

On-line remote monitoring of radioactive waste repositories

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Abstract. A low-cost array of modular sensors for online monitoring of radioactive waste was developed at INFN-LNS. We implemented a new kind of gamma counter, based on Silicon PhotoMultipliers and scintillating fibers, that behaves like a cheap scintillating Geiger-Muller counter. It can be placed in shape of a fine grid around each single waste drum in a repository. Front-end electronics and an FPGA-based counting system were developed to handle the field data, also implementing data transmission, a graphical user interface and a data storage system. A test of four sensors in a real radwaste storage site was performed with promising results. Following the tests an agreement was signed between INFN and Sogin for the joint development and installation of a prototype DMNR (Detector Mesh for Nuclear Repository) system inside the Garigliano radwaste repository in Sessa Aurunca (CE, Italy). Such a development is currently under way, with the installation foreseen within 2014.

1. Introduction

Among the many issues associated to the disposal of short and medium term radioactive waste worldwide produced, there is the storage inside suitable sites where a high level of safety must be guaranteed. In order to detect possible leaks of radioactive material and to efficiently reduce the risks of contamination for the operators and for the environment, the IAEA suggests the possible adoption of real time monitoring systems [1].

Detector Mesh for Nuclear Repositories (DMNR) is a project for a prototype demonstrator of the online monitoring of short-medium term radioactive waste, currently under development at INFN-LNS Catania. Such a system is planned to be distributed, fine-grained, robust, reliable, and based on low-cost components, providing a 3-dimensional map of the radioactivity produced by the waste inside the storage area.

This way a possible radioactive leak from a waste drum, could be recognized by means of an increase of the local activity. Therefore we have suggested to adopt a mesh of low cost radiation detectors, namely scintillating fibres, arranged as a grid of sensors around each waste drum (Fig. 1), readout by means of SiPM (Silicon PhotoMultiplier) photosensors capable of detecting the tiny light signals of few photons ([2, 3] and references therein). These allow to record continuously the measured activity, in order to

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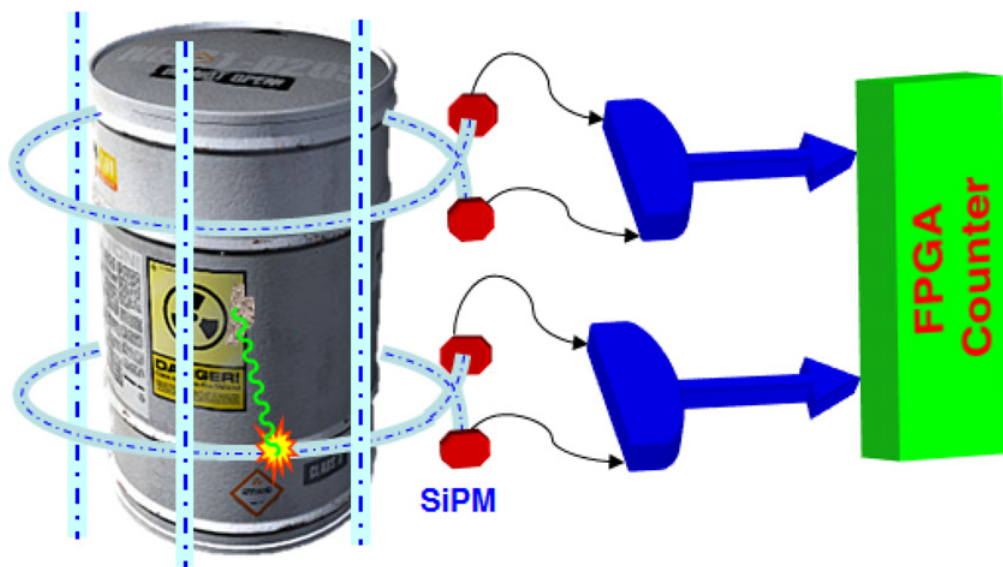


Figure 1. A possible layout of the fibres around the drum.

check the instant rate and also the counting history around each drum. This system could also open new perspectives on the modality of waste packaging and storage [4].

In order to build such a system one needs to perform a characterization of the photosensors to be employed, and this was done for several families of SiPM in terms of gain, photon resolution, overall efficiency, noise, cross-talk. The cross talk evaluation, in particular, is crucial in order to determine the lowest threshold attainable. This is why a simple yet powerful analytical method was developed to measure it [3]. Front-end electronics and an FPGA-based counting system were developed, in order to handle the data flow coming from the field sensors. Such a system also deals with the redundant data transmission toward a console with a graphical user interface and a data storage system. The redundant transmission is to be done simultaneously on differential cables and wireless, using powerful low-cost units. A robotic arm is being developed for remote ad-hoc inspection, both visual and by using high resolution radiation detectors; other operations around the waste drums should also be possible using the same robotic arm.

