ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR75

THERMAL AND VIBRATIONAL STUDIES OF A NEW GERMANIUM DETECTOR FOR X-RAY SPECTROSCOPY APPLICATIONS AT SYNCHROTRON FACILITIES

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Abstract

The European LEAPS-INNOV project has launched a Research and Development program dedicated to the design of a new generation of germanium detectors for X-ray spectroscopy applications. The present article shows the results of the thermomechanical simulations of this design, based on finite element analysis (FEA) studies, under vacuum and cryogenic conditions. The first results of these simulations were published at IPAC23 [1]. In this new work, the final results are presented, which includes the thermal optimization of the detector with respect to the previous study, as well as new numerical simulations to investigate the effects of vibration transmission from the cryocooler to the head detector.

BACKGROUND

Within the framework of work package 2 (WP2) of the European project LEAPS-INNOV [2], a new generation of Germanium (Ge) detector is being designed for X-ray Absorption Fine Structure experiments (XAFS). To achieve its objective, the WP2 is performing technical aspects as specifications of the Ge pixel sensors; development of a new front-end electronics (multi-channel integrated preamplifiers); development of interconnections between the front-end electronics and the Ge sensor; thermal mechanical simulations for design and manufacture a suitable cryocooler, the cooling system and the housing of the electronics; procuring a digital pulse processor suitable for the purpose of this project, among others.

In this context, the content of this work is focused on the thermal mechanical simulations of the new Ge detector. The first results of the numerical simulations were published at IPAC23 [1]. In that first study, a set of optimization proposals were presented, focalized on the thermal part of the design, aiming to comply with the design requirements defined in [2]: (i) Minimize the temperature of the Ge Crystal as closest as possible to 77 K and below 100 K, (ii) Uniform temperature distribution in the sensor: the temperature gradient over the Ge crystal should not exceed 5 K, (iii) For the multi-channel integrated preamplifier, its working temperature has been specified in the range of 77 K up to 330 K, and (iv) For vacuum, the pressure working condition is fixed at $1x10^{-7}$ mbar.

In this work the results of the latest thermo mechanical simulations are presented [3], which include a new thermal optimization step and vibrational studies. A simplified model of the detector is shown in Fig. 1. It consists of three parts: (i) The Detector Head, which includes the Ge Crystal ($21x21x4\ mm^3$) and its mechanical holder, the front-end electronics, some interconnections between the Ge Crystal and the front-end electronics, and the Beryllium window. The simplified geometry of the Detector Head is shown in Fig. 2, (ii) The Cooling, made up of the Cryocooler, Cu Braid, Cu Arm, Cu Holder and the Arm Holder, and (iii) The Vacuum Chamber. To support the cooling, a concentric inner cylinder has been included.

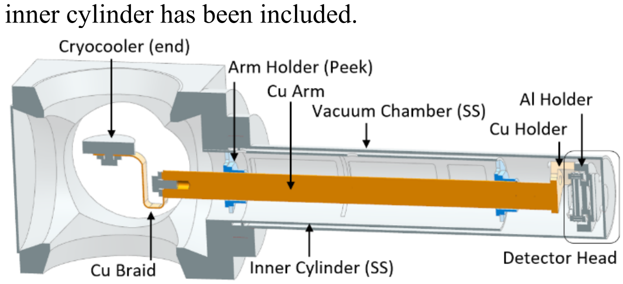

Figure 1: Simplified model of the Germanium detector prototype.

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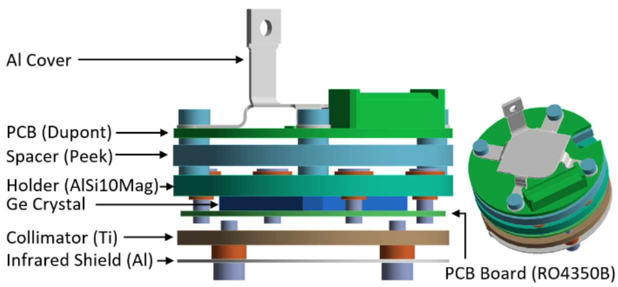

Figure 2: Simplified model of the main components of the Detector Head.

