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LIST OF ACRONYMS AND ABBREVIATIONS

CsI(Tl)	Scintillator crystal material, Tl doped: CsI(Tl)
FEBEX3B	Digitizer board developed at GSI
LaBr	Scintillator crystal material, Ce doped: $LaBr_3$(Ce)
Phoswich	Sandwich of two scintillator crystals with single readout
FPGA	Field-Programmable Gate Array
SiPM	Silicon Photo Multiplier
Raspberry Pi-3	Micro-computer, 5x3x2 cm3, developed by the Raspberry Pi foundation
S13361-3050AS-08/NG	Hamamatsu SiPM array

Executive Summary

The European Internal Security Strategy emphasizes the need to enhance measures against CBRNE (chemical, biological, radiological, nuclear, explosives) threats, including the development of minimum detection and sampling standards. Novel detection technologies can impact nuclear security in many ways: new technologies can directly replace existing detection systems, providing gradual improvements to the detection capability. The nuclear security detection architecture as a whole needs re-assessing. E.g. detectors with automated source localization capability can be installed that are more flexible and with greater automation and fewer human resources are required in the field. Combined with reliable data transfer, the final data analysis can be performed in a centralized expert support centre by optimally utilizing data from multiple sensors.

In this report we present a more detailed the discussion on the R&D towards societal applications that are performed within the PASPAG project. Especially we evaluate the characteristics of detection systems for homeland security as defined by the Thematic group for Radiological and Nuclear threats within the European Reference Network for Critical Infrastructure Protection (ERNCIP) [1] .

Introduction

The PASPAG collaboration exploits novel scintillator materials and explores new techniques and concepts such as phoswich detectors and segmented or hybrid scintillators in order to simultaneously detect high-energy gamma rays, neutrons and charged particles. The emphasis is on a modular approach both in the scintillator crystals and photosensors as well as in the electronics with improved throughput and effective data processing, which will allow for compact scalable devices.

Technology out of basic science will be exploited for societal applications within, for example, in the areas of nuclear medicine and homeland security. Depending on the applications, features like energy resolution, position sensitivity, high rate capability, and insensitivity to magnetic fields or radiation hardness are of differing importance. The characterization of new materials is followed by the construction of small-size phoswich prototypes and hybrid detectors, to be used in applications.

A wide range of new scintillators are becoming commercially available, such as CeBr3, CLYC [2], GAGG, GYGAG:Ce, CLLB, CLLC, and also it was recently discovered that co-doping inorganic scintillators might increase the crystal proportionality and significantly improve the energy resolution [3]. It is not clear, however, how these developments in scintillator performance might translate into practical applications for nuclear physics and the new materials need to be characterized in this regard.

For the application in homeland security, features like energy resolution, position sensitivity, high rate capability, and insensitivity to magnetic fields are of importance. Further, for autonomous use, low power- consumption, low weight and compact size are important features.

SECTION 1 HYBRID ARRAYS AND SCINTILLATOR CHARACTERIZATION

Hybrid arrays are highly segmented assemblies of different scintillator materials in combination with photosensors on the same detector package. For example, position sensitivity is achieved with SiPMs on one side and on the other a PMT to obtain the best energy or timing resolution. One kind of hybrid detector is the phoswich-detector for which two different scintillators are optically coupled. Typically, the scintillators are chosen so that the light output of the two materials has very different timing properties. This allows that the energy deposited in the two parts of the phoswich can be extracted. Phoswich solutions are attractive for discriminating high-energy charged particles and gamma rays. Here we also address societal applications outside fundamental research. Such applications span a broad range from medical imaging to homeland security.

The ideal scintillator should provide not only a high light yield but also a high effective atomic number for good stopping power, a short decay time constant for fast response, and a good level of linear response for good energy resolution. In addition, chemical and mechanical robustness are needed to allow the scintillator detector to be used in many different applications and environments. The Figure displays a schematic ordering of the existing materials as function of the expected energy resolution that can be obtained with each of them. A strand of this project investigates hybrid detector arrays, where we combine different scintillator materials and readout sensors.

