Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

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To cite this article: E.N. Gimenez *et al* 2025 *J. Phys.: Conf. Ser.* **3010** 012144

Journal of Physics: Conference Series **3010** (2025) 012144 doi:10.1088/1742-6596/3010/1/012144

Development of a New Generation Multi-Element Monolithic HPGe sensor for XAFS applications

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Abstract. Recent upgrades in synchrotron radiation facilities, which now produce highly brilliant and coherent beams, result in a broader array of experiments challenging the available detectors. In X-ray Absorption Fine Structure (XAFS) experiments, detector performance is often a limiting factor, especially with the high photon fluxes from upgraded facilities. Within this context, a consortium of European facilities has joined under the LEAPS-INNOV project to push the current technologies and develop a germanium detector that can operate under high photon fluxes. The latest status of the XAFS detector development is presented here. The project has moved from the design and simulations phase to the assembled stage, with the sensor, electronic chain and mechanics being manufactured and tested. Next steps are focused on integrating all parts together and characterize the detector performance with X-ray beam.

1. Introduction

X-ray Absorption Fine Structure spectroscopy (XAFS) is crucial to investigate the electronic and atomic structure of different kinds of samples [1]. The efficacy of this technique, widely deployed at synchrotron facilities, is constrained by the performance limitations of the current generation of germanium detectors. To perform XAFS measurements, energy-resolving detectors capable of handling high count rates [2] are advantageous, particularly in certain scenarios. While efforts have been focused on developing arrays of Silicon Drift Detectors (SDDs), less attention has been given to enhancing the performance of High Purity Germanium (HPGe) detectors for synchrotron applications. HPGe detectors offer better detection efficiency at high energies compared to SDDs.

To address this, a detector consortium under the European project LEAPS-INNOV [3] launched an ambitious R&D program aimed at developing a new generation of multi-element monolithic HPGe detectors specifically tailored for X-ray detection [4]. Two detector prototypes were designed considering simulations of the detector prototypes conducted to optimize the detector performance. Each prototype is equipped with a 10-element monolithic HPGe sensor, one with a 5 mm^2 area pixels and another with 20 mm^2 area pixels. Additionally, a novel electronic chain was engineered, allowing crosstalk and charge-sharing correction, and enabling the processing of higher count rates ranging from 20 kcps/mm^2 up to 250 kcps/mm^2, while preserving reasonable energy resolution and minimizing dead time within the required energy range.

This work presents an overview of the detector development status, including final mechanical design details, HPGe sensor and electronic chain specifications and their individual performance after being manufactured. Currently, the detector prototypes are undergoing assembly, with forthcoming laboratory and beamline tests planned at the beginning of 2025.

2. Detector design

To minimize the leakage current of HPGe sensors, they need to be operated at cryo-cooling temperatures (for this prototype is 77 K). This results in a complex detector system design defined by three main parts: a detector head, a detector body and the external components. The detector head is a compact, vacuum-sealed, cryogenically cooled section, which houses the detector window, germanium sensor, mechanical holder, and front-end electronics. The detector body has both vacuum/cryogenic and room-temperature sections, with the cryogenic system that cools the detector head, shielded connections, the cryostat, and flanges equipped with feedthroughs. It also houses the back-end electronics at room temperature. The external components section includes the Digital Pulse Processor (DPP), power supplies, and computers responsible for equipment monitoring, control, and data recording. This structured design supports the HPGe detector's operational requirements and facilitates integration with associated electronics.

2.1 Detector simulations

A comprehensive simulation chain was developed to model the detector's response to X-ray interactions, from initial interaction to the sensor to a reconstructed energy spectrum, using Geant4 and COMSOL Multiphysics™, linked to the Allpix-squared [5] framework and SDD software package. This chain utilizes detailed information about the HPGe detector, including its geometry, impurity density, and bias voltage, to calculate the necessary detector electric fields. With these electric fields defined, interactions between X-rays and the detector are simulated to produce charge pulses. The time evolution of charge pulses induced in the readout electrodes is analyzed to fine-tune acquisition parameters, maximizing detector performance. Additionally, pulse shape analysis enhances both position reconstruction accuracy and background rejection efficiency. Specifically, identifying and rejecting multi-site events—where energy deposition occurs across multiple electrodes—is crucial for reducing background noise and improving energy resolution. Finally, the signal amplification and electronics noise are included and a waveform is produced for each event. This simulation work was conducted before finalizing the sensor and electronics design, providing valuable feedback to the design development stages, and is discussed in detail elsewhere [6,7]. On those studies, simulations to define other critical parts of the mechanics, such as the collimator were also performed. The detector specifications were presented in [4].

