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Disclaimer

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LIST OF ACRONYMS AND ABBREVIATIONS

HPGe	High-Purity Ge Detectors
T10/90	rise-time ratio between the time needed to reach 10% of the amplitude and the 90% of amplitude

Executive Summary

In the framework of the PSeGe JRA task 4 "Network Activity on Demonstration of Imaging Applications and Associated Detector technologies" four workshops, with sizeable participation (40 to 60 participants), have been organised, i.e. in Paris in October 2016 https://indico.in2p3.fr/event/13462/,
Milan in September 2017 https://indico.in2p3.fr/event/14457/,
Strasbourg in September 2018 https://indico.in2p3.fr/event/17160/ and
Padova in September 2019 https://agenda.infn.it/event/19438/.
The workshops have featured contributions from world leading scientists working on detector technologies and applications of imaging detector technology based on germanium semiconductor. The events have provided the opportunity for members of the network and industry to interact and share best practice in technology R+D, signal processing and image reconstruction. The know-how dissemination initiatives have provided hands-on, school and technical training with more than 32 international actions.

Introduction

The European experimental gamma-ray spectroscopy community has a long-standing tradition of coordinated efforts. Since the early nineties, it has been joining forces to build instruments with the highest possible sensitivity, e.g., the escape-suppressed spectrometer EUROBALL (1995-2004), which contributed in a significant way to the impressive progress of nuclear-structure research achieved in the last decades. In recent years, new important technical developments, namely HPGe detector segmentation, pulse-shape analysis and gamma-ray tracking, opened the possibility to obtain unprecedented detection efficiencies and at the same time improved energy resolution. These high performances persist under the extreme experimental conditions expected for the new generation of facilities for intense radioactive-ion beams (FAIR, SPIRAL2 and SPES) and high-intensity stable-ion beams (ECOS facilities), requiring unprecedented levels of sensitivity and count-rate capabilities.

The present project contributes to the R&D of detector technology for position-sensitive HPGe detector arrays, in key areas such as detector production technology, the basic characteristics of the novel detectors, electronic instrumentation and software developments.

Our collaboration is strongly committed to the development of new applications especially in the field of high-resolution gamma-ray imaging. In this respect, the exchange of technologies and know-how is crucial to advance the expertise within our community. Task 4, of Work package 10 has, through the networking activity, contributed to dissemination of the know-how and recent R&D activities in the field, to coordination of activities on the demonstration of imaging applications and to dissemination of know-how on associated detector technologies such as the detector encapsulation techniques, electronics and pulse-shape analysis.

Section 1 Imaging and detector technology networking task

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 are a penetrating form of electromagnetic radiation that interacts in matter through three main mechanism photoelectric absorption, Compton scattering and 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, one 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 PSeGe JRA has organised four workshops

- Paris in October 2016
- Milan in September 2017
- Strasbourg in September 2018
- Legnaro in September 2019

In addition to the organisation, more than 31 participants to the workshops have been supported with Task 4 funds.

The workshops have featured contributions from world-leading scientists working on applications of imaging detector technology based on germanium semiconductor. 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 large-scale germanium-based neutrino-less double-beta decay experiments.
- New development of Ge detectors at ORTEC - G. Geurkov
- HPGe detectors manufacturing for ultra-low background applications - V. Gostillo, Baltic Scientific Instruments Ltd.
- Versatile acquisition systems for segmented detectors: CAEN case history: Paola Garosi from CAEN SPA.

The focus of these workshops has covered the broad areas of (1) the extraction of position information from large-volume semiconductor detectors, (2) the reconstruction of Compton imaging data and the subsequent multi-modality image fusion to rebuild a scene, and (3) industrial applications of detector technology.

An example of what the potential of 3D gamma imaging is, when combined with multiple-sensor technologies, is illustrated in the figure below. This “scene data fusion”, courtesy of the LBNL (USA), indicates with a red arrow the determined source location with reference to the surrounding environment.

