DESIGN AND DEVELOPMENT OF THE TRIGGER SYSTEM FOR PROTON COMPUTED TOMOGRAPHY APPLICATIONS

PASSAKORN PUMMARA

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วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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คำสำคัญ: หน่วยไมโครคอนโทรเลอร์/ ระบบทริกเกอร์/ การสร้างภาพตัดขวางจากโปรตอนด้วยคอมพิวเตอร์/ ลำแสงโปรตอน

วิทยานิพนธ์นี้ได้ทำการออกแบบและสร้างระบบกำหนดลำดับการทำงานของส่วนประกอบในเครื่องต้นแบบของระบบสร้างภาพตัดขวางจากโปรตอนด้วยคอมพิวเตอร์ (pCT) ที่เรียกว่าตัวควบคุมทริกเกอร์ (pCT Trigger Controller) ตัวควบคุมนี้ได้ออกแบบโดยใช้บอร์ด MEGA2560 pro mini เป็นหน่วยควบคุมหลักเชื่อมต่อกับหน้าจอสัมผัส SAMKOON SK-070FE HMI สำหรับพัฒนาเป็นส่วนต่อประสานกราฟิกกับผู้ใช้โดยใช้การสื่อสารแบบ Universal Asynchronous Receiver/Transmitter ตาม Protocol Modbus เพื่อสร้างสัญญาณไปยังแต่ละส่วนประกอบของเครื่องต้นแบบ pCT ตัวควบคุมทริกเกอร์นี้ถูกทดสอบโดยการส่งสัญญาณที่ตั้งโปรแกรมไว้ไปยังส่วนประกอบหลักของต้นแบบ pCT ได้แก่ ฐานหมุน และเซนเซอร์อัลไพด์ จากนั้นได้นำไปทดสอบด้วยการเชื่อมต่อกับเครื่องกำเนิดโปรตอนที่ศูนย์โปรตอนโรงพยาบาลจุฬาลงกรณ์เพื่อกำหนดและควบคุมระยะเวลาการปล่อยของลำอนุภาคโปรตอน ซึ่งระยะเวลาการปล่อยอนุภาคโปรตอนในแต่ละช่วงที่ถูกควบคุมโดยตัวควบคุมทริกเกอร์นั้นจะสอดคล้องกับการบันทึกข้อมูลตำแหน่งของอนุภาคโปรตอนของเซนเซอร์โดยในเบื้องต้นจะเป็นการทดสอบการบันทึกข้อมูลของเซนเซอร์อัลไพด์เพียงเซนเซอร์เดียว

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PASSAKORN PUMMARA : DESIGN AND DEVELOPMENT OF THE TRIGGER SYSTEM FOR PROTON COMPUTED TOMOGRAPHY APPLICATIONS. THESIS ADVISOR : ASST. PROF. CHINORAT KOBDAJ, Ph.D. 60 PP.

Keyword: Microcontroller Unit/ Trigger system/ Proton computed tomography/ Proton beam

This thesis focused on the design and construction of a synchronizing system, called the pCT trigger controller for the proton computed tomography (pCT) prototype. This controller was designed using the MEGA2560 pro mini as a microcontroller unit (MCU). It connected to the SAMKOON SK-070FE HMI touchscreen by using Universal Asynchronous Receiver/Transmitter (UART) to create a graphical user interface (GUI). Its communication is based on Modbus protocol via C language program to generate desired signals to each component. The pCT trigger controller was tested by sending the programmed signals to the rotational stage and ALPIDE sensor connected with the proton cyclotron at the Proton Center of King Chulalongkorn Memorial Hospital (KCMH) to control the timing of the proton beam gating. It was found that the pCT trigger controller can control the gating of the proton cyclotron. It can also communicate with an ALPIDE sensor to start detecting protons and record their positions. At this stage, we expected to test with only one ALPIDE sensor as the position sensitive detector.

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Passakorn Pummara

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LIST OF ABBREVIATIONS

CT	Computed Tomography
CAT	Computerized Axial Tomography
xCT	X-ray Computed Tomography
pCT	Proton Computed Tomography
PSD	Position-Sensitive Detector
RERD	Residual Energy Rang Detector
DAQ	Data Acquisition
ALPIDE	Alice Pixel Detector
LHC	Large Hadron Collider Experiment
MAPS	Monolithic Active Pixel sensor
RHIC	Relativistic Heavy Ion Collider
ITS	Inner Tracking System
RSP	Relative stopping power
MIP	Minimum Ionizing Particles
MCU	Microcontroller unit
TTL	Transistor-Transistor Logic
RAM	Random Access Memory
EPROM	Erasable Programmable Read-Only Memory
EEPROM	Electrically Erasable Programmable Read-Only Memory
LCD	Liquid Crystal Display
RTC	Real-Time Clock
UART	Universal Asynchronous Receiver Transmitter
USART	Universal Synchronous/Asynchronous Receiver Transmitter
USB	Universal Serial Bus
RS232	Recommended Standard 232
HMI	Human Machine Interface

CHAPTER I

INTRODUCTION

Computed Tomography (CT) or Computerized Axial Tomography (CAT) is cross-sectional imaging that has useful abilities to see inside the scanned object or internal organs such as brain tumors, bones, and blood vessels without any surgical operations as shown in Figure 1.1 (Caldemeyer and Buckwalter, 1999). Nowadays one of the CT techniques used in medical diagnostics is x-ray Computed Tomography (xCT). The x-ray was discovered by Wilhelm Rontgen in 1895. Later, he was awarded Nobel prize in physics in 1901. After that, the x-ray technology had been continuously developing till 1920. The first xCT proposed by Sir Godfrey N Hounsfield, Nobel Prize winner in Physiology or Medicine in 1979. The x-ray combined with tomography technology to achieve x-ray Computed Tomography is one of the most useful tools in doctor's surgical planning. Unfortunately, the xCT has some crucial disadvantages because of some interaction with tissues in the patient's body. When x-ray beam passing through the patient's body, it effects every tissue along the pathway. This disadvantage causes problem to the patient's safety when using an x-ray on fragile organs.

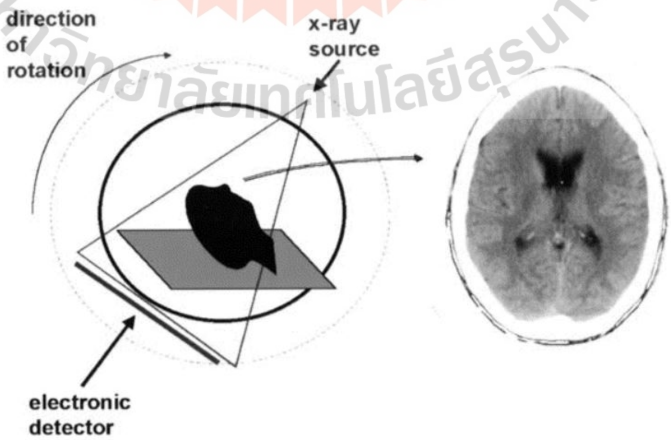


Figure 1.1 The conceptual of CT scanner that used x-ray as a source and cross sectional image of a human brain (Caldemeyer and Buckwalter, 1999).

Proton Computed Tomography (pCT) has been developed to the high performance of cross-sectional images based on the same concept as that of xCT but used the Charged particles (proton) instead of x-ray (Schulte et al., 2004). The pCT has an advantage over using the x-ray CT because tissues nearby are not damaged by high dose radiation. The main goal of pCT is to produce cross-sectional images for proton treatment planning to accurately determine radiation dose delivered to target abnormal tissue's position according to the Bragg peak as shown in Figure 1.2. The proton treatment is attractive for cancer curing since it could enhance abnormal tissue killing harming the surrounding healthy tissues.

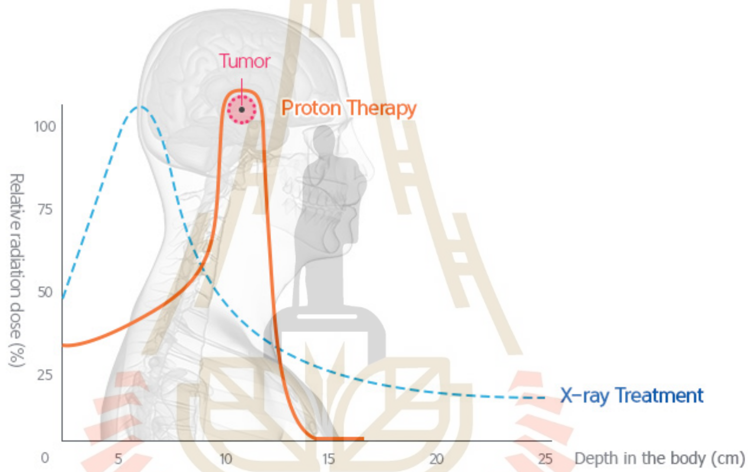


Figure 1.2 The relative dose releasing at the tumor point as a depth of proton and x-ray therapy (Samsung Medical Center, 2016).

One of the pCT prototypes has been proposed by (Bashkirov et al., 2016) consisting of five main parts as shown in Figure 1.3. There are a position-sensitive detector (PSD), residual energy range detector (RERD), data acquisition board (DAQ board), rotational stage, and image reconstruction programming on a computer.

Since then, several pCT prototypes have been developed by many research groups in medical radiology and high energy physics. The position-sensitive detector (PSD) is the readout unit to detect and record of the scatted proton's position passing the scanned object. Another one is Residual Energy Range Detector (RERD) or calorimeter that is used to measure the individual proton's energy loses.

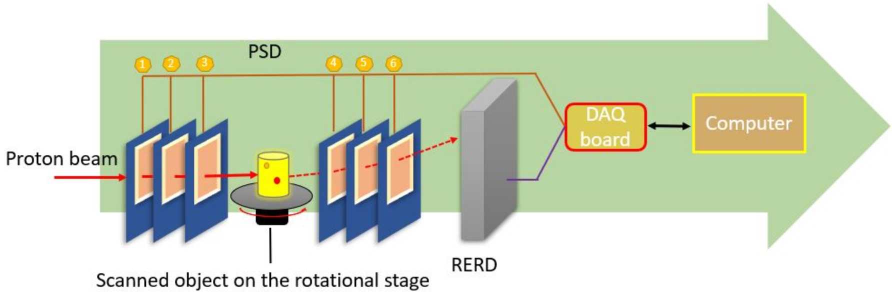


Figure 1.3 The pCT prototype model which consist of proton beam, rotational stage, position-sensitive detector(PSD), residual energy range detector, data acquisition board (DAQ board), and computer.

Monolithic Active Pixel Sensor (MAPS), the first of MAPS called ultimate had been introduced in the STAR detector (Solenoidal Tracker) as one of the four experiments at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory, United States. Later, this MAPS technology has been adopted to use for the upgrade of the inner and outer barrels in the new Inner Tracking System(ITS), which is planed for a new version upgrade on Long Shutdown (LS2) at ALICE in 2019-2020 as shown in Figure 1.4 (Mager, 2016). In this work, we use the silicon pixel sensor called ALPIDE as shown in 1.5.

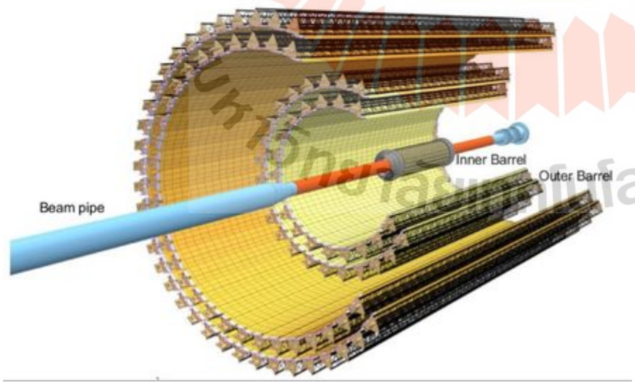


Figure 1.4 The ITS upgraded conceptual layout consists of inner and outer barrels in 2019-2020 (Mager, 2016).

Figure 1.5 The ALPIDE sensor and buit-in readout circuit part.

Currently, there are several substantial research groups published their work related to proton computed tomography. Suranaree University of Technology has been participated and formed a research group with University of Bergen and King Chulalongkorn Memorial Hospital to study and develop applications of proton computed tomography. The primary goal of our research group is to build a pCT prototype in Thailand by working together with the Bergen pCT collaboration. This thesis is a part of the project which focuses on the pCT trigger controller system design and construction. The pCT trigger controller is used to synchronize three main components in the prototype to work together.

The thesis is organized as follows. Chapter I gives an overview and introduction to our work. In chapter II we provide the background knowledge and related physics. Next, pCT trigger controller design and construction are given in Chapter II and IV. Our testing results are describe in Chapter V and the conclusion is presented in chapter VI.

CHAPTER II
BACKGROUND KNOWLEDGE

2.1 Radiation

By fundamental definition, radiation is the emission and propagation of energy through space or material. Radiation is characterized in two types ionization and non-ionization.

Ionizing radiation is composed of subatomic particles or electromagnetic waves which have high enough energy to remove electrons from atoms or molecules of materials. While non-ionizing radiation consists mainly of electromagnetic waves with less energy than ionizing radiation. It does not remove electrons from atoms or molecules of materials including air, water, and living tissues.

In this work, we emphasize on the particle radiation which often referred to as a particle beam since particle travel in the same direction similar to a light beam. Particle radiation is made up of any subatomic particles such as photons, neutron, and heavy ion.

