Summary: thermal analysis, CFD simulations

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Workshop on SiPM cooling for Fiber Tracker, 17 October 2013

Contents

A. Computational Fluid Dynamics (CFD) simulations for design optimization and heat load estimation

B. Comparison among different cooling options
(air cooling, liquid cooling, two-phase cooling)

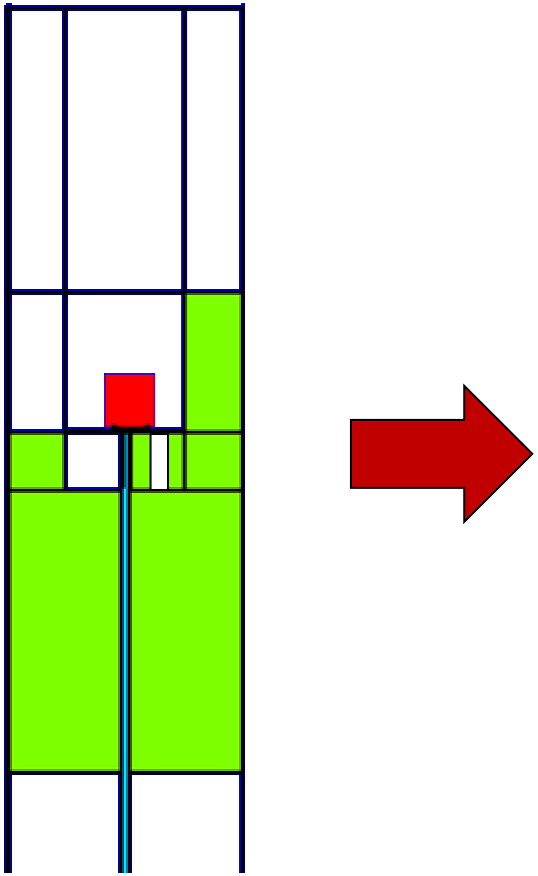
CFD simulations

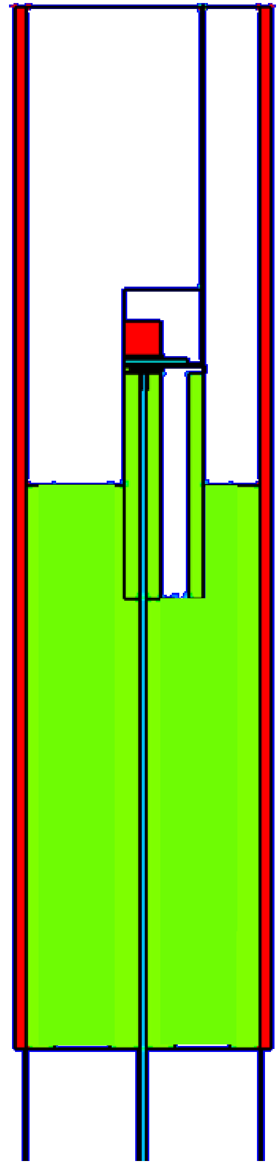
- 2D and 3D Computational Fluid Dynamics simulations were run to support the design optimization and identify bottlenecks.
- Direct simulation of natural convection of air around the module and heat conduction inside the modules.

- Main parameters to check:

1. Total module heat load;
2. Module surface temperature (avoid vapor condensation);
3. Scintillating fiber temperature (should be as uniform as possible);
4. Refrigerant to silicon-die temperature difference.

Optimization of module end-cap





Major optimization steps/issues:

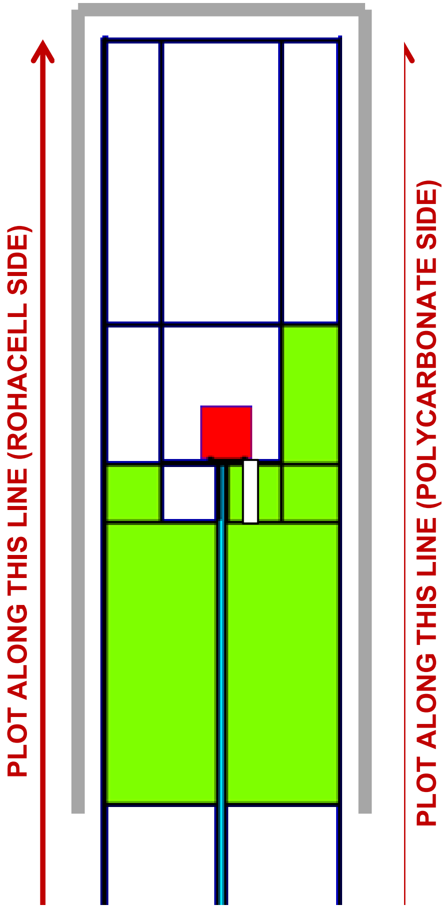
1. Carbon fiber -> kapton;
2. Polycarbonate -> rohacell;
3. Aluminum skin;
4. Grooves to reduce conduction through polycarbonate;
5. Stiffener material choice;
6. Gap fill between modules.

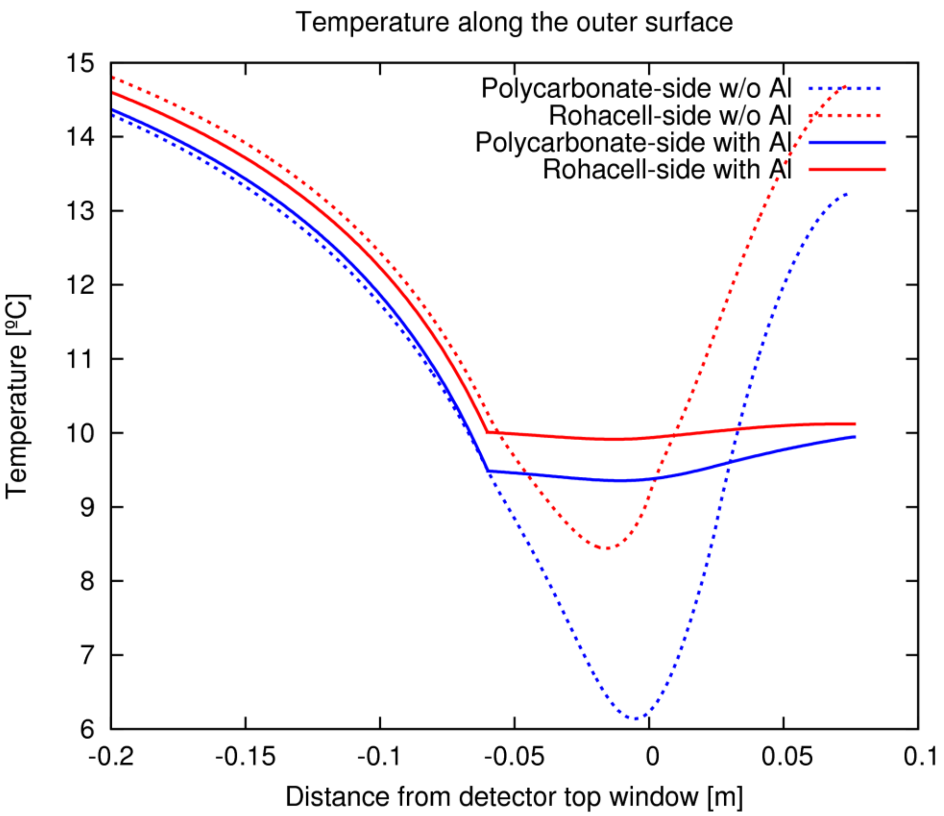
rohacell/air (k ~ 0.03-0.025 W $m^{-1}K^{-1}$)

