

Multichannel board to characterize fast timing sensors

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1 Description of the summer project

The Upgrade II of the LHCb detector, foreseen for 2033, will operate at an instantaneous luminosity of $1.5 \times 10^{34} \text{ cm}^2 \text{ s}$. To cope with the estimated pile-up of 42 and 2000 charged particle tracks per event, precise timing will be added to the tracking and vertexing sub-systems. A new Vertex Locator (VELO) is needed, one capable of managing the expected 7.5-fold increase in data rate, occupancy, and radiation fluence. In terms of sensors, different technologies are being explored: LGAD, 3D and planar. The LHCb VELO R&D group designed a sensor testing board that can study pico-second timing and interpixel performance of up to 16 pixels. The goal of the summer student project was to characterize the 16-channel board and to contribute to the R&D of different sensor technologies, including LGADs, 3Ds and planar, and test them in terms of radiation damage effects and timing properties.

2 Introduction

The main goal of my project was to characterize the 16-channel board, so it can be used to study fast timing sensors in the LHCb VELO Upgrade II. This report is focused on the characterization studies done during my summer student stay at CERN in 2024.

The overall goal of the characterization is to verify if the 16-channel board is compliant with the design specifications, in particular:

1. **Gain:** to verify if the input signal is sufficiently amplified by the board.
2. **Signal-to-noise ratio (SNR):** to verify if the signal is clearly separated from the noise floor.
3. **Jitter:** to verify if time resolution is sufficiently good to measure the time of arrival of the particles passing through a sensor mounted on the board.

The 16-channel board was tested under different conditions:

1. In the laboratory, with a pulser connected to the board.
2. In a test beam, with an LGAD sensor installed on the board.

3 Technical details of the 16-channel board

The 16-channel board was designed by Edgar Lemos Cid and Federico De Benedetti as part of the LHCb Upgrade VELO group R&D. The board is composed of two parts: the **base board** and the **sensor board**.

Base board amplifies signals coming from the silicon sensor hosted by the sensor board. The amplification stage is composed of a two-stage Transimpedance Amplifier circuit based on an NPN BJT SiGe technology (Infineon BFR840L3RHESD). Technical specifications of the transistor are shown in Table 1. The base board was originally smaller, but the design was modified to fit into the Timepix4 telescope [1] setup installed in the test beam area. Picture of the base board is shown on Figure 1.

Infineon	BFR840L3RHESD
G_{max}	26.5 dB
I_C max	35.0 mA
NF	0.5 dB
OIP3	17.0 dBm
OP1dB	4.0 dBm
V_{CEO} max	2.25 V
Frq. Range	Up to 12 GHz

Table 1: Electrical characteristics of the transistor installed on the base board.

Sensor board, shown in Figure 2 on the right, is a passive board hosting a silicon sensor wire bonded to the pads. Sensor board is connected to the base board through an interface as shown in Figure 2 on the left. Interface to the sensor board is compatible with various board shapes and allows a quick sensor turnaround.

4 Extraction of noise and falling edge from a signal

To properly characterize the 16-channel board, I needed to extract the noise, the falling edge and the gain (peak, respectively trough) of the signal.

To extract the various components of the signal, I developed an algorithm in C++. This algorithm has been generalized for any possible input shape and it separates the noise from the falling edge.

