PROCEEDINGS OF SCIENCE

Towards the validation and assembly of the CMS MTD Barrel Timing Layer

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In preparation for the High Luminosity era of the LHC, a substantial upgrade to the accelerator will be undertaken to substantially boost the achievable luminosity compared to its current state. To withstand the harsh experimental conditions in terms of pileup and radiation at the HL-LHC and maintain the current excellent performance, substantial upgrades of the experiments are ongoing. In particular, the CMS upgrade will include a novel timing layer, the MIP Timing Detector (MTD), designed to measure the time of arrival of charged particles with a resolution of about 30-60 ps. The MTD will equip both the barrel and the endcap part of CMS. The sensor technology chosen for the central part of the MTD is based on LYSO:Ce scintillating crystals readout by silicon photomultipliers. In this talk we will present an overview of the Barrel Timing Layer design and describe the optimization of the sensors. Protoype sensors were tested both in laboratory and at test beam, showing a time resolution performance compliant with the design goal. These results represent an important reference for the detector validation, which will shortly lead the CMS MTD collaboration to the assembly phase of the BTL.

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1. Introduction

A High Luminosity phase of the LHC is scheduled to start in 2029, bringing a fivefold increase in luminosity [1]. However, this anticipated boost comes with the challenge of higher radiation damage and pileup levels, as illustrated in fig. 1, posing particular challenges in the accurate reconstruction of vertices. In response to these challenges, experiments are actively undergoing multiple upgrades to maintain the current performance. Among the upgrades of the CMS experiment [2], the integration of a new MIP Timing Detector (MTD) has been planned. This addition will provide the capability to precisely measure the arrival times of charged particles with a precision of 30-60 ps. Such precision will allow for the disentanglement of overlapped vertices that would otherwise remain unresolved when relying solely on spatial information, as depicted in fig. 1 [3].

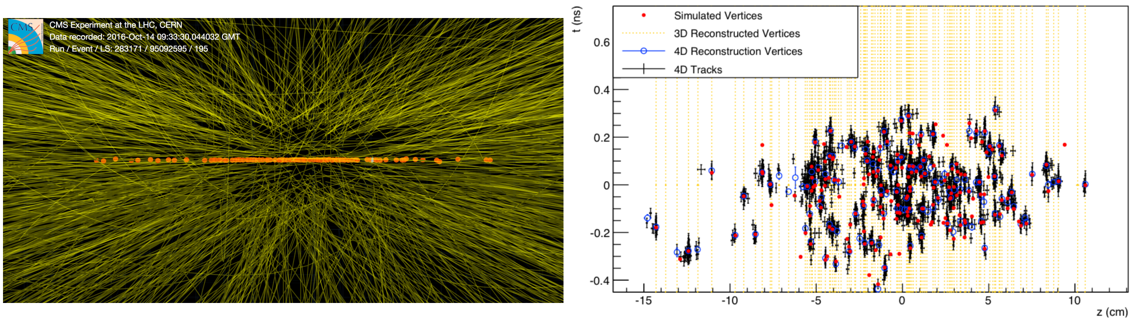

Figure 1: Left: Event display of 100-interaction pileup in a 2016 run. Right: Simulated and reconstructed vertices with 200 pileup interactions using a 30 ps timing detector, showcasing 3D-reconstructed vertices, and 4D tracking and vertices. [4]

The integration of MTD will enhance the detector's capabilities (e.g. identifying charged particles based on the time-of-flight, searching for long lived particles, etc.) and it will decrease the number of tracks originating from pileup vertices being erroneously assigned to the primary interaction vertex. This enhancement will result in improved efficiency in reconstructing physics objects. It will enhance the isolation of leptons, enable more accurate tagging of b-jets, and reduce the rate of pileup jets. These improvements will, in turn, enhance the statistical sensitivity of many benchmark measurements, including the self-coupling of the Higgs boson.

The MTD will cover the pseudorapidity (η) region up to η = 3 and will consist of two parts, the central one (the Barrel Timing layer) up to η =1.5, and the forward one (the Endcap Timing Layer). Different sensors technologies are chosen for the two regions because of different requirements on the radiation resistance, constraints on integration, cost and power budget. The Endcap Timing Layer (ETL) will consist of modules of Low-Gain Avalanche Diodes, whereas the Barrel Timing Layer (BTL) will be constructed using arrays of LYSO:Ce crystal bars read out at both ends by Silicon Photomultipliers (SiPMs). The studies discussed here focus on the characterization and validation of the final design of the BTL modules. The fundamental element of the BTL detector is the sensor module, comprising an array of 16 LYSO:Ce crystal bars coupled to SiPMs at both ends, showed in fig. 2. Two sensor modules connected to the readout ASIC (TOFHIR) [5] and enclosed within a copper housing form the detector module and twelve detector modules compose a readout unit. The BTL's surface is equipped with 72 trays, each incorporating 6 readout units, as shown in fig. 2.

