Electrical cooling of HPGe detectors

I. Kojouharov, GSI Darmstadt

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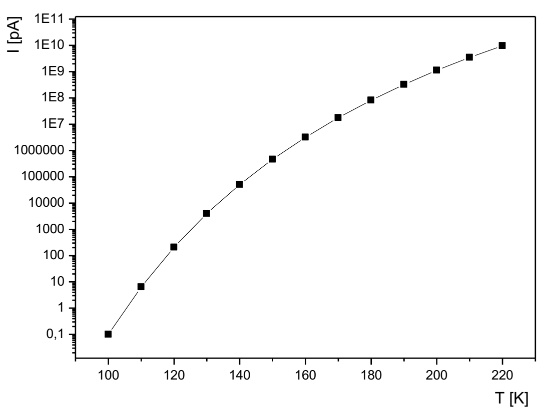
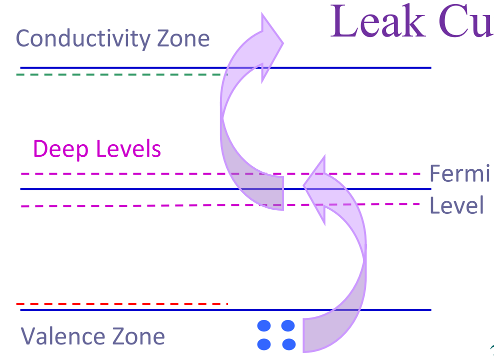
1. Cooling and coolers

$$I_{\text{det}} = I_s + I_b$$



Leak Current



$$I_b \approx T^{3/2} e^{-\frac{E(T)}{2kT}}$$

The HPGe detectors must be cooled, typically liquid nitrogen (LN2)

Why at LN2 Temperature: $I_{vol} \approx T^2 e^{-E(T)/2kT}$, Leak Current Noise $v \approx \sqrt{I_{tot}}$

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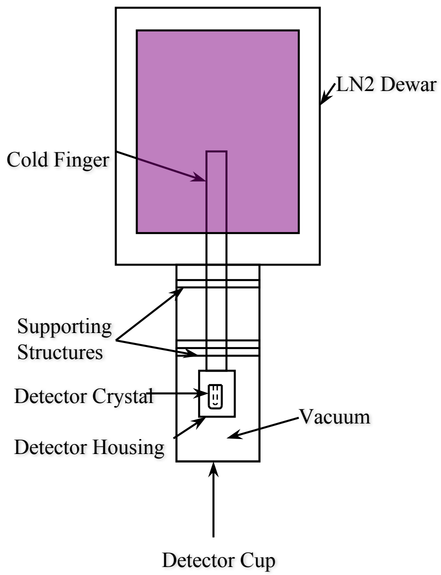
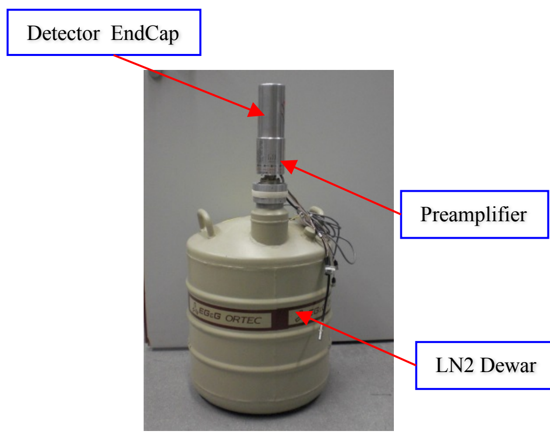
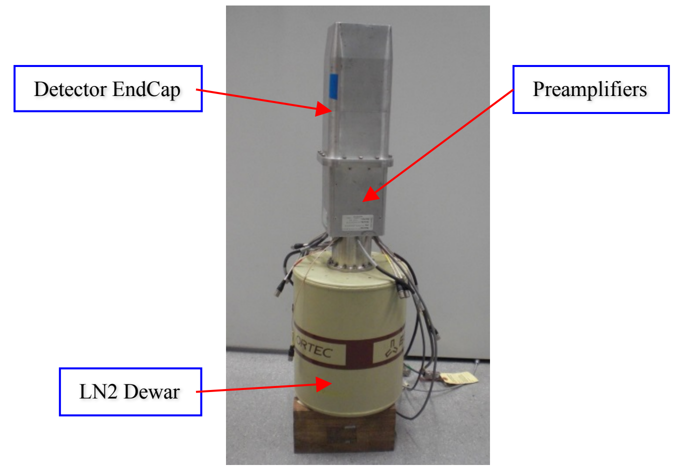
1. Cooling and coolers – LN2





