



Hochschule Karlsruhe
Technik und Wirtschaft
UNIVERSITY OF APPLIED SCIENCES

Faculty of Electrical Engineering & Information Technology
Program: Sensor Systems Technology, Thesis Nr. 310

Master of Science Thesis

Visualisation of Radioactivity in Real-Time on a Tablet Measured by a Hybrid Pixel Detector

Oliver Michael Keller

March 2015

CERN-THESIS-2015-169
10/07/2015



Referee: Prof. Dr. Michael Bantel
Co-Referee: Prof. Dr.-Ing. Ulrich Grünhaupt
Supervisor at CERN: Dr. Rolf Landua

Contents

1	Introduction	5
2	Hybrid Pixel Detector Principles	8
2.1	Pixellated Silicon as a Sensor	10
2.2	Interaction of Radiation with Silicon	11
2.2.1	The Charge Sharing Effect	14
2.2.2	Pattern Recognition	16
2.3	The Timepix Readout Chip	20
2.3.1	The Charge Conversion Path	21
2.3.2	The Readout Device	23
2.3.3	Threshold Equalisation	24
2.4	Sensor Properties	26
2.5	Energy Calibration	30
2.5.1	Measurement Workflow	30
2.5.2	THL Calibration	31
2.5.3	TOT Calibration	36
3	iPadPix Hardware Setup	39
3.1	The Tablet	41
3.2	Optical Setup	43
3.3	Inertial Sensors	45
3.4	Timepix readout	47
4	iPadPix Software Setup	50
4.1	Batchpixel - Image Readout	51
4.2	MAFalda - Image Analysis	54
4.3	Data Transport	57
4.4	Augmented Reality Application for iOS	59
4.4.1	Camera Feed	59
4.4.2	Overlay of Cluster Data	60
4.4.3	User Interaction	63
4.5	Further Ideas	66
5	Conclusion	67
	Bibliography	68

Abstract

This work explores a method to visualise and interact with radioactivity over time and space by means of augmented reality on a screen. A prototype, iPadPix, was built to demonstrate use as an intuitive new tool for educative and training purposes. Measured by a hybrid pixel detector, Timepix, traces of radioactive decays are displayed in real-time on a mobile device. Its detection principle and properties are detailed as well as the calibration of the sensor. An embedded board is used to process and forward the sensor data to a tablet over a wireless network connection. Software was developed to processes and overlay signatures of ionising radiation and particles on a live camera feed. It is described here and published as open source.

Acknowledgements

I would like to thank Rolf Landua for his supervision, encouragement and the confidence he showed in me to conduct this fascinating thesis topic at CERN. Various colleagues have supported me along this path, with many helpful advices and valuable knowledge, namely: Mariusz Sapinski, Bernd Dehning, Jerome Alozy, Stuart George, John Idarraga, Eric Bosne, Xavier Llopart and Michael Campbell.

What I cannot create, I do not understand.

– Richard Feynman

1 Introduction

Radioactivity is among the things that accompany us 24 hours a day, whether we are at home, in an airplane or undergo certain medical examinations. Yet, most laymen have little knowledge about its nature, properties and commonness. It is often seen as a scary topic and considered a taboo that has to be avoided as much as possible. One of the main reasons for this repudiative behaviour is, that we have no human sense to detect radioactive decays. From disasters such as radioactive fallouts and atomic warfare, we know it can have very dangerous consequences. However, as with most things, the effects depend on the amount we are exposed to.

Means to detect ionising radiation and particles, caused by radioactive decays, such as Geiger counters exist since almost a hundred years. These provide rather abstract information by counting the number of decay emissions crossing a certain sensitive volume over time. The functional principle allows no discrimination of energies or estimation of the decay mode. Other devices, which can recover the energy of the incident radiation, consist as well only of one sensing element in most cases. While this is sufficient to estimate the radioactive dose (the amount of exposure), it does not allow a more intuitive imaging of radioactive decays. Only single numbers are provided that need expert knowledge to be interpreted.

The presented device prototype, iPadPix, is an attempt to improve the knowledge and understanding of laymen on this topic by making invisible radioactivity visible. With the help of a two-dimensional imaging sensor, that is sensitive to ionising radiation, the patterns of radioactive decay are displayed in an intuitive new way on a mobile device by means of augmented reality. This allows to explore environmental radioactivity, such as radon gas in household cellars, minerals from the countryside, cosmic radiation or any object that contains radioactive material. Radioactivity becomes experienceable in time and space, revealing the random nature of its decay processes. An inspiration for this work is the cloud chamber, where radiation quanta and particles leave directly visible traces in a chamber filled with a special vapour. Figure 1.1 shows characteristic clouds formed by a weak radioactive material in a cloud chamber at CERN's S'Cool LAB.

A similar combination of imaging sensors is used in the GAMPIX gamma camera developed by CEA LIST [Carrel2012]. Its use case is to provide a heat map of γ -radiation on top of a real image, similar to a thermal imaging camera. However, a high number of photons is required to generate this kind of gamma images. The application is therefore exclusively targeted at professional purposes like characterising radioactive waste. Nevertheless, it served as well as an inspiration for the development of iPadPix.



Figure 1.1: A weak radioactive welding stick in a cloud chamber emitting ionising radiation (tracks on the left side of the stick). The stick is made of tungsten and enriched with 4 % of thorium, which is an α , β and γ -radiation emitter.

Project Proposal This work was conducted within the Education and Public Outreach Group at CERN in Geneva, Switzerland. To convey the concept and the conceived user experience, the mock-up shown in figure 1.2 was developed based on the following core criteria:

Intuitive exploration and classification of radioactivity in everyday objects by scanning across an area of interest with a mobile device. Learning about α , β and γ -radiation in an immediate and visually attractive way. Debunking common myths and fears by engaging the user with an interactive device that is educative and fun to use at the same time.

The following use cases are considered for iPadPix:

- School labs (CERN's S'Cool LAB)
- Interactive exhibitions (CERN's new Microcosm Exhibition)
- Professional trainings
- Radiation protection

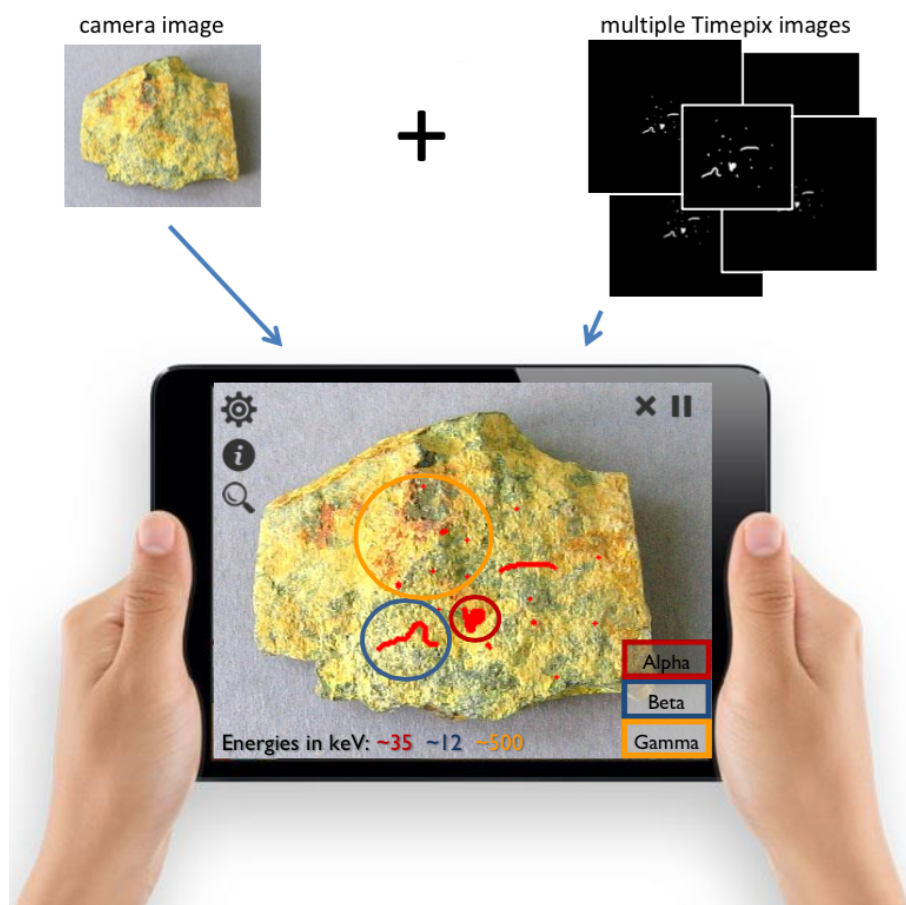


Figure 1.2: Concept drawing created to convey the iPadPix of idea. A live camera feed is combined in real-time with data from a Timepix detector augmenting the screen with traces from radioactive decays.

2 Hybrid Pixel Detector Principles

The detector used in this work in order to sense emissions from radioactive decay is a so called *hybrid pixel detector* (HPD). These imaging devices are comparable to the sensors in digital consumer cameras. They are flat structures composed of a number of equal sensing elements, pixels, arranged in a regular matrix. However, cameras are optimised to detect the visible range of light and typically at frame rates that are relevant for video recordings (30 Hz to 60 Hz). In contrast, HPDs are designed to detect higher energetic radiation, such as X-ray photons or elementary particles. The former need to accumulate several photons until one pixel detects the presence of light while the latter is sensitive to single radiation quanta (e.g. one electron or photon). In the case of particle colliders such as the LHC at CERN, HPDs are used in all of the four big particle physics experiments: ATLAS, CMS, ALICE and LHCb [Rossi2006]. They measure the direction in which collision products travel to capture the properties of rare and very short lived elementary particles. The LHC collision rates for its second run in 2015, are foreseen at 40 Mhz which requires very fast HPDs. A second characteristic is their composition of two main components as shown in figure 2.1.

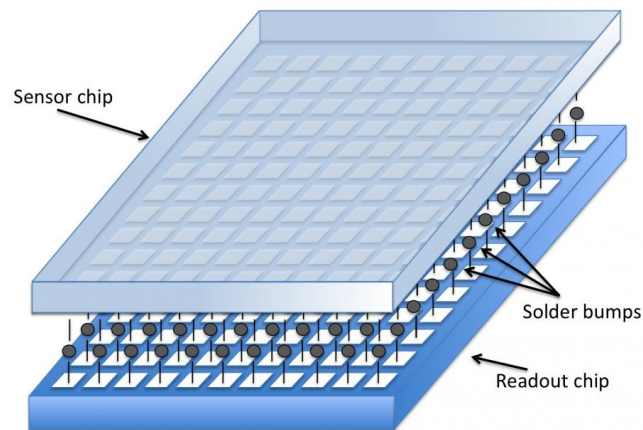


Figure 2.1: Illustration of the hybrid pixel detector concept, consisting of two main components. Reprint from *Designing pixel readout chips at CERN: From dream to reality*.¹

¹<http://ph-news.web.cern.ch/content/designing-pixel-readout-chips-cern-dream-reality>

A sensitive element is *bump-bonded* via small solder balls onto the actual readout chip which converts and transmits the sensor signal. This allows to choose the optimal material for each functional part. In the case of silicon: High-resistivity material in the $\text{M}\Omega \cdot \text{cm}$ range for the electronic readout chip and low-resistivity material in the $\text{k}\Omega \cdot \text{cm}$ range for the sensor [Hartmann2009]. Other sensor materials such as cadmium-telluride (CdTe) can be selected if their properties fit better to the measurement conditions. Similar to the CMOS active-pixel sensor in consumer cameras, a HPD reassembles an array of semiconductor diodes followed by analog charge conversion circuits in every pixel. Both, the sensor and the readout chip are pixelated according to the same dimensions.

It is important to understand, that the registered signal is an abstraction of the interaction between the incident radiation and the sensor. The detected patterns do not picture the original dimensions and shape of the incident particle or radiation. Only a result of the interaction, free charges in the sensor material, is imaged.

The following sections describe the principle of operation and features of the particular readout chip chosen for iPadPix. Comprehending the detector characteristics is essential to interpret and visualise the recorded data in a meaningful and correct way. A considerable part of this work was therefore dedicated to study possible implications of various operation parameters and the calibration method of the selected HPD.

2.1 Pixellated Silicon as a Sensor

The sensor used in this work is a silicon semiconductor which is made of n-type bulk material and features local p^+ -implants in each pixel. It is pixelated in the same way as the underlying readout chip, spanning 256×256 pixels at a size of $55 \mu\text{m} \times 55 \mu\text{m}$ each. Figure 2.2 shows the structure of one pixel including the bump-bonding region which connects the sensor to the charge sensitive amplifier in the readout chip (c.f. chapter 2.3).

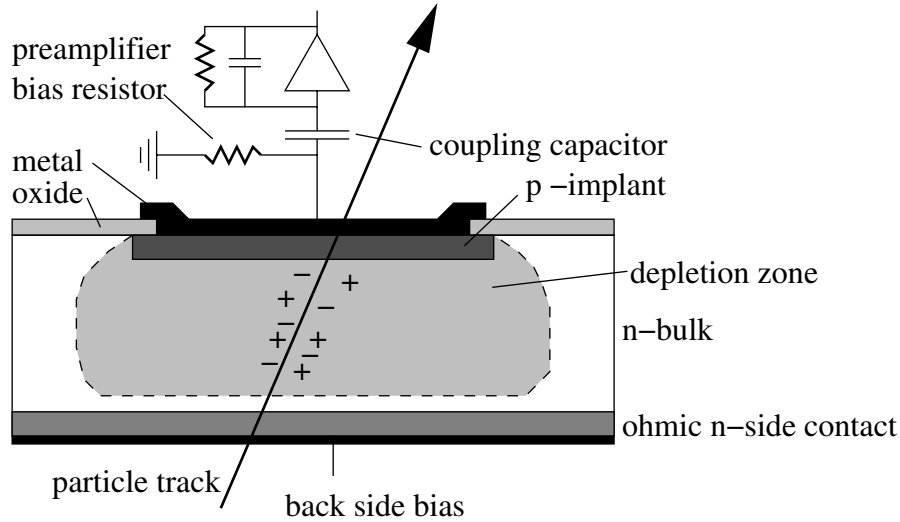


Figure 2.2: Schematic cross section through one pixel of a p^+ -in-n hybrid pixel detector. Reprint from [Rossi2006].

The pn-junctions of the pixel matrix are operated in reverse-bias mode. With p^+ -in-n sensors, the back side is connected to a positive bias voltage while the p^+ -implants are grounded in the readout chip. The bias voltage generates an electric field which suppresses most of the leakage current composed of thermally generated free charge carriers. This allows an operation at high signal-to-noise ratios where a difference of few hundred electrons is enough to distinguish the signal reliably from the background. The typical leakage current of a reverse-biased silicon sensor is less than $0.1 \mu\text{A cm}^{-2}$ [Kalliopuska2013][Rossi2006]. As the region enclosed by the electric field has almost no mobile charge carriers, it is called depletion zone and defines the sensitive volume of the sensor according to the depletion depth. This depth depends on the bias voltage and material parameters of the silicon as is shown in chapter 2.4. When a charged particle or photon traverses the sensor as depicted in figure 2.2, this can initiate the generation of new free charges. Electron-hole pairs are created along the path of interaction within the depletion zone by transferring discrete energy quanta of 3.6 eV . This is the ionisation energy which is required to free one electron-hole pair in silicon [Knoll2009][Rossi2006]. With a positive bias voltage, the electrons flow towards the back side while the electron vacancies are collected in the pixel implants and registered as a current by the charge sensitive amplifier in the readout chip.

2.2 Interaction of Radiation with Silicon

Ionising radiation quanta interact with matter in different ways. This work focuses on the use and detection of weak radioactive materials. They are characterised by the type of emitted radiation, their energy levels and intensity. The term *weak* refers to a low energy value per quantum and low intensities. Typical weak emitters considered in this work are minerals containing traces of radioactive ores, thorium or uranium enriched products and radon in the air. The major decay modes of those are charged particles from α and β^+/β^- decays, as well as photons from γ and X-ray radiation. The following section focuses on the properties of these interacting with silicon, since the sensor of the iPadPix's hybrid pixel detector is made of this material.

Charged Particles Interaction of a charged particle like an electron with matter can be quantified by the *linear energy transfer* (*LET*) or also called, the *stopping power* $S(E)$ which describes the loss and is therefore negative:

$$LET = \frac{dE}{dx} = - S(E) \quad (2.1)$$

On a macroscopic level, this process can be compared with the phenomenon of mechanical friction where energy is continuously deposited in discrete units per segment. The stopping power can be approximated to an average value along the track within materials like silicon and depends mainly on the energy of the charged particle. Until the point where it finally stops, it travels the range R which can be calculated as the integral from the initial energy E (when the material is entered) to the final rest energy E_0 divided by the stopping power. Since E_0 is typically only in the order of a few eV, it can be neglected and the range definition can be simplified to the *continuous slowing down approximation* (CSDA) range R_{CSDA} :

$$R = \int_{E_0}^E \frac{dE}{dE/dx} \approx \frac{E}{S(E)} = R_{CSDA} \quad (2.2)$$

Figure 2.3 shows the calculated range of electrons in microns between 10 keV and 1 MeV for a silicon density of 2.33 g cm^{-3} . Electrons of up to 20 keV energy are stopped within one pixel's dimension of less than $55 \mu\text{m}$.

The graph also suggests that the maximum electron energy which can be deposited in a $300 \mu\text{m}$ thick silicon sensor should be less than 210 keV in case of a perpendicular irradiation. This assumption is wrong, because the path of an electron in this energy range does not follow the angle of incidence. On the contrary, it is scattered along its path and travels on curly tracks further in the plane direction of the sensor than it is traversing along the incident direction. The actual maximum range along the thickness of the sensor is therefore higher and difficult to quantify [Knoll2010]. Absorption measurements show that almost no electrons escape $300 \mu\text{m}$ of silicon at energies below $\sim 300 \text{ keV}$ [Leroy2012]. These considerations are valid for electrons emitted from β^- decays as well as for positrons emitted from β^+ decays.

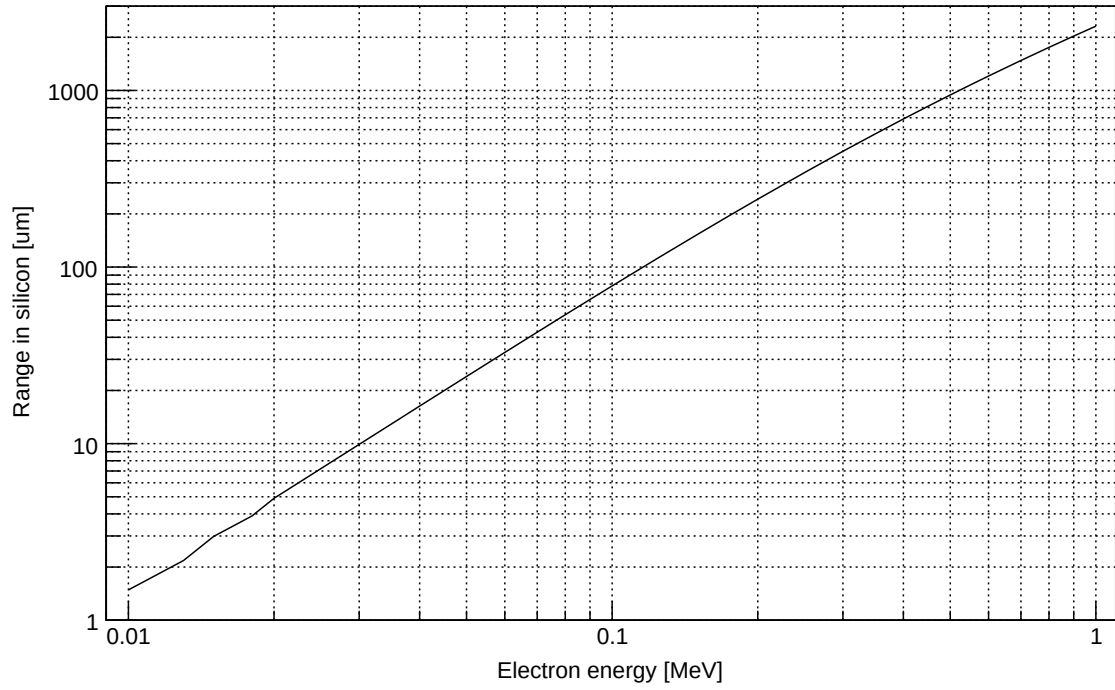


Figure 2.3: Range of electrons in silicon, based on R_{CSDA} values published in the NIST database: <http://www.nist.gov/pml/data/star>. ($100\text{ }\mu\text{m Si} = 23.3\text{ mg cm}^{-2}$)

Protons, alpha particles and other ions follow the same linear energy transfer relation with specific stopping powers in silicon. Figure 2.4 shows the range values of several different charged particle types. In contrast to electrons, their path follows the angle of incidence through the sensor. Therefore, the maximum alpha energy that can be recorded in $300\text{ }\mu\text{m}$ thick silicon (under a perpendicular angle of incidence) is $\sim 24\text{ MeV}$ according to the calculated CSDA range .

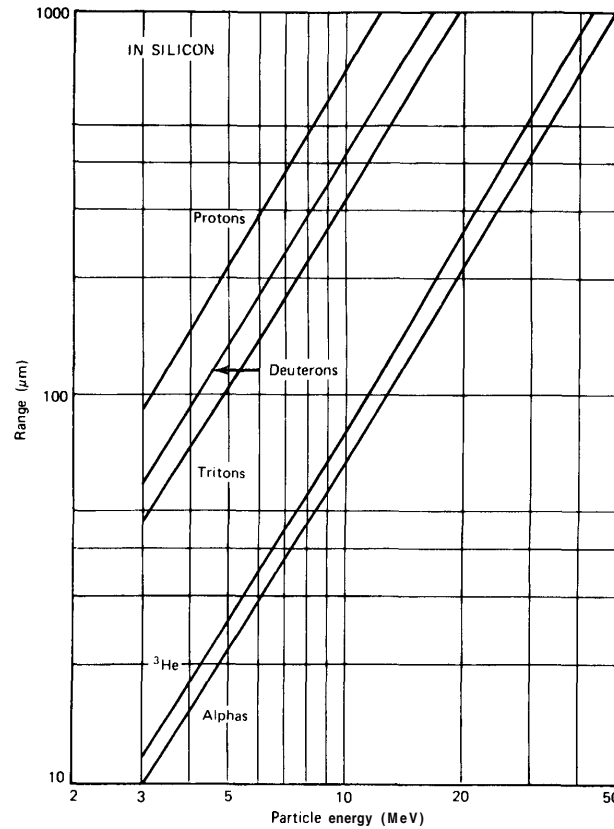


Figure 2.4: Range of protons, alphas and other ions in silicon. Reprint from [Knoll2010].

