Commissioning of a Beta Setup for Time Resolution Measurements

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Abstract

The High Luminosity Large Hadron Collider will produce a higher number of primary proton-proton collisions per bunch crossing (pileup) with respect to the Large Hadron Collider. To reduce the effect of pileup on the physics analysis timing detectors will be used. ATLAS and CMS will be using the Low Gain Avalanche Detector (LGAD) for time measurements. The CERN Solid State Detectors team is planning to do timing studies of detectors using a beta setup, with possibilities of varying temperature and bias voltage. A reference detector has been characterized with time resolution ranging from 34 to 39 ps for the setup.

1 Introduction

CERN's Large Hadron Collider (LHC) produces 30 to 50 primary proton-proton (p-p) collisions per bunch crossing (pileup), the High Luminosity LHC (HL-LHC) upgrade will produce a pileup of 140 to 200 [1]. For the HL-LHC, if we assume that the vertex separation resolution from tracking is around 250 to 300 µm along the beam direction, which is what currently Atlas and CMS have, then there will be 10 to 15 % of merged vertices [2, 3]. This will then cause reconstruction problems and loss of events. A solution is to add a time dimension to the track measurement. The time of spread of primary p-p collisions per bunch is around 150 ps. If a time resolution of 30 ps is achieved then the events can be grouped in 5 groups which will allow 30 to 40 collisions to be analyzed separately and will help improve vertex identification. Atlas and CMS decided to use the Low Gain Avalanche Detector (LGAD) for timing.

LGADs are P-type silicon detectors that have an additional doping layer of p+ close to the p-n junction which creates a high electric field in that region as shown in Figure 1.

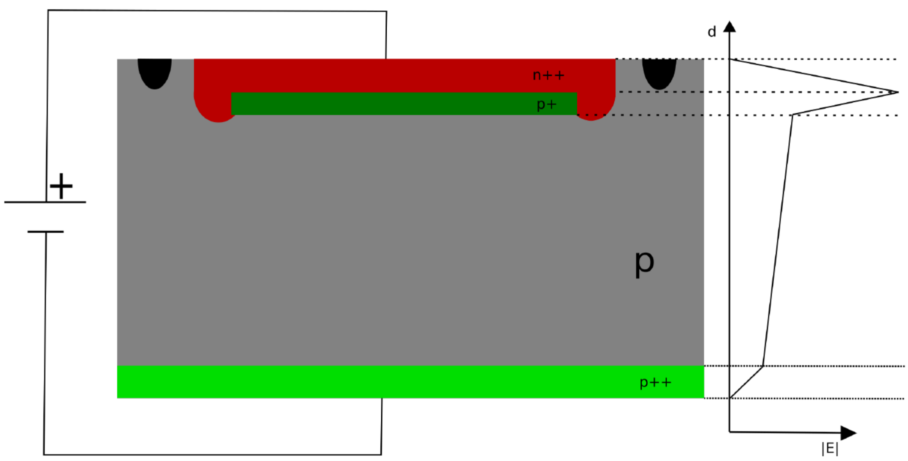

Figure 1: Schematics of a LGAD with electric field as a function of depth.

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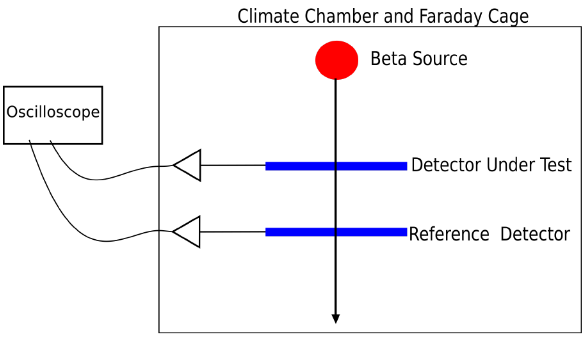
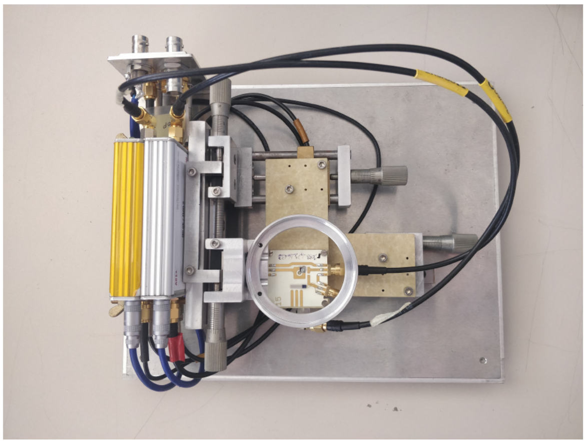
The high electric field allows the collected charge to be multiplied, which increases the amplitude of the signal and thus increases the signal to noise ratio. This allows the detector to have a time resolution of around 30 ps [4]. The CERN Solid State Detectors team needs a setup to measure time resolution of their detectors under different conditions with a beta source. Section 2 describes how the setup was built and all the problems encountered. Section 3 showcases how the setup could be used for characterizing detectors. Finally the appendices have extra details on the setup, its operation and the analysis.

