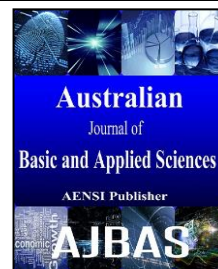




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Development of a compact radiation detection system based on the use of silicon photomultipliers.

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ABSTRACT

In this work we describe the development and the prototype of a new compact radiation detection system based on the use of the recent solid-state photosensors, the silicon photomultipliers (SiPMs). Scintillation exploits atomic or molecular excitation due to the passage of a charged particle. De-excitation then results in the emission of light, a process known as fluorescence. This light then acts as a detectable signal. For the detection system prototype, we used an organic scintillator from Eljen (EJ-204). Light travels along the thin scintillator undergoing many total internal reflections. To avoid losses and improving light collection efficiency, scintillator had been wrapped with an aluminum foil. Scintillation light readout is performed by using the Multi-Pixel Photon Counters (MPPCs) series (S10931-100P), Hamamatsu Japan. Each MPPC photosensor has $3 \times 3 \text{ mm}^2$ active area and consists of 900 avalanche photodiodes (APDs), with a fill factor of 78.5 %. The maximum photo-detection efficiency is 55 % at 440 nm. For testing the prototype detection system, it has been irradiated with an energetic beta-particles emitted from Strontium-90 (Sr^{90}) radioactive isotope. The preliminary results showed that in response to the penetrating radiations, detector system prototype has succeeded to monitor beta-particles with good efficiency. The proposed prototype module could be a valuable option for a broad range of experiments if cost-effectiveness and small form factor are required.

INTRODUCTION

Most of the radiation detector systems are based on the use of photomultiplier tubes (PMTs). Recently, a new types of detectors, based on silicon diodes working in the avalanche regime have been developed and proved to be extremely interesting candidates to replace the existing PMTs, these are the silicon photomultipliers (SiPMs) (D. Renker, 2009; D. Renker, 2006). Like PMTs, they are capable of measuring extremely low light intensity. However, compared to PMTs, SiPMs offer the 'solid-state' advantages of lower operating voltages, smaller physical size and lighter weight (G.S.M. Ahmed *et al.*, 2009; D.P. McElroy *et al.*, 2007). Alongside recent advances in scintillators and high-speed digital technologies, offer the prospect of developing light-weight and reliable radiation detection technologies for novel applications such as scintillating fiber readout and imaging Cherenkov applications (Ahmed Gamal *et al.*, 2011; L. Gruber *et al.*, 2011).

The growing variety of available SiPMs which could be delivered from different manufactures requires the necessity to test and to characterize them in order to select and find the optimum operating conditions for a given application (I. Ostrovskiy *et al.*, 2015). The performance of SiPMs depends mainly on the operation voltage and or the operating temperature (P K Lightfoot *et al.*, 2008). Measurements of dark count rate, gain and time resolution of these devices have been presented elsewhere (G.S.M. Ahmed *et al.*, 2011).

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Unlike many other particle detectors, which exploit the ionization produced by the passage of a charged particle, scintillation occurs in materials possessing an appropriate energy band structure, whereby the interactions of energetic particles may excite electrons into higher energy states. The following relaxation of the excited electrons may cause some of the excess energy to be emitted as fluorescence; this light then acts as a detectable signal. (G. F. Knoll, 2000; C. Piemonte, 2006). A photo-detector is used to convert this light into an electronic signal. Finally, specialized electronics are used to amplify and process the signals for the desired information. As there is a broad range of scintillating materials available, a material with the most suitable properties may be selected for the particular application. This makes scintillators a highly versatile detection modality. SiPMs are sensitive in the blue light range (400 – 500 nm) which matches well with the light emitted by many scintillating materials. The combination of SiPM and small plastic scintillator represent a compact, inexpensive detection solution for different radiation measurements (Emilie Roncali *et al.*, 2011; G.S.M. Ahmed, 2016).

Detector Prototype:

The aim of the current study is to develop a compact radiation detection system prototype based on the use of a scintillator in combination with SiPMs for photons read out. The performance of such detector systems crucially depends mainly on the characteristics and performance of the chosen SiPM as well as the scintillator material.

