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Precision Timing with the CMS MIP Timing Detector for High-Luminosity LHC

Fabio Cossutti for the CMS Collaboration

Abstract

The Compact Muon Solenoid (CMS) detector at the CERN Large Hadron Collider (LHC) is undergoing an extensive Phase 2 upgrade program to prepare for the challenging conditions of the High-Luminosity LHC (HL-LHC). A new timing detector for CMS will measure minimum ionizing particles (MIPs) with a time resolution of 30-40 ps. The precise timing information from the MIP timing detector (MTD) will reduce the effects of the high levels of pileup expected at the HL-LHC, bringing new capabilities to CMS. The MTD will be composed of an endcap timing layer (ETL), instrumented with low-gain avalanche diodes and read out with the ETROC chip, and a barrel timing layer (BTL), based on LYSO Ce crystals coupled to SiPMs and read out with the TOFHIR2 chip. This contribution will provide an overview of the MTD design and its expanded physics capabilities, describe the latest progress towards prototyping and production, and show the ultimate results demonstrating the achieved target time resolution.

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PROCEEDINGS OF SCIENCE

Precision Timing with the CMS MIP Timing Detector for High-Luminosity LHC

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The Compact Muon Solenoid (CMS) detector at the CERN Large Hadron Collider (LHC) is undergoing an extensive Phase 2 upgrade program to prepare for the challenging conditions of the High-Luminosity LHC (HL-LHC). A new timing detector for CMS will measure minimum ionizing particles (MIPs) with a time resolution of 30-40 ps. The precise timing information from the MIP timing detector (MTD) will reduce the effects of the high levels of pileup expected at the HL-LHC, bringing new capabilities to CMS. The MTD will be composed of an endcap timing layer (ETL), instrumented with low-gain avalanche diodes and read out with the ETROC chip, and a barrel timing layer (BTL), based on LYSO:Ce crystals coupled to SiPMs and read out with the TOFHIR2 chip. This contribution will provide an overview of the MTD design and its expanded physics capabilities, describe the latest progress towards prototyping and production, and show the ultimate results demonstrating the achieved target time resolution.

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1. The MIP Timing Detector: purpose and layout

The Compact Muon Solenoid (CMS) detector [1, 2] at the CERN Large Hadron Collider (LHC) has started a large upgrade program in view of the high luminosity stage of its data-taking HL-LHC, planned to begin in 2029. A significant increase of the number of simultaneous collisions per bunch-crossing, known as pileup (PU), is expected, with the average PU ranging from 140 to 200, to be compared with the present value of about 60. The availability of sensor technologies capable of a time resolution of few tens of picoseconds has led the CMS Collaboration to include a novel MIP Timing Detector (MTD) [3] in its upgrade plan, with the main target to determine the time of a track at the origin with a resolution of the order of 30-40 ps. The luminous region will have a spatial extension of about 5 cm, that will translate into a temporal spread of primary interaction vertices of $\mathcal{O}$(200 ps). Knowing the charged track time at its origin with an uncertainty about 5 times smaller should make it possible to separate spatially overlapping vertices by using the time coordinate, bringing the line density of vertices in different time frames down to a level comparable with the present one. In this way, the PU rejection strategies developed during the past LHC runs might be still effective. On top of that, the ability to measure temporal distances can be instrumental to a number of beyond-standard-model physics searches in the sector of long-lived and heavy stable charged particles.

The MTD detector is composed by a barrel and two endcap sections, as shown in Fig. 1 (left), ensuring a hermetic coverage in the region $|\eta| < 3$. The Barrel Timing Layer (BTL) is constituted by a layer of cerium-doped lutetium–yttrium oxyorthosilicate (LYSO:Ce) crystals, read by silicon photomultipliers (SiPMs), covering the acceptance $|\eta| < 1.45$ with a surface of about 38 m^2. It will be installed inside the Barrel Tracker Support Tube, in front of the electromagnetic calorimeter ECAL, being sensitive to charged tracks with $p_T > 0.7$GeV/c. The Endcap Timing Layer (ETL), composed on each side by two disks instrumented on both faces by fast silicon Low Gain Avalanche Diode (LGAD) sensors, will be installed in front of the forward High-Granularity calorimeter HGCal, outside the forward tracker volume. Overall the acceptance $1.6 < |\eta| < 3$ will be covered, for a surface of about 14 m^2.

