Optimization of Electrically Cooled Complex HPGe Detector

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Abstract— **This article presents a novel technique used for design and optimization of a composite HPGe detector with two or three encapsulated Ge-crystals and based on electromechanical cooling engine. In this technique is accentuated on the detailed investigation of the heat transfer processes – each one separately and in complex, and their impact on the detector performance. The dominating heat transfer mechanisms have been identified and appropriate mathematical model has been applied. Temperature distributions within the detector structure are calculated for various environment and cooling conditions and the functional characteristics of the assembly as well the minimal necessary cooling power of the cooling engine, needed to reach the operational temperature range, are determined. For the typical cooling power of the engine X-Cooler II of 3 W, the temperature of the crystal is found to be comfortably within the operational range of the HPGe detectors.**

Keywords- high purity Ge Detector; cooling

I. INTRODUCTION

Germanium (Ge) detectors are key instruments in nuclear structure physics for measuring electromagnetic radiation from excited nuclei. Typically they are cooled by liquid nitrogen. For some applications however, an electromechanical cooling engine may be a better choice. Its cooling power is lower than the liquid nitrogen based cooling technology and this requires a detailed investigation of the thermal processes and an optimization of the inner cold structure.

A composite detector made of two or three large volume encapsulated germanium [1] crystals and cooled by the electromechanical cooling engine X-Cooler II (ORTEC) [2] are planned to be used within the PANDA [3] project. A study of the cooling of a single encapsulated detector [4] and its experimental realization [5] has proven the feasibility of composite detector electromechanical cooling.

II. PHYSICAL MODEL

The germanium crystals and the cold structure are installed in a vacuum cryostat where three processes, schematically presented in Fig. 1, determine the energy transfer between the room temperature cryostat walls and the low temperature assembly – heat radiation, thermal conductivity and residual molecular heating. A careful design of the components and appropriate material choice may substantially reduce the heat absorbed by the germanium crystals, thus making achievable the goals of electromechanically cooled HPGe detectors.

The HPGe detectors are typically operated within the range of 77-110 K which determines a temperature difference between the warm cryostat walls and the cold frame of about 220 K. The assembly displayed on Fig.2 possesses large surface of the detector cup surrounding the capsules hence predetermining an elevated radiative heating which may dominate even the overall heat transfer.

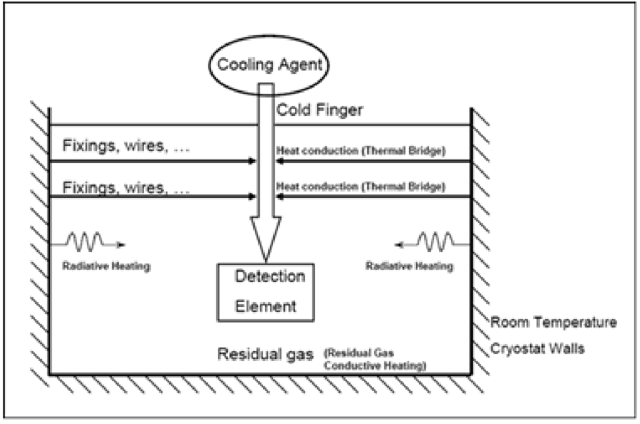

Figure 1. Heat transfer schematic within the detector assembly.

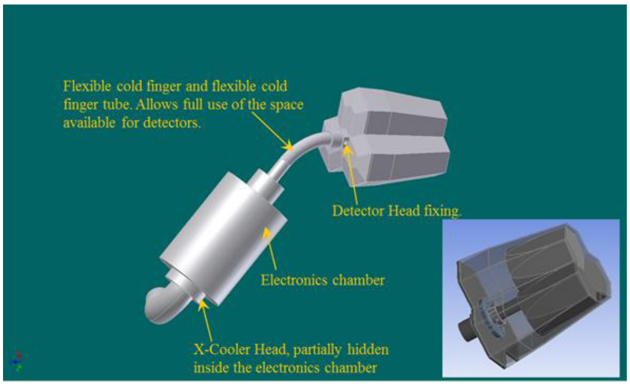

Figure 2. Schematic drawing of the detector assembly.