SiPMs characteristics:

An important characteristic of photon-counting sensors such as SiPMs is the pulse shape produced when a single photon is detected. This is known as the single photoelectron response (P Eckert *et al.*, 2012). Figure. 1 represents MPPC (S10931-100P), charge distributions spectrum measurements when illuminated with very low-light intensity using a picosecond blue laser from (Advanced Laser Diode Systems) (PIL063SM) equipped with a 408 nm head with a pulse width of < 45 ps.

The light intensity on the SiPM is controlled by the tunable laser power and an attenuation filter. The repetition rate can be regulated from single shot to 1 MHz. The attenuated light was delivered to the SiPM by an optical fiber of 1 mm diameter.

The MPPC signal output line was connected to a charge-to-digital converter (QDC, LeCroy ADC-2249W, 0.25 pC/ch), for the charge measurements. Where the discrete single pulses exploring the nature of SiPM signal output when illuminated by brief pulses of low-intensity light. Single photon peaks are resolved which can be explored to determine the gain of the device at the given operation condition.

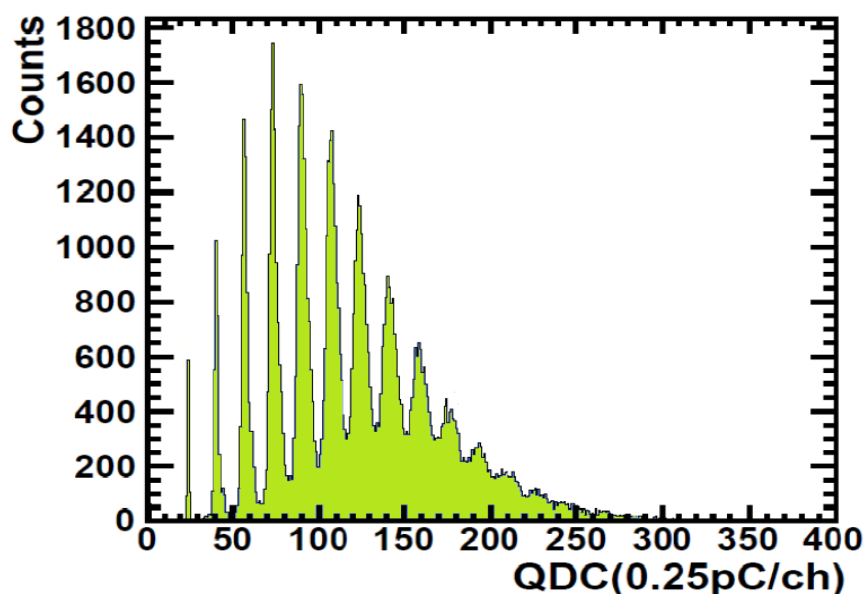


Fig. 1: MPPC pulse height distributions using a brief, low-intensity light. Single photon peaks are resolved corresponding to a different number of photo-electrons, which can be explored to determine the gain of the device at the given operation condition.

The operating bias voltage should be as stable as possible to reduce gain fluctuations. At varying temperatures the gain remains stable as long as an adequate bias voltage is applied (Francesco Licciulli *et al.*, 2013; Zhengwei Li *et al.*, 2016). Although operating the SiPM at large over-voltage (over-voltage = bias voltage

– breakdown voltage) has a positive effect on the gain performance (M. J. Yang *et al.*, 2016). Operating the SiPM at large over-voltage is accompanied by an increase of the dark counts. This can be a severe drawback in applications where only few photons are available for detection (N. Dinu *et al.*, 2010), see figure. 2.

