CERN summer student 2024 lab exercise: Characterisation of silicon pixel detectors

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Abstract

This laboratory exercise provides an introduction to the technology of silicon pixel detectors. Following a discussion of the basic principles of silicon detectors, a characterisation and analysis setup is used to perform measurements for a Timepix hybrid pixel-detector assembly and analyse the acquired data sets. The measurement program includes electrical characterisations, equalisation and calibration of the detector response using a radioactive photon source, as well as detection of minimum-ionising particles from a radioactive electron source.

Keywords

Laboratory teaching exercise; silicon pixel detectors.

1 Overview

This lab course offers a glimpse into the research and development for silicon pixel detector technologies used in High-Energy Physics (HEP) tracking applications. The objectives are 1) to understand the working principle of silicon pixel detectors and 2) to conduct characterisation measurements of a hybrid pixel detector assembly.

Prerequisites: The course requires basic textbook knowledge in the field of semiconductor physics. The participants should be familiar with properties of intrinsic and doped silicon, the concepts of p-n-junctions and silicon diodes, and the mechanisms for energy loss of relativistic charged particles as described by the Bethe-Bloch formula. A particular background in particle physics is not necessary. The exercises can be carried out without prior knowledge in the area of data analysis or programming, as necessary skills will be acquired throughout the exercise.

Preparation: In preparation for the lab course, please read this manual, focusing on the introduction part (Sect. 2). More information on the relevant concepts of semiconductor physics and on silicon detectors can be found in lecture materials [1], review articles [2] and textbooks [3, 4].

Dosimeter: All participants need to obtain a **temporary personal dosimeter** from building 33/R-007, before arriving to the laboratory.

Location: The exercise takes place in **building 1, 1st floor, room 15**.

Tutors: Dominik Dannheim, Philipp Gadow, Younes Otarid, Peter Svihra.

2 Silicon pixel detectors

Silicon pixel detectors are widely used in particle physics detector systems. Prominent examples comprise the inner detection layers of the four large experiments at the Large Hadron Collider (LHC) (ALICE, ATLAS, CMS and LHCb), which are tasked with identifying the trajectories of particles produced in high-energy collisions. Pixel detectors are also used in medical and industrial applications for the detection of X-ray photons.

2.1 Hybrid pixel detectors

Fig. 1 introduces the schematic cross-section of a hybrid pixel detector consisting of a silicon sensor coupled to a hybrid readout ASIC (Application Specific Integrated Circuit). The sensor part consists of
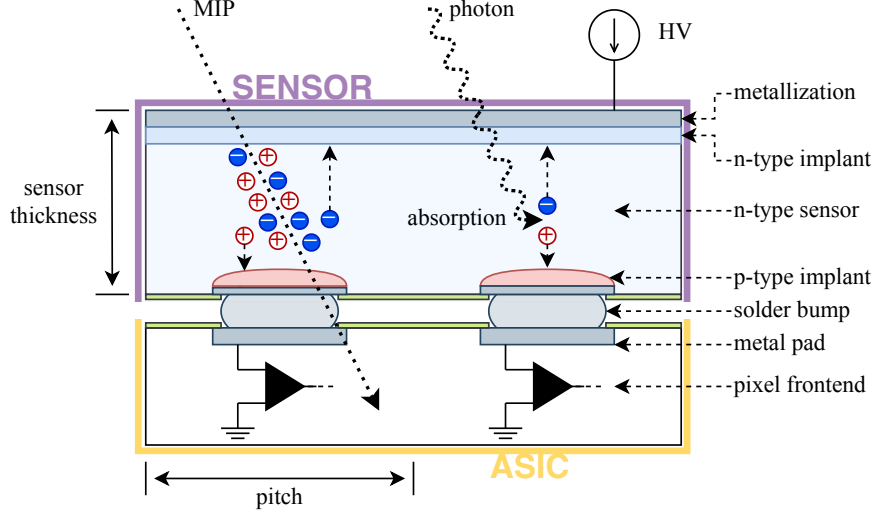

Figure 1: Schematic cross-section of a hybrid pixel detector consisting of a silicon sensor on top bump-bonded to a readout ASIC below. The relevant cases of signal generation, induced signal from a traversing MIP as well as from an absorbed photon, are shown.

an array of silicon diodes, which are operated in reverse bias mode to deplete the silicon bulk from free charge carriers and create an electric field between the sensor backside and the readout electrode at the p-n-junction.