Polycarbonate (k = 0.20 W $m^{-1}K^{-1}$)

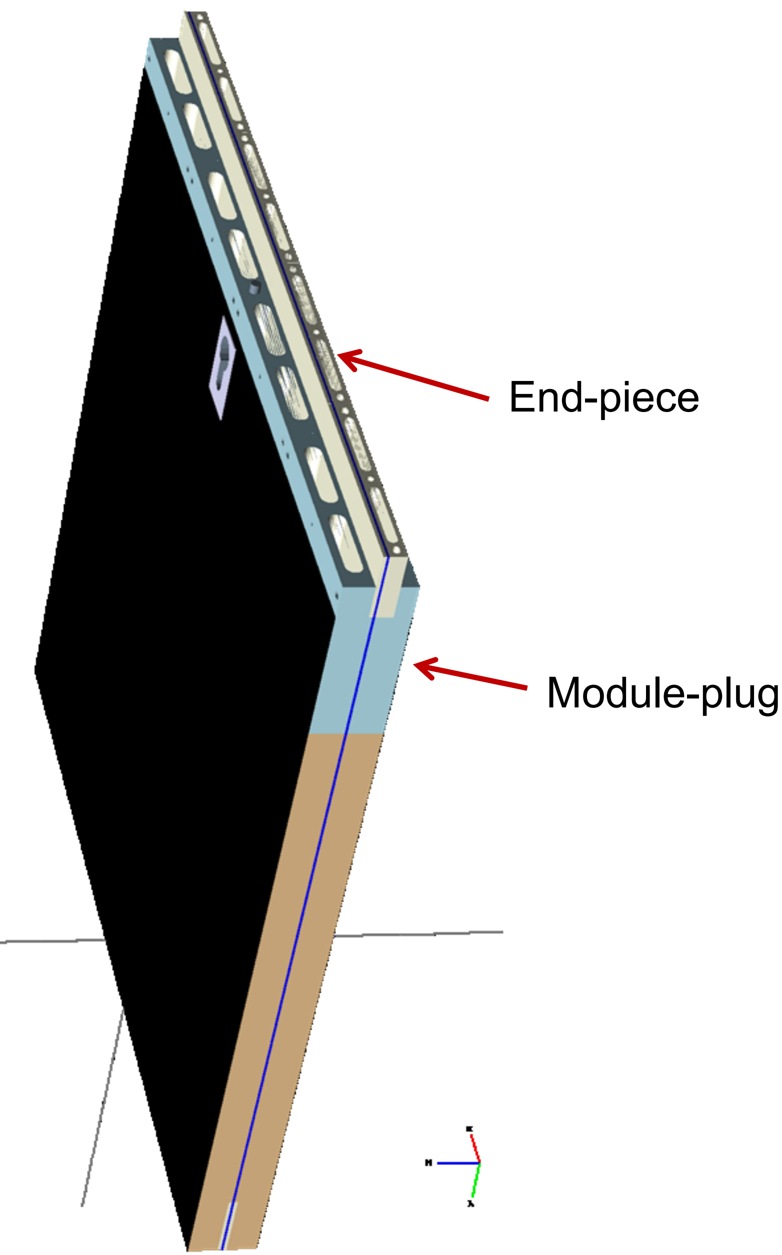
aluminum/copper (k >= 200 W $m^{-1}K^{-}$

Examples: 2 mm aluminum skin





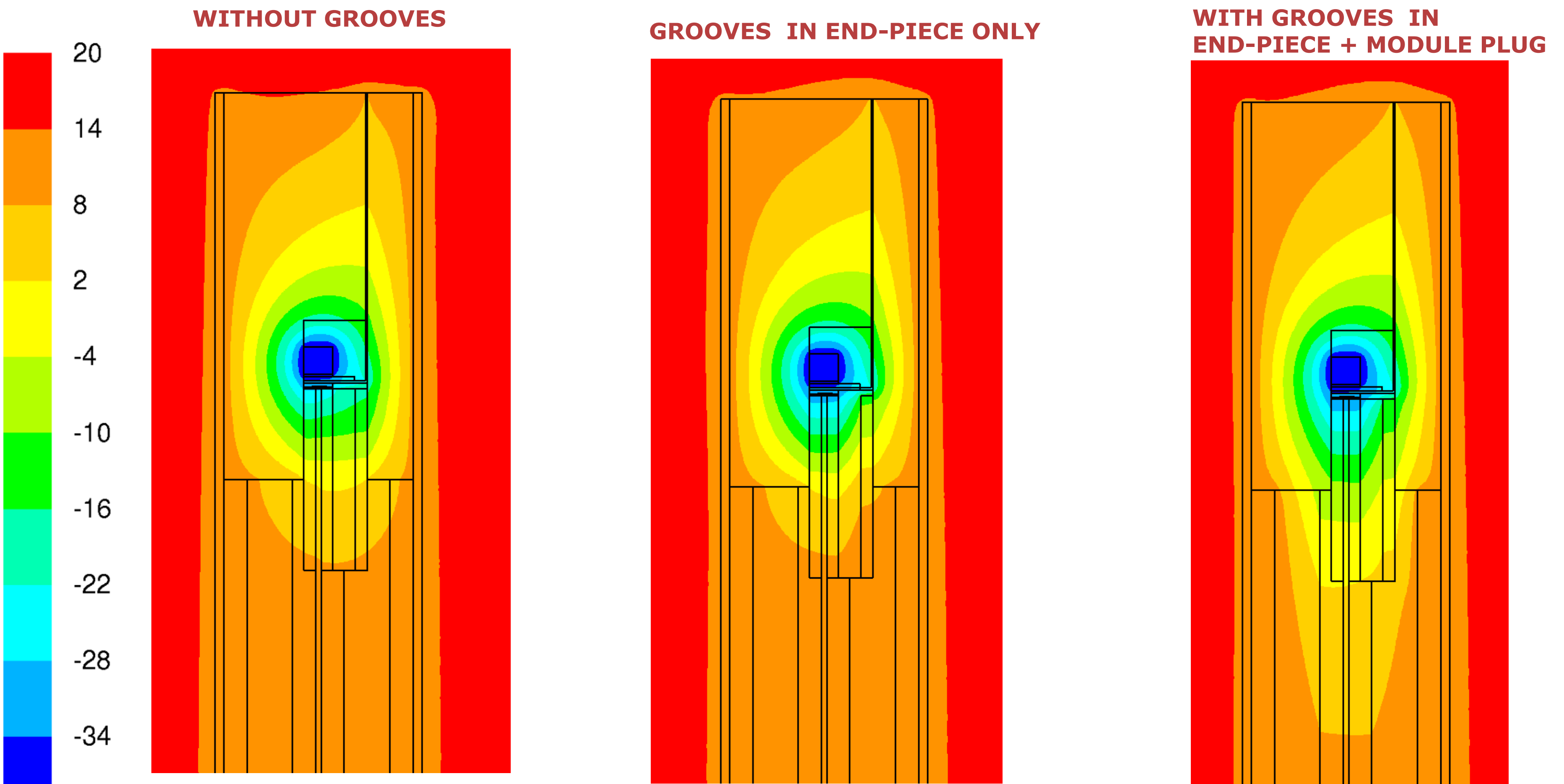
- 2 mm thick aluminum skin covering the module down to the polycarbonate "module plug" (see sketch).
- Temperature in the cold-spot on polycarbonate side is increased by more than 3 K.



