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Thermal design for the CLAS-DVCS calorimeter

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Abstract

The CLAS-DVCS calorimeter is composed of 424 PbWO4 crystals. The mechanical design is achieved by the R&D Detectors department of the IPN Orsay. This document presents the thermal aspects of the detector concerning the heat transfer calculations and the consequences on the mechanical design. The physics and electronics signals quality requires a stabilized temperature of 18°C +/- 0.1°C. The heat sources and flow coming almost from the electronic preamplifiers and the environment are defined and compared to the cooling system heat flow. The calculation of the temperatures inside the calorimeter and the crystal block are presented in order to get the time constant of the system and the temperature variation along the cooling path.

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1. Presentation of the detector and thermal requirements

The principle of the calorimeter is presented on figure 1 and general information is available on the web site http://ipnweb.in2p3.fr/~rdd/projects/DVCS/index.html. The calorimeter is composed of 424 crystals of lead tungstate (PbWO4). The crystals are placed in aluminium frames stacked in a cradle. Each crystal is equipped on its back face with an avalanche photo diode (APD) connected to a preamplifier. The mechanical design is shown on figure 2. The temperature has a large influence on the behaviour of the crystal and APD. On one hand, a relative variation of 0.1°C gives significant variation on the signal. On the other hand, better efficiency of the crystal and APD is possible with low temperature. However due to the dew point which is estimated around 12-13°C [ref. 6], the detector temperature will stay above this value. Finally the temperature requirement is to keep the crystal block around 18°C with 0.1°C temperature stabilization.

The material properties of the calorimeter elements are listed in appendix 1.

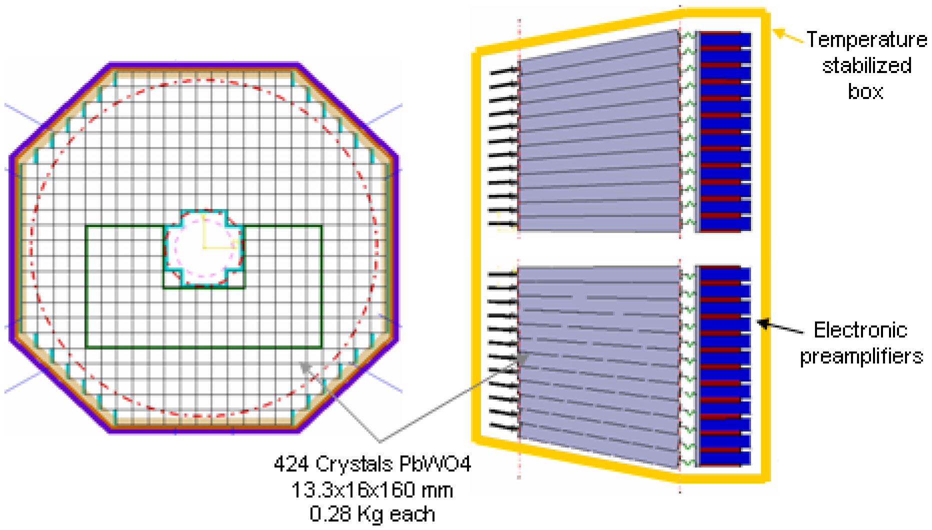


Figure 1: Assembly principle of the CLAS-DVCS calorimeter

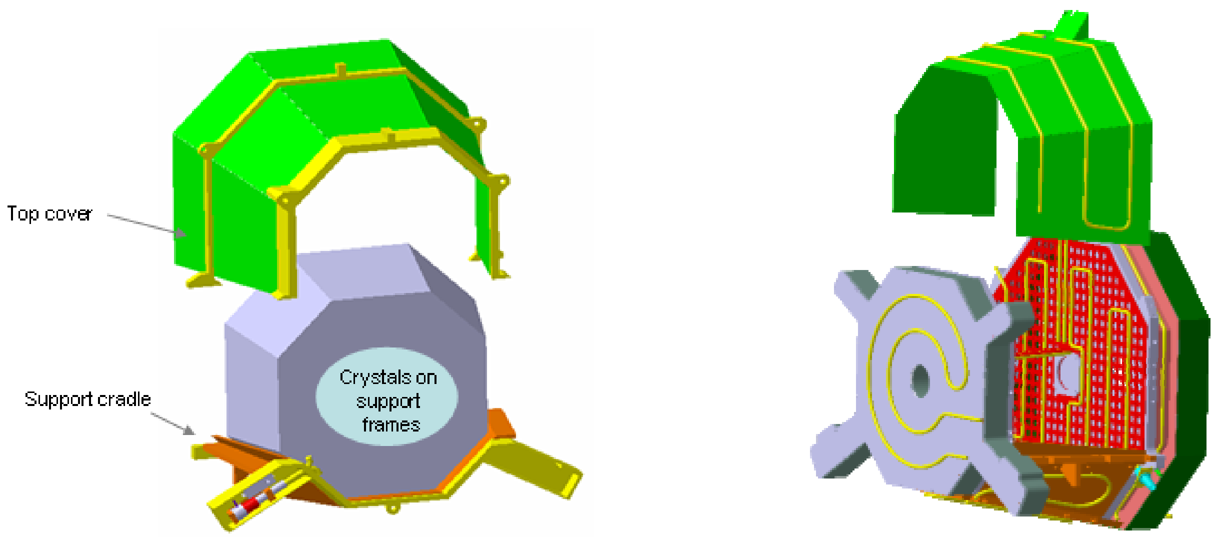


Figure 2: Principle and final design with the cooling tubes

2. Thermal environment, heat sources and cooling facility

2.1. Environment around the calorimeter

The detector is placed in the center of the CLAS detector. The air is turbulent and pulsed by fans (estimating air velocity 1 m/s), and the air temperature can rise up to 30°C. For the calculation, it is assumed that the temperature surrounding the calorimeter called "out air" is fixed at this maximum value.

In order to minimize the convection-conduction heat transfer, the crystals are isolated from outside with help of Depron material and refrigerated copper covers. Some reflective material wraps the detector to minimize also the radiation heat transfer.

2.2. Internal heat sources

The main heat source comes from the electronic preamplifier. The initial cooling of the crystals to the desired temperature is calculated with a transient approach and considered as a heat source.

2.3. Cooling facility and regulation system

The cooling of the detector is based on a liquid cooling system. Some pulsed air in the electronics is additionally applied but its effect is neglected in the calculation. The refrigerated liquid is provided by a refrigerated bath circulator (called "chiller" in the following chapters) whose characteristics are listed in appendix 2. The pump capacity at q=0 is 0.49 bars with a power of 800 W.

The thermal regulation is controlled by the software developed by the Jefferson Lab team. A positioning of the RTD sensors inside the thermal box is proposed in chapter 7.

3. Heat transfer between the cooling system and other elements.

This chapter presents the different heat flows which are summarized in one picture (appendix 4).

3.1. Heat flow through covers with outside

3.1. a. Convection and conduction heat transfer

The covers are made of 1 mm copper and 12 mm Depron insulation (figure 3). The copper plate is at a fixed temperature of 18°C and surroundings are estimated to be at a maximum of 30°C. This delta temperature creates a heat transfer by convection and conduction.

