QUALITY ASSURANCE FOR THE HL-LHC BEAM SCREEN PRODUCTION

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Abstract

The HL-LHC project is currently in the fabrication and assembly phase for numerous components and systems, in particular the new beam-screen assemblies to be installed inside the upgraded final-focusing superconducting magnets operating at 1.9 K. These complex beam screens integrate tungsten absorbers and exist in two variants: the Q1 and Q2 types, with absorber thicknesses of 16 mm and 6 mm, respectively. In total, 24 assemblies will be installed. Their successful implementation requires complex design work, non-standard and demanding manufacturing processes, and stringent quality assurance. Fabrication has proven to be very challenging in terms of welding and assembly and requires close follow-up and dedicated qualification processes throughout the manufacturing phase. To maintain a high standard of manufacturing, a Quality Management approach derived from industrial standards and based on ISO 9001 principles, has been implemented. This paper presents how the quality-management framework is deployed throughout the project phases and how it ensures traceability, smooth process execution, and compliance with the required workflows and technical specifications.

INTRODUCTION

The HL-LHC project aims to upgrade the current LHC infrastructure, in particular in the regions close to the two large, general-purpose experiments, ATLAS and CMS. The primary objective is the increase of luminosity which leads to a high heat load reaching the beam screen cryogenic vacuum system operating at 60 to 80 K installed in the 1.9 K superconducting magnets. [1]. One of the key internal components of the new final focusing magnets is the design and production of new beam screens. To protect the superconducting coils from premature radiation-induced damage caused by particle beam collision debris and to intercept heat load created by the collision debris to preserve cryogenic cooling capacity, it is necessary to add external shielding to the beam screen [2]. Each side of interaction points 1 (ATLAS) and 5 (CMS) includes six magnets: four quadrupoles (Q1, Q2a, Q2b and Q3), one corrector package (CP) and one dipole magnet (D1), leading to 24 shielded beam screens to install in the machine. The design of the shielded beam screen is shown in Fig. 1. It relies on a co-laminated and perforated octagonal beam screen tube, actively cooled by four spot welded cooling tubes. Tungsten absorbers are positioned in both vertical and horizontal planes. Thermal links brazed on the absorbers are welded to the cooling tubes to ensure efficient heat transfer to the cryogenic cooling system [2].

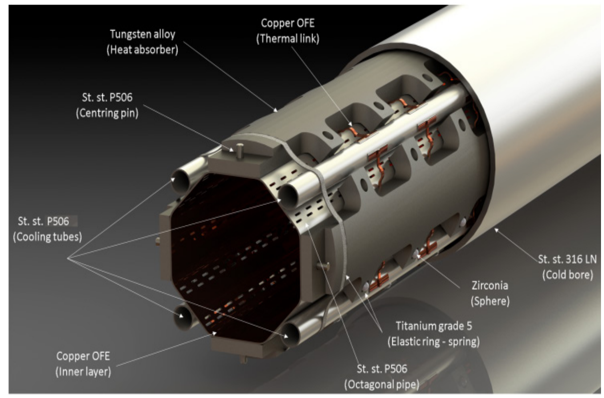

Figure 1: Beam screen design [3].

QUALITY ASSURANCE AND QUALITY CONTROL STRATEGY FROM MATERIAL SELECTION TO INTEGRATION IN THE MAGNETS

During the manufacturing and integration phases, all critical parameters must be verified and validated to eliminate the risk of chemical contamination, as well as mechanical defects and ensure full compliance with all specifications. Due to the high criticality and precision requirements specified in the technical documentation, the processes of component sourcing, preparation, and installation require exceptionally tight tolerances and specialised verification methods that differ significantly from those used in standard manufacturing. To maintain the manufacturing quality, a series of interrelated activities are carried out depending on the progress of each installation stage. These stages are divided into three phases:

Phase 1 – Material Preparation

During the first phase, components are chemically cleaned to eliminate any possible contamination within the vacuum system. The first quality checkpoint is a vacuum acceptance test that includes a Residual Gas Analysis (RGA) [4]. During this procedure, the mass spectrum is measured using a quadrupole mass spectrometer at room temperature. Analysis of the mass spectrum, presented in the form of diagrams, confirms the absence of unwanted molecules or contaminants as shown in Fig. 2. The test for the standard beam screen components such as titanium compression rings, titanium springs, ceramic balls, and pumping slot shields is carried out once on 100% of the parts, or twice for the parts that undergo additional thermal treatment processes such as the tungsten absorbers (Fig. 3). In the latter case, only 20% of the batch is tested as a final verification step before storage and installation. To ensure the compatibility of the tungsten absorbers with the required magnetic field quality, a chemical compliance certificate is requested, particularly regarding iron (Fe) content [5]. Magnetic permeability is measured for each production batch by the company. Non-compliance of Fe content was identified on 11 absorbers. But after measuring the magnetic permeability they were nevertheless validated. In addition, a pre-series run was carried out on about 20 absorbers of the two thickness. Mechanical property measurements were performed on cut samples and testing was conducted for the brazing of thermal links. Mechanical properties are measured by the company on each production batch and additional specimens are sent to CERN. About 3000 tungsten absorbers have been produced and all have been engraved individually with a unique identifier to ensure traceability. In addition to the RGA, other operations were carried out at CERN before assembly included metrological measurements for all components, pressure testing of all cooling tubes, mechanical measurements on titanium components and ultrasonic tests on the ceramic balls.

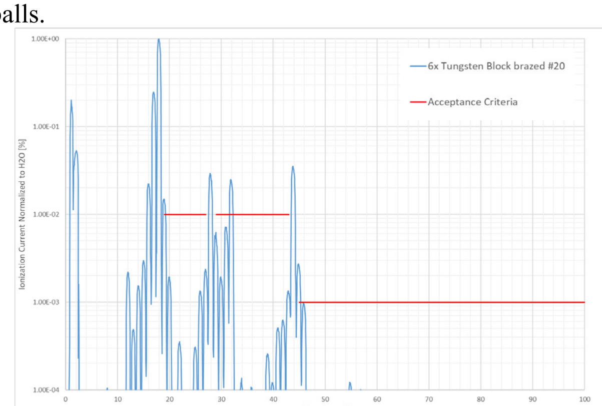

Figure 2: RGA analysis for batch 20 [6].


Figure 3: Tungsten absorbers - Q1 type.

Phase 2 – Beam Screen Assembly

During the beam screen assembly phase, two types of quality verification is carried out:

1. Standard process control, which follows defined installation procedures and step-specific activities. Activities are described on the Manufacturing Inspection Plan (MIP) [7], and it is mandatory to prepare and publish complete documentation. The documents must be clear, accurate, and include the information regarding the tools used and sequence of the operations. Examples of such operations include:
   - 3D scanning of the beam screen tube metrology,
   - Visual inspection and adjustment of thermal links before welding,
   - Visual inspection after welding,
   - Manual recording of the tungsten absorbers installed on each beam screens.
2. Test-based control, which relies on defined test procedures [8] and their corresponding references. For beam screen assembly, this includes visual inspection [8] of welds between thermal links and cooling tubes, as well as general visual inspection. Helium leaks are absolutely forbidden in the cryogenic vacuum system and given the high added value of the tungsten absorber integration, a combined pressure [9] and leak test [10] is performed twice, i.e. before absorber integration at room temperature and up to 36 bars helium pressure and after thermal link welding [11] at cryogenic temperature (~80 K) and up to 36 bars helium pressure. During the two combined pressure/leak tests, the beam screens are installed in a vacuum vessel and the absence of potential contamination is confirmed by RGA. Beam screen positioning pins, welded by electrical capacitor discharges, are 100% tested with a shear force up to 2 kN, corresponding to twice the conservatively estimated force occurring during a magnet quench [3]. The final manufacturing step is the amorphous carbon coating of the beam screen assembly. Test samples are installed at the extremities of the beam screens and treated during the same coating run. Secondary electron yield is measured on the samples and a final RGA is also carried out.

The example shown in Fig. 4 and Fig. 5 below illustrate the assembly of the tungsten absorbers. This is a two-person procedure followed by cross-verification. The approach of individual self-control is not used.


Figure 4: Beam screen without shielding.