The width of the depletion zone, w, depends on the applied reverse bias voltage, V_{bias}, and on the effective doping concentration of the sensor, N:

$$w \approx \sqrt{\frac{2\varepsilon}{qN} V_{\text{bias}}} \tag{1}$$

where q is the elementary charge and $\varepsilon = 11.68 \times 8.854 \times 10^{-12} \text{F} \cdot \text{m}^{-1}$ is the permittivity of silicon. To maximise the ionisation signals originating from traversing particles, the sensor should be operated at a bias voltage equal to or greater than the full-depletion voltage, V_{dep}, which corresponds to the voltage necessary to deplete the entire thickness of the sensor, d:

$$V_{\text{dep}} = \frac{qNd^2}{2\epsilon} \tag{2}$$

2.2 Leakage current

The electric field causes thermally generated charge carriers as well as charges created by defects and surface effects to drift towards the adjacent readout electrode at the p-n junction on the sensor surface. This drift is resulting in a small continuous *leakage current* across the sensor. The leakage current I increases with temperature, T, doubling approximately every $8 \, \text{K}$:

$$I(T) \propto T^2 \text{e}^{-\frac{E_g}{2k_{\text{B}}T}}, \tag{3}$$

where $E_g = 1.12 \, \text{eV}$ denotes the band-gap energy and k_B is the Boltzmann constant.

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For very high fields ($\gtrsim 30\,\text{V/µm}$), an *avalanche breakdown* can occur, resulting in a sudden steep increase of the leakage current at the *breakdown voltage* V_{bd}. Local defects and inhomogeneities at the sensor edge can reduce V_{bd} and thereby impair the safe operation window of the sensor ($V_{\text{dep}} < V_{\text{bias}} < V_{\text{bd}}$).

2.3 Signal formation

Besides the small continuous leakage current, local short current pulses of a few nanoseconds can be created from the interaction of relativistic particles and X-rays in the sensor layer.

High-momentum charged particles passing through the sensor volume interact mostly through ionisation with the silicon atoms along their path (mean ionisation energy: $3.62\,\text{eV}$), leading to local charge depositions proportional to the path length in the depleted volume (Fig. 1 left side). The mean charge deposition per unit length depends on the particle type and energy and is given by the Bethe Bloch formula. For *Minimum Ionising Particles* (MIPs) from radioactive sources or high-energy particle collisions, the *Most Probable Value* (MPV) of the created charge corresponds to 76 electron-hole pairs per micron.

The absorption of low-energy ($< 100\,\text{keV}$) X-rays from radioactive sources proceeds through photo absorption, leading to local ionisation charges proportional to the initial photon energy (Fig. 1 right side).

The charges created from MIPs or X-rays drift in the electric field of the depleted volume towards the adjacent readout electrodes and are measured with dedicated signal-processing circuitry in the readout layer.

2.4 Signal processing in the readout circuitry

Each readout electrode in the sensor layer is electrically coupled with a solder bump to an amplification, shaping and digitisation circuit in the readout ASIC layer. An example circuit is shown schematically in Fig. 2.

The preamplifier amplifies and transforms the input ionisation signal to a triangular-shaped pulse, with a duration proportional to the amount of ionisation charge collected by the sensor. Only pulses above an adjustable detection threshold, a voltage level controlled by a Digital-to-Analog Converter (DAC), pass the following discriminator stage. This global threshold for all pixels in the matrix is typically set to a value above the observed random noise fluctuations of the signal, such that only pulses originating from interactions in the sensor are detected. Small processing imperfections lead to pixel-by-pixel variations of the effective threshold, which are equalized with a local threshold fine-adjustment applied per pixel.

The discriminated pulses are digitised in the digital front-end during the time an externally provided *shutter* signal is raised, as schematically shown in Fig. 3. Depending on the chosen readout mode, the Time-of-Arrival (ToA) of the first pulse, the total amount of ionisation charges (Time-over-Threshold - ToT) or the number of pulses are measured and digitised using clock counters. The coordinates of the hit pixel and the digitised ToA, ToT or counting signals are sent to an external data-acquisition (DAQ) system for further processing and analysis.