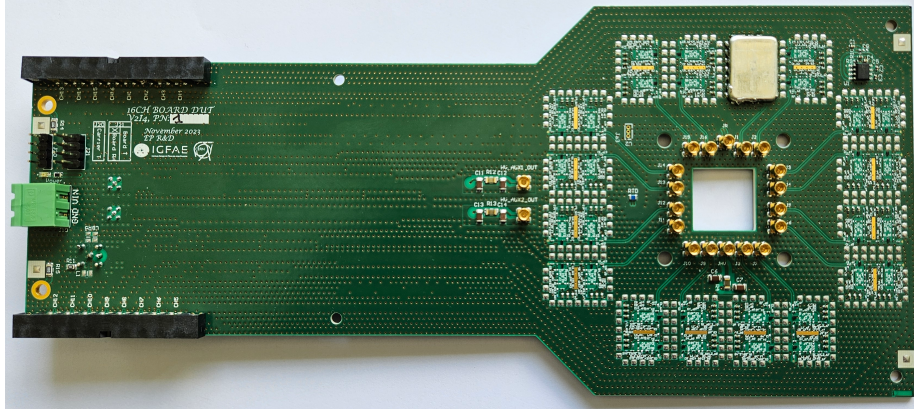


Figure 1: 16-channel board base board

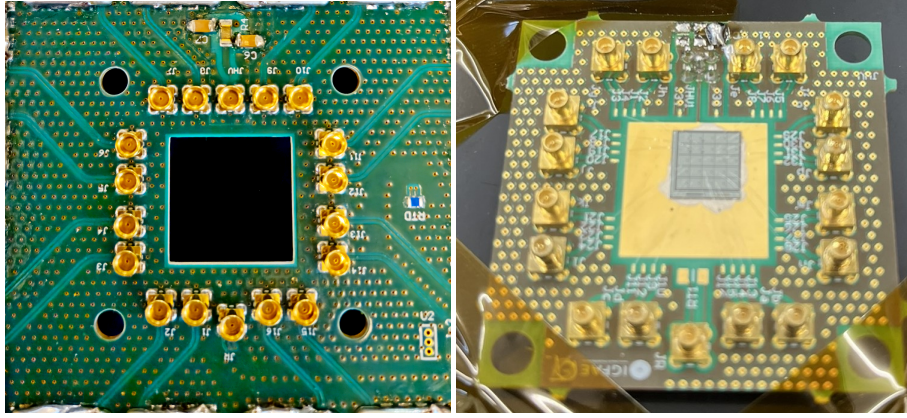


Figure 2: On the left is shown the interface between the base board and the sensor board, on the right is shown the sensor board with an LGAD sensor installed and wire bonded.

The algorithm applies the following procedure for every acquisition:

1. If needed, it eliminates empty data through a voltage threshold.
2. Smooth data with Savitzky-Golay filtering [2], with these parameters:
 - S-G coefficients: $\{-253, -138, -33, 62, 147, 222, 287, 343, 387, 422, 447, 462, 467, 462, 447, 422, 387, 343, 287, 222, 147, 62, -33, -138, -253\}$
 - Polynomial order: 2
 - Window size: 25
 - Normalization factor: 5175

3. Calculate the first derivative with Savitzky-Golay filtering:
 - S-G coefficients: $\{-10,-9,-8,-7,-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6,7,8,9,10\}$
 - Polynomial order: 2
 - Window size: 21
 - Normalization factor: 770
4. Find the minimum of the first derivative and its position.
5. Find the maximum of the first derivative in a small window on the left of the first derivative position.
6. Cut the data into two sets to separate the noise and the falling edge.
7. Calculate the second derivative of the falling edge dataset and find the minimum. The position of the minimum is the exact moment where the noise ends and the signal starts to fall.
8. Separate the voltages and the corresponding time into 2 datasets: noise and falling edge.

5 Pulser measurements

The experimental setup for the pulser measurements is shown in Figure 3. A voltage pulse is injected into the input of the 16-channel board and the amplified signal is measured by an oscilloscope. Channel 1 of the oscilloscope is directly connected to the pulser, which generates a reference periodic signal of a given voltage (yellow signal on the oscilloscope picture in Figure 3). For the first batch of pulser measurements, the settings of the pulser were the following:

1. Period of pulse: $T = 2000$ ns.
2. Width of pulse: $W = 500$ ns.
3. No delay between the output signal and pulse.

J1 output of the 16-channel board (blue signal in Figure 3), is connected to oscilloscope channel 2. The input of the base board is connected to a second channel on the pulser through a 40 dB attenuator, that reduces the amplitude of the signal.

The first batch of measurements with the pulser was done with an oscilloscope configuration that resulted in an unexpected shape of the noise standard deviation. The reason was the scale changes during the measurements.

After an analysis of the reason for this behavior, a new batch of measurements was repeated improving the oscilloscope settings:

1. High-Resolution acquisition setting.
2. Sample: 12 bits.

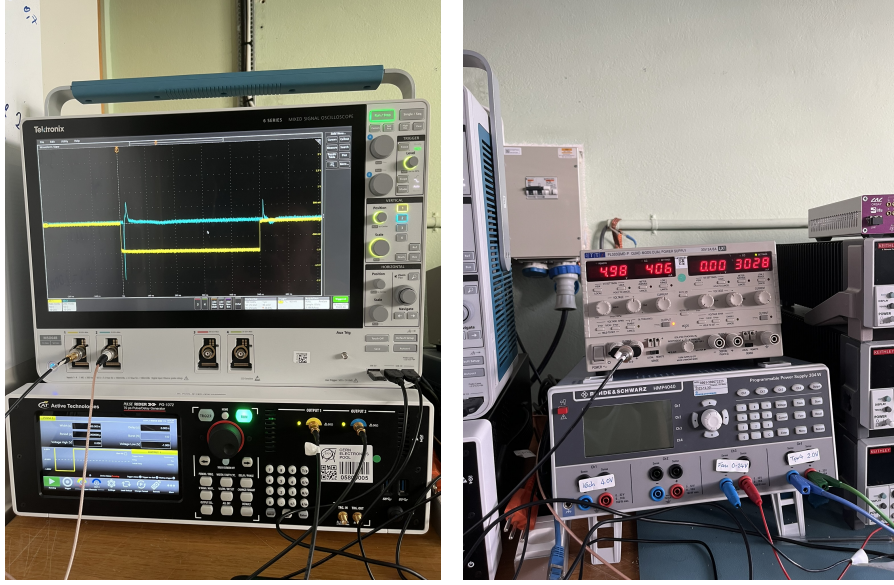


Figure 3: Experimental setup of pulser measurements. The pulser and the oscilloscope are shown on the left. The low voltage supply for the 16-channel board is shown on the right.

