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NEW BEAM LOSS MONITOR IONISATION CHAMBERS ENGINEERING

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Abstract

More than 4000 Beam Loss Monitor (BLM) systems are operating at CERN. About 93% of them are installed in the LHC machine. The Ionisation Chambers (IC) are the part of the system where the lost beam particles ionise nitrogen gas in a chamber with electrodes at high voltage. The resulting current indicates the quantity of beam lost. In the last 20 years, all BLM ICs were produced in collaboration with external institutes.

Control of all details of the materials and processes are required to ensure instrument sensitivity and precision across the large series.

CERN took back this production process in 2022 and much of the specific knowledge of design details and production technology required re-engineering.

This paper presents production specifications, design of tooling and test facilities for the first prototypes of a new series to be produced including their test at CERN facilities with beam. The future ramp-up to an industrial process to allow for a production of 1000 units in the years to come is discussed.

INTRODUCTION

The BLM ICs are the signal pick-up element of the beam loss monitoring system. The signal is measured by acquisition modules in the LHC tunnel, followed by processing and decision modules on the surface as part of the beam protection and interlock system. The BLM system latency to trigger a beam abort needs to remain below 3 beam revolutions around the LHC, corresponding to 267 µs. The beam losses in the LHC are discussed in [1]. CERN has long experience with the production of BLM ICs in collaboration with external institutions [2]. The objective of the present manufacturing campaign of 1000 BLM ICs is to prepare for the CERN High-Luminosity LHC (HL-LHC) [3] upgrade and to complete the BLM renovation in the LHC injector complex.

The design criteria is to make BLM ICs resistant to radiation in the CERN environment for to up to 30 years of operation. To achieve this objective, only metals (aluminium, copper and stainless steel) and ceramic such as Al_2O_3 can be used. Experience has shown that very strict control of all components, processes and assembly is essential in keeping the required precision.

ENGINEERING REQUIREMENTS

The standard BLM IC monitor is about 50 cm long with a diameter of 9 cm (Fig. 1). The internal volume is about 1.5 l. There are 61 parallel aluminium plates separated by 0.5 cm, filling most of the vacuum container. Between each of the plates, there is a voltage of 1.5 kV. They are equipped with a low-pass filter outside the vacuum envelope. A key element of the BLM IC is a very high impedance ceramic supporting the rods to which the parallel electrodes are fixed. The maximum current permissible across the ceramics of the assembled electrode stack is 1 pA when a voltage of 1.5 kV is applied.

Figure 1: Finished BLM (left) and electrode stack of the ionisation chamber with ceramic insulators on either side (right).

The technically admissible leak rate for the BLM ICs, with a pressure difference of 100 mbar over a 30-year span, is $1*10^{-6}$ mbar.l/s. Assuming possible leak degradation, allowing for contingencies and adhering to standard leak test practices in industry, a maximum leak rate of $1*10^{-9}$ mbar.l/s is calculated as the engineering criterion for the delivery of the ICs.

To minimise the risk of leaks, low inclusion content stainless steels of type 304L, according to CERN internal specifications [4, 5] are used for the IC chamber parts.

All welds are executed by Tungsten Inert Gas (TIG) arc welding under argon atmosphere without filler material. Alternative welding methods, such as laser or electron beam welding, may be proposed by future manufacturers but must be as cost effective as the TIG welds. The most challenging weld to perform is that of the “pinch-off” tube, an annealed copper tube welded to the end plate made of stainless steel, as shown in Fig 2. CERN has experience in performing these welds in a leak-tight and cost-effective manner using TIG welding. The welds are leak checked at the end of the BLM End Plate production.

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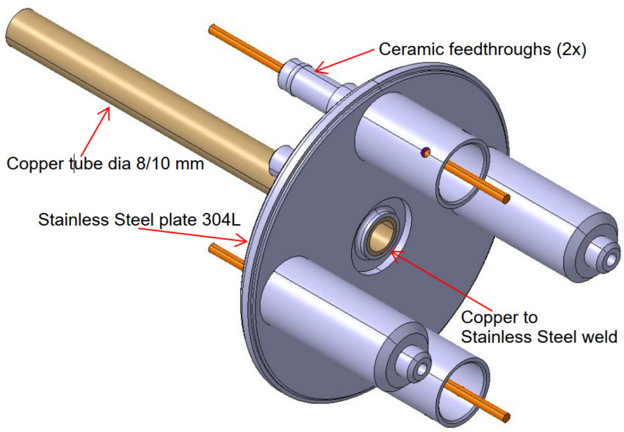

Figure 2: BLM End Plate requiring ultra-high vacuum compatible welds of copper to stainless steel (SS) and SS to SS.

