DESIGN AND PROTOTYPING OF NEW CERN COLLIMATORS IN THE FRAMEWORK OF THE LHC INJECTOR UPGRADE (LIU) PROJECT AND THE HIGH-LUMINOSITY LHC (HL-LHC) PROJECT

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Abstract

In the framework of the Large Hadron Collider (LHC) Injectors Upgrade (LIU) and the High-Luminosity LHC (HL-LHC) Projects at CERN (European Organization for Nuclear Research, in Geneva, Switzerland), collimators in the Super Proton Synchrotron (SPS) to LHC transfer lines as well as ring collimators in the LHC will undergo important upgrades in the forthcoming years, mainly focused during the Long Shutdown 2 foreseen during 2019-2020.

This contribution will detail the current design of the TCDIL collimators with a particular emphasis on the engineering developments performed on the collimator jaws, aiming at getting a stringent flatness while considering also the integration of thermal shock resistant materials. The prototyping phase done at CERN will be also described.

The activities ongoing to prepare the series production for other LHC collimator types (TCPPM, TCSPM, TCTPM, TCLD) will be presented, describing the role that each of these collimators play on the HL-LHC Project. A focus on the series production processes, the manufacturing and assembly technologies involved and the quality and performance assurance tests will be given.

INTRODUCTION

The transfer lines joining the SPS to LHC shall be protected by two sets of six TCDIL (Target, Collimator, Dump, Injection, Long) collimators aiming at attenuating the LHC ultimate beam intensity to safe levels in case of erroneous beam transfer [1]. The beam power density is driving the machine damage potential. The Batch Compression, Bunch Merging and Splitting (BCMS) beam is driving the main TCDIL design parameter as it presents the worst (smallest) spot size and intensity combination (σ_x = 0.32 mm, σ_y = 0.51 mm and 5.76×10^{13} protons), expected to happen for collimator TCDIV.87804, the third collimator of the TI8 transfer line. Considering a material density of 1.8 g/cm^3, a new TCDIL absorbing length of 2.1 m is calculated to provide sufficient machine protection, and the related engineering studies are developed in this paper [2].

In the framework of the HL-LHC project, the LHC rings will store a beam energy up to 700 MJ at 14 TeV centre of mass energy). The higher beam intensity and the associated higher energetic proton losses require an upgraded LHC collimation system with the following functionality [3]:

- Efficient cleaning of the beam halo;
- Minimization of the halo background in the particle physics experiments;
- Passive protection of the machine aperture against abnormal beam loss;
- Minimization of the impedance through a highly electrical-conductor absorber.

The new HL-LHC collimators shall be produced with the scope of achieving those specifications.

TRANSFER LINES COLLIMATORS

The TCDIL collimators are 2.3 m long objects designed to precisely position two 2.1 m long jaws (beam diluters) around the proton beams. While the jaws are installed inside in a stainless steel Ultra-High Vacuum (UHV) vessel, an actuation system with four degrees of freedom insures the positioning. The collimators are mounted on “plug-in” structures, allowing fast installation and removal, including its alignment and the electrical connectivity.

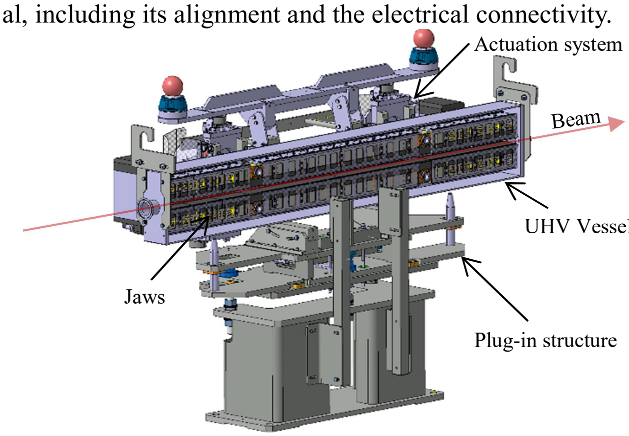

Figure 1: TCDIL collimator design.

