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XAFS-DET: a new high throughout X-ray spectroscopy detector system developed for synchrotron applications

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Abstract:	The high brilliance and coherent beams resulting from recent upgraded synchrotron radiation facilities open the way for a large range of experiments, where detectors play a key role in the techniques and methods developed to fully exploit the upgraded synchrotron. For instance, one of the major limitations of XAFS experiment is the performance of the detectors. In order to be able to measure more challenging samples and to cope with the very high photon flux of the current and future (diffraction limited) sources, technological developments of detectors are necessary. In this

	<p>framework, the germanium detector developed in the European project LEAPS-INNOV aims at improving several technological aspects. This type of detector represents a very important class of instruments for X-ray spectroscopy due to the fact that they enable to detect efficiently photons of considerable higher energy with respect to silicon detectors. The objective of this project consists in pushing the detector performance beyond the state-of-the-art. Preliminary layout and main choices for the design studies of this new detector are presented in this paper.</p>
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XAFS-DET: a new high throughout X-ray spectroscopy detector system developed for synchrotron applications

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Abstract

The high brilliance and coherent beams resulting from recent upgraded synchrotron radiation facilities open the way for a large range of experiments, where detectors play a key role in the techniques and methods developed to fully exploit the upgraded synchrotron. For instance, one of the major limitations of XAFS experiment is the performance of the detectors. In order to be able to measure more challenging samples and to cope with the very high photon flux of the current and future (diffraction limited) sources, technological developments of detectors are necessary. In this framework, the germanium detector developed in the European project LEAPS-INNOV aims at improving several technological aspects. This type of detector represents a very important class of instruments for X-ray spectroscopy due to the fact that they enable to detect efficiently photons of considerable higher energy with respect to silicon detectors. The objective of this project consists in pushing the detector performance beyond the state-of-the-art. Preliminary layout and main choices for the design studies of this new detector are presented in this paper.

Keywords: Germanium detectors, X-rays spectroscopy, XAFS, Synchrotrons Applications

1. Introduction

With continuous improvements and upgrade of synchrotron radiation facilities, detection technologies beyond current capabilities are essential. In particular, in X-rays spectroscopy ap-

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plications, germanium detectors are a class of detectors which offer energy resolution not far from the Fano limit. They are generally used in synchrotron experiments which require excellent energy resolution, for instance, when it is necessary to separate the fluorescence photons of an element from the elastically scattered radiation used to excite the sample. Spectroscopy grade Silicon detectors (either Si(Li) or SDD) are the only other class of detectors which offer similar energy resolution but they are not as effective when the photon energy becomes higher than 30 keV because of the lower stopping power of Silicon with respect to Germanium. In addition, Silicon detectors can lead to some artefacts in techniques such as XAFS (X-rays Absorption Fine Structure) because of the close distance of the escape peak from the main peak.

At synchrotron facilities, the major challenge is to exploit effectively all the photons produced by the machine and this means that the detector must have high throughput. Multi-element detectors enable to enhance the throughput by distributing the incoming photon flux on different detecting elements with independent readout channels. If the elements are built on the same sensor material, i.e. the detector is monolithic, the size of the system turns out to be particularly compact, which is an important advantage for many applications.

In this context, the detector workpackage of the European project LEAPS-INNOV [1], also named XAFS-DET project, aims at pushing germanium detector performance beyond the state-of-the-art in the energy range from 5 to 100 keV that suits to a large number of synchrotron facilities. In this project, the throughput per unit area for X-ray spectroscopy will be enhanced by developing a multi-element monolithic detector. In one version of the detector prototype, shrinking the germanium element size will also entail challenges such as the development of new miniaturized front-end electronics and the use of advanced Digital Pulse Processors (DPP) to avoid collimators in front of the sensing elements. The new technological developments proposed in this project would push the limit of current available detectors and open up new experimental possibilities.