Vertical Dipstick,
single crystal,
Pop Top Capsule



Common Vacuum,
All directions,
CLOVER

The LN2 cooling option

Electrical cooling of HPGe detectors

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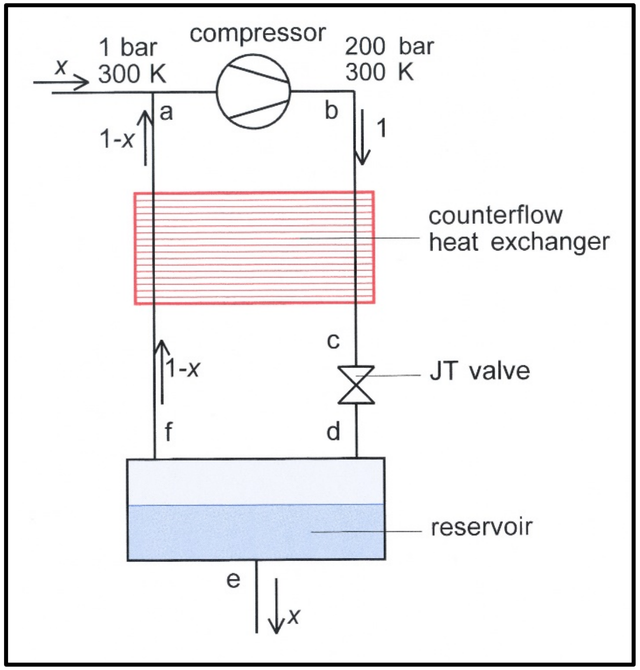
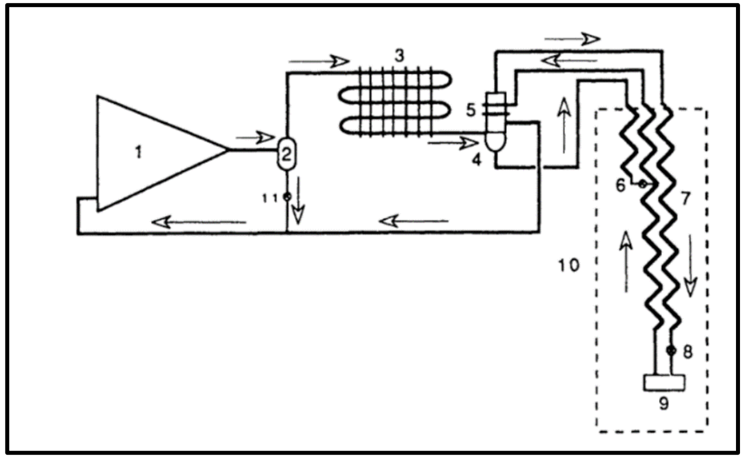
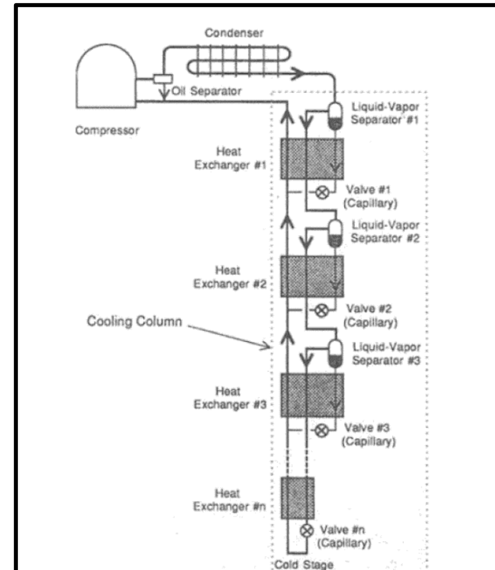
1. Cooling and coolers – the Linde cooler (Joule-Thompson cooler) and the Kleemenko cooler







From Cryocoolers 9, edited by R.G.Ross Jr.

Kleemenko cycle(right) and the MMR cooler X-Cooler (left). Uses multicomponents cooling agent.