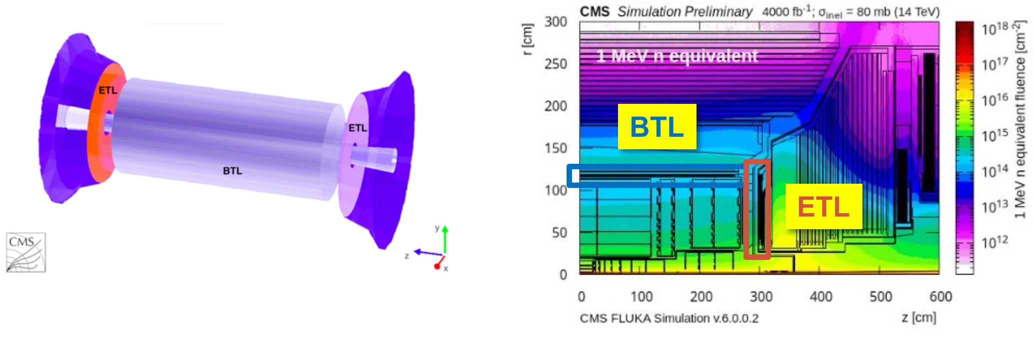

Figure 1: Schematic layout of the MTD detector (left) [3]. Expected radiation flux, in 1 MeV neutron equivalent, as a function of the position within CMS (right) [4].

The choice of different sensor technologies for different detector regions is dictated primarily by radiation hardness needs, besides cost and readout structure considerations. In Fig. 1 (right) the radiation flux in terms of 1 MeV neutron equivalent, as predicted by simulations [4] after an integrated luminosity of 4 ab^{-1}, is shown. It is evident that the region where the ETL will be installed, particularly in the highest η acceptance region, will need to withstand an integrated radiation dose approximately ten times higher than that of the barrel sector.

2. Barrel Timing Layer: sensor technology and achievable performances

The BTL sensitive elements are LYSO:Ce scintillator crystals, with a final geometry of $3.75 \times 3.12 \times 54.7\,\text{mm}^3$, organised in arrays of 16 bars each, named sensor modules. This material has been chosen because of its fast response, having a 40 ns decay time, its high density ensuring a most probable energy loss of about 0.86 MeV/mm for a MIP particle, and a high light yield of 40000 photons/MeV, that translates into a reduced photostatistics fluctuation component of the time resolution. Furthermore, this material is radiation-hard up to several tens of kGy, and therefore perfectly suitable for the level of integrated dose expected in the barrel region.

The light signal produced by each crystal is read at each bar end by a SiPM, with a cell size of 25 μm. The advantage of this layout is to provide two time measurements per bar t_1 and t_2, with an average $t_{ave} = (t_1 + t_2)/2$ that is practically independent on the position of the track crossing along the bar itself, so without the need of a precise determination of such a position. Besides this, the uncertainty on the average time is reduced by a factor $\sqrt{2}$ compared to each single measurement.

The signal produced by the SiPMs is processed by a custom readout ASIC, the TOFHIR [5] (Time-Of-Flight, HIgh Rate), providing high signal gain and noise filtering. Its most relevant feature is the Differential Leading Edge Discriminator: the input signal from the sensitive element is duplicated, and one of the copies is delayed, inverted, and overlapped to the other. The net resulting signal is in such a way squeezed to stay mostly within the 25 ns time window, corresponding to a bunch crossing time span, even if the tail of the photon signal is significantly longer, and with a sharp leading edge, that is used to define the output time from a threshold crossing.

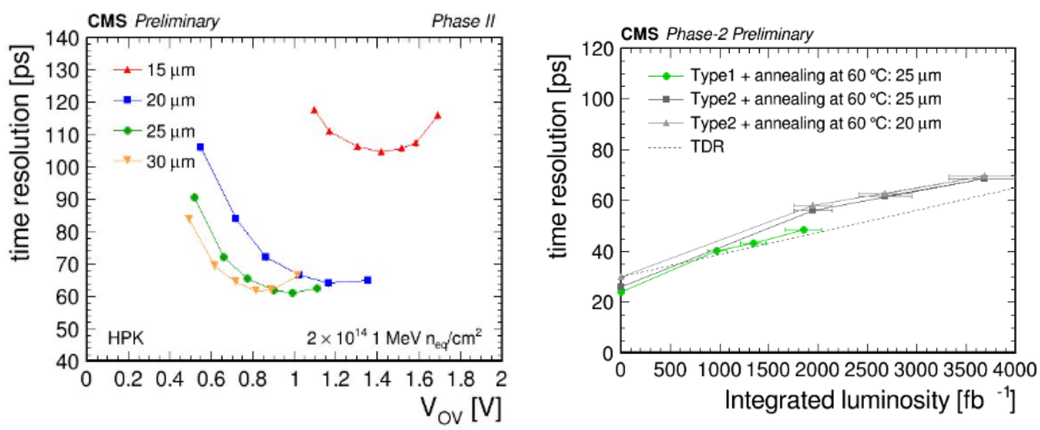

Figure 2: Time resolution measured for different values of the SiPM cell size as a function of the overvoltage V_{OV} (left) [6]. Evolution of the time resolution with integrated luminosity (right) [7]. The crystal type refers to its thickness, the final choice being Type 1 (3.75 mm).