The exchange convection coefficient is calculated with a model based on a vertical plate of 30cm height with some air in forced convection on it [ref. 3]. It makes use of the following parameters:

Reynolds number $\mathrm{Re} = \frac{r \times u_m \times H}{m} = \frac{1.293 \times 1 \times 0.3}{19.26e-6} = 20140$ (laminar flow)

Prandtl Number $\mathrm{Pr} = \frac{m \times Cp}{l} = 0.718$ Nusselt number = 84.8

Convection coefficient (W/m²/°K) => $h = \frac{l}{H} \times \frac{2}{3} \times \mathrm{Re}^{0.5} \times \mathrm{Pr}^{0.33} = 7.63$

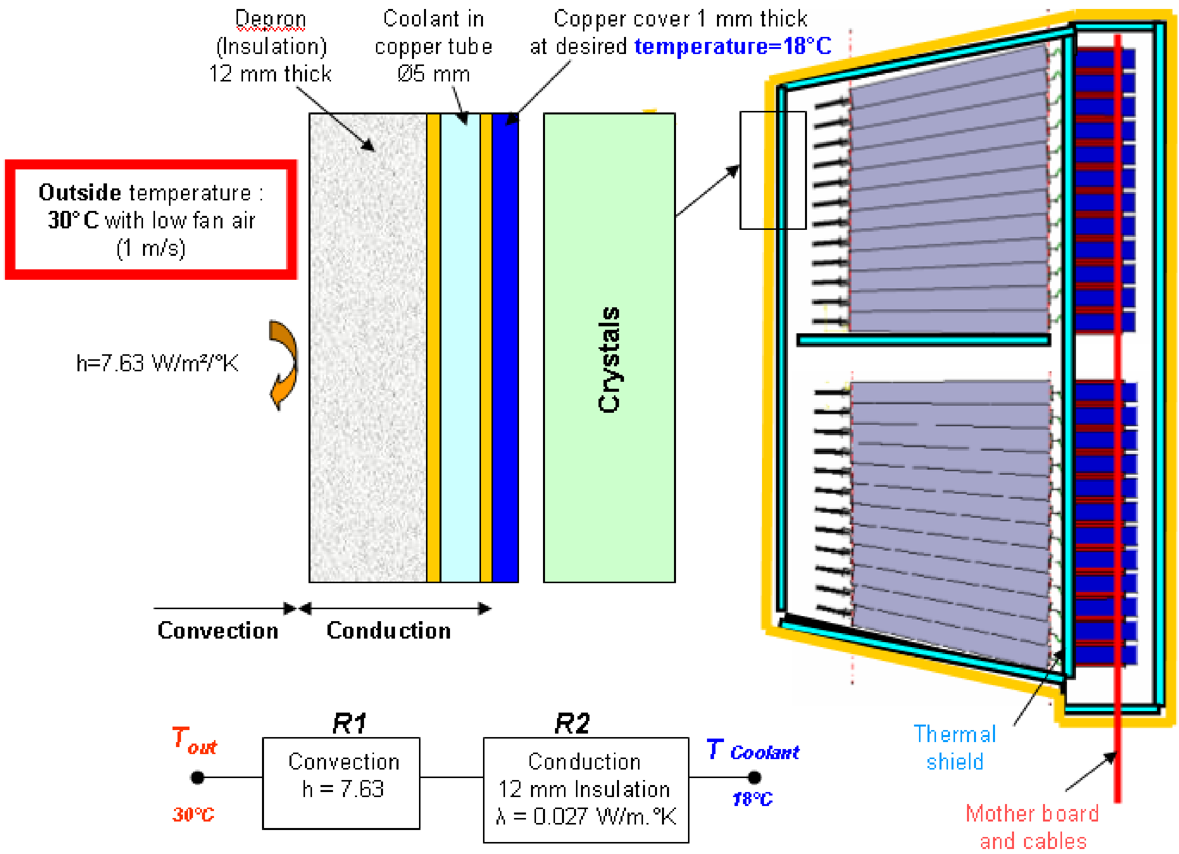


Figure 3: Definition of the thermal behaviour of the covers

The equivalent thermal resistance is:

$$Req = \frac{1}{h \cdot Surface} + \frac{thickness}{l_{ins} \cdot Surface}$$

The heat flow is $$P = \frac{\Delta T}{Req}$$

The covers are partitioned in 3 different parts: the cylinder around crystals, the front plate and the back part. This helps to define the exact heat flow on distinct areas and associated parts of the cooling circuit. From the surface values given by the CAD system, the heat flows are calculated:

$P_{perimeter}$ = 5.83 W; P_{front} = 2.31 W; P_{back} = 5 W

Other elements as the mother board and cables bring some heat flow. This is estimated around 5 W. As much as possible, low conductive materials as plastics, stainless steel, and teflon are used to keep negligible the eventual areas where some heat transfer could exist (as the links with the calorimeter supports and optical fiber system).

3.1. b. Radiation heat transfer

The calorimeter is placed in an enclosed cavity made by the inner chamber of the CLAS detector. The radiation heat flow from the surroundings to the calorimeter is:

$$P = s \cdot e \cdot S \cdot (T_{CLAS}^4 - T_{calo}^4) = 4\ W$$

The emissivity e is 0.09 corresponding to an aluminium commercial sheet that will wrap the calorimeter. This material helps to minimize the radiation effect.

The total heat flow is finally 22.2 W.

3.2. Heat flow from the electronic preamplifiers

The consumption of each preamplifier is around 125mW. That gives a total power of 53 W. This heat flow is dissipated mainly by conduction through the support rails fixed on the thermal screen (shown on figure 3). This screen is equipped with a serpentine tube in which the cooled liquid circulates.

3.3. Heat flow from the transient cooling of the crystals

The cooling of the crystals needs a time which is calculated by a transient approach. A 3-dimension model with finite element analysis was performed as shown on figure 4. The equivalent conductivity coefficient of the block has to be known and its value (0.998 W/m/°K) is obtained by calculations presented in appendix 3. The FEA model consists in crystals surrounded by aluminium frames and air. A temperature of 17.5°C is applied on boundaries and the initial temperature is 30°C. The curve of figure 4 shows the evolution of the temperature of the heart. A time of 9 hours is necessary to get the equilibrium. This long time constant could help in the temperature stabilisation.