2.2 Proton Computed Tomography

Using protons in cancer treatment has been developed continuously and has been widely used nowadays. The unique property of protons is that their deposited energy is dominated at their stopping positions inside a target. The deposited energy spectrum of protons is called Bragg peak. Currently, in proton treatment planning using image from x-ray computed tomography (xCT) have been used. An uncertainty has been established when determining the relative stopping power (RSP) caused by a conversion from the Hounsfield unit (HU). Proton Computed Tomography (pCT) can reduce this uncertainty because it can reconstruct the RSP map directly. The pCT technique is based on a measurement of the proton's energy loss and momentum diversion while passing through an object. The pCT components comprise of a proton beam, position-sensitive detector (PSD), rotational stage, and residual energy range detector (RERD).

2.2.1 Limitations of Proton Computed Tomography

When the proton which has charged passing through a medium, it effected by atom in that medium causing

- nuclear interaction with nuclei in a medium which generates secondary particles
- electromagnetic interaction of proton with nuclei and electrons, which results in changing protons direction.

2.3 Charged particle radiation in Matter

In order to detect particle, we consider particle travelling through the material of a detector. Interaction generates the signal that is usually recordable. The interaction occurrences depend on either type or energy of an incoming particle. The energy losses of traverse through matter determined by the Bethe-Bloch as shown in equation 2.1 (Mompart et al., 1996). The Bethe-Bloch defines stopping or the mean energy loss per unit length of incoming charged particles in matter.

$$-\frac{dE}{dx} = 2\pi N_a r_e m_e c^2 \rho \frac{Z\,z^2}{A\,\beta^2}\left[\ln\frac{2m_e\gamma\nu W_{max}}{I^2} - 2\beta^2 - \delta - 2\frac{C}{Z}\right] \tag{2.1}$$

where:

$$W_{max} = \frac{2m_e c^2 \eta^2}{1 + 2s\sqrt{1+\eta^2} + s^2} \tag{2.2}$$

with $s = m_e/M$, $\eta = \beta\gamma$, and M is particle mass.

The I parameter defines the mean energy loss for electron-hole pair generating in a semiconductor, but it can't calculate directly. However, The mean energy loss can be observed by the experiment.

with:

$2\pi N_a r_e m_e c^2 = 0.1535$ MeVcm^2/g

r_e: electron radius (2.817×10^{-13} cm)

m_e: electron mass

N_a: Avogadro's number

Z: atomic number of absorbing material

A: atomic weight of absorbing material

z: charge of incident particle

β : c/v of incident particle

ρ: density of absorbing material

γ: $1/\sqrt{1-\beta^2}$

δ: density correction

C: shell correction

I: mean excitation potential

W_{max}: maximum energy transferable in single collision

2.3.1 Energy loss of charged particles

Charged particles crossing material deposit part of their energy by means of scattering processes with the electrons in medium, causing approximately uniform ionization along the path. For particles heavier than electrons, this process is described by the Bethe-Bloch formula,

$$-\frac{1}{\rho}\left\langle\frac{dE}{dx}\right\rangle = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left(\frac{1}{2}\ln\left(\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2}\right) - \beta^2\right) \tag{2.3}$$

with:

- N_A: Avogrado's number;
- z: charge of the traversing particle in terms of unit charge;
- Z: atomic number of the absorption medium (14 for silicon);
- A: atomic mass of the absorption medium (28g/mol for silicon);
- $m_e c^2$: rest energy of the electron;
- r_e: classical electron radius;
- β: velocity of the traversing particle in units of c;
- γ: Lorentz factor $1/\sqrt{1-\beta^2}$;

- I: mean excitation energy (137 eV for silicon);
- $T_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1+2\gamma m_e/M+(m_e/M)^2}$: maximum energy loss for a particle with mass M in a single collision;

Equation 2.3 represents the average differential energy loss per mass surface density, typically expressed in $\left[\frac{\text{MeV}}{\text{g/cm}^2}\right]$. There exists additional correction term to equation 2.3 as the density correction for high energy particles and the shell correction for low energy ones. For electrons and positrons, additional modifications to the Bethe-Bloch formula are required due to their low mass and the fact that they interact with identical particles (i.e., electrons) while traversing the medium. Furthermore, additional energy-loss mechanisms such as bremsstrahlung have to be considered.

2.3.2 Proton interactions with matter

Proton is one of the components in an atom and nucleus which has positive charge. Proton passing through any object produce some interaction with charged particles those are proton and electron. The types of proton interaction are shown in Figure 2.1. Those consist of Coulomb interaction with the electron and nucleus in an atom, Bremsstrahlung, and nuclear reaction (Newhauser and Zhang, 2015).

A proton continuously losses their kinetic energy via inelastic interaction. The trajectory of most proton travels almost straight line since its mass is 1832 times greater than electron mass. In another case, protons pass near atom which have mass close to a proton or more, this cause the elastic interaction that deflects the proton from its originally straight-line. In fact, in the matter there are many nucleus causes proton to deflect many times called Multiple Coulomb Scattering (MCS).

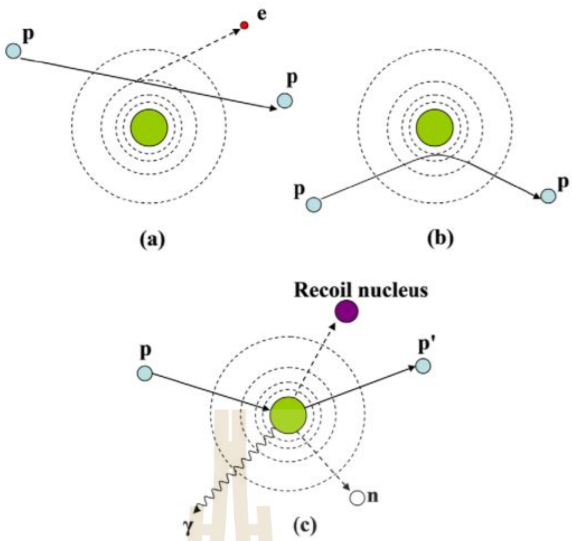


Figure 2.1 Illustration of proton interactions: a) the energy loses due to inelastic Coulomb scattering, b) Proton deflection due to elastic scattering with nuclei (same positively charged with proton), and c) Removal of primary proton and secondary particles creation due to nonelastic nuclear interaction. (e is election, p is proton, n is neutron) (Newhauser and Zhang, 2015).

2.4 Silicon in sensor applications

The sensor is a type of the detector where the interaction with radiation or particles occur. It measures the detected signal produced by ionization in sensor materials through to the readout electronics such as an amplifier or gainer. The sensor material usually are semiconductor. Semiconductor materials such as silicon (Si), germanium (Ge), and elements in the IV group have electrical properties between the insulator and conductor. They have few free electrons because of their electronic structure called crystal lattice. But those electron are still able to move as shown in the case of silicon in Figure 2.2. Silicon is dominant in the semiconductor material that widely uses in particle sensing applications in high-energy particle physics. The minimum ionizing particles (MIP) is based on the excitation and ionization of atom in the medium caused by the passing of charged particles. The ionization produces the electron-hole pair in the silicon medium that will be discussing in the next subsection.

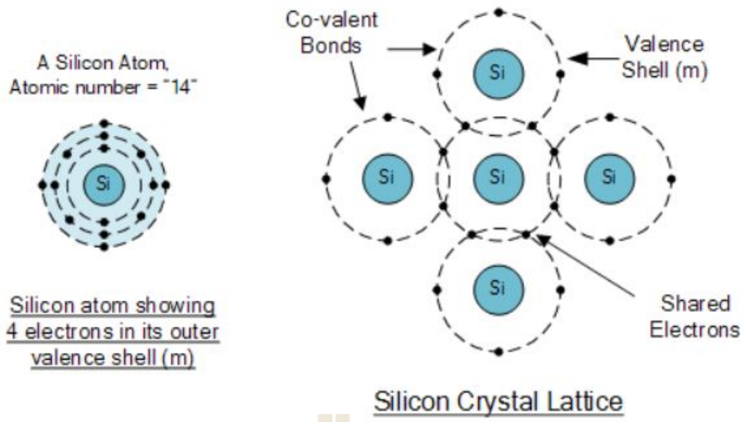


Figure 2.2 The structure and lattice of a normal pure crystal of Silicon (KCSE PHYSICS, 2012).

2.4.1 Charge Generation in Silicon

The principle of solid state detectors is based on the energy loss of traversing particles or radiation in the sensor material. Part of the energy loss is used for the generation of free electron-hole (e-h) pairs, which by their motion induce a signal current on their respective collection electrodes.

For silicon, the mean energy w required to create a single e-h pair is about 3.6 eV, which three times larger than the band gap (1.12 eV). The difference goes to the generation of photons and the dissipation of thermal energy.

Due to the varying fractions of deposited energy used for charge carrier and phonon generation, the variance of the number of e-h pairs $N_{e\text{-}h}$ generated by a deposited energy E is reduced by the Fano factor F according to

$$\langle \Delta N_{e\text{-}h}^2 \rangle = FN_{e\text{-}h} = F\frac{E}{w} \tag{2.4}$$

For most semiconductors being in the order of 0.1, the Fano factor determines the best possible energy resolution of semiconductor sensors.

2.4.2 Introduction to ALPIDE sensor

The one of detector that is used for readout the charged particles trajectory/position is called ALPIDE (ALice PIxel DEtecctor). It is fabricated by the TowerJazz with 180 nm CMOS Imaging Process for Inner Tracking System upgrade (van Hoorn, 2015) as shown in figure 2.3 for ALICE (Large Ion Collider Experiment). The ALPIDE is a very thin sensor of 1.5 cm x 3 cm size and buit-in readout circuity see figure 2.3.

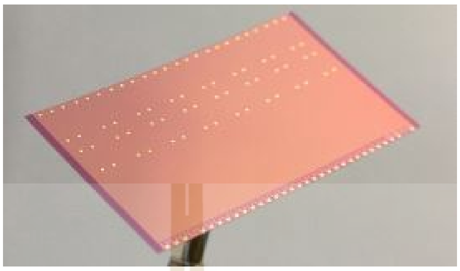


Figure 2.3 The ALPIDE chip with a size of 30mmx15mm and the thickness of 50μm.

2.4.3 ALPIDE characterization

The ALPIDE is based on a Monolithic Active Pixel Sensor(MAPS) that consists of 3 layers. The lowest layer is a substrate that was doped by high concentrate p-type materials (p++) acting as a structural support and electron blocking. The middle layer is an epitaxial layer (silicon layer) that was doped by p-type materials but lower concentration than the substrate. The top layer is n-type and p-type implants of the top is called well as the front-end circuitry.

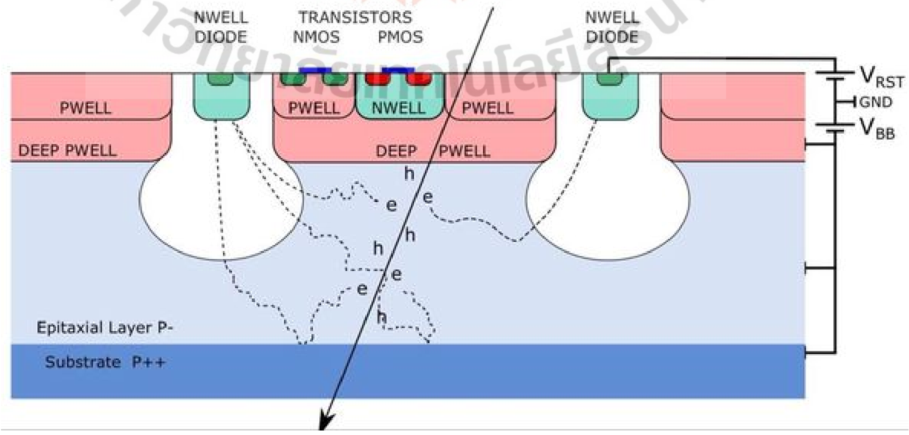


Figure 2.4 The ALPIDE cross section, solid line represented charged particles passing through sensor and dashed lines represented exited electrons.

A charged particle passing through MAPS loses energy due to ionization that excite the electrons from the valence band to the conduction band and produce the electron-hole pair in the epitaxial layer as discussed in previous section. The electron can not go into the substrate layer because of the p-type doped concentration difference at the junction. The junction created a highly-potential barrier to reflect the electrons back to the depleted region. After that, the electrons are attached by the n-well diode that acts as collecting the electrons signal by applying negative (reverse) bias voltage. Then collected electrons were sent to circuity to analyze.

The sensing area of the ALPIDE is the pixel matrix that consists of 512x1024 pixels, in each pixel comprises of an amplifier, a multi-event buffer, and a discriminator. These are aligned in double-column as shown in Figure 2.5.

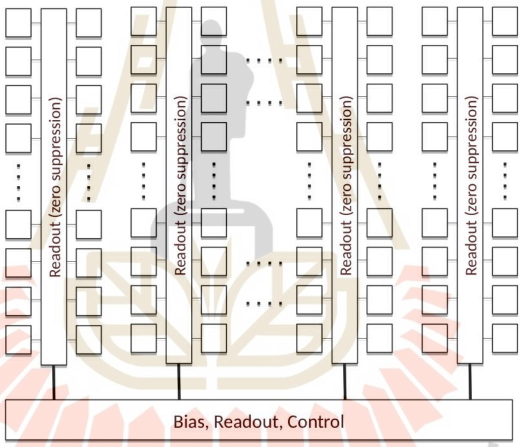


Figure 2.5 The ALPIDE architecture (Suljic, 2017).

