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Thermal Simulations of the Inner Module

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1 FEA Simulations

The thermal properties were simulated using FEA analysis. Following assumptions were made:

- The module is cooled entirely by the cooling block. No heat transfer to and from the ambient gas is allowed.
- The coolant is assumed to be a fluorocarbonat with 3750 W/m^2K heat transfer coefficient. This could be reached with C_3F_8, for C_4F_{10} the value is lower, we assume 2700 W/m^2K. Baseline coolant temperature is -15^{o}C, although the cooling specifications allow for lower temperatures.

The cooling block properties are taken from a separate FEA analysis. They are then parameterized like:

$$T_{detector} = R_{11}Q_{detector} + R_{12}Q_{hybrid} + T_0 \tag{1}$$
$$T_{hybrid} = R_{21}Q_{detector} + R_{22}Q_{hybrid} + T_0 \tag{2}$$

$T_{detector}$ is the surface temperature on the detector part of the (main) cooling block, T_{hybrid} the surface temperature of the hybrid part, $Q_{detector}$ the heat flow from the detector and Q_{hybrid} the heat flow from the hybrid. R_{ij} are the thermal resistivities taken from a simulation of the cooling block. Typical values for various block designs are shown in table 1. As

	AP(1)	AP(2)	AP(3)	TS
R_{11}	2.84	2.30	2.45	3.72
R_{12}	0.85	0.69	0.97	0.00
R_{21}	0.85	0.69	0.97	0.00
R_{22}	2.35	1.73	1.95	3.98

Table 1: *Parameterization of cooling block performance (see text).*
AP(1): Andy Pilling's partial split block with C=3750 W/m^2/K.
AP(2): Improved split, C=3750 W/m^2/K.
AP(3): Improved split, C=2700 W/m^2/K.
TS: Perfect split, C=2700 W/m^2/K.

standard for a partial split block we use AP(1). It assumes a high value of the coolant pipe transition (C=3750 W/m^2/K). However, with some improvements to the split (still partial) it performs very similar with C=2700 W/m^2/K (AP(3)). For the totally split block the values used correspond to C=2700 W/m^2/K. The high cooling block is used throughout.

The temperature dependence of the silicon power density is modeled using:

$$Q(T) = Q_0 \frac{T^2 \exp\left(-\frac{E_g}{2kT}\right)}{T_0^2 \exp\left(-\frac{E_g}{2kT_0}\right)} \tag{3}$$

material	conduction W/m/K	thickness (mm)	comment
Silicon	136	0.26	thin detectors
TPG	1700	0.5	thinned to 0.225 mm at joints
TPG	8		transverse
AlN	180	0.5	two layers of 0.225 mm
glue	0.42	0.1	Silicon/TPG
glue	0.42	0.05	TPG/AlN
BeO	260	0.5	Hybrid
quartz	1.5	0.30	pitch adaptor

Table 2: Material properties used in simulation

For silicon, the nominal band gap is $E_g = 1.1$ eV. Measurements of irradiated silicon detectors indicate a slightly larger value ranging from 1.15 to 1.26 eV. As worst case 1.26 eV is used in the calculations.
The thermal conduction coefficients and dimensions of various material can be found in table 2. Recently the power produced by the readout electronics on the hybrid has increased from 4.5 W to 7 W (worst case). This leads to an deterioration of the thermal properties. Firstly the heat flow from the hybrid to the detector part of the block is increased, resulting in a higher temperature of the cooling block. Secondly some heat flows via the fan-ins from the hybrid to the detectors.
Even with 4.5 W hybrid power the module fails the specs (runaway at $Q_0 = 180\ W/m^2$). With 7 W hybrid power the situation is even worse ($Q_0 = 110\ W/m^2$). While with 4.5 W power a reduction of the coolant temperature to $\approx -18^oC$ cures the problem, for the 7 W case a rather low coolant temperature of -22^{o}C is necessary (all using the partial split block AP(1)).
Several variations were tried to improve the performance:

- Use of a totally split block.
- Reduction of the thickness of the pitch adaptors from 300 μm to 210 μm and a thicker glue (200 μm instead of 100 μm for them (It was assumed that the glue covers the full area of the pitch adaptors. A similar effect can be obtained by gluing only narrow strips or using a dot pattern). This should reduce the heat flow from the hybrid to the detector.
- A hybrid material with $C = 800\ W/mK$ was used instead of the standard BeO with $C = 260\ W/mK$ (which can be reached using carbon based substrates).

All these steps result in considerable improvements (Table 3, Fig. 1). A complete split (if possible) and an improved fan-in would allow the module to be operated safely at $\approx -17^o$C, a temperature which is also required for the outer module and the barrel. Using a high conductive hybrid substrate could improve things further, allowing safe operation at $= -16^o$C. Such a substrate together with the improved fan-in and the standard partial

	runaway at -15 C W/m^2	T_{min} for Q0=240 W/m^2 ^{o}C
standard (4.5W)	180	-18.0
standard	110	-22.0
total split	170	-18.5
+ improved fan-in	190	-17.2
+ carbon hyb.	215	-16.0
imp. fan-in, carbon	190	-17.2

Table 3: *Performance of various design options. Hybrid power is 7W, unless quoted otherwise*

split block would also solve the problem. However, it must be mentioned that the FEA description of the hybrid is rather crude. Only the thermal conductivity of the substrate was changed from 260 W/m/K (BeO) to 800 W/m/K. No attempt was made to model Kapton and glue layers. Clearly a TPG substrate may reach 1700 W/m/K so the value assumed has some safety margin. It is clear that this has to be studied in more detailed if the thermal performance can significantly be improved by using such a high conductive substrate. If so, this must have some impact on the hybrid decision.

