CHAPTER IV
PRELIMINARY: THE FPGA TRIGGER CONTROL SYSTEM INTERFACING THE TELESCOPE WITH KCMH BEAM TEST

This chapter describes the telescope construction utilized in the KCMH experiment. It is made up of six ALPIDE monolithic active pixel sensors. The EUDAQ framework is responsible for the telescope's control and data collection. The output data is in the form of a binary or raw file. The purpose of this chapter is to give preliminary results of the KCMH proton beam test with the telescope utilized at SLRI for electron beam testing. This chapter also includes the development of a novel trigger system for sending an external signal for EUDAQ run.

4.1 Introduction

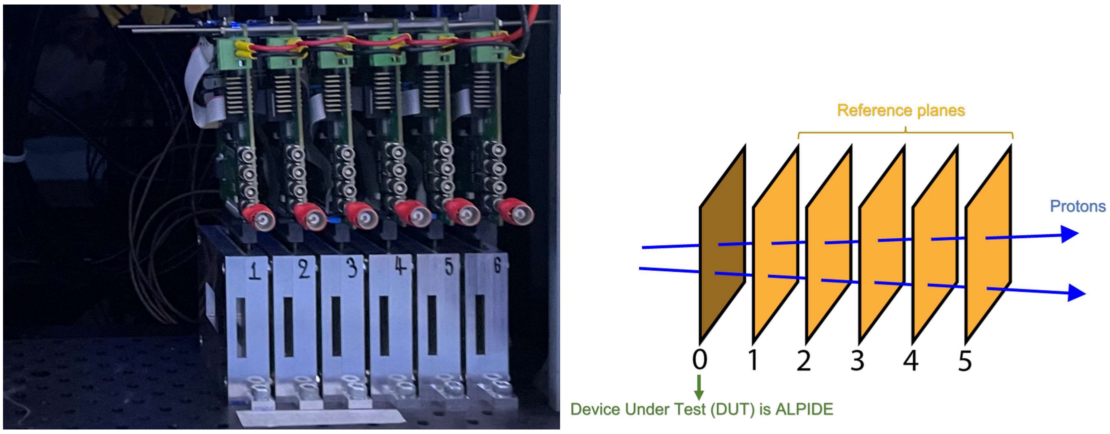
ALICE's inner tracking system (ITS) currently consists of seven layers of Monolithic Active Pixel Sensors centered as a cylinder. By testing the six-plane telescope, we want to determine the treatment proton beam profile. The geometry configuration is comparable to the electron beam test at SLRI, and it includes a new trigger system. The experiment demonstrates proton detection and indicates the best telescope for the pCT prototype.

The telescope's sensor section, which is made up of six ALPIDE planes, can detect particle hits. These 512x1024 pixels serve as an active area for the generation of electronic signals. By collecting numerous frames of hit data, the signal can be quantified as a stack of proton hit signals. The detector must deliver low intensity per frame based on the readout rate of a typical pCT. As previously stated, the excessive number of primary particles used in the track reconstruction technique results in low track efficiency. To make the experiment as similar to the pCT system as possible, we built a module that controls the behavior of ALPIDE sensors in the telescope by sending a signal to a DAQ board linked to the sensor.

4.2 Material and method

4.2.1 Pixel sensor telescope

The majority of ALPIDE prototypes are tested using charged particles with several beam test facilities including CERN (Mager, 2016). In general, a pixel sensor telescope, which consists of seven planes of ALPIDE sensors positioned perpendicular to the particle stream, is used in the measuring setup with one Device Under Test (DUT) placed in the middle (Kaewjai et al., 2019). However, our telescope is made up of six sensor planes, five reference planes, and one Device Under Test (DUT). As illustrated in Figure 4.1, the pixel sensor telescope was situated in the KCMH experiment for sensor evaluating the track reconstruction of the PBS proton beam.



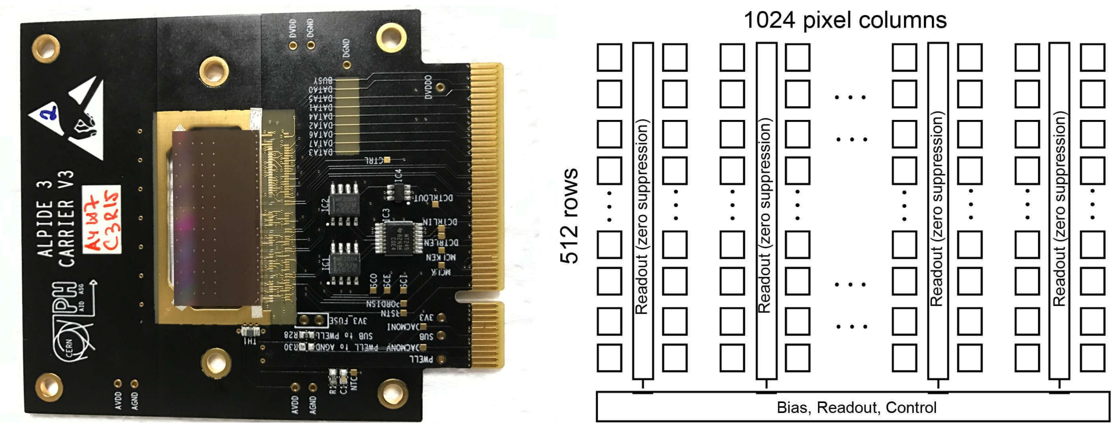
(a) Telescope construction. (b) Telescope layout.

Figure 4.1 The pixel sensors telescope which consists of six ALPIDE sensor and DAQ boards. (a) Each DAQ connects to single ALPIDE chip and wired to external trigger signal and the power. (b) The DUT is set to the layer 0 and the rest are references.

4.2.2 ALPIDE Monolithic Active Pixel Sensor

The pixel matrix and related readout circuits are integrated on a single sub-strate in a monolithic active pixel sensor (MAPS). This functionality enables MAPS to have greater granularity while using less power. Peripheral circuitry and power supply can also be simplified for MAPS (Abelev and ALICE Collaboration, 2014). Prior to 2006, the European Detector Research and Development towards the International Linear Collider (EUDET) collaboration proposed using MAPS as a sensor plane in the construction of a new generation of high-precision beam telescopes (Haas, 2006). The pixel telescope can benefit from MAPS's outstanding spatial resolution, low material budget, quick readout time, and suitable sensitive area size. The Minimal Ionizing MOS Active sensor (MIMOSA) is used in the construction of EUDET-type telescopes (Hu-Guo et al., 2010). A series of EUDET-type telescopes is in operation around the world, including Advanced European Infrastructures for Detectors at Accelerators at CERN, DATURA and DURANTA at DESY, CALADIUM at the Stanford Linear Accelerator Center (SLAC), and others (Jansen et al., 2016).

ALPIDE is a 1.5×3.0 cm^2 MAPS that reads in binary hit/no-hit mode 512×1024 (row $\times$ column) 28×28 pixels. It combines a continuously active and low-power in-pixel discriminating front-end with a fully asynchronous, hit-driven combining circuit (Mager, 2016). As demonstrated in Figure 4.2, analog biasing, control, readout, and connectivity operations are implemented on a 1.2×30 mm^2 peripheral region (Aglieri Rinella, 2017).



(a) Single ALPIDE chip.

(b) Architecture of the ALPIDE chip.

Figure 4.2 The monolithic active pixel sensor ALPIDE.

4.2.3 EUDAQ framework

The Electronic Universal Data Acquisition (EUDAQ) framework is primarily based on the trigger trigger logic unit (TLU). The framework's many modules can run on separate machines and communicate with one another via an Ethernet network utilizing TCP/IP connections. This provides for more flexible DAQ network architecture, which is especially useful for test beams where detectors and users may change often.