Photons While charged particles will always interact with silicon and deposit a certain amount of energy, photons interact in a more complex way. In a silicon sensor they can be detected only indirectly by freeing charges which does not occur with the passage of every single photon. X-ray and γ photons deposit energy in matter through several processes which occur randomly while following certain probabilities depending on the photon energy and the material composition. The three dominant absorption processes are:

- **Photoelectric absorption**
- **Compton scattering**
- **Pair production**

The photoelectric effect is the only process where the photon transfers its energy completely into an electron bound to an inner shell of an atom. As a result, the electron is freed from the lattice structure of the material and the photon completely absorbed. This process is dominating up to a photon energy of about 100 keV. The total absorption probability in silicon is already reduced to around 90 % with 10 keV photons.

The Compton effect is dominating for energetic photons above ~ 100 keV. It describes the elastic collision of a photon with an almost unbound and free electron of an outer atom orbital. The result is a distribution of the original photon energy between a scattered, lower energetic photon and a freed Compton electron which both travel in different directions

from the incident photon. Depending on the residual energy of the scattered photon, it can undergo further absorption processes in the material.

High energetic photons with an energy above 1.022 MeV (twice the rest energy of electrons) are able to produce an electron-positron pair. This pair production effect is dominant for photon energies above 10 MeV.

Figure 2.5 shows the probability ratios of the three main interaction processes for a photon energy range from 1 keV to 100 GeV in silicon.

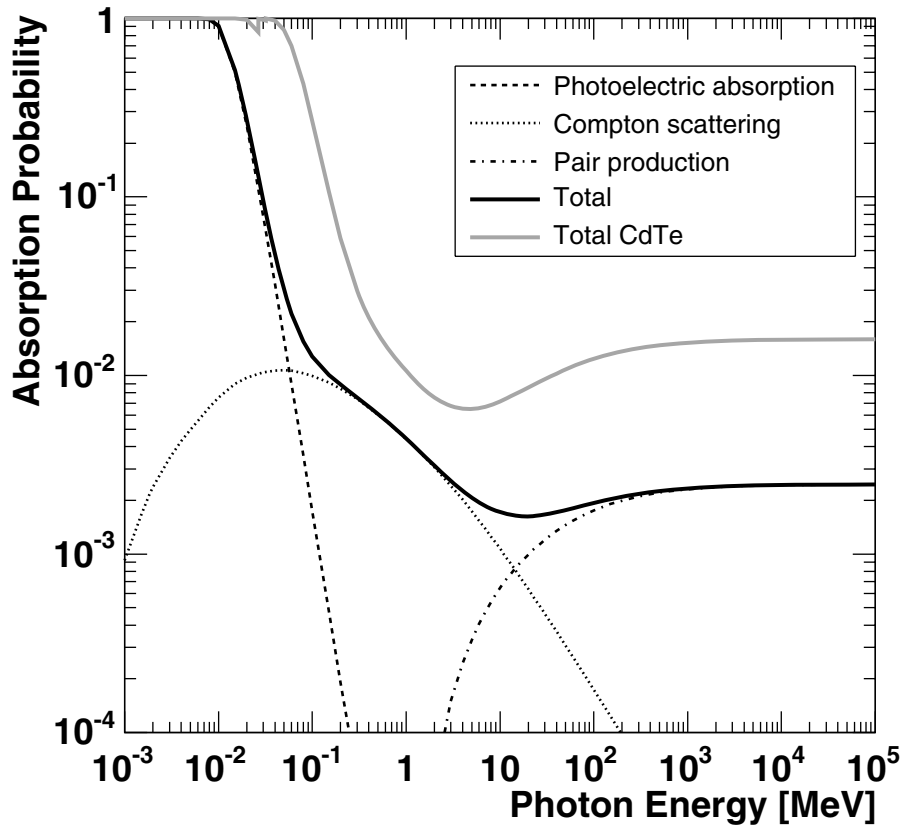


Figure 2.5: Total absorption probability of X-rays and γ -radiation in 300 μm thick silicon (solid black) and CdTe (solid grey) for comparison. Reprint from [Rossi2006].

For comparison, the total absorption in cadmium-telluride is given representing a sensor material with a higher atomic number and a more than doubled material density. It should be noted, that the total absorption probability for photons around 100 keV lies within the 1 % region.

2.2.1 The Charge Sharing Effect

When ionising radiation or a particle travels through a hybrid pixel detector, its path is likely to span several pixels. This phenomenon is called *charge sharing* and depends mainly on the radiation type and energy (defining its specific range, c.f. chapter 2.2), but also the bias voltage level applied to the sensor and of course its pixel dimensions. The stronger the electric field established by the bias voltage, the higher is its impact on compensating

lateral drift of the freed charges due to diffusion processes. Figure 2.6 illustrates charge sharing caused by perpendicular incident radiation on the left and an inclined irradiation on the right. The closer the charge cloud is created at the collection point (the p^+ implants in the sensor of this work, c.f. figure 2.2) the smaller is the possible spread which increases linearly [Jakubek2009].

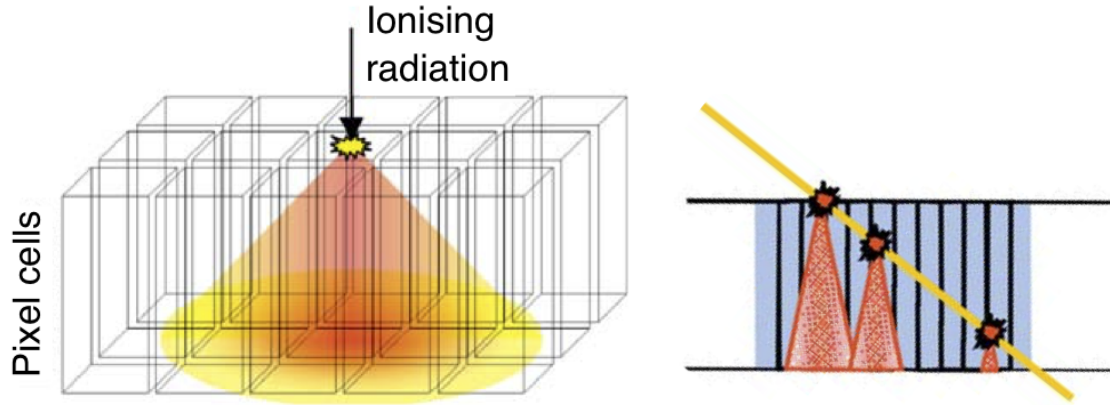


Figure 2.6: Illustration of the charge sharing effect in silicon sensors. The right shows its dependence on the depth in the sensor at inclined irradiation. Drawings adapted from [Jakubek2009].

When energy from one radiation quantum is deposited in more than one pixel, the resulting pattern is called a *cluster*. Low energetic electrons up to ~ 20 keV from β -decays or converted electrons from X-ray/ γ -photons travel only a few microns and cross predominantly one or two pixels. In the rare case, when the quantum hits the matrix exactly in the corner space between the pixels or when scattering occurs, three or four pixels can become activated. The average probability for three and four pixel clusters is $\sim 6\%$ in the photon range from 50 keV to 100 keV [Fiederle2008]. Because of the smaller cluster sizes, low and mono-energetic radioactive sources are preferred to calibrate the individual pixel response (c.f. chapter 2.5).

Figure 2.4 shows, that typical low energetic alpha particles from thorium or radon decays of ~ 5 MeV will travel considerably shorter than electrons in the $55\ \mu\text{m}$ of one pixel. Yet, a single alpha particle produces a cluster size spanning several pixels, depending on the bias voltage. This can be explained as follows: Alpha particles experience a high energy loss in silicon due to their relatively high mass and low velocity. Because of the large energy deposit, several hundreds of thousands of mobile charges are created in a relatively small volume establishing plasma conditions.² The collection field established by the bias voltage becomes locally distorted which supports lateral diffusion of the charges during the plasma time [Leroy2012, Chapter 5.3.4.1]. This movement takes place before the charge cloud starts to travel towards the edges of the depletion region following the electrical field lines of the bias voltage. The result is a large cluster spreading over several pixels.

²One electron-hole pair is produced in silicon per 3.6 eV of absorbed energy, c.f. section 2.5.2.

2.2.2 Pattern Recognition

Because of the charge sharing effect, it is possible to classify converted radiation quanta in the sensor based on particular cluster shapes. Corresponding to the specific pixel dimensions of Timepix, the six cluster pattern categories which are generally referenced in the literature are shown in figure 2.7. Most of these shapes depend on one or both of the two main detector parameters: the threshold and the bias voltage setting. They should be changed with caution once the classification parameters have been identified. The frame acquisition time should be kept as short as necessary to prevent overlapping patterns of separate radiation quanta. Concrete selection criteria for these patterns can be found in [George2015].

Dots		Photons and electrons
Small blobs		Photons and electrons
Heavy blobs		Heavy ionizing particles
Heavy tracks		Heavy ionizing particles → Incidence is not perpendicular to the detector's surface (Bragg curve)
Straight tracks		MIP
Curly tracks		Energetic electrons

Figure 2.7: Basic cluster patterns in pixelated silicon sensors. Reprint from [Bouchami2011].

Electrons and Photons The interaction pattern of electrons in silicon cannot be distinguished from the one of photos. Both produce either dots (<20 keV), small blobs (~ 50 keV) or curly tracks (>50 keV) [Holy2008]. Since the β -decay spectrum is continuous and not discrete, it is difficult to distinguish between β -particles and X-ray/ γ -photons solely based on assumptions about the expected signatures from known sources. However, from the low absorption probability of energetic photons in silicon, it can be roughly estimated that curly tracks stem more likely from β -decays than from Compton electrons. A second assumption can be done regarding low energetic electrons: Below ~ 10 keV, electrons are likely to be either stopped completely or slowed down to a value below the threshold by the thin aluminium layer on top of the sensor.

Figure 2.8 shows two Timepix frames of typical background radiation found at sea level. Heavy blobs and curly tracks are straight forward to classify. For the majority of low energetic clusters caused by the background, it is difficult to attribute them to one category since their shapes are random and cannot be correlated with an individual decay mode.

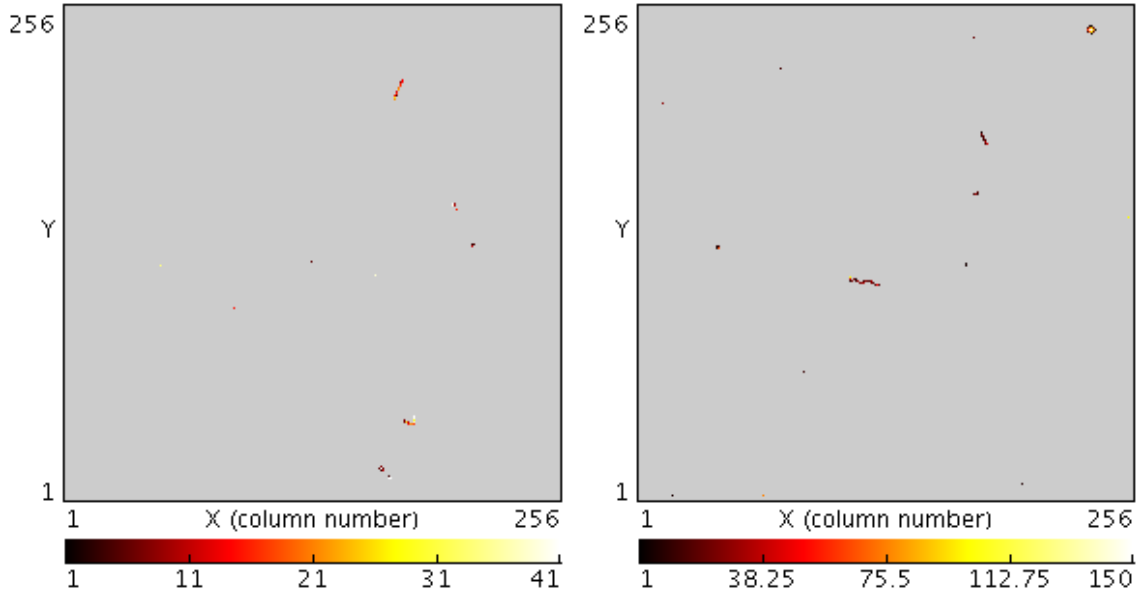


Figure 2.8: Two frames showing the background radiation in an office at CERN/Meyrin, recorded at 40 V bias, 1 minute exposure and a threshold corresponding to 3.7 keV. The colour scales represent energy in keV. The top ends of the ranges are set lower than the registered maximum to reveal the energy distribution of the low energetic hits. The heavy blob in the upper right corner is a ~ 5 MeV α -particle.

Heavy Ionising Particles Alpha particles, heavy ions and protons above 1 MeV produce huge and round clusters named *heavy blobs* if incident perpendicular to the sensor plane. When the angle of incidence becomes smaller, approaching a parallel direction, *heavy tracks* can be observed at particle energies of several MeV. With a range larger than one pixel, the energy deposition will follow a Bragg curve and create a deformed heavy blob shape [George2015]. Figure 2.9 shows two recordings of a thorium enriched welding stick with a diameter of 1.6 mm placed directly on the readout device and facing the sensor at a distance of ~ 3 mm (The same stick was put in the cloud chamber in figure 1.1). The thorium series emits β -particles between 50 keV and 5 MeV and α -particles between 5 MeV and 9 MeV. The predominant cluster patterns are therefore curly tracks and heavy blobs.

A decrease of the bias voltage causes larger heavy blobs as the charges drift further in the lateral directions due to repulsive forces. Since the silicon of this detector is significantly under-depleted at 20 V, fewer and smaller curly tracks appear in the right image of figure 2.9. Contrary to intuition, the detection efficiency of low range α -particles is not influenced at all by the reduced sensitive volume due to under-depletion. The *field-funneling effect*, based on the high density of deposited charges, modifies locally the low bias voltage and guides the mobile charges into the depletion region where they are finally registered [Campbell2007].

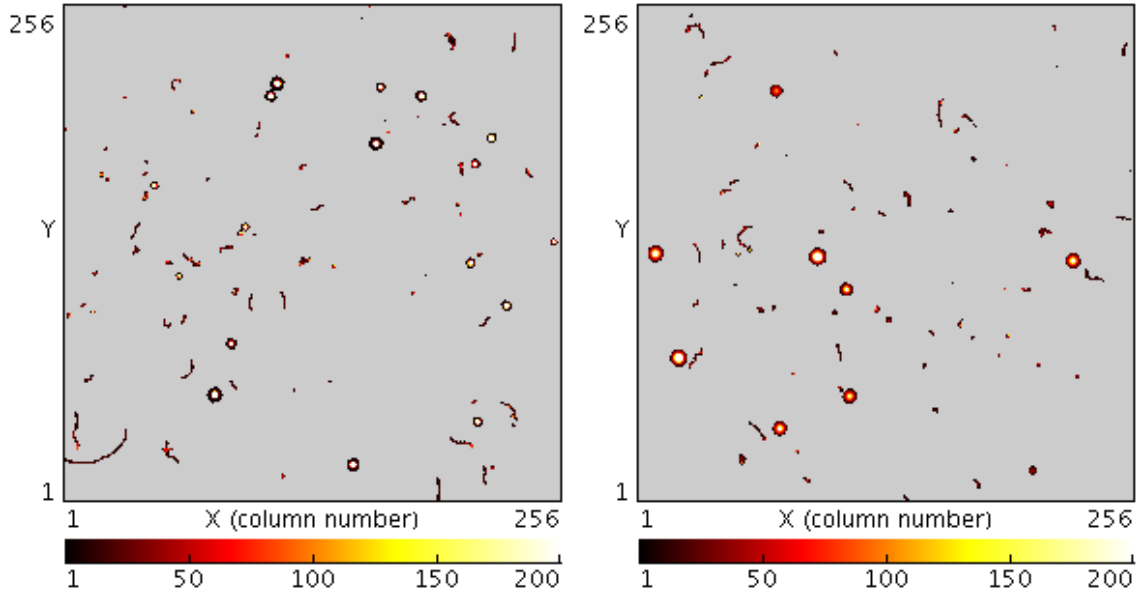


Figure 2.9: Two Timepix frames of a weak thorium emitter. Recorded over 1 minute exposure time and a threshold corresponding to 3.7 keV. The heavy blob shape depends on the bias voltage: 40 V on the left, 20 V on the right. The colour scales represent energy in keV. The top end of the range is set lower than the registered maximum to reveal the energy distribution of the low energetic hits.

Minimum Ionising Particles If the cluster pattern reassembles a reasonably long and straight track, it is caused by a *minimum ionising particle* (MIP) as these deposit a characteristic minimal energy value per track length. The main type of MIPs present at sea level are muons. They are produced at 15 km altitude in the atmosphere by cosmic particle showers and reach the sea level with an average flux $I \approx 1/\text{cm}^2/\text{min}$ and a mean energy of $\sim 4\text{ GeV}$ [PDG2014]. They can be considered as MIPs in silicon detectors and are expected to deposit a most-probable energy value following the curve depicted in figure 2.10. In case of muons crossing the sensor laterally, the deposited energy depends on the track length.

The recording of one muon is shown in figure 2.11 together with an energy histogram of the pixels composing the whole track. The histogram shows a peak in the pixel spectrum at $\sim 14\text{ keV}$. With a track length of $\sim 0.5\text{ cm}$ (93 pixel), the expected energy deposit is $\sim 330\text{ eV}/\mu\text{m}$. Over the width of one pixel, an average value of $330 \cdot 55 \approx 18.2\text{ keV}$ should be recorded. This is well in line with the measured peak considering a reduced resolution of Timepix in this low energy range and per pixel variances due to the calibration method.

For exactly vertically incident muons, the expected energy deposit would be $\sim 280\text{ eV} \cdot 300 \approx 84\text{ keV}$. Since the sensor was not calibrated on a pixel per pixel basis and charge sharing in a second pixel can cut off a part of the energy up to the threshold level, this value is broadened to vary at least between 75 keV to 90 keV. Taking further into account that the expected energy deposit is only a most-probable value following a Landau distribution convoluted with a Gaussian (c.f. the envelope shape of the histogram in figure 2.11), it is not possible to discern single vertical muons explicitly. The mean rate of single pixel hits caused by atmospheric muons is around 2/min within the sensor area of $\sim 2\text{ cm}^2$.

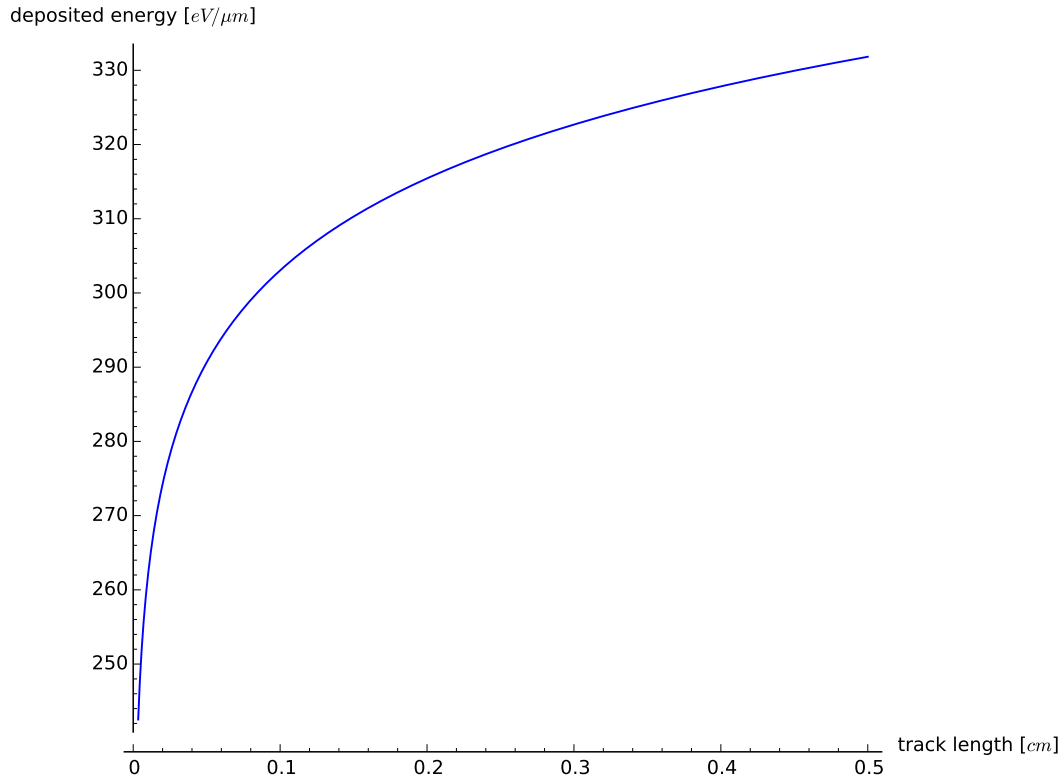


Figure 2.10: Estimation of the most-probable energy loss for relativistic charged particles ($z=1$) in silicon as a function of the track length along the material thickness. The calculation follows [Leroy2012, Chapter 1.1.1.5].

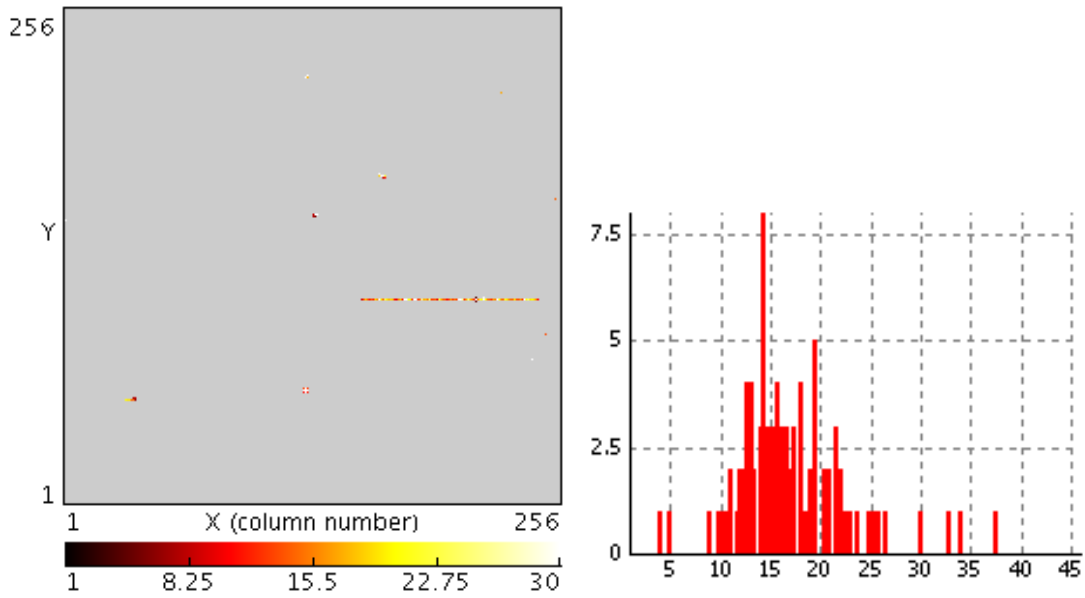


Figure 2.11: An atmospheric muon captured in one Timepix frame. Recorded with a threshold of 3.7 keV and by placing the sensor vertically on an office table at CERN/Meyrin. The right side of the frame corresponds to the sensor edge that was aligned upwards. The 3 pixels appearing along the track could stem from delta-rays or separate events as the exposure time was 1 minute. The colour scale and horizontal histogram axis are in keV. The top end of the colour range is set lower than the registered maximum to reveal the energy distribution inside the track. The histogram shows the distribution of the pixel energies within the muon track.

