(SiPM) Cooling for the LHCb Upgrade SciFi tracker(*)

Presented by
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on behalf of the LHCb SciFi Tracker group

TIPP 2014, Amsterdam, 2 June 2014

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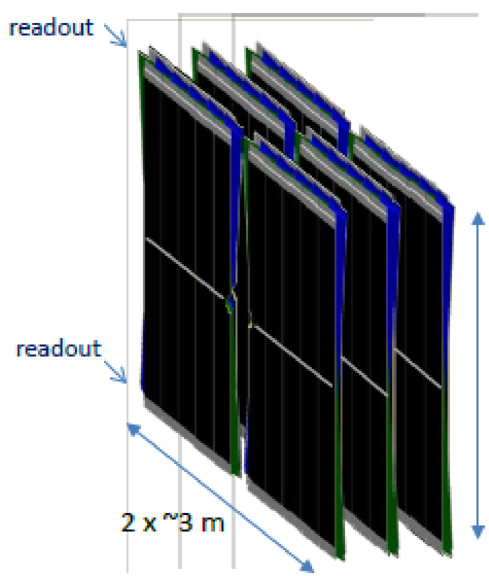
(*) SiPM = Silicon Photo-Multiplier(s); SciFi = Scintillating Fibres

SciFi Tracker

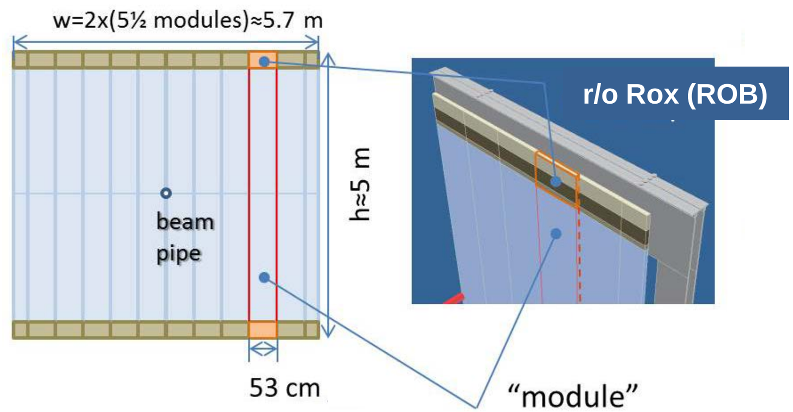
- Motivation, design – covered by separate presentations at TIPP 2014:
  - B.Leverington, Experiments & Upgrades Session, 6 June – SciFi tracker, general
  - Z.Xu, Photon Detectors , 4 June – SiPMs
  - M. Deckendorff, Novel Technologies, 4 June – Scintillating Fibres
- LHCb Tracker Upgrade TDR: CERN/LHCC 2014-001, LHCb TDR 15

SciFi Tracker – by 2019

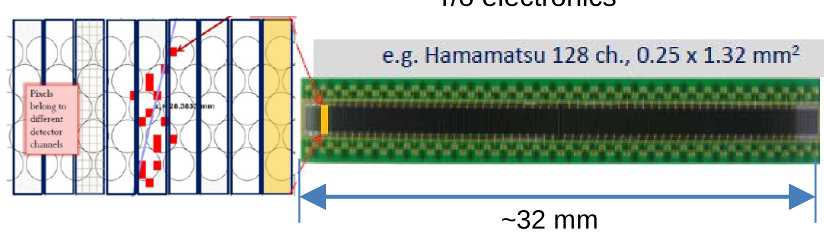


3 stations of X-U-V-X scintillating fibre planes (≤5°).
Every plane is made of 5 layers of Ø250 μm fibres, 2.5 m long.

2 x ~ 2.5 m



ROB: - fibre/photodetector interface (**16 SiPMs**)
- SiPM enclosure and cooling structures
- r/o electronics



Why SiPM cooling ?

