

COLLIMATOR PRE-SERIES PRODUCTION FOR CERN'S HIGH LUMINOSITY LARGE HADRON COLLIDER OPERATION*

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Abstract

In the framework of the High Luminosity Large Hadron Collider (HL-LHC) project, the accelerator's collimation system will be upgraded. Thirty-six new collimators of five different designs will be produced, including units of completely new designs, as well as replacements for existing collimators and spare units. The production of these collimators is taking place in two stages: starting with a pre-series of three units (first stage), to validate the subsequent production of the 33 remaining series units (second stage). This paper describes the production and testing process of the three pre-series collimators, from the production of the jaws, through vacuum vessel manufacturing and collimator assembly, to their delivery and acceptance testing at CERN. It details relevant production methods, including electron beam welding, vacuum brazing and bending of cooling pipes. The extensive testing campaign carried out on the pre-series units is described here, including both Quality Assurance (QA) assessments during production as well as the Site Acceptance Test (SAT) campaign upon reception of the collimators. The goal is to validate both the collimator functionality and the production capabilities.

INTRODUCTION

The High Luminosity Large Hadron Collider (HL-LHC) necessitates extensive upgrades of the entire LHC accelerator ring, including its collimation system [1] (Fig. 1). A total of 36 new collimators, including operational and spare units, of 5 different designs will be produced for installation during Long Shutdown 3. The quantities to be produced and attributes for each collimator type are given in Table 1. The production includes two types of the presently installed single-beam collimators: TCSPM and TCTPM [2, 3], as well as devices of three new types: TCLPX, TCTPXV and TCTPXH [3, 4] (Fig. 2). The pre-series include one TCLPX, one TCTPXH and one TCSPM collimator.

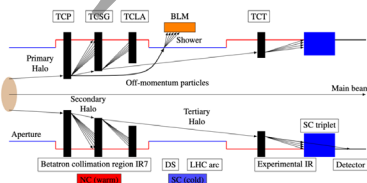


Figure 1: LHC multi-stage collimation schematic.

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These new types, also called double-beam collimators, will be installed in the recombination regions near Interaction Points 1 and 5, where the beams approach each other transversally as they get close to the collision point. Both counter-rotating beams share the same vacuum vessel (collimator tank); the un-collimated beam circulates through a drift tube while the collimated beam is centered between the collimator jaws. With this new design, the double-beam collimators can cope with the reduced intra-beam distance, whereas the single-beam collimators, with separate vacuum chambers for both beams, cannot.

Table 1: Collimator Types

Type	Qty	Attributes
TCSPM	12	Single beam secondary collimator with Cu-coated graphite jaws
TCTPM	10	Single-beam tertiary collimator with Tungsten Heavy Alloy (WHA) jaws
TCLPX	5	Double-beam physics debris collimator with WHA jaws
TCTPXV	5	Double-beam tertiary vertical collimator with WHA jaws
TCTPXH	4	Double-beam tertiary horizontal collimator with WHA jaws

Before launching the series production, CERN has prototyped two collimators, a TCTXH and a TCLPX, to validate their new designs, master the production processes, and check their compliance with functional specifications. The pre-series includes a TCLPX, TCTPXH and TCSPM collimator. The production has been set up in a build-to-print fashion according to a Technical Specification [5]. The design of the collimators, production drawings, testing procedures and test-benches are provided before the start of the production. The raw materials and commercial components were thoroughly inspected and validated before assembly. The fabrication and metrology of components, assembly of collimators and execution of tests are defined in the Manufacturing and Inspection Plan [6].



Figure 2: Three pre-series collimators at CERN.

COLLIMATOR PRODUCTION

The collimators can be divided into three main sub-assemblies (Fig. 3): the jaws (two per collimator) providing the beam-collimation functionality, the vacuum vessel enclosing the jaws, and the mechanical tables (two per collimator) mounted on the outside of the vessel, supporting and moving the in-vacuum jaws. The construction of the collimators consists in the production and assembly of the various components, with specific tests and acceptance criteria linked to each step. These criteria are based on operational requirements and return of experience.

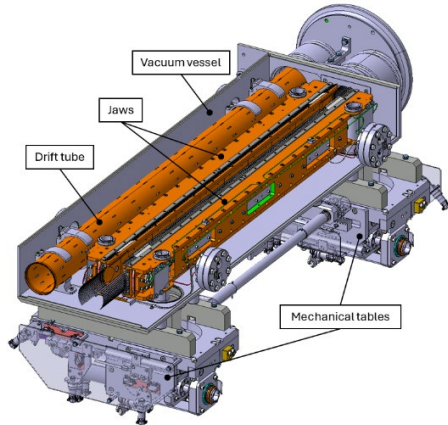


Figure 3: TCTPXH collimator with cut-view of tank.