2 Methods

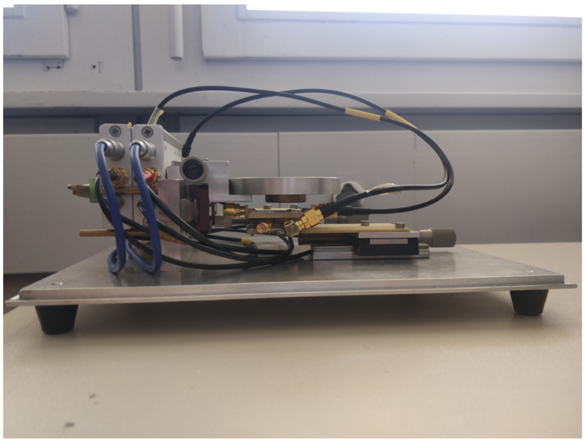
A set of three 50 µm thick LGADs, {LGAD1, LGAD2, LGAD3}, was provided with unknown time resolution, for more information about the material used refer to appendix A. To measure the time resolution of a detector (σ_{dut}) using a beta source, a reference detector with known time resolution (σ_{ref}) is required. The setup consists of two detectors which are placed parallel to each other. A beta source is placed above both detectors with a collimator in order for beta particles to pass through both detectors. Each detector is connected to its own amplifier. The amplifiers and the detectors are placed in a Faraday cage to reduce external noise pick up as shown in Figure 2.



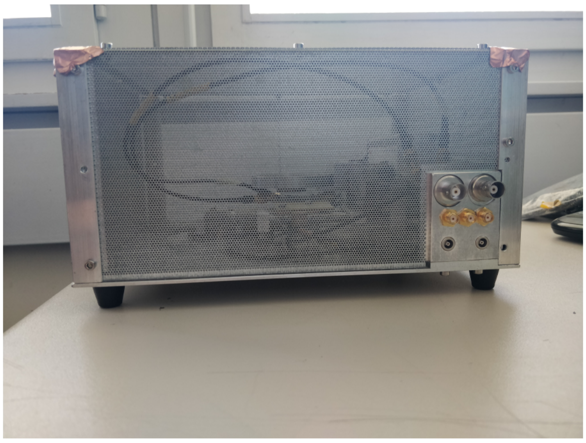
(a) Schematics.



(b) Top view.



(c) Side view.



(d) Faraday cage.

Figure 2: Schematics and three views of the setup.

Signals from both amplifiers are fed into two channels of a digital oscilloscope that triggers on the bottom detector. Figure 3 shows the waveforms of an event in both detectors.