- Small light yield (≤20 p.e./MIP)
  - *decrease* with time (fibres ageing)
- Competing background hit rate: from dark noise
  - 50-100 fold *rise* by the end of LHC Phase II – due to radiation damage ($6x10^{11}$ n_{eq}/cm^2)
- **Solution: sub-zero cooling**
  - (noise is suppressed by factor ~2/10C)
- For satisfactory tracking performance after 50 fb^{-1} , the **SiPMs have to operate at down to -40C**
  - The cooling system should permit to vary the SiPM temperature
- Design challenges:
  - Large system extent (total length of SIPM arrays: ~150 m)
  - Tight space envelope : ΔZ ≤ 70 mm, no “guard” volume is possible
  - Potential condensation and frost formation issues
  - Difficult distribution/manifolding: 288 ROBs, over twelve 5x6 m2 planes, flexible sections

Other system requirements

- Temperature uniformity in : **$\Delta T<1°C$** per sub-array of four SiPM (~132 mm)
  - common gain and threshold adjustment for all channels in s/array
  - a gradient along the entire SiPM array is tolerable (up to 10°C over 3 m)
- Temperature stability in time: **±1°C** between calibrations (LHC fills?)
  - SiPM gain affects the detection efficiency (should be constant at 98-99%)
  - Can be relaxed for new generation of SiPMs
- Modularity
  - To match the modular design of the FT: each ROB has its own cooling structure!
- Safety
  - General LHC standards (flammability, toxicity etc); safe for detectors in case of failure
- Environment friendliness: ozone, GWP,…
- Desirable features: simplicity, flexibility, performance margin, low cost

Choice of cooling technology

- Observations:
  - **External heat exchanger** (discrete SiPMs, no internal cooling)
  - Expected **heat load of O(10 W)/ROB** is dominated by parasitic influx through the insulation, flex PCB and fibres
  - No concerns about material budget (outside of acceptance) and radiation resistance (~50 Gy, ~10^{12} neq/cm^2)

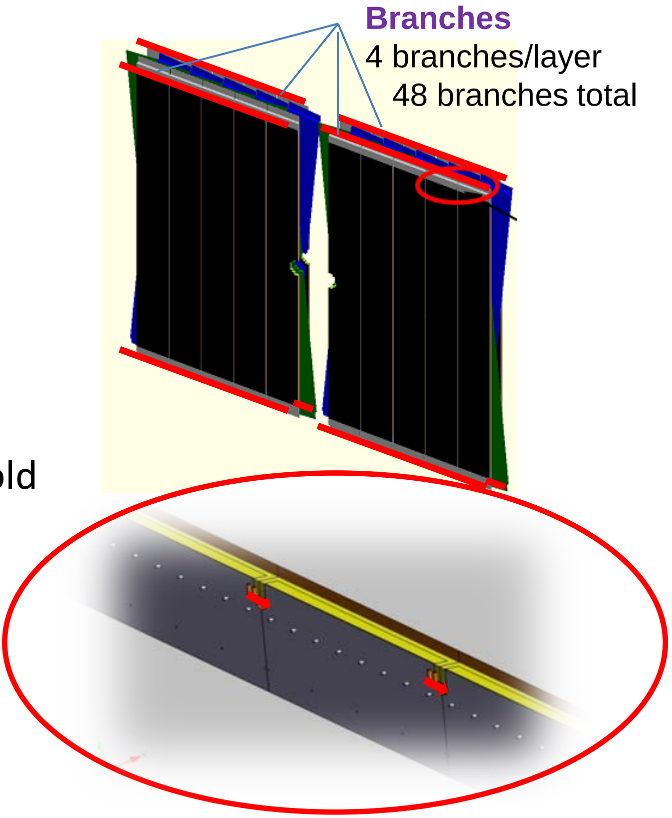
- The cooling options considered at pre-TDR phase:
  - Thermoelectric, with low-temperature heat pipes
  - Chilled air, with local vortex tubes
  - 2-phase evaporative, C3F8, CO2, …?
  - **Mono-phase liquid**