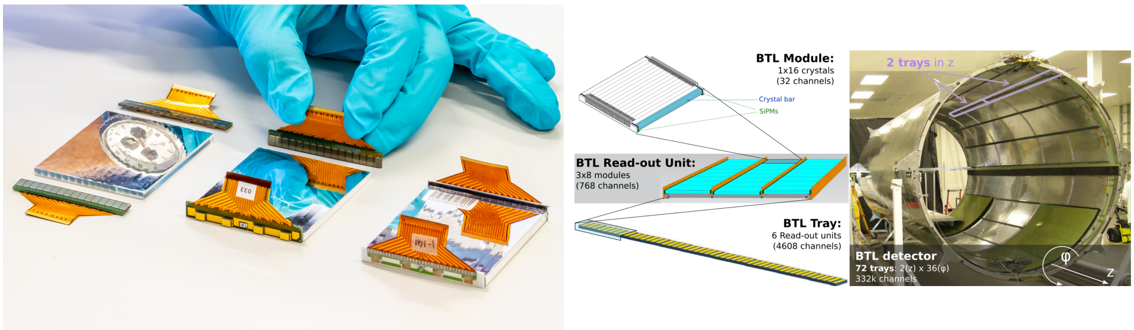

Figure 2: Left: Picture of BTL sensor modules. Right: Hierarchical structure of the BTL components (left) and trays enclosed within the mechanical support (right).

The choice of LYSO:Ce crystals is driven by their significant light yield, fast scintillation time, and good radiation tolerance. The elongated crystal bar shape is chosen to optimize the light collection efficiency by capturing optical photons within the angle of total internal reflection. SiPMs offer excellent tolerance to magnetic fields, a compact design, and rapid timing characteristics. In the initial MTD TDR design [4], the different crystal thicknesses are used in three different pseudorapity regions, going from the thickest at $\eta = 0$ to the thinnest at $\eta \sim 1.5$. These geometries are referred to as type 1 (3.75 mm), type 2 (3.00 mm), and type 3 (2.75 mm), and result in a more uniform slant thickness along η, as shown in fig. 3. In each region, the crystals are coupled to 15 μm cell size SiPMs, matching exactly the crystal end face dimensions.

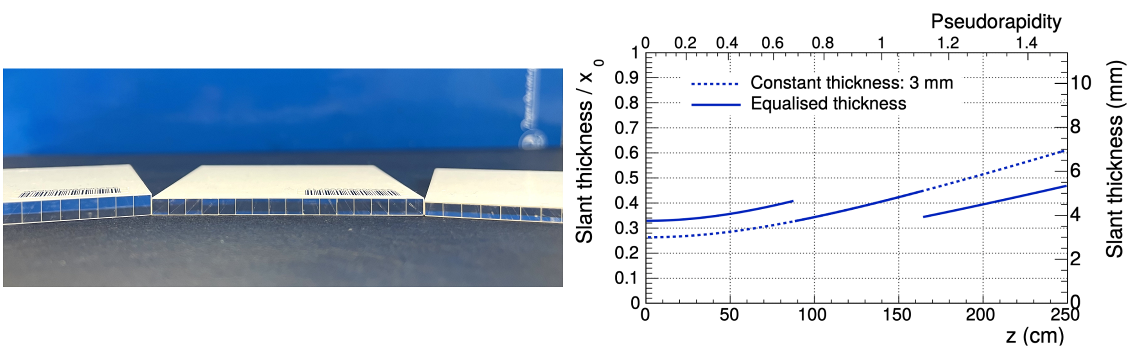

Figure 3: Left: Different LYSO array types (from left to right: type 1, type 2 and type 3). Right: BTL slant thickness along detector axis z.

2. Tackling BTL challenges at HL-LHC

The BTL goal is a time resolution of 30-60 ps throughout the operation of HL-LHC and the factors that contribute to time resolution are reported in Eq. 1:

$$\sigma_t^{BTL} \sim \sigma_t^{ele} \oplus \sigma_t^{phot} \oplus \sigma_t^{DCR} \quad (1)$$

During the initial phases of operation, the contribution of the electronics noise (σ_{ele}) and of the stochastic fluctuations in the time of arrival of photons detected at the SiPM (σ_{phot}) will dominate the time resolution. Throughout the HL-LHC operation, sensor modules will be exposed to an accumulated radiation levels of 32 kGy of ionizing dose and a neutron fluence of 2×10^{14} 1 MeV n_{eq}/cm^2. While the crystal transparency is only marginally affected, the primary effect is radiation-induced damage to the SiPMs, leading to a significant increase in the Dark Count Rate (DCR). In the original design, SiPMs were planned to be operated at -30ºC and annealed at room temperature during technical stop periods to mitigate radiation-induced DCR. In recent years, further optimization studies on the sensors have been conducted, with a focus on reducing the impact of radiation damage and enhancing sensor light output.