2. Main specifications for the germanium detector and general layout

The main requirements for the High Purity Germanium (HPGe) detector and its associated electronics are summarized in the following table 1 and presented in the CDR of the project [2].

One of the particularities of the HPGe detector is the need to be cryo-cooled to limit the leakage current of the germanium sensor. This condition leads to a complex detector layout as schematically illustrated with Figure 1. The detector consists of three main blocks:

- A very compact detector head under vacuum and cryogenic temperature. This part includes the detector window, the germanium sensor and its mechanical holder, the front-end electronics composed of boards equipped with specific readout preamplifiers, and the interconnections elements between the germanium sensor and the front-end electronics;
- A detector body with a part under vacuum and cryogenic temperature and another part that may include the back-end electronics in air and room temperature. This part includes the cryogenic cooling system needed to cooldown the detector head, some shielded connections, the cryostat, and the flanges equipped with feedthroughs;
- Some external parts with the Digital Pulse Processing electronics, the power supplies and computers for the monitoring and control of the whole equipment and data recording.

The following sections give a general description of the main components with the on-going mechanical design of the whole detector.

Table 1: Main requirements for the XFAS-DET detector prototype.

X-ray energy range	From 5 to 100 keV
Number of pixels	10
Pixel size and thickness	Small pixel version of 5 mm ² and large pixel version of 20 mm ² , both versions are 4 mm thick
Energy resolution	< 200 eV FWHM at 5.9 keV and an Input Count Rate of 100 kcps/pixel and a shaping time (or equivalent) of 1 μ s
Detector efficiency	> 90% in the required energy range
Input Count Rate (ICR) range per unit area	From 20 kcps/mm ² up to 250 kcps/mm ²
Dead time (%) at 5.9 keV	30% at 1 Mcps and maintained at reasonable level at high energy (20-100 keV)
Peak to Background Ratio	> 1000 at 5.9 keV, defined as the ratio between the counts in the peak channel and the average background
Detector temperature	77 K (detector head and body)
Detector vacuum	1 \times 10 ⁻⁷ mbar
Input Window	Beryllium window
Germanium sensor collimator	Multi-layer collimator

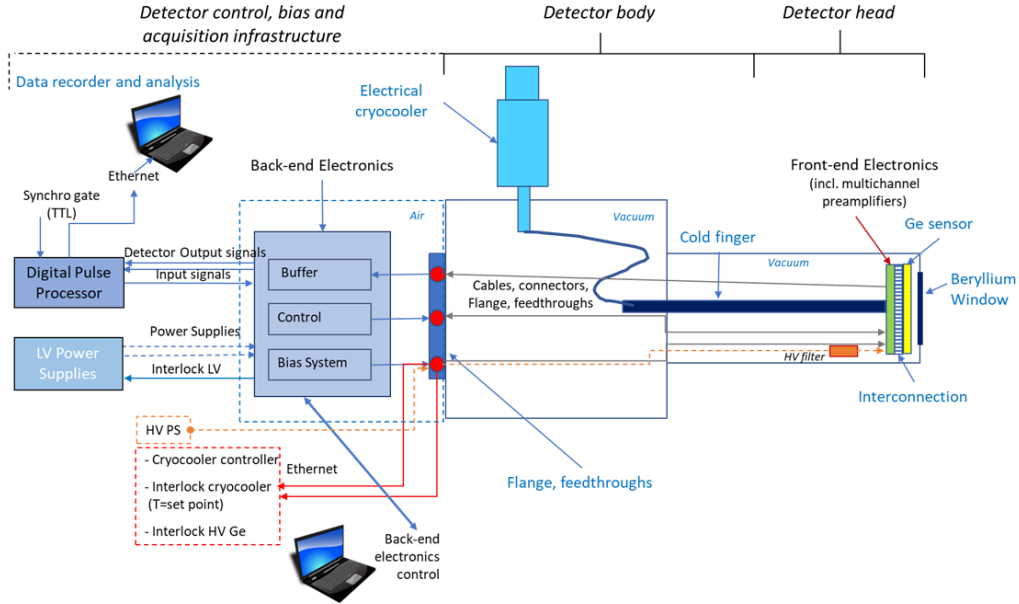


Figure 1: General layout of the XFAS-DET detector with main components.