DETECTOR HEAD: THERMAL OPTIMIZATION

According to the results obtained in [1], the maximum temperature on the PCB (Preamplifiers) (336.3 K) was slightly higher than the design criteria (330 K). This result is because the total power generated on the PCB is distributed in a small area, corresponding to the three preamplifier units, resulting in a high power density. To reduce this peak temperature, a thermal bridge has been implemented to dissipate the heat accumulated in the PCB. The thermal bridge is an extension added to the Al Cover, which joins with the Cu Holder, creating a path to evacuate part of the power from the PCB (see left part of Fig. 3). With this new configuration, the maximum temperatures in the PCB and Ge Crystal are 237.7 and 94.668 K, respectively (see Fig. 3, a and b). For the thermal simulations, the boundary conditions, the thermal contacts, as well as the physical properties have been kept the same as those defined in reference [1].

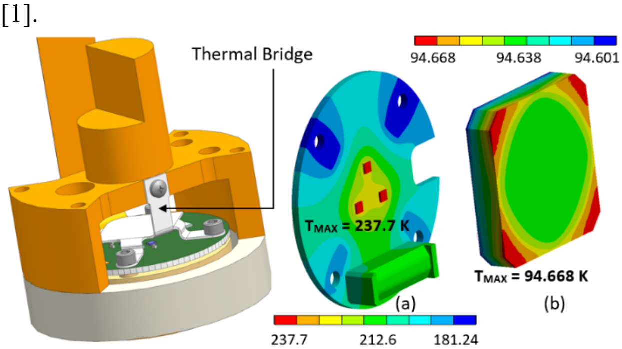

Figure 3: Detail of the thermal bridge implemented in the Al Cover, and temperature distribution in (a) the PCB, and (b) Ge Crystal.

A summary of the results for the cases with and without thermal bridge is presented in Table 1. For the case with thermal bridge, a significant reduction in the maximum temperature of the Preamplifiers is obtained, compared to the case without thermal bridge. But in the case of Ge Crystal, an inverse effect is obtained, its maximum temperature increases.

Table 2 presents a study on the effect of thermal contact conductance (TCC) on the screw that fixes the thermal bridge with the Cu Holder. In the case of Ge Crystal, a negligible variation is observed between the maximum temperatures (approx. 1 K), when we compare the cases of good thermal contact (10000 W/m2K) with respect to the case with bad thermal contact (500 W/m2K). This does not happen in the case of the Preamplifiers, where the sensitivity is significant, for example a variation in the peak temperature of 36.7 K is obtained when we compare the cases of good and bad thermal contact.

Table 1: Comparative Study for the Cases With and Without Thermal Bridge

Al Thermal Bridge	T_{MAX} Ge Crystal (K)	T_{MAX} Preamplifiers (K)
With	94.668	237.7
Without	89.162	336.33

Table 2: Study of the Effect of Thermal Contact of the Thermal Bridge Screw on Temperatures

TCC (W/m^2K)	T_{MAX} Ge Crystal (K)	T_{MAX} Preamplifiers (K)
10000	94.908	226.34
2000	94.668	237.7
500	93.905	262.99

Table 3 analyses the thermal effect assuming new materials for the Al Cover: Copper and Stainless Steel. According to these results, the sensitivity in the variation of the peak temperature for the Ge Crystal is low, compared to the variation in the Preamplifiers. For example, for Ge Crystal there is a variation of –3.6 K if Aluminium is replaced by Stainless Steel, while a variation of 76.6 K is obtained in the case of the Preamplifiers, when we compare the same materials.

Table 3: Study of the Effect of New Materials for Al Cover (Case TCC = 2000 W/m^2K)

Thermal Bridge	T_{MAX} Ge Crystal (K)	T_{MAX} Preamplifiers (K)
Stainless Steel	91.078	314.26
Aluminum	94.668	237.7
Copper	95.276	197.05

VIBRATIONAL STUDIES

The main source of vibration of the detector is the Cryocooler. This component is connected to the Cu Arm through the Cu Braid. From the thermal point of view the efficiency of heat transfer increases as the thickness of the Cu Braid increases, but from the point of view of vibration transmission it is advisable to choose the Cu Braid with the smallest thickness to mitigate the transmission of vibrations to the Detector Head.

During the development of this project two models of Cu Braid have been identified, with equivalent thicknesses (CbT) of 1.25 and 1.75 mm. In this context, the simulations in this section are aimed at calculating the vibrations in the Detector Head for the two mentioned Cu Braid thicknesses.

15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
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These studies also include static structural calculations and modal analysis of these configurations.