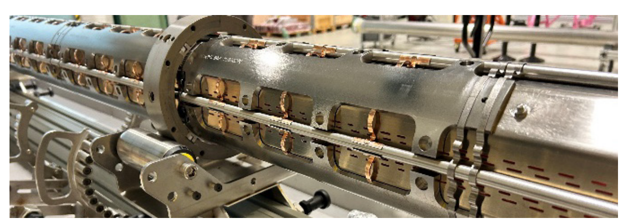
Figure 5: Beam screen with the Q2 shielding assembly.

Phase 3 – Cryomagnet Assembly

In Phase 3, the frequency of verification tests increases as the number of steps required to prepare the magnet (Fig. 6) for installation rises. The activities which are carried out include:

- Cleaning of the cold bore tube and leak test of the cold bore flange,

- Visual inspections,
- Pressure and leak test on a dedicated bench used for the fixed-point assembly, including the BPM,
- Electrical test (BPM),
- Alignment measurements,
- Final Pressure and leak check;

The process and progression through each stage are documented in a dedicated form. This form is attached outside the magnet at the beginning of the magnet installation and is returned once the system is ready for use, serving as confirmation that the magnet has been correctly assembled.

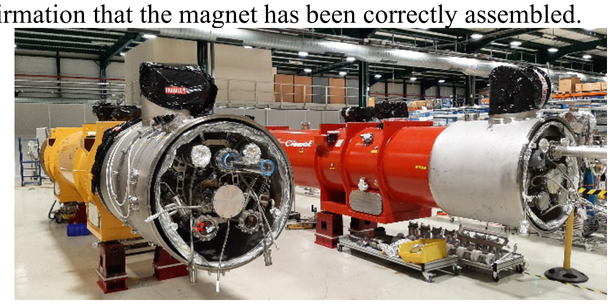

Figure 6: Cryomagnet assembly for Q1(right) and CP (left).

IMPLEMENTATION IN THE CERN ENVIRONEMENT

All manufacturing data are collected internally. The first elements initiating the data chain are 2D drawing and 3D Catia models, which are named according to the internal CERN standard [12]. They are subsequently supplemented with the technical documentation providing information on materials and components are stored in the internal documentation databases EDMS and MTF. The system for assigning and cataloguing parts is designed to remain as close as possible to the original MIPs and Tracking sheet. In this way, the data remains secure and accessible to all individuals involved in the project. The system does not perform operations such as job scheduling, productivity calculations or production time estimation. Its function is solely to collect data. This allows documentation to be uploaded in various file formats and from different environments that are fundamentally distinct from one another (e.g. MS Office and CATIA V5).

OUTCOMES

The output data obtained during the inspection primarily includes compliance with specification requirements, as well as the time, date and location of the assembly activities. The operating environment enables efficient and in-depth quality control. Each issue, i.e. non-conformity (e.g. Fig.7), can be easily tracked and analysed. If a non-conformity is detected, the inspector is required to report it, after which the documentation is completed with a detailed specification of the root cause:

- What is defect?
- Who is in charge of this case?
- When was the defect detected?
- Where was it detected?
- Why it happened?
- How it can be solved?
- How many elements are affected?

For each non-conformity, corrective actions are defined to recover the component. Preventive actions are also implemented to ensure that the issue does not recur.

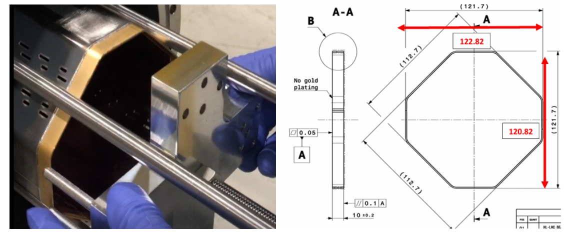

Figure 7: Non-conformity of the golden ring for the Beam Screen edge – incorrect dimensions [13].

CONCLUSION

The first cryomagnets for the High Luminosity upgrade of the LHC have been successfully completed, including beam screen insertion, and the remaining cryomagnets are currently being assembled. Underground installation is expected in the coming years. An effective quality control strategy for the beam screen preparation is defined within the Manufacturing Inspection Plan in advance. It relies on appropriate quality checks and controls performed before, during and after each activity. To improve the accuracy, dedicated quality inspectors are assigned to every manufacturing step. To enhance data transfer between activities, documentation including procedures and test results is regularly updated. In addition, practical validation of each newly developed procedure has been introduced to ensure that the documentation effectively supports the management of each process.

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