PROCEEDINGS OF SCIENCE

Precision Timing with Low-Gain Avalanche Diode Sensors with the CMS Endcap Timing Layer for HL-LHC

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The CMS MTD will provide accurate timestamps with a resolution of 30-40 ps for all charged tracks up to a pseudo-rapidity of $|\eta|$=3. This upgrade will mitigate the effects of pile-up expected under the HL-LHC running conditions and bring new and unique capabilities to the CMS detector. The endcap region of the MTD, called ETL, will be instrumented with LGAD sensors, covering the high-radiation pseudo-rapidity region $1.6 < |\eta| < 3.0$. The LGADs will be read out with the ETROC readout chip, which is being designed for precision timing measurements. We present recent progress in the characterization of LGAD sensors for the ETL and development of ETROC, including test beam and bench measurements.

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1. The CMS MIP Timing Detector

Starting from 2027, the Large Hadron Collider (LHC) will enter the Phase-2 of its operations, also called High-Luminosity era of LHC (HL-LHC), which will be characterized by an increase in the luminosity delivered to its experiments [1].

The increased luminosity will lead to 140-200 concurrent (pile-up) collisions per bunch crossing, causing a spatial overlap of tracks and energy deposits that will degrade the performances of the Compact Muon Solenoid (CMS) [2]. Hence, the CMS collaboration decided to upgrade its detector with a new MIP Timing Detector (MTD), which will measure the timing of charged tracks with a resolution of 30-40 ps [3].

The addition of timing in CMS will allow distinguishing vertices overlapping in space but not in time, helping CMS to maintain the excellent performances of Phase-1.

The CMS MTD will be divided in the Barrel Timing Layer (BTL), covering the pseudorapidity region $|\eta| < 1.45$, and the Endcap Timing Layer (ETL), covering the forward region $1.6 < |\eta| < 3.0$. The focus of this work is on ETL.

2. The MTD Endcap Timing Layer

ETL will be mounted on the nose of the CMS CE calorimeter, 3 m away from the interaction point, covering the pseudorapidity region $1.6 < |\eta| < 3.0$. It will be instrumented with Low-Gain Avalanche Diode (LGAD) sensors, for a total active area of 14 m^2 [3, 4].

ETL will be made of 2 double-sided disks for each endcap region (4 disks in total), assembled into D-shaped modules. The double-sided disks are needed to achieve a large geometrical acceptance (85%/disk), while the use of two disks will provide two independent timestamps, which are required to achieve a track time resolution of 30-40 ps up to the end of the ETL lifetime.

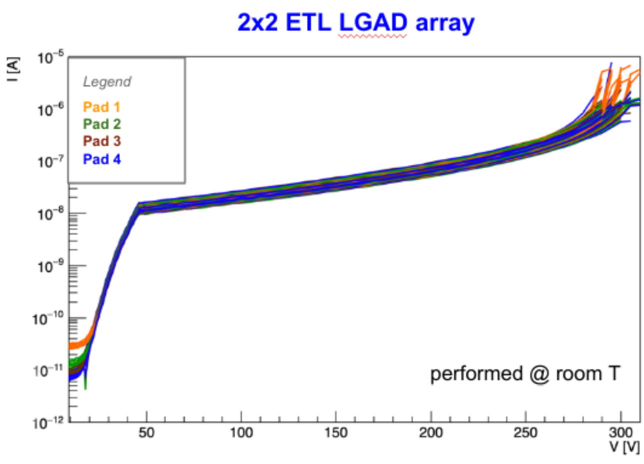

Figure 1: IV curves of the four pads of 2x2 arrays from the latest LGAD production by FBK, UFSD3.2 [5].

ETL will operate in a large range of radiation fluences, and the goal is to have its performances unchanged up to the end of its lifetime. At the end of HL-LHC operations, the levels of radiations received by ETL, considering an integrated luminosity of 3000 fb^{-1}, will range from $1.5 \cdot 10^{14}$ n_{eq}/cm^2 in the outermost part of the detector, to $1.6 \cdot 10^{15}$ n_{eq}/cm^2 at high values of pseudorapidity. The nominal, maximum expected fluence is $1.6 \cdot 10^{15}$ n_{eq}/cm^2 , which then grows to $2.5 \cdot 10^{15}$ n_{eq}/cm^2 when considering a $\times 1.5$ safety factor.

The fluence of $1 \cdot 10^{15}$ n_{eq}/cm^2 is the turning point in terms of performance degradation, since, above this level, the LGAD may start to deliver not enough charge for the desired time resolution. Fortunately, only 2% of overall dataset will be collected above this value.

3. Sensors for ETL

ETL will be instrumented with 50 μm-thick silicon sensors based on the LGAD technology, which consists in the implantation of a p^+ gain layer underneath the n^{++} electrode, to obtain a high electric field (above 300 kV/cm) in that region, so that charge multiplication can occur. As a result, a moderate (10-30) internal gain is achieved in the sensor bulk, which is key to obtain an excellent time resolution.