Baseline cooling option

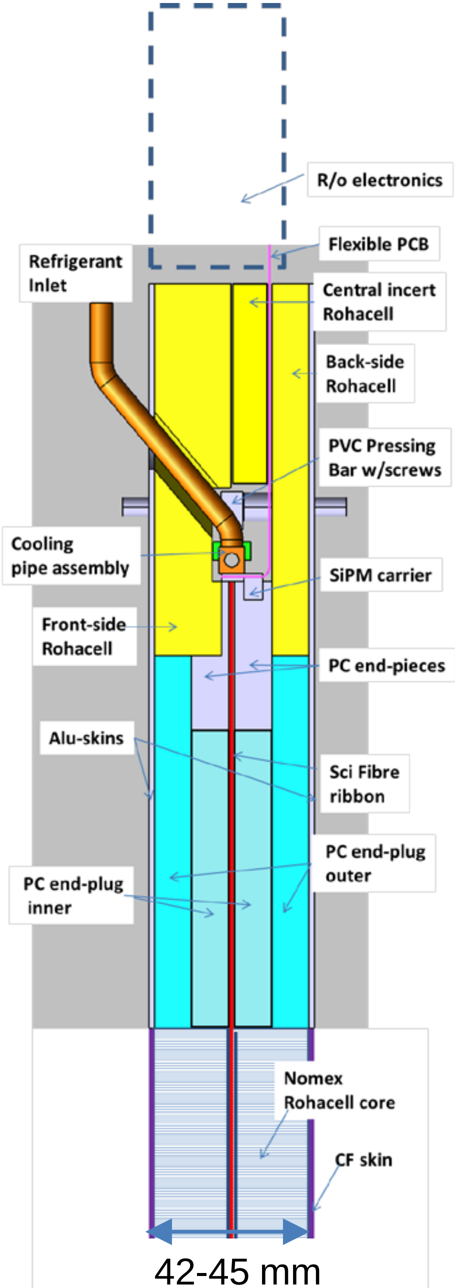
Mono-phase liquid cooling, with serial connection of ROBs in a branch (a branch=6 ROBs, ~3 m) and low-GWP "Novec 649" refrigerant

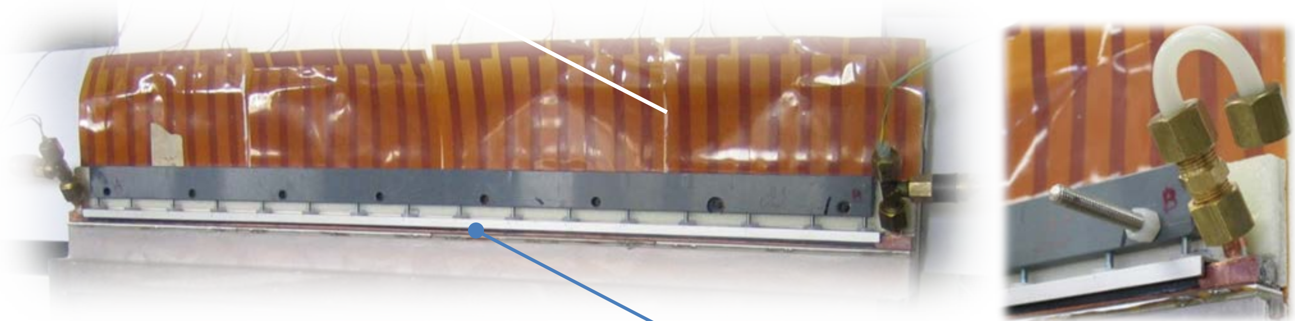
+ No compelling reasons to use 2-phase cooling
+ Established technology, commercial components
+ Big reserve in cooling power, room for optimization
+ Probably, the simplest and least expensive option
– Low-loss cold transfer lines (~100 + 100 m)