3. Filtering: 5 GHz (bandwidth).
4. SR 50 GS/s.

The pulser measurements were done varying the input voltage from 0.25 mV to 20 mV in steps and with three different power supply voltages: 3, 4 and 5 V.

5.1 Amplification of input voltage

First analysis done with these data was to measure the amplification of signals and calculate the gain of the 16-channel board. Figure 4 shows the output voltage scan for different input amplitudes. The gain is calculated as:

$$gain = \frac{V_{out}}{V_{in}} \quad (1)$$

The gain scan is repeated varying the supply voltage to investigate and verify the gain dependence with the power supply. Few mV of the pulser voltage can be amplified up to volts at the output of the 16-channel board. We can see that the output voltage rises also with the supply voltage.

Plot with the calculated gain versus input voltage is shown in Figure 5. The gain for the 16-channel board is around 200 before it starts to saturate around $V_{in} = 5$ mV. After that point, the gain drops to around 50. We have a fairly large amplification before saturation, which rises with increasing voltage.

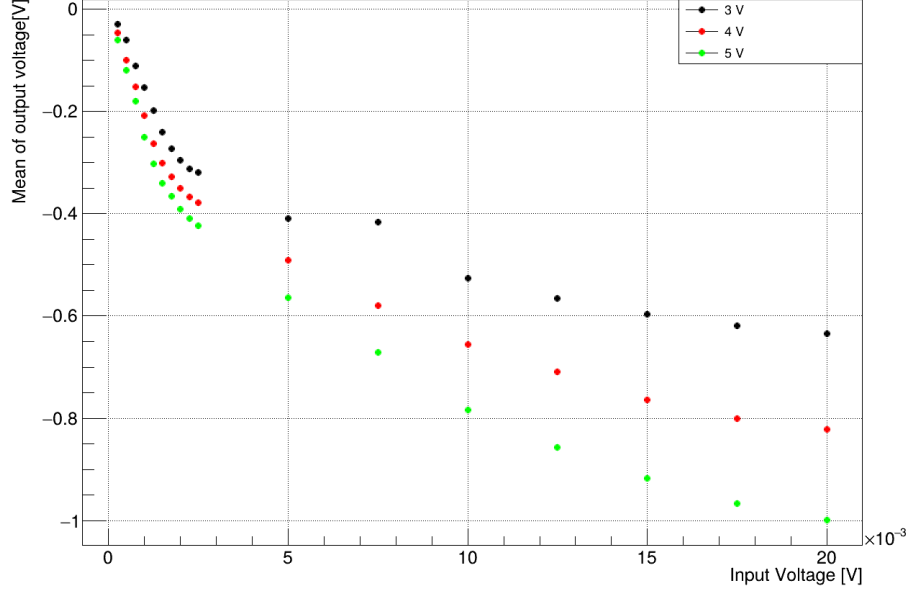


Figure 4: Output voltage amplitude scan in the function of the input voltage from the pulser.

The 16-channel board has two transistors and due to their characteristics, a maximum of 5 mV input voltage can be applied before reaching saturation. The maximum gain of a single transistor is 26.5 dB, which is approximately equal to a factor of 21. Two transistors then correspond to a factor of 441. The maximum V_{CEO} of the transistor is 2.25 V, which gives us a maximum input voltage of 0,005 V when divided by a factor of 441. The behavior of gain then seems legitimate.

5.2 Voltage scans

Figure 6 shows a typical voltage waveform acquired during a pulser test. On the top image, the reference from pulser channel 1 is shown, meanwhile, on the bottom image, the signal shape from the board output is shown. The negative output voltage peak on channel 2 is generated by the negative voltage step in the reference signal on channel 1. The second positive output voltage peak on channel 2 is generated by the positive voltage step in the reference signal on channel 1. Because of this, it would be better to use a current source, rather than a voltage source as input for the 16-channel board.

