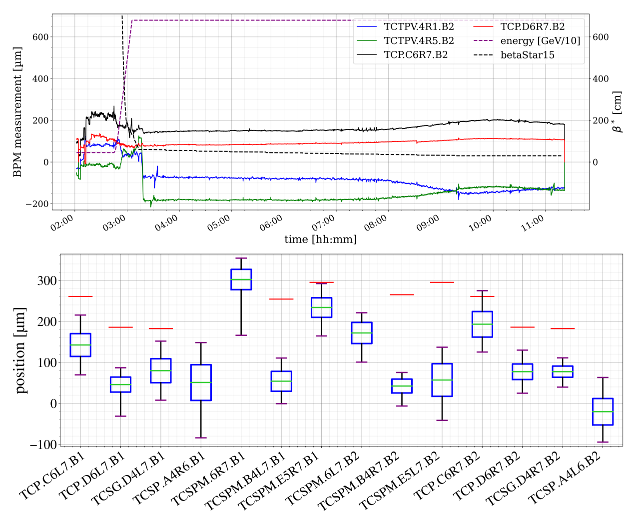

Figure 5: Beam orbit measured with the new BPM collimators during a typical LHC fill (top) and statistics of average orbit in measurements at the new IR7 collimators during collisions. The red line corresponds to the 1 σ beam size.

UPGRADE PLANS FOR RUN 4

Following the successful LS2 installations of the HL-LHC upgrade, the collimation teams are now focused on the main upgrades that will take place during LS3: (1) a second low-impedance upgrade that involves installing 10 more low-impedance TCSs in IR7. The new TCSs use Cu-coated isotropic-graphite (SGL R4550) jaws, following the observation [22, 23] that this choice is slightly more robust

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP49

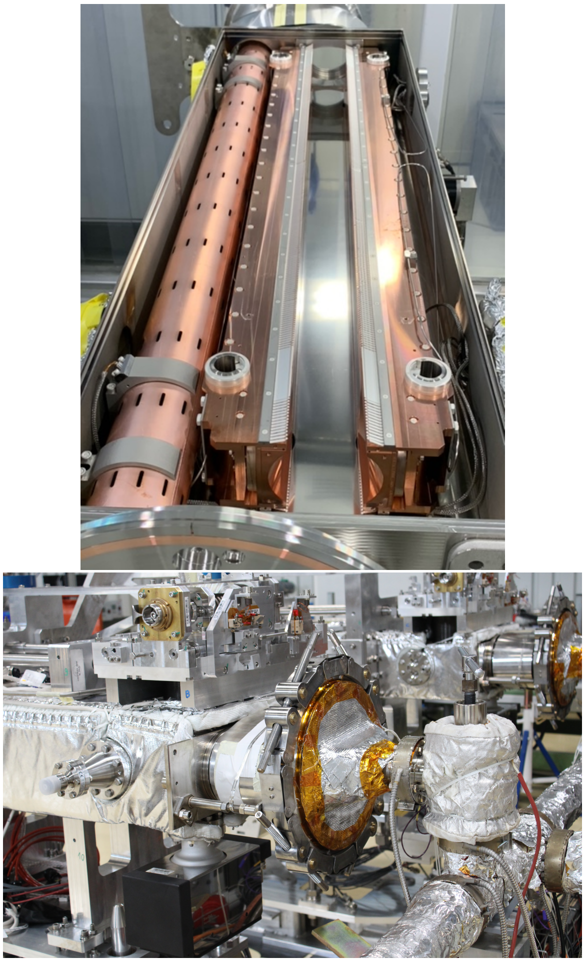

Figure 6: Photographs of the TCTPXH tertiary collimator for HL-LHC. Four of these collimators will be installed on both sides of IR1 and IR5 during LS3.

against grazing beam impacts in case of injection failures and minimises budget risks; (2) a complete re-design of the IR collimation systems around ATLAS and CMS, which requires a total of 32 new collimators to be installed. New tertiary collimators, physics debris absorbers (made of a heavy tungsten alloy called Inermet180) and fixed masks (Cu or Inermet180 depending on their location) are planned. See Ref. [3] for details.

