



The Compact Muon Solenoid Experiment
Conference Report

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The CMS MTD Endcap Timing Layer: Precision Timing with Low Gain Avalanche Diodes

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Abstract

The MIP Timing Detector (MTD) of the Compact Muon Solenoid (CMS) will provide precision timestamps with 40 ps resolution for all charged particles up to a pseudo-rapidity of $|\eta| = 3.0$. This upgrade will mitigate the effects of pile-up expected under the High-Luminosity LHC running conditions and bring new and unique capabilities to the CMS detector. The endcap region of the MTD, called the Endcap Timing Layer (ETL), will be instrumented with silicon low gain avalanche detectors (LGADs), 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 the development of ETROC, including test beam and bench measurements.

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The CMS MTD Endcap Timing Layer: Precision Timing with Low Gain Avalanche Diodes

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Abstract

The MIP Timing Detector of the CMS detector will provide precision timestamps with 40 ps resolution for all charged particles up to a pseudorapidity of $|\eta| = 3.0$. This upgrade will mitigate the effects of pile-up expected under the High-Luminosity LHC running conditions and bring new and unique capabilities to the CMS detector. The endcap region of the MIP Timing Detector, called the Endcap Timing Layer, will be instrumented with silicon Low-Gain Avalanche Diodes, covering the high-radiation pseudorapidity region $1.6 < |\eta| < 3.0$. The LGAD sensors will be read out by the ETROC readout chip, which is being designed for precision timing measurements. We present recent progress in the characterization of LGAD sensors for the Endcap Timing Layer and the development of ETROC, including test beam and bench measurements.

Keywords: CMS MTD, LGAD

1. The CMS MIP Timing Detector

During the Large Hadron Collider (LHC) Phase-2, called High-Luminosity LHC (HL-LHC), the instantaneous luminosity will increase by a factor ~ 5 , leading the number of proton-proton collisions per bunch crossing up to 140-200 [1]. In this environment, the spatial overlap (pile-up) of particle tracks will increase, degrading the performances of the vertex reconstruction and particle identification in Compact Muon Solenoid (CMS) [2]. Hence CMS collaboration approved to upgrade its detector with a MIP Timing Detector (MTD) [3] with the aim to add timing information to charge particle tracks. The MTD aims to mitigate the effects of pile-up in the Phase-2 environment to the value of Phase-1, providing a timing resolution of 30-40 ps per track.

The MTD detector will be divided into a Barrel Timing Layer (BTL) and an Endcap Timing Layer (ETL), Figure 1. The BTL will be instrumented with LYSO Crystals coupled to Silicon Photomultipliers (SiPMs) readout by the TOFHIR ASIC, covering the pseudorapidity region $|\eta| < 1.45$, for a total surface of $\sim 38 \text{ m}^2$. The ETL will be instrumented with LGAD sensors [4, 5] readout by the Endcap Timing Layer Read-Out Chip (ETROC) ASIC, covering the pseudorapidity region $1.6 < |\eta| < 3.0$, for a total surface of $\sim 14 \text{ m}^2$. The choice to instrument barrel and endcap regions with different sensor technologies is mainly due to the larger difference in area and irradiation fluences to which these regions will be exposed. In the barrel region the irradiation fluence will reach $2 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$, while in the endcap it will exceed $10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$.

2. The MTD Endcap Timing Layer

The ETL of the MTD detector will be mounted on the nose of the High Granularity Calorimeter, 3 m away from the inter-

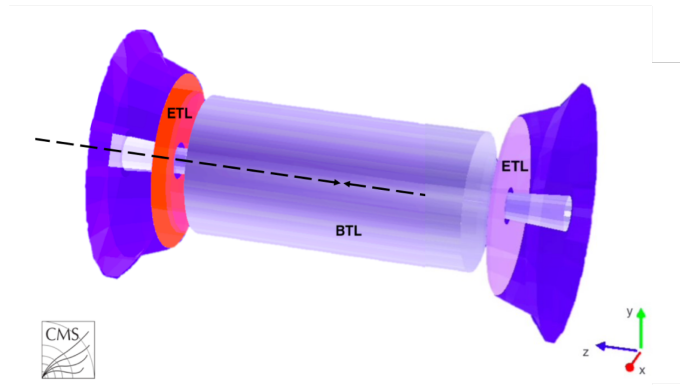


Figure 1: A schematic view of the MTD detector, divided into a Barrel Timing Layer and an Endcap Timing Layer.