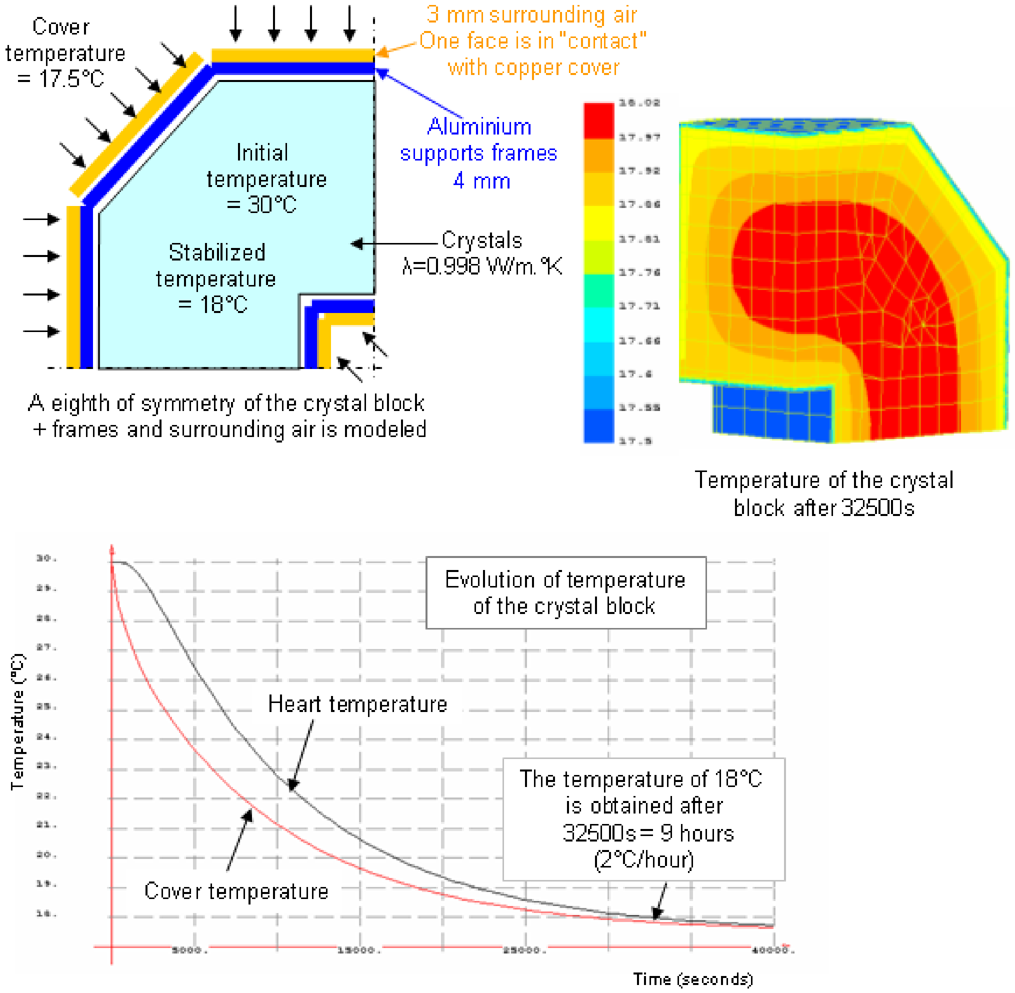


Figure 4: Transient analysis of the crystal block

The mean heat flow during all the cooling time is found from the following formulae (steady-state approach with specific heat [ref. 3]). This value is taken in account to keep an efficient system at any time:

$$P = \frac{Q}{t} = \frac{M \times Cp \times \Delta T}{t} = \frac{424 \times 0.28 \times 262 \times 12}{32500} = 11.5W$$

But the real heat flow is the integration of the heart temperature curve which gives 367 W. The chiller capacity is still enough to regulate it.

4. Cooling liquid flow – equilibrium between the chiller and the calorimeter

The chiller has a theoretical flow (will be noted "q_m") function of the pressure (noted d J) as shown in appendix 2. This leads to a first function d J = $f_1(q_m)$. The pressure is also function of the length and diameter of the circuit (fixed at 5 mm for mechanical reasons) and of the flow. The design detailed in chapter 5 has been done with a flow assumed to be at 1 litres/min. This assumption closed of the final solution is necessary to find the length of the circuit (method detailed in §5.3). With this length, the pressure losses are calculated in function of the flow (method detailed in chapter 6). This new relation defines the second function d J = $f_2(q_m)$. The two functions f_1 and f_2 are drawn on figure 5. The exact flow is solution of these functions and is represented by the equilibrium point which is 1.06 litres/min. In the following chapters, every numerical analysis will be done with this value.

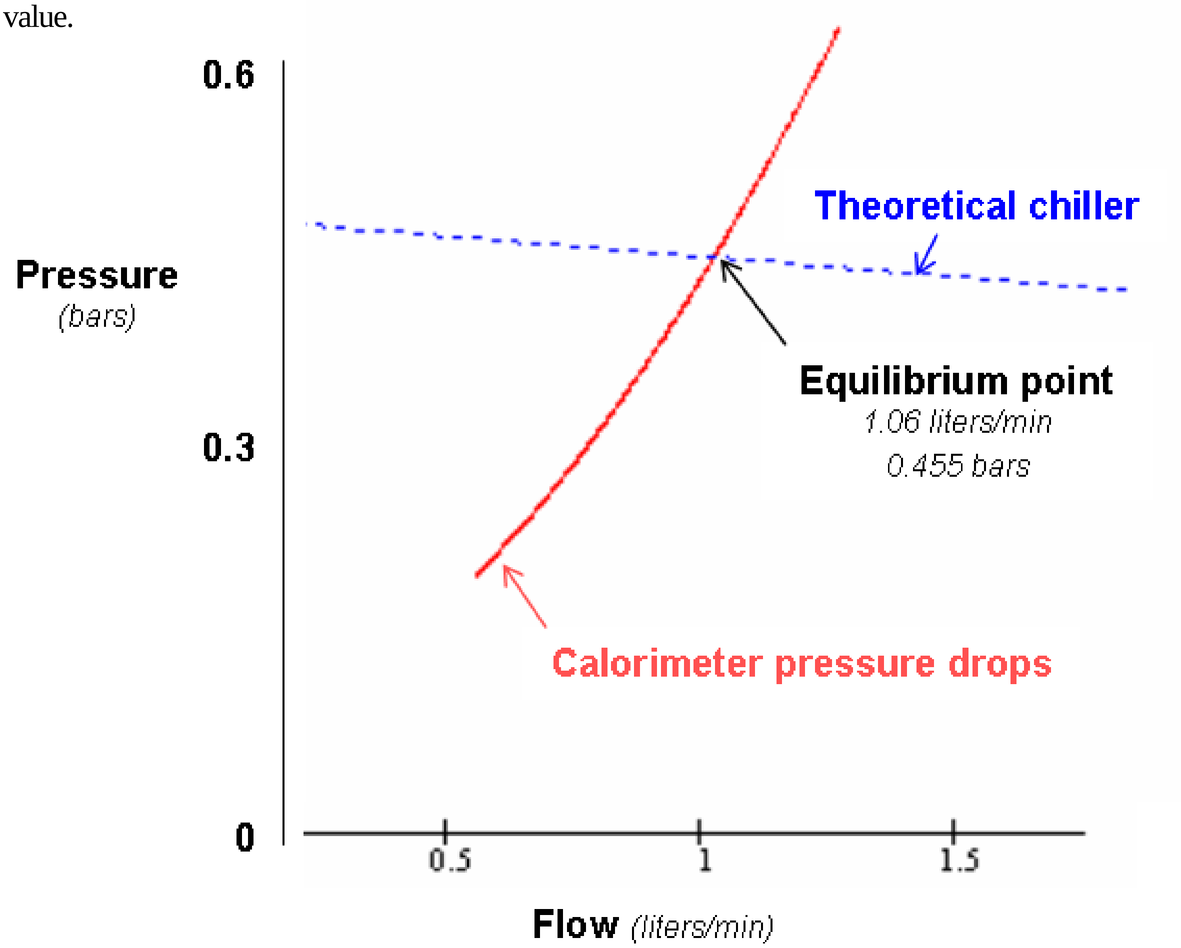


Figure 5: The flow is function of the pressure drop of the calorimeter and of the pump capacity of the chiller

5. Temperature in the calorimeter – design of the cooling circuit

5.1. Global temperature variation of the coolant

The global temperature variation of the coolant between inlet and outlet is defined by the following [ref. 4]:

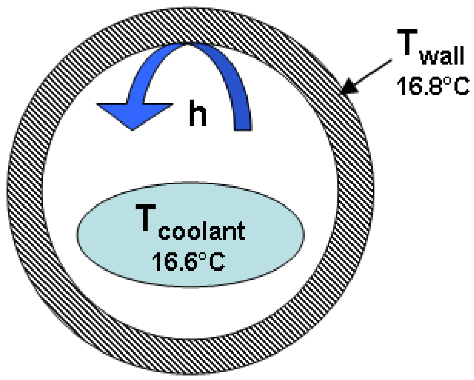
$$\Delta T = \frac{P}{Cp \cdot q_m} = 1.2°C$$

Where q_m is the fluid mass flow rate defined above, Cp is the specific heat of the coolant and P is the total power or heat flow to be removed from the calorimeter.