3 Measurements

This section describes a set of measurements with a hybrid pixel-detector assembly, based on the concepts introduced in the previous section. The measurement program is foreseen to be completed within approximately 3 hours.

3.1 Measurement setup

A photograph of the measurement setup used for the exercise is shown in Fig. 4. The measurements are performed with a hybrid pixel detector assembly consisting of a Timepix readout ASIC [5] with
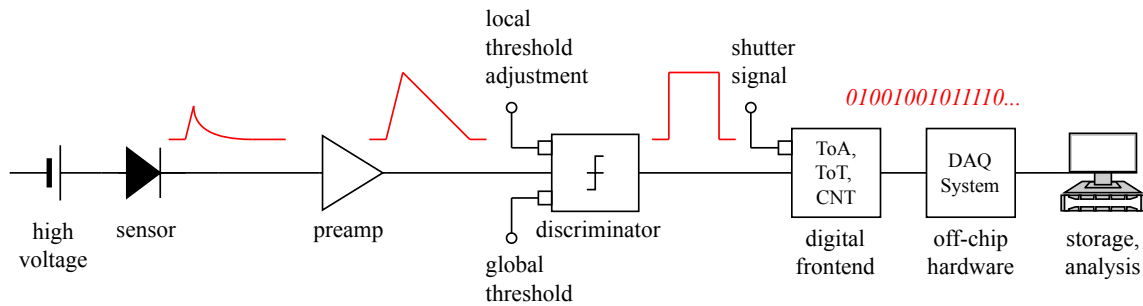
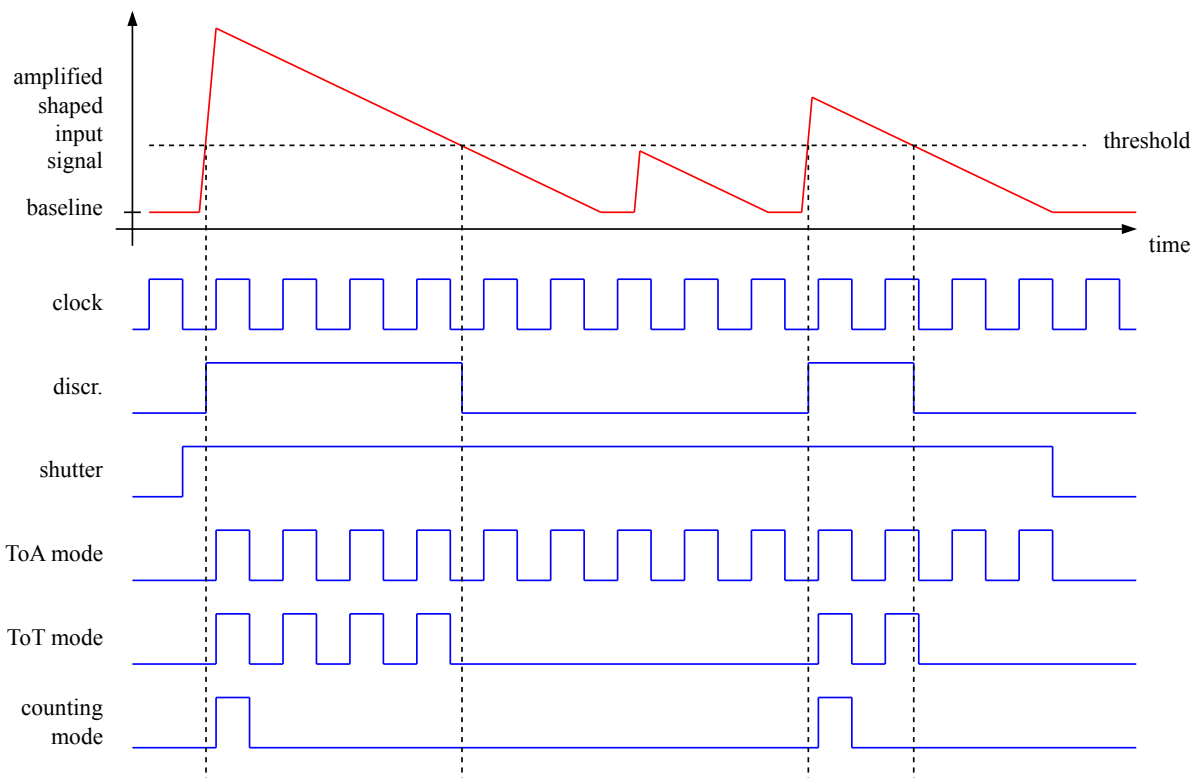Figure 2: Processing of the sensor signal in the readout circuitry.