2.3 The Timepix Readout Chip

The Timepix readout chip was developed within the Medipix collaboration hosted at CERN. Its first chip generation, called Medipix, was initially geared towards medical imaging applications and optimised for counting of X-ray photons. Since Medipix2, all products of the collaboration are designed for the same sensor size and pixel density configuration: $1.4\text{ cm} \times 1.4\text{ cm}$ containing 256×256 pixels. With the development of Timepix, more particle physics related applications were aimed for by the collaboration. The first use case scenario was a *time projection chamber* (TPC) that was build as a feasibility study prototype for the future International Linear Collider. Similar to tracing ions in a mass-spectrometer, the deviation of particles flying through a magnetic and electric field is recorded in a TPC with a position sensing element. A Timepix equipped TPC is able to measure not only the position within the pixel matrix but also the time of arrival, allowing a kind of 3D tracking of the particle's path. In total, every pixel can be operated independently in one of four different modes. They are stated in the following list:

- **Medipix mode** Counts the number of incoming photons/particles.
- **1-Hit mode** Indicates that at least one photon/particle appeared.
- **Timepix mode** Measures the time of arrival.
- **Time-over-threshold mode** Measures the input charge.

Due to its versatility, Timepix is used in various measurement tasks, ranging from energy sensitive X-ray analysis [Jakubek2009] of ancient paintings to dosimetry on the International Space Station [Pinsky2012] as shown in figure 2.12.

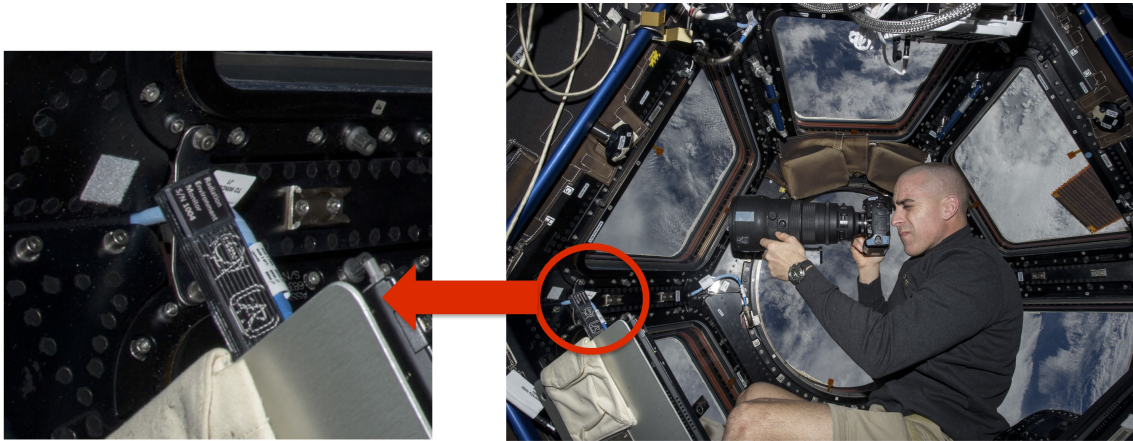


Figure 2.12: Timepix USB stick connected to a laptop on the ISS to track the radiation field in space. This device has the same form factor and readout interface as the detector used in this work. Reprint from S.P. George, original courtesy of NASA and the University of Houston.

At CERN, the chip is employed to monitor the background radiation field in the LHCb experiment cavern (ATLAS [Heijne2013] and CMS used Medipix2 in the past and are

upgrading to Timepix), for material sciences with heavy ions at the ISOLDE facility and various tasks where the particle beam is measured indirectly to monitor and safe-guide the operation of the accelerator chain [George2015].

The author was involved in another project at CERN [Keller2014], where the application of Timepix3 (available since spring 2014) for beam size measurements is studied and lab experiments were conducted based on the first generation of Timepix. Since Timepix3 allows an increased readout rate of 80 Mhits/s, a continuous beam size measurement of every few turns becomes feasible - even at the high bunch rate of 40 MHz in the forthcoming LHC runs.³ The speed requirements for iPadPix are orders of magnitudes less demanding which is why the first Timepix version was selected as the readout chip in this work.

2.3.1 The Charge Conversion Path

Timepix measures the deposited charge in each pixel through a charge sensitive amplifier that is modelled following the *Krummenacher* scheme [Krummenacher1991]. It features a feedback circuitry which automatically compensates for the static leakage current of the sensor and converts the charges deposited in the pixel into a voltage. The amplifier output is connected to a discriminator which compares the amplitude to a global threshold value. If it is higher, a pulse will be generated with a width that is proportional to the time over threshold. Depending on the configured pixel mode, the arrival time of the pulse, its length or the event itself (counting mode) is registered in the digital section of each pixel. Figure 2.13 shows the schematic of a complete pixel cell divided into an analog front-end and a digital back-end.

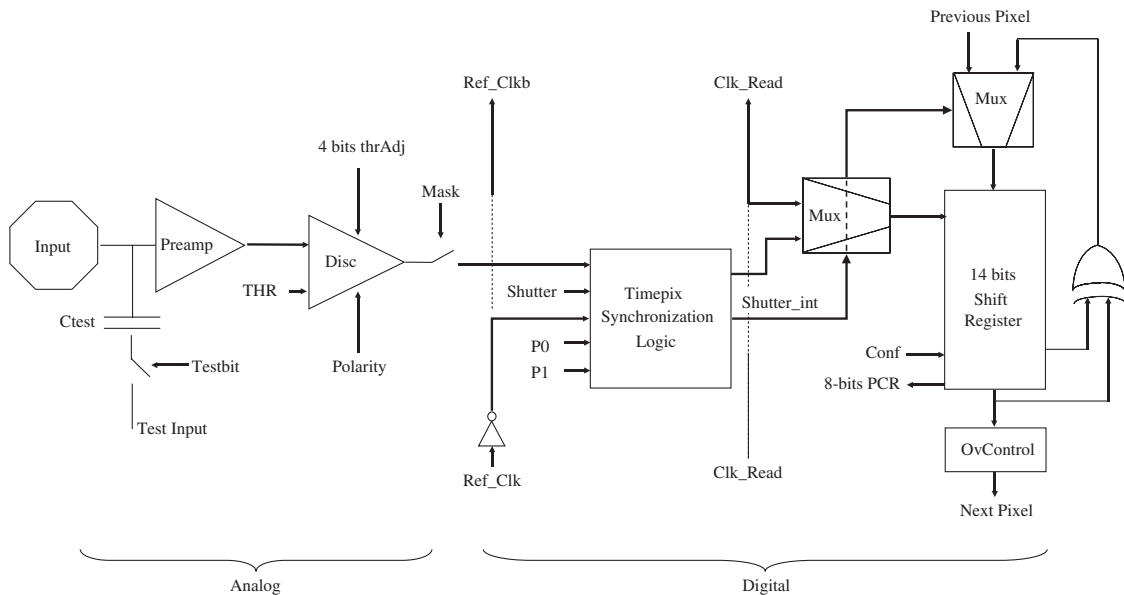


Figure 2.13: Schematic of one Timepix pixel cell. Reprint from [Llopart2007b].

³Timepix3 has also other new features like simultaneous recording of arrival time and energy per pixel. Due to higher data sizes and rates, the interface is of the SLVS type (400 mV_{pp}) and must be clocked at least at 40 MHz. This makes it more complex to interface with than the first Timepix generation.

A pulse of the discriminator will only be evaluated by the subsequent synchronisation logic if the global shutter signal is present. This defines the acquisition period analogous to the exposure time of a conventional camera. To configure the matrix, 8-bits have to be set per pixel: Two to select the mode (P0 and P1 in 2.13), one to enable or disable the pixel (mask bit), four to adjust the local pixel threshold and one to enable a test pulse (test bit). In addition, there are twelve global 8-bit DACs to fine tune various currents/voltages of the chip and one 14-bit DAC to set the global threshold level (THL).

The result of a conversion is forwarded into a 14-bit shift register. These values are collected on a column by column basis in a fast 256-bit shift register of the periphery section (it operates 256 times faster than the rest of the matrix). Figure 2.14 shows the floor plan of Timepix. Since the I/O circuits are all placed on one side, multiple chips can be mounted side-by-side to form a bigger sensitive area without gaps.

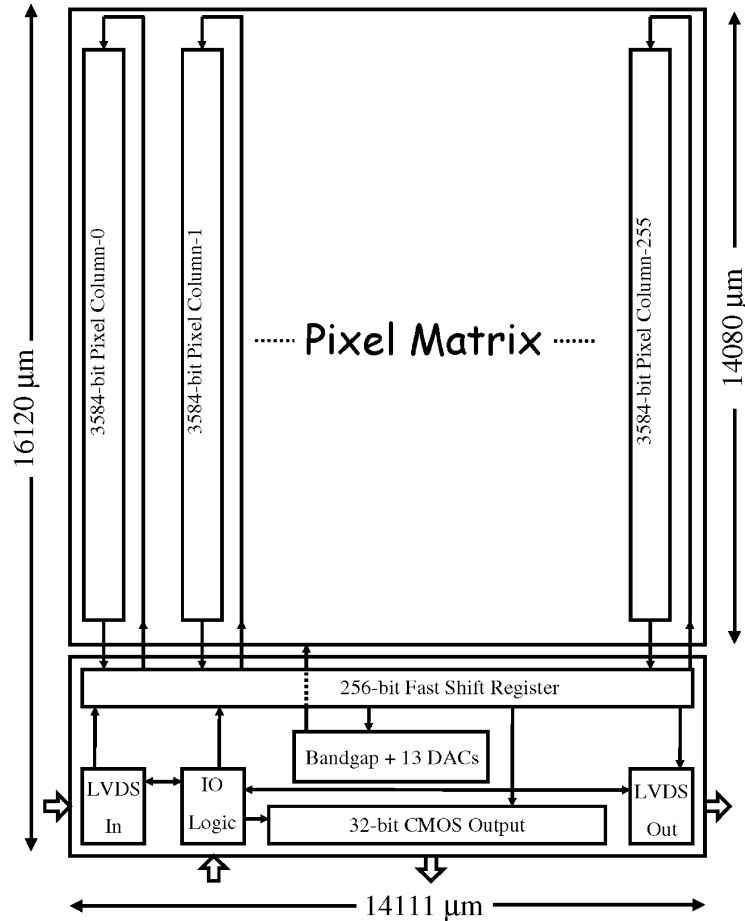


Figure 2.14: Timepix floor plan. Reprint from [Llopart2007b].

Operation in TOT mode With the iPadpix prototype, all pixels of the Timepix chip will be operated in TOT mode. Figure 2.15 illustrates the process of pulse digitisation in this configuration.

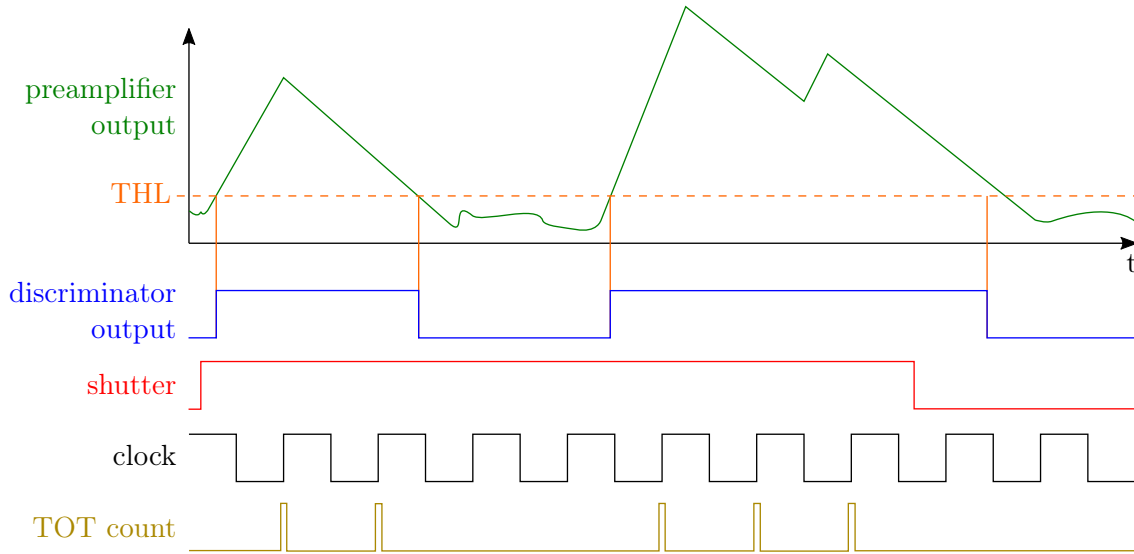


Figure 2.15: Illustration of the time-over-threshold counting process. The counter is incremented at positive clock edges when both, the discriminator and the shutter signals are active. In this scenario, the TOT counter registered five counts during the frame acquisition period.

When the input charge is above the set threshold level, the discriminator output is high. If the pixel is not masked and the shutter signal is present, the pulse width will be sampled at every rising edge of the clock. Consecutive pulses can be recorded within the same shutter period. If the shutter closes before the end of a pulse, the recording is truncated and the energy measurement is therefore defective. The rising time of the Timepix preamplifier is kept constant at ~ 100 ns until the peak value is reached and can be fine tuned by the I_{Preamp} DAC setting. The return-to-zero slope can be adjusted by the I_{Krum} DAC and is one of the main sources of pixel-to-pixel variations in terms of energy resolution. The return-to-zero time rises linear with the amount of input charge up to ~ 200 ke $^{-}$ and is therefore proportional to the signal amplitude [Llopart2007b]. Due to this relation, the energy measurement can be transformed into the time domain by digitally recording the pulse width compared to the more demanding analogue way of sampling the peak height with an ADC.

Configured in TOT mode, Timepix will count to five if a pixel is exposed to the input signal depicted in figure 2.15. In the Medipix/photon counting mode, the count value would be only two for the same case: One count for every pulse which is higher than the threshold. This mode is useful for imaging applications and certain chip characterisation tasks conducted in chapter 2.4 and 2.5 where only intensities are of interest.

2.3.2 The Readout Device

The pixel configuration must be loaded via a low-voltage differential signal (LVDS) serial interface into the Timepix chip. The readout of the matrix is possible via LVDS or a parallel 32-bit port. At a readout clock of 100 MHz, the maximum frame rate is about 3333 fps with the parallel connection and ~ 100 fps with the serial interface. Furthermore, the readout time of one frame is independent from the number of active pixels (pixels that

fired and thus have counts higher than zero), since all $256 \times 256 \times 2^{14}$ pixel register contents are always transmitted as a whole off the chip.

To connect the chip with a computer via a common standard like USB or Ethernet, a dedicated readout interface is needed. As of July 2014, the smallest readout device on the market is manufactured by the IEAP institute of the Czech Technical University in Prague, a member of the Medipix collaboration. Their products are distributed with the accompanying Pixelman software, available for Mac OS X, Windows and Linux. The readout device used in this work is named *USB Lite* and shown in figure 2.16.



Figure 2.16: The USB Lite Timepix readout, measuring $1 \times 2 \times 6.8 \text{ cm}^3$ with a mini-USB cable attached. The slider in the middle can be moved towards the left to protect the sensor.

The USB Lite's nominal speed of 4 fps is rather slow compared to the maximum speed Timepix is capable of. The shutter period can be controlled by the readout interface. This enables accurate and short frame acquisition periods down to 1 ms. It is an important feature in order to differentiate between single radiation quanta of rather strong emitters, since consecutive charge depositions in the sensor can add up during the shutter time (c.f. the two peaks in figure 2.15). During the frame reading process, the pixels are inactive. The readout rate defines therefore the minimum dead time between measurements. An event-based readout, that does not requiring a shutter signal, is only available with the newer chip generation Timepix3.

The possibility to build ones own small readout interface within in this work was considered, but finally not pursued in favour to focus more time on the main topics. The design of USB Lite is described briefly in [Vykydal2011]. Its internals are similar to the bigger readout device documented in [Vykydal2005]. It was original designed for the Medipix2 chip and later adapted to be compatible with Timepix.

2.3.3 Threshold Equalisation

Due to manufacturing variances between the pixels or radiation damage caused by high doses, the individual threshold levels can differ. To compensate for this, a 4-bit DAC can set an adjustment value in the discriminator circuit. Therefore, the first action that is typically done with any new Timepix detector assembly is the so called threshold equalisation procedure: The threshold level is raised stepwise towards the noise region for each

pixel at each of the 16 possible adjustment settings. The onset of noise follows a Gaussian distribution across these settings. Therefore, the adjustment values with the least distance to the mean value of both extremes are chosen as the final threshold equalisation result for each pixel. Figure 2.17 shows the equalisation plugin for Pixelman after a finished run. The blue distribution corresponds to the lowest DAC adjustment value (0) and the red to the highest (15). Their mean distribution values correspond to $\sim 230 e^-$ (one THL DAC step is $\sim 25 e^-$). The black distribution represents the result and has in this case a mean value of $\sim 54 e^-$.⁴

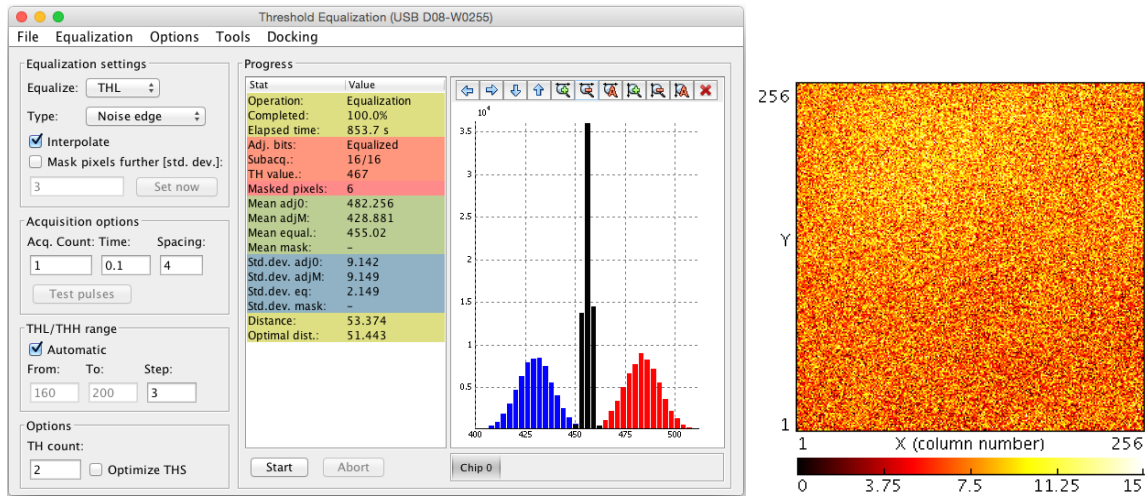


Figure 2.17: Threshold equalisation window of Pixelman. The image on the right shows the resulting distribution of the THL adjustment values across the pixel matrix.

If single pixels appear faulty and are more active than the rest of the matrix, they are also identified in this procedure. This Timepix assembly has six noisy pixels which are masked in order to disable them. Pixelman uses a simple *binary pixel configuration* file format to store the result of the adjustment process. Each byte corresponds to the 8-bit configuration register for each pixels. Furthermore, the default settings for the 13 global DAC values are stored as well in a separate ASCII text file.

The result of this equalisation run is a mean THL value of 455. To operate the detector explicitly out of the noise region, an additional margin is added. In this case it was manually verified that at $THL = 434$, output signals are repeatedly stable and no spurious pixel activity is observed (at root temperature). It is the minimal threshold setting used in this work.

⁴Without a sensor, the compensation can be down to $\sim 35 e^-$ [Llopart2007b].

2.4 Sensor Properties

The silicon sensor slab bonded to the Timepix chip used in this work has a thickness of 300 μm . On top (c.f. the back side in figure 2.2) is a very thin layer of aluminium. This blocks most photons in the ultra-violet, visible and infrared range since silicon is very sensitive to this energy spectrum. It also distributes the positive bias voltage properly across the whole sensor surface. Thin bond wires are needed only in one corner to connect the bias voltage source to the aluminium as is shown in picture 2.18.



Figure 2.18: USB Lite readout equipped with Timepix and a 1.4 cm $\times$ 1.4 cm sensor on top. The circle on the lower right marks the three bond wires that supply the bias voltage.⁵

As mentioned in chapter 2.1, the depletion zone defines the sensitive volume of the sensor. With p^+ -in-n sensors, it grows from the side where the readout chip is connected towards the back side of the sensor. The latter is usually the side which is facing radioactive decays or particles that should be measured. For low energetic radiation, this leads to the requirement of establishing a depletion depth that is as thick as the silicon. Otherwise, the examined radiation could be already fully absorbed before the sensitive volume is reached. The depletion depth W is mainly influenced by the bias voltage and the resistivity of the material.

⁵Since the sensor is very fragile, it is safer to not remove dust and dirt. They will not influence the measurements.

It can be approximated by the following formula for silicon semiconductors which are dominated by one type of impurity [Hartmann2009]:

$$W \approx \sqrt{2\epsilon\rho\mu V_{bias}}, \text{ with} \quad (2.3)$$

$\epsilon = \epsilon_0 \cdot \epsilon_{Si}$, the product of the permittivities of air and silicon,

ρ = the resistivity of the silicon,

μ = mobility of the majority charge carriers (electrons with n-type bulk material),

V_{bias} = reverse bias voltage across the pn-junction

Unfortunately, it was not possible to obtain the resistivity value of the silicon sensor from the manufacturer. Since the sensor slab is already bonded to the Timepix chip, it cannot be measured anymore through C-V or I-V curves. The only possibility is to expose the detector to a known source of ionising radiation and observe the count rates while the bias voltage is stepwise raised. The sensor is fully depleted when the count rate saturates and only few additional pixels are activated per measurement period and voltage step [Rossi2006].