The final sensors for ETL will be 16×16 pixel arrays read out by the ETL ASIC (ETROC, see section 4). The main sensor requirements are: (i) 3-4 pF capacitance, hence pixels need to be few mm^2; (ii) uniform breakdown voltage; (iii) low leakage current; (iv) single-hit time resolution 30-40 ps; (v) no-gain distance between adjacent pads < 50 μm.

3.1 Laboratory Measurements

LGAD sensors are always firstly tested in the laboratory with a probe station; one of the most important measurement is the leakage current as a function of the bias voltage (IV curve).

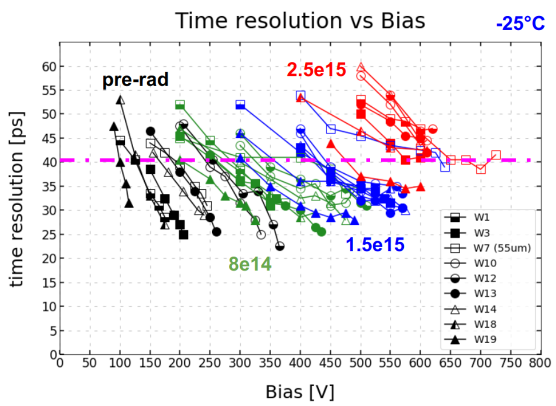

Figure 2: Time resolution as a function of the bias voltage of ETL LGAD sensors produced by FBK. Each color defines an irradiation fluence: (black) new sensors; (green) $8 \cdot 10^{14}$ n_{eq}/cm^2 ; (blue) $1.5 \cdot 10^{15}$ n_{eq}/cm^2 ; (red) $2.5 \cdot 10^{15}$ n_{eq}/cm^2 . Taken from [7].

Figure 1 shows the IV curves of 25 2×2 arrays from one of the wafer of the latest ETL LGAD production manufactured by Fondazione Bruno Kessler (FBK, Italy), UFSD3.2 [5]. All pads of each device have been tested, as indicated in the plot's legend. The same measurements have been performed on all wafers of the production.

Figure 1 demonstrates that the tested sensors feature a low leakage current, well below 1 μA before breakdown, and a uniform breakdown voltage. Similar performance have been observed also in the other wafers of the production.

The same IV tests have been also performed on the HPK2 production ([6]), manufactured by Hamamatsu Photonics (HPK, Japan), finding similar results. Hence, both FBK and HPK productions satisfy the ETL specifications for the leakage current uniformity.

Another crucial test is the characterization of LGADs using a β-source telescope, which allows measuring fundamental quantities such as the time resolution and the collected charge.

A setup based on a ^{90}Sr β-source has been developed at the University of Torino specifically for this characterization. All measurements are performed within a climate chamber that ensures stable temperature and humidity; the characterization has been performed at -25 °C.

Figure 2 shows the results of the time resolution as a function of the bias voltage, coming from the characterization with the β-setup. All the sensors shown in the figure belong to the FBK UFSD3.2 production, which has some designs studied to enhance the radiation hardness.

Each marker type in 2 indicates a different sensor design, whereas each color indicates the fluence at which the device has been irradiated: black represents new sensors ; green $8 \cdot 10^{14}$ n_{eq}/cm^2 ; blue $1.5 \cdot 10^{15}$ n_{eq}/cm^2 ; red $2.5 \cdot 10^{15}$ n_{eq}/cm^2 .

The results are excellent: all sensors are able to reach a time resolution of 30 ps up to a fluence of $1.5 \cdot 10^{15}$ n_{eq}/cm^2 , which raises to 40 ps at $2.5 \cdot 10^{15}$ n_{eq}/cm^2 .

Similarly, two different designs of the HPK 2 production (not shown in figure 2) have been measured at different radiation levels. Both designs achieved a time resolution of ~30 ps up to a radiation fluence of $8 \cdot 10^{14}$ n_{eq}/cm^2 and 40 ps up to $2.5 \cdot 10^{15}$ n_{eq}/cm^2 .

Hence, both FBK and HPK productions are able to deliver the target time resolution up to the end of the ETL lifetime.

3.2 Beam test

ETL has a dedicated beam test setup at the Fermilab Test Beam Facility, where they are characterized with 120 GeV protons [10, 11]. The facility has a precise tracker that provides information on the particles hit positions, as well as a dedicated cold box [12] to run at cold with monitored temperature and humidity. With this setup, it is possible to study a limited number of sensors with high precision.

The results shown in this work concern a 4×4 LGAD array with 1×3 mm^2 pads, coming from the HPK 3.1 production [9]. The sensor was new and measured at -20 °C. Figure 3 (a) shows the measured time resolution, which is ~40 ps and constant across the entire array active area, proving the good uniformity of the device. Figure 3 (b), instead, shows the sensor hit efficiency, which is ~100% and uniform across the entire sensor active area.