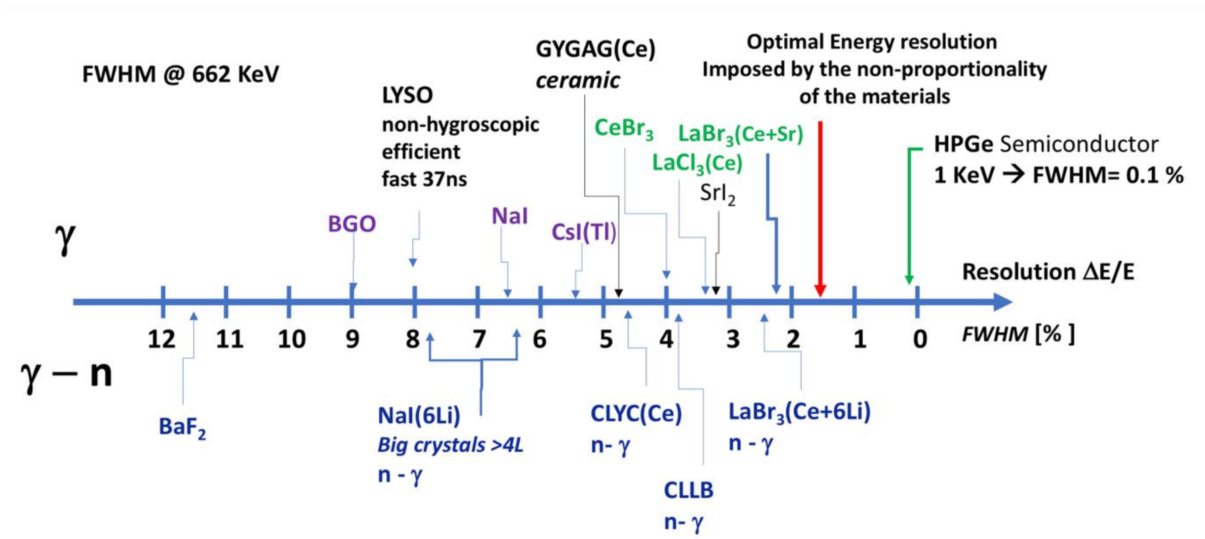

Figure 1: Existing high-resolution scintillator materials ordered according to the energy resolution obtained: FWHM as DE/E in % at 662 keV.

For the characterization of the scintillators and sensors, a collimated beam scanning system has been commissioned at the University of York, (see figure 2). The system was designed in-house in the mechanical and electronics workshops. The system comprises a strong, highly-collimated Cs-137 source mounted at the top. The beam illuminates' detectors mounted on a motorised x-y table positioned on a sliding table which is also motorised in the z direction. In principle, the system is spacious enough to study large detectors such as high-purity germanium detectors. Digital data acquisition systems are used in conjunction with the scanning system. There are two available – one based on commercial CAEN digital system and a second using FEBEX3B read-out boards developed at GSI. In total, over 400 channels can be read-out. The system was fully commissioned and working and will be available on request to members of the PASPAG consortium for their detector development work.

Figure 2: Photo of the scanning system at Univ. York

Initial work with the scanning system involves characterising the gamma ray emission cone and the quality of the collimation obtained. This indicates the presence of a scattered beam halo, however, this can be removed by energy-gating. First experiments were carried out with a cuboid crystal (2” X 2” X 0.5”) of CsI(Tl) (see Figure 3). The crystal is coupled to an 8 x 8 array of SensL J-series silicon photomultipliers (SiPMs) each with an area of 6 X 6 mm. This ensures essentially full coverage of the back face of the crystal. The remaining faces of the crystal are wrapped with reflective material.