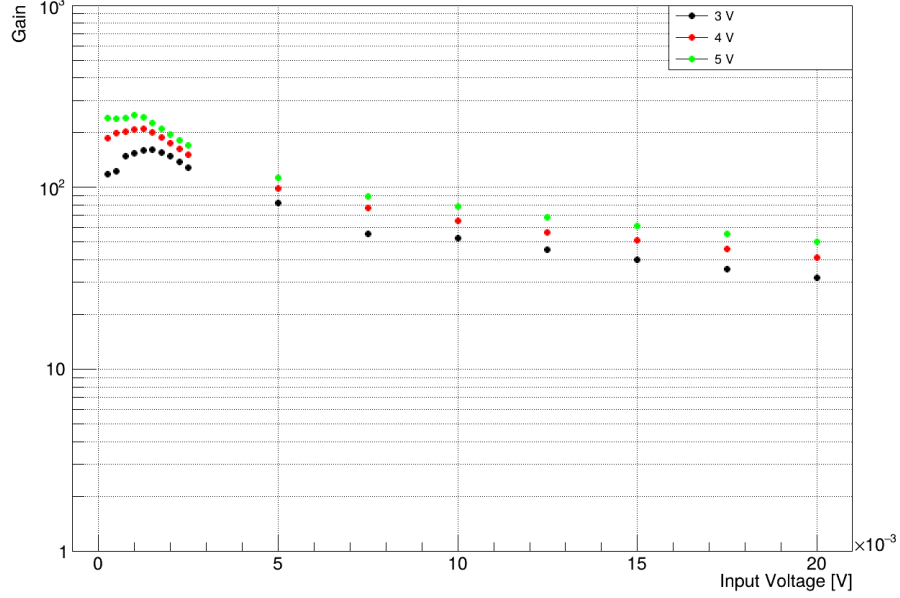


Figure 5: Gain scan in function of the input voltage and power supply voltage.

5.3 Signal-to-noise ratio (SNR)

A very important property of the 16-channel board is whether the signal will be differentiated enough from the noise. This is called signal-to-noise ratio (SNR). We calculate the SNR in the following way:

$$SNR = \frac{V_{out}}{\sigma_{noise}}, \quad (2)$$

where V_{out} is the minimum of the output signal amplitude and σ_{noise} is the standard deviation of the noise.

We can get V_{out} in a simple manner, calculating the minimum of the signal in a given time window. σ_{noise} has to be calculated from the extracted data containing noise only. This is done using the Savitzky-Golay filtering algorithm, as explained in Section 4. When the noise is calculated, we make a histogram with a Gaussian fit. From the fit, we take the standard deviation which is σ_{noise} . Then the SNR is evaluated using the equation above. We repeat this for every signal of every measurement. For every dataset with specific input and power supply setting, we have 250 frames. For every dataset, we compute the 250 signal-to-noise ratios, make a histogram and take the mean value. These values in function of the input voltage are shown in Figure 7.

The behavior of SNR, that it rises with input voltage and also with supply voltage is compliant with what we expect from the 16-channel board. The SNR goes all the way up to 200. This means that the signal read from the 16-channel

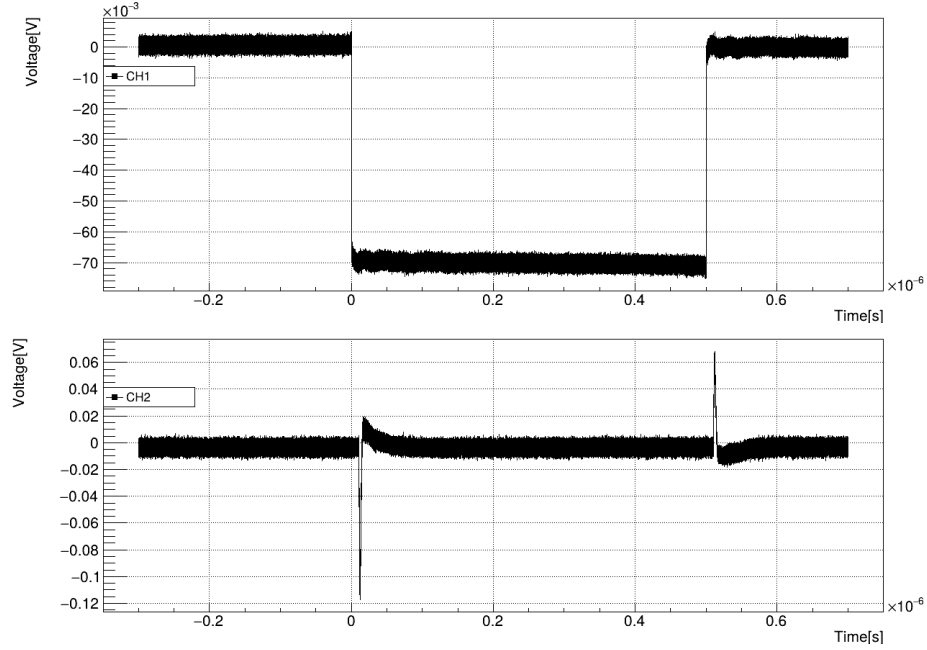


Figure 6: Original 250 frames dataset acquired through the oscilloscope. CH1 on the top is the pulser voltage reference attenuated by a factor of 100 before being injected into the base board. CH2 on the bottom is the output voltage coming from the 16-channel board.

board is clearly visible and distinguishable from the noise. An increase of SNR with supply voltage means that the signal increases.

In Figure 7 two inconsistent SNR measurements can be seen

- For supply voltage of 4 V between 12.5 mV and 15 mV.
- For supply voltage of 5 V between 7.5 mV and 10 mV.

