UNIVERSITY OF WEST BOHEMIA

FACULTY OF ELECTRICAL ENGINEERING

Department of Applied Electronics and Telecommunications

DOCTORAL THESIS

Precise position sensitive spectroscopy of energetic ions with adapted pixel device

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Pilsen, June 2015

Keywords

VHDL, FPGA, Experimental physics, Alpha spectroscopy, Heavy charged ion, Energetic ion, Radiation, Nuclear instrumentation, Timepix, Medipix, Pixel detector, Read-out interface, Data processing, Signal processing, Detector, Calibration.

Abstract

The hybrid semiconductor pixel detector Timepix has proven to be a powerful tool in radiation detection and radiation imaging. Energy loss and directional sensitivity as well as particle type resolving power are possible by high resolution particle tracking and per-pixel energy and quantum-counting capability. The spectrometric resolving power of the detector can be significantly enhanced by analyzing the analog signal of the detector common sensor electrode (also called the back side pulse).

The thesis deals with the study of the backs side pulse signal analysis, processing and its exploitation. The results of the study are used in the subsequent development of the precise instrumentation with enhanced parameters (e.g. simultaneous acquisition of the back side pulse waveforms as well as pixelated matrices of the Timepix detector, high spectroscopic resolution, well-done synchronization, self-trigger capability on base of particle energy, etc.) in comparison to previously available solutions. The results of the research and development open a new application of the Timepix detector for further study of energetic ions.

Klíčová slova

VHDL, FPGA, Experimentální fyzika, Alfa spektroskopie, Těžký nabitý iont, Radiace, Jaderná instrumentace, Timepix, Medipix, Pixelový detektor, Čtecí rozhraní, Zpracování dat, Zpracování signálů, Detektor, Kalibrace.

Anotace

Hybridní pixelový detektor Timepix prokázal, že je velmi užitečným nástrojem v oblasti detekce ionizujícího záření a zobrazovaní. Vykazuje výjimečné schopnosti dovolující přesné měření energie částic, včetně směru jejich dopadu. Tyto schopnosti jsou dány vlastnostmi jako je velmi jemné prostorové rozlišení, či vysoké energetické rozlišeni dovolující registrovat kvantum energie od jednotlivých interagujících částic (fotonů). Spektroskopické schopnosti detektoru mohou být dále umocněny při zpracování analogového signálu ze společné elektrody pixelové matice detektoru.

Tato práce se zabývá analýzou, zpracováním a využitím signálu ze společné elektrody pixelového detektoru. Výsledky získané předchozí studií jsou využitý k návrhu precizní jaderné instrumentace, která vyniká oproti ostatním již existujícím řešením díky svým vlastnostem (schopnost souběžné akvizice matic pixelového detektoru v kombinaci se záznamem signálu ze společné elektrody, vysoké spektroskopické rozlišení, vzájemná synchronizace, spouštění kombinovaného měření na základě velikosti energie interagující částice, atd.). Výsledky výzkumu a vývoje otevírají prostor pro nové využití detektoru Timepix na poli sledování těžkých nabitých iontů.

Glossary

List of symbols

α	Alpha
β	Beta…..
γ	Gamma
Al	Aluminum
Am	Americium
As	Arsenic
Au	Gold
Cd	Cadmium
Cm	Curium
Cu	Copper
Ga	Gallium
Pu	Plutonium
Si	Silicon
Te	Telluride

List of abbreviations

ADC	Analog to Digital Converter
C	Capacitor
CERN	Conseil Européen pour la Recherche Nucléaire
CMOS	Complementary Metal-Oxide Semiconductor
CS	Chip Select
CSDA	Continuous Slowing Down Approximation range
CTU	Czech Technical University
DAC	Digital to Analog Converter
DAQ	Data AcQuisition
DLL	Dynamic Link Library
FIFO	First In First Out memory

FITPix	Fast Interface for the TimePix detector
FITPix COMBO	COMBined with spectroscopy
FPGA	Field Programmable Gate Array
FSR	Fast Shift Register
FTDI	Future Technology Devices International Ltd.
FWHM	Full Width at Half Maximum
GUI	Graphic User Interface
HW	Hardware
ID	IDentifier
IEAP	Institute of the Experimental and Applied Physics in Prague
I/O	Input / Output
IP	Intellectual Property
LDO	Low DropOut
LVDS	Low Voltage Differential Signal
MPX	Medipix
MUROS	Medipix re-Usable Read-Out System
MUX	Multiplexer
NIKHEF	National Institute for Subatomic Physics
PCB	Printed Circuit Board
PCI	Peripheral Component Interface
PLL	Phase Locked Loop
R	Resistor
RISESat	Rapid International Scientific Experiment Satellite
ROI	Region Of Interest
ROM	Read Only Memory
RX	Reception
SATRAM	Space Application of Timepix based Radiation Monitor
SPI	Serial Periphery Interface
SW	Software
TI	Texas Instruments
TMP	Temperature

TOT	Time Over Threshold
TPX	Timepix
TX	Transmission
USB	Universal Serial Bus
VHDCI	Very High Density Cable Interconnect
VHDL	VHSIC Hardware Description Language
WTG	Watchdog

Preface

This doctoral thesis summarizes my research carried out for the past five years at the Faculty of the Electrical Engineering of the University of the West Bohemia in Pilsen done in the tight cooperation with the Institute of Experimental and Applied Physics of the Czech Technical University in Prague. The thesis describes problematics of the heavy ion spectroscopy done with the pixelated particle detector Timepix regarding to the performance enhancement done through the processing of back side pulse signal from the common electrode of the pixelated matrix. The result of the research was successfully used in subsequent development of the instrumentation including integrated support for the pixelated part of the Timepix detector as well as for analysis of the back side pulse signal.

The first introductory part summarizes the most important facts about the alpha spectroscopy that will be used later in other chapters. Further, it makes a reader familiar with the advanced Timepix detector, its properties and demands placed on the necessary supporting electronics (called as the read-out interface).

The second part is concerned about the specific Timepix detector application – study of heavy charged ions with the focus put upon the energetic spectroscopy. There are described two possible approaches (i.e. processing of the back side pulse signal and the recognition & evaluation of particle tracks left in the pixelated matrix of the detector). The both can provide equivalent output information. The consideration of their dis/advantages follows. The potential benefits and contribution of the combined approach is explained. In the end of the chapter the state-of-the-art in combined approach is mentioned.

The third part makes a detailed analysis of the most limiting factors preventing from further enhancements in the back side pulse signal processing and improvement of its resolution. The new complex solution is proposed regarding to the possibility of the back side pulse signal analysis running in parallel to the measurement done the pixelated part of the Timepix. The design concept ranges from the level of hardware till the level of the application software.

The following chapters (4, 5 and 6) serve as design documentation. They describe more in detail how the entire solution works and what the implemented functionality is. The hardware documentation part describes a design of the read-out interface board. The focus is put on the spectroscopy chain (to minimize noise coupling and to increase achievable spectroscopic resolution). The firmware part describes a custom a logical circuit architecture and its implementation done in the field programmable array. The supporting application software part describes how integration to already existing measurement control tools was solved.

The chapter 7 describes key findings that contribute to the significant improvement of the achievable resolution of the back side pulse signal spectroscopy. The way how the main noisy factor elimination was done is documented here.

The chapters 8, 9 contain description of several tests and experiments done with the newly designed instrumentation. The experiments (detector calibration and thin Mylar foil absorber) are undergone to get exact characterization of the device performance regarding to the achieved spectroscopic resolution and ability of the well synchronized measurement (back side pulse analysis done in parallel to the measurement done in the pixelated part of the detector). Further, the long term stability test determines variation of the spectroscopy chain response over time. The software toolchain through-put test determines limits of the acquisition ability (data download).

Finally, the chapter 10 summarizes all the results of the research and its contribution to further study of energetic ions done by the Timepix detector.

Acknowledgement

I am very grateful to all my colleagues who I have been cooperating with during the time of the research and development. I would like to thank namely to the following people for they help and support: Carlos Granja, Joshy Madathiparambil Jose, Petr Kouba, Vaclav Kraus and Milan Petřik.

Especially, I am grateful for collaboration between the Faculty of Electrical Engineering and the Institute of Experimental and Applied Physics in Prague, Czech Technical University that was established due to effort of the institute director Stanislav Pospíšil and the thesis supervisor Vjačeslav Georgiev.

The research was carried out in frame of the Medipix Collaboration.

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Declaration

I hereby submit this work (written during my studies at UWB Pilsen) for review and advanced defense. I declare that all work has been done independently. All used literature and sources are cited and listed in this document. Only legal and licensed software was used.

In Pilsen ....

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1 Introduction

1.1 Radiation spectroscopy – general description

The spectroscopy is a quantitative study of the energetic spectrum formed by the observed radiation field [1]. The energy spectrum is created from numerous individually detected particles. The spectrum represents energetic distribution of contributing particles. The resulting form of the spectrum is determined by the nature of present constituting radiation sources. Therefore the spectrum analysis is a way for recognition of particular contributors according to their typical characteristics. Detailed description of the radiation field can be obtained.

1.1.1 Standard processing chain of the radiation spectroscopy

The chain of the processing electronics is needed for analysis of the radiation field. The chain involves a wide range of necessary components from the very beginning of the particle detection till the very end of the data recording and visualization. A sample spectroscopy chain is shown on the following Figure 1-1. There is demonstrated how the spectroscopy signal is passed through all stages of the chain.

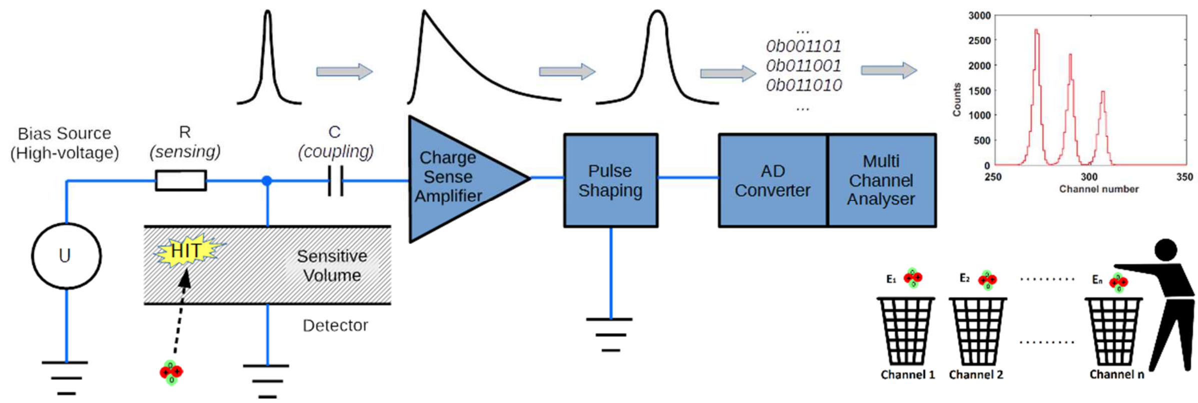


Figure 1-1 Example of the standard spectroscopy signal processing chain

1.1.1.1 Detector – Source of the signal

A radiation detector is an active element where ionization radiation interacts. It acts as a converter of radiation into a measurable value. A semiconductor detector is considered in the presented example of the spectroscopy chain. Free charge carriers are created during interaction of the particle in the detector sensitive volume. Subsequently, the free charge is collected by electrodes while a current pulse is formed.

1.1.1.2 Charge sense amplifier

It is the very first component in the signal processing chain. It prepares a signal from the detector for further amplification and processing. The charge signal is converted into voltage signal while it is provided at the amplifier output. It increases a signal energy. In fact, it serves as an impedance transformation block. There is a high impedance input and a low impedance output. After transformation, the low impedance output is not as sensitive to noise intrusion as the high impedance input. An amplifier is usually placed in the short distance from a detector (ideally as close to as it is possible) to avoid unwanted noise intrusion.

1.1.1.3 Pulse shaping

Although the detector signal is amplified by the previous stage it is still not in a convenient form for processing. The signal shaping has to be done to get a more convenient form of the pulse. In principle, the pulse shaping is a kind of signal filtration. A signal bandwidth is narrowed when a pulse is passed through a shaping circuitry. The frequencies that do not carry any effective information about the interacting particle energy are cut-out from the spectrum of the input signal. The signal to noise ratio is significantly increased when the signal bandwidth is narrowed from the “infinite range” to the defined band. The required pulse shape also depends on the following stage of the signal processing chain. Properties of the shaped pulse have to be suitable with processing abilities of the pulse analyzer (e.g. maximal sampling frequency of the ADC is common limiting factor for pulse shaping time).

1.1.1.4 Multi-channel analyzer

It evaluates energy distribution of input pulses. A sequence of ingoing pulses is successively processed. Input pulses are sorted into individual bins (called as channels) according to their amplitude which is proportional to the particle energy. Therefore a channel with higher index means recording of event with higher particle energy. Pulse height evaluation is done after analog to digital conversion. AD converter resolution determines a number of analyzer channels. The maximal value in a pulse data sequence is found and recoded in the end by incrementing of the corresponding channel counter. Output of the analyzer is a histogram, the energy spectrum of interacting particles is provided for further analyzes.

1.1.2 Alpha particle spectroscopy

The spectroscopy response of the alpha particle is determined by the way of interaction and by nature of the alpha decay. Both factors contribute into creation of the resulting energy spectrum.

The alpha decay process is characterized by emission of exact energy quantum. Alpha particles originating from the same isotope have the same initial energy. They are mono-energetic by nature. Thus two or more different isotopes can be clearly recognized by analysis of their energy spectrum. The most of natural alpha sources well fit within the decaying energy range from 3 to 10 MeV. The exemplar spectrum comprised of several alpha sources can be seen in the Figure 1-2 from [2].

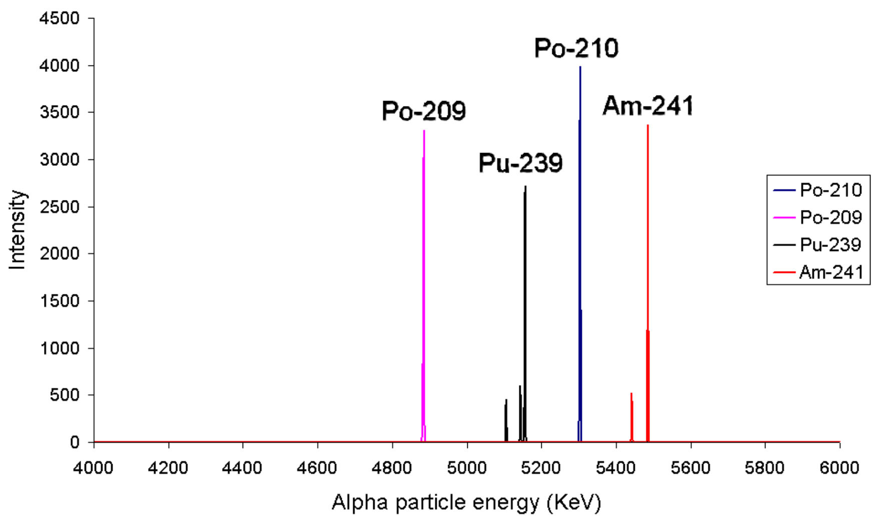


Figure 1-2 Exemplar spectrum containing peaks originating from several alpha sources (Po-210, Po-209, Pu-239, Am-241)

As an alpha particle is a charged element it interacts mainly through electric forces with electrons in material. Free charge is created while an alpha particle is gradually slowed down. It loses energy from the point of detector entrance till the end of a track when it is fully stopped. The characteristic track of an alpha particle interacting in matter is straight forward because of significantly smaller mass of electrons in comparison to the alpha mass. The penetrating depth of an alpha particle is quite small, thus the full energy is deposited in the detector from interaction. Therefore a charge signal from the detector can provide exact information about the particle energy. The energy peak is not spread in the resulting spectrum while measured in vacuum. Air also acts as matter of interaction for alpha particles and it causes a loss of particle energy.

Distance between the alpha source and the detector is also important factor influencing a spectroscopic response. A shorter distance means higher detection efficiency while more particles interact in a detector. But the radiation source proximity also means deterioration of the FWHM due to geometrical effects. Contamination of the detector surface by the recoil of radioactive progeny from their parents can be the consequence of the too close detector-source placement.

1.1.2.1 Region of Interest

It represents a window within the entire range of the channels (spectrum). The region of interest (ROI) should be established when energies of measured particles are known and expected. All the events belonging to the particular region of interest are directly related to one radionuclide source. The channel counts belonging to the region of interest are summed together to get information about activity. The Figure 1-3 shows exemplar spectrum of the compound radiation source. Two ROIs are highlighted by the different colors.

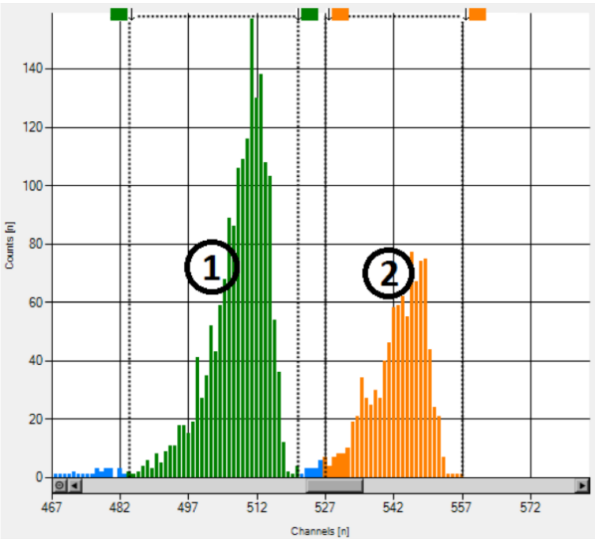


Figure 1-3 Spectrum of the compound radiation source with highlighted regions of interest. Green region 1 for Am-241, orange region 2 for Pu-239

1.1.2.2 Full Width at Half Maximum (FWHM)

It is a quantitative measure of the spectroscopy chain resolution. It can be determined from the spectrum while the mono-energetic particle source is used. In the ideal case there would be just the single line in the energy spectrum as a response to detected mono-energetic particles. However, due to disturbing factors the resulting spectrum is more spread over a wider range of energy forming a peak.

The FWHM measure is determined by following steps (as it is demonstrated in the Figure 1-4 below). The first step is to find the point at the peak maximum in the energy spectrum. It is marked with the point E_0 N_0. The next step is to get the value of the half maximum $N_0/2$. Two points where the half maximum level intersects the peak are determining for the FWHM. The left value is subtracted from right energy value while resulting in ΔE and this value is the FWHM.

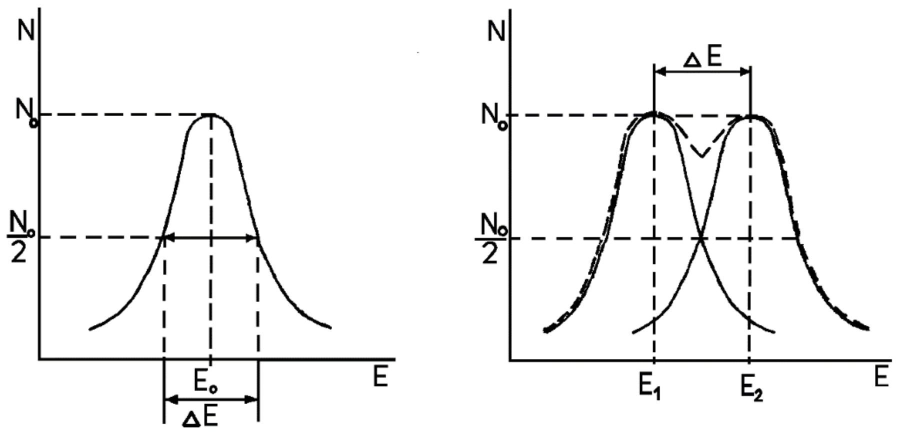


Figure 1-4 Definition of the values used for evaluation of the FWHM measure

Another equivalent measure of the energy resolution "sigma" could be also used. The relation between the FWHM is as following [24].

$$\mathrm{FWHM} = 2\sqrt{2\sigma^2 \ln 2} = \sigma\sqrt{8 \ln 2}$$

Which gives **2.35482004503** as the conversion factor.

Energy resolution is a very important factor for recognition of two adjacent energy peaks in the spectrum originating from different radiation sources (as it is shown in the Figure 1-4). Only the peaks which are separated from each other by the FWHM value can be distinguished. When the energy distance would be smaller than a value of the FWHM they would be merged together forming just one common peak without possibility of recognition.

1.1.2.3 Alpha Spectrometer Calibration

Because the channel analyzer works on voltage levels it cannot directly provide energy information. It counts events that fall within the range of the given channel. However, the pulse height is directly proportional to the energy of the interacting alpha particle. After calibration process is done the exact energy value is assigned to the analyzer channels. Calibration is essential and very important action for correct identification of the present alpha emitter.

At least two known alpha source standards are needed for alpha spectrometer calibration. Energy of emitted alpha particles has to be significantly different (at least non overlapping peaks in the spectrum). Ideally it should be one at the lower end, one at the higher end and one at the middle of the range. The channel where the most of the events is accumulated is associated with the well-known alpha particle energy of the standard. Number of calibration points is same as number of involved standard sources. Energy value associated to rest of the channels is computed afterwards. It is assumed that the pulse height is linearly dependent on the particle energy. Thus channels are also in the linear scale. The following Figure 1-5 is output from the application for spectrometer calibration.

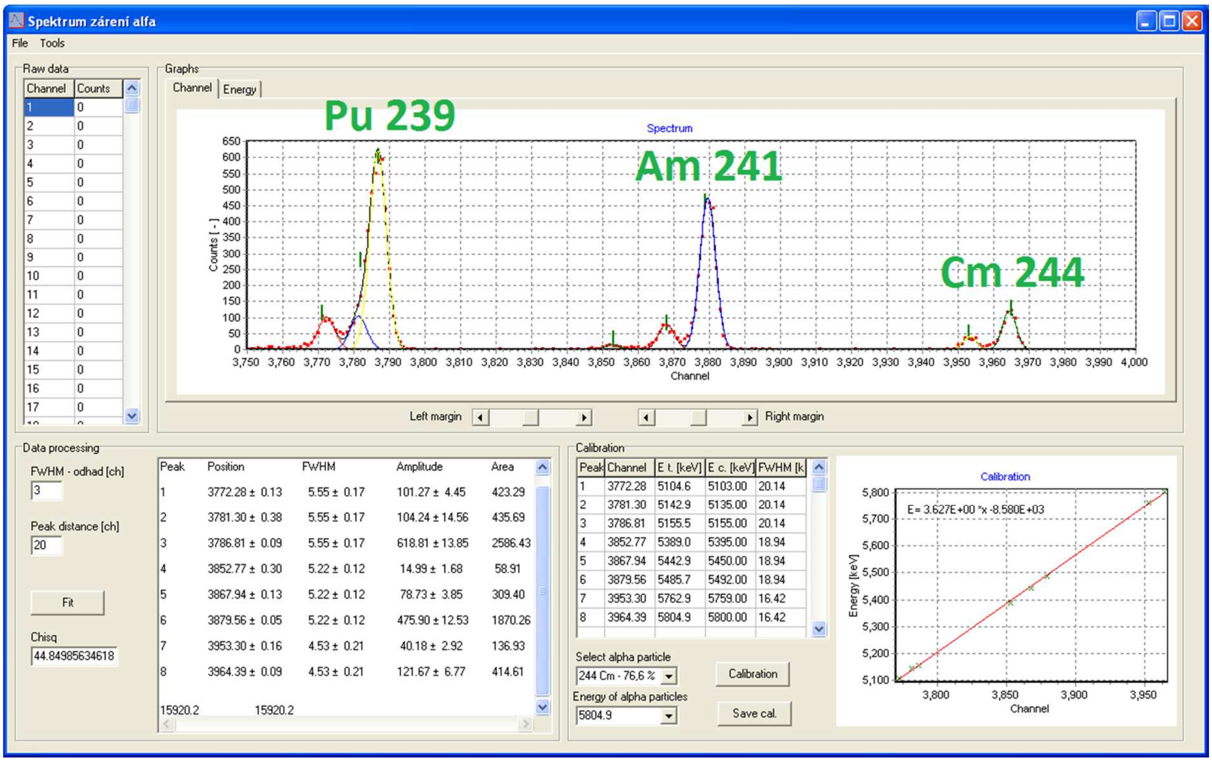


Figure 1-5 Output window of the application dedicated for spectrometer calibration (Tested with compound radiation source Am-Pu-Cm)

1.1.3 Spectroscopy of other heavy charged particles

Other heavy charged elements (protons, fission fragments, accelerate heavy ions) interact in the same way as alpha particles do (direct matter ionization through electric forces). Free charge carriers are also created along the interaction track while particle energy is linearly decreased.

Energy of the fission fragments (commonly in order of hundreds of MeV) is significantly higher than the regular energy of alpha particles (up to 7 MeV). A spectrometer has to be able to accept this range of energies. Resulting spectrum is also significantly different. It is continuous. It is caused by nature of the fission decay process. Energy released during the decay is distributed between several products (fission fragments of various mass and neutrons). Released energy is divided according to the mass of products. Detection of fission fragments is more demanding on detector properties. As the fragment penetrating depth is significantly smaller in comparison to alpha particles. Even thin insensitive surface layer of the detector acts an important role.

1.1.4 Difference between the heavy and light charged particle spectroscopy

The beta decay process produces light charged particles (electrons or positrons) and neutrinos. The energy released during the decay is shared between the products and the daughter nucleus. Due to the energy sharing and kinematics the resulting beta spectrum is continous. It ranges till the maximum end point – the energy of the beta reaction but it not observable (see the Figure 1-6).

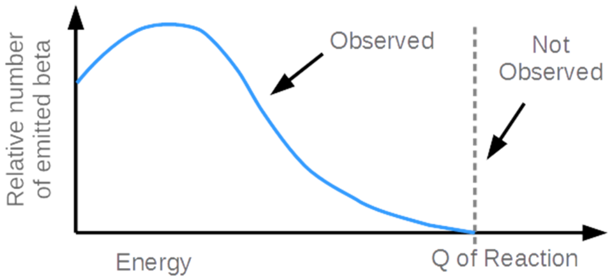


Figure 1-6 General distribution of the beta particle energy

The light mass of beta particles influences interaction behavior in matter. The mass of the interacting particle is the same as the mass of electrons in the detector matter. Initial direction of the beta particle can be significantly changed even in single particular interaction with an electron. Therefore the final track of the beta particle is quite curled. Even the scattering out of a detector is common. In this case just part of the beta energy will be detected. It contributes to further spectrum spreading.

1.1.5 Difference between the Gamma spectroscopy and heavy charged particle spectroscopy

The gamma ray spectrum is much more complex in comparison to the alpha particle spectrum. Even gamma photons of the identical energy will not produce a single peak response (full peak). The resulting energy spectrum is continuous. The complex wide spread spectrum is caused by the gamma interaction process. Gammas do not cause direct ionization of the detector matter as it possesses no charge. There are more ways of the gamma interaction in comparison with a charged particle (Photo electric effect, Compton effect and pair production). Not all the gamma photon energy is usually absorbed while interacting with a detector. A common case is partial energy absorption while the rest of the energy escapes detection. Evaluation of the gamma spectrum is a quite difficult task even for one radiation source. It gets more complicated when a compound radiation source is observed. It is really demanding to distinguish what sources contributed to creation of the composed radiation field. The following example shows a gamma spectrum of the Co-60. See the Figure 1-7 taken from the [25]

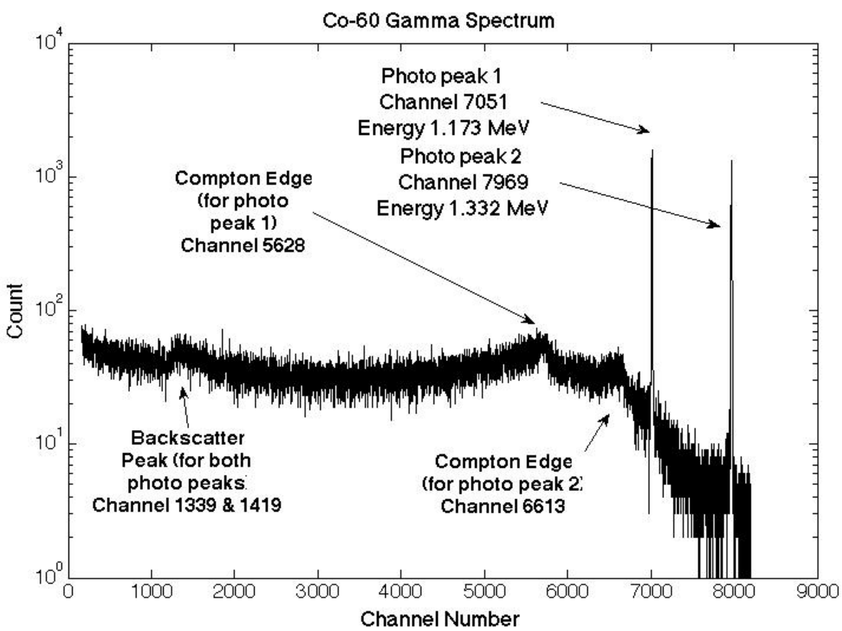


Figure 1-7 Exemplar spectrum of the gamma source Co-60

1.2 Timepix detector

1.2.1 Medipix Collaboration

The association [6], was started with the primer aim to disseminate a hybrid pixel detector technology from high energy physics to other fields. The collaboration involves numerous universities and research institutes. After years of existence, technologically advanced Medipix [11] and Timepix [12] single photon counting pixel detector readout chips were developed. They expanded into more applications than it was initially foreseen.

Figure 1-8 Logo of the CERN organization

Figure 1-9 Logo of the Medipix collaboration

1.2.2 Timepix detector characteristics

The semiconductor hybrid technology pixelated detector Timepix consists of the array of 256 x 256 square pixels with 55 µm pitch. In addition to high spatial granularity the single quantum counting detector Timepix can provide also energy or time information in each pixel. The hybrid architecture consists of a readout chip and a bump-bonded sensor. The sensor directly converts interacting ionizing particles into electric signals. The Timepix is a very powerful tool for radiation imaging as well as for particle tracking.

1.2.3 Hybrid technology detector

The Timepix detector is designed using a hybrid technology. The sensor chip and the read-out chip of the hybrid detector are manufactured separately. Both parts are soldered together using the bump bonding technology in the final state of the detector production process. The resulting sandwich structure product is a detector assembly. See the Figure 1-10 showing the assembly drawing.

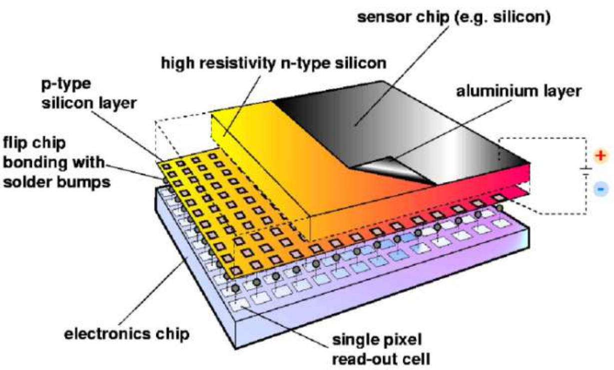


Figure 1-10 Composition of the hybrid pixelated detector Timepix

1.2.4 Sensor chip

The sensor chip would be manufactured from various types of materials. The most common materials are Si, GaAs, CdTe. Different materials prove different detection sensibility to interacting ionizing particles according to their band gap energy. The thickness of the sensor chip may vary as well. It is also a very important factor of the detection efficiency. Thus sensor selection strictly depends on the targeting application of the detector.

1.2.5 Read-out chip

It is an ASIC chip designed using the standard CMOS technology. It accepts a charge signal deposed in the sensor volume at the time of the particle interaction. There are integrated necessary analog as well as digital circuits for signal processing. The read-out chip fully manages conversion of analog charge signal into the digital form. Conversion is done in each pixel in parallel. Every pixel cell contains its own processing electronics. The read-out chip is also fitted with the communication interface. It serves for reading of the measured data and for writing of the detector configuration. The communication interface manages also selection of currently performed operation.

1.2.5.1 One pixel electronics

An each pixel cell is equipped with own signal processing electronics. It is fitted within the square of size 55 x 55 µm. See the Figure 1-11 showing the pixel cell composition. It can be divided into two parts (Analog and digital). The analog part comprises a charge sense amplifier, a pulse shaper and a threshold comparator. The digital part comprises a multi-purpose pseudo random counter and logics for the selection of an operation mode. The selection determines a currently selected value. Following operation modes are available.

- **Time over threshold mode**
  The pixel counter is incremented during the time when the threshold is exceeded. An input analog pulse is integrated. The resulting counted value corresponds to the energy of the interacting particle.
- **Hit Counting mode (Medipix mode)**
  The pixel counter is incremented just about one in the case of threshold exceeding. Further incrementing is inhibited till the input analog signal gets back under the threshold. The resulting counter value represents a number of interacted particles.
- **Time arrival mode**
  The pixel counter incrementing is started when threshold is crossed. It keeps on counting till the end of the acquisition cycle (shutter de-asserted). It does not matter if input signal gets back under the threshold or not. Resulting value corresponds to the time span passed before the end of the measurement.

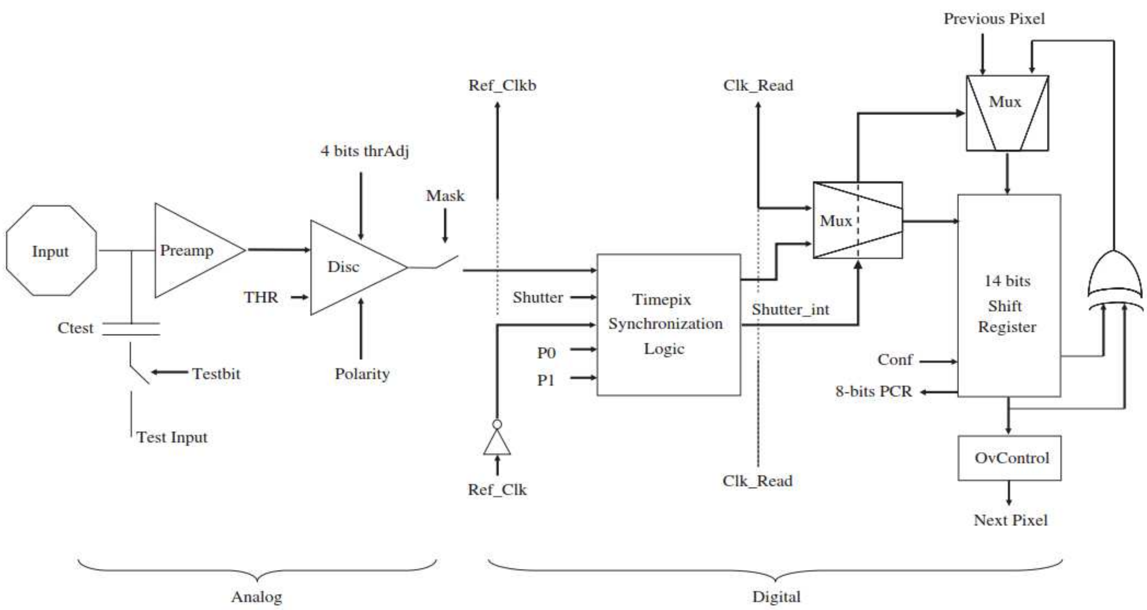


Figure 1-11 Timepix pixel cell floorplan

1.2.5.2 Detector matrix

The detector matrix is composed of 256 by 256 pixels. Pixel counters can be reconfigured to form a long shift register (see the Figure 1-12). Such formation serves to read-out of the measured data or for uploading of the pixel configuration.

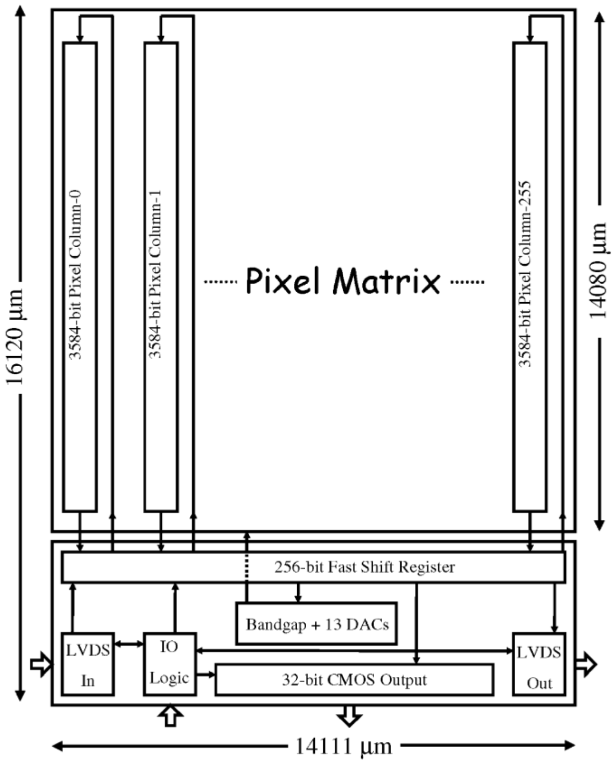


Figure 1-12 Timepix read-out chip floorplan

1.2.5.3 Integrated periphery

Aside to the matrix of pixels the Timepix detector also contains an additional electronics serving for operation of all pixels. There is a set of internal DACs serving for global threshold configuration, amplifier biasing, etc. The DACs can be sensed on the external analog output. Detector also implements potential by-passing of one of the internal DACs. It can be done over the external analog input connected to the voltage source.

1.2.5.4 Communication Interface

A dedicated communication interface is integrated in the read-out chip for connection with an outer system. Measured data can be read-out through the serial interface (LVDS) or the parallel interface (32 bit CMOS bus). Pixel configuration can be uploaded just through the serial input interface (LVDS). Current detector operation (reset, read-out, write configuration, measurement, etc.) is selected through the dedicated bus (CMOS). It has to be selected before any operation is initiated.

1.2.5.5 Powering

Detector requires separate power supply. The analog part as well as the digital part uses 2.2 V powering. Consumption of the detector is about 500 mW (mostly given by static current drained by analog circuitry).

1.2.5.6 Bias voltage

High voltage source is needed for operation of a sensor. Necessary voltage significantly depends on the sensor material and required level of depletion. It is not expected to be a constant. Voltage may vary during detector operation according to the currently running measurement.

1.2.6 Standard distribution of the Timepix to users

Timepix chips are distributed in the form of chipboards (see the Figure 1-13 and Figure 1-14). It became a common way of distribution. The Timepix detector assembly (read-out chip & sensor) is wire bonded on the surface of the chipboard PCB. The chipboard is fitted with the standard VHDCI connector. It serves for connection of data lines and for powering. The sensor biasing is connected over the second on board connector - LEMO. After plugging of the chipboard to a read-out interface the Timepix is ready for use.

Figure 1-13 Standard CERN Timepix chipboard

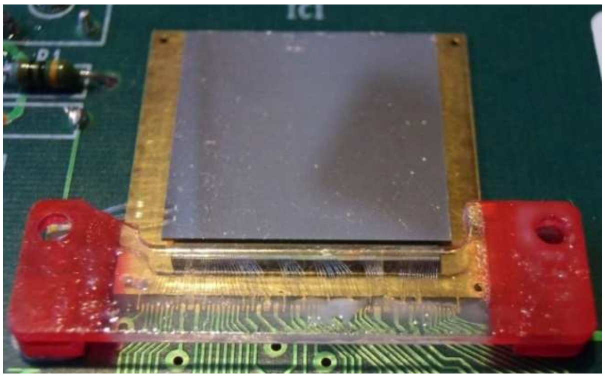


Figure 1-14 Detail of the Timepix chip that is assembled on the chipboard

1.2.7 Detector applications

1.2.7.1 Radiography/Imaging application

Imaging was a primer purpose of the Medipix detector (direct predecessor of the Timepix). The detector possesses ability to count single photons interacting in the sensor. A very high dynamic range of images should be reached [35]. Noise is effectively eliminated and filtered by the threshold setting. The achievable dynamic range is linearly dependent on the time of a measurement (number of integrated events – counted photons). High resolution images are composed from partial sub-acquisitions (due to a limited range of the internal pixel counter).

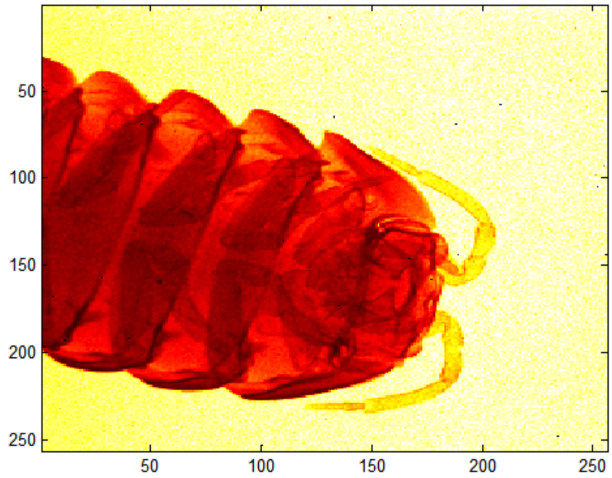


Figure 1-15 Exemplar X-ray image 1 – Woodlouse insect observed in-vivo

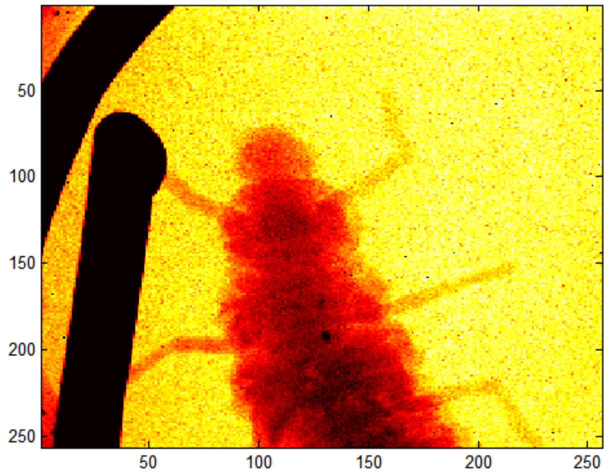


Figure 1-16 Exemplar X-ray image 2 – Larva of a seven-spot ladybird insect observed in-vivo

1.2.7.2 Particle tracking application

The Medipix detector was a powerful tool on the field of the particle tracking application. But its measurement abilities are quite limited in comparison to the Timepix detector successor. The energy measurement TOT (Time over Threshold) mode and the time of arrival measurement mode radically extended possible detector exploitation.

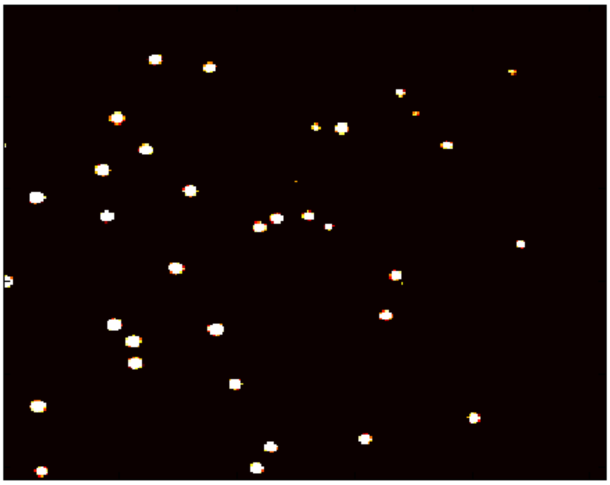


Figure 1-17 Alpha particle tracks left in the Timepix detector matrix

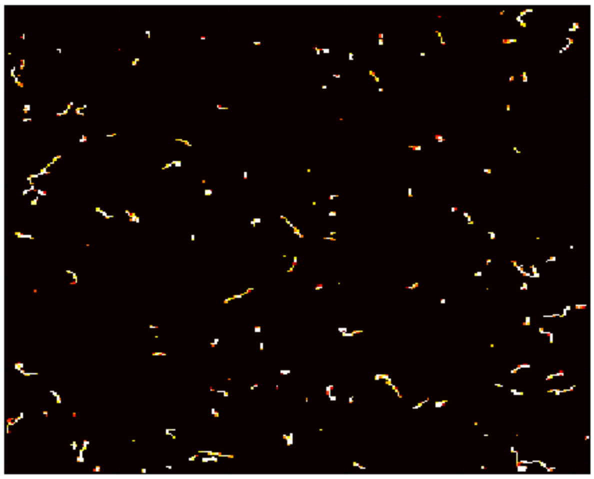


Figure 1-18 Beta particle tracks left in the Timepix detector matrix

The particle tracking should be conceived as observation of individually interacting particles. Usually short acquisition time is set to get a spare matrix (image containing non-overlapping records). Each interacting particle leaves characteristic track in a detector. Analysis of particle tracks provides valuable descriptive information about the particle nature, type, process of interaction, angle of impact etc. Even decay process can be observed in vivo. Classification of tracks can provide exact composition of the radiation field.

1.3 Read-out interfaces

The read-out interface is an electronic device that is absolutely necessary for utilization of the pixel detector Timepix. It provides a support to the detector itself. It manages detector acquisition process, reading of the measured data, configuration of the detector registers. It also provides necessary powering, sensor bias voltage, etc.

1.3.1 MUROS (Medipix re-Usable Read-out System)

It is the very first read-out interface for Medipix family detectors (see the Figure 1-19 and Figure 1-20). It was developed by the NIKHEF institute in Netherlands [13]. The read-out interface is based on the FPGA platform. It covers necessary requirements for acquisition control of the Medipix/Timepix detector. Device communication with a personal computer is done over a dedicated interface provided by the National instruments PCI card. An external power supply as well as an external detector bias voltage is needed for the read-out operation. Mechanical dimensions of the device are quite limiting for Medipix/Timepix detector applications.

Figure 1-19 MUROS read-out interface

Figure 1-20 MUROS read-out interface (opened device casing)

1.3.2 USB 1.1 Read-out

Disadvantages of the primer read-out system were quite limiting. The next available detector interface was the USB 1.1 Read-out [14] (see the Figure 1-21 and Figure 1-22). It was developed by IEAP CTU in Prague. It promptly became widespread in usage because of its robustness. Connection of the read-out interface is done over standard USB 1.1 (commonly available on each personal computer and laptop). Dimensions of the read-out itself were significantly reduced to be of pocket size. Device was based on the well-known 8051 microcontroller. Read-out speed was about 5 frames per second. All necessary detector powering was integrated within the read-out device itself. Internal bias source was also part of the design. An integrated concept of read-out interface opened new field of detector applications. Just few thinks were needed (Timepix/Medipix, a pocket size read-out interface and a laptop) to build-up a measurement set-up even while operating in vacuum.

Figure 1-21 USB 1.1 Read-out interface (opened device casing)

Figure 1-22 USB 1.1 Read-out interface (Chip board connected)

1.3.3 USB 1.1 Light

It is a derivative variant of the previously mentioned USB 1.1 Read-out interface. Main focus was put on mechanical dimensions [15]. The aim was to make it of the common USB dongle size (see the Figure 1-23 and Figure 1-24). The hardware platform is almost the same just components in suitable packages were selected.

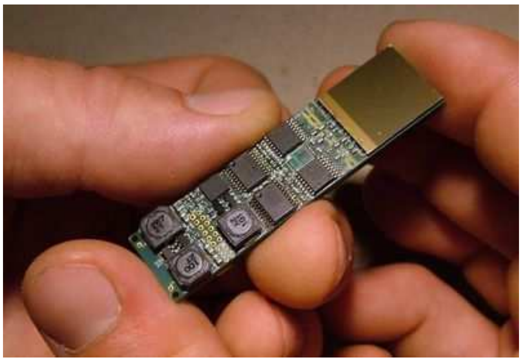


Figure 1-23 USB 1.1 Light (without casing)

Figure 1-24 USB 1.1 Light

1.3.4 FITPix 2.0 (Fast Interface for TimePix detector)

The next step in the development of Medipix/Timepix read-out interfaces was the FITPix device [16]. All beneficial features of the previous interface were preserved (size, integrated power sources, etc.) while limiting factors of the predecessor were improved – especially the read-out speed was quite unsuitable for some detector operation/measurement (e.g. calibration time). Reaction on external triggering events was also not suitable (It prevented detector usage in some time critical applications like a coincidence measurement).

Figure 1-25 FITPix 2.0 Read out interface

The platform of the read-out interface was altered. It was newly based on a FPGA circuit. A microcontroller concept was abandoned. The migration to the FPGA base allowed creation of the fully customized design. The interface really proved to be very flexible with regard to the firmware and implemented functionality. The maximal read-out speed was really significantly increased to be up to 90 frames per second. The device reaction on external signals was in order of tens of ns. The FITPix 2.0 opened new fields of applications due to its advanced properties.

1.3.5 MX10

It is an application specific read-out interface developed by the Jablotron Company [8]. The MX10 strictly aims to the educational sector (as it was agreed by the CERN Medipix collaboration licensing). It is distributed as a part of the Edu-kit. Mechanics for construction of the basic measurement set-up is optionally included. A sample radiation source can be also a part of the delivery.

Figure 1-26 MX10 read-out interface

Figure 1-27 Accessory of the MX10 Edu kit

MX10 interface was created under cooperation of the IEAP CTU in Prague. It is based on the concept of the FITPix 2.0 device. But a significant portion of electrical components was modified. Different family of the FPGA circuit was chosen (Altera Cyclone) as well as periphery or power source components were selected. The detector chipboard was also re-designed (including introduction of parallel data read bus). The MX10 allowed a significant read-out speed enhancement. Due to parallel bus access the frame rate of 800 frames per second was achieved.

1.3.6 FITPix 3.0

A new revision of the FITPix device was developed almost in parallel to the MX10 device. The component base for the new FITPix is quite similar to the MX10 (FPGA, ADC DAC periphery circuits, etc.). But a targeting application of the new FITPix is still utilization in physical experiments. Main device enhancement is modification of the read-out interface concept (to make it more scalable). The read-out interface hardware was separated in the two boards. There is a variable detector specific part – "Interface board" and a common part – "Base board". According to the detector type a matching combination of boards is assembled together and equipped with appropriate firmware before it is shipped. The base board provides support for the interface board. It contains an external I/O interface, communication interface (USB) and control logics within the FPGA circuit. An interface board provides all necessary detector powering, bias voltage, proper signal interconnection to the I/O ports of the FPGA on the base bard. It is also equipped with the ADC and DAC periphery needed for a management of the detector analog I/O channels. An interface board exists in several variants according to a targeting detector of the Medipix family (Timepix, Medipix3, Timepix2….). Even interface board sub-variants exist (Timepix parallel/serial read-out variant).

Figure 1-28 FITPix 3.0 Read-out interface (variant assembled with the serial interface board for Timepix)

Figure 1-29 FITPix 3.0 (Detail of the sandwich assembly of the Base board and the Interface board)

1.3.7 Other FITPix derivatives

During several years of the FITPix development several spin-off devices were created. They were designed as a single purpose instrument strictly dedicate for specific application. Nevertheless, original FITPix platform is significant basic part of their design. (FPGA architecture, VHDL firmware). Most significant derivatives are presented in following text.

1.3.7.1 SATRAM (Space Application of Timepix based Radiation Monitor)

The device was designed as a part of the scientific equipment of the PROBA-V mini-satellite [9]. Development was funded by the European space agency. It was the very first application of the Timepix detector when it was directly exposed to the space. The SATRAM device monitors a radiation field along the PROBA-V satellite earth orbit. See the radiation field distribution shown in the Figure 1-31.