CHAPTER III

PCT TRIGGER CONTROLLER DESIGN AND CONSTRUCTION

3.1 pCT configurations

The pCT prototype has been developed by many research groups worldwide. The components of the pCT prototype include (1) a proton beam unit as a source of configurable energetic protons, (2) a position-sensitive detector (PSD) which is an ALPIDE sensor for tracking of proton position before and after passing through a scanned object, (3) residual energy range detector (RERD) for energy losses of protons measurement after passing through a scanned object, and finally (4) a rotational stage for changing the scanned object's angle for the next shooting. These four components of the pCT system need to be synchronized by our trigger system, as shown in Figure 3.1.

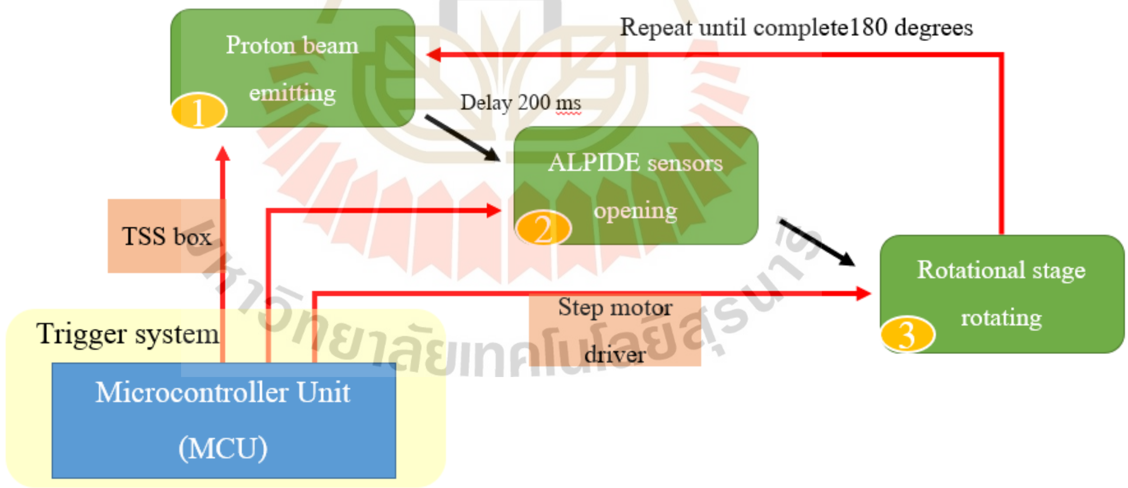


Figure 3.1 pCT configuration.

3.2 The signal requirement of the pCT trigger controller

The pCT trigger controller was designed to synchronize generated signals between incoming protons, the starting time of the PSDs, and a rotational stage.

- For the first step, the trigger will send square signals to the switch rely for opening the proton beam gating of the proton cyclotron machine. Then the proton beam comes to PSD and the object.

- Then after 200 ms, the trigger will send the square signals which require 5V to trigger the PSD to record a traversed protons.

- The trigger will send the square pulse which require 5V to the rotational stage for the next angle rotation.

After finishing the last step, then the process repeats again until the traversed protons data of the scanned object is recorded in 360 degrees.

3.3 pCT system sequencing design

The trigger system for the pCT prototype comprises an microcontroller unit (MCU), A5W-K DIP relays, resistors, and transistors. The MCU act as a master to control and order other components in the system which are slave as shows the technical concept as Figure 3.2.

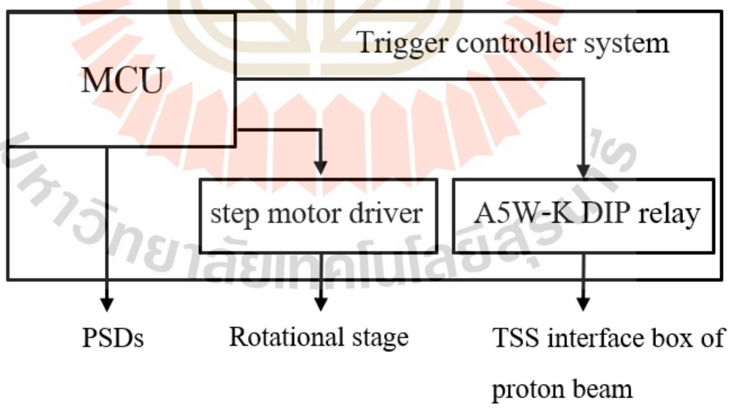


Figure 3.2 The design of the trigger system shows MCU and A5W-K DIP relay for sending a sequenced signals to Rotational stage, PSDs, and TSS interface box of proton beam.

The microcontroller unit (MCU) is used to generate a programmed electrical signal of a voltage level of 5 V to each component in the system. The signal is delivered to the TSS interface box of proton beam unit, ALPIDE sensors, and a rotational stage as shows the sequencing conceptual in Figure 3.2. The three-working steps are shown below sequentially,

1. The signal is sent to the TSS gating interface box of the proton beam unit. The TSS gating interface box consists of 4 main connectors; (1) gating beam on, (2) ground, (3) reference voltage, and (4) gating enable. The A5W-K DIP relay could turn the gating beam on and off by switching the connections to each other.

2. After the signal from the relay module is delivered to the TSS interface box, another signal of 5 V square pulse is sent to ALPIDE sensors 200 milliseconds later due to the proton beam's delay time.

3. Finally, the TTL signal of 5 V is sent to the rotational stage through the step motor driver to change the angle of the scanned object.

3.3.1 Microcontroller Unit (MCU)

A microcontroller is a small integrated circuit that is used in embedded systems to perform specific functions. In one chip, a microcontroller is made of a Central processing unit (CPU), memory, and input/output (I/O) peripherals.

A microcontroller is a device that is integrated into a system and controls a particular function. It accomplish this by using its core CPU to evaluate received data from its I/O peripherals. The microcontroller's temporary data is saved in its memory. The processor enters, interprets and applies the incoming data using instructions stored in its program memory. It then communicates with its I/O peripherals and executes the required action.

The core element of a MCU comprise of:

- Analog to Digital Converter (ADC): An ADC is a circuit that converts a measured signal in the real world from analog to digital. The concept of ADC is to snapshot a waveform at a moment of analogue signal then interpret it either HIGH or LOW logic level in binary code.

- Digital to Analog Converter (DAC): An DAC is a circuit that converts input signal from digital signal into a real world.

- System bus: The system bus is the connective wire that links all components of the microcontroller together.

- Serial port: The serial port is one example of an I/O port that allows the microcontroller to connect to external components. It has a similar function as a USB or a parallel port.

Microcontroller processor are varied due to applications. Whose options ranged from the simple 4-bit, 8-bit or 16-bit processors to more complex 32-bit or 64-bit processors. Microcontrollers can equip with volatile memory types such as random access memory (RAM) and non-volatile memory types. This includes flash memory, erasable programmable read-only memory (EPROM) and electrically erasable programmable read-only memory (EEPROM).

At present, the C programming language is a popular in various option that used to program MCUs. There are also other popular programming language such as Python and Matlab.

MCUs have an important feature input and output pins to implement peripheral functions from the measured signals from a real world or device-device communication. Such functions include liquid crystal display (LCD) controllers, analog-to-digital converters, real-time clock (RTC), universal asynchronous receiver transmitter (UART), universal synchronous/asynchronous receiver transmitter (US-ART), and universal serial bus (USB) connectivity.

3.3.2 MEGA2560 pro mini board

The MEGA2560 pro mini board or Mega pro MINI CH340G is a type of the MCU family. It is based on ATMEGA2560 microcontroller with the Universal Serial Bus-Universal Asynchronous Receive Transmitter (USB-UART) protocol. It uses the original ATmaga2560 chip and a 16 MHz high-quality quartz resonators as shown in Figure 3.3. The key advantage is that it has many I/O for using with control application.

There are many commercial MCU avaiable in the market. But main reason for us to use the MEGA2560 pro mini as the MCU as following:

- electrical characteristics such as clock speed which is 16 MHz, and It has many digital output ports.

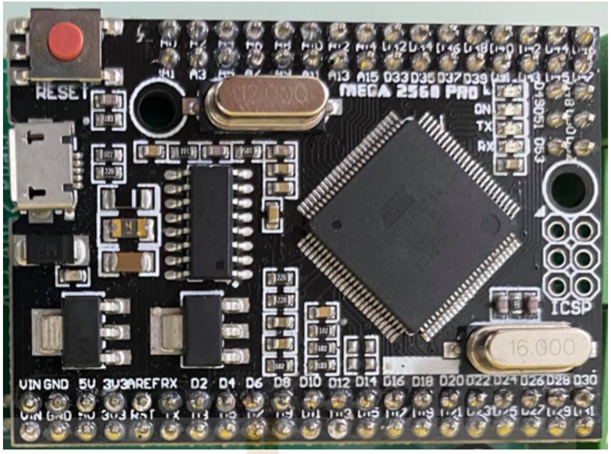


Figure 3.3 The actual view of ATMEGA2560 pro mini board.

- It support serial communication and Modbus protocol.
- It is suitable for C language programming.
- there are many I/O peripheral ports.

3.3.3 Communication protocol

The protocol is the method allows any different industrial manufacturer's devices to properly communicate with each other. The most common communication of connecting industrial electronic devices used today is Modbus. Modbus provides common language for devices and equipment to communicate among each other. Several versions of the Modbus protocol exist for serial port and Ethernet. The most common protocol are Modbus RTU, Modbus ASCII, Modbus TCP, and Modbus Plus. Modbus communications over several types of physical media such as a Recommended Standard 232 (RS232), RS485, RS422, and over Ethernet.

The original and widely used interface that we chose is RS232 serial communication because its flexibility application and characteristics meet our desired. The RS232 interface supports to use in serial communication which has two communication lines are the Rx and Tx.

For coding, the C language code is needed to add a header line as include <ArduinoModbus.h> to define and access Modbus library.

3.3.4 Communication of MCU

The basic purpose of any interface is to allow the microcontroller to communicate with other devices, peripherals, as well as other microcontrollers. The interface can be either parallel or serial, synchronous or asynchronous. The devices in a system communicate with each other as a master-slave principle. The bit of binary in both serial and parallel transmission are needed to transfer corresponding to the pulsed clock signal.

- Serial communication, it is a method for sending and receiving bits of binary digits each one at a time in one data line. Serial communication takes many different forms to communicate from one device to another. Example, the letter A having ascii value of (MSB)0,1,0,0,0,0,0,1(LSB) will be transmitted 1 bit at a time. LSB is the transmitted starting bit and MSB is the transmitted ending bit as shows in Figure 3.4.

- Parallel communication, the system needs to use many lines at least 8 to send a signal for each data channel. It uses more than one bit at a time in each channel as shows in Figure 3.5.

Serial and parallel transmission are used in different tasks. there are some strengths and weaknesses differently depending on used applications as shown in Table 3.1.

Figure 3.4 Serial transmission.

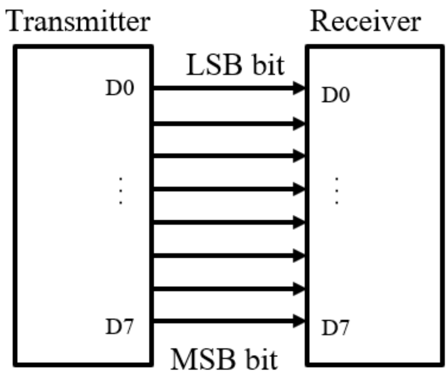


Figure 3.5 Parallel transmission.

Table 3.1 The comparison between the serial and parallel transmission.

Specifications of transmission	Serial	Parallel
No. of bits transmitted per pulse clock	1 bit	n bits
No. of lined required to transmit n bits	1 lines	n lines
Speed of transfer	Slow	Fast
Cost of devices	Low	High
Application	Long distance	Short distance

3.3.5 Speed of data transmission

The speed of data transmission is defined by the baud rate. Baud rate is the measure of the maximum frequency of signal changes from high to low level in a transmission line. It is the number of bits (binary digits) that can be sent per second. In Arduino family, baud rate can be chosen from 300, 600, 1200, 2400, 4800, 9600, 14400, 19200, 28800, 38400, 57600, or 115200. However, 9600 is the standard baud rate usually used in any asynchronous communications.

3.3.6 TSS interface box of proton beam

The TSS interface box is a part of the proton beam machine at King Chulalongkorn Memorial Hospital (KCMH) that is used to control the proton beam gating before at the beam nozzle. Protons were produced by the cyclotron behind the treatment room, then delivered along beam pipe and blocked by proton beam gating at the nozzle before reaching the patient. As mentioned in previous section, The TSS interface box consists of 4 connectors which are gating beam ON, GND, reference voltage, and gating enable for opening and closing the proton gating beam. We use a DB9 female sub connector to connect to the TSS interface box. The gating enable connector needs reference voltage of 12 volt to define the active status of proton beam machine that is preparing a protons behind proton beam gating as shows in Figure 3.6a. The inside of TSS interface box includes electronics components and relay modules for switching the proton beam gating to open and close as seen in Figure 3.6b

(a) The DB9 female sub connector of TSS interface box.

(b) The inside of TSS interface box.

Figure 3.6 The TSS interface box connecting ports and inside.

3.3.7 Rotational stage

The rotational stage is used to rotate the scanned object to different angle for the projection image capturing of pCT. The selected rotational stage is Electric rotational stage SHINANO KENSHI model Y07-43D1-4275 as shows in Figure 3.7 . It consists of stepper motor and cogs.