The time resolution of the crystal signal can be decomposed in various terms:

$$\sigma_t^{BTL} = \sigma_t^{stat} \otimes \sigma_t^{elec} \otimes \sigma_t^{DCR} \otimes \sigma_t^{digi} \otimes \sigma_t^{clock}$$

accounting respectively for the photon emission statistical fluctuation, the electronic noise, the dark count rate (DCR) of SiPM, the digitization and the clock distribution contributions. The first three terms all depend on the light output N_{pe} as $\propto 1/\sqrt{N_{pe}}$, $\propto \sigma_{noise}/N_{pe}$, $\propto \sqrt{DCR}/N_{pe}$, respectively. A lot of effort has been invested in the optimization of the signal-to-noise ratio, so as to improve as much as possible the resolution terms directly dependent on it.

In order to maximize the light output, the maximal crystal thickness has been finally chosen for the whole detector acceptance, contrary to the initial design proposed in [3], and the LYSO packaging has been optimised. The dependence of the resolution on the SiPM cell size has been extensively investigated, as larger sizes imply a larger photon detection efficiency and SiPM gain, and consequently the possibility to operate the detector at lower overvoltage, where the noise has a smaller impact. The resulting dependence of the time resolution is shown in Fig. 2 [6] (left). The trade-off between this aspect and the maximal allowed power consumption has driven the choice .

The dominant contribution to the resolution at the detector end of operation (EoO) is expected to be the DCR, due to the radiation damage to the SiPM. The CO_2 cooling system is designed to maintain the temperature at -35 °C, which is instrumental to limit the radiation damage. In order to keep the overall resolution at the EoO within the anticipated budget of 60 ps, a further temperature reduction down to -45 °C is provided by thermo-electric coolers (TECs) installed on the SiPM package. A partial recovery of the detector damage is ensured by in situ annealing cycles outside the operation period, as shown in Fig. 2 [7] (right). TECs are planned to be used, with reverse bias, to bring the annealing temperature up to 60 °C.

3. Endcap Timing Layer: sensor technology and achievable performances

The sensitive elements chosen for ETL are LGAD silicon sensors, with a layout of 16×16 pads of size $1.3 \times 1.3\,\text{mm}^2$ each. The active thickness of the sensor is 50 μm, with a gain implant close to the readout electrode (to enhance the signal by a factor 10-30), aiming to ensure for the whole operational life of the detector a collected charge above 8 fC. This choice is a trade-off between the signal amplitude and the primary ionization time jitter, affecting the time response of the detector. The moderate gain is beneficial for the signal-to-noise ratio. This type of sensor is capable to stand the fluence also in the innermost region of the detector, where it is expected to be of the order of 10^{15} 1 MeV neutron equivalent per cm^2. The sensor will be read by a custom ASIC, the ETROC (Endcap Timing ReadOut Chip), bump-bonded on the sensor itself, providing a time-to-digital converter measuring the time of arrival and the time over threshold of each signal. The design resolution of the sensor-ASIC system is around 50 ps.

These sensors will cover both faces of two disks in each endcap section of CMS, in the radial acceptance $0.30\,\text{m} < R < 1.19\,\text{m}$, staggered in such a way that the areas for readout, power and cable infrastructure, disposed along lines in between sensor rows on one face, will be covered by sensors on the opposite face, so as to maximize the hermeticity. With such a layout, up to 85% of tracks could have two hits with time information, one per disk, with a combined time resolution reduced by a factor of $\sqrt{2}$ compared to that of a single hit.