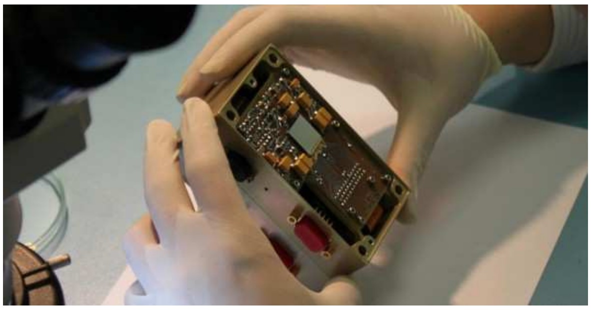


Figure 1-30 SATRAM radiation monitor

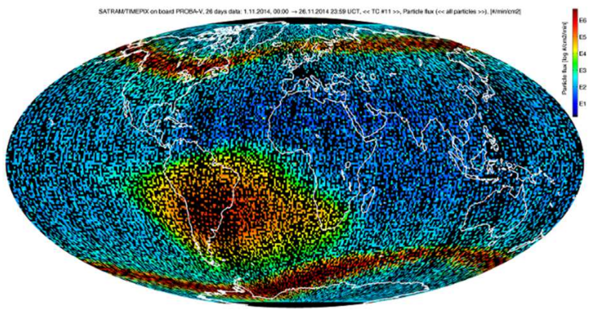


Figure 1-31 Radiation field measured with the SATRAM monitor along the earth orbit of the PROBA-V Satellite

1.3.7.2 RISESat (Rapid International Scientific Experiment Satellite)

It is a micro-satellite constructed as a carrier of the scientific equipment. The satellite was developed by the Tohoku University for scientific experiments in space. The Timepix detector is involved in the project as a customized lightweight and low-power radiation micro-tracker [10].

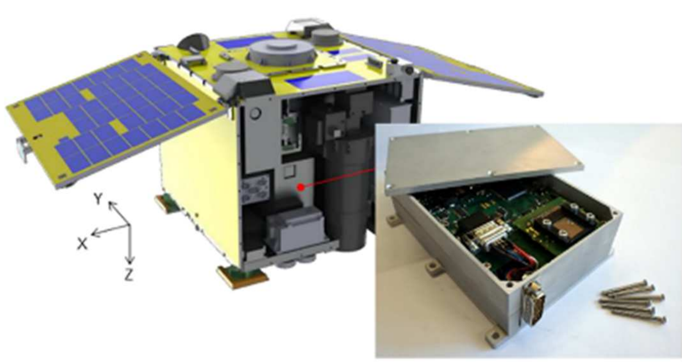


Figure 1-32 RISESat device and its placement on the micro-satellite

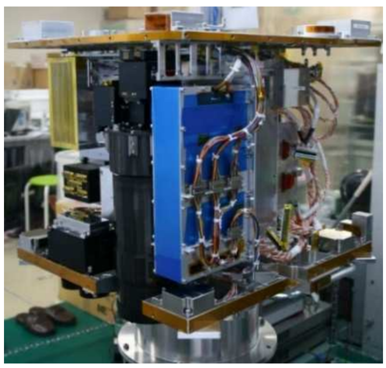


Figure 1-33 Micro-satellite carrier

2 Spectroscopy by means of the Timepix

2.1 Spectroscopy analyzing particle tracks

Particle tracks left in the detector matrix can provide detailed information about interacting particle property [4]. Sum of energy deposed during the particle interaction is just one value of all potentially recognizable. Therefore the spectroscopy should be conceived as a subset of the particle tracking field.

Analysis of particle tracks requires an application of quite sophisticated algorithm [33], [34]. Measured data is usually evaluated offline due to the complexity. The Figure 2-1 and Figure 2-2 show an exemplar track of heavy charged particles (On the right side - particle path is perpendicular to the detector surface, on the left side - a proton interacts under an angle). A sequence of following actions has to be done to get information about particle energy. Matrix read-out operation has to be performed. Energy calibration matrix has to be applied on the measured data matrix (because pixels are not identical and their response is different even when considering same input [36]). The next step is separation of an image into individual areas containing particle tracks. Charge sharing analysis and fitting is done for each individual track. Finally, a resulting sum of energy belonging to one interacting alpha particle is obtained.

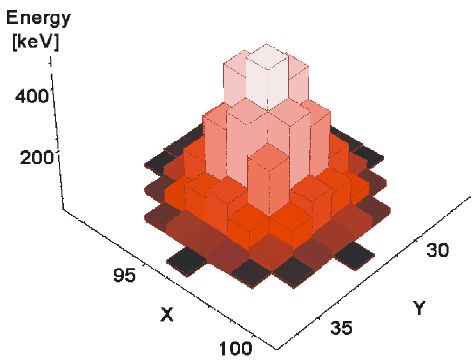


Figure 2-1 Track of the alpha particle hitting the detector in perpendicular direction

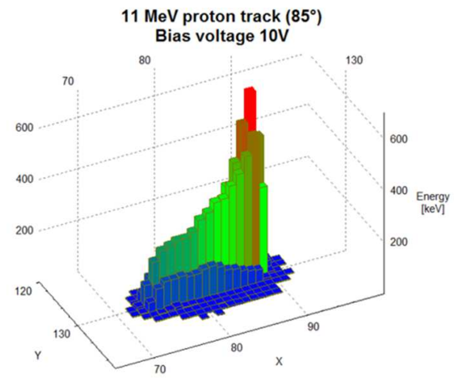


Figure 2-2 Track of the proton hitting the detector under angle 85°

2.1.1 Charge sharing issue

Free charge is created after particle interaction. Charge is distributed in the volume of the sensor due to electrostatic repulsion and diffusion process [5], [31]. The charge cloud expands during the collection process. Charge cloud should expand over area of several adjacent pixels. Spreading process is significantly influenced by the applied bias voltage. Higher the voltage is faster the collection process is and cloud spreading is also smaller. Thickness of the detector is also important factor. Thicker the detector is wider areas is due to longer time of collection time.

When considering interaction of the heavy charged particle (alpha) energy quantum in order of MeV is usually deposed. A charge cloud is spread in several adjacent pixels each time. Not just one pixel is usually affected due to a great amount of the charge. Thus resulting track of the particle involves more activated pixels (forming a cluster). Some part of deposed energy is not to be detected by pixelated detector. Just pixels where threshold was exceeded will contribute to formation of the cluster. Pixels on the border of the cluster will not detect any energy if input signal was under preset energy threshold (see the Figure 2-3). Thus detector pixelation possesses potential deterioration for energy spectrum resolution. The energy loss issue becomes more crucial when the charge cloud is spread into a wide area.

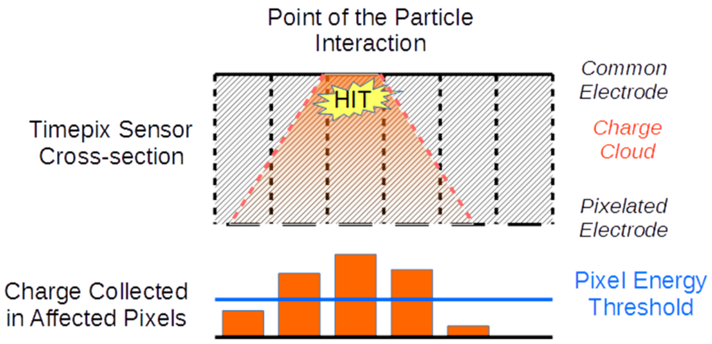


Figure 2-3 Visualization of the charge sharing between adjacent pixels

2.2 Spectroscopy analyzing signal from the common electrode of the pixelated detector

Although the Timepix detector was designed to be used as a pixelated particle detector it should be conceived in another way. Beside its primer purpose, in principle, it is still a single pad detector. See the Figure 2-4 for an equivalence schema. From the outer perspective individual separated pixels should be perceived as if mutually interconnected to the ground potential [3]. The virtual grounding is provided internally by the read-out chip. So, a single pad detector is a fully equivalent component in this case.

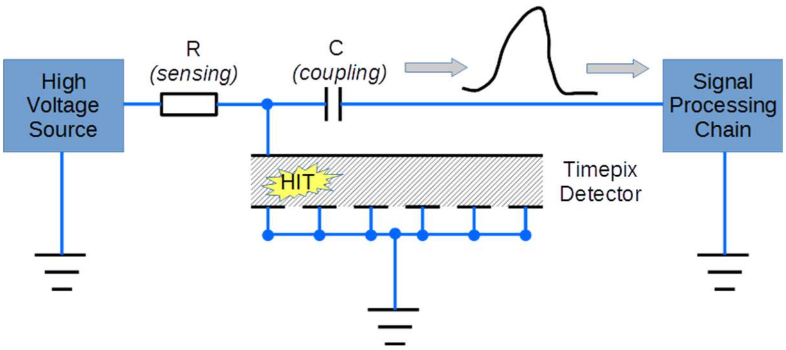


Figure 2-4 Timepix as a simple single pad detector

Once the high impedance sensing resistor is added in series with a bias source and an external spectroscopy signal processing chain is connected (over a capacitor that provides AC coupling) a standard spectroscopy chain is set-up. The common electrode signal can be processed and evaluated to get necessary spectroscopy information.

The signal from the common electrode of the pixelated detector is often called back-side-pulse (BSP). This denomination originates from the fact that the pixelated electrode is of the primer interest (front side). The back side pulse signal is considered to be marginal for the most of detector applications.

2.3 Simultaneous operation of pixelated part and back side pulse spectroscopy

Both previously mentioned approaches of the spectroscopy can be combined together. The measurement running in the pixelated part of the detector as well as the analysis of the back side pulse signal can be performed in parallel. See the Figure 2-5 [3] demonstrating simultaneous operation and the analogy between two different approaches. Almost equivalent energy information about an interacting heavy charged particle can be gained simultaneously from two different sources. It is obvious that combination of both spectroscopy approaches is advantageous.

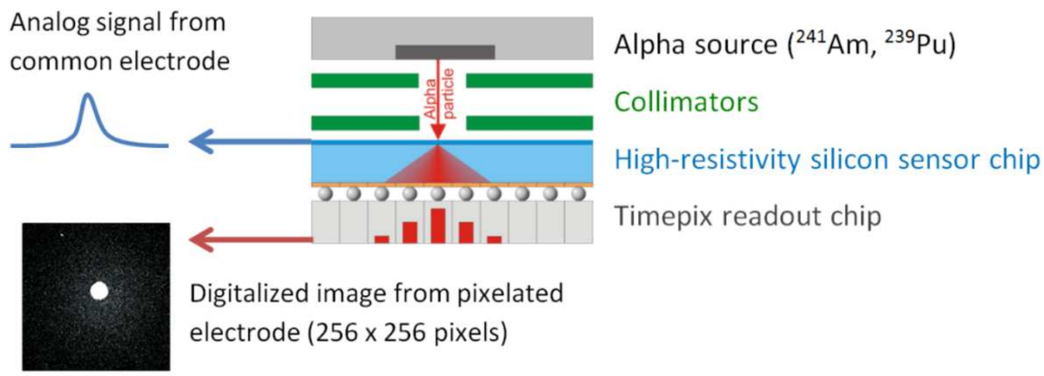


Figure 2-5 Analogy between the pixelated part and the common electrode of the Timepix sensor

2.3.1 Charge sharing effect suppression

Influence of the charge sharing effect on the spectroscopy resolution is not a case in the back side pulse spectroscopy approach. The common electrode signal involves contribution from all the pixels. Entire sum of the charge deposed by an interacting particle is provided for evaluation. Therefore the combined spectroscopy can contribute to the improved energy resolution.

2.3.2 False and irrelevant event filtration

Due to availability of the redundant information a filtration of false events can be done in the post processing phase. Influence of the pile-up effect of the back side pulse signal on the resulting spectrum can be significantly eliminated. Tracks left in the pixelated matrix clearly show number of interactions within the partial acquisition cycle. If more tracks are registered than partial acquisition data is not included in the final result evaluation. Interactions in the border region near to the edge of the detector matrix can be also simply recognized and filtered out. Even uncorrelated events can be excluded from evaluation. When a back side pulse event is registered without its counterpart in the pixelated matrix (and wise versa) it is considered as an irrelevant input for evaluation.

2.3.3 Self-triggering functionality

Very important fact of the back side pulse signal is that particle energy information can be obtained in very short time after interaction unlike in the track analysis method. Evaluation times are incomparable while considering both energy analysis approaches. As the particle energy information is available in the real time it can be utilized with a great profit. The self-trigger signal can be generated to initiate a measurement of the Timepix detector [32]. Due to the minimal delay of the self-triggering only the negligible portion of energy will not be registered by pixels. But it does not possess any issue because sum energy information is available from the back side pulse counterpart.

A presence of the self-triggering functionality opens a new field of Timepix application. The detector acquisition can be active within the narrow and well defined time window. A background is effectively filtered out. The blind acquisition of data is not performed any more. A focus is put just upon the wanted events while ignoring the rest. It is getting even more important when observing rare events. A probability of the rare event recording, while considering a random start of the acquisition, is very poor. The Timepix can also be employed as a part of a multi-detector system dedicated for observation of the complex nuclear processes. More than one particle interaction is to be observed in this case. The coincidence (or anti-coincident) event is a usual triggering condition of the measurement. Prompt knowledge of the particle interaction in the Timepix can be well exploited by a coincidence detection unit while evaluating triggering condition for start of the measurement of the multi-detector set-up.

2.3.4 Mutual substitution of energy information

As the particle energy information is gained from the back side pulse signal it is not needed to get the equivalent information from the matrix (while pixels are operated in the time over threshold mode). Operation mode of pixels can be switched. For example the time of particle arrival measurement can be done to get additional information. Short lived heavy ions can be observed in vivo while decaying in detector after previous implantation to the sensor.

2.4 Original concept of the back side pulse spectroscopy

The primer processing of the back side pulse signal was conceived like an addition of the standard spectroscopy chain in parallel to the already operated Timepix detector and the read-out interface. The approach requires utilization of a “heavy-weight” aperture. When considering such a set-up the most of the already gained benefits is getting lost. The portable pocket size detection system (Timepix & read-out interface) connected to several apparatus of the rack frame size. The spectroscopic resolution of the set-up has also never been satisfying enough. When the Timepix read-out chip was powered and operated the alpha particles of common energies could not be recognized in the back side pulse spectrum.

2.5 Dedicated tool for the back side pulse analysis

The next step in the back side pulse processing was development of the dedicated spectrometric device [17], [14]. It was still operated independently in parallel to the main read-out interface device. But the size of the additional spectroscopy device was the same as the read-out interface. Benefits of a pocket size detection system are preserved in this case. Although both devices are operated relatively close together the spectroscopic resolution is not much better as it was achieved in the original concept of the back side pulse spectroscopy. The Figure 2-6 shows how the read-out interface and the dedicated spectroscopy tool are arranged in the measurement set-up. The read-out interface FITPix provides all necessary detector powering and controlling. The spectroscopy tool Spectrig is a source of the bias voltage. It senses back-side pulse signal and performs its processing. If interaction is registered the trigger signal is generated to start the Timepix measurement.

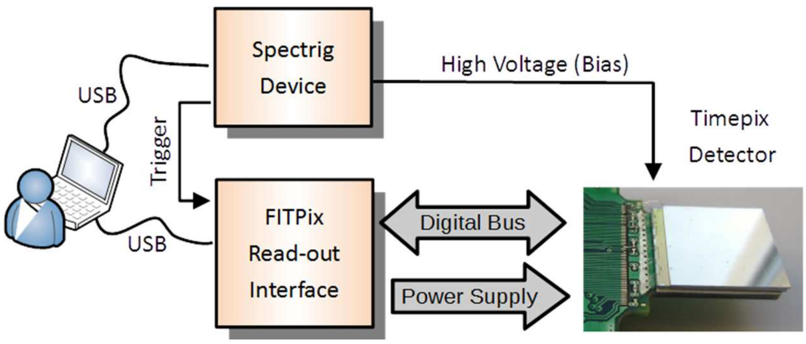


Figure 2-6 Concept of the additional tool dedicated for back side pulse signal processing. Set-up interconnection of the read-out interface FITPix and the spectroscopic signal processing tool Spectrig

The idea to integrate the back side pulse processing was considered even in the primer version of the Timepix USB read-out interface. It can be equipped with an additional module containing analog circuits needed for the back side pulse processing. The module is connected with the read-out interface board through the optional expansion header. The pre-processed back side pulse signal is routed to the dedicated channel of the AD converter periphery placed on the read-out interface board. Performance of the microcontroller (8051) did not allowed to create a firmware capable of parallel processing of the back side pulse signal and of the Timepix controlling. There was created extra variation of the firmware dedicated for the spectroscopy purpose.

The same idea of the back side pulse processing was kept while the FITPix 2.0 was developed. The read-out interface also allowed connection of the additional analog module for the back-side pulse processing. But even the new read-out interface version was released it did not proved significant improvement of the back side pulse resolution. Main limiting factors (will be discussed in separately in the section 3.1) were inherited also. The concept of the additional spectroscopic tool has not proved to be the right way leading to the improvement of the back side pulse spectroscopy resolution. The Figure 2-7 shows arrangement of the read-out interface FITPix 2.x and the Spectrig (that is also based on the FITPix hardware).

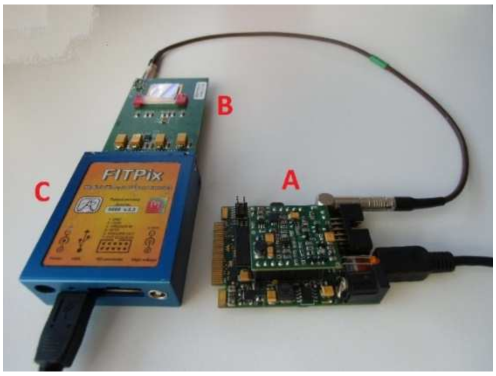


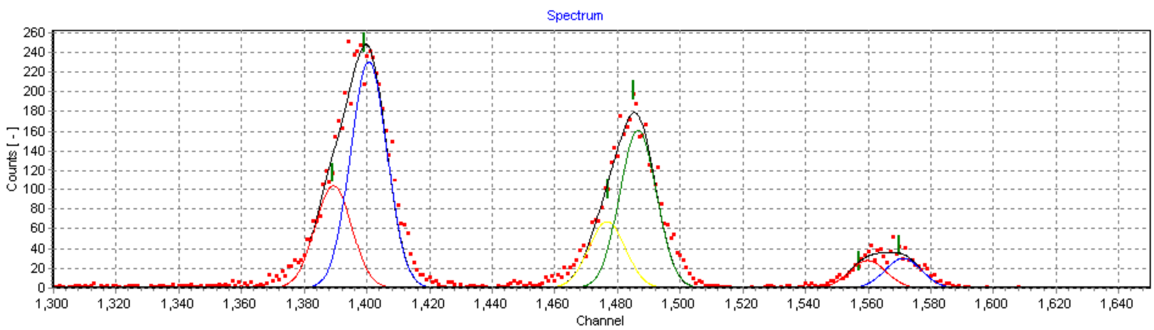
Figure 2-7 Spectrig, back side pulse processing tool, B - Timepix chipboard, C - FITPix read-out interface

Figure 2-8 Detailed view on the uncovered Spectrig device (utilization of the FITPix hardware – bottom board. Additional spectro-module – top board)

2.6 Limiting spectroscopic resolution of the Timepix detector

The Timepix detector as the part of the spectroscopy chain is limited in term of the maximal energy resolution. A large area of the sensor (in comparison to the common single pad detector) is characterized by a higher capacitance that presents a negative influence on the energy resolution. Larger area can also be characterized by conductivity that possesses higher leakage current with negative impact on the energy resolution. Above all, the underlying digital read-out chip possesses the main factor of deterioration while it is powered and active.

It was proved that the achievable spectroscopy resolution of the back side pulse signal for the Timepix detector is about 50 keV. The results of the sample measurement are presented in the



Calibration

Peak	Channel	E t. [keV]	E c. [keV]	FWHM [k
1	1389.33	5142.9	5126.00	50.73
2	1400.64	5155.5	5168.00	50.73
3	1476.64	5442.9	5451.00	50.73
4	1486.59	5485.7	5488.00	50.73
5	1559.85	5762.9	5760.00	50.73
6	1571.18	5804.9	5802.00	50.73

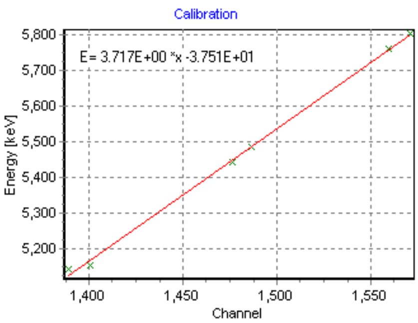
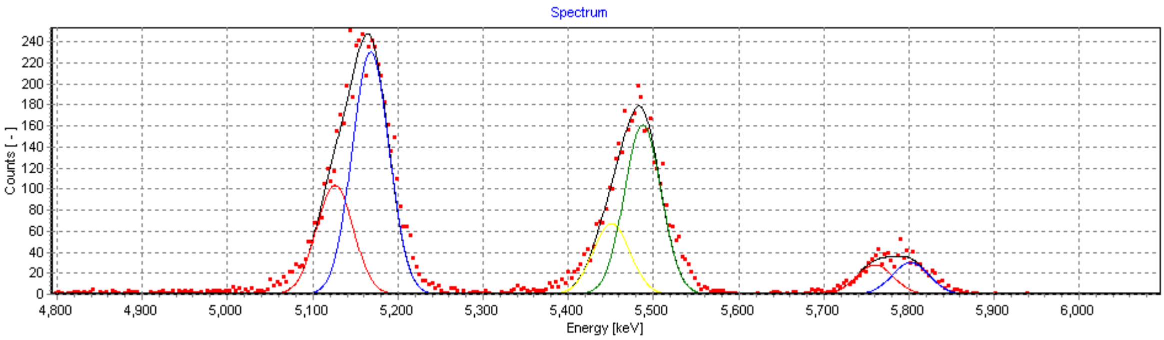
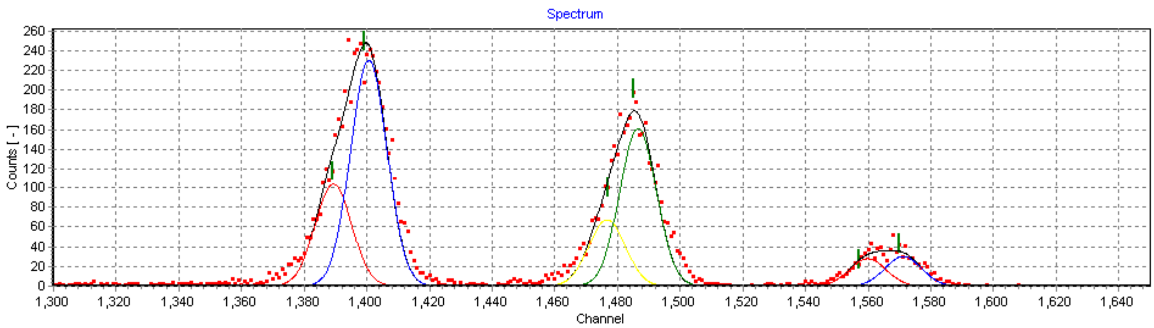


Figure 2-9 (There is shown an output of the calibration done for the Timepix with 300 µm Si sensor. Measurement was done in vacuum with the compound source Am-Pu-Cm). However, the back side pulse resolution of the Timepix detector may significantly vary piece by piece. The detector has to be carefully selected before its usage. The pieces with a high sensor leakage current or the pieces with noisy pixels are getting unusable for the spectroscopy application at all.





Calibration

Peak	Channel	E t. [keV]	E c. [keV]	FWHM [k
1	1389.33	5142.9	5126.00	50.73
2	1400.64	5155.5	5168.00	50.73
3	1476.64	5442.9	5451.00	50.73
4	1486.59	5485.7	5488.00	50.73
5	1559.85	5762.9	5760.00	50.73
6	1571.18	5804.9	5802.00	50.73

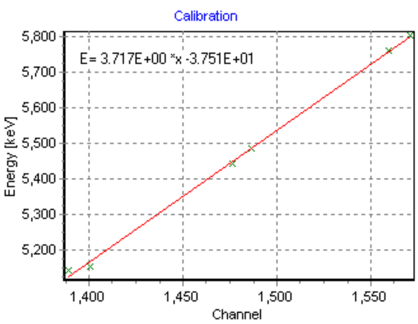


Figure 2-9 Calibration results (FWHM = 51 keV), Timepix with 300 µm Si sensor using a compound alpha source Am Pu Cm and 60 V bias voltage

Slightly better results of the spectroscopic resolution were published in the source [14]. There was presented resolution about 45 keV in the FWHM measure for the Am-Pu-Cm source (to be seen in the Figure 1-11).

However, these results are related to the Medipix detector (It is a direct predecessor of the Timepix on the line of development). Same value was not confirmed for the Timepix detector (considering several samples of the Timepix detector that were available for testing during the time of the thesis research).

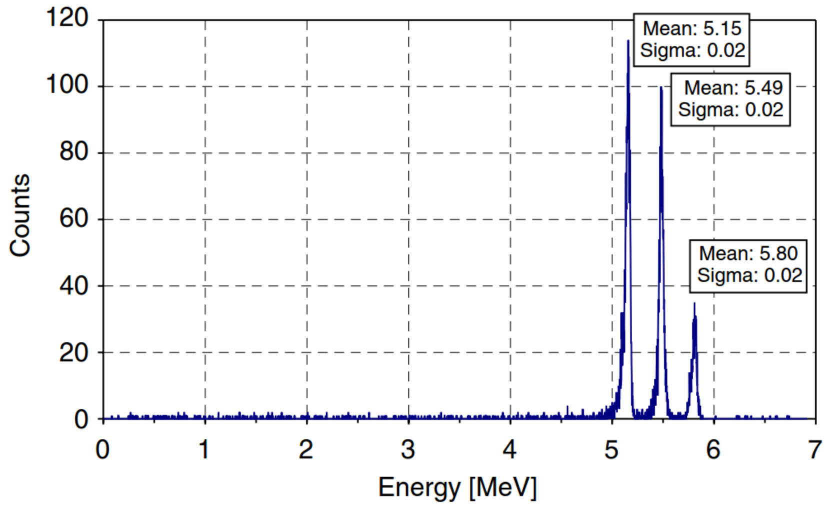


Figure 2-10 Spectrum of the mixed alpha source (239Pu, 241Am and 244Cm) measured in vacuum by Medipix2 with 300 µm Si sensor via the USB 1.1 interface (see the section 1.3.2)

The last example (see the Figure 2-11) demonstrates an impact on spectroscopic resolution of the back side pulse signal in the case when the read-out chip of the Timepix detector was powered and active (a measurement was running in the pixelated part simultaneously to the back side pulse measurement). The energy peaks of the individual isotopes of the Am-Pu-Cm radiation source are merged together. They are not recognizable from each other anymore. Note that other conditions of the test were same as in the previously presented calibration outputs (Figure 2-9).

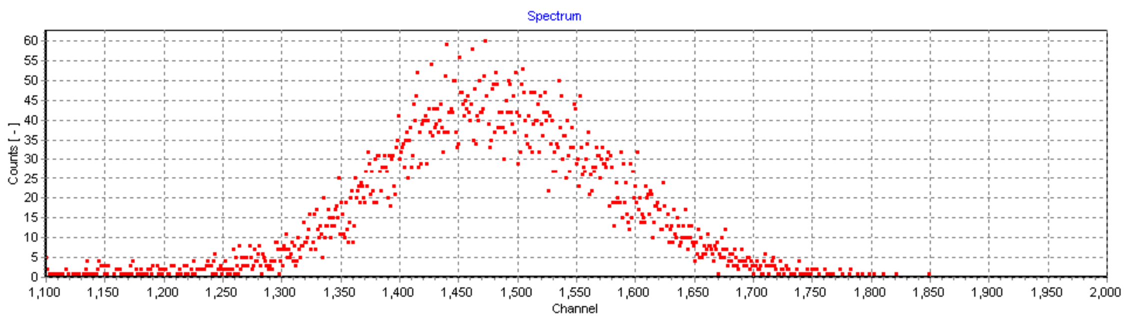


Figure 2-11 Deterioration of the energetic spectrum for the Timepix with 300 µm Si sensor in dependence on the simultaneously running measurement in the pixelated part of the detector and back side pulse measurement

2.7 State of the art – Solution for the back side pulse signal measurement and analysis

Previous research on back side pulse analysis problematics has been done in the IEAP CTU. Evaluation of the noise sources and most important factors were published in the article [3]. There was proposed and designed solution for improvement of the spectroscopic resolution. The concept based on the galvanic separation of the Timepix detector and the read-out interface was constructed and successfully tested. The Figure 2-12 shows composition of the designed solution.

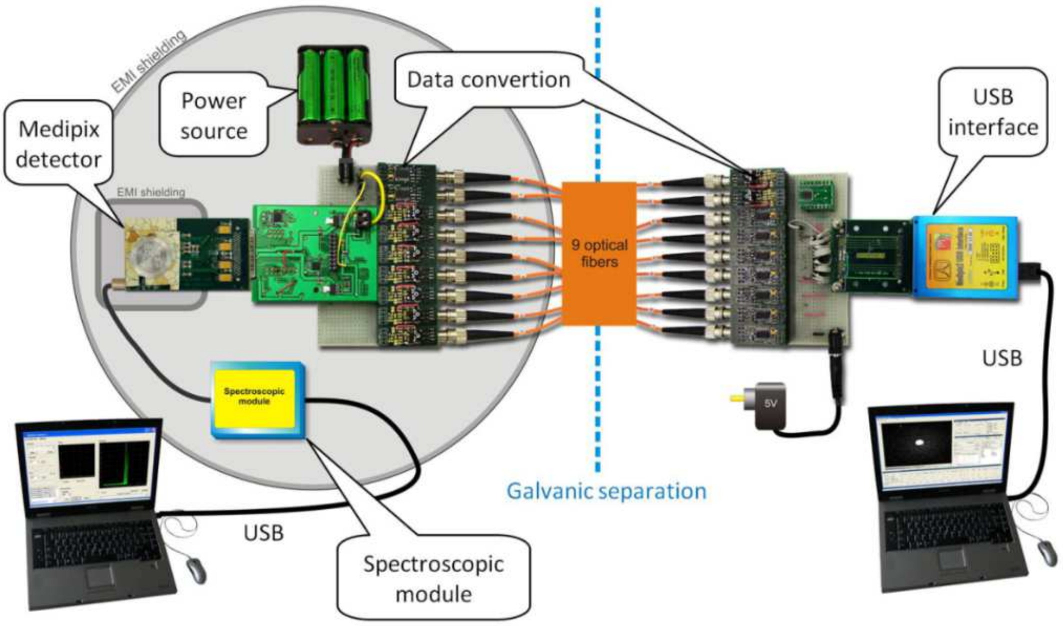


Figure 2-12 Concept of the galvanicaly separated read-out interface and the Timepix detector

Significant improvement of the spectroscopic resolution was achieved when both parts (Timepix detector & read-out interface) were operated galvanicaly separated. A resolution enhancement was reported even in the case when the read-out chip of the Timepix detector was powered and active. See test results shown in the Figure 2-13. There is a comparison of the alpha spectrum gained with the Am-Pu compound radiation source; all measurements were done in air. The spectrum B represents non-powered Timepix detector that is disconnected from read-out interface. Just a spectrometer is connected. Both energy peak are clearly to be recognized (FWHM is about 82 keV). The spectrum A represents a direct connection of the Timepix detector to the read-out interface. The detector is powered and active. The peaks from Am and Pu are almost unrecognizable forming one common peak (FWHM about 275 keV). The spectrum C represents the case of the galvanicaly separated read-out interface. The Timepix detector is powered and active. Both Am-Pu peaks are still seen as separated in the spectrum (FWHM about 191 keV). Undergone tests proved that a read-out interface is a significant source of the interference.

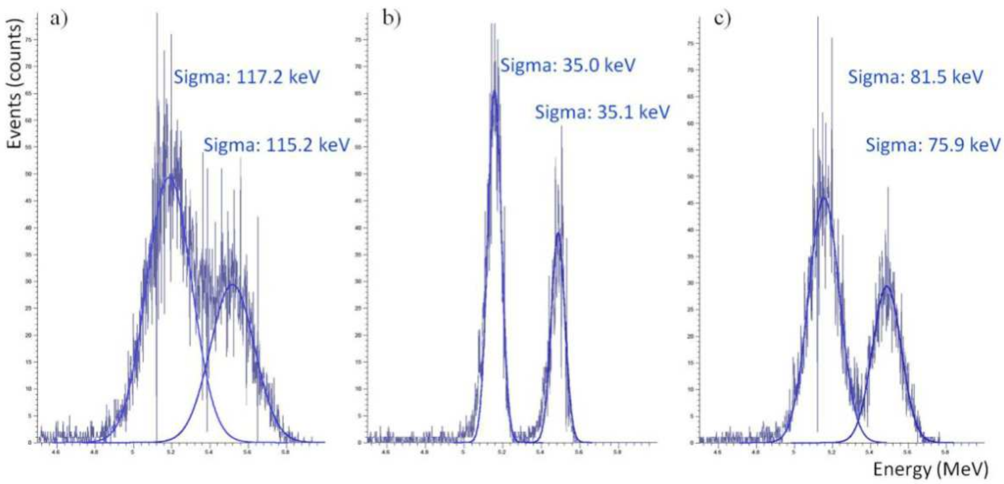


Figure 2-13 Comparison of energetic spectra – Various configuration of the measurement set-up (B – no read-out interface utilization – just observation of back side pulse signal, C – Timepix connected through opto-coupler to the read-out interface, A – Timepix directly connected to the read-out interface)

However, the proposed solution proved a couple of weak points. A read-out speed (in term of frames per second) was quite low due to utilization of galvanic signal couplers (different propagation delay of individual signal lines). Successful operation of the entire set-up in the vacuum is quite problematic, almost impossible). Its dimension and the electronic component base possess a significant limiting factor. Nevertheless, the research proved that the back side pulse spectroscopy is practicable even when the Timepix detector is in the active state.

3 Development of the merged platform

The previous development did not provided a sufficient output that would enable to use potential benefits of the back side pulse signal processing. All previously developed designs were in principle single purpose tools. They were focused just on one part of the problematics while omitting the rest. More sophisticated solution is needed to achieve an appreciable progress. Progressive solution has to be much more complex. A wide range of related subjects has to be considered altogether. The detector read-out interface design, spectroscopy signal processing, data acquisition software, etc. have to be involved.

3.1 Analysis of the weak points and requirement specification

There are several weak points that possess significant limitation for further improvement of the back side pulse spectroscopy resolution. The following discussion pinpoints main weak points that were known before a development of the new merged platform was initiated. Limiting factors were identified during the previous research while developing the dedicated tool Spectrig (see 2.5) for the back side pulse spectroscopy.

3.1.1 Back side pulse signal connection

The source (Timepix sensor) of the back side pulse signal is operated on high impedance (i.e. in order of mega-ohms). Therefore the signal is very sensitive for intrusion of any additional noise. A long distance wire connection between the Timepix and the spectroscopy processing device is utmost unsuitable. Even if shielded coaxial wiring is used it is still not possible to prevent effective signal from deterioration. Connectors at the both sides of the wire interconnection also possess weak points on the sensitive signal path.

3.1.2 Grounding issue

The parallel operation of two autonomous devices (read-out interface and spectroscopy signal processing tool) opens up a question of the grounding. Each device requires its own powering. In principle, the detector bias voltage source is operated on the different ground level than the detector read-out chip. Difference of the ground potentials is dependent on the resistance of the bias interconnection. External I/O signals, needed for trigger connection, also forms unwanted relation. Abrupt change in current power consumption of both involved device causes shift of its grounding potential. The study (mentioned in 2.7) definitely proved that galvanic separation leads to significant improvement of energy resolution.

3.1.3 Uncorrelated data issue

As the both devices are operated in parallel they produce separated data outputs while acquisition is running. It is almost impossible to find exact correlation between the spectroscopic information and the pixelated frames. There was not considered implementation of any mechanism allowing retrospect correlation. Only the available synchronizing information is a personal computer time that performs data recording. Unfortunately, the computer provided time resolution is too coarse to be useful for analysis of physical experiments. Recorded data streams also miss any kind of mechanism for detection of the partial data drop-out. If just one event gets lost (it does not matter if a drop-out is related to the side of the frame recording or the spectroscopic pulse recording) mutual correlation is irretrievable lost. Finally, all the bunch of the records is useless and has to be excluded from result evaluation.

3.1.4 Response time and synchronized operation

Both main functional parts of the merged platform has to be well synchronized together. Fast reaction in order of several clock cycles is needed. Utilization of the FPGA circuit can guarantee to meet the requirement while considering internal connection of the logical signals (even reaction to other optional external signals of the device can be simply managed). The most demanding task constitute propagation of the information about current value of the back side pulse signal. It has to be converted to the digital form and evaluated while satisfying maximal propagation delay of several clock periods.

3.1.5 Connection of the device

A minimal number of connection points is required to avoid unwanted coupling. In ideal case all data transfer as well as powering would be done over one common bus. Previous solution composed of two independent units used two separated USB buses. It is not considered for the merged platform any more. However, the USB 2.0 bus itself can be kept. It can cover necessary powering needed for operation of the merged device. An available data transfer bandwidth is also sufficient when considering a frame rate in order of tens per second.

3.1.6 Analog to digital signal conversion

Previously presented tools dedicated for the back-side pulse processing were in principle re-designed read-out interfaces. Their primer focus was not a spectroscopy. They were retrofitted with the analog front-end (additional analog module) while using already present on board resources (general purpose AD converter). Therefore a design compromise, that possesses some limitation, had to be done. The pulse shaping time was set according to the sampling speed of the AD converter (one mega-sample per second does not allows shaping time to be less than in order in micro seconds). However, shorter shaping time would be more beneficial. Trigger signal generation was done by the analog comparator while using unfiltered output of the charged sense amplifier. Utilization of a faster AD converter would enable a possibility of direct generation of the trigger signal on the basis of converted data.

3.1.7 Mechanical arrangement of the device

The most common way of the Timepix chip distribution is CERN chipboard assembled with the wire bonded Timepix detector connected to the read-out interface over the VHDCI connector and the LEMO connector for biasing. Although the standard distribution is well fitting for most of the users and applications it is not a case of spectroscopy. It possesses a significant limitation for further spectroscopy resolution improvement. A mechanical concept of the standard chipboard does not respect any requirement defined for the back side pulse signal that is very sensitive for noise introduction. Therefore the Timepix detector placement has to be re-arranged to respect previously defined requirements. The Timepix detector has to be placed near to the amplifier as close as it is possible. The bias source has to be also placed on the same board. That is why a new board has to be designed.

3.2 Concept of the merged platform

The top level of entire solution is presented in the Figure 3-1. All the constituting parts of the acquisition chain are involved in the abstracted drawing. The concept covers the chain from the very beginning, represented by the Timepix detector, till the very end, represented by application software running on a personal computer.

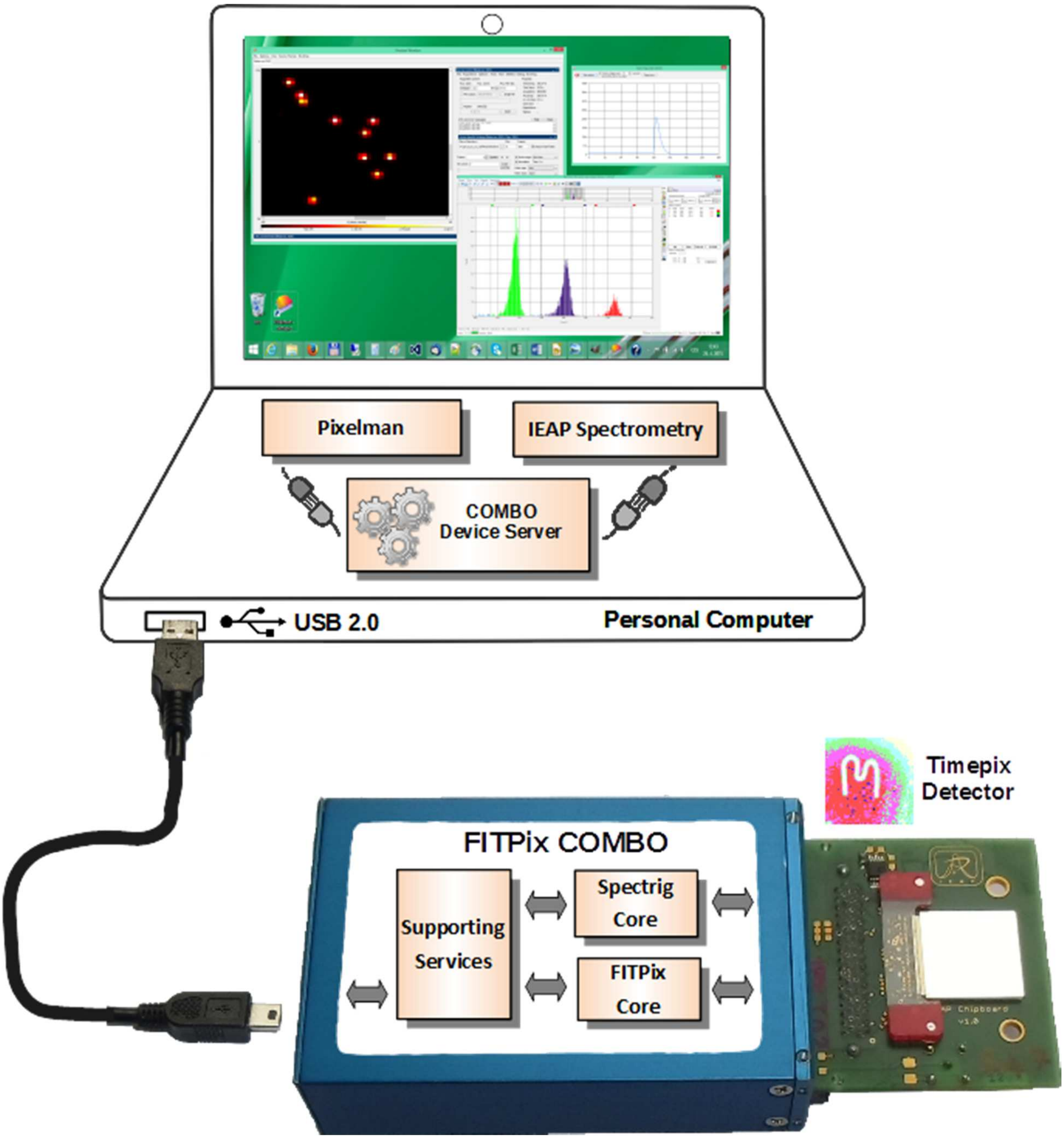


Figure 3-1 Concept of the merged platform. The presentation of the top level architecture that covers solution from the hardware level till the application software layer

In principal there are realized two independent acquisition channels. One channel involves back side pulse spectroscopy processing. It is correlated with the IEAP spectrometry DAQ application. The second channel involves the Timepix controlling and it is correlated with the Pixelman DAQ software package. Mutual cooperation of the merged device and heterogeneous applications is essential.

The merged device implements the Timepix control functionality as well as the spectroscopic functionality while both running in parallel without any blocking. Denomination of the new merged device was decided to be the “FITPix COMBO”. The name was derivate from the already well-known name of the read out interface “FITPix” and the fact that it is COMBined with the back side pulse processing.

The computer side application software controls operation of the merged device. More than one controlling application is considered. Parallel run of applications is enabled by presence of an additional server. It directly communicates with the device while it enables sharing between more endpoint applications over virtual channels.

3.3 Data correlation and synchronized operation

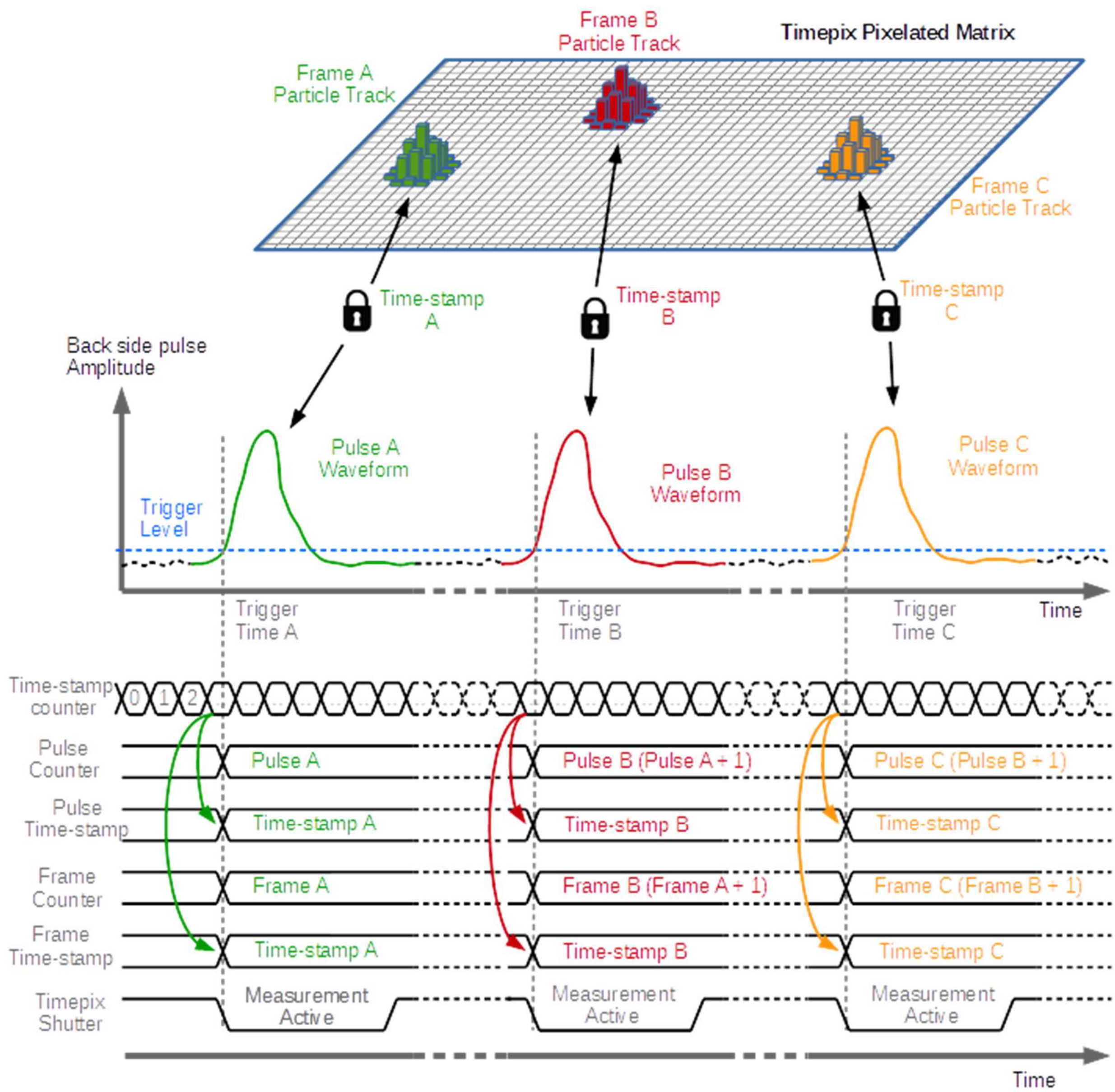


Figure 3-2 Solution for mutual correlation of spectroscopic events and Timepix frames

As it was mentioned (2.3) the tight correlation of the back side pulse signal and the Timepix frames is absolutely necessary. Therefore the following mechanism is introduced as a mean of the data correlation. The Figure 3-2 demonstrates how back side pulse events and Timepix frame events are locked together. The timestamp is assigned to each recorded event. The value of the timestamp that is tagged to a spectroscopic pulse event matches the value tagged to the Timepix frame event. The timestamp counter is linearly increased with the time-flow. Each recorded event can be distinguished by the unique timestamp afterwards. The figure contains three exemplar independent events recorded in the sequence A, B and C. The Timepix events are shown together in one frame to make a more transparent view. As it was mentioned the interaction of the particle A in a sensor will cause the event A. The event will be independently recorded as the Frame A on the side of the Timepix acquisition and it will be also recorded as the Pulse waveform on the side of the spectroscopy processing. The same timestamp A will be assigned to both partial records as the additional data field. In the same manner the reminding events B and C will be recorded afterwards. Once both channels (spectroscopy acquisition and the Timepix acquisition) assign timestamps to events all the saved records can be unambiguously identified while performing data post-processing. The timestamp mechanism can even reveal partial data drop-out when unpaired events are detected without its matching counterpart. However, one more mechanism was added for detection of the partial event drop-out. The free running event counter is added to both recording channels. Frames are counted in the Timepix acquisition part and pulses are counted in the spectroscopy acquisition channel. Each time the event is registered the event counter is increased about one. The value of the event counter is also tagged to the record as in the same way as the timestamp. The data post processing can simply reveal any event drop-out if a non-linearly increasing value of the event counter found is detected.

3.4 Utilization of the FITPix 3.x hardware platform

The FITPix 3.x base board was used as the part of the merged platform. The reuse of the already existing base board allows concentrating effort on the design of a new interface board and firmware. The potential functionality provided by the base board is well-fitting to the concept of the merged device. The Figure 3-3 shows relation between the base board, interface board and detector. The base board integrates all necessary digital circuits (FPGA, USB controller). There is no need to design a board that contains the same circuitry and that provides the same functionality. The base board can also provide sufficient powering for a new interface board.

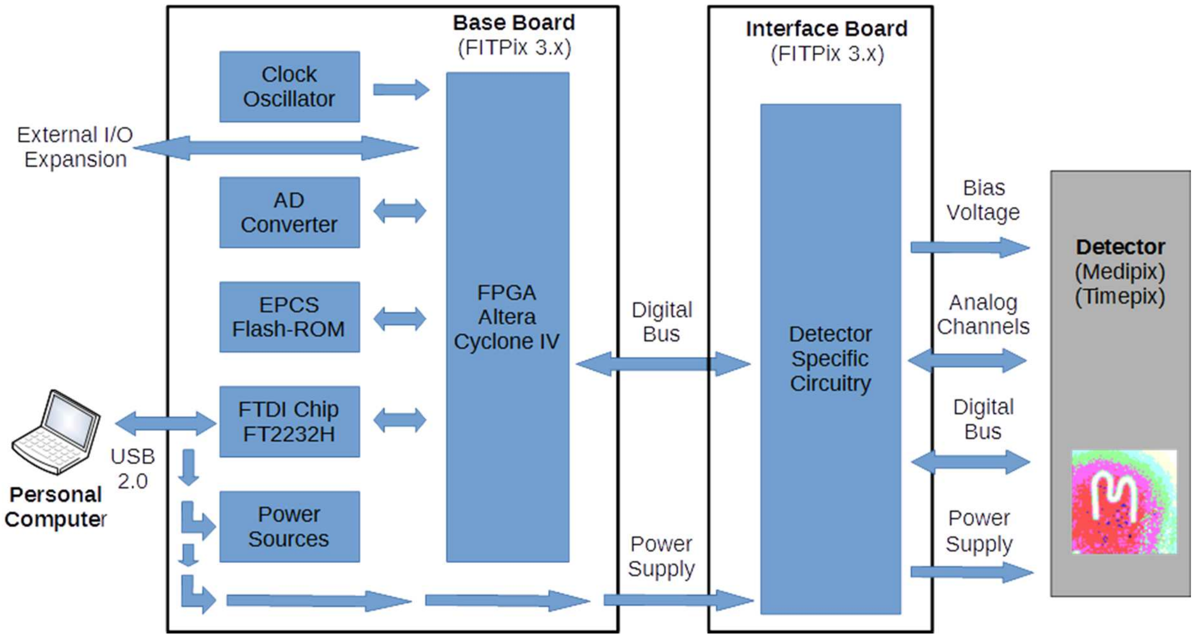


Figure 3-3 Relation between the FITPix 3.x base board and a generic interface board. Division of the functionality between both boards regarding to detector operation

3.5 Integration of the FITPix and Spectrig firmware

The previously introduced FITPix read-out interface device was designed to manage operation of the Timepix detector [16]. The FPGA firmware (using the VHDL programming language) has been developed several years. During the time all the necessary functionality (measurement control, data-read out, configuration etc.) was implemented. Similarly, the Spectrig device was designed as the tool for a spectroscopy signal processing

[17]. All the functionality is also implemented in the FPGA firmware. Both parts of the firmware are fundamental elements of the new merged platform. Unfortunately, they cannot be simply included and operated in the new architecture. The both were designed independently. The most of the implemented interfaces is device application specific and incompatible with each other. Significant demanding modification is mandatory for successful integration. A wrapper for the FITPix and Spectrig firmware has to be designed to allow to include it as a functional component. The Figure 2-5 shows architecture of the original FITPix device.