The stepper motor is a bipolar electric motor with two poles at the stationary field. The stepper motor is controlled by two programmed signals from the Micro Controller Unit (MCU) which are a direct pin and step pin. The direct pin defines the direction of rotation, whether clockwise or counterclockwise, and the step pin defines the pulsed signals sent to the two motor coils.

The MCU control a stepper motor through a A4988 stepper motor

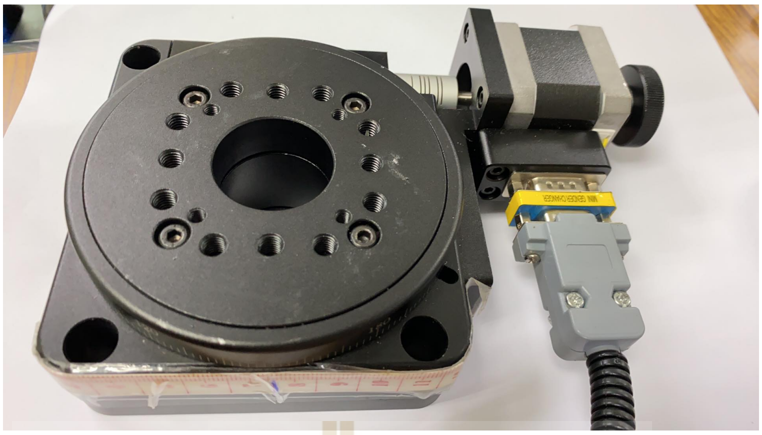


Figure 3.7 Electric rotational stage SHINANO KENSHI model Y07-43D1-4275.

driver as shows in Figure 3.8. The stepper motor can be set the resolution of rotating by defining a pin of MS1, MS2, and MS3. There are five micro-step resolution consists of five options which are Full step, Half step, Quarter step, Eight step, and Sixteen step as shows in Table 3.2. The default resolution of SHINANO KENSHI model Y07-43D1-4275 is 1.8 degrees/step, which is the coarsest resolution under Full step. The finest resolution is 0.1125 degree/step under sixteen step. The sixteen step motion has a better resolution than the Full step but it takes longer time to rotate for the same angular displacement.

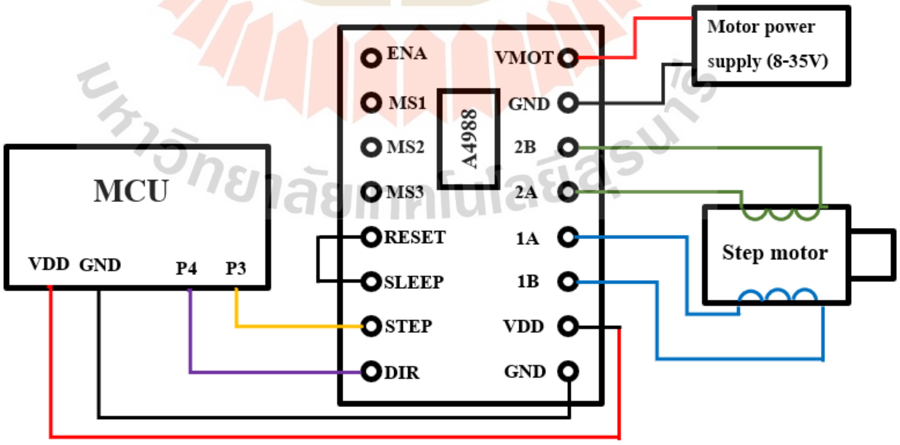


Figure 3.8 Schematic view of step motor controlled by A4988 step motor driver.

Table 3.2 Micro step resolutions of SHINANO KENSHI model Y07-43D1-4275 defined by MS1, MS2, and MS3.

MS1	MS2	MS3	Micro-step resolution	Degrees/step
LOW	LOW	LOW	Full step	1.8
HIGH	LOW	LOW	Half step(1/2)	0.9
LOW	HIGH	LOW	Quarter step(1/4)	0.45
HIGH	HIGH	LOW	Eight step(1/8)	0.225
HIGH	HIGH	HIGH	Sixteen step(1/16)	0.1125

3.4 Software design

For the software design of the pCT trigger controller, the MEGA2560 pro mini board was used as a MCU to control the main components of our pCT prototype. The MEGA2560 pro mini is completely controlled by SAMKOON SK-070FE HMI that is an LED touchscreen. The LED touchscreen and MCU communicate with each other by connecting via universal asynchronous receiver-transmitter (UART) communication with modbus RTU through Recommended Standard 232 (RS232) protocol. The speed of data transmission between master and slave was determined by the baud rate, which is recommended at 9600 bps in normal serial communication.

The MCU can generates and interpret a logic that has a limited level in the range of 0-5 volts. The MCU can transmit and classify a digit of binary called Transister-Transister logic (TTL) which has 0 and 1 bit determined by 0 and 5 volt respectively. The SAMKOON can interpret a logic to digit binary in the range of -12 to +12 volts. For the correct logic interpretation, they need to use a converter called MAX232 IC to convert a logic level 0-5V TTL to -12 to 12 V for digit binary interpretation between master-slave devices.

In the case of UART communication, there are two devices connected in the system which are Master and Slave. In our design, the MCU acts as a slave and the LED touchscreen acts as a master. Master and slave are connected to each other by using two wires at Rx and Tx ports. The Rx port of a Master connects to the Tx port of slave and vice versa.

User can easily configure needed parameters on the LED touchscreen.

The There are three important parameters to operate our pCT prototype which are exposure time, rotation angle, and working mode. The MCU generates TTL signal to each component in the pCT system step by step as mentioned in the previous section. The sequencing of the signal generation at one period is given in Figure 3.9.

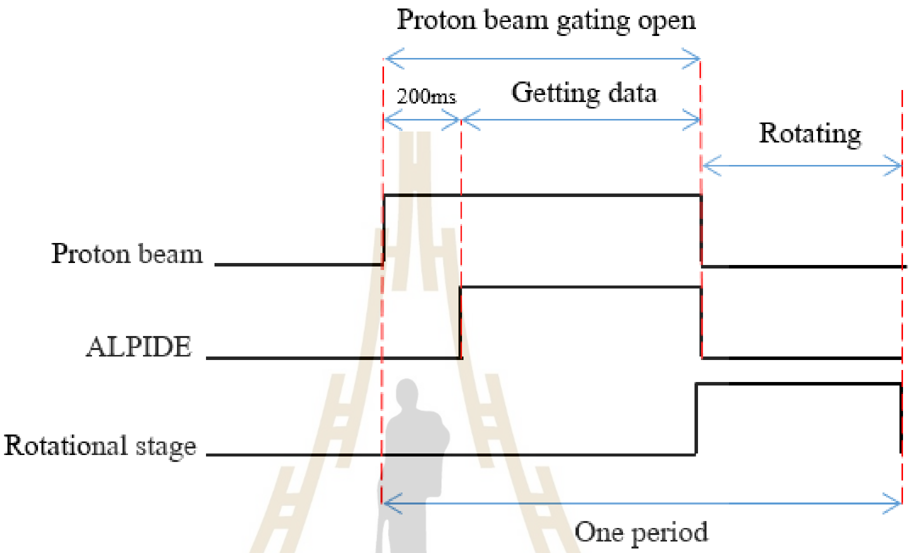


Figure 3.9 The sequencing of signal generation to each component generated by MCU.

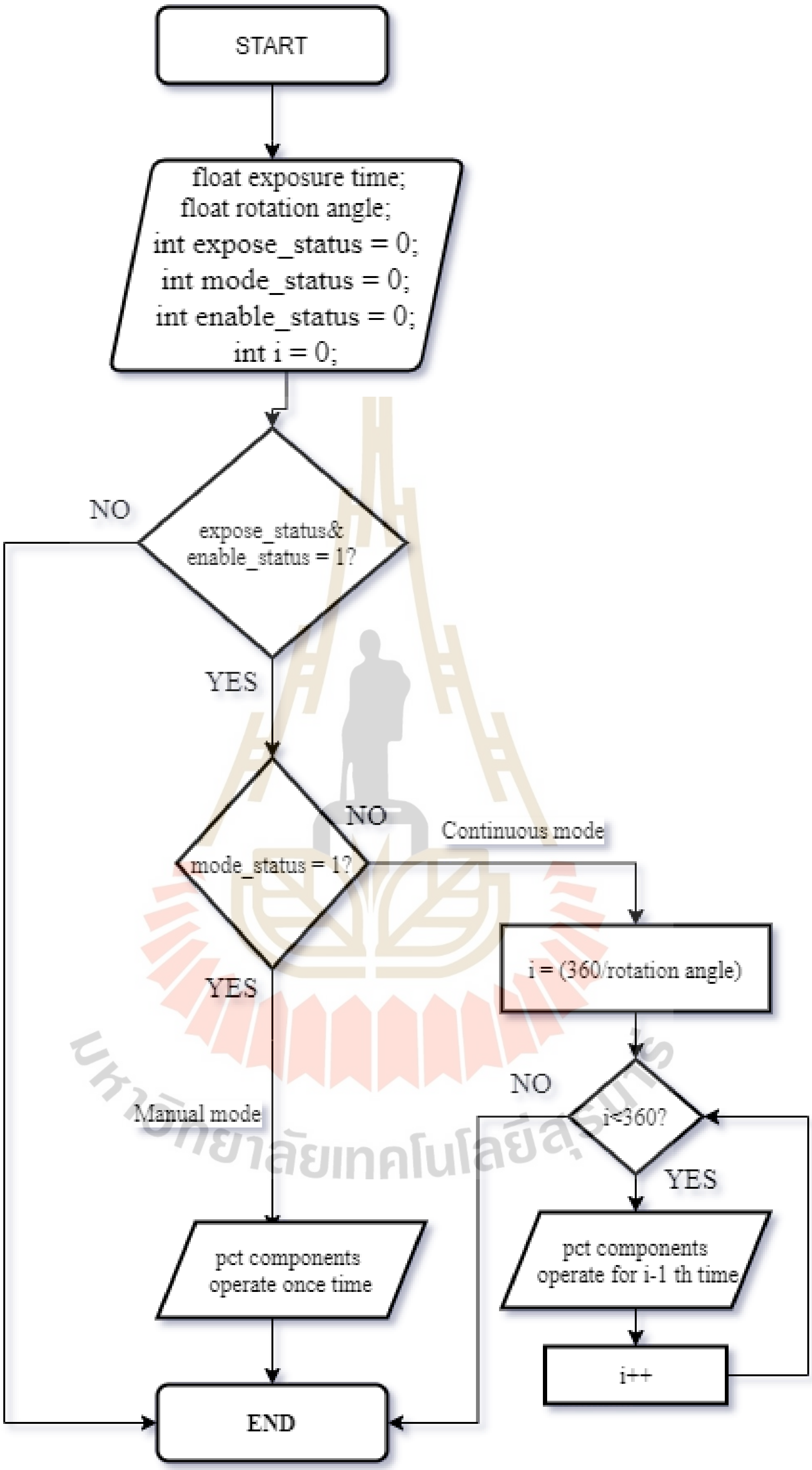


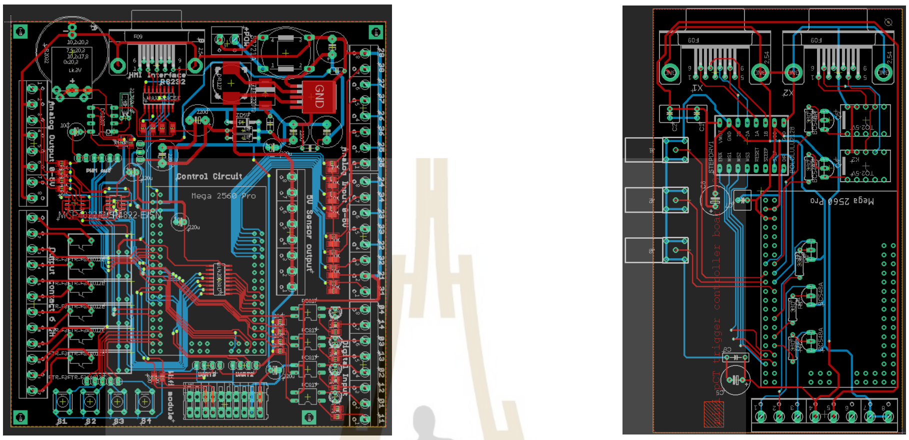
Figure 3.10 The flow chart of programming design.

3.5 Hardware and Printed Circuit Board (PCB) design

The pCT trigger controller was designed to support the communication between the MCU and the LED touchscreen. The hardware was design by taking into account of the software capabilities to support the signal generation to LED touch and pCT's components. The significant pCT trigger controller board is a MCU which is a MEGA2560 pro mini board and customized electronic board with the software provided. The customized electronic board that is needed for the pCT trigger controller has two boards which are called the HMI control board and trigger control board. The customized electronics board was designed by the EAGLE 9.6.0 program and sent to an abroad manufacturer for fabrication.

