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HL-LHC SERIES COLLIMATORS: KEY TECHNICAL REQUIREMENTS, CRUCIAL PRODUCTION CHALLENGES AND RISK MITIGATION PLAN*

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Abstract

In view of High Luminosity (HL) - Large Hadron Collider (LHC) project, an upgraded collimation system has been developed to accommodate a rise of ten times of the integrated luminosity compared to the LHC. A new series of collimators will be produced and installed in the machine during the Long Shutdown 3 (LS3) to take place during 2026-2028. The updated design incorporates cutting-edge technologies to meet the demanding operating requirements.

Multiple production activities are recognized as critical to ensure the quality of the collimators. Comprehensive qualification checks of the production procedures are planned, and functional tests will be conducted to validate the performance of each unit produced.

INTRODUCTION

The main objective of HL-LHC project is to achieve an integrated luminosity of 250 fb^{-1} per year, approximately ten times greater than that of LHC. This is attained via implementation of new operation modes and several innovative technologies, including the collimators [1].

The role of the collimation system is to safely dispose beam losses and to reduce the risk of damages for accelerator components. A high-performance collimation system is fundamental for the machine's operation. The main challenges of the foreseen upgrade are the following:

- Redesign of configuration for collimators in upgraded LHC Insertion Regions (IR) 1 and 5 [2]. These collimators are denominated as “Double Beam”;
- Improved protection of LHC Dispersion Suppressor (DS) regions;
- Reduction of coupling impedance generated by collimators;
- Optimization of designs across all versions of collimators to streamline series production.

A total of 36 new collimators, comprising various versions, will be produced, and installed in Interaction Point (IP) 1, IP 5 and IP 7.

The “Double Beam” collimators are characterized by a new configuration which sees both collimated and non-collimated beams passing through the same vacuum thank (Figure 1). This innovative solution was driven by space constraints, namely [3]:

- The shorter distance between Dipoles 1 and 2 (D1-D2) leading to reduced intra-beam;
- Thicker active part of the collimator jaw (i.e. the absorber blocks) required to shield the D2 coil;
- Due to larger Betatron functions at the collimators, a larger aperture is needed between the two jaws.

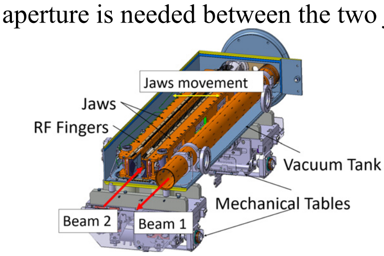

Figure 1: Double Beam Collimator.

Three versions of “Double Beam” collimators exist: the TCTPXV and TCTPXH collimators act on the beam incoming the physics experiment to absorb beam losses; TCLPX absorbs debris from beam outcoming interaction points and going toward the magnet (Figure 2). Two different prototypes (TCTPXH and TCLPX) have been produced at CERN for design and production feasibility validation.

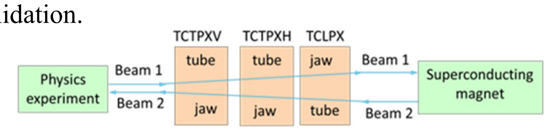

Figure 2: Collimators layout in IP 5 & 1 of HL-LHC [2].

TECHNICAL AND PRODUCTION REQUIREMENTS

Each sub-component of the collimators must satisfy several fundamental criteria. This chapter outlines how challenging technical requirements are addressed by specific essential production processes.

Efficient Heat Removal System

An efficient heat removal system is fundamental for the jaws to dispose beam-induced heat loads during operation. Debris from interaction points generate up to 240 W on one jaw (TCLPX). Other collimators installed in other points of the machine, can absorb up to 2.25 kW per jaw. In the latter, the cupro-nickel cooling tubes are vacuum brazed onto the structural part of the jaws, whereas the formers are mechanically clamped [4]. Brazing maximizes the quality of thermal contact; however, proficiently executing this process is challenging because it must be performed homogeneously, spanning the entire length of the jaw, on each of the six tubes, and on both sides (Figure 3).

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A thermal test bench has been developed and commissioned at CERN to measure the Thermal Contact Conductance (TCC) of the series jaw assemblies. A TCC of 10 000 W/(m^2·K) at jaw's interface is required.