A schematic diagram of a JT liquefier is shown left. It consists of a compressor, a counterflow heat exchanger, a JT valve, and a reservoir. The pressures and temperatures refer to the case of a nitrogen liquefier. At the inlet of the compressor the gas is at room temperature (300 K) and a pressure of 1 bar (point a). The compression heat is removed by cooling water. After compression the gas temperature is ambient temperature (300 K) and the pressure is 200 bar (point b). Next it enters the warm (high-pressure) side of the counterflow heat exchanger where it is precooled. It leaves the exchanger at point c. After the JT expansion, point d, it has a temperature of 77.36 K and a pressure of 1 bar. The liquid fraction is x. The liquid leaves the system at the bottom of the reservoir (point e) and the gas (fraction $1 - x$) flows into the cold (low-pressure) side of the counterflow heat exchanger (point f). It leaves the heat exchanger at room temperature (point a).

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HPGe detectors

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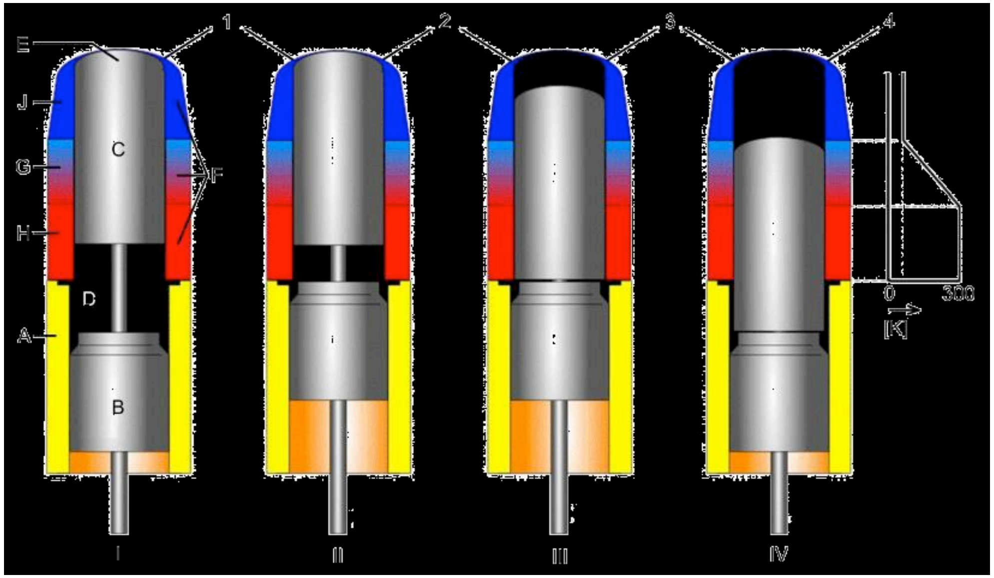
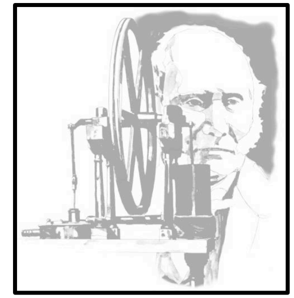
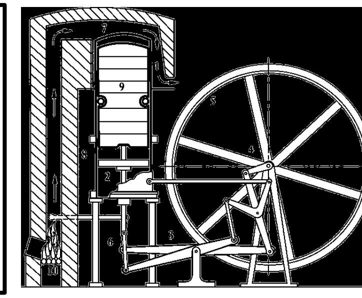
1. Cooling and coolers – the Stirling cooler

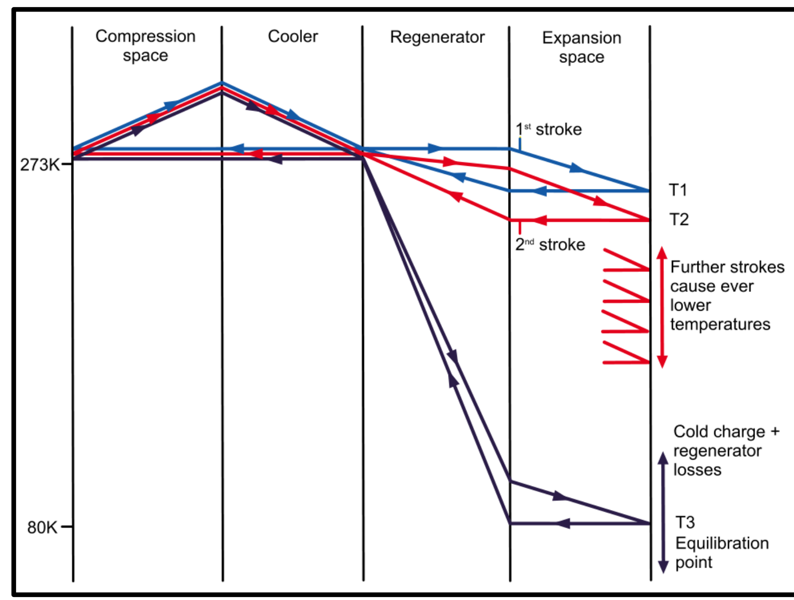






The Stirling cycle is a thermodynamic closed cycle invented in 1816 by the Scottish minister Robert Stirling.