Figure 2.19 shows such a bias voltage scan with ^{55}Fe in front of the sensor. It is an almost monochromatic source of weak 5.9 keV X-ray photons that are produced while the radioisotope decays via electron-capture to ^{55}Mn . It can be estimated from the graph, that this silicon sensor is fully depleted when operated with a bias voltage of at least 40 V which is where the count rate saturates.

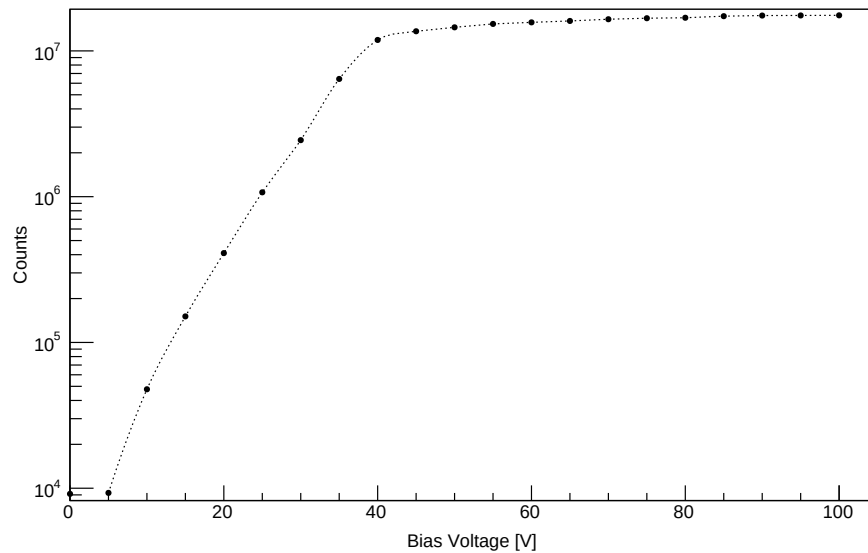


Figure 2.19: The count rate increases with the bias voltage until a plateau region is reached. The onset of this saturation region marks the bias voltage which fully depletes the sensor.

The additional increase between 40 V to 85 V could be attributed to surface effects. Some low energetic photons of this source can be already attenuated in the thin aluminium layer

before they reach the silicon.⁶

The nomogram in figure 2.20 shows the relation of the three sensor parameters presented in formula 2.3. The blue line is placed on the conditions 40 V bias and 300 μm depletion depth (the desired depth should equal the sensor thickness). A resistivity of $\sim 8 \text{ k}\Omega \text{ cm}$ can be inferred for the n-type bulk material of the examined sensor. This is in line with common values of modern sensors [Hartmann2009].

Operating the sensor at higher bias voltages than required for full depletion, is a common practice to ensure a maximal sensitive volume. An increased bias has however a side effect in reducing the charge-sharing with α -particles considerably as shown in figure 2.9 and explained in [Campbell2007]. It reduces not only the visually more interesting heavy blob cluster shape, but leads also to distorted and wrong measurements of alpha particles [Jakubek2011]. If more than $\sim 900 \text{ keV}$ are deposited in one pixel, the response of the analog circuit is not anymore linear. With charge sharing supporting the lateral distribution of charges, it is favourable to operate the sensor at lower bias voltages if high energetic particles are of interest. The optimal bias voltage setting for iPadPix is therefore just at the level of full depletion. This trade-off value ensures sensitivity to low energetic radiation quanta while maintaining accurate energy determination of higher energetic particles.

Figure 2.20 shows also typical ranges of charged particles in silicon from absorption measurements, since those depend mainly on the sensitive volume and thus the depletion depth (assuming frontal irradiation under an angle of 0°). This sensor is able to measure α -particles up to $\sim 24 \text{ MeV}$. Higher energetic alphas would be only measured partially, because they are not stopped completely in the sensor. From electrons of β -decays, the nomogram suggest up to $\sim 260 \text{ keV}$ can be deposited on average. Due to the curly paths which higher energetic electrons cover (c.f. chapter 2.2.2) the sensor area influences also the maximum amount of deposited energy. For the electron absorption measurements this figure is based on, the area of the sensor is not stated. The denoted ranges of electrons can therefore serve only as a rough reference point.

The minimum detectable energy with each radiation/decay type is more difficult to asses, since the thickness of the small aluminium layer deposited on the sensor is not known exactly (typically $< 1 \mu\text{m}$). Other comparable Timepix-based readout devices, equipped with a similar silicon sensor, state detection efficiencies of 100 % for alpha particles with a minimum energy of 1 MeV and 10 keV for electrons.⁷

⁶The result might be clearer if higher energetic photons, that travel mostly through the sensor, were used [Rossi2006]. Such a source, with a similar monochromatic spectrum consisting only of photons, was not available which is why ^{55}Fe was used.

⁷<http://www.particlecamera.com/index.php/about-mx-10/timepix-chip>

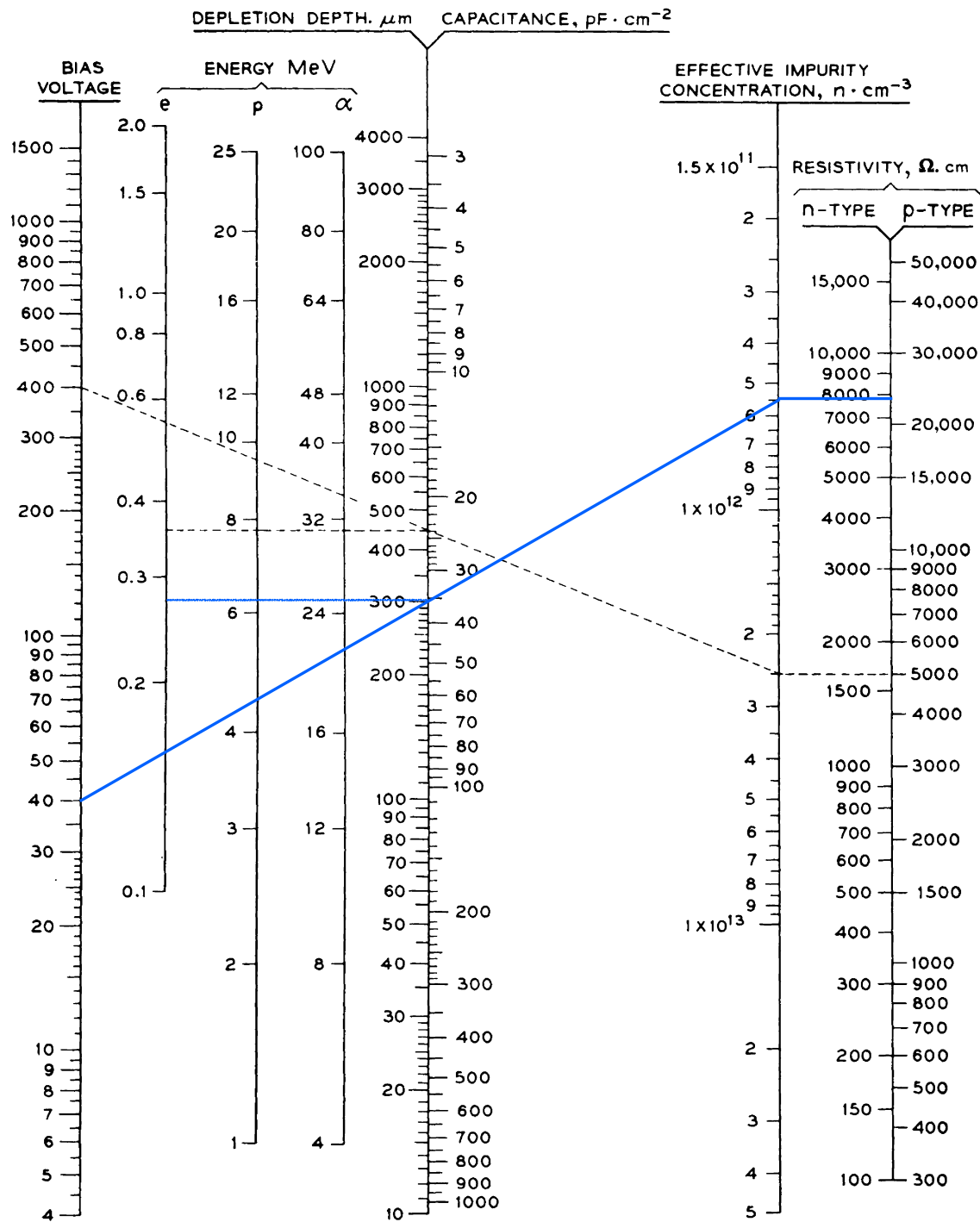


Figure 2.20: Nomogram showing the interrelation between parameters of silicon detectors according to formula 2.3. The blue line marks the properties of the sensor used in this work: A measured depletion voltage of 40 V and thickness of 300 μm . The range of particles in silicon is also shown in proportional scales referenced to the depletion depth. The original nomogram is reprinted from [Siegbahn1965].

2.5 Energy Calibration

While Pixelman features the required functions to record batches of frames automatically and conduct the initial threshold equalisation, the energy calibration of detector assemblies is not covered. It is a non-standardised process and different methods are available depending on the application scenario. Timepix can generate an internal test pulse simulating an input charge on all pixels [Llopart2007b]. This method is interesting if the chip is operated without a sensor, directly converting electrons from e.g. a gas-filled ionisation chamber or if the calibration accuracy demands are not high. If a sensor is attached to the chip, the response of the whole assembly to different energies and particle types is influenced by its own properties. Because iPadpix is aimed at differentiating between various kinds of ionising radiation, the preferred calibration method is to use radioactive sources. Evaluating Timepix frames generated by irradiation with reference sources also increases the understanding of general sensor properties like charge-sharing and other side effects.

For an optimal energy calibration, every pixel should be characterised independently due to manufacturing tolerances in the sensor bonding process and variances in the charge conversion process [Llopart2007b, figure 10]. With the 65 k pixels of Timepix, several tens of thousands of frames must be recorded at each chip setting to provide enough statistical data per pixel. Given the slow frame rate of the readout device (c.f. chapter 2.3.2), the decision was made to calibrate the pixel matrix as a whole, neglecting individual pixel variances. In percent of energy per recorded charged particle or radiation quantum, the expected resolution error is only a few digits higher compared to a single pixel calibration procedure. The later can achieve a resolution of 2.3 keV (RMS) with 60 keV X-rays and 35 keV with 5.5 MeV alpha particles in vacuum [Jakubek2011]. This is very good, but not needed with iPadpix in the aimed application area of education.

2.5.1 Measurement Workflow

The calibration measurements in this work were all conducted following the same data processing workflow. Most of these software components were also used in the construction of the iPadpix prototype described later.

1. Pixelman

This GUI software records the frames from IEAP's readout devices via USB at given settings such as shutter time, bias voltage and THL value. The frames are stored as binary files or as ASCII numbers in text files following the X_Y_C format. Each line holds the X/Y coordinates and the counter value C of the corresponding active pixel. The meaning of C depends on the selected mode of the pixel.

2. Mpxdataconverter

The command line tool converts the raw frames of Timepix into the native file format of ROOT, a data analysis framework developed at CERN [ROOT]. This converter is distributed together with the MAFalda framework.

3. MAFalda

This image analysis framework is based on ROOT and dedicated to the analysis of frames recorded by the Medipix/Timepix chip family. It features a number of tools and algorithms to process and extract data frame by frame in C++ [MAFalda].

4. ROOT macro

The processed data from MAFalda is finally plotted and displayed with the help of ROOT macros written in C/C++. The Root framework includes tools to display and analyse data for particle physics related tasks. It has its own binary file format where large data sets can be stored and loaded efficiently in a tree/branch structure.

In the following measurements two Timepix chip properties were calibrated with reference sources that emit a known energy spectrum: The overall *threshold level* (THL) at which the device operates above noise and the *time-over-threshold* (TOT) counter values which correspond to the recorded charge per pixel.

2.5.2 THL Calibration

The THL setting of the Timepix chip can be calibrated by placing various sources that emit characteristic X-rays in front of the detector. Photon sources are preferred, because they excite typically just one pixel at a time in the sensor. The THL setting is then scanned from low to high values while Timepix is operated in the photon counting mode. Since the relation between the actual energy threshold and the THL value is reversed, this corresponds to a stepwise transition from high towards low energy levels [Llopart2007a, chapter 5.6]. Figure 2.21 shows the result of three THL scans using photon sources: A ^{55}Fe radioisotope with an activity of 370 MBq and a peak spectrum of 5.9 keV photons [Knoll2010, p. 16] and two different target materials in an X-ray generator operated at 35 kV and 0.01 mA. Figure 2.22 shows the measurement setup with the X-ray machine.

The copper target's most intense and lowest spectral line is 8.05 keV ($K_{\alpha 1}$) while the molybdenum target emits a strong double line at 17.5 keV (K_{α}) and 19.6 keV (K_{β})⁸ [Thompson2009, table 1-3]. These spectral lines appear in the recorded count rates as a sudden increase once the threshold is crossed. The relative changes can be evaluated by calculating the derivative of each plot and fitting four different Gauss functions to map the corresponding THL values to the known energy peaks. The recorded X-ray tube spectra exhibit a broad energy spectrum due to the continuous bremsstrahlung. This by-product of the generation principle influences the measurements accuracy and widens the recorded peak lines considerably. The mean values of the Gaussians represent the original peak energy of the source in arbitrary THL units. Fitting these four number pairs to a first order polynomial function as shown in figure 2.23 results in the two linear equation parameters $a = -0.08515$ and $b = 40.61$.

⁸The individual $K_{\alpha 1}$, $K_{\alpha 2}$ and $K_{\beta 1}$, $K_{\beta 2}$, $K_{\beta 3}$ lines of molybdenum are indistinguishable in this measurement since the resolution is too coarse. The same applies to the other lines of copper and ^{55}Fe .

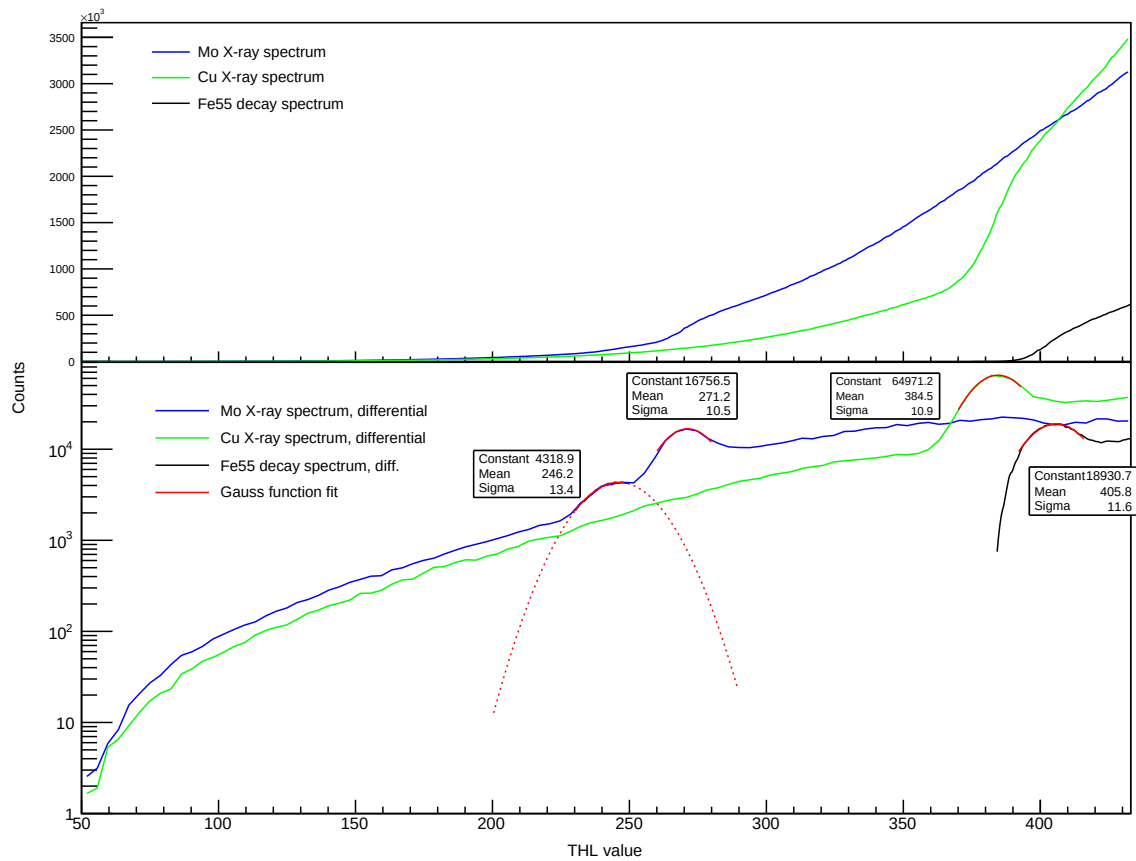


Figure 2.21: Three independent THL scans with different X-ray sources. The upper graph shows the recorded count rates and the lower diagram depicts the corresponding derivatives which were fitted to four Gauss functions. The boxes state the result of each fit. The ^{55}Fe emission was recorded over a shorter THL interval than the X-ray tube spectra.

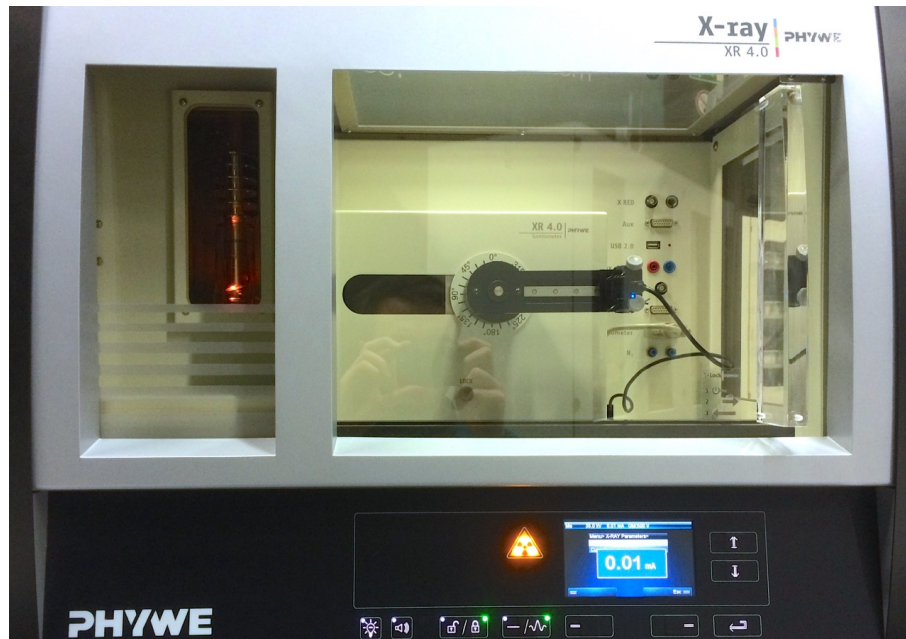


Figure 2.22: The X-ray machine in operation with the glowing tube on the left and the Timepix on the right, attached to a goniometer inside the irradiation chamber which is sealed with leaded acrylic glass.

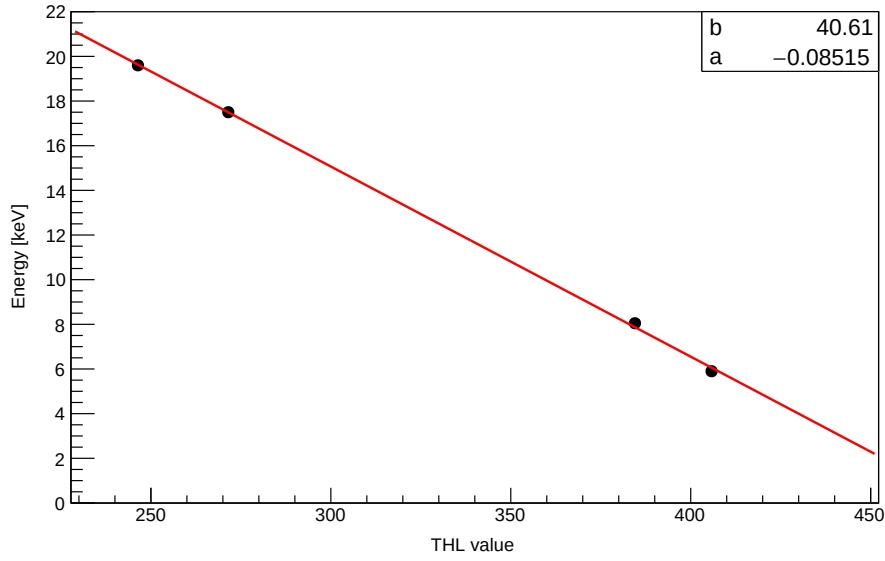


Figure 2.23: The four measured energy/TOT value pairs obtained from the THL scans plotted as dots and fitted to a first order polynomial function. The box shows the fit results a and b .

The energy E corresponding to the set threshold is calculated via the following linear relation:

$$E = a \cdot \text{THL} + b, \quad [E] = \text{keV} \quad (2.4)$$

With the previously determined operational setting of $\text{THL} = 434$, this means that the Timepix detector used in this work is sensitive to ionising radiation and particles with a minimum energy of:

$$-0.08515 \cdot 434 + 40.61 \approx 3.7 \text{ keV} \quad (2.5)$$

The minimal detectable charge of the Timepix chip itself is $\sim 650 e^-$ [Llopart2007b]. With an energy of 3.6 eV needed to free an electron-hole pair in silicon at room temperature this corresponds to a minimum threshold of $650 \cdot 3.6 \text{ eV} \approx 2.3 \text{ keV}$. The silicon sensor and its bump-bonding introduce additional parasitic resistances and capacitances which explains the higher threshold of a complete detector assembly.

