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Version 1.2 October 14, 2013

Draft SiPM cooling system specification for the FT in the upgraded LHCb

Contents:

1. Introduction

1.1. Generalities

The LHCb outer tracker upgrade project, described in detail in Refs. [1-3], foresees a replacement of the existing straw tube Outer Tracker (OT) with a new detector based on 2.5 m long and 250 µm thick scintillation fibres read out with silicon photomultipliers (SiPM). Currently (in particular, in [3]), the option to replace both the OT and the existing silicon microstrip-based Inner Tracker (IT) with the scintillation fibre tracker (the Fiber Tracker, FT) is being discussed. This tracker technology will be able to cope with the largely increased occupancy at the IT and the most central OT, expected at the LHCb after the Phase-2 upgrade of the LHC.

The subject of this document is the cooling system for the FT photodetectors, SIPMs. The SiPM technology [4] is chosen because of its high resolution in detecting very weak light signals from the fibres (from a single photon to dozens of photons). However, SiPM performance is compromised by the dark noise which sharply increases after irradiation with the neutrons[1] . The expected neutron fluence of $6{\cdot}10^{11}$ neqv/ cm^2 for the integrated luminosity of 50^{-1}fb of the upgraded LHCb will result in 50…100 fold increase of the dark count rate [5], compared to the non-irradiated case. The situation with the SiPM radiation damage is aggravated by the fact that the light yield from the fibres also drops with the radiation dose (the worst case is the “far end” of the fibres situated near the beam pipe). This requires keeping the *photo-detection efficiency* (PDE) at the maximum level. Another key performance parameter, which eventually determines the track reconstruction efficiency, is the *cluster noise rate* which is a complicated function of many parameters (including the radiation dose, the SiPM gain and the temperature) and can be simulated, based on calibration measurements performed on the FT prototypes [3][2]

The radiation damage effects, as well as the general performance, are numerically different for the two SiPM candidate types (Hamamatsu and KETEK), but qualitatively, the FT viability study concludes that **cooling** is the most effective (and, essentially, the only) measure to keep the dark noise at an acceptable level (<10 MHz / channel ??) and also to obtain some room for increasing the SIPM gain and its PDE. As a rule of thumb, the dark noise depends exponentially on the operating temperature, decreasing by a factor of 2 for every temperature drop by 10°C. Thus, to reduce the noise by a factor of 2^6=64, *one needs to lower the temperature by about 60°C*, thus operating the SiPMs at -40°C or lower. This constitutes the most important requirement on the SiPM cooling design, directly or indirectly affecting other requirements.

Other challenges are related to the large extent of the OT and the facts that

- The OT is essentially external device and no protecting gas volumes are conceivable to encapsulate cold surfaces, pipes and connections;
- The upgraded OT should fit into the space envelope of the existing tracker, which was not intended for sub-zero cooling (little space for thermally insulated communications);
- Manifolding is significant: the 12 FT layers are arranged in 3 stations split in halves which can move apart to access the beam pipe. Thus, there will be 24 half-layers with symmetric top and bottom readouts requiring 48 cooling branches (see Figure 1).
- The “x-layers“ with upright modules are interspersed with “u-“ and “v-“ layers, having modules tilted by 3…5 degrees. The currently preferred option is a “saw-tooth” like arrangement shown in Figure 3. The cooling method should be insensitive to the tilt.
- The dead space between the FT modules has to be minimal, thereby permitting no significant insulation between the modules. The problem is the protection of the module edges against condensation (Section 2.3).
- The SiPMs will be rigidly fixed to the fibre end-pieces. The cooling structure must be detachable. The challenge is to secure a reliable thermal contact between the SiPM and the cooling, that will be stable in time and, at the same time, permit mutual displacements of the end-pieces and the cooling structure due to different CTEs.

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[1] Neutrons with the peak energy of about 1 MeV represent the main radiation background at the location of the FT read-out – out of the tracker acceptance.

[2] We note here that the dark noise and another SiPM property influencing the cluster noise rate, *the cross-talk*, are both strong functions of the SiPM gain (primarily determined by the over-voltage above the breakdown voltage).

1.2. Requirements

1. SiPM working temperature of -40…-50°C.
2. Operating temperature stable in time within ±1°C between consecutive calibrations (between LHC fills?)
3. The total heat dissipation of the end caps of ~3 kW (excluding pickups in all transfer and connecting lines).
4. Temperature uniformity of better than 1°C (peak-to-peak) over the extent of a single SiPM, 33 mm.
5. The cooling system components withstanding the neutron fluence of $6{\cdot}10^{11}$ neqv (1 MeV)/ cm^2 and the ionizing radiation dose of 50 Gy.
6. An accurate match of thermal expansion of the cooling structure and the fiber end-pieces. The thermal interface between the cooling structure (pipe) and the SiPM assembly should be sliding or elastic and have constant thermal properties aver the lifetime.
7. No condensation or frost formation on all end cap parts exposed to the ambient. A particular attention to the module-module junctions ("module edges problem").
8. Use of dielectric and fully volatile coolants inside the SiPM enclosure.
9. The cooling system modularity matching the FT modularity. The end-cap cooling structure should be integrated in the end-cap at a pre-assembly stage, with only external (inter-) connections to manage at the layer assembly stage.
10. The in/out cooling connection not interfering with the r/o electronics box. The electronics cooling must be totally decoupled from SiPM cooling.
11. A preference for a solution with warm external connections. The thermal insulation of all connections and services should match a limited spacing between the modules.
12. No electro-mechanical appliances at the detector location. The cooling plant situated ~70 m away from the detector.
13. Cooling distribution system (Figure 1) serving 48 branches distributed around the 5x6x1.6(?) m3 tracker and permitting lateral half-station movements by 4(??) m along X-direction. (Flexible pipes!)
14. The cooling method insensitive to a slight (3…5°) deviation from the horizontal orientation (for U- and V- modules).