- Polycarbonate display a thermal conductivity ~10x air conductivity.

- Grooves can be made in the polycarbonate pieces (module-plug and end-piece) to reduce the heat load.

Examples: grooves in the polycarbonate 2/2

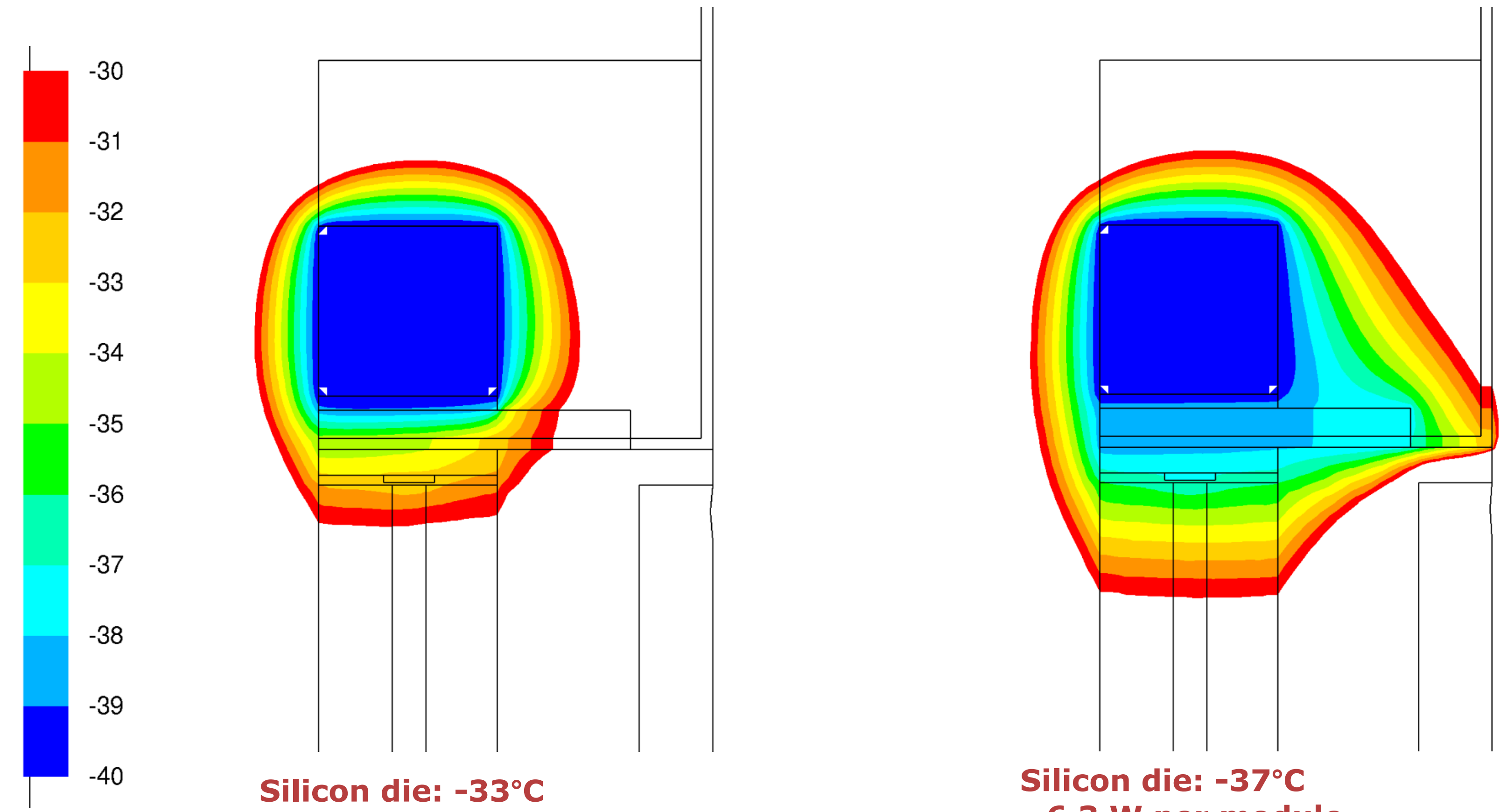


~7.3 W per module **~6.2 W per module** **~5.7 W per module**

- Grooves in polycarbonate reduces the total heat load;
- On the other hand, grooves in the module-plug reduces the temperature of the scintillating fibers over the last 0.1 m;

Example: influence of stiffener

k = 0.25 W m⁻¹K⁻¹ STIFFENER (FR-4) | *k* = 37 W m⁻¹K⁻¹ STIFFENER (CERAMIC)

