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Performance evaluation of SiPM's for low threshold gamma detection

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In the context of the on-line monitoring of short and medium term for radioactive waste repository, a new system has been planned. Such system makes use a new kind of detector, named Silicon Photomultiplier, coupled to scintillating fibres to be positioned around each waste drum in shape of fine grid. The purpose of this design is evaluate the variations of the radioactivity distribution by counting the gamma radiation.

1. INTRODUCTION

The DMNR project (Detector Mesh for Nuclear Repositories) has started to develop an integrated solution for on-line monitoring of short and medium term radioactive waste, as recommended by the International Atomic Energy Agency (IAEA) [1]. The aim is to guarantee a high level of safety of the waste storage, by detecting possible leaks of radioactive material in a short time, thus reducing the risks of contamination for the operators and for the environment. A distributed mesh of low-cost detectors provides a real time 3-dimensional map of the radioactivity produced by a waste repository. When a leak occurs in a drum, it is recognized because of the increase of the local activity, so that robots or operators could be driven in case for a high accuracy inspection around the drums [2] (Figure 1).

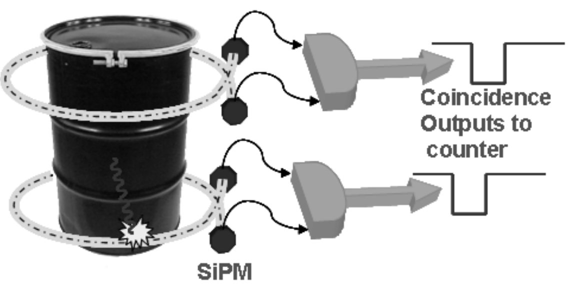

Figure 1. Grid of fibres around the drum.

2. THE EXPERIMENTAL APPARATUS

Each detector consists of a scintillating optical fibre, 1-2 m long. The fibre is a plastic one made of a scintillating core of polystyrene and a PMMA cladding, manufactured by Saint-Gobain Crystals. It has a 1 mm diameter with a 30μm thick cladding and an attenuation length λ of 3.3 m. Its minimum trapping efficiency for isotropic light emission is 3.4% at each fibre end, as can be easily calculated starting from the refraction index values $n_1 = 1.60$ (core) and $n_2 = 1.49$ (cladding) [3] [4] [5]. The decay time of the scintillation light, $\tau \sim 3$ ns, allows to measure activities of the order of MHz (the expected count rate is in the range $10^3 – 10^5$ /fibre/s). The scintillation spectrum lies in the green region with a maximum around 520 nm.

From the point of view of radiation hardness, even though it is low for this kind of fibres, as the overall efficiency is low, the damage will be kept low as well. A reference drum contains 20 liters of waste incorporated in concrete and surrounded by a layer of mortar, with a total activity of ~ 10^{12} gamma/s corresponding to a dose rate of 10 – 100 mGy/h. Under these assumptions we estimated, for a detector placed close to a drum, a life of the order of at least 100 years [6].

The fibres are arranged around each drum in a ring geometry, as in figure 1. Each fibre can intercept radiation coming out of the drum wall, mostly

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gamma rays, so that the energy released inside its active volume is converted into scintillation light, that propagates to both ends of the fibre itself. The light yield of these fibres is of the order of 8000 photons/MeV. Taking into account the average energy released in a fibre (about 100 KeV), the trapping efficiency and attenuation, the number of photons to be detected can be as low as 2 – 30.

We have decided to use a rugged photodetector to be coupled to each fibre end, with a sensitivity down to the single photon and capable of fast timing, in order to select events in strict coincidence between the two fibre sides (figure 1).

3. THE SiPM PHOTOSENSOR.

As to the photosensor, we choose the newly born SiPM (Silicon PhotoMultiplier), a promising cheap detector that is reliable and easy to handle. The device consist in 2-dimensional array of a Single Photon Avalanche Diode (SPAD) cells. A SPAD is a p-n junction operating slightly above their breakdown voltage, in Geiger avalanche regime (≈ 10% of the breakdown voltage itself). The outputs of all cells are connected together to form one common signal [7]. When a fast light pulse is detected by the SIPM, its output is the sum of the identical pulses produced by each fired pixel. Its sensitivity can be as low as the single photon, but such a lower limit is strongly affected by dark noise. It is also affected by cross-talk, each time a cell is triggered the electrons in the avalanche can themselves reach the neighbouring cells and trigger them.

The cross-talk effect can be put into evidence by plotting the dark noise rate versus the threshold, expressed in number of equivalent pixels (figure 3). One would expect the dark noise dropping when the threshold is set above 1 pixel, since it is unlikely that two uncorrelated pixels fire simultaneously.

3.1 Measurements with SiPM

In this perspective we have tested four SiPM models, produced respectively by Hamamatsu photonics, SensL, FBK–IRST and STMicroelectronics (not yet available on the market) [8] [9]. The overall size of the sensors are 1 x 1 mm^2 and 0.5 x 0.5 mm^2 for the STMicroelectronics device. In order to estimate the dark-count of the devices, we counted the number of noise pulses generated per unit time as a function of the discriminator threshold.