TCDIL Jaw Design

TCDIL jaws consist of 3D carbon/carbon composite and isostatic graphite absorbing blocks supported by a stiffening assembly. Absorbing materials have been selected for their very good thermal shock resistance [4]. Indeed, in case of accidental miss-steered beam, very fast (7.8 μs) and large gradient of temperature are expected inside the material with peak temperature above one thousand degrees. For nominal operation, the specification of the jaws requires flatness below 200 μm over the faces highlighted in Figure 2, whereas it is supported in any direction by two cylindrical shafts.

* Research supported by the HL-LHC project
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The stiffening assembly of the jaws includes a 2.1 m long stainless steel 316L girder and a clamping system including springs. Engineering development and iteration allow optimizing the design while considering the integration limitations. A numerical model developed in ANSYS® estimates a maximum bow of 55 mm (Figure 3). In order to validate the conceptual design and regarding the geometrical imperfections from machining, a prototype of the TCDIL jaw was developed at CERN.

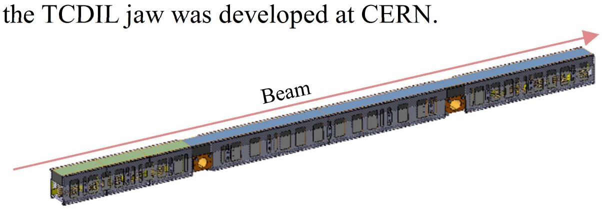


Figure 2: TCDIL-Jaw design. In green and blue, respectively the 3D C/C and graphite blocks faces with 200µm-flatness requirement.

Metrology controls with a precise MMT machine show a 71 µm flatness, and consequently validate the design.

Figure 3 compares the numerical model developed in ANSYS® and the prototype. The mean position of the absorbing block faces is plotted in the frame of reference defined by the theoretical shaft axis. The blue peaks at the jaw right extremity are due to the 3D C/C blocks. The red dotted line highlights the theoretical continuity of the jaw flatness if the graphite and 3D C/C blocks would have had the same thickness. In such a context, a slightly larger bow is reached with the prototype (90 µm) compared to the simulation (55 µm). The difference is explained by the influence of the clamping system, which tends to increase the deformations. However, these values are still within the acceptable limits and do not compromise the functionality of the TCDIL collimators, allowing the project to move to the production phase.

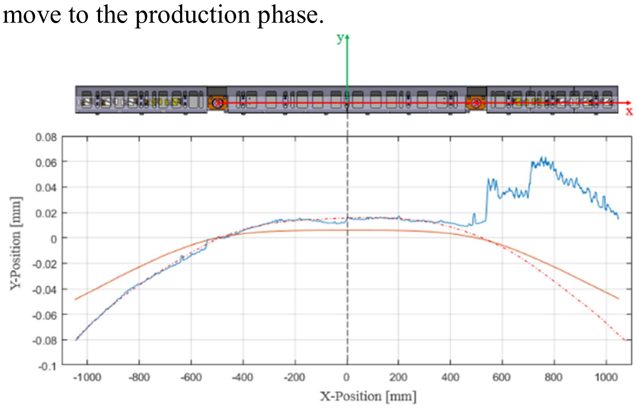


Figure 3: Comparison of the ANSYS® model (in red) and experimental prototype (in blue) of the TCDIL jaws.

LHC RING COLLIMATORS

The collimation system must be sufficiently robust to protect the LHC machine and has therefore been designed with a high level of redundancy and variety by using different types of materials, ranging from carbon composite and graphite for robustness, to higher atomic number materials like copper and tungsten alloys to stop the energetic particles. Very stringent tolerances for surface flatness and straightness of the absorbing jaws are required to assure the requested precision necessary for the correct functioning of the collimators with such high beam intensity and the required small beam size. The LHC collimation system is, by far, the highest contributor to the accelerator beam coupling impedance [5], which may significantly limit the machine performance: the use of jaw materials with low electrical resistivity is one of the possible impedance reduction strategies and is part of the present HL-LHC upgrade. Their lifetime and cleaning efficiency should be preserved under long-term particle irradiation.