3. Germanium sensors

The sensing part consists of a High-grade Purity Germanium (HPGe) sensor. To avoid excessive complexity and costs of the prototype, it was decided to limit the number of segmentation elements of the germanium sensor to a reasonable and pragmatic maximum of ten pixels. Two-pixel versions will be designed in the project bearing in mind two different type of applications: the 5 mm² pixel area is dedicated to XAFS experiments and the future needs to scale up the number of channels [3], whereas the 20 mm² pixel area is considered for the needs of XRF experiments, where the solid angle of collection needs to be maximized. The two versions, illustrated in Figure 2, differ only in a scale factor. The hexagonal and trapezoidal shape of pixels is appropriate to limit the charge sharing among only fewer neighbouring pixels. The unusual ring-shape configuration of the three outermost pixels has been conceived to use them as ancillary pixels to electronically reject the charge sharing effect. All the pixels of one version have the same area so as the counting rate will not differ excessively between the pixels.

The frontside (facing the incident X-rays) is phosphorus implanted (N+ doped electrode) while the backside (segmented side with 2 pixels versions) is boron implanted (P+ doped). The inter-pixel spacing will be defined precisely later on by the manufacturer (depending on their process) to be compatible with an insulation of 10 TOhms. Aluminum contact will be evaporated on the implants (pixel surface) and on the frontside of the sensor. A bias voltage of +200 V is applied on the frontside, and the pixel electrode is grounded. The detector works in holes collection mode.

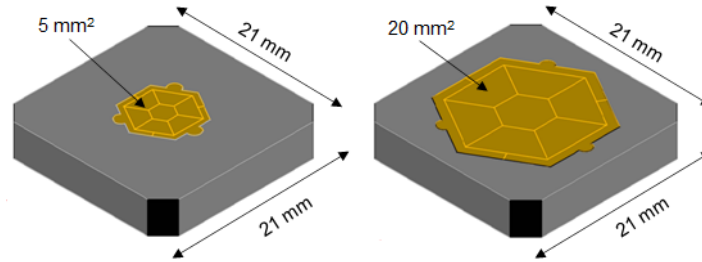


Figure 2: Germanium sensor segmentation on the back side: 10 pixels of 5 mm² each (left) and 10 pixels of 20 mm² each (right). The germanium dice is 21×21×4 mm³.

4. Electronic chain

To cope with high segmented and compact germanium detector, operating in a large energy range from 5 to 100 keV, it is necessary to foresee a new electronic chain able to perform signal processing of several channels simultaneously.

The electronics of the project can be considered as a three-blocks system designed specifically for this development. The first block is the multi-channel integrated preamplifier (micro-electronic circuit in CMOS technology). The second block is the front-end electronics equipped with the ASICs (shown in Figure 3-left), followed by the third block, i.e. back-end electronics (shown in Figure 3-right). The two first blocks share the same environment under vacuum and cold temperature and are very close to the germanium sensor (as shown in Figure 1). The three blocks are strongly interfaced together.

78 The design studies of the new multi-channel integrated preamplifier will start in the coming
79 months and the specifications are quite ambitious. The new ASIC must be compatible with the
80 detector capacitance estimated to be from 1 pF to 3 pF for small and large pixels respectively. One
81 discriminator per channel is required, as well as the possibility to disable individual channels.
82 The implementation of three gains, compatible with the 3 energy ranges of interest of the detector
83 (5-15 keV / 15-37.5 keV / 37.5-100 keV) is a constraint for the design. The power consumption
84 is also an issue and it should be limited to 60 mW maximum per ASIC. The reset time duration
85 should be as small as possible: $< 2 \mu\text{s}$ (including possible artefacts before and after the reset
86 slope) and the number of events between two resets should be at least 20 events in the high
87 energy end of the gain range of the preamplifier, in order to avoid energy resolution degradation
88 and large increase of the total dead time due to reset time at high counting rate and high photon
89 energy.