Figure 3: Measurement of Time-of-Arrival (ToA), Time-over-Threshold (ToT) and number of pulses in the digital frontend.

256×256 square pixels of $55\,\mu\mathrm{m}$ pitch, bonded to a silicon sensor of $100\,\mu\mathrm{m}$ thickness. The Timepix assembly is mounted on a chip board protected by a plastic enclosure.

The sensor bias high voltage and the measurement of the leakage current is provided by a Keithley 2450 source meter [6], which connects to the Timepix chip board using standard LEMO [7] cables.

The biasing, control and readout of the Timepix ASIC is handled by the FITPix DAQ box [8]. It consists of a field programmable gate array (FPGA) for the control of the ASIC, a USB 2.0 interface chip and digital-to-analog converters (DACs) to generate bias voltages and currents.

The FITPix DAQ box and the Timepix chip board are connected via a VHDCI connector. The data recorded by the FITPix DAQ box is sent to a DAQ computer using a USB 2.0 interface.

Three sealed radioactive sources are used for the measurements , which need to be handled with care and only with direct supervision by your tutors:
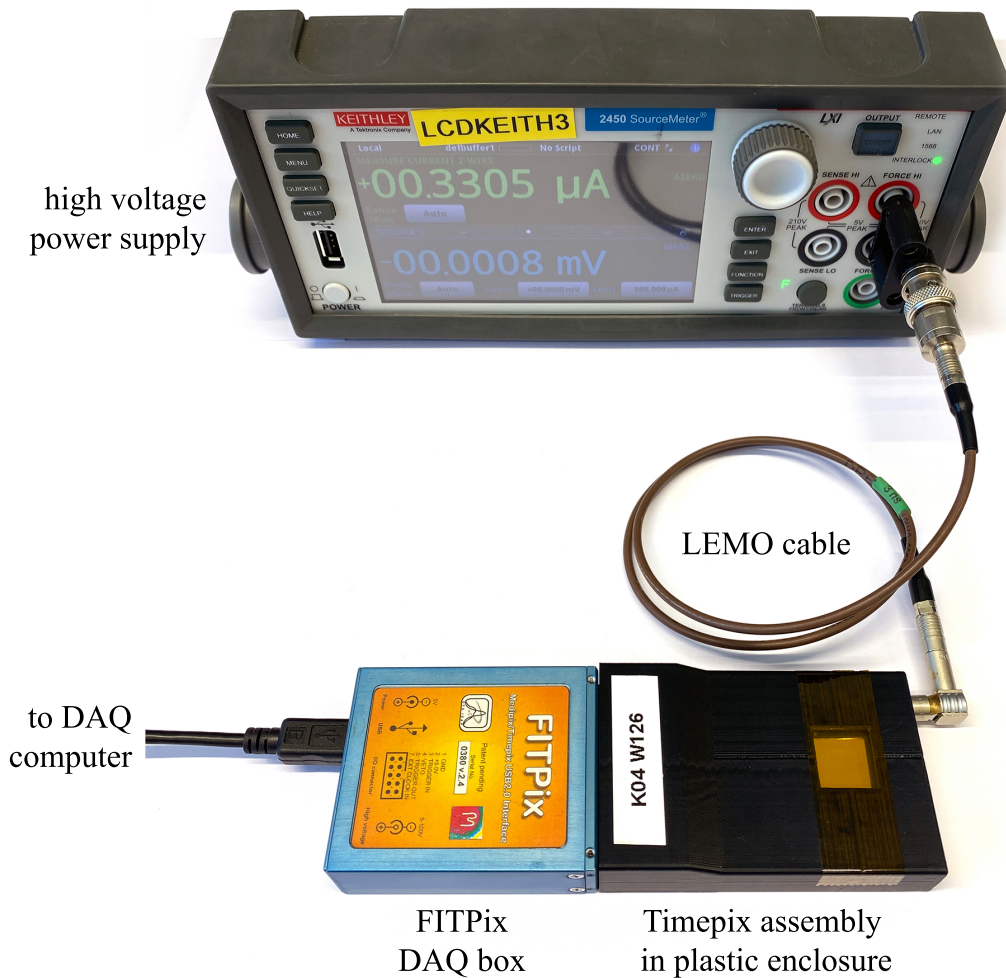
Figure 4: Measurement setup: Timepix assembly connected to FITPix DAQ box and high-voltage power supply.