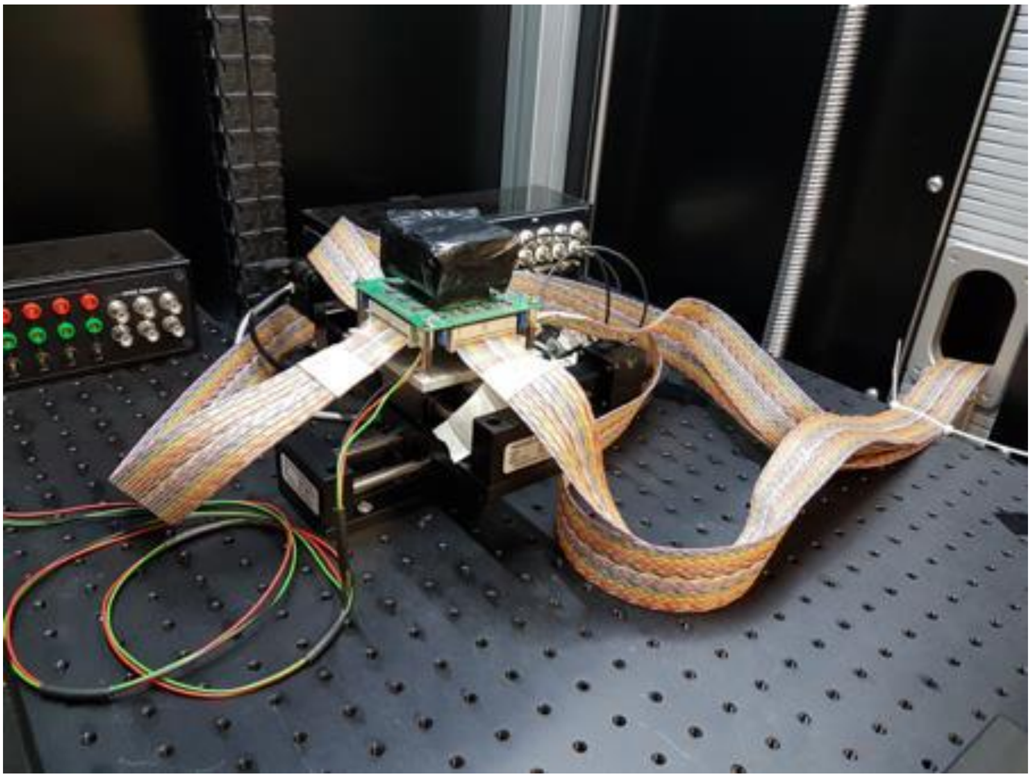

Figure 3: CsI(Tl) scintillator mounted on 8X8 SiPM array inside the scanning table system

The initial data has been taken using the CAEN digital data acquisition system, illuminating the centre and corners of the crystal with the collimated Cs-137 gamma-ray beam. Figure 4. Shows some data taken where the the crystal is illuminated at different positions. Some of the recorded events show good correspondence to full energy deposition (photoelectric absorption) while more complicated light distributions are observed in other events likely representing Compton scattering. GEANT4 simulations are in progress to understand whether the distribution of events observed correspond well with simulation. We are implementing a coincident detector to separate the two classes of events but don’t have those results as now. In the next phase, more detailed position-by-position scanning will be implemented to build up a large database of events. We will be investigating available machine learning tools to allow us to characterise and identify different interaction geometries.