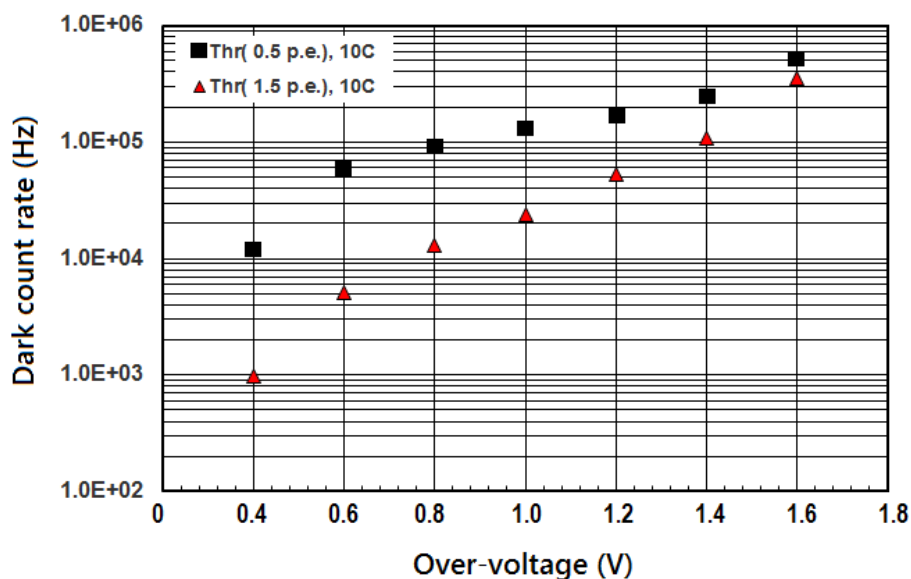


Fig. 2: MPPC dark count characteristic behavior as a function of the over-voltage at 10°C. Black Square and red triangle symbols correspond to data points at 0.5 p.e. and 1.5 p.e. thresholds level, respectively.

Scintillator characteristics:

For the detector prototype, an organic scintillator from Eljen (EJ-204) had been used (Eljen Technology, USA). EJ-204 has been chosen because it has the high scintillation efficiency, along with the combination of high speed and good attenuation length. It is particularly well suited for high-performance detector systems for nuclear and high-energy physics research. Photons produced by a particle traversing the scintillator are supposed to be totally reflected on the internal surfaces of the scintillator and to be guided to its ends. For enhancing the internal light reflections and improving light collection efficiency, scintillator had been wrapped with an aluminum foil (Figure. 3).

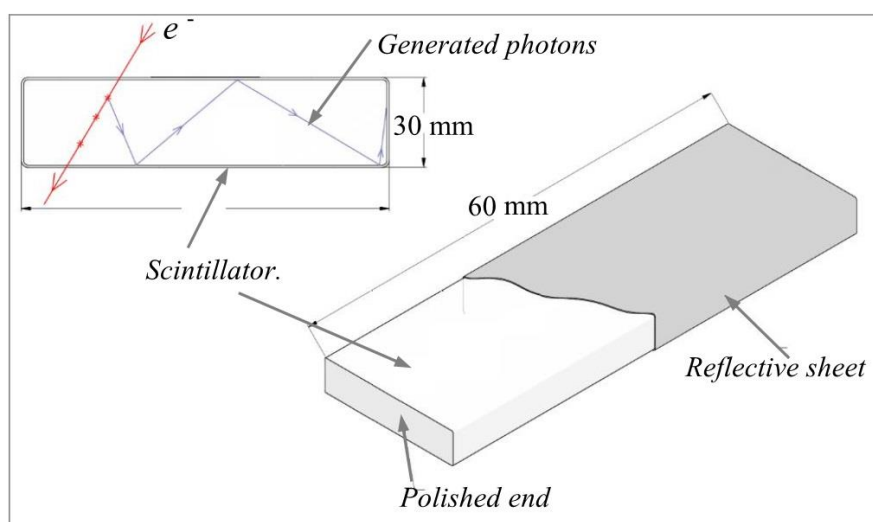


Fig. 3: A schematic representation showing scintillator flash of light production when penetrated with energetic particles. Scintillator has been wrapped with a reflective sheet for improving light collection.

Frontend electronics:

For the detection system frontend electronics, a special custom designed printed circuit board (PCB) had been developed at Stefan Meyer Institute (SMI), Vienna/Austria (H. Schneider, SMI), see figure. 4. The PCB

had built-in step-up power supply with an accurate bias voltage controller. While the PCB circuit board needs around 12 volt to operate, the built-in step-up power supply is there to provide SiPMs photosensors with the necessary operating bias voltage (~ 70 V). PCB design incorporates maximum current control to protect SiPMs if it was inadvertently forward biased. The bias voltage was connected to the SiPMs cathode via a bias-decoupling network, located near the SiPM. This consists of a series resistor followed by one or more parallel capacitors to the ground. The bias decoupling prevents the drop of bias across the detector due to microcells recharging after the detection of scintillation photons. Due to the high intrinsic gain ($10^5 - 10^6$) provided by typical SiPMs, the current pulses were converted to a measurable voltage through the use of a small load resistor connected to ground. Consequently, the SiPM signals feed through a built in four channels differential amplifier to provide the necessary voltage gain. In addition a leading edge discriminator circuit featuring time over threshold is embedded in the circuit.