In position I, all helium is at room temperature in space D. Going to position II, this gas is compressed by piston B increasing the gas temperature to about 80°C, refer to figure 2, column 1. When the displacer C moves down from position II to III, the gas is displaced from space D to space E, forcing it first through the cooler H where the compression heat is dissipated into the cooling water, reducing the gas tempe-rature to about 15°C (column 2). Next, the helium flows through regenerator G. Using the cold which was stored in the regenerator by the previous cycle, the helium gas is cooled to almost the final liquefaction temperature when arriving in space E (column 3). The final and main action is the displacer and piston moving down to position IV, expanding the helium gas. This expansion creates the actual cooling power in the cold heat exchanger J (column 3), cooling the customers process.



Graphics by Stirling Cryogenics BV, Netherlands

Electrical cooling of HPGe detectors

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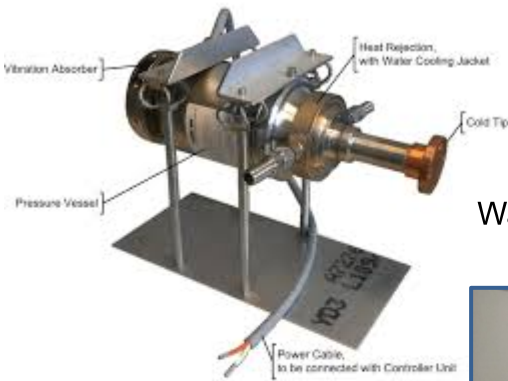
1. Cooling and coolers – available engines

MMR/ORTEC X-Cooler II or III

Air cooled



Water cooled

SunPower/ORTEC Type CT or GT

Electrical cooling of HPGe detectors

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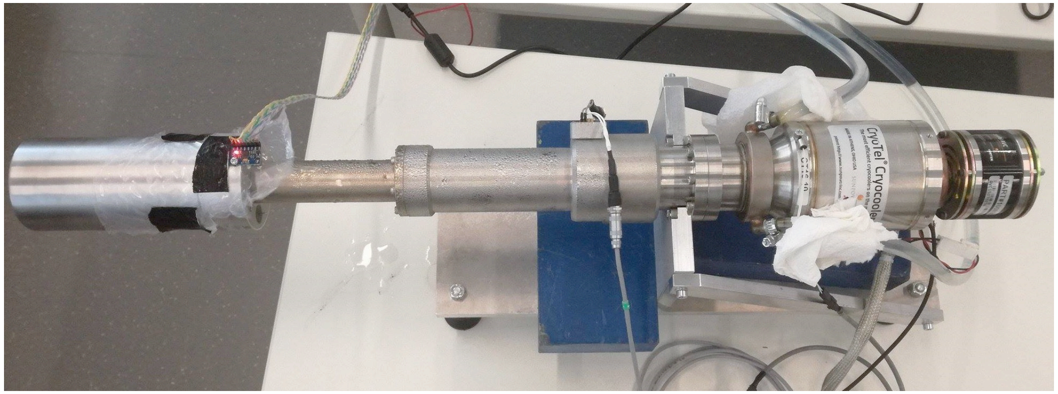
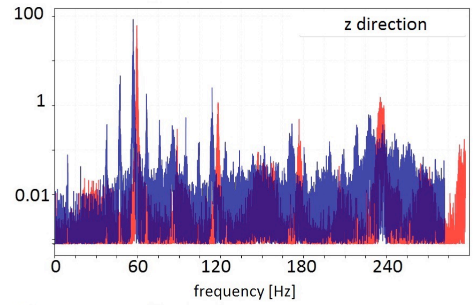
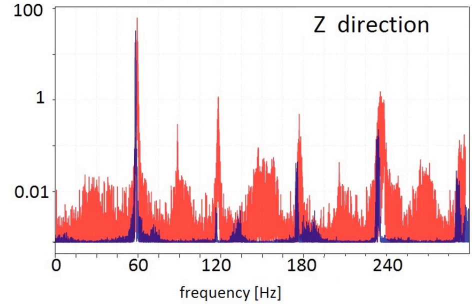
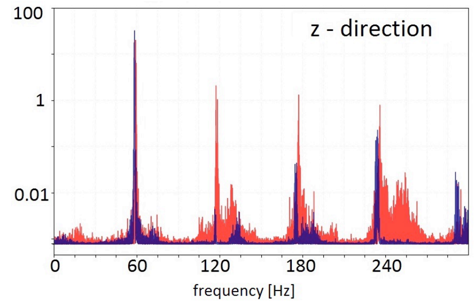
1. Cooling and coolers – available engines