Requirement 1: In order to be able to saturate the PDE and keep the cluster noise rate at a tolerable level of 1-2 MHz per 128 channels, after a nominal integrated luminosity of 50^{-1} fb, the *SiPMs have to be operated at low temperatures, down to -40°C* (at the level of the silicon die). The lower limit of about -50°C is imposed by structural constraints of the FT (for example, the minimal temperature of the fibre tips which will be in direct contact with the cooled SiPMs). The initial operation might require a less aggressive SiPM cooling. The upper limit of -40°C is strictly applicable to the modules within ±1 m from the beam axis (i.e. 4 central modules of the 12 modules/plane, see Section 2.3). The outer modules can be operated at a marginally higher temperature, according to the neutron fluence distribution quoted in [3] (-35°C, TBC, see also the Requirement 4 below).

Requirement 2: The tracker functionality does not impose particularly strong requirements on the SiPM gain stability, because the hits are reconstructed from the cluster baricenters, rather than their amplitudes. However, the gain, indirectly, affects the hit detection efficiency (required to be at the level 98-99%), through the amplitude cuts used in different versions of cluster reconstruction algorithms. The principal (and, in the simplest case, the only) one is the "seed cut", imposed on the highest channel in a hit cluster. The test beam studies show [6] that, for an optimal operation regime, the dependence of the cluster efficiency on the SiPM gain is weak: it changes only by 4% with the gain changing by 25-30% (for Hamamatsu) and by 1% for 30-45% gain variation (for KETEK)[3]. Since the gain, for a fixed operating voltage, is sensitive to the temperature (through the breakdown voltage, which is, approximately, a linear function of temperature, with the slopes of 56 mV/°C for Hamamatsu and 26 mV/°C for for KETEK), and given the usual overvoltage values of about 1.5V and 6V (for Hamamatsu and KETEK, respectively[4]) we can (roughly) derive that *the operating temperature should be stable in time within ±1°C* (for the worst case of Hamamatsu SiPM) during one LHC fill (8 – 20 hours)[5].

Requirement 3: *the net heat dissipation (without losses in transfer and manifold lines) is about 3 kW.* The heat load inside the module is dominated by parasitic heat influx through the insulation[6]. The CFD simulations predict O(10W) for the heat load at the coolant T of -40°C. The test bench measurements with a 2-phase cooling, at -56°C in the evaporator, with a loose insulation of the cold inlets, indicated the total heat load of less than 20W (Vic Vacek et al., […]). For a liquid cooling option, assuming a worst case of 20W per module and 20-25% heat pick-up along the lines, the required cooling plant capacity should be about 7.5 kW [10].

Requirement 4: the cooling system should provide *the temperature uniformity of better than 1°C (peak-to-peak) over the extent of a single SiPM*, 33 mm. The reason is that the channel-to-channel current gain adjustment within a single SiPM is not foreseen in the current r/o electronics design. However, SiPM-to-SiPM gain adjustment will be available, therefore permitting a temperature gradient along the module. The latter is limited only by the margin between the lowest anticipated working temperature and the lowest temperature defined by the FT structural constraints (see Requirement 1) and the above <1°C/33 mm constraint. In the case of a finite gradient of the SiPM temperature across the beam (in X-direction), the cooling system should provide the lowest temperature for the modules closest to the beam.

Requirement 5: radiation-hardness. *The cooling system components must withstand the neutron fluence of* $6\cdot10^{11}$ *neqv (1 MeV)/* cm^2 *and the relatively low ionizing radiation dose of 50 Gy*, over the lifetime of the experiment. Even least radiation-hard materials, like Teflon, should be OK for this environment. However, the active cooling elements, like Peltier modules, have to be demonstrated

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[3] In both cases, the measurements were performed with the 2.5 m long module; the quoted numbers are for the mirror installed on the far end of the fibers.

[4] Note the big difference between Hamamatsu and KETEK chips; this explains the weaker cluster efficiency on the gain for KETEK.

[5] A linear gain-overvoltage dependence is assumed. Normally, the gains will be regularly re-calibrated between the fills. No dynamic gain adjustment is foreseen for this system.

[6] At any time the noise rate per SiPM channel should not exceed 10 MHz . At 10 MHz/ch, for Hamamatsu ($G=0.7\cdot10^6$, V=70V) one gets about 10 mW/128 ch, for KETEK ($G=3\cdot10^6$, V=25V) – about 15 mW/128 ch. This corresponds to ~160 mW per module for Hamamatsu and ~1 mW for KETEK.

to be stable against neutron radiation[7]. The choice of refrigerant should take into account possible formation of aggressive radicals and compounds as a result of radiolysis (e.g., HF, in case of HFC refrigerants)[8]. The metals used should not exhibit a strong long-lived induced activation (avoid silver!).

Requirement 6: The objects to be cooled (SiPMs) are fragile. Maximal normal and sheer stresses per SiPM should not exceed: … (to be specified). This is particularly important because thermal expansions of the end-piece (polycarbonate, polystyrene) and metallic cooling structures (copper, aluminum) are very much different (linear CTE of ~70 ppm/°C and 17-23 ppm/°C, respectively). For example, at ΔT of 60°C a 53 cm-long copper cooling pipe will contract by 0.54 mm, while a PC piece – by as much as 2.2 mm. *Thermal contacts to the SiPMs should be, therefore, sliding, or elastic* . In addition, the end-piece and end-plugs should be designed so as to match the thermal expansion at the SiPM stiffener level with the one of the cooling structure (pipe, heat spreader etc), as close as possible. The target *average ΔT of the end-piece should be roughly 4 times smaller than the ΔT of the cooling pipe.*

Requirement 7: *No condensation or frost formation should occur, neither inside the cold enclosure, nor on the external surfaces*. The enclosure must be flushed with a dry gas (ISO Class 1, dew point ≤-70°C) and be gas-tight. The temperature of the external surface of the module should stay above the dew point in the cavern (between 10 and 12°C). Possibly, consider dry gas envelope around the end caps.

Requirement 8: No “dirty”, non-volatile refrigerants (like mineral or silicon oils, anti-freeze etc) cooling agents should be used. *Use only dielectric and fully volatile coolants inside the SiPM enclosure*, to avoid damage to SiPMs in case of leaks.

Next group of requirements is related to the mechanical design of the tracker and its situation in the experimental cavern.