Fig. 4: A picture of the prototype detector system PCB circuit board, with built-in bias control, discriminator and signal offset level control. On board SiPMs current monitoring connections is visible.

Laboratory test and results:

In order to test circuit board functionality, a small cubic piece of a plastic scintillator, with a 2.2 cm length and 1.0 cm thickness was optically coupled on one side to 3×3 mm² MPPCs (S10931-100P) from Hamamatsu Photonics, Japan. The combination had been covered with a Teflon tab and then with a black tab for light protection. After it has been attached to the PCB board, the covered scintillator has been irradiated with energetic beta-particles from Strontium-90 (Sr^{90}). Sr^{90} is a radioactive isotope of strontium, with a half-life of 28.8 years undergoing β^- decay into yttrium-90 (Y^{90}), with a decay energy of 0.544 MeV. Y^{90} decays subsequently to stable Zirconium-90 (Zr^{90}) with decay energy of 2.294 MeV see figure. 5. (Modern lab manual).

Emitted beta-particles penetrating the scintillator interact with its medium and producing light which is guided by total reflection on the internal surfaces of the scintillator to its ends, where one MPPC photosensor are waiting for. On the board each photosensor input connection had been checked out one by one, where each signal output line had been connected to a fast oscilloscope from LeCroy (WavePro 735Zi 40 Gs/s), see figure. 6.

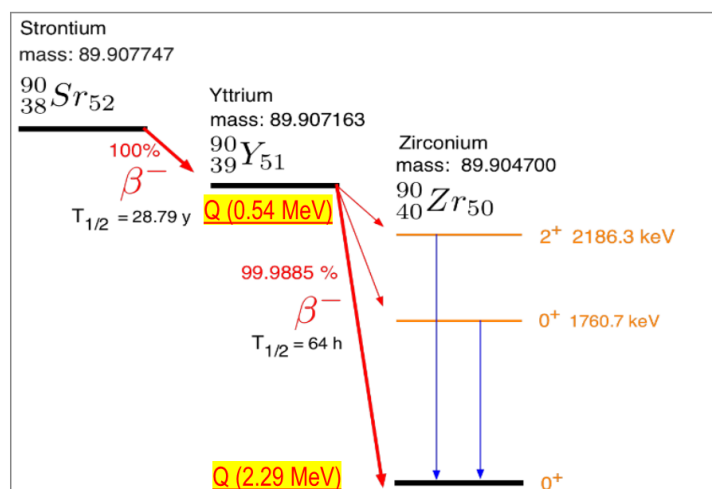


Fig. 5: Sr^{90} energy decay scheme diagram.

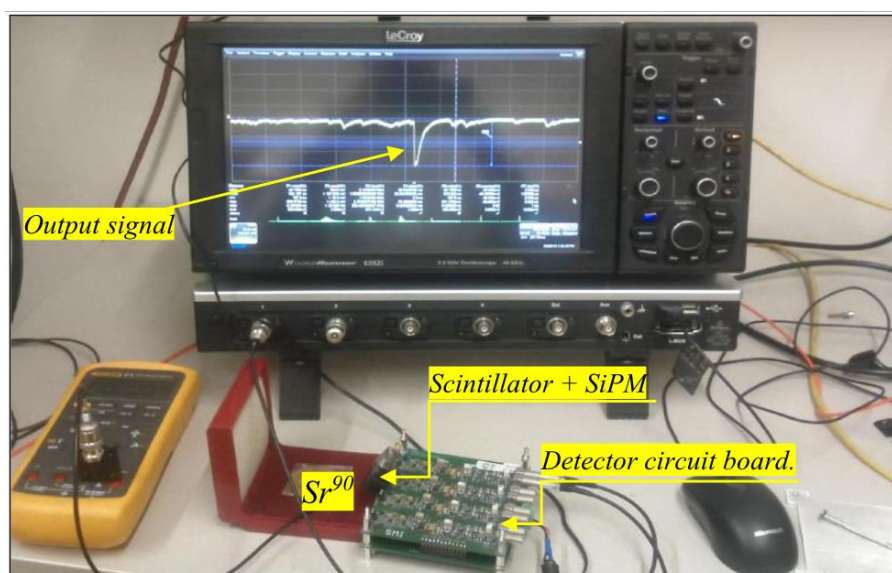


Fig. 6: A picture of the prototype circuit board test setup. A small cubic piece of a plastic scintillator with attached MPPC had been covered with a black tab. Each signal output line had been monitored using a fast oscilloscope from LeCroy.