action point. The ETL will be composed of two double-sided disks for each endcap region (four disks in total, $0.31 \text{ m} < \text{disk radius} < 1.20 \text{ m}$), with a geometrical acceptance of $\sim 85 \text{ \%/disk}$. The pairing of disks will provide two hits on most tracks, providing a timing resolution $< 50 \text{ ps}$ per single hit and $< 35 \text{ ps}$ per track, up to the end of ETL lifetime. The ETL will have Fill-Factor (ratio between active and total detector's area) as high as possible, and low occupancy to avoid double hits and ambiguous time assignment: the required occupancy is below 0.1% at low η and $\sim 1\%$ in the inner region of the detector. ETL will operate at a temperature of $-25 \text{ }^\circ\text{C}$.

2.1. Radiation environment in ETL

The ETL will operate in a large range of radiation fluences, aiming to ensure unchanged timing performances up to the end of the HL-LHC program.

Figure 2 shows the simulated irradiation fluence in $\text{n}_{\text{eq}}/\text{cm}^2$

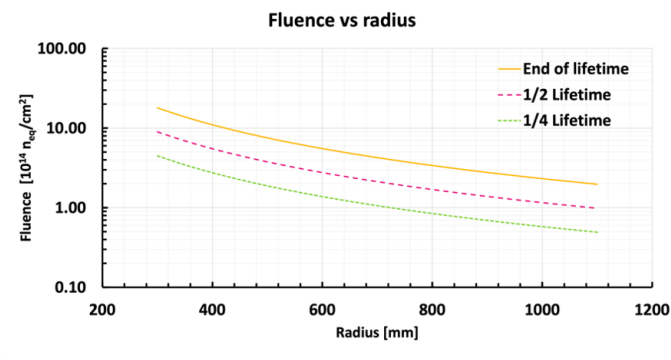


Figure 2: Expected irradiation fluence as a function of the ETL radius for three different period of operation of the detector: 1/4 (dotted line), 1/2 (dashed line) and end of lifetime (continuous line).

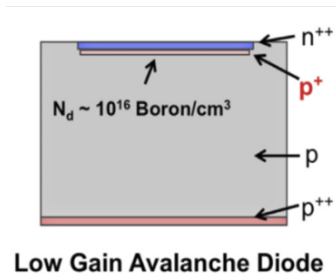


Figure 3: A schematic view of LGAD sensor with its p^+ gain layer implanted underneath the p - n junction.

as a function of the disk's radius, at three moments of the detector lifetime (1/4, 1/2 and 1). The fluence increases towards the inner region of disks, growing up to $1.7 \cdot 10^{15} \text{ neq/cm}^2$ at $|\eta| = 3.0$, at the end of lifetime of the detector. This maximum expected fluence increases to $2.5 \cdot 10^{15} \text{ neq/cm}^2$ when considering a safety factor $\times 1.5$.

The fluence of $1 \cdot 10^{15} \text{ neq/cm}^2$ is a benchmark for the timing performances of LGADs; below this, LGADs provide a large signal with which the desired timing resolution can be readily achieved. At higher fluences, it is more challenging to maintain large signals and a special radiation-resistant LGAD designs are necessary to provide them. The fluence $1 \cdot 10^{15} \text{ neq/cm}^2$ will be exceeded only in 12% of the detector surface, starting after about 50% of the HL-LHC expected luminosity. The LGAD technology has been designed in order to guarantee unchanged timing performances up to the end of HL-LHC.

3. The ETL sensors

An LGAD is a n -in- p silicon sensor with a p^+ boron-doped layer, called gain layer, implanted underneath the n^{++} electrode (see Figure 3). The gain layer has a thickness of $\sim 1 \mu\text{m}$ and a concentration of $\sim 10^{16} \text{ atoms/cm}^3$. When the LGAD operates in reverse bias, the high p^+ concentration generates an electric field greater than 300 kV/cm into the gain layer region. This field is high enough to start avalanche multiplication by impact ionization when charge carriers generated by particles pass through the high field region.