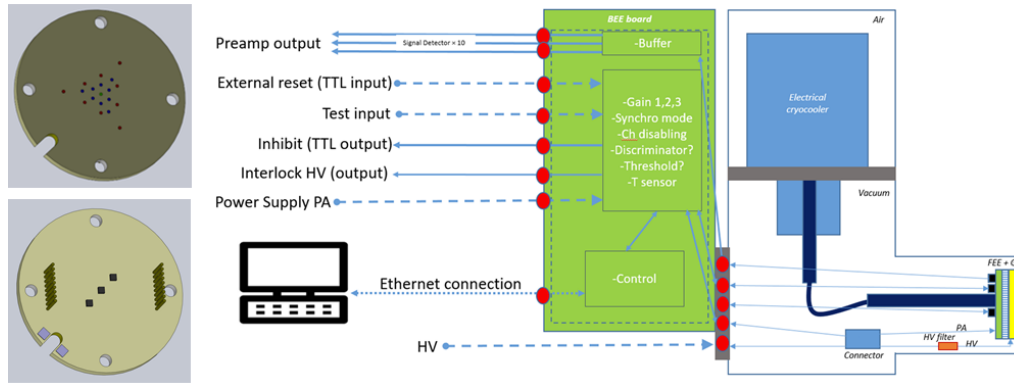


Figure 3: Overview of the front-end board electronic (left): top side of the board matching both the small and large pixels arrangement (top-left) and its back side (bottom-left); Schematic overview of the functionalities of the back-end electronics (right).

90 The front-end board consists of a multi-layer printed ceramic board, equipped with the inte-
91 grated low-noise multi-channel preamplifiers. This board, also under design, will also enclose
92 a set of resistances and decoupling capacitances and connectors for I/O signals and power sup-
93 plies. The front-end board must be compatible with high vacuum (10^{-7} mbar) and liquid-nitrogen
94 temperature (77 K).

95 The back-end electronic board is the third electronic block at the interface between the de-
96 tector head and the ‘external world’ with I/O communication lines. This electronic board will
97 include different functionalities, as providing and filtering the different power supplies to the
98 front-end board, managing the reset mode, the multi-channel preamplifiers internal gain, and
99 buffering/amplifying the outputs signals. The overall design of the back-end boards will be low
100 noise (few tens of μV max for each power supply). The Figure 3-right illustrates the schematic
101 of this board with its various functionalities.

102 The readout system, also called the Digital Pulse Processor (DPP), will reconstruct the energy
103 of X-ray events impinging on each Ge pixel and will present the resultant energy spectra to
104 the user. To do this, it digitises the analogue output associated with each pixel and transferred
105 by the back-end electronics, then uses digital algorithms to identify any events in the digital
106 stream and measure their amplitude (energy). Each measured X-ray energy is then binned in a

107 histogram of all those previously measured to form an energy spectrum. The DPP for this project
 108 should comprise a minimum of 10 channels with the analogue inputs matching the electrical
 109 characteristics of the back-end electronics.

110 The main specifications for the Digital Pulse Processor have been defined by the consortium
 111 early in the project, and after a review of existing commercialized systems, it was decided to
 112 purchase a 10-channel modified Xspress4 DPP developed by DIAMOND. One of the unique
 113 features of the Xspress4 is its ability to characterise and potentially correct for inter-pixel effects
 114 in segmented monolithic detectors [4].