Fe-55 A photon source containing the radioactive iron isotope Fe-55 [9]. It decays by electron capture into the manganese isotope Mn-55, with a half-life of 2.737 years. For the purpose of this exercise, the produced photons are considered mono-energetic with an energy of $5.9\,\mathrm{keV}$.

Cd-109 A photon source containing the radioactive iron isotope Cd-109 [10]. It decays by electron capture into the isomeric state of Ag-109, with a half-life of 462 days. A photon with a characteristic energy of $22.0\,\mathrm{keV}$ is emitted in the transition to the Ag-109 ground state.

Sr-90 An electron source containing the radioactive strontium isotope Sr-90 [11]. It decays by β-decay into the yttrium isotope Y-90, with a half-life of 28.8 years and a decay energy of $0.546\,\mathrm{MeV}$. Y-90 undergoes β-decay into the zirconium isotope Zr-90 with a maximum electron energy of $2.274\,\mathrm{MeV}$ and a half-life of 64.1 hours. The resulting electron energy spectrum contains a significant fraction of energies near the ionisation minimum ($\beta\gamma \approx 1 - 4$), making Sr-90 a source of MIPs.

3.2 Software setup

The data acquisition and analysis is facilitated using the Pixet Pro Software [12] and custom high-level python code available through the local lab computers.
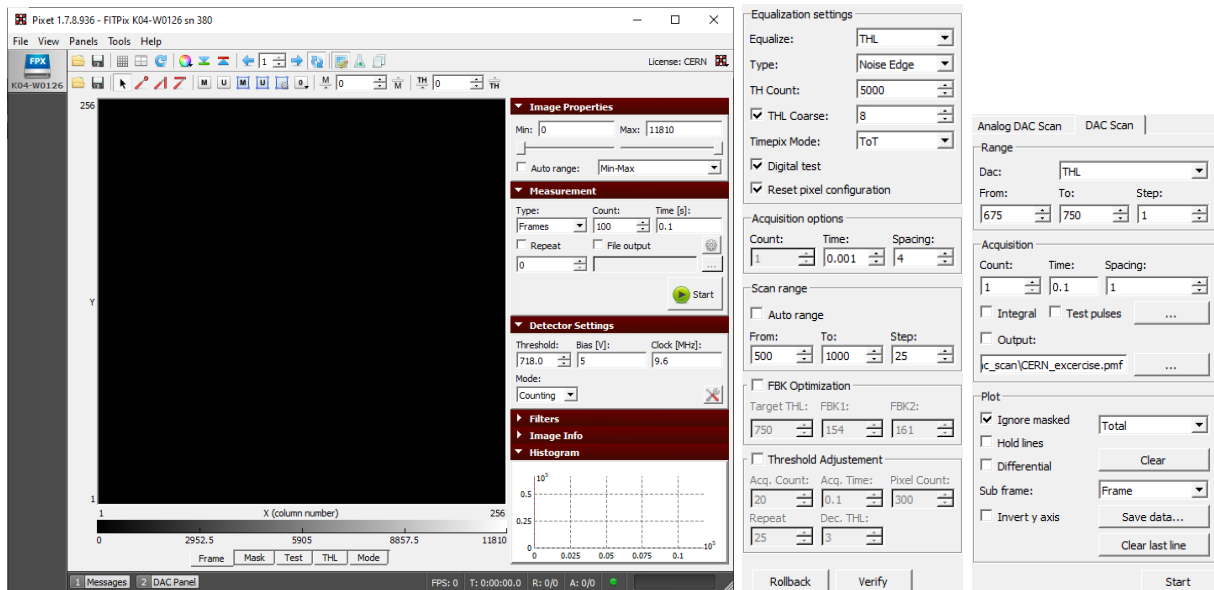
(a) Main window with hitmap (with option below to show pixel configurations) and standard data acquisition options.