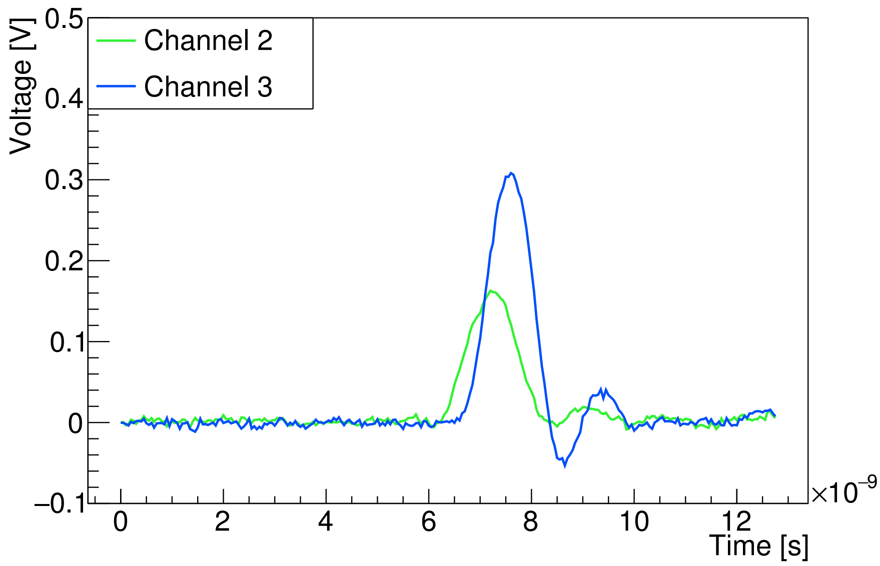


Figure 3: Waveforms of two LGADs.

The time difference between the two signals (Δt) is determined using a digital constant fraction discriminator algorithm on both waveforms. Collected time difference data from multiple events are plotted into a histogram and fitted using a Gaussian distribution as shown in Figure 4.

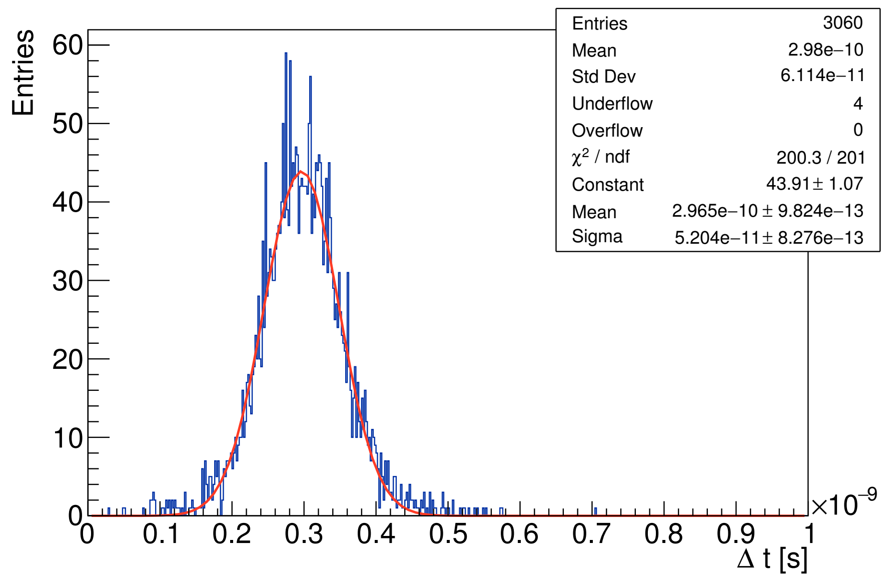


Figure 4: Distribution of time difference of LGAD3 on bottom operated 190 V and LGAD2 at 195 V at 0 °C. Futher details about the choice of operation voltage are given in Table 1 and 2 and the associated text before.

The fitting parameter sigma, the standard deviation, gives us the time resolution of our system of two detectors (σ_{sys}). By assuming that the σ_{dut} and σ_{ref} are not correlated we get

$$\sigma_{sys}^2 = \sigma_{dut}^2 + \sigma_{ref}^2$$

so,

$$\sigma_{dut} = \sqrt{\sigma_{sys}^2 - \sigma_{ref}^2} \tag{1}$$

with error

$$\delta_{dut} = \left(\frac{(\sigma_{sys}\delta_{sys})^2 + (\sigma_{ref}\delta_{ref})^2}{\sigma_{sys}^2 - \sigma_{ref}^2} \right)^{\frac{1}{2}}. \tag{2}$$

The following notation will be used:
For $1 \leq i \leq 3$, $1 \leq j \leq 3$ and $i \neq j$, the time resolution of LGADi will be σ_i. When referring to a system with LGADi on bottom and LGADj on top, the system will be denoted as s_{ij} and its time resolution will be denoted as σ_{ij}. Please note that $s_{ij} \neq s_{ji}$ but $\sigma_{ij} = \sigma_{ji}$. Since no reference detectors were provided, a minimum of three LGADs is required to compute the time resolution of the LGADs. This is because for three LGADs there is a three combination of time resolutions of systems to compute (σ_{ij}), so three equations and three unknowns(σ_i). As for two LGADs there is just one combination of time resolution of systems to compute, so one equation and two unknown. Therefore,

$$\sigma_{21}^2 = \sigma_2^2 + \sigma_1^2, \quad \sigma_{13}^2 = \sigma_1^2 + \sigma_3^2, \quad \sigma_{32}^2 = \sigma_3^2 + \sigma_2^2.$$