Measurement Scripts To illustrate how MAFalda and ROOT were used to process the pixel data, a part of the code developed for the THL scan analysis is shown here as an example. To extract the total active pixel counts per frame, a MAFalda algorithm named `EasySum` was written with the following `Execute()` function - which is called on a frame-by-frame basis (refer to chapter 4.2 for a detailed description on this software):

```

1  void EasySum::Execute(){
2      m_myhits.totalHits = 0;
3      int xDim = GetMatrixXdim();
4      int yDim = GetMatrixYdim();
5      int rowItr = 0, colItr = 0, tot = 0;
6      for(colItr = 0; colItr < xDim ; colItr++) {
7          for(rowItr = 0; rowItr < yDim ; rowItr++) {
8              if(GetMatrixElement(colItr, rowItr) > 0) {
9                  // Get the TOT value
10                 totalHits += GetMatrixElement(colItr, rowItr);
11                 m_myhits.totalHits += GetMatrixElement(colItr, rowItr);
12             }
13         }
14     }
15     cout << "FrameSum " << GetTHL() << "\t" << m_myhits.totalHits << endl;
16     getMyTree()->Fill();
17 }

```

MAFalda has an internal global counter named `totalHits` which accumulates the number of pixel counts over the whole set of frames per batch. To store only the counts of each frame, the class member struct `m_myhits` is created as part of the `EasySum` module and reset with each frame. The function `GetMatrixElement(int x, int y)` returns the counter value per pixel coordinate and `GetTHL()` the corresponding THL setting of this frame. When the end of a frame is reached, the accumulated count sum is printed on the command line together with the THL value. The last line saves all member variables to a new Root tree per frame in the output file. In this way, the results of the whole frame set are stored in Root's own `.root` binary file format and can be reused for further processing within Root macros.

A Root macro is a script that can be run in an interactive and interpreted or compiled mode. It is usually used to display and analyse preprocessed data in a Root canvas. Such a canvas features various GUI options to adjust graphs or histograms and most importantly a fit panel which is useful for matching functions to data sets interactively. The following listing is an excerpt of the `plot_THLScans.C` macro which was written to generate the ^{55}Fe THL scan in Figure 2.21 (formatting related options are omitted):

```

1  TGraph *FeGraph;
2  TF1 *fFe;
3
4  Double_t myFe(Double_t *x, Double_t *t) {
5      return FeGraph->Eval(x[0]);
6  }
7  Double_t myFeDeriv(Double_t *x, Double_t *t) {

```

```

8     return fFe->Derivative(x[0], 0, 0.35);
9 }
10 void plot_THLScans() {
11     TCanvas *c1 = new TCanvas("c1","THL scan",900,700);
12     TPad *pad1 = new TPad("pad1", "pad1", 0, 0, 1, 1);
13     c1->cd();
14     pad1->Draw();
15     pad1->cd();
16     FeGraph = new TGraph("~/cernbox/thesis/calibration/THL_Scans/Fe55_Scan_Sum.txt");
17     // (...) load Mo and Cu data sets
18     TMultiGraph *mg = new TMultiGraph();
19     mg->Add(FeGraph,"1");
20     // (...) add other graphs
21     mg->Draw("AL");
22     // evaluate the original data continuously in the recorded range
23     fFe = new TF1("Fe",myFe,375,433,0);
24     // calculate the derivative
25     TF1 *fdFe = new TF1("dFe",myFeDeriv,384,433,0, "FeDerivative");
26     // (...) calculate other derivatives
27     // (...) set axis ranges
28     // (...) define legend
29     c1->Update();
30     TPad *pad2 = new TPad("pad2", "pad2", 0, 0, 1, 1);
31     c1->cd();
32     pad2->Draw();
33     pad2->cd();
34     gPad->SetLogy();
35     TGraph *FeFitGraph = new TGraph(fdFe);
36     // create Gauss function with range identified via the interactive fit Panel
37     TF1 * FeGauss = new TF1("gauss","gaus",392,416);
38     FeFitGraph->Fit(FeGauss,"R");
39     // (...) create other Gauss functions with different ranges and fit them
40     TMultiGraph *mg2 = new TMultiGraph();
41     mg2->Add(FeFitGraph,"1");
42     // (...) add other graphs
43     mg2->Draw("AL");
44     // (...) set axis ranges
45     // (...) define legend
46     c1->Update();
47     // (...) set format and position of fit result boxes
48     c1->Update();
49     c1->Print("THL_Scan.pdf");
50 }

```

This script defines two pads within the plotting canvas. An upper one to hold the original data and a lower one to show the derivatives and Gauss fits on a logarithmic scale. The discrete pixel counts are loaded from simple tabulator separated text files into TGraph objects (in this case: THL in the 1st column, counts in the 2nd column). This is simpler than using .root database files, because it allows immediate data integrity checks if only few variables are recorded per measurement and separate data sets are recorded in series. The data is

converted into a continuous, one-dimensional TF1 function object via the graph's `Eval()` function which interpolates between the discrete points. This step is needed to enable the calculation of the first derivative of the recorded data displayed in the second pad. At this stage, the result is plotted for the first time and the interactive fit panel is used to apply a Gauss fit on the energy peak. In order to reproduce the fit automatically in the script, the fit range with the best result is written down and a corresponding Gauss function object is defined and based on these values (c.f line 37). The last statement saves the whole canvas as a PDF file. All measurement diagrams of the Timepix detector in this work have been created with similar analysis code in MAFalda and macros in Root.

2.5.3 TOT Calibration

As explained earlier, the Timepix readout electronics convert charges into voltage pulses in order to measure them. The resulting counter value that represents this pulse width, TOT, is calibrated with known reference energy spectra in the following section. In order to avoid the charge sharing effect, X-ray and γ -radiation sources are preferred. Table 2.1 lists the used sources together with the corresponding acquisition settings of the Timepix readout device.

Source, Activity	Photon Peak (average)	No. of frames	Shutter Period [ms]
⁵⁵ Fe, 370 MBq	5.9 keV	500	1
²⁴¹ Am, 498,2 MBq	59.5 keV	1000	10
²⁴¹ Am plus copper foil	8.05 keV	1000	8
²⁴¹ Am plus indium foil	24.1 keV	1000	8

Table 2.1: Properties of the radioactive sources used for TOT calibration and corresponding acquisition settings. Peak energies taken from [Knoll2010] and [Thompson2009].

The spectrum of each source was processed with similar workflow scripts as described earlier. In addition, MAFalda's clustering filter *BlobsFinder* was used to include only single pixel clusters in the analysis. This is especially important with the ²⁴¹Am source, as it is also a strong emitter of α -particles. The indium and copper foils were placed between the ²⁴¹Am source and the Timepix detector as shown in Figure 2.24. In this arrangement, the foils are excited by the emissions of the source and emit their own characteristic photons due to the *X-ray fluorescence* phenomenon. Figure 2.25 shows the resulting spectra.

The peaks are fitted with Gauss functions according to the procedure described by [Jakubek2008] and the mean TOT values are noted. The relation between TOT value and deposited energy is not linear for energies close to the threshold. This can be seen with the low energetic peaks in figure 2.25a and 2.25c as they are not symmetrical.⁹ The following

⁹According to [Jakubek2011], the resolution can be improved by fitting a Gaussian convoluted with the surrogate function 2.6. This was not done here, since the precision is considered good enough.



Figure 2.24: The upper measurement setup shows the ^{241}Am source (positioned at the end of the stick with the red handle) irradiating through a small window on the indium foil which is placed on the Timepix detector underneath. The white blocks are lead shielding covered with tape. The lower picture shows the ^{55}Fe source sealed in acrylic glass.

surrogate function is used to account for this discrepancy and maps the energy values x to the TOT values $f(x)$:

$$f(x) = ax + b - \frac{c}{x - t} \quad (2.6)$$

A plot of the four found TOT/energy value pairs together with the minimum threshold, as measured in chapter 2.5.2, is shown in figure 2.26. The surrogate function is fitted to these reference points to obtain the calibration curve and its four parameters.

Correction Matrix With the results of the fit, a correction matrix can be calculated that maps each TOT value to an energy. If the pixel matrix of this Timepix detector should be calibrated pixel per pixel, the resulting correction would feature different a , b and c values per pixel. The parameter t is only related to the selected threshold. To obtain calibrated images, the MAFalda algorithms expect a complete correction matrix in an ASCII text file format, one file per parameter. Each parameter file contains 256 lines with 256 space separated values, one for each pixel. A small script is used to generate this four files with

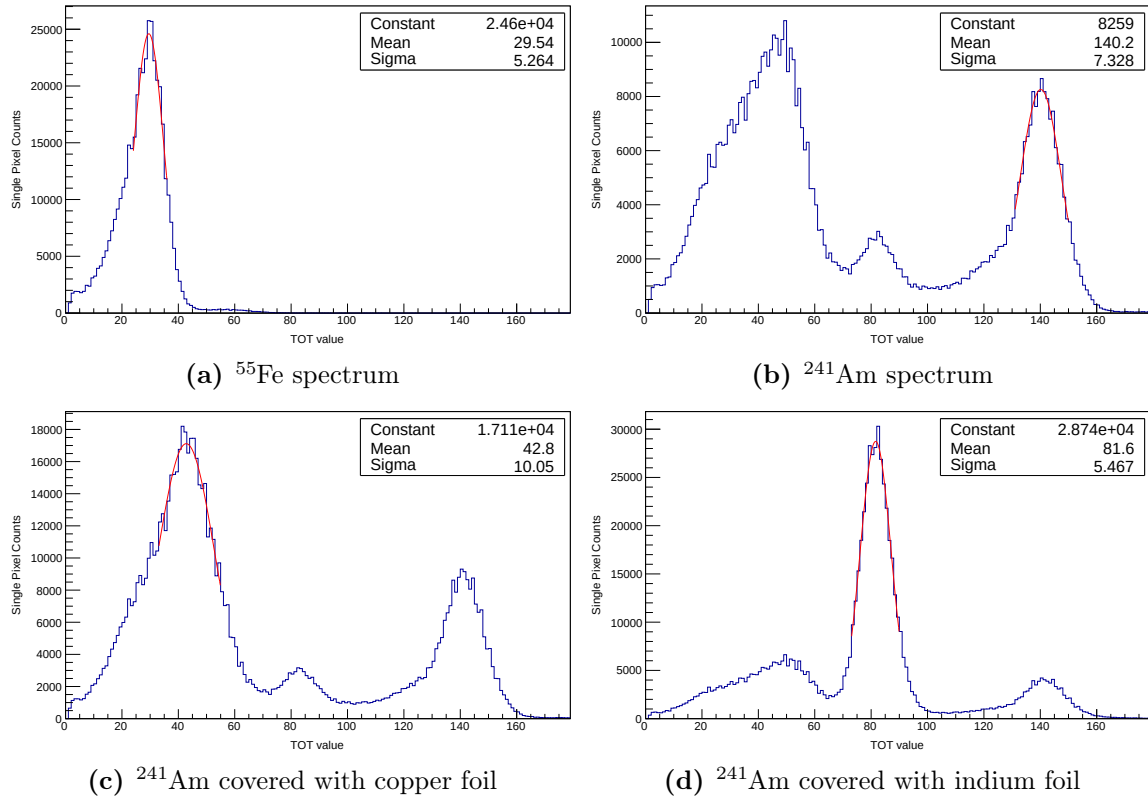


Figure 2.25: Single pixel counts of the Timepix detector operated in TOT mode in four different radiation fields. Due to the low absorption probability of 60 keV photons in silicon (c.f. figure 2.5), the peak in figure (b) is rather low in intensity compared to the others.

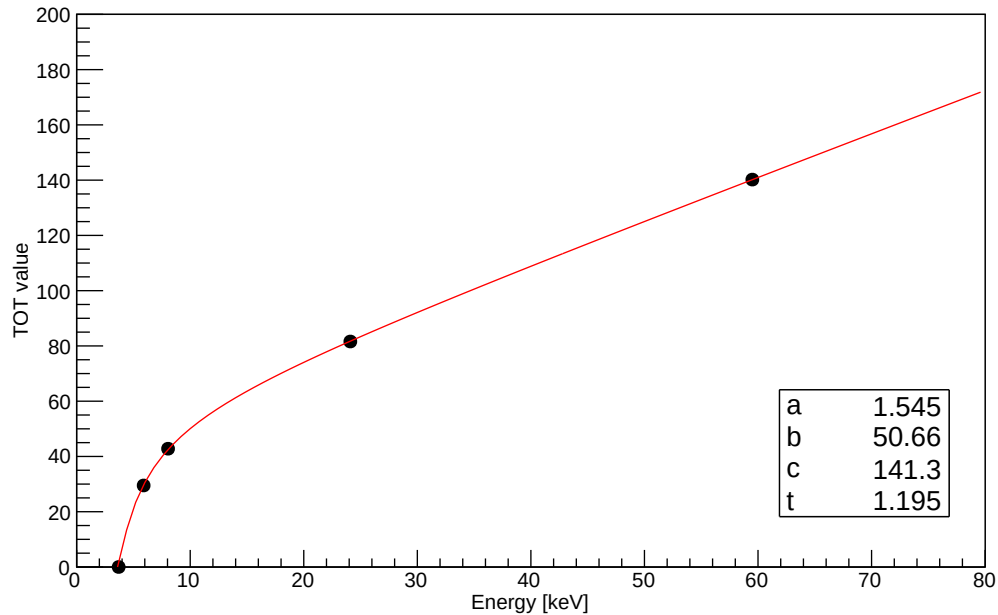


Figure 2.26: The measured energy/TOT value pairs obtained from the irradiation measurements plotted as dots together with the value for the used minimum THL setting. The red line depicts a fit of the formula 2.6. The box shows the fit results a, b, c and t.

the fit results of figure 2.26. Since the calibration here is done for all pixels as a whole, these files contain the same a, b, c and t value, 256×256 times, in the required format.

3 iPadPix Hardware Setup

This chapter discusses the hardware components that have been selected for the iPadpix prototype. With the aim of visualising and exploring radioactivity spatial and by means of augmented reality, the need for a display and a camera is evident. The main requirements for the mobile computing platform, which should host both of them, were identified as follows:

- **spatial position determination in relation to the observed object**
- **ability to read, process and display Timepix frames**

The first item requires read access to the auto-focus setting of a camera and inertial/orientation sensors. An alternative solution would be a mobile device equipped with a 3D depth sensor like the *Project Tango Tablet* development kit from Google¹, which is to date (February 2015) not available in Europe.

The possibility to integrate a simple, one-dimensional depth sensor based on infrared absorption or similar principles was excluded early. The expected accuracy would be low and an unambiguous determination of the distance between the Timepix and the radioactive object prone to errors. Especially with objects that have an uneven surface like mineral rocks, the distance information of one single point is likely to represent not the mean distance. In contrast, the lens system of a camera has to be adjusted anyway, so the distance information from the focusing mechanism can be reused.

After reviewing recent tablet devices issued in 2014, it was found that many of them contain cameras equipped with a fixed focus lens. Those are not a viable option, as the absence of an auto-focus mechanism means a tablet/object distance information cannot be provided. Most of the recently introduced Windows-based tablets state few details about the internal cameras at all. They seem to be targeted exclusively for a usage as low quality 'webcam'. Furthermore, inertial sensors are not present in most of the tablets as they are geared towards business use. With the few devices where such sensors are present, it is not documented whether they can be accessed through an open API.

The second item of the two main requirements concerns the software that is provided with the USB Lite readout interface. Pixelman and its libraries to access the readout device are limited to Intel x86 processor architectures. Only on these, it is available for Windows, Linux and Mac OS X. As of August 2014, no x86-based Intel tablet with native Windows or Linux support, featuring documented camera and inertial sensor access was

¹<https://www.google.com/atap/projecttango>

found on the market. Due to this reason, the decision was made to split the computing platform further into two sub components:

- **Tablet based on a mobile operating system with camera and sensor API**
- **Embedded board to transmit the frames from the USB Lite to the tablet**

The diagram in figure 3.1 gives an overview of the selected main hardware components, the flow of data and essential external inputs.

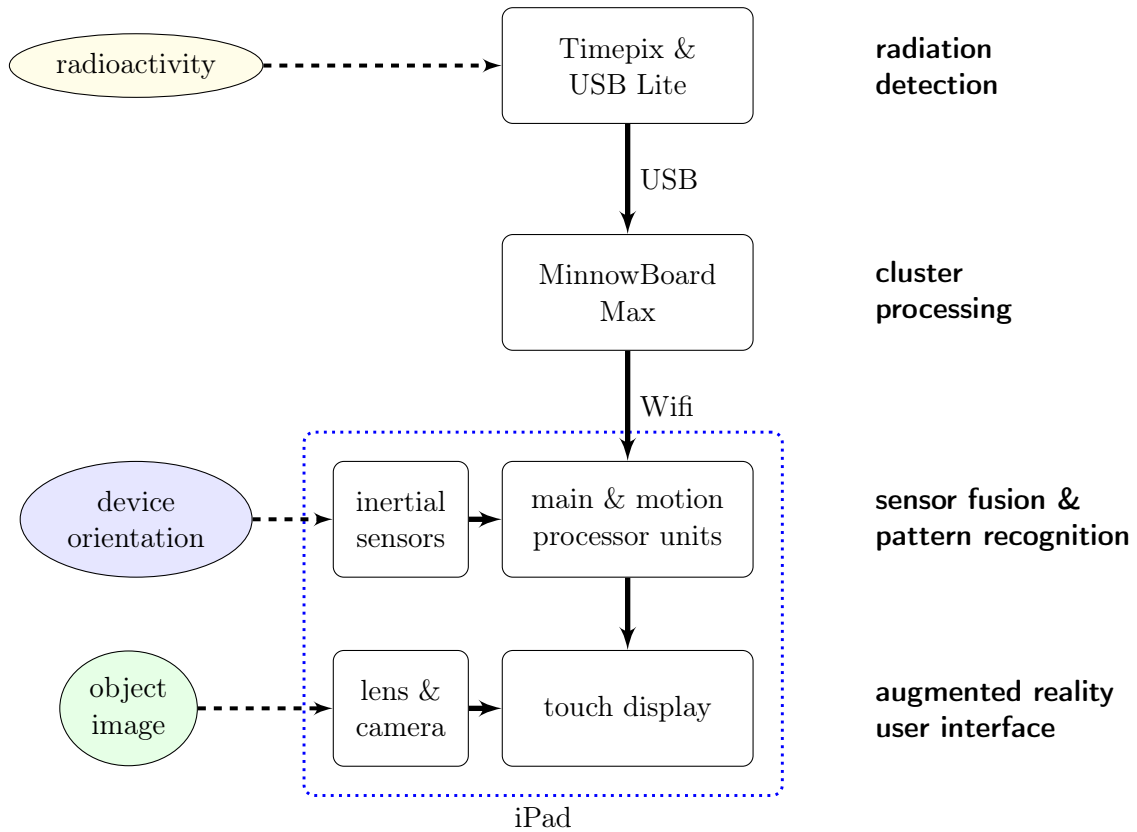


Figure 3.1: iPadPix Hardware overview with the main components in square blocks and external inputs as ellipses. The corresponding functions are denoted on the right.

The corresponding functional descriptions, defining three major software components, are denoted on the right. Those will be discussed in chapter 4. In the following sections, the hardware components are presented in detail.

3.1 The Tablet

An *iPad mini 2* ('retina') was finally selected in favour of an Android-based device due to its unique combination of features relevant for the prototype:

- adequate form factor
- high quality back-side camera
- flat backside that can host a Timepix detector next to the camera
- auto-focus feedback from the camera (since iOS 8)
- high quality, third party add-on lenses
- sensors: magnetic compass, accelerometer, gyroscope

This iPad variant features a camera with an auto-focusing unit and several sensors that can be used to estimate its position in space. Both can be accessed flexibly from user applications running on its mobile operating system iOS. The *Application Programming Interface* (API) is documented in detail in the iOS Developer Library² and can be accessed with an iOS developer account from Apple. The latter is also needed to execute own code on iOS devices. Figure 3.2 shows the outer dimensions of the iPad mini. The display has a resolution of 2048×1536 pixels and size of $16 \text{ cm} \times 12 \text{ cm}$ which corresponds to an aspect ratio of 4:3.

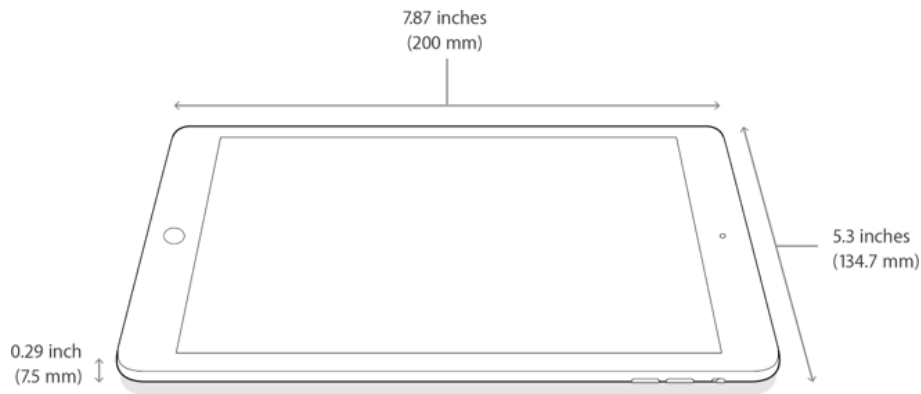


Figure 3.2: iPad mini dimensions. Reprint from www.apple.com.

Camera Specifications The back camera of the iPad mini 2 has a resolution of 5 megapixel at a maximum frame size of 2592×1944 pixels (4:3 ratio) in still photo mode. In video capture mode, the maximum resolution is lower: 1920×1080 pixels resulting in a 1080p HD video format (16:9 ratio) with a frame rate of 30 fps. In order to provide a live image in the photo capture mode, it can be conveniently operated in preview mode at an aspect

²<https://developer.apple.com/library/ios/navigation/>

ratio of 4:3. This is an important detail for augmented reality applications, as the live feed from a camera should match the screen dimensions as closely as possible to improve the visual perception. The camera lens has a minimal aperture of $f/2.4$ and focal length of 3.3 mm. A *field of view* (FOV) resulting from these parameters is not stated by the manufacturer and cannot be calculated as the sensor size is also not known. It was experimentally verified, that the minimum focus distance is about 6 cm and the horizontal FOV at this distance equals $\sim 54^\circ$.³ The horizontal FOV of the camera is more relevant in order to cover the area in front of the Timepix as much as possible even at close distances.

Lens Specifications The minimum focus distance is too large to observe typical α -particles of ~ 5 MeV. Those travel shorter than 4 cm in air and would not reach the Timepix sensor mounted next to the iPad camera. As the original FOV is also rather small for operating close to objects of interest, the best solution is to add a wide-angle lens. These improve both parameters towards the desired direction. A set of high quality, amateur-photography level, add-on lenses are manufactured by Schneider Optics under the product series iPro Lens System. The *wide angle lens S2* and the *super wide angle lens S2* have been both tested. The former scales the original focal length by 0.65, the latter by 0.45.