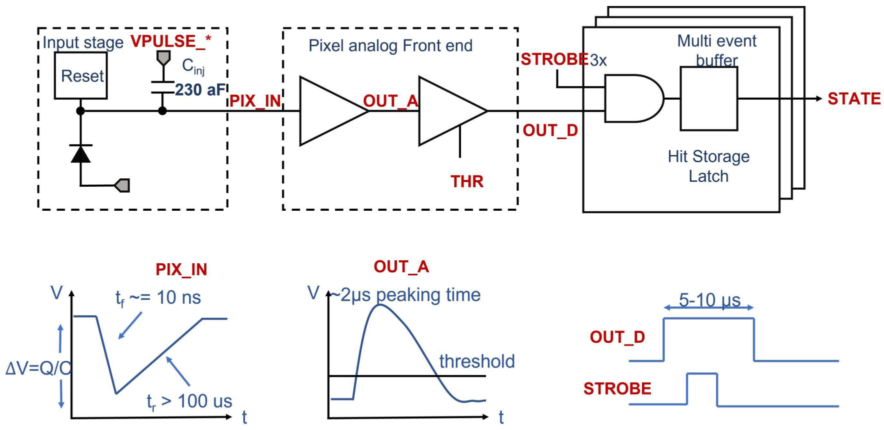


Figure 4.3 Block diagram of the ALPIDE pixel cell.

A typical EUDAQ network is depicted in Figure 4.4. To begin, the EUDET TLU (Cussans, 2009) was employed in conjunction with renowned EUDAQ for the DAQ of EUDET-type Mimosa26 sensing telescopes (Jansen et al., 2016; Hu-Guo et al., 2010).

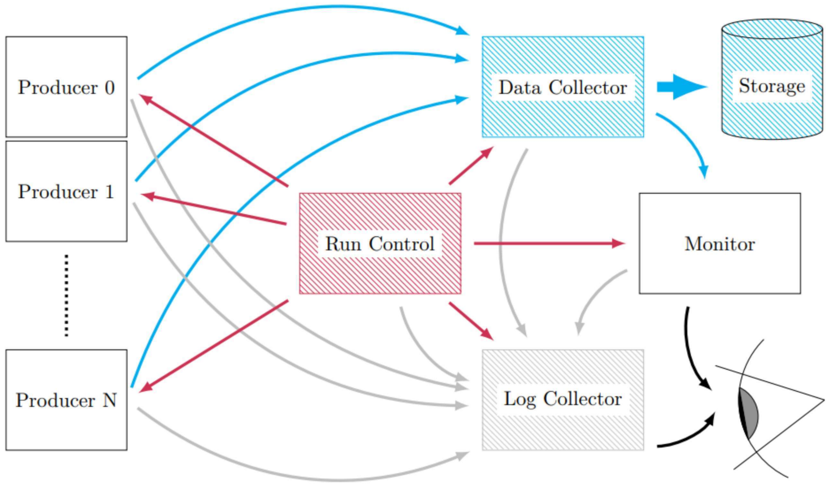


Figure 4.4 The EUDAQ network typically consists of several components, including the central command and control server known as Run Control, the Data Collector, which is responsible for creating global events and storing them on disk, the Log Collector, which manages and displays log messages, and the monitor application, which allows for real-time monitoring of data quality (Spannagel, 2016).

The EUDAQ version 2 is used in this work. The firmware must be installed in the Data acquisition (DAQ) board that contains the Field programmable gate array (FPGA) chip over USB. The configuration files are edited to match the experiment setup, such as the number of sensors, output file path, ALPIDE characteristics, and so on. The Terminal Multiplexer (TMUX) is used to execute the EUDAQ Graphical user interface (GUI) process while waiting for the signal from the trigger to initiate the execute. The GUI interface needs the user to enter the frequency as well as the optional HIGH/LOW signal per pulse. As illustrated in Figure 4.5, the microcontroller accepts the serial signal from the interface and stores user input in another FPGA register for creating a trigger signal to the DAQ.

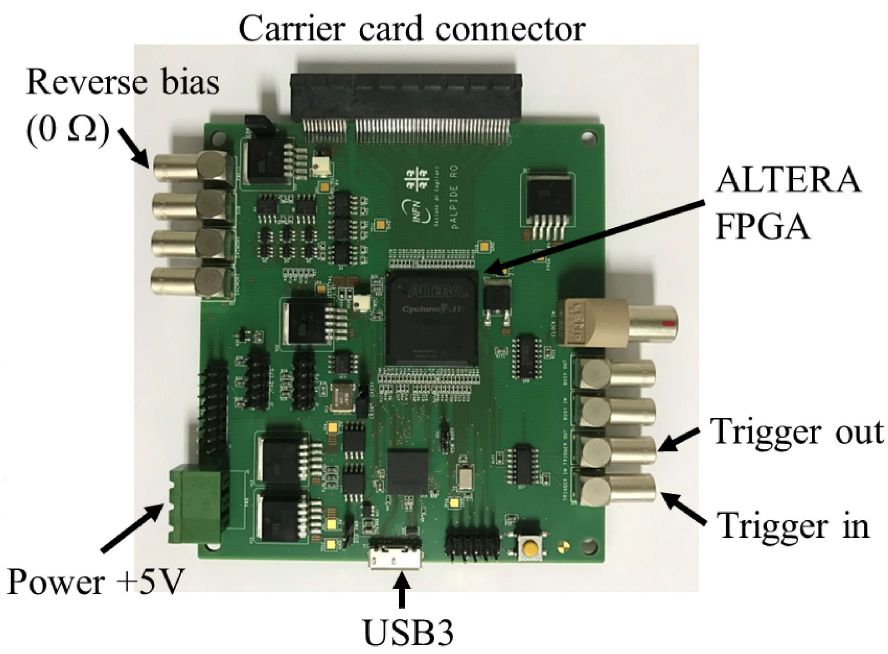


Figure 4.5 This figure shows a board for data collecting. The external signal from the trigger system is received through the trigger-in port. The same signal is used as an output in the trigger-out. The Alterla FPGA is included in the board and is used to operate the EUDAQv2 firmware.

4.2.4 FPGA trigger system

Typically, the EUDAQ architecture collects data from DAQs event by event using an external signal from the trigger system. The square wave signal is ideal for DAQ trigger-in port input. The first generation trigger may also activate telescope DAQs and open the proton beam gate of the KCMH cyclotron. It is constructed with a microcontroller (Arduino) to provide pulses to DAQs and a signal to the KCMH trigger system in the control room in order to operate a proton beam in patient mode. The frequency is approximately 0.2 kHz, which is generated using counting loop logic in C++ Arduino code. The FPGA trigger was constructed with a 100 MHz clock speed to achieve a more reliable and high-speed frequency. The system was designed to be installed in a treatment room and wired with telescopic DAQs because the system's function is to handle only Quality Assurance (QA) mode. The pCT telescope is used in this chapter to measure the QA mode of the KCMH proton beam using an FPGA trigger.

