Temperature Distribution Study of Composite Germanium Detector

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Abstract: Temperature distributions of cooled Germanium (Ge) detectors are calculated by the COMSOL MULTIPHYSICS software in order to determine the necessary cooling power of an electromechanical cooling engine. For a single Ge-crystal heat losses of 2.5 W are determined which increase to 5.7 W for a composite detector with three Ge-crystals. The energy transfer may be reduced substantially by a heat reflector which will allow the electromechanical cooling engine to keep also the composite Ge-detector under desirable temperature.

Keywords: Mechanical cooler for Germanium detectors, Heat transfer, Heat radiation

1. Introduction

Germanium (Ge) detectors are key instruments in nuclear structure physics for measuring electromagnetic radiation from excited nuclei. Typically operated in the temperature range of $77-115\,K$, they are cooled by liquid nitrogen. However, for some applications, an electromechanical cooling engine may be used. Its cooling power is limited which requires a detailed investigation of the temperature distribution and an optimization of the inner cold structure for utilizing such a cooling engine.

A composite detector made of three large volume encapsulated Ge [1] crystals and cooled by the electromechanical cooling engine X-Cooler II (ORTEC) [2] has been considered. The individual Ge crystals are sealed in an aluminum can and installed in a common vacuum cryostat (Fig.1), where the heat radiation process determines the energy transfer between the room temperature cryostat walls and the low temperature detector assembly.

An intermediate thermal shield may be applied in order to act as a heat reflector thus reducing the heating of the encapsulated Ge crystals.

In chapter 2 the physical model of the heat transfer will be introduced. The calculated results for a single Ge crystal and a composite detector are presented in chapter 3, which is followed by the conclusion.

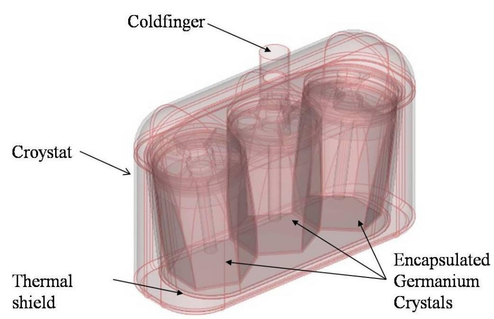

Fig.1. The technical drawing of the detector assembly shows the three encapsulated Ge crystals, the thermal shield working as a heat reflector, the common cryostat and the interface to the cooling engine (coldfinger).

2. Physical Model

The heat transfer in the detector assembly is determined by the heat exchange between the outer parts of the cryostat which are at room temperature and the inner cold structure which is at near liquid nitrogen temperature. The path of the transfer leads through the coldfinger to the cold frame which holds the encapsulated detectors and further to the capsules structure which cools the Ge crystal. The thermal shield attached to the cold frame also contributes to the heat transfer directly by heat exchange with the cold frame and indirectly by heat exchange with the capsule. Therefore a “Surface-To-Surface-Radiation” model could be applied. However, the radiative geometric configuration factors which have to be considered would need large computing power. Due to limitations in computer main storage (4 GB) this approach has been abandoned and the model has been simplified properly.

The temperature difference between the crystals and the capsules and between the capsules and the heat reflector are negligible compared to the temperature difference between the heat reflector and the cryostat. And thus the heat losses defined need not be accounted.

Choosing an appropriate effective surface emissivity ε, the heat exchange between the heat reflector and the cryostat has been described by an effective radiation from the ambient vacuum on to the heat reflector surface, which causes the warming up of the surface. Therefore the "Surface-to-Ambient" COMSOL MULTIPHYSICS model could be applied.

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

$$\lambda \Delta T = \rho c \frac{\delta T}{\delta t}, \qquad (1)$$

where the symbols have the following meaning

- $T\ [K]$ temperature,
- $\lambda\ \left[Wm^{-2}K^{-1}\right]$ thermal conductivity,
- $c\left[Jkg^{-1}K^{-1}\right]$ specific heat capacity
- $\rho\ \left[kg\ m^{-3}\right]$ mass density
- $t\ [s]$ time

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

$$T(x,y) = T_{cf}\ . \qquad (2)$$

Here T_{cf} is the temperature of the coldfinger.

The heat radiation flux at the heat reflector is given by

$$\dot{q} = \varepsilon\sigma(T^4 - T_a^4)\ . \qquad (3)$$

Therefore, at that interface the following condition takes place:

$$\lambda \frac{\partial T}{\partial \vec{n}} = \varepsilon\sigma(T^4 - T_a^4)\ , \qquad (4)$$

with

- $T_a\ [K]$ ambient temperature
- $\sigma\ [Wm^{-2}K^{-4}]\ =\ 5.6704 \cdot 10^{-8}$ Stefan-Boltzmann-constant
- $\vec{n}$ the normal vector to the boundary.

3. Result and Discussion

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

For the calculations the ambient temperature and the temperature of the coldfinger are set to $300\ K$ and $77\ K$, respectively.

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 can not be re-processed. Therefore the heat transfer can only be reduced by a polished heat reflector made out of aluminum.

3.1 Single Germanium-detector

A single Ge-detector has been investigated in order to assess the cooling power which should be reached by the electromechanical engine X-Cooler II (ORTEC).

Fig.2 and Fig.3 present the temperature distributions of a single encapsulated detector where the cooling interface is the upper base of the capsule. In Fig.2 the temperature distribution is given along the capsule surface and in Fig.3 the temperature is displayed in a cross section of the capsule. Here the surface area is $0.02\ m^2$ and the surface emissivity is taken to be 0.14. Due to the heat transfer the temperature may increase up to $82.6\,K$ and the temperature variations are in the fully acceptable level of $6\ K$.

