PROCEEDINGS OF SCIENCE

Progress on characterization of LGAD sensors for the CMS ETL

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Installation of a Minimum Ionizing Particle Timing Detector (MIP TD, also MTD) at the CMS detector will introduce new capabilities and will allow precise timestamp assignment to traversing charged particle up to pseudorapitidy of $|\eta| = 3$. Targeted timing resolution is 40 ps per track, which will help reduce the pile-up conditions expected at the High-Luminosity LHC. The endcap region of the MTD, Endcap Timing Layer (ETL), will be instrumented with silicon Low Gain Avalanche Diods (LGADs), covering the pseudorapidity range $1.6 < |\eta| < 3.0$. Progress on characterization of LGAD sensors for the ETL will be presented.

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1. Motivation

Starting from 2029, the Large Hadron Collider (LHC) will enter a new era, the so-called High-Luminosity era (HL-LHC) [1]. Main characteristic of this era will be increased instantaneous luminosity, with projected increase by a factor ~ 5, which will lead to the increased number of proton-proton collisions per bunch crossing up to 140-200. These concurrent collisions (pile-up) will cause spatial overlap of tracks and energy deposits, degrading the performance of the Compact Muon Solenoid (CMS) detector [9, 10]. Hence, the CMS detector will be upgraded with a MIP Timing Detector (MTD) [2]. The purpose of an MTD is mitigation of pile-up effects, providing a timing resolution of $30 - 40$ ps per track. On top of it, the addition of timing information will allow distinguishing between vertices overlapping in space but not in time, helping CMS to maintain achieved performances, as shown in Figure 1. The simulated vertices are the red dots. The vertical yellow lines indicate 3D-reconstructed (i.e. no use of timing information) vertices, with instances of vertex merging visible throughout the display. The black crosses and the blue open circles represent tracks and vertices reconstructed using a method that includes the time information and is therefore referred to as "4D". Many of the vertices that appear to be merged in the spatial dimension are clearly separated when time information is available.The MTD will be comprised of two major parts, the Barrel Timing Layer (BTL), covering the pseudorapidity[1] range $|\eta| < 1.45$, and the Endcap Timing Layer (ETL), covering the range $1.6 < |\eta| < 3.0$, as shown in Figure 2. The BTL will be instrumented with LYSO Crystals coupled to Silicon Photomultipliers (SiPMs) readout by the TOFHIR ASIC, while the ETL will be intrumented with LGAD sensors [3, 4] readout by the Endcap Timing Layer Read-Out Chip (ETROC) ASIC. Difference in technologies used mainly comes from the fact that the BTL and ETL have large differences in area and irradiation fluences to which they will be exposed to (up to $1.7 \times 10^{15} n_{eq}/cm^2$ for $\eta = 3$).

The ETL of the MTD detector will be mounted on the nose of the High Granularity Calorimeter and will be composed of two double-sided disks for each endcap region (four disks in total with radius spaning between 0.31 m < disk radius < 1.20 m), with a geometrical acceptance of $\sim 85\%$ disk.

2. Sensors

An LGAD is a n-in-p silicon sensor with a p+ boron-doped layer, called gain layer, implanted underneath the n++ electrode (Figure 3). When the LGAD operates in reverse bias, the high p+ concentration generates an electric field ($>$ 300kV/cm) in the gain layer volume that is high enough to start avalanche multiplication by impact ionization. LGAD sensors are designed to have a moderate internal gain, between 10 and 30, to maximize the signal to noise ratio.

The main ETL sensor requirements are:

- active thickness of $\sim 50\ \mu$m

[1]The coordinate system adopted by CMS has the origin centered at the nominal collision point inside the experiment, the y-axis pointing vertically upward, and the x-axis pointing radially inward toward the center of the LHC. Thus, the z-axis points along the beam direction toward the Jura mountains from LHC Point 5. The azimuthal angle ϕ is measured from the x-axis in the x-y plane and the radial coordinate in this plane is denoted by r. The polar angle θ is measured from the z-axis. Pseudorapidity is defined as $\eta = lntan(\theta/2)$