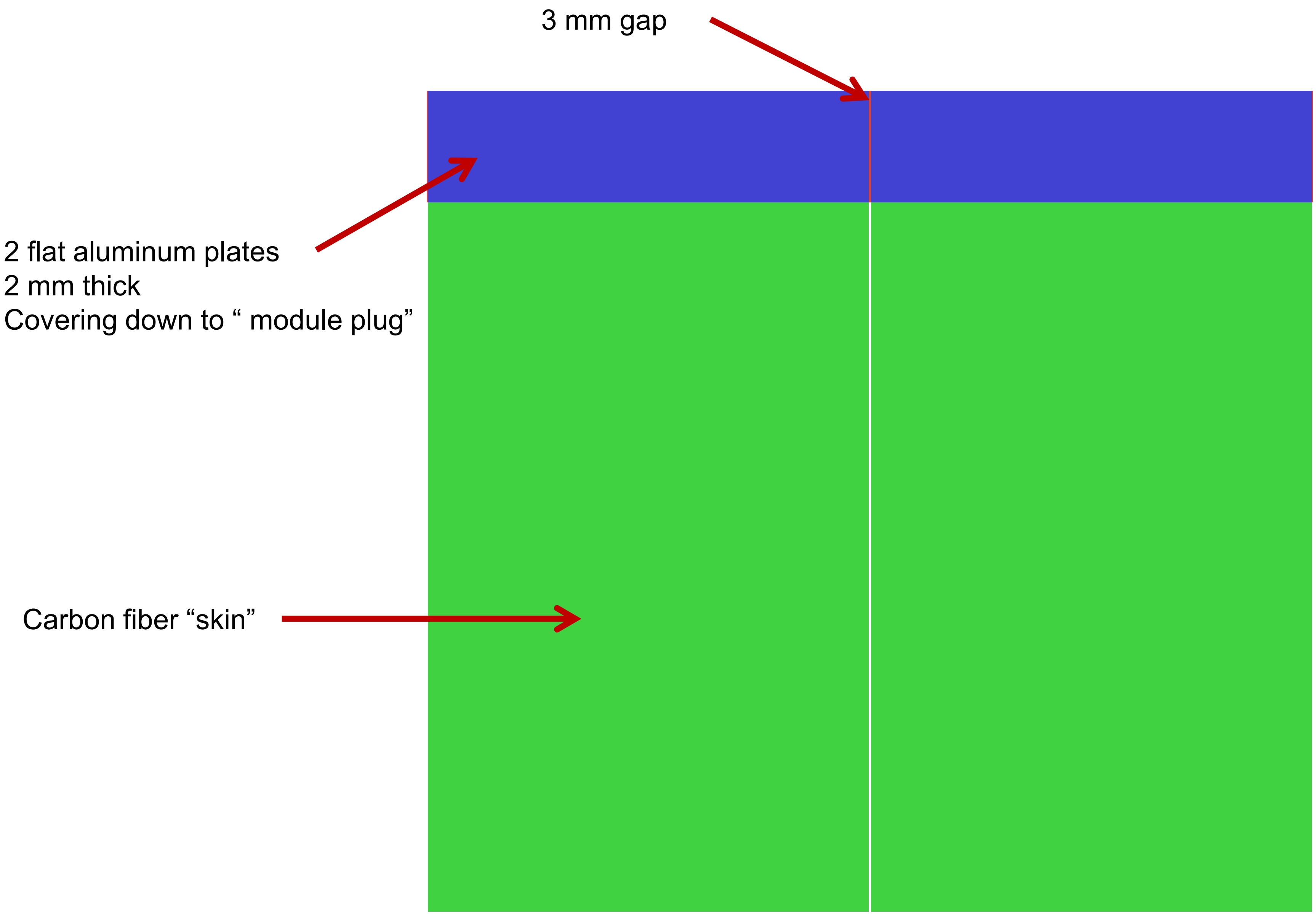


Silicon die: -33°C
~5.7 W per module

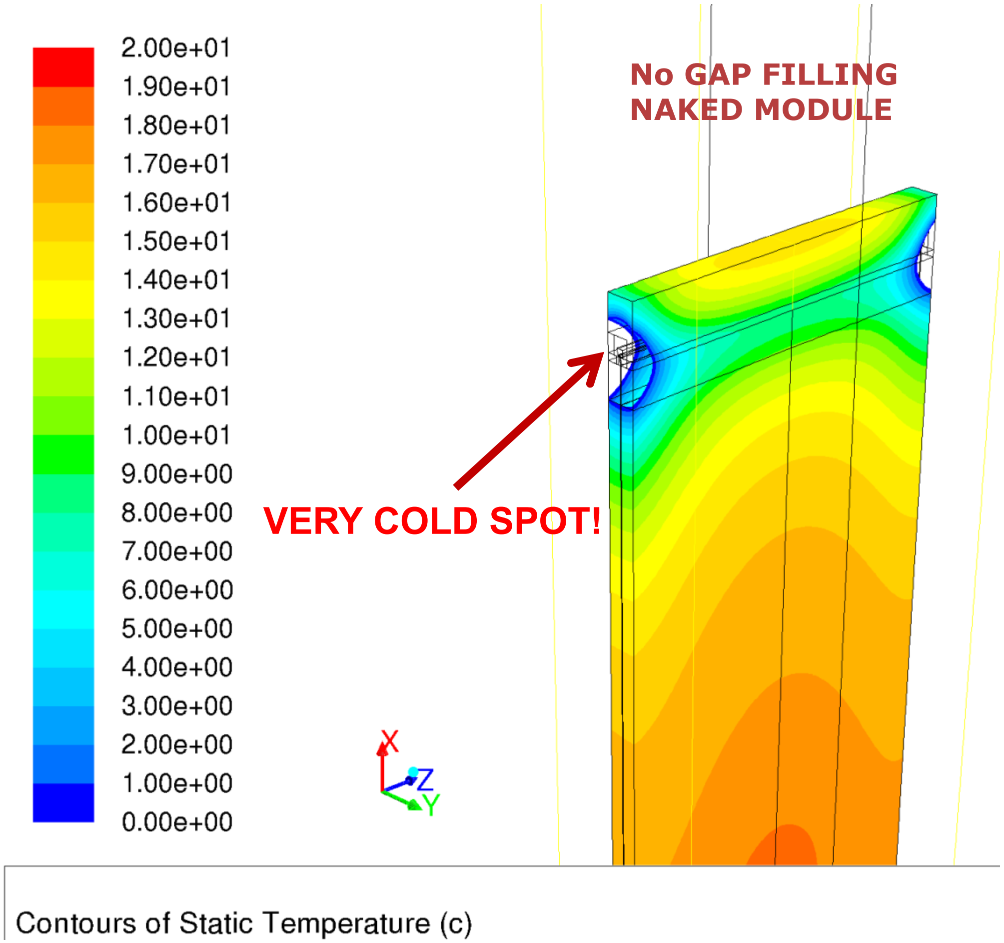
Silicon die: -37°C
~6.3 W per module
(more heat through flex-cable)

- Despite the heat load increase, high-conductivity stiffener is to be preferred to reduce the refrigerant-to-silicon-die temperature difference (higher refrigerant temperature required).

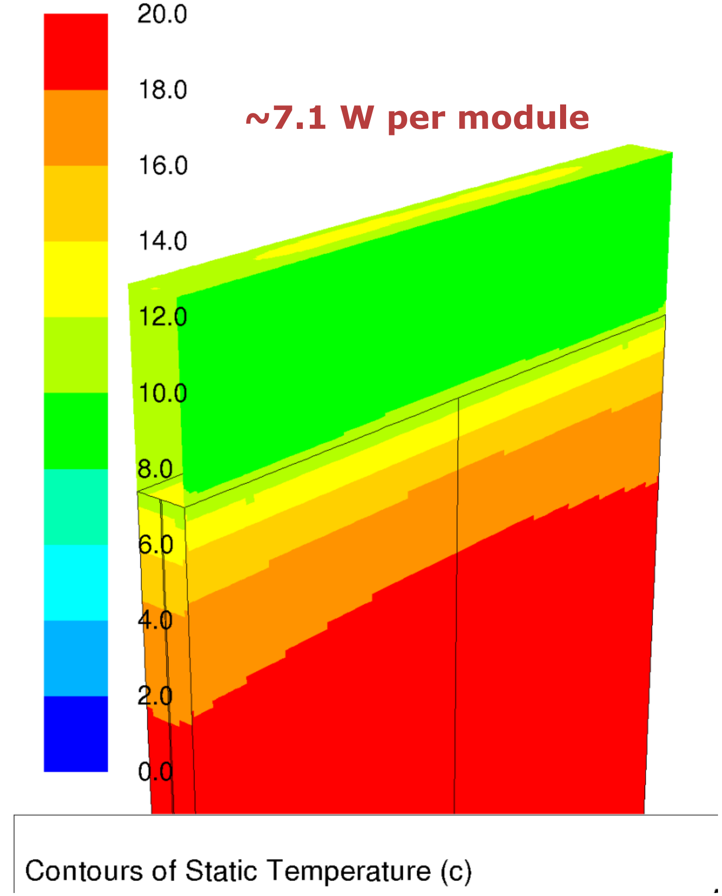
Example: gap fill between modules 1/2



Example: gap fill between modules 2/2



2 mm ALUMINUM PLATES + CF SKIN + 3mm GAP FILLED WITH k=0.1 $Wm^{-1}K^{-1}$ MATERIAL



- Gap between modules must absolutely be filled with some material, in order to avoid condensation and even frost formation;
- Suggested design: 3 mm gap filled + aluminum plates covering down to module plug + carbon fiber skin on the rest of the module.