Solving for the σ_i's we get,

$$\sigma_1 = \left(\frac{1}{2} \left(\sigma_{21}^2 + \sigma_{13}^2 - \sigma_{32}^2 \right) \right)^{\frac{1}{2}}, \quad \sigma_2 = \left(\frac{1}{2} \left(\sigma_{21}^2 - \sigma_{13}^2 + \sigma_{32}^2 \right) \right)^{\frac{1}{2}}, \quad \sigma_3 = \left(\frac{1}{2} \left(-\sigma_{21}^2 + \sigma_{13}^2 + \sigma_{32}^2 \right) \right)^{\frac{1}{2}} \tag{3}$$

with error

$$\begin{aligned} \delta_1 &= \frac{\left((\sigma_{21}\delta_{21})^2 + (\sigma_{13}\delta_{13})^2 + (\sigma_{32}\delta_{32})^2 \right)^{\frac{1}{2}}}{2\sigma_1}, \\ \delta_2 &= \frac{\left((\sigma_{21}\delta_{21})^2 + (\sigma_{13}\delta_{13})^2 + (\sigma_{32}\delta_{32})^2 \right)^{\frac{1}{2}}}{2\sigma_2}, \\ \delta_3 &= \frac{\left((\sigma_{21}\delta_{21})^2 + (\sigma_{13}\delta_{13})^2 + (\sigma_{32}\delta_{32})^2 \right)^{\frac{1}{2}}}{2\sigma_3}. \end{aligned} \tag{4}$$

After having measured and computed the time resolution of those three detectors, one of them will be selected as the reference detector of the setup.

To determine the optimal bias voltage for a detector. A current versus Voltage (IV) measurement was performed. For LGAD1, the IV curves at 20, 10, 0, -10 and $-20\,°C$ are plotted in Figure 5.

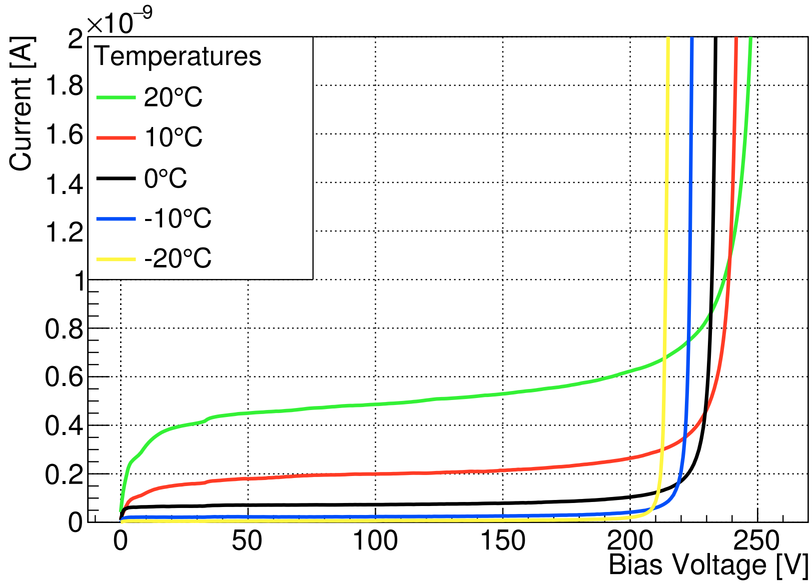


Figure 5: LGAD1 current vs voltage characteristic at different temperatures.

Similar measurements where taken for the two other detectors. To maximize the gain, a voltage about 5 V below breakdown was initially chosen for the bias voltage for each detector and temperature, as displayed in Table 1.

Temperature [°C]	LGAD1 [V]	LGAD2 [V]	LGAD3 [V]
20	228	239	219
10	219	228	208
0	220	219	197
−10	210	209	186
−20	200	199	175

Table 1: Initial bias voltage at different temperatures.

After taking some measurements with these bias voltages it was observed that the Δt distribution presented some non-Gaussian tails. After lowering the bias voltage, those tails were not present anymore in the distribution. The bias voltage was too high which created events that were not from particle interaction but from breakdown, which was probably the cause of those tails. To solve this problem lower bias voltages were chosen for operation and are shown in Table 2.