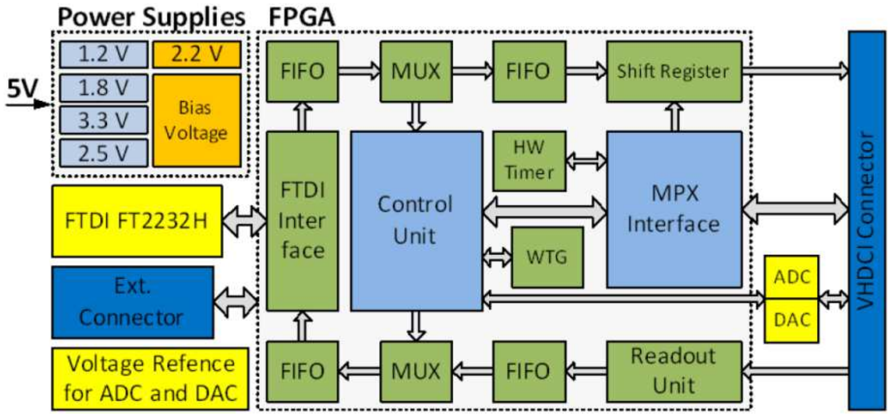


Figure 3-4 Presentation of the functionality implemented within the read-out interface FITPix 2.x

The Figure 3-5 and Figure 3-6 show architecture of the original Spectrig firmware. The left side block diagram stands for the top-level firmware architecture. The right side block diagram is detailed view of one partial block (Pulse recognition and pulse recording unit) of the top-level diagram.

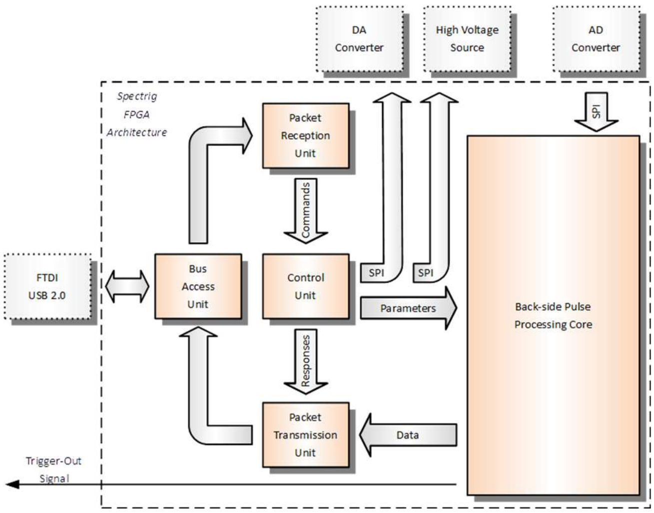


Figure 3-5 Presentation of the functionality implemented within the spectroscopic tool Spectrig (top level)

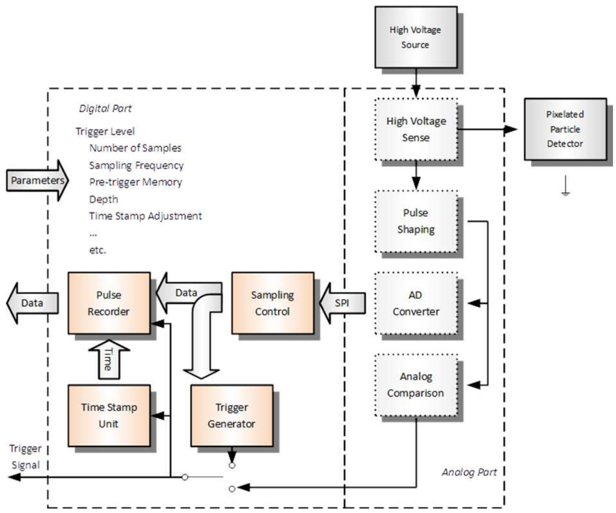


Figure 3-6 Presentation of the functionality implemented within the Spectroscopic tool Spectrig (Detail - Back side pulse processing)

3.6 Introduction of the server-client approach into the supporting software architecture

Integration of heterogeneous applications requires solution that would provide an environment for the non-blocking and non-restrictive run. Otherwise exclusive assignment of the device to one application would have to be done. Managed access to the shared device can significantly contribute to solve such restriction.

3.6.1 Direct access to the device

The Figure 3-7 represents a usual way of software support implementation on the side of a personal computer. There is considered just one device and one application accessing its resources. The access is done through the interface provided by the control library. The presented basic solution is fully sufficient in the cases when the whole device functionality should be managed by one high-level software tool (application). However, this approach is not suitable in all cases. When a device implements quite complex functionality it is almost impossible to ensure proper management by one user application. More software tools have to be involved to provide all the needed device management. The basic direct device access approach has to be modified. Software architecture has to be robust enough to allow parallel execution of all involved applications. The parallel resource sharing and collision resolving mechanism has to be implemented also.

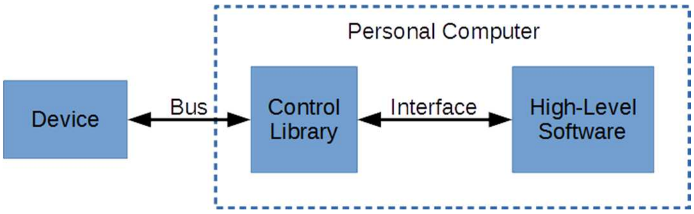


Figure 3-7 Approach of the direct access to a device

3.6.2 Sever managed access to the device

A more sophisticated way of the device access represents implementation based on the server/client mechanism (see the Figure 3-8). In principle just one server is necessary for numerous group of clients. The server provides a private communication channel for each connected client. The server accepts requests from clients and redirects them to the managed device that is connected over the shared bus. But communication with the device is fully transparent from the client point of view. The device resource sharing is becoming much easier due to the server-client approach.

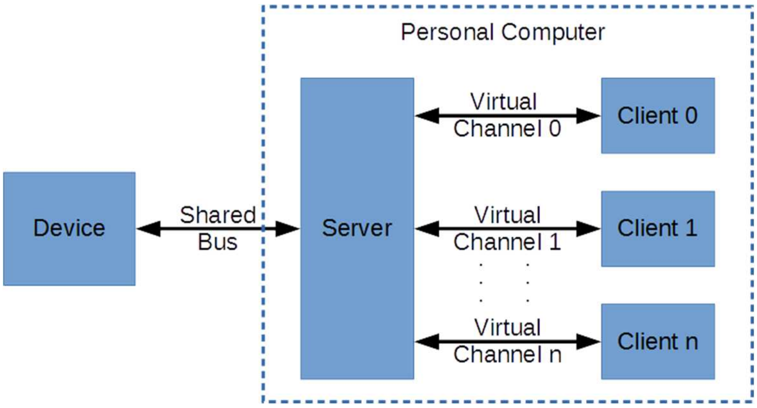


Figure 3-8 Approach of the indirect access to a device using a server/client principle

3.7 Separation of the solution into partial tasks

Realization of the previously presented solution can be divided into partial tasks. Each one can be solved almost separately while not affecting another. The following list summarizes all the tasks to be solved. The thesis structure is also arranged according to the list of the following partial tasks.

3.7.1 Interface board schematics design

Design of the schematics of the interface board has to be done while respecting all the previously discussed requirement on the device functionality. Components have to be selected according to the operating conditions (size, vacuum operation, power consumption).

3.7.2 Interface board PCB design

The printed circuit board of the new interface board has to be designed. It has to be fully compatible with already existing base board of the FITPix 3.x. Proper component placement is crucial for the maximal achievable device performance. The layout of the analog part of the spectroscopy chain is of great importance.

3.7.3 Optimal Tuning of the spectroscopy chain

It is not possible to predict Initial design of the spectroscopy. Modification of the parameters of the spectroscopy chain is expected. Source of distortion should be eliminated or suppress to level when resolution is not significantly affected.

3.7.4 Firmware design

The FPGA firmware architecture has to reflect integration of the Spectrig Core, used for back side pulse spectroscopy processing, and the FITPix Core, used for the Timepix management. Operation of both functional cores has to possible in a parallel run while not blocking each other. Sharing of common on board resources has to be solved. The firmware has to also integrate a management of the outer communication regarding to the software support on the personal computer side.

3.7.5 Supporting application software for personal computer

The software support on the personal computer side is essential for the device utilization. The user applications (Pixelman, IEAP Spectrometry...) cannot access device functionality without drivers. A separated run of independent user applications has to be solved as well. The suggested server implementation is a part of the software support.

4 Hardware design - New interface board

4.1 Interface board purpose

The parallel Interface board is designed to enable maximal exploitation of the Timepix detector performance. The Timepix chip is placed directly on the PCB of the interface board (It does not serve as a simple interconnection equipment of the FITPix 3.x as other previously designed interface boards do so). The board provides full support for Timepix function regarding to the power supply, data connection (serial as well as parallel bus), sensor biasing, and the spectroscopy processing of the back side pulse signal. Such a combination of features was never available before.

4.2 Spectroscopic signal chain

The block diagram in the Figure 4-1 shows signal propagation through the stages of the on-board implemented spectroscopic chain. Almost all the blocks are represented by the analog circuitry. The shaded FPGA block is placed on the base board (not a part of the interface board). Its presence in the drawing is just for completeness.

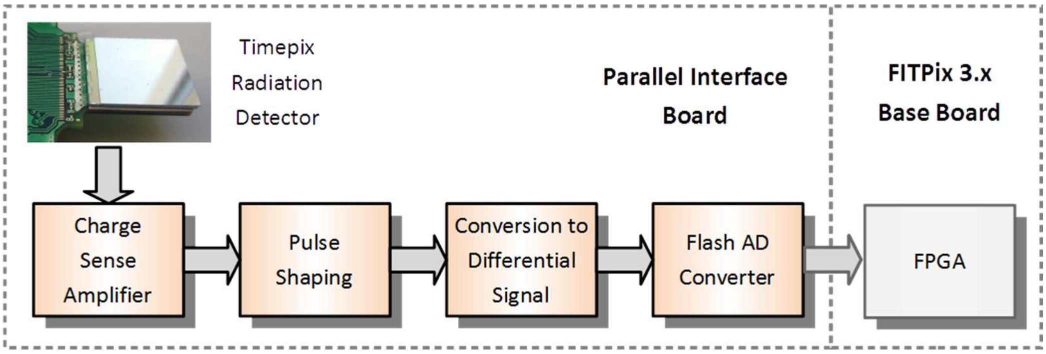


Figure 4-1 Spectroscopy signal processing chain – implementation done on the new interface board

4.2.1 Charge Sense Pre-Amplifier

It is the very first stage in the analog signal processing chain. The pre-amplifier receives a charge signal collected from the common electrode of the pixelated particle detector (also called the back side pulse signal). The input signal is AC coupled over the capacitor because the common detector electrode is connected to the high voltage potential. The amplifier connection is shown in the Figure 4-2.

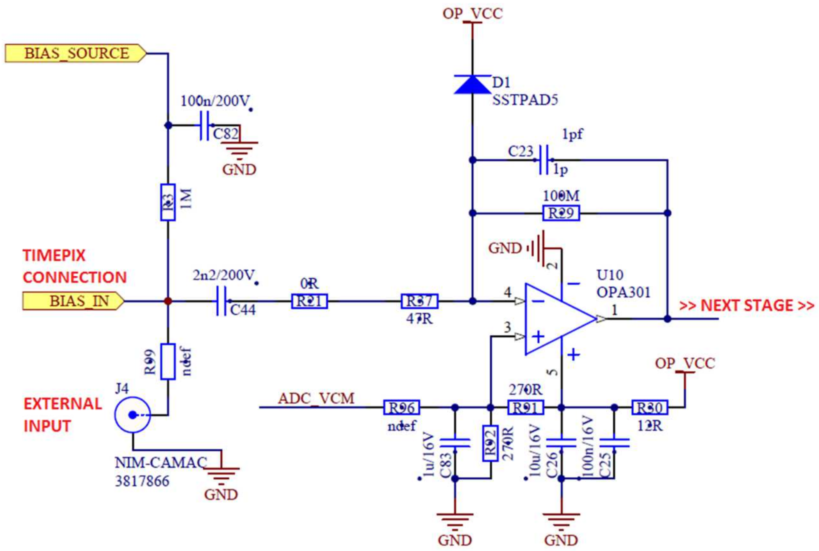


Figure 4-2 Charge sense amplifier and coupling of the back side pulse signal to the processing chain

The right placement of the charge sense pre-amplifier is of the great importance. The analog signal from the common electrode of the sensor proves very high vulnerability to noise distortion. The hi-impedance signal requires reduction of the path length to be as short as possible. Therefore the pre-amplifier circuit is placed directly under the detector on the bottom side of the PCB (top side is occupied by digital signal lines routed between the detector and the base board).

4.2.2 Differential Driver

The differential amplifier is essential for proper function of the flash AD converter. It performs signal conversion from the single-ended to the differential signal type. A next important function of the differential amplifier is to perform signal filtration. The spectroscopy signal has to be shaped. The surrounding network of the differential amplifier serves as a band pass filter. Due to the necessity of a differential signal the filter has to be implemented twice (once for the positive polarity branch, once for the negative polarity branch). Both branches have to be symmetric. See the Figure 4-3 showing connection of the differential amplifier. Exact tuning of the filter and shaping characteristics will be described later in the separate part 7.1.

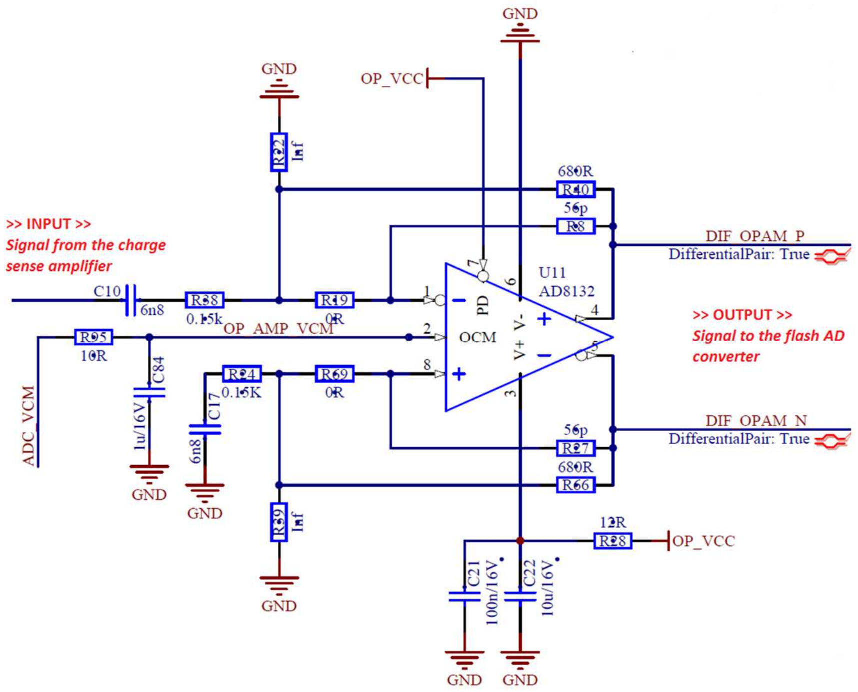


Figure 4-3 Signal filtration and conversion into differential signal output (driver for the flash AD converter)

A common level of the differential outputs has to be shift because a single channel power supply source is used. The output shift is done by the OCM (output common mode) that is a dedicated input of the differential amplifier. The output range of the differential amplifier has to be set in dependence on the flash ADC input range. Therefore the voltage range of the output spectroscopy signal is expected to be 1V (-0.5V to +0.5V around the common voltage ADC_VCM 1V).

4.2.3 Flash ADC

The interface board is equipped with the flash AD converter ADS6125 from TI. See the Figure 4-4 showing its connection. The converter allows sampling rate up to 120 MS/s. The interface board is designed and intended to be operated up to 100MHz (because of limitation on the side of the FPGA circuit). The converter has to be fed with the LVDS clock-in signal. The converter provides 12 bit parallel data, input overflow signalization and the clock-out signal. All converter outputs are operated as CMOS signals. The output data bus is synchronized with the clock-out signal. The separate SPI bus is used for configuration of the flash ADC operational parameters. Several parameters have to be set before the start of the conversion (Gain of the input signal, the operational mode, I/O gates settings and the output data format).

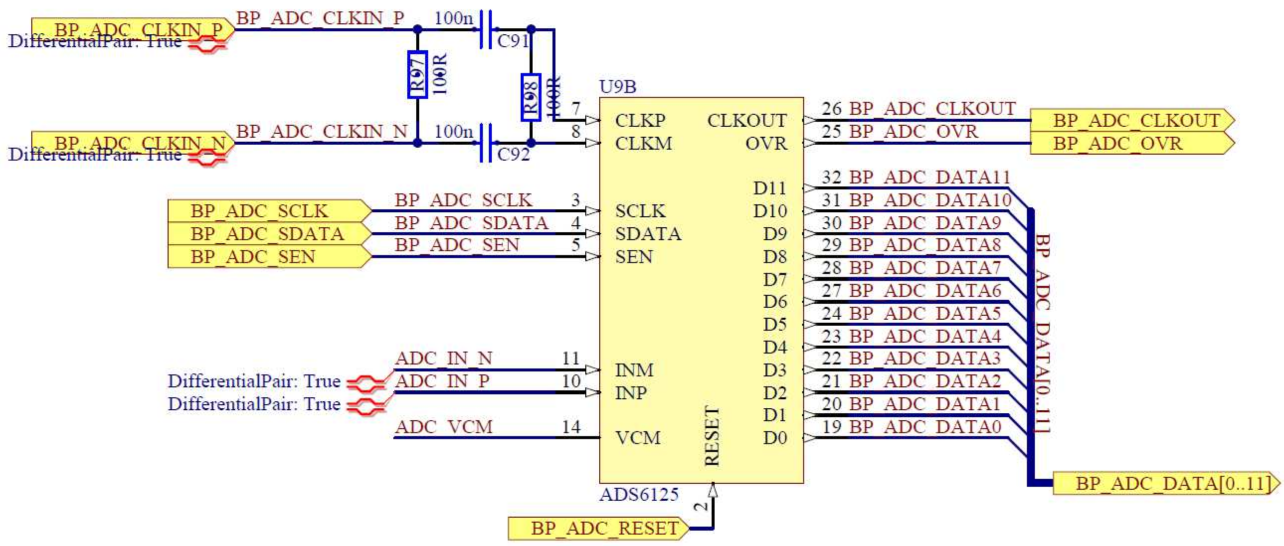


Figure 4-4 Flash AD converter connection

The flash ADC has to be fit with the termination network for the converted analogue signal. Configuration of the interface board termination network is shown in the Figure 4-5. It corresponds with the recommended configuration released in the device datasheet [30]. Aside to the main purpose of the impedance termination the network also provides a common offset to the input differential signal. The common level is given by the signal ADC_VCM. Its value is automatically driven by the flash ADC itself. Next function of the termination network is to make AC coupling between the flash ADC input and the rest of the signal processing chain. The AC coupling behaves as a low pass filter and it improves the signal-to-noise ration while it cuts-out a low frequency spectrum that does not contains any relevant information. It also provides self-stability against the DC offset originating in previous parts of the spectroscopy chain. But the AC coupling also brings a negative effect. The effective input signal range of the ADC is reduced to half (just eleven of twelve bits are used while considering that the negative polarity signal range is not used).

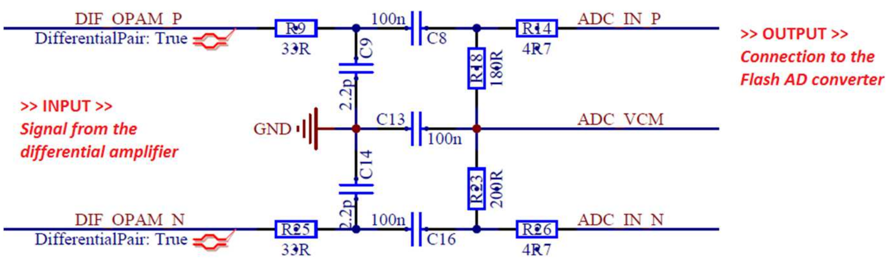


Figure 4-5 Differential signal termination network

4.3 Power management

The interface board is powered from the FITPix base board. The power is originally drained from the USB (as well as the base board does). The base board interconnects USB power lines to the interface board. It also provides 3.3 V for digital circuitry (like a Flash ROM, etc.). However, the parallel interface board needs more power sources than just these two for proper function of all on-board circuits. Therefore the interface board was equipped with several more power sources. For more details see the powering scheme in the Figure 4-6.

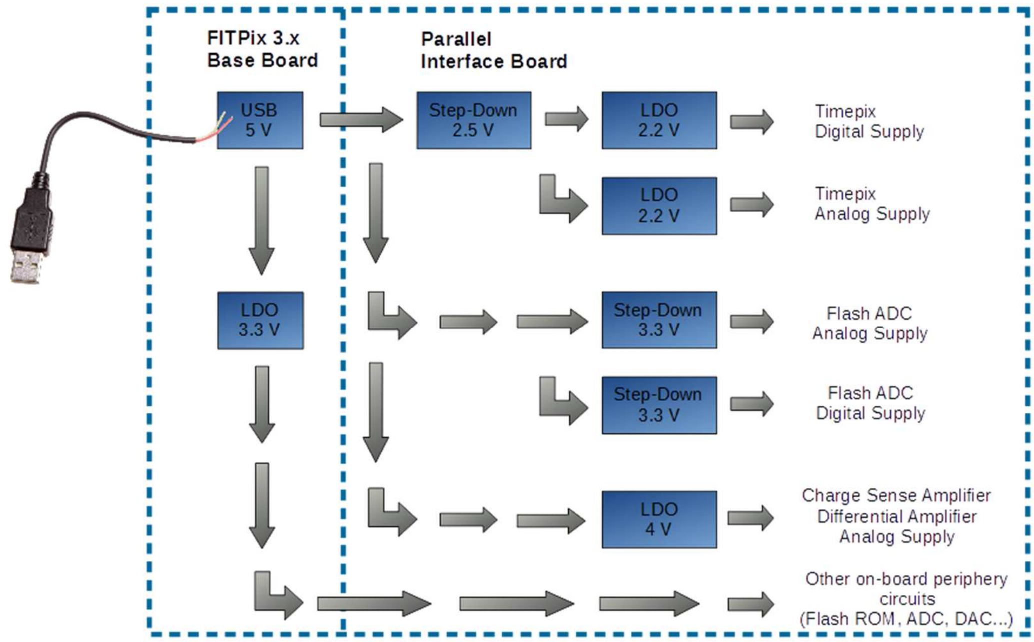


Figure 4-6 Timepix interface board powering scheme

4.3.1 Timepix detector power sources

Powering of the Timepix detector is done by the multi-stage power source. See the power source cascade in the Figure 4-7. The first stage is implemented as a step-down converter with 2.5 volts output. The switched regulator (NCP1599 from ON Semiconductor) is used because of efficiency and thermal power dissipation. The second stage is implemented as a LDO regulator (TPS74801 from TI). There are two LDO regulators with 2.2 V output. The analog part and the digital part of the detector is fitted with own separated regulator to decrease a mutual coupling. An influence of a potential drop in the digital part is avoided from introduction into the analog part.

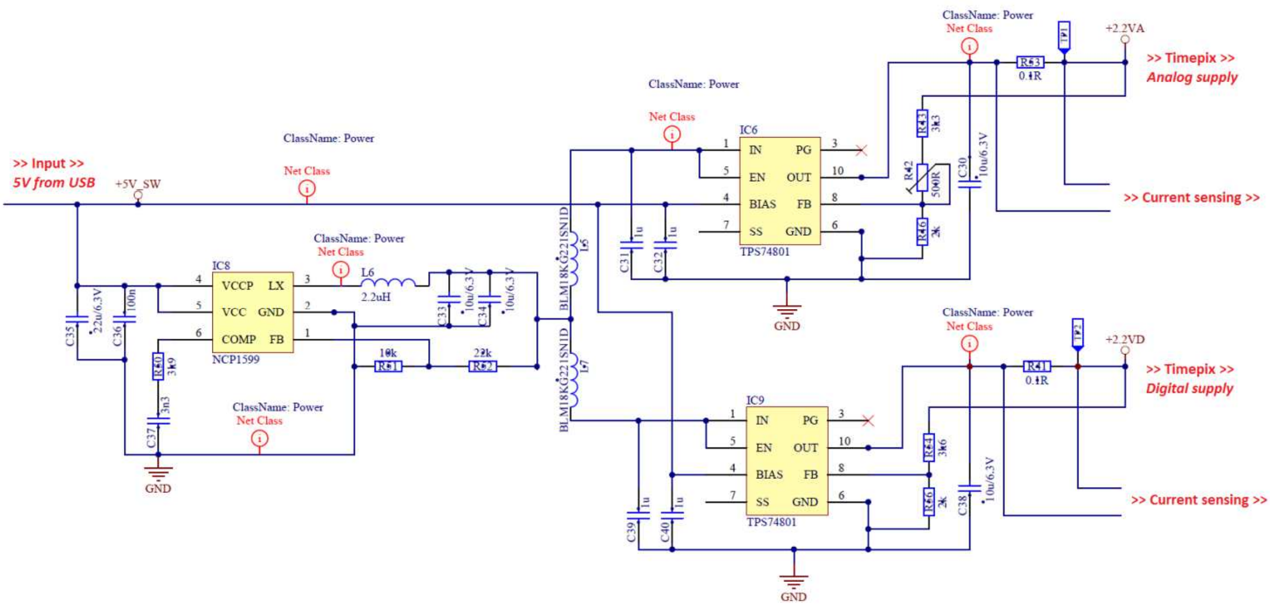


Figure 4-7 Powering of the Timepix detector (cascade of the sources)

4.3.2 Flash AD Converter power sources

The flash AD converter requires a separated power supply. The extra 3.3V power source is needed for the analog part and for the digital part. Both sources are based on the circuit TPS60500 from TI. It is a switched capacity step-down converter. The source of the analog supply is equipped with additional filtration on its output.

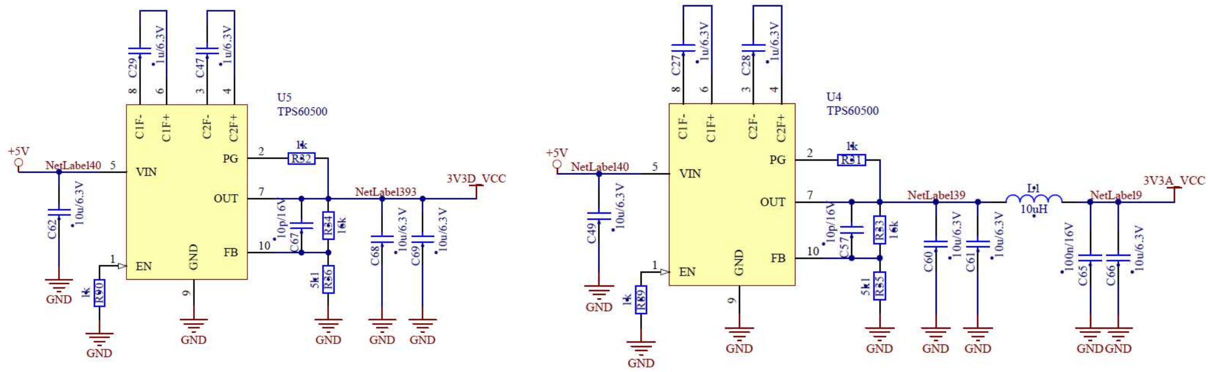


Figure 4-8 Powering of the Flash AD converter (Left side – 3.3 V source for the digital part, Right side – 3.3V source for the analog part)

4.3.3 Spectroscopy chain power source

Analog circuits within the spectroscopy signal pre-processing chain (the charge sense amplifier and the differential amplifier) are powered by the separated power source. It is implemented as a LDO regulator based on the circuit TPS77001 form TI. The output voltage is set to be 4.4V. The power source is equipped with additional filters to improve stability against introduction of the unintended interference.

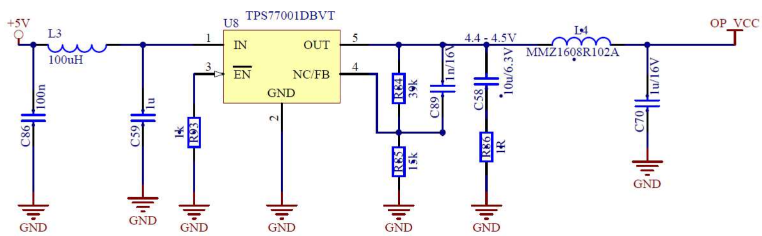


Figure 4-10 Powering of the components in the spectroscopy chain

4.3.4 Timepix power-off

The interface board power management possesses a local power-down capability. The CMOS transistor switch is implemented for switching on/off the powering of the Timepix detector (see the Figure 4-9). The main aim of the power-down functionality is to enable a safe and reliable restart of the Timepix. In some cases the restart done by the dedicated reset signal does not prove to be a sufficient mean of the detector restart. Not all registers of the Timepix are cleared when the reset signal is applied. When considering operation of the detector in a high-intensity radiation field the break-down caused by the single event effect is getting more probable. The power-down and power-up action is a reliable mean for the detector restart (more effective than application of the reset signal).

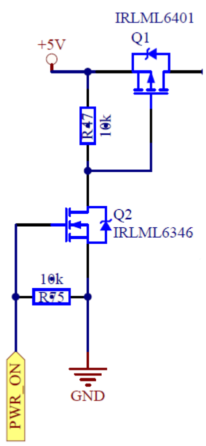


Figure 4-9 Timepix power switch

4.3.5 Voltage and current monitoring

The interface board is capable of the online monitoring of supply voltages and drained currents. Most of the supply channels is observable (as important are considered supply channels directly related to the detector). The monitored channels are described in the part 4.4.3 (related to the AD Converter).

4.4 Other on board peripheries

4.4.1 Bias Voltage Source

The board is fitted with the integrated 0 - 100 V bias source. See the Figure 4-11. It is implemented as an adjustable step-up converter based on the MAX1932 circuit. The source is fed from 5V input. The high voltage output is passed through the several stages of the passive RC filter. The Timepix detector is connected over 1 mega-ohm sensing resistor (not shown on schematic cut-out).

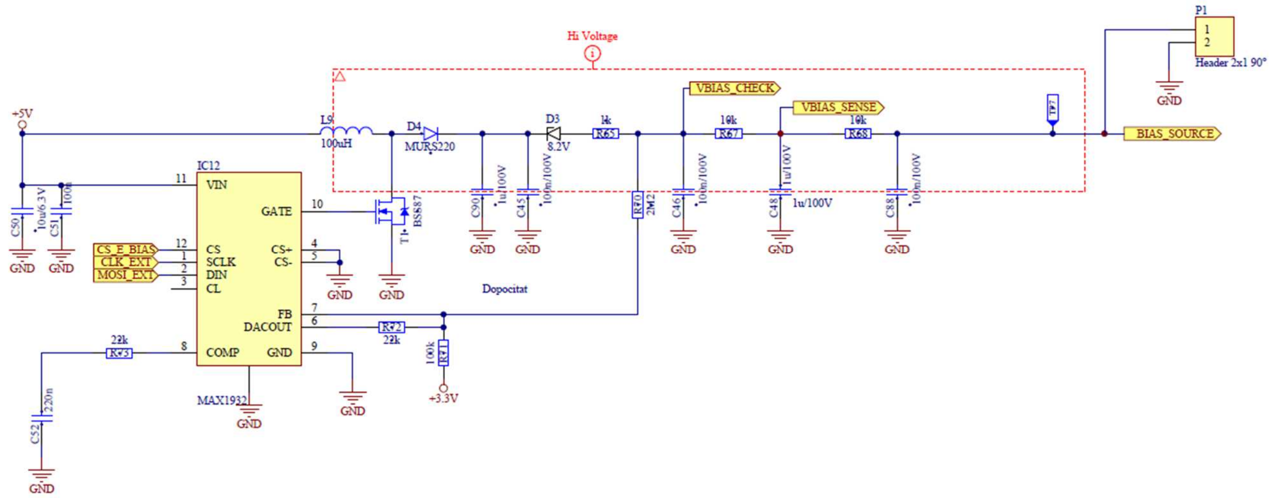


Figure 4-11 Bias voltage source circuit connection

4.4.2 DA Converter

The main purpose of the on-board DAC is to by-pass internal DACs of the Timepix detector. One of the internal DACs can be substituted by the external voltage source. The next purpose of the on-board DAC is generation of test-pulses for the Timepix detector. Two DACs channels are needed to generate test pulses. The TEST_IN signal is get by switching between two independent DAC channels (done by the CMOS switch TS5A3159). The exact circuit interconnection is shown in the Figure 4-12 below. The DAC7564 from TI was chosen as the appropriate DAC (4 channels, buffered output and SPI connection).

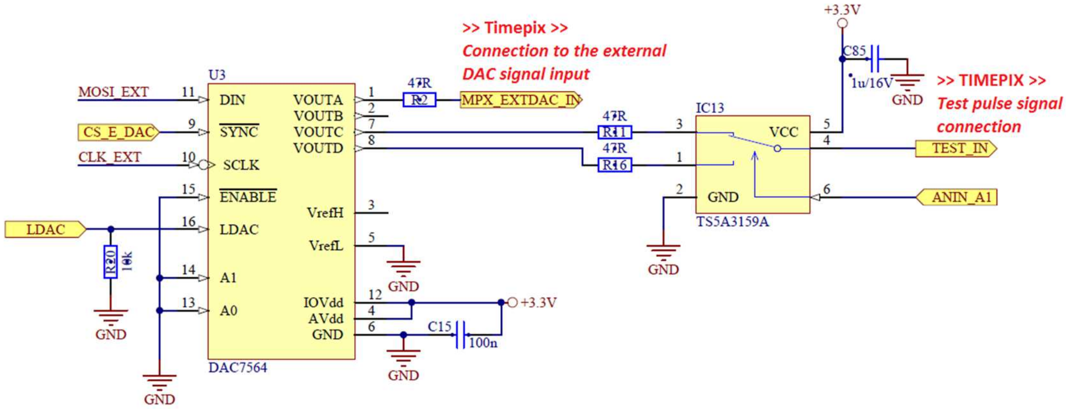


Figure 4-12 DA converter as a source for analog inputs of the Timepix detector

4.4.3 AD Converter

Main purpose of the on-board AD converter is to read analog outputs of the Timepix detector. The possibility of sensing of internal analogue signals (internal DACs) of the Timepix chip is important for verification of its function. The next purpose of the ADC periphery is to monitor supply channels. It enables functional on-line diagnostics of the read-out interface. The ADS7953 from TI was selected as a suitable converter (16 input channels, SPI connection and selectable input range). See the Figure 4-13 showing the ADC periphery connection. There are observed 6 voltage channels (detector 2.2 V analog and digital, 5 V USB, common 2.5 V and bias sensing) and 4 current channels (common 2.5V, detector 2.2 V analog and digital, 5 V USB).

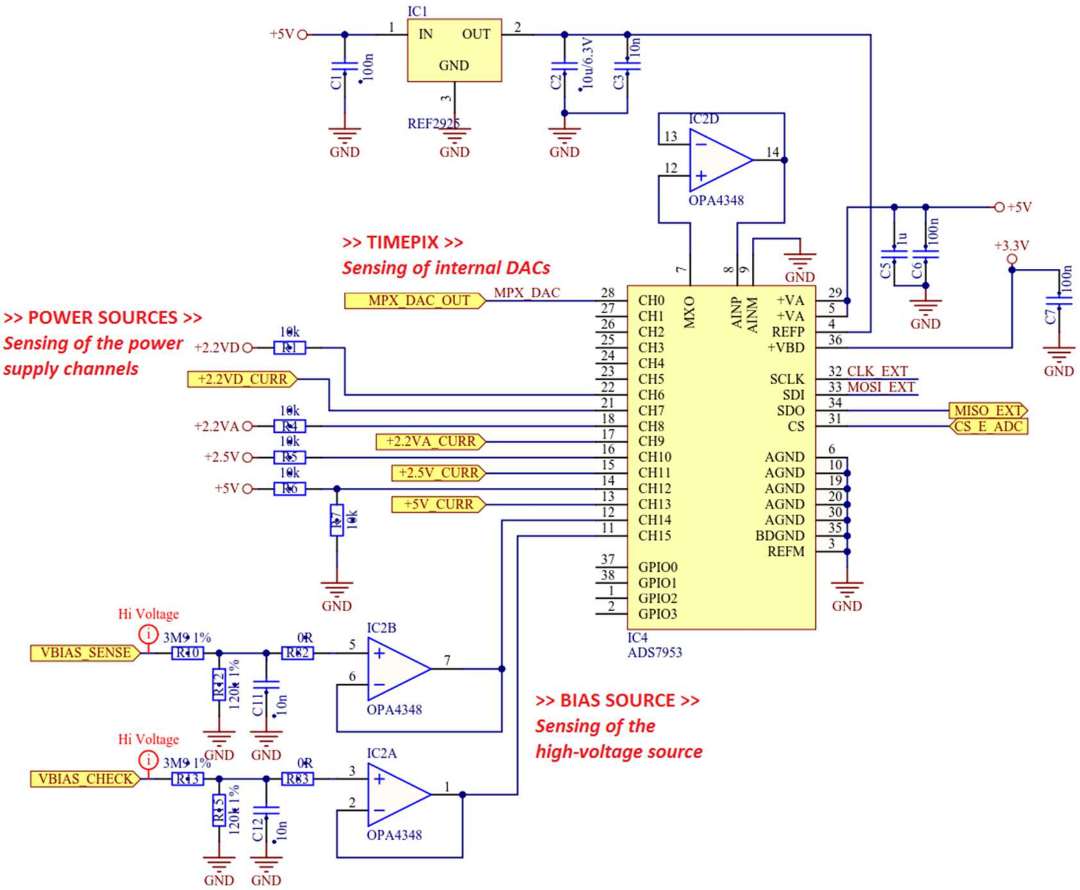


Figure 4-13 AD converter as a monitor of voltages and currents

4.4.4 Flash ROM

The purpose of the flash ROM memory is to contain calibration/configuration data related to the Timepix detector that is currently assembled on the interface board. The data would be available whenever a device is connected to a personal computer. The data can be downloaded and immediately applied.

4.5 Connectors

4.5.1 Altera Board interconnection

There is a set of connectors placed on the Altera base board that serves for connection of an interface board. Position and type of interconnection connectors was fully determined by Altera base board while designing the parallel interface board. There are used three HIROSE DF12 connectors (in variant of 50, 60, 20 pins). All digital signals and interface board powering is conducted through them. See the Figure 4-14, Figure 4-15 and Figure 4-16 showing a placement and detail of the connectors.

Figure 4-14 Interconnection – Side of the Base board

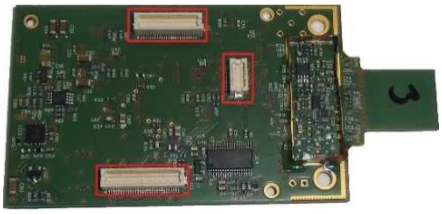


Figure 4-15 Interconnection – Side of the Interface board

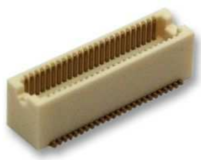


Figure 4-16 Detail of the Hirose connecter

4.5.2 External analog signal input

An external analog signal can be fed into the spectroscopic chain. When it is required the external signal is routed through the optional LEMO connector (by default it is not assembled, for detail see the Figure 4-17). Main purpose of the external input option is to enable testing of the signal chain response. In this case well defined test pulses (gained from the generator) are introduced into the spectroscopy chain input. The external signal input can be also used for connection of another radiation detector (not just the Timepix). The interface board serves as a pure spectrometer in this case (digital connection to the Timepix read-out chip is not used).

Figure 4-17 Detail of the PCB - External Signal input and external bias source input

4.5.3 External Bias source input

An external source of the bias voltage can be connected when it is needed. There is prepared position for the additional pin header (It is not assembled by default). When the external bias source is to be used the internal source has to be disabled (by disconnection). It can be done by dis-soldering of a resistor in the bias source RC filter.

4.5.4 Timepix bonding pads

The layout of the bonding pads was derived from the MX10 (see the introductory section 1.3.5) design of the Timepix chipboard done by Jablotron company. The layout of bonding pads is designed for connection of all Timepix I/O pins to allow parallel data reading. Previous read-out solutions supported just a serial data interface with the reduced number of used I/O signals. The parallel data read-out enables better exploitation of the Timepix detector performance.

Wire bonding of the Timepix chip on the interface board requires Au plating on the top Cu layer. Other PCB surfaces than Au do not allow right adhesion of the Au bonding wires. Before the chip boding is done the bonding pads have to be covered with a capton sticker to protect them from the surface contamination (Sn solder or impurities) that should happened during an assembling process of other electrical on-board components. The Figure 4-18 shows a bonding scheme and the Figure 4-19 contains a detailed view on the PCB prepared for the detector assembling process.

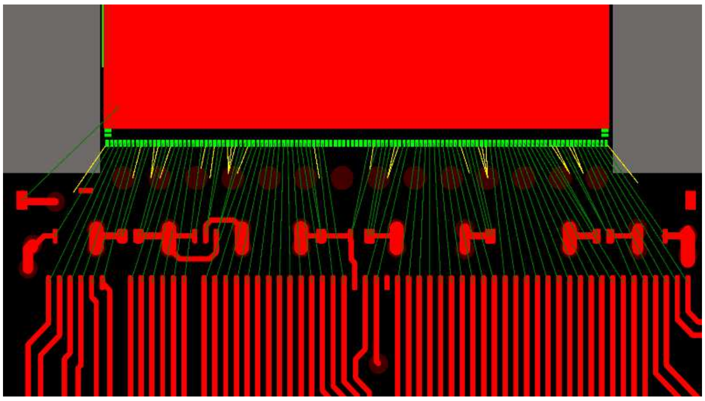


Figure 4-18 Timepix bonding scheme for the Parallel interface board

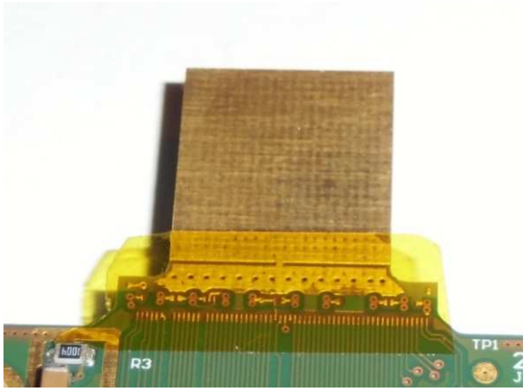


Figure 4-19 Detail view on the un-assembled interface board PCB

4.6 Electro-magnetic noise shielding

The interface board has to be fit with additional shielding to protect a sensitive amplifier from the noise introduction into the spectroscopic signal. The shielding is done as the Cu box soldered directly to the PCB surface. The extra surface layout was created (unmasked region with ground potential). See the Figure 4-20 and Figure 4-21 showing the opened and closed board shielding.

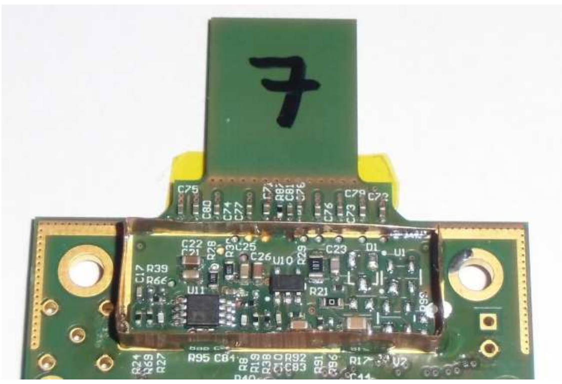


Figure 4-20 Shielding of the analog part of the spectroscopy chain - Opened Cu box

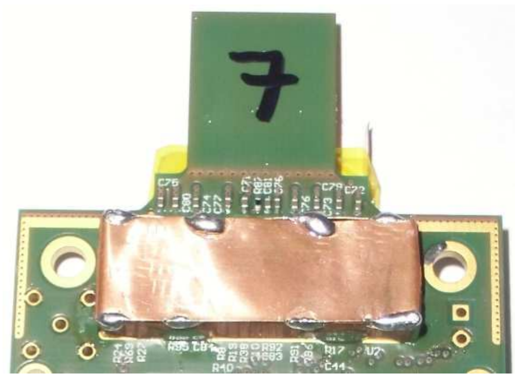


Figure 4-21 Shielding of the analog part of the spectroscopy chain - Closed Cu box

4.7 Heat management and cooling

There are several significant heat sources on the interface board. The Timepix detector and the flash AD converter are main contributors to the board warm-up. Cooling problematics gets even more crucial when the device is operated in vacuum. The effective surface of the device is too small to irradiate enough heat to let the device stay at the suitable operational temperature. Without any additional heat management the device should not be operated in the vacuum. When the detector is over-heated the significant deterioration of the measured signal is observable. The back side pulse signal gets useless at all (due to the increase of the detector leakage current the bias voltage falls down and proper charge collection is no more possible).

To avoid the over-heating issue the following temporary solution was done. A tailor made aluminum cooler was designed to be mounted on the interface board (See the Figure 4-22). Heat conduction is done through the bottom side of the detector. The heat flows from the detector to the PCB and then to the aluminum cooler. Besides heat conduction, the cooler serves as a mean of protection against a mechanical damage. The detector is embedded within the aluminum mass. Without any protection the detector is easy to be hindered by handling (bonding wires especially).

Figure 4-22 FITPix COMBO assembled with the additional aluminum cooler for the Timepix detector

4.8 Board shape and mechanical dimensions

Dimensions of the interface board were mainly determined by the already existing FITPix 3.x base board. They were partially derived from other previously created interface boards (serial interface board for Timepix, interface board for Medipix 3). There was one extra requirement put upon the PCB shape. The shape of the interface board shall allow making of the set-up of several devices to form a small multi-detector array. Possible arrangements of the multi-detector array are following - 2 x 2 or 4 x 1 (see the arrangement sketch in the Figure 4-23 and Figure 4-24).

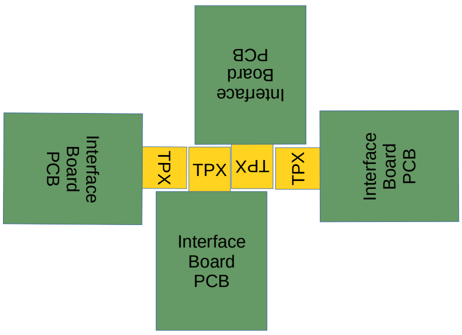


Figure 4-23 Line arrangement of the Parallel interface boards

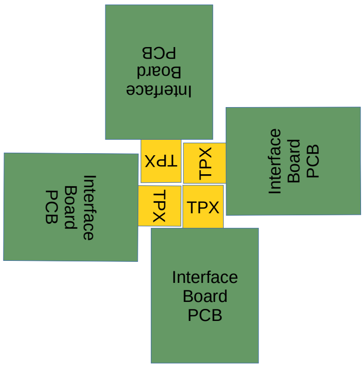


Figure 4-24 Square arrangement of the Parallel interface boards

Exact interface board dimensions are quoted in the mechanical drawings shown in the Figure 4-25. There are three 2 mm mounting holes to bind the interface board with the base board to form a sandwich. Other two 3 mm mounting holes serve for fastening of the device to the experiment set-up.

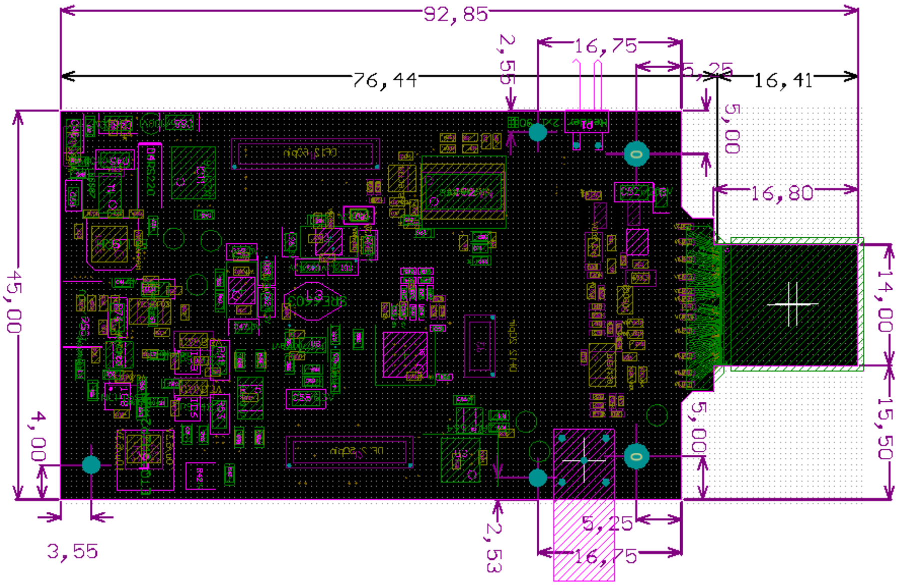


Figure 4-25 Mechanical drawing of the Parallel interface board

4.9 PCB composition

The interface board PCB consists of 8 metallic layers with 35 µm Cu thickness. The surface of the top layer is plated with Au to allow proper adhesion of bonding wires. Overall thickness of the PCB is 1.55 mm. The minimal track width is 0.1 mm and the minimal hole diameter is 0.2 mm. See the Figure 4-26 and Figure 4-27 displaying exemplar output from the Altium Designer software.

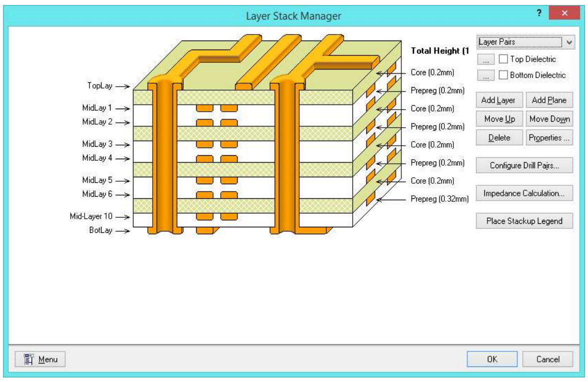


Figure 4-26 New interface board - PCB composition layer stack – output from the Altium Designer software

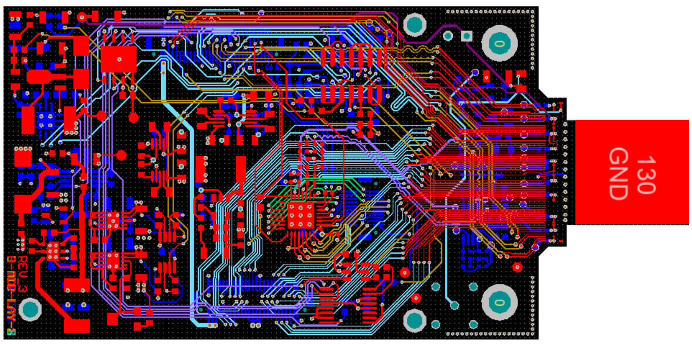


Figure 4-27 New interface board - PCB design - visualization of signal layers - Output from the Altium Designer

5 Design of the FITPix COMBO firmware

5.1 Over all architecture description

At the first glance the FITPix COMBO firmware can be divided into two basic layers. See the Figure 5-1 below. The bottom one is the layer of the common supporting services. The top one is the layer of user functional cores. Both layers are interconnected by unified interfaces. The Common supporting services are available and accessible for all the user cores when appropriate interfaces are implemented. Such a division significantly simplified a development of the user cores. A lot of functionality should be implemented just once within the common supporting layer. Duplicate implementation of the same functionality is avoided.