A. CONCLUSIONS

- **Total heat load is expected to be O(10 W);**
- Water vapor condensation is expected not to be a major problem for the present module design;
- Grooves are suggested only in the polycarbonate end-piece;
- Aluminum plates covering the module-plug are suggested to ‘flatten’ the surface temperature distribution and avoid condensation;
- The 3 mm gap between module must be filled;
- High thermal conductivity stiffener is to be preferred to reduce the refrigerant-to-silicon-die temperature difference.

B. Comparison among different cooling options:
-) air cooling
-) liquid cooling
-) two-phase cooling

Three main parameters to be checked

1. Refrigerant temperature rise ($\Delta T_{out\text{-}in}$):

- It must be low enough to achieve the desired temperature uniformity along the silicon die (< **10 K**);
- For "air-cooling" and "liquid-cooling" it depends on:

  -) mass flow rate [kg/s];

  -) specific heat [J/(kg K)].
- During "two-phase" boiling there is no temperature rise, just some temperature drop due to the pressure drop (usually negligible);
- "Two-phase" better than "liquid-cooling" better than "air-cooling".

2. Temperature difference between wall and refrigerant ($\Delta T_{wall\text{-}ref}$):

- Must be low in order to keep the refrigerant temperature reasonably close to -40°C (ì.e. >-50°C);
- It depends on:

  -) Heat Transfer Coefficient (HTC) [W/(m^2K)];

  -) Surface [m^2] available for heat transfer;
- The HTC heavily depends on thermodynamic properties and turbulence;
- "Two-phase" better than "liquid-cooling" better than "air-cooling".

3. Pressure drop:

- It must be reasonably low.

Generally speaking:

Air-cooling

Liquid-cooling

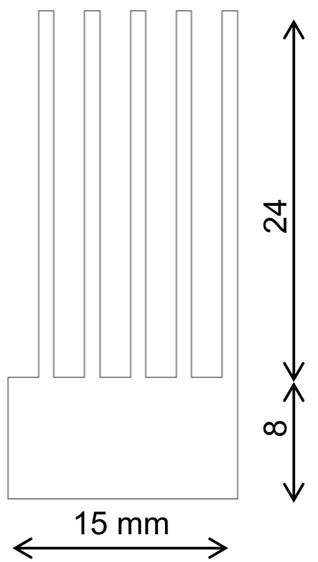
Two-phase cooling

Temperature uniformity↑
HTC↑
Smaller ducts
Smaller heat transfer surface

System complexity
\$↑ (?)

Air-cooling with Vortex Tube

Pitch: 3 mm
Fin thickness: 1 mm



- Compressed air and vortex tube to produce cold air (-50°C);
- Heat-sink can be closed to create channels, air leaks could anyhow be beneficial to keep the enclosure in overpressure;
- Estimation based on 10 W assumption:

Refrigerant	$\Delta T_{out\text{-}in}$ [K]	HTC [W m^{-2} K^{-1}]	$\Delta T_{wall\text{-}ref}$ [K]	Δp [Pa]	Flow Rate [Nl min^{-1}]
Air (-50°C)	**10.6**	26	**3.0**	63	48

- Due to the low temperature uniformity and low power density required, air cooling would provide acceptable temperature uniformity, HTC and pressure drop;

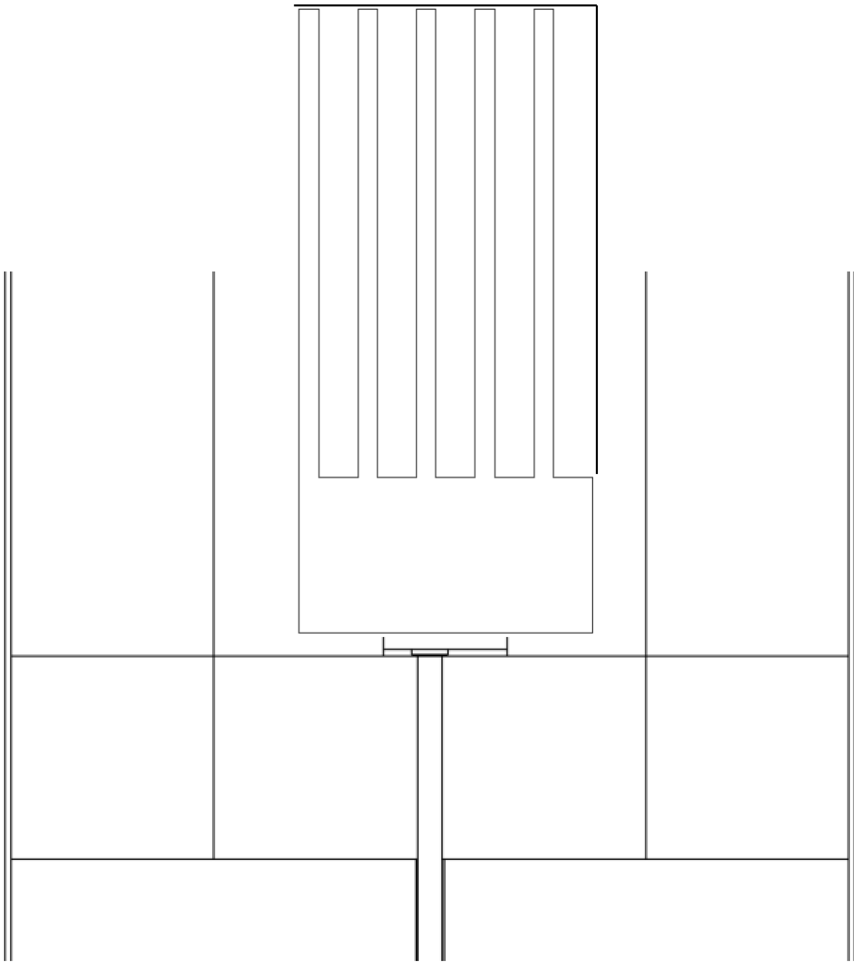
BUT

- Compressed air needed @ room temperature is around 8x times the cold air produced @ -40°C;
- Air must be dry (dew point -70°C!) to avoid ice formation in the vortex tube.