The value of the SNR jumps down and starts to rise again. From Figure 4 we don't see any jump in the output voltage so the effect on the SNR can be traced back to a jump in the sigma. This hypothesis was proven by analyzing the sigma of noise in function of the input voltage, shown in Figure 8. The physical explanation of this effect resides in the oscilloscope scale setting that has to be changed for different output voltage amplitudes. The oscilloscope has an intrinsic noise that is added to the noise of the board when we are changing the scale from 100 mV to 200 mV. Both jumps occurred at these exact moments and they didn't happen for the supply voltage of 3 V, because the amplitude of the output signal wasn't large enough and the scale was kept the same. Taking into consideration this effect, we can observe a nice logarithmic rise of the SNR that has a plateau of around 200.

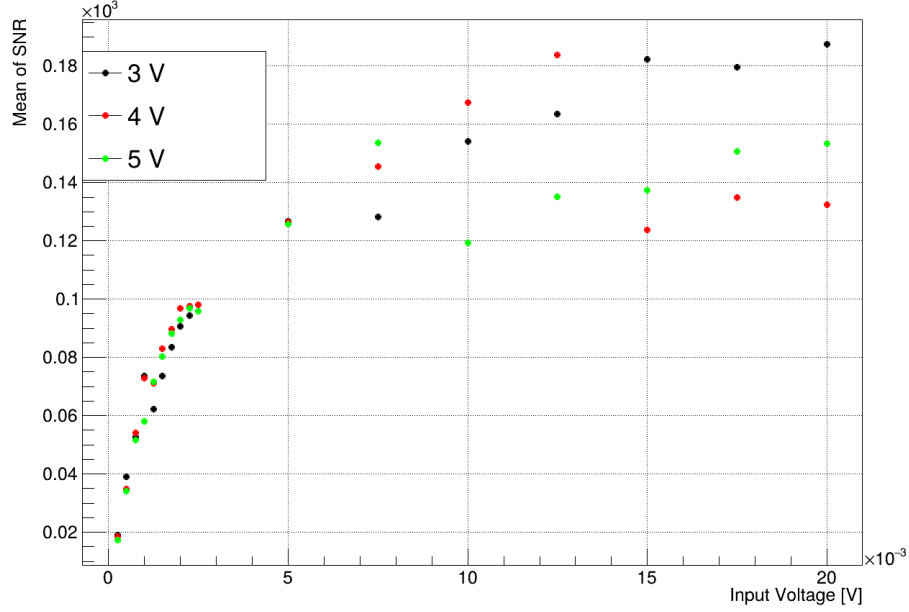


Figure 7: Dependence of the mean value of SNR on input voltage.

Next, we looked at the dependence of the standard deviation of the SNR and σ_{SNR} versus input voltage shown in Figure 9. The standard deviation is taken analogically to the mean of SNR and shows no dependence on the input voltage. Compared to the mean of SNR, the standard deviation is more than two orders of magnitude smaller. This means that the spread of SNR doesn't depend on input voltage and also it's negligible compared to the mean value.

5.4 Noise histograms for different supply voltages

While extracting noise from signals for every measurement, we can also look at the behavior of overall noise while varying only the supply voltage. This was done by taking noise from every frame for every input voltage and separating these arrays of noise by the supply voltage. With this method, we get three arrays of noise associated with the three supply voltages. The corresponding plot is shown in Figure 10. We can notice from the Gaussian fit of histograms that the noise behaves as it should and the shape increases with increasing supply voltage. The right plot of Figure 10 shows the dependence of standard deviation of the noise on the supply voltage.

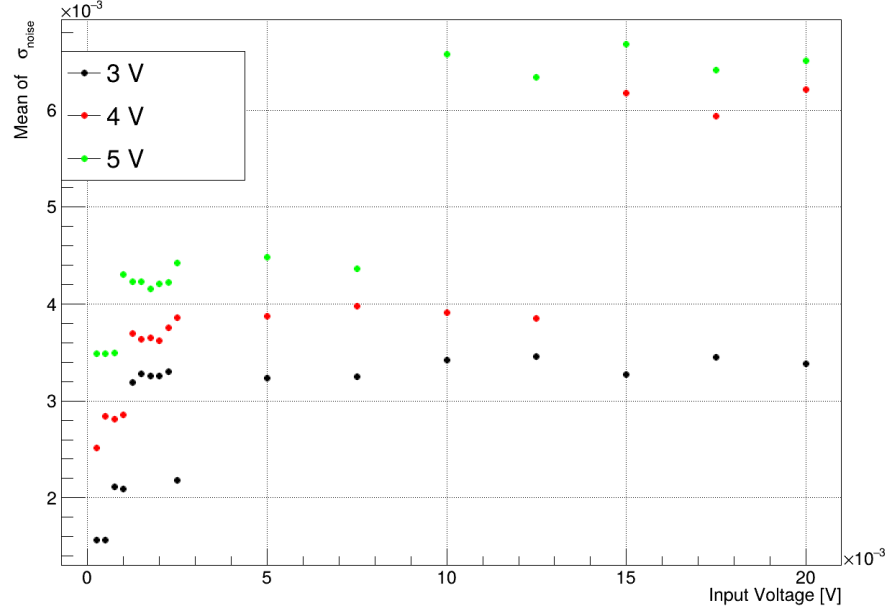


Figure 8: Dependence of σ_{noise} on input voltage.