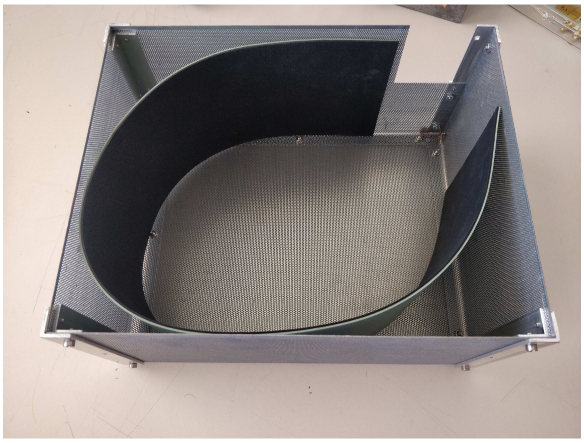
Temperature [°C]	LGAD1 [V]	LGAD2 [V]	LGAD3 [V]
20	215	215	205
10	205	205	198
0	195	195	190
−10	185	185	183
−20	175	175	175

Table 2: Final bias voltage at different temperatures.

High frequency signals were observed and were discovered to come from the power supply used for the amplifiers. A low pass filter was installed at the entrance of the Faraday cage. Those signals were eliminated.

Later on, additional high frequency signals were observed and discovered to come from within the Faraday cage. It might have been standing waves resonating within the Faraday cage. To eliminate them, two shielding methods were found. First, steel sponges were placed very close to the detectors as shown in Figure 6a. Second, a grounding rubber mat used for electrostatic discharge protection was placed around the inside of the cage as seen in Figure 6b.

(a) Steel sponge.



(b) Rubber mat.

Figure 6: Noise reduction methods.

Both methods were successful to reduce the rate of those signals. Also, it has been observed that the time resolution of a system of LGADs is very dependent to the root mean square of the voltage baseline (noise). These two shielding methods are efficient at reducing the noise. The steel sponges shielding is more efficient for reducing the noise than the rubber mat shielding but the steel sponge shielding is not consistent as the noise varies a lot depending on their position. For example, taking the s_{21} at 20 °C with the steel sponge shielding the average noise computed on the oscilloscope was 4.51 mV for LGAD2 and 4.36 mV for LGAD1, this led to a time resolution of 52.4 ± 0.9 ps. Again with the same system at 20 °C with steel sponge shielding, the average noise was 4.96 mV for LGAD2 and 4.63 mV for LGAD1 yielding to a time resolution of 57.8 ± 0.9 ps. Finally, using the grounding rubber mat shielding with the same configuration, the average noise was 4.69 mV LGAD2 and 5.23 mV for LGAD1 and the time resolution was 65.2 ± 1.0 ps. For the future of this setup a more efficient shielding solution is necessary. The solution will have to be consistent and have low noise.

3 Results

Time resolution was chosen to be measured with the steel sponge shielding while trying to stay as consistent as possible with the noise, for more information about the operating conditions refer to Appendix B and for more information about the analysis refer to Appendix C. Those measurements were performed at 20, 10, 0, −10 and −20 °C with all systems of detectors and led to the results in Table 3.

Temperature [°C]	σ_{21} [ps]	σ_{13} [ps]	σ_{32} [ps]
20	53.9 ± 0.8	56.3 ± 0.8	50.8 ± 0.8
10	56.3 ± 0.9	54.5 ± 0.7	52.8 ± 0.9
0	55.3 ± 0.9	54.4 ± 0.7	52.0 ± 0.8
−10	53.0 ± 0.8	54.6 ± 0.7	50.7 ± 0.8
−20	52.3 ± 0.7	53.3 ± 0.7	51.9 ± 0.9

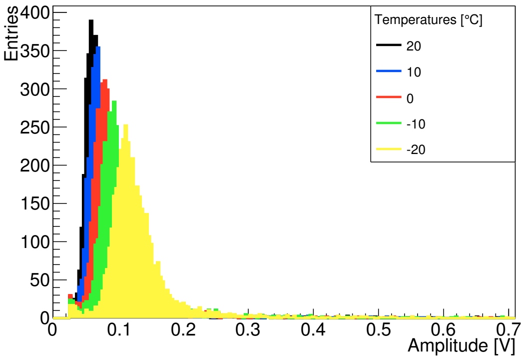
Table 3: Time resolution of each system of LGADs at all temperature and operated at voltages of Table 2.