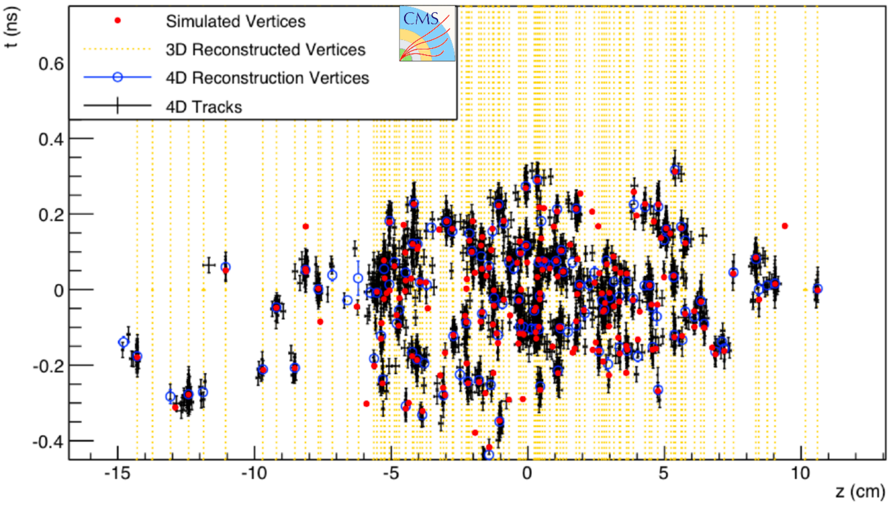

Figure 1: Simulated and reconstructed vertices in a bucnch crossing with 200 pileup interactions assuming a MIP timing detector with ~ 30 ps time resolution covering the barrel and endcaps. The horizontal axis is the z position along the beam line, where the "0" is the center of the IR. The vertical axis is the time with "0" being the point in time when the beams completely overlap in z. Figure is taken from [2].

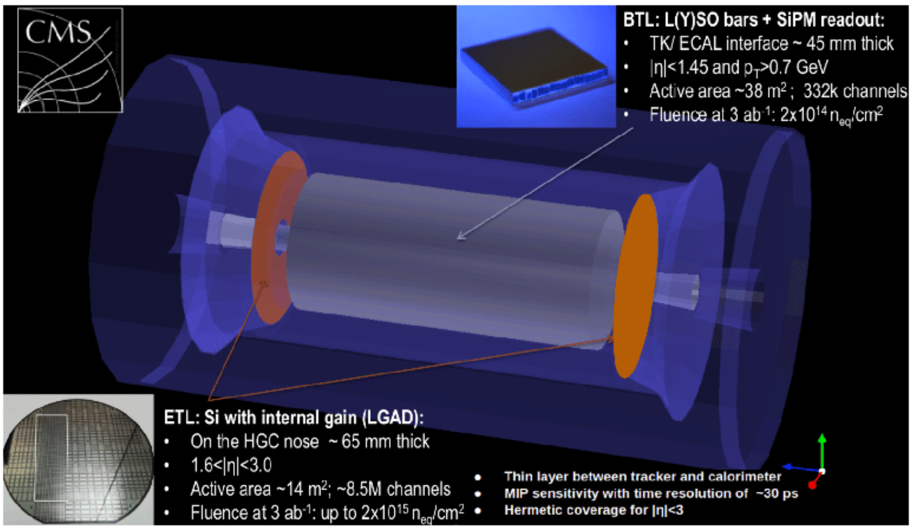

Figure 2: Schematic view of the MTD detector, divided into Barrel Timing Layer and an Endcap Timing Layer.

- pad capacitance below 3–4 pF
- low ($< \mu A$) and uniform pad leakage current
- uniformity of gain layer implants to provide uniform breakdown voltage
- signal greater than 8 fC (new sensors) and 5 fC (end of lifetime)
- per-track timing resolution of $\sim 30 - 40$ ps

Large prototypes of LGADs have been produced by Fondazione Bruno Kessler (FBK) and Hamamatsu Photonics (HPK) in two RD productions called UFSD3.2 and HPK2, respectively. Both foundries produced LGADs with several different p+ doses and inter-pad layouts.

Timing resolution measurements have been performed in Torino [5] and at Fermilab [6], with Beta-source setups based on Sr90 sources. As the sensors' performances have been benchmarked using very fast low-noise electronics, results might be different when reading out the LGADs with the ETL ASIC. The most performing prototypes can reach a timing resolution < 40 ps (Figure 4).

3. Readout Electronics

The goal of the Endcap Timing Readout Chip (ETROC) [5] is to measure the arrival time of small charge signals with low power consumption. The design target for the sensor+electronics time resolution is less than 50 ps per hit, to achieve a 35 ps arrival time measurement for a MIP track with an ETL hit in each of the two layers. Hence, the jitter from the preamplifier/discriminator stage has to be kept below 40 ps. The target should be achieved with reasonable power consumption (< 1 W/chip and < 4 mW/channel), signal efficiency and maintained even after irradiation. The choice of 16×16 channels is motivated by the clock (timing reference) distribution, which will be laid out as a 4-stage H-tree. The pad cell size is a compromise between small capacitance (3.4 pF), which translates to a higher signal-to-noise ratio in the front-end, and the overall channel count, which affects the total power consumption. At the cell level, each channel consists of a preamplifier, a discriminator, a Time-to-Digital Converter (TDC) used to digitise the TOA Time Of Arrival (TOA)

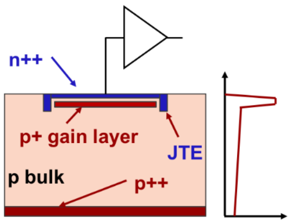

Figure 3: Schematic design of a LGAD sensor, with increasing electeric field shown on the right.