3. Germanium sensors

The project involves two versions of pixellated HPGe sensors each aiming at specific X-ray applications. One is for X-ray Absorption Fine Structure (XAFS) experiments with a smaller 5 mm^2 pixel area (Small Pixel Pitch - SPP) which allows a higher pixel density and enables to scale up the number of channels. The other is dedicated to X-ray Fluorescence (XRF) experiments with a larger 20 mm^2 pixel area (Large Pixel Pitch - LPP), where maximizing the collection solid angle is critical. The two versions vary only by a scale factor and feature hexagonal and trapezoidal pixel shapes to minimize charge sharing among adjacent pixels. Additionally, three outer ring-shaped pixels serve as auxiliary pixels to help reject charge-sharing effects electronically. Each version maintains uniform pixel area across all pixels to ensure consistent counting rates. Figure1 shows the manufactured sensors with a thickness of 4.1 mm and 4.4 mm for the LPP and SPP respectively.

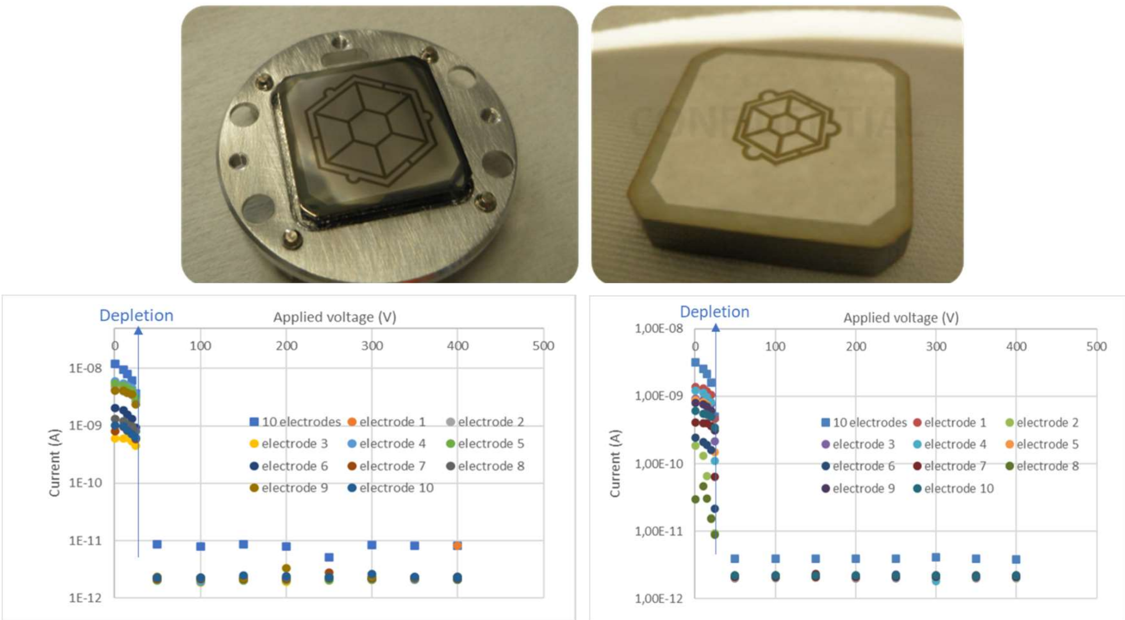

Figure 1. LPP HPGe sensor and its leakage current (left) and SPP HPGe sensor and its leakage current (right).

Both sensors are operated in hole collection mode. A bias voltage of +200 V is applied to the sensor side facing the incident X-rays which is phosphorus implanted (N+ doped electrode), while the pixel electrode side is boron implanted (P+ doped) and grounded. Aluminum contacts were evaporated on both sides and the inter-pixel spacing provides an insulation of 10 TOhms. The HPGe sensor leakage current was tested by placing the sensor in a vacuum chamber at 10^{-7} mbar. After reaching that vacuum level, a cryocooler was used to bring the sensor temperature to 77 K. Once the sensor was under this conditions a positive bias voltage was applied using a Keithley 2410 source metre increasing slowly the voltage value, while measuring the current at each voltage with a picoammeter CP13 from Cooknell Electronics. This procedure was performed for each pixel individually while the rest of the pixels were grounded. The leakage current obtained is less than 1 pA per pixel for a depletion voltage of 37 V and 33 V for the LPP and SPP HPGe sensor respectively (Figure 1).