Along that, the warming effect of the thermal bridges -- mechanical components used for fixing the cold structure to the warm section of the cryostat and the internal cabling between the crystal housing and the vacuum feedthrough, may play substantial role. The fixing elements of the detector system under optimization – labyrinths and spacers seem to be critical parts and an accurate dimensioning is needed in order to achieve minimal heat transfer at the same time preserving gamma-spectroscopy properties and the functionality required.

The space limitations and the efficiency constraints impose minimal gap between the capsules assembly and the cryostat walls. However, at some critical gaps width, the residual gas of the evacuated inner space contributes significantly to the detectors warming and this effect depends on the vacuum level [6]. The impact of the residual gas warming on the detector assembly temperature will be discussed elsewhere.

The heat transfer within the interior domain of the assembly is being carried out under a broad temperature interval typically ranging from 77 K up to 300 K. The thermal conductivity displays a temperature dependent behavior in such a wide-stretched domain and its values at room temperature may not be a good base for calculations.

III. MATHEMATICAL MODEL

The temperature distribution has been calculated using the time dependent heat transfer equation

$$\nabla\cdot(\lambda\nabla T)=\rho c\partial T/\partial t \qquad (1)$$

where

T is the temperature [K]
λ is the thermal conductivity [W/m^{2}K]
c is the specific heat [J/kg.K]
ρ is the mass density [kg/m^3]
t is the time [s].

The temperature dependent behavior of the thermal conductivity has been also accounted.

The boundary condition at the interface between the cooling engine and the detectors assembly is defined as follows

$$T=T_{cf} \qquad (2)$$

Here T_{cf} is the temperature of the cold finger.

The outer part of the detector assembly is supposed to be equal to the room temperature T_{am} so that

$$T=T_{am}. \qquad (3)$$

Radiation heat flow rate from surface *i* to surface *j* is based on Stefan-Boltzmann law and given by

$$q=\varepsilon\sigma A_{ij}F_{ij}(T_i^4-T_j^4) \qquad (4)$$

where

σ =5.6704•10-8 W/m^{2}K4 is the Stefan-Boltzmann constant
ε is the surface emissivity
A_i is the area of surface I
F_{ij} is the form factor from surface *i* to surface *j*
T_i is the absolute temperature of surface *i* and
T_j is the absolute temperature of surface *j*.

Finally the model has been completed by taking into account the irradiation between the capsules surfaces and the cryostats wall as well as the irradiation between the cold frame, cold finger and the cryostats wall. The irradiation between the Ge-crystals and the capsule walls has been neglected due to the minor temperature difference there.

IV. RESULTS AND DISCUSSIONS

Four main factors influence the heat losses: the surface emissivity, the surface area, the ambient temperature and the temperature of the cold finger.

The emissivity ε depends strongly on the surface quality of the material. For polished aluminum it is typically 0.05 and for oxidized or rough surface it increases to 0.14. The surface of the crystal capsules has a rather rough appearance and cannot be re-processed.

First problem under investigations is the determination of the time needed by the Ge-detectors to reach the operational temperature and additionally the holding time of the cold detector when the active cooling has been switched off. The second one determines the technological time for installation of the detector system onto the array frame and the troubleshooting time. Clearly, the relation between the heat capacity and the surface area of the cold structure determines the cooling and holding time of the detector. To give a quantitative answer of these questions the detector assembly has been numerically simulated. The dependence of detector cooling on the surface emissivity is presented in Fig. 3 and Fig. 4.

Detector warming is presented in Fig.5. The warming up phases of a single detector has been numerically calculated by means of ANSYS (assuming emissivity of 0.2). Based on 77 K cold frame temperature and 300 K warm aluminum detector cup temperature, the heat loads has been evaluated and found to be 450 W/m^2.

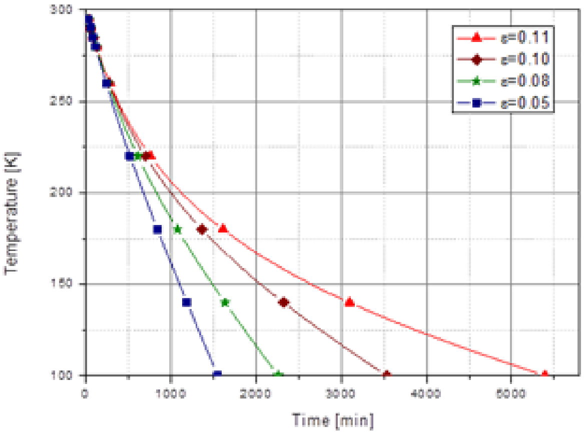

Figure 3. Double detector cooling as a function of the capsules emissivity.