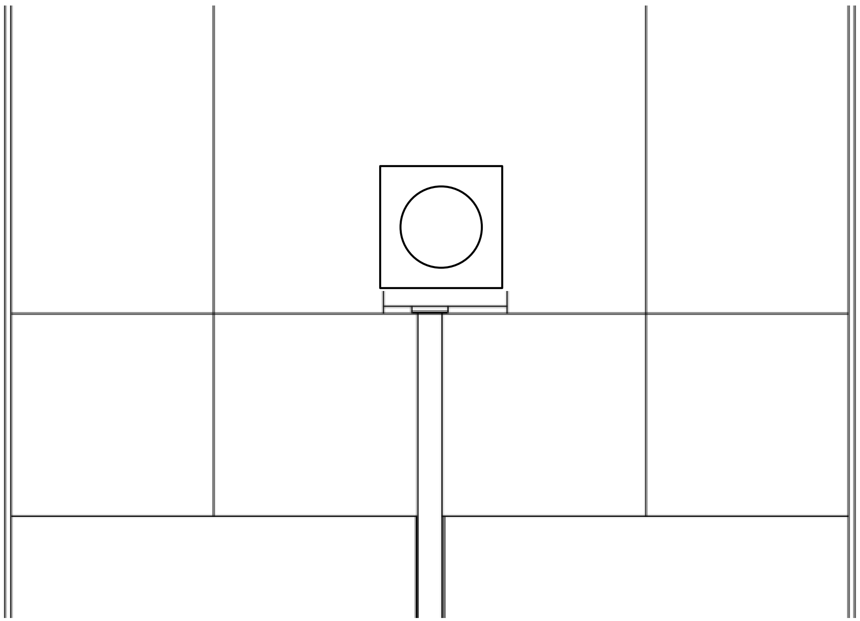
Solution to be discarded because of the huge flow rate of compressed needed (**~10000 m³/h**) and the energy needed (to compress + dry).

Size comparison: air vs liquid

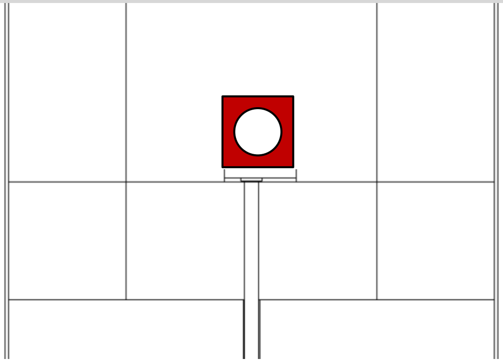
Air-cooling



Liquid-cooling



Some examples of liquid-cooling options



ASSUMPTIONS

- Pipe dimensions: 4 mm i.d. (round)
- Refrigerant velocity: 1.5 m s^{-1}
- Refrigerant temperature: -50°C
- Cooling load per module: 10 W

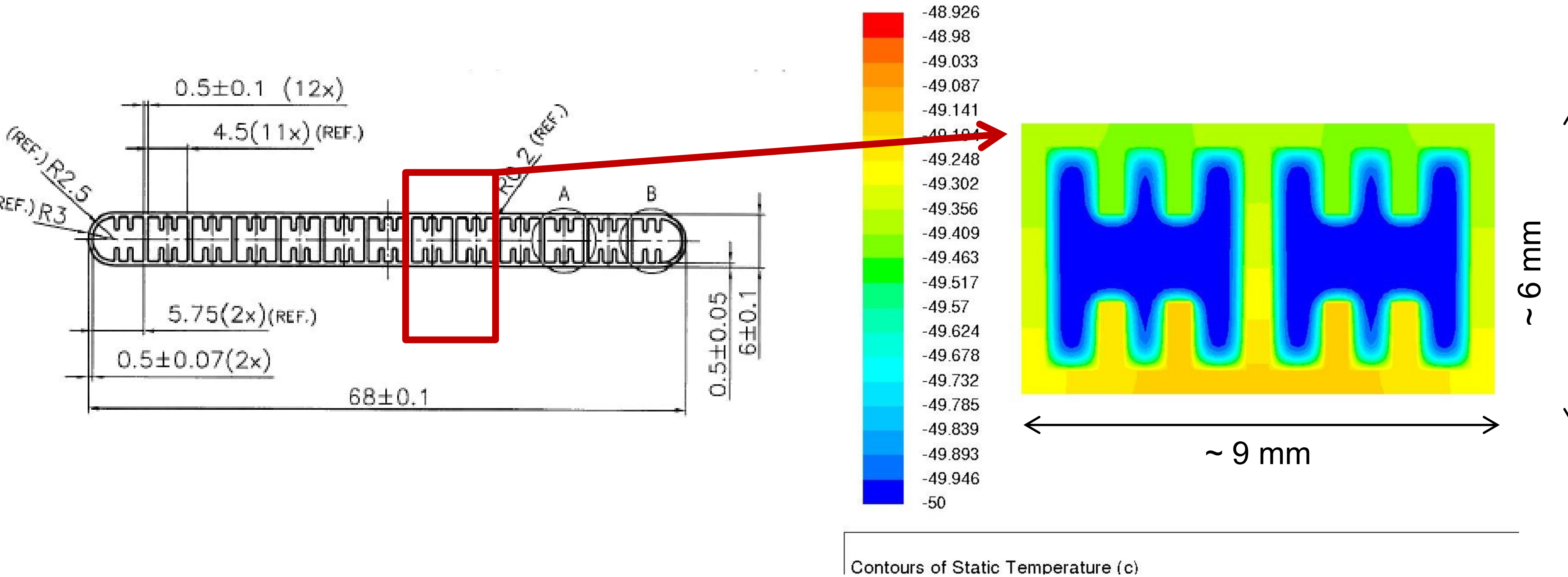
Refrigerant	ΔT_{out-in} [K]	HTC [W m^{-2} K^{-1}]	$\Delta T_{wall-ref}$ [K]	Δp [bar]	Flow Rate [kg s^{-1}]
Dynalene*	0.36	120	12	0.20	0.015
Dowterm J**	0.35	138	11	0.06	0.017
C_6F_{14}	0.3	1200	1.3	0.10	0.035
NOVEC649	0.28	1100	1.4	0.11	0.034
CO_2 liquid***	0.24	6000	0.3	0.004	0.022
NH_3 liquid****	0.17	11000	0.14	0.005	0.013

** Aliphatic hydrocarbon blend* *** Mixture of isomers of an alkylated aromatic*

**** Saturation pressure @ 30°C: 72 bar, freezes at -56°C* ***** Saturation pressure @ 30°C: 11.6 bar; copper must be avoided*

- The "default" CERN solution for single-phase detectors cooling (C_6F_{14}), as well as its "green" substitute (NOVEC649), would fit without problem;
- Fluids such as Dynalene or Dowterm J display low HTC and my need an higher heat transfer surface.
- CO_2 and NH_3 display thermodynamic properties far better than what needed;
- Almost any two-phase cooling option would work with this configuration;

Example of increased heat transfer surface for liquid-cooling



Fluid	Velocity [m s^{-1}]	Δ*T*out-in [K]	Δ*T*wall-ref [K]	Δ*p* [bar]	Flow Rate [kg s^{-1}]
Dynalene	1	0.17	**1.4**	0.31	0.0320
Dowtherm-J	1	0.17	**1.3**	0.10	0.0357

- Low HTC issue can be easily solved by increasing the heat transfer surface.