If the desired temperature is 18°C, which is the maximal temperature in the calorimeter, the inlet temperature must be 16.8°C with a value of P equal to 86.7 watts.

5.2. Inlet temperature of the coolant

The desired inlet temperature for the circuit is not the coolant temperature but the wall temperature (wall = tube soldered on copper plates) as shown on figure 6.



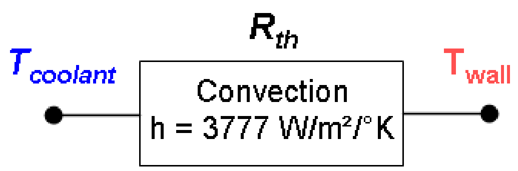


Figure 6: Convection transfer inside the tube

The coolant temperature is defined by the relation [ref. 4]:

$$P = h \cdot S \cdot \Delta T \Rightarrow T_{coolant} = T_{wall} - \frac{P}{h \cdot \frac{S}{2}} = 16.6\,°C$$

Only half of the exchange surface is considered in order to get an optimized design.

h is the convection exchange coefficient (turbulent flow) defined by the formula [ref.4]:

$$h = \frac{l}{D}(0.023 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{0.33}) = 3777 \quad W/m^2 \cdot °K$$

5.3. Temperature of the covers – analytical and finite element analysis approaches

The circuit is made of a tube soldered on copper plates as the thermal shield or the covers. The circuit of the tube is designed in order to get a uniform temperature on any plate. The half distance between two tubes is modelled as shown on figure 7. This approach permits to get the following relation which is developed in appendix 5:

$$Tm = \frac{Ps \cdot L^2}{l \cdot e} + Te$$ Ps is the heat flow per unit area

The half distance L between two tubes is around 35 mm. The middle temperature “Tm” must not exceeded by 1°C the “Te coolant” one (which starts at 16.8°C).

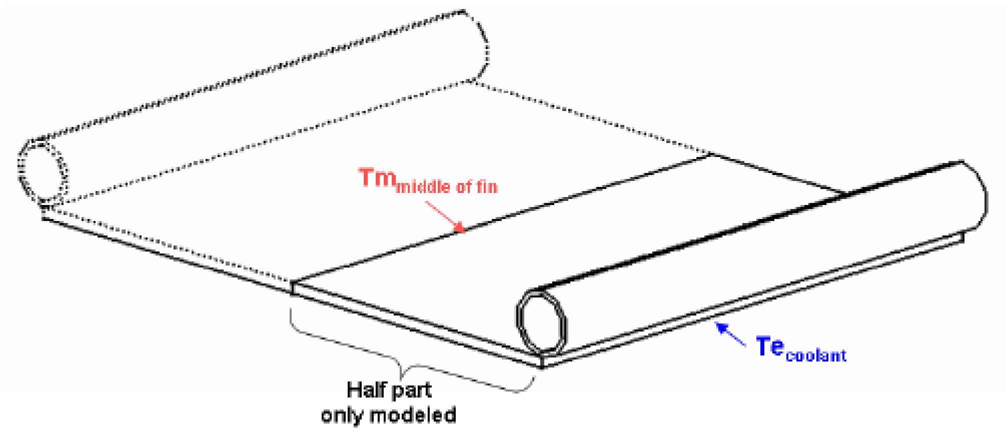


Figure 7: Fin model approach to get the distance between tubes for the thermal screen and covers

The number of tubes is calculated by dividing the area by the distance 2L. For each covers, a length is defined and it will be refined with help of the CAD system.

With the same model, the evolution of the Te coolant temperature is calculated in order to know the inlet temperatures for each covers or screens. The relation developed in the appendix 6 is:

$$Tf(y) = \frac{-2Ps \cdot L}{qm \cdot Cp} \cdot y + Te$$ Where *y* is the length of the tube

The figure 8 presents the temperatures of the thermal shield calculated by FEA analysis with SAMCEF package. The shield is made of a 2 mm thick copper plate, heated by the 53 W power coming from the electronics (§3.2). The serpentine is 2.2 m long. The temperatures on inlet and outlet are calculated analytically. The temperature between two tubes is satisfactory as it is just below 18°C. The maximum is 18.5°C but it is located on the boundaries where a complete model would be necessary to see the influence of the peripheral covers.

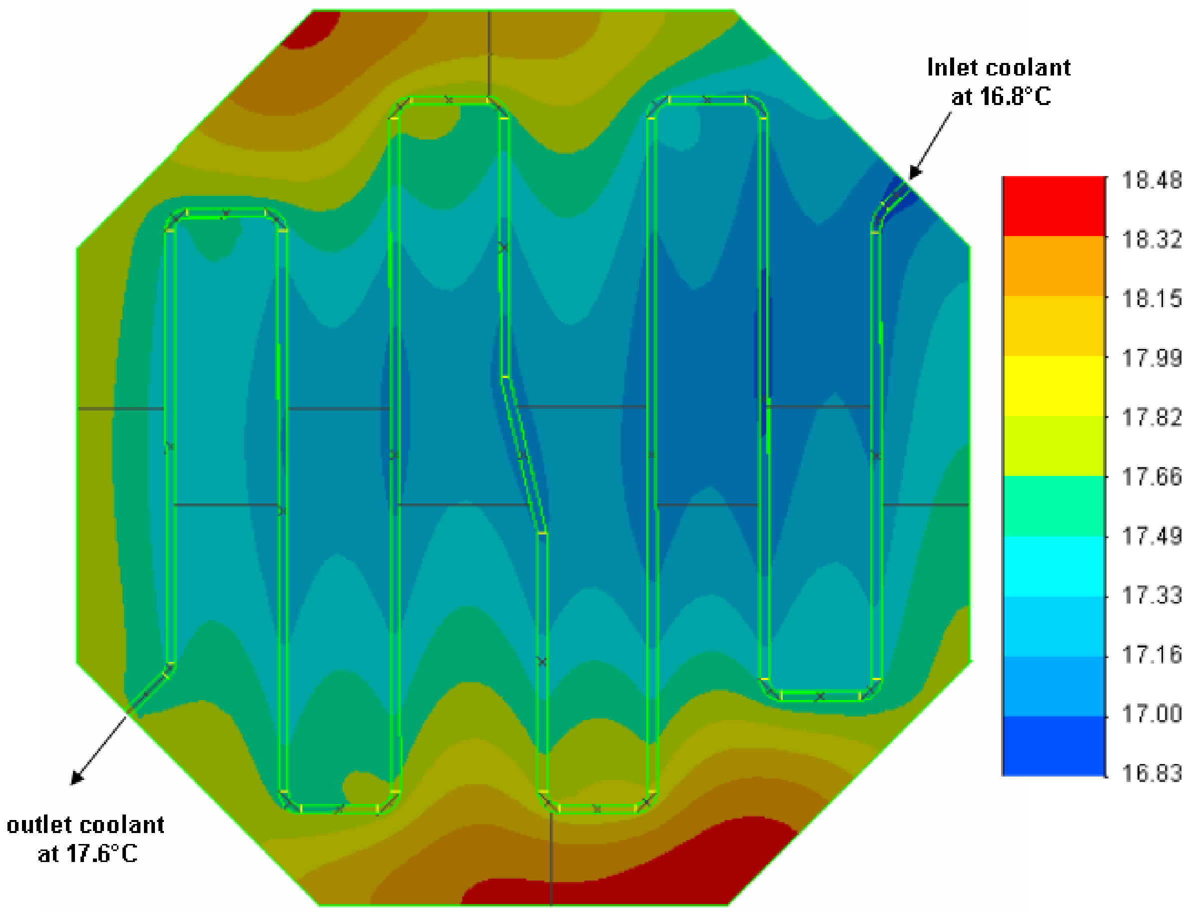


Figure 8: Temperatures on the thermal shield heated by the electronics

5.4. Definition of the cooling path and temperatures on each cover

The temperatures of all the covers are shown in figure 9. The path design for the cooling circuit is the following:

1- Thermal shield. It is the place of the highest heat source and it needs the lowest temperature.
2- Upper perimeter covers around the crystals in order to isolate the block against surroundings
3- The front cover in front of the crystals
4- The cradle under crystals
5- The back covers to maintain a low temperature for the electronic box.

The coolant temperature in the cooling circuit is given at each step as well as the maximum value. This has been calculated with Matcad package from a simplified shape.
The aim is to keep the temperature lower than 18°C everywhere around the crystals.

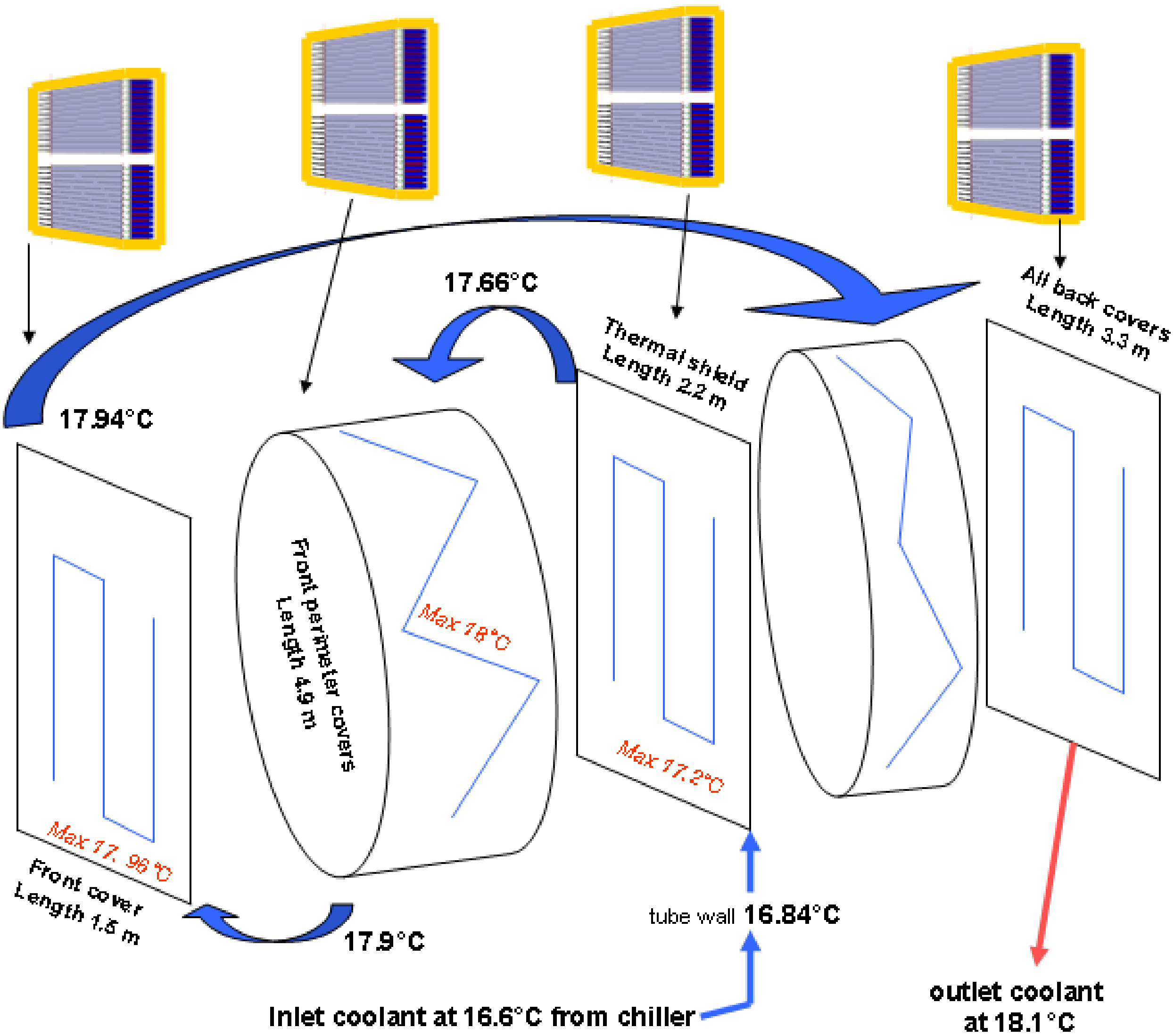


Figure 9: Summary of the temperatures and design of the cooling path

6. Pressure drop

The evaluation of the pressure drops following the [ref.5] are detailed in the appendix 7. The cooling circuit has a total pressure drop of 0.456 bars divided in two parts:

- 0.011 bars for the external part to the calorimeter due to a length tube of 12 m. The different level of 1 m between calorimeter and chiller produce an additional pressure drop of 0.098 bars not taken in account in the design because the circuit is making a round trip and this drop happens only during the fulfilment of the circuit.
- 0.401 bars for the calorimeter due to 11.9 m of 5 mm diameter tube inside the calorimeter. The bends of the cooling tubes gives 0.044 bars.

The pressure drops are relatively high because the tube inside the calorimeter must have an outer diameter of 6 mm for mechanical reasons.

7. Thermal sensors and regulation

For the thermal regulation and a good analysis of the heat exchange during the functioning of the calorimeter, 25 RTD sensors are used and placed as indicated below:

- 2 RTDs for the inlet and outlet cooling liquid (on the connectors)
- 2 RTDs outside of the calorimeter (bottom and top)
- 12 RTDs on crystals block boundaries in front (optical fibers), middle (aluminium frames) and back (closed to the first APDs)
- 3 RTDs in the centre of the crystal block in front, middle and back
- 4 RTDs in the electronic box on preamplifier rails
- 2 RTDs for the inlet and outlet of the gas (in the electronic box)

Four specific connectors of 29 pins will be mounted on the top of the calorimeter to connect every RTDs wires. The regulation can be based on the crystals block boundaries RTDs as its time constant is long.

8. Conclusion

From this document, some points must be kept in mind:

1- The total heat flow for the cooling is lower than the available chiller power.
2- The pressure drop of the system is high and the coolant flow can not be exactly the one calculated as many parameters can change.
3- The flow is enough to obtain a temperature variation inside the calorimeter lower than 1°C.
4- The time constant of the crystal block is long and will help in the stabilization of 0.1°C.