To assure consistent performance of the BLM ICs, all metal parts are cleaned to Ultra High Vacuum (UHV) standard to avoid contamination with hydrocarbons. The ceramic insulators and feedthroughs are not intended to be cleaned after reception. The cleanliness of these components is guaranteed by the manufacturing process and will be sample-checked upon arrival at CERN. The cleaning of the ceramic might hamper the very high electrical resistance of the ceramic if conductive residuals from the cleaning bath remain on the surface or in the matrix of the ceramic. To further standardise the cleanliness quality of the items housed in the closed volume, the chambers are baked at 220 °C while being pumped. The ramp rate to heat up and cool down is 50 °C/h with a minimum plateau time of 12 h. At the end of the bakeout cycle, nitrogen class 50 is used to re-fill the BLM to the absolute final pressure of 1100 mbar, i.e., 100 mbar overpressure.

To reduce dependency on a small number of suppliers and ensure that the know-how is well documented, a series of technical specifications have been developed. The structure of these specifications and documents is shown in Fig. 3. This enables CERN to choose from several options for BLM IC chamber production: in-house, in collaboration with partner institutes, through industry or a combination of these options.

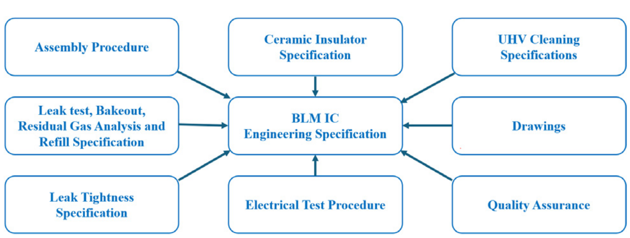

Figure 3: Schematic of the Specifications, Procedures, Drawings and Quality Assurance.

MANUFACTURING STEPS

CERN's strategy is to procure all raw materials following quality assurance and materials availability, irrespective of the assembly location, to minimise dispersion in performance. The feedthroughs and ceramic insulator will be procured ready for assembly. CERN will then deliver these materials to the sub-component industrial manufacturer where applicable.

The most challenging items to procure are the above-mentioned end plates and ceramic insulators. The assembly of the cleaned parts as seen in Fig 1. (right) must happen in a low dust and low volatile carbon environment to avoid contamination. The full assembly must be checked for completeness of all 330 parts. The final tightening of the assembly is made with a torque wrench pre-loading a Belleville washer stack to prevent differential thermal expansions during bakeout from overstressing the ceramic insulator. The assembly will then be integrated into the chamber ensuring good electrical connections towards the end plate. The welds on either side of the tube will terminate the assembly of the BLM IC. The performance of the ceramic insulators is then checked to be below the required 1 pA at 1.5 kV. The assembly will then be installed on the Test Stand as shown in Fig. 4.

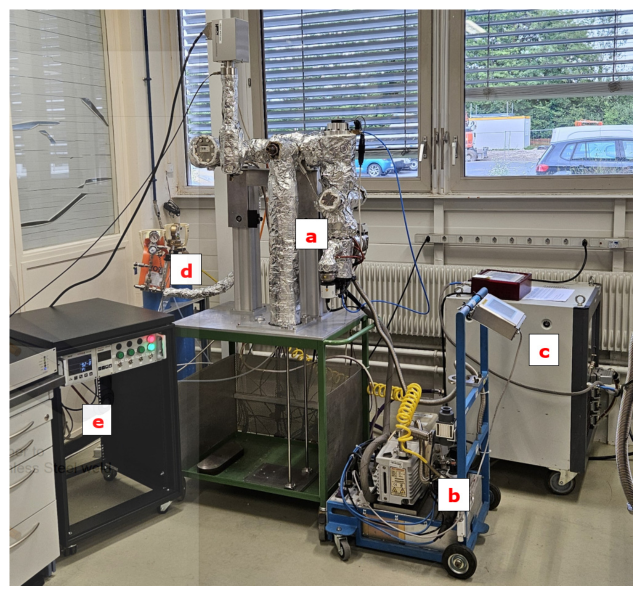

Figure 4: BLM IC Test Stand including: a) bakeout and injection device with vacuum gauges and Residual Gas Analyser (RGA); b) pumping group; c) bakeout controller; d) nitrogen and helium bottle; e) control rack for the gauges and valves.