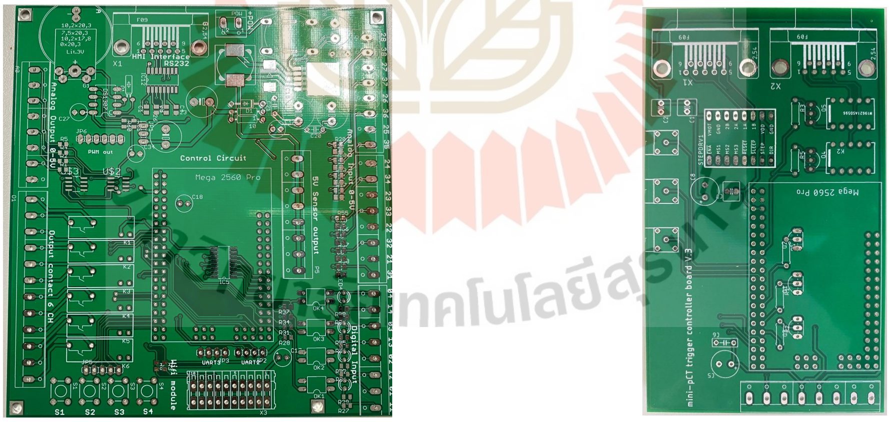
- Human Machine Interface (HMI) control board: The HMI control board is designed for a general-purpose related to control system applications. It helps the MCU could get an incoming analog/digital signal to process, then generate a new signal controlled by the LED touch screen completely. In our design, it is used for sending and receiving the digit binary between the MCU and LED touchscreen for the system user interface. The electronic components that are needed to assemble in the HMI control board are MAX232 IC and the power supply section. According to software design, the MCU needs to communicate to LED touchscreen using RS232 protocol which uses MAX232 IC as a converter. The Rx and Tx pins of the MCU wired to MAX232 IC, Max232 IC is connected to the on-board DB9 male sub connector to the LED touchscreen by using a 1 meter DB9 male-female cable. The designed schematic view and finished PCB board of the HMI control board designed by EAGLE 9.6.0 program are shown in Figure 3.11a and Figure 3.12a respectively.

- Trigger control board: The trigger control board is an important electronic board in the pCT trigger controller system. it is used to generate signals to each component sequentially in the system controlled by the MCU. The generated signals are sent to 3 components of the pCT prototype, which are the TSS interface box of the proton beam, the ALPIDE sensor, and the rotational stage. The electronics components that were assembled onto the board are an A5W-K relay 5V and an A4988 module. The trigger control board requires use three levels of supply voltage that are 5, 12, 24 volts. The designed schematic view and finished PCB board of the trigger control board designed by EAGLE 9.6.0 program are given in Figure 3.11b and Figure 3.12b respectively.



(a) The schematic view of HMI control board. (b) The schematic view of trigger control board.

Figure 3.11 The schematic view of the board design.



(a) The PCB board actual view of HMI control. (b) The PCB board actual view of trigger control.

Figure 3.12 The actual view of the board design.

3.6 Graphical user interface design

The MEGA2560 pro mini acts as a MCU for full control of the pCT components. Parameters to be programmed into the MCU can be done by importing valueson the LED touch screen into a Human Machine Interface (HMI) based on the software design mentioned in the previous subsection. The input parameters required details are exposure time, rotation angle, and mode of the operation that will be presented in the next section. The graphical user interface is designed using SKTOOL 7.0 released by the SAMKOON touchscreen's makers as shown in Figure 3.13.

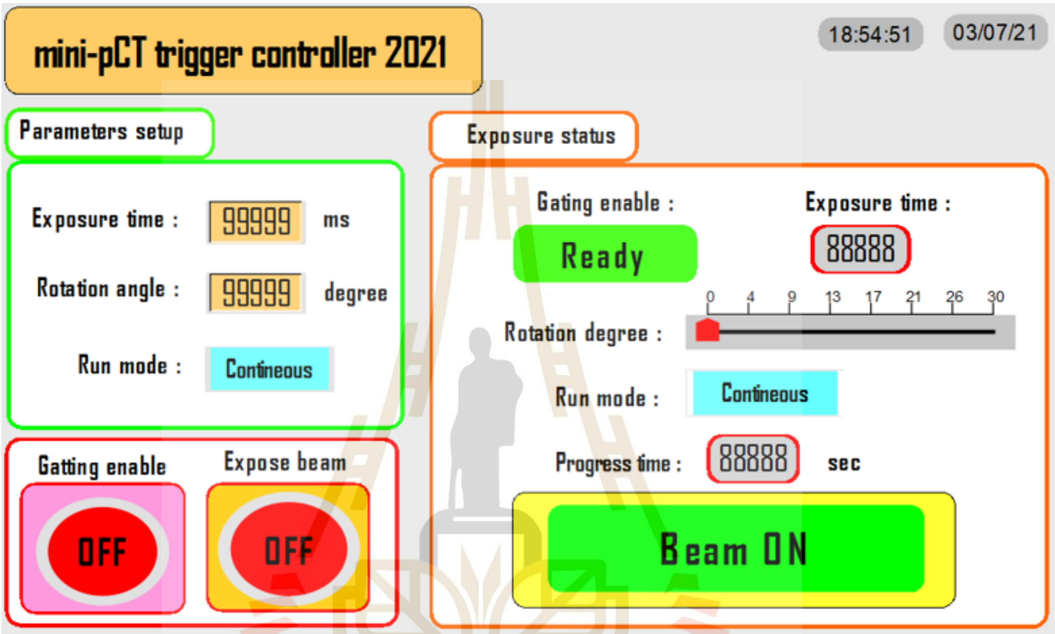


Figure 3.13 The user interface design of pCT trigger controller.

CHAPTER IV
SPECIFICATIONS TEST OF PCT TRIGGER CONTROLLER

4.1 Proton beam facility

The Proton Therapy center has been in operate in Thailand at King Chulalongkorn Memorial Hospital. It was established to celebrate 65 years anniversary of Her Royal Highness Princess Maha Chakri Sirindhorn since September 2021.

The proton machine version Dok. Nr.: PT-BAG-XXXX-00 is established by Varian medical system company The proton beam comes from cyclotron with the energy in the range of 70-245 MeV which can be referred to 4-37 cm of water equivalence path length (WEPL). The diameter of the beam at isocenter is fewer than 5 mm by maximum energy and less than 7 mm by 100 MeV. The proton beam rate is 1,000,000,000 proton/second at least. It is a Hospital based proton therapy center with single gantry scanning nozzle provided by Varian. Proton Therapy Machine The proton machine version Dok. Nr.: PT-BAG-XXXX-00 is shown in Figure 4.1. The tracking system use real-time scanning with x-ray cone beam computed tomography (CBCT) imaging. The proton beam from this machine is the pencil scanning for medical treatment.

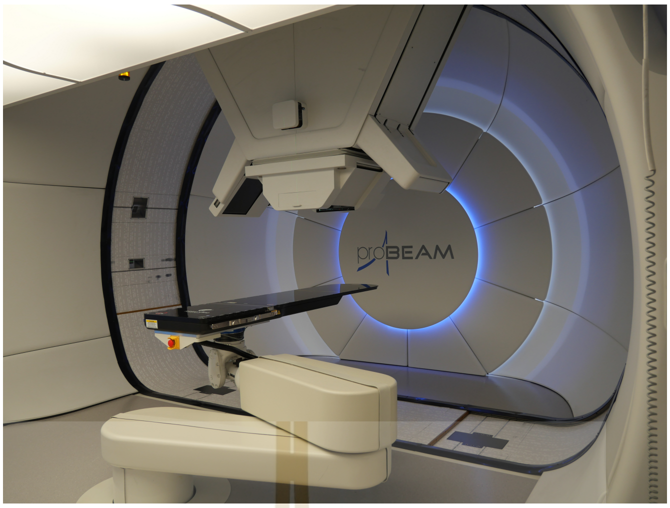


Figure 4.1 Proton beam launched by varian medical system company at King Chulalongkorn Memorial Hospital.

4.2 Description of pCT trigger controller

The pCT trigger controller is used to synchronize the timing of the pCT prototype's components consisting of the proton beam, rotational stage, and ALPIDE sensor. The pCT trigger controller board is designed for the specific outlet: 2 ports for DB9 female sub connectors and 1 port for LEMO female connector as show in Figure 4.2. The pCT trigger controller board generates specific signals for synchronizing each component to work sequentially. The outlet ports that connect from the pCT trigger controller to three components are:

- DB9 male sub-connector to TSS interface box of the proton beam.
- LEMO connector to ALPIDE sensor.
- DB9 male sub-connector to rotational stage.

4.2.1 Operating Guidance

The pCT trigger controller can be completely controlled by importing the desired parameters on a touchscreen monitor via SAMKOON SK-070FE HMI. The graphical user interface touch screen can be seen in Figure 4.3. The user

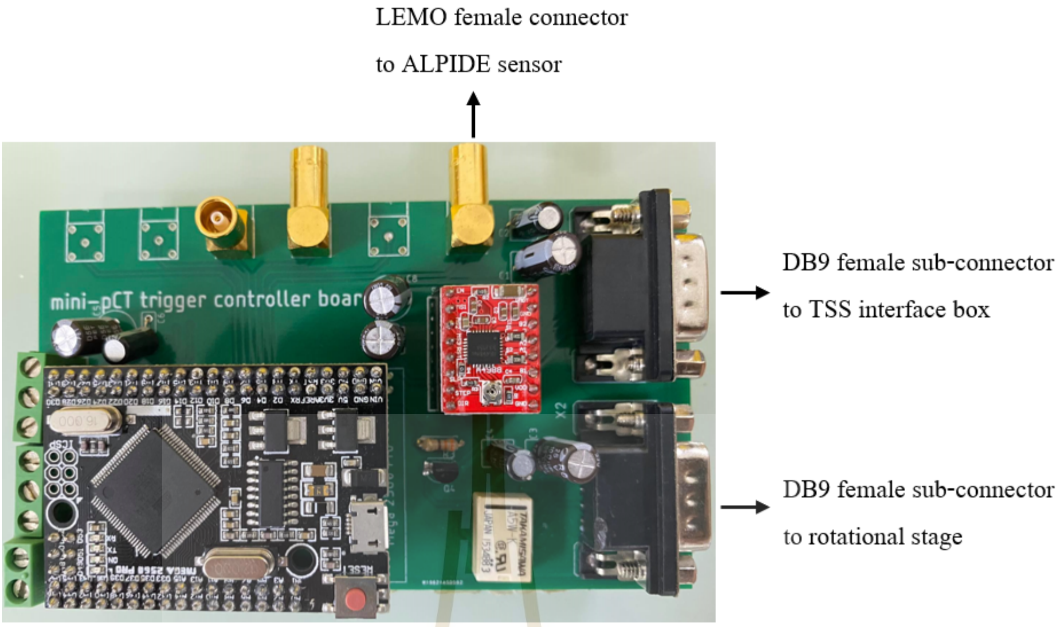


Figure 4.2 The specific outlet ports on assembled circuit board of the pCT trigger board.

interface consists of 3 parts which are parameter setup, control button, and exposure status.

4.2.2 Parameter setup

- Exposure time: the exposure time is the time that the proton beam emits protons leave a nozzle. The exposure time can be set in millisecond unit that can be increased or decreased by 1 millisecond. The exposure time has a limitation that is it needs to be started at 1 millisecond.

- Rotational stage: the rotation angle can be started from 1 to 360 degrees maximum by increasing or decreasing in 1-degree at a time.

- Run mode: The operation mode can be chosen to be 1 out of 2 operation modes which are manual and continuous mode. Manual mode is the mode for the system to run only once after push a gating enable and exposure beam respectively according to imported parameters. Continuous mode is the mode for the system to run continuously according to imported parameters until the 360-degree rotational process is completed.

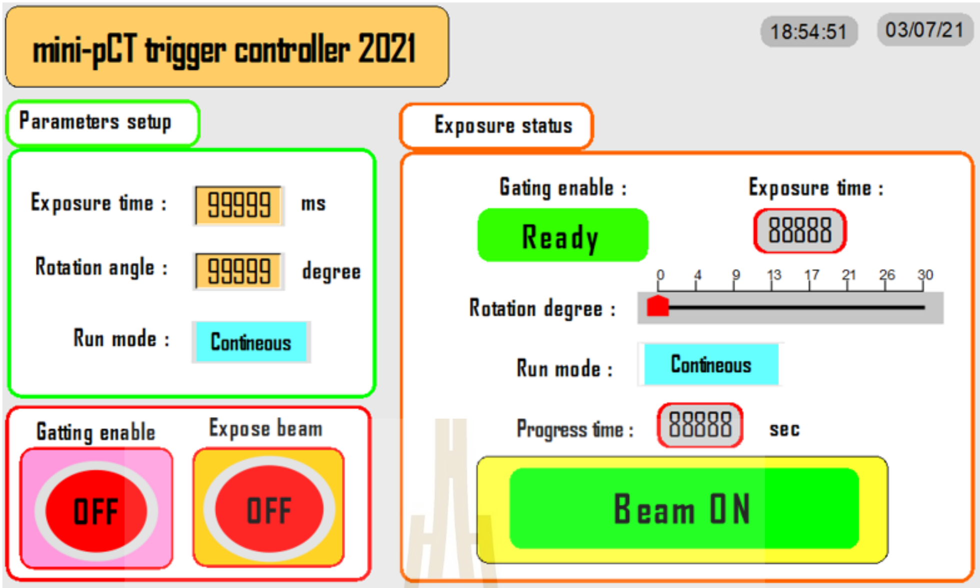


Figure 4.3 The user interface design of the pCT trigger controller on SAMKOON SK-070FE HMI touchscreen.

4.2.3 Control click button

The control button is the last command button after the parameters have been configured successfully. The gating enable click button and exposure beam click button need to be pushed respectively for the system to properly work. The gating enable is used to request protons from the cyclotron system, the exposure is used to release protons out the nozzle.