Requirement 9: (*modularity).* The current working version of the FT construction concept (Section 2.3) implies that the FT layer are assembled of 53 cm wide fully equipped and tested modules, each containing only “inputs/outputs” and “inlets/outlets” for external services like primary cooling, dry gas source for ventilation, power, read-out. This excludes, for example, a single cooling pipe running through all end caps in a (half-) layer.

Pre-assembled 53 cm-wide modules should be self-contained, with no access to inner structures at the FT integration stage. The cooling system, in particular - connections to external services, should permit an access to SiPM assemblies for maintenance (replacement!), or a temporary isolation of a single module. This requirement means that a) the essential cooling structures should be integrated in the end cap, “with only in/out connectors sticking out” and b) it should be possible to detach single module’s connections (e.g. inlet and return cooling pipes) without a capital intervention into the rest of the corresponding cooling branch. An implementation permitting a partial dismounting of

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[7] There is no data on this subject in the open literature and the unpublished sources give conflicting information. We have irradiated samples of Peltier coolers at the Ljubljana reactor[8] and are awaiting the samples to be tested at CERN.

[8] For the expected neutron fluence, these effects will be very small for common HFC refrigerants, like R-125 (C2F5H), see Section…

the SiPM enclosure will be preferable to the one requiring the removal of the entire module for maintenance. Note, that this requirement does *not* impose independent (parallel) connection of the module to the cooling services. In the case of a serial connection of modules (say, within a half-layer), the bridges between the modules must be made accessible and serviceable, for example, to permit installing a by-pass, if needed.

Requirement 10: *The inlet and outlet structures should not pass through the r/o electronics box.* This requirement a) favors a solution with inlets and outlets situated at the module sides; b) can be lifted for a solution with warm external connections.

Requirement 11: The clearance between the FT planes can be as small as ~40 mm (*TBC*). Together with the Requirement 8, this limits the amount of insulation on the in/out piping and *strongly favors a solution with warm external connections* (or permitting a compact insulation: very thin pipes or a serial module connection with compact bridges).

Requirement12: *The cooling plant should be located away from the detector.* No electro-magnetic devices are allowed near detector, because of the LHCb dipole magnet stray field. This excludes using fans, pumps etc in the cooling distribution area. The existing cooling plant is situated in a service cavern ~70 m away from the detector. The depth of the LHCb experimental cavern is 110 m[9].

Requirement 13: The cooling distribution system will contain 48 branches (one per 6 end caps of every half-layer side (top/bottom). The half-layers will slide apart, therefore the distribution lines going to each of 24 half-layers will have a flexible section matching the 4 m-long chain (“caterpillar”) cable support trays.

Requirement 14: See Section 1.1.

More requirements can be added….

There are also a number of observations, imposing or relaxing constraints on the cooling system design:

1) **A preference should be given to an environmentally-friendly option;**
2) **No constraints on the material budget,** for example, copper pipes and massive copper or aluminium heat exchangers can be used;
3) **Possible use of existing infrastructures**: mixed water, C6F14 transfer lines for the existing tracker.

1.3. Summary

The photodetectors (SiPMs) will have to be operated at low temperatures of -40°C to -50°C. They will be arranged horizontally (or with a few degrees tilt, for u-/v- layers) in ~0.53 m arrays within end caps of the FT modules. The end caps are situated outside of the LHCb detector acceptance, so there are no severe restrictions on the material budget and radiation hardness. The area to be cooled is only 1.3 mm wide but it is not directly accessible and have to be cooled through a SiPM substrate, a flex PCB and a SiPM stiffener (plus a thermal interface between the SiPM stiffener and the cooling

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[9] LHC Design report 2, the LHC Infrastructure and General Services, p.175; http://cds.cern.ch/record/815187

structure). The SiPMs themselves will generate a relatively small amount of heat (at most, about 0.2-1.0W per module, or less than 200W for the entire system), but they have to be in physical contact with warm scintillating fibres and their supporting end pieces, while the SiPM housing and signal flex cables going to a ("hot") readout electronics, provide the parasitic heat influx dominating the overall heat load of O(10 W) per module.

2. SiPMs and draft design of the service area

2.1. SiPMs

The SiPMs (Figure 2 shows the details of a 128-channel Hamamatsu device) can be approximated by a sandwich of a 0.9 mm thick (teflon-glass laminate??) substrate and 0.36 mm thick epoxy window, both having the 6.1x33 mm2 footprint[10]. The photo-detector – the object to be cooled! – is a 1.3 mm wide and 0.250 mm thick silicon wafer is embedded in the bulk of the epoxy window. We shall further refer to this structure as a “detector”. In the current version of the SiPM assembly, the SiPM package is bonded to a 0.150 mm thick10 double-sided flexible PCB (“flex-cable”, or “flex”), the other side of which is glued (with cyanoacrylate?) to a 1-mm thick stiff plate (“stiffener”), made of carbon or aluminum [7]. The “stiffener” has two holes through which the SiPM assembly is screwed to a common SiPM carrier made of polycarbonate. The entire tracker will contain from ~4100 to ~4600 such SiPMs arranged in arrays inside the end-caps of 12 tracker planes.

2.2.Scintillating Fibres

The 1.25 mm thick and 33*4=132 mm wide fibre “mat” is sandwiched between two thin kapton sheets which, in turn, are placed in the middle of a 4 cm thick honeycomb-carbon fiber sandwich forming a rigid support plate for the fibres. The SiPM end of this structure is glued to a polycarbonate end-piece (Figure 4), about 10 mm thick, through which the fibre tips come in contact (optical, but also mechanical and, hence, thermal) with the SiPM window. The end-piece surface facing the SiPM is diamond-cut to ensure a reasonable optical contact with the SiPM without any optical grease.

One fibre “mat” is read out by 4 SiPM chips, aligned with their photo-detectors along the “mat” edge, with minimal gaps (normally, not exceeding 0.25 mm (TBC)). SiPM are pressed against the end-piece and this creates one of major sources of heat load for the cooling system.

2.3.The FT module

The system building block is a 53-cm wide and 5 m long vertical “module” containing 16 SiPMs in each of the top and bottom end-caps (Figure 3). The modules will share the external services (primary cooling, ventilation, power etc), but otherwise be hermetic and largely independent from each other.