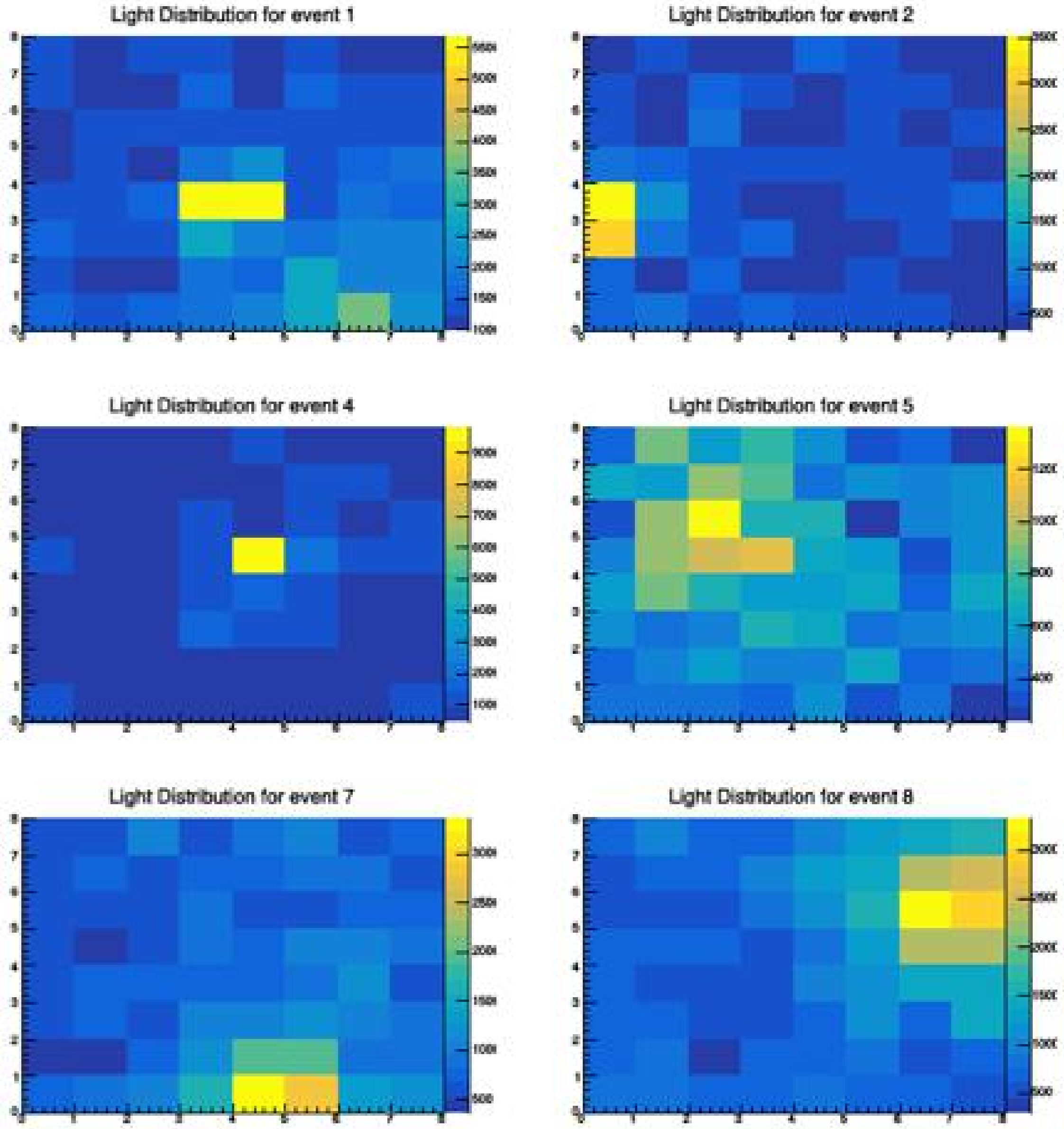

Figure 4: Light distribution as detected by the 8x8 pixel SiPM, for individual events where the crystal has been illuminated with a collimated Cs-137 gamma-ray beam at different positions of the crystal, some events are well localised - these are presumably photo peak events while the more complicated (5 & 8) are Compton scattered events. A coincident detector is being implemented to separate the two classes of events.

This work indicates that there is a correlation between gamma-ray interaction and the light distribution detected by the segmented SiPM. Earlier work show that this result can be achieved by the use of segmented photomultiplier tubes. However, the SiPM array is a more attractive device for light collection as individual SiPMs are very self-similar in response while different elements of a segmented PMT will need significant correction factors to be applied.

In the next phase, we continue these investigations towards a phoswich detector for homeland security purposes. By having multiple layers of crystal and SiPM arrays (i.e. effectively phoswich detectors), we can develop a Compton camera which would provide directional information on the location of gamma ray sources in the field. This will need to involve further investigations of the effects of varying the depth of the crystal used. We will also explore the performance of $LaBr_3$(Ce) crystals since here the light output is higher and this will mitigate the statistical effects of the light being spread over multiple pixels. A suitable crystal exists within the collaboration at Krakow.

SECTION 2 HOMELAND SECURITY & IMPROVED RADIATION DETECTION SYSTEMS FOR NUCLEAR SECURITY

As previously mentioned for societal applications, features like energy resolution, position sensitivity, high rate capability, and insensitivity to magnetic fields are important. Further, in the case of applications within homeland security of highest importance is the autonomous use and very often detectors are carried by drones and thus the detectors have to have low power- consumption, low weight and very compact size. There is a need for detectors with directional detection-ability and with simultaneous gamma ray and particle identification. Emphasis should be on a modular approach both in the scintillator crystals and photo sensors as well as in the electronics with improved throughput and effective data processing that can allow for compact scalable devices.

There are several measurement and sampling scenarios that are too risky for humans to carry out. It is especially identified the need for remote-controlled radiation measurements and sampling using unmanned vehicles (robots or drones). Such devices need to incorporate Time- & Geo- stamping. Applications envisaged are:

- Accidents: reactor and other accidents,
- Dirty bombs before and after explosion,
- Search of sources out of regulatory control etc.

Time and Geo-stamped continuous data-streaming (listmode) make directional location of sources possible which is of highest importance for scanning big areas e.g. after radioactive fallout or container storage in harbours. Also, it enables correlation of and movement of sources over long distances.

Short timescale:

- Coincidences between different types of detectors; γ-n, or n-particle etc.
- A radioactive source can be found by an airplane or car passing scanning big areas.

Long timescale:

- Transport of illicit material can be tracked within a town or even within a building.
- Transport of radioactive material can be followed passing different border points.