The transverse space constraints around IR1 and IR5 at the HL-LHC, in particular in the area were the beams share a common beam pipe around the collision points [3], require the development of a new, two-in-one collimator design where the same vacuum vessel houses the movable collimator jaws and the chamber for the opposing, non-collimated beam. Two variants of this design are needed for the horizontal tertiary collimators (TCTPXH) and physics-debris absorbers (TCLPX). The prototyping phase for these new devices, carried out at CERN ahead of the series production in industry, is close to completion. One unit of each design was built and these two prototype collimators are presently being tested for vacuum compliance. Two photographs of the TCTPXH collimators are shown in Fig. 6, before closing

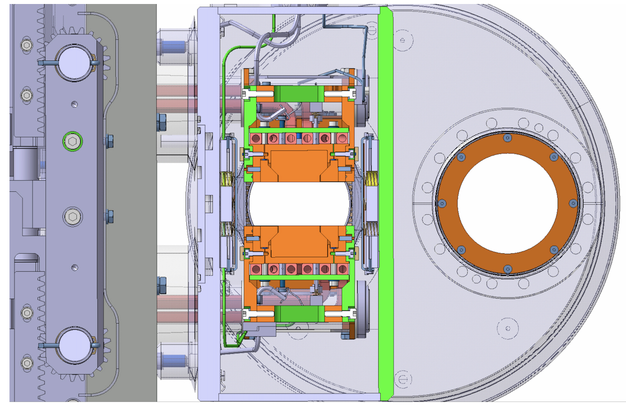

Figure 7: Drawing of the new vertical tertiary collimator, TCTPXV, for the IR1 and IR5 at the HL-LHC. Four TCTPXV will be installed. *Courtesy L. Gentini, CERN.*

the vacuum vessel (top) and after the successful closure of the vessel (bottom). The latter picture shows the prototype being tested for vacuum.

In the same area, immediately downstream of the TCTPXH, a vertical tertiary collimator is also needed for the inner-triplet magnet protection from incoming-beam losses [3]. This also requires a new design, called TCTPXV, with enlarged jaw stroke compared to the IR7 collimators. It uses the same jaw design as the TCTPXH installed in a vertical vessel configuration, as shown in Fig. 7. In this case, sufficient transverse space is available to deploy a single-beam collimator design, with the pipe of the opposite beam separated from the TCTPXV vessel. No prototype is planned for this, more conventional, design.

CONCLUSIONS

The first upgrade phase of the LHC collimation system was successfully completed in the second long shutdown (2019-2021). Fourteen movable collimators, two fixed masks and four crystal collimators were installed and are now regularly used to push further the Run 3 performance, through significant improvements in the impedance, the collimation cleaning and the overall operational efficiency. Important performance boosts are expected for the 2023 Pb ion run: the upgrade enables the six times larger peak luminosity in ALICE with a nearly doubled beam current. Beam experience with the new collimation system allowed a validation of the new solutions for HL-LHC. So far, the key design choices have been confirmed and the preparation of the second-stage upgrade is being actively pursued. One salient design change involves a more economic solution for the TCS jaw material, based on considerations that are unrelated to the excellent performance of the new MoGr collimators in the LHC. Novel collimator designs are planned for the devices in the beam-recombination regions around IR1 and IR5. In particular, a two-in-one design is needed for the new horizontal collimators. The prototyping phase is well advanced, with two full-scale prototypes successfully completed and being tested at the time of writing.

ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP49

REFERENCES

[1] O. S. Brüning *et al.*, *LHC Design Report*. CERN, Geneva, Switzerland, 2004. doi:10.5170/CERN-2004-003-V-1

[2] http://hilumilhc.web.cern.ch/HiLumiLHC/index.html.

[3] S. Redaelli, R. Bruce, A. Lechner, and A. Mereghetti, "High Luminosity LHC Design Report, Chapter 5: Collimation system," *CERN Yellow Rep. Monogr.*, vol. 10, pp. 87–114, 2020. doi:10.23731/CYRM-2020-0010.87

[4] L. Evans and P. Bryant (editors), "LHC machine," *J. Instrum.*, vol. 3, S08001, 2008. doi:10.1088/1748-0221/3/08/S08001

[5] J. Guardia-Valenzuela, A. Bertarelli, F. Carra, N. Mariani, S. Bizzaro, and R. Arenal, "Development and properties of high thermal conductivity molybdenum carbide - graphite composites," *Carbon*, vol. 135, pp. 72–84, 2018. doi:10.1016/j.carbon.2018.04.010