LGAD sensors are designed to have a moderate internal gain, between 10 and 30, to maximize the signal to noise ratio. A large signal-to-noise ratio combined with a thin active thickness of the sensor are the key ingredients to achieve excellent timing resolution σ_t :

$$\sigma_t^2 \approx \left(\frac{N}{S/t_{rise}}\right)^2 + \sigma_{landau}^2. \quad (1)$$

The terms N and S are the noise and signal amplitude, which depends on the internal gain of the sensor as well as the characteristics of the read-out electronic. The terms t_{rise} and σ_{landau} are the rising time of the signal and the contribution to timing resolution due to Landau fluctuation (non-uniform charge deposition), both depending on the sensor active thickness, [6].

The main ETL sensor requirements are: i) active thickness of $\sim 50 \mu\text{m}$; ii) pad capacitance below 3-4 pF; iii) low ($< \mu\text{A}$) and uniform leakage current; iv) uniformity of gain layer implants to provide uniform breakdown voltage; v) signal greater than 8 fC (new sensors) and 5 fC (end of lifetime); vi) per-track timing resolution of ~ 30 -40 ps. The final ETL sensor will be a 16×16 pad array with pads of active area of $1.3 \times 1.3 \text{ mm}^2$.

Large prototypes of LGADs have been produced by Fondazione Bruno Kessler (FBK) and Hamamatsu Photonics (HPK) in two R&D productions called UFSD3.2 and HPK2, respectively. Both foundries produced LGADs with several different p^+ doses and inter-pad layouts. FBK produced sensors with carbonated gain layers to improve the radiation resistance of LGAD technology [7, 8]. These two productions have been extensively tested in laboratory and during beam test activity at Fermi National Accelerator Laboratory (FNAL) facility [9].

3.1. Production uniformity

A large number of LGAD sensors have been tested in laboratory using a probe station, performing DC measurements of the leakage current as a function of the bias voltage. In this way by this measurement, the uniformity of FBK and HPK LGAD productions have been characterized in terms of breakdown voltage and leakage current.

Figure 4 shows the leakage currents of each pad in 25×2 LGAD sensors arrays from a wafer of the FBK-UFSD3.2 production. These measurements show a very high uniformity of: i) breakdown voltage ($280 \text{ V} < V_{BD} < 300 \text{ V}$); ii) leakage current before the breakdown, which is also very low ($< 1 \mu\text{A}$). Similar measurements have been performed on other wafers from the FBK-UFSD3.2 production and on sensors from HPK2 production.

3.2. No-gain region distance

Another important measurement performed on LGADs is the estimation of the no-gain (inter-pad) distance between two adjacent pads. This parameter determines the fill-factor (active area on total area) of the detector, the smaller the inter-pad the better the fill-factor is. For example, for ETL sensors, inter-pads of $\sim 40 \mu\text{m}$ and $\sim 100 \mu\text{m}$ correspond to fill-factors of $\sim 94\%$ and $\sim 85\%$, respectively.

This measurement was performed using the Transient Current Technique (TCT) setup developed by Particulars [10]. The

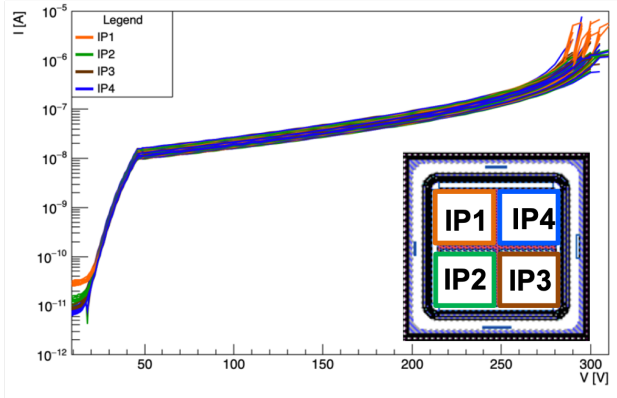


Figure 4: Current-Voltage measurements of 25 2×2 LGAD sensors arrays produced by FBK. The measurements have been performed at room temperature.

TCT setup is equipped with a pulsed and focused (spot diameter $\sim 10 \mu\text{m}$) infrared ($\lambda = 1064 \text{ nm}$) laser, that simulates the passage of a Minimum Ionizing Particle. The LGADs under test were wire-bonded on dedicated test boards and read-out by current amplifiers. The inter-pad distance measurement has been made by performing a laser scan between two adjacent pads along optical slits, on the surface of the sensors.