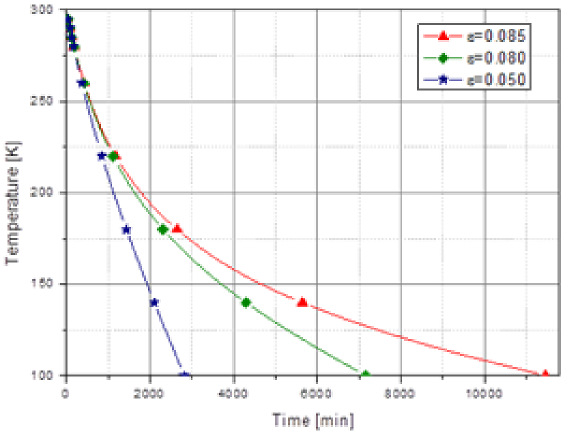

Figure 4. Triple detector cooling as a function of the capsules emissivity.

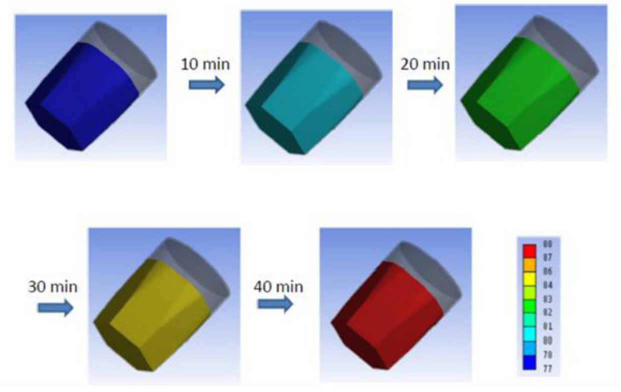

Figure 5. Temperature increase of the HPGe detector in stand-alone regime.

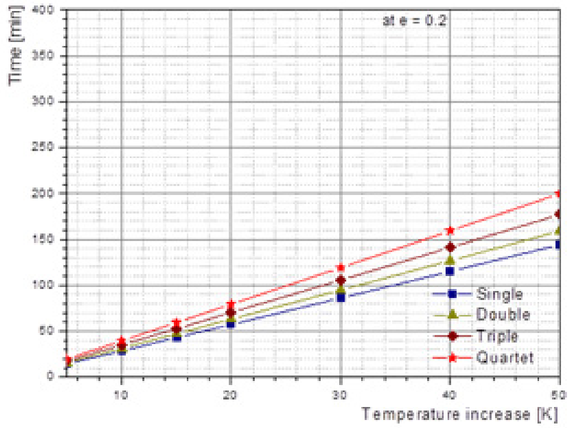

Figure 6. Temperature evolution as a function of the detector configuration and ε=0.2.

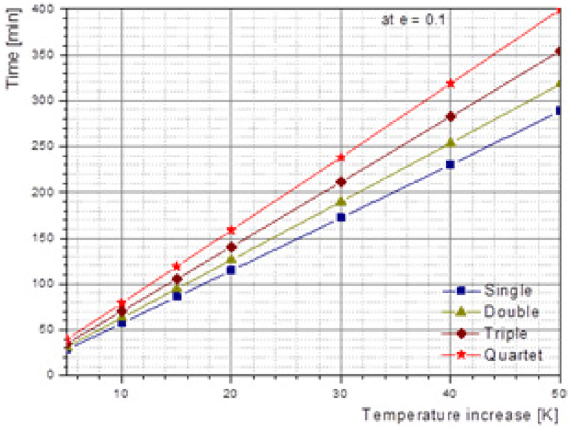

Figure 7. Temperature evolution as a function of the detector configuration and ε=0.1.