[6] The ALICE Collaboration, "The ALICE experiment at the CERN LHC," *J. Instrum.*, vol. 3, no. 8, S08002, 2008. doi:10.1088/1748-0221/3/08/S08002

[7] W. Scandale *et al.*, "Observation of channeling for 6500 GeV/c protons in the crystal assisted collimation setup for LHC," *Phys. Lett. B*, vol. 758, pp. 129–133, 2016. doi:10.1016/j.physletb.2016.05.004

[8] S. Redaelli *et al.*, "First observation of ion beam channeling in bent crystals at multi-TeV energies," *Eur. Phys. J. C*, vol. 81, no. 2, p. 142, 2021. doi:10.1140/epjc/s10052-021-08927-x

[9] C. Bahamonde Castro *et al.*, "Improved Protection of the Warm Magnets of the LHC Betatron Cleaning Insertion," in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 72–75. doi:10.18429/JACoW-IPAC2017-MOPAB004

[10] D. Wollmann *et al.*, "Beam feasibility study of a collimator with in-jaw beam position monitors," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 768, p. 62, 2014. doi:10.1016/j.nima.2014.09.024

[11] G. Valentino *et al.*, "Successive approximation algorithm for beam-position-monitor-based LHC collimator alignment," *Phys. Rev. ST Accel. Beams*, vol. 17, p. 021 005, 2 2014. doi:10.1103/PhysRevSTAB.17.021005

[12] F. Van der Veken *et al.*, "Collimation performance of the 400 MJ LHC beam at 6.8 TeV," Venice, Italy, May 2023. doi:10.18429/JACoW-IPAC2023-TUPM119

[13] M. D'Andrea *et al.*, "Crystal collimation performance at the LHC with a 6.8 TeV proton beam," in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 563–566. doi:10.18429/JACoW-IPAC2023-MOPL023

[14] R. Bruce *et al.*, "First results of running the LHC with lead ions at a beam energy of 6.8 Z TeV," in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 555–558. doi:10.18429/JACoW-IPAC2023-MOPL021

[15] W. Höfle *et al.*, "Controlled Transverse Blow-Up of High-energy Proton Beams for Aperture Measurements and Loss Maps," in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, pp. 4059–4061. https://jacow.org/IPAC2012/papers/THPPR039.pdf

[16] A. Waets *et al.*, "Power Deposition in Superconducting Dispersion Suppressor Magnets Downstream of the Betatron Cleaning Insertion for HL-LHC," in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 37–40. doi:10.18429/JACoW-IPAC2021-MOPAB001

[17] S. A. Antipov *et al.*, "Transverse beam stability with low-impedance collimators in the high-luminosity large hadron collider: Status and challenges," *Phys. Rev. Accel. Beams*, vol. 23, p. 034 403, 2020. doi:10.1103/PhysRevAccelBeams.23.034403

[18] N. Mounet *et al.*, "High intensity beam dynamics challenges for HL-LHC," presented at HB'23, Geneva, Switzerland, Oct. 2023, paper THA1C1, these proceedings.

[19] R. Bruce, R. W. Assmann, and S. Redaelli, "Calculations of safe collimator settings and β^* at the CERN Large Hadron Collider," *Phys. Rev. ST Accel. Beams*, vol. 18, p. 061 001, 2015. doi:10.1103/PhysRevSTAB.18.061001

[20] R. Bruce *et al.*, "Reaching record-low β^* at the CERN Large Hadron Collider using a novel scheme of collimator settings and optics," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 848, pp. 19–30, 2017. doi:10.1016/j.nima.2016.12.039

[21] F. F. Van der Veken, R. Bruce, M. Hostettler, D. Mirarchi, and S. Redaelli, "LHC Beam Collimation During Extended β^*-Levelling in Run 3," in *Proc. IPAC'22*, Bangkok, Thailand, 2022, pp. 2138–2141. doi:10.18429/JACoW-IPAC2022-WEPOTK034

[22] F. Carra *et al.*, "Beam-Impact Validation of HL-LHC Collimator Materials: the "MultiMat-2" Experiment," in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 3822–3825. doi:10.18429/JACoW-IPAC2023-WEPM109

[23] C. Accettura *et al.*, "Overview of material choices for HL-LHC collimators," in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 2999–3002. doi:10.18429/JACoW-IPAC2023-WEPA148