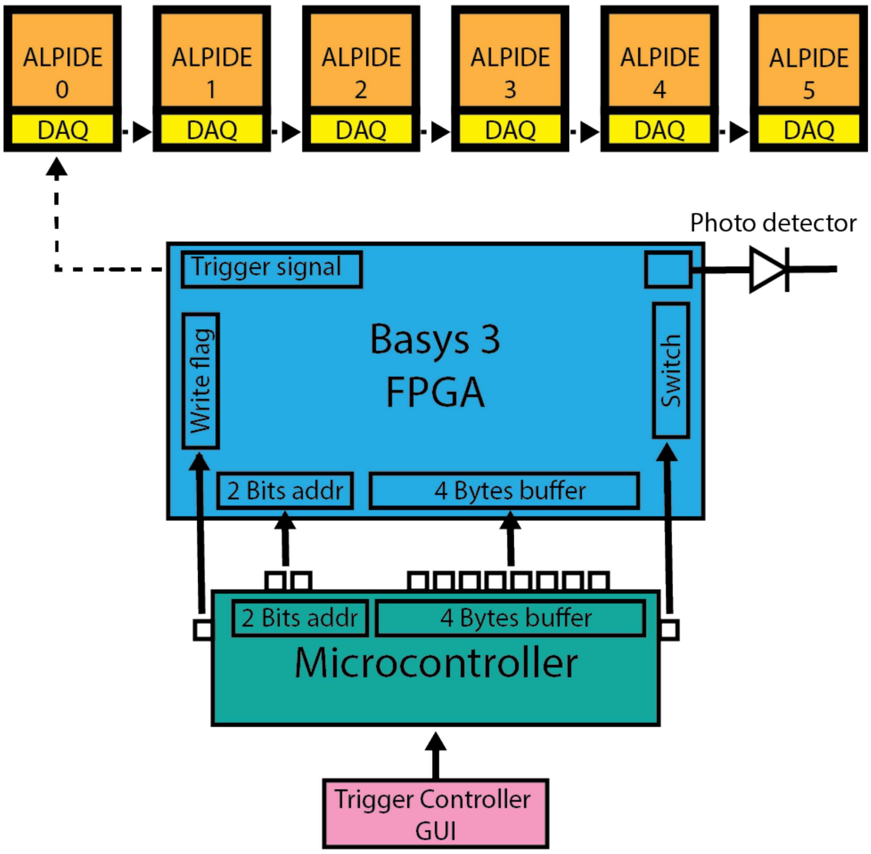


Figure 4.6 The trigger control system scheme for FPGAs. The GUI accepts frequency values from the user. The microcontroller converts frequency to a binary value and sends it to the FPGA along with the register address. Finally, the FPGA sends a trigger signal to the ALPIDEs through the DAQ board.

As seen in Figure 4.6, the GUI communicates with the microcontroller through serial port. The microcontroller converts the frequency to binary and sends it to the FPGA through the buffer address. The GUI can also allow the FPGA to register data and wait signals from the GUI ON signal. The GUI ON signal will activate the FPGA by turning on the Switch flag in the FPGA, indicating that it is ready to generate a trigger signal to the DAQ.

4.2.5 The first generation of trigger

The trigger controller system was designed using the MEGA2560 pro mini as the microcontroller unit. It was linked to the SAMKOON SK-070FE HMI touchscreen through the Universal Asynchronous Receiver/Transmitter (UART) to provide a graphical user interface. The controller's communication used the Modbus protocol via a C language software to send signals to each component. The functionality of the pCT trigger controller was tested by sending programmed signals to the rotational stage and ALPIDE sensor, which were linked to the proton cyclotron at the King Chulalongkorn Memorial Hospital (KCMH) Proton Center for controlling the timing of the proton beam gating. The results showed that the pCT trigger controller was capable of controlling the gating of the proton cyclotron as well as communicating with an ALPIDE sensor for detecting and recording proton positions. At this stage, only one ALPIDE sensor was intended to be employed for testing as the position-sensitive detector.

4.2.6 Basys3 FPGA

Basys3 is created by Digilent Inc. which is a usable digital circuit based on Artix®-7, a Xilinx® Field Programmable Gate Array (FPGA) (XC7A35T1CPG236C). The Basys 3 is compatible with Xilinx's sophisticated Vivado™ Design Suite, which includes a variety of unique tools and design workflows that support cutting-edge design methods. Vivado is more efficient, makes better use of FPGA resources, and allows designers to spend more time investigating design choices. The System Edition (SE) includes an on-chip logic analyzer, a high-level synthesis tool, and other cutting-edge features, but the free WebPACK™ edition allows Basys 3 designs to be created without incurring any additional fees (Xilinx, 2017). Table 4.1 describes the Basys 3 components labeled in Figure 4.7.

The voltage regulator circuits in Linear Technology create the necessary 3.3V, 1.8V, and 1.0V power supplies from the primary power input. In the trigger system, the Pmod component is interfaced with a 3.3V microcontroller through Pmod pins. The 100

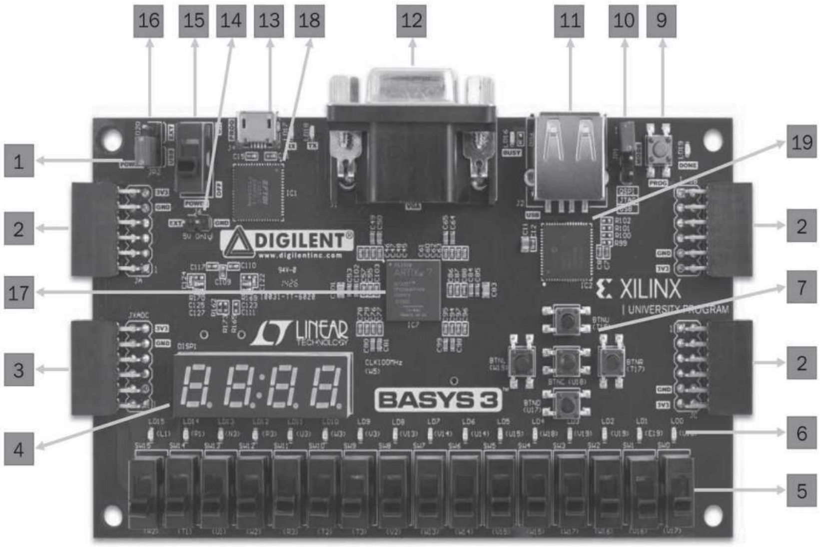


Figure 4.7 The Basys3 board layout and labels

Table 4.1 Basys 3 labeled components and descriptions.

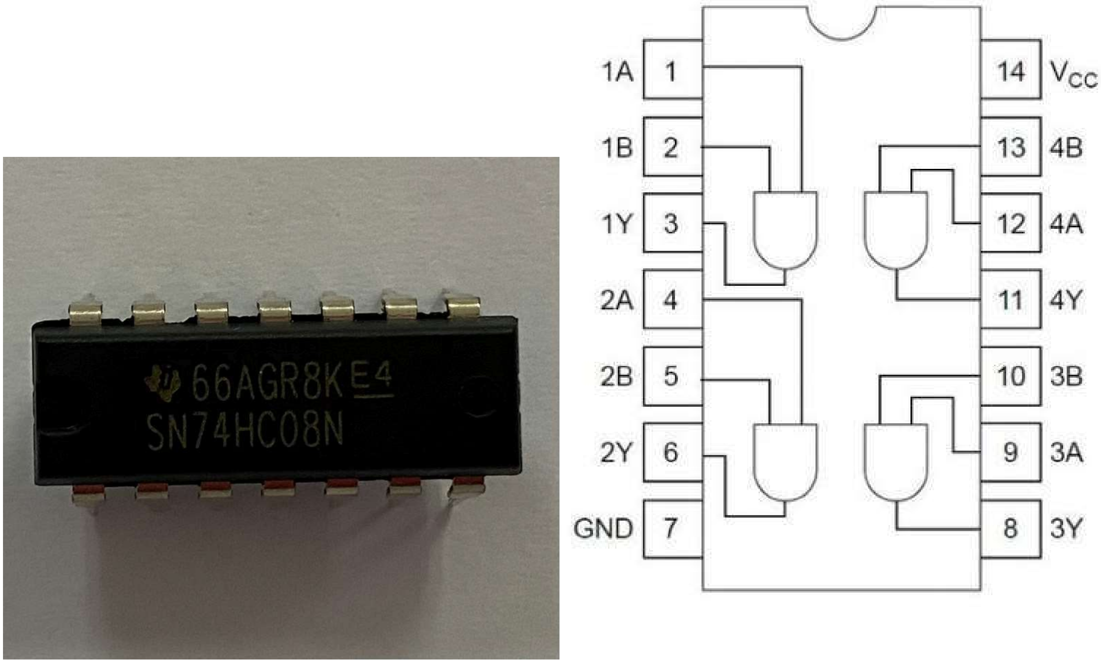
No.	description	No.	description
1	Power good LED	9	FPGA configuration reset button
2	Pmod port(s)	10	Programming mode jumper
3	Analog signal Pmod port (XADC)	11	USB host connector
4	Four digit 7-segment display	12	VGA connector
5	Slide switches (16)	13	Shared UART/ JTAG USB port
6	LEDs (16)	14	External power connector
7	Pushbuttons (5)	15	Power Switch
8	FPGA programming done LED	16	Power Select Jumper

MHz clock from the Basys 3 oscillator, which is linked to pin W5, is divided by Resistor Transistor Logic (RTL) to generate a trigger signal for the DAQ board.