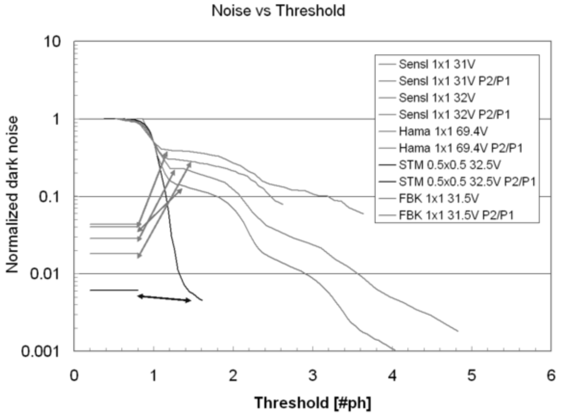

Figure 3. Dark noise as a function of threshold for four different SiPM.

The normalized dark noise for all devices is showed in Figure 3. In the lower left part of same plot is showed the noise level expected in case of no cross-talk in correspondence of the arrow. The plot show that the count rate of the STM device has an effective drop of the curve, while for the other SiPM it still remains high, mainly as a consequence of the cross-talk effect.

3.2 The Amplifier

To characterize the dark-count and the response to light of the SiPM's, given their low gain, we have first used a commercial amplifier manufactured by Ortec, (FTA 810b), with a nominal gain of 200 and 400 MHz bandwidth. According to our intentions to implement in a board the whole front-end electronics featuring bias supply, amplifiers, discriminators and coincidence units, a new amplifier has been developed from our electronic department.

Such amplifier is divided in 5 stages with the following functions: (i) very low noise preamplifier with 18 DB gain preceded by detector impedance adapter; (ii) passive attenuator net (-3 db) with a 2 matched impedance stubs; (iii) amplifier with 25 DB gain followed and preceded by 2 matched impedance stubs; (iv) amplifier with 6 db gain ; (v) impedance adapter and output driver for a 50 ohm coaxial cable.

The device design was performed using mixed techniques MMIC (Monolithic Microwave Integrated Circuits) and BJT(Bipolar junction transistor) in order to achieve a good compromise among gain, bandwidth and power dissipation.

Moreover a CAD/CAE design with signal integrity and matching impedance was focused to match the high frequency and high gain requirements, to prevent oscillations and signal degradation. The PCB was build using Rogers material instead of standard FR4 due to its low loss and stable dielectric constant that permits a predictable impedance. The main characteristic of the amplifier are a 46 DB gain with a bandwidth in the range 1 MHz – 4 GHz. It is an inverting amplifier with a 2.8 DB of noise figure.

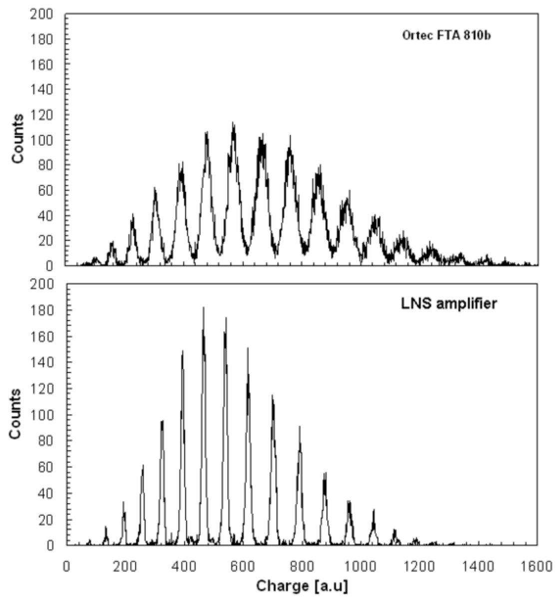

Figure 4. Charge spectrum of a SiPM (10x10 cells, produced by ST Microelectronics) illuminated by means of a pulsed laser, taken using the ORTEC amplifier (a) and the new one developed at INFN-LNS (b). The 3-sigma peak resolving power is respectively ≈ 20 and ≈ 115 [10].

4. THE PROTOTYPE

We have arranged our first prototype using three fibres arranged in a ring geometry around a drum made from an empty 35-liters plastic bottle. Every fiber was coupled with two SiPM (1mm x 1 mm by SensL) one at each end operating in coincidence in order to reduce the spurious counts. For every SiPM was set a threshold corresponding to 5 triggered cells. A box containing three different gamma radioactive sources with a total activity of 2.7 MBq, was positioned in two different positions inside the drum while recording the counting rates from the three fibres. The plot in Figure 5 shows the results obtained, where it is evident that the system arranged is quite sensitive to variations of the radioactivity distribution, in our case produced by the displacement of the source.

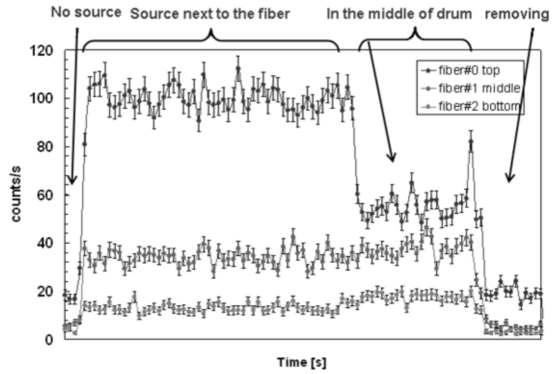

Figure 5. Test results with three fibres around a plastic drum of 35 liters. The counting rate of the three fibres is reported.

5. CONCLUSIONS

The system has demonstrated an efficient real time monitoring of the radioactive distribution around the drum. The prototype allows to record the measured activity thus providing on line access to the counting rates and also the history on each drum and fibres.

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