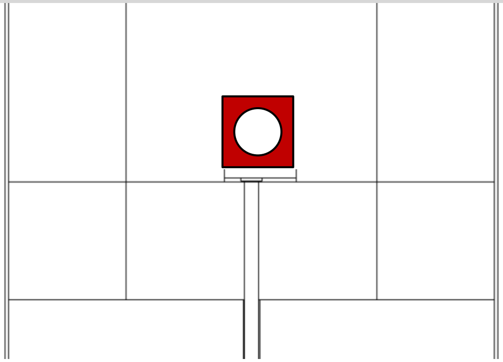
B. CONCLUSIONS

- Requirements in terms of cooling load and power density (O(10W) over 0.5 m length) and temperature uniformity (10 K per module) are not very demanding;
- Air-cooling with vortex tubes could in principle cope with these requirements, but this solution is to be discarded because of the huge amount of compressed air needed (O(10000 m^3/h) with -70°C dew point);
- Liquid-cooling with C_6F_{14} or NOVEC649 would fit the requirements in terms of heat transfer coefficient and silicon die temperature uniformity;
- Depending on the fluid used, a round 4 mm pipe or a multiport pipe (augmented heat transfer surface) may be needed;
- From the point of view of the heat transfer process inside the module, there is absolutely no need to use “high-performance” solutions such as evaporative cooling.

THANKS FOR YOUR ATTENTION

BACK-UP SLIDES

Liquid cooling, secondary fluids



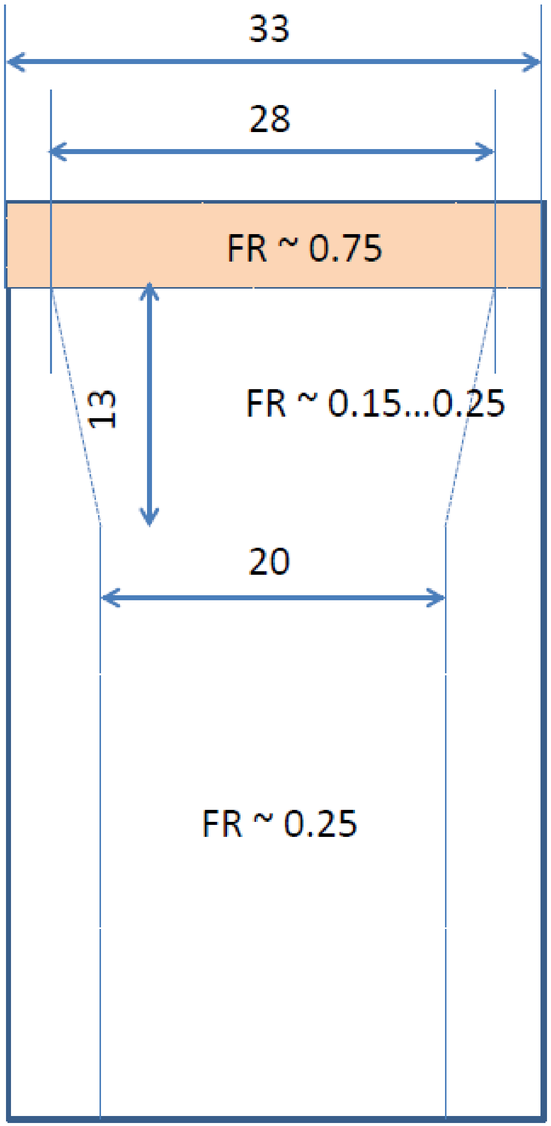
Fluid	ΔT_{out-in} [K]	HTC [W m^{-2} K^{-1}]	$\Delta T_{wall-ref}$ [K]	Δp [bar]	Flow Rate [kg s^{-1}]
Water/70% methanol *	0.17	354	4.3	**0.54**	0.018
Water/29.9% calcium chloride **	0.15	463	3.3	0.36	0.025
Syltherm XLT	0.40	111	**14**	0.09	0.017
Thermogen VP1869	0.25	158	**10**	**0.80**	0.019
Dynalene	0.36	120	**12**	0.20	0.015
Dowterm J	0.35	138	**11**	0.06	0.017

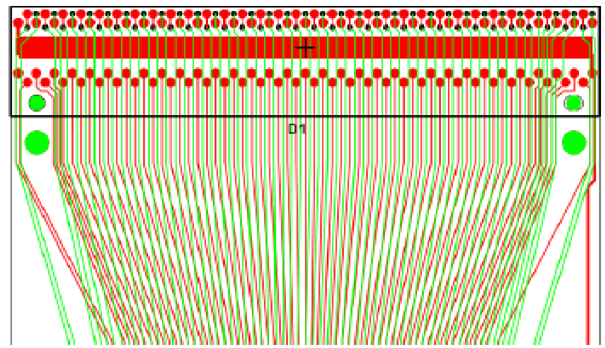
** Minimum temperature -57°C*

*** Minimum temperature -55°C*

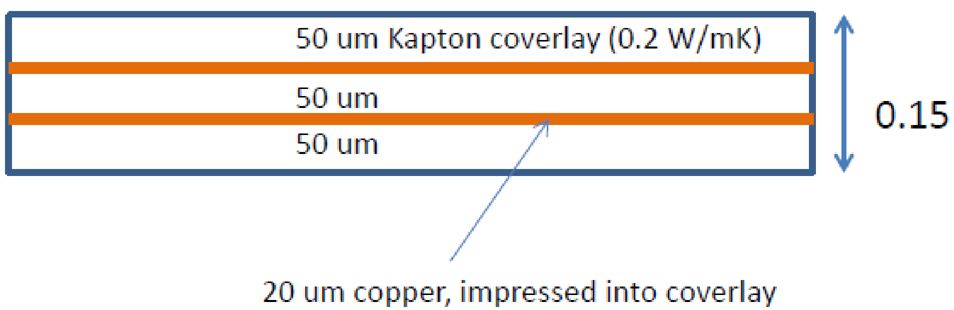
- Water mixtures with methanol or calcium chloride would work, but the freezing point ~ -55°C could be a problem.