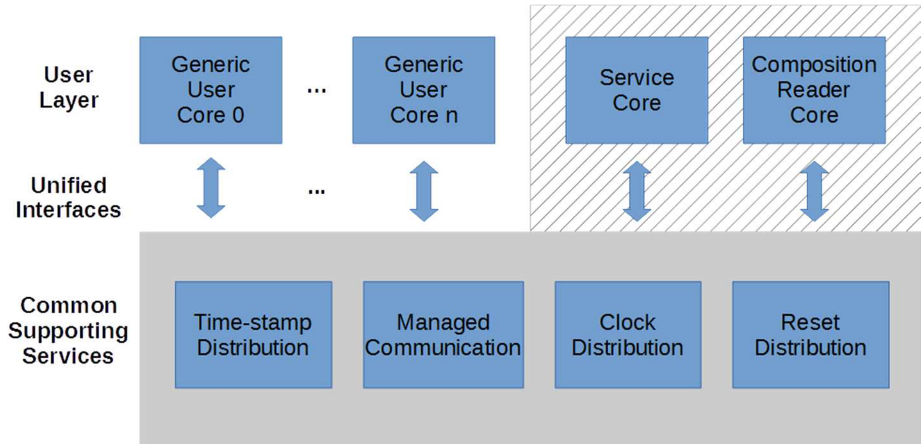


Figure 5-1 Layered structure of the FITPix COMBO firmware

Partial functionality of the Common supporting services layer was implemented by means of dedicated functional cores (Service Core and Composition reader Core). They are placed on the same level as other generic cores are. Dedicated cores are implemented in the same way as other generic cores. Their cohesion is with common supporting layer is marked with by hatched area. Together they form basic frame of the COMBO device firmware.

5.1.1 Firmware content

Exact composition (including all user cores) of the FITPix COMBO device firmware can be seen in the Figure 5-2. There is also marked relationship between outer circuits/peripheries and cores implemented in the FPGA. Function and purpose of each functional block will be described further separately.

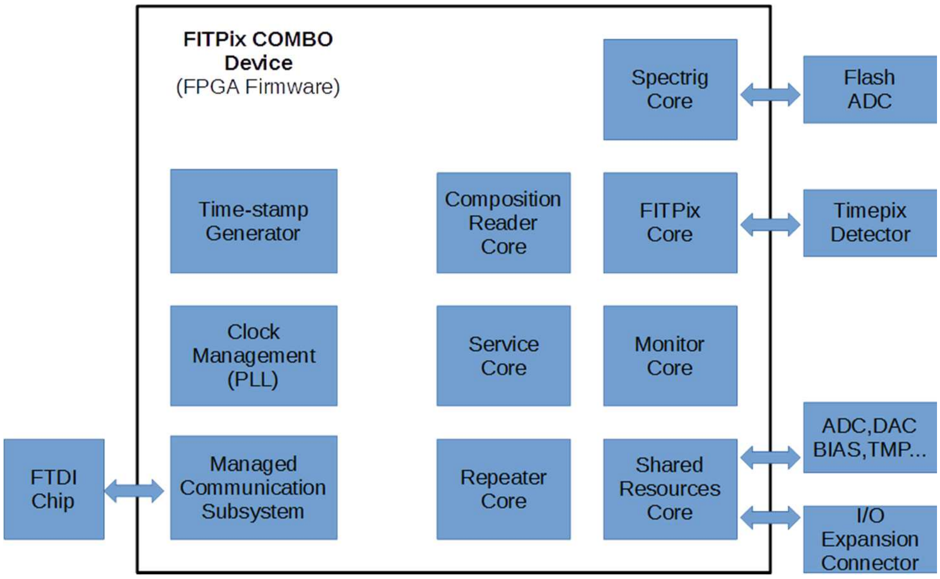


Figure 5-2 Content of the FITPix COMBO firmware (with marked relation to external components)

5.1.2 Core oriented design

The design of the COMBO device is constituted mainly of individual core modules. Each core represents a block implementing specific functionality according to its purpose. An effort was put upon minimal coupling and maximal mutual module independence. However, still some necessary inter-connections between separated cores have to remain.

5.1.3 Utilization of unified interfaces

To simplify a design of the COMBO architecture and subsequent implementation there was defined a set of unified interfaces. The Figure 5-3 below serves as an insight on types of interfaces of a generic user core in the COMBO design. Some unified interfaces are obligate to implement for each particular user core. They are essential for proper operation. Some unified interfaces are optional for implementation. A user core can be operated without them. The rest of presented core interfaces does not belong into any category of unified interfaces. They are entirely core specific. They indisputably depend on a purpose of a particular user core.

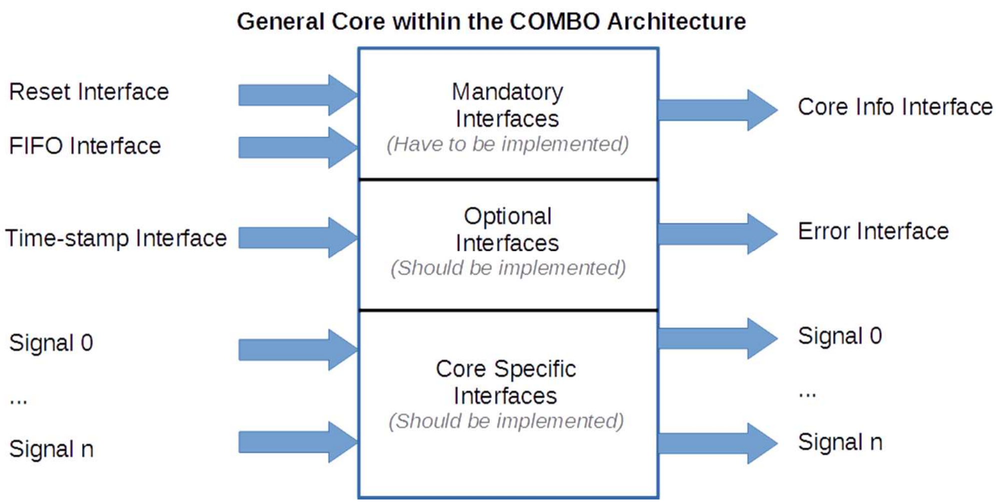


Figure 5-3 Unified interfaces defined for user cores that are present in the FITPix COMBO firmware

- **Reset Interface**
  It serves for distribution of the reset signal. Global an local reset signal are provide through the interface
- **Core Info Interface**
  It serves for handling of the build information about core. Detailed description of the interface is to be found in section [link to composition reader core].
- **Error Interface**
  It is used for signalization of the core functional state. Errors, events, failures, debug and trace information are reported through this interface [Link to service core].
- **Unified FIFO Interface**
  It serves for handling of the ingoing/outgoing data between virtual device and multichannel receiver/transmitter unit. [Link to multichannel receiver/transmitter].
- **Time-stamp Interface**
  It is used for synchronization of operation among individual cores in the design. Information about current time is transferred over this interface. [Link to time-stamp description]
- **Other Interfaces**
  There are core specific interfaces. Their description is to be found in sections that are related partial cores.

5.1.4 Virtual Channel Ideology

User cores within the COMBO device communicate over virtual channels with an outstanding software driver (on the side of a personal computer). Just one common communication bus is used for data transfer of all virtual channels/devices. The bus transfer capacity is equally divided among virtual devices. The virtualization approach was used to simplify a development of individual user cores. From their point of view a data transfer seems to be fully straightforward. No extra functionality has to be implemented on their side to access a shared bus. They do not have to recognize incoming packets and to create outgoing packets transferred within a common data stream. All that is done by managed communication services.

5.2 Managed Communication Subsystem

The managed communication subsystem provides virtual channels for user cores. They are accessible through FIFO interfaces (one interface for incoming data – receiver side, one interface for outgoing data – transmitter part). The Figure 5-4bellow presents a structure of the Managed communication subsystem. It consists of three main parts. Their implementation will be described later in separated sub-sections.

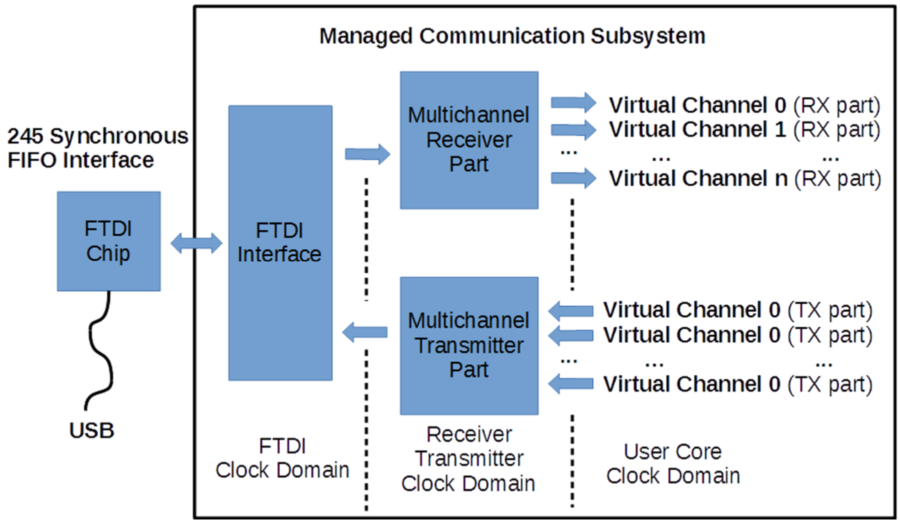


Figure 5-4 Architecture of the Managed communication subsystem

5.2.1 FTDI Interface

It is an interfacing block that serves as a driver for bi-directional communication with the FTDI chip (externally connected to the FPGA). It handles a transfer of raw data from/to the FTDI chip. It separates a bi-directional FTDI data stream into 2 one-way streams (reception/transition branch). The FTDI interface block is operated in a different clock domain (synchronous to the FTDI 60 MHz clock). Re-synchronization with the rest of the managed communication entity is done by means of the dual clock FIFO.

5.2.2 Multichannel Receiver

It receives raw data gained from the FTDI interface. The COMBO packet structure is recognized by the receiver. If a structure of the ingoing data is unknown then the data are ignored. If the packet structure is found then a payload data extraction process is done. In dependence on the virtual channel index (gained from the packet header) the payload data are routed into the appropriate virtual channel (RX part). If non-existing channel index is detected the payload data cannot be routed and it will be lost.

5.2.3 Multichannel Transmitter

It monitors all virtual channels (TX part) connected to user cores. When a pending data transmit request is registered it initiates transmission of user core data. A new COMBO packet is built-up by the transmitter. The COMBO packet serves as an envelope for virtual channel data. The user core data stream is placed into the position of the payload field of the packet frame. Further, the completed packet is handed to the FTDI Interface block.

5.2.4 Common bus access priority

All virtual channels are equal in term of access rights for outer communication. None of user cores requires a prioritized access. An unpredictable transmission delay would be a result if priority levels are assigned to virtual channels. Therefore the priority access approach was abandoned. A fully deterministic approach for a common bus access was chosen instead. Virtual channels are periodically pooled if they possess some data to be transferred. Each channel is allowed to transfer data only once per a pooling cycle. It grants almost the same maximal response delay for each virtual channel. (In the case of the strictly priority driven access an unpredictable blocking of the common bus would be caused if some user core continuously sends data).

5.2.5 Packet like transmission

Transmission of virtual channel data is done on basis of packets. Raw data of individual user cores are enveloped by COMBO packets. The data stream is divided into smaller chunks. See the Figure 5-5 below. There is shown a principle of the user core data stream enveloping. The Communication subsystem handles data packeting and de-packeting operations automatically. Virtual channels is transparent for user cores.

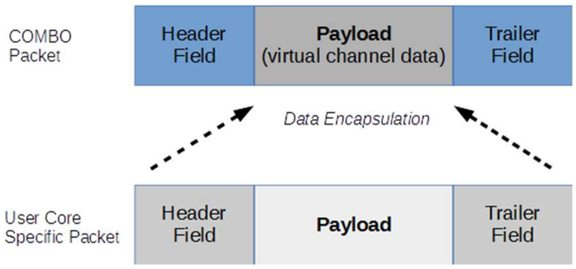


Figure 5-5 Data encapsulation principle

5.2.6 Packet format

The packets used on the reception and transmission side are of the same format. The COMBO packet is initiated with the constant start byte. Then 2 byte field, containing pay-load length information, follows. By definition a size of the payload can vary between 0 to 65536 bytes. However, a size of several kB is reasonable (depending on the limited size of memory buffers within the FPGA). After the payload length field the byte containing channel identification is sent. It allows distinguishing between virtual channels. (The maximal number of virtual channels is up to 256). Then the pay-load data stream follows. The number of payload stream bytes matches the value previously issued on the position of the payload length information field (already described in the packet header part). The packet is ended with the constant stop byte.

Field Meaning	Start Byte	Data Length	Channel Index	Payload	Stop Byte
Number of Bytes	[1B]	[2B]	[1B]	[0 – 65535]	[1B]

Figure 5-6 Packet format used by the Managed communication subsystem

5.3 Clock Management

Most of the functional cores are expected to be operated in the mutually different clock domains. Requirements on the count of clock channels and their frequencies differ core by core. Specific requirements mainly originate from a unique core purpose. It is almost impossible to connect all the cores to the same (common) clock signal and to preserve a full functionality of the entire device. Such a compromise would significantly hinder a resulting performance.

5.3.1 Clock distribution

The COMBO firmware design requires distribution of the separated clock signals to user cores. The distribution of clock signals is provided by the Quartus [29] generated IP core (see the Figure 5-7). It allows proper usage of the on-chip PLL module. The PLL module is configured to be operated in the static mode (constant frequencies). No possibility to change clock signal parameters on the fly is allowed. PLL clock outputs provide constant frequencies during whole device run.

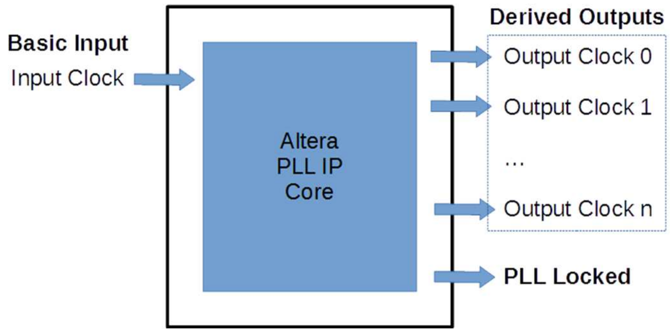


Figure 5-7 PLL IP core used for clock distribution

5.3.2 Basic clock source

A stable (as required in Altera cyclone specification [28]) crystal oscillator is expected to be a source of the basic input clock for the Altera PLL core.

5.3.3 Clock domains

The multi clock domain issue has to be taken into account as parts of the COMBO device design run at different clocks. The signals passed between different clock domains have to be resynchronized before usage. Otherwise when neglected the metastability would be induced and the entire system failure should be a result.

5.4 Timestamp Generator

A real time measurement requires appropriate means for synchronization of the impendent user cores. Information about a time is quite valuable for post processing of the measured data. Precision of the time synchronization is also of great importance. Time resolution provided by a personal computer is useless when considering a physical experiment background. Because of it the tailor made solution was implemented directly on the firmware layer. Achievable resolution is straightly dependent on the frequency of a clock signal which is used for driving of the timestamp generator logics (in order of several periods of the clock signal)

5.4.1 Purpose of time-stamps

The common Timestamp generator distributes timestamps to all user cores within the COMBO firmware. See the Figure 5-8 showing the Timestamp generator architecture. The central distribution ensures that the time information will be tightly correlated in all cores. It also simplifies a design of individual user cores. The timestamp generation design is done once only. A user core does not have to implement its own timestamp solution. Only the necessary presumption is that the common Timestamp Interface is supported by a user core.

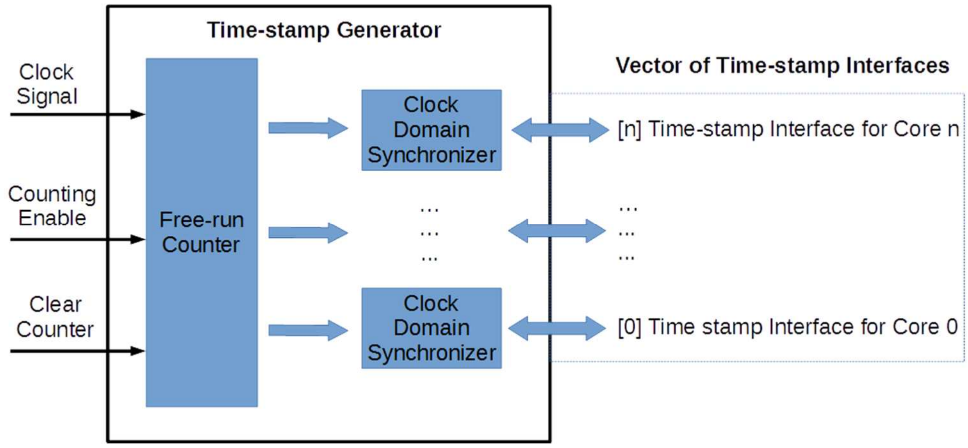


Figure 5-8 Architecture of the Time-stamp generator block

5.4.2 Principle of time-stamp generation

The relative system time is defined as a number of ticks counted by the free-run counter. The timestamp counter starts counting just after a device power-up. By default, zero is the initial value. A current counter value is further distributed to user cores. It is assumed that a user core and the Time-stamp generator are operated in the different clock domains. Because of it each output channel is equipped by the Clock domain synchronizer unit. It manages safe transition of a time-stamp value from the Time-stamp generator clock domain to the user core clock domain. Synchronization is done by means of the dual clock FIFO memory.

5.4.3 Timestamp Interface description

The Timestamp interface consists of two components. The first one is 48 bit long vector representing a current value of the timestamp counter. The second component is a (user domain) clock signal used for timestamp synchronization. A user core has to provide this clock signal. The Timestamp generator synchronizes the timestamp vector to the user clock domain.

5.5 Reset Signal Distribution

The block diagram in the Figure 5-9 presents a scheme of the reset signal distribution in the COMBO device firmware. There are shown sources of the global reset (power-up and PLL locked) and source of the local resets (Service Core) for partial user cores.

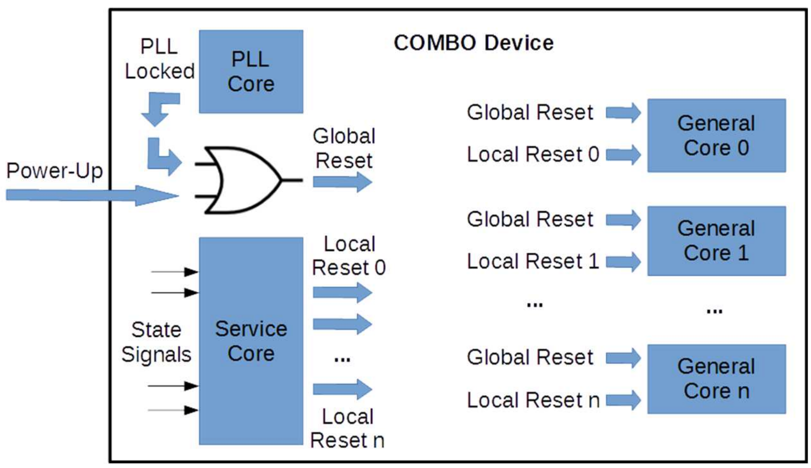


Figure 5-9 Reset signal distribution scheme

5.5.1 Power-up

A device is not able to run properly during the power-up phase. The system has to be kept in the reset state till the power-up transition is finished. Thus the outer signal is used as a source of the global reset.

5.5.2 PLL locked

It is not possible to operate a device while clock signals are not stable. Otherwise a system failure should be a direct consequence. The PLL Core that is used as a system clock source provides an extra signal informing about the lock state of phase locked loop circuit. The lock state signal is used for generation of the global reset signal.

5.5.3 Global Resetting

The entire device is restarted when the global reset is applied. It affects all parts of the architecture. There are two sources that can generate the global reset signal. One reset source is a device power-up. The second one is the PLL lock state signal generated by the PLL IP core.

5.5.4 Local Resetting

The partial core reset implementation is also needed in the COMBO device design. Local resetting enables independent operation of individual functional cores. Thus the design is divided into several separated reset domains. Each core is located within own reset domain. It allows core independent function (without relation on the other cores running in parallel). In the case of a partial dead-lock the affected non-properly-running core can be restarted. Only a partial reset is generated while a reminder of the system keeps on normal operation. A source of the local reset is the Service core (described more in detail in chapter xxx). It supervises other parts of the device. According to the system state it generates local reset signals.

5.6 Composition reader Core

The Composition reader Core is an essential part of the COMBO firmware architecture. It provides overall descriptive information about individual user cores assembled in the firmware. All the provided composition information is static in the time of the descriptor read-out. Just constants are handled through the dedicated Core info interface (descriptive data are defined before the firmware synthesis). No status like information can be obtained by means of the Composition reader core.

5.6.1 Architecture of the Composition reader Core

The core design is quite simple in a term of the implemented functionality. Integrated modules and interfaces are shown in the Figure 5-10. The core is composed of the Command reception unit, the Control unit and the Enpacketing block. Core communication is done over the virtual channel represented by the unified FIFO interface. The Composition reader Core is a receiver of the composition information. A vector of the Core Info Interfaces is connected on its input. Individual items of the vector are gained from other functional cores in the design. The Composition reader possesses ability to read own descriptive information as well. There is implemented a feedback for own descriptor to simplify a read-out process (then all vector items can be treated in the same manner).

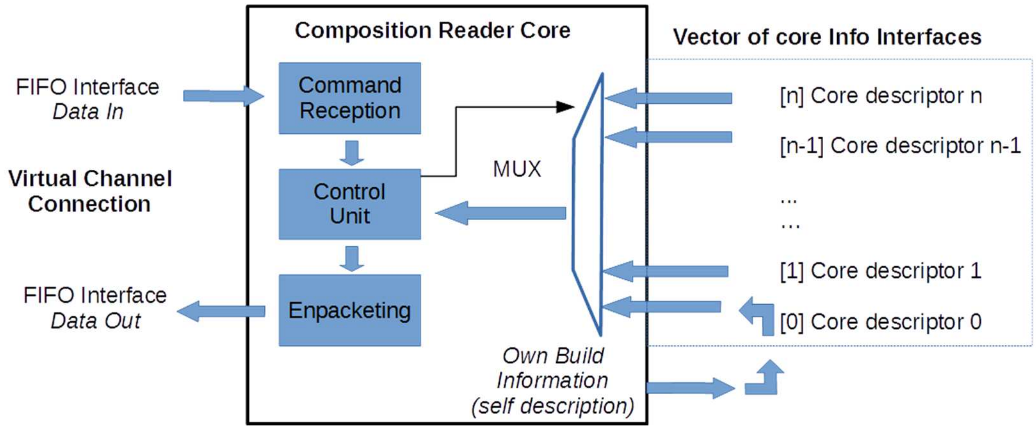


Figure 5-10 Architecture of the Composition reader Core

5.6.2 Function Description

When an appropriate command is received then a process of the composition read-out is initiated. The descriptive data that are provided by external cores are sequentially read by the Control unit. Core descriptors are read one by one. The Control unit forms one long data stream containing all the descriptive information. The descriptive stream is enveloped into the packet frame as payload by the Enpacketing block.

5.6.3 Firmware build information

As it has been mentioned above the Composition Reader Core serves as a source of the firmware build information. Detailed descriptive information about individual cores that are embedded within the COMBO device can be read-out. Also information about the COMBO device architectural structure is to be obtained (location/address in order of virtual device channels is gained along the core descriptive information).

It is up-to each user core to provide meaningful descriptive information. No validation of the content could be done during the firmware synthesis or on the side of the Composition reader core itself. It just passes raw data without any modification. Items that are handled over interface are described more in detail in the following part.

5.6.4 Core Info Interface - description

Each core within the COMBO device shall implement the Core Info Interface. It is dedicated to carry build information. It is implemented in the form of constant signal ports (not to be changed during the device run state). The Core Info interface consists of following data components.

- **Build version – Major**
  The major part of the core firmware version information (8 bit vector size)
- **Build version – Minor**
  The minor part of the core firmware version information (8 bit vector size)
- **Build Flags**
  Informative flags describing purpose of the given user core and which unified interfaces are implemented (e.g. release build, debug build, extension descriptor implemented, implements error interface …)
- **Build year**
  The year when the core firmware was designed (11 bit vector size)
- **Build month**

The month when the core firmware was designed (4 bit vector size)

- **Build day**
  The day when the core firmware was designed (5 bits vector size)
- **Build hour**
  The hour when the core firmware was designed (5 bits vector size)
- **Build text label**
  The ASCII string containing name of the core (16 bytes array)
- **Build extension**
  The extra byte array dedicated to be a container for core specific information. Meaning of the content depends up to each core. Exact meaning and description is to be find in the documentation of the individual cores (32 bytes array)

5.6.5 Location of the core in the firmware

The Composition reader Core is defined as omnipresent in any COMBO device firmware configuration. It has to be always connected to the virtual channel with the index zero. The constant mapping of the Composition Reader Core to the same virtual channel is very important. Zero index configuration allows to encounter all necessary system information still at the same location. An out-standing user would easily connect to the Composition reader Core and the composition information will be gained from the same endpoint of the COMBO device. No sophisticated algorithm is needed for a device scan when an initialization phase is to be done. (Otherwise iterative connection/communication/disconnection approach would be needed on the side of the user till composition reader core is found)

5.6.6 Implemented commands

- **Get version of the info stream format**
  The command is used to get version of the composition info stream format. It is implemented to allow checking of version compatibility by application software.
- **Read composition info steam**
  The command starts a read-out of the composition info stream. Descriptors of all user cores will be read-out at once.

5.7 Service Core

The Service Core should be found as an out-standing unit. It performs supervising over other independent user cores that are running in parallel. The Service Core also provides state information about other cores (data traffic monitoring, error event monitoring). The core is dedicated to perform automatic maintenance of proper function of the device. Restart and recovery action is performed by the Service Core to make device working once more in the case of the dead-lock event.

5.7.1 Architecture of the Service Core

The Service Core can be divided into several main parts (see the core architecture in the Figure 5-11). One part consists of functional blocks implementing outer communication that is done over the unified FIFO interface (Command reception block and Enpacketing block). A next part is the Control unit. It executes incoming commands and it provides settings and parameters for the entire core. The last and the most important part is a group of blocks implementing supervising services (Event capture unit, State monitoring and Data flow monitoring blocks).

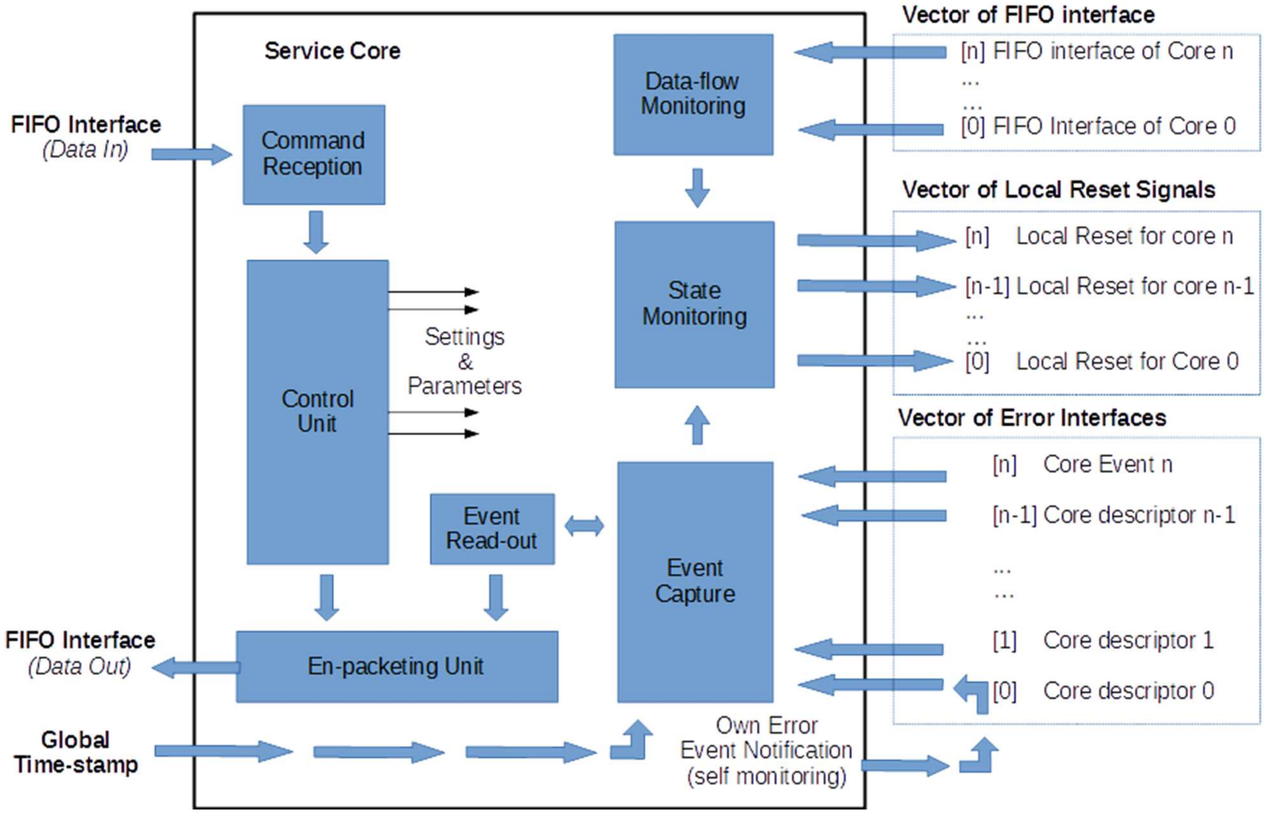


Figure 5-11 Architecture of the Service Core

5.7.2 Data flow monitoring

The Service Core implements dataflow monitoring. Unified FIFO Interfaces between the block of managed communication and user cores are observed. The interface access violation is immediately reported to the State monitor block (writing when a FIFO buffer is full or reading when a FIFO buffer is empty). The data stuck event is also reported to the State monitor (Data are not read from non-empty FIFO buffer within a timeout).

5.7.3 Event Registering

The Service Core monitors run of other cores. It registers error events reported by other cores. Error event monitoring is done over the dedicated Error interface. Each core in the COMBO device has to implement the Error interface. In dependence on the error severity level and current settings the Service Core can decide about subsequent system recovery action. In the case of a partial core dead-lock it possess a capability to make a restart (just local reset should be applied to it). Or event occurrence can be just notified by a message sent over the virtual channel.

5.7.4 Error Interface - description

It is unified interface dedicated for reporting of the error state occurrence within user cores. It significantly simplifies error monitoring and reporting. The Error Interface is composed of the following components.

- **Event code vector**
  Event code is dedicated to describe event more in detail. Exact meaning of the event code is described in the documentation of each core. It varies core by core.
- **Event severity level**

It is used to determine significance of the error event. Meaning is common for all user cores in the architecture. (Implemented levels - info, debug, warning, error, failure).

- **Event write signal**
  Signal serve as acknowledge for receiver of the error event. Whenever some error event is reported be any user core write signal is set active.

5.7.5 Event capture unit

The Service Core is able to capture error events from individual supervised cores. See the unit architecture in the Figure 5-12. Each supervised core is equipped with its own error event generation logic. It is up-to each core to manage event reporting. The Event capture unit is just a receiver of error events. The Event Capture unit is able to register just one complete event. Till read-out action is done no other complete error event can be captured for a particular event channel (supervised user core). If a new event occurs before previous one is read-out then just the event counter is incremented. So, detailed descriptive information about the event type is lost. In the normal case the following information about an event is recorded – the error code, severity and time-stamp. The event severity level can be set to prevent a capture of insignificant events. Just severe error events are logged afterwards. If the device is operated in the debug mode the severity level should be lowered to catch rather more informative events than errors of failures.

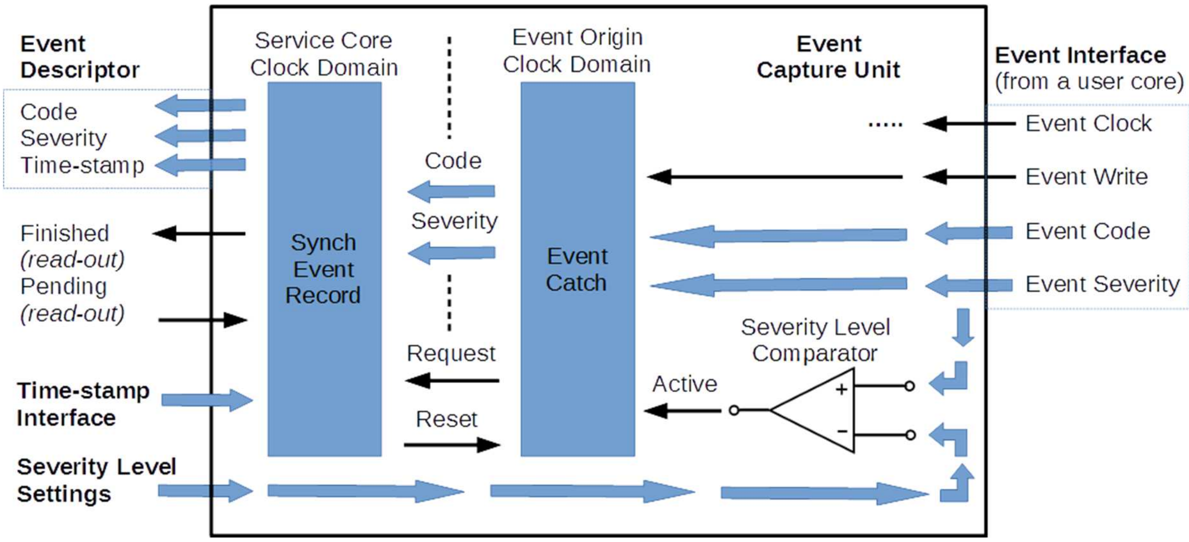


Figure 5-12 Architecture of the Event capture unit

5.7.6 Event readout mechanism

During the event read-out operation the Event capture unit is not able to catch newly coming events. It is temporary inhibited. It prevents from data mismatch due to internal handshake mechanism between different clock domains. After event read-out is finished all capture registers are cleared. Event capture unit is ready to catch a new error event.

5.7.7 Power-up behavior

After a power-up the automatic failure and error event notifying is switched off (implemented as a default behavior). Other system supervising functions are also disabled. The Service Core has to be configured before its primer usage. Supervising functions can be switched to the enabled/disabled state by a proper command.

5.7.8 Implemented commands

- **Set notification severity level**
  The command is used to set the severity level of recorded/captured error events. Each particular supervised core can be configured with a different event severity level.
- **Start/Stop auto read-out**
  It serves to enable/disable the automatic event read out functionality. When the auto read-out is enabled then packets containing event information are sent immediately after the time of the event registration.
- **Single read-out**
  It serves for initiation of the manual event read-out. When the command is received all the already capture events are sent as a response.
- **Single core restart**
  The command performs a restart of one particular user core (other cores are not affected). The targeting core is selected by the index.
- **Entire system restart**
  The command performs a reset of all user cores in the design.
- **Set-up automatic restart**
  It serves to enable/disable the automatic core reset functionality. When enabled the targeting core is reset according to the severity level settings. The core reset is performed in the case of occurrence of the error event that exceeds a configured severity level

5.8 Spectrig Core

The Spectrig Core is a module that performs acquisition of spectroscopic pulses. Its primer function is to control operation of the AD converter, to recognize spectroscopic pulses within a continuous data stream, to acquire pulses and to send pulse waveforms over a virtual channel. The Spectrig Core was created as derivation of the previously designed firmware for an autonomous device dedicated for spectroscopy purposes only [17].

5.8.1 Architecture of the Spectrig Core

The core is composed of two main parts (see the Figure 5-13). The first part manages outer communication and serves as a support for operation of the second part. The second part is the Stream processing unit which performs pulse acquisition. The following paragraphs describe function of individual components more in the detail.

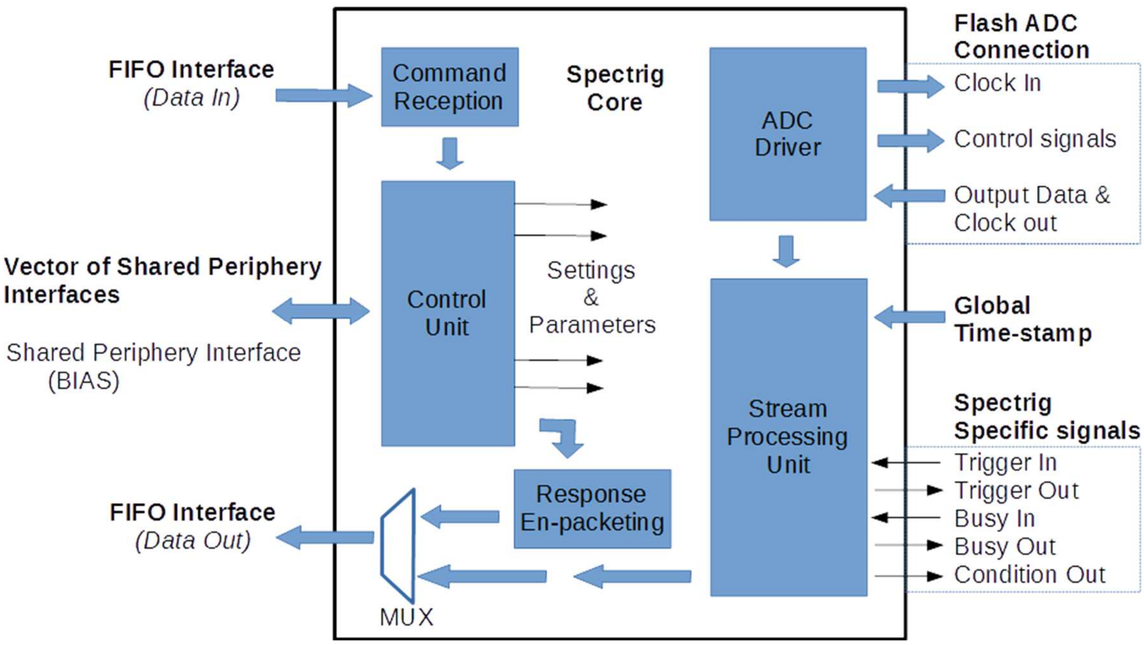


Figure 5-13 Architecture of the Spectrig Core

5.8.1.1 Command reception

A verification process is done prior to the command execution. Inconsistent command frames are considered as inappropriate for execution and they are rejected without any response to a command sender. Unknown commands (even if a consistent frame is recognized) are also ignored without notification. Only supported commands are processed further to the Control unit.

5.8.1.2 Control Unit

The unit drives overall function of the Spectrig Core. It is fully responsible for driving of other entities in the architecture. It processes incoming commands and also generates responses accordingly. The control unit is a source of parametric signals that are used as inputs for other components in the Spectrig Core architecture.

5.8.1.3 ADC driver

The ADC driver module serves as a hardware abstraction layer for the adjacent Stream processing unit. The driver allows simple connecting of the ADC to the rest of the Spectrig architecture. The ADC driver communicates with the ADC component using specific communication protocol defined by a manufacturer. On the other side it provides a continuous stream of spectroscopic signal samples that are transferred over the FIFO interface. The following Stream processing unit acts as a data consumer. It is not aware of the hardware specific details. A future change of the ADC type would just require designing a new driver letting the rest unaffected.

The ADC driver module implements two main functionalities. The essential functionality is to manage proper ADC initialization (it has to be done after the device power-up and just before the start of a measurement). Initialization prepares the ADC for proper function. The next essential function of the ADC driver is to manage conversion with equidistant sampling. Some properties of the output stream can be modified by ADC driver itself in dependence on the entity input parameters (e.g. division of the sampling frequency). The implemented functionality is demonstrated by the diagram in the Figure 5-14.

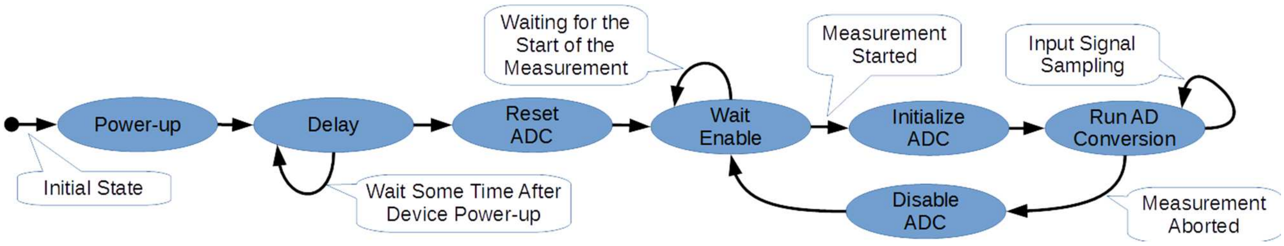


Figure 5-14 ADC driver state diagram

5.8.2 Stream processing unit

It is the main part of the Spectrig Core design. It performs processing of the continuous input data stream gained from the ADC driver. The unit recognizes and acquires spectroscopic pulses. See the unit architecture shown in the Figure 5-15.

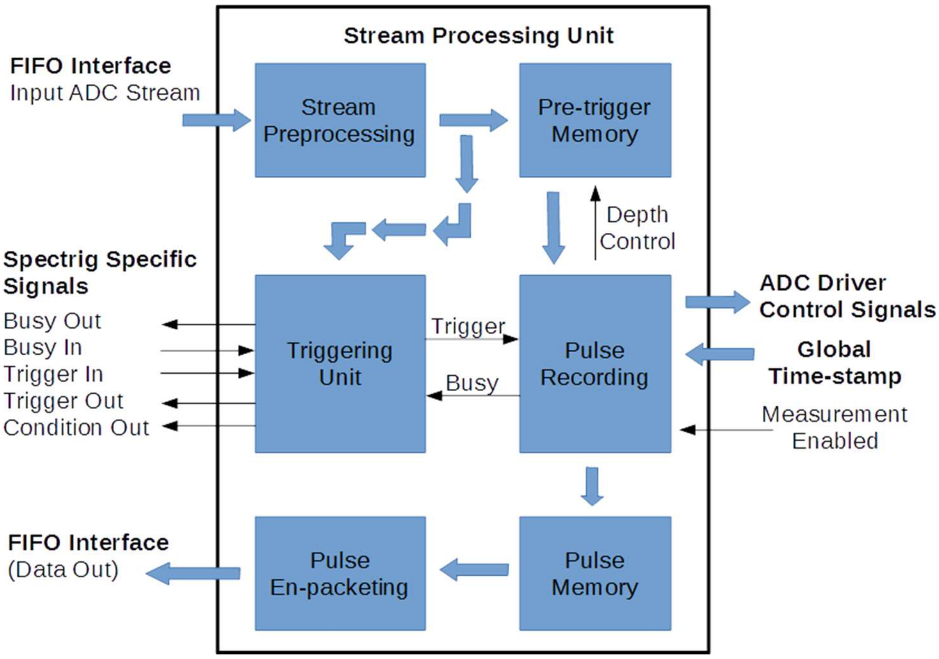


Figure 5-15 Architecture of the Stream processing unit

5.8.2.1 Signal Pre-processing

Basically, the analog input signal of the Spectrig can be of the positive or negative polarity. The digital signal processing chain implemented within the Stream processing unit is designated to support just the positive polarity of the signal only. The easiest way how to make the unit more robust is to implement a support for the programmable data negation. According to the entity input parameter the input data inversion can be switched on/off.

5.8.2.2 Pre-trigger memory

It is storage of signal samples that precede a trigger event. The pre-trigger memory enables a possibility to "look back in time" since the samples were captured before the trigger moment. The configurable depth of the buffer allows setting how long time in the past is to be recorded.

5.8.2.3 Triggering unit

It is used for generation of the trigger signal. It serves for initiation of the pulse acquisition and for the timestamp capturing. Several sources for the trigger generation can be utilized. Each source will be discussed more in detail bellow.

The Triggering unit serves also as a source of the Condition-out signal. This signal is generated in the same way like a trigger signal (same logics is applied for evaluating). The Condition-out signal could be considered also as a shadow trigger. The difference is in the purpose of the Condition-out signal. The signal is not used internally by the Spectrig Core while the trigger signal is. The Condition out signal is dedicated for an external device (like a coincidence detection unit).

A list of the available sources for generation of the Trigger and Condition-out signals

- **External trigger**
  The source of the signal is an external device. It can be gained from the I/O port or from the FITPix core specific signals. The triggering unit reacts on the edge of the signal. When it is detected a trigger event is generated.
- **Threshold trigger**
  There is evaluated value of the sampled data. Triggering event is generated when data value exceeds pre-set threshold which is one input parameter of the trigger generator. Threshold level should be any number within the range of sampled data. See visualization in the Figure 5-16.

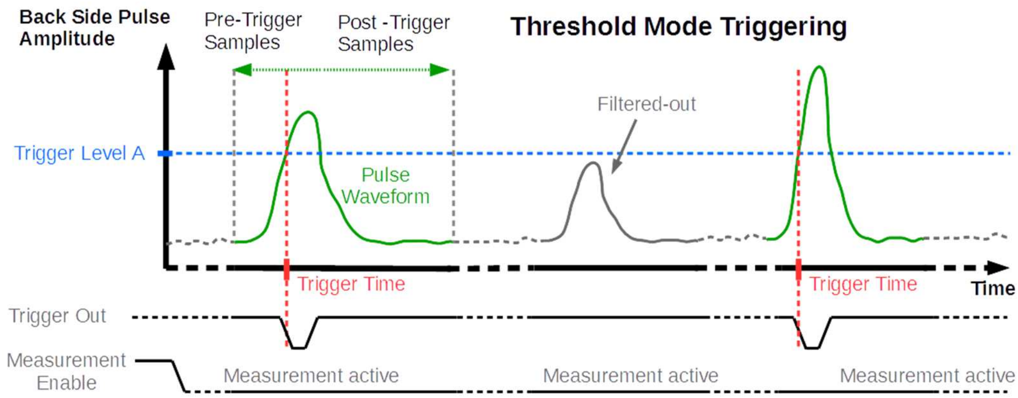


Figure 5-16 Trigger generation -Threshold mode

- **Window trigger**
  There is implemented window comparator function. Trigger event is generated when data value exceeds and subsequently it drops back under the threshold A while it is lower than threshold B level. If sample value exceeds threshold B no trigger event is to be generated. See the visualization in the Figure 5-17.

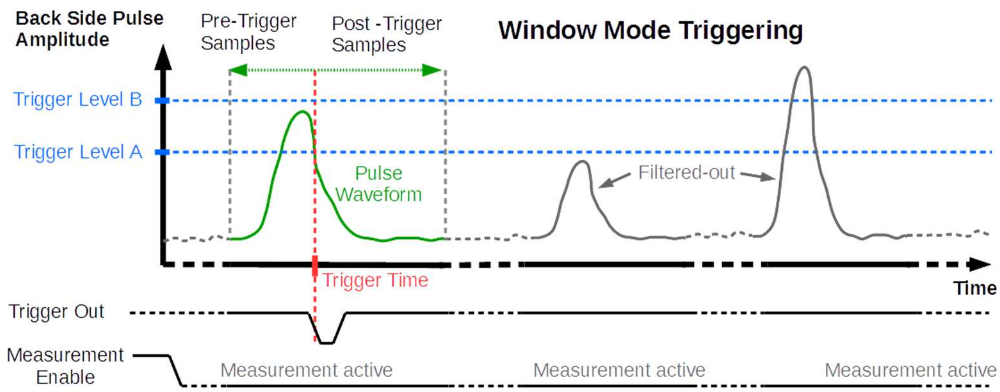


Figure 5-17 Trigger generation - Window mode

- **Software trigger**
  As the source for trigger signal generation is used signal from control unit. Trigger event is generated by demand each time control unit receives command for software trigger generation. Is serves mainly for system test purposes to validate viability and function of the chain.

A different time is needed for evaluation of each type of the trigger source (it also implies to the condition-out signal). Some extra delay is appended to the time of the original event occurrence. A selected trigger path can significantly prolong a propagation delay of an event occurrence. Utilization of a particular trigger source has to be considered while planning a coincidence measurement. For example, the window trigger can start a measurement in the time of the trailing phase of a pulse waveform while in the case of the threshold trigger a measurement can be started at the very beginning just in the pulse rising phase.

5.8.2.4 Pulse recording unit

It handles a pulse acquisition process. It is designed to store pulses into the internal FIFO buffer. The pulse acquisition begins when the triggering condition gets true (see the previously stated list of the available trigger sources). Along to the saved pulse waveform other additional information is stored. The unique time-stamp is registered at the beginning of the pulse recording. The time-stamp is gained from the Timestamp interface. The next additional registered information is a value of the pulse counter (each registered pulse increases the counter about one). It serves for subsequent identification of the data integrity of the recorded pulses.

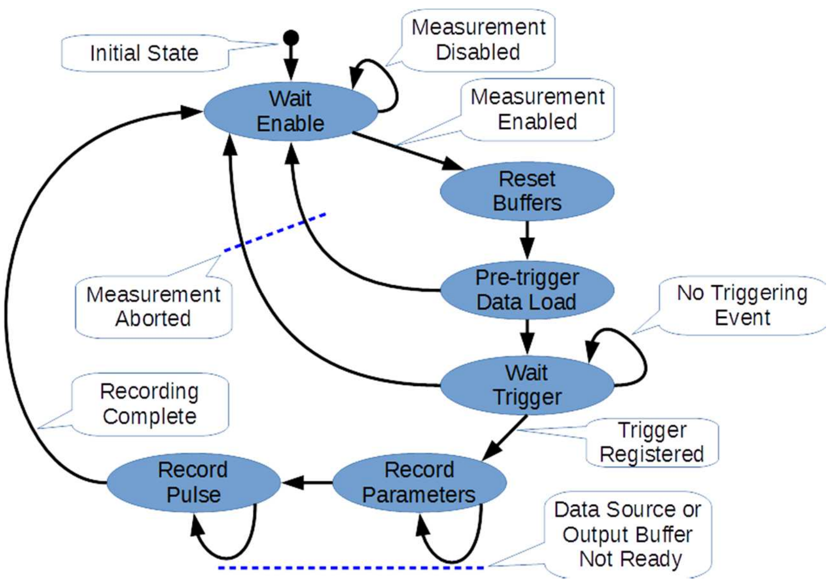


Figure 5-18 State diagram of the Pulse recording unit

The state machine function is documented by the diagram in the Figure 5-18. The initial state is Wait enable. In this state it waits till a measurement is started by the enable signal (driven from the Control unit). After the start the state machine gets into the measurement preparation phase. There is performed a clean-up of the internal data buffer (old data are deleted). After the clean-up the pre-trigger data load operation is performed. When it is done the state machine waits for the triggering event. If the trigger is registered then the state machine makes transition into the pulse properties recoding phase. The unique timestamp (related to the event occurrence) is recoded. Also a value of the pulse counter is recorded. The pulse counter is subsequently incremented about one. Next, transition into the pulse recording phase is done. A pulse waveform is saved. When it is finished the state machine returns to the wait enable state (waiting for initiation of another pulse acquisition).

5.8.2.5 Pulse Packeting

Once a pulse is saved into the internal FIFO buffer in the raw data form it has to be prepared for transmission. The raw data are packetized. Depending on the pulse properties (number of samples) the raw data are divided and enfolded into corresponding number of packets (packet length is constant and there is given a maximal payload length for each packet). Along to the pulse data some additional information is added to the packets (to allow identification and back composition packets into pulse waveform on the other side).

5.8.3 Virtual AD convertor

The COMBO device firmware can be synthesized with the virtual AD convertor by setting of a generic constant. In such a case an AD converter model is used instead of the real AD converter. The main purpose of the virtual AD converter implementation is to ease system debugging. A software development could be done without a presence of any external signal stimulus.

The AD driver component is substituted by a data stream generator. A periodical saw waveform is a new stimulating stream. Such a generated waveform is suitable for testing of the reminder of the signal processing chain. The virtual source is implemented as a free-running up-counter.