(b) Equalization.

(c) DAC scan.

Figure 5: Screenshots of the Pixet Pro software.

Pixet Pro The Pixet Pro DAQ software can be executed by double-clicking the icon found on the desktop of the local machine. Make sure the connected device is recognized by the software and shows up in the bar on the left-hand side of the program window.

The main window provides simple setup and control options for the data taking, prominently showing the pixel hitmap. More advanced menus and options are available through the toolbars. A screenshot of the setup is shown in Fig. 5.

Jupyter notebook The data-analysis setup uses python Jupyter notebooks [13], which enable the user to easily combine Markdown text and executable Python source code on one canvas. Within the notebook the user can run a series of singular code cells using the *Run* icon to the left of each cell (Ctrl + Enter) or the entire code by pressing the *Run All* icon above the code (Shift + Enter). The output will subsequently appear directly below the executed code cell.

The python notebooks have been set up for the recording and the analysis of measurement data and can be reached from within the CERN network by the url address `http://exercise` in the folder `pixel-lab-exercise/codebase`.

3.3 Measurement 1: electrical tests

The goal of this measurement is to investigate the properties of the sensor p-n junction and establish its default working condition (full depletion). The measurement of the current-voltage (I/V) characteristic of the device allows for an electrical characterisation and to confirm a voltage range in which it can be safely operated.

The leakage current of the sensor is measured for a selection of set voltages. The measurement setup is prepared by using a LEMO cable and appropriate miscellaneous adapters to connect the Keithley 2450 source meter output to the bias voltage connector on the front edge of the Timpepix assembly chipboard. The setup is supposed to closely resemble Fig. 4.

Measurement 1 Tasks:

Before connecting the device to the power supply, make sure that no voltage is being applied and the

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current limit (compliance) is set to $10\,\mu A$. *The power supply is operated manually. Do not yet connect the provided USB cable to the FITPix DAQ box.*

1. Prepare the setup for the measurement and apply $0\,V$. Suggest a method how to establish whether the connected device is a silicon diode without applying any voltage.

2. Test the junction type of the device by carefully applying small ($0.1\,V$ to $1.0\,V$) positive as well as negative voltages.
   What does the observed current response tell you about the dopants and construction of the device? Draw the diode with the p-n junction and discuss the observed behaviour.

3. Based on the resulting diode polarity, perform a reverse-bias scan of the sensor from $0\,V$ to the maximal voltage available by the power supply. Make sure the sensor is not exposed to any light before taking the data. Start with an initial fine step size of $0.2\,V$, adapt the step size based on the changes in current. Record the measured values in the provided `IV.ipynb` notebook.
   Discuss the observed shape of the I/V curve.

3.4 Measurement 2: detector response equalisation and determination of the noise

The goal of this measurement is to investigate and equalise the non-uniformity of the pixel response, and to understand the noise and the precision of the digitisation process.

In order to correct for non-uniformity, each pixel is designed with circuitry that is able to apply a local *threshold adjustment offset*, modifying the globally set detection threshold value. An equalisation procedure is performed to adjust the local offsets such that a uniform signal response is achieved across the whole pixel matrix. This is done by performing two global detection threshold scans – one for zero and a second one for the maximum value of the local offset range; recording the settings of the global threshold for each pixel as it starts responding to the baseline noise. An example is shown in Fig. 6, sketching the two aforementioned threshold scans for two different pixels. Relying on the linearity of the adjustment values, the equalized response is obtained by interpolating the per pixel results of the two scans to a common target threshold value.

Measurement 2 Tasks:

Make sure that the reverse bias voltage is turned off before proceeding.

1. Connect the provided USB cable to the FITPix readout box and only then set the reverse bias voltage to a value above the full depletion voltage. Start the Pixet Pro software and observe the increase in the leakage current. Can you explain its origin?