4.2.7 Signal amplification

The standard voltage levels of the Basys3 FPGA, according to section 4.2.6, are 3.3V, 1.8V, and 1.0V. The DAQ board, on the other hand, requires 5V to generate the run event for the EUDAQv2 run control. In this work, the IC SN74HC08N Quad 2-

input AND gate (DIP) was coupled to a trigger signal created by an FPGA as an input AND gate. Voltage Common Collector (VCC) provides another input, and the amplified trigger pulse is obtained from the output of two inputs.



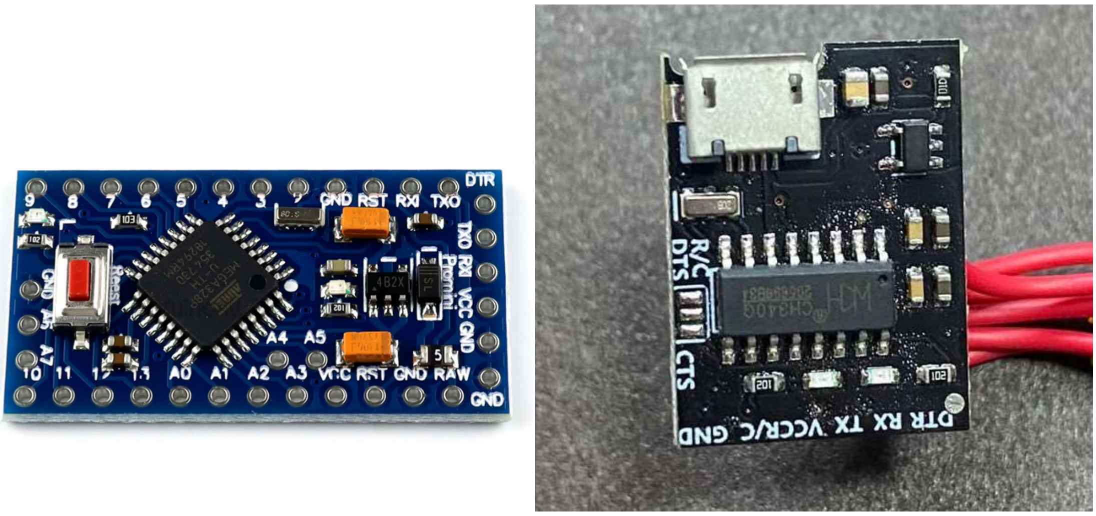
(a) SN74HC08N IC component. (b) The AND logics of SN74HC08N IC.

Figure 4.8 SN74HC08N.

4.2.8 Microcontroller

Section 4.2.6 states that the operational voltage levels that can be coupled with the FPGA portion are 3.3V, 1.8V, and 1.0V. In contrast, the most popular Microcontroller board, the Arduino Uno R3, operates at 5.0V, which can damage FPGA boards if they are coupled. As a result, by using Logical Voltage Conversion 3.3V-5V, the Uno R3 can be safely linked. Fortunately, there is a 3.3V Arduino board named the Arduino Pro Mini 328 - 3.3V/8MHz. It has an 8MHz clock speed and no USB programmable port. As shown in Figure 4.9, the Pro Mini 328 must connect Data Terminal Ready (DTR), Transmit Data (TXO), Receive Data (RXI), VCC, and ground connector to USB CH340 in order to program the board with Arduino Integrated Development Environment (IDE).

Analog and digital pins are directly wired to Basys3 FPGA. From the Table 4.2,



(a) Pro Mini 328(3.3V/8MHz).

(b) USB CH340 module.

Figure 4.9 The microcontroller part that consists of Pro Mini 328 board and USB programming module.

the Pro Mini 328 pins used for the connection are shown. The write flag means the signal that allow binary data from Arduino transferred to FPGA along its bits address. The switch flag is ON when the FPGA is ready to generate the trigger signal to the DAQ.

Table 4.2 Arduino Pro Mini 3.3V (3.3V/8MHz) pins connecting to Basys3 FPGA and the usages.

Pro Mini pins	Basys3 pins	Usage
2 - 9	K3, J3, M3, L3, M1, M2, N1, N2	8 bits data
10 - 11	H1, J1	2 bits address
12	K2	Write flag
13	L2	Switch flag

4.2.9 GUI interface

The Graphical User Interface (GUI) was created using the Python programming language in conjunction with the PyQt5 package. The GUI needs the user to enter a frequency value before sending it to the microcontroller via serial connection. Signal pulse width and module value are optional fields. The frequency input is used to generate the generic square wave. In the GUI, there are three push buttons, each of which has a particular function. To communicate all parameters in the fields to the microcontroller, the *set* button must be pressed. When the *run* button is pressed, a 1-bit signal is sent to the FPGA through the microcontroller to release the trigger signal to the telescope. Finally, the *stop* button must be pressed to stop the trigger generating signal. The backend of the trigger program is also written in Python and uses Pyserial. Figure 4.10 depicts the GUI for the trigger system controller.

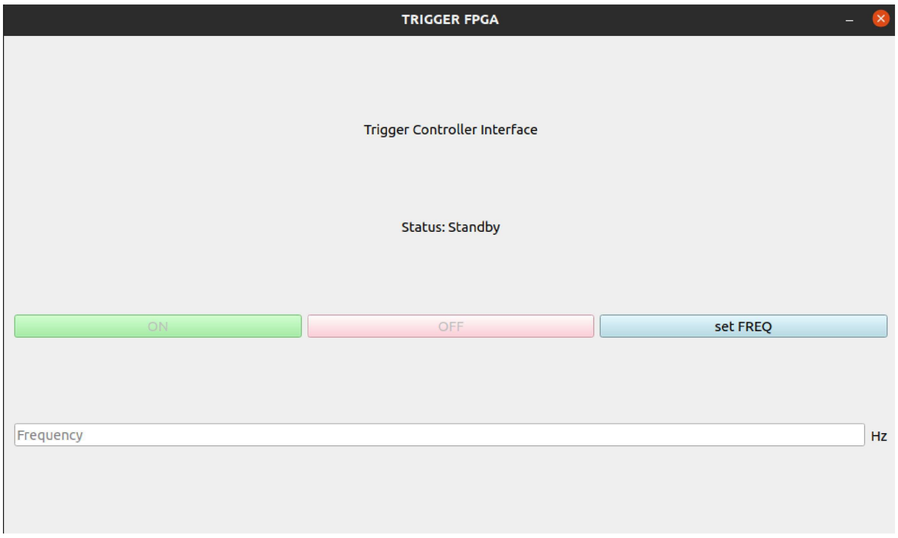


Figure 4.10 The Graphical User Interface (GUI) of FPGA trigger.