References

1- Temperature in the CMS end cap calorimeter from Justin Greenhalg, RAL, October 1999. TDL 00
2- Transferts thermiques by J.Ouin Editor Casteilla 1998
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5- Guide du calcul en mécanique by D.Spenle Editor Hachette
6- CMS The electromagnetic calorimeter report TDR CERN/LHCC97-33

Appendixes

1- Thermal characteristics of materials used in the calorimeter
2- Product specification of the RTE 740 chiller
3- Calculation of the equivalent conductivity coefficient
4- Heat flow summary
5- Analytical calculation of the temperature of a fin separated by two tubes
6- Analytical calculation of the temperature of the coolant along a fin
7- Pressure losses of the calorimeter-chiller system

Appendix 1: Thermal characteristics of materials used in DVCS calorimeter

	Density Kg/m^3 r	**Specific heat** J/Kg/°K **Cp**	**Conductivity** W/m/°K l	**Dynamic viscosity** Pa.s **µ**	**Sources**
Aluminium	2800	880	180		
Crystal-PbWO4	8280	262	3.22		Reference 1
Coolant Propanol glycol + water	1000	4200	0.5765	1.306^e-3	*Values from water specifications*
Insulation Depron			0.027		
VM2000			0.03		
Air	1.293	1005	0.027	19.26^e-6	

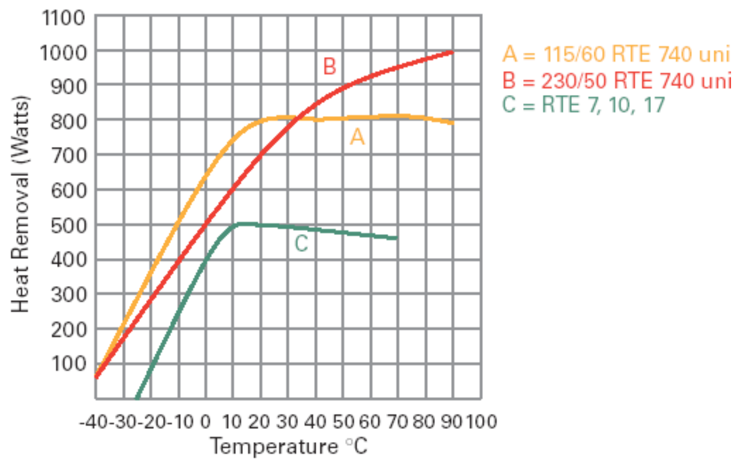
Appendix 2: Product specification of the RTE 740 chiller

NESLAB RTE 740 / Product specification

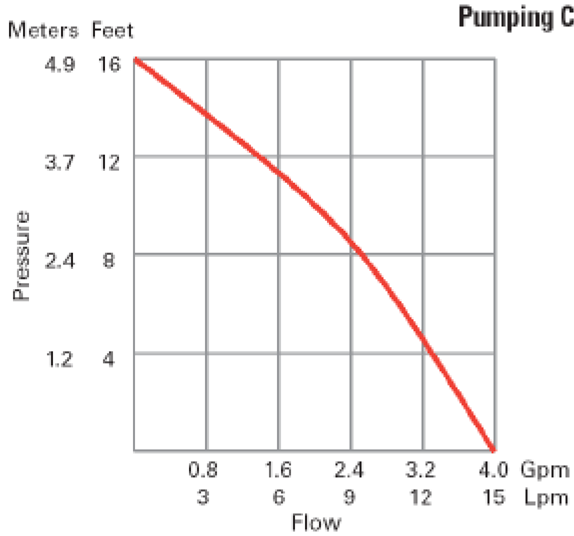
From www.thermo.com/tc

	RTE 740
Temperature range	- 40ºC to + 200ºC
Temperature stability	±0.01ºC
Cooling capacity	
60 Hz	800 watts at 20ºC
230V/50 Hz	700 watts at 20ºC
Heater	
60 Hz	800 watts
230V/50 Hz	2000 watts
Bath volume*	
gallon	1.9
liter	7
Pumping performance	
60 Hz (LPM)	15 LPM @ 0' head
230V/50 Hz (GPM)	4 GPM @ 0' head
Pump	force/suction
Pump head	
60 Hz	Max head 16' (4.9M)
50 Hz	Max head 11' (3.3M)
Unit dimensions	
H x W x D in	26.6 x 11.4 x 18.9
H x W x D cm	67.6 x 28.9 x 47.9
Bath opening/Bath depth	
W x L/D in	6.6 x 6/7.2
W x L/D cm	16.8 x 15.2/18.3
Power requirements	
115V, 60 Hz	16 amps
100V, 50-60 Hz	16 amps
230V, 50 Hz	12 amps
Unit weight	
lb	87
kg	39.5

Cooling Capacity

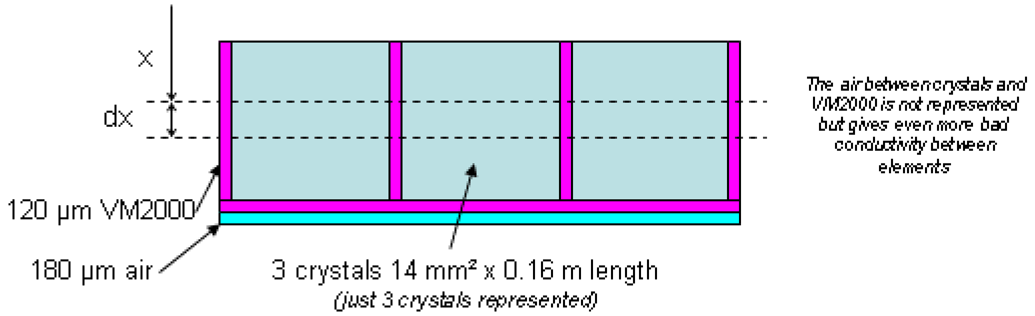


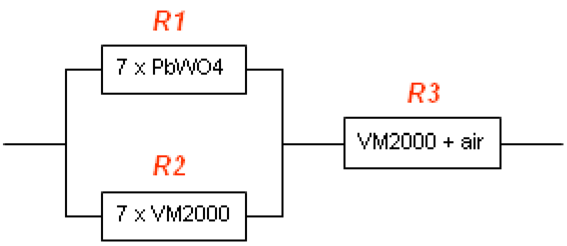
Pumping Capacity



Appendix 3: Calculation of the equivalent conductivity coefficient

For each direction, vertical and horizontal, a simplified model of the crystals block is modelled with only 7 crystals wrapped with VM2000. This helps to find the equivalent conductive coefficient by calculating the equivalent thermal resistance.