4.2.4 Exposure status

The exposure status shows the configured parameters and the progress time while the system is running. The exposure status shows the system readiness before starting to work. which are gating enable, exposure time value, rotational stage, working mode, progress time, and beam indication.

4.3 Specification test

Specification test is to test the performance and working characteristics of the constructed devices. The test will be considered into 2 kinds which are electrical and mechanical characteristic.

4.3.1 Electrical characteristics test

The electrical characteristics were test in terms of the electrical signal inlet and outlet of the pCT trigger controller we constructed. The inlet and outlet of electrical characteristics that we focused including operating voltage, controller board, ALPIDE sensor, rotational stage, and DB9 TSS interface box. The pCT trigger controller is completely supplied with the ROHDE & SCHWARZ HMP2030 programmable power supply. The power supply was configured the voltage of 5, 12, and 24 VDC with limited current of 1 A in each channel. In each channel supply to MEGA2560 pro mini, indication lamps, and SAMKOON HMI touch screen in the pCT prototype system. The testing considered of the minimum, typical, and maximum limitations of the pCT trigger controller for usage. The generated signals of the pCT trigger controller were measured by TELEDYNE LECROY Wave runner 8254 2.5 GHz oscilloscope. The experiment was set and performed at the laboratory in Suranaree University of Technology as shown in Figure 4.4. The results are given by Table 4.1.

Figure 4.4 The experimental setup of the pCT trigger controller's characteristic test was performed at SUT.

Table 4.1 Electrical characteristics test of the pCT trigger controller under fixed conditions.

Testing with limit current of 2A, Voltage can be varied				
Parameter	**Min.**	**Typ.**	**Max.**	**Unit**
Operating voltage				
- SAMKOON Touchscreen	-	24	-	VDC
- MEGA2560 pro mini	-	5	-	
- Stepper motor	8	12	35	
- Stepper motor driver	3	5	5.5	
Controller board				
- Clock speed	-	16	-	MHz
- Current per I/O port	30	-	50	mA
ALPIDE sensor				
- Logic level consumption	4.8	5.0	5.1	VDC
- Rising time	-	7.27	-	ns
- Voltage supply	-	5	-	VDC
- Current consumption	290	260	240	mA
Rotational stage				
- Driver voltage	-	568	-	mA
- Driver current limit	-	330	-	mA
DB9 TSS interface box				
- Carrying current	-	-	2	A
- Switching power	-	-	30	Watt
- Switching voltage(contact)	-	220	-	VDC
- Switching current	-	2	-	A
- Coil resistance	-	5	-	ohm
(Time conditions)				
- Operate	-	6	-	ms
- Released	-	4	-	ms
- Exposed time limit	1	-	65535	ms

4.3.2 Mechanical characteristics test

The mechanical characteristics test is to test the specific data in terms of the mechanical performance by focusing on the rotational stage. The mechanical characteristics of the rotational stage that we focused including rotation angle, rotation step, rotational, angular velocity, gear ratio, and maximum load. The experimental setup is the same as the electrical characteristic test. The rotational stage is supplied with 12VDC and pulse frequency of 500 Hz with duty cycle of 50%. The results are given by Table 4.2.

Table 4.2 Mechanical characteristics test of the pCT trigger controller under fixed conditions.

Testing with 12 VDC supply to motor, freq. 500Hz, duty circle 50%				
Parameter	**Min.**	**Typ.**	**Max.**	**Unit**
Rotation angle	1	-	360	deg
Rotating step				
- Full step	-	1.8	-	
- Half step (1/2)	-	0.9	-	deg/step
- Sixteenth step (1/16)	-	0.112	-	
Rotating angular velocity				
- Full step	4.938	4.946	4.954	
- Half step (1/2)	2.467	2.470	2.473	deg/step
- Sixteenth step (1/16)	0.308	0.309	0.309	
Gear ratio	-	180	-	-
Max. load	-	45	-	Kg

4.4 Rotation efficiency of the rotational stage

The rotational stage which is SHINANO KENSHI model Y07-43D1-4275 can be set the rotating resolution with five options. We have tested three mostly used resolution which are Full step, Half step, and Sixteenth step. In this testing, the time that used to rotate for 90, 180, and 360 degrees of three different resolutions were observed using the serial monitor as shown in Figure 4.5.

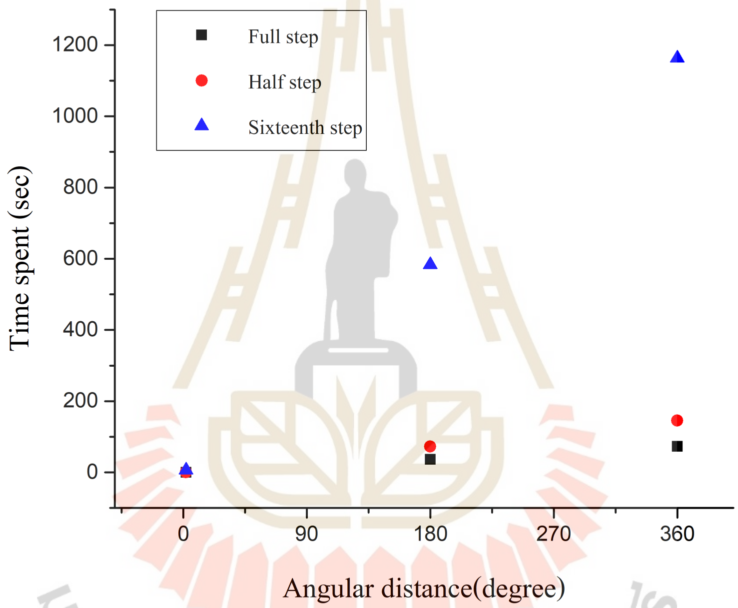


Figure 4.5 The time spent for 90, 180, and 360 degrees of three different resolutions measured by serial monitor.

The angular velocity of three different resolutions also were calculated by rotated degrees per time spent in each resolution as show in Figure 4.6. The figure 4.5 and 4.6 indicate that the high resolution takes longer time to rotate than low resolution for the same angular displacement.

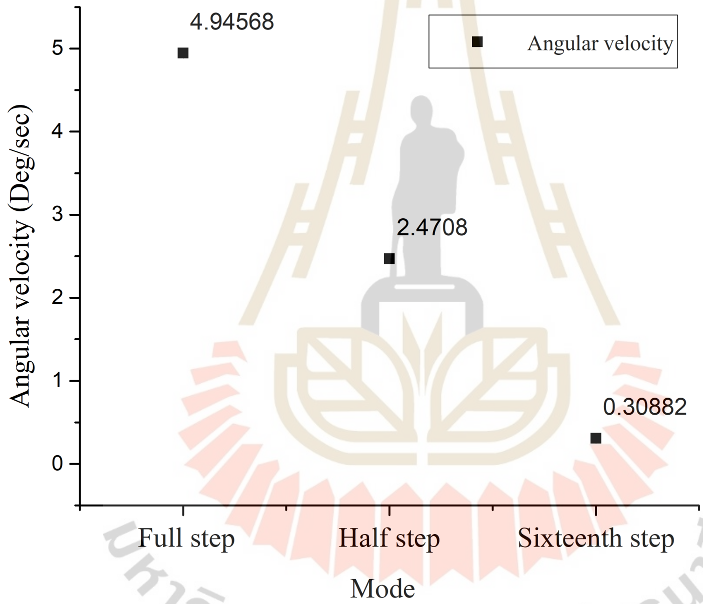


Figure 4.6 The angular velocity of three-resolutions.

CHAPTER V
TESTING RESULTS OF PCT TRIGGER CONTROLLER WITH PROTON BEAM AT KCMH

5.1 The setup of ALPIDE single-chip test

The laboratory test is to setup for a functional testing of an ALPIDE single chip. We connect an ALPIDE to a DAQ board and from a DAQ board to a computer for a data retrieval and analysis. The schematic diagram is shown in Figure 5.2, and the actual ALPIDE chip connecting with the DAQ board are presented in Figure 5.2 The DAQ board is connected to a power supply with 5V at limited current of 1A.

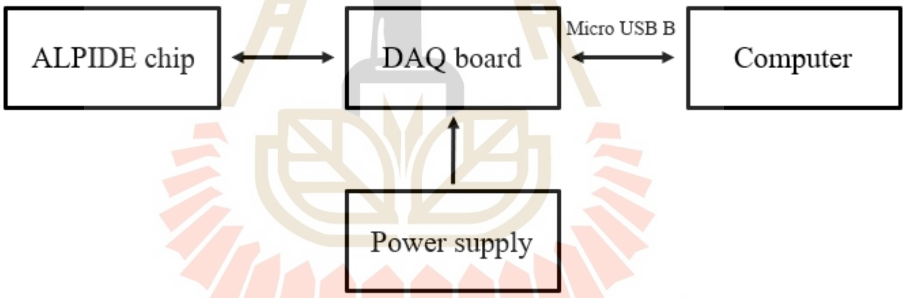


Figure 5.1 The diagram of ALPIDE single chip laboratory setup.

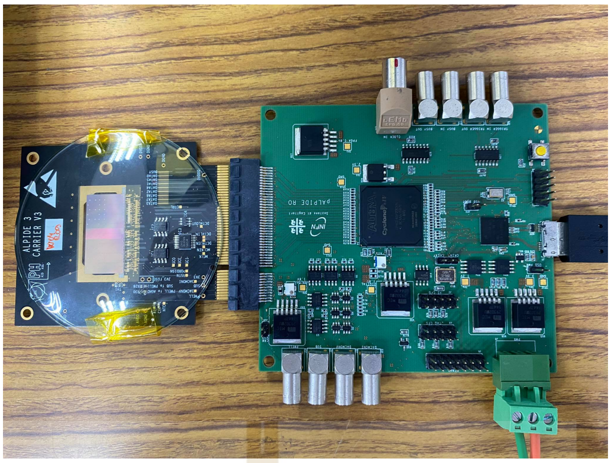


Figure 5.2 The ALPIDE chip connected with DAQ board.

5.1.1 Functional test of ALPIDE single chip

The functional test is used to test the functionality and characterizations of an ALPIDE chip. The functional test consists of three types: a First-In First-Out (FIFO) test, an On-chip Digital to Analog Converter (DAC), and a threshold scan. The functional test was performed using Linux platform.

- The FIFO test is used to test a basic communication between an ALPIDE chip and DAQ board by measuring a current consumption before and after configuration of a chip. The command is: alpide-fifo.
- The One-chip DAC test is used to test binary data converted into an analog signal in the range of 0-255. The command is: alpide-dac.
- The threshold scan is used to test the analog detection performance of pixels on a chip. The way to test in each pixel is starting from the top-left pixel and moving to the right until the last pixel in the bottom-right corner. The output of the threshold scan provides a raw file that can be reconstructed hit map pictures. The command is: alpide-thrscan.

The source code and all data of a required functional test are located in the local directory which is called alpide-daq-software-master folder.

5.2 Using and setup of proton beam facility

To test the pCT trigger controller with the pCT prototype, we need to use the real proton beam. The pCT trigger controller has to be setup at Her Highness Princess Maha Chakri Sirindhorn Proton center, King Chulalongkorn Memorial Hospital (KCMH). The Proton Center now offers radiotherapy to patients already since September 2021. We have been setting up experiment in two operating rooms which are the treatment room and the control room. The treatment room allows only patients that will be irradiated to stay inside during radiation. The room next to the treatment room is the control room. The control room is the place where a doctor, a radiologist or a medical physicist to control and assess the irradiation.

In our experiment, the aluminum structure that combines an ALPIDE single-chip and a rotational stage will be put on the patient bed inside the treatment room for proton irradiation as shown in Figure 5.3 and Figure 5.4. While the pCT trigger is located at the control room to allow a user control. The pCT trigger controller connect the three components of the pCT prototype which are:

- the TSS interface box located inside the control room using DB9 cable.
- the rotational stage also placed inside the treatment room using 20-meter DB9 cable of 20 meters through the hole between the treatment room and the control room.
- the ALPIDE single-chip and a DAQ board. They stand next to the rotational stage. But we can not use a TTL triggering signals directly from our pCT trigger controller. It has to be controlled by a laptop using Linux terminal for alpide threshold scan test.

5.2.1 Hit map of the functional test

The hit map is obtained from the alpide-thrscan of the ALPIDE single-chip functional test. alpide-thrscan is a command that is used to test the threshold functionality of every pixel on the sensor. We observe the hit map of the threshold on ALPIDE when the proton beam passes through an ALPIDE

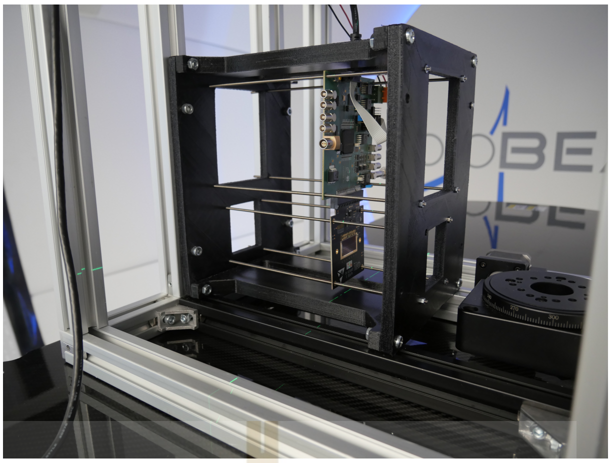


Figure 5.3 The ALPIDE sensor connected to DAQ board located inside the supporter in proton treatment room.