Figure 3.3 shows a picture of the iPro wide angle lens mounted on the back of the iPad via its clip-on holder. The lens itself can be detached and exchanged with another one by a bayonet fitting.



Figure 3.3: The iPro wide angle lens attached to an iPad mini with a modified clip. On the left side is the super wide angle lens showing its bayonet fitting.

³The FOV varies slightly with the focus setting as it is common with such small sensor/optics assemblies.

3.2 Optical Setup

The camera lens and the Timepix sensor must be placed close together to picture the same area. Both add-on lenses have a diameter of 2.8 cm and the USB Lite is 2 cm wide. Placing them horizontally next to each other on the back of the iPad mini results in the configuration depicted in figure 3.4. Because radioactive decay is an isotropic process which randomly emits radiation quanta in any direction, the FOV of the Timepix sensor is actually 360°. However, for low energetic radiation not penetrating the sensor, an approximation can be done that most radiation is registered from the area opposite to the sensor surface. The closer the sensor is placed in front of the object, the higher is the probability that the detected radiation originated from the opposing area and not next to it. To account for this dependency, the term *projected FOV* is defined within this work as equaling the parallel projection of the sensor area onto the imaged object (c.f the dashed red lines in figure 3.4).

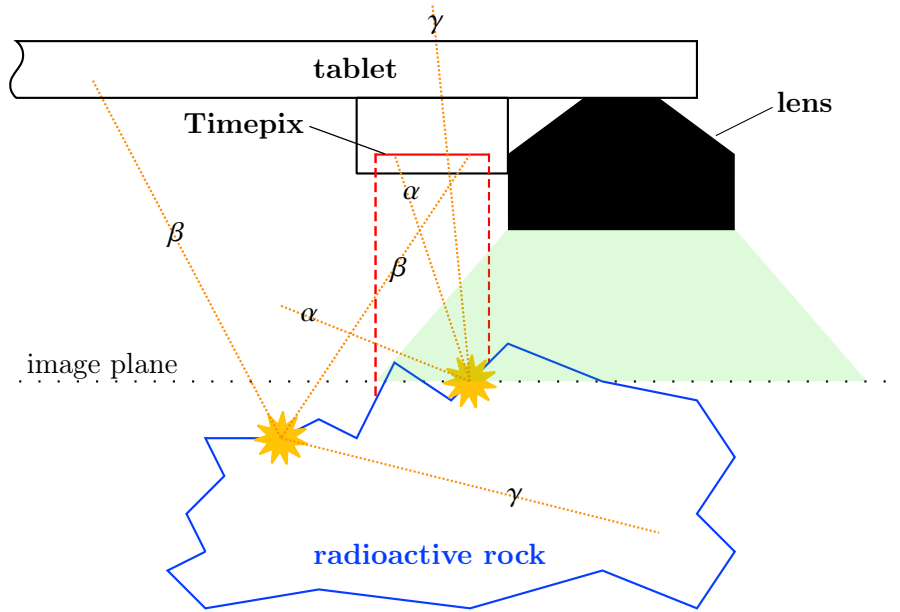


Figure 3.4: Schematic cross section of the optical setup consisting of an iPad mini with add-on lens and a Timepix detector pointing to a radioactive object. Some of the idealised decay products originate from the projected FOV of the sensor and hit it. Another radiation quantum which is not even within the camera FOV is also reaching the sensor. Scale 1:1.

While the green area, depicting the camera FOV, extends with increasing distance to the object, the projected FOV of the Timepix chip has always the same area of 2 cm². To observe weak sources, it is favourable to maintain proximity. The highest priority for the optical setup is therefore to enable an operation as close as possible to the objects of interest. This is achieved with the wide angle add-on lens as it allows a reduced minimal focus distance at around 2 cm. Together with the increased FOV, it is possible to picture objects at a magnification factor of $\times 3.3$ (at minimal distance). Adding a factor of $\times 2.5$ by digitally zooming into the iPad camera image, the sensor FOV of 1.4 cm $\times$ 1.4 cm can

be stretched almost completely to the full iPad display height of 12 cm. With the chosen configuration, the projected sensor area is covered completely by the camera FOV at operating distances higher than ~3 cm. Figure 3.5 shows the final setup. The Timepix readout housing is raised compared to the position in figure 3.4 to place the sensor as close as possible in front of the imaged object. In this configuration, the housing remains just outside of the camera FOV and does not obstruct it. A flexible USB LED light is added to improve the lighting. When approaching the iPadpix prototype close above objects of interest, a dark shadow can cast on the whole scene.

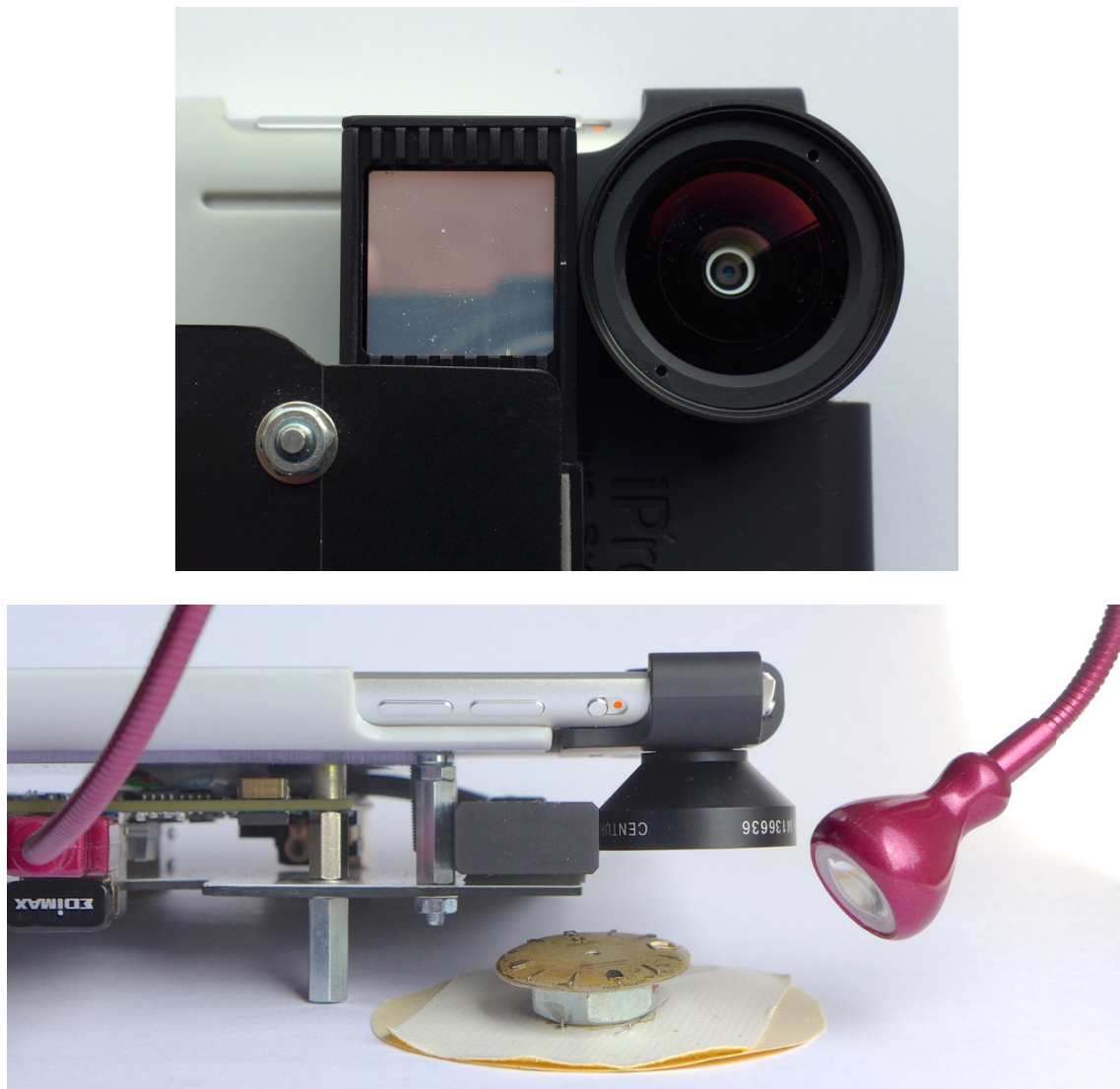


Figure 3.5: The upper photograph depicts how the lens and the Timepix chip are aligned next to each other. The lower image shows a side view of the created iPadPix prototype. The Minnowboard Max is screwed via 5 mm distance tubes under the back cover of the iPad mini. Its USB ports are occupied by the WiFi dongle and the gooseneck LED lamp. The object in front of the camera and the sensor is an old radioactive watch face from Omega. The Timepix USB Lite case is fixed on a plastic plate that also covers the embedded board to protect it.

3.3 Inertial Sensors

As many other current mobile devices, the iPad mini contains an *inertial measurement unit* (IMU). It consists of a three-axis accelerometer and a three-axis gyroscope. These provide a direct measurement of the device acceleration and angular rate ($\dot{\phi}$) along all three spatial axes. Figure 3.6 illustrates the coordinate system that is employed to report the values.

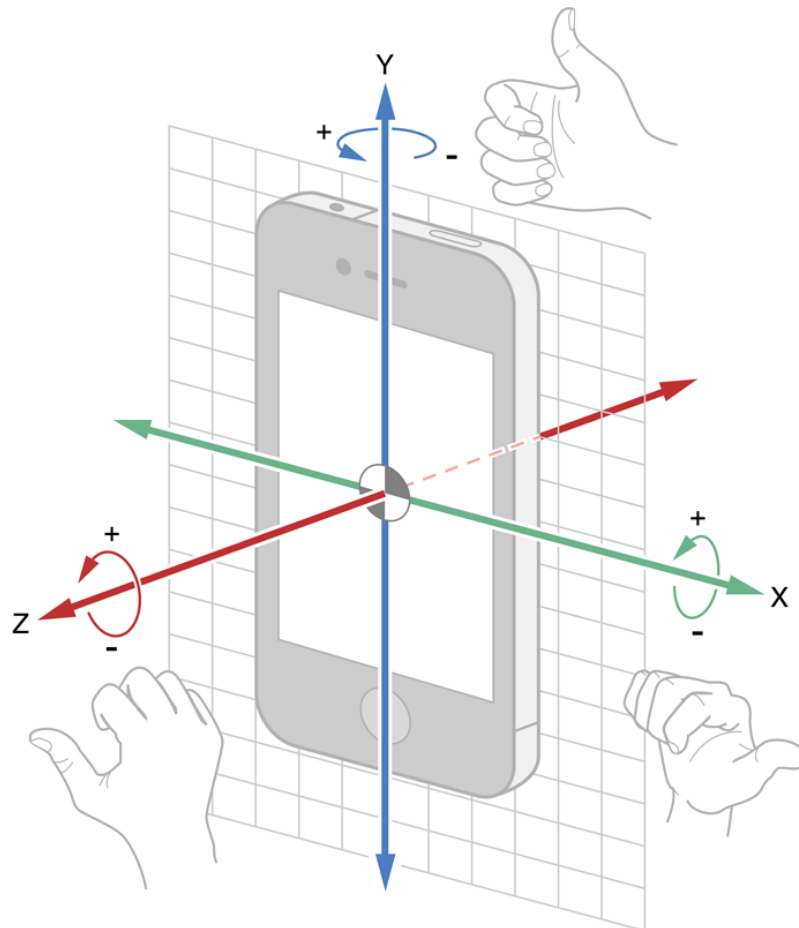


Figure 3.6: Coordinate system for multi-axis accelerometer and gyroscope sensor data of an iOS device. Reprint from developer.apple.com.

In addition to these six sensor values ($\ddot{x}, \ddot{y}, \ddot{z}, \dot{\phi}_x, \dot{\phi}_y, \dot{\phi}_z$), recent iPads feature also a magnetometer. It provides a three-axis measurement of the magnetic field strength and reveals the orientation of the magnetic earth field. This can be used as reference point in a process called *sensor fusion* where different IMU measurement values are cross-correlated and -compensated. Resulting from there, the *CoreMotion* iOS API offers readings of the following derived data, in addition to the raw sensor values:

- gravity
- user acceleration
- device attitude

The maximum update rate that can be configured is 100 Hz. Based on the accelerometer raw data, the actual device acceleration by the user and the partial gravity component along each axis is distinguished. By integrating once over the angle rates $\dot{\phi}_x, \dot{\phi}_y, \dot{\phi}_z$, the relative device orientation angles ϕ_x, ϕ_y, ϕ_z are gained. Those are further converted into absolute device orientation angles, called *attitude* in iOS, by using the magnetic field vector of the earth as a fixed reference point.

It was tried to recover the tablet displacement from relative changes of its position $\Delta_x, \Delta_y, \Delta_z$ by integrating two times over the user acceleration values. However, the accumulated sensor errors introduce a drift which rises exponentially after the two necessary integration steps. Even with various attempts of low-pass filtering certain components, a repeatable estimation of movements along one axis could not be done.

With the detection of displacement, it would be possible to stitch several Timepix frame acquisitions together in one big segmented image while the user continuously scans the area of interest. This could be still attempted by introducing a reference point measurement. An image processing algorithm like *optical flow* could be applied on the camera images. It identifies and tracks characteristic pixel patterns which can serve as reference under the assumption that only static scenes are observed. Due to time constraints, this approach was not pursued.

In the case of slightly stronger radioactive material, which is capable of producing a few pixel clusters per second (depending on the distance), the mentioned stitching process is less relevant. On the contrary, the displayed clusters can be too many to oversee conveniently. The information of recorded radiation quanta should then rather disappear than be kept on display indefinitely. This is achieved graphically as explained in the software chapter 4. In addition, the spatial tablet orientation is exploited as means to navigate among the registered pixel clusters. The device attitude angles are used to shift the cluster position in real-time on the screen relative to the tilting movements of the user.

3.4 Timepix readout

The closed-source libraries provided with the Pixelman software to retrieve Timepix frames from the USB Lite readout device are only available for the Intel x86 architecture. This was considered first a disadvantage, since popular and small ARM-based embedded boards (e.g. Beagle Bone Black or Raspberry Pi) cannot be used as processing platform. However, in summer 2014, Intel released a compact embedded board called *MinnowBoard Max*. It is geared towards the maker community supporting the release of a new generation of passively cool-able, yet capable Atom processors. The board is manufactured in two variants, the relevant features of the one selected for iPadpix are as follows:

- 64-bit Intel Atom E3825, 1.33 GHz dual-core processor
- 2 GB DDR3 RAM
- microSD card slot or SATA for the system disk
- 1 x USB 2.0, 1 x USB 3.0 port
- Gigabit Ethernet port

Figure 3.7 shows the top side of the board and denotes the connectors. Due to its small dimensions ($99 \times 74 \times 20 \text{ mm}^3$), it occupies less than one third of the iPad mini's backside.

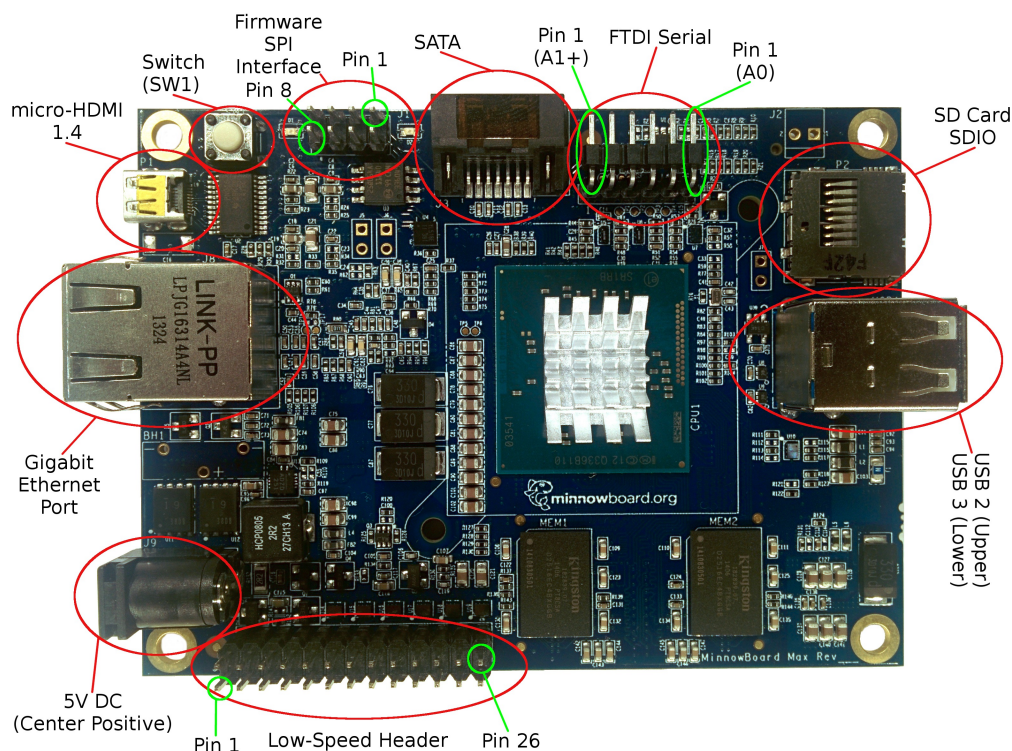


Figure 3.7: The MinnowBoard Max, its main connectors and expansion sockets on the top side. Reprint from <http://elinux.org/Minnowboard:MinnowMax>.

When placed vertically in the middle, all fingers of both hands are still able to rest next to it in the typical way of holding a tablet in landscape orientation. Figure 3.8 shows how the Minnowboard Max is screwed to a piece of acrylic glass which is in turn glued to the back of a modified polycarbonate plastic cover from Targus.



Figure 3.8: View on the back side of the modified cover, which is hosting an iPad mini during operation. The USB Lite is attached to the MinnowBoard Max via a soldered mini-USB cable. The small USB device on the right is the selected WiFi dongle.

The mini-USB cable is soldered directly onto the board to avoid the possibility of accidentally detaching it and to keep the clutter low. In this way, the USB gooseneck lamp (c.f. figure 3.5) can be connected to the otherwise occupied port and share the 5 V USB power supply with the USB Lite readout device. Both consume less than the max. port current of 500 mA and the lamp is internally not connected to the bus lines.

Originally, it was considered to communicate between the tablet and the board via wired Ethernet. For the envisaged transmission of pixel clusters in real-time, this is advantageous as it allows in general an operation at higher bandwidth and - most important - lower latencies compared to wireless Ethernet. Apple's iOS has the undocumented feature (still true as of version 8) to support USB-Ethernet adapters via the *Camera Connection Kit* (CCK) and an USB hub in between.⁴ This option was discarded, as it requires three additional adapters that are difficult to house in the space constrained back of the tablet. Furthermore, a connector would be attached permanently on the right edge of the iPad

⁴The USB hub is required to circumvent maximum power restrictions, as the CCK provides only very little power from the internal iOS device battery. The system switches the port off, if the requested demand is too high. Interestingly, it was found that a small, passive and non-powered USB hub is enough to circumvent the current check. It re-enables compatibility with various USB devices.

which would reduce the user ergonomics significantly for mobile scenarios. A side effect with not using the iPad's expansion port for data transmission is, that the connector remains free for occasional recharging during usage. Also for other planned applications like in the redesigned Microcosm exhibition at CERN, the tablet can be permanently powered. It is foreseen to mount iPadPix on a movement constrained fixture as one of the exhibits.

Instead of wired Ethernet, a small USB WiFi dongle (c.f. 3.8) is used to forward the processed Timepix cluster data to the tablet. It is based on the Realtek chip RTL8188CUS and supports the 802.11n/b/g wireless standards. This chip is supported under Linux and can be configured in *access point mode*. The iPad can be paired with it in the same way as with any other wireless access point.

The Minnowboard Max needs itself a 5 V, 2.5 A power supply. It was not considered to include an additional battery in order to keep the whole iPadPix prototype cordless at all costs. Instead, not adding weight is preferred. The whole cover structure in figure 3.8 extends the back of the iPad just up to 28 mm at its deepest point and only on about 1/3 of the backside area.⁵ All these properties allow a semi-mobile operation and the weight of the extension is almost neglect-able. Even with the additional power supply cable needed for the Intel board, the goal of building a sufficiently mobile demonstration prototype of the initial idea can be considered as met.

For a future revision of a more integrated version of the iPadPix concept, the most reasonable choice would be to build a dedicated readout interface for the Timepix chip on a custom printed circuit board. The shortcomings of the USB Lite could then be overcome and the Timepix readout functionality would be facilitated together with the wireless data transmission function in one compact module.

Besides a number of community supported Linux derivatives, the Minnowboard Max supports officially Windows 8.1 and Debian GNU/Linux as operating system. The latter was chosen since the author is more familiar with UNIX/Linux software development methods than programming on the Windows platform.

⁵Two distance holders were added to offer an angled default position with the screen slightly tilted towards the user (when placed on a flat horizontal surface).

4 iPadPix Software Setup

This chapter describes the software components of iPadPix. The individual hardware functions outlined in figure 3.1 are partitioned into four software modules as shown in figure 4.1.

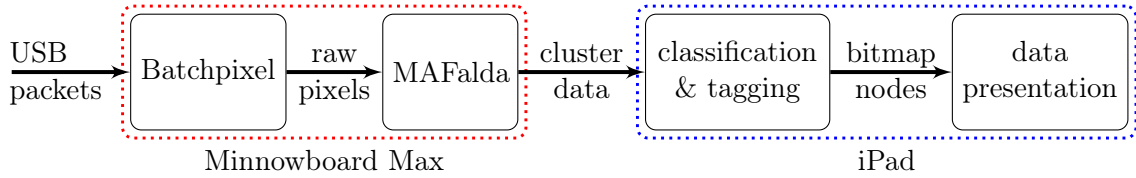


Figure 4.1: Software overview of iPadPix with the main components and data flow.

Within the Minnowboard Max, Batchpixel provides the raw pixel data from Timepix, which is calibrated, grouped and processed as clusters in the MAFalda framework [MAFalda]. The clusters are forwarded to the iPad, where they are classified and annotated with tags according to patterns described in chapter 2.7. The cluster data is finally rendered in real-time as transparent bitmap overlays on a live feed of the tablet camera. A considerable data reduction takes place between the Timepix chip, which sends always 256×256 pixel counts per frame (including zeros), and the iPad which only displays interpreted cluster data.

In the following sections, the developed software and used frameworks are described. As the data transmission between the embedded board and the tablet is considered critical, an additional section details the chosen data format.