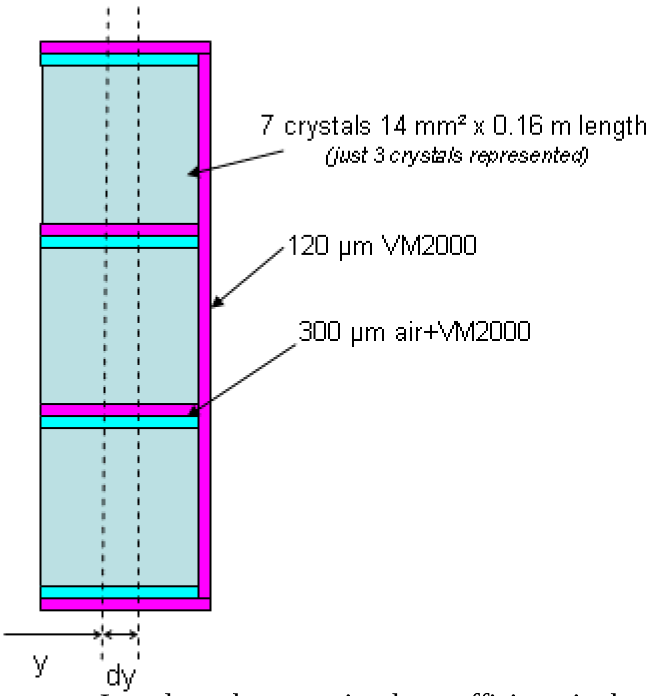
$$R_1 = \frac{e_{PbWO4}}{?_{PbWO4} \times S_{PbWO4}} = \frac{0.014}{3.22 \times 7 \times 0.014 \times 0.16} = 0.277$$

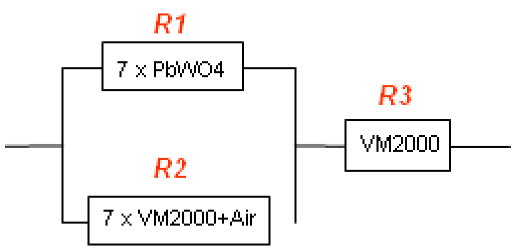
$$R_2 = \frac{e_{VM2000}}{?_{VM2000} \times S_{VM2000}} = \frac{0.014}{0.03 \times 8 \times 0.00012 \times 0.16} = 3038.2$$

$$R_3 = \frac{e_{VM2000+air}}{?_{VM2000} \times S_{VM2000}} = \frac{0.0003}{0.03 \times 7 \times 0.014 \times 0.16} = 0.637$$

$$R_{eq} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}} + R_3 = 0.914$$

$$l_{eq_x} = \frac{e_{PbWO4} + e_{VM2000+air}}{R_{eq_x} \times S_{PbWO4}} = \frac{0.014 + 0.0003}{0.914 \times 7 \times 0.014 \times 0.16} = 0.998$$

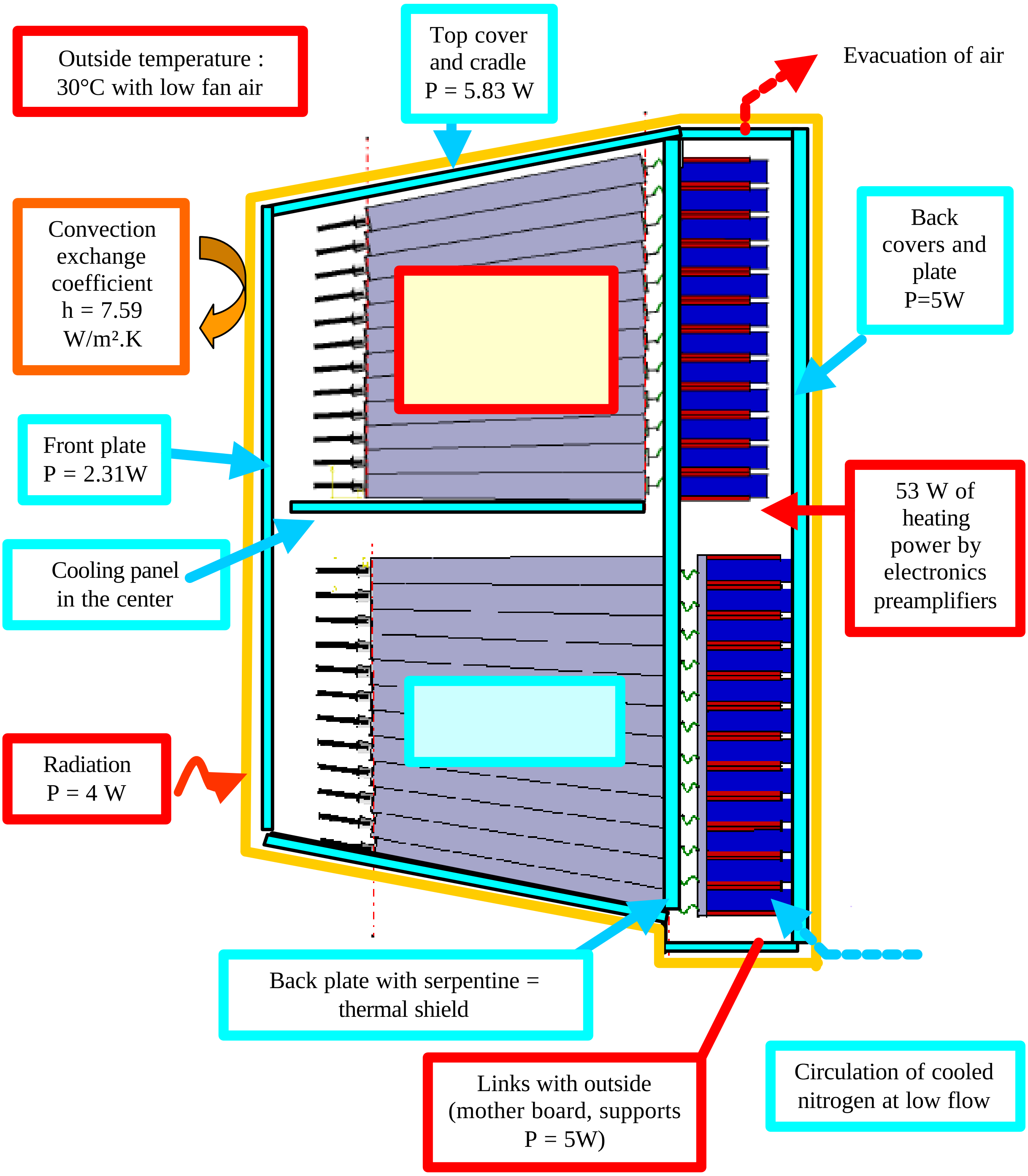




$$l_{eq_y} = \frac{e_{PbWO4} + e_{VM2000}}{R_{eq_y} \times S_{PbWO4}} = \frac{0.014 + 0.00012}{0.5319 \times 7 \times 0.014 \times 0.16} = 1.69$$

In order to homogenise the coefficients in the crystal block, the lowest value of the equivalent conductivity coefficient is chosen as 0.998 W/m/°K.