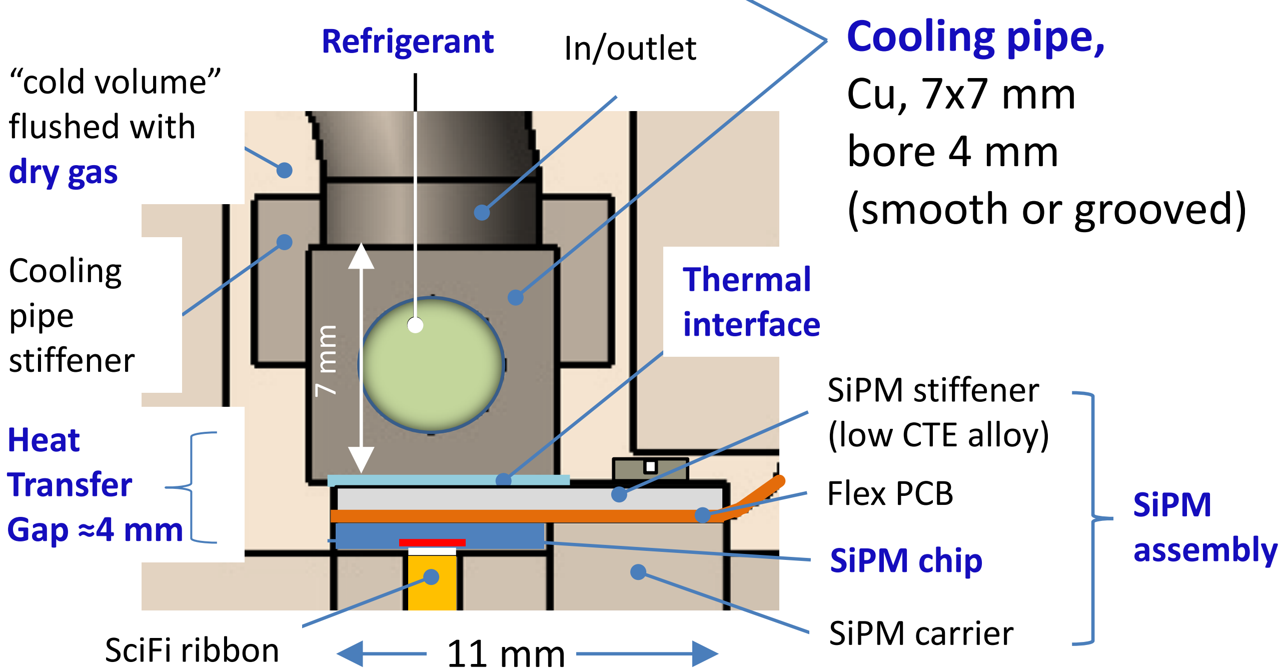
- **Serial connections**:
  - "modularity" is slightly compromised, but…
  - pipework and overall system flow rate are reduced ~6-fold
  - optimal balance between ΔT and ΔP – to be further studied in mock-up tests



Inside Read-Out Box (ROB)