5.8.4 Specific I/O Signals

- **Busy In**
  It is the input signal that allows inhibiting of the acquisition. The Spectrig Core will get into the busy state. (If inhibition is required during the already initiated pulse acquisition the transition into busy state is postponed after current pulse is completely acquired). When inhibition is deactivated (it means return to the ready state) The Spectrig makes a restart and new initialization of the stream processing chain. Same actions are made as in the start of the measurement action. (Level reaction)
- **Busy out**
  The signal informs about the current Spectrig ready state for reaction on a triggering event. If the Spectrig is busy then no spectroscopic pulse will be acquired. If the Spectrig is ready a spectroscopic pulse will be acquired after triggering condition gets true. (Level reaction)
- **Trigger In**
  The input signal that is used to start acquisition be an external entity. Acquisition of one pulse is performed if the external triggering is enabled in the Trigger generation block and the trigger in signal gets active. (Reaction on the falling edge)
- **Trigger Out**
  It is the output signal that informs an external entity that the pulse acquisition process within the Spectrig Core was initiated (edge reaction). The pulse recording unit is a source of the trigger out signal. The signal will be generated when the Spectrig measurement is currently running and the busy in signal is not active.
- **Condition out**
  It is the output signal that informs if the internal evaluation of the triggering condition gets true or false (edge reaction). Several conditions (same as for the trigger) can be selected for generation of the Condition-out signal. It is primary dedicated to be fed to an external coincidence detection device. Such a device decides when acquisition is to be started according to a state of the condition out signal. Using this approach it allows to set-up a coincidence measurement with multiple-devices (several COMBO devices or any other measurement tools).

5.8.5 Implemented commands

The Control unit implements a set of the following commands needed for operation of the Spectrig Core.

- **Start/Stop measurement**
  Command starts or stops acquisition of the spectroscopic pulses.
- **Set trigger source**
  It selects one of the available trigger sources (how pulse acquisition will be initiated).
- **Set pre-trigger buffer**
  It determines how many signal samples will be stored before triggering event occurrence (time past before triggering condition gets true).
- **Set number of samples**
  It configures number of signal samples that will be stored as one spectroscopic pulse (including pre-trigger samples).
- **Set sampling frequency**
  The command sets a frequency used for AD convertor sampling. The adjustable clock divider will be set according to the command parameter.
- **Set Bias voltage**
  The command sets a value of the bias voltage used for the detector.
- **Set Threshold**

The command serves for configuration of the data trigger when threshold or window triggering is used for pulse acquisition. The level or window value will be set according to the command parameter.

5.8.6 Core specific information – Implementation of the optional part of the Core Info Interface

The extended descriptive information is supported by the Spectrig Core. The necessary system information about the core is available for an outer user. There are provided following data items.

- **ADC sampling clock frequency**
  The frequency of the clock signal that is used by the AD converter for sampling of the input spectroscopic signal.
- **ADC bit resolution**
  The bit width of the AD converter that is used for sampling of the input spectroscopic signal.
- **ADC input range**
  The voltage input range of the AD converter that is used for sampling of the input spectroscopic signal.
- **ADC sampling clock division**
  The maximal division factor that can be applied to the base sampling frequency of the AD converter.
- **Pulse buffer size**
  The maximal number of signal samples per one pulse waveform.
- **Pre-trigger buffer size**
  The maximal number of spectroscopic signal samples that can be stored retrospectively prior a triggering event of the pulse waveform acquisition.
- **Bias range**
  The voltage range of the adjustable high voltage source (periphery).
- **Trigger sources**
  The set of the supported triggering channels (external, threshold comparison, window comparison, software trigger, etc.).

5.9 FITPix Core

The FITPix Core serves as an interface for the pixelated particle detector Medipix/Timepix. It manages all operations needed for utilization of the detector (reset, start-up procedure, data matrix read-out, write pixel configuration matrix, setting of the special function register, measurement operation control, test-pulse generation and so on). The FITPix Core handles low-level signal communication with the detector. On the other side it provides high-level access to pixelated detector services.

The FITPix 2.x firmware served as a base for the FITPix Core development [16]. The former firmware architecture was conceived as a compact device strictly dedicated to be a read-out interface for the Medipix/Timepix detector. It was not planned to support any future multi-core operation in time when it was designed. A lot of changes had to be involved when it was redesigned to let it be one of the user cores in the COMBO firmware. The most of changes are related to the Control unit. It was perceptible simplified. Not all the original functionality is still needed when there is available layer of Common supporting services in the COMBO firmware.

5.9.1 Architecture of the FITPix Core

The core is composed of several main parts (see the Figure 5-19 showing a top-level of the core architecture). The most important part is the Timepix Universal interface. It implements direct communication with the Timepix detector. The Command reception block, the Control unit and the Response Enpacketing block forms a support for the Universal Timepix interface. They manage outer communication of the FITPix Core and execution of ingoing commands. More detailed description of all functional blocks follows.

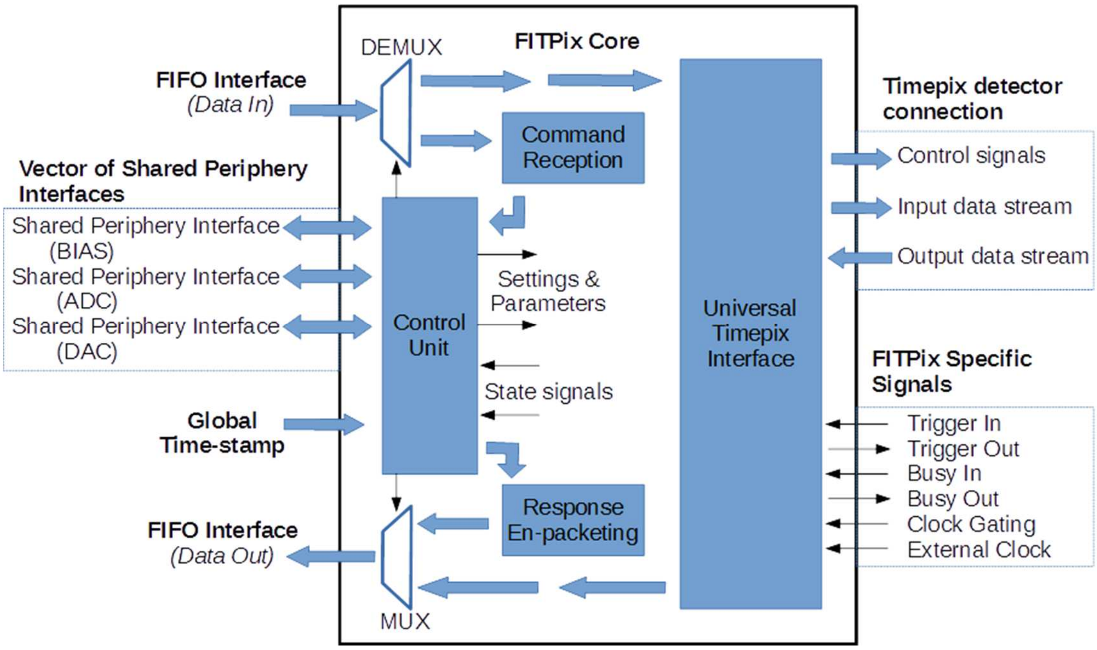


Figure 5-19 Architecture of the FITPix Core

5.9.2 Command Reception

The entity receives a raw data stream. Incoming command frames are recognized within the data stream. A recognized command frame is handed further to the Control unit if a data integrity verification test is passed (checksum is correct). In the case of inconsistent frame detection no further action is performed. The corrupted frame is discarded.

5.9.3 Response enpacketing

The entity envelopes each command response generated by the Control unit into the packet frame (same frame as it is used for incoming commands). The created response packet is further passed to the output data channel (unified FIFO interface).

5.9.4 Input data de-multiplexing

The ingoing data has to be de-multiplexed between the Control unit and the Timepix detector branch. The data path switching is done by a simple signal multiplexer. The read enable signal is switched between the Control unit and the Timepix Universal Interface entity. An active data receiver is allowed to assert the read enable signal. An inactive receiver is prevented from the FIFO interface access.

5.9.5 Output data multiplexing

Data multiplexing is done by a dedicated state machine while it is represented in the architecture block diagram as a simple multiplexer. The multiplexing entity re-sends data from sub-channels (Control unit, Universal Timepix interface) to the outer unified FIFO interface. A currently active data transmitter is selected by a configuration signal (driven by the Control unit). A data resending process is initiated immediately if there is some data in a currently active path. But a stop of the data resending is delayed. The end of the resending and the path switching will be done if there is no more pending data in the recently selected path. This mechanism is a mean of protection against the data mismatch. If paths would be switched immediately some data remaining in the buffers would be prevented from sending. So a data inconsistency would be detected on the other side of communication.

5.9.6 Control Unit

It is implemented as a complex state machine. It performs a set of various functions needed for operation of the entire Spectrig Core. The implemented functionality of the state machine is described separately one by one.

- **Command processing**
  It accepts incoming commands from the Command reception unit. Only one command can be executed at one time. The Control unit cannot perform any other action till the last command processing is finished. It is blocked for a particular time. To avoid a risk of the dead lock caused by some commands (e.g. detector control operations) The Control unit implements a watchdog. When a command execution timeout is exceeded the Control unit breaks a currently executed command. The unit gets ready for acceptation of the next one.
- **Response generation**
  It generates responses to incoming commands. Response content is handled to the Response Enpacketing block for formation of a response frame and further data transmission.
- **Universal Timepix interface controlling**
  The control unit supervises the Universal Timepix interface entity. All detector oriented operations are performed according to a request from the Control unit. The unit is responsible for selection of the detector operation mode (run measurement, abort measurement, read data matrix, write pixel configuration, reset detector, etc.).
- **Data Path Switching**
  The FITPix Core is connected over the unified FIFO interface. But there are two data consumers and two data sources within the core. The Control unit as well as the Universal Timepix Interface entity needs an access to the outer data channel. Therefore the data path switching is implemented. Routing of data paths to the Control unit is initial configuration. In this state commands can be received and responses can be transmitted in return. But when operation like a detector matrix read-out, write pixel configuration, etc. is performed data paths has to be reconfigured. The Universal Timepix Interface entity has to be allowed to access the outer data interface. The Control unit communication is temporary blocked during this temporary state. When specific detector oriented operations are finished the data path configuration is returned to the initial state. In the case of a detector operation failure there is implemented an automatic recovery mechanism based on the timeout (watchdog). If the end of the partial detector operation is not acknowledged within the preset timeout then data paths are switched back using initial configuration.
- **Shared periphery controlling**

The Control unit implements shared periphery interfaces. They are used to read necessary analog inputs, write analog outputs and to set a bias voltage. All these services are provided by the Shared resource Core. Control unit just generates an appropriate request using a Shared periphery Interface.

5.9.7 Timepix Universal Interface

The entity manages low-level communication with the Timepix detector. It is implemented as a complex state machine which is driven by the main Control unit of the FITPix Core (previously described). Interface action is selected by the Operation mode bus and a vector of parameters. A feedback is provided by a vector of state signals. See the Figure 5-20 showing a simplified structure of the Universal Timepix interface. Description of the functionality implemented within the complex state machine follows.

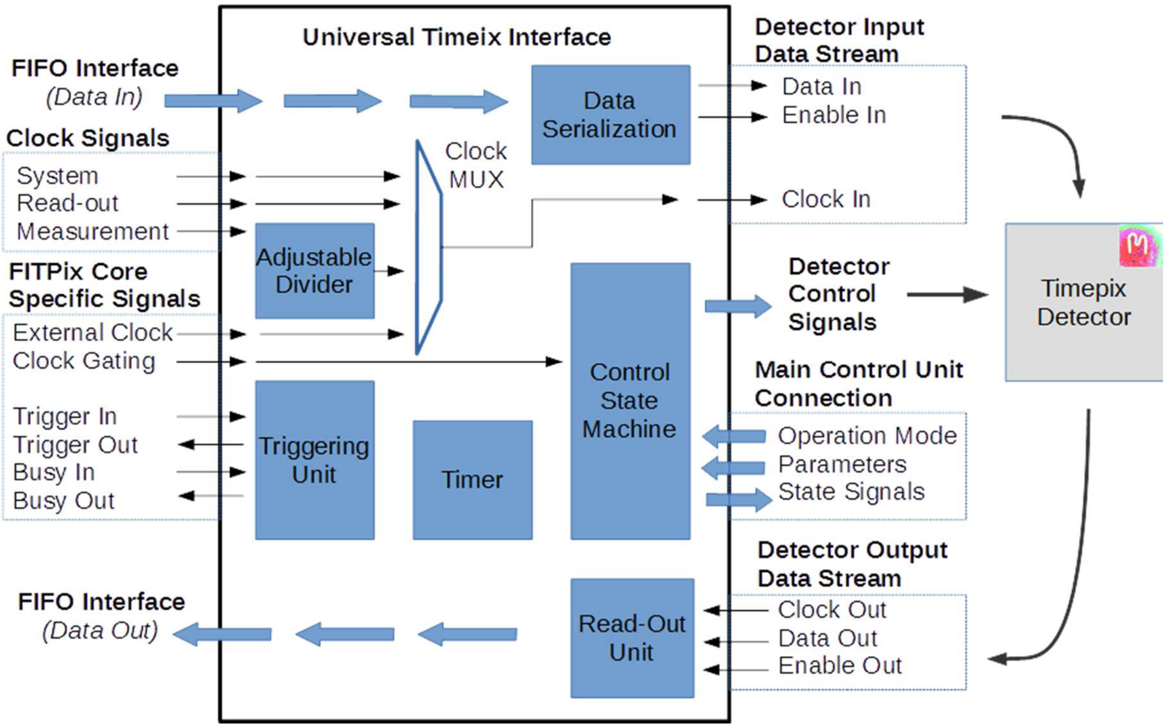


Figure 5-20 Architecture of the Universal Timepix Interface

- **Detector Initialization**
  Proper detector initialization is needed before it is used. The detector is kept in the reset state till its power sources are stabilized. After the start-up phase a subsequent primer test of the detector presence and response is done. The dummy read operation is performed (just detector reaction is observed, received data are not used).
- **Acquisition control**
  The Interface handles an acquisition process of the Timepix detector. The measurement clock signal can be generated with variable frequency (using the adjustable divider block). The detector shutter signal is under the full control of the interface. The exact exposition time is ensured by the internal Timer block. The measurement start and stop can be also synchronized with the external signals (Trigger In, Busy In). The acquisition control process is performed according to current parameters applied by the Control unit.
- **Read data matrix**
  After end of the measurement phase the data content of the pixelated matrix has to be read-out. The Read-out unit is dedicated for reception of the data stream from the detector. The unit is operated in a different clock domain than the rest of Universal interface (the Timepix Clock-out signal

is asynchronous to the Clock-in signal due to a propagation delay). The Read-out unit performs signal re-synchronization using a dual clock FIFO memory.

- **Clear data matrix**
  Erasing of the detector matrix is implemented as parallel read-out operation. In comparison to the normal matric read-out operation the gained data are ignored (not passed to a further block) Difference is that data are ignored during read operation.
- **Write pixel configuration**
  Detector pixels need to be configured before the start of a measurement. The configuration stream has to be written into pixel setting registers. The Universal interface implements the operation. Stream of the defined size has to be provided at the entity input.
- **Write FSR / Read Chip ID**
  Configuration of the common detector (internal DAC settings) can be done by writing of the Fast shift register. When the Universal interface is requested to perform the operation a configuration stream is taken from the input FIFO channel and the data are resend to the detector. The unique chip ID read operation has to be done simultaneously to the configuration writing. It is given by a detector nature. When configuration data are shifted-in the chip identifier data are shifted-out. A stream of the same size is gained and passed to the output FIFO channel after end of the operation.
- **Test pulse measurement**
  Automatized test pulse generation and detector measurement is integrated in the function set of complex state machine. According to the input parameters of the Universal interface a required number of test pulses of predefined period is generated.
- **Detector reset**
  The detector can be reset by the Universal interface. The reset signal of the well-defined timing is generate when the operation is requested. The reset signal affects just some internal registers of the Timepix detector (a content of pixel counters and pixel configuration registers is kept unaffected)
- **Power down/up**
  The operation implements safe handling of the detector powering. A detector power source has to be managed by the Universal Interface because the well-defined power-up sequence has to be met to ensure proper initialization of the detector.

5.9.8 Specific I/O Signals

- **Trigger In**
  The signal serves as the external trigger for a measurement start of the Timepix detector. The appropriate measurement mode has to be configured before utilization of the external trigger. When internal triggering is used the trigger in signal is ignored.
- **Trigger Out**
  The trigger out signal is generated just in the time when a measurement of the Timepix detector is started (Shutter signal gets to the active state). The trigger out signal can be used for synchronization with other outstanding device. The measurement the entire set-up can be initiated by the Trigger out signal.
- **Busy In**
  The input signal serves for inhibition of detector acquisition when it is applied. Even if a triggering condition is true the acquisition is not started. If inhibition is active the busy out signal is also set to the active state to inform that the FITPix Core is not ready for acquisition. (Level reaction)
- **Busy Out**
  The output signal informs about the ready state of the FITPix Core. When it is active the FITPix Core is not ready to start new acquisition of the detector and to react on a trigger signal.

- **Clock In**
  The FITPix Core allows selection of an optional source of the measurement clock for the Timepix detector. By default internal clock signal is used. When requested the Clock In signal serves as the external source of the measurement clock.
- **Clock Enable**
  The input signal that enables/disables a measurement clock for the Timepix detector. It serves as a clock gating circuit. If the Timepix detector is not clocked during a measurement run then pixel counters are not active. Their function is temporary inhibited.
- **External Clock**
  It serves as an input of the detector measurement clock signal. The internal source of the measurement clock signal can be bypassed by external one. When the external source is selected then detector clocking is under a full control of the external entity during a measurement run.

5.9.9 Virtual Detector

The virtual detector can by synthesized within the FITPix Core architecture. Inputs and outputs leading to the detector in the normal design are rerouted to the model of the detector. The rest of the core behaves as if a regular Timepix detector is connected. All detector operations are still available. However, just a partial functionality of Timepix is implemented within the detector model. The read operation always returns a stream containing constant data. The write pixel configuration operation and write special function register operation will not affect a current state of the virtual detector (no memory function is implemented within the model)

The firmware assembly with the virtual detector option is dedicated mainly for system debugging purposes. It serves as a tool for verification of function of a software chain. It offers reliable target for testing that cannot be affected by an unexpected behavior of the real detector. The detector read/write operation fail events can never occur.

5.9.10 Implemented commands

- **Test command**
  The command that serves for verification of the core presence and readiness. Just a dummy response is generated. No controlling action is performed.
- **Read matrix**
  It is a command that starts a read-out of the measured data. A content of the pixelated matrix is received as a response. The acquisition specific data (timestamp, time of measurement, frame counter, etc.) are attached to the raw matrix stream.
- **Write matrix**
  The pixel configuration is written through the command. A stream of the pixel configuration data has to be sent after issuing of the command.
- **Write FSR/Read chip ID**
  The command serves for writing of the settings of the internal DACs of the detector. The unique chip identifier is received as a response to the command
- **Start measurement**
  A start of the detector measurement is done by the command.
- **Stop measurement**
  Interrupt of the already running detector measurement.
- **Set measurement parameters**

The command sets parameters of the detector measurement (trigger source selection, number of frames, etc.). The parametrization has to be done prior to the measurement start.

- **Generate test pulses**
  The command initiates detector acquisition using test pulses as a source of the measured signal.
- **Set bias voltage**
  The bias voltage of the detector is set.
- **Set analog outputs**
  It performs setting of analog outputs related to detector operation (external DAC of the detector, test pulse amplitude)
- **Read analog inputs**
  The command performs sensing of analog outputs of the detector. It serves for verification of internal detector references.

5.9.11 Core specific information – Implementation of the optional part of the Core Info Interface

The extended descriptive information is supported by the FITPix Core. The necessary system information about the core is available for an outer user. There are provided following data items.

- **System clock frequency**
  The frequency of the clock signal that is used for operation of the FITPix Core logics.
- **Read-out clock frequency**
  The frequency of the clock signal that is used to drive the Timepix clock in signal during the data read-out phase.
- **Measurement clock frequency**
  The frequency of the clock signal that is used for derivation of the Timepix clock in signal during the measurement phase.
- **Bias voltage range**
  The voltage range of the high voltage source that is used for biasing of the Timepix sensor.
- **Feature flags**
  The bit field informing about the presence of the optional read-out interface functionality in a current firmware synthesis (involves functionality like a serial/parallel data read-out support, watchdog supervision, detector data stream deserialization, etc.).

5.10 Shared resources Core

Some resources within the COMBO device do not logically belong to one user core only. Resources have to be shared between two or more user cores. The system of multiplexing and accessing has to be integrated to allow resource sharing. Therefore the Shared resources Core was created. It fully manages assignment of the shared resources between other user cores in the design.

5.10.1 Architecture of the Shared resources Core

The core consists of the three main parts. See the Figure 5-21 containing the architecture block diagram. The basic part consists of the communication interface (Command reception block, Enpacketing block) and the Control unit. This part receives incoming commands and it provides settings for the rest of the core. The second main part manages routing and interconnection of user core specific signals and common external I/O signals. The last part implements a management of the external periphery circuits (i.e. ADC, DAC, Bias and Temp.). It provides a hi-level (hardware independent) access to peripheries for any user core.

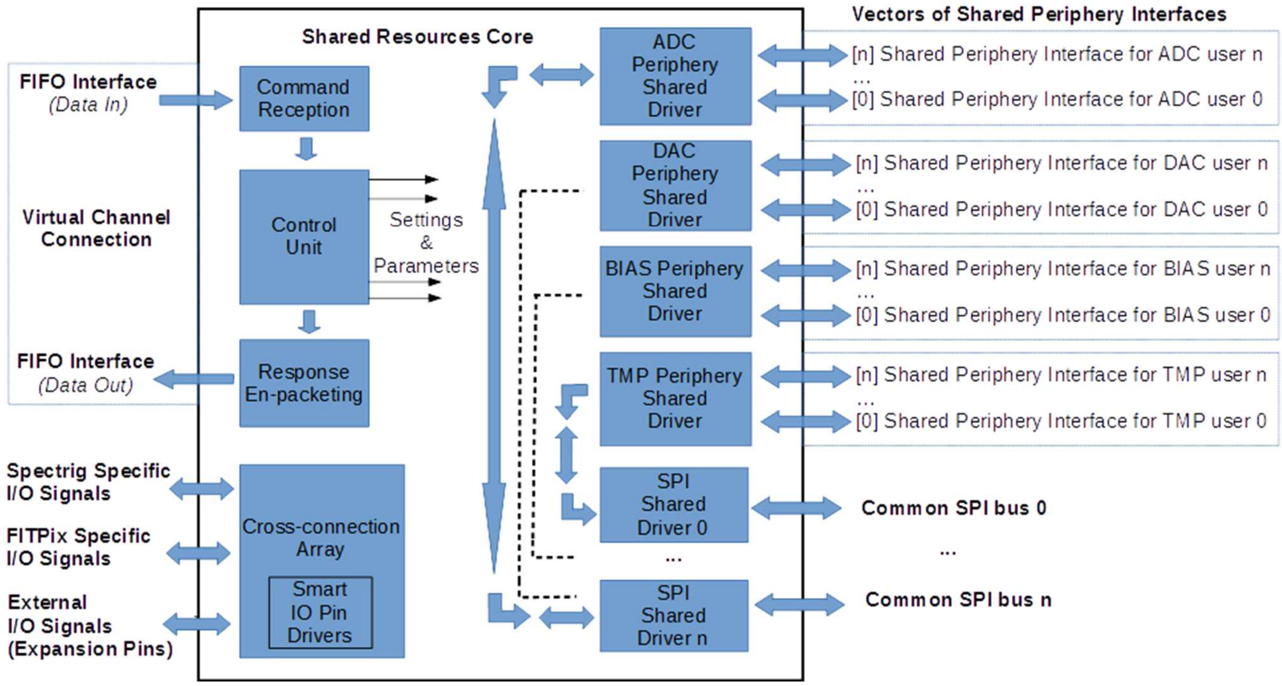


Figure 5-21 Architecture of the Shared resources Core

5.10.2 Shared Signals

The core manages interconnection between three groups of O/I signals (a vector of the Spectrig specific signals, FITPix specific signals and external extension header I/O signals). Synchronized operation of the FITPix and Spectrig Cores requires dynamical reconnection of specific I/O signals (Interconnection is to be changed during the device run time). Synchronized operation of the COMBO device with an external entity is also required. Thus a bus of external signals has to be involved into the system of mutual interconnection. External I/O pins do not logically belong to one user core only. That fact also gives a reason to involve external signals into the system of mutual interconnection. Moreover, a number of external I/O pins is quite limited.

5.10.2.1 Cross connection array

It manages interconnection of signals according to applied configuration. The Figure 5-22 shows how the cross connection array is build up. The main element is the Smart Pin entity. It is present in multiple instances (count is given by a number of external pins and a number of user core specific input signals (e.g. Spectrig Trigger in, FITPix Busy in…). According to the applied configuration the Smart Pin entity selects on of the source signals. As source signals are used core specific output signals (e.g. Spectrig Trigger out, FITPix Trigger out…) and external pins (see feedback in the figure). The output of the Smart pin entity is synchronized with associated clock signal that is provided by vector of clock signals. Internal composition of the Smart pin and its function is described more in detail in the following section.

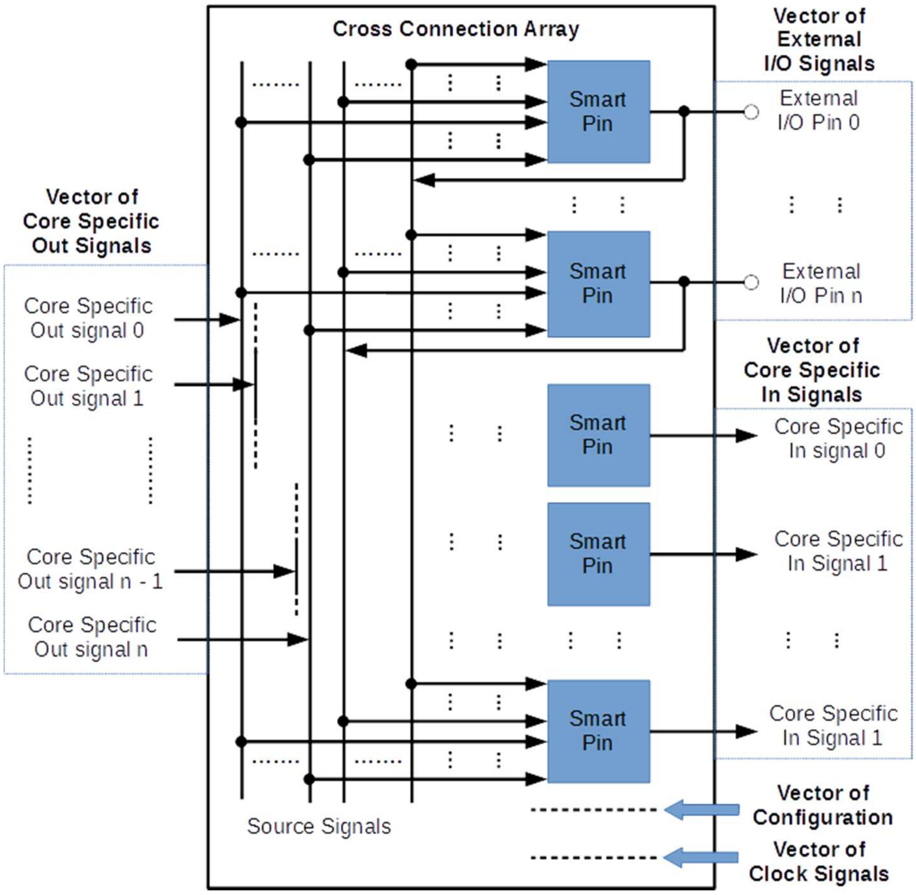


Figure 5-22 Cross connection array structure (routing of the external and core specific signals)

5.10.2.2 Smart Pin entity

It is a basic element that is necessary to build-up a cross connection array. At the first sight the Smart Pin entity is a configurable multiplexer with following options. The Figure 5-23 shows a structure of the smart pin entity.

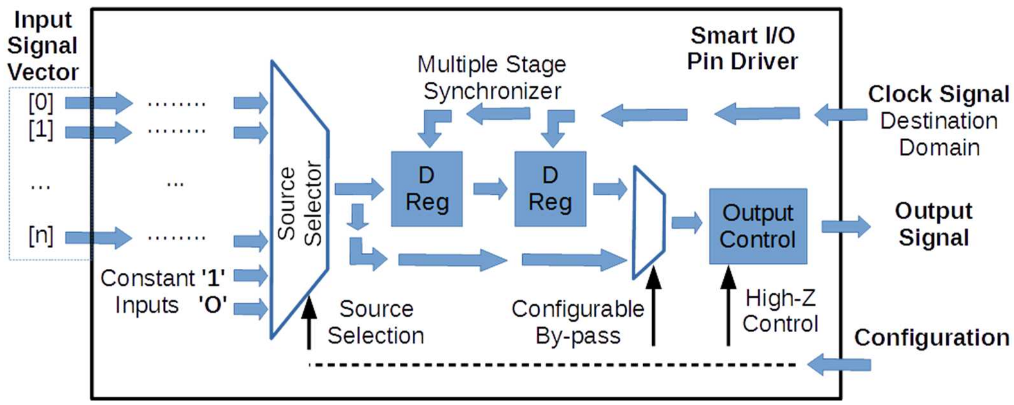


Figure 5-23 Architecture of the Smart pin entity

- **Target clock synchronization**
  By default, all input signals are expected to be asynchronous with an output signal (destination clock domain). Signal resynchronization has to be done to avoid intrusion of the metastability into the destination clock domain. Therefore a multiplexer output (source selector) is equipped with the N stage synchronizer (the stage order N is defined before the firmware build-up by a generic constant).

Nevertheless, clock signals need a different treatment than a simple logical signal does. When the clock signal is routed through the Smart Pin entity there is option for by-passing of the synchronizer (to avoid clock signal disruption).

- **Input selection**
  Selection of the input signal is done by configurable multiplexer (Source selector). According to the applied configuration one source is selected (from the vector of input signals). In appendix to the Input Signal vector there are two more internal signals that can be selected as a source. These two addition selectable signals are constant drivers (Logical 0, logical 1).
- **Output inhibition**
  When the Smart Pin entity is used to drive an external pin there is an option to bring an external pin into the high-Z state. Once it is configured so the external pin should be used as an input. The hi-z option is not available for internal signals.

5.10.3 Sharing of the external peripheries

The FITPix COMBO device hardware is equipped with several external periphery circuits connected over the SPI bus. To allow an access of each user core in the firmware to the external SPI periphery there was implemented a managed access through driver entities.

The Figure 5-24 shows how the external periphery sharing is implemented in the firmware. Several layers of abstraction (shared periphery drivers, shared SPI driver) are used to prevent user cores from hardware specific details. A data exchange between the adjacent layers is done through unified interfaces. The handshake mechanism (request and acknowledge) is used for mutual communication. Function of each layer is described more in detail in appropriate following sections.

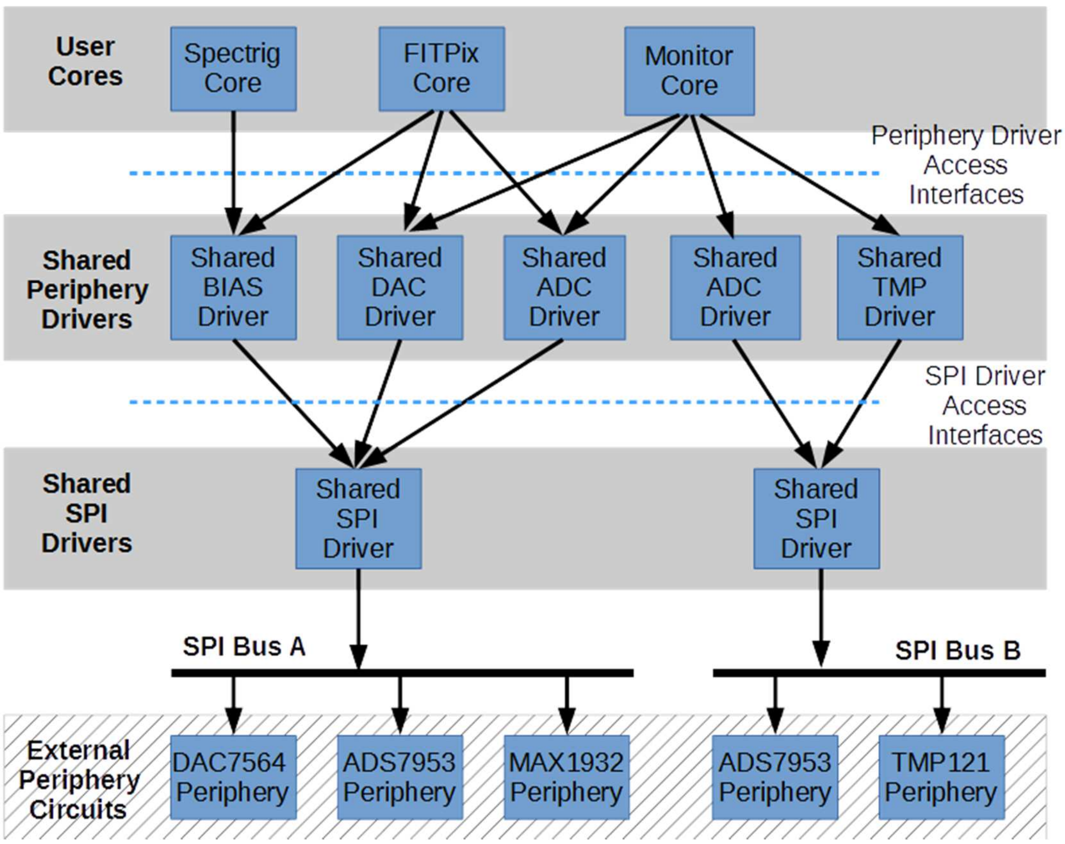


Figure 5-24 Implementation of the periphery sharing - relation between users and drivers

The access requests are sequentially past and processed from the top (user core) to the bottom (external periphery). See the diagram in the Figure 5-25 showing exemplar processing of a user core access to an external periphery. At the beginning the user core generates a request (e.g. set a DAC channel) toward the Shared periphery driver. It promptly reacts. Interpretation of the set channel value command is translated into data recognized by the external periphery circuit. Further, a SPI transmission request is passed by the Shared periphery driver to the Shared SPI driver. It manages physical SPI transmission. When the data transmission to the external periphery circuit is finished the Shared SPI driver generates an acknowledgement back to the Shared periphery driver. In the same manner an acknowledgement is generated back to the user core to inform that the operation (set DAC channel) was finished.

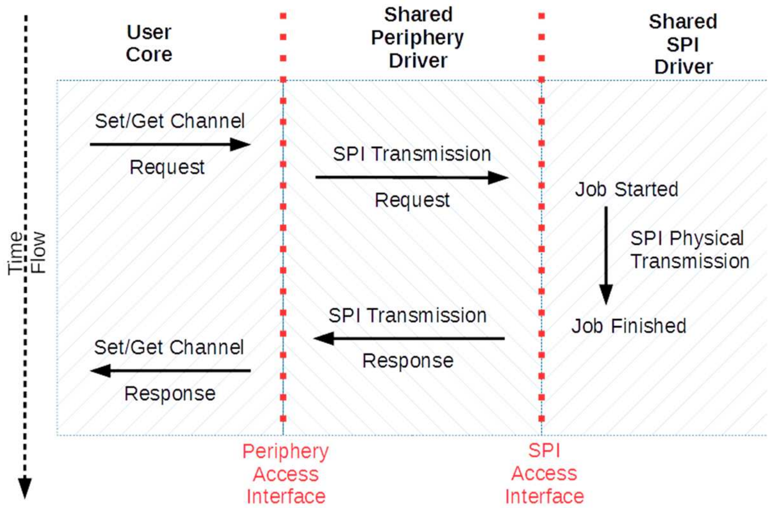


Figure 5-25 Transaction diagram - Request processing through interfaces of the shared drivers

5.10.4 Mastering of the shared resources

By default, the resource sharing is not restricted after a device power-up. However, it is considered not to be quite safe to let all user cores manipulate with the same shared resource at the same time and at any will and without letting any notification to other user cores. Therefore some restriction and control mechanisms have to be established for a resource access. It is not possible to decide which user core should be a master of shared resources on the device level itself. Some out-standing entity has to decide which user core will be granted to access shared resources. A restrictive access mode shall be configured by an application software. Once it is applied a resource is locked just to one user core. (E.g. the bias voltage source of the Timepix detector can be locked for a private usage of the FITPix Core).

5.10.5 Shared Periphery Drivers

They serve as an abstraction layer for user cores. Periphery services are accessible through the Shared periphery access interface (see the description and definition of the interface signals in the next section). It provides a set of the indexed read/write channels (in dependence on the type of an external: e.g. the ADC driver implementation requires read channels while the DAC implementation requires write channels). Individual channels should be accessed by a request from any user core. Therefore each shared periphery driver implements multiple inputs (Periphery access interfaces) while the output (SPI access interface) is implemented just once.

5.10.5.1 Restrictive or random access mode

By default all shared drivers within the Service Core design are configured to accept requests from every connected user core (operation in the random access mode). But shared drivers can be reconfigured to accept just requests from one user core only (operation in the restrictive access mode). Requests originating from other user cores will be rejected (even if the requested shared driver is not busy).

5.10.5.2 Implemented shared periphery drivers

There were implemented several shared periphery drivers within the COMBO device. All of them are needed for overall function of the device. List of implemented drivers follows.

- **ADC Shared driver**
  Implements a support for the ADS7953 circuit. It is an ADC converter with 16 channels.
- **DAC Shared driver**
  Implements a support for the DAC7564 circuit. It is a DAC converter with 4 channels.
- **Bias Shared driver**
  Implements a support for the MAX1932 circuit. It is an adjustable source of the bias voltage. It should be imagined as 1 channel DAC converter.
- **TMP Shared driver**
  Implements a support for the TMP121 circuit. It is digital temperature sensor. It should be imagined as 1 channel ADC converter.

5.10.5.3 Shared periphery access interface

The Shared periphery access interface consists of a set of the following items.

- **Index**
  Selection of the periphery channel index that will be manipulated by a user core.
- **Value**
  A numeric value that represents either an input or output value related to the selected channel of a particular shared periphery.
- **Request**
  It is a user core controlled signal. It serves for initiation of the periphery access operation.
- **Acknowledge**
  It is a shared periphery controlled signal. It informs about completion of the previously requested operation.
- **Timeout/Reject**
  A state signal informing about a result of the last processed access operation. The successful or unsuccessful result can be gained along the acknowledge signal.

5.10.6 Shared SPI Driver

It serves as the end point for multiple Shared periphery drivers. All services are accessed through the Shared SPI interface (its description will follow). The Shared SPI driver fully manages low level communication done with externally connected periphery circuits. All the external periphery circuits associated with one common SPI bus are managed by one instance of the Shared SPI driver. It acts as the SPI master while external periphery circuits are considered to be SPI slaves. Selection of the currently active communicating periphery circuit is done over the CS signal assertion. To guarantee compatibility with each particular periphery circuit it implements dynamical reconfiguration of SPI physical layer parameters. Options like a bit transfer speed, clock polarity, sampling, active edge selection, data frame width, data bit order are adjustable according to the request from a higher layer (Shared periphery drivers).

5.10.6.1 Restrictive or random access mode

The Shared SPI driver also implements the restrictive or random access mode. It is implemented in the same way like the previously described Shared periphery drivers do. See the description of the principle in the text of 5.10.5.1.

5.10.6.2 Shared SPI access Interface

The interface is designed to arrange transmission of one SPI data frame. One frame is considered to be a particular SPI job. The interface provides handling of jobs by means of the handshake mechanism (the request and acknowledge principle). The request signal is generated from a higher layer (Shared periphery driver). It informs about pending data to be transmitted. The acknowledge signal is generated by the Shared SPI driver. It informs about the request completion and periphery data response validity.

- **Master data**
  The data to be transmitted over a SPI bus by the SPI master
- **Slave data**
  The data to be received by the SPI master
- **Request**
  A start of a new SPI transfer job. The signal is asserted by a user of the driver.
- **Acknowledge**
  The SPI job finished notification. It is asserted by the shared SPI driver.
- **Configuration**
  Parameters of the SPI transmission (a field of values). Specific values needed for each external SPI periphery circuit.
- **Mastership**
  A state signal. It informs if the SPI driver was accessed by another user core from the time when the last SPI transmission was requested by the current core (that receives the Mastership signal).

5.10.6.3 SPI Configuration

The following field of values is needed for configuration of the SPI transmission parameters. It is a sub-part of the Shared SPI access interface.

- **Speed**
  The SPI clock frequency settings. It is stated as a divider factor of the basic clock signal used for the Shared core.
- **Polarity**
  The setting of an idle state of the SPI clock signal. The low or high state (negative or positive polarity) can be selected.
- **Bit order**
  The order of the data bits transited over the SPI bus. It is the selection between the most significant bit first or least significant bit first.
- **Edge**
  Setting of the active SPI clock edge used for data sampling. Selection between the leading and trailing edge are the possible choices.
- **Words**

A number of bytes transmitted within one SPI job. Just partial range of data should be transmitted (There is available selection from 1 to 4 bytes).

- **CS index**
  The index of the CS select signal. It serves for selection of the active external SPI periphery circuit that will be involved in the data transmission
- **Keep CS**
  Behavior of the CS signal after the end of the last job. The CS signal can be immediately de-asserted after the end of the job. Or it can be kept active. However, automatic de-assertion will be done in the case when another CS index is selected in the following job.

5.10.7 Resource assignment settings

Settings for all shared resources are stored within one common register map. An access to the register map is implemented as the pure memory read/write functions (An application software can change a resource assignment using these functions). The map registers are directly connected to the corresponding configuration input ports of shared resources (drivers). When a new value is written into selected memory location the new configuration is applied immediately. There is no additional propagation delay between the register update and the shared resource driver reaction. There is only one exception of the delay re-configuration. It can happen when a request for reconfiguration is issued in the time when relation between user core and drivers is still in the processing state (e.g. Get ADC channel value is in progress). The new resource configuration will be accepted after the end of the currently running transfer relation.

5.10.8 Implemented command

A presence of the common register map significantly simplifies a design of the Control unit. Just two commands (read/write memory) are needed to cover entire configuration needs within the Shared resources Core. But one more command was added. The read register map version command is implemented for verification of the compatibility (between application software and the current version of the device firmware).

- **Write configuration register**
  The command performs the data writing to the given address. The write operation is accomplished if a requested write address belongs into the defined area. If the write operation is performed successfully the acknowledge response is generated. A content of the response frame is same as the command frame. If the write address is undefined the error response is generate instead.
- **Read configuration register**
  Command performs read of the data stored on the given address. Valid data are read when requested address belongs into defined area. Read data are send within data field of the response frame. Address field of the response frame contains same address as read command. If undefined address is requested the unit generates error response instead.
- **Get register map version**
  The command serves to get a version of the register map configuration synthesized in the currently operated device. The response to the command contains the register map version information.

5.11 Monitor Core

The purpose of the Monitor Core is to provide an independent system diagnostic channel. The Monitor Core acquires values provided by shared periphery drivers. Information about supply voltages, drained currents and temperatures are available while other user cores (Spectrig, FITPix, etc.) perform their independent action (e.g. measurement). Such system information can be quite valuable while evaluating acquired data in the post-processing phase. The system information can also ease finding of defective devices (when monitored values exceed predefined operating limits then warning can be issued on the side of an application software). The Monitor Core does not directly influences function of other user cores within the firmware. It cannot control any outputs.

5.11.1 Architecture of the Monitor Core

The core consists of two main parts (see the Figure 5-26). The first one is a group of Command reception entity, Control unit and Enpacketing block. It manages outer communication that is done over the unified FIFO interface. Further, it provides settings for the rest of the Monitor Core. The second part is the Periphery read-out unit. It communicates with outer shared peripheries. It acquires all the diagnostics data.

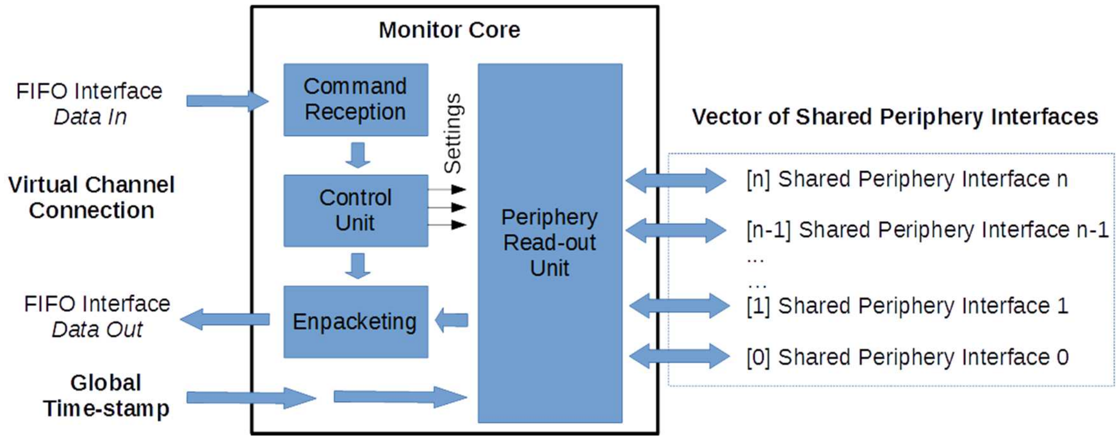


Figure 5-26 Architecture of the Monitor Core

5.11.2 Diagnostic data acquisition

The diagnostic data can be acquired in the synchronous or asynchronous mode. The difference between the modes is in the way how the diagnostic data are acquired. A format of the gained diagnostic data stream is same in both modes.

When performing acquisition in the asynchronous mode the diagnostic data stream is received as a response to the previously issued asynchronous read-out command. Scanning of the shared peripheries channels is initiated in the time of the command reception. The diagnostic data stream is formed and sent just once. After it is finished the Control unit waits for the next command.

When performing acquisition in the synchronous mode the diagnostic data stream is sent periodically. Start of the periodical acquisition is initiated by the command synchronous read-out. This command also sets a time of the repetition period. The synchronous acquisition is performed till the abort action is not requested.

5.11.3 Monitored values

The Monitor Core is designed to read all accessible analog inputs. It is done through shared periphery drivers located in the Shared resources Core. The Periphery read-out unit implements a state machine that is capable of scanning of all channels of the related shared periphery drivers. There are involved two instances of the Shared ADC driver and one instance of the Shared TMP driver in the design (the Shared TMP driver is also involved because a temperature value is also considered to be an analog input).

5.11.4 Implemented Commands

- **Asynchronous read-out**
  Command initiates instantaneous acquisition of the diagnostics values. The frame of the diagnostic data will follow as a response.
- **Synchronous read-out**
  The command configures periodical acquisition of the diagnostics values (start/stop). The time period will be configured according to the command parameter. Diagnostic frames will be sent in predefined time period till it is not aborted.

5.12 Repeater Core

A purpose of the Repeater Core is to a extend device diagnostics/debug ability while an application software is being developed. The Repeater Core does not interact with other user cores in the design. Only the implemented functionality is resending of the ingoing data. It is done in the raw form. The input stream is binary the same as the output stream. Data are re-sent immediately without any additional delay. See the Figure 5-27 showing a data flow through the core.

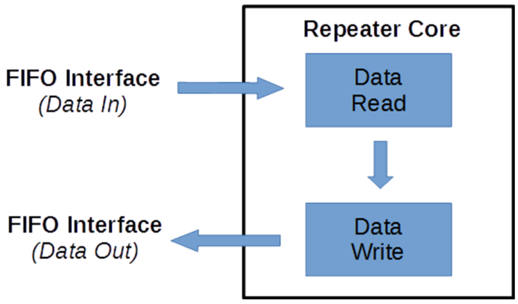


Figure 5-27 Architecture of the Repeater Core

6 Supporting application software

6.1 Server/Client solution for the FITPix COMBO device

The software architecture based on the server-client structure is fully convenient solution for the composited FITPix COMBO device and its resource sharing issue. Therefore it was decided to design the COMBO server. The server is directly connected to the managed device while other user applications are connecting to virtual channels. The user applications – Pixelman (acting as the Timepix DAQ control tool) and IEAP spectrometry (acting as the back side pulse DAQ control tool) are well fitting actors in such a scenario. The Figure 6-1 shows the exact arrangement of the presented server/client software solution. There are more client applications connected to the server. The colored client blocs are considered to be essential for a device run. The shaded blocs are not needed for device operation. They are considered as optional (as they provide diagnostic and system information).

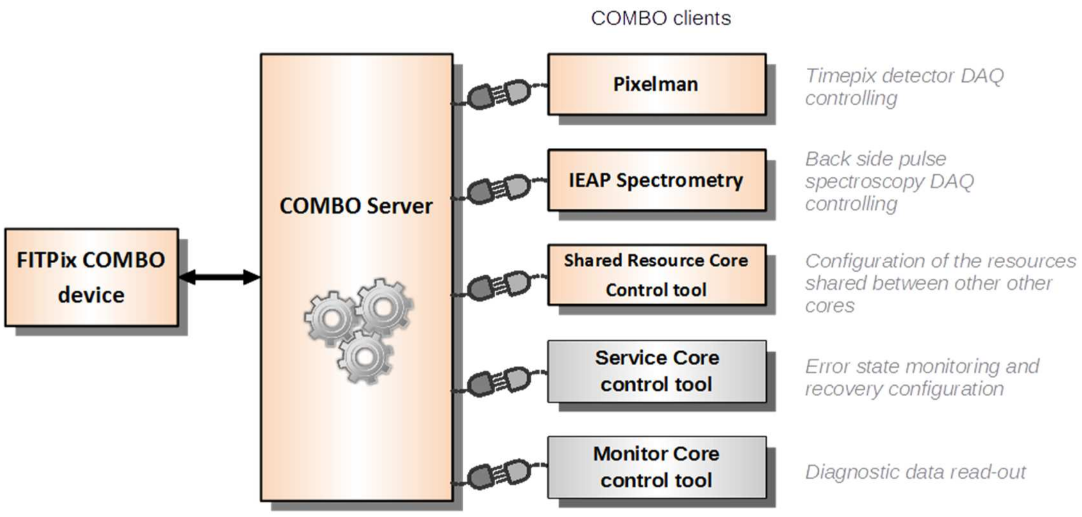


Figure 6-1 Server/Client solution for the FITPix COMBO device

The architecture of the FITPix COMBO firmware has a great impact on the complexity of the server application. The firmware design takes this fact into account. A well planned communication protocol used for data transmission over the shared bus to the server and the segmentation of the firmware functionality into individual user cores (virtual devices) is the most positively contributing feature. Thus the firmware design makes the server design easier and it also lowered an effort needed for its implementation.

Virtual channels of the COMBO server are implemented by the Named Pipes (Service provided by the hosting operating system). The Named Pipes behave as the standard data streams. The server application was implemented in the high level C# language using .NET framework by means of the Visual studio development environment.

6.2 COMBO Server application architecture

The Figure 6-2 presents software architecture of the server solution including a sample client. On the left side there is shown the COMBO server itself. On the right side there is an instance of one client (potential user of the FITPix COMBO device). The server consists of the main application (representing a high software layer) and several DLL libraries (forming a low software layer).