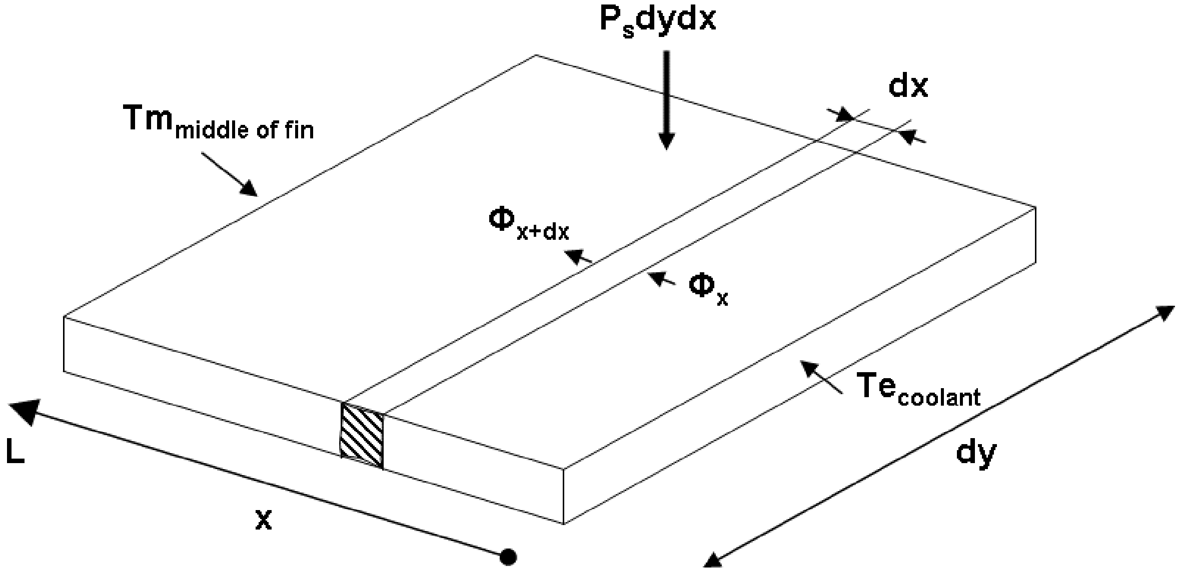
Appendix 4: Heat flow summary



Thermal components and amounts of thermal power to dissipate by cooling system
The total power of this system is 86.7 W

All elements in blue are cooled at 17°C minimum to obtain 18°C on crystals

Appendix 5: Analytical calculation of the temperature at the middle of the fin separated by two tubes



The heat transfer by conduction is equal to the applied heat power.

$$-d\Phi_x + P_s dy dx = 0$$

$$l \cdot e \cdot dy \cdot \frac{d^2T}{d^2x} dx + P_s dy dx = 0$$

$$\frac{d^2T}{d^2x} = -\frac{Ps}{l \cdot e} \quad \Rightarrow T(x) = -\frac{Ps}{l \cdot e} x^2 + A \cdot x + B$$

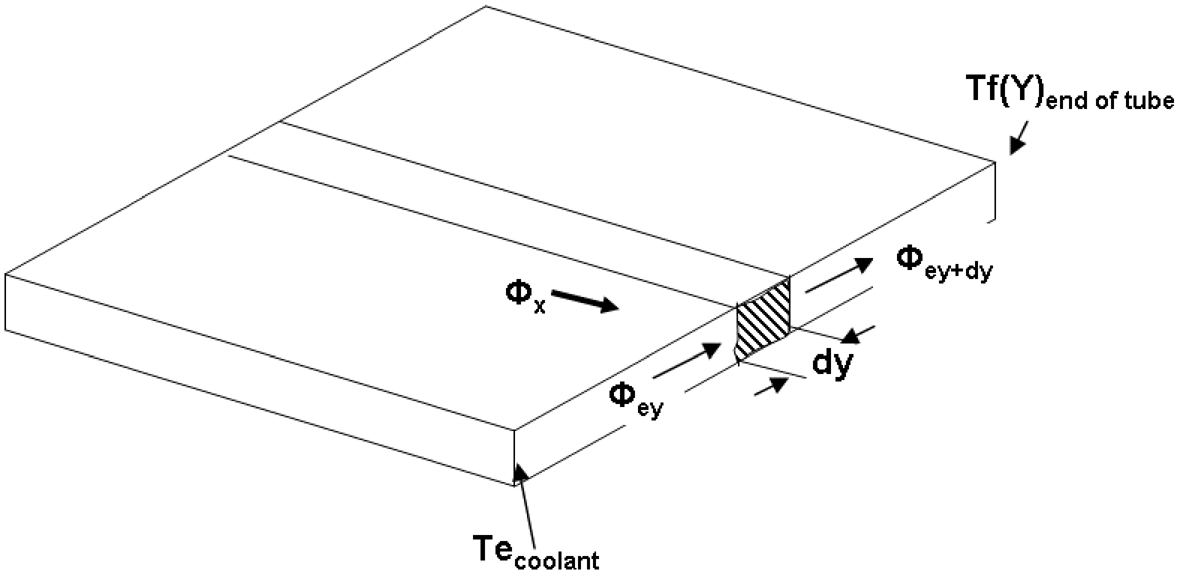
$$CDL1: \ x = 0 \quad T = Te$$

$$CDL2: x = L \quad \frac{dT}{dx} = 0 \quad (adiabatic)$$

$$T(x) = -\frac{Ps}{2 \cdot l \cdot e} x^2 + \frac{Ps \cdot L}{l \cdot e} \cdot x + Te$$

$$\Rightarrow Tm = \frac{Ps \cdot L^2}{l \cdot e} + Te$$

Appendix 6: Analytical calculation of the temperature of the coolant along a fin

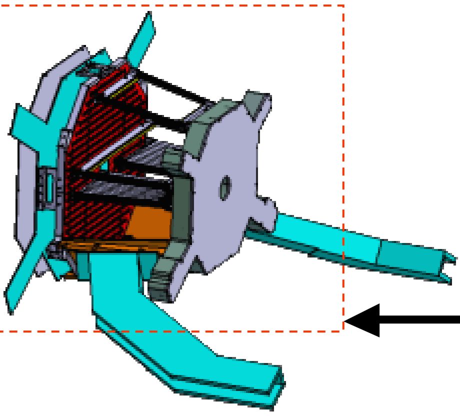


All the conduction at the base is heating the coolant along the tube.

$$-d\Phi_e+2d\Phi_x=0$$
$$d\Phi e=qm\cdot Cp\cdot dTf(y)$$
$$d\Phi x=-l\cdot e\cdot dy\cdot \left.\frac{dT}{dx}\right|_{x=0}=-l\cdot e\cdot dy\cdot\frac{Ps\cdot L}{l\cdot e}=-Ps\cdot L\cdot dy$$
$$\Rightarrow -qm\cdot Cp\cdot dTf(y)-2Ps\cdot L\cdot dy=0$$
$$\frac{dTf(y)}{dy}=\frac{-2Ps\cdot L}{qm\cdot Cp}$$
$$with\quad A=Te\ \Rightarrow\ Tf(y)=\frac{-2Ps\cdot L}{qm\cdot Cp}\cdot y+Te$$

Appendix 7: Pressure drop calculations of the calorimeter-chiller system

Internal calorimeter *= 0.445 bars*



$$Internal\,tubes: D=0.005; L=11.9\,m$$

$$Mean\ velocity \quad u_m=\frac{\frac{q_m}{r}}{A}$$

$$\mathrm{Re}=\frac{r \cdot u_m \cdot D}{m}=3455 \quad \rightarrow Turbulent\ flow$$

$$\Delta J_{int}=\frac{1}{(100\cdot \mathrm{Re})^{0.25}}\cdot\frac{u_m^2\cdot L}{2\cdot D}\cdot\frac{r}{10^5}=0.401\ bars$$

The bends effect give 0.044 bars more of pressure drop.

Length = 2 x 6 m

External to the calorimeter *= 0.011 bars*

$$Supplying\,tube: D=0.01; A=\frac{pD^2}{4}$$

$$Mean\,velocity \quad u_m=\frac{\frac{q_m}{r}}{A}$$

$$\mathrm{Re}=\frac{r\cdot u_m\cdot D}{m}=1727 \quad \rightarrow Laminar\ flow$$

$$\Delta J_{ext\_length}=\frac{64}{\mathrm{Re}}\cdot\frac{u_m^2\cdot L}{2\cdot D}\cdot\frac{r}{10^5}=0.011\,bars$$

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=> The total pressure drop is 0.456 bars