The beam test results prove that the HPK 3.1 multi-pad array is highly uniform and efficient, able to deliver the target resolution, demonstrating that large-scale LGADs have excellent performances.

4. ETROC: the ETL ASIC

ETROC is the ETL read-out ASIC [13]. It is required to achieve a time resolution, when bonded to an LGAD, lower than 50 ps up to the end of ETL lifetime; therefore it needs (i) low noise, (ii) fast risetime and (iii) low power-budget (1 W/chip, 3 mW/channel). Three prototype

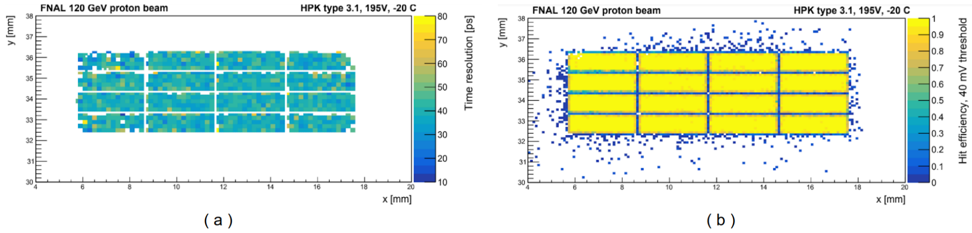

Figure 3: Beam test results on the time resolution (a) and hit efficiency (b) uniformity of a 4×4 LGAD array from the HPK3.1 production. Measurements performed at the Fermilab Test Beam Facility. Taken from [8].

versions are foreseen: ETROC0 has a single analog channel; ETROC1 is a 16-ch ASIC with a Time-to-Digital-Converter and a 4×4 clock tree; ETROC2 aims at full functionality and full size.

ETROC0 and ETROC1 have been produced and tested, whereas ETROC2 is being designed.

The goal of ETROC0 is to measure the core front-end analog performance. The charge injection tests demonstrated that the discriminator leading-edge jitter agrees with chip post-layout simulation, and the power consumption for the discriminator and pre-amplifier are consistent with expectation. The Total Ionizing Dose tests have been successful up to 100 MRad.

ETROC1 features 16 channels and a TDC using simple delay cells with self-calibration, optimized for low-power. The ETROC0 front-end is used directly into ETROC1.

A 40 MHz noise has been observed in a ETROC1 bump-bonded to an LGAD, which couples through the sensor and it is caused by a clock activity of the same frequency in the circular buffer memory. It is suppressed setting the discriminator threshold to 8 fC.

Intense work has been put to understand and eliminate this issue, and the gained knowledge has been highly valuable to design ETROC2, which will introduce several design improvements to decouple the read-out channels from the source of noise.

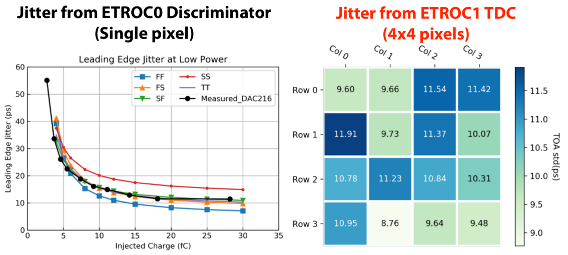

Figure 4: Jitter measurements from ETROC0 discriminator (left) and ETROC1 TDC (right). Taken from [14].

The time resolution of a single LGAD pad bonded to ETROC1 has been measured during a beam test at Fermilab with 120 GeV protons and found to be 42-46 ps [14], within expectations.

5. Conclusions

The CMS ETL will provide time measurements of charged tracks with 30-40 ps resolution, helping the CMS detector to maintain its excellent performances in the very challenging environment of the HL-LHC. ETL will be equipped with thin LGAD sensors and read out by the ETROC ASIC.

LGADs from the FBK UFSD3.2 and HPK2 productions have been measured both in the laboratory and during beam tests, finding that they meet all the specifications:

- Breakdown voltage and leakage current are within expectations and the production uniformity is good for both FBK and HPK.
- The time resolution has been measured with a β-telescope: it is equal or lower to 40 ps up to a radiation fluence of $2.5 \cdot 10^{15}$ n_{eq}/cm^2 , well within specifications for both producers.
- Beam test results showed 100% efficiency and uniform time resolution across the whole active area of a large HPK LGAD array

ETROC is the ETL ASIC, required to consume low power while providing excellent timing performances: the latest prototype version is ETROC1, which uses the analog front-end of the previous version, ETROC0. ETROC1 has 16 channels and low-power TDC, the time resolution, when bonded to an LGAD, is 42-46 ps, as measured during a Fermilab beam test.

ETROC2, the final version of the ASIC, is being designed and will profit from the knowledge gained during the ETROC1 testings. It will be submitted in 2022.

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