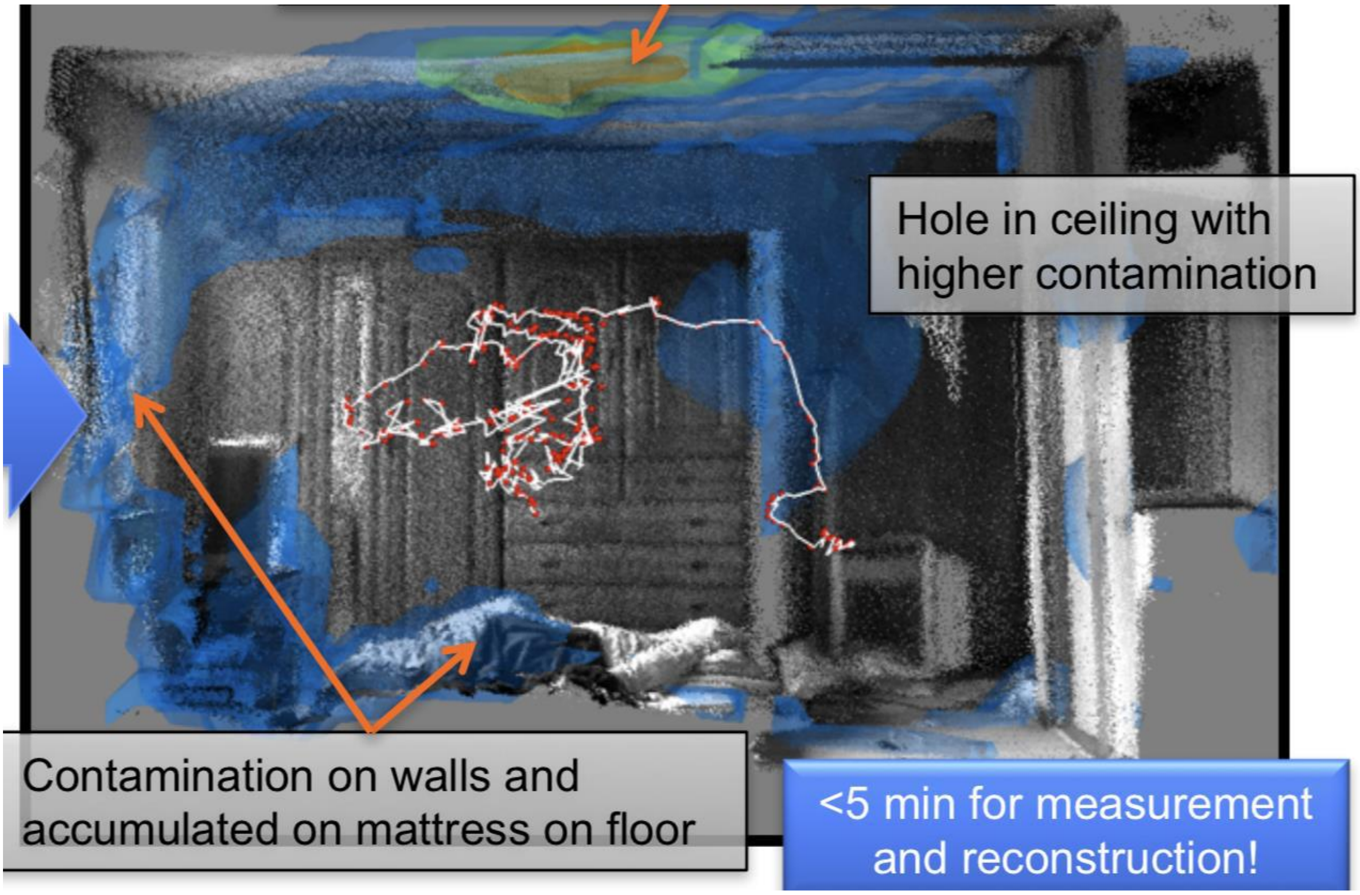

Figure 1: Example of scene data fusion (courtesy LBNL)

The other goal of the networking activity, within this task, was the dissemination of the know-how on detector and detector-associated technologies within the laboratories of the collaboration, as well as the participation of the members of the collaboration in schools aiming to disseminate the knowledge on Ge detectors.

Several collaborators could participate in the "Hands-on workshop on operation, test and repair of Ge detectors", held in Cologne on September 4-7, 2018. They have also been trained to maintain and repair encapsulated, segmented detectors mounted in cryostats by a series of 5 stays at Cologne in 2017 and at GSI in December 2018.