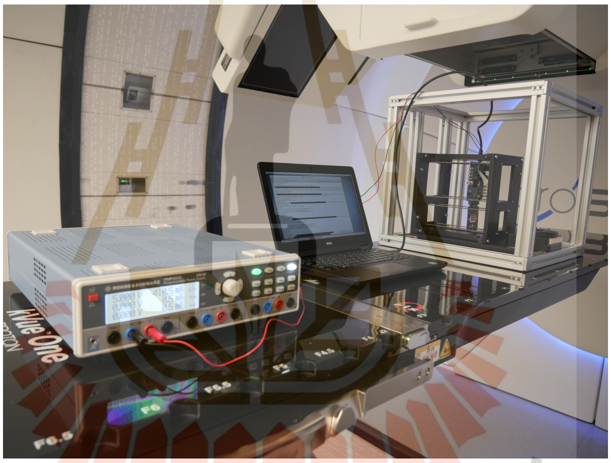


Figure 5.4 The set of ALPIDE single-chip test in the treatment room that comprise of the power supply, the laptop, and the ALPIDE single-chip inside the PLA and the aluminum structure on the patient bed.

sensor. The results of the hit map are used to verify that the sensor can detect incoming protons.

Each green dot gather in a circular shape in Figure 5.5 represents the hitting position of protons on the sensor. The x-axis and the y-axis in the graph are the numbers of pixels in the horizontal and vertical of the sensor respectively and colored scale is the number of protons that excite the threshold per pixel.

In our requirement, we need to know that our pCT trigger controller can control the time of protons emitting by looking at the hit map of ALPIDE single-chip test.

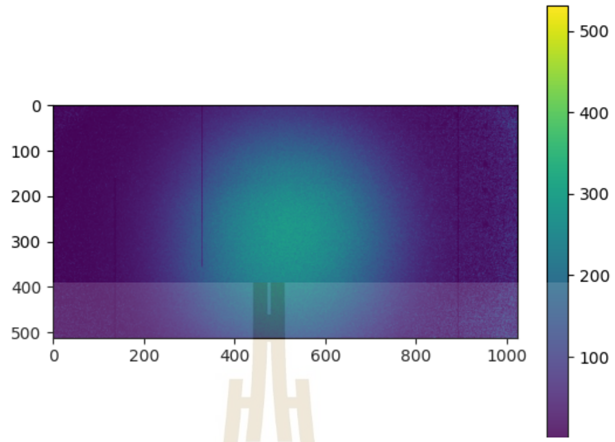


Figure 5.5 The hit map of proton beam at proton center captured by ALPIDE single-chip.

5.3 pCT trigger controller testing with the proton beam at KCMH

To test the function for the pCT trigger controller, the pCT trigger controller was put to test with the real proton beam at KCMH. This test is to verify that our pCT trigger controller can control the opening and closing the proton beam gating according to the our desired time. The method to check our pCT trigger controller performance is to examine the hit map graph of the released proton captured by the ALPIDE single-chip test.

The pCT trigger controller is located in the control room and connected with the TSS interface box via DB9 cable as shows in Figure 5.6. Besides that, the laptop used for controlling ALPIDE single-chip. Another laptop in the treatment room is used for monitoring via the Team viewer program.

Figure 5.6 The pCT trigger controller and the laptop are in the control room.

Before every treatment, a radiotherapist and a medical physicist need to do the treatment planning by verifying characteristics of the proton beam using treatment mode. The characteristic of the proton beam that could be set of 2 parameters are proton energy and MU. In experiment, we configured a proton energy and MU to be 100 MeV and 200000 MU respectively. After proton machine's parameter and pCT trigger controller configured, The proton beam was released by clicking on Enable and Expose beam button on pCT trigger controller' s touchscreen according to configured time. At the same time, The ALPIDE single-chip test has to execute the command alpide-thrscan for getting released proton hit map by click on a laptop. The clicking on exposure and laptop needs to be done simultaneously by user. The results of released proton hit map according to desired time captured by ALPIDE single-chip are shown in Figure 5.7 and Figure 5.8.

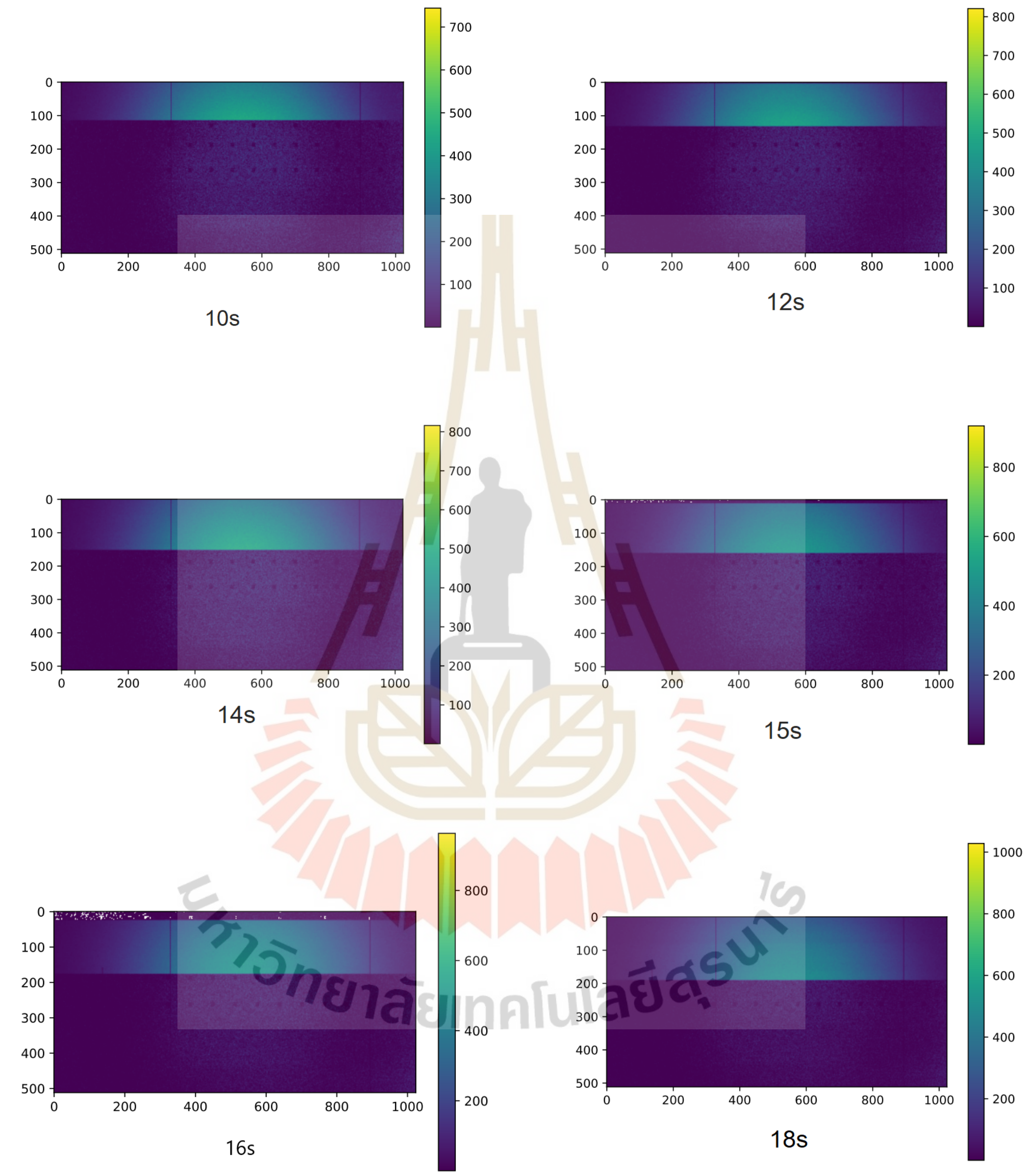


Figure 5.7 The ALPIDE single-chip hit map indicates the proton emitting period controlled using a pCT trigger controller.

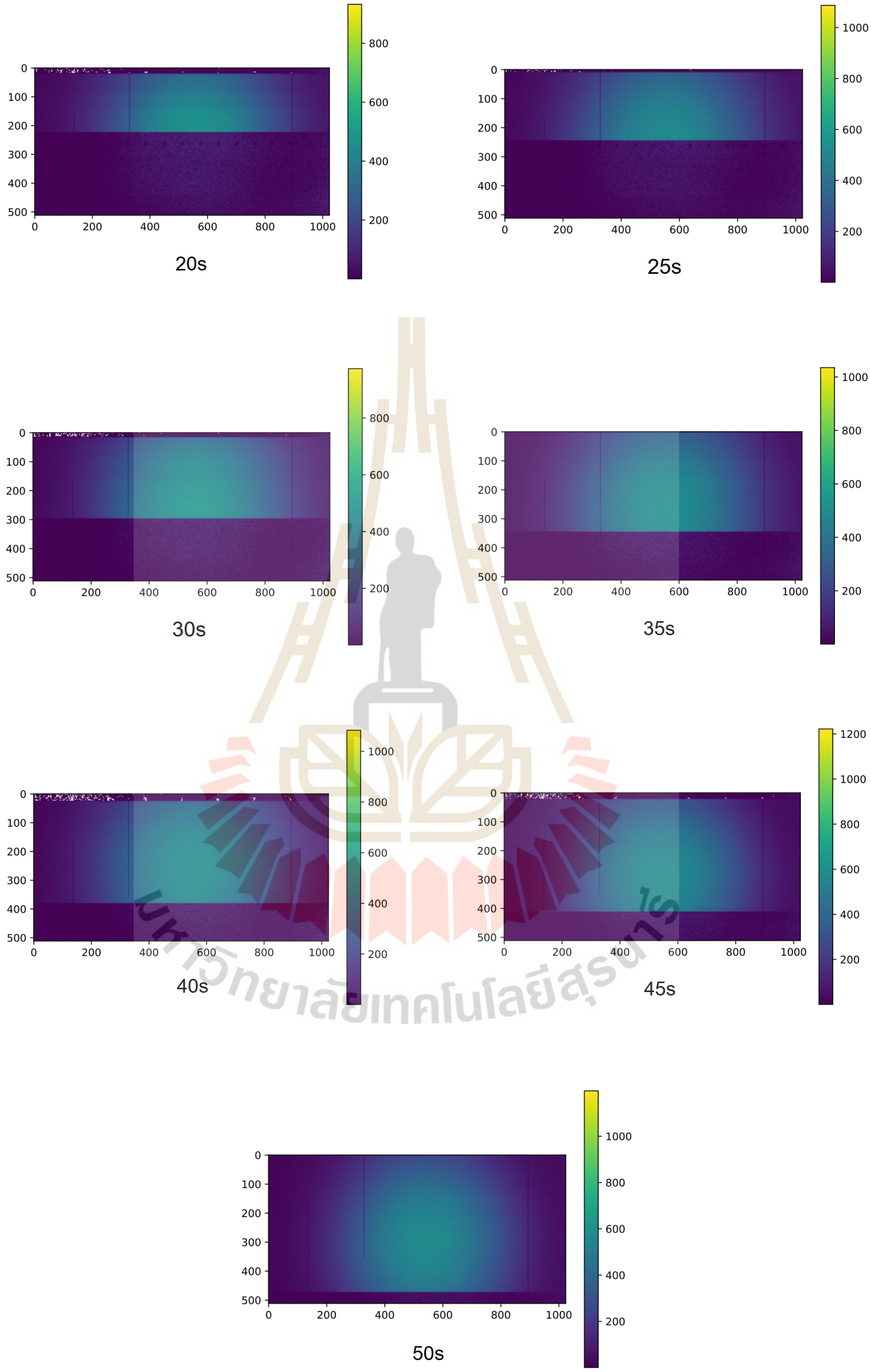


Figure 5.8 The ALPIDE single-chip hit map indicates the proton emitting period controlled using a pCT trigger controller (Continued).

According to the Figure 5.7 and Figure 5.8, the number of rows recorded increases as the proton emission period increases. The R-square of the relationship between a range of row record and a period obtained by graph fitting is 0.98968 as shown in Figure 5.9. The R-value indicates that the two data sets are linear.

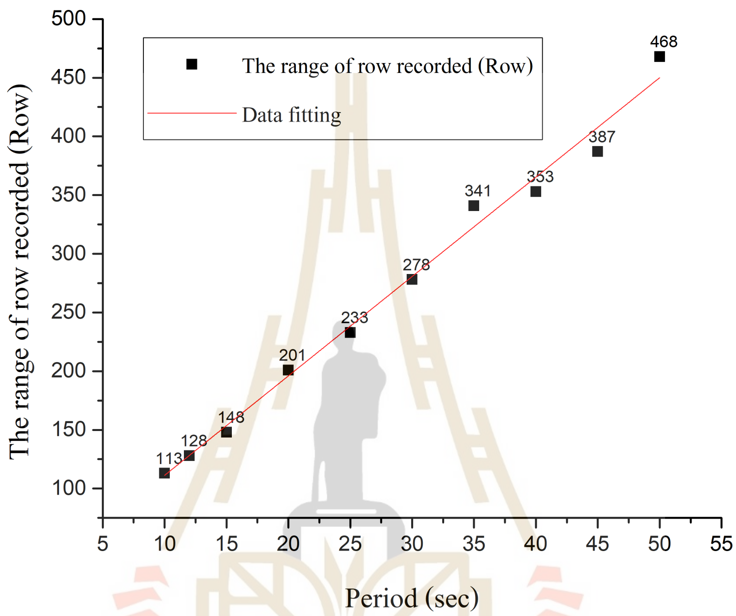


Figure 5.9 The range of rows was recorded at different desired times.