Geometry and Boundary Conditions

Fig. 4 represents the simplified model used in the simulations. The structure is composed of the Cu Braid, the Cu Arm, the Cu Holder, and the Detector Head. The Stainless Steel inner concentric cylinder is also included, which is connected to the main chamber and to the Cu Arm, in the latter case through the Arm Holders. Zones A and B are assumed to be fixed boundaries in the simulation (zero displacement). The effect of gravity is added to calculate the stresses and deformations due to the weight of the components. In zone A, a real acceleration distribution map is applied for a specific range of frequencies, whose data comes from values measured by [4] during the commissioning of the cryocooler (lower part of Fig. 4). Depending on the position of the Arm Holders, two configurations have been studied, called case 1 (C1) and case 2 (C2), as represented in the upper right part of Fig. 4.

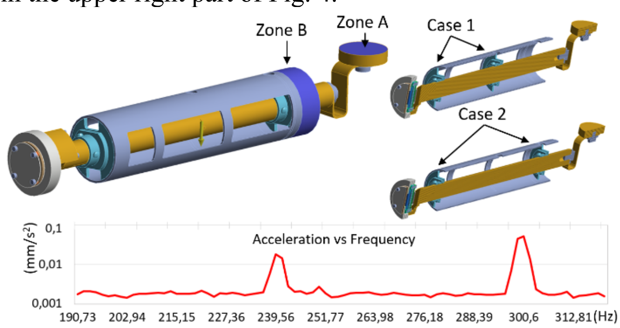

Figure 4: Simplified model used for mechanical simulations. Zones A and B are assumed to have zero displacement. Depending on the position of the Arm Holders, cases 1 and 2 are proposed. In the lower part, a map of real accelerations imposed as a boundary condition in zone A is represented.

Results

Table 4 presents a summary of the obtained results. Static structural simulations result in low values of deformation (Def) and stress (ST): the stresses are below the elastic limit for Copper and Stainless Steel. For the modal analysis, similar values of the natural frequency are obtained for the four studied cases, for example the difference for the first natural frequency (1stF) between all cases is less than 3%. In the case of the maximum acceleration in the vertical direction Z (AcZ), similar results to each other are obtained for all configurations, all of them located in the Detector Head. In particular, the similarity is closer for the cases of configuration C2.

Fig. 5 shows the results of the simulations for the case CbT = 1.25 mm and C2. In the upper part the behavior of the deformation due to the effect of gravity is observed, whose maximum value is 10 µm, while in the lower part the distribution of the maximum acceleration in the vertical Z direction is presented, whose maximum value is 0.003 mm/s^2.

Table 4: Summary of the Mechanical Simulations, for Configurations C1 and C2, and Two Thickness of the Cu Braid

	C1		**C2**	
CbT (mm)	**1.25**	**1.75**	**1.25**	**1.75**
Def (µm)	9.55	11	10	11
ST (MPa)	4.85	7.7	3.76	7.7
1stF (Hz)	191	193	188	190.5
AcZ (mm/s^2)	2.8E-3	3.5E-3	3E-3	3.03E-3

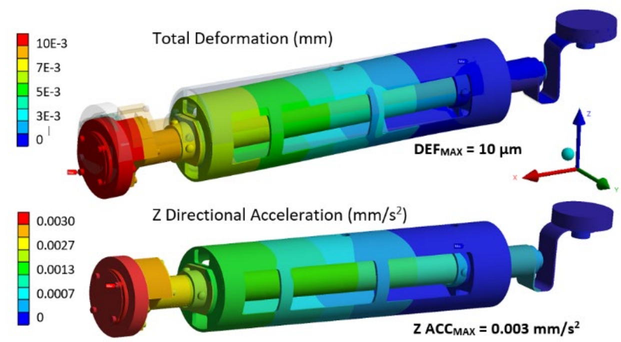

Figure 5: Results of numerical simulations for the case CbT = 1.25 mm and C2. The distributions of the total deformation and the Z directional acceleration are presented.

CONCLUSION

The results of the latest thermal and mechanical simulations for the design of a new generation of Germanium detector have been presented.

In the thermal part, a modification of the Al Cover has been proposed, in order to optimize the thermal behaviour of the PCB. With this modification, the temperature obtained on the PCB and the Ge Crystal meet the design criteria as defined in the technical specifications.

In the mechanical part, the vibration simulations confirm that the transmission of the acceleration map imposed at the end part of the cryocooler results in similar values of vibrations in the Detector Head, for the two thicknesses of simulated Cu Braid. This result allows us to make the decision to select the thicker Cu Braid, because the heat transfer is more efficient compared to the thinner case.

ACKNOWLEDGEMENTS

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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