With Table 3 the time resolution of each detector can be computed using the equation 3 and 4. The values are shown in Table 4.

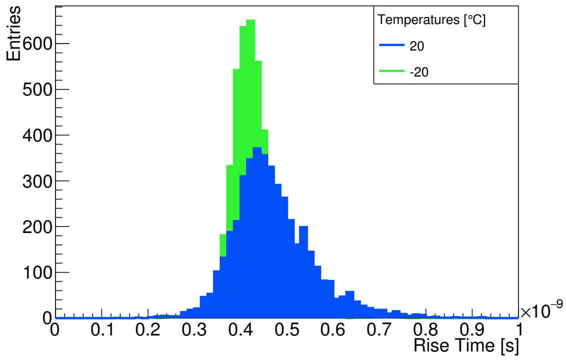
Temperature [°C]	σ_1 [ps]	σ_2 [ps]	σ_3 [ps]
20	41.8 ± 0.9	34.0 ± 1.1	37.7 ± 1.0
10	40.9 ± 1.0	38.6 ± 1.0	36.0 ± 1.1
0	40.7 ± 0.9	37.4 ± 1.0	36.1 ± 1.0
−10	40.1 ± 0.9	34.6 ± 1.0	37.0 ± 0.9
−20	38.0 ± 0.9	36.0 ± 1.0	37.4 ± 0.9

Table 4: Time resolution of each LGAD at all temperatures and operated at voltages of Table 2.

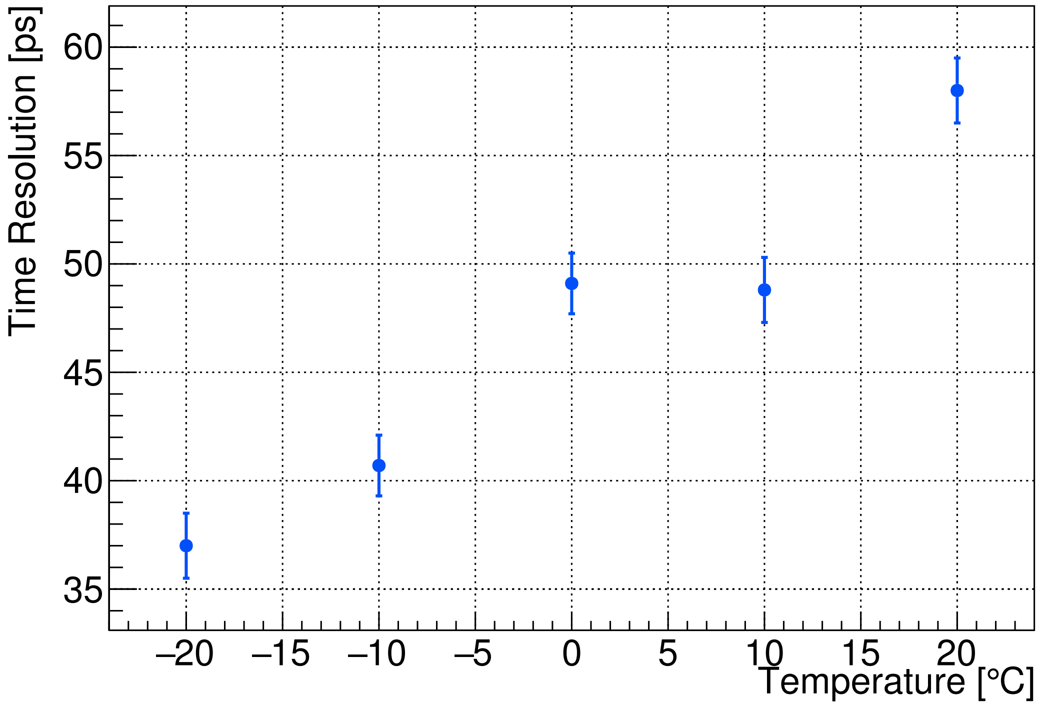
LGAD2 has the best time resolution compared to the others. For this reason it will be selected as the reference detector for the setup. Now that we have a reference detector we can perform some studies on some detectors. The reference detector, LGAD2, will always be operated at the same conditions that the time resolution was computed in Table 4 for each temperature, i.e the bias voltage of Table 2. So that the time resolution of the detector being studied can be computed using equation 1 and 2. For sake of illustration studies will be performed on LGAD1. The bias voltage of LGAD1 was fixed at 175 V and measurements where taken at different temperatures. Figure 7a shows how the amplitude distribution of LGAD1 varies with temperature. Figure 7b is the distribution of the time difference from 20% to 80% of the signal (rise time) for LGAD1 and how it varies with temperature. Figure 7c shows how the time resolution of LGAD1 varies with temperatures.