	MMR XC	SP CT
Cooling (total) power	11 W (240V/500W)	11W (24V/120W)
End temperature	-187 °C	-220 °C
Vibrations	very low	high
Life (reliability)	unknown, 3-7 Years	unknown, >200 000 h
Compactness	low	high
Functionality	medium	medium









2. Why electrical cooling?

Limited deployment space and long term unattended operation of Composite HPGe Detectors.

- Network of automatized radiation monitoring stations (German Weather Service), some of them in difficult to access places,
- For gamma spectroscopy of hyper nuclei at collider facilities like FINUDA or PANDA the limited space for detector deployment
- DEGAS optimal box geometry which maximizes the efficiency,

makes LN2 cooling technologically unrealistic.

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2. Why electrical cooling?

LN2 Hazard reduction

- Use of LN2 cooling by the medical application of the HPGe detectors (full body counting etc.) is not permitted due to risk to injure the patient. Or a special system has to be designed to meet the safety standards.

- Use of the LN2 cooling requires Autofill System based on buffer tanks in the experimental area. Storage of a certain amount of LN2 (in order to secure a limited autonomy of the Autofill) pose danger. A failure of the tank or pipe may release intolerable amount of LN2 in the experimental hall.

- Requires a complicated monitoring and emergency system in order to meet the safety standards.

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2. Why electrical cooling?

Enhanced functionality

- Utilization of LN2 based cooling technology requires considering also logistic issues – Autofill System, LN2 Tank, Pipeline, Filling lines, Control etc. The cost of such a system usually is close to the price of the coolers.

- The reliability of such a system is not very high due to the plastic tubes used. Under the pressure of the buffer tanks (typically 4 bars) they may crack. The LN2 itself causes accelerated aging of the plastic, thus reducing the reliability of the supply system. The LN2 may contain small amounts of CO2 and H2O (in frozen state) which are clogging the supply bayonets.

- System management, deliveries, sustainability etc.

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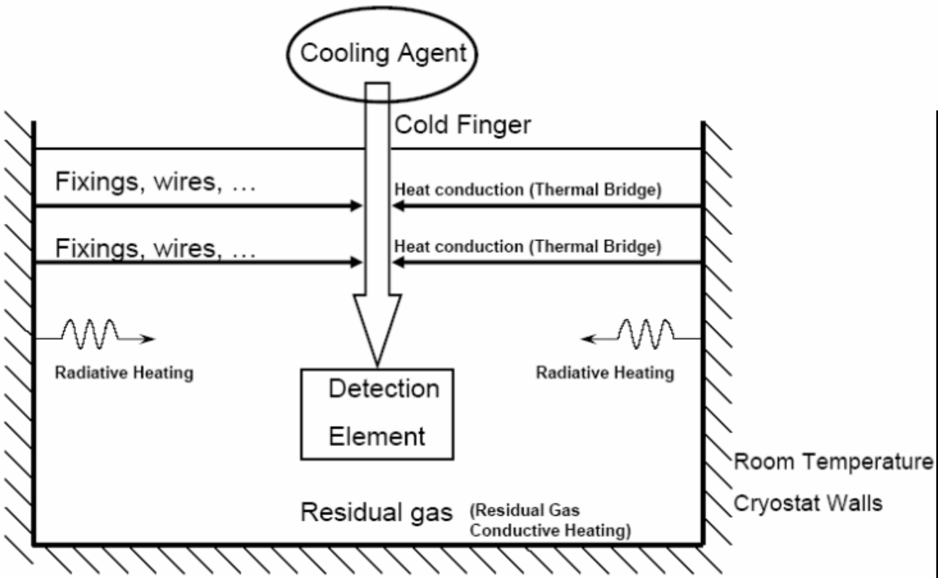
2. Why electrical cooling?

Nevertheless …

- The use of the LN2 cooling for single detectors is preferable, if the safety standards and the operational requirements are met.
- The use of LN2 cooling by sporadically operated detector(s) is preferable.
- The use of LN2 cooled detectors in small scale experiments/measurements and/or limited in the time is preferable.

Therefore, do not hurry up to electrical cooling. The old LN2 cooling is still fine for many applications. The electrical cooling engines do not possess large cooling power and cooling of big germaniums is a tricky issue.