The warm up time is evaluated based on typical crystal housing sizes and also is presented on Fig.6-7. It is worth to note, that the physical model is valid for the initial phase of one or two hours of the warming up process. More extended time range would require further elaboration of this model.

As a comparison, the warming up of a single HPGe detector with 15% efficiency (commercially available PopTop capsule by ORTEC), which corresponds of 344 g Ge is presented on Fig.8. The temperature has been calculated for emissivity 0.1 and 0.2 and a good agreement has been found if ε=0.1or slightly less is assumed. This measurement also indicates what emissivity should be expected utilizing a standard manufacturing technology.

Thermal field simulations have been performed for 3-capsules (triplet) and 2-capsules (doublet) detector assembly

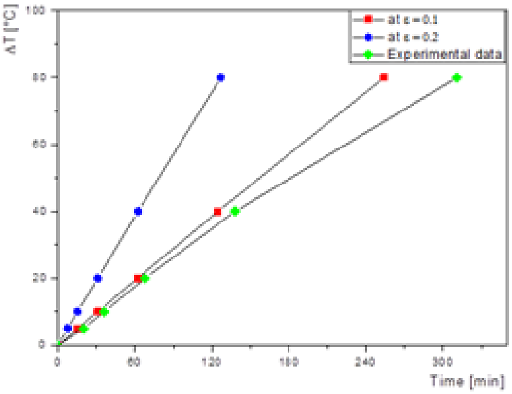

Figure 8. Warming up of a single HPGe detector with 15 % efficiency.

respectively. Here only the results concerning the triple detector are to be discussed.

The calculations have been performed for two different temperature of the cooling part (70 K and 100 K) while the environment temperature varies from 293.15 K up (20 °C) to 313.15 K (40 °C). The study of the thermal processes at such an extended temperature range is determined on the significant impact of the ambient temperature on the performance of the HPGe crystal. The emissivity of the Ge-capsules is supposed to vary between 0.2 und 0.1 while the emissivity of the other parts of the assembly is taken to be 0.1.

The simulation has been carried out at temperature of the cooling part 70 K and the ambient temperature 295.15 K. The emissivity of the Ge-capsules is taken to be 0.2, when the emissivity of the processed inner surface of the cryostat is 0.1. The temperature distribution is presented in Fig. 9.

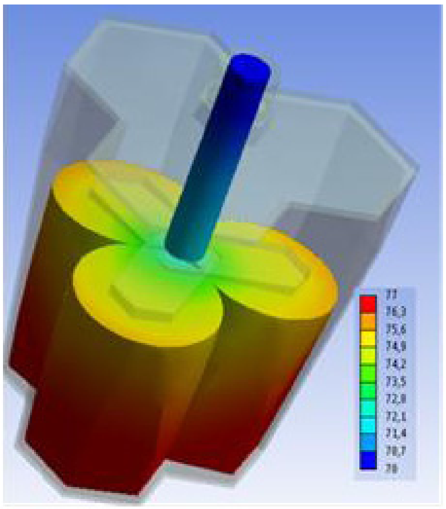

Figure 9. Temperature distribution along the Ge-capsules and the cold finger when the temperature of the cooling part is 70 K and the ambient temperature is 295.15 K. The emissivity of the Ge-capsules is 0.2, when the emissivity of the processed inner surface of the cryostat is 0.1.

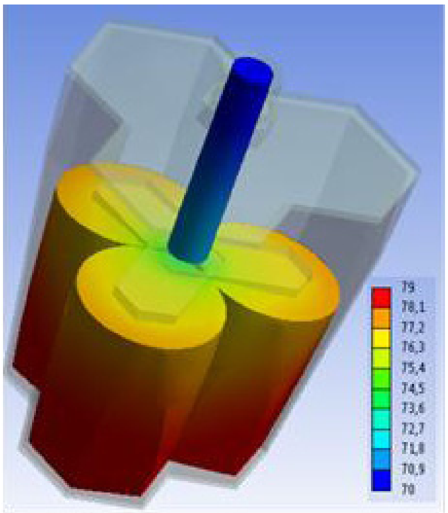

Figure 10. Temperature distribution along the Ge-crystals and the cold finger when the temperature of the cooling part is 100 K and the ambient temperature is 295.15 K. The emissivity of the Ge-capsules is 0.2, when the emissivity of the processed inner surface of the cryostat is 0.1. Thermal conductance is 6000 W/m².K.