To effectively reduce the DCR, Thermo-Electric Coolers (TECs) [6] have been integrated into the SiPM package. This integration enables the reduction of the operational temperature to -45°C and an increase in the annealing temperature to 60°C, resulting in a DCR of 10-30 GHz per SiPM, toward the end of operation. Simultaneously, efforts have been addressed to enhancing light output. Using SiPMs with larger cell sizes was expected to enhance photon detection efficiency (PDE) and gain. Moreover, the potential benefits of optimizing the packaging have been explored. A reduction in the amount of glue used between the LYSO array and the external wrapping was projected to increase light output by approximately 10%. Additionally, studies involving modules of different thicknesses were conducted to evaluate the potential for improved performance due to greater energy deposition and light collection efficiency in the thickest crystals compared to thinner ones.

To validate the outcomes of these studies, a combination of laboratory measurements and testing during dedicated beam campaigns were executed.

3. Performance validation

To explore the impact of different cell sizes on the timing performance, SiPMs with cell sizes of 20 and 25 μm were produced and measured both in laboratory and during test beam campaigns. For non-irradiated sensors, which emulate the conditions at the beginning of HL-LHC operations, the test beam results confirmed the expected performance improvement with sensor modules with larger cell-size SiPMs. The test beam data were in excellent agreement with laboratory measurements using UV-induced scintillation light, as depicted in Figure 4, for the type 2 geometry. Our analysis showed that the larger cell size modules achieve improved stochastic contribution due to the higher PDE, alongside reduced electronics noise due to the augmented gain.

Assessing the SiPMs' performance under radiation-induced degradation is also crucial. SiPMs with cell sizes of 20 and 25 μm were irradiated, simulating the cumulative radiation dose expected for the BTL at the conclusion of HL-LHC (2×10^{14} 1 MeV n_{eq}/cm^2) and underwent accelerated annealing at high temperature equivalent to the annealing expected on the detector at the end of

HL-LHC. These SiPMs were then coupled to LYSO arrays and tested at different temperatures to mimic different stages of the HL-LHC lifetime in terms of DCR level. Remarkably, with both cell sizes a time resolution of about 65 ps was achieved, at end of operation conditions.

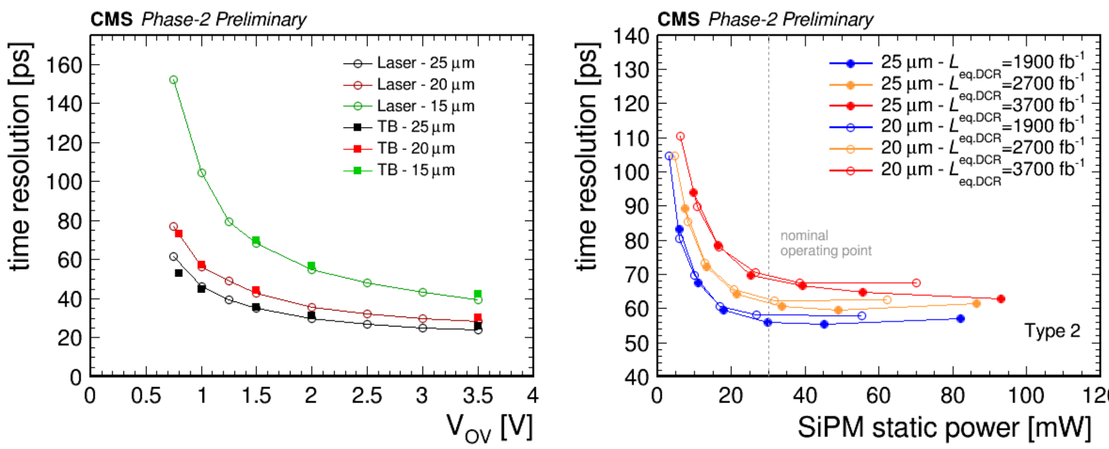

Figure 4: Left: Time resolution as a function of the SiPM over-voltage for three type 2-modules with non-irradiated SiPMs featuring different cell size dimensions (15, 20, 25 μm). The results obtained with data from beam tests (full markers) are compared to laboratory measurements (open dots). Right: Time resolution as a function of the SiPM static power for two type2-modules with irradiated SiPMs. Modules were tested at various operating temperatures to emulate different points along the detector lifetime.

