

# HL-LHC BGI MECHANICAL DESIGN: INTEGRATION, IMPEDANCE, AND VACUUM ASPECTS

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## Abstract

A new Beam Gas Ionisation monitor is being designed for the High Luminosity LHC era. The paper describes the challenges for the mechanical design of the instrument taking into consideration the instrument functionality, impedance compatibility, vacuum acceptance and tunnel integration. The new design also takes into consideration the lessons learnt from the operation of these monitors in the LHC injector chain (PS and SPS) throughout the past 10 years. Four new instruments will be installed during the Long Shutdown 3, providing transverse beam profile measurements in the horizontal and vertical planes for both beam 1 and beam 2 of the LHC.

## INTRODUCTION

The Beam Gas Ionisation (BGI) monitors are ionisation profile monitors (IPMs): non-invasive transverse beam profilers based on the detection of electrons produced by the beam – residual gas interactions [1]. They are beam energy independent, offering the possibility of a continuous bunch by bunch acquisition of the evolution of the transverse beam profiles.

Several monitors are installed in the Proton Synchrotron (PS) and Super Proton Synchrotron (SPS), providing the above-mentioned monitoring [2, 3]. A new development for the High Luminosity LHC era is underway, it being the best candidate for high energy and high intensity continuous bunch by bunch monitoring. Despite the basic principle being straightforward, the underlying challenges are far from being trivial:

- To extract the electrons produced in the vacuum chamber, a high voltage cathode, biased at -30 kV, defines some material choices as well as the geometry of the instrument chamber to avoid discharges.
- Compensation of the space charge effects that would lead to a distortion of the beam profile implies the use of 0.6 T magnets, which will be defining the outer envelope for the instrument itself.
- Electrons are being detected with a TimePix4 detector and acquired by a Printed Circuit Board (PCB), that needs to be compatible with the Ultra High Vacuum environment.
- The TimePix4 produces 2 W during operation, requiring active water cooling to ensure its functioning.
- The whole instrument needs to match the impedance requirements for the HL-LHC era, both in terms of transparency to the beam and energy deposition to the instrument, induced by RF coupling with the beam. Only the latter aspect will be treated in this paper.

- The beam RF field interacts with the in-vacuum electronics which needs to be protected with a Faraday cage.
- Finally, the beam aperture at the beamline location needs to be respected as well as the transparency to the beam trajectory that the magnets could affect, constraining even more the integration of the instrument into the beamline. Corrector magnets upstream and downstream each of the instrument are needed to close the beam orbit.

## MECHANICAL DESIGN OVERVIEW

Figure 1 shows the latest version of the mechanical design of the HL-LHC BGI:

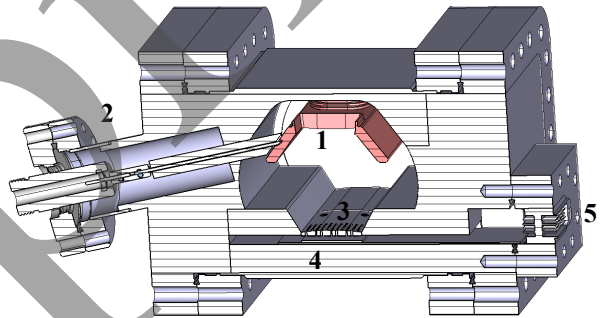


Figure 1: HL-LHC BGI mechanical design.

The High voltage cathode (1) with its feedthrough (2) have been dimensioned and designed to optimise the uniformity of the electromagnetic field accelerating the electrons. These latter fly through the RF grid (3), designed to maximize the signal while shielding the detection and acquisition electronics lying just underneath from the beam induced field (4). The lateral, rectangular CF flanges allow for compactness of the overall design, while accommodating the UHV feedthroughs for both the HV cathode and signal extraction (5).

Due to the space constraint imposed by the magnet aperture, the overall instrument height at the instrument location is 105 mm. This design is an evolution of the PS and SPS designs [3, 4] in many aspects: the HV feedthrough is now decoupled from the sensor flange; the RF shielding for the electronics and the detector is largely improved to cope with shorter bunches and the cathode shape presents a new and more optimised shape for a better field homogeneity in a very compact design; The detector is using a single Timepix4 sensor, larger in size compared to the Timepix3,

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allowing for a more compact design of the overall instrument. Figure 2 shows the Timepix4 detector stack, where several bonding techniques are being explored allowing a thermal and electrical optimised contact between different materials:

- Soldering TimePix4 to ceramic insulator (AlN): Au-Sn filler at 285 °C or glueing, with a MgO based glue, curing at 100 °C for 3h.
- Brazing the ceramic insulator to the cooling plate (W80Cu20): Cusil-ABA (A high-purity Active Braze Alloy of silver, copper and titanium developed for direct application to ceramic surfaces) at 400 °C.