The Figure 5 shows an example of an inter-pad distance measurement performed on a new FBK-LGAD biased at 200 V. The blue and red markers define the profiles of the collected charge, obtained moving the laser spot from a pad to the adjacent one. The shape of the charge profile has been fitted with an S-curve, given by convolution of a Step function that approximates the edge region of the pad and of a Gaussian function that approximates the laser beam profile. The no-gain distance has been estimated as the distance between the two step functions, which is located at the 50% point of the S-curves.

FBK and HPK LGADs with three and four different inter-pad layouts have been characterized, finding no-gain distances between $35 \mu\text{m}$ and $120 \mu\text{m}$.

3.3. Timing resolution of LGADs

An important characterization of LGADs is the timing resolution when new and irradiated. This characterization has been performed at the University of Turin and the Fermilab SiDet Laboratory, using ^{90}Sr - β -source telescopes and very low noise electronics to benchmark the sensors performances. Timing resolution has been measured at $-25 \text{ }^\circ\text{C}$ on FBK and HPK LGADs, irradiated with neutrons up to $2.5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ and $1.5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, respectively.

Figure 6 reports the timing resolution measurements on FBK (top) [11] and HPK (bottom) [12] LGADs of ETL prototypes. All sensors irradiated up to $1.5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ achieved a resolution below 40 ps. The FBK sensors irradiated to $2.5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ were able to reach 40 ps.

All tested sensors satisfied the ETL single-hit timing resolution requirement $< 50 \text{ ps}$, including the ASIC additional contribution to the timing resolution (see Section 4).

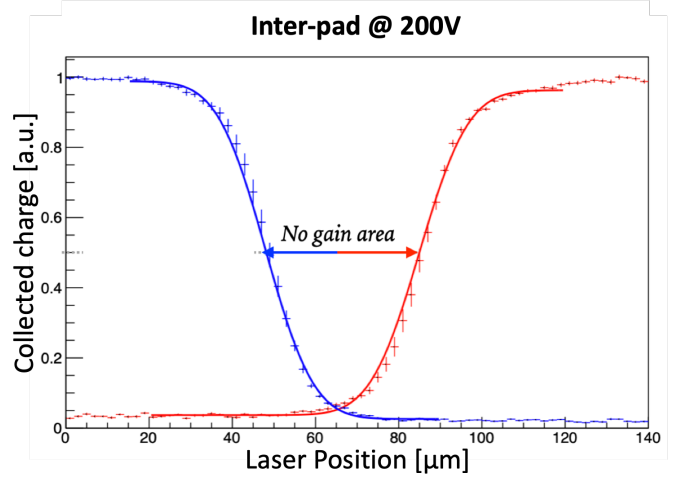


Figure 5: Collected charge profiles on two adjacent pads of a ETL FBK-LGAD. This measurement has been obtained by performing a TCT scan across two adjacent pads. Solid lines are the fit functions given by the convolution of Step and Gaussian functions.

