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THERMAL MECHANICAL SIMULATIONS OF A NEW GERMANIUM DETECTOR DEVELOPED IN THE EUROPEAN PROJECT LEAPS-INNOV FOR X-RAY SPECTROSCOPY APPLICATIONS AT SYNCHROTRON FACILITIES*

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Abstract

For X-ray spectroscopy applications it has been verified that Germanium detectors are used to detect efficiently photons of considerable higher energy with respect to Silicon detectors. For cases like fluorescence detectors for absorption spectroscopy (XAFS), Germanium detectors do not show artefacts due to features like the escape peak interfering with interesting peaks being measured. In this context, the European project LEAPS-INNOV has launched a Research and Development program dedicated to the design of a new generation of Germanium detectors for X-ray detection. From the thermal mechanical point of view, in order to optimize the efficiency of the new Germanium detector, finite element analysis (FEA) studies have been carried out on different geometrical models. In this paper, the thermal mechanical calculations of the current prototype are presented, as well as the details of the modifications implemented since the beginning of the project, with the main objective of optimizing the operating conditions of the Germanium sensor and its associated components. For numerical simulations the ANSYS WORKBENCH software has been used.

INTRODUCTION

One of the requirements of High Purity Germanium (HPGe) detectors is their operation under high vacuum and cryogenic conditions. Under this premise, for the design of a prototype of the HPGe detector the XAFS-DET project has defined the following criteria [1]: (i) Minimize the temperature of the Germanium crystal as closest as possible to 77 K and below 100 K, (ii) Uniform temperature distribution in the sensor: the temperature gradient over the Germanium crystal should not exceed 5 K, and (iii) For vacuum, the pressure working condition is $1x10^{-7}$ mbar. In the case of the multi-channel integrated preamplifier, its working temperature has been specified in the range of 77 K up to 330 K.

In the mechanical part, the behaviour of stress and deformation due to the effects of gravity and vacuum pressure in the chamber is analysed. In the current phase, experimental studies of vibration due to cryocooler operation are being carried out [2], while numerical vibration simulations are still in a preliminary stage of research.

Since the beginning of the project, the prototype of the Germanium detector has undergone several modifications. The most recent version discussed in Hamburg [3] is presented in this paper, focused mainly on issues related to thermomechanical simulations FEA (Finite Element Analysis).

GEOMETRY DESCRIPTION

In Fig. 1 the simplified 3D model of the detector is presented. The geometry is made up of three interconnected parts: (i) The Detector Head. This part includes the Germanium sensor ($21x21x4$ mm^3) and its mechanical holder, the front-end electronics composed of boards equipped with specific readout preamplifiers, some interconnections between the Germanium sensor 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, the Cu Braid, the Cu Arm, the Cu Holder and the Arm Holder, (iii) The Vacuum Chamber. To support the cooling, a concentric inner cylinder has been included. The Beryllium Window is attached to the vacuum chamber, close to the Detector Head.

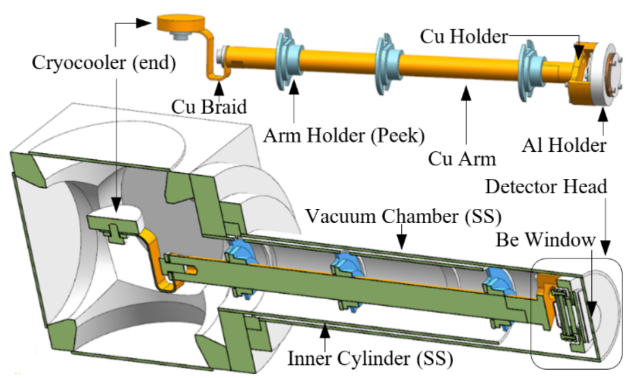

Figure 1: Simplified 3D model of the Germanium Detector prototype.

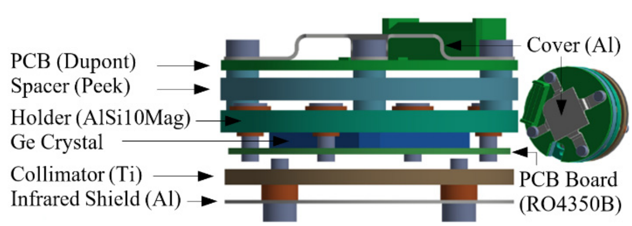

Figure 2: Simplified 3D model of the main components of the Detector Head.

FEA MODEL

Numerical simulations have been studied for the steady state regime. The first part of this investigation is purely thermal, in order to obtain the distribution of temperatures. The second part is purely mechanical, with the objective of

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evaluating the deformations and stresses due to gravity and the effects of the vacuum inside the chamber.

For the heat transfer processes, natural convection of the air is assumed in the external part of the chamber, while in its internal part, heat transfer by conduction and Stefan Boltzmann radiation are studied.

For all cases, previous meshing studies have been carried out to evaluate the independence of the results with the number of elements. The optimal value for the simulations has been approximately one million elements.