4.2.10 Signal operation

The data from the microcontroller is stored in the trigger generator's buffer. To generate a wide range of trigger frequency values, data must be provided simultaneously with the address of the FPGA buffer. When all data in the data buffer is fully occupied, the microcontroller will transmit the ready signal to the GUI, informing the user that the trigger system is ready to send a signal to the sensor. The ALPIDE sensor, which is linked to the DAQ board, can measure proton hit from numerous frames. The trigger system regulates the readout rate. The trigger signal is a periodic square wave generated by FPGA programming's clock divider logic. The Basys3 provides a 100MHz programming clock from the W5 pin. However, the maximum frequency that the DAQ board can discern is around 9.5 kHz. So, in this experiment, we set the trigger to maximum and the amount of occurrences to 5000. The sensor waited for the proton beam from the KCMH cyclotron to be irradiated before storing the detection data at the trigger on signal.

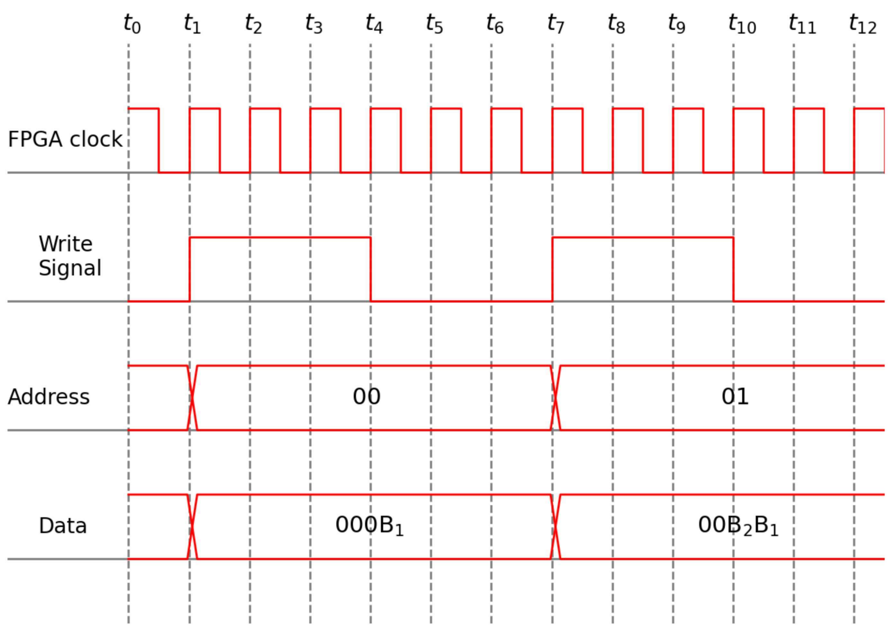


Figure 4.11 FPGA trigger operational signal of registering the frequency value to FPGA buffer along its 2-bit address.

The interface sends the GUI ON signal to the microcontroller, which turns on the Switch signal. As shown in Figure 4.12, the divided clock signal is created as a trigger signal. When the GUI is turned off, the trigger signal is reset.

4.2.11 Varian ProBeam proton PBS system

king chulalongkorn memorial hospital (KCMH) had installed the proton therapy machine since 2019 and started treatment in 2020. It is a cyclotron based accelerator by Varian named the ProBeam Compact proton therapy system with single Grantry. The intensity of the proton beam is controlled by the cyclotron. The beam intensity is checked again when it exits the cyclotron. The proton energy can be continuously modified between 70 and 240 MeV, and between 240 and 250 MeV in 1 MeV increments. The beam automatically turns off if the intensity is deemed too high. The switching of beams between treatment rooms during a patient's therapy can be pre-planned, minimizing the time required to move between patients. The system's parameter control can be divided into devices and sections, allowing machine maintenance to be done

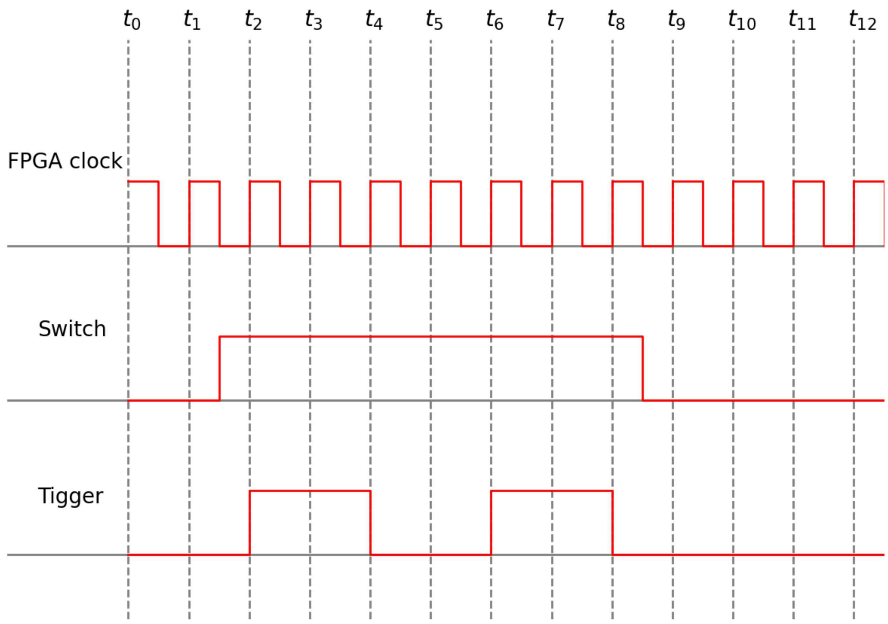


Figure 4.12 FPGA trigger operational signal with turning ON Switch signal.

in sections and preventing failures from affecting the entire machine. Remote beam diagnostics are also an option.

Treatment room

The treatment room consist of gantry and the treatment table to ensure that proton beam can be delivered to precise position of the tumor volume in a patient. The treatment room is essentially a 3.5-meter-long, cylindrical tube with an inner diameter of around 5 meters and an enclosing that is patient-friendly. It offers sufficient room for the table to be positioned in any recommended therapeutic position. A customized workflow engine guides the user through the process via the Proton Treatment Console system. It starts with identifying the patient and the patient-specific equipment before guiding the user through position verification, treatment, and report production. The system is designed as a client-server application, allowing two persons to operate simultaneously - one in the therapy room prepping the patient and the other in the control room setting up the treatment. The QA mode of proton beam was used in this experiment. Figure 4.13, the experimental setup is shown as it is in the treatment room.

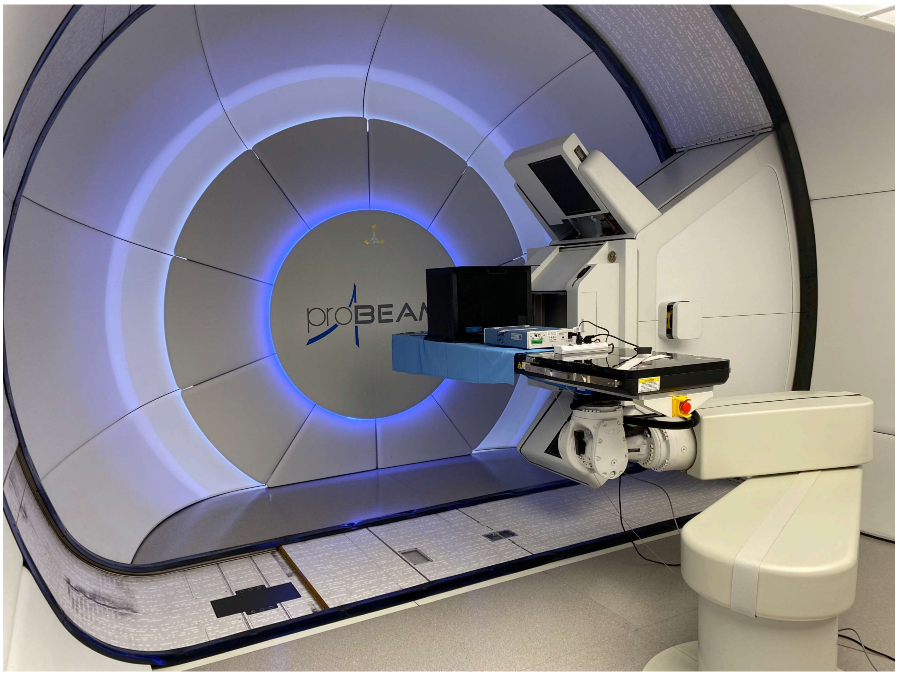


Figure 4.13 The treatment room at KCMH where the experiment setup is placed.