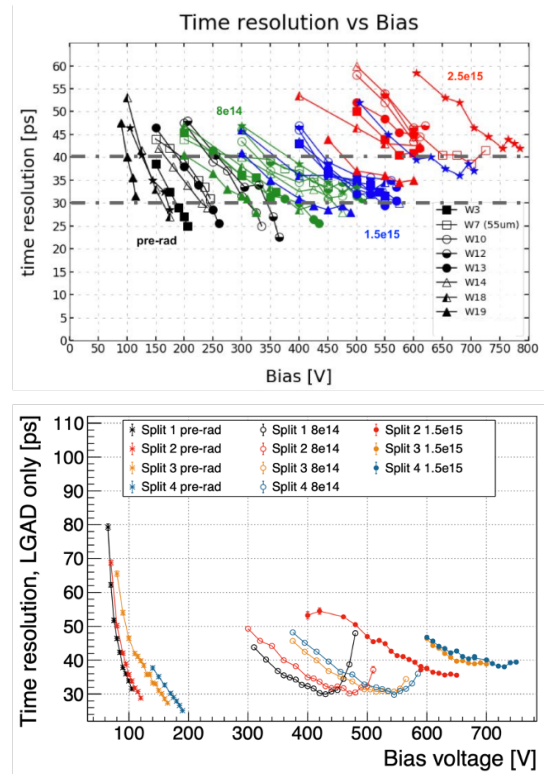


Figure 6: Timing resolution as a function of bias voltage of FBK (top) and HPK (bottom) LGADs. On the top the FBK sensors irradiated up to $2.5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$: each marker type identifies a different gain layer design, while each grey tone identifies different irradiation fluences: new; $8 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$; $1.5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$; $2.5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, [11]. On the bottom the HPK sensors irradiated up to $1.5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, where grey tone identify gain layer designs, while marker types identify irradiation fluences: new (star); $8 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ (empty circle); $1.5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ (filled circle), [12].

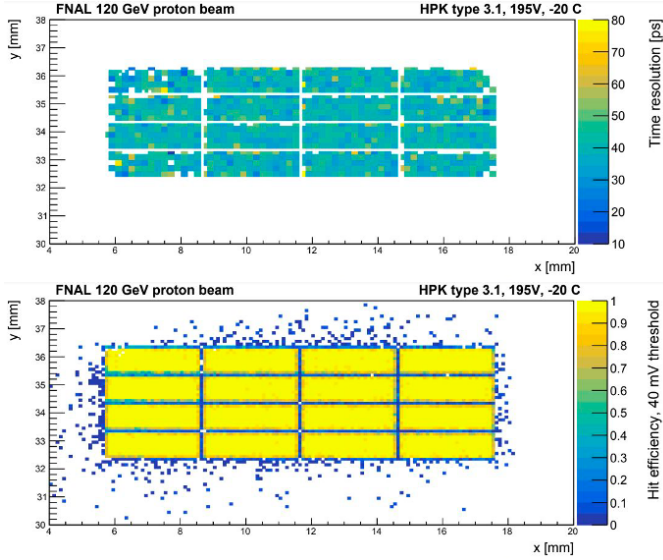


Figure 7: Timing resolution (top) and hit efficiency (bottom) maps of a new 4×4 LGAD array with 3 mm^2 pads [14]. These measurements have been performed at FNAL beam test facility, at $-20 \text{ }^\circ\text{C}$, and biasing the sensors at a fixed voltage of 195 V.

3.4. Beam test

Several LGADs sensors has been characterized and tested at the FNAL beam test facility. The facility used a 120 GeV/c protons beam, is instrumented with a strips and pixels telescope to provide particle hit position, and a High-Speed Photek Micro-Channel Plate with a timing precision of $\sim 10 \text{ ps}$ to provide timestamp [13].

An example of two measurements performed at the FNAL facility are timing resolution and hit efficiency maps on large size pad-array LGADs. Figure 7 shows these two maps for a 4×4 LGAD array, produced by HPK, with 3 mm^2 pads. The map on the top shows a very good uniformity of timing resolution ($\sim 40 \text{ ps}$) all across the sensor active surface, while the map on the bottom shows a very uniform hit efficiency of $\sim 100\%$, [14]. These results qualify large LGAD sensors array in term of timing resolution and efficiency performances.

4. The ETL Read-out ASIC

The ETL LGAD sensors will be read out by a new ASIC so-called ETROC, designed in 65 nm technology. The aim of the ETROC-LGAD system is to provide a timing resolution below 50 ps up to the end of the lifetime of the detector. To achieve this target ETROC needs a front-end that combines low noise with a fast rise time. The power budget is 1W/chip (3 mW/channel).

Three prototype versions of the chip are foreseen before the full-size 16×16 ASIC. ETROC0 and ETROC1 are the two first prototypes produced, both tested in laboratory and during beam test activity [15]. A schematic view of the block diagram of an ETROC single channel is shown in Figure 8.

ETROC0 is a single analog channel chip based on a preamplifier and discriminator stage. Charge injection tests showed

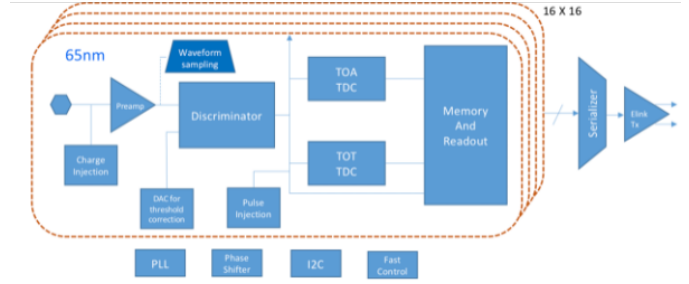


Figure 8: Block diagram of an ETROC single channel, with a preamplifier, a discriminator and a TDC stage.