2. The experimental apparatus

The mesh of detectors has to be properly distributed, fine-grained, robust, reliable, and should be based on low-cost components. In addition, the sensors have to be operated in Geiger mode (on/off), since they are just needed to count the ionizing radiation events.

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.

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 $\sim 10^{12}$ 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 [5].

The fibres are arranged around each drum in longitudinal and/or ring geometry, as in Fig. 1. Both geometries can be adopted, as the most likely leak position has to be determined. Each fibre can intercept

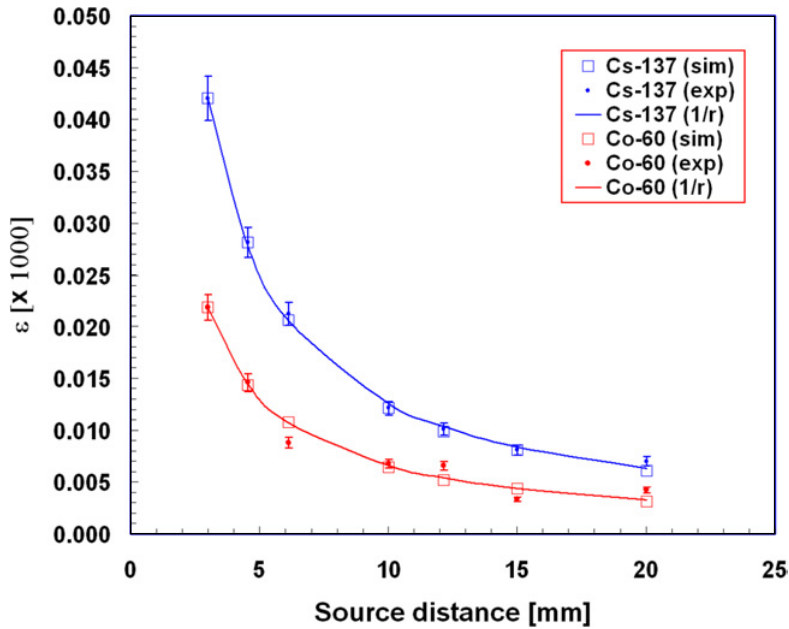


Figure 2. Detection efficiency of the fiber sensor to gamma radiation, as a function of the source distance, for two different sources: ^{60}Co and ^{137}Cs . Open squares: simulation; full circles: measured data; line: calculation assuming a $1/r$ dependence.

radiation coming out of the drum wall, mostly 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 to be detected by the photosensor.

In order to evaluate the scintillating fibre response to the gamma rays, and to choose the most appropriate geometry of the detector mesh and the number of fibres to be placed around each drum as a trade off between the efficiency of the overall system and its cost, we have carried out several simulations based on Geant Monte Carlo code.

The simulations were performed for a plastic scintillating fibre 1.2 m long and 1 mm diameter. The considered sources were a point-like piece of ^{60}Co and ^{137}Cs . So we performed several runs with source-fibre distance variable from 3 mm to 20 mm, considering only those events producing a detectable light signal at both fibre ends in order to evaluate the fibre efficiency. After that, in the same geometrical conditions we had conducted experimental tests to estimate the intrinsic efficiency of the fibers, employing the source of ^{60}Co and ^{137}Cs in order to validate the Geant simulations. The evaluated and measure fiber efficiency is reported in Fig. 2.

Moreover, by assuming a point-like source and an infinite fiber length, one can easily calculate the fiber solid angle as seen from the source. The geometrical efficiency thus resulting, i.e. the ratio between the fiber solid angle and the 4π total solid angle, is $d/2\pi r$ where d is the fiber diameter and r is the distance from the source. Two curves proportional to $1/r$ were reported on the same plot (Fig. 3) after normalization to the first data point of each series. The conclusion, as can be easily verified on the plot, is that both the simulation and the $1/r$ behavior reproduce pretty well the measured data.

The output signal of a SiPM is generally small and needs further amplification. To characterize the SiPM sensors, given their low gain, we have used an innovative amplifier developed from our electronic department featuring a linear gain around 200 and a bandwidth of 4 GHz.