Consequently, the IPHC laboratory has been recognised in 2017 as a site for characterisation and validation of position-sensitive Ge detectors. In addition, the staff is now prepared to maintain autonomously complex detectors like the triple clusters of AGATA.

CSNSM-Orsay, not only participated in the PSeGe workshop and organised the first one, but also launched a collaboration between the AGATA and GRETINA communities, which results in meetings devoted to discussions about common challenges related to position-sensitive tracking arrays and hence segmented Ge detectors. These meeting are organised on a yearly or biennial basis, alternating between meeting places in the US and the EU and the second workshop dedicated a full session to the developments of PSeGe and related topics
(https://indico.in2p3.fr/event/16944/timetable/?view=standard).

Furthermore, a training of young PhD students was organised in 2019 by CSNSM in the framework of AGATA but deeply connected to PSeGe activities. This offers a unique opportunity for the young students in understanding the highly segmented detectors and hence perform a robust data analysis (starting from the calibration steps to the PSA and tracking of the interaction points in the Ge detectors). Summarising, more than 32 training actions have been supported by this task and still some funds are available for the extension of ENSAR2.

SECTION 2 DEMONSTRATION OF IMAGING APPLICATIONS

The group at the Nuclear Physics Institute, University of Cologne UCO developed, improved and refined methods for gamma-ray imaging with detector configurations 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 characterised 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 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 optimise 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 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 imaging capabilities of position-sensitive, highly segmented, High-Purity Germanium (HPGe) detectors rely on the Pulse-Shape Analysis (PSA), which reconstructs the position of the individual gamma-ray interactions through the detector. PSA utilises the measured pre-amplified signals of the 36 segments and of the core electrode, which are characteristic for each interaction position. The comparison of the measured pulse shapes with reference signals provides the interaction positions of the gamma rays. The reference signals are simulated with the ADL and the measured and simulated signals are compared with an adaptive grid search algorithm. By employing ADL and the adaptive grid, unexpected clustering of hits and a surplus of hits at certain single interaction positions were observed, which cannot be explained by statistical fluctuation. Therefore, quantities were developed to describe the homogeneity of the hit distributions as well as the correlation of the number of hits of neighbouring grid points. The obtained results confirm that the hit distributions are less homogeneous than expected and that the number of hits in neighbouring grid points are correlated.

The pulse shapes simulated with ADL were analysed in detail and compared with the corresponding measured signals. Systematic deviations of measured and simulated signals were determined and possible solutions are discussed. In particular, the T10/90 rise times ratio of the pulse shapes and the evolution of the difference of measured and simulated signals during the process of charge collection were inspected. The adaptive grid search determines the best fitting reference signal by minimising a figure of merit. The working principle of the adaptive grid search and its results were investigated in detail. The impact of employing different figures of merit on the PSA is discussed. Results regarding the position sensitivity were extracted from an inspection of the figure of merit landscape.

The various results related to imaging and position sensitivity were presented and discussed at the four PSeGe workshops.

Section 3 Detector encapsulation techniques

A new encapsulation technology was developed in recent years for highly segmented hexagonally shaped HPGe detectors. The development was pursued at Nuclear Physics Institute, University of Cologne UCO together with the industrial partner Canberra, France – MIRION. The main advantage of the new technology to close hermetically the capsule is a non-destructive solution, which allows reusing the detector capsule after opening the detector container and modifications or repair of the delicate HPGe

crystal. This is in strong contrast to previous solutions like electron beam welding which did not allow to recycle the aluminium container more than once or two times.
The new encapsulation technique is based on a metal-elastic seal, which has to provide excellent vacuum tightness in the temperature range from 73,15 K to 373,15 K. The development focused first on new test equipment for measurement of leak rates in the ultra-high vacuum regime. Extensive development work and prototyping of new detector capsules were performed and were concluded successfully. Final measurements demonstrated the applicability of the new technology as a function of temperature, UHV conditions and endurance tests. HPGe detectors with the new encapsulation technology were delivered to IKP Cologne and were subject of extensive test measurements especially on the mechanical performance, impact of the microphonic effect, cross talk contributions and energy resolution of the detectors.

CONCLUSION

In this document, we report on the activities of Tak 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 other important goal was to provide the means for know-how exchange and training for the participant institutes.