5.4 pCT trigger controller testing with the telescope

The telescope is a stack of the ALPIDE sensors. The experimental setup of the telescope is like an ALPIDE single-chip test as shown in Figure 5.10 but adding one more layer of an ALPIDE chip. In our testing, the telescope comprises two ALPIDE sensors.

The telescope needs to use TTL pulse signals for data recording. The TTL pulse signal can be generated using our pCT trigger controller in continuous mode as shown in Figure 5.11. The triggering signal from the pCT trigger controller is connected to the DAQ board of the first ALPIDE sensor via a trigger in the LEMO port through the coaxial-LEMO cable of 0.5 meters. Then, the second ALPIDE sensor connected the trigger signal from the trigger out port in serial connection form. The single pulse of TTL signals causes each ALPIDE in the telescope to start recording data called event. The runing screen of telescope testing shows in Figure 5.12.

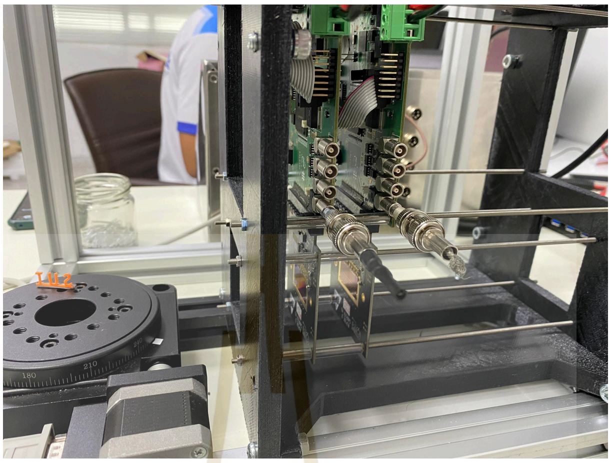


Figure 5.10 The telescope setup comprises two ALPIDE sensors assembled inside the PLA structure.

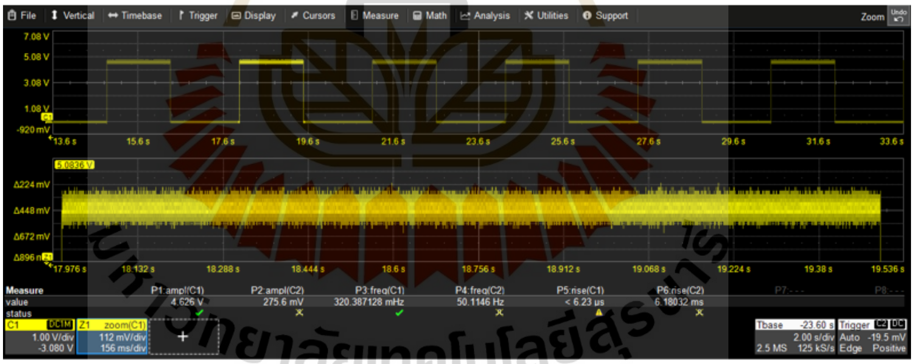


Figure 5.11 The TTL pulse generated using a pCT trigger controller in continuous mode measured by an oscilloscope.

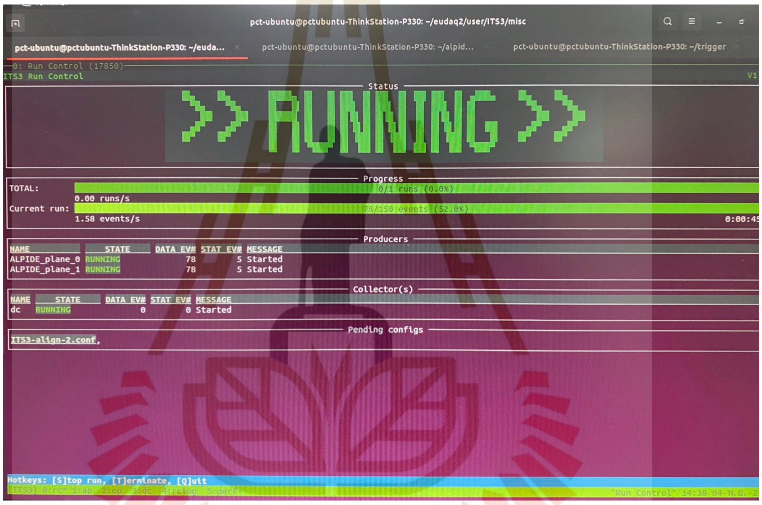


Figure 5.12 The program window of telescope test using EUtelescop program shows data recording events generated using triggering signals from the pCT trigger controller.

CHAPTER VI
CONCLUSION

In this work, we designed and developed a pCT trigger controller to synchronize each component of the pCT prototype. The working principle are as follows. Second, another generated signal is sent to the rotational stage to rotate a target sample at the desired angle. Third, the controller generates a square wave pulse to the ALPIDE sensor, which acts as the position-sensitive detector, delayed for 200 microseconds according to the delayed time of the beam from the gating to the beam nozzle or our sensor. The delayed time can be selected by the controller. The controller was verified by testing with the realistic proton beam at KCMH in September 2021. The opening gating time of the proton beam has been demonstrated by the detected positions of protons impinging on the ALPIDE sensor.

To verify that the controller can generate a signal properly to the ALPIDE sensor, we performed another experiment by arraying two planes of the sensor as a simple telescope. The first sensor was triggered by receiving a TTL wave pulse generated by the controller. We obtained the desired root file containing all necessary information that needs to be further analyzed.

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APPENDICES

APPENDIX A
ARDUINO MODBUS SOFTWARE

A.1 C language with modbus protocol design for MEGA2560 pro mini uploading

```
====== MODBUS =======
# include <modbus.h>
# include <modbusDevice.h>
# include <modbusRegBank.h>
# include <modbusSlave.h>
# include <EEPROM.h>
modbusDevice regBank;
//Create the modbus slave protocol handler
modbusSlave slave;
———DAC Paremeter————
int sen_gas1;
int sen_gas2;
int sen_gas3;
int pwm1 = 5; //dirpin ROTA
int pwm2 = 6; //gatting ON, enable
int pwm3 = 7; //ALPIDE
int pwm5 = 9; //Buzzer
int pwm6 = 10; // beam ON lamp
int pwm7 = 22; // trigger
int pwm8 = 12;
int em_status=0;
int expose_status = 0;
int mode_status = 0;
int enable_status = 0;
byte adr = 0x08;
byte num = 0x00;
```

```
//————-Status————-
unsigned int i;
int count = 0;
//————-Setpoint————–
float gas1 = 90;
float gas2 = 90;
float gas3 = 90;
float f_gas1;
float f_gas2;
float f_gas3;
//————–-MODBUS————–-
//————–Setpoint————–
//——-Timer interrupt rutine———
int int_counter = 0;
int int_counter2 = 0;
unsigned long second = 0;
unsigned long second2 = 0;
ISR(TIMER1_OVF_vect)

int_counter += 1;
int_counter2 += 1;
if (int_counter == 490)

second += 1;
second2 += 1;
int_counter % = 0;

if ((int_counter2 100) == 0)
modbus();


void modbus()
count++;
regBank.set(40011, f_gas1);
```

```
regBank.set(40012, f_gas2);
regBank.set(40012, f_gas2);
regBank.set(40006, second2);
if (count romcheck();
count = 0;

get_parameter();
slave.run();
}
void setup()
Serial.begin(9600);
//————PinMode—————
pinMode(5, OUTPUT);
pinMode(6, OUTPUT);
pinMode(7, OUTPUT);
pinMode(8, OUTPUT);
pinMode(12, OUTPUT);
EEPROM_Read();
digitalWrite(13, LOW);
regBank.setId(1);
//Add Digital Output registers 00001-00016 to the register bank
for (i = 1; i < 100; i++)
regBank.add(i);

//Add Digital Input registers 10001-10008 to the register bank
for (i = 10001; i < 10020; i++)
regBank.add(i);

for (i = 40001; i < 40100; i++)
regBank.add(i);

slave._device = regBank;
// Initialize the serial port for coms at 9600 baud
slave.setBaud(9600);
```

```
TCCR1B |= ((0 « CS12) | (1 « CS11) | (1 « CS10)); //Timer2 Settings: Timer Prescaler /1024
TIMSK1 |= (1 « TOIE1); //Timer2 Overflow Interrupt Enable
TCNT1 = 15536;
sei();
EEPROM_Read();
}
void EEPROM_Read()
gas1 = EEPROM.read(1);
gas2 = EEPROM.read(2);
gas3 = EEPROM.read(3);
}
void loop() {
count++;
modbus();
second2=0;
if (mode_status == 1   enable_status == 1   expose_status == 1 )
Serial.print("Manual_Running...........");
tone(9,500,gas1); //Buzzer
digitalWrite(5, HIGH); //Dirpin
digitalWrite(6, HIGH); //Gatting ON TSS, gatting enable
digitalWrite(16, HIGH); //beam on lamp
delay(200); //Delay 200ms after proton emitting
digitalWrite(7, HIGH); //ALPIDE
delay(gas1-200);
digitalWrite(6 , LOW);
digitalWrite(7, LOW);
digitalWrite(16, LOW); //beam on lamp
digitalWrite(22, HIGH);
for (int x = 0; x < (gas3 * 100); x++)

digitalWrite(12, HIGH); //step
delay(1);
digitalWrite(12, LOW);
```

```
delay(1);

digitalWrite(22, LOW);
delay(1000);
Serial.print(" Stop manual...");
enable_status == 0;
expose_status == 0;
mode_status == 0;
regBank.set(1, 0);
regBank.set(2, 0);
delay(500);
}
else if (mode_status == 0   enable_status == 1   expose_status == 1)
for (int x = 0; x < (360 / gas3); x++ )

Serial.print("Continue_Running.....");
tone(9,500,gas1); //Buzzer
digitalWrite(5, HIGH);
digitalWrite(6, HIGH);
digitalWrite(16, HIGH); //beam on lamp
delay(200);
digitalWrite(7, HIGH);
delay(gas1-200);
digitalWrite(6, LOW);
digitalWrite(7, LOW);
digitalWrite(16, LOW); //beam on lamp
digitalWrite(22, HIGH);
for (int x = 0; x < (gas2 * 100); x++)

digitalWrite(12, HIGH);
delay(1);
digitalWrite(12, LOW);
delay(1);
```

```
digitalWrite(22, LOW);
delay(1000);

Serial.print(" Stop Cons......");
enable_status == 0;
expose_status == 0;
regBank.set(1, 0);
regBank.set(2, 0);
delay(500);

output();
Serial.println();
delay(100);
void read_comp(){}
void sensors_Read(){}
void Control(){}
void output(){
if(regBank.get(1) == 0)
{enable_status=0;}
else
{enable_status=1;}

if(regBank.get(2) == 0)
{expose_status=0;}
else
{expose_status=1}

if(regBank.get(3) == 0)
{mode_status=0;}
else
{mode_status=1;}
}
void get_parameter() {
```

```
        //———get  gas1_sp———
if  (regBank.get(40001)  ==  0)  {
regBank.set(40001,  gas1);
}  else
gas1  =  regBank.get(40001);
regBank.set(40001,  gas1);

//———get  gas2_sp———
if  (regBank.get(40002)  ==  0)  {
regBank.set(40002,  gas2);
}  else
gas2  =  regBank.get(40002);
regBank.set(40002,  gas2);

//———get  gas3_sp———
if  (regBank.get(40003)  ==  0)  {
regBank.set(40003,  gas3);
}  else  {
gas3  =  regBank.get(40003);
regBank.set(40003,  gas3);
}


        }
void  romcheck()  {
if  (  (gas1  ==  EEPROM.read(1)))  {
EEPROM.write(1,  gas1);
}
if  (  (gas2  ==  EEPROM.read(2)))  {
EEPROM.write(2,  gas2);
}
if  (  (gas3  ==  EEPROM.read(3)))  {
EEPROM.write(3,  gas3);
}
}
```

APPENDIX B
ACADEMIC CONFERENCE

B.1 Conference attendance and award

This year, The manuscript was submitted in topic of Development of the trigger system for proton computed tomography in the 2rd International Virtual Conference on Science and Technology (IVCST2021). This manuscript got the best paper award in Physical and Life Science as shown the certification in Figure B.1.

IVCST 2021

The Scientific Committee of
The 2nd International Virtual Conference on Science and Technology (IVCST 2021)
Takes pleasure in presenting

SUT-IVCST 2021 Best Paper Award
to
P. Pummara and C.Kobdaj
for the manuscript
Development of the trigger system for proton computed tomography
6th August 2021, Nakhon Ratchasima, THAILAND

Assoc. Prof. Dr. Weerapong Pairsuwan
Honorary Chair
Rector of Suranaree University of Technology

Assoc. Prof. Flt. Lt. Dr. Kontorn Chamniprasart
Conference Chair
Vice Rector for Academic Affairs and Internationalization

At Suranaree University of Technology

Figure B.1 The best paper award of submitted proceeding in SUT-IVCST 2021.

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Publications :

1. P. Pummara and C. Kobdaj (2021). Development of the trigger system for proton computed tomography. **The 2th International Virtual Conference on Science and Technology (IVCST 2021)**