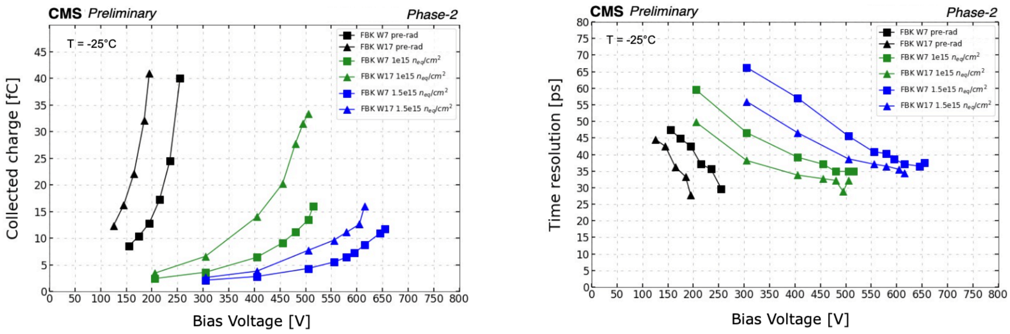

Figure 3: Response of LGAD sensors as a function of bias voltage for different level of irradiation: collected charge (left) and time resolution (right) [8].

Sensor optimization studies have been performed in collaboration with multiple vendors. Irradiation tests performed with a β ^{90}Sr source have shown that the target performance at the EoO is achievable by increasing the operational voltage. Sensor burn-out problems observed in test beam campaigns for high electric field, above 11.5 V/μm, suggest that the sensors can be safely operated at bias voltages below 600 V. The results shown in Fig. 3 [8], summarizing the response of LGADs in terms of both collected charge and time resolution as a function of bias voltage for different irradiation levels, prove that the original goal is achievable.

An initial version of the ASIC, ETROC1, implementing a limited 4×4 channel clock tree and wire-bonded to a LGAD, showed in a test beam a system time resolution in the range 42 - 46 ps. The test beam performed with the full 16×16 layout of ETROC2, bump-bonded to a LGAD, confirmed at the beginning of 2024 similar performances, with an average resolution of 45 ps.

4. 4D vertex reconstruction with MTD: strategy and challenges

As discussed in Ref. [3], the physics exploitation of MTD is based on the association of charged tracks reconstructed in the tracker detector to clusters with timing information, one per track in BTL and up to two in ETL. The time is back-propagated to the point of closest approach to the beam line, to serve as an additional information in 4D vertex reconstruction algorithms that exploit time measurements together with the space coordinate along the beam line. The request that a collection of tracks has compatible times in the candidate origin vertex is used as a constraint to remove the PU contamination, but simultaneously is needed to solve the ambiguity intrinsic in the propagation of time along the track path, since only the momentum is provided by the tracking system, and the mass of the particle is a priori not known. An iterative procedure is used to implement this approach in steps, starting with a common pion hypothesis and refining possible alternative assignments once a first set of vertices has been reconstructed. A recent development in this sense is the revised calculation of the vertex time, once tracks are clustered. A new Deterministic Annealing algorithm [9] has been designed to determine the optimal common time from a collection of clustered tracks without previous assumptions on their masses, accounting simultaneously for all the commonly expected hypotheses (pion, kaon, and proton) with some predefined probabilities.

Figure 4 shows the improvement obtained with this new algorithm, compared to the previous simpler track time weighted average, for the resolution and pull of reconstructed vertex times.

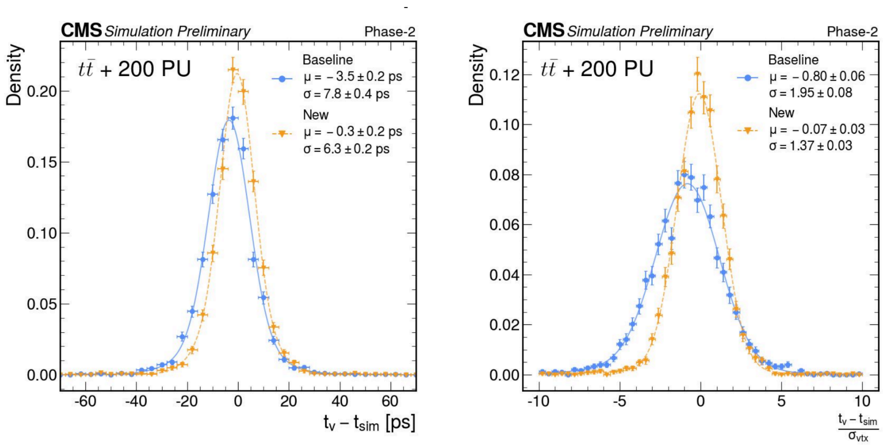

Figure 4: Comparison between the reconstructed vertex time resolution (left) and pull (right) obtained with the old time weighted average algorithm and with the new Deterministc Annealing approach [9] .

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