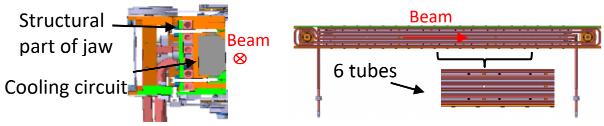

Figure 3: Orthogonal (left) and longitudinal (right) cross-section of a jaw.

Nonetheless, in view of an outsourced series production, samples have been produced by specialists in industry and have been tested, via ultrasound examination, to evaluate the vacuum brazing quality (with respect to predefined acceptance criteria) and validate the most suitable process.

Figure 4 shows a comparison of three qualities of brazing: from the lowest (left side) to the highest (right side). The top line represents echo amplitude scans from the external plate to tubes' bores, while the bottom line represents eco from the external plate to interface tube-plate. The more the shape of the tube is distinct, the higher the quality of brazing.

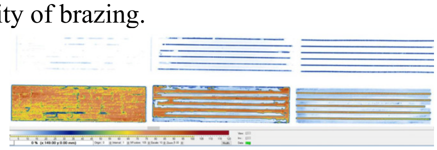

Figure 4: Ultrasound tests on a portion of brazed circuits.

High-Precision Jaws

The collimator jaws must intercept the beam with a very precise positioning to ensure optimal performance, given the high beam power present within a narrow beam size. Also, overall flatness must be such to guarantee that the correct hierarchy among different families of collimators is always respected [5]. For this reason, a flatness lower than 100 µm on the active surface of a jaw assembly (~1000 mm length) is necessary. The active surface is defined as the surface of the absorber blocks exposed to the beam; it is assembled via clamps, stiffeners, and other structural sub-components.

To guarantee this specification, the optimal production processes have been identified during prototyping phase, in view of the series production. Stress relief heat treatment is fundamental for long sub-components, to guarantee dimensional stability during production as well as during the entire lifetime. It is essential to precisely machine each jaw's sub-components (all tolerances and geometrical specifications are defined adequately) and precisely assemble them together. Bolts tightening sequence and torque values are pre-defined [6]. Systematic metrology tests (via Coordinate-Measuring Machine) are then foreseen, at several phase of the production, to verify compliance with the requirements.

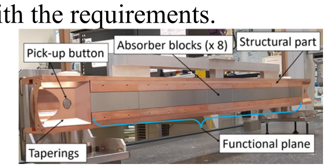

Figure 5: Jaw prototype during metrology controls.

All these production steps have been performed during prototypes production, including metrology controls (Figure 5). A measured flatness of the active surface of 22 µm demonstrated the soundness of production process.

UHV Compliance

Collimators, as LHC in general, operate under Ultra High Vacuum (UHV) conditions: the absolute operating pressure inside the tank is close to $1{\cdot}10^{-10}$ mbar. CERN therefore developed a UHV compliant design and production process to guarantee such requirements [7]: this includes the use of UHV compliant materials, silver-plated bolting and suitable heat-treated absorbing blocks (to minimise the outgassing rate). Dry machining, UHV cleaning of each component as well as full assembly in clean room is required. A bake-out of the full collimator at 250°C for 48 hours is foreseen.

Precise acceptance tests and criteria (for several phases of the production) have also been established, namely RGA spectra, and outgassing rate measurement. Reference acceptance values of UHV tests are reported in [8].

All these production procedures have been implemented for prototypes production at CERN, and tests were successfully performed confirming their UHV compliance. Table 1 presents the main results from these tests, more details are reported in [9]. The same process will apply for the series production.

Table 1: Results of UHV Tests on Collimator Prototypes

Prototype	RGA spectrum	Final pressure [mbar]
TCLPX	Compliant	$1.9{\cdot}10^{-10}$
TCTPXH	Compliant	$2.4{\cdot}10^{-10}$

Leak Tightness

Vacuum tank and edge-welded bellows shall guarantee leak tightness all over the lifetime of collimators. Bellows serve as connection between the vacuum tank and the mechanical tables, system which enables the movement of the jaw (Figure 6). A maximum leak rate of $1{\cdot}10^{-10}$ mbar·l/s is required. Specific design and production means have been implemented to ensure this aspect: use of ConFlat® flanges, selection of Stainless Steel with grain sizes according to specification defined in [10]. Joining technique are either electron beam welding (for tank plates) or TIG welding (for flanges); minimum welding thicknesses and geometries have been defined. Several leak tests during production are foreseen [6].