Prototype detector system is composed mainly of two aluminum holder for supporting the scintillator and housing SiPMs while being attached to it (Figure. 7). The photons produced by a particle traversing the scintillator are supposed to be totally reflected on the internal surfaces of the scintillator and to be guided to its ends (see Figure. 3). For enhancing the specular reflector, the scintillator with a volume of $60 \times 30 \times 5 \text{ mm}^3$, had been wrapped with an aluminum foil. At the scintillation ends, photons readout are performed by means of two tiles of SiPMs (each tiles comprising 2 identical SiPMs with $3 \times 3 \text{ mm}^2$ active area). SiPMs are optically coupled to scintillator using a transparent silicone (General Electric RTV615) for improving light collections. Teflon tape was used to cover small gaps in the reflector.

For photosensor selection, we have used the Multi-Pixel Photon Counters (MPPCs) series (S10931-100P) from Hamamatsu (Hamamatsu Photonics, Japan). These particular SiPMs are sensitive in the blue light range ($\sim 400 \text{ nm}$) which matches well with the light emitted by many scintillators. The device consists of 900 Avalanche Photo Diodes (APDs) of $100 \times 100 \mu\text{m}^2$ with a total fill factor of about 78.5%.

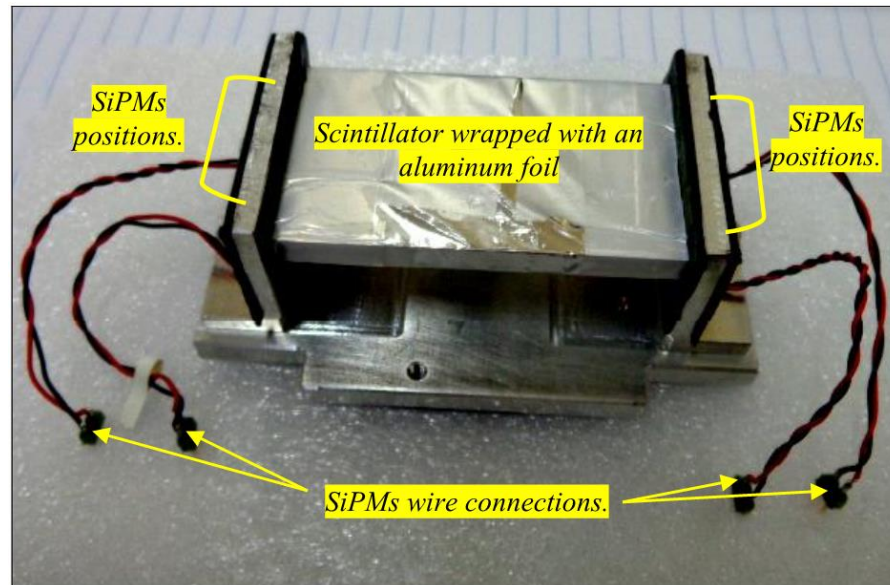


Fig. 7: Photograph of the detection system prototype, where an aluminum holder had been designed to support the scintillator and housings SiPMs.

After the assembling between the scintillator /SiPMs (Figure. 7) and the PCB board, the completed prototype detector system (Figure. 8), has been irradiated with Beta-particles using the Sr^{90} radioactive isotope. The signal output from each MPPC is split into two lines. One is connected to QDC for charge measurements. The other line is fed into the oscilloscope. Figure. 9 illustrates an oscilloscope screen shot showing the detector four channels output pulses which represents the response of prototype detector to the penetrating radiations.



Fig. 8: Photograph of the prototype detector system assembly, where an aluminum holder for supporting the scintillator while being attached to SiPMs. SiPMs on-board wire connections are visible.