During these test beam campaigns we also measured the performance of modules with different geometries both with non-irradiated and irradiated SiPMs. Due to the increase in energy deposit within thicker modules, an enhanced timing performance is expected. Tests performed on non-irradiated modules with 25 μm SiPMs showed an improvement in time resolution for the thickest module (type 1) with respect to the thinnest one (type 3), as shown in fig. 5 (left). While larger irradiated SiPMs are expected to exhibit higher DCR and power consumption, potentially affecting the observed improvement in time resolution with non-irradiated sensors, simulations suggest that the increase in light output would outweigh the impact of the increased DCR. Indeed, the collected data indicate that module thickening is beneficial even in the case of irradiated SiPMs, as reported in fig. 5 (right).

4. Conclusions and outlook

With the prototyping phase successfully completed and the performance targets met, we are now transitioning into the production phase. This phase will involve assembling the detector modules across four different assembly centers: the University of Milano-Bicocca, Peking University, the California Institute of Technology, and the University of Virginia, with plans to produce and test two trays per month, per site. Subsequently, these trays will be sent to CERN for integration at the Tracker Integration Facility, followed by further testing. The final installation within the BTL Tracker Support Tube is scheduled for May 2025, and the commissioning is expected to be completed by 2027.

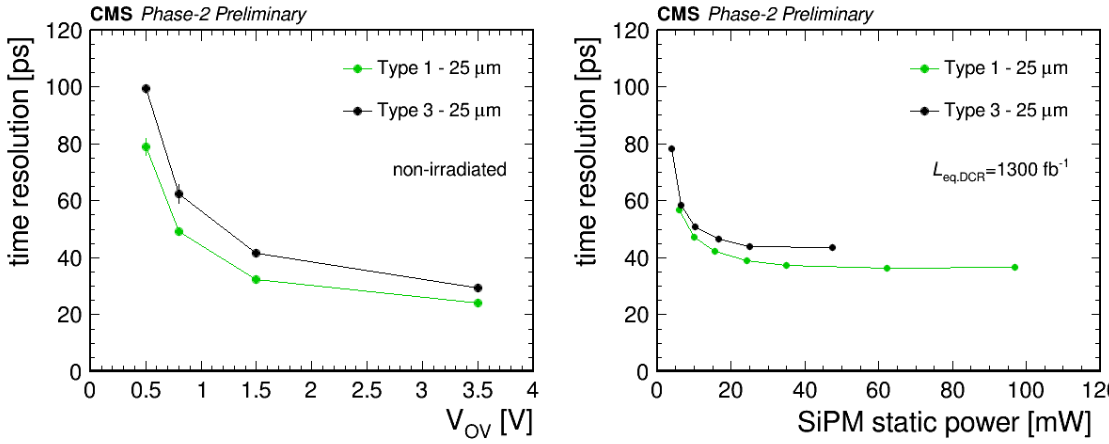

Figure 5: Comparison of the time resolution achieved with type 1 and type 3 modules. A better time resolution with thicker modules is achieved both with non-irradiated (left) and irradiated SiPMs (right).

In summary, the BTL prototyping phase has reached its conclusion. The optimization studies and validation processes have led us to select SiPMs with a 25 μm cell size due to their superior performance. Also, we will be using type 1 modules to cover the entire pseudorapidity region, as they have demonstrated significant improvements in time resolution, both with non-irradiated and irradiated devices. Test beam measurements have shown that these choices allow reaching the design goal of 30 ps for BTL beginning of operation conditions and 65 ps at the end of operation, in line with the projections from TDR, as shown in fig. 6.

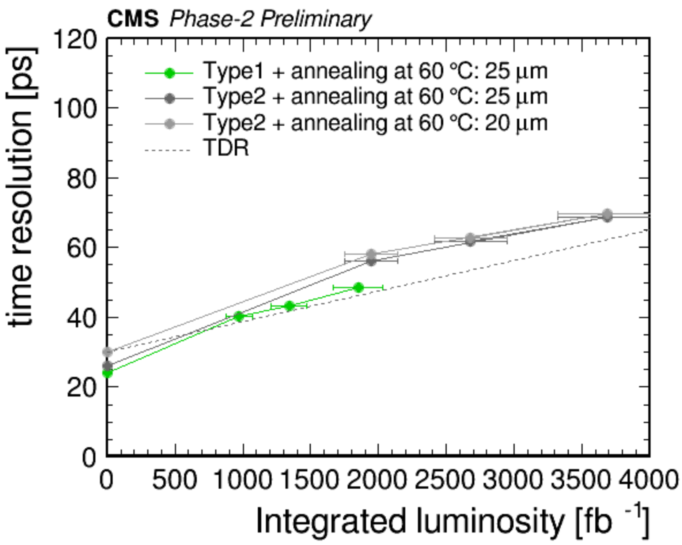

Figure 6: Time resolution as a function of the equivalent integrated luminosity (operation at T = -45°C and SiPM annealing at T = 60°C). Data are from test beam measurements of modules (both type 1, in green, and type 2, in grey) with non-irradiated and irradiated SiPMs and tested at various operating temperatures to emulate different points of detector lifetime.

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