5.5 Fall time of the output signal

The fall time, t_{fall} , is the measure of how fast a signal reaches the peak (respectively the trough) starting from the baseline. It is typically calculated as the time difference between 10% and 90% of the amplitude swing. For noisy signal, it can be alternatively calculated as 20% and 80% of the amplitude swing. The latter approach has been chosen for this analysis. The calculated t_{fall} dependence on input voltage is shown in Figure 11. We can see that the fall time decreases with the input voltage and that it's in orders of hundreds of picoseconds.

To understand the importance of these results, we need to note that the standard deviation of the fall time is connected to the time of arrival, which is a very important measure for particle detection. We can expect that the time of arrival value will be slightly below the value of $\sigma_{t_{fall}}$.

Let's then look at the values of $\sigma_{t_{fall}}$ and how they change with the input voltage. This dependence can be seen in Figure 12. The magnitude of the standard deviation of t_{fall} is in the order of tens of picoseconds. This is very good as we want the time resolution to be in this range.

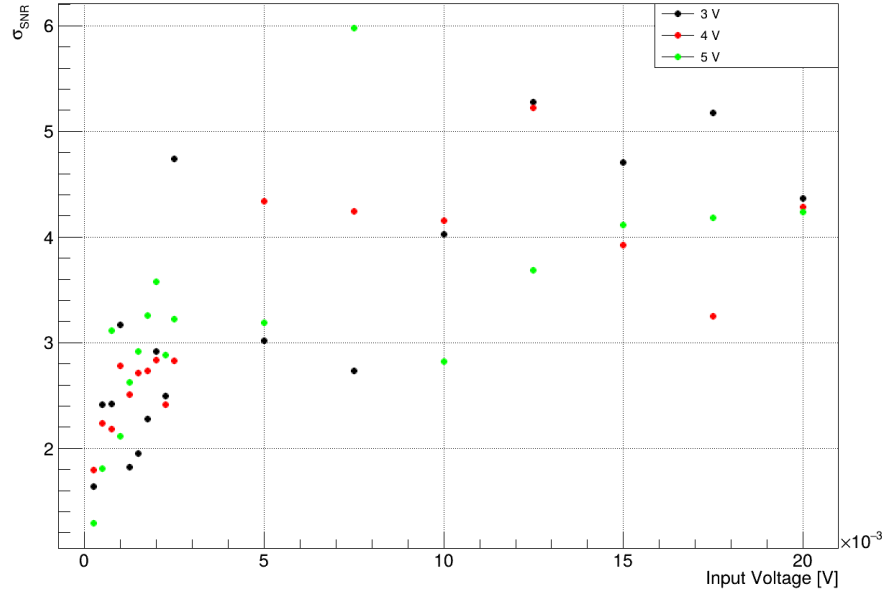


Figure 9: Dependence of σ_{SNR} on input voltage.

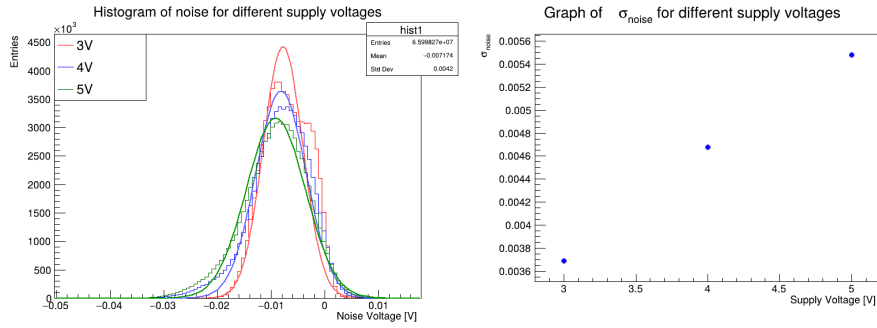


Figure 10: On the left: histograms of the overall noise corresponding to the three supply voltages: 3 V, 4 V and 5 V. On the right: dependence of the noise standard deviation with supply voltage.