Drones can also be used in forensic investigations after a malicious incident for gathering proofs on a radiological-dirty crime scene.

The PASPAG collaboration has thus adopted the aforementioned features and is aiming for a lightweight compact detector device that can be carried by an unmanned remote-controlled vehicle for measurements in areas of high radiation. It should be equipped with an accurate small sized computer and wireless communication to a base station.

Novel scintillator materials with γ-n capability that are insensitive to humidity and magnetic field are emerging. Coupled with light-weight low-powered sensors like SiPM, they are ideal to be used in Nuclear Security. We have tested different systems to analyse the signals produced in the scintillator when exposed to gamma radiation and tested different types of photo- sensors in order to optimize and reduce the weight of the detector. We have obtained good performance with the SiPM, which is similar to that of a standard photo-tube that we use as reference.

At the end the system should be equipped with a computer of small size with built-in GEO and TIME- stamping including wireless communication to a base station. The computer chosen for this purpose is the Raspberry Pi-3 [4]. It is a programmable device, with Linux as the default operating system. It can be equipped with peripherals such as a camera, GPS and incorporates wireless LAN and Bluetooth; it is small 8x6x2 cm, has a low power consumption (5V) and low weight. The GPIO (general purpose input output) connects the Pi-3 to physical extensions as ADCs (Analog to Digital Converter). The Raspberry Pi comes with preinstalled libraries to access the IO using Python, C or C ++. The detected signals are digitized by the ADC and transmitted over a wireless LAN to the base station (Fig. 5). This work was presented to the EMIS2018 conference https://indico.cern.ch/event/616127/ at CERN, and is being published in the proceedings of the conference in Nuclear Instruments and Methods.

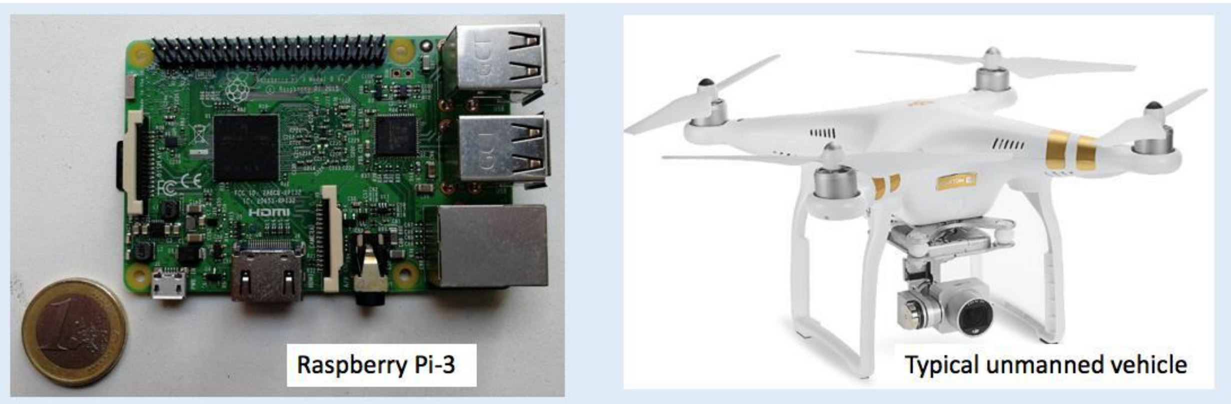

Fig 5. To the left is shown the Raspberry Pi-3; compact, light-weight and low energy micro-computer, excellent example to be carried as shown to the right.