Control room

The Proton Treatment Console system employs a customizable workflow engine that directs the user through the process. The control room consists of the Proton Treatment Console (PTC) which is the front end of the proton machine. Control of the treatment is handled by a dialog screen. It displays the dose rate, the MUs, and the proton energy. Throughout all work processes, the PTC shows the patient’s picture and data along with system and machine status information and the beam waiting time. The beam parameters can be optimized by the PTC in the room. In this experiment, the QA mode of proton beam was used. The beam parameters and patient bed position are configured by the monitor in the control room as show in Figure 4.14.

Proton beam in QA mode

Quality assurance (QA) is used to guarantee that accurate input data for treatment machine setup in a therapy planning system, appropriate dosimetry equipment is needed for base data measurements. It requires specialized sensors and dosimetry equipment. Dosimetry equipment for scanned proton beams is comparable to that

Figure 4.14 The control room has monitors for requiring users to adjust patient bed position, parameterise proton beam and creating treatment plan.

used in photon treatment, with the extra requirement of meeting longer operational ranges, particularly in terms of time duration and dose rates, as well as better spatial resolution. Based on its knowledge, Varian can assist each customer in selecting appropriate dosimetry equipment from third-party providers. The beam current of various beam energies provided by the KCMH technician are shown in Table 4.3.

Table 4.3 Proton beam parameters in Quality Assurance (QA).

Beam energy (MeV)	Current (nA)
70	300
100	200
120	160
150	150
180	50
200	10

PBS beam

As already described in Section 3.2.2 about KCMH beam spot sigma, the beam shape can be represented as Gaussian model that is spreading along the traveling path because of the scattering with air. In the simulation section, the curve fit achieved for optimising beam spot at Nozzle position of 42.1 cm apart from ISOCENTER and the beam energies was use of 70MeV and 200MeV. In Table 4.4, the spot sigma data are shown in various energies of the source with the distance apart from ISOCENTER point measured by Lynx PT from IBA dosimetry.

Table 4.4 Lynx PT measured the proton spot size (sigma, mm) of the KCMH proton center from IBA dosimetry.

Distance from ISOCENTER (cm)	**-20**	**-10**	**0**	**10**	**20**
Energy (MeV)	**σ (mm)**	**σ (mm)**	**σ (mm)**	**σ (mm)**	**σ (mm)**
70	7.10	6.45	5.95	5.45	5.00
100	5.65	5.20	4.95	4.65	4.35
120	5.05	4.70	4.50	4.35	4.15
150	4.45	4.30	4.15	4.00	3.85
180	4.20	3.95	3.80	3.80	3.55
200	3.95	3.75	3.65	3.60	3.50
220	3.80	3.70	3.50	3.50	3.40

4.2.12 Experiment setup

The components of the experiment are outlined in Chapter IV's content. The ALPIDEs telescope, EUDAQv2 software, FPGA trigger, and its GUI serially interfaced with the microcontroller comprise the experiment setup. As shown in Figure 4.15, a dark box contains practically all of the experiment setup to limit light source detection in the treatment room. The dark box was put on the patient's bed, and the bed was adjusted to align the telescope's orientation with the proton beam nozzle.

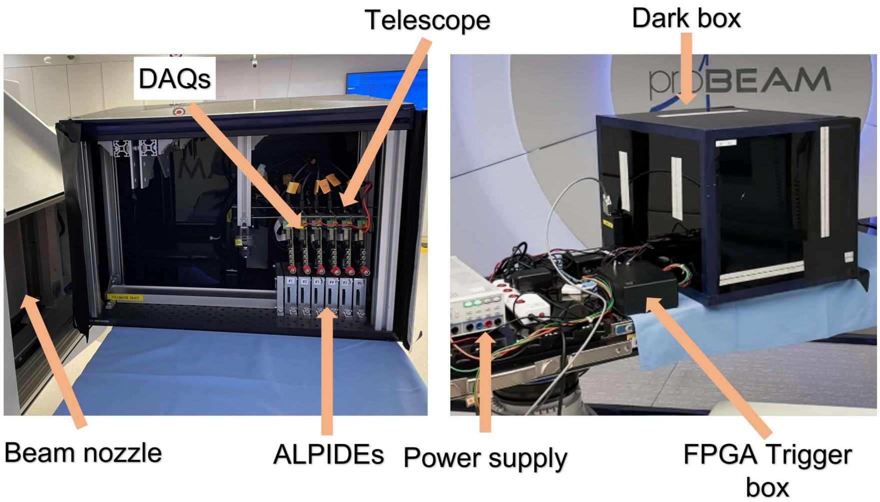


Figure 4.15 For the KCMH beam test, the experiment configuration of the FPGA trigger controlling system interfaced with ALPIDEs telescope. While the telescope was inside, the power source and trigger were wired out of the dark box. The telescope was likewise linked to the power supply.

4.3 Results and Discussion

4.3.1 Trigger signal

The Basys3 FPGA was programmed using Vivado ML Edition 2021.2 to serve as the Telescope's trigger. To configure the logic blocks of an FPGA, the Verilog language is written as RTL. The Verilog module requires four input variables: switch, write flag, write address, and write data value, as shown in Table 4.2 in section 4.2.6, which demonstrates the implementation of FPGA PINs on their operations. Figure 4.16 depicts the FPGA writing procedure in the Vivado signal simulation.

Figure 4.17 displays the operational signal of the FPGA trigger in Vivado software simulation after the frequency value of the trigger is registered to the FPGA trigger register. The frequency of 9.5 kHz is chosen as the maximum value to which the Telescope's DAQ can respond.

Figure 4.18 shows the WaveRunner 8254 oscilloscope, which provides an amazing user experience as well as a wide range of capabilities to speed up the debugging process. The oscilloscope has unrivaled touch capabilities in the market, allowing for maximum efficiency in operation. The device has a wide bandwidth ranging from

Figure 4.16 The simulation signal used to write a frequency value to an FPGA register. A particular address is assigned to each of the various 1-bit input values.

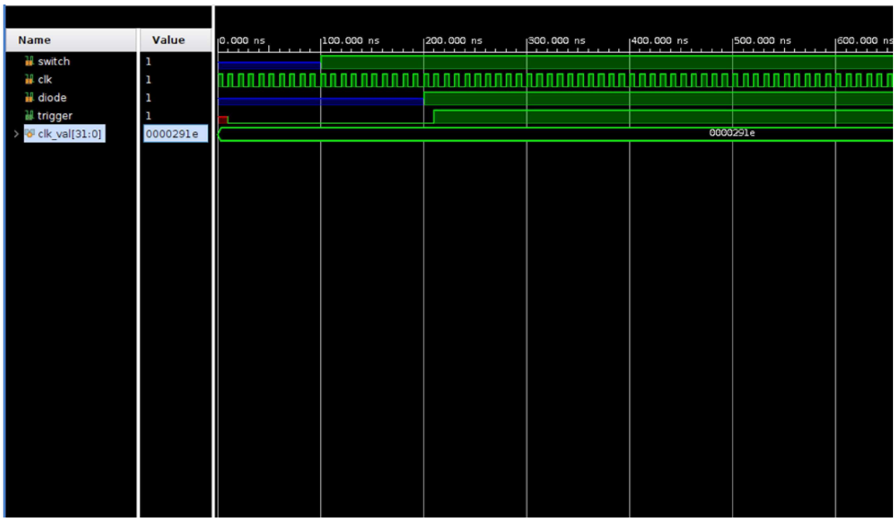


Figure 4.17 The generating trigger simulation signal. The frequency is set to 291E of Hexadecimal.