4.1 Batchpixel - Image Readout

Batchpixel is a C/C++ program developed by John Idarraga within the Medipix collaboration to control readout interfaces that host Medipix or Timepix chips and are supported by Pixelman. The main use case is to operate the frame acquisition in batch mode without any graphical user interface. Furthermore, certain chip parameters can be changed step-wise and frame by frame. Additional hardware like a bias voltage supply can be adjusted synchronously if a corresponding C/C++ API exists. Its original source code is available here: <http://svnweb.cern.ch/world/wsvn/idarraga/batchpix/PixelmanBatch>.

Batchpixel uses four shared libraries, part of the Pixelman package, needed to establish the low-level communication over the USB interface: `libmpxctrl.so`, `libmpxlicmgr.so`, `libmpxmanager.so` and `libmpxusb.so`. It loads a text file as command line parameter which is used to configure the readout device. The following listing shows the configuration used with iPadPix:

```
V | 40
THL | 434
THLCoarse | 7
IKRUM | 1
AcqCounts | 0
AcqTime | 0.2
BPConfig | tpxlite_6masked.bpc
Dataset | /var/frame_
```

The first line sets the bias voltage to the measured full depletion level of the sensor at 40 V. The three following parameters correspond to global DAC settings of Timepix. `AcqCounts` and `AcqTime` define the number of frames to be recorded and the shutter period for each. The interpretation of the parameter `AcqCounts` was modified for this work. If set to zero, the frame acquisition occurs continuously in a new *real-time mode*. The `.bpc` file holds the per pixel configuration, such as the pixel mode (all in TOT) and THL adjustment levels as identified in the equalisation procedure and generated in Pixelman. The last line defines the folder location and file name prefix for retrieved frame data. In real-time mode, the data is always written to the same file name. A special *first-in first-out* FIFO file was created via the system command `mkfifo /var/frame_` to support a flexible and efficient data exchange between applications. A FIFO file in UNIX/Linux behaves like a named pipe which programs can use to read from and write to like with a regular file.¹ The performance advantage is, that no access to the filesystem is involved. FIFO data stays always in the main memory. It has also the benefit, that raw Timepix data can be observed by a simple system command like `cat /var/frame_` during the development process without changing the whole data flow.

A typical signature of an α -particle, in this case a heavy blob with a size of 5×4 pixels, is shown in the following output of the `frame_ fifo`:

¹Pipes connecting separate processes is the preferred UNIX/Linux method to construct a chain of data manipulation tasks. This is an alternative model to monolithic multi-thread programs.


```
21     if (control != 0) {
22         cout << "[WARNING] file: " << filename << " | error: " << control << endl;
23     }
24 }
25 (...)
26 }
27 }
28 }
```

In order to pause the frame acquisition, another application can send the SIGUSR1 signal to Batchpixel's process id. On the command line, this can be done via the following statement: `kill -SIGUSR1 'pgrep batchpixel'`. The complete source code of Batchpixel, as it was adapted for the iPadPix prototype, can be found in this Git repository:

- <https://github.com/ozel/batchpix>

4.2 MAFalda - Image Analysis

MAFalda is as well created within the Medipix collaboration at CERN by John Idarraga [MAFalda]. It is a powerful framework designed to process and analyse Medipix and Timepix frames based on ROOT and written in C++ [ROOT]. A set of frames can be processed interactively, frame-by-frame with a viewer component, or automatically in batch mode. The result is a ROOT file that holds analysed values such as pixel clusters and their properties for further handling within ROOT. MAFalda provides a set of modules, called *algorithms*, that can modify, extract or reuse various properties of a Timepix frame. A script (ROOT macro) is then used to drive the whole run on a particular dataset and define a sequence of algorithms applied on each frame. The framework is initially designed, as ROOT itself, to operate on prerecorded data and enable an extensive offline analysis.²

In this way MAFalda was employed to calibrate the detector, c.f. chapter 2.5. For the iPadPix prototype, it was modified to support real-time processing of live Timepix data. The following code listing shows the corresponding ROOT macro that was created for this purpose:

```

1  void runNetworkSender(const char * hostname = "ipad"){
2      // Load the MediPix analysis lib
3      gSystem->Load("libMediPixAnalysisCore.so");
4
5      // Get an instance of the analysis manager and load data
6      AnalysisManager mpxAnalysis("/var/frame_",kTRUE);
7
8      // BlobsFinder is a clustering algorithm
9      BlobsFinder * bf = new BlobsFinder;
10     mpxAnalysis.ConnectAlgo("BlobsFinder", bf);
11     bf->changeOutputLevel(MSG::INFO);
12
13     // NetworkSender forwards the clusters via Ethernet/UDP and libAVRO to the iPad
14     NetworkSender * ns = new NetworkSender;
15     ns->changeOutputLevel(MSG::INFO);
16     mpxAnalysis.ConnectAlgo("NetworkSender", ns);
17     ns->SetHostname(hostname);
18     ns->SetCalibrationConfigFile_a("../calib/a.txt");
19     ns->SetCalibrationConfigFile_b("../calib/b.txt");
20     ns->SetCalibrationConfigFile_c("../calib/c.txt");
21     ns->SetCalibrationConfigFile_t("../calib/t.txt");
22     ns->SetCalibClk(10); // MHz
23     ns->ReadConfiguration();
24     //ac->OutputLevel(MSG::DEBUG);
25
26     // This is an special algorithm that works as a frame viewer
27     //MPXViewer * v1 = new MPXViewer;
28     //v1->changeOutputLevel(MSG::DEBUG);

```

²ROOT was build for post-processing of enormous data sets produced by the particle detectors and instrumentation equipment at CERN.

```

29  //mpxAnalysis.ConnectAlgo("MPXViewer", v1);
30
31  mpxAnalysis.Run();
32  }

```

After the libMediPixAnalysisCore.so library is loaded, an instance of `AnalysisManager` is created pointing to the FIFO file filled by Batchpixel. If the second parameter is true, the newly added real-time mode is activated and an indefinite number of frames in the raw ASCII format, as shown in chapter 4.1, is expected as input. The `BlobsFinder` module is responsible for identifying clusters by grouping adjacent pixels together in one blob. A number of properties such as size, area, center and linearity are calculated. The clusters are finally forwarded to the `NetworkSender` algorithm. It was programmed within this work to send the clusters in a special format described in chapter 4.3 to the tablet. It also applies the four TOT/energy calibration matrices as obtained from the calibration procedure. The last commented code block loads optionally a viewer module. This feature of MAFalda was used extensively during development to see the clusters in every Timepix frame as they were sent over to the iPad. In this scenario, Batchpixel and MAFalda were running on a computer instead on the embedded board. The final code was compiled without the viewer to run on the Minnowboard Max without any user interaction. The whole script is started via the following command line: `root -l runNetworkSender.C`.

Figure 4.2 shows a screen shot of the MAFalda viewer processing the cluster of the raw pixel values listed in chapter 4.1 representing an α -particle signature. On top, the standard representation of the whole Timepix frame as 2-D histogram. Below is a zoomed 3-D histogram revealing the spatial TOT value distribution. This investigation is possible due to the flexible ROOT framework which allows interactive modifications to diagrams. The 'Viewer Control' control window shows options of the MAFalda algorithms and frame information.³ Furthermore, an 'RT mode' button was added to the viewer. It enables a live update of the histogram window with every new frame and the acquisition can be stopped once an interesting frame was captured. The arrow buttons are for the original offline operation mode, where a prerecorded dataset is processed.

In order to pause the newly introduced real-time frame processing mode of MAFalda when running in the background, a similar signal handler was added as described for the Batchpixel software in chapter 4.1. The pause mode can be toggled by issuing the SIGUSR1 signal to the ROOT process which can be done via the following command line:

```
kill -SIGUSR1 'pgrep root.exe'.
```

The complete source code of MAFalda, as it was extended with real-time capabilities for the iPadPix prototype, can be found in this Git repository:

- <https://github.com/ozel/mafalda>

³Some of the MAFalda Viewer informations, e.g. the THL value, local time, acquisition time and frame id are not meaningful, because this meta information is not registered in the real-time mode.

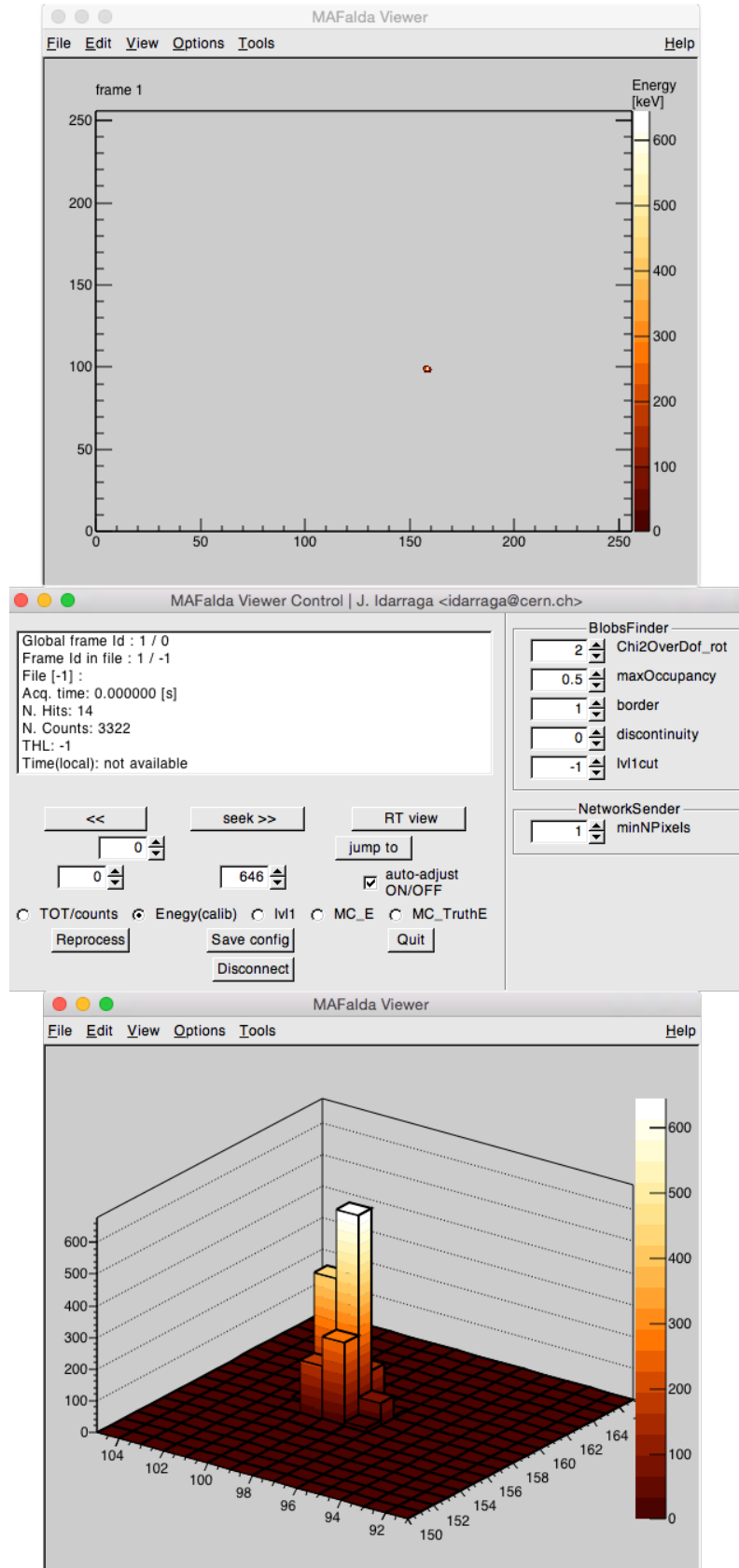


Figure 4.2: MAFalda viewer showing a heavy blob pixel cluster from an α -particle. On top, the full pixel matrix is depicted similarly to the Pixelman GUI in 2-D. Below, a zoom-in on the cluster converted into a 3-D histogram is shown. Both colour scales are in keV.

4.3 Data Transport

Wireless Ethernet was chosen to facilitate the cluster data transfer from the embedded board to the tablet. As Ethernet is by design based on best-effort delivery, an application in real-time scenarios must take a number of factors into account. However, in the case of iPadPix, the constraint is not a hard time limit. The goal is to provide the cluster data faster than the on-screen presentation takes. That should ensure a user experience which gives a realistic sense of the temporal behaviour of radioactive decay. Therefore, a few milliseconds latency in packet delivery can be tolerated, as it is intrinsic especially with wireless Ethernet. To prevent large deviations in packet transmission delays, a low-level Ethernet transport was chosen with the following properties:

- Dedicated 802.11n WiFi access point on the Minnowboard Max
- The iPad mini is the only connected client
- UDP on top of IPv4
- Maximum UDP payload size of 1472 bytes
- Efficient AVRO-based data format for clusters

UDP/IPv4 packets can be used at a relatively high effective bandwidth ratio. The required preceding number of header bytes is only 46 (Ethernet frame, IPv4 and UDP header) and the *maximum transmission unit* (MTU) in terms of UDP/IPv4 payload size is 1472 bytes large. If such a packet is filled up to the MTU, the transmission and processing latencies for involved components are typically minimised while the bandwidth is efficiently used.

The cluster data must be converted into a format that can be interpreted on both sides. In the iPadPix prototype, sender and receiver software are neither compiled with the same tools nor executed on the same processor architectures. A simple C-structure can therefore not be used as means of data exchange. Instead, a platform independent data serialisation format is required.⁴ The *protobuf* library from Google and Apache *AVRO* seem the most widely spread libraries for this task. AVRO is preferred, because it does not tag every datum with type information, which makes the format even more efficient. Instead, it employs schemas written in the user-friendly JSON format, which both transmission partners must have in order to communicate. Furthermore, AVRO features a byte array format which can represent the Timepix pixel coordinate range (256×256 bits) without any overhead. The developed JSON schema to store the clusters and their properties as evaluated by MAFalda, is shown in the following listing:

⁴ROOT features also efficient data serialisation, but is optimised for filesystem usage and finite datasets. Furthermore, including the whole framework in the iPad application seemed less attractive than using a dedicated and small library for the purpose of serialisation.

```

1  { "name": "tpxFrame",
2    "type": "record",
3    "fields": [ {
4      "name": "clusterArray",
5      "type": {
6        "type": "array",
7        "items": {
8          "name": "Cluster",
9          "type": "record",
10         "fields" : [
11           {"name": "id", "type": "int"},
12           {"name": "energy", "type": "float"},
13           {"name": "center_x", "type": "float"},
14           {"name": "center_y", "type": "float"},
15           {"name": "xi", "type": "bytes"},
16           {"name": "yi", "type": "bytes"},
17           {"name": "ei", "type": "bytes"}
18         ]
19       }
20     }
21   ]
22 }
```

The superlattice is a record named `tpxFrame`, containing an array of clusters. Each item in this array carries a record holding the cluster properties: Id, total energy, center and pixel values. The geometrical center is needed to reference the cluster within the original frame area. The total energy is transmitted in keV while the pixel values (`ei`) are the raw TOT counts. To save space, they are scaled from the maximum Timepix range of 11810 counts down to 8-bit values. The raw values are only used to draw the cluster shape, which makes the introduced inaccuracy tolerable.

4.4 Augmented Reality Application for iOS

This chapter outlines the iOS application that was developed to present and interact with the pixel clusters on an iPad mini. Its goal is to make invisible radioactivity in an intuitive way experienceable by overlaying the Timepix clusters on the live feed of an iPad camera.

The project consists of several source code files and is therefore only shown in excerpts. The complete sources of the iPadPix iOS app can be found in this Git repository:

- <https://github.com/ozel/ipadpix>

The application was written entirely in Objective-C and developed in Xcode 6 with the iOS 8 SDK. Apart from built-in iOS APIs, the following external libraries were used:

CocoaAsyncSocket

A convenient library to handle TCP and UDP packets asynchronously, in parallel to the main application.

Source code: <https://github.com/robbiehanson/CocoaAsyncSocket>

ObjectiveAvro

A wrapper around the libAvro C-library for Objective-C.

Source code: <http://cocoadoocs.org/docsets/ObjectiveAvro>

4.4.1 Camera Feed

In order to achieve the desired impression of an augmented reality on the screen, it is necessary to get a live feed from the iPad camera. As photography applications typically feature a live preview of the image area, this was considered a good starting point. The *AVCam-Manual* code is such an app, provided from Apple for iOS developers and demonstrates several new camera features that are available since iOS 8. One of those features is the auto-focus setting which can be obtained as relative fractional number between 0.0 and 1.0. A *key-value observer* (KVO) must be registered with the `lensPosition` property of the camera device. The global KVO handler can then check for a change in the `LensPositionContext` status indicator and retrieve the updated value. The relevant code lines are as follows:

```
1 // register new KVO pair in main function
2 [self addObserver:self forKeyPath:@"videoDeviceInput.device.lensPosition"
3     options:(NSKeyValueObservingOptionOld | NSKeyValueObservingOptionNew)
4     context:LensPositionContext];
5 // global KVO handler
6 - (void)observeValueForKeyPath:(NSString *)keyPath
7     ofObject:(id)object change:(NSDictionary *)change context:(void *)context {
8     if (context == LensPositionContext) {
9         float newLensPosition = [change[NSKeyValueChangeNewKey] floatValue];
10        // react accordingly to new focus setting
11    }
12 }
```

According to the WWDC14 session 508⁵, an iOS developer training, the `lensPosition` values are not absolute, because they vary from device to device due to mechanical reasons. Furthermore, they are expected to change over time and with device orientation (dependance on gravity). At mostly horizontal usage of the iPadPix prototype, it was found, that the values are repeatable enough to convert them into an absolute distance. Between the interesting range of 2 cm to 10 cm, the accuracy results in a maximum error of 2 mm in terms of projected sensor area dimensions on the screen. More restricting is the frequency at which the refocusing occurs and the time it takes until this is finished. To shorten this delay, the autofocus range is reduced and the point of interest always fixed to the middle of the projected sensor area. The following listing shows the main camera related configuration options of iPadPix (the preview session definition is excluded):

```

1  // create instance of back camera
2  AVCaptureDevice *videoDevice = [AAPLCameraViewController
3                                  deviceWithMediaType:AVMediaTypeVideo
4                                  preferringPosition:AVCaptureDevicePositionBack];
5  // enable preview at photo resolution and aspect ratio:
6  [session setSessionPreset:AVCaptureSessionPresetPhoto];
7  // restrict focus range, set continuous white balance, exposure and auto-focus
8  [videoDevice setAutoFocusRangeRestriction:AVCaptureAutoFocusRangeRestrictionNear];
9  [videoDevice setFocusPointOfInterest:point]; // shifted with lensPosition
10 [videoDevice setExposureMode:AVCaptureExposureModeContinuousAutoExposure];
11 [videoDevice setWhiteBalanceMode:AVCaptureWhiteBalanceModeContinuousAutoWhiteBalance];
12 [videoDevice setFocusMode:AVCaptureFocusModeContinuousAutoFocus

```

At operation in close proximity to the object of interest, the center of the camera and the sensor area differs considerably. This shift is compensated by translating the camera preview layer horizontally in relation to the focus distance once a refocusing procedure is finished. Also with every newly determined focus setting, the projected sensor area is rescaled on the screen (12×12 cm at 2 cm minimum distance) and the focus point of interest adjusted according to lateral shift.

The AVCamManual source code, that served as a starting point for iPadPix, can be found here: <https://developer.apple.com/library/ios/samplecode/AVCamManual>

4.4.2 Overlay of Cluster Data

The clusters are received by a callback function of the CocoaAsyncSocket library listening on the UDP port 8123 (an arbitrarily chosen free port number). Incoming binary packets are parsed by the ObjectiveAvro library according to the JSON schema presented in chapter 4.3. It follows a classification into the decay modes α , β and γ (the latter is used as generic term for X-ray and γ -photons) by a simple decision tree based on cluster geometry and deposited energy⁶ according to the flow chart in figure 4.3.

⁵<https://developer.apple.com/videos/wwdc/2014/>

⁶For mathematically more advance calculations, the preferred location for this classification procedure is MAFalda. During the development of iPadPix, it was more convenient to handle this part inside the iOS app, as verification and testing could be done faster than on the embedded board.

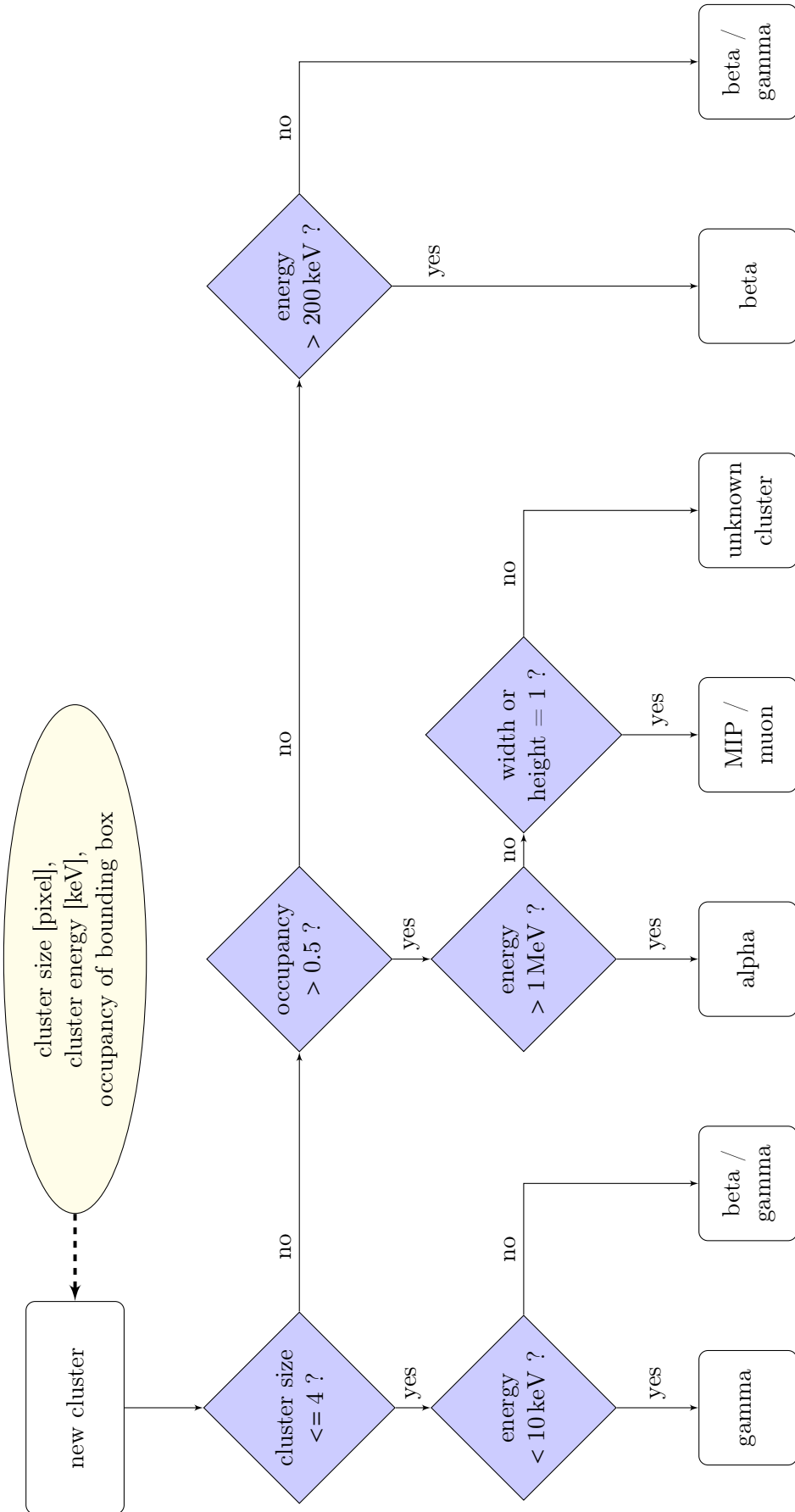


Figure 4.3: Flow chart of the cluster classification process. Taking into account the total cluster size, energy and occupancy of the bounding box. This occupancy is defined as $cluster\ size / (width \times height)$. Diagonal muon tracks are not covered as long tracks caused by MIPs are in general rare with a horizontal sensor orientation. They could be easily included by exploiting the cluster linearity property within MAFalda.