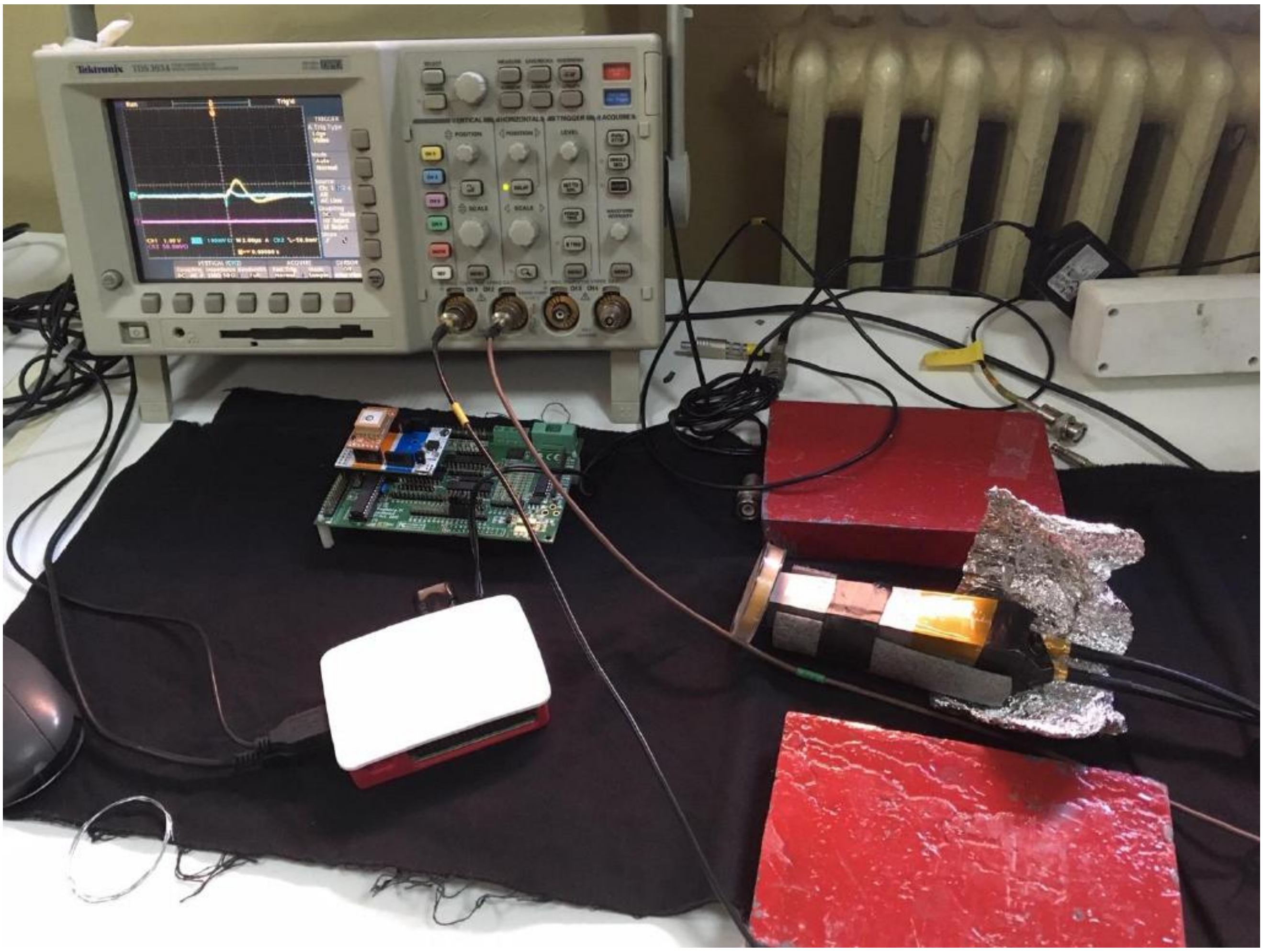

Fig 6. The test set-up: Phoswich LaBr/LaCl in the form of truncated pyramid mounted with a Hamamatsu S13361-3050AS-08/NG SiPM array, the Raspberry Pi-3 with associated electronic-board with WiFi and GPS.

A potential set-up with all necessary elements is shown in Fig. 6. The system has been assembled and taken into operation. It is still necessary to improve the wireless communication with the base station and the conversion of signals from the detector to spectra for its final analysis.

Outreach

The development of the scanning system is also proving of high value to final-year undergraduate student projects. In addition, six South African students from University of the Western Cape and University of Zululand have visited York under a GCRF (Global Challenges Research Fund) project. They have received training on scintillators and SiPMs and had access to the scanning system and digital data acquisition system thereby benefitting from the PASPAG program.

Figure 7: South African students taking part in the testing of the scanning system during a visit to the laboratory at the University of York

Summary

The development towards societal applications of novel scintillators and readout technology is ongoing. The features of scintillators and sensors together with different digitizer options are being characterized especially for the possibility to disentangle the imaging possibilities using segmented sensors. There is still R&D work and comparisons of the different methods to be done before an actual performing detection system can be obtained. Especially the wireless communication together with time and GEO stamping is presently being studied in more detail, here an initiative for a collaboration with JRC-Geel and to participate in their tests Robots has been taken. The work is ongoing; we are on the point where we believe a real system is achievable within the timeframe of the PASPAG project.