500 MHz to 2.5 GHz, a sample rate of 20 GS/s, and a large memory. The WaveRunner 8254 is a highly powerful instrument that is also incredibly user-friendly, thanks to MAUI's innovative user interface and a flexible range of capabilities.

The Waverunner 8254 was utilized to measure the FPGA trigger signal. According to Section 4.19, the 3.3V output of Basys3's trigger signal is shifted to 5V by

Figure 4.18 The WaveRunner 8254 oscilloscope.

using the IC SN74HC08N in the amplifier circuit. Figure 4.19 depicts the outcome of the Trigger signals.

4.3.2 Background measurement

The new trigger was first tested with EUDAQv2 by sending a 9.5 kHz trigger signal to the first DAQ board. The RUN's STROBE was set to 100 cycles. The output data was collected from the EUDAQv2's binary RAW format and exported in ROOT format. As shown in Figure 4.20, the background data was calculated as the mean of activated pixels on each ALPIDE layer. The first plane, which serves as the reference layer, has an extremely low background since its mean is close to zero. However, the background signal was discovered to be approximately 3.1 in the layer 4 as a mean of activated pixels in multiple event detection as the strongest signal when compared to the remainder layers.

Figure 4.21 shows the total number of active pixels for each occurrence. There are 6907 events that take place on the RUN. The average number of activated pixels on each layer was 6.518 pixels, with a standard deviation of 1.957 pixels.

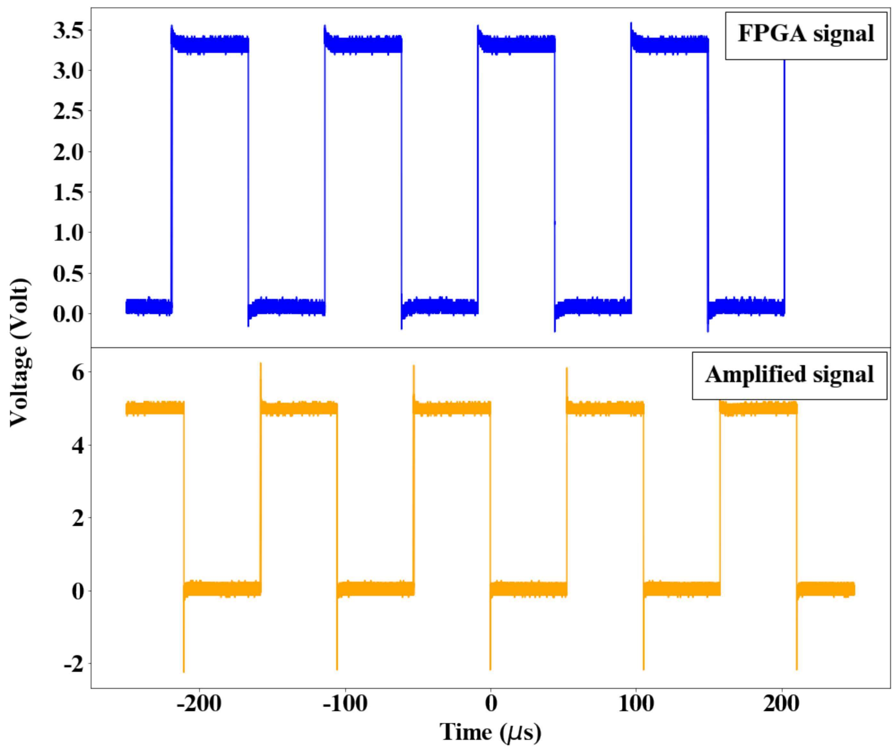


Figure 4.19 The FPGA trigger pulses of regular and amplified signals measured by the Waverunner 8254.

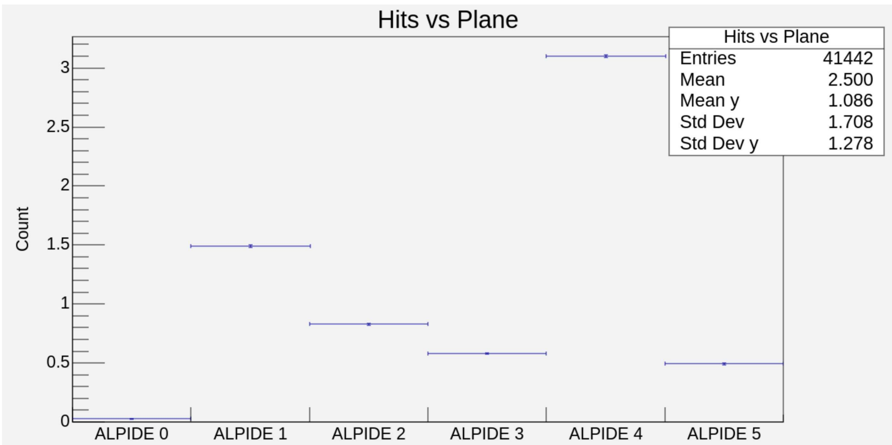


Figure 4.20 The mean of activated pixels of background measurement in 6907 events.

4.3.3 KCMH beam test

The first test for KCMH proton beam detection used the same setup as the background measurement detailed in section 4.3.2. In a configuration file, the number

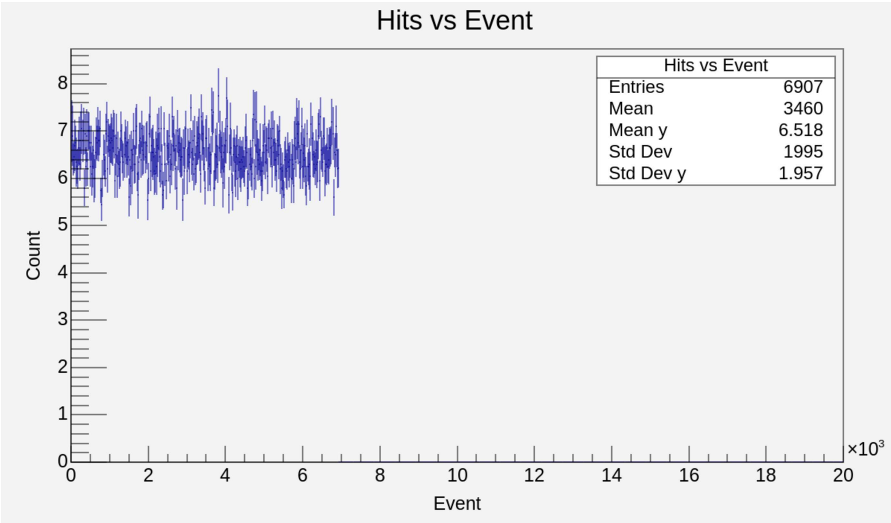


Figure 4.21 The number of activated pixels of individual event that is provided FPGA trigger as pulse signal.

of RUN events was set to 5000. Figures 4.22 and 4.23 illustrate the results of proton detection at 70 MeV and 200 MeV, respectively.