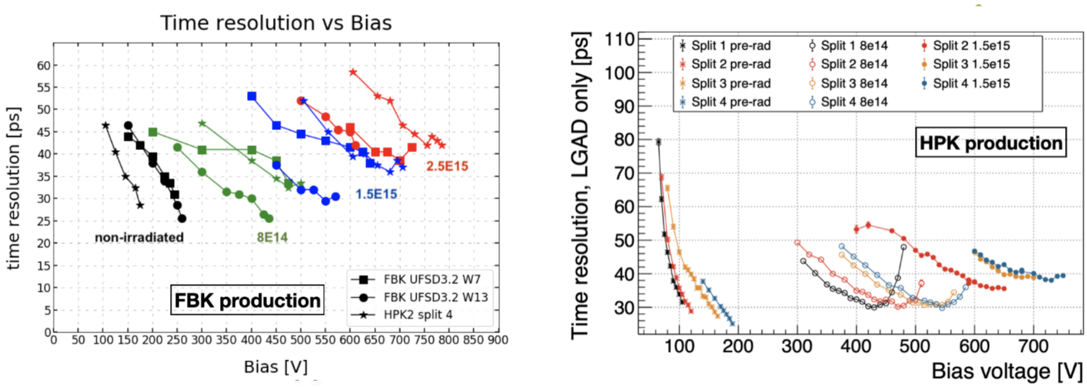

Figure 4: Timing resolution results pre- and post-irradiation for prototypes from FBK (left) and HPK (right) latest productions [7].

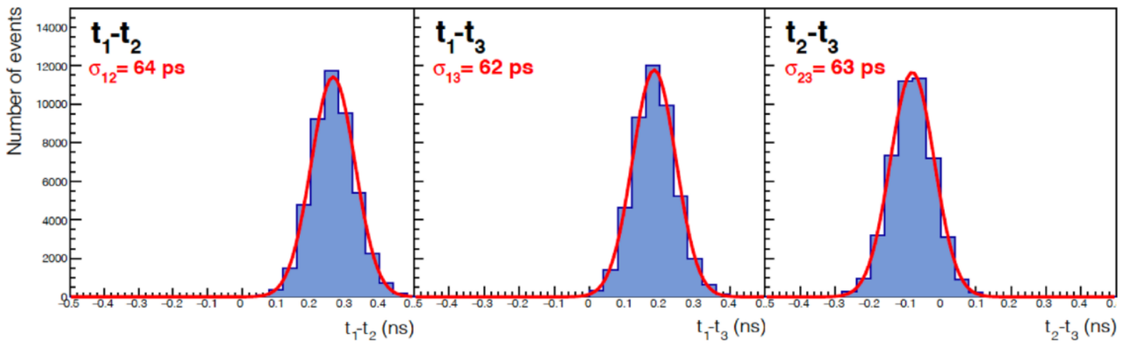

Figure 5: The timing resolution measurement of the ETROC+LGAD system performed using a three-plate telescope of ETROC1 boards. Here the distributions of the time difference between the time of arrivals of particles for pairs of layers is shown [8].

and Time Over Threshold (TOT) measurements, with bin size < 30 ps and < 100 ps, respectively, and a memory for data storage and read-out. The TOT is used for time-walk correction of the TOA measurement. Additional peripheral circuits include a phase-locked loop (PLL), a phase shifter, an I2C receiver, a fast-control block, a serialiser, and a data driver. The design path has started with the analog front-end study and characterisation, followed by the development of a 4×4 channels ASIC with full front-end, including a new low-power TDC, and proceeded with the design and test of the clocktree, the digital components, and the supporting circuitries, into ETROC1. Preliminary test beams where performed using a telescope with three layers of LGAD+ETROC1. From preliminary analysis of the test beam data shown in Fig 5, the total timing resolution per hit for each LGAD+ETROC1 layer can be extracted following the $\sigma_i = \sqrt{(\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)/2}$. This timing resolution has reached ~ 42-46 ps. The ETROC2 builds on the ETROC1 design by increasing the number of pixels to the final 16×16 and includes the remaining core functionalities such as the slow and fast control interfaces, PLL, phase shifter, and pixel read-out.

4. Conclusion

The CMS Endcap Timing Layer will provide time measurements of charged particles with single-hit timing resolution below 50 ps, maintaining the CMS detector excellent performances. ETL will be instrumented with LGAD sensors read out by the new ETROC ASIC. LGADs from FBK and HPK productions have been tested in laboratory and during beam tests at FNAL. Irradiated LGADs showed excellent timing resolution, below 40 ps up to irradiation fluence of $2.5 \times 10^{15} n_{eq}/cm^2$ in FBK sensors and of $1.5 \times 10^{15} n_{eq}/cm^2$ in HPK ones, fulfilling the ETL requirement of 50 ps per single hit. The ETL Read-out chip will ensure excellent timing performances (< 50 ps). ETROC will have 256 channels. ETROC bonded to LGAD achieved a timing resolution of 42–46 ps, measured during beam test.

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