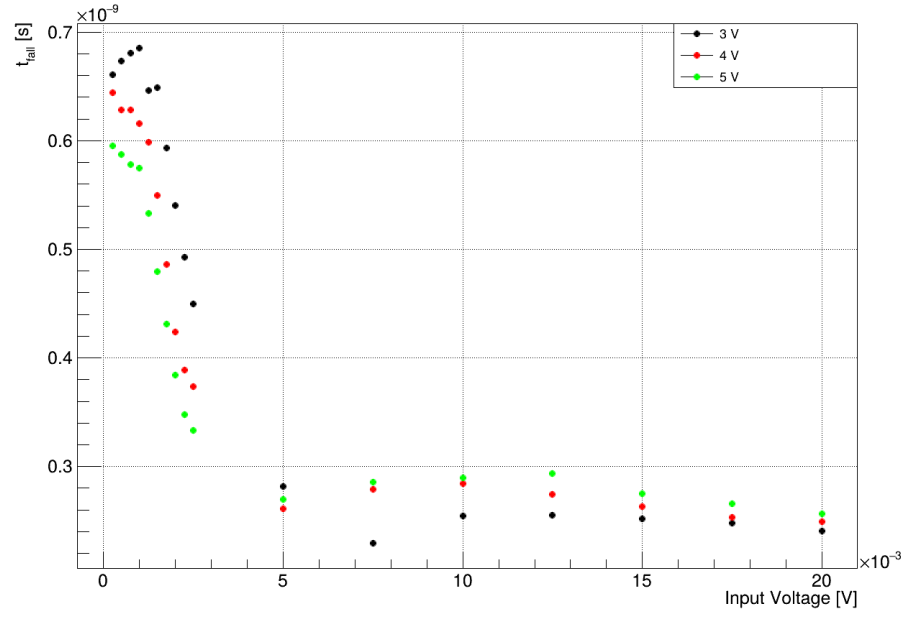


Figure 11: Dependence of t_{fall} on input voltage.

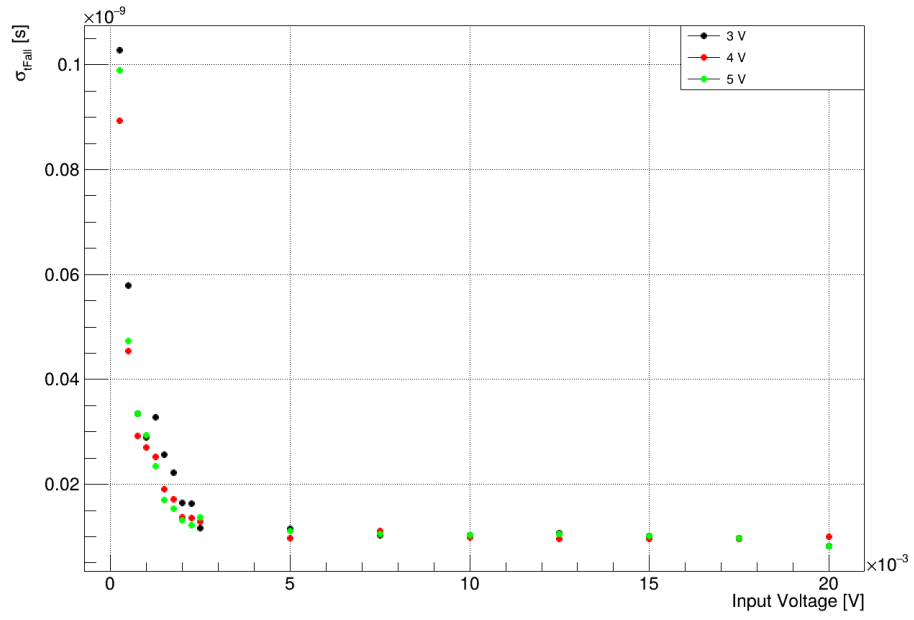


Figure 12: Dependence of $\sigma_{t_{fall}}$ on input voltage.

6 Test beam measurements

During my summer student project, I was also part of test beam measurements. The 16-channel board with an LGAD sensor mounted on top was installed in the North Area as part of the Timepix4 test beam, where the SPS provides a 180 GeV mixed hadron beam. As shown in Figure 13, the 16-channel board was positioned after the telescope (the beam is coming from the left side). Two MCPs installed after the 16-channel board form the timing reference system of the board and the Timepix4 telescope. The data was acquired by an oscilloscope and the SAMPIC acquisition system. The LGAD sensor was tested by scanning different angle positions and bias voltages. During the measurements, various pixels were scanned and the alignment with the beam was adjusted using the hitmap generated with SAMPIC data.

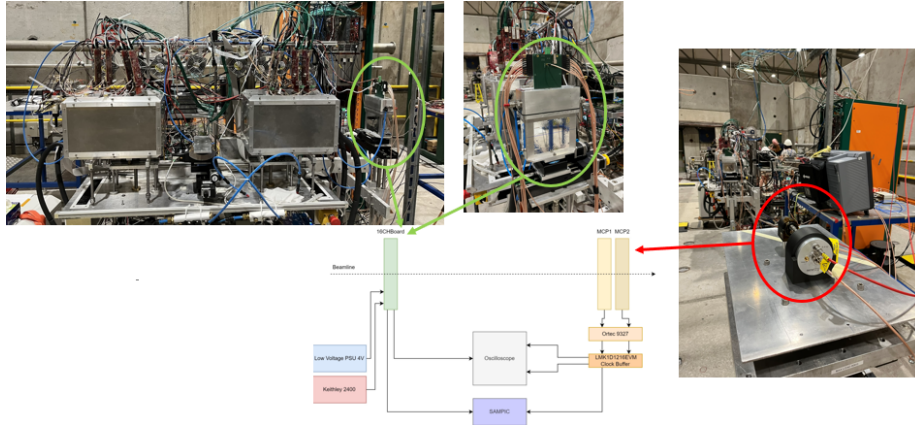


Figure 13: Test beam setup - diagram and corresponding photos.