3. Detector thermodynamics



Thermodynamic model of the detector

The ***radiative 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 by infrared rays. The path of the transfer leads through the cold finger to the heat reflector and further to the detectors housing which holds the Ge crystals.

Thermal bridges are the 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 feedthroughs. The heat exchange is realized by thermoconductivity.

The ***residual gas heating*** takes place typically at low vacuum, however the specifics of the process must be taken into account.

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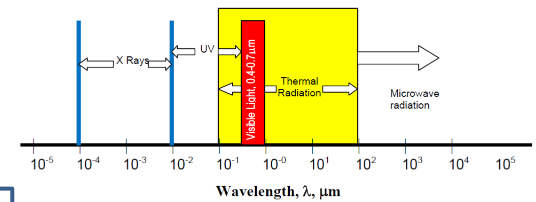
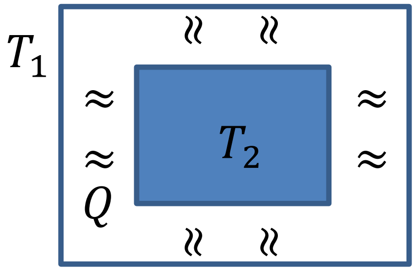
3. Detector thermodynamics – radiative transfer

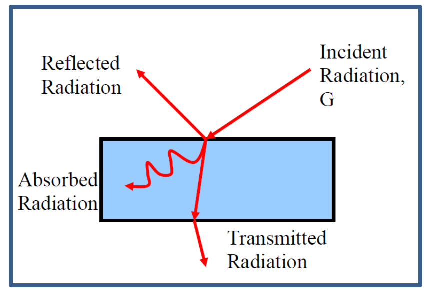


Stefan-Boltzmann law:

$$E_b = \sigma T_{abs}^4$$

where σ = 5.670 373 (21)×10^{-8} W·m^{-2}·K^{-4}

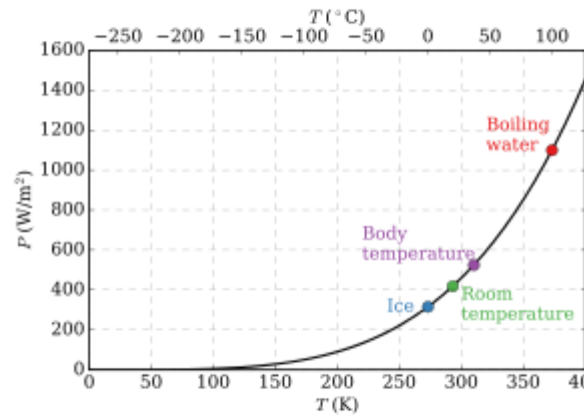




The heat (energy) transferred Q from body 1 to body 2 is given by:

$$Q = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\epsilon_1}{A_1\epsilon_1} + \frac{1}{A_1 F_{1\to 2}} + \frac{1-\epsilon_2}{A_2\epsilon_2}}$$

Where ϵ_1 and ϵ_2 are the emissivity of the surfaces 1 and 2, T_1 and T_2 are their temperatures, A_1 and A_2 are the area of the surfaces, $F_{1\to 2}$ is the view factor.



Power emitted by a black body plotted against the temperature according to the Stefan–Boltzmann law

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3. Detector thermodynamics – conductive transfer

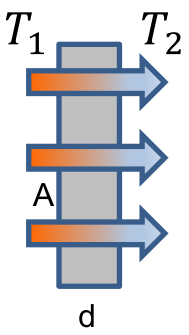
Derived from the Fourier's law

$$q = -k\nabla T$$

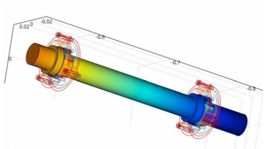
where k is the thermal conductivity, the thermal conductivity equation (with volumetric thermal sources q_v) is

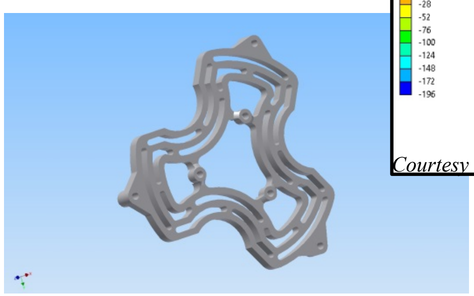
$$\rho c_p \frac{\partial T}{\partial t} - \nabla.(\mathrm{k}\nabla T) = q_v$$

