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LIST OF ACRONYMS AND ABBREVIATIONS

DSSSD	*Double-Sided Silicon Strip Detectors*
HPGe	High-Purity Germanium Detectors

Executive Summary

The PSeGe JRA has organized two workshops to date in Paris in October 2016 and Milan in September 2017. The workshops have featured contributions from world leading scientists working on applications of germanium semiconductor based imaging detector technology. The events have provided the opportunity for members of the network and invited colleagues from the academic community and industry to interact and share best practice in R&D on detector technology, signal processing and image reconstruction

Introduction

The PSeGe JRA within ENSAR2 contributes to the R&D of detector technology for position-sensitive HPGe detector arrays. Key areas are detector production technology, the basic characteristics of the novel detectors, electronic instrumentation and software developments. In particular the tasks aim to the following goals.

Task 1: to investigate new technologies on passivation and segmentation,

Task 2: to perform R&D on novel Ge-detector geometries for ultimate position resolution and efficiency,

Task 3:to perform R&D on segmented p-type coaxial detectors.

Task 4: networking efforts on Demonstration of imaging applications and associated detector technologies. Several European institutions contribute with their specific expertise through workshops and personnel training visits.

The present Advancement Report will inform about the work performed in the first 30 months of the ENSAR2 PSeGe JRA on the Tasks 4.

Section 1: Advancement Report on the Network activity on Demonstration of Imaging Applications

The detection of gamma radiation is at the heart of nuclear structure physics experiments and of many industrial and medical applications involving gamma-ray imaging. Gamma-ray photons, the most penetrating of the electromagnetic radiations, interact with matter through three main mechanism (1) Photoelectric Absorption (2) Compton Scattering and (3) Pair Production, with the resultant energy deposited inside the target material.

Conventional gamma imaging devices utilise scintillator based detector technology, which offers relatively poor energy resolution. They derive their position resolution from a collimator system, which limits the energy, sensitivity and field of view of the camera. An alternative approach is a Compton camera which instead relies on electronic collimation derived from the kinematics of the gamma-ray interaction with the sensors. This innovation offers a much more compact and less weighty camera head, potentially leading to a lightweight, portable device. The systems offer a large field of view (typically 180°) and full 3D imaging sensitivity. Combined, these advantages offer the ability to image much lower source activities and/or real-time imaging. Crucially for this application, they also offer the ability to image gamma-radiation up to relatively high energy – something impossible with a collimator based system.

The biggest advantage of Compton systems over collimator based solutions is the fact Compton cameras provide a full 3D gamma-ray image. With knowledge of at least two vertex points where the gamma ray has interacted and the total energy of the photon, you can back project a cone in 3D space. The axis of the cone is defined by the position of two vertex points, while the precision in measurement of the energy deposited determines the width of the cone – effectively the angular uncertainty. With overlapping cones projected into 3D space, a 3D location of the source distribution is produced.

The group at the Nuclear Physics Institute, University of Cologne UCO is developing improved and refined methods for gamma-ray imaging with detector configurations, which are based on highly segmented High-Purity Germanium (HPGe) detectors in combination with segmented double-sided silicon strip detectors DSSSDs. The fields of applications are very broad; in astronomy, this allows to distinguish between different sources and to correlate the observed gamma radiation with the residual electromagnetic spectrum of known astronomical objects. In medical applications, the knowledge of the radiation source allows to monitor therapy, with radioactive markers. In nuclear waste management, large areas can be scanned at once and radioactive contamination or activation can be characterized and located at the same time.

The experimental setup of the Compton camera in Cologne is a novel approach to build a Compton telescope based on a large-volume HPGe detector. This kind of detector ensures both excellent energy resolution and high detection efficiency. Combined with a DSSSD and a digital read out the setup can be operated in two modes. In the coincidence mode, the DSSSD and the HPGe are operated in coincidence, yielding a high angular resolution with moderate efficiency. To achieve a higher efficiency, the HPGe is operated in a stand-alone mode with lower angular resolution. Both operation modes are combined simultaneously.