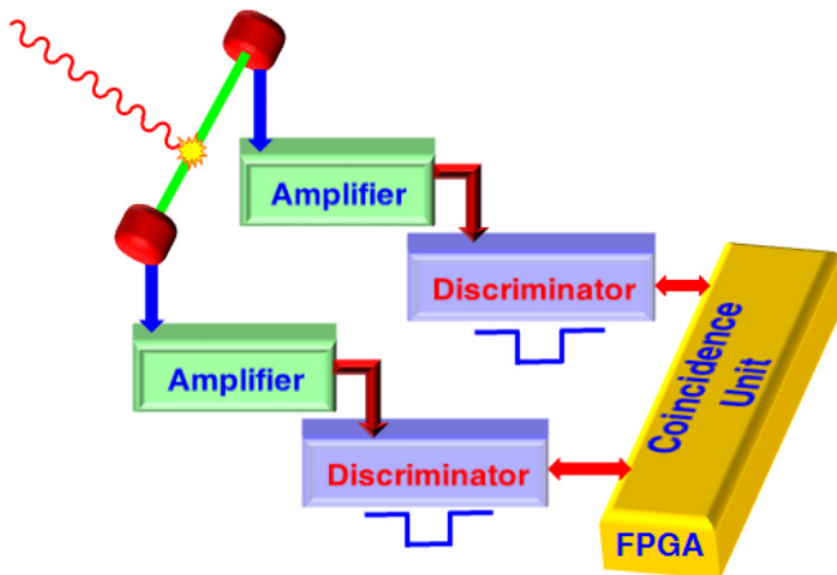


Figure 3. Scheme of the front-end electronics for one fiber. The output signal shape and type are represented near each component. It is worth to remark that a single FPGA can handle many fibers at once.

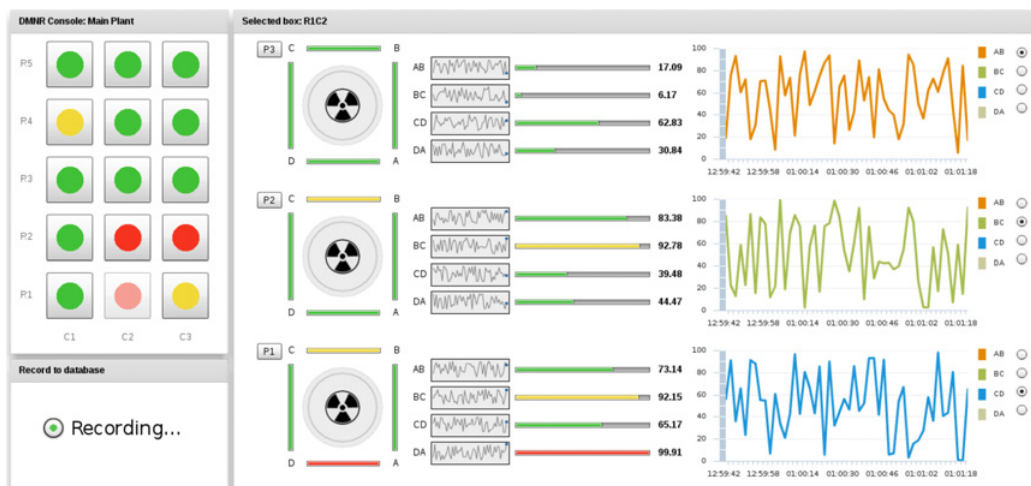


Figure 4. Graphical user interface.

In particular a discrimination circuit was developed, in order to generate a digital output pulse whenever an input pulse overcomes a predefined threshold value, along with a fast digital coincidence circuit that only generates a digital output pulse when its two digital inputs are true. Each of the two SiPM outputs from a fiber is fed to an amplifier, whose output goes into a discriminator. The outputs of the two discriminators are combined by the coincidence unit, that will thus produce an output pulse only when a predefined amount of light is detected at both fiber ends. Figure 4 shows a sketch of the front-end electronics architecture for one fiber. The output signal shape and type (analog or digital and