Physical Properties

Table 1 shows the values of the physical properties, taken from the literature and from the manufacturers. In most cases it has not been possible to obtain their values as a function of temperature, especially important in cryogenic conditions.

Table 1: Physical Properties TC (Thermal Conductivity), D (Density), YM (Young Modulus) and P (Poisson Ratio)

Material	TC (W/mK)	D (Kg/m^3)	YM (MPa)	P
Al	102	2770	71000	0.33
AlSi10Mg	85	2660	69500	0.33
Be (295 K)	204	1848	287000	0.07
Cu (81K)	461	8960	124000	0.34
Dupont	3	3100	9590	0.22
Ge (90K)	270	5320	130000	0.30
Peek	0.25	1320	4000	0.4
RO4350B	0.69	1860	22000	0.28
SS (290 K)	15	7850	198000	0.29
Ti (90 K)	32	4510	120000	0.33
Vespel	0.35	2151	1530	0.46

Boundary Conditions

The following thermal boundary conditions have been set (i) Power dissipation of 0.14 W in each preamplifier of the PCB (Fig. 3a), (ii) Constant temperature in the cryocooler. This component is represented by a small cylinder, where a constant temperature of 77 K is fixed (Fig. 3b), and (iii) For the outside air, natural convection is simulated assuming a convection coefficient equal to 5 W/m^2K at 23 C.

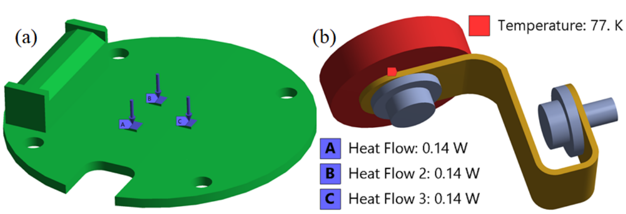

Figure 3: Boundary conditions: (a) Power dissipated in each preamplifier and (b) Constant temperature at the tip of the cryocooler.

For the heat transfer by radiation between the internal surfaces of the chamber and the detector, constant average emissivity values are assumed: AlSi10Mg (0.1), Al (0.008), Be (0.18), Cu (0.004), Dupont (0.8), Ge (0.02), RO4350B (0.8), SS (0.1 at 23 C and 0.05 under cryogenic conditions), Ti (0.2), Vespel (0.8), and Peek (0.5).

For the static structural analysis, the effect of gravity and external pressure of 1 atm have been studied, considering zero pressure inside the chamber as a conservative value.

Thermal Contact Conductance (TCC)

The model has generated 94 contact surfaces. As an approximation criterion, the values of 2000, 6000 and 10000 W/m^2K are assumed as bad, regular and good contacts. In the special case of PCB screws, the mean value of 500 W/m^2K is applied.

THERMAL OPTIMIZATION

During the annual LEAPS meeting in Hamburg [3], the temperature values TGe =153.12 K and TPCB = 272.31 K were reported for the Ge crystal and the PCB, respectively. These values were calculated for the geometry described in Fig. 1. In the same meeting, several optimization strategies were proposed that would allow us to approach the design criteria defined in [1]. Prior to the implementation of the new studies, an update of the dissipated power in each of the three preamplifiers has been carried out: 0.14 W instead of 0.12 W. With this new condition, the results TGe =153.73 K and TPCB were obtained = 280.41 K, which represent the new starting point for optimization studies:

- Modification 1 (M1). Previous simulations have confirmed a significant heat transfer between the Cu Arm and the Inner Cylinder, through the Arm Holder. To minimize this effect, it has been proposed to fix each Arm Holder only with the tips of three screws made of Peek, instead of having full contact as described in Fig. 4. With this change, the temperatures TGe = 125.99 K and TPCB = 266.12 K are obtained.

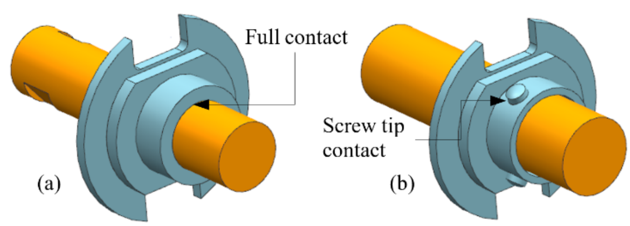

Figure 4: Fixation of the Arm Holder on the Cu Arm. (a) Total contact between surfaces and (b) Contact only through the tips of the 3 screws made of Peek. Case (b) is more effective in minimizing heat transfer.

- Modification 2 (M2). Fix the Cu Arm with only 2 Arm Holder, instead of using all three units. If we include this change and maintain the M1 strategy, we obtain the temperatures TGe = 123.44 K and TPCB = 264.78 K.
- Modification 3 (M3). To optimize the heat transfer between the Cryocooler and the Detector Head it has been proposed to increase the diameter of the Cu Arm from 19 to 22 mm. Combining the modifications M1 and M3, the temperatures TGe = 124.31 K and TPCB = 265.24 K are obtained. While if we combine the

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modifications M1, M2 and M3, we obtain TGe = 121.61 K and TPCB = 263.82 K.