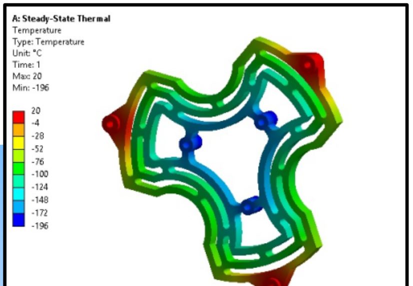
where ρ is the density of the material and c_p is the heat capacity.



$$\frac{Q}{t} = \frac{kA(T1-T2)}{d}$$







Courtesy of J.Kojouharova

Main supporting labyrinth of DEGAS, Vespel SP21, 110 mW

Calculation of the conductive heat transfer of complicated 3D shapes can be done numerically by appropriate software products – ANSYS etc.

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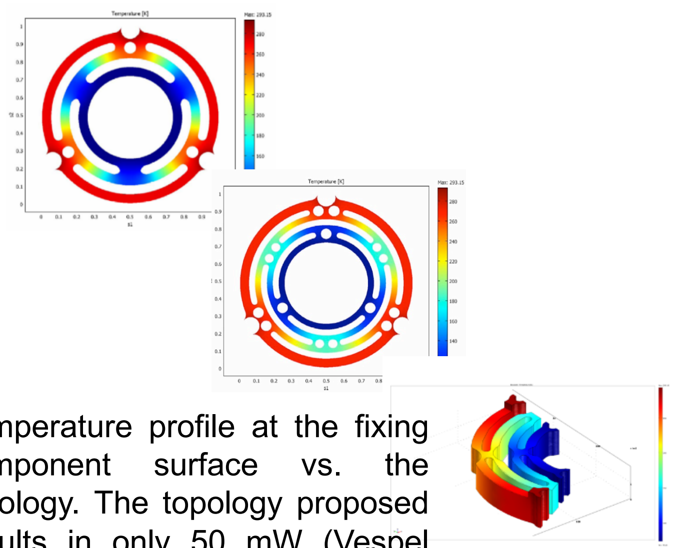
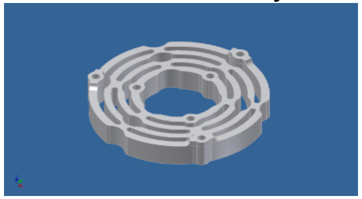
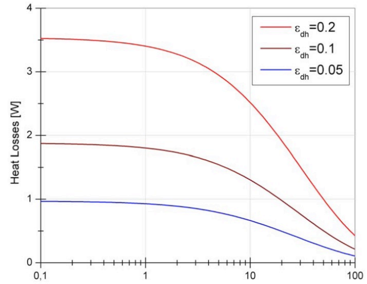
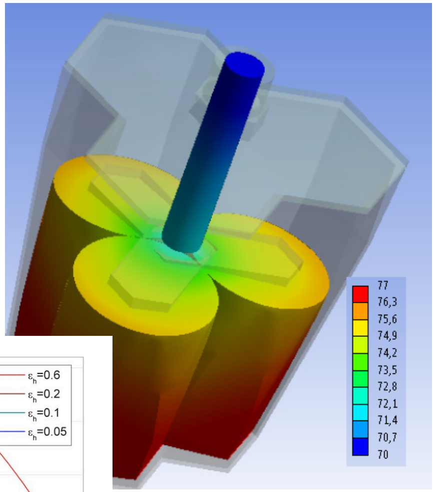
3. Detector thermodynamics – examples

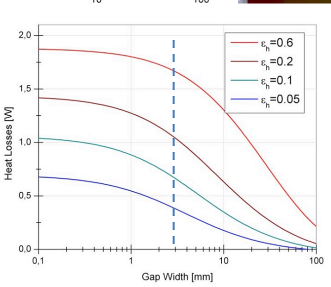


Temperature profile at the fixing component surface vs. the topology. The topology proposed results in only 50 mW (Vespel SP21) heat losses and good mechanical stability.