Leak tightness is critical for edge-welded bellows, being part of a dynamic system: they are subject to lateral movements during operation, resulting in cyclic stresses. In the framework of the design and procurement of these bellows, several considerations have been addressed to ensure reliability of the component. Among others, (1) rigorous validation of materials deployed: this shall fulfil specific requirement in terms of inclusion content, maximum grain size, chemical composition, mechanical properties, and heat treatments undergone [11]. (2) Meticulous design and dimensioning of the bellows: the definition of the optimal number of convolutions is based

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on operational requirements such as stroke, lifetime, and bake-out conditions. (3) Holding high standards in weld quality is equally fundamental.

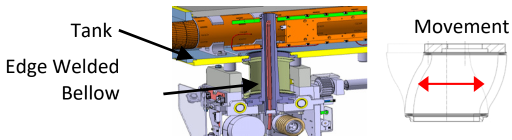

Figure 6: Edge-welded bellow installed in collimator (left) and bellow with movement details (right).

Impedance Limitation

Transverse impedance can lead to beam instability resulting in beam losses, and increase of beam size, reducing the luminosity. Collimators are among the main contributors of this phenomenon in the LHC machine due to their proximity to beam, the use of resistive materials and the variation in shape encountered by the beam as it passes through [12]. For impedance limitation purpose, RF-fingers are installed in the system: their design shall guarantee electrical continuity -from entrance to exit of collimator- and smooth shape transition to avoid cavities. Wear resistance and robustness are fundamental aspects to be preserved over the lifetime, being movable components.

To identify a final design that satisfy all the mentioned conditions and operating requirements, multiple RF-finger solutions have been developed and tested. The production phase is equally crucial, necessitating precise cutting and meticulous shaping of the fingers, proper heat treatment of the CuBe C17410 sheet (to ensure optimal balance between elasticity and fatigue resistance). To prevent cold welding on sliding contacts, specific coating of the surfaces is foreseen: RF-fingers are silver coated and the fixed structure on which the fingers slide is rhodium coated [13].

Reliability in Radioactive Environment

Each subcomponent of the mobile table needs to guarantee accurate and reliable movements in a radioactive environment during the lifetime of a collimator (4000 fb^{-1}). A Total Ionizing Dose (TID) of 4 MGy in mixed field is expected on the leadscrew of the most charged collimator (the TCLPX) [14]. These screws are critical subcomponents, being precise movable parts which directly initiate the jaw's translation. They are susceptible to thread deterioration due to cycling and degradation of grease caused by radiation exposure [15]. Figure 7 gives an example of damages which occur on a screw that undergone 20 000 mechanical cycles and gamma radiation of 5 MGy, namely surface corrosion and surface discontinuities. The evolution of grease under irradiation is represented, namely colour and viscosity variations as a function of total dose (Table 2). These aspects pose the risk of leadscrew blockage. With the purpose of avoiding this scenario, extensive R&D activities have been performed: the behaviour of different types of grease (after gamma irradiation[#]) has been compared. Lubricated screws have been irradiated and cycled; operational parameters have been monitored to assess quality and stability of performance. The most reliable combination of grease and leadscrew has been selected for series collimators.

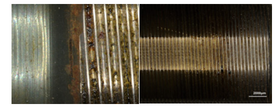

Figure 7: Lubricated thread after irradiation and cycling.

Table 2: Evolution of Lubrilog LX AGFA 2 Grease After Gamma Irradiation

Dose [MGy]	0	1	2	5	10
Kinematic viscosity at 40°C [cSt]	337.4	367.5	418.9	502.1	857.9

[#]Compared to mixed field irradiation representative of the accelerator environment [16], gamma radiation is faster and does not cause material activation. However, it requires higher integrated dose to be representative of LHC operating conditions.