This classification algorithm is based on probability considerations discussed in chapter 2.2.2 with the aim of keeping it simple and fast. The following listing shows the implementation of the flow chart written in Objective-C:

```

1  float occupancy = cluster_size/(width*height*1.0);
2  if (cluster_size <= 4) {
3      if (energy < 10) {
4          // assuming electrons would be stopped in the metal layer
5          sprite.name=@"gamma";
6          gamma_cnt++;
7      } else {
8          sprite.name=@"beta/gamma";
9          unknown_cnt++;
10     }
11 } else {
12     if (occupancy > 0.5) {
13         if (energy > 1000) {
14             // heavy blob
15             sprite.name=@"alpha";
16             alpha_cnt++;
17         } else if (width==1 || height==1) {
18             // most likely a muon track
19             sprite.name=@"muon";
20             unknown_cnt++;
21         } else {
22             // overlapping clusters?
23             unknown_cnt++;
24         }
25     } else {
26         // curly track
27         if (energy > 200) {
28             // assumption based on decreased photon absorption
29             sprite.name=@"beta";
30             beta_cnt++;
31         } else {
32             sprite.name=@"beta/gamma";
33             unknown_cnt++;
34         }
35     }
36 }

```

The *SpriteKit* API of iOS is used to render the clusters in a transparent overlay on top of the live feed from the camera. Based on the classification result, the clusters are tagged and stored in a sprite object which holds the raw TOT values as a bitmap. *SpriteKit* organises sprites as a tree of nodes referenced to a main scene object. Its scene class provides methods to recalculate sprite properties like position or visibility and allows drawing updates on a frame-by-frame basis. A custom *TPXClusterScene* class derived from *SKScene* and a *ClusterFieldNode* class derived from *SKSpriteNode* was developed. The former controls the animation and display of cluster information. The latter is the root node for all cluster pixel nodes, holds additional cluster annotation and is constantly scaled with the lens

position value to reflect the projected sensor area on the screen.

The position of the cluster within the sensor area is recovered from the geometrical center coordinates calculated in MAFalda. Each cluster is displayed with a zoom and fade animation depending on the cluster size and energy. This puts an emphasis on more interesting clusters like α -particles and long curly tracks, as they are displayed for a longer time and scaled up. The following listing shows the corresponding code excerpt executed for each cluster sprite:

```

1  // set energy dependant scale, time and alpha factors
2  float scaleFactor = energy/40;
3  if (scaleFactor > 8.0) scaleFactor = 8.0;
4  else if (scaleFactor < 1.0) scaleFactor = 1.0;
5
6  float timeScale = 2.0f*energy/2000;
7  if(timeScale > 3.5) timeScale= 3.5f;
8  else if (timeScale < 2.0) timeScale = 2.0;
9
10 float alpaFactor = 0.2*energy/1000;
11 if (alpaFactor > 1) alpaFactor = 1;
12 else if (clusterSize < 5) alpaFactor = 0.9; //preserve visibility of small clusters
13 else if (alpaFactor < 0.3) alpaFactor = 0.3;
14
15 SKAction * zoom = [SKAction scaleBy:scaleFactor*(1+lensPosition) duration:timeScale];
16 zoom.timingMode = SKActionTimingEaseOut;
17 SKAction * fade = [SKAction fadeAlphaTo:alpaFactor duration:timeScale];
18 SKAction *remove = [SKAction removeFromParent];
19 SKAction * zoomFade = [SKAction group:@[zoom, fade]];
20 [sprite runAction: [SKAction sequence:@[zoomFade,remove]]];

```

Animated in this style, the clusters appear and disappear in a harmonic fashion re-assembling the aesthetics of particles crossing a cloud chamber which served as a source of inspiration.

Additionally, a label denoting the cluster type (if successfully classified) and the energy value are displayed along each cluster. Depending on the cluster location, the label is drawn to the right or left and constantly adjusted to avoid overlapping with new clusters. Necessary adjustments are calculated by the constraints feature of SpriteKit. Since it is originally developed for games, it allows to detect collisions and set minimum/maximum ranges between individual sprites.

4.4.3 User Interaction

The main mode for the user to interact with iPadPix, is by moving it around an interesting scene and observe pixel patterns caused by radioactive decay drifting across the screen. To enhance the augmented reality experience, each new cluster is registered including the particular spatial orientation of the tablet at that time (as measured by the IMU c.f. chapter 3.3). When the tablet is tilted during the time a cluster is on display, its location and orientation is updated accordingly. A parallax effect is established by shifting bigger

clusters (which are zoomed in proportion to the energy) more than smaller ones based on the tilt angles. This increases the perceived depth and also allows the user to spread overlapping clusters. If the object is rather strong radioactive or a big number of decays appear randomly in a short time, this is an intuitive way to reduce the information density on the screen. The clusters will drift laterally on the screen and separate proportionally to the tilt angles.

Furthermore, by tapping with one finger on the display, the scene freezes and no new clusters are displayed. This gesture toggles a pause mode, where existing clusters are still affected by tilt movements and thus can be examined without fading away. A two finger tap triggers a demo mode, where prerecorded clusters are played back to observe them again. The five finger tap triggers the corresponding recording mode to store clusters for the demo playback.

On the bottom of the screen, *count rates per second* (cps) are displayed. The four counter variables, increased by the cluster identification process, are averaged over three seconds. The fourth count rate represents unidentified clusters and is denoted with a question mark. Figures 4.4 and 4.5 show screenshots of the developed iPadPix iOS application and a picture of a user interacting with the device.

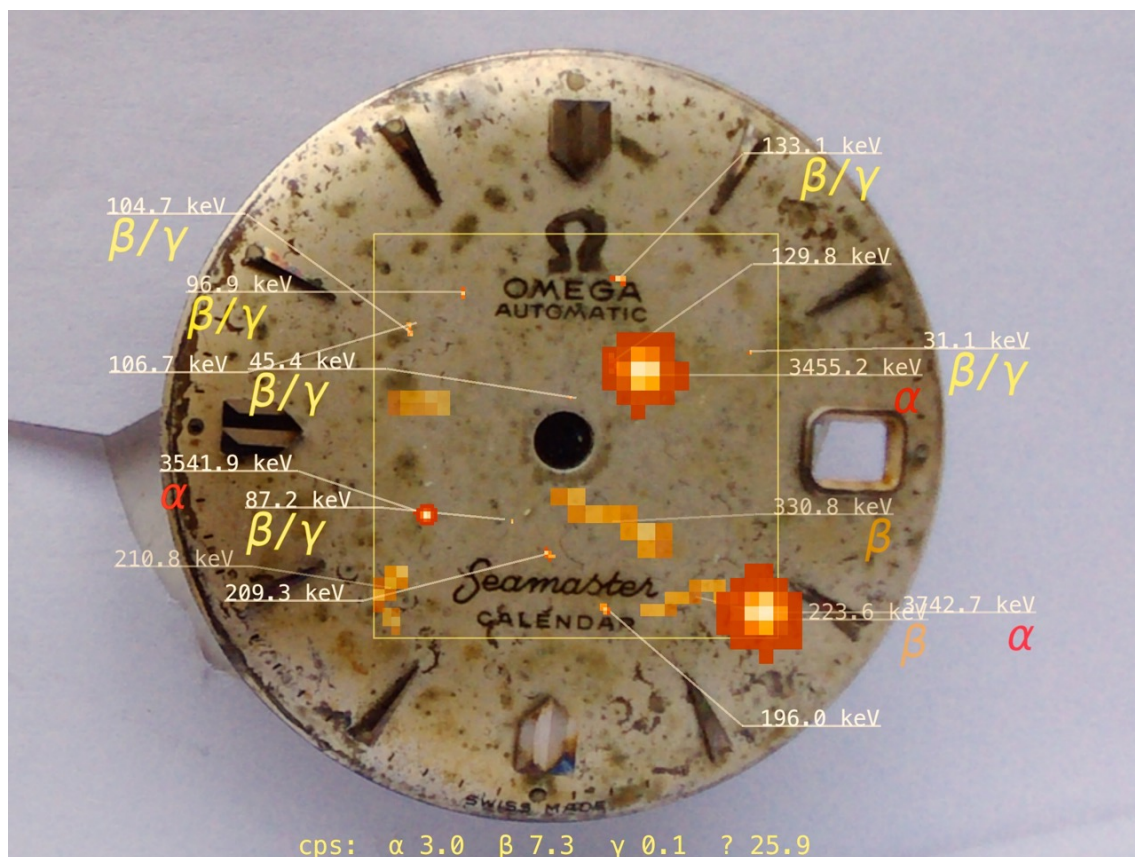


Figure 4.4: Screenshot of iPadPix imaging an old radioactive watch face. Radium was used to create fluorescent marks, therefore all three decay modes can be observed. The yellow rectangle marks the projected sensor area (1.4×1.4 cm). The dial has a diameter of 2.8 cm.

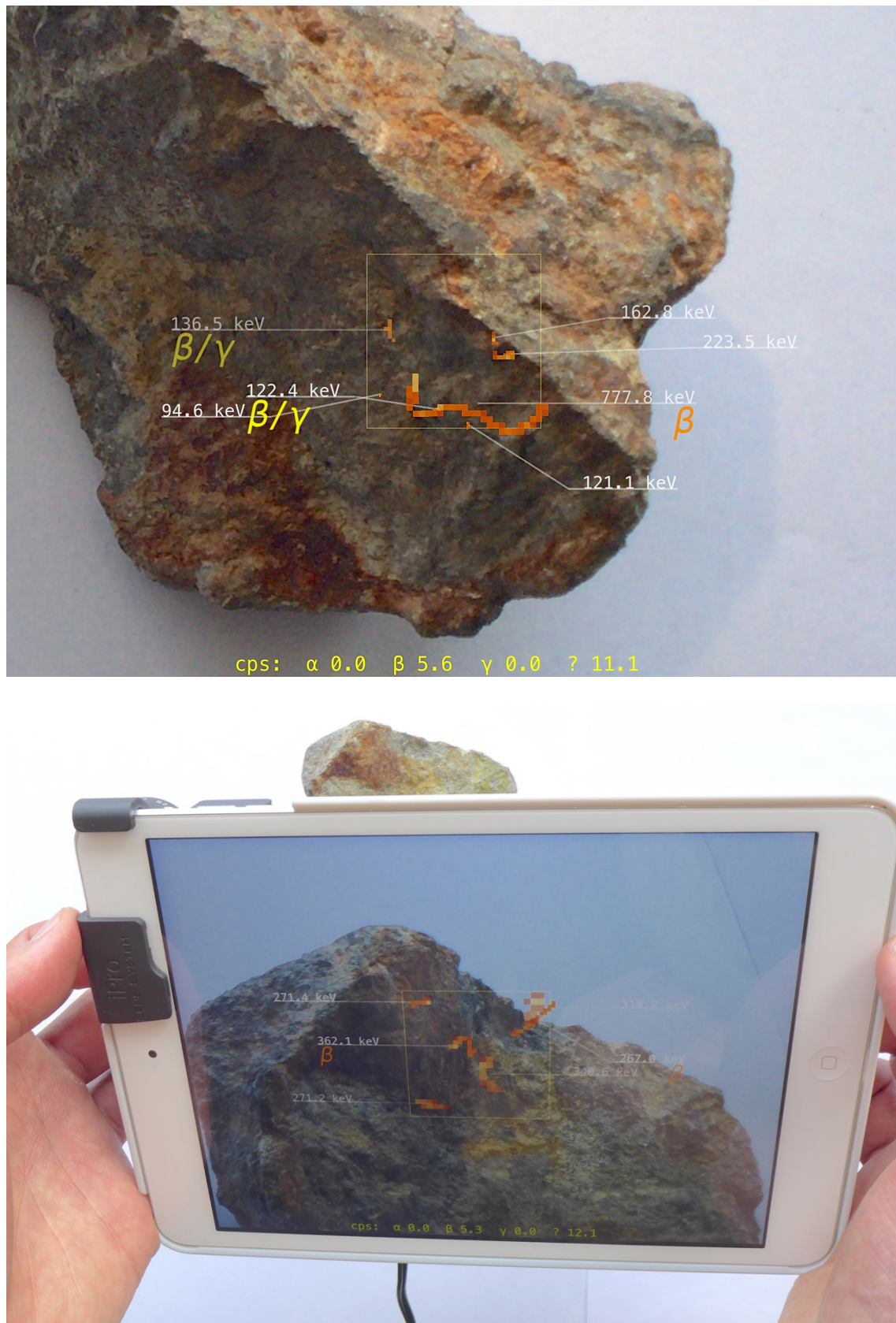


Figure 4.5: Imaging of a radioactive rock with iPadPix. The upper screenshot is an example how clusters with higher energy, such as the β -particle (supposedly) on the lower right, is more zoomed-in and thus emphasised. The lower picture demonstrates the whole user experience, with the object of interest in front of the tablet and an augmented reality on the screen.

4.5 Further Ideas

The presented iPadPix prototype is a framework with many possibilities to explore Timepix detector data in an educative and interesting new way. The following ideas build on this work and were not explored due to time constraints.

Information Display Currently, each cluster bitmap is scaled independently to a common colour range with its highest energy per pixel. This is an advantage, because the distribution in each cluster is better revealed than with applying only the same scale to all clusters in the frame (c.f. Pixelman screenshots in chapter 2.2.2). However, the meaning of the colours can only be known if a scale is shown together with energy ranges. A mode to display a small scale with every cluster or a double scale, that changes in a smart way to reveal distributions of heavy and curly tracks equally well, would be an interesting feature.

Furthermore, based on the count rates and distance information, dose equivalent values could be calculated. Muon signatures and other rare events, could be observed over time by collecting their cluster energies in a histogram view.

As mentioned in chapter 3.3, computer vision algorithms could be employed to expand the device response from tilt movements to displacement movements. The distance measurement could also be enhanced to cover a larger range in a more precise way with those methods.

Building on the cluster identification and count rates, a mode to discern signatures of particular decay chains seems feasible. Radioisotopes present in the observed object could be guessed by comparison with a set of known count rates prerecorded at different distances.

Advanced Readout With increased detection of unrecognisable blob clusters due to overlaps, a feed-back loop could compensate this by actively controlling the acquisition time of the Timepix chip. Also the bias voltage could be made adjustable from the tablet application to operate the sensor at different sensitivity settings.

A smaller and dedicated hardware could be build, which integrates the Timepix chip on an embedded board and allows to combine readout and cluster processing steps. It could be optimised for higher readout speeds to make single pixel calibration viable.

Adaption of the Optical Setup For radio protection purposes and in case of larger measurement distances, the optical setup could be improved to include collimation in front of the sensor. The FOV of the sensor would be reduced, but enable preciser estimation of the place where the radioactive decay occurred on the object. In addition, movable external absorption layers could be added to characterise the radiation quanta less ambiguous.

5 Conclusion

The iPadPix prototype created reassembles the initial mock-up proposal quite closely. It is able to demonstrate the general idea that a hybrid pixel detector can indeed be used to visualise radioactivity in an intuitive and educative way.

Many sensor-related outcomes had to be studied and considered, most importantly the fact that X-ray/ γ -photons and electrons from β -decays can only be distinguished based on additional assumptions. However, other ionising radiation quanta such as α -particles and cosmic particles like muons can be unambiguously classified.

The useful imaging range as defined by the optical setup, spans from ~ 3 cm to 12 cm. At these distances, ionising radiation can be observed in a magnified area between $12\text{ cm} \times 12\text{ cm}$ and $3\text{ cm} \times 3\text{ cm}$ on the tablet display which provides a reasonable user experience.

Overall, this work can serve as a multipurpose framework and starting point for further developments. It is possible to adapt it for various radioactivity related educational and training purposes. By refining the optical setup, it could even serve as a precise measurement tool - for example to map out hot spots on radioactive materials.

The real-time requirement proofed to be the most complex part to develop. The only commercially available and small Timepix detector readout is not designed for immediate processing and on-line display of pixel data on a mobile platform. Therefore, an intermediary embedded board is employed as a workaround. Although it increases the complexity and requires an additional power cable, a reasonable mobility is maintained. For a future revision, developing a custom readout and housing of all components in one battery powered module for mobile devices would be the best solution.

With the choice of iOS as a closed tablet platform, the restriction to interface with custom hardware only over a few specific communication channels was imposed. This was however straightforward to handle and the advantages gained by using an iPad mini confirmed the correctness of the choice. Its optical hardware features, the availability of suitable add-on lenses and the programming capabilities turned out to work well in creating the desired augmented reality user experience within the given time.

Regarding the processing of pixel clusters, it was possible to build upon and profit from freely available software developed within the Medipix collaboration hosted at CERN. The author hopes that future projects will be able to leverage in a similar way from the source code published together with this work.

Bibliography

- [Bouchami2011] J. Bouchami et al., *Measurement of pattern recognition efficiency of tracks generated by ionizing radiation in a Medipix2 device*, Nucl. Instr. and Meth. A 633 (2011) 187–189
- [Campbell2007] Michael Campbell et al., *Charge collection from proton and alpha particle tracks in silicon pixel detector devices*, IEEE Nucl. Sci. Symp. Conf. Rec. (2007) 1047
- [Carrel2012] Frederick Carrel et al., *GAMPIX: a new generation of gamma camera*, DASIP conference (2012) IEEE
- [Fiederle2008] M. Fiederle et al., *Energy calibration measurements of MediPix2*, Nucl. Instr. and Meth. A 591 (2008) 75–79
- [George2015] Stuart P. George et al., *Measurement of an accelerator based mixed field with a Timepix detector*, JINST 10 (2015) P03005
- [Hartmann2009] Frank Hartmann, *Evolution of Silicon Sensor Technology in Particle Physics*, (2009) Springer
- [Heijne2013] Erik Heijne et al., *Measuring radiation environment in LHC or anywhere else, on your computer screen with Medipix*, Nucl. Instr. and Meth. A 699 (2013) 198–204
- [Holy2008] T. Holy et al., *Pattern recognition of tracks induced by individual quanta of ionizing radiation in Medipix2 silicon detector*, Nucl. Instr. and Meth. A 591 (2008) 287–290
- [Jakubek2008] Jan Jakubek et al., *Pixel detectors for imaging with heavy charged particles*, Nucl. Instr. and Meth. A 591 (2008) 155–158
- [Jakubek2009] Jan Jakubek, *Energy-sensitive X-ray radiography and charge sharing effect in pixelated detector*, Nucl. Instr. and Meth. A 607 (2009) 192–195
- [Jakubek2011] Jan Jakubek, *Precise energy calibration of pixel detector working in time-over-threshold mode*, Nucl. Instr. and Meth. A 633 (2011) 262–266
- [Kalliopuska2013] J. Kalliopuska et al., *Processing and characterization of edgeless radiation detectors for large area detection*, Nucl. Instr. and Meth. A 731 (2013) 205–209

- [Keller2014] Oliver Keller et. al, *Feasibility study of a novel, fast read-out system for an ionization profile monitor based on a hybrid pixel detector*, MOPAB41, proceedings of HB2014
- [Leroy2012] Claud Leroy and Pier-Giorgio Rancoita, *Silicon Solid State Devices and Radiation Detection*, (2012) World Scientific
- [Knoll2010] Glenn F. Knoll, *Radiation Detection and Measurement*, 4th ed. (2010) Wiley
- [Krummenacher1991] Francois Krummenacher, *Pixel detectors with local intelligence: an IC designer point of view*, Nucl. Instr. and Meth. A 305 (1991) 527-532
- [Llopart2007a] Xavier Cudie Llopart, *Design and characterization of 64K pixels chips working in single photon processing mode*, (2007) CERN-THESIS-2007-062
- [Llopart2007b] Xavier Cudie Llopart et al., *Timepix, a 65k programmable pixel readout chip for arrival time, energy and/or photon counting measurements*, Nucl. Instr. and Meth. A 581 (2007) 485–494
- [MAFalda] John Idarraga et al., *MAFalda - Medipix Analysis Framework*, Medipix Collaboration
<http://twiki.cern.ch/twiki/bin/view/Main/MAFalda>
<http://svnweb.cern.ch/world/wsvn/mafalda>
- [Pinsky2012] Lawrence Pinsky et al., *Preparing for the First Medipix Detectors in Space*, Aerospace Conference (2012) IEEE
- [PDG2014] K.A. Olive et al., *Particle Data Group*, Chinese Physics C38, 090001 (2014)
- [ROOT] *ROOT Data Analysis Framework*, CERN, <http://root.cern.ch>
- [Rossi2006] Leonardo Rossi et al., *Pixel Detectors*, (2006) Springer
- [Siegbahn1965] Kai Siegbahn, *Alpha-, beta- and gamma-ray spectroscopy*, (1965) Elsevier
- [Thompson2009] Albert Thompson et al., *X-Ray Data Booklet*, (2009) LBNL Berkeley, <http://xdb.lbl.gov>
- [Vykydal2011] Zdenek Vykydal et al., *USB Lite—Miniaturized readout interface for Medipix2 detector*, Nucl. Instr. and Meth. A 633 (2011) 48–49
- [Vykydal2005] Zdenek Vykydal, *Microprocessor controlled USB interface for Medipix2 detector*, diploma thesis (2005) Czech Technical University in Prague