The hitmap findings show that the beam profile of 70 MeV is wider than the result of the simulation section. When comparing the first layer, the mean and standard deviation in the X axis of the beam profile for the 70 MeV beam are 516.1 and 213.4 pixels, respectively, while the 200 MeV beam has 506.7 and 143.5 pixels. Because to the overflow of source size, the Y axis is omitted. Another beam test result is the number of activated pixels on event number, as shown in Figure 4.24.

Unfortunately, the default histogram is provided by the event-hit result of raw data from EUDAQv2 by optimizing the bins. The total number of activated pixels given in the event-hit result is not the same as the result from the raw 2D hitmap presented in Figures 4.22 and 4.23. By observing individual event in EUDAQ data, the mean and standard deviation of activated pixels are shown instead of exact number of pixels as shown in hitmap results.

4.4 Summary

This section describes the configuration of six ALPIDEs telescopes and the FPGA trigger system used to send additional signals to the DAQ boards coupled with

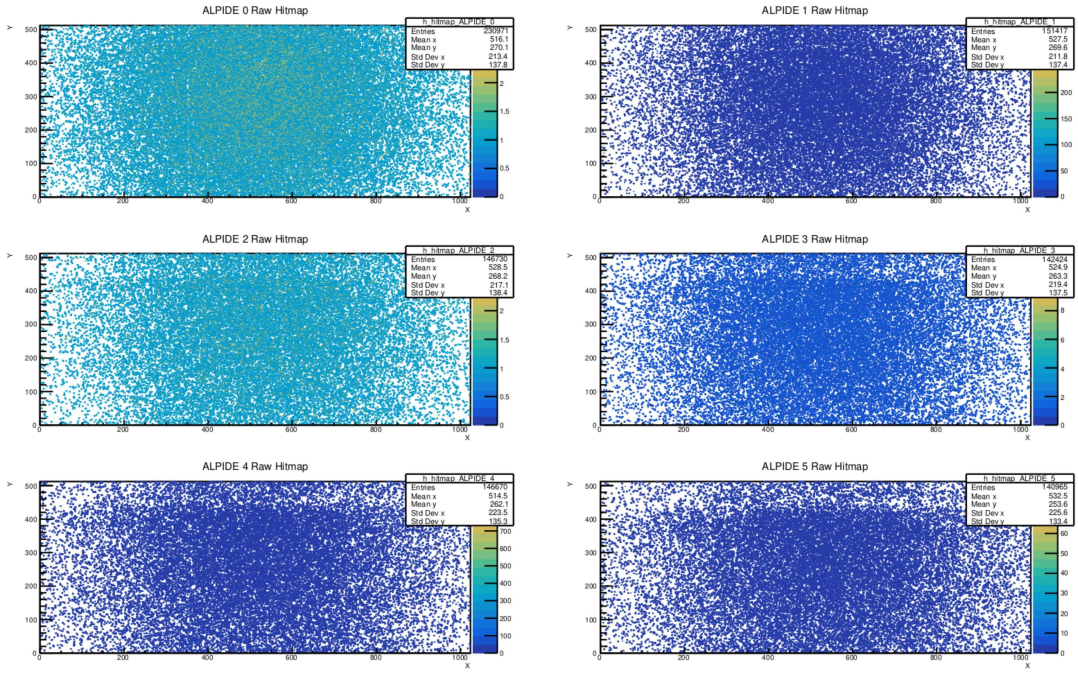


Figure 4.22 The 2-dimensional hitmap of six ALPIDE planes with 70 MeV proton source in 10 MU by applying 10000 events of trigger.

ALPIDEs. As a result, the FPGA trigger can send square waves to the telescope for background and real-beam testing. The output is pure RAW data generated from the EUDAQv2 software via image snapping. Multiple events are used to calculate the total number of active pixels. As a result, the method of selecting a single event to get individual EUDAQv2 result data must be implemented for analyzing data as event by event, as described in the following section.

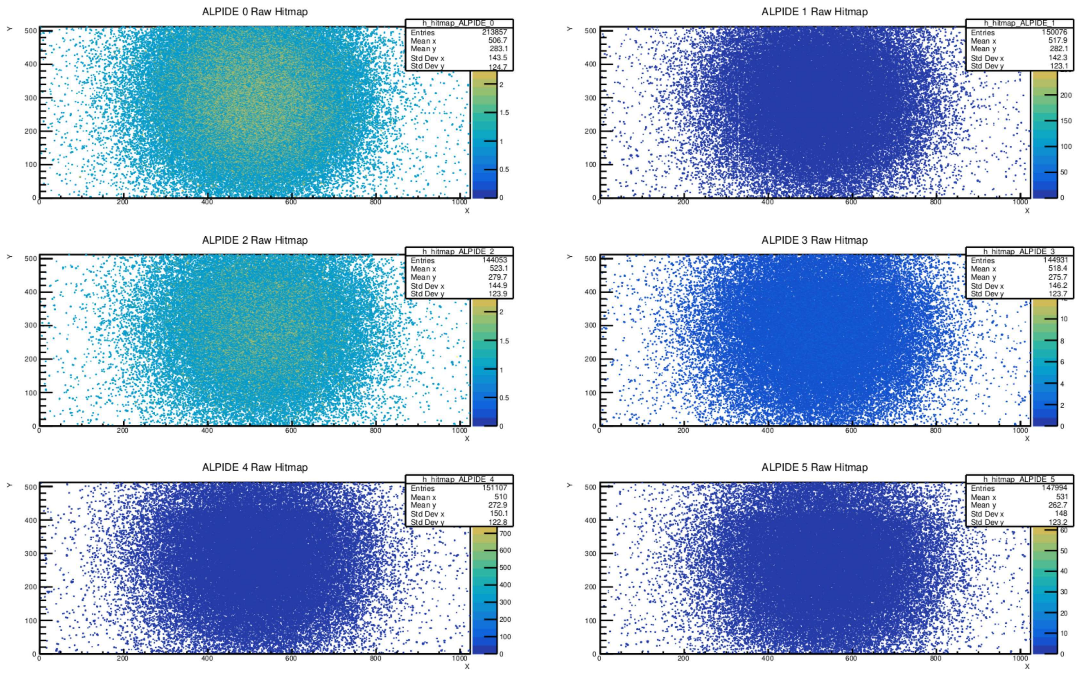
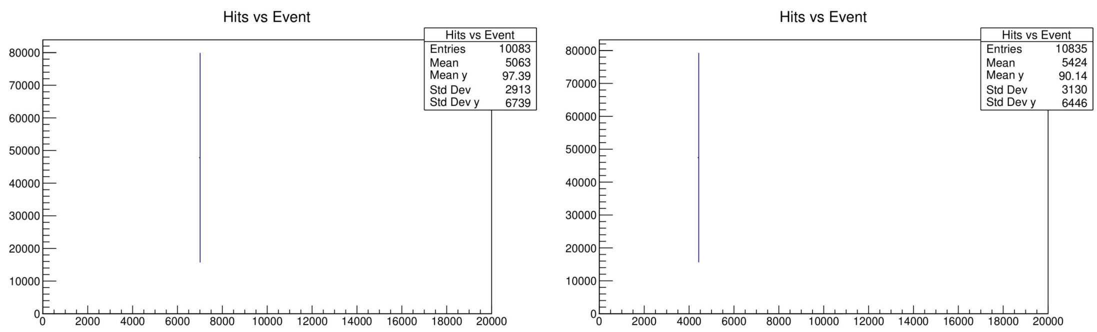


Figure 4.23 The 2-dimensional hitmap of six ALPIDE planes with 200 MeV proton source in 10 MU by applying 10000 events of trigger.



(a) 70 MeV.

(b) 200 MeV.

Figure 4.24 The histogram of EUDAQv2 output for 70 MeV and 200 MeV of KCMH proton beam on 10000 trigger events.