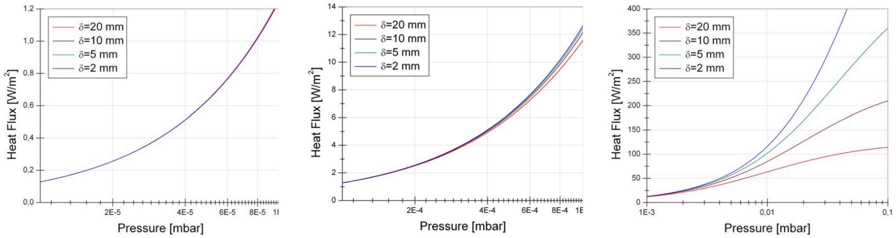






of J.Kojouharova

Vacuum effects



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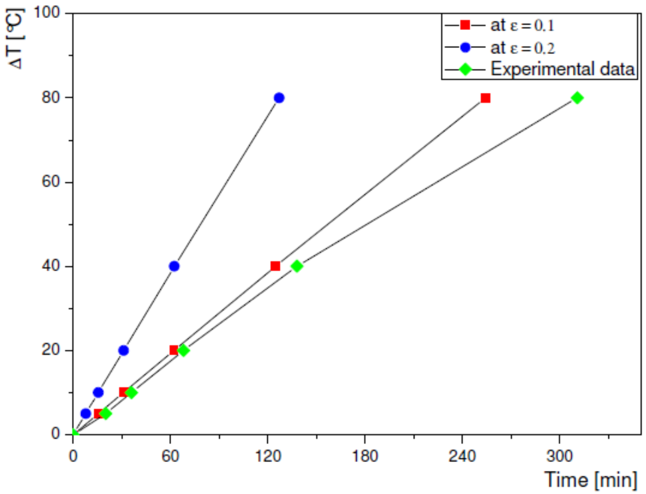
3. Detector thermodynamics – examples

What emissivity one can expect by a certain mechanical processing of the components?



Warming up of a single HPGe detector with 15 % efficiency (commercially available PopTop), which corresponds of 344 g Ge. The warm up time is evaluated based on typical crystal housing. The surface quality of the crystal housing suggests that by regular mechanical manufacturing technology an emissivity of <0.1 can be achieved.

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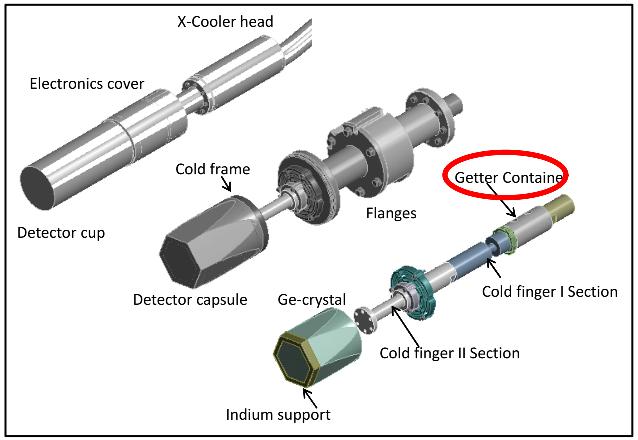
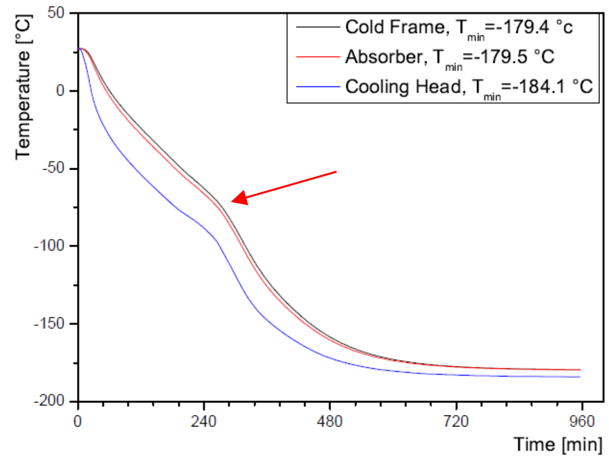
3. Detector thermodynamics – examples

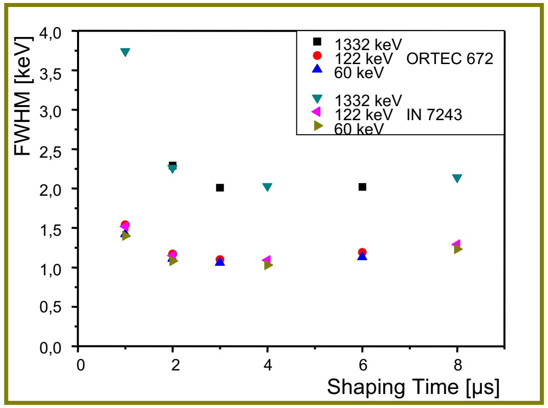
Single capsule detector





Cooling of the single capsule detector

Energy resolution of HEX 146 vs. shaping time. Energy resolution at 1332 kev and LN2 cooling in Lab – 1.96 keV (GSI cold board !)



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Thank you