QDC signals were recorded by a personal computer via Wiener CAMAC-CC32 PCI bus interface and stored for offline analysis. Figure. 10 shows charge distribution spectrum representing the detector response to the interactions of the different beta particle energies form Sr^{90} radioisotope. Each peak corresponds to pulses with different number of photoelectrons.

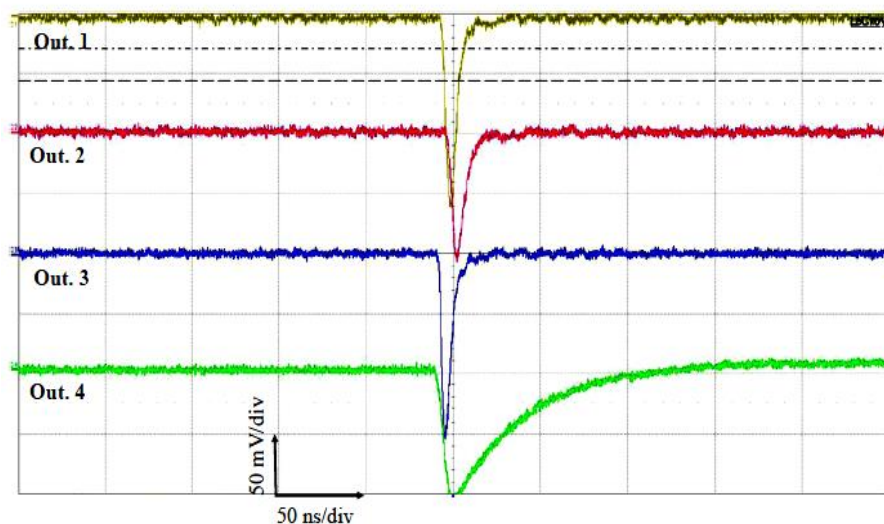


Fig. 9: An oscilloscope screen shot showing the prototype detector signal output pulses as response Beta-particles irradiation.

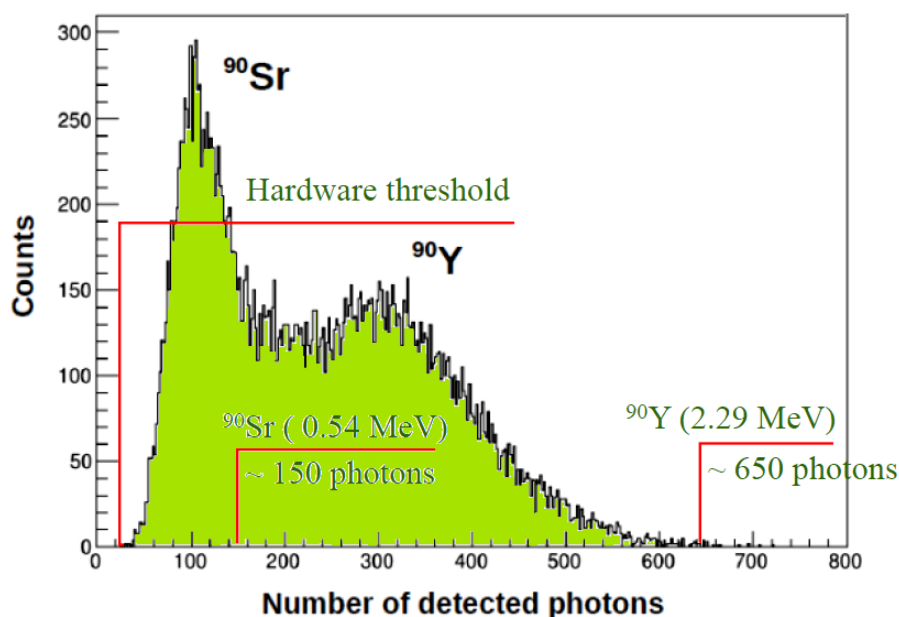


Fig. 10: Charge distribution spectrum measured with the prototype detector system as response to the interaction of beta-particles with the detector scintillator. Each peak corresponds to pulses with different numbers of photoelectrons.

Discussion and Conclusions:

Development and a prototype of a compact radiation detection system has been successfully built and tested in the lab using beta-particles from Sr^{90} radioactive isotope. Results revealed that our detection system prototype has succeeded to monitor beta particles with good efficiency exploiting that both charge and time information obtained. We think there is a room for improving our detector system module especially in the electronic side part.

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