(a) Histogram of amplitudes of different temperatures.



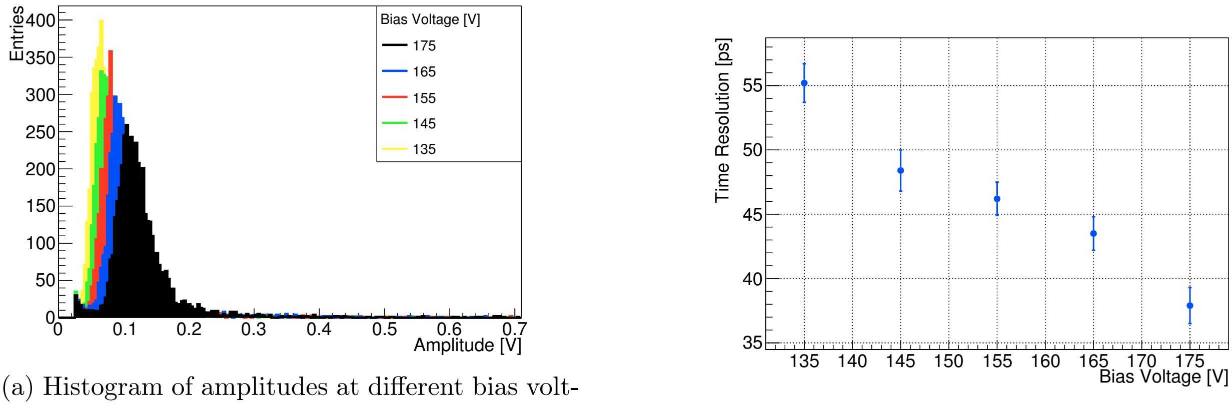
(b) Histogram of rise time of different temperatures.



(c) Time resolution vs temperature.

Figure 7: LGAD1 with bias voltage fixed at 175 V.

Figure 7a show that the amplitude gets bigger as the temperature decreases. Figure 7b shows how the rise time increases with increasing temperature due to the change in drift velocity of the charge carriers. The signal to noise ratio decreases with increasing temperature, making the distribution broader. Figure 7c show that the time resolution gets worse as the temperature increases. These follow the trends expected for LGADs [3]. Other studies could be done. For example, measurements can be taken at fixed temperature of $-20\,^{\circ}$C and the bias voltage of LGAD1 varied. Figure 8a shows how the amplitude distribution of LGAD1 varies with bias voltage. Figure 8b show how the time resolution of LGAD1 varies with bias voltage.



(a) Histogram of amplitudes at different bias voltage.

(b) Time resolution vs bias voltage.

Figure 8: LGAD1 with temperature fixed at −20 °C.

As expected the Figure 8a shows that the amplitude of LGAD1 gets larger as the bias voltage gets higher. Figure 8b show that the time resolution becomes better as the bias voltage gets larger.

4 Conclusion

After series of measurements and testing, a reference detector has been characterized with a time resolution ranging from 34 to 39 ps in a temperature range from −20 to 20 °C. The beta setup will be used for future characterization and studies of detectors, some examples are shown in section 3. Further improvements to the setup are needed, especially the shielding in order to reduce the noise and keep it consistent. This setup will give the possibility to users to measure the time resolution of their detectors.

Acknowledgement

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References

[1] G. Apollinari et al., "High-Luminosity Large Hadron Collider (HL-LHC) : Technical Design Report V. 0.1", CERN, CERN Yellow Reports: Monographs, 2017. DOI:10.23731/CYRM-2017-004

[2] The CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", IOP Publishing, Journal of Instrumentation, vol. 9, no. 10, p. P10009, 2014. DOI:10.1088/1748-0221/9/10/p10009

[3] Hartmut F-W Sadrozinski and Abraham Seiden and Nicolò Cartiglia, "4D tracking with ultra-fast silicon detectors", IOP Publishing, Reports on Progress in Physics, vol. 81, no. 2, p. 026101, 2017. DOI:10.1088/1361-6633/aa94d3

[4] M. Carulla et al., "50 µm thin Low Gain Avalanche Detectors (LGAD) for timing applications", Nuclear Instruments and Methods in Physics Research, Section A, vol. 924, p. 373 - 379, 2019. DOI:10.1088/1361-6633/aa94d3

Appendices

A Material Used

All LGADs have a depletion voltage of approximately 35 V. Each LGAD has an associated Cividec C2-HV Broadband current amplifier with an analog bandwidth of 2 GHz and 40 dB gain. Table 5 shows each LGAD's official name and its associated amplifier serial number.