Cooling through flex-cable 1/3

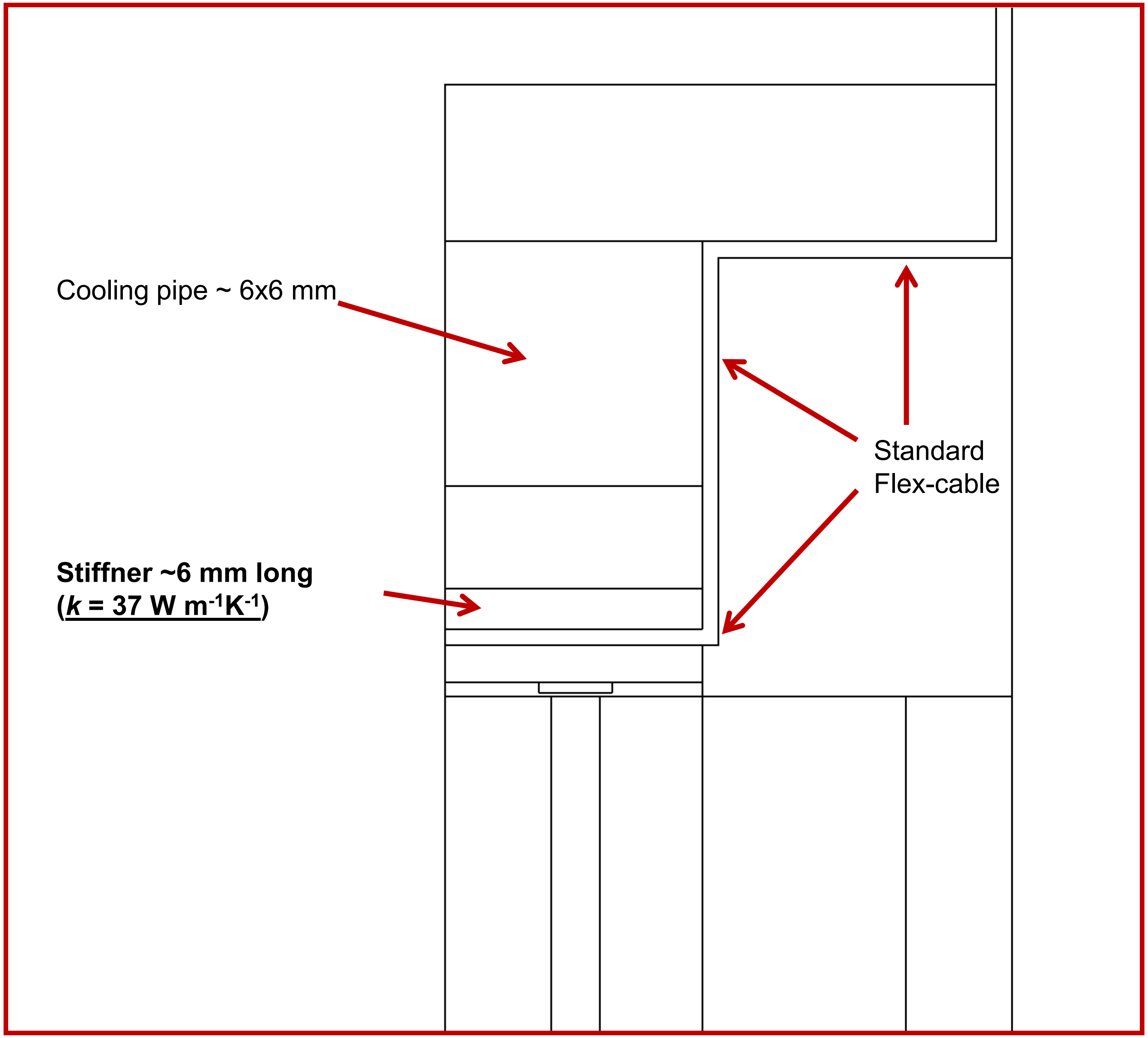




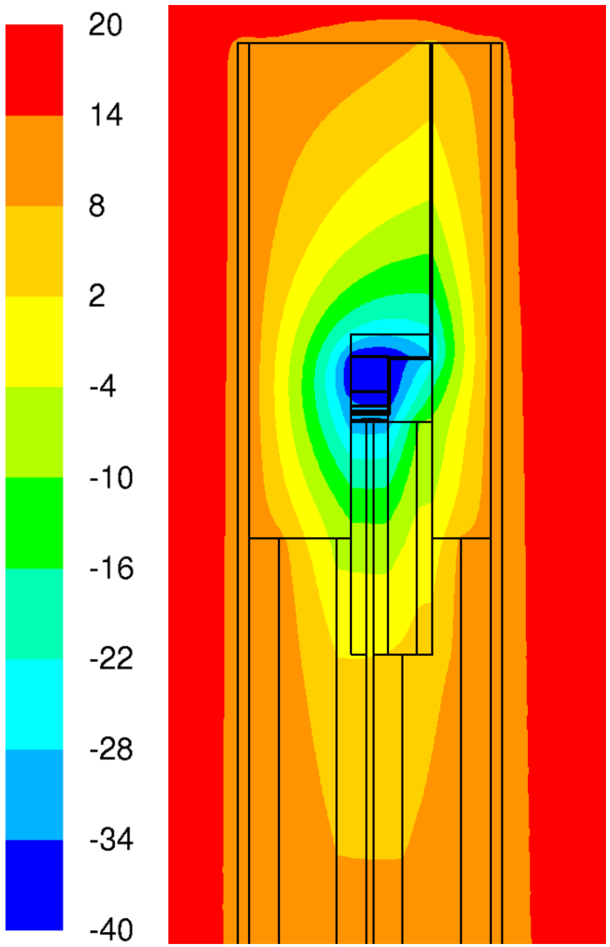
FR=fill ratio = copper/empty
130 conductors, 75 um wide, 20 um thick
IMO, a reasonable approximation would be a bulk copper band, 28x5.56 mm2

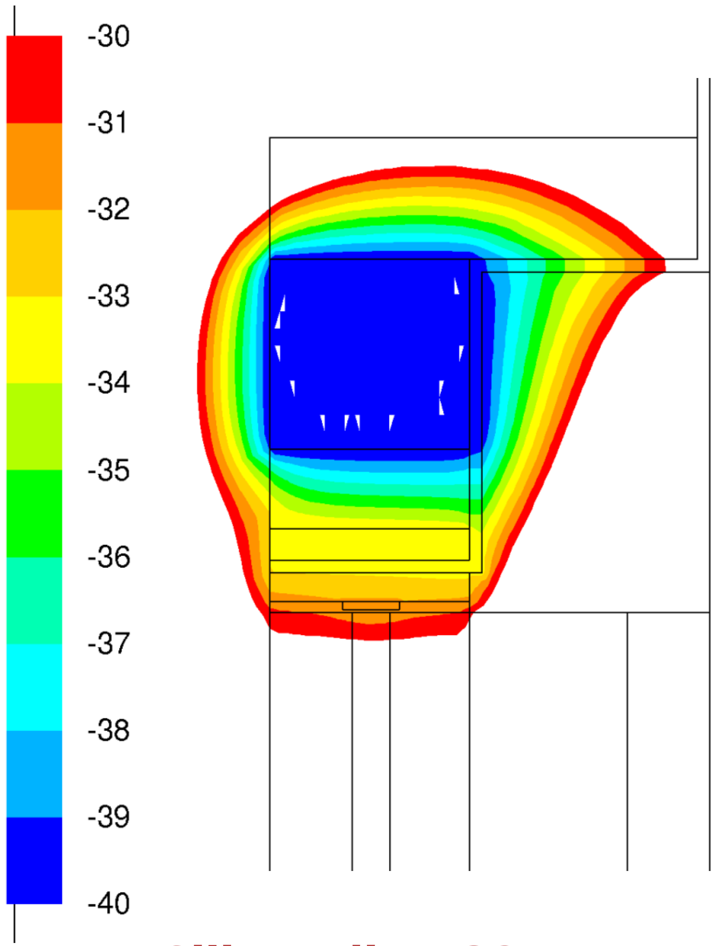


Cooling through flex-cable 2/3



Cooling through flex-cable 3/3





Silicon die: -32°

- Copper must be added to the flex-cable in order to reduce the refrigerant-to-silicon temperature difference.