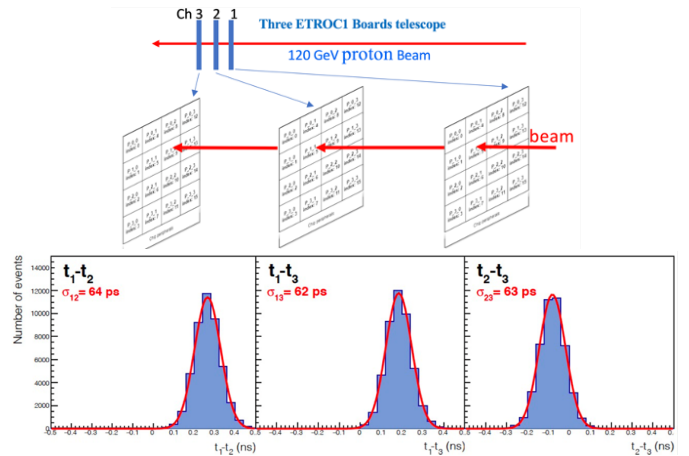


Figure 9: Top: ETROC1 boards telescope assembled and tested during FNAL beam test. Bottom: time difference distributions of the particles time of arrivals for pairs of ETROC1 boards; 1, 2 and 3 are the indexes of the boards, while σ_{12} , σ_{13} and σ_{23} are the widths of the time difference distributions [15].

a discriminator leading-edge jitter below 20 ps, for injected charges greater than 8fC; this result is in agreement with post-layout simulation. Moreover, ETROC0 bonded to LGAD sensor has been characterized during beam test, achieving a promising timing resolution of 31 ps.

ETROC1 is a 16 channels ASIC with integrated Time-to-Digital-Converters (TDCs) to perform Time-of-Arrival and Time-over-Threshold analysis. The TDC design has been optimized for low power, using a simple delay cells with self-calibration. The front-end (preamplifier and discriminator) implemented in ETROC1 is the same as ETROC0. The timing resolution of ETROC1 bump-bonded to LGAD has been measured during beam test at FNAL, and a value of 42-46 ps has been found. The contribution of the TDC to this timing resolution has been estimated to be $\sim 6 \text{ ps}$. The timing resolution measurement of ETROC-LGAD system has been performed using a three-plate telescope of ETROC1 boards (Figure 9-top). Figure 9-bottom reports the distributions of the time difference between the time of arrivals of particles for pairs of ETROC1 boards, while the widths of these distributions give the timing resolution of each pair pf boards.

The third prototype of the chip will be ETROC2, which will have the full functionality and size of the final chip. This chip version will be submitted in 2022.

5. Conclusion

The CMS Endcap Timing Layer will provide time measurements of charged particles with single-hit timing resolution below 50 ps, helping the CMS detector to maintain its excellent performances in the very challenging environment of the HL-LHC. 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 test at FNAL, with the following results: i) the sensors showed high uniformity of leakage current and breakdown voltage proving the good uniformity of the productions; ii) no-gain region width $< 120 \mu\text{m}$ have been measured in different FBK and HPK sensor layouts; iii) irradiated LGADs showed excellent timing resolution, below 40 ps up to irradiation fluence of $2.5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ in FBK sensors and of $1.5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ in HPK ones, fulfilling the ETL requirement of 50 ps per single hit; iv) beam test results showed uniform timing resolution (~ 40 ps) and efficiency ($\sim 100\%$) all across the active area of large LGAD sensors arrays.

The ETL Read-out chip will ensure excellent timing performances (< 50 ps) while consuming 3 mW/channel. ETROC will have 256 channels. ETROC1 is the second prototype version of the chip produced and tested; this version is a 16 channels chip with the same front-end of the previous version (ETROC0) and with integrated TDC. ETROC1 bonded to LGAD achieved a timing resolution of 42-46 ps, measured during beam test.

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