TCPPM Collimators

Presently, the primary collimators of the LHC, called TCP, feature carbon-fiber-composite (CFC) active jaw material. In total, 8 TCPs are installed: 3 in the Insertion Region (IR) 7 and 1 in IR3 for each beam. In the context of the consolidation of the collimation system, a new modular design featuring Molybdenum Graphite (MoGr) as absorbing material and integrated orbit pickups (BPM) has been conceived: the TCPPM (Fig. 4). This design ensures a robustness comparable to that of the TCP [6,7], reduces the electrical resistivity by a factor 5 compared to the TCP and allows faster alignment of the collimator and continuous orbit monitoring. These collimators are aligned more often than any other type and therefore, deploying the BPM functionality in this case is particularly useful. The in-jaw BPM design has been successfully tested for other collimators (TCSP, TCTP) that were installed in the LHC during Long Shutdown (LS) 1 [8]. A TCP prototype with BPMs and CFC jaws, called TCPP, was installed in 2017 [9]. The external production and installation during the LHC LS2 of 4 new TCPPM is foreseen.

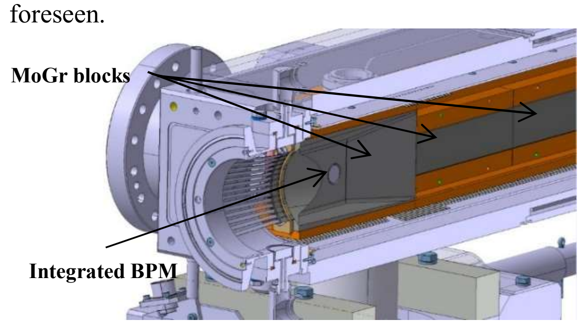


Figure 4: TCPPM-Jaw design with MoGr absorbing blocks and integrated BPM.

TCSPM Collimators

Presently, the secondary collimators of the LHC betatron collimation system in IR7, or TCSG, feature carbon-fiber-composite (CFC) absorbers. The design is essentially the same as that of the TCP. In total, 11 TCSG are installed per beam. The TCSG make up a large part of the LHC impedance [5], which should be minimized in order to push the beam stability limits on intensity and emittance. Therefore, a new design of secondary collimators, the TCSPM, has been conceived featuring a Molyb-

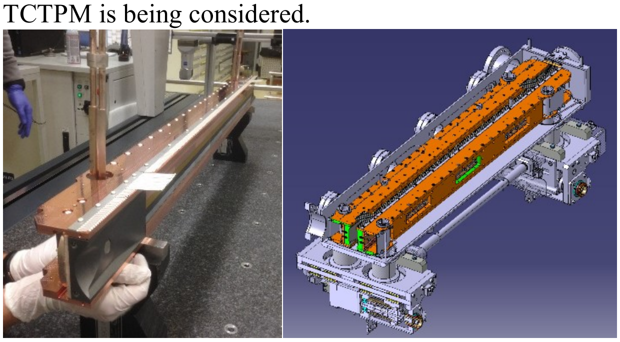
 ISBN 978-3-95450-182-3

denum-Graphite (MoGr) composite absorber with an additional metallic coating (Fig. 5). This design ensures a robustness comparable to that of the TCSG [6,7] and provides a reduction of 90% of the individual collimator impedance compared to the present TCSG, thanks to a reduction of resistivity by about a factor 100 [10].

A TCSPM prototype has been manufactured and tested at CERN and was installed in the LHC during the last LHC-Extended YEarly Technical Stop (EYETS) [11]. The external production and installation during the LHC LS2 of 8 new TCSPM is foreseen.

TCTPM Collimators

Presently, the tertiary collimators of the LHC, or TCTP, are required in all LHC experimental insertions to protect cold magnets with squeezed beams. In total, 8 TCTP are installed per beam. The HL-LHC baseline in IR1 and IR5 poses a new challenge in terms of machine aperture and require additional tertiary collimators compared with the present LHC layout that features only one pair of horizontal and vertical collimators protecting the triplet magnets [3]. Therefore, a new design of tertiary collimators, the TCTPM (Fig. 6), has been conceived featuring a Copper-Diamond (CuD) absorber material to improve the robustness against high losses while maintaining high-absorption, as required for an effective protection of the accelerator components downstream [6,7]. The external production and installation during the LHC LS2 of 4 new TCTPM is being considered.



Figures 5 and 6: TCSPM prototype jaw with coated MoGr absorbing blocks and integrated BPM (left) and TCTPM collimator design (right).