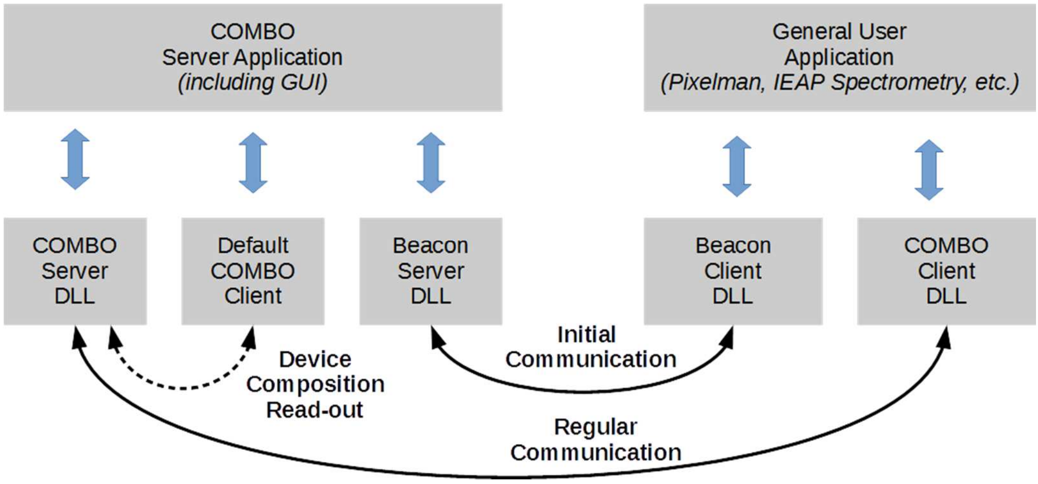


Figure 6-2 Software architecture - Server / Client solution used for the FITPix COMBO device sharing between user applications.

The software architecture implies that the COMBO server does not provides just sharing of the FITPix COMBO resources among a group of clients. It also provides additional Beacon services. They are not of the primer focus but they are very important for clients. The beacon services helps to find the right virtual channel that is assigned to the specific user core within the FITPix COMBO device. Detailed description of the constituting parts of the server follows.

6.3 COMBO server DLL

It is the heart and the most significant part of the entire software solution. The library implements all the functionality related to the FITPix COMBO device management (initialization, data transfer, data de/coding) and it also implements the client related management (creation of virtual channels, de/connection, and data transfer…). A structure of the DLL library is shown in the Figure 6-3.

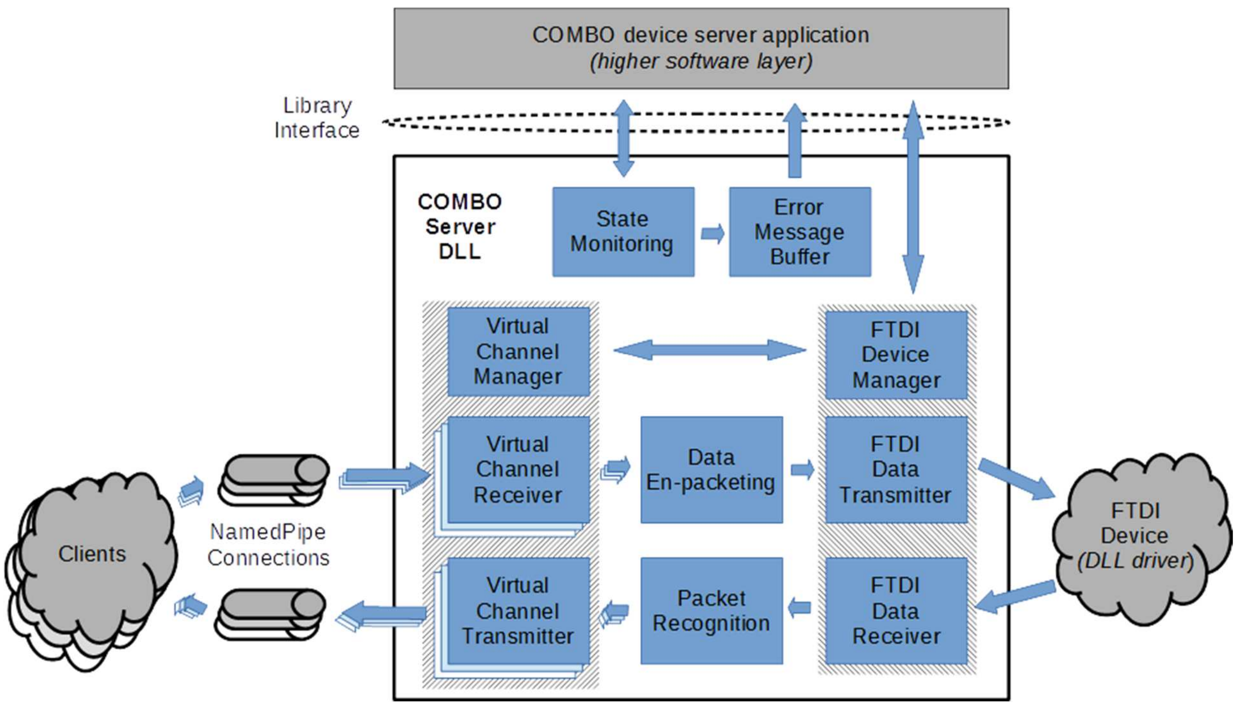


Figure 6-3 Structure of the COMBO server DLL

Execution of the functionality, presented in the block above, is done through the threads running in parallel. Each thread performs a particular task within the server library. Functional blocks can be divided into two groups. The first group associates the functionality that is directly related to the data routing between the device and Clients (Virtual channel Receiver/Transmitter, Packet recognition, Data enpacketing, FTDI data transmitter/Receiver). The second group associates the functionality that is related to the management of a program run (FTDI Device Manager, Virtual Channel Manager, State monitoring and error reporting). Both functional groups are described in the following text.

6.3.1 Data routing

The Figure 6-4 below demonstrates how the data routing is implemented within the COMBO server library. There are two branches. One branch begins in the FITPix COMBO device and it ends in a general virtual channel. The second branch is oriented exactly in the opposite direction. It begins in the virtual channel and it leads to the FITPix COMBO device. The data processing done within both branches is just the inversion. All branch stages are interleaved by memory buffers (queues). The pipeline structure is quite obvious. It enables to implement parallel execution of the data processing. Each pipeline stage is executed by own thread.

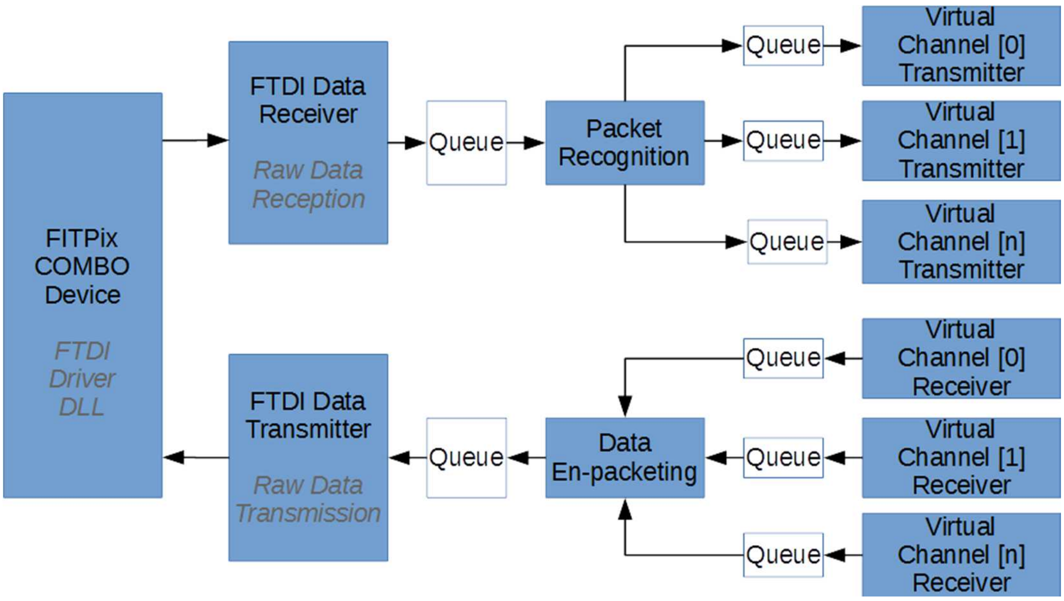


Figure 6-4 Data path routing implementation within the COMBO server DLL

- **FTDI data receiver**
  The thread is dedicated for data the read-out from the FTDI device. It reads all the data provided by the FTDI and puts them into the associated output queue. Any communication failure or data loss is reported.
- **FTDI data transmitter**
  The thread is dedicated for data resending. It reads data from the associated queue and immediately writes it into the FTDI device. Any communication failure or data loss is reported.
- **Virtual Channel receiver**
  It represents a pool of threads. Each particular virtual channel is managed by one instance of the Virtual channel receiver thread. So the number of threads depends on the number of currently used virtual channels. The Virtual channel receiver is responsible for data reception from an outer client (done over the Named Pipe). It immediately passes received data to the associated queue for further

processing. If there is no new client data the thread is blocked and it gets into the sleep state. See the Figure 6-5 showing a related state diagram.

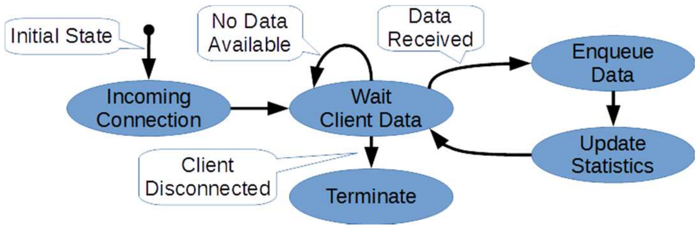


Figure 6-5 Virtual channel receiver state diagram

- **Virtual channel transmitter**
  The way of the Virtual channel transmitter implementation is quite similar to the Virtual channel receiver implementation. Each particular virtual channel transmission is done by own thread. The Virtual channel transmitter reads data from the associated queue and it immediately writes it to the virtual channel (pipe). If no data are present in the queue it is blocked and it gets in the sleep state. See the Figure 6-6showing a related state diagram.

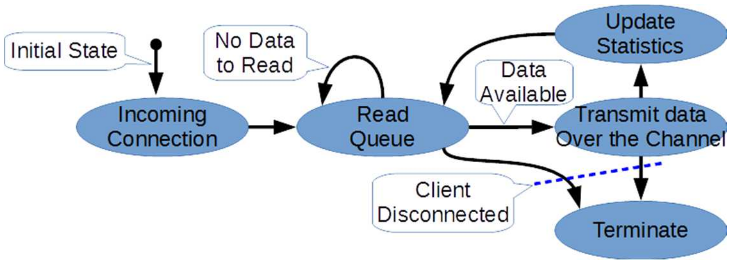


Figure 6-6 Virtual channel transmitter state diagram

- **Packet recognition**
  The thread serves as a state machine dedicated for packet recognition. Packets are decoded from the ingoing raw byte stream. The source stream is read from the input queue that contains data previously received from the FTDI chip. If a packet is successfully recognized than its payload is extracted. Next, the payload data is routed to an output. There are several output queues. Each virtual channel is associated with one output queue. Depending on the virtual channel index (gained from the packet service field part) the payload data is stored into the appropriate queue. In the case of non-existing virtual channel the data cannot be delivered. It is disposed then.
- **Data stream enpacketing**
  Thread serves as a state machine that reads data from one of the inputs (queues belonging to the virtual channels connected to outer clients). The read data is used as a payload for the newly formed packet. The packet data is saved into the output queue when the packet build-up process is done. Subsequently, the data is taken from the queue by the FTDI data transmitter.

6.3.2 Run Management

Some kind of the run management is absolutely necessary for the server library operation. The library initialization has to be solved as well as the normal run state has to be maintained. All the server data paths are dynamically created when they are needed. Thus, the run management is responsible for on-fly configuration of the data paths. Allocation of memory buffers and instantiation of any other objects needed for the data path build-up is also a part of the run management responsibility. Even the client connecting/disconnection, FTDI device maintenance is a part of the implemented functionality.

- **FTDI device manager**
  Thread manages the FTDI device of the FITPix COMBO device. Its purpose is to seek for a presence of the compatible device. It performs device initialization and it makes it ready for future data transmission. It also performs automatic FTDI device reconnection and re-initialization in the case of the temporary device loss. The thread allocates resources (memory queues, virtual channels) needed for data transfer over data paths. The state diagram in the Figure 6-7 shows operation of the FTDI manager.

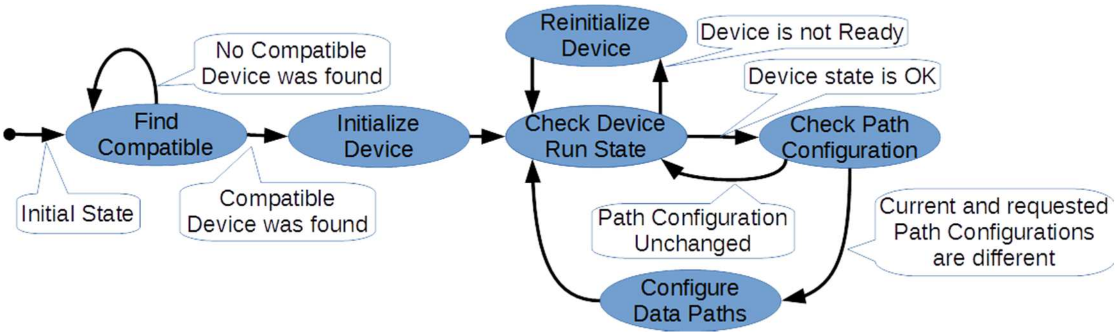


Figure 6-7 FTDI device manager state diagram

- **Virtual channel manager**
  The thread monitors a state of all managed virtual channels. The supervising function is presented by the state diagram in the Figure 6-8. The thread performs its action periodically. During the each cycle the check of the employed and unemployed virtual channels is done. Employed channels are tested if they are already engaged or if they ready to accept new client connection. If client disconnection is detected the channel resource are disposed and the state of the channel is modified to be unemployed. Afterwards, in the second check, all unemployed channels are reinitialized to be ready for new incoming client connection. The last function of the thread is to manage over-all number of virtual channels present in the system. According to the outer request a number of virtual channels is increased or decreased. After the start-up, just one virtual channel is created by default.

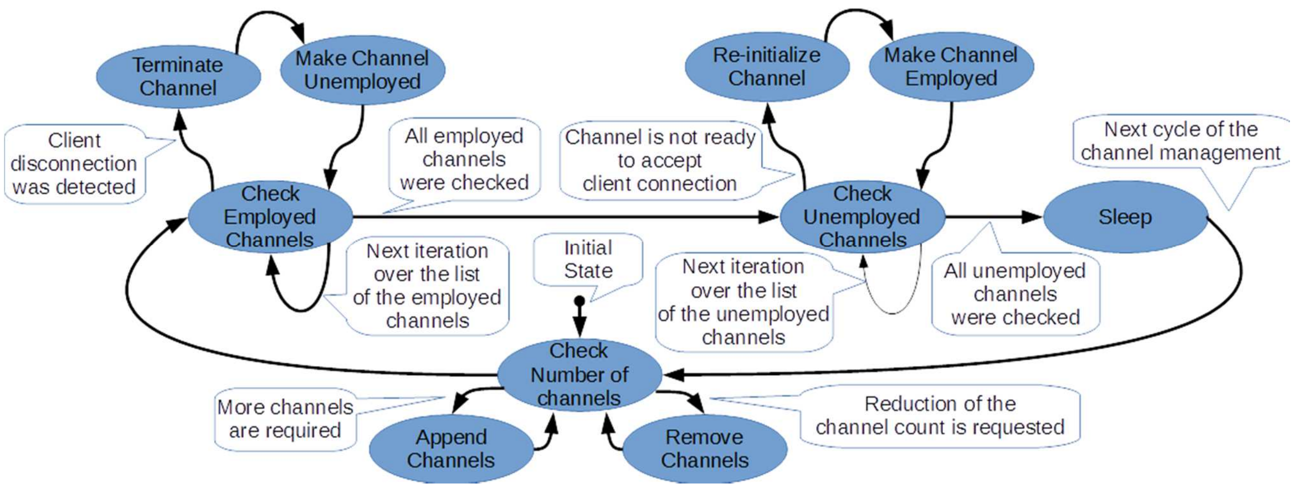


Figure 6-8 Virtual channel manager state diagram

- **Channel state and data traffic monitoring**
  The state monitoring involves continuous recording of the traffic information. The statistical data are recorded during the entire server run involving all the data paths that are currently instantiated. Information like a time of client connection, a number of transferred bytes, a number of transferred

packets, channel state (dis/connected). All the statistical data is available for the higher software layer when it is requested.

6.3.3 Error state reporting

The server library implements a system for the error event reporting. Error events arising during the server run (in each previously described functional module) are saved into the Error message buffer. Recording of the error events can be filtered by the severity level settings. It allows preventing from recording of unimportant messages. Just severe events should be collected during a normal application run. More detailed reporting is getting useful during the software debug session. The server library does not implement any logics for the error state resolving. Error events have to be read-out and evaluated by the higher software layer. Decision about subsequent recovery action is under its competence.

6.4 Beacon mechanism integration

Although each functional core within the FITPix COMBO device is granted with the separate communication channel it is still not the optimal solution. From the client application point of view it is not possible to arrange connection without knowledge of the virtual channel existence. Therefore the COMBO server has been equipped with an additional supporting service. The Beacon service significantly simplifies a finding process of the compatible connection point (channel). As it was mentioned in the previous description in the section 6.2 and it was shown in the Figure 6-2 the initial communication between the Beacon client and the Beacon server is done during the client application start-up phase. The client receives essential information about a presence of the compatible virtual devices. In the case of the positive response the client application proceeds in establishing of connection to the right virtual channel of the COMBO server.

6.4.1 Default client – device composition read-out

The COMBO server integrates one client within its architecture. The default client is a single purpose program that serves for the read-out of the device composition information. As it was mentioned in the firmware description part 5.6 the Composition reader Core is always located at the virtual channel zero. Therefore the default client still connects to zero index channel to get a data stream containing the composition information there. The data stream is decoded by the default client and the composition information is provided to the higher software layer. After that, the default client is disconnected to let channel with zero index free for any other client application.

6.4.2 Beacon Server

It distributes information about the FITPix COMBO composition for all client applications. It is started automatically just after the default client finishes its job. Till the composition evaluation process is not finished the beacon server cannot provide any relevant composition information to client applications. Once the beacon is started-up it is kept active during the entire COMBO server run time.

6.4.3 Beacon Client

A purpose of the beacon client is to receive the complete device composition information and to make its filtration. According to the applied filtering criterion the right connection point associated with the requested compatible functional core can be get. The beacon client is implemented as a DLL library to allow a reuse of its functionality. The beacon client services are available for each user application by simple inclusion of the library.

6.5 COMBO Server start-up

The sequence diagram in the Figure 6-9 explains interaction between all actors participating during the start-up phase of the COMBO device server. On the left side there is a COMBO server application side. On the right side there is a user application part. In the first phase the server application creates an instance of the COMBO server library. Then the server library is initialized (i.e. initialization of the FITPix COMBO device and default configuration of the data paths). In the second phase the server application creates a default client. It is immediately requested to read-out the composition information from the FITPix COMBO device. The default client connects to the server library and it communicates with over the virtual channel zero (dedicated for the Composition reader Core). After decoding of a raw data stream, the default client returns the composition information to the server application. In the third phase a beacon server is created and started. The previously obtained composition information is distributed further by means of the Beacon server to other users. In the fourth phase the user application uses beacon services to find a compatible virtual device to operate up-on. The beacon client receives the composition information and it performs filtration to get a reference to the compatible virtual device. In the last step the user application establishes connection to the referenced virtual device.

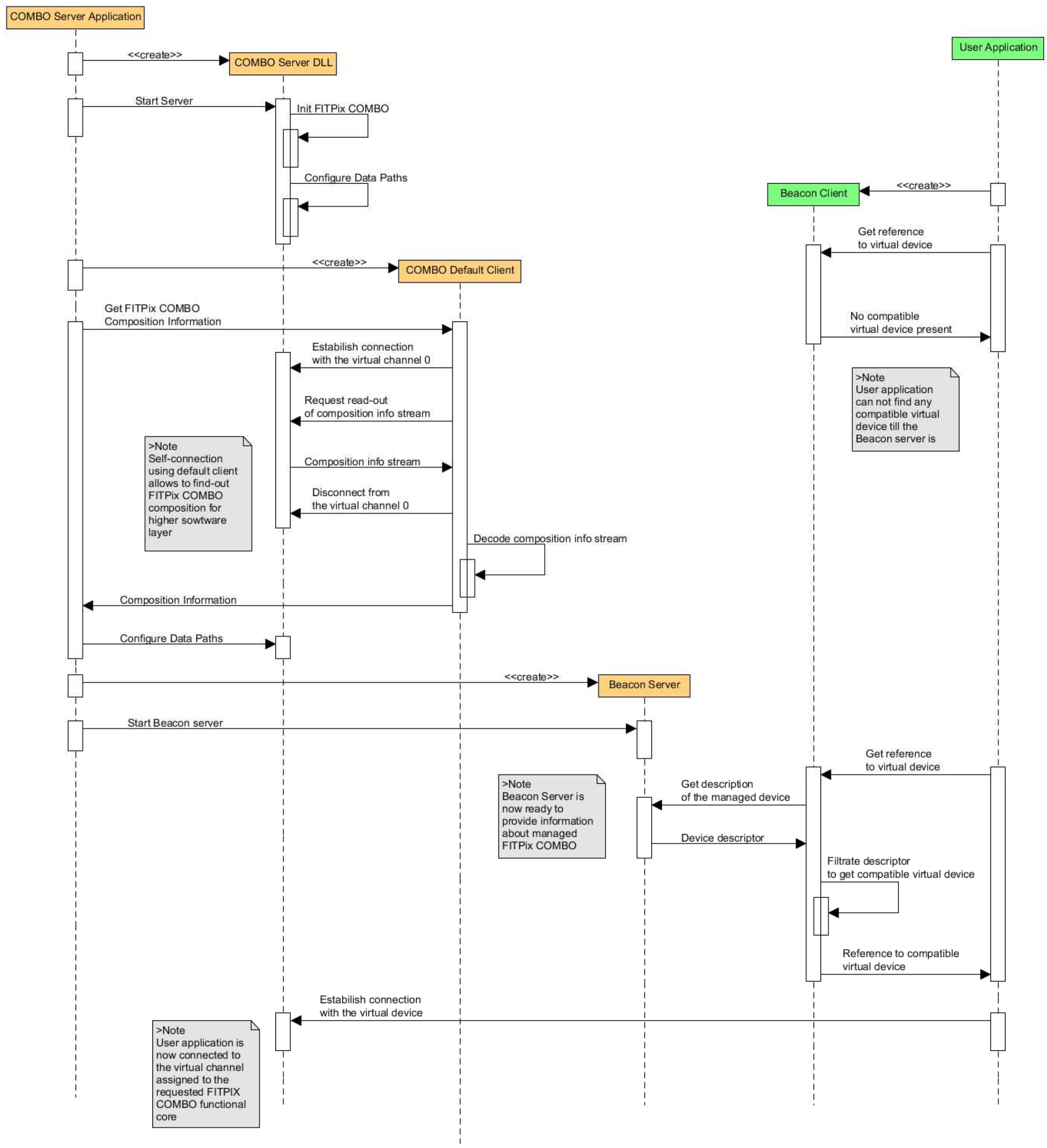


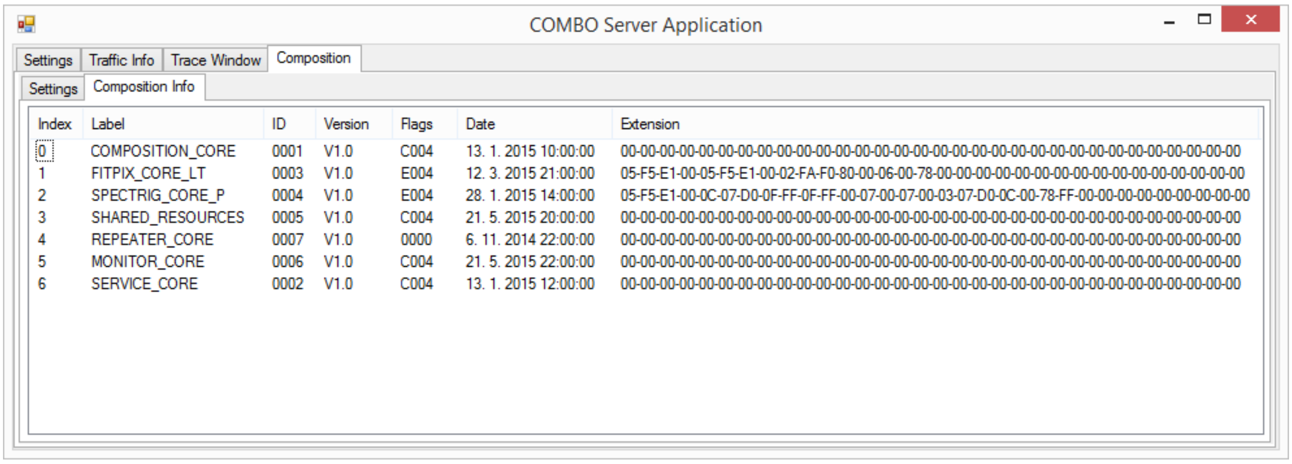
Figure 6-9 Sequence diagram showing the initial interactions between the COMBO server and the user application during the start-up phase

6.6 COMBO Server application GUI

Following parts demonstrates how interaction between the user and the COMBO server application is solved. The graphical user interface allows simple handling (controlling and monitoring of its activity) of the server to a user.

6.6.1 Device composition information window

The Figure 6-10 is a screenshot of the COMBO server window displaying composition information. There are shown all the user cores (virtual devices) synthetized within the currently connected FITPix COMBO device. Detailed descriptive information of each particular core is available for an application user through the Beacon services.

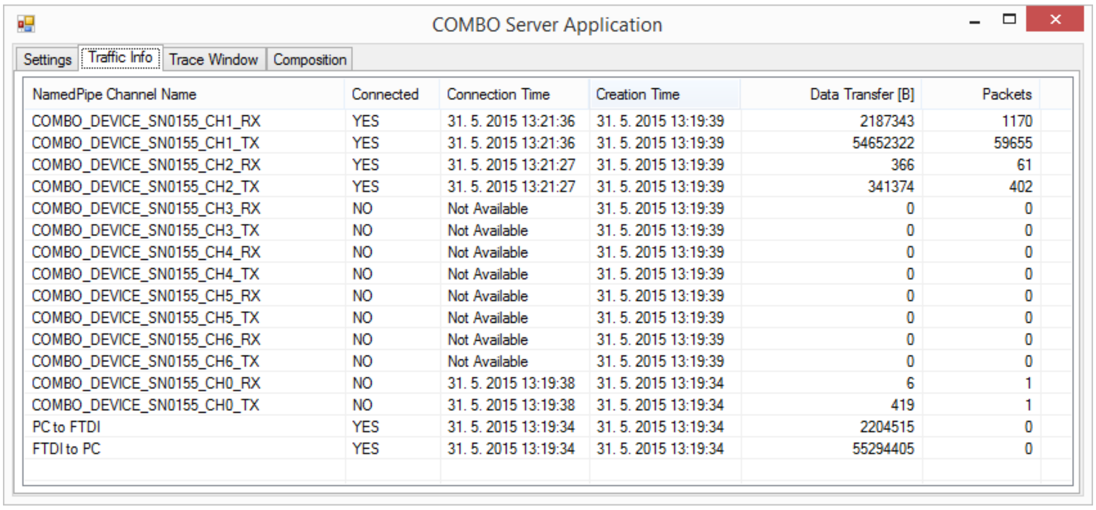


Index	Label	ID	Version	Flags	Date	Extension
0	COMPOSITION_CORE	0001	V1.0	C004	13. 1. 2015 10:00:00	00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00
1	FITPIX_CORE_LT	0003	V1.0	E004	12. 3. 2015 21:00:00	05-F5-E1-00-05-F5-E1-00-02-FA-F0-80-00-06-00-78-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00
2	SPECTRIG_CORE_P	0004	V1.0	E004	28. 1. 2015 14:00:00	05-F5-E1-00-0C-07-D0-0F-FF-0F-FF-00-07-00-07-00-03-07-D0-0C-00-78-FF-00-00-00-00-00-00-00-00-00
3	SHARED_RESOURCES	0005	V1.0	C004	21. 5. 2015 20:00:00	00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00
4	REPEATER_CORE	0007	V1.0	0000	6. 11. 2014 22:00:00	00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00
5	MONITOR_CORE	0006	V1.0	C004	21. 5. 2015 22:00:00	00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00
6	SERVICE_CORE	0002	V1.0	C004	13. 1. 2015 12:00:00	00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00-00

Figure 6-10 COMBO server - Composition information window

6.6.2 Traffic information window

The Figure 6-11 shows an output of the Traffic monitoring service of the COMBO device server. There are shown statistical information for all the currently managed virtual channels: information about the client connections state, FTDI connection state, raw data counters as well as packet counters.

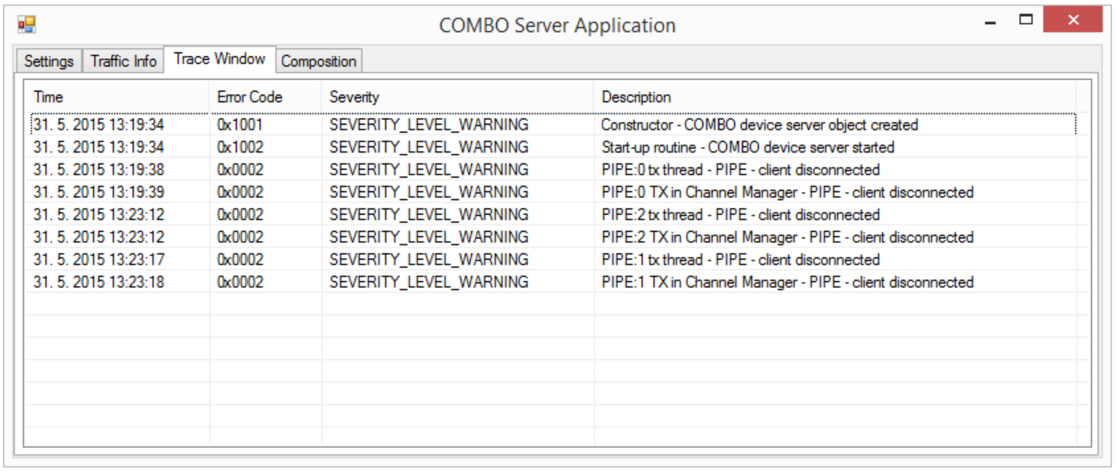


NamedPipe Channel Name	Connected	Connection Time	Creation Time	Data Transfer [B]	Packets
COMBO_DEVICE_SN0155_CH1_RX	YES	31. 5. 2015 13:21:36	31. 5. 2015 13:19:39	2187343	1170
COMBO_DEVICE_SN0155_CH1_TX	YES	31. 5. 2015 13:21:36	31. 5. 2015 13:19:39	54652322	59655
COMBO_DEVICE_SN0155_CH2_RX	YES	31. 5. 2015 13:21:27	31. 5. 2015 13:19:39	366	61
COMBO_DEVICE_SN0155_CH2_TX	YES	31. 5. 2015 13:21:27	31. 5. 2015 13:19:39	341374	402
COMBO_DEVICE_SN0155_CH3_RX	NO	Not Available	31. 5. 2015 13:19:39	0	0
COMBO_DEVICE_SN0155_CH3_TX	NO	Not Available	31. 5. 2015 13:19:39	0	0
COMBO_DEVICE_SN0155_CH4_RX	NO	Not Available	31. 5. 2015 13:19:39	0	0
COMBO_DEVICE_SN0155_CH4_TX	NO	Not Available	31. 5. 2015 13:19:39	0	0
COMBO_DEVICE_SN0155_CH5_RX	NO	Not Available	31. 5. 2015 13:19:39	0	0
COMBO_DEVICE_SN0155_CH5_TX	NO	Not Available	31. 5. 2015 13:19:39	0	0
COMBO_DEVICE_SN0155_CH6_RX	NO	Not Available	31. 5. 2015 13:19:39	0	0
COMBO_DEVICE_SN0155_CH6_TX	NO	Not Available	31. 5. 2015 13:19:39	0	0
COMBO_DEVICE_SN0155_CH0_RX	NO	31. 5. 2015 13:19:38	31. 5. 2015 13:19:34	6	1
COMBO_DEVICE_SN0155_CH0_TX	NO	31. 5. 2015 13:19:38	31. 5. 2015 13:19:34	419	1
PC to FTDI	YES	31. 5. 2015 13:19:34	31. 5. 2015 13:19:34	2204515	0
FTDI to PC	YES	31. 5. 2015 13:19:34	31. 5. 2015 13:19:34	55294405	0

Figure 6-11 COMBO server - Traffic information window

6.6.3 Event trace output

Window serves as the visual log of all error events registered during the server run. Time of event occurrence, unique error code, severity and additional description is available for application user.



Time	Error Code	Severity	Description
31. 5. 2015 13:19:34	0x1001	SEVERITY_LEVEL_WARNING	Constructor - COMBO device server object created
31. 5. 2015 13:19:34	0x1002	SEVERITY_LEVEL_WARNING	Start-up routine - COMBO device server started
31. 5. 2015 13:19:38	0x0002	SEVERITY_LEVEL_WARNING	PIPE:0 tx thread - PIPE - client disconnected
31. 5. 2015 13:19:39	0x0002	SEVERITY_LEVEL_WARNING	PIPE:0 TX in Channel Manager - PIPE - client disconnected
31. 5. 2015 13:23:12	0x0002	SEVERITY_LEVEL_WARNING	PIPE:2 tx thread - PIPE - client disconnected
31. 5. 2015 13:23:12	0x0002	SEVERITY_LEVEL_WARNING	PIPE:2 TX in Channel Manager - PIPE - client disconnected
31. 5. 2015 13:23:17	0x0002	SEVERITY_LEVEL_WARNING	PIPE:1 tx thread - PIPE - client disconnected
31. 5. 2015 13:23:18	0x0002	SEVERITY_LEVEL_WARNING	PIPE:1 TX in Channel Manager - PIPE - client disconnected

Figure 6-12 COMBO server - Event trace window

6.7 Pixelman client support

6.7.1 Pixelman software package

The Pixelman software package [22] is used worldwide as the main tool for the control and DAQ of pixel detectors of the Medipix family (see presentation in the Figure 6-13). The Pixelman provides a full support for all the Medipix family detectors. But not just the DAQ is in a scope of the Pixelman. It represents really complex solution for the data processing, advanced analysis, detector calibration, result visualization etc. Due to the sophisticated software structure (shown in the Figure 6-14) it allows further extension of the functionality by addition of newly created plugins and libraries.

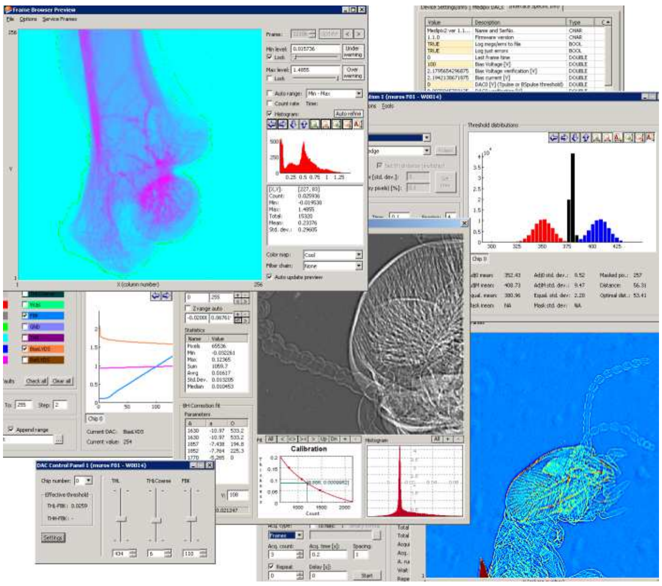


Figure 6-13 Pixelman software package demonstration

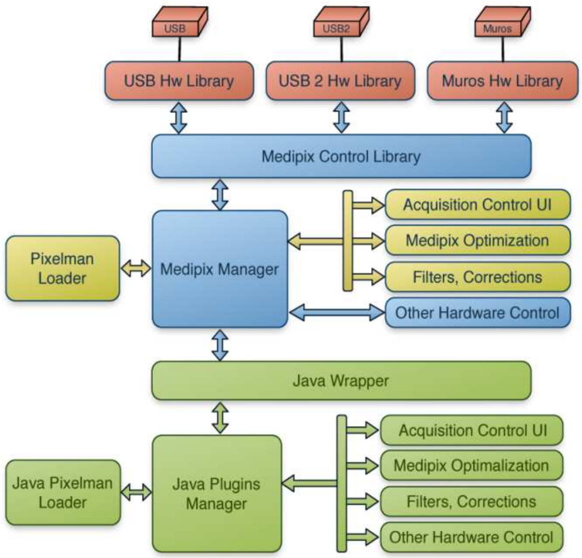


Figure 6-14 Architecture of the Pixelman software package

6.7.2 Concept of the hardware control libraries

A support of various types of read-out interfaces is provided by means of the hardware control libraries. They represent a low level layer of the Pixelman software architecture. All hardware specific details are abstracted for a higher level of the Pixelman. Services offered by the read-out device are accessible through the common interfacing methods. When a support to a newly designed read-out interface is needed a new hardware control library has to be implemented. This is also the case of the FITPix COMBO device.

6.7.3 FITPix COMBO hardware control library

The hardware control library for the FITPix COMBO device was derived from already existing one. The FITPix 3.x control library was used as a template for the development. The Figure 6-15 shows a structure of the original library. The Figure 6-16 shows modifications in the new library that were needed and implemented to enable a support to the FITPix COMBO device.

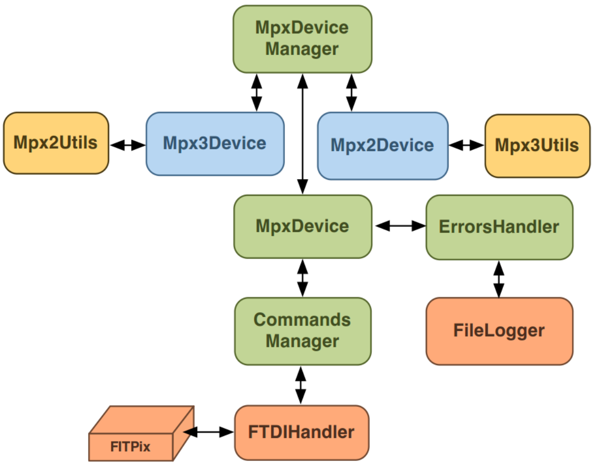


Figure 6-15 Structure of the HW control library used for the standard FITPix device

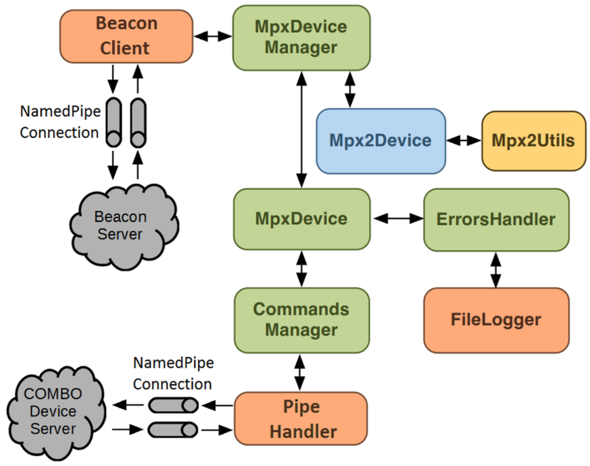


Figure 6-16 Modified structure of the FITPix HW control library implementing connection to the COMBO server

The main difference is to be seen in the outer connection of the FITPix. Previously, the FTDI handler block was dedicated for direct communication with the FITPix. It is no more possible in the server/client oriented solution. Therefore the FTDI handler was replaced by the Pipe Handler. It manages the indirect connection with the FITPix Core provided by the COMBO device server. The Pipe Handler transfers raw data and it keeps channel (based on the named pipes) opened. The second main modification is integration of the Beacon Client into the library. Services of the Beacon are used just during the initialization phase of the hardware control library. The MPX Device manager gets a list of all available compatible FITPix Core devices from the Beacon client. In the original library version the device list was gained by scanning of all FTDI chip identifiers. The rest of the library architecture was left almost unchanged because a format of the exchanged data stream between the FITPix Core and the library is quite similar to original one. Just a parametric content of some commands (like a Read AD channel, set DA channel, Set bias voltage…) were redefined to reflect the FITPix Core design.

6.8 IEAP Spectrometry client support

6.8.1 IEAP Spectrometry software package

It is a software tool dedicated for the control of the spectroscopy acquisition and data processing (see the tool presentation in the Figure 6-17). The tool provides all the necessary functionality (like data recording, visualization, analysis, detector calibration, etc.). The tool was developed under the IEAP CTU in Prague. A support to the new front-end device can be done by implementation of the hardware control library while integrating all the mandatory interfacing methods.

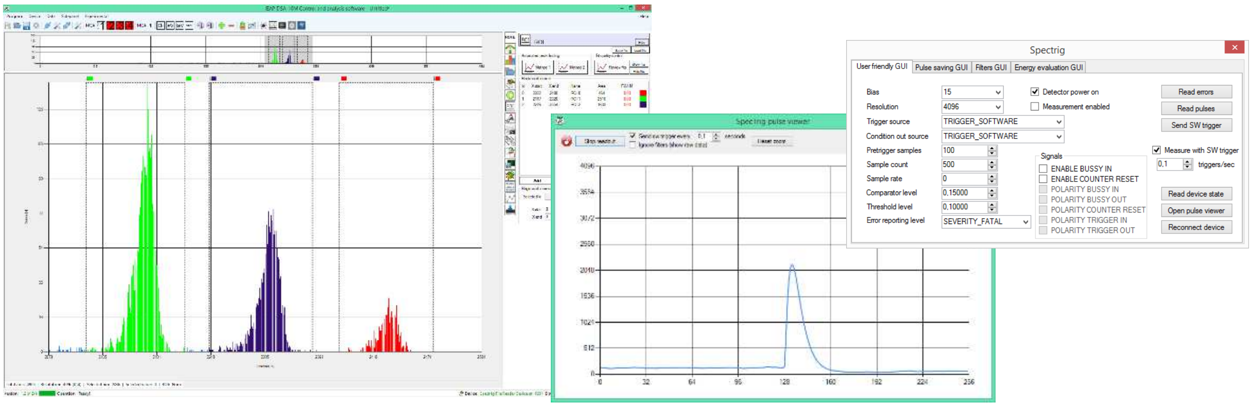


Figure 6-17 Presentation of the IEAP Spectrometry tool

6.8.2 Spectrig control library

A new hardware control library was created to allow utilization of the FITPix COMBO under the IEAP Spectrometry tool. A structure of the Spectrig Core DLL library is shown in the Figure 6-18. A purpose of the presented functional blocks is following. The device manager performs all the activity related to the driver initialization. Services of the Beacon client are used to find a connection point to the compatible Spectrig Core within the FITPix COMBO device.

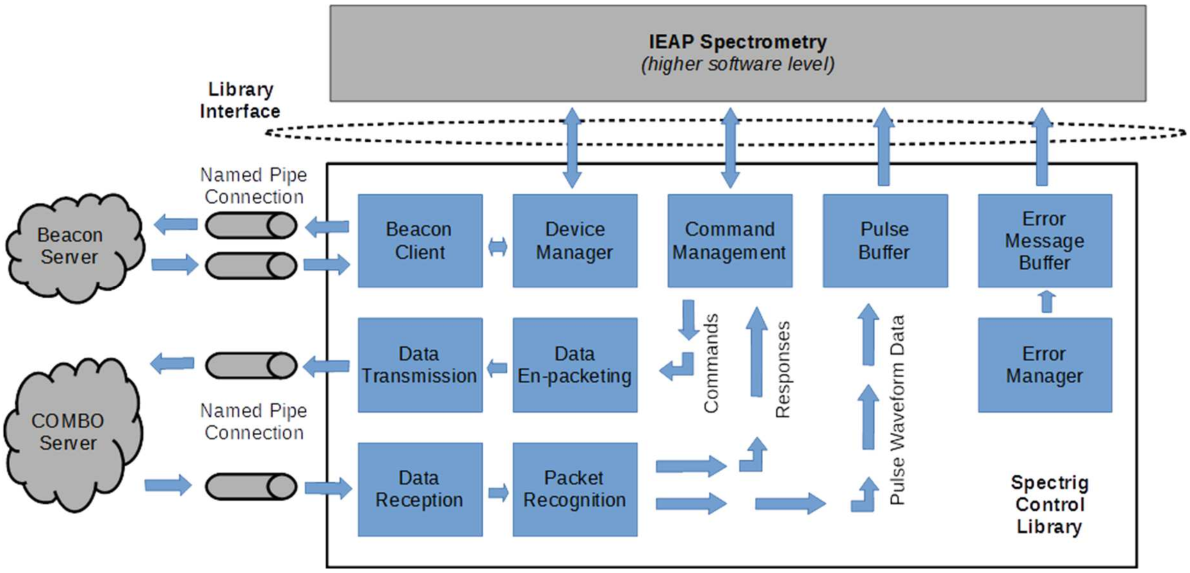


Figure 6-18 Architecture of the Spectrig Core control library

In direction to the Spectrig there are transmitted just command packets. In the opposite direction there are transmitted two different types of packets. They are decoded from the raw input data stream by the Packet recognition unit. In dependence on the packet type following routing is chosen. The packets containing command responses are directed to the Command management block while the packets containing pulse waveform data are directed to the Pulse buffer. Pulse data is accumulated in the buffer till the higher software layer performs the read-out operation or the buffer clean-up. In parallel to all other actions there is performed state monitoring by the Error management block. Error events are recorded into the Error message buffer where they are getting available for the higher software layer. Resolving of the error events is not up to the control library.

6.9 Other necessary supporting software tools

The FITPix COMBO device does not contain just the FITPix Core and the Spectrig Core. There are integrated several more functional cores. Some software support is also necessary to control operation of other integrated functional cores. Therefore the following single-purpose software tools were designed. Epecially in the case of the parallel run of the FITPix and the Spectrig Core measurement they become necessary. A dedicated software tool for the handling of the device shared resources is of the great importance (otherwise mutual dependencies would be undefined and measured data would be uncorrelated). These single purpose tools are most likely an objective for the further development as they were created with aim to enable testing of the FITPix Combo device.

6.9.1 Shared resources control tool

As it was mentioned in the 5.10, the solution of the shared resources issue is important for operation of the composite device. The Shared resources control tool was created to allow a management of the shared resources of the FITPix COMBO device. The most important function of the tool is to configure mutual connection between internal and external signals (see the Figure 6-19 showing an exemplar tool screenshot containing signal configuration interface). It is absolutely necessary for an arrangement of the well synchronized measurement of the Spectrig Core and FITPix Core. The signals trigger (in/out), busy (in/out) have to be properly interconnected. The tool can also lock peripheries to let just one core utilize them or to let them accessible for all in parallel (see the Figure 6-20 showing exemplar periphery assignment configuration).

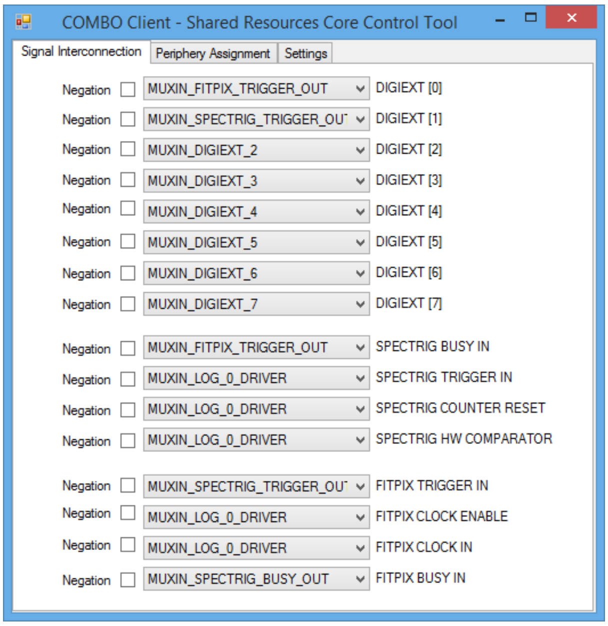


Figure 6-19 Shared resources control tool - Configuration of the signal interconnection

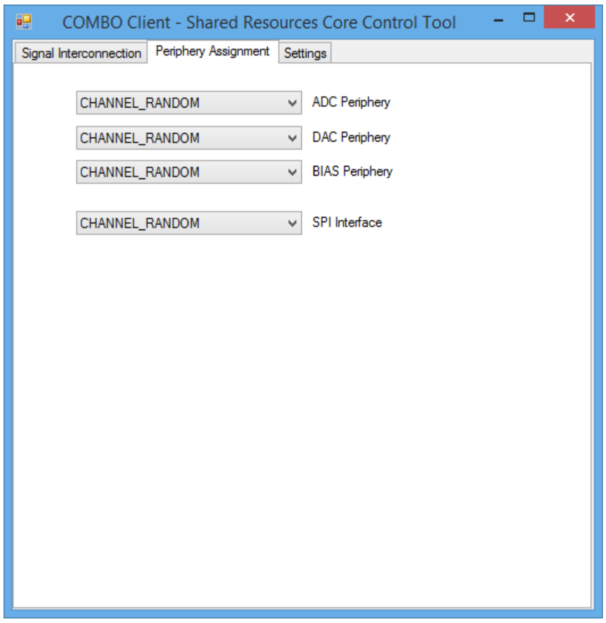


Figure 6-20 Shared resources control tool - Configuration of the periphery access

6.9.2 Service Core control tool

A purpose of the tool is to configure Service Core of the FITPix COMBO device. Error event recording, read-out, and automatic recovery of other user cores (see the Figure 6-21 showing the tool interface with the exemplar configuration). Next, the error event recording and logging is also the objective of the tool (see the Figure 6-22 showing the exemplar output of the error event recording).

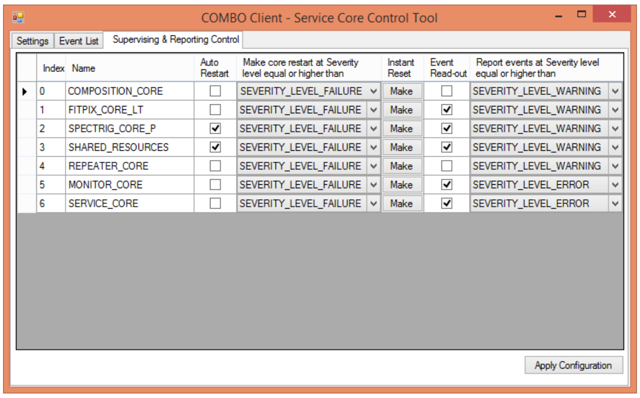


Figure 6-21 Service Core control tool - Configuration of the core operation

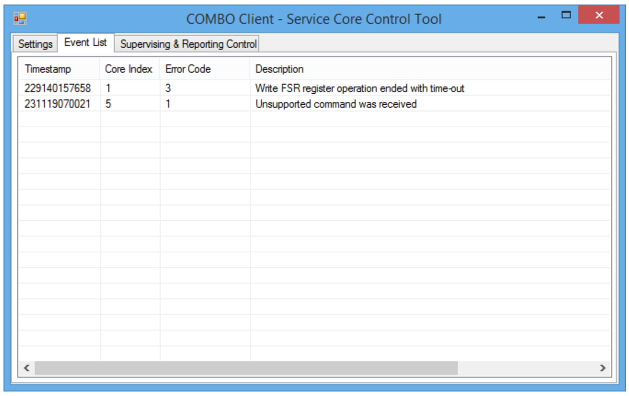


Figure 6-22 Service Core control tool - Recording of the error events occurring within the FITPix COMBO device

6.9.3 Monitor Core control tool

The tool was created to provide a mean for collecting and recording of the diagnostic data. Main purpose of the tool is to log a stream of the diagnostic data gained during the measurement running in the FITPix Core or Spectrig Core. The diagnostics data contains information about supply voltages, currents and device temperature, etc. (See the exemplar outputs of the Monitor control tool - the Figure 6-23 showing the ADC channel scan and the Figure 6-24 showing the temperature scan)

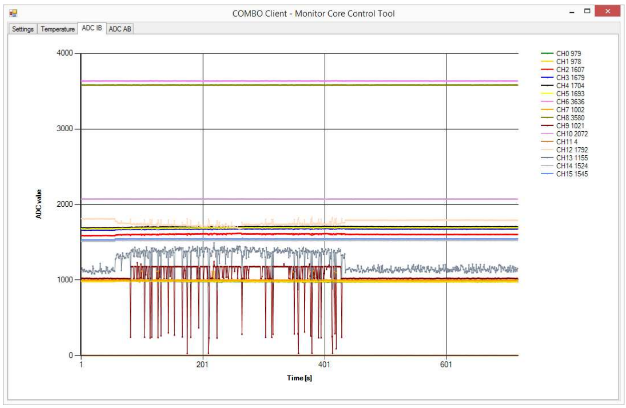


Figure 6-23 Monitor Core control tool – ADC channel scan

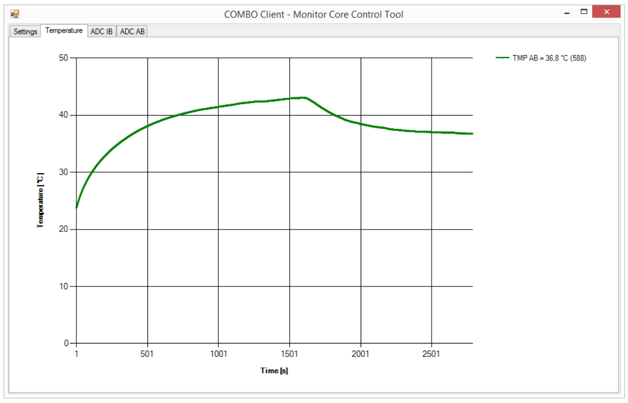


Figure 6-24 Monitor Core control tool - Temperature scan

7 Optimal tuning of the spectroscopy chain

The correct adjustment of the spectroscopy chain had to be done to meet a requirement on the acceptable spectroscopic resolution. The final adjustment was determined by the Timepix detector properties. During the research the key influencing factors were discovered (as it is described in following text).