The SiPMs , together with the polycarbonate end-pieces are enclosed into a rigid shell (“SiPM Enclosure”) encapsulating the 16 SiPMs, part of the flex-cables and the entire cooling structure of

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[10] The most recent samples obtained from Hamamatsu have a 7.0 mm wide package [7,9]. The latest flex PCB is also thicker (~0.2 mm) and contain a continuous copper ground plane. All copper layers are 18 um thick [7].

the module. Figure 5 shows a cross-section of a full-size mockup of a FT end cap. This design[11] illustrates important factors related to the SiPM cooling: a) SiPMs are attached to the scintillating fibre end-piece, b) they are pressed against the cooling pipe through some sort of a thermal interface and c) the cold parts are isolated from the outer ambient space and read-out electronics by the end-cap walls and an "outer plug".

The side walls are made of insulating foam (e.g., Rohacell 51 RIMA […], with K=0.030 W/m.K) and have 2 mm aluminium outer skins acting as heat spreaders to avoid cold spots. A relatively small module width (about 40 mm) will make condensation control on the walls a challenging task. A heat leak through the walls accounts for another major fraction of the total heat load.

One of design challenges is the insulation at the module edges. The dead space between the modules should be kept to a bare minimum, therefore the SiPM arrays will be practically touching the module edges (Figure 6), leaving no space for insulation. Therefore, the current intent is to thermally bridge the neighbouring module edges together, for example, by sealed the edges with a thin light-tight membranes, and filling the 2-3 mm inter-module gaps with elastic insulating gaskets. The elasticity is needed to absorb thermal length variations of the end-caps during cooling/warming-up cycles. The inter-module gaps can be also used as exhaust points for the dry gas flushed through the end cap (Section …).

The module design is currently being actively discussed. For the purpose of SiPM cooling considerations, we shall use the simplified concept shown in Figure 5.

3. Cooling system options

3.1. Liquid cooling (single-phase)

Section to be written…

Conceptually, the system will be like in Figure 5. The refrigerant must be liquid within the working temperature range and have a sufficiently low viscosity at the lowest T. It should also be non-toxic, possibly inert and non-conductive. There is a vast choice of thermal fluids [], especially because we are not restricted to fluorocarbons (FC), but can use commodity HFC and even HCFC refrigerants.

The main advantage is that commercial industrial chillers with the required cooling capacity are off-the-shelf (COTS[12]) items. The working pressure depends on the refrigerant and can be either atmospheric for common refrigerants (C6F14, HFCs) or elevated for liquefied gases (CO2, N2O, NH).

The main disadvantage is the need for massive insulation of the transfer lines and distribution piping. By definition, this option contradicts the Requirement 11 (Section 1.2) of light and preferably warm module connection to the services. This favours low-viscosity and high cooling capacity refrigerants, permitting very thin piping and, hence, compact insulation.

- pFC refrigerants require oil-free pumps.
- All "safe" commercial coolants are either too viscous, or (e.g. Dynalene) require inner-finned multiport extrusion pipes.
- Temperature control (internal in the chiller or a separate buffer volume with a heater).

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[11] It corresponds to the draft concept discussed in July 2013.

[12] Commercial Off-The-Shelf

3.2. 2-phase cooling (evaporative)

Section to be written...

- Refrigerant choice (pFCs, HFCs, pFC blends). Consider C2F6, R125 or CO2, N2O
- Conventional (compression/evaporation/condensation) or 2PACL
- Compressor lubricants (oil-free for pFCs)
- Temperature control
- Capillaries, heat exchangers, precooling, local (embedded) heater on the exhaust
- Report on summer tests with C3F8 with an undrepressure at the suction side (separate document)

3.3. Thermoelectric cooling

Section to be written...

Primary cooling: mixed water at about 14°C. Secondary cooling: double-stage Peltier module (TEM). Advantages: modularity, use of a "warm" primary cooling, fine temperature adjustment. Problems:

- the TEMs with appropriate cooling power are too small (>3W/cm2) compared to the linear size of the SiPM array -> need large "cold spreaders" -> losses ->inefficiency
- For big TEMs, at ΔT of ~30°C (optimal cooling capacity per Peltier stage), the power generated by the TEMs will be O(10W) per unit
- Require multi-channel (linear!) power and control
- Unclear how to provide reliable and non-deforming thermal contacts
- Unknown mechanical stability under neutron radiation (no literature, alarming info from CRN sources [A.Tsirou]

An option with external (water-cooled) coolers attached to the module sides and cooling the internal heat spreader attached to SiPMs:

- "Thermacore solution" with ammonia heat pipes (separate report)
- Copper bar option (to be studied by Heidelberg, numerical estimates, pictures to be added).

3.4.Direct cooling with chilled air

Section to be written...

Cold dry air, chilled by an external or embedded (vortex tube) chiller, is blown through the SiPM enclosure. Closed ventilation circuit (the used dry air can be re-circulated). Thick outer insulation required, big temperature drop along the module.

- The SiPM "stiffeners" carry high-density fin radiators. Advantage: no need in mechanical thermal contacts: cooling through convection.
- Cooling pipe with inner structure, pressed against the SiPMs, like with the liquid cooling
- Summer tests report (separate document)

A very attractive method, but practically next to impossible: for external air cooling the heat losses will be too high, for vortex tubes the amount of compressed air is enormous (tens of thousands m3/h).

3.5.Cooling via flex-cables

The copper-loaded flex-cables, going to the sweet spot (SiPM wafers), can be quite efficient cold conductors. This can be used in combination with the conventional cooling. Additional flex cable, with contiguous copper sheet, can be glued to the stiffener. Advantage: no pressure on SiPMs, a possibility to create a robust thermal contact between the cooler and the flex.