A first Compton camera based on a hexagonal, tapered, 36-fold segmented HPGe detector and a DSSSD was developed, tested, and put into operation at IKP, Cologne; the origin of radiation was determined successfully. The Compton camera was operated in two different modes. Coincidences from Compton-scattered gamma-ray events between DSSSD and HPGe detector allowed for best angular resolution; while the high-efficiency mode took advantage of the position sensitivity of the highly segmented HPGe detector. In this mode, the setup is sensitive to the whole 4π solid angle. The interaction-point positions in the 36-fold segmented large volume HPGe detector were determined by pulse-shape analysis (PSA) of all HPGe-detector signals. Imaging algorithms were developed for each mode and were successfully implemented. The angular resolution sensitively depends on parameters such as geometry, selected segment multiplicity and interaction-point distances. Best results were obtained by taking into account the crosstalk properties, the time alignment of the signals and the distance metric for the PSA for both operation modes. An angular resolution between 13.8◦ and 19.1◦, depending on the minimal interaction-point distance for the high-efficiency mode at an energy of 1275 keV, was achieved. In the coincidence mode, an increased angular resolution below 5.0◦, was obtained for the same energy.

A second detector configuration is based on a closed-ended, coaxial shaped 36-fold segmented HPGe detector that is expected to produce improved position resolution for the interaction points after PSA due to its higher uniformity. Moreover, the cylindrical detector has a larger volume and provides higher *detection efficiency with a measured improvement in efficiency of 41% with respect to the hexagonal tapered detector. The detector was put into operation at IKP-Cologne and the electronic data acquisition was tuned to achieve best energy resolution values for this detector. Here electronic properties like signal rise times and decay times were determined carefully to optimize performance of the digital acquisition system. The energy resolution of all core and segment signals were measured at 60 keV and 1.3 MeV. The measured values (FWHM) were well within the specification of $\Delta E < 1.2$ keV at 60 keV. For the segments the measured average value was $\Delta E = 1.045$ keV and for the core signal $\Delta E = 1.00$ keV. At higher energies of 1.3 MeV, the specification was $\Delta E < 2.1$ keV. The measured average value of the segments was $\Delta E = 2.008$ keV and the core yielded $\Delta E = 2.21$ keV. The crosstalk properties of the detector were measured carefully. Expected crosstalk contributions on the level of 10^{-3} were carefully determined and included into a two dimensional cross talk correction matrix of this detector. The full characterization work of this detector is on going at the moment of writing this report.*

The PSeGe JRA has organized two workshops to date in Paris in October 2016 and Milan in September 2017. The workshops have featured contributions from world leading scientists working on applications of germanium semiconductor based imaging detector technology. The events have provided the opportunity for members of the network and invited colleagues from the academic community and industry to interact and share best practice in technology R&D, signal processing and image reconstruction. Some example highlights include:

- *Applications of Imaging Detectors, Kai Vetter, LBNL (USA): An overview of the application of Compton and Coded aperture semiconductor based imaging systems for environmental imaging applications.*
- *New detector technology at MIRION, Benoît Pirard, MIrion technologies: Update on the latest developments in segmented germanium technology from a commercial perspective.*
- *HPGe detector development for GERDA/LEGEND, Yoann Kermaidi (MPI): Latest developments in point contact germanium detector technology and the associated signal composition necessary for the largescale germanium based neutrinoless double beta decay experiments.*

The focus of these workshops has covered the broad areas of (1) the extraction of position information from large volume semiconductor detectors and (2) The reconstruction of Compton Imaging data and the subsequent multi-modality image fusion of the to rebuild a scene with the optical image and the radiation map. An example of scene data fusion courtesy of the LBNL (USA) group is shown in the figure below. The red arrow indicates the determined source location.