115 5. Mechanical design and preliminary thermal simulations

116 The current mechanical model under design is illustrated in Figure 4-left. This design is
 117 preliminary and progress iteratively with the thermal simulation studies. There is a wide-but-
 118 close interaction between the mechanical design, the thermal simulations, the components under
 119 development and the overall system integration.

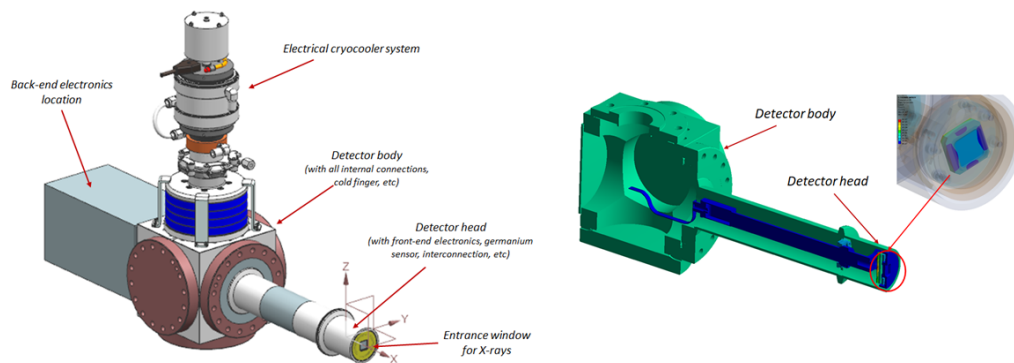


Figure 4: Simplified mechanical model of the XAFS-DET detector (left); Preliminary results of the thermal studies (in case of optimized contacts and copper braid, and a ceramic front-end electronic board)(right).

120 The preliminary thermal studies have been performed based on the current mechanical de-
 121 sign. The very first results feature an efficient cooling of the germanium sensor close to 77 K, in
 122 case of optimized contacts and copper braid, and with a ceramic front-end electronic board, as
 123 illustrated on Figure 4-right. As the thermal contacts are essential in this project and are based
 124 on 'ideal' assumptions for the moment, a dedicated set-up is foreseen to get soon more realistic
 125 experimental values which could be included in the thermal simulations.

126 6. Cooling system

127 The baseline option for the cooling at 77 K consists of replacing the usual LN2 cryostat by
 128 an electrical cryocooler. The goal is to simplify detector operation, make it more compact, and
 129 suppress the tedious LN2 refilling. In practice, it requires a meticulous selection of components
 130 under vacuum to avoid high level of outgassing and reduce the needs of power cooling. After a
 131 survey of different commercialized systems, and due to budget constraints, a SunPower system
 132 has been chosen.

133 This system is operated by the Stirling cycle, that compress and expands a fixed quantity of
 134 Helium gas. The available 11 W cooling power is large enough for our needs. Nevertheless, this
 135 system can induce high vibration to the cold finger, and this aspect can be an issue on beamlines
 136 requiring low induced vibration for high beam stability. In order to assess this potential negative
 137 effect, a dedicated test bench is under preparation to study the efficiency of a vibration cancella-
 138 tion system, inspired from the existing Maroon-X detector system [5] (as shown in Figure 5) and
 139 first results are expected in the coming months.

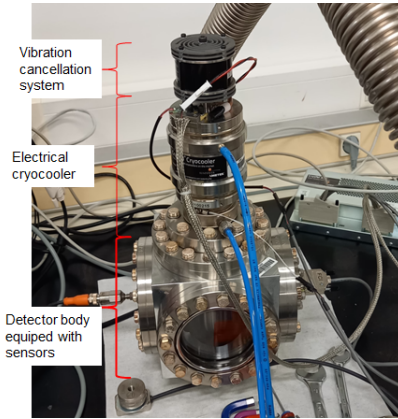


Figure 5: Vibration induced by the electrical cryocooler under assessment with a dedicated testbench.