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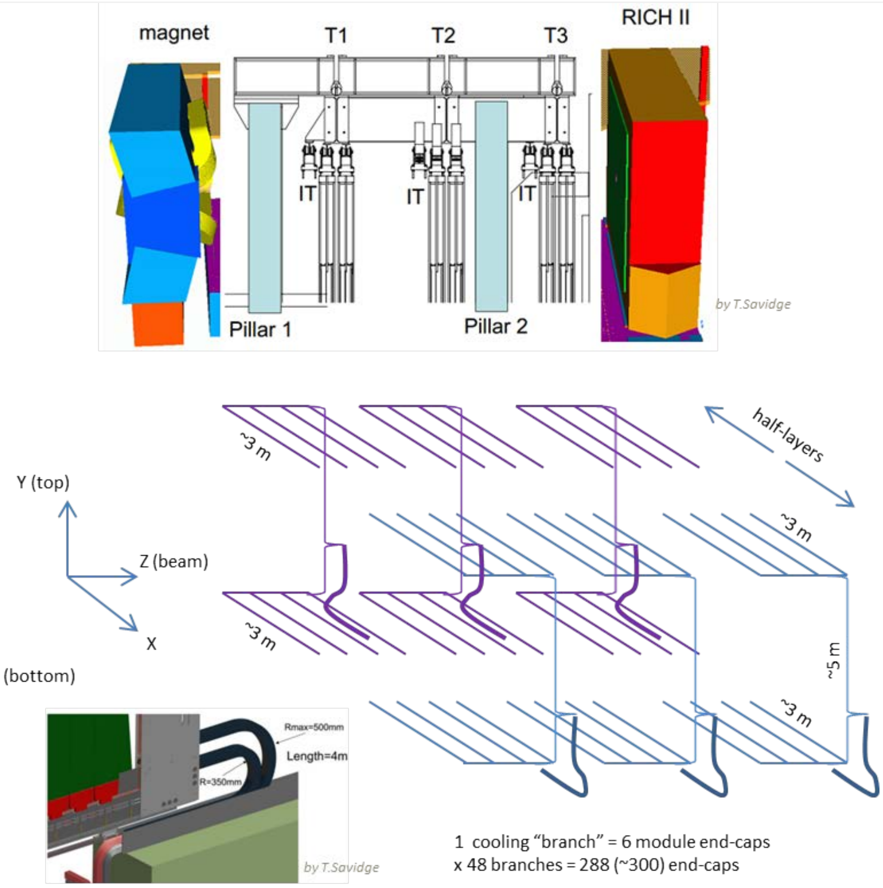
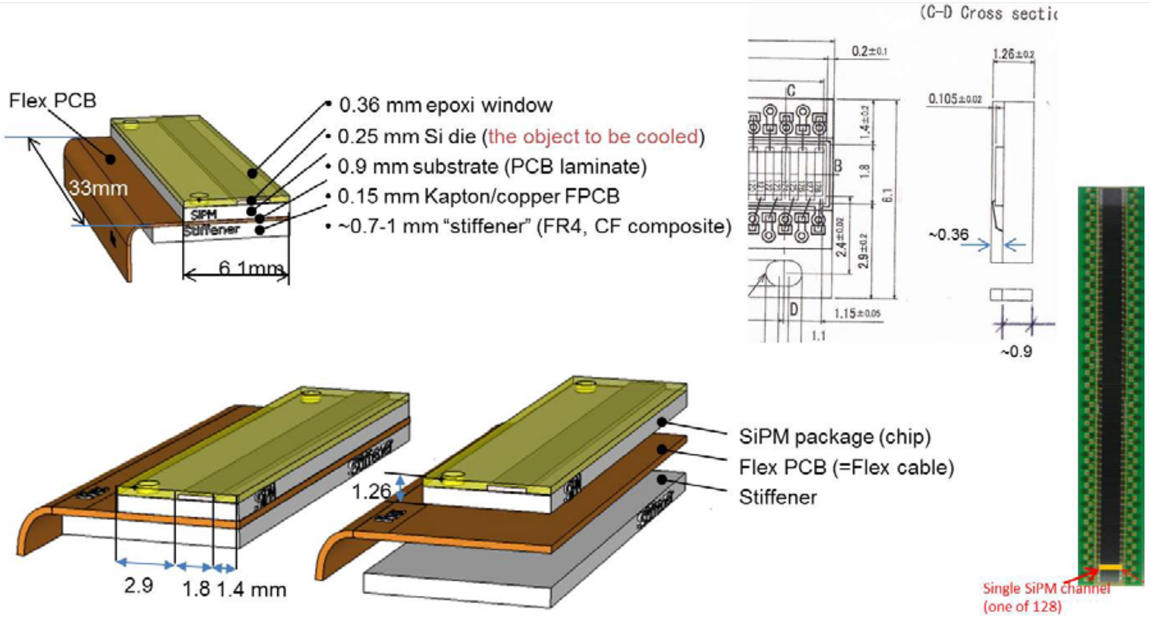


1 cooling "branch" = 6 module end-caps
x 48 branches = 288 (~300) end-caps

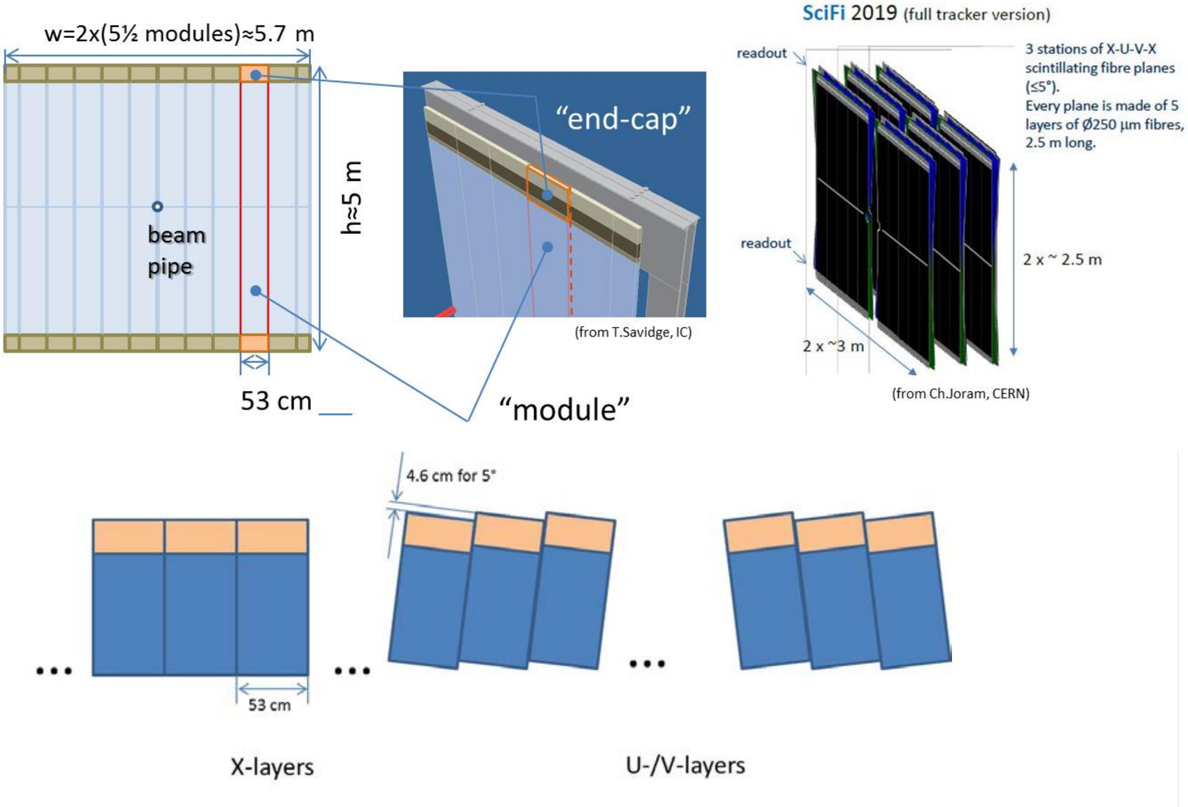
Figure 1 Fiber Tracker: manifolding for SiPM cooling. Inserted images are from []