The SAMPIC data has to be decoded from binary so this report is focused on the oscilloscope data sets only.

The plot of minima of signals, reconstructed into a Landau distribution can be seen in Figure 14 on the bottom, and plots with time differences between MCP and DUT and between MCPs is shown in Figure 14 on the top. The results of the analysis show that:

- Landau distribution can be reconstructed from the dataset and it's above the noise level.
- Time difference between MCP and DUT is 49ps, which is in the order of tens of picoseconds.
- Time difference between MCPs is at 29ps, which is consistent with the same measurement obtained with the Timepix4 telescope.

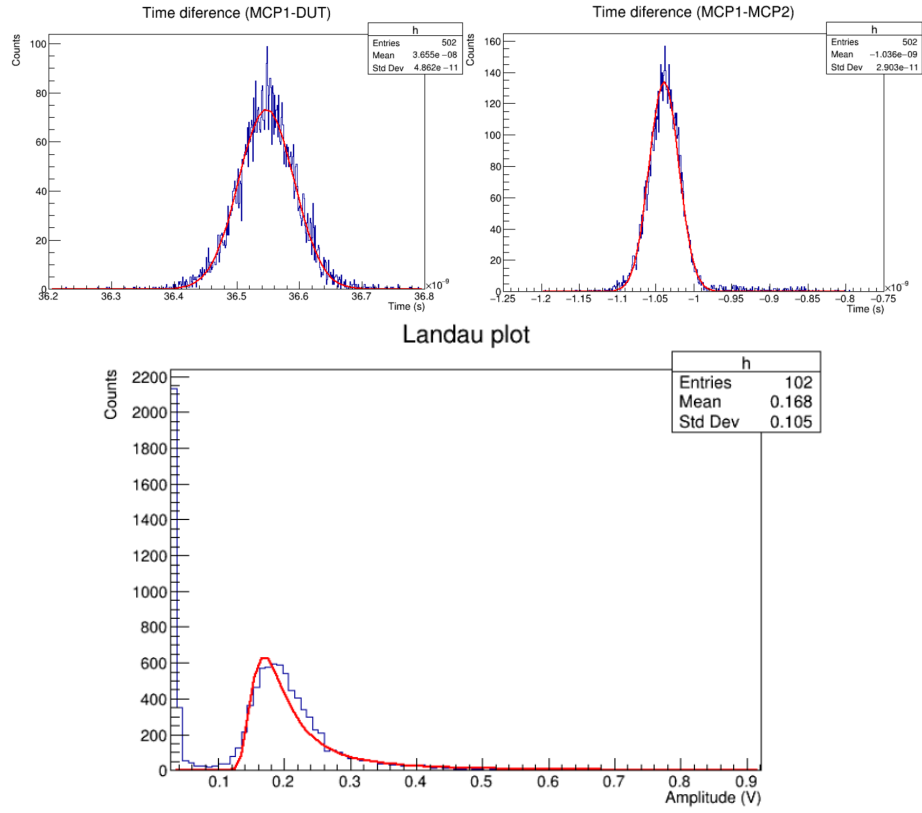


Figure 14: Top left: time difference from test beam data between the MCP1 and DUT. Top right: time difference between MCP1 and MCP2. Bottom: Reconstructed Landau distribution from test beam data.

7 Conclusion

- We can see from this analysis that the 16-channel board can be used for the characterization of sensors for 4D tracking in the upcoming LHCb Upgrade II.
- Gain and SNR are good enough to distinguish Landau distribution when used with a sensor.
- Time resolution is in order of picoseconds.
- A software in C++ has been developed and it can be used for future analyses of characterizations of the 16-channel board and sensors.

References

- [1] K. Akiba, M. van Beuzekom, V. van Beveren, W. Byczynski, V. Coco, P. Collins, E. Dall'Occo, R. Dumps, T. Evans, R. Geertsema, E.L. Gkougkousis, M.M. Halvorsen, B. van der Heijden, K. Heijhoff, E. Lemos Cid, T. Pajero, D. Rolf, and H. Schindler. Reconstruction of charged tracks with timepix4 asics. *Journal of Instrumentation*, 18(02):P02011, feb 2023.
- [2] Savitzky and Golay. Savitzky-golay filter. Online: https://en.wikipedia.org/wiki/Savitzky%E2%80%93Golay_filter.