140 7. Simulation of detector performances

141 A strong effort has been made by the project consortium on simulations tools to provide
 142 guidelines for the detector design studies. A dedicated simulation chain has been implemented
 143 and it includes all the steps from the interaction of X-rays with matter to a reconstructed energy
 144 spectrum using simulated raw-data-like waveforms. This simulation chain, based on Geant4,
 145 COMSOL Multiphysics™ (Semiconductor module) linked to Allpix-squared framework [6] and
 146 also on SSD software packages, is schematically represented in Figure 6-left and is described in
 147 details in [7].

148 As an example of output, the energy spectrum obtained for one configuration of our detector
 149 has been simulated with an incident 30 keV direct beam (with 2 millions of photons). The results
 150 are presented in Figure 6-right. In this figure, the Signal-to-Background ratio is of the order
 151 of 800 for the large pixels, which is close to our requirements. This work will continue with
 152 more realistic parameter definitions inserted in the simulations (detector secondary component
 153 material, front-end electronic features, etc) as the design will be refined.

154 8. Summary and next steps

155 The XAFS-DET project is an ambitious R&D European project launched in April 2021 for
 156 the development of a new generation of monolithic pixelized germanium detectors for syn-
 157 chrotron applications. Several design studies have started in parallel (germanium sensor, me-
 158 chanics, thermics, cooling, etc). Multi-physics simulations are used to guide the detector design
 159 and will assess the future detector performances.

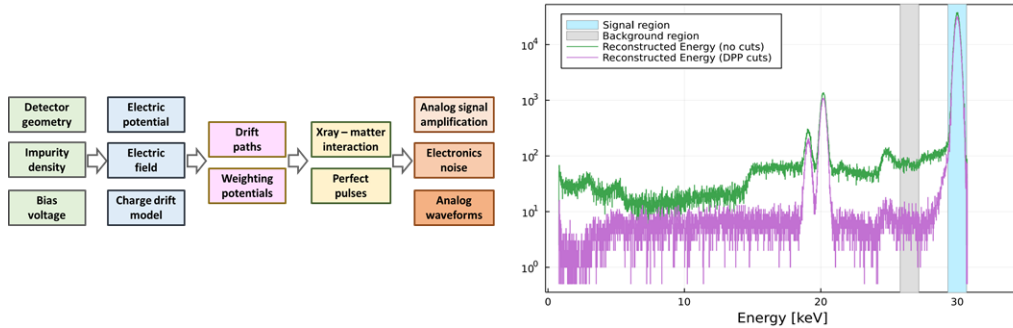


Figure 6: Flowchart of the multiphysics simulation chain (left), reconstructed energy spectrum for a direct X-ray beam of 30 keV. The two peaks around 20 keV come from the germanium fluorescence peaks (right).

The next steps in the coming months will consist in finalizing the mechanical and thermal design studies of the detector ‘head’ (taking into account the integration of all the critical components which compose the ‘head’ and which are already under development in different tasks), finalizing the design studies of the multi-channel preamplifier and front-end and back-end electronics, manufacturing the 2 germanium sensors (one of each version), assessing the vibration cancellation system of the cooling system with a dedicated set-up, and progressing in the thermomechanical design of the complete detector (including the ‘body’ part and the electrical cryocooler).

9. Acknowledgments

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Dear Referees and Editor,

Please find in the attached file my manuscript entitled “XAFS-DET: a new high throughput X-ray spectroscopy detector system developed for synchrotron applications”. This manuscript follows the poster presented at the NDIP20 conference in Troyes in July 2022.

This paper presents a new multi-element germanium detector developed for synchrotron radiation facilities, in the framework of the European project LEAPS-INNOV. In this new development, several technological aspects, as the germanium crystal and the electronic chain, are expected to be improved compared to existing detectors of the same type. Preliminary layout and main choices for the design studies of this new detector are presented in this paper.

With regards,

Fabienne ORSINI on behalf of the LEAPS-INNOV detector consortium.