- 0.36 mm epoxi window
- 0.25 mm Si die (the object to be cooled)
- 0.9 mm substrate (PCB laminate)
- 0.15 mm Kapton/copper FPCB
- ~0.7-1 mm "stiffener" (FR4, CF composite)

SiPM package (chip)
Flex PCB (=Flex cable)
Stiffener

Figure 2: The SiPM assembly, consisting of a SciPM package ("chip") bonded to the flexible PCB ("flex cable") and a isolating "stiffener" glued to the flex cable. At the right, a photograph of the sensitive area of a Hamamatsu SiPM is shown.



(from T.Savidge, IC)

(from Ch.Joram, CERN)

Figure 3: SciFi tracker layers: consist of two half-planes, each of which contains 5½ 52 cm-wide upright "modules" (stereo-angle planes are tilted at +-5°). Every module has two identical "end-caps" at the top and at the bottom. The end-cap contains 3 functional layers: (a) the fiber end-piece (an interface to the SiPMs), (b) a compartment with 16 SiPMs and their cooling structure ("SiPM Enclosure"), and (c) the read-out electronics. At the top right, the entire FT is shown: 3 stations, each containing 4 layers (X-U-V-X). The bottom picture shows the end-cap arrangements in the upright and tilted layers.

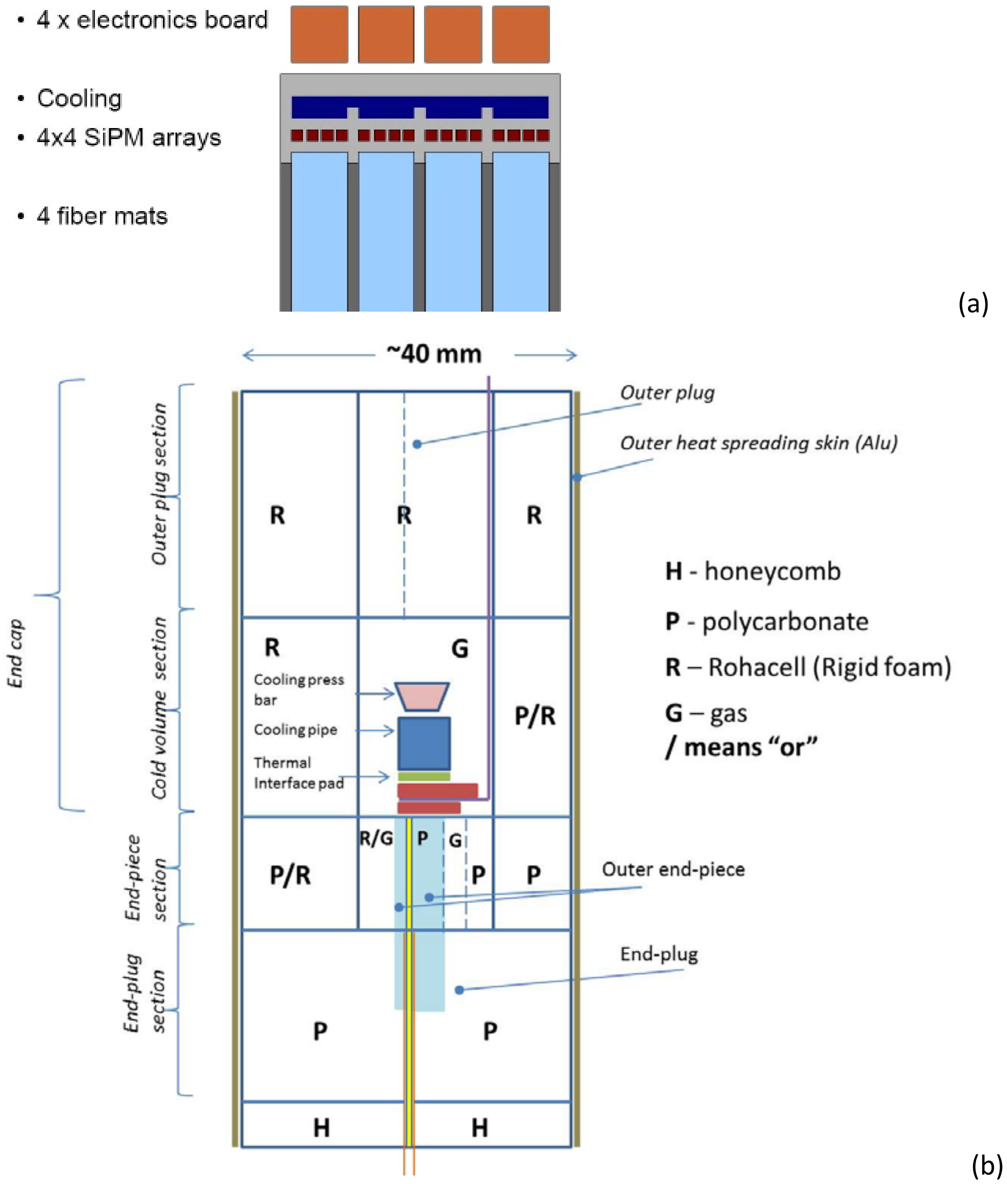
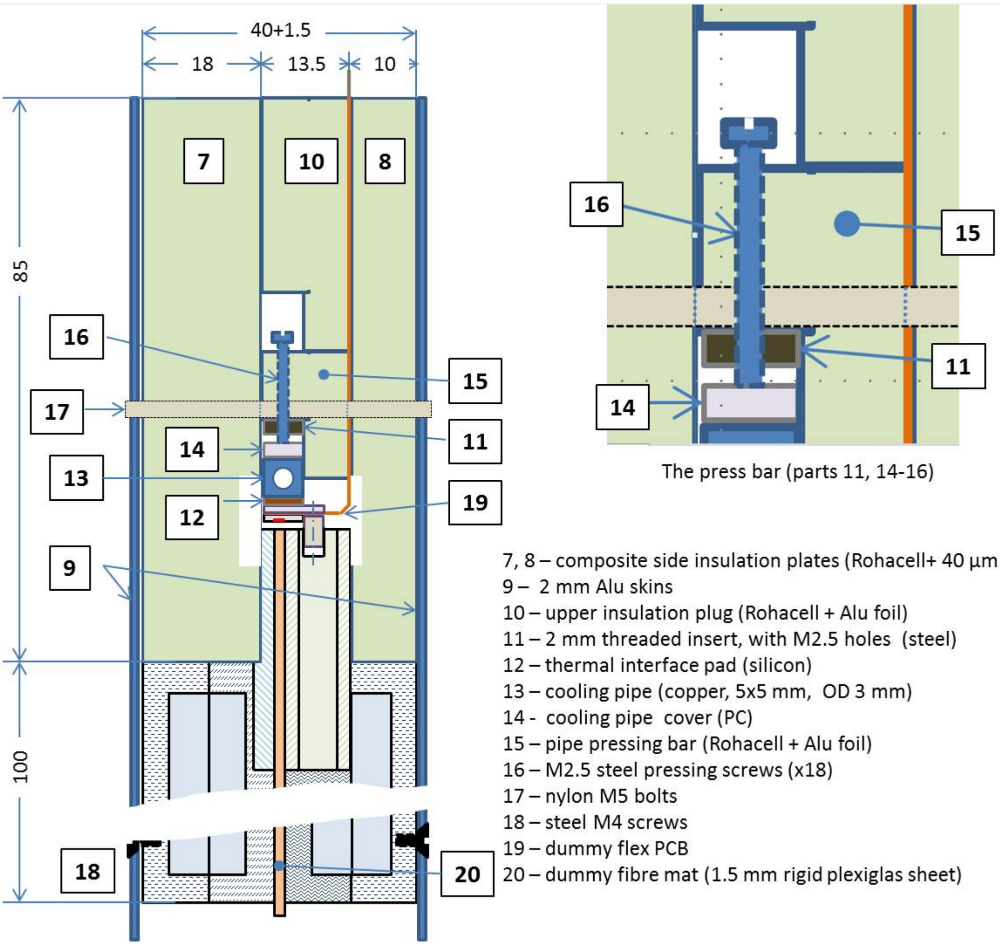


Figure 4: (a): a schematic structure of a half-module in Y-X plane; it contains four SciFi "mats", an array of 16 SiPMs (split into 4 sections matching the mats), 4 readout electronic boards and the SiPM cooling structure; (b): a schematic structure of a module end cap in Y-X plane ("anatomy of end cap", end-cap naming convention).



7, 8 – composite side insulation plates (Rohacell+ 40 µm Alu foil)
9 – 2 mm Alu skins
10 – upper insulation plug (Rohacell + Alu foil)
11 – 2 mm threaded insert, with M2.5 holes (steel)
12 – thermal interface pad (silicon)
13 – cooling pipe (copper, 5x5 mm, OD 3 mm)
14 - cooling pipe cover (PC)
15 – pipe pressing bar (Rohacell + Alu foil)
16 – M2.5 steel pressing screws (x18)
17 – nylon M5 bolts
18 – steel M4 screws
19 – dummy flex PCB
20 – dummy fibre mat (1.5 mm rigid plexiglas sheet)

Figure 5: *A sketch of the end cap mock-up used forSiPM cooling tests in summer 2013, illustrating an implementation of a generic concept of Fig. Figure **4**b. The bottom end-cup is identical to the this one, but is flipped vertically.*