- Modification 4 (M4). Updating of thermal contacts at critical points. The TCC values considered in previous studies are conservative, having set TCC = 6000 W/m^2K in critical areas of the Cu Braid, Cu Arm and Detector Head. If we assume the most realistic value of TCC = 10000 W/m^2K and while maintaining the strategies M1, M2 and M3, the temperatures TGe = 119 K and TPCB = 262.08 K are obtained.
- Modification 5 (M5). Modification of the effective section of the Cu Braid: 35 instead of 25 mm^2. Considering this modification plus the changes M1 to M4, the temperatures TGe = 113.57 K and TPCB = 259.2 K are obtained.
- Modification 6 (M6). Previous thermal simulations confirm a significant heat transfer from the PCB to the Ge crystal through the stainless-steel screws as indicated in Fig. 5. To mitigate this effect, it is proposed to use screws made of very low thermal conductivity material such as Peek. At the same time, the thermal contact of the screws is updated to 500 W/m^2K, considering that in previous models the optimistic value of 1000 W/m^2K has been applied. With these modifications and introducing the changes M1 to M5, the temperatures TGe = 99.575 K and TPCB = 337.24 K are obtained.

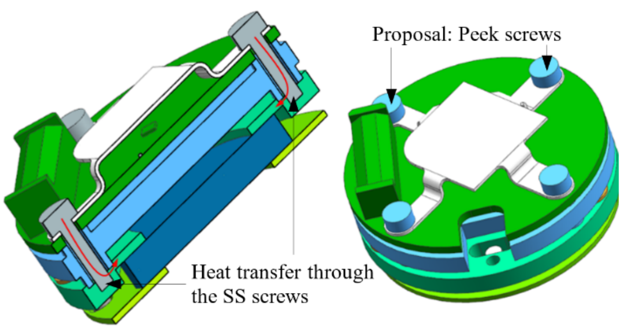

Figure 5: Description of the heat transfer from the PCB to the Ge crystal, through the stainless-steel screws.

- Modification 7 (M7). This point is related to a proposal for a change in the cryocooler working point: set the value of the operating temperature at 67 instead of 77 K. Considering this possibility plus the modifications from M1 to M6, the temperatures TGe = 89.162 K and TPCB = 336.33 K are obtained

RESULTS

In Fig. 6 (a and b) the temperature values obtained after applying all the optimization steps proposed in the previous section are presented. The results for the Ge crystal are within the defined criteria (T_{MAX} = 89.162 < 100 K, and temperature gradient 0.084 K < 5 K). In the case of the multi-channel integrated preamplifier and PCB, the value is 6.33 K above the maximum set temperature. From the point of view of the best temperature on the PCB, this is obtained when we apply steps M1 to M5 (259.2 K), but in contrast, the value of the maximum temperature on the Ge crystal rises to 113.57 K. This indicates a new way to investigate in the same step M6: it is necessary to restrict the heat transfer but with the condition of not affecting too much the cooling of the PCB. In this new study, a new material for the screw and the adequate value of its thermal contact with the other parts should be investigated.

The results of the static structural simulations are within the acceptable values, the maximum stress is 15 MPa for the vacuum chamber and the maximum deformation of the detector is 5 um (Fig. 6c).

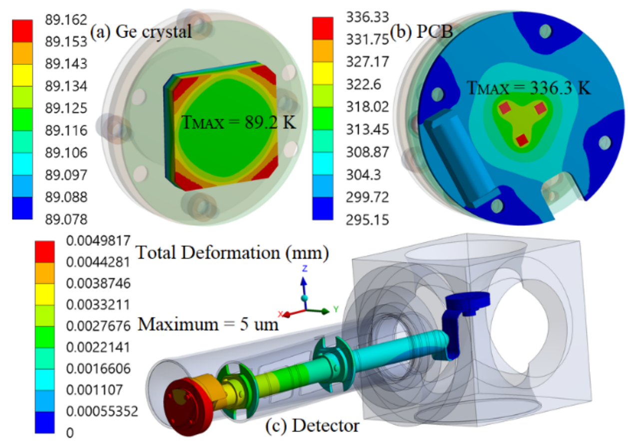

Figure 6: Results of the thermomechanical simulations, after having applied the optimization steps M1 to M7. (a) Temperature distribution in the Ge crystal, (b) Temperature distribution in the PCB, and (c) Deformation in the detector.

CONCLUSION

The current prototype of the Germanium detector has an important advance in its design. The thermal results based on the numerical simulations are close to the desired order of magnitude, however we consider that an improvement of the current thermal behaviour is viable, tasks that are part of the development of the project. The structural static results show acceptable deformation and stress values.

The results of the numerical simulations are strongly dependent on the thermal contacts and the physical properties of the materials. The values applied in this work deserve a constant revision and investigation, having found limited information and especially for vacuum and cryogenic conditions.

The selection of Cu Braid, which has not been part of this publication, is an important step that is in progress, due to its implication in thermal optimization, as well as its role in the transmission of vibrations from the cryocooler to the Detector Head.

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