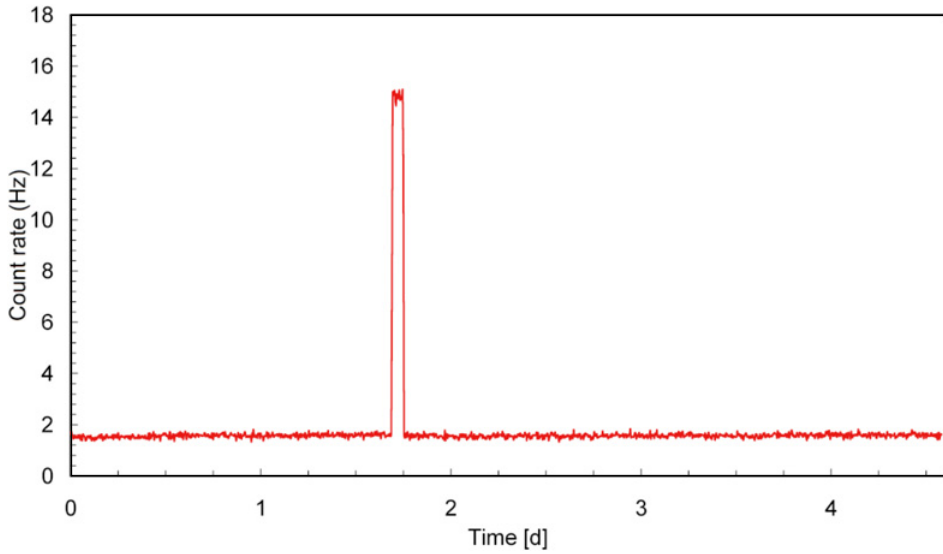


Figure 5. Bench test of the fiber sensor L30-2 over four and a half days. Three radioactive sources (^{60}Co , ^{137}Cs , ^{152}Eu) with a total activity of 2.7 MBq were placed at ≈ 8 cm from the fiber during two hours.

polarity) are represented near each component. It is worth to remark that a single FPGA can handle many fibers at once.

The FPGA implements a set of digital counters, along with a clock and the USB interface towards a computer where the graphical user interface allows the online control and the log data storage [Fig. 4].

3. The test

Several tests were performed with the fiber sensors on the bench with and without laboratory sources, in order to verify the capability of gamma detection, the sensitivity, the stability, to measure the noise level and the ambient radiation count rate. As an example we show in Fig. 5 the result of a 4-day data acquisition with the L30-2 sensor. The counting rate is rather stable with respect to night-day temperature fluctuations of a few degrees. After about 40 hours we placed a small box containing three radioactive sources (^{60}Co , ^{137}Cs , ^{152}Eu , total activity 2.7 MBq) at about 8 cm from the fiber, leaving it there for two hours and then removing it again.

A step further with realistic bench-tests was the construction of a prototype, shown on the Fig. 6. The phantom drum was made from an empty plastic bottle 40 cm high placed at the center of an array of five fibers.

The fibers with their sensors were arranged three vertical and two horizontal. In the middle of Fig. 6 a simple 3D image is shown, roughly representing activity levels around the drum, obtained by combining the horizontal and vertical information from the log data shown in the plot in the Fig. 6 right. The counting rate versus time is reported for a short test where the same multi-source mentioned above was placed at the position marked with a “X” on a phantom drum. This attests that a geometry with crossed fibers can actually provide position information.

The most important test, however, was to be performed in a real environment of radwaste. This is why we decided to perform a measurement inside a temporary storage site at a Sogin installation in Sessa Aurunca (CE) Italy (Fig. 7).

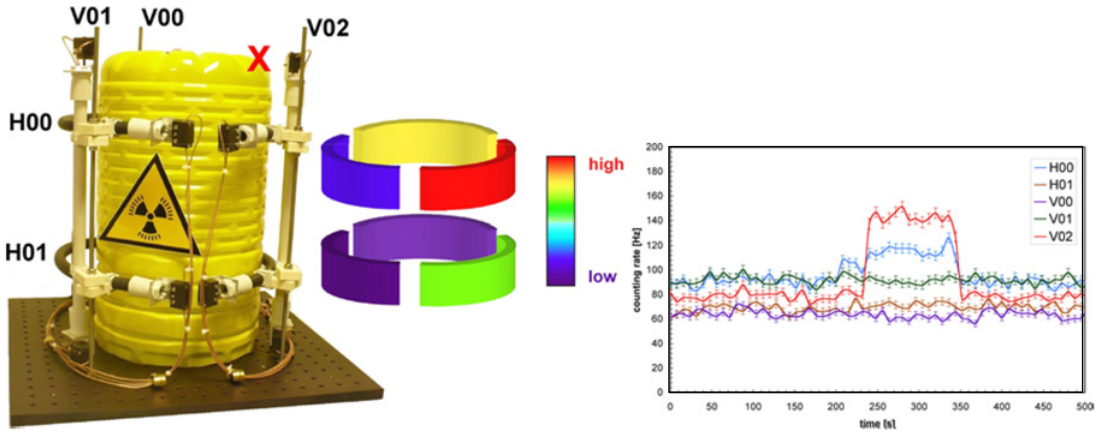


Figure 6. The prototype mini-drum with two horizontal and three vertical fibers. The “X” indicates the position where the gamma source was placed. The graph in the middle represents the 3D rough activity levels obtained by combining the horizontal and vertical information from the log data shown on the right.