4. Electronic chain

A new electronic chain was developed to handle high segmented and compact monolithic germanium sensors, aiming to operate across a wide energy range from 5 to 100 keV, which must be capable of processing signals from multiple channels simultaneously. The electronic chain consists of three distinct blocks specifically designed for this project. The first block is a multi-channel integrated preamplifier built with CMOS technology. The second block is the front-end electronics equipped with the ASICs, and the third block is the back-end electronics. The first two blocks operate in a vacuum and cold-temperature environment and are positioned close to the germanium sensor, while the third block operates at ambient temperature and is located at the other end of the germanium sensor.

The three blocks are interfaced together via reliable interconnections and have been successfully tested at room temperature, complying with the design specifications.

4.1 Preamplifiers and front-end electronics

The design studies of the new multi-channel integrated preamplifier were completed and complied with demanding specifications. The ASIC is compatible with detector capacitances from 1.5 pF for small pixels to 6 pF for large pixels, and each channel includes a discriminator, as well as an option to disable individual channels as needed. Additionally, it supports three gain settings aligned with the detector's targeted energy ranges: 5–15 keV, 15–37.5 keV, and 37.5–100 keV. Power consumption is capped at 60 mW per ASIC, with a reset time of under 2 µs (including pre- and post-reset artifacts). To avoid degrading energy resolution and increasing dead time at high counting rates and photon energies, the ASIC can handle at least 20 events between resets at the upper end of the gain range. The front-end board is a multi-layer printed ceramic board which includes the low-noise, multi-channel preamplifiers. It is also equipped with resistors, decoupling capacitors, and connectors for I/O signals and power supplies. Designed for robustness, the board is compatible with high-vacuum conditions (10^{-7} mbar) and can operate at liquid-nitrogen temperatures (77 K).

4.2 Back-end electronics

The back-end electronic board is the third electronic block at the interface between the detector head and the *external world* with I/O communication lines. This electronic board provides the filters and different power supplies to the front-end board. It manages the reset mode, the multi-channel preamplifiers internal gain, and buffering/amplifying the outputs signals, and it has a low noise designed of few tens of µV max for each power supply.

4.3 Digital Pulse processor

The Digital Pulse Processor (DPP) is the readout system responsible for reconstructing the energy of the X-ray event on each pixel. It accomplishes this by digitizing the analogue output from each pixel, delivered by the back-end electronics, and applying digital algorithms to detect events and measure their amplitude, which is proportional to the photon energy. Each detected X-ray energy is subsequently binned into a histogram to create an energy spectrum. The DPP for this project is designed to handle 10 channels, with inputs tailored to match the electrical specifications of the back-end electronics. After evaluating existing commercial systems, the consortium chose to procure a modified 10-channel Xspress4 DPP [8], developed by DIAMOND. A key advantage of the

Xspress4 is its capability to characterize and potentially correct for inter-pixel effects in segmented monolithic detectors, enhancing its suitability for this project's requirements.

4.4 Interconnection

The interconnection setup consists of two main parts. In the first, pogo pins transfer signals from each sensor pixel to its corresponding front-end electronic (FEE) channel, allowing for future scalability in pixel number and readouts. In the second part, a custom-designed flexible PCB carries signals from the FEE channels to the back-end electronics (BEE) and DPP stages.

5. Mechanics and thermal simulations

The mechanical model was optimized through iterative thermal simulations, with continuous collaboration between mechanical design, thermal analysis, component selection, and system integration. The final thermal simulations, based on the current mechanical design, indicate effective cooling of both the germanium sensor and front-end electronics to the specified temperature, and are discussed in more depth in [9]. These simulated values will require experimental verification once the detector is fully assembled, including the sensor and electronics. After testing, the experimental results will be used to refine and validate the thermal simulation models.

5.1 Cooling sytem

The detector in vacuum operation at 77 K, requires a meticulous selection of components to avoid high level of outgassing and reduce needs of power cooling. A SunPower electrical cryocooler of 11 W cooling power was selected to keep the detector at the operational temperature of 77 K, replacing the usual LN2 cryostat (shown in Figure 2). This option makes the detector more compact while suppressing the LN2 refilling, which simplifies the detector operation.