RISK MITIGATION PLAN

CERN is performing a wide range of activities to mitigate the risks of non-conformity of the HL-LHC collimators series production. (1) Two "Double Beam" collimators prototypes have been produced and tested. This act as a validation of the new design and a demonstration of production feasibility. (2) Solid and comprehensive documentations, including instructions for production process and test, have been developed reflecting the experience from prototyping. (3) Comprehensive Quality Control and functional tests have been defined to validate the performance of each unit. (4) Critical sub-components of collimators (e.g. leadscrews, UHV compliant raw material and bellows, absorbing blocks) are directly sourced by CERN. This allows a precise delineation and definition of all technical criteria, a meticulous oversight of production processes, and extensive testing of each unit. Each subcomponent is catalogued within a dedicated platform to detail all information including production methods, technical datasheet, tests performed, and relation with respect to main assemblies thereby ensuring thorough traceability and quality control.

CONCLUSION

CERN has a long experience in production of collimators (both in-sourced and outsourced) required for its accelerator complex ([17, 18]).

Small series limit scale-factors optimization, but allows attention to details, fundamental for non-standard particle accelerators components. The combination of various materials, high precision, UHV cleanliness, requires several manufacturing technologies spanning from surface chemistry, different joining methods, CNC machining, electro discharge machining, chemical etching and more. The production process is applicable in specific industries although requiring an intense initial preparation phase. Thus, extensive activities have been undertaken to ensure the quality of the devices and to decrease the risk of non-conformity.

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REFERENCES

[1] G. Apollinari *et al.*, "High-Luminosity Large Hadron Collider (HL-LHC). Technical Design Report V. 0.1," Office of Scientific and Technical Information (OSTI), Jan. 2017. doi:10.2172/1767028

[2] F.-X. Nuiry, "IP1/5 layout for WP5 collimators and masks," EDMS 2723809, 2023.

[3] R. D. Maria, "Update on tolerance for remote alignment in IR1/5 for HL-LHC," Collimation Upgrade Specification Meeting #108, INDICO: 757667, 2018.

[4] F. Carra, "TCPPM & TCSPM Collimators: engineering specification" EDMS 2896918, 2023.

[5] O. Bruning, "LHC Design Report - Vol 1: The LHC Main Ring" CERN, 2004.

[6] "Annex 3 of Technical Specifications for Manufacturing and Supply of HL-LHC Collimators" EDMS 2963854, 2023.

[7] J. Jimenez, "Vacuum Requirements for the LHC collimators" EDMS 428155, 2003.

[8] G. Bregliozzi, "Vacuum Acceptance Tests For LHC" EDMS 1113402, 2011.

[9] G. Cattenoz, "Vacuum acceptance test report for HCTCLPX and HCTCTPXH prototypes for HL-LHC" EDMS 2962747, 2024.

[10] S. Sgobba, "Technical Specification: Stainless steel sheets/plates AISI 304L" EDMS: 790767.

[11] S. Sgobba, "Technical Specification: Stainless steel 1.4429 forged blanks for ultra-high vacuum applications," EDMS 790773.

[12] N. Mounet *et al.*, "Collimator Impedance Measurements in the LHC", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper TUPWA047, pp. 1817-1819.

[13] S. Calatroni, "RF contacts for the LHC collimators" Elsevier, pp. 205-211, 2006.

[14] M. Sabaté-Gilarte, "Total Ionizing Dose on collimators and interconnecting elements in cell-4" HL-LHC TCC #141 - EDMS 2629304.

[15] M. Ferrari, D. Senajova, K. Kershaw, A. Perillo Marcone, and M. Calviani, "Selection of radiation tolerant commercial greases for high-radiation areas at CERN: Methodology and applications," *Nucl. Mater. Energy* , vol. 29, p. 101088, Dec. 2021. doi:10.1016/j.nme.2021.101088

[16] M. Ferrari *et al.*, "Design development and implementation of an irradiation station at the neutron time-of-flight facility at CERN," *Phys. Rev. Accel. Beams*, vol. 25, no. 10, Oct. 2022. doi:10.1103/physrevaccelbeams.25.103001

[17] F.-X. Nuiry *et al.*, "Design and Prototyping of New CERN Collimators in the Framework of the LHC Injector Upgrade (LIU) Project and the High-Luminosity (HL-LHC) Project", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 80-83. doi:10.18429/JACoW-IPAC2017-MOPAB006

[18] R. W. Assmann *et al.*, "LHC Collimation: Design and Results from Prototyping and Beam Tests", in *Proc. PAC'05*, Knoxville, TN, USA, May 2005, paper TPAP007, pp. 1078-1080.