7.1 Signal shaping time

Several facts were taken into account while considering the optimal shaping time of the back side pulse signal. The most significant requirement on the signal processing is propagation of the information about particle hit from the Spectrig to FITPix Core (also called as self-trigger generation). The faster shaping time allows faster reaction (a threshold value is reached earlier). Such a fast reaction is needed because of measurement in the pixelated part is running in parallel to back side pulse sampling. Note that the shaping time of the in the individual pixel can be configured (see the pixel cell description 1.2.5.1) to be in order of µs. In this case just a small portion of charge would be undetected in the affected pixels even if their measurement is initiated with some delay after the particle interaction time (the signal in pixel electronic is still in a rise-up phase when the self-trigger is generated).

The next significant factor influencing selection of the fast shaping time is the coupling between the pixelated part of the detector and the common electrode. Once the Timepix shutter is activated then unwanted noisy signal is introduced into the effective spectroscopic signal. See the Figure 7-1 showing an exemplar response to an alpha particle originating from the Am 241 radiation source. If slower shaping time would be used then the effective spectroscopy signal and the parasitic signal coupling joint together to form a single common pulse. It is impossible to recognize them during the post-processing. The resulting spectroscopic resolution would be significantly deteriorated in this case. It is getting even more important factor than filtration of the high-frequency background noise to avoiding the aliasing effect. The achievable sampling frequency of the used flash AD converter is 100 MSa/s. It allows setting the shaping time to be 100 ns (faster shaping would not provide sufficient count of sampling points around the peak maximum for evaluation of energy information)

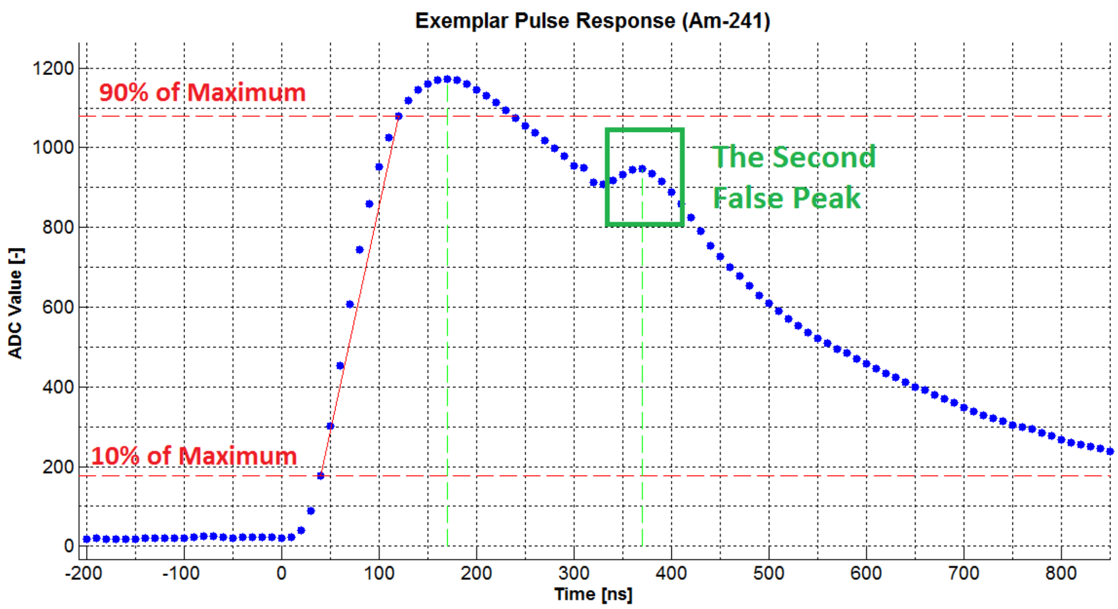


Figure 7-1 Exemplar spectroscopic response for Am alpha source while using fast 100 ns shaping time. Signal rise marked with the red line. The negative influence of the Timepix shutter on the spectroscopic signal marked with green box.

The next plot shown in the Figure 7-2 shows more in detail how the shutter noise signal influences effective spectroscopic signal. In this case a start of the Timepix measurement in the pixelated part was intentionally delayed. It was postponed about 2 µs to let the spectroscopic signal to return on the basic level. The amplitude of the noisy signal is clearly to be seen. There is also shown one more shutter originating peak with the negative polarity. It signifies the end of the measurement when the Timepix shutter signal was de-asserted. The acquisition window of the Timepix measurement is 5 µs in this case.

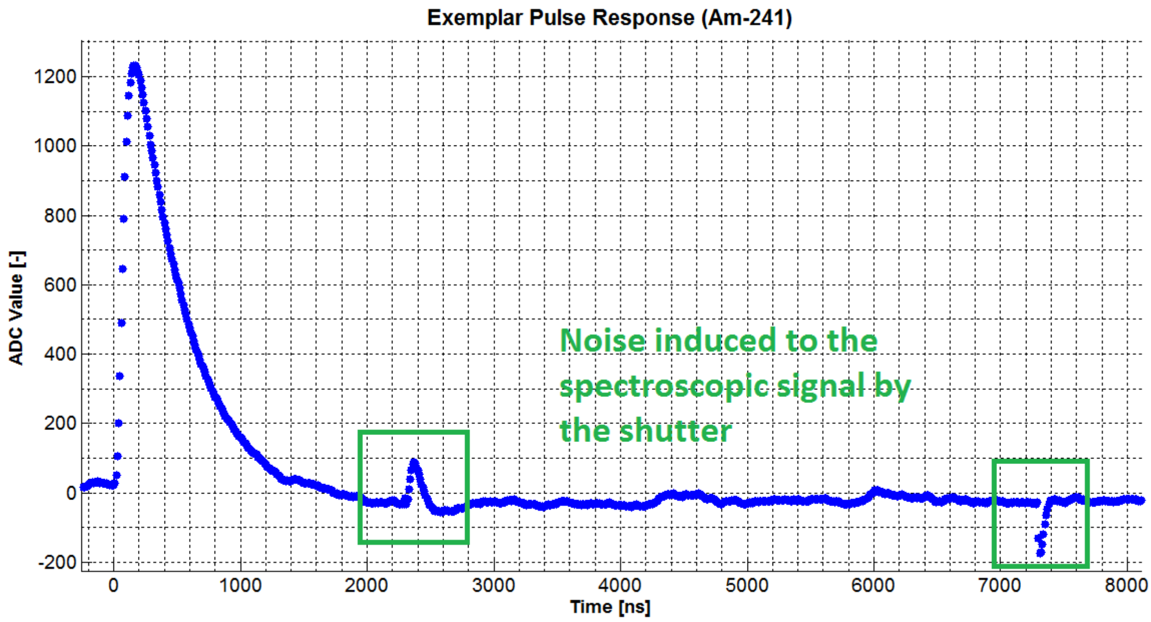


Figure 7-2 Exemplar spectroscopic response for Am alpha source while using fast 100 ns shaping time. The start of the measurement in the pixelated part is intentionally delayed to show how big the noisy signal originating from the Timepix shutter is in comparison to the response from an alpha particle.

7.2 Selection of the sensing resistor vs leakage current

The usual value of the Timepix sensor leakage current could be in order of micro-amperes (it is quite high value when compared to the standard single pad detector). It predetermines the maximal reasonable value of the bias sensing resistor. The mega-ohm resistor forms a bias drop in order of volts while considering several µA current. This is an acceptable value for the on-board integrated bias voltage source (that can provide 0 to 100 V output range). A higher value of the sensing resistor would produce an excessive bias drop in comparison to the source output range itself. A smaller value of the sensing resistor is not also a reasonable choice. It was proved that the reduced value has a significant impact on the spectroscopic resolution of the detector (as it is demonstrated in the following comparative test).

The comparative test was done in the past with 1M and 100K ohm sensing resistors and Timepix detector with 300 µm Si sensor. Just the back side pulse signal was connected to the spectroscopy measurement aperture (read-out chip was unconnected and not powered). For both values of the resistor there was done a similar measurement with the compound alpha source spectra (Am-Pu-Cm). Resulting spectra clearly shows that 1M ohm case (FWHM = 51 keV, see the Figure 7-5 and Figure 7-6) is significantly better in term of the achieved spectroscopic resolution than the 100 k-ohm case (FWHM = 70 keV, see the Figure 7-3 and Figure 7-4).

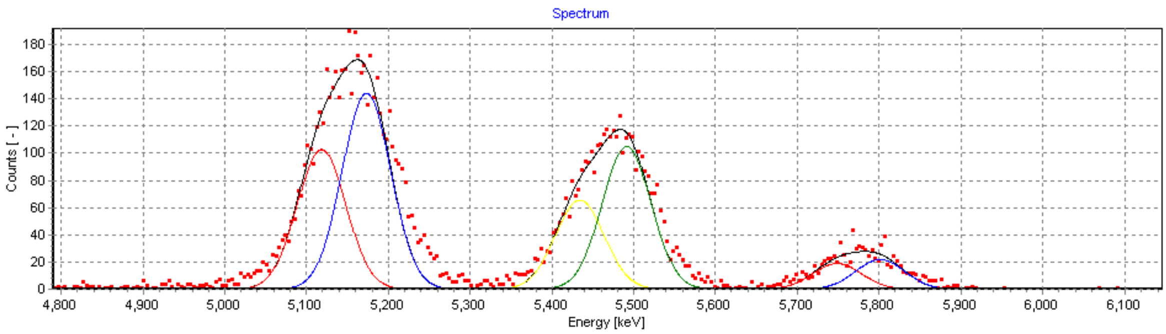
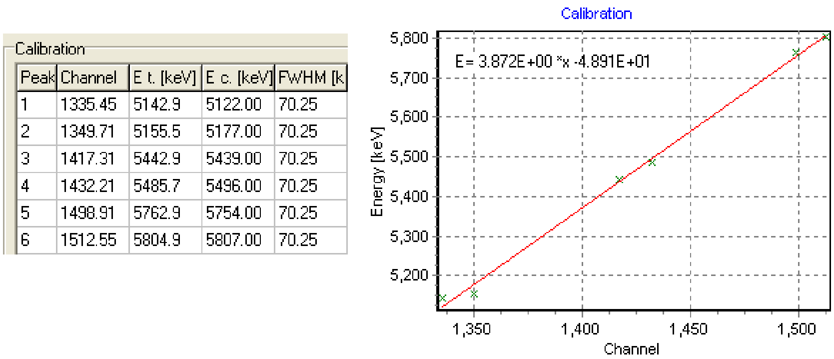


Figure 7-3 Energy spectrum for the Timepix detector with the 300 µm Si sensor using 100 k-ohm sensing resistor, 60 V bias voltage and Am-Pu-Cm alpha source



Calibration

Peak	Channel	E t. [keV]	E c. [keV]	FWHM [k
1	1335.45	5142.9	5122.00	70.25
2	1349.71	5155.5	5177.00	70.25
3	1417.31	5442.9	5439.00	70.25
4	1432.21	5485.7	5496.00	70.25
5	1498.91	5762.9	5754.00	70.25
6	1512.55	5804.9	5807.00	70.25

Figure 7-4 Calibration results (FWHM 70 keV) for the Timepix detector with the 300 µm Si sensor using 100 k-ohm sensing resistor, 60 V bias voltage and Am-Pu-Cm alpha source

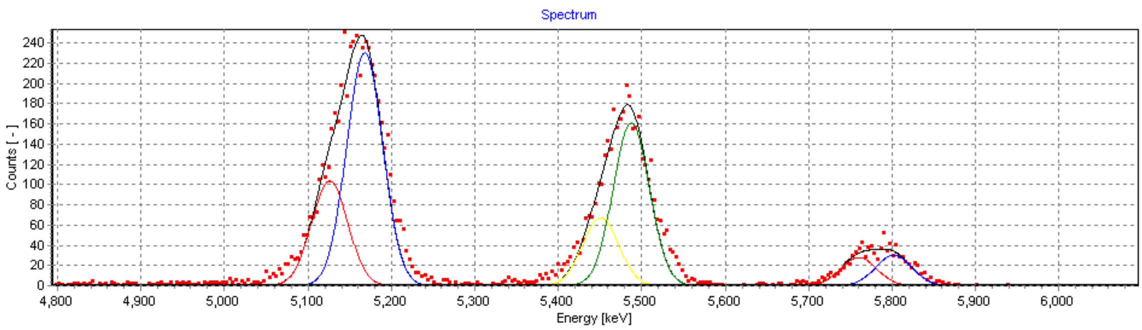
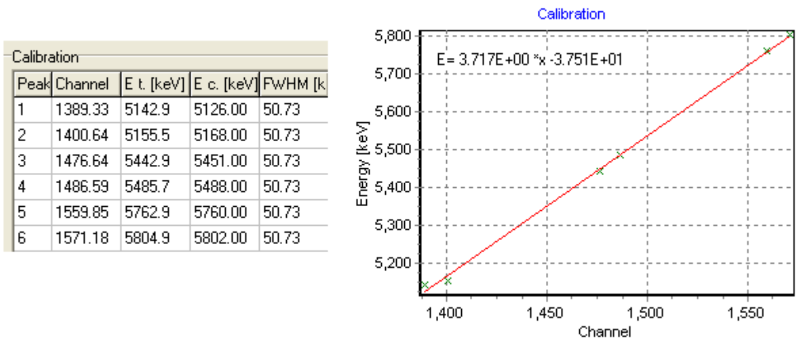


Figure 7-5 Energy spectrum for the Timepix detector with the 300 µm Si sensor using 1 Mega-ohm sensing resistor, 60 V bias voltage and Am-Pu-Cm alpha source



Calibration

Peak	Channel	E t. [keV]	E c. [keV]	FWHM [k
1	1389.33	5142.9	5126.00	50.73
2	1400.64	5155.5	5168.00	50.73
3	1476.64	5442.9	5451.00	50.73
4	1486.59	5485.7	5488.00	50.73
5	1559.85	5762.9	5760.00	50.73
6	1571.18	5804.9	5802.00	50.73

Figure 7-6 Calibration results (FWHM 51 keV) for the Timepix detector with the 300 Si µm sensor using 1 Mega-ohm sensing resistor, 60 V bias voltage and Am-Pu-Cm alpha source

8 Basic device function verification

8.1 Software tool chain through-put test

As it was already described in the 3.2, there are several software tools participating on the data transfer (line between the Timepix detector and the data storage). The introduction of the managed access through the server/client services brings new architectural blocks in the chain. Each part of the chain can cause significant deterioration of the through-put. As it is a chain structure just one weak point has impact on the overall performance. The following test was done to find what the limits are and what the performance of designed the solution is.

8.1.1 Object of the test

There was examined data acquisition ability of the FITPix COMBO device and its accompanying software tools. Only the data download way was in the focus (i.e. Timepix frames gained from the FITPix Core and recorded by the Pixelman tool. The spectroscopic signal waveforms gained from the Spectrig Core and recorded by the IEAP spectrometry application). Tests were done for several variations of the measurement configurations. These above stated end-point software tools were used for the performance test to get useful result for common user of the FITPix COMBO device.

8.1.2 Results of the test

The Table 8-1 shows mainly the Timepix frame acquisition performance. The best achieved result is rate of 102 frames / second. There is perceptible significant difference between the burst and pooling acquisition mode. The pooling mode means that the data download is initiated after reception of the command. In the burst mode data are sent immediately once the partial measurement cycle is finished (without any waiting). Next, there is state download speed for externally triggered measurement and for the case of the self-trigger. This result is determining for performance while considering combined operation of the Timepix and back side pulse spectroscopy (signal waveforms are downloaded together with the Timepix frame).

Table 8-1 Comparison of the download speed for the FITPix Core - Timepix data path

Frames Downloaded	Test Run Time [s]	Frame Rate	Trigger Source	Acquisition Mode	Note
1000	9,8	**102,0**	Internal - HW Timer	Burst	No spectroscopic signal acquisition
1000	22,6	44,2	Internal - HW Timer	Pooling	No spectroscopic signal acquisition
1000	27,7	36,1	External trigger	*Not applicable*	No spectroscopic signal acquisition
1000	31,5	31,7	Self-trigger *(spectroscopy signal)*	*Not applicable*	Waveform of 3000 samples acquired together with the Timepix frame

The second Table 8-2 presents performance of the spectroscopic branch alone. There are measured values of the waveform download speed in dependence on the number of samples forming one waveform. As one would expect the best result is achieved for the shortest waveform configuration– about 23 000 events per second.

Table 8-2 Comparison of the download speed for the Spectrig Core – back side pulse signal data path

Waveforms Downloaded	Test Run Time [s]	Waveform Rate	Samples per one waveform
100000	4,3	**23202**	256
100000	16,6	6017	1000
100000	33,8	2963	2000
100000	50,9	1965	3000
100000	65,7	1521	8000

8.2 Long term stability of the spectroscopic chain

Aim of the test is to evaluate a long term stability of the signal processing chain designated on the parallel interface board. There was observed a response to well-defined stimulus. Just influence of the analog part of the spectroscopy chain is considered in this test. The following components form the spectroscopic chain – the charge sense amplifier, the pulse shaping (filtration) circuit and the flash AD convertor (see the Figure 8-1).

8.2.1 Test set-up description

The Figure 8-1 shows an arrangement of the tested set-up. The FITPix COMBO device was assembled with an additional LEMO connector to allow connection of the external analog signal. A radiation detector was replaced by the precise pulse generator ORTEC 419. Well defined pulses were used as stimulus for the signal processing chain of the device (proprieties of the generated pulses were constant during the entire test). The presented set-up was operated during 120 hours without any break. Pulses were continuously acquired by the tested device. But data was saved in more parts. Each batch of the data represents 30 minute long interval of acquisition. So there were gained 240 subsets.

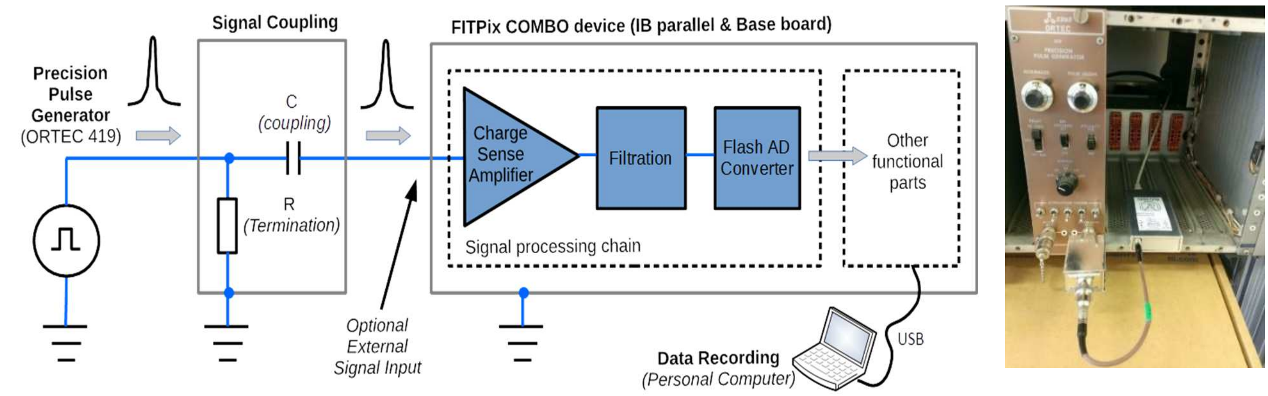


Figure 8-1 Arrangement of the long term stability test of the spectroscopic chain

8.2.2 Data evaluation

For each partial acquisition (of 0.5 hour long period) a separated spectrum was created (from the appropriate data set). All the partial spectra consist of one peak only (due to constantly generated stimulus). Then the position of the peak mid-point channel was found. Walking of the midpoint over time was observed. Smaller variation signifies a better stability. In the ideal case there would be no shift detected during the entire run of the test. The FWHM measure for each partial peak was also evaluated for each partial data set. The Figure 8-2 is visualization of the very first partial data set that was acquired in the time interval 0 to 0.5 hour after the start of the measurement. In the same way all other data sets were processed.

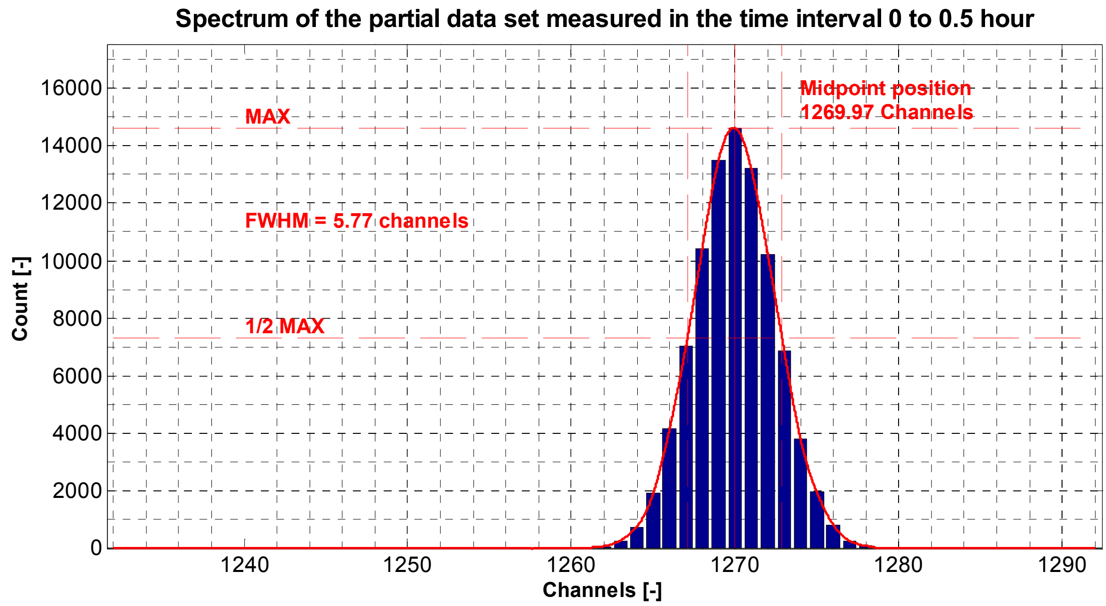


Figure 8-2 Spectrum of one partial data set

8.2.3 Test result

The all partial data sets are visualized in the Figure 8-3. They are shown as slices in the waterfall plot. Each 0.5 hour long interval is shown as on curve. Variation of the spectroscopic response is most perceptible on the ridge formed from individual layered time slices.

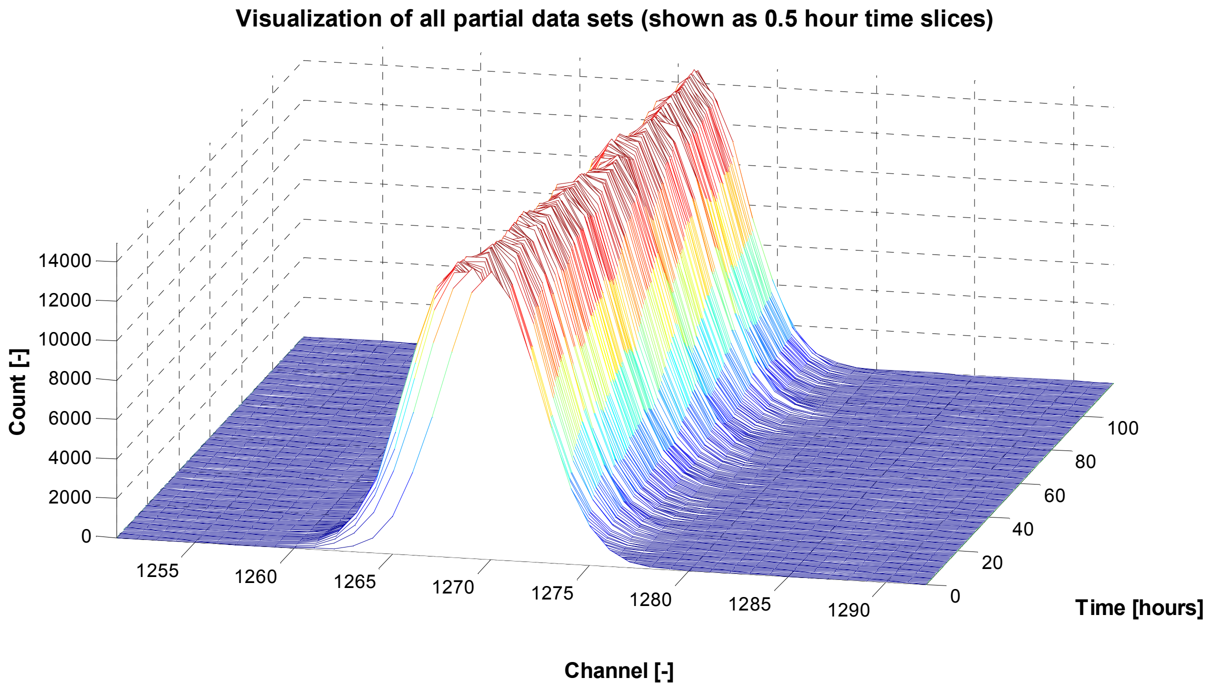


Figure 8-3 Variation of the spectroscopic response along the time – Overview

The more detailed look on the spectroscopic response variation renders the next Figure 8-4. There is shown just the ridge with annotations describing quantitative measured of the variations. The black curve highlights the mid-point walk over time. There is to be seen initial drop just after the start of the device measurement. After that there is apparent rising tendency with steady tendency with minor oscillations. The absolute difference in mid-point variation over the entire test run is 3.26 channels (given by max value 1271.31 – min value 1268.05). When assuming 10 MeV input energy range (exact range is obtained after the calibration process) for detected particles then guessed variation in energy scale is about 15.9 keV. *Computed as 3.26 channels * (10 000 keV / 2048 channels).*

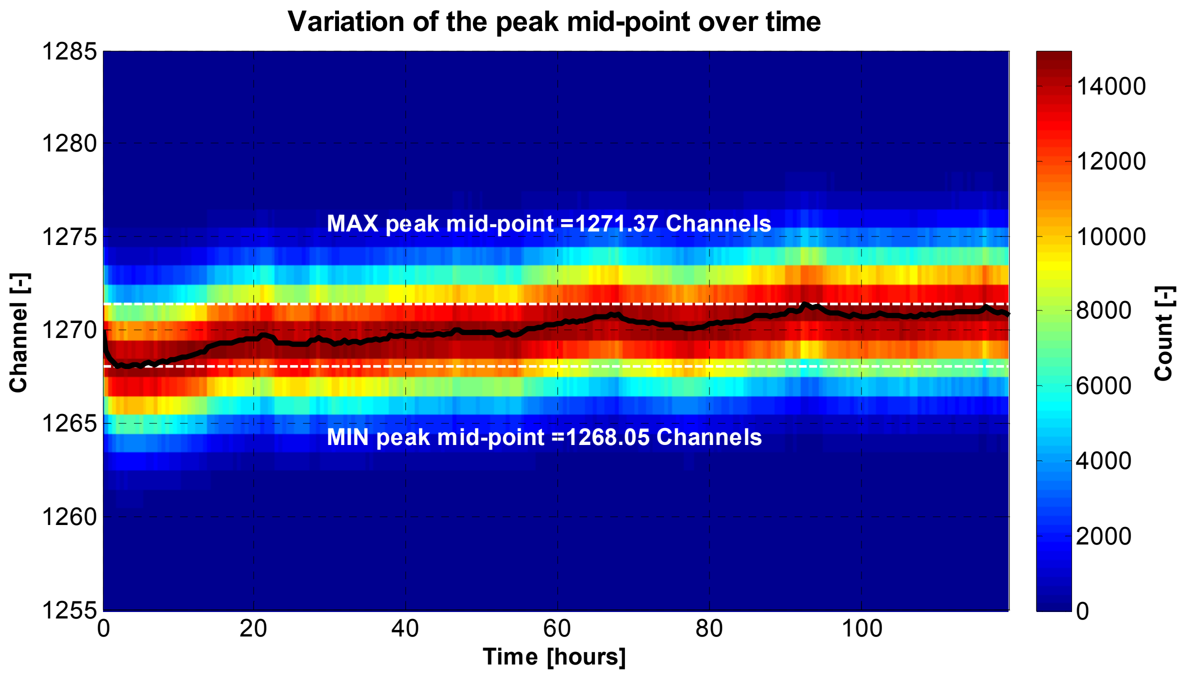


Figure 8-4 Variation of the spectroscopic response over time of the long term test– Focus put up on the peak mid-point shift

The next observed measure was variation of the FWHM over time. The FWHM value was also computed for each partial data set as the mid-point value. The Figure 8-5 presents resulting variation over time. There are highlighted minimal and maximal levels. The absolute difference of FWHM is 0.3 channels (given by maximal value 5.91 – minimal value 5.61). Again when assuming input energy range 10 MeV then resulting FWHM variation is 1.46 keV.

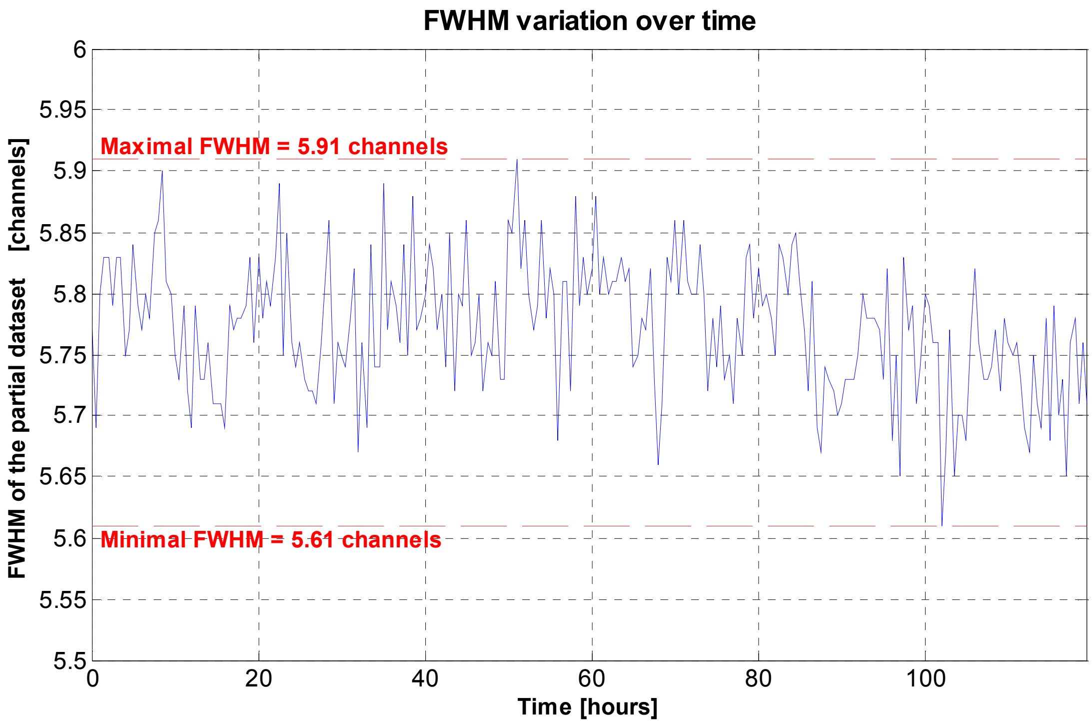


Figure 8-5 Variation of the FWHM over time of the long term test

9 Undergone physical experiments

9.1 Introduction

The following two sub-chapters serve as introduction to the subsequently described undergone experiments. It describes the way how the Timepix detector was calibrated for the alpha spectroscopy. Introduction also describes how the device was operated and how synchronism between pixelated data and back side pulse data was achieved.

9.1.1 Necessity of the Timepix detector calibration

To get precise information about the achievable energetic resolution of the Timepix and the FITPix COMBO device it is necessary to perform energetic calibration. Unless it is passed the spectroscopic performance of the device is unknown. Basic principle of the alpha calibration of a detector was already mentioned in the very beginning of the thesis in 1.1.2.3.

As it was stated a compound radiation source is absolutely necessary to make energetic calibration. Several distant calibration points are needed to get a correct channel to energy assignment. Therefore the Am-Pu and Am-Pu-Cm standards of the well-known energies were used as alpha source during the acquisition of the date sets needed for the calibration process. The Table 9-1 describes spectrum of the Am 241, Pu 239 and Cm 244 isotopes [26].

Table 9-1 Spectrum of the Am, Pu and Cm alpha sources

Radionuclide	Alpha particle energy [MeV]	Intensity [%]
Pu 239	5.105	11.5
	5.143	15.1
	5.155	73.4
Am 241	5.388	1.4
	5.456	12.8
	5.486	85.2
Cm 244	5.763	23.3
	5.805	76.7

1.1.1 Configuration of the device to be ready for synchronized operation

The absolutely necessary precondition for utilization of the FITPix COMBO device in the parallel running measurement of the pixelated part and the back side pulse spectroscopic part is well managed synchronization of both. The FITPix Core (stands for the pixelated measurement) & Spectrig Core (stands for the back side pulse measurement) has to be prepared for synchronized operation at first. If synchronization is not managed then acquired data cannot be linked together and it becomes useless.

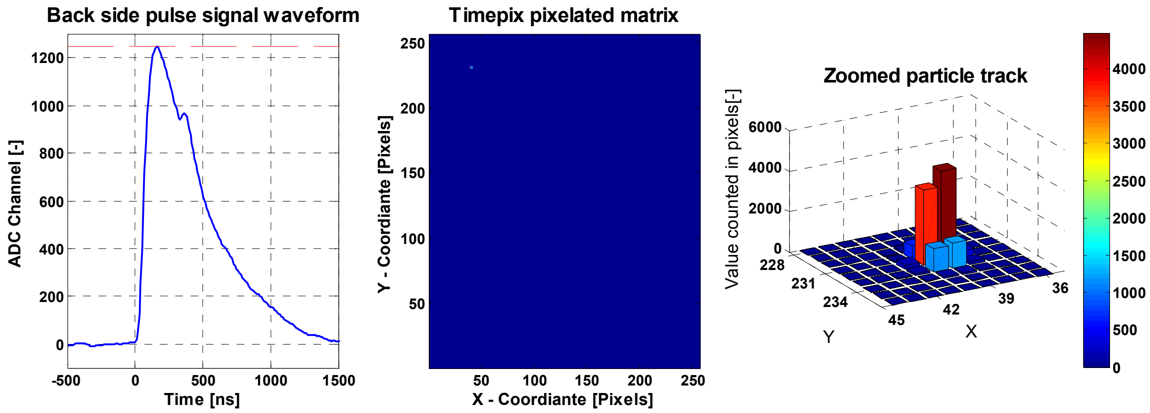


Figure 9-1 Equivalence between the Back side pulse signal and pixelated matrix of the Timepix detector

The undergone experiments exploit self-triggering capability of the device (Pulse detected in by the Spectrig Core triggers pixelated measurement done by the FITPix Core). It allow to open Timepix detector shutter for a very short time window (in order of ms or even less) while other background is effectively filtered-out (i.e. just one event is observed). See the Figure 9-2 showing applied configuration of the FITPix COMBO device. Along with the trigger signal routing (direction from Spectrig to FITPix Core) there is also shown interconnection of the other important signals. The busy in/out signals have to be mutually connected between both cores. Such a configuration ensures that a start of acquisition would be done just in the case when both cores are ready. The cores wait for their counterparts.

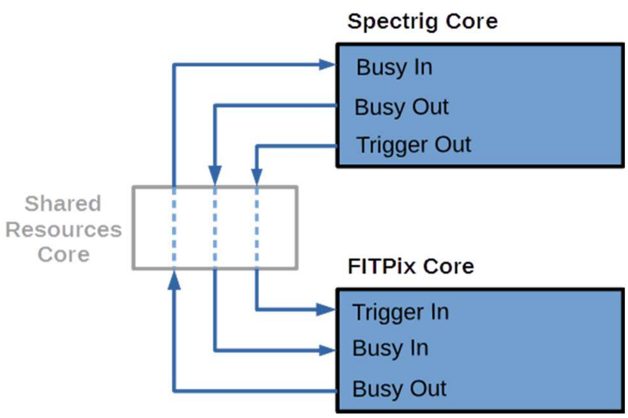


Figure 9-2 Necessary configuration of the FITPix COMBO device for self-triggering and for synchronized operation

9.2 Energetic calibration of the Timepix with the 300 μm thick Si sensor

There were acquired two different data sets for the detector calibration. One measurement was performed using the compound Am-Pu radiation source and the second was performed using the Am-Pu-Cm source. The measurements were not done in the close time window. The time distance between them was about one month. But conditions of measurement for both were kept the same.

9.2.1 Measurement set-up and conditions

The measurements were done in vacuum. The FITPix COMBO device and a radiation source were placed in a vacuum chamber Distance between the detector and the source was 10 cm. Bias voltage was set and kept at the level of 60 V during the entire acquisition run. Radiation source was placed perpendicularly to the sensor surface.

9.2.2 Data evaluation

In the first step of data evaluation the amplitude histogram was created by processing all acquired events. The resulting histogram was used in the second step as an input for the peak fitting software tool Alpha fit. It performs fitting of energy peaks of the well-known radiation source on the input histogram. After finishing of the fitting process there is available information about the spectroscopic resolution and equivalent energy to one ADC channel (bin of the histogram). Outputs of calibration follow.

9.2.3 Calibration of the Interface board assembled with the Timepix with the 300 µm sensor using the Am-Pu radiation source

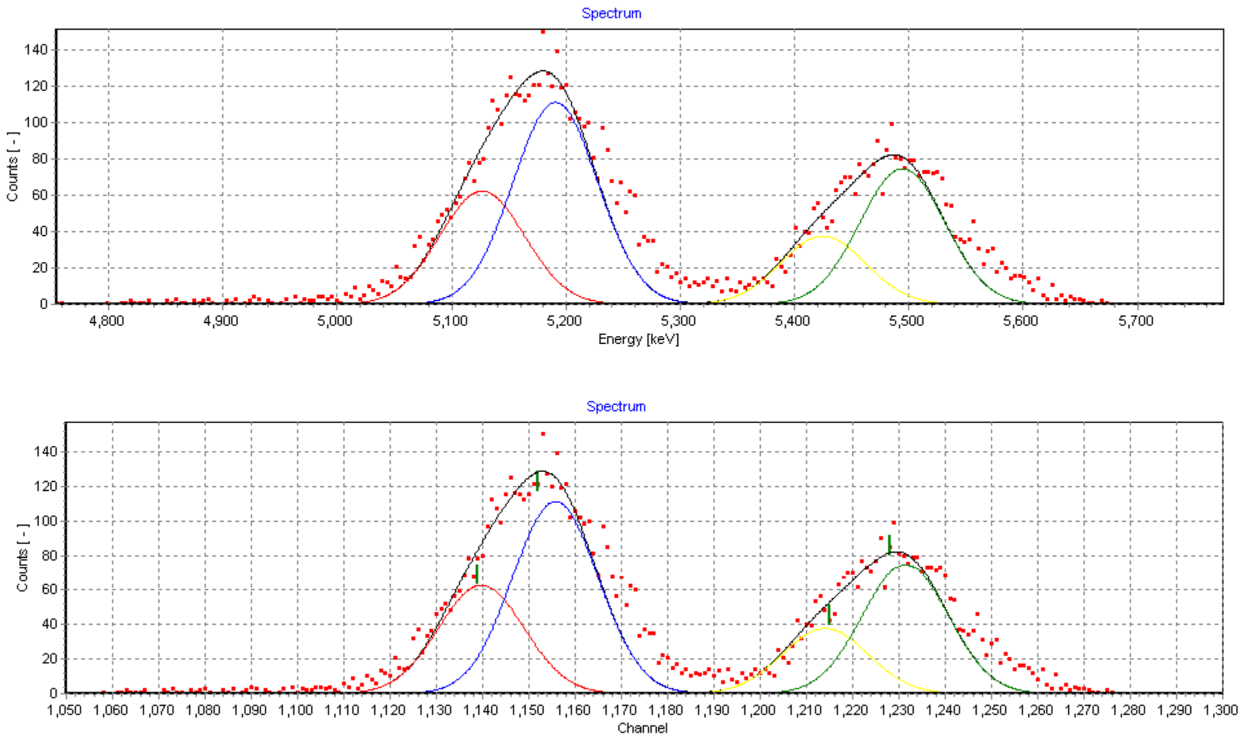


Figure 9-3 Energy spectrum for the Timepix with 300 µm sensor using the Am-Pu alpha source and bias voltage 60 V

Calibration

Peak	Channel	E t. [keV]	E c. [keV]	FWHM [k
1	1139.72	5142.9	5121.00	88.72
2	1155.75	5155.5	5186.00	88.72
3	1214.06	5442.9	5424.00	88.72
4	1231.41	5485.7	5495.00	88.72

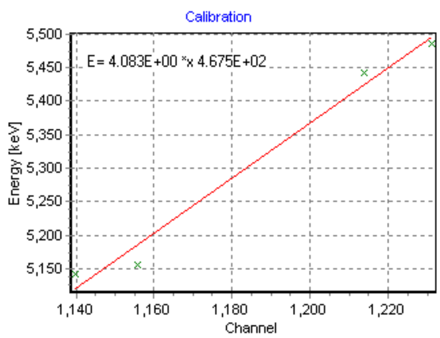


Figure 9-4 Calibration outputs for the Timepix with 300 µm sensor using the Am-Pu alpha source and bias voltage 60 V, (FWHM = 89 keV)

9.2.4 Calibration of the Interface board assembled with the Timepix with the 300 µm sensor using the Am-Pu-Cm radiation source

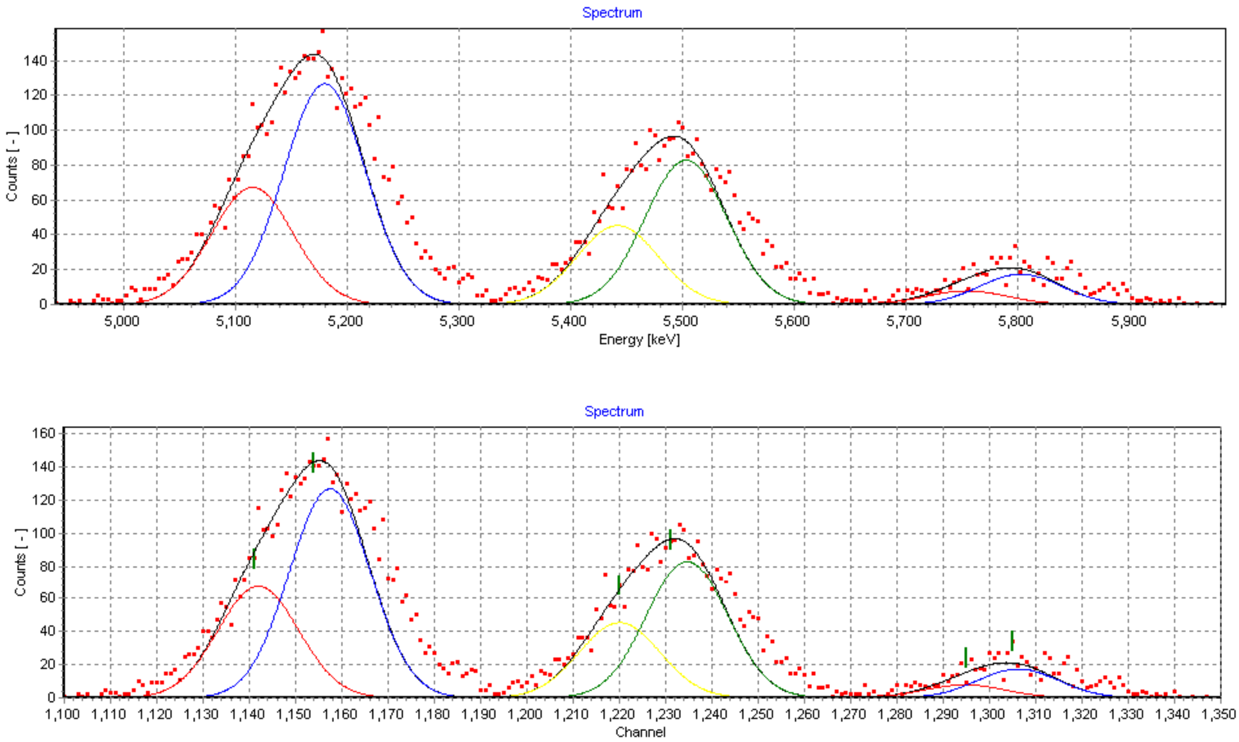


Figure 9-5 Energy spectrum for the Timepix with 300 µm sensor using the Am-Pu-Cm alpha source and bias voltage 60 V

Calibration

Peak	Channel	E t. [keV]	E c. [keV]	FWHM [k
1	1141.96	5142.9	5115.00	85.85
2	1157.45	5155.5	5180.00	85.85
3	1220.05	5442.9	5442.00	85.85
4	1234.65	5485.7	5503.00	85.85
5	1294.64	5762.9	5754.00	85.85
6	1306.19	5804.9	5802.00	85.85

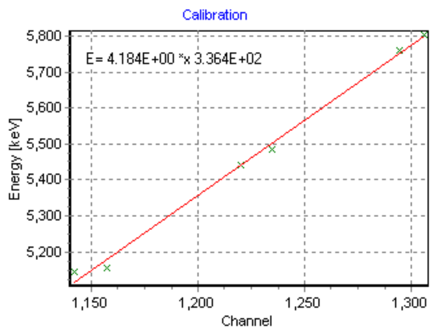


Figure 9-6 Calibration outputs for the Timepix with 300 µm sensor using the Am-Pu-Cm alpha source and bias voltage 60 V, (FWHM = 86 keV)

9.2.5 Final energetic resolution

Both calibration (using 2 isotopes Am-Pu and 3 isotopes Am-Pu-Cm source) provides quite comparable results. However, the Am-Pu-Cm calibration is considered to be more precise and reliable (as three are more calibration points). The equivalent energy of one ADC channel is 4.18 keV. It determines maximal energy range about 8.6 MeV while considering 11bit ADC scale (i.e. 2048 channels). The achievable energetic resolution of the tested 300 µm sensor Timepix is about 86 keV.

The presented results, gained by the calibration process, will be used further. Next chapter will present exemplar physical experiment. The calibration data will be used as one of the inputs for the final result evaluation.

9.3 Experiment with a thin Mylar foil absorber

9.3.1 Aim of the experiment

There are two main goals to be achieved. The experiment should serve as a proof of the device performance and its readiness for further deployment in other experiments.

The key feature of the FITPix COMBO device (i.e. well synchronized operation of the FITPix Core and the Spectrig Core) will be definitely verified. Because once the tight correlation between the interacting alpha particle energy (provided by Spectrig Core data) and its place of interaction (provided by FITPix Core data) would be lost then the acquired data gets useless at all. This information is mandatory for evaluation of the results. Next, there is required sufficient spectroscopic resolution of the heavy charged particles. To get any relevant results the particles of several energy levels (not so distant) has to be successfully distinguished.

9.3.2 Purpose of the Mylar foil

A very thin Mylar foil was used to cover a part of the Timepix detector surface. The small thickness of the foil allows an alpha particle to penetrate through it while losing just portion of initial energy. Observation of this energy loss is the main physical objective of the experiment.

9.3.3 Detector arrangement

Exactly, the detector area was separated into three parts almost equivalent in size (see the sketch in the Figure 9-7). One third of the surface was left opened (Area A), one third was coved with one layer of the Mylar foil (Area B) and the last third was covered with two layers of the Mylar foil (Area C). Detailed look on the detector-foil arrangement is presented by the Figure 9-8.

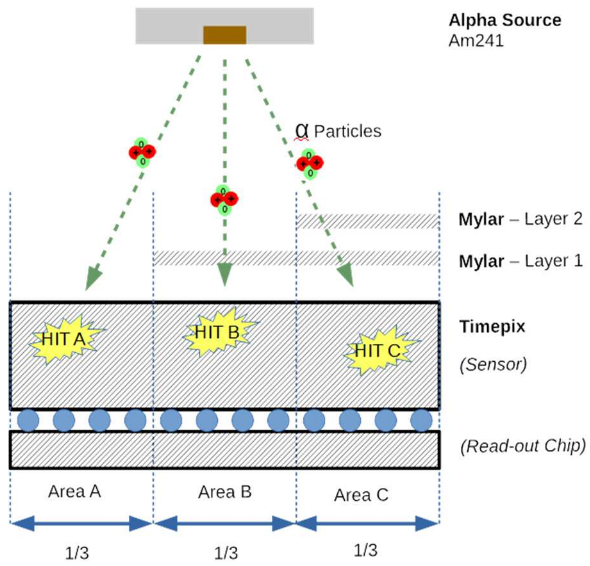


Figure 9-7 Arrangement of the alpha source, Timepix detector and Mylar foil coverage

Figure 9-8 Detail view on the Timepix detector covered with the Mylar foil

9.3.4 Experiment set-up

The experiment set-up consists of the FITPix COMBO as the detection apparatus (assembled with Timepix with the 300 µm thick Si sensor). The Am 241 was used as an alpha source. It was fixed by a holder in distance of 10 cm from the Timepix detector. The entire set-up was placed within a vacuum chamber. See the photo in the Figure 9-9 showing arrangement of the described set-up. The entire vacuum chamber stand workplace is shown in the Figure 9-10.

Figure 9-9 Arrangement of the FITPix COMBO device and Am alpha particle source in the vacuum chamber

Figure 9-10 Vacuum chamber stand – experiment under progress

9.3.5 Measurement conditions and process

The set-up was operated in vacuum all the time of the running data acquisition. The Timepix sensor was biased with 60 V (It is necessary to comply with same bias configuration as it was used for previous detector calibration). The self-triggering capability of the device was used to start acquisition of the partial events. During the entire measurement run there was acquired more than 100 000 of events. They form input for further post-processing.

9.3.6 Evaluation of the measured data

All the acquired data were processed by the Matlab tool. A single purpose script was written to make a merge of the two separated data sets (Back side pulse signal spectroscopy data and the Timepix pixelated matrix data). Information about the particle energy was taken from the back side pulse signal; information about the place of particle interaction was taken from a track left in the pixelated matrix. These two basic values were used for further analysis. The absolute values of energy state in the presented results are given by the previously gained detector specific calibration constants.

9.3.7 Estimation of the expected energy loss in a thin absorber

The raw estimation of the energy loss in the thin absorber was done. The method "Energy loss in Thin Absorbers" published in source [1] chapter 2-E. The loss is determined from the Energy – Range plot (see the Figure 9-11). Alpha particle of the initial energy E_0 enters to material with the thickness t. The particle leaves absorber on the opposite surface with the energy E_t that is diminished about the loss ΔE. The absorber thickness t and initial energy E_0 are known values. Thus the estimated loss ΔE can be get as $E_0 - E_t$ while using the Energy – Range plot for given absorber material.