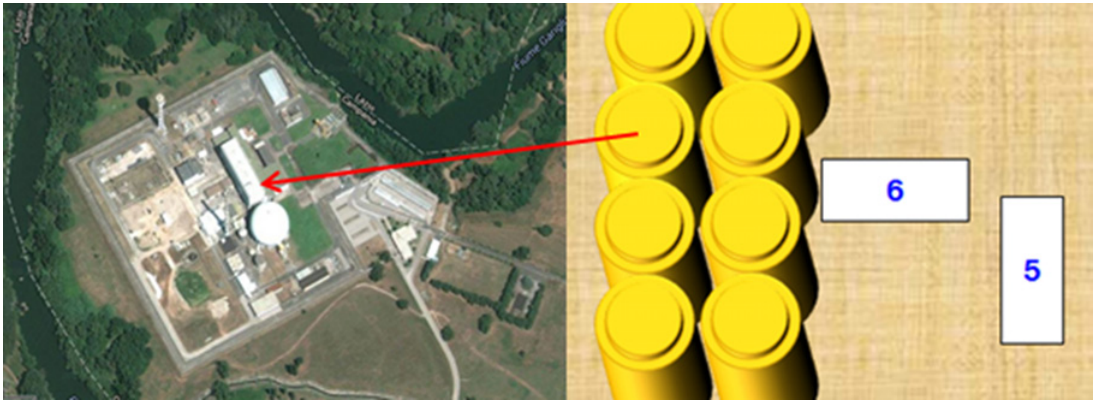


Figure 7. Google map view of Garigliano Nuclear plant (Sogin S.p.A) and a sketch of the trolley positions inside the storage.

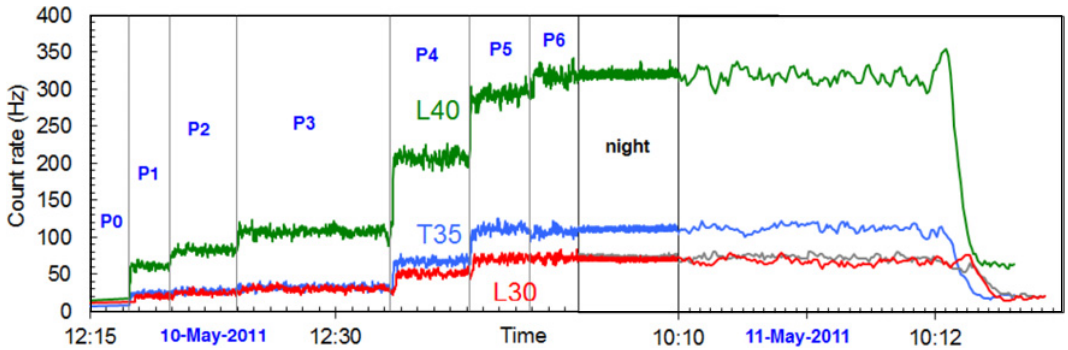


Figure 8. Counting rates as a function of time. First phase when the operator move the trolley along the seven positions, second phase the trolley is left in P6 position and at the and the quickly removal of the trolley.

For this purpose we installed four of our fiber sensors onto a trolley. The same trolley also hosted the front-end electronics, whereas the output digital pulses travelled on long cables towards the FPGA data acquisition system, placed outside, in order to be counted and recorded. The measurements were done in seven positions from the P0 position, outside the storage site, to the P6 positions inside the storage close to a rows of drums (Fig. 7). On the left of the plot is shown how the counting rates change while the operator move the trolley inside the storage. After that the trolley is left in P6 position for all night. On the right of the same plot is shown the quick removal of the trolley from the storage.

4. Conclusions

Subsequent a phase of study, simulation, prototyping and characterization of these new fiber sensors, we performed a protracted series of laboratory tests using radioactive sources. After that was possible to perform a more realistic test with real waste drums in a real storage. The test result shows quite clearly that the fiber sensor can play the promised role in the monitoring process.

The DMNR project has shown that a real time online monitoring system for radioactive waste is feasible. The test performed inside a storage site has shown performance beyond the expectation.

After the agreement between INFN and Sogin S.p.A signed on November 2012, next year will be installed a pilot demonstrator system inside a Radwaste storage site (Garigliano Nuclear plant, Sessa Aurunca (CE)) for an extended period of time.

References

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