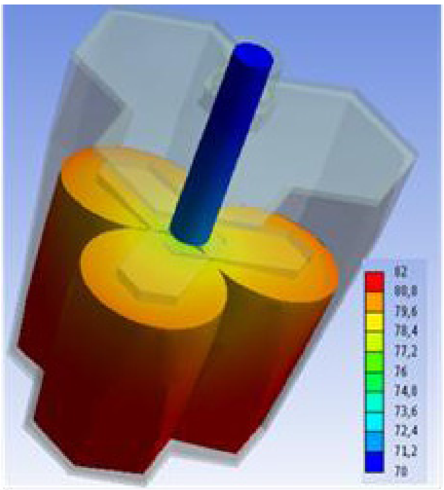

Figure 11. Temperature distribution along the Ge-crystals and the cold finger when the temperature of the cooling part is 100 K and the ambient temperature is 295.15 K. The emissivity of the Ge-capsules is 0.2, when the emissivity of the processed inner surface of the cryostat is 0.1. Thermal conductance is 2000 W/m².K.

It is seen that the temperature variation is within 5 grad range along the Ge-capsule, which may be attributed to the good germanium and aluminum thermal conductivity especially at cryogenic temperatures.

In that peculiar case the calculated total heat losses are equal to 3.06 W which is slightly above the limit typical for X-Cooler II. Due to the wide production variations of the cooling engine, the operational temperature of the Ge-detectors may not be reached. To decrease the warming effect of the cryostat walls the capsules surfaces should be additionally protected.

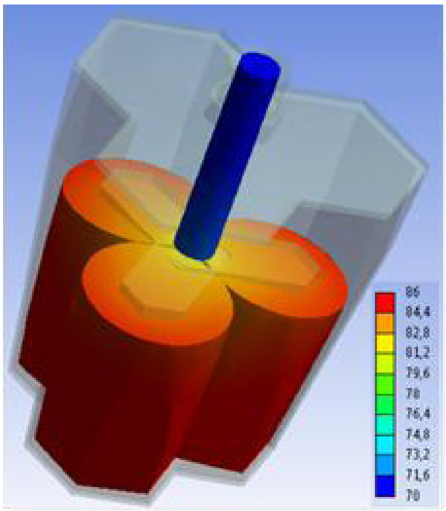

Figure 12. Temperature distribution along the Ge-crystals and the cold finger when the temperature of the cooling part is 100 K and the ambient temperature is 295.15 K. The emissivity of the Ge-capsules is 0.2, when the emissivity of the processed inner surface of the cryostat is 0.1. Thermal conductance is 1000 W/m².K.

Contact between the cold finger and the cold frame is of paramount importance for the thermal management of the whole detector assembly and different scenarios have been evaluated in this study.

In most of the literature the thermal contact conductance is associated with two solid surfaces together under applied load. But recently an experimental study of thermal conductance was conducted with pairs of aluminum alloy specimens jointed by bolts [7].

The calculations have been performed for a typical configuration when the cooling part is at a temperature of 70 K when the environment temperature is 295.15 K. Ge-capsules emissivity is taken to be 0.2 and the emissivity of the other parts of the assembly is 0.1. The thermal conductance serves as a figure of merit of the thermal contact quality. The temperature distribution along the Ge-capsules is presented in Fig. 10-12 for thermal conductance considered to be 6000 W/m².K; 2000 W/m².K and 1000 W/m².K respectively.

The contact quality slightly influences the heat losses but has a strong impact on the temperature increase along the crystal surface as it is seen from Fig. 10-12.

V. CONCLUSION

It is clear from this study that by simulation of the thermal processes at the HPGe detector assembly important parameters can be assessed and thus an optimization of the design to be carried out. As a result not only an optimal performance of the detector should be expected but also an enhanced functionality of the whole array may be achieved. Certainly, novel technologies are to be used and these results may serve as a guide at the ongoing technical design. It worth to note, that cooling power of the electromechanical cooling engine plays important role and its accurate measuring is necessary.

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