Mechanical tables

After machining of all parts and metrology of the critical components, the mechanical tables were assembled according to the drawings and procedure detailed in [7]. Each pair of mechanical tables was subjected to a torque test [8] before assembly onto the vacuum tank, to confirm that the mechanism behaves as expected: the tables' performance is evaluated in terms of required torque to move the table along its course, both static and dynamic, in both directions.

Jaws

The jaws must fulfill Ultra High vacuum (UHV) requirements [9]. After machining and metrology, all jaw parts were cleaned and assembled in a UHV-compatible clean environment. For the jaws' cooling circuits, two 4.5 m long CuNi pipes with a circular (inside) and rectangular (outside) cross-section were machined at the extremities and bent to cover the jaws surface area. An annealing treatment was performed on the pipes before bending to increase their ductility and ensure the pipes' integrity and leak-tightness [10].

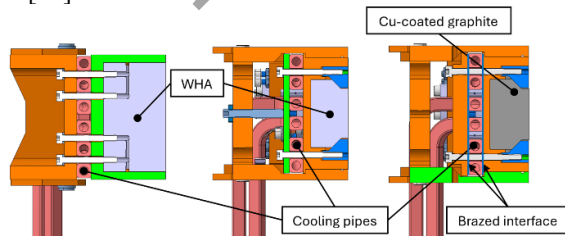


Figure 4: Jaws sections: TCLPX, TCTPXV, TCSPM.

Before installation on the jaws, the cooling circuits were subjected to a 20 min pressure test at 50 bar. For TCLPX and TCTPXV, the cooling pipes are mounted on the jaws in a "sandwich-like" assembly, whereas for TCSPM jaws, which are positioned closer to the beam, and thus experience higher heat loads, the pipes are vacuum brazed to the jaw's housing, to obtain optimal thermal contact (Fig. 4). Before brazing, the contact surface on the housing was plated with copper (10-15 μm), followed by Watt nickel plating (2 μm) [11].

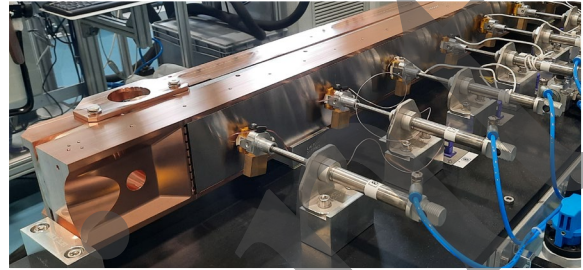


Figure 5: TCLPX jaw during thermal test.

After assembly, the jaws were submitted to a thermal test to evaluate the thermal performance of the jaws, using two dedicated test benches [12] (Fig. 5). At the start of this test, water at 80 $^{\circ}\text{C}$ is pumped through the cooling circuits, and the temperature on the active surface is measured with thermocouples. Performance is evaluated by the "characteristic time", i.e. the time required for the temperature on the jaws' active surface, which is the surface of the absorber blocks exposed to the beam, to go from 35 $^{\circ}\text{C}$ to 55 $^{\circ}\text{C}$. This cycle is repeated five times. The pre-series TCTPXV jaws were compliant, whereas the characteristic times for the two outermost thermocouples for the TCLPX jaws, and all thermocouples for the TCSPM jaws exceeded the limit on average by 11.5% and 23.4% respectively [13]. Through simulations, the flatness deviation during operation due to thermal deflection was evaluated to increase from 8 μm to 11 μm for TCLPX and from 13 μm to 16 μm for TCSPM, which was deemed acceptable.

In addition to thermal performance, the jaws must comply with very strict geometrical tolerances. Over the approximately 1 m long active surface of the jaws the straightness must be within 40 μm to 130 μm , depending on the collimator type. Greater accuracy is required for the secondary collimator jaws, since they sit closer to the beam. The Beam Positioning Monitors (BPM) integrated at each end of the jaws must be positioned with respect to the active surface with an accuracy of ± 0.05 mm.

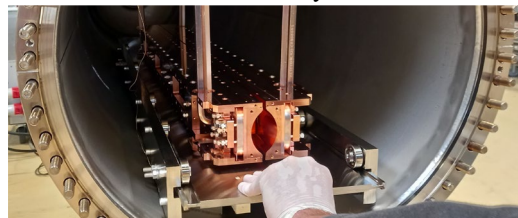


Figure 6: TCTPXV jaws in the bakeout oven.

After the thermal test and first metrology, the jaws underwent bakeout and a UHV test (Fig. 6), followed by another round of metrology. The results of the metrology

measurements were compared, and it was found that the jaws were geometrically stable during both transport and bakeout. The bakeout cycle was performed on one pair of jaws at a time in a vacuum furnace. It consisted of a ramp up to an external bakeout temperature of 250 °C, held for a duration of 48 h and followed by a cool-down period of 8 days. After reaching room temperature, a Residual Gas Analysis (RGA) was performed. All jaw-pairs showed outgassing rates below the allowed value of $5.0 \cdot 10^{-8}$ mbar·l·s⁻¹. For the RGA, the TCLPX jaws were below the defined limits, whereas the TCTPXV and TCSPM jaws were slightly above for certain masses, but this was deemed acceptable [14].