TCLD Collimators

Dispersion Suppressor (DS) collimators, or TCLD, featuring a Tungsten alloy absorber with a new actuation system and tank geometry (Fig. 7) will be integrated in the cold DS region in order to locally clean losses that otherwise would occur in the cold dipoles and quadrupoles. These collimators are warm and, around IR7, will be installed between two 5.5 m long 11 T dipoles that will replace a standard LHC dipoles [12]. Around IR2, 1 TCLD collimator per side of the IR is necessary to allow high luminosity ALICE operation while remaining safely below quench limits of the superconducting magnets [12]. In this insertion, TCLDs will be installed at the location of the connection cryostat without need for 11 T dipoles.

A TCLD prototype is being manufactured and tested at CERN. The external production and installation during the LHC LS2 of 4 new TCLD is foreseen.

Collimators Series Production

The collimator series production process requires several technologies and capabilities in order to achieve the quality and functionalities demanded. High precision dry machining in order to manufacture pieces complaint with UHV requirements and made out of divers materials (Carbon based materials, Stainless Steel, Aluminium, Copper

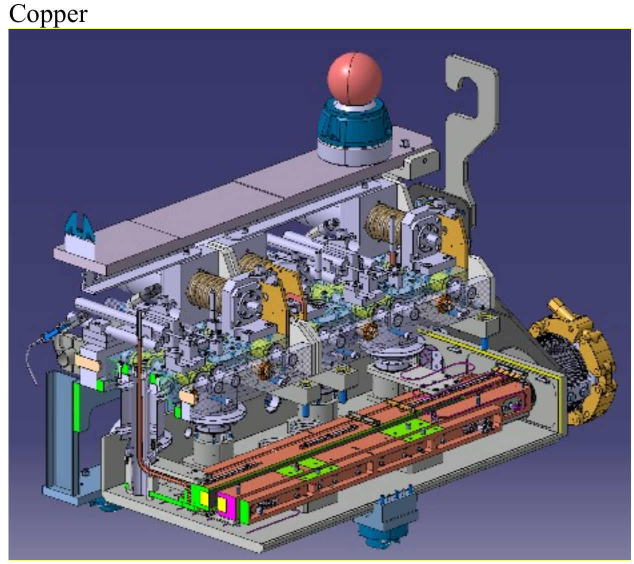


Figure 7: TCLD collimator design.

and Tungsten based alloys), featuring challenging geometrical tolerances, is a fundamental process. Surface treatments such as electroplating (Ag, Ni, Rh, Cu), etching and passivation are key for the preparation of elements between processes as well as thermal treatments and UHV cleaning. The vacuum brazing of the sandwich-like configuration of the back stiffener-cooling circuit-block housing is a critical step to assure a thermal contact capable of dissipating the heat generated on the absorbing blocks. High quality welded joints are essential to maintain the UHV condition of the collimators. Electron Beam Welding (EBW) is used in several forms (on parallel lips, circular butt and transparency) on the main joints of the vacuum tank. TIG welding is also used on areas non-accessible by EBW. All welds must have 100% penetration, no ground finish and must assure a leak rate less than 5×10^{-10} mbar.l.s^{-1}. The assembly, adjustment and alignment of precise mechanisms in a clean and controlled environment is imperative.

Several tests are to be perform along the production process as part of the quality plan: 3D metrology control of key pieces and sub-assemblies, the jaw movement is tested thorough a motor torque measurement, the quality of the bonded contact achieved is measured by a thermal contact conductance test bench. The vacuum quality is to be checked by a leak tests and a bake-out cycle followed by an outgassing measure and RGA. Electronics and BPMs are also subjects for validation. An impedance evaluation shall be conducted and all transports shall be closely monitored by means of accelerometers.

CONCLUSIONS

Intense engineering development allowed to get a mature TCDIL design, compliant with LIU project requirements. CERN recently launched the production of 16 TCDIL collimators for an installation foreseen in 2020.

CERN is currently in the process of a series production of 4 TCPPM, 8 TCSPM, 4TCTPM and 4 TCLD. These collimators are part of the HL-LHC project and will be installed during the last part of the LHC LS2.

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ISBN 978-3-95450-182-3