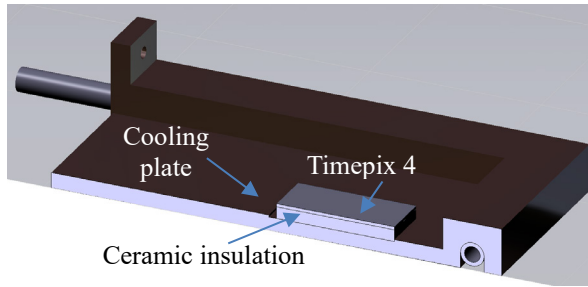


Figure 2: HL-LHC BGI Timepix4 Detector Stack assembly on its cooling plate.

The efficiency of the stacking in terms of thermal conductivity and accuracy in the positioning will be evaluated in dedicated thermal load tests.

## MACHINE INTEGRATION

Four BGIs in total will be installed in the LHC tunnel in Long Straight Section 4: one per beam per plane (horizontal and vertical profilers). The integration of the instruments is constrained by the following:

- Longitudinal space availability in LSS4;
- Transverse space availability in LSS4 both in terms of beam lines spacing for beam 1 integration and the cryogenics distribution and beam line spacing for beam 2 integration;
- Symmetry of the two systems with respect to the IP4, to allow having the same  $\beta$  function at the location of both detectors;
- Corrector magnets upstream and downstream of the instrument to suppress the transverse kick induced on the beam trajectory due to the presence of the BGI magnet;
- Access to the instrument for maintenance;
- Access to the instrument for alignment and mechanical connections to the neighboring vacuum chambers.

After several iterations and optimizations, the integration of the BGI instrument that fulfills the above-mentioned criteria is shown in Figure 3. The BGI magnets slide horizontally to allow access to the instrument for installation and maintenance (Figure 4). The common girder between the main magnets and one of the corrector magnets is needed because of space constraints but each of the elements can be aligned independently, within the required  $\pm 200 \mu\text{m}$  tolerance.

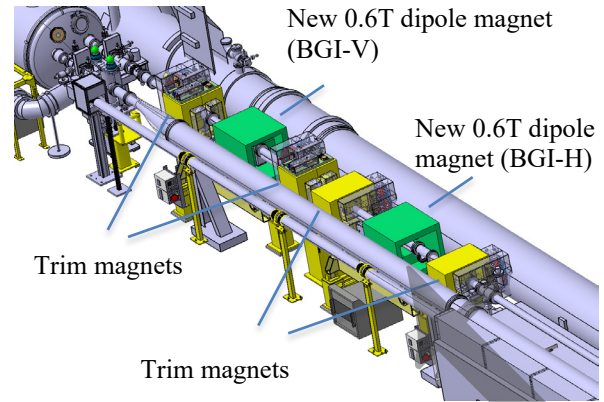


Figure 3: HL-LHC BGI tunnel integration in Long Straight Section 4 Right.

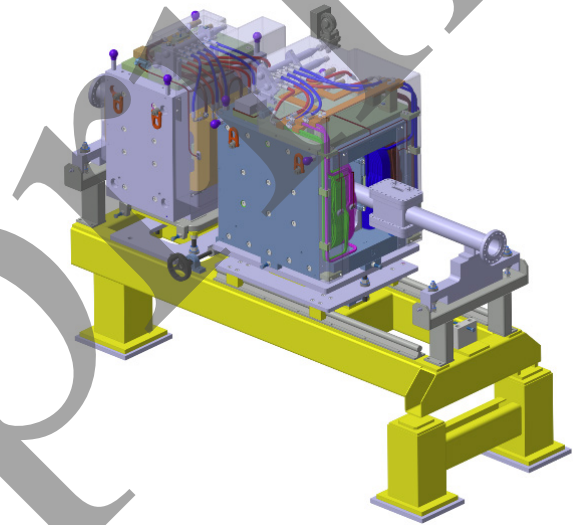


Figure 4: Instrument magnets in maintenance (sliding) position.

## IMPEDANCE EVALUATION

The HL-LHC BGI design has been evaluated for impedance with respect to the nominal HL beam parameters:  $2.3 \cdot 10^{11}$  p/b, 1 ns bunch length, with HL-LHC filling schemes as detailed in [5]. According to the results of CST simulations, the proposed design induces resonances, mainly outside of the beam spectrum, with a low frequency shoulder (Figure 5): a total of 78 W of beam-induced power is expected. The power loss map indicates that 80% of the power will be captured by the HV feedthrough, while the remaining 15 W are shared between the vacuum chamber and the cathode. A dedicated thermal analysis is ongoing to evaluate the thermomechanical effects. A thorough design of a matched load to absorb the deposited power on the high voltage feedthrough is crucial to ensure the functioning of the instrument: Figure 6 shows the electric field monitor and its coupling with the cathode and the HV feedthrough in the unmatched case.