Vacuum vessels

The flexible connection between the mechanical tables and the vacuum vessel is ensured by the bellows and shafts assemblies (Fig. 7). The shafts were Electron Beam (EB) welded [15] to edge-welded bellows, and helium leak tested.

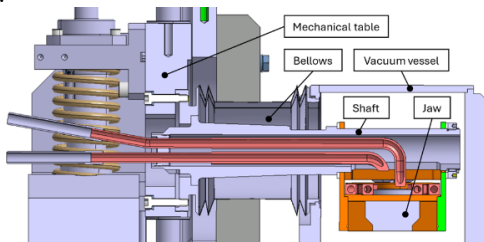


Figure 7: Section view of a bellows and shaft assembly.

The vessels' walls were waterjet-cut, vacuum fired and pickled before they were machined to their final size, along with the machining of the cooling circuits. Flanges, cooling plates, transition collars and studs were machined, measured, and all components were UHV cleaned. The cooling circuits were EB welded and subjected to a 20 min pressure test at 30 bar. The five sides of the vessels (without cover), flanges and collars were tack- and then EB welded together, followed by the final machining, metrology and UHV cleaning of the five-sides vessel. The edge-welded bellows and shaft assemblies were tack- and EB welded to the vessels. A second metrology was performed, including the flange flatness and knife profiles. After finishing the top cover, a helium leak test was performed on the completed vacuum vessels.

Collimator assembly

The collimators were assembled by mounting a pair of mechanical tables to each vessel, the shafts were bolted to the tables, the jaws inserted onto the shafts and the drift tube (for TCLPX only) mounted in the vacuum vessel. The BPM's and PT100 sensors were connected to the feed-through flanges and tested. Final metrology was performed, evaluating the jaws' straightness, BPM positions, as well as the jaws position in the vessels against the stroke's limits [16] (Fig. 8). Then, the limit switches were adjusted. Before the next torque test, the jaws are manually cycled through their full strokes to exclude any clash. The jaws cooling lines were subjected to a helium leak test followed by a pressure test at 30 bar for 20 min.

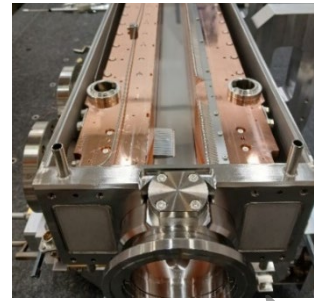


Figure 8: Metrology on the TCSPM collimator.

After these tests, the cover was tack- and EB welded onto the vessel, closing the collimator. After pumping down a leak test was performed. Still under vacuum, another torque test and BPM test were performed. Using a dedicated test bench, the pre-series collimators were then subjected to a vacuum acceptance test [17] (Fig. 9). During this test, the collimators were pumped down and ramped up to a plateau of 250 °C, held for 48 h. After the collimators had cooled down back to room temperature, an RGA and a helium leak test were performed. All collimators were below the requirements of $1 \cdot 10^{-10}$ mbar·l·s⁻¹ for leak rate, $1 \cdot 10^{-7}$ mbar·l·s⁻¹ for outgassing rate and within the specified thresholds for contamination detected with the RGA. Still under vacuum, a torque test, BPM test and PT100 test were performed. Before transport, the collimators were filled with pure nitrogen up to 1005 mbar.

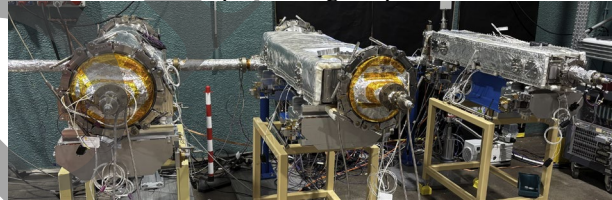


Figure 9: Bakeout test bench.

SITE ACCEPTANCE TESTS

The goal of the Site Acceptance Tests (SAT) is to evaluate the full conformance of the collimators to the specifications and prepare them for installation into the LHC ring (operational units) or long-term storage (spares). A procedure specifies the required steps and records results for each collimator. Among others, the major steps are the following: sensors and switches tests, torque test, impedance test, assembly onto the cradle and assembly of auxiliary components, cabling, and the vacuum acceptance test. To precisely align the collimators in the LHC machine, their beam axis' spatial positions are reported to the cradle external references using 3D laser tracking.

CONCLUSION

Three pre-series collimators for HL-LHC are fully assembled, all tests have successfully been completed, and the SAT have been finished. With this, the production process is entirely validated, and series production is fully underway, with production and assembly of mechanical tables, jaws and vessels happening in parallel to deliver the collimators to CERN in time for their installation into the HL-LHC.

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