2. In the main window of Pixet, select "Counting" mode. Click on the icon "Edit Pixel Configuration" and select "THL" at the bottom. This allows you to change the 4-bit threshold adjustment offset for each pixel. Use the `Set Pixel Cfg Bits` tool from the `Pixel Configuration` panel. Select `Region = Full Matrix` and `Threshold Low = 0`. This sets all pixel to a value of 0. Perform a threshold (THL) DAC scan using the `Tools/Dac Scans` tool of Pixet Pro. Choose tab `Dac Scan` and set `DAC` to `THL`. Set the range from 600 to 1000 and step 10. Select "Hold lines" and start the scan. Now set all adjustment offsets to a value of 15 and repeat the scan.
   Compare the two curves and discuss the observed difference.

3. Use the equalization tool in the Pixet Pro software `Tools/Equalization`. Set the range and step size for the threshold equalisation procedure based on the results observed in the previous task. The rest of the configuration should match that of Fig. 5b. Start the equalization process. Observe the process on the hitmap screen and check the resulting adjustment offset configuration in the main Pixet window. Repeat the threshold scan from the previous task 2 with this new configuration.
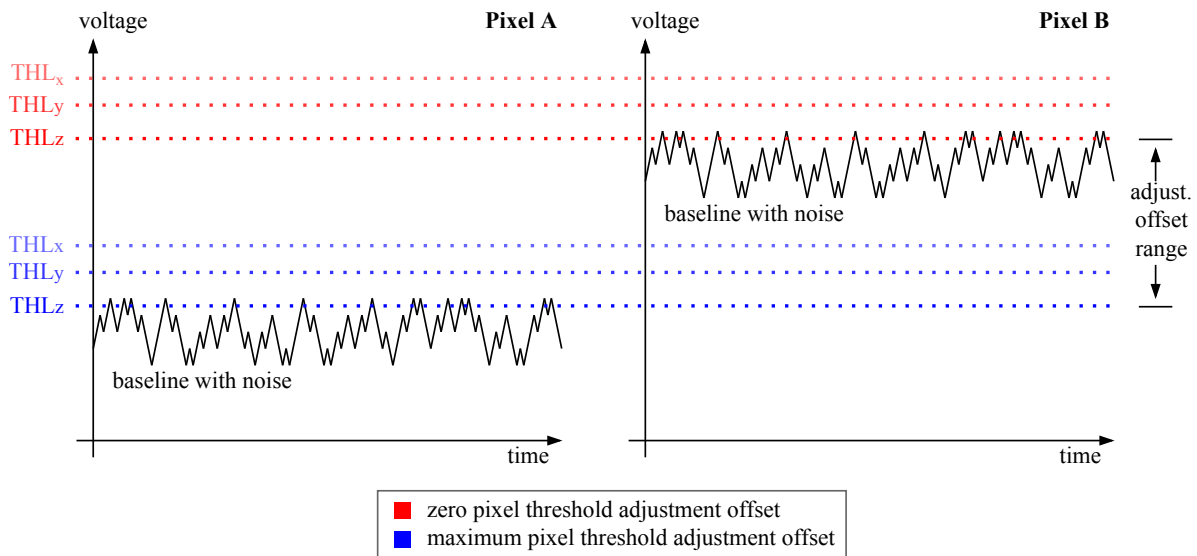
Figure 6: Fluctuations in the processing of silicon devices causes a non-uniform pixel response, shown as two different baselines for pixels A and B. The global threshold is scanned ($THL_{x,y,z,...}$) over a wide range for both zero (red) and maximum (blue) values of the local threshold fine-adjustment offsets. An optimal offset is found for each individual pixel through interpolation between the two extremes. In the sketched example, the equalized result would be achieved by setting the adjustments to maximal and zero for pixels A and B, respectively, both pixels then observe the noise at threshold THL_z.

> *optional:* observe and discuss what difference the pixel spacing value in the acquisition options makes (change from 4 to 1 and finally to 2). Which values are better and why?
> *Discuss the observed curves and write down the estimated threshold for the noise baseline.*

4. *optional:* Uncheck `Hold Line`, enable `Output`, create a folder to save the data (provide any file name and choose `*.pmf` format) and re-run the DAC scan. Using the provided `threshold-scan.ipynb` notebook, upload the `*.pmf` files into the created folder and analyse them.
   Equalization results - what do you see in both plots? Write down the estimated DAC noise value. What does it physically correspond to?

3.5 Measurement 3: calibration with photon source

The goal of this measurement is to observe the response of the detector to the Fe-55 and Cd-109 photon sources and to use them to calibrate the ToT energy response.