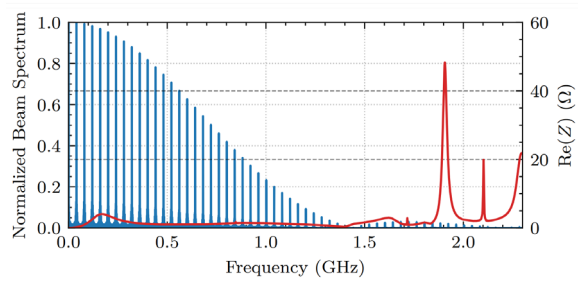


Figure 5: HL-LHC Normalised beam spectrum (blue) and the expected BGI Longitudinal impedance (red).

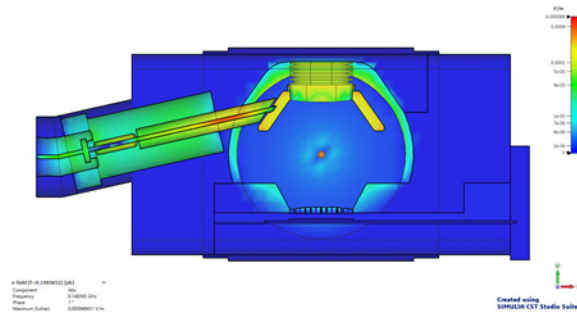


Figure 6: Electric Field map of the main RF mode coupling to the beam (frequency  $\sim 148$  MHz).

As mentioned above, one of the new features of the HL-LHC BGI with respect to the previous designs of the instrument is the thorough RF shielding of the detector stack and its electronics. The SPS-BGI proved the importance of such shielding as EMI interferences were experienced during its commissioning when 25 ns LHC type beams were circulating in the SPS, hindering the acquisition of the beam profiles.

Figure 7 compares the newest version of the grid made of 1mm diameter holes in a hexagonal pattern, inducing an attenuation estimated at 200 dB with a cut-off frequency of 176 GHz. This design is a compromise between allowing enough electrons through the grids to be able to reconstruct an accurate beam profile and an efficient shielding of the detection and acquisition systems.

For sake of comparison, the figure shows the design and electric field map of the honeycomb RF grid previously integrated into the SPS-BGI design, highlighting its transparency to the beam-induced frequencies.

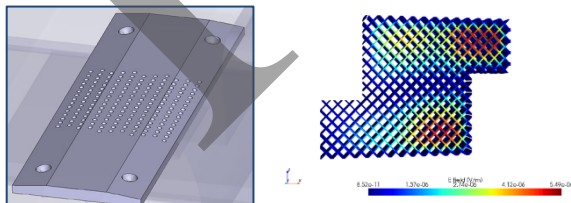


Figure 7: HL-LHC BGI vs the SPS – BGI RF grid pattern.

## VACUUM ASPECTS

The vacuum compatibility of the instrument is a balance between compliance with the LHC UHV vacuum requirements, and the possibility for the instrument to detect not

only the electrons produced by the core of the beam, but potentially also its tails and halo (beyond  $3.5\sigma$ ). The target pressure for the installation is therefore in the  $10^{-9}$  mbar range. For this reason, neighboring vacuum chambers, which would normally be NEG coated, will be aC coated, leading to a slightly higher-pressure profile in the region, while guaranteeing electron cloud suppression in the area.

The whole instrument assembly must comply with the maximum allowable outgassing rate, according to LHC vacuum specifications.

The most complex components in terms of vacuum compliance are the Timepix4 detector stack and the in-vacuum electronics. For the latter, the PCB material has been tested and proved its compliance in terms of outgassing rate. For the detector stack several techniques are used to assemble the detector to the ceramic plate and the ceramic plate to the WCu cooling plate, as mentioned in the first paragraph, which are UHV compatible.

Finally, from the PCB the signals are transferred to the feedthrough via bare copper wires. No polymeric clad wires are foreseen in this installation.

## CONCLUSION

The design of the HL-LHC BGI instrument has been detailed in most of its critical aspects including impedance, UHV and tunnel integration aspects.

A careful study of the HV feedthrough is ongoing to reduce further the deposited power by the beam.

Thermal tests are foreseen during 2026 to assess the thermal properties of the detector stack and the cooling capacity of the cooling circuit, to ensure correct functioning of the TimePix4. Before and after these tests the sensor position will be measured to monitor any possible displacement when a thermal load is applied. This test will be crucial for assessing the contribution of this subassembly to the overall alignment budget of  $\pm 200 \mu\text{m}$ .

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