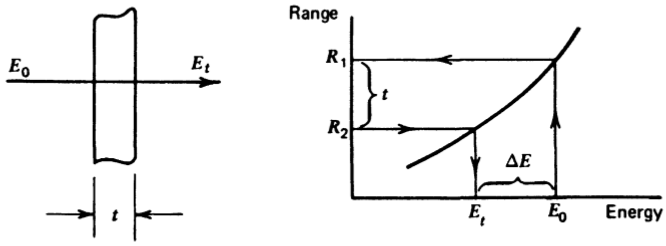


Figure 9-11 Method of determination of the energy loss of alpha particles in the thin absorber

The exact Energy - Range plot can be found at source [27] (see the used plots for Mylar and Aluminum in the Figure 9-12 and Figure 9-13). This source also provides tabled values with a finer grid than shown demonstrative plots of the Range – Energy dependency. Note that Mylar foil, used at experiment, contains also a metalized layer of Aluminum. Therefore estimation has to count with this layer also. The properties of the foil are following – 2 µm of aluminum and 2 µm of Mylar (values are not guaranteed but it is sufficient input to get a raw estimation, precise values are not necessary).

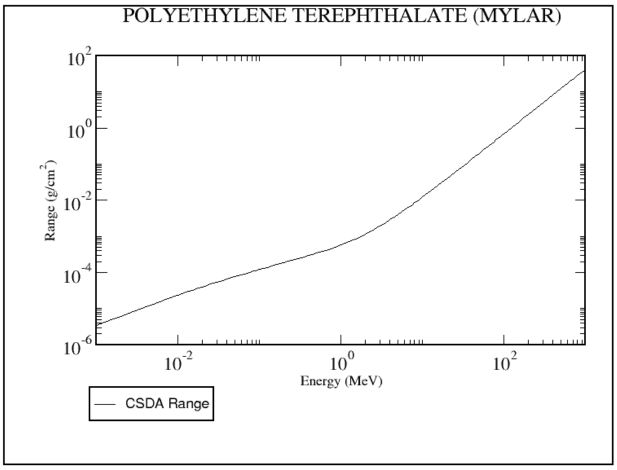


Figure 9-12 Energy - Range plot for the Mylar

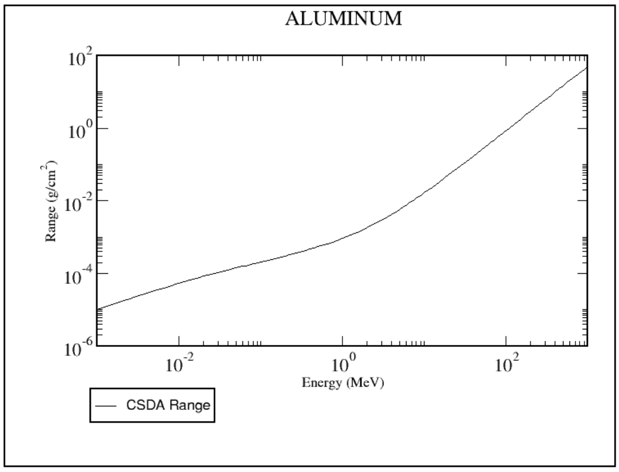


Figure 9-13 Energy - Range plot for Aluminum

When considering an initial energy of alpha particles to be 5.486 Mev (Am source) while applying previously described technique the following results are gained. The first foil absorber makes the energy loss 538 keV *(312 keV for Aluminum + 226 keV for Mylar)*. This value is applicable for area B (see the detector surface division in the Figure 9-7). The second foil absorber makes the energy loss 581 keV *(336 keV for Aluminum + 245 keV for Mylar)*. In total, it forms the loss 1119 keV *(538 keV + 581 keV)*. This value is applicable for Area C.

9.3.8 Visualization of the measured results

Distribution of hitting alpha particles along the detector surface is to be seen in the Figure 9-14. Each colored point signifies a pixel where particle interaction occurred. Color is determined by the energy (see the colorbar for exact value assignment). As it was expected, there are three areas clearly to be distinguished. On the left, there is the Area A – with dominating yellow color. In the middle, you see the Area B – with dominating orange color. Finally, on the right, it is the Area C – with dominating dark red color. In addition to the particle distribution there are plotted auxiliary lines. Thin blue lines marks where the border between partial areas was defined. The magenta lines define space that was excluded from further data evaluation. Events registered within these lines are considered not to be belonging to any particular area A, B or C. (This measure was done because of area borders cannot be defined as straight lines. To avoid unintended mixture the dead zones were defined to be 20 pixel width).

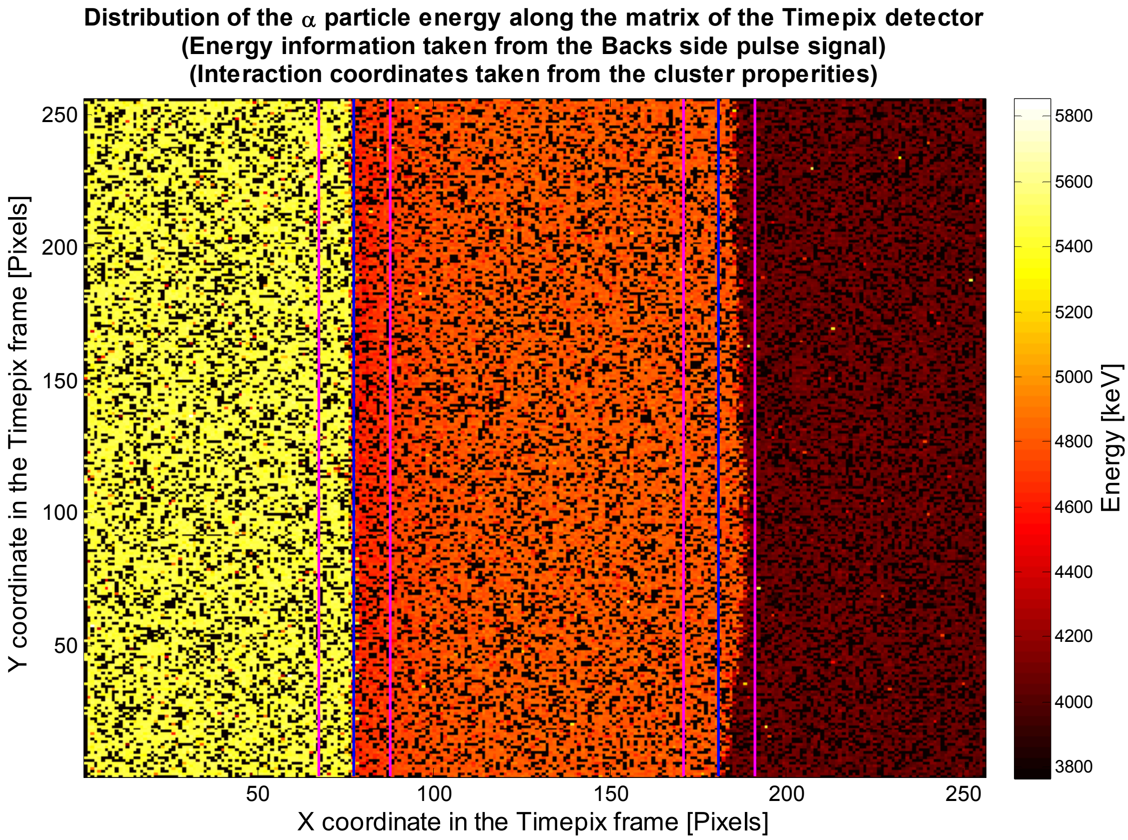


Figure 9-14 Distribution of alpha particles along the Timepix matrix

The next plot in the Figure 9-15 shows energy created from the events belonging to the individual areas (A, B and C) while excluding border regions as it was state above. It brings more descriptive information. Each partial spectra is quite spaced from its adjacent ones. The median energy value was computed each. The particle energy loss within a thin Mylar foil can be simply computed from them. So, difference between A and B forms 5458 – 4801 = 657 keV energy loss for the first layer of the foil and difference between the B and C forms 4801 – 4081 = 720 keV energy loss for the second layer of the foil. In total, there is 1 377 keV loss in two layers of the foil.

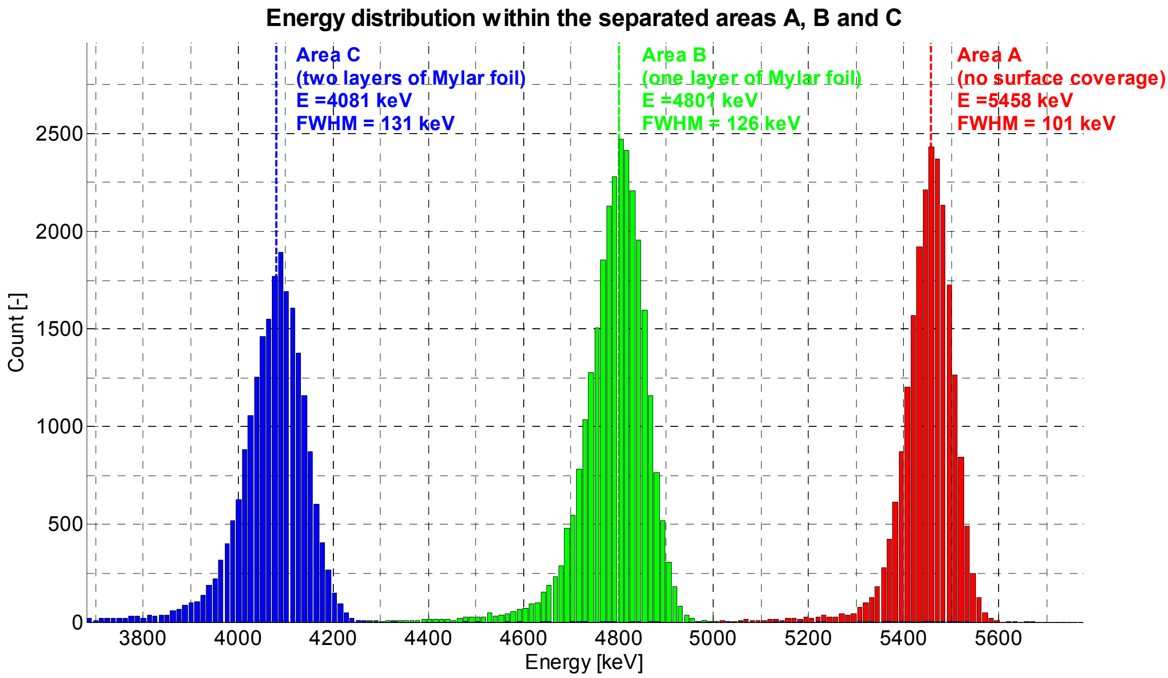


Figure 9-15 Partial energy spectra for Area A, B and C

In addition to the spectra, the plot in the Figure 9-16 shows variation of the spectroscopic response along the X coordinate of the pixelated matrix. The thin vertical red lines mark a median energy value of the each partial area A, B or C. The blue curve is value that was computed from all events belonging to one column of the matrix (It can be considered as a cross-section in the y axis. The steep steps between the adjacent areas are quite evident in the plot.

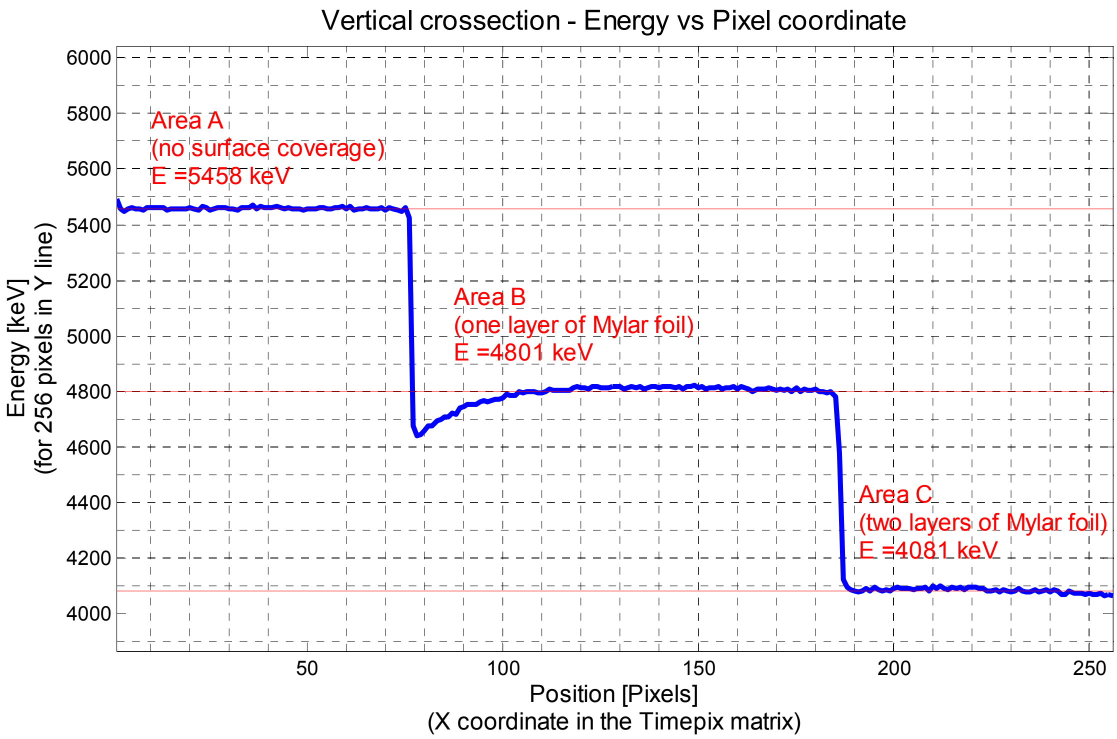


Figure 9-16 Variation of the spectroscopic response along the X coordinate of the pixelated matrix

The last graphics in the Figure 9-17 shows interpolated spectroscopic response of the Timepix sensor to the hitting particles. The presented image communicates quite similar information as the Figure 9-14 does. The points where no particle interaction was detected the substitutive value was used instead (applying interpolation technique to compute it from surrounding pixels). The borders between the A, B and C areas are also clearly to be seen. However to get more precise result it will be needed to get much more events (at least several events in each pixel) to get better statistical results. When considering a matrix of 256 by 256 = 65 536 pixels then the average event rate is per pixel is about 1.5 (given by 100 000 measured events / 65 536 pixels).

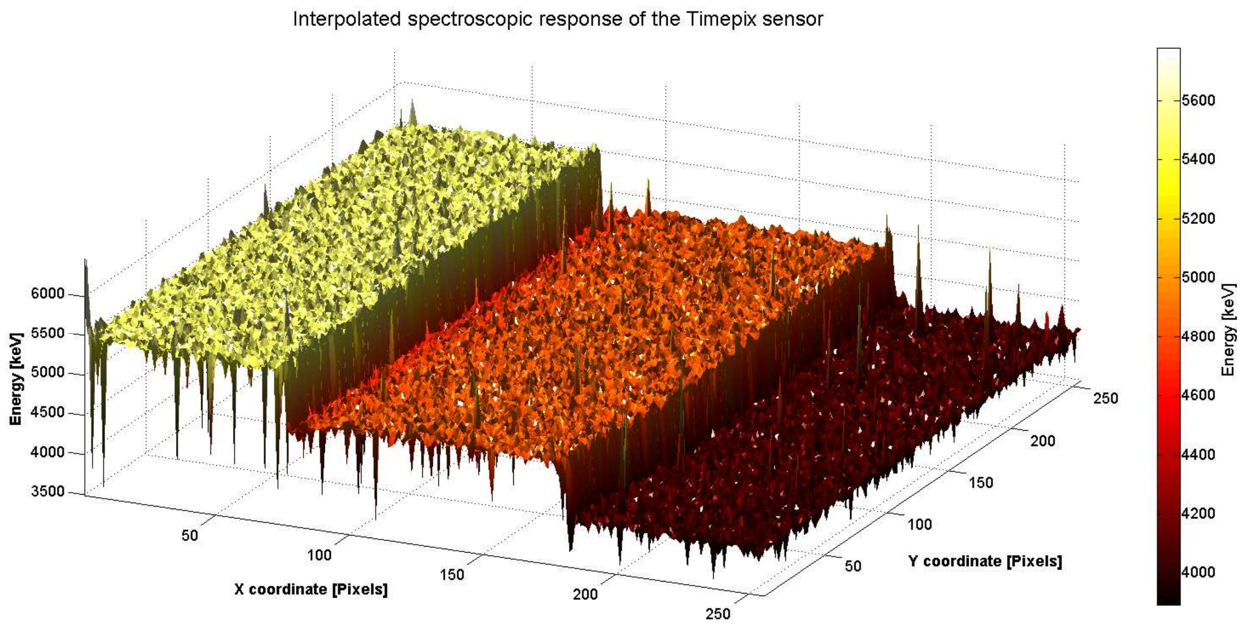


Figure 9-17 Interpolated spectroscopic response of the Timepix sensor (energy value for pixels with no hit was computed from the neighboring pixels using interpolation to get a continuous surface for visualization)

9.3.9 Experiment conclusions

The results of the experiment indisputably prove that the FITPix COMBO device is capable of the self-triggering operation and well synchronized operation. Both independent data sets (gained from the FITPix & Spectrig Core) were correctly put together to form common resulting outputs. The energy loss of the alpha particles, caused by the Mylar foils, was clearly recognized. The spectroscopic resolution of the back side pulse signal (about 100keV) would be sufficient to recognize even less thick foils.

When considering estimated values it is apparent a difference in results (relatively about 20%). The inaccuracy is most likely caused by unguaranteed properties of the used Mylar foil. However, the main objective of the experiment is not to measure property of the foil but to test FITPix COMBO device. Therefore the difference is acceptable.

9.4 Characterization of the spectroscopic response of the Timepix with the 600 µm thick sensor

9.4.1 Aim of the test

The aim of the test is to provide detector spectroscopic response characterization in dependence on the bias voltage. The Timepix detector with the 600 µm thick Si sensor was used for the test. As the stimulus there was used compound radiation source Am Pu Cm. The bias voltage was being gradually set in 10 V steps from the level of partial sensor depletion when energy peaks of the compound source were non evident in the spectrum. Voltage was increased till the level of full sensor depletion when energy peaks were clearly to be recognized.

9.4.2 Arrangement of the test

The Timepix with 600 µm thick sensor requires significantly higher voltage than it is needed in the case of the 300 µm thick sensor. About 130 - 150 V is needed to make sensor fully depleted. Unfortunately, the required voltage level is out of range of the internal on-board bias source (it can provide output up to 100 V). However, the interface board is prepared for connection the external bias source. This option was used during the entire test of the spectroscopic response. Measurement was done in the vacuum chamber.

9.4.3 Response evaluation

Overview of the spectroscopic responses of is shown in the Figure 9-18. It is clearly to be seen how the spectroscopic response is formed while increasing sensor bias voltage. See on the left, at low voltages, the spectrum of compound radiation source forms one joint peak. Individual spectrum contributors cannot be distinguished. It is apparent that charge collection at these voltages is not quite good. When moving focus more to the right the spectrum becomes to separate into several peaks. Individual contributors are getting recognizable (at bias level of 100 V there are firstly to be seen three peaks). When moving focus even more to the right the individual peaks are getting clearly separated from each other.

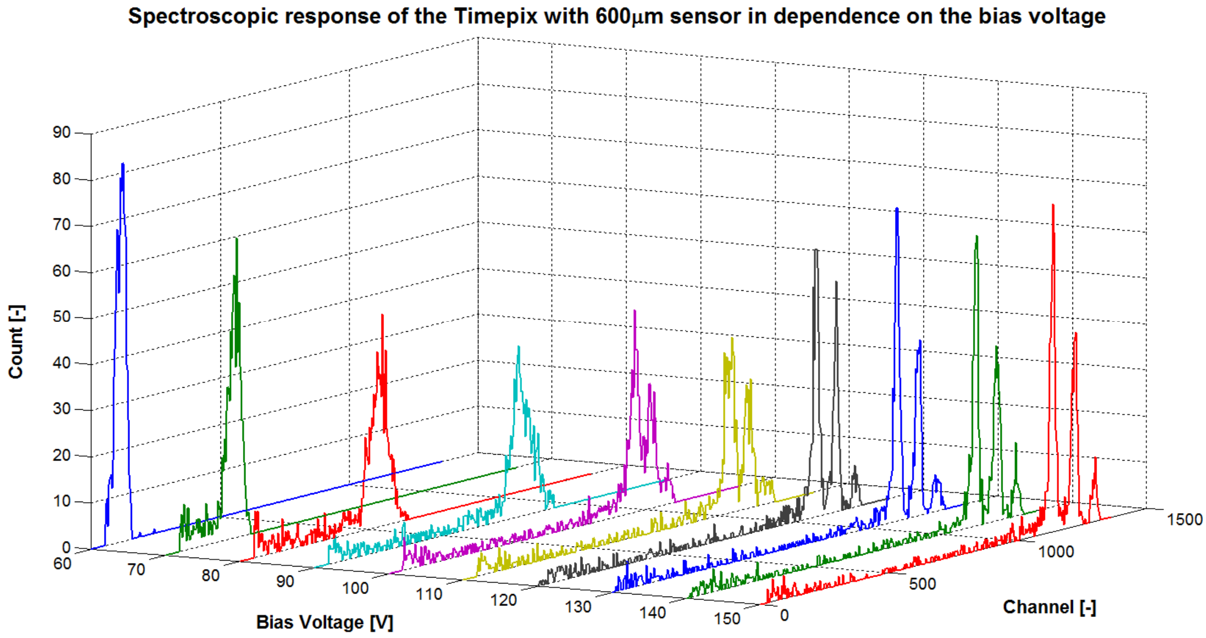


Figure 9-18 Spectroscopic response of the Timepix with 600 µm thick Si sensor in dependence on the applied bias voltage using Am-Pu-Cm alpha source

To get detailed characterization of a spectroscopic response the calibration process was done for representative data sets. The responses at 110, 130 and 150 V bias were measured acquiring more events to achieve better statistics for the calibration. Other data sets were considered to be used just for the common overview. The outputs of the calibration tool are show on the following figures.

9.4.3.1 Calibration results for the Timepix with the 600 µm sensor using the Am-Pu-Cm radiation source and bias voltage 110 V

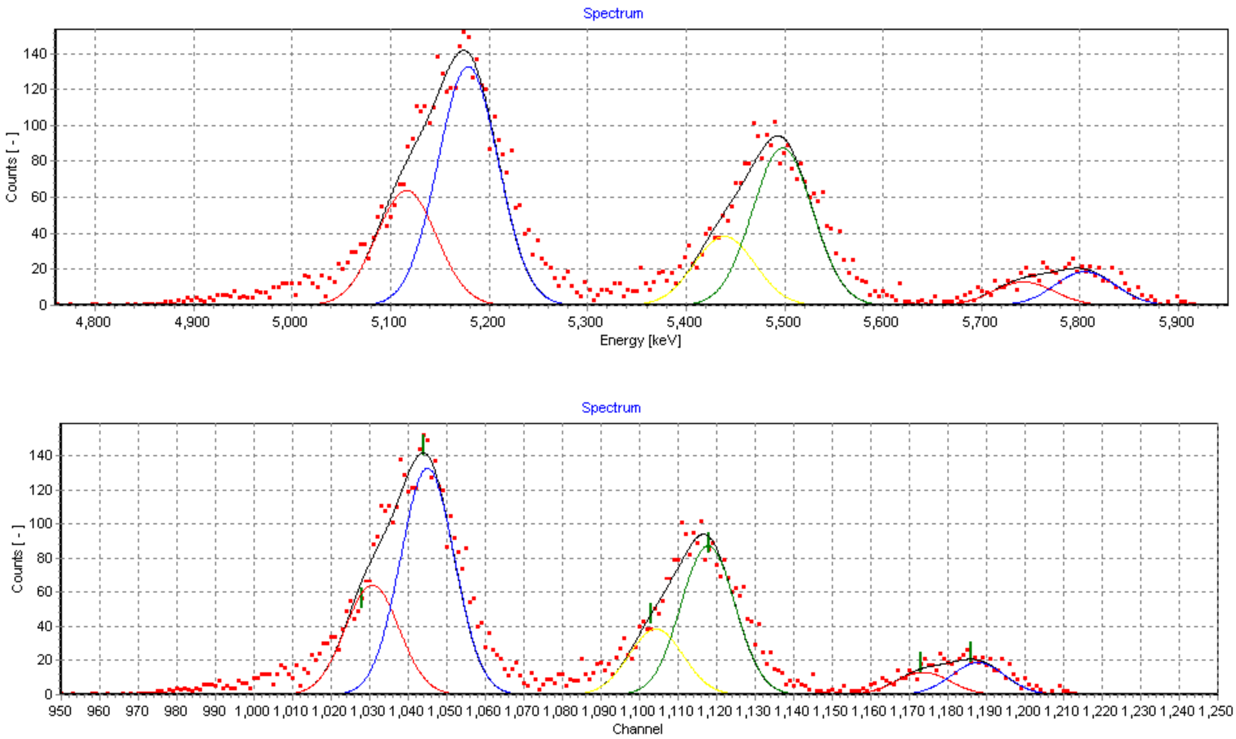


Figure 9-19 Energy spectrum for the Timepix with 600 µm sensor using the Am-Pu-Cm alpha source and bias voltage 110 V

Calibration

Peak	Channel	E t. [keV]	E c. [keV]	FWHM [k
1	1030.69	5142.9	5117.00	72.36
2	1044.96	5155.5	5180.00	72.36
3	1104.28	5442.9	5441.00	72.36
4	1117.77	5485.7	5501.00	72.36
5	1173.50	5762.9	5747.00	72.36
6	1187.77	5804.9	5810.00	72.36

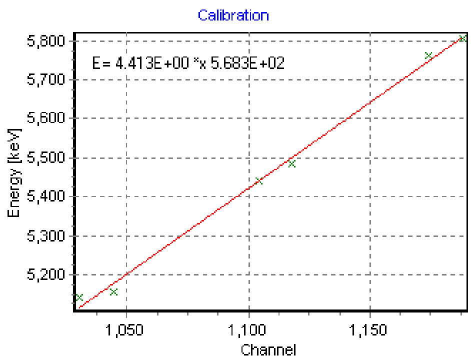


Figure 9-20 Calibration outputs for the Timepix with 600 µm sensor using the Am-Pu-Cm alpha source and bias voltage 110 V, (FWHM = 72 keV)

9.4.3.2 Calibration results for the Timepix with the 600 µm sensor using the Am-Pu-Cm radiation source and bias voltage 130 V

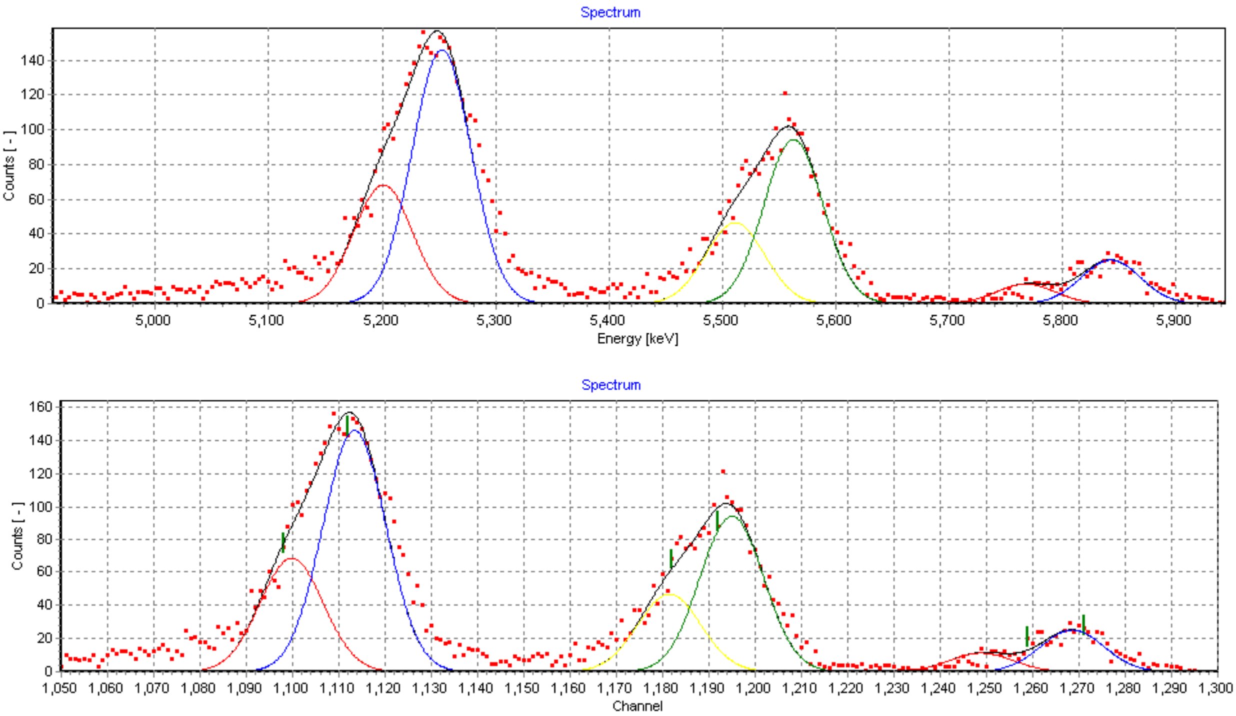


Figure 9-21 Energy spectrum for the Timepix with 600 µm sensor using the Am-Pu-Cm alpha source and bias voltage 130 V

Calibration

Peak	Channel	E t. [keV]	E c. [keV]	FWHM [k
1	1099.80	5142.9	5116.00	66.39
2	1113.38	5155.5	5172.00	66.39
3	1181.41	5442.9	5453.00	66.39
4	1194.96	5485.7	5509.00	66.39
5	1248.82	5762.9	5732.00	66.39
6	1268.55	5804.9	5813.00	66.39

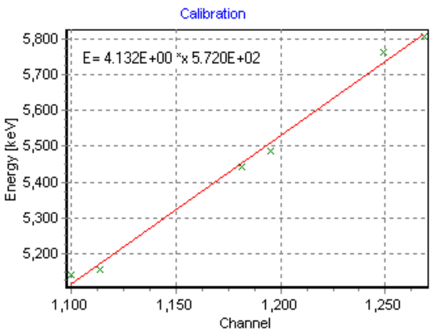


Figure 9-22 Calibration outputs for the Timepix with 600 µm sensor using the Am-Pu-Cm alpha source and bias voltage 130 V, (FWHM = 66 keV)

9.4.3.3 Calibration results for the Timepix with the 600 µm sensor using the Am-Pu-Cm radiation source and bias voltage 150 V

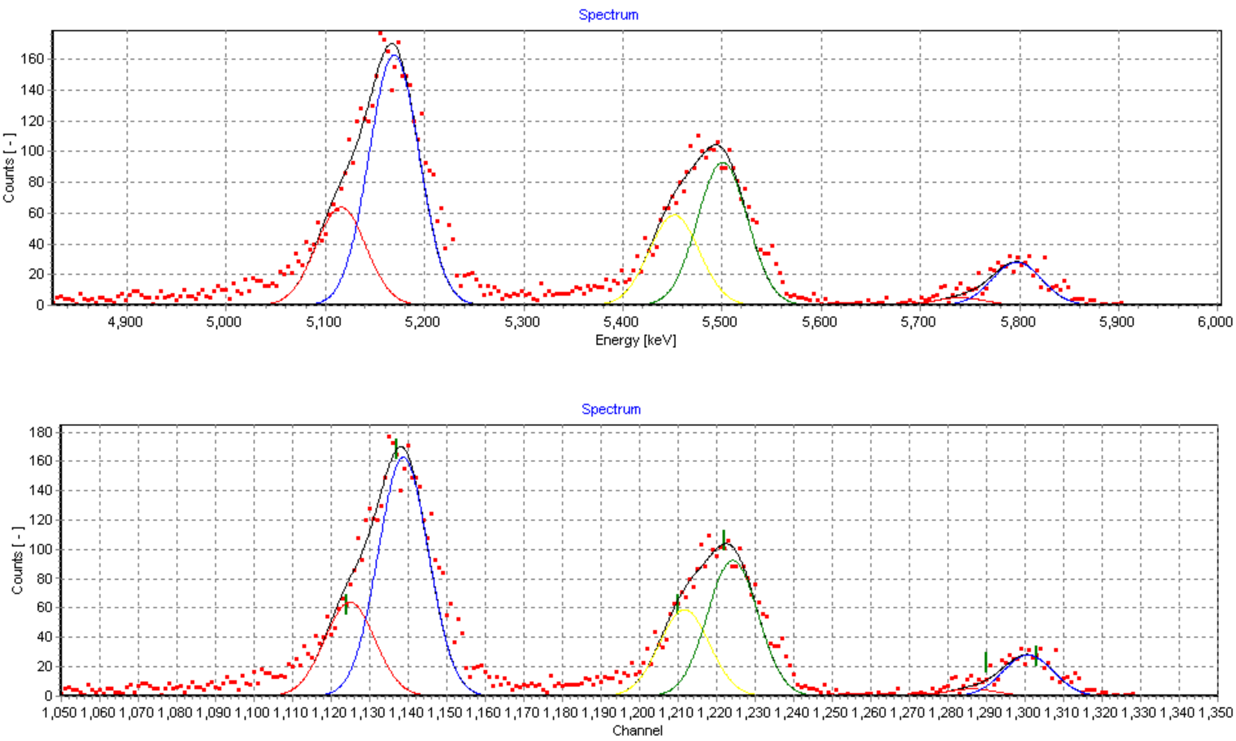


Figure 9-23 Energy spectrum for the Timepix with 600 µm sensor using the Am-Pu-Cm alpha source and bias voltage 150 V

Calibration

Peak	Channel	E t. [keV]	E c. [keV]	FWHM [k
1	1124.88	5142.9	5116.00	59.15
2	1138.74	5155.5	5169.00	59.15
3	1211.65	5442.9	5452.00	59.15
4	1224.23	5485.7	5501.00	59.15
5	1286.04	5762.9	5740.00	59.15
6	1300.81	5804.9	5797.00	59.15

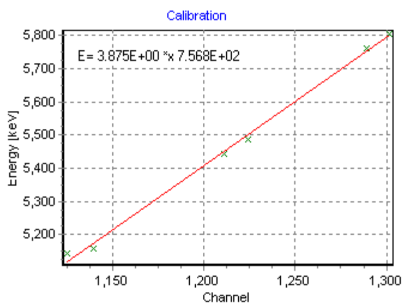


Figure 9-24 Calibration outputs for the Timepix with 600 µm sensor using the Am-Pu-Cm alpha source and bias voltage 150 V, (FWHM = 56 keV)

9.4.4 Comparison of the partial results

The result of the test proves that the energy resolution is getting better while increasing bias voltage. The calibration done over the representative data sets provides exact values of the spectroscopic resolution (72 keV for 110 V, 66 keV for 130 V and 59 keV for 150 V). The equivalent energy of one ADC channel is 4.41 keV for 110 V, 4.13 keV for 130 V and 3.88 keV for 150 V. When considering comparison of 130 and 150 V data sets there is still apparent a slight shift of the spectrum to higher channel values. It indicates that charge collection is not yet ideal. Therefore even higher bias voltage would be reasonable to get better spectroscopic resolution.

10 Conclusions and perspectives

10.1 Contribution of the research

The results gained from the undergone tests and experiments clearly prove a performance of the newly designed read-out interface FITPix COMBO dedicated for the Timepix detector. It is evident that it became a really valuable instrumentation applicable for further study of heavy charged ions done by analysis of the back side pulse signal while operating pixelated part of the Timepix detector in parallel. As there has never been created any comparable solution for Timepix detector before it shall be considered as a leading technology by the time of the thesis publishing. Above all, the following features make the FITPix COMBO instrument unique.

- **Enhanced spectroscopic resolution**
  A breakthrough in spectroscopic resolution of back side pulse signal was achieved in the case of active read-out chip (while measurement is running in the pixelated part of Timepix). The value about 60 keV in measure of FWHM was confirmed (applicable for the Timepix with 600 µm Si sensor, the value about 86 keV was confirmed for 300 µm sensor).
- **Self-triggering capability**
  The Timepix measurement can be newly started just in time of particle interaction in dependence on the deposed energy. The exact energy range is fully adjustable while forming really profitable triggering condition. Thus, the effective filtration of events of interest from the undesired ones and background is possible.
- **Simultaneous data acquisition**
  The back side pulse signal analysis as well as measurement in the pixelated part of Timepix is possible without any restriction. The well designed software architecture enabled utilization of several data acquisition tools independently in parallel.
- **Position sensitive spectroscopy**
  The well-done synchronization (with time resolution of 10 ns) done on the hardware level allows exact assignment of energy information (taken from the back side pulse signal) to the particle track (taken from the pixel matrix of the Timepix detector).

10.2 Field of application of the FITPix COMBO device

The FITPix COMBO was conceived as a nuclear instrumentation apparatus from the very beginning of its development. The integrated functionality and its mechanical dimensions makes it a powerful tool for research on the field of experimental physics. As already mentioned, its primer target is application the study of heavy charged ionizing particles.

The integrated back side pulse spectroscopy enables a new shorter way for extraction of energetic information about an interacting particle. The exact information about energy can be gained while only the precondition is fulfilled - quite simple energetic calibration of the Timepix sensor is done (using the same approach as for a common single pad detector). Once the information is known, by extraction from the back side pulse, the sophisticated and time-demanding pixel-by-pixel calibration can be avoided afterwards.

The presented instrument is ready to be operated in the more complex experiments where cooperation of multiple detectors and other apparatus is required (e.g. coincidence measurement). The integrated mechanism for data acquisition triggering and synchronization allows it to be a fully-fledged part of the system.

10.3 Further need for development of the supporting application software and data processing software

To become a more useful instrument there has to be done further progress on the side of the supporting application software. A full potential of any electronic device can be exploited just in the case when appropriate support is available. This fact is also well-fitting for the FITPix COMBO device. Once the appropriate support is missing there is no way how the “buried gold” can be mined. The integrated services of online diagnostics are a good example (detector over-heating, supply voltage out of range, extensive power consumption are information that can really important while measurement is being performed). It also opens a way for subsequent study of the detector response in relation to the external conditions (temperature, supply voltage). Next, there is a newly arising question about the data post-processing. As there was not any solution with comparable output the appropriate data processing and evaluation methodic is missing. Therefor a significant progress is to be expected here.

References

[1] Knoll, Glenn F. Radiation Detection and Measurement Glenn F. Knoll. 3rd ed. New York: Wiley, 2000. Print.

[2] Wikipedia, Alpha particle spectroscopy, (April 2015), web. https://en.wikipedia.org/wiki/Alpha-particle_spectroscopy

[3] M. Platkevič, J. Jakůbek, Z. Vykydal, C. Granja, "Analogue signal from common electrode of pixelated detector for triggering and spectroscopy", Journal of Instrumentation 6 C11023 doi:10.1088/1748-0221/6/11/C11023 (2011)

[4] Carlos Granja, Jan Jakubek, Ulli Köster, Michal Platkevic, Stanislav Pospisil, Response of the pixel detector Timepix to heavy ions, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 633, Supplement 1, May 2011, Pages S198-S202, ISSN 0168-9002, http://dx.doi.org/10.1016/j.nima.2010.06.166.

[5] J. Bouchami, A. Gutierrez, A. Houdayer, J. Jakůbek, C. Lebel, C. Leroy, J. Macana, J. Martin, M. Platkevič, S. Pospíšil, C. Teyssier, "Study of the charge sharing in silicon pixel detector by means of heavy ionizing particles interacting with a Medipix2 device", Nucl. Instr. Methods A. Vol. 607, Issue 1, 1 p. 196-198, doi:10.1016/j.nima.2009.03.147 (2011)

[6] CERN, Web presentation of the Medipix Collaboration, web. www.cern.ch/medipix

[7] C. Granja, M. Holík, J. Jakůbek, V. Kraus, T. Kuwahara, M. Platkevič, S. Pospíšil, D. Tureček, O. Valach, Z. Vykydal, "Timepix-based Miniaturized Radiation Micro-Tracker for the Micro-Satellite RISESAT", Transactions of JSASS, Aerospace Technology Japan, Vol. 12 No. ists29 p. Tr_7-Tr_11 doi: http://dx.doi.org/10.2322/tastj.12.Tr_7 (2014)

[8] Jablotron, The MX-10 Digital particle camera, (2014), web. http://www.jablotron.com/en/about-jablotron-1/about-us/international-cooperation/jablotron-mx-10-1.aspx

[9] Michael Francois, Stefano Santandrea, Karim Mellab, Davy Vrancken & Jorg Versluys (2014) The PROBA-V mission: the space segment, International Journal of Remote Sensing, 35:7, 2548-2564, DOI: 10.1080/01431161.2014.883098

[10] C. Granja, M. Holík, J. Jakůbek, V. Kraus, T. Kuwahara, M. Platkevič, S. Pospíšil, D. Tureček, O. Valach, Z. Vykydal, "Timepix-based Miniaturized Radiation Micro-Tracker for the Micro-Satellite RISESAT", Transactions of JSASS, Aerospace Technology Japan, Vol. 12 No. ists29 p. Tr_7-Tr_11 doi: http://dx.doi.org/10.2322/tastj.12.Tr_7 (2014)

[11] X. Llopart, M. Campbell, R. Dinapoli, D. San Segundo Bello, E. Pernigotti: Medipix2, a 64k pixel readout chip with 55 mm square elements working in single photon counting mode, In: Proceedings of the IEEE Nuclear Science Symposium and Medical Imaging Conference, San Diego, 4–10 November, 2001.

[12] X. Llopart, R. Ballabriga, M. Campbell, L. Tlustos and W. Wong, “Timepix, A 65 k programmable pixel readout chip for arrival time, energy and/or photon counting measurements”, Nucl. Instrum. Meth. A 581 (2007) 485.

[13] San Segundo Bello, David and Beuzekom, Martin van and Jansweijer, Peter and Verkooijen, Hans and Visschers, Jan (2003) An interface board for the control and data acquisition of the Medipix2 chip. Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 509 (1-3). pp. 164-170. ISSN 0168-9002

[14] Zdenek Vykydal, Jan Jakubek, Stanislav Pospisil, USB interface for Medipix2 pixel device enabling energy and position-sensitive detection of heavy charged particles, Nuclear Instruments and Methods

in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 563, Issue 1, 1 July 2006, Pages 112-115, ISSN 0168-9002, http://dx.doi.org/10.1016/j.nima.2006.01.114.

[15] Zdenek Vykydal, Jan Jakubek, USB Lite—Miniaturized readout interface for Medipix2 detector, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 633, Supplement 1, May 2011, Pages S48-S49, ISSN 0168-9002, http://dx.doi.org/10.1016/j.nima.2010.06.118.

[16] V Kraus, M Holik, J Jakubek, M Kroupa, P Soukup and Z Vykydal, “FITPix — fast interface for Timepix pixel detectors”, J. of Instrumentation JINST 6 (2011) C01079.

[17] M. Holik, V. Kraus, J. Bartovsky, A. Krutina, V. Georgiev, V., "SPECTRIG — Device for triggering and spectroscopy with the pixelated particle detector," Telecommunications Forum (TELFOR) 2012, vol. 20, (2012) pp.959-962; doi: 10.1109/TELFOR.2012.6419368

[18] Holik, M.; Kraus, V.; Broulim, J.; Georgiev, V., "The interface for the pixelated particle detector with the capability of the spectroscopy function and the coincidence measurement operation," Telecommunications Forum (TELFOR), 2013 21st , vol., no., pp.557,560, 26-28 Nov. 2013, doi: 10.1109/TELFOR.2013.6716290

[19] C. Granja, V. Kraus, J. Jakubek, S. Pospisil, P. Masek, Z. Vykydal, M. Platkevic, Z. Kohout, Y. Kopatch, S.A. Telezhnikov, “Spatially Correlated and Coincidence Detection of Fission Fragments with the Pixel Detector Timepix”, Nuclear Science Symposium IEEE NSS/MIC, Knoxville, Conf. Record (2010) 1578-1584.

[20] C. Granja, V. Kraus, Yu. Kopatch, S. Pospisil., S.A. Telezhnikov, “Online Coincidence Detection of Fission Fragments and Light Charged Particles”, ISINN19, Dubna

[21] T. Holy, J. Jakubek, S. Pospisil, J. Uher, D. Vavrik, Z. Vykydal, Data acquisition and processing software package for Medipix2, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 563, Issue 1, 1 July 2006, Pages 254-258, ISSN 0168-9002, http://dx.doi.org/10.1016/j.nima.2006.01.122.

[22] D. Tureček, T. Holý, J. Jakůbek, S. Pospíšil, Z. Vykydal, "Pixelman: a multi-platform data acquisition and processing software package for Medipix2, Timepix and Medipix3 detectors ", Journal of Instrumentation 6 C01046, doi: 10.1088/1748-0221/6/01/C01046 (2011)

[23] CERN, Knowledge transfer - Medipix, webpage, http://knowledgetransfer.web.cern.ch/life-sciences/from-physics-to-medicine/medipix

[24] Brainder, Gaussian kernels: convert FWHM to sigma, (2011), web. http://brainder.org/2011/08/20/gaussian-kernels-convert-fwhm-to-sigma/

[25] WordPress, High Resolution Gamma Spectroscopy, web. https://lexieslogofphysics.wordpress.com/2013/02/18/experiment-1-high-resolution-gamma-spectroscopy/

[26] K.A. Olive et al. (Particle Data Group), The Review of Particle Physics , Chin. Phys. C, 38, 090001 (2014)

[27] M.J. Berger, J.S. Coursey, M.A. Zucker and J. Chang, Stopping-Power and Range Tables for Electrons, Protons and Helium Ions, NIST, Physical Measurement Laboratory, http://www.nist.gov/pml/data/star/index.cfm

[28] Altera Inc., Cyclone IV Device Handbook, web. https://www.altera.com/content/dam/altera-www/global/en_US/pdfs/literature/hb/cyclone-iv/cyclone4-handbook.pdf

[29] Altera Inc., Quartus II Handbook, web. https://www.altera.com/content/dam/altera-www/global/en_US/pdfs/literature/hb/qts/quartusii_handbook.pdf

[30] Texas Instruments, ADS6125 device datasheet, web. http://www.ti.com/lit/ds/symlink/ads6125.pdf

[31] J. Marchal, “Theoretical analysis of the effect of charge-sharing on the Detective Quantum Efficiency of single-photon counting segmented silicon detectors”, Journal of Instrumentation, 5, P01004

[32] J. Jakubek, Michal Platkevic, C. Granja, U. Köster, S. Pospisil, Direct observation of decay of radioactive nuclei with spatial and time coincidence technique, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 633, Supplement 1, May 2011, Pages S203-S205, ISSN 0168-9002, http://dx.doi.org/10.1016/j.nima.2010.06.167.

[33] Hoang, S., Vilalta, R., Pinsky, L., Kroupa, M., Stoffle, N., & Idarraga, J. Data Analysis of Tracks of Heavy Ion Particles in Timepix Detector. In: Journal of Physics: Conference Series. IOP Publishing, 2014. p. 012026.

[34] Asbah, N., Leroy, C., Pospisil, S., & Soueid, P. Measurement of the efficiency of the pattern recognition of tracks generated by ionizing radiation in a TIMEPIX detector. Journal of Instrumentation, 2014, 9.05: C05021.

[35] J. Jakůbek, Semiconductor Pixel detectors and their applications in life sciences, 2009 JINST 4 P03013., doi:10.1088/1748-0221/4/03/P03013

[36] Jan Jakubek, Precise energy calibration of pixel detector working in time-over-threshold mode, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 633, Supplement 1, May 2011, Pages S262-S266, ISSN 0168-9002, http://dx.doi.org/10.1016/j.nima.2010.06.183.

[37] M. Campbell, E. Heijne, T. Holý, J. Idárraga, J. Jakůbek, C. Lebel, C. Leroy, X. Llopart, S. Pospíšil, L. Tlustos, Z. Vykydal, Study of the charge sharing in a silicon pixel detector by means of α-particles interacting with a Medipix2 device, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 591, Issue 1, 11 June 2008, Pages 38-41, ISSN 0168-9002, http://dx.doi.org/10.1016/j.nima.2008.03.096.

List of Publications

[A1] Kraus, V. - Holík, M. - Jakůbek, J. - Kroupa, M. - Soukup, P. - et al., FITPix - fast interface for Timepix pixel detectors, In: Journal of Instrumentation [online]. 2011, vol. 6, art. no. C01079, p. 1-6. Internet: http://dx.doi.org/10.1088/1748-0221/6/01/C01079. ISSN 1748-0221.

[A2] Kraus, V. - Holik, M. - Jakůbek, J. - Georgiev, V., FITPix data preprocessing pipeline for the Timepix single particle pixel detector, Journal of Instrumentation [online]. 2012, no. 7, art. no. C04011, Internet: http://iopscience.iop.org/1748-0221/7/04/C04011. ISSN 1748-0221.

[A3] Holík, M. - Kraus, V. - Granja, C. - Jakůbek, J. - Georgiev, V. - et al., Influence of electromagnetic interference on the analog part of hybrid Pixel detectors, Journal of Instrumentation [online]. 2011, vol. 6, art. no. C12028, Internet: http://dx.doi.org/10.1088/1748-0221/6/12/C12028. ISSN 1748-0221.

[A4] Vykydal, Z. - Holík, M. - Kraus, V. - Pospíšil, S. - Šolc, J. - et al., A Highly Miniaturized and Sensitive Thermal Neutron Detector for Space Applications, IX LATIN AMERICAN SYMPOSIUM ON NUCLEAR PHYSICS AND APPLICATIONS. Melville, New York: American Institute of Physics, 2012, p. 393-396. ISSN 0094-243X. ISBN 978-0-7354-1003-9.

[A5] Granja, C. - Holík, M. - Jakůbek, J. - Kraus, V. - Kuwahara, T. - et al., Timepix-based Miniaturized Radiation Micro-Tracker for the Micro-Satellite RISESAT, Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan 01/2014; 12(ists29):Tr_7-Tr_11. DOI: 10.2322/tastj.12.Tr_7

[A6] Žemlička, J. - Jakůbek, J. - Kraus, V. - Holík, M., Fast Spectroscopic Imaging with Pixel Semiconductor Detector Timepix and Parallel Data Reading, Journal of Instrumentation [online]. 2014, vol. 9, art. no. C04007, Internet: http://iopscience.iop.org/1748-0221/9/04/C04007/pdf/1748-0221_9_04_C04007.pdf. ISSN 1748-0221.

[A7] Vavřík, D. - Holík, M. - Jakůbek, J. - Kraus, V. - Krejčí, F. - et al., Modular pixelated detector system with the spectroscopic capability and fast parallel read-out, Journal of Instrumentation [online]. 2014, vol. 9, art. no. C06006, p. 1-9. Internet: http://iopscience.iop.org/1748-0221/9/06/C06006. ISSN 1748-0221.

[A8] Holik, M.; Kraus, V.; Broulim, J.; Georgiev, V., "The interface for the pixelated particle detector with the capability of the spectroscopy function and the coincidence measurement operation," Telecommunications Forum (TELFOR), 2013 21st , vol., no., pp.557,560, 26-28 Nov. 2013, doi: 10.1109/TELFOR.2013.6716290

[A9] M. Holik, V. Kraus, J. Bartovsky, A. Krutina, V. Georgiev, V., "SPECTRIG — Device for triggering and spectroscopy with the pixelated particle detector," Telecommunications Forum (TELFOR) 2012, vol. 20, (2012) pp.959-962; doi: 10.1109/TELFOR.2012.6419368

[A10] V. Kraus, M. Holik, J. Bartovsky, V. Georgiev, J. Jakubek, D. Schneider, “Space Weather Monitor Based on the Timepix Single Particle Pixel Detector”, Telecommunications Forum (TELFOR), 2010, ISBN 978-86-7466-392-9