Finally it should be mentioned that those improvements can be used for the other modules as well. The short middle ring module has the same problems than the inner and these modifications must be used there anyway. The long middle ring module may suffer from the long second cooling block (going through the disk) and such improvements might be necessary (and sufficient) as well. Studies are needed. For the outer such improvements are not really necessary, but add to the safety.

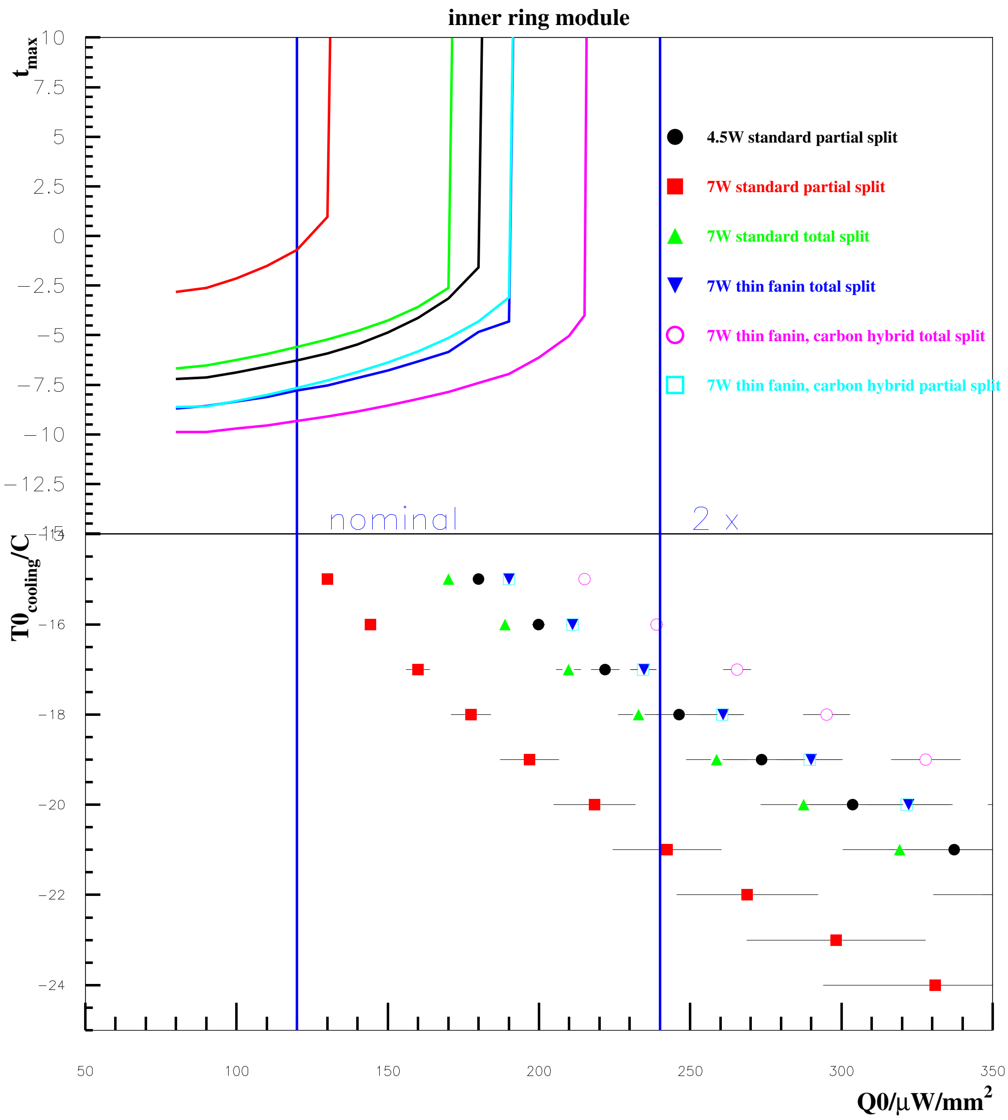

Figure 1: Upper plot: thermal runaway curves for various design variations of the inner module (Coolant temperature -15^{o}C). Lower plot: Coolant temperature needed for safe operation as function of the nominal power density. The vertical lines indicate the nominal power density (120 $\mu W/mm^2$) and the 2$\times$ safety margin. Design variations studied:

●: standard design, partially split block, 4.5 W.

■: standard design, partially split block, 7 W.

▲: standard design, totally split block, 7W.

▼: thin fan-in, totally split block, 7W.

◯: thin fan-in, carbon hybrid, totally split block, 7W.

□: thin fan-in, carbon hybrid, partially split block, 7W.