The BLM IC is mounted on the Test Stand and a leak check to a minimum sensitivity of 10^{-9} mbar.l/s is performed. If no leak is detected, the bakeout cycle can start once the electronics of the RGA are removed. The RGA is degassed once the system is stable at 150 °C towards the end of the bakeout, followed by a cool-down to room temperature. After over-night pumping of the system, an RGA scan is performed. If the absence of leaks and hydrocarbon levels of atomic masses above 40 relative to hydrogen can be demonstrated to be a factor of 100 lower, the scan is registered, and the so-called "pinch-off" is performed. The pinch-off is the cut of the soft copper tube using a special

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plyer tool allowing for a leak tight cut of the tube from the test stand. If the remaining part of the tube on the test stand is leak tight, the opposite side on the BLM IC is considered leak tight from experience. Currently the BLM test stand allows only one BLM IC at a time. However, an extension is planned to enable the simultaneous testing of up to 20 units during series production.

The final assembly of the electronic parts is performed on the BLM IC.

ELECTRICAL QUALIFICATION

The proper functionality of the BLM IC is evaluated through the electrical qualification process. Its primary phase examines critical IC components prior to assembly, while its secondary phase validates the detector at the end of its production cycle.

The focus of the primary phase is directed towards the rigorous testing of the aforementioned ceramic insulators and feedthroughs, therefore, guaranteeing that the procured elements comply with the specification. A dedicated custom-made test bench, controlled via a PC, was built to perform an automated screening process that identifies electrically defective ceramic insulators. The instrument simulates the operational electrical conditions of the detector and classifies any ceramic as faulty after measuring a leakage current above 10^{-12} A. The delicate measurements of the test bench are susceptible to environmental conditions such as electromagnetic noise, temperature, humidity, and the chemical or biological contamination of the ceramic. Therefore, the use of silicon gloves, the enclosure of the ceramic inside a Faraday cage, the implementation of various verification steps, as well as the recording of environmental data assure the proper functionality of the device and evaluation of the ceramic.

A similar validation is performed on the feedthroughs via a commercial insulation meter also controlled by a PC. A voltage of 3000 V is applied for two minutes across the feedthrough and the component is classified as defective if its resistance is inferior to 1 TΩ. Due to the sensitivity of the test, various metadata are recorded such as the test environment's temperature and humidity conditions as both of these factors greatly influence the resistivity readouts. On average the duration of the primary qualification phase requires four minutes per element.

Once the detector is fully assembled, a secondary validation phase consisting of two definitive tests is made to qualify the IC as operation-ready. The first uses the forementioned test bench to repeat the ceramics test and the second deploys a tunnel installation simulator that supplies a modulating voltage to the detector and assesses the signal response.

QUALITY ASSURANCE

All metallic semi-products are purchased by CERN, using CERN specifications on stainless steel for vacuum applications. Assemblies and high added-value components are tracked individually as assets, all other parts as batches. Individual tracking is made for ceramic insulators, electric feedthroughs, BLM end plates with the welds, welded BLM IC vacuum chambers and the full assembly of the BLM with the electrical components.

All relevant parameters as defined in the corresponding technical specifications are recorded and uploaded in the CERN asset management system based on an Oracle database. For the elements with lower criticality, the batches are recorded including the material certificates, certificates of conformity and statistical checks to assure the conformity of the item.

SERIES PRODUCTION OF 1000 PARTS

CERN has gained experience using the newly developed specifications with a production of 5 units which were successfully tested in the CERN HiRadMat irradiation facility. These tests will be discussed in future publications. All raw material is being procured. Companies that can produce the ceramic insulators and end plates for the series have been identified. A test stand design is prepared to allow for bakeout and refilling of 20 BLM ICs in one bakeout cycle. All BLM IC connections will have individual valves to allow elimination of one unit in case of a leak or other issues without changing the bakeout planning of the remining BLM ICs.

The ramp-up of CERN in-house production is ongoing to achieve a production of 400 BLM ICs by the end of 2025. CERN is looking forward to identifying industrial partners from CERN member states or to set up collaborations with institutes to produce a total of 600 BLM ICs starting in 2026.

SUMMARY

CERN established several detailed procedures to allow for the production BLM ICs. A series of prototypes show that in-house production successfully fulfils the requirements of the BLM system. Systematic control and documented quality of components is essential for this instrument. The scaling up to a production of a total production of 1000 BLM IC is underway with both CERN in-house and industrial production.

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