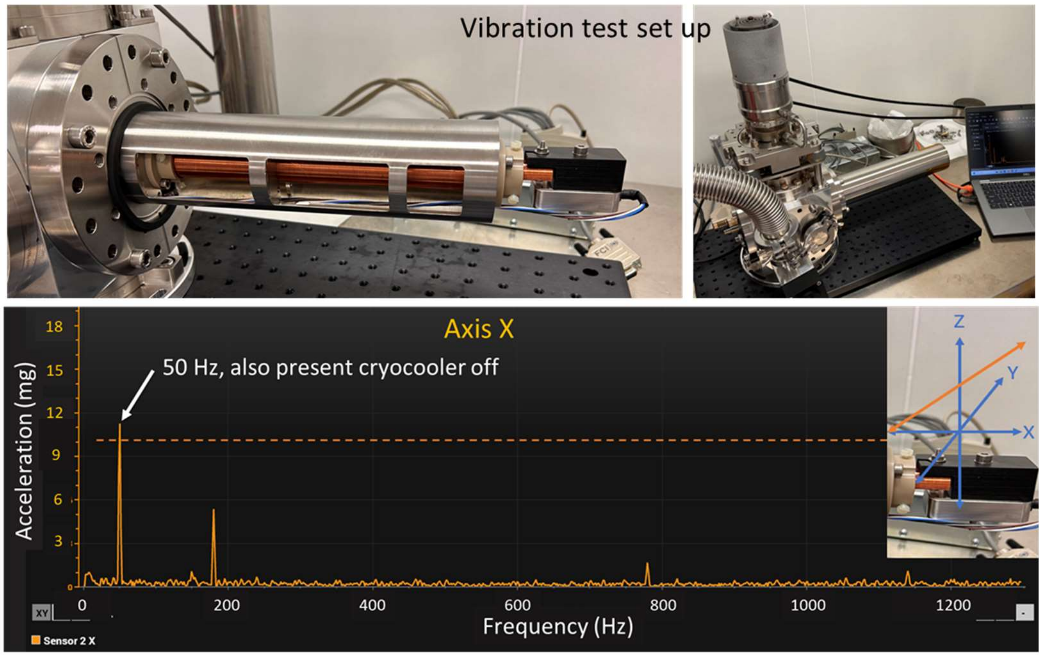

Figure 2. Detector mechanics and vibration tests setup with the accelerometer at the end of the copper arm (top) *and spectra for axis X (bottom).*

This cryocooler system is operated by the Stirling cycle, that compress and expands a fixed quantity of helium gas. Nevertheless, this system can induce high vibration to the cold finger, and this aspect can be an issue on beamlines requiring low induced vibration for high beam stability. To assess this potential negative effect, a dedicated test bench evaluation (shown in Figure 2) was performed to study the efficiency of a vibration cancellation system, inspired from the existing Maroon-X detector system [10]. The vibration tests were made with an accelerometer sensor installed at the end of the copper arm, as shown in Figure 2. The measured value for each axis is provided by the most intense peak at a frequency higher than 50 Hz. The sensor measured acceleration values of 5, 7 and 4 mg in X, Y and Z, for 185, 120 and 780 Hz respectively. These values are within specifications (less than 10 mg) and would not affect the system.

6. Summary and next steps

The XAFS-DET project, launched in April 2021, is an ambitious European R&D initiative aimed at developing advanced monolithic pixelized HPGe detectors for synchrotron applications. Early in the project, extensive simulations were used to optimize design choices, guiding the development of essential components including the germanium sensor, mechanical structure, thermal management, and cooling system. Design studies for these components were concluded, ensuring full integration of critical parts.

To date, all primary components have been manufactured, delivered, and rigorously tested. The mechanical structure has been successfully assembled, passing both vacuum and vibration tests. The germanium sensors were produced to meet all specified requirements, and the complete electronics chain—including preamplifiers, front-end and back-end electronics, and the DPP—has been delivered, each element meeting project specifications, and successfully tested.

The next phase will focus on integrating all key components and evaluating the temperature stability of the HPGe sensor and electronics, as well as assessing X-ray detection performance. The detector is scheduled for deployment in real XAFS experimental tests by 2025, marking a significant advancement for synchrotron-based spectroscopy.

7. Acknowledgments

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101004728.

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