For the measurements the source is placed closely above the sensor surface which is visible through an opening in the plastic chip board cover. The known energy of the emitted photons is used as an energy reference in order to convert ToT counts into physical units.

Measurement 3 Tasks:

Make sure the detector assembly is still fully connected, depleted and the Pixet Pro software is running.

1. In the main window of Pixet Pro set the `threshold` to the baseline as resulting from the equalization, set the measurement time to $0.1\,\mathrm{s}$, and enable the `Auto-range` and `Repeat` options in the measurement part of the window. Start and stop the data acquisition with toggling the `Start` and `Stop` button. While measuring, change the global threshold setting and observe its effect. Find a value where the detector operates noise-free.

Discuss the difference between the baseline and the operational threshold, how does this relate to the noise? Write down the global operational threshold.

2. Place the Fe-55 source on top of the plastic enclosure of the detector assembly. Verify the detector response using data acquisition and align the beam spot with the centre of the pixel matrix. Observe the `Counting mode` at the default clock $9.6\,\mathrm{MHz}$. Change to `Energy mode` (ToT) at same clock and evaluate the change. Once again change to `Time mode`, modifying the clock to $1\,\mathrm{MHz}$ and measure at $0.01\,\mathrm{s}$.
   Summarize the differences between the acquisition modes.
   Optional: Re-run the DAC scan from Measurement 2, Task 4 for the counting and energy modes and explain the difference. Make sure to remove the radiation source and close it.

3. Set `energy mode`, $9.6\,\mathrm{MHz}$ clock, an acquisition time of $0.1\,\mathrm{s}$, and open the spectrum tool `Tools/Spectra Imaging` of the Pixet Pro software. From within perform multiple measurements while adjusting the histogram range and step size such that the peaks are fully resolved.

4. Observe the impact of the shutter (acquisition) time.
   Discuss the result of the shape of the spectrum and identify such acquisition time that produces good results. Based on the dominant peak calculate the calibration of ToT counts to energy. Estimate the ToT values of the other photon energy peaks and discuss the results.

5. Repeat the steps above for the Cd-109 source and compare the results for the two sources.

3.6 Measurement 4: detection of minimum-ionising particles

The goal of the measurement is to investigate the response of the detector to MIPs from the Sr-90 source.

Measurement 4 Tasks:

Make sure the detector assembly is still fully connected, depleted and the Pixet Pro software is running. Using the optimised threshold and data acquisition time, continue with the spectral evaluation of particles and detector performance.

1. Still using the Cd-109 source, open the Pixet Pro clustering tool in `Tools/Clustering` and choose spectrum mode `Per clstr size volume` to re-record a ToT spectrum (the summed ToT from the pixels in the cluster is called volume). The tool runs independently of the data acquisition, therefore the acquisition options are set in the main window from where the data taking needs to be started. Afterwards starting the clustering automatically performs a combination of hits in neighbouring pixels into clusters and produces results for different cluster sizes.
   Observe the difference of the spectrum compared to the previous measurement results. Can you explain why do we observe two-and-more pixel sized clusters?

2. Change over to the Sr-90 source placed above the detector and align it based on the observed hit rate. Retake the per cluster size spectrum (first reset the histogram by pressing `clear data` in the clustering window).
   Observe the difference between X-ray and MIP source. Based on the form of the energy loss of the MIP, suggest how to obtain the point of full depletion of the sensor. Can you do the same with the photon source?

3. Measure the spectra for 2000 acquisitions during a reverse-bias voltage scan in the range of $1\,\mathrm{V}$ to $100\,\mathrm{V}$ (determine the step size based on the observed changes in the peak values), save the results after finishing each step by pressing `Save All` on the `Spectrum` panel on the right. Use the applied voltage as filenames ("1V", "2V", ...). Upload all scan results to an empty folder on the server and use the `clustering.ipynb` notebook to analyse the dependency.
   Evaluate the dependency. Extract the point of the full depletion of the sensor. Does it match with the results from Measurement 1? Estimate the total charge deposited in the sensor based on the calibration obtained from exercise 1. Estimate the thickness of the sensor assuming a most

probably MIP energy deposition of 76 electrons per micron (Sect. 2.3).

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