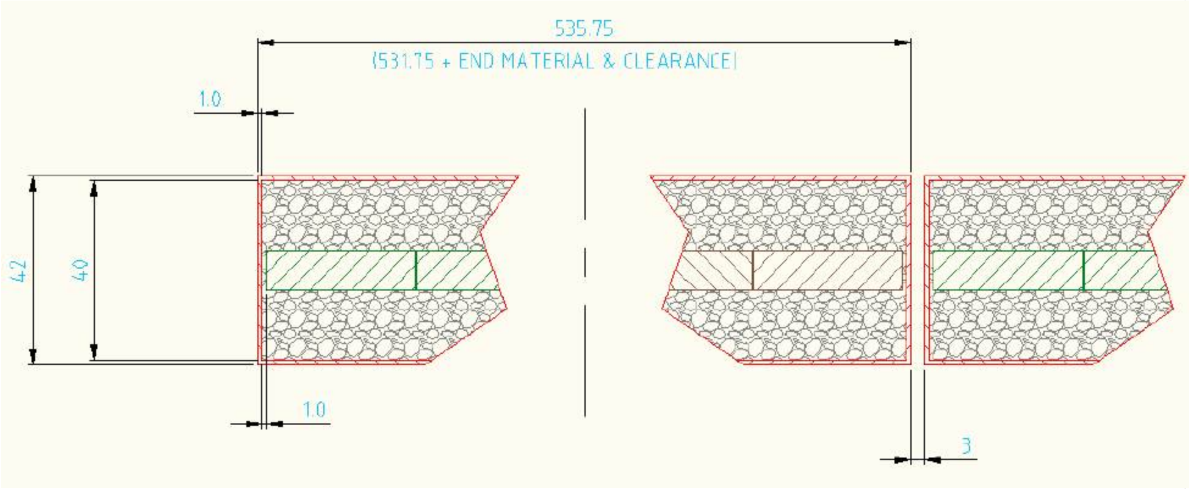
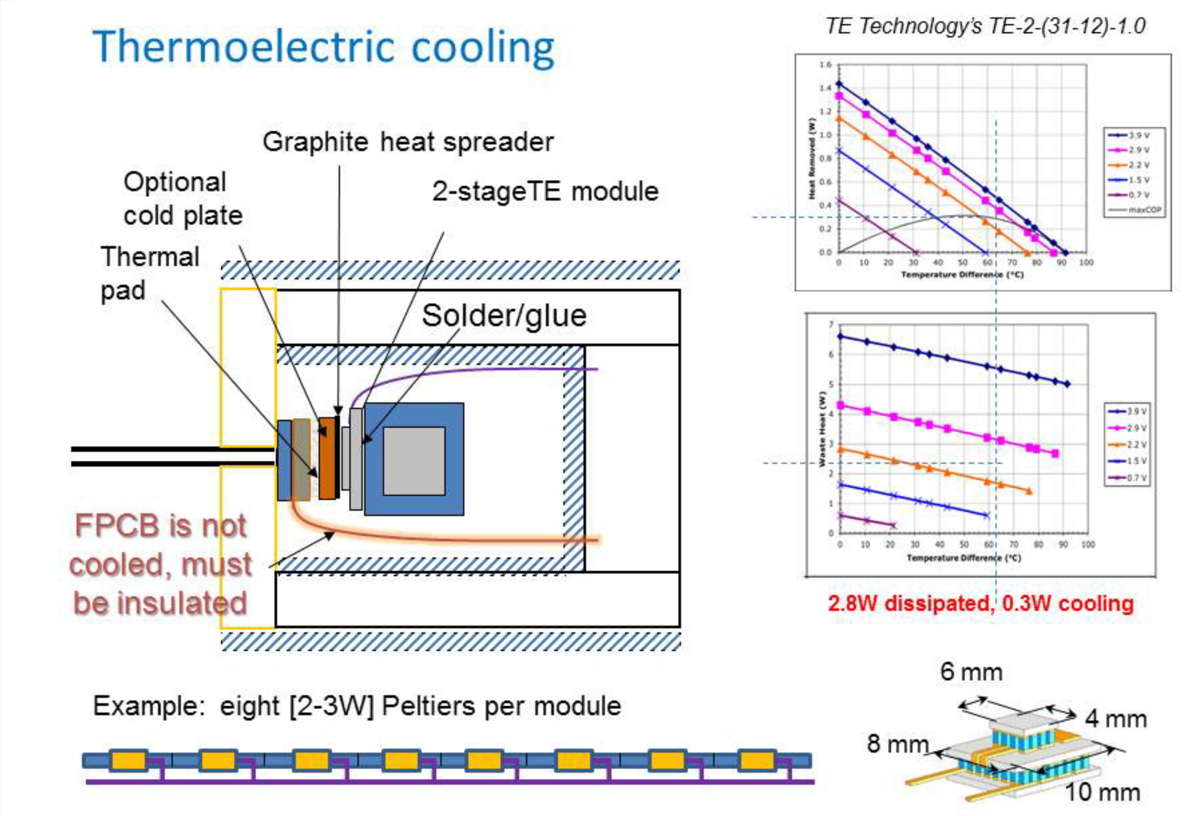


Figure 6: Inter-module gaps.



Thermoelectric cooling

TE Technology's TE-2-(31-12)-1.0

2.8W dissipated, 0.3W cooling

Example: eight [2-3W] Peltiers per module

Figure 6: A sketch of a thermoelectric SiPM cooling option.

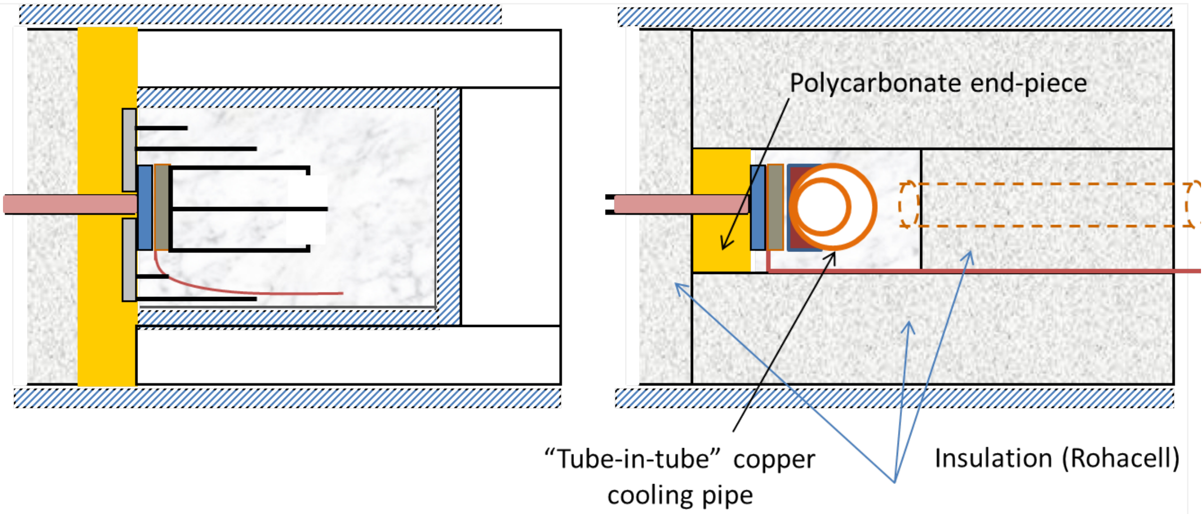


Figure 7: A sketch of a chilled air SiPM cooling option.