LGADs	Official name	Amplifier serial number
LGAD1	r9088_W9_LGA33	C2HV0165
LGAD2	r9088_W9_LGA41	C2HV0188
LGAD3	LGADs_CNM_11748_W11_DB09	C2HV0189

Table 5: Detectors and amplifiers names.

To power the amplifiers a GW INSTEK GPC-3030D Laboratory DC POWER SUPPLY was used. To bias the LGADs a Iseg SHQ 222M High Voltage Power Supply was used. The oscilloscope is an Agilent Technologies infiniium DSO9254A. The climate chamber is a BINDER MKT 115.

B Operating conditions

To get the time resolution computed in Table 3 and 4 for each temperature, the LGADs were operated at the bias voltage in Table 6.

Temperature [°C]	LGAD1 [V]	LGAD2 [V]	LGAD3 [V]
20	215	215	205
10	205	205	198
0	195	195	190
−10	185	185	183
−20	175	175	175

Table 6: Bias voltage for each temperature.

The noise (root mean square of the voltage baseline) was computed on the oscilloscope at 20 °C using 100 mV per division and offset of −300 mV for the vertical scale and 2 ns per division for the horizontal scale and is tabulated in Table 7.

s_{21} [mV]		s_{13} [mV]		s_{32} [mV]	
LGAD2	LGAD1	LGAD1	LGAD3	LGAD3	LGAD2
4.50	4.44	4.36	4.48	5.13	4.56

Table 7: Noise for each system at 20 °C.

The triggering was done for all system of LGADs on the bottom detector at −20 mV for all temperatures.
For data collection the following Acquisition Setup was used. Sampling Mode: Segmented, Interpolation: Off, Segmented Memory: 1024 of Segments, Samples per Segment: Manual 256 pts, Sampling Rate: Manual 20 GSa/s, Acquisition Mode: Normal.

C Analysis

To analyze the data, cuts were applied on the noise and the amplitude. The only events that were kept had noise smaller than 0.01 V on both LGADs and amplitude smaller than 0.7 V due to the scale of the oscilloscope. In addition, only events that had an amplitude larger than the values in Table 8 were kept.

Temperature [°C]	LGAD1 [V]	LGAD2 [V]	LGAD3 [V]
20	0.09	0.10	0.12
10	0.09	0.11	0.13
0	0.09	0.11	0.13
−10	0.08	0.11	0.12
−20	0.08	0.11	0.11

Table 8: Amplitude threshold for analysis at each temperature.

With those cuts, the Δt distribution can be plotted and fitted with a Gaussian distribution. This will give you the σ_{sys}. Table 9 shows σ_{ref} for the chosen reference detector and temperature.

Temperature [°C]	σ_1 [ps]	σ_2 [ps]	σ_3 [ps]
20	41.8 ± 0.9	34.0 ± 1.1	37.7 ± 1.0
10	40.9 ± 1.0	38.6 ± 1.0	36.0 ± 1.1
0	40.7 ± 0.9	37.4 ± 1.0	36.1 ± 1.0
−10	40.1 ± 0.9	34.6 ± 1.0	37.0 ± 0.9
−20	38.0 ± 0.9	36.0 ± 1.0	37.4 ± 0.9

Table 9: Time resolution of each LGAD at all temperatures and operated at voltages of Table 6.

Then with σ_{sys} and σ_{ref}, σ_{dut} can be computed using equation 5.

$$\sigma_{dut} = \sqrt{\sigma_{sys}^2 - \sigma_{ref}^2}, \quad \text{with error} \quad \delta_{dut} = \left(\frac{(\sigma_{sys}\delta_{sys})^2 + (\sigma_{ref}\delta_{ref})^2}{\sigma_{sys}^2 - \sigma_{ref}^2} \right)^{\frac{1}{2}} \tag{5}$$