In the present case the heat losses are $2.5\ W$ and might be considered as a measure of the cooling power of the electromechanical cooler X-COOLER II because comparable industrial crystal assemblies with similar Ge sizes are typically operated by this cooling engine.

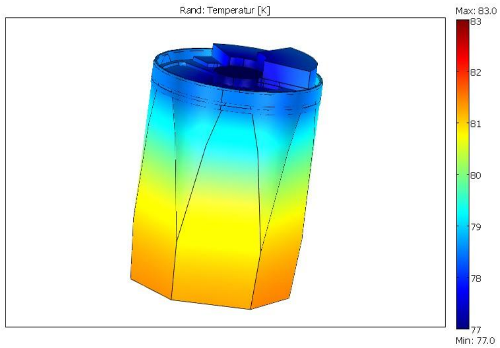

Figure 2. Surface temperature distribution of a single Ge-detector.

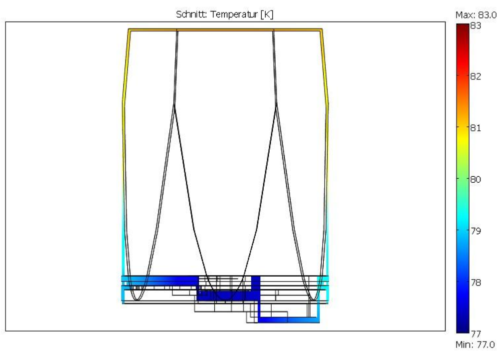

Figure 3. Temperature distribution of a single Ge-detector in a cross section of the capsule.

3.2 Composite Germanium detector

Two typical configurations – one with and the other without heat shield - have been studied. A heat reflector reduces the active surface area and its material surface can be polished in order to decrease its emissivity as well.

The effective interaction surface area is $0.041\,m^2$ and reduces to $0.036\,m^2$ with heat reflector.

It is worth mentioning that at the same emissivity the heat reflector slightly influences the temperature distribution. The surface temperature distribution at an emissivity of 0.14 is presented in Fig.4 and Fig.5. The maximal temperature achieved is $84.7\,K$.

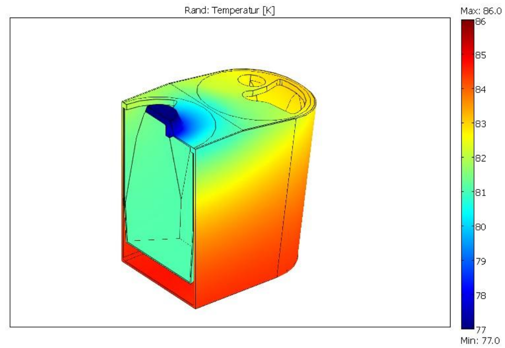

Fig.4 Surface temperature distribution of the composite Ge-detector ($\varepsilon = 0.14$).

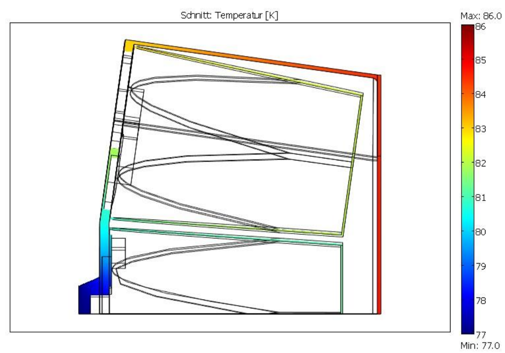

Fig.5 Temperature distribution of the composite Ge-detectors in a cross section of the capsule ($\varepsilon = 0.14$).

As it has been expected the emissivity strongly influenced the maximal temperature $T_{\max}$ achieved and the heat losses $\dot{q}$ which are given in Table 1.

Table 1. Heat flux $\dot{q}$ and the maximal temperature $T_{\max}$ for the composite Ge-detector as function of the emissivity ε .

ε	$\dot{q}\ [W]$	$T_{\max}\ [K]$
0.02	0.82	78.14
0.04	1.64	79.27
0.06	2.45	80.41
0.08	3.27	81.54
0.10	4.09	82.68
0.12	4.91	83.81
0.14	5.72	84.94
0.16	6.74	86.07

For a standard aluminum reflector the cooling power is increased to $5.7\ W$ relative to a single Ge-crystal. However, if a polished aluminium reflector ($\varepsilon = 0.06$) is installed, the same cooling power is sufficient as for the single Ge crystal.

The investigation of the reflector thickness on the heat transfer has shown minor impact. As it has been expected, increase of the heat reflector thickness leads to a more uniform temperature distribution, but does not significantly reduce the heat losses, respectively the thermal power needed. For instance an increase of the thickness from $1\ mm$ to $2.5\ mm$ decreases the maximum temperature by less than $3\ K$ at an emissivity $\varepsilon = 0.14$.

4. Conclusions

The investigation has shown that the heat losses for a single Ge crystal amount to about $2.5\ W$ when assuming a conventional cryostat design. For a triple detector assembly the cooling power would increase to $5.7\ W$, which can not be provided by a cooling engine of the X-Cooler II type. However, a reflector foil, acting as heat shield, reduces the heat transfer to values similar to the case with one crystal without shield. The temperature variation across the detector stays below $10\ K$. Therefore the proposed cooling engine may be used.

5. Reference

[1] J.Eberth, H.G.Thomas, et al. *NIM A369 (1996), 135-140.*

[2] ORTEC. *X-Cooler™ II - Mechanical Cooler for HPGE Detectors - User Manual*. http://www.ortec-online.com.