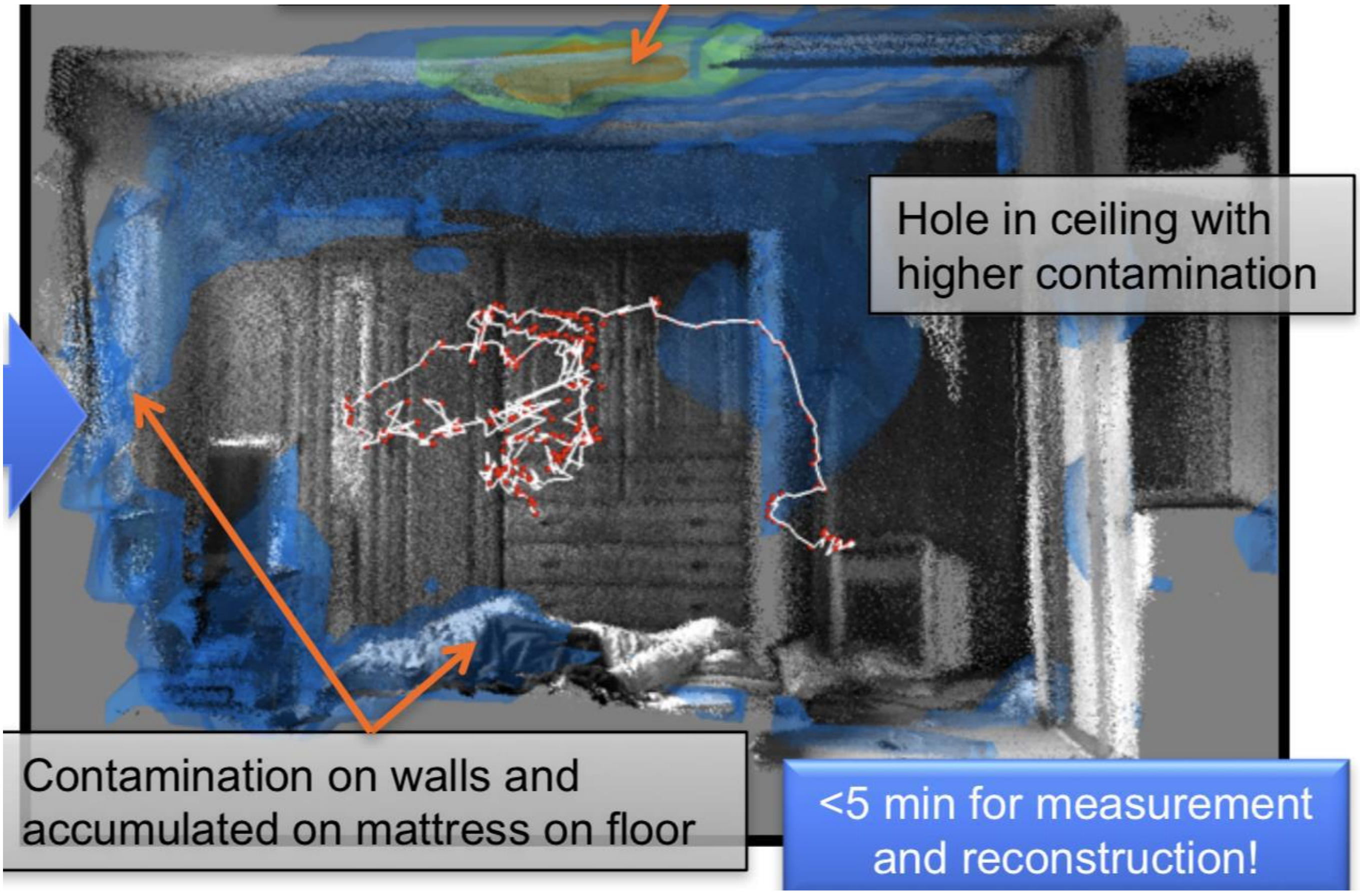

Figure 2: Example of scene data fusion (courtesy LBNL)

Measurement good practice and optimised methodologies which were discussed at the previous workshops have been further developed and will be discussed at the next workshop meeting in September 2018.

CONCLUSION

In this document we report on the advancement of Tasks 4 of the work package 10, the PSeGE JRA, within ENSAR2. Task 4 is a networking activity for Imaging applications of position sensitive Ge Detectors and associated technologies.

As reported in the text, the main goals of the networking activity, i.e. to have periodic meetings of the collaboration with companies as well as other interested actors, has been very successful. The activities will continue in fall 2018 and 2019.