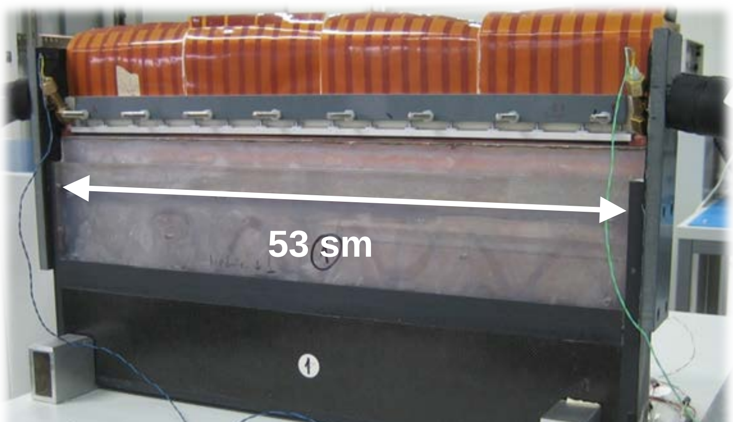


Mock-up tests

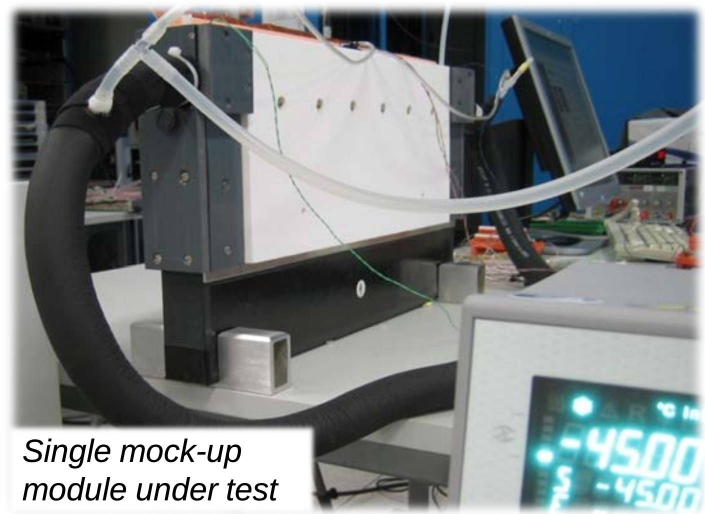
- Direct heat load measurement

  P=Mass flow rate x ΔT(inlet/oulet) x C(T_{fluid})

- ΔT (fluid/SIPM), cooling uniformity, ΔP and ΔP(in/out), external temperature distribution
- Refrigerant flow optimization (currently, with C6F14)
- Validation of predictions from CFD simulations
- Input for engineering designs of the ROB and cooling plant



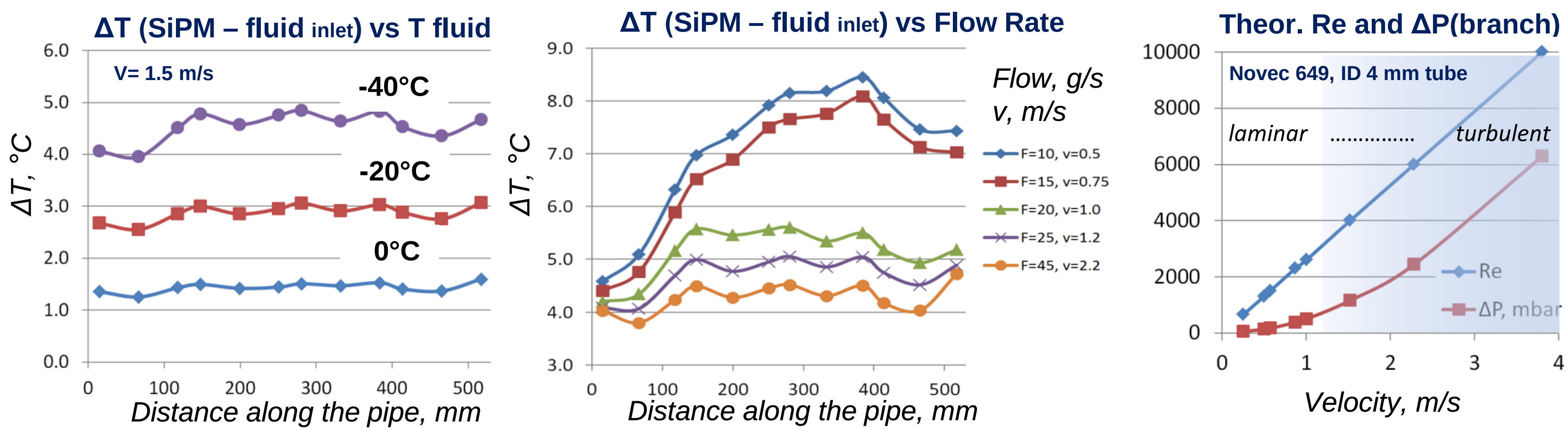
ROB thermal mock-up, with front cover removed


Single mock-up module under test

Mock-up = Cooling pipe + insulation + 10 cm of support plate +
4 **dummy SiPM sub-arrays** with flex cables and calibrated PT1000 sensors instead of SiPMs
Chiller: down to -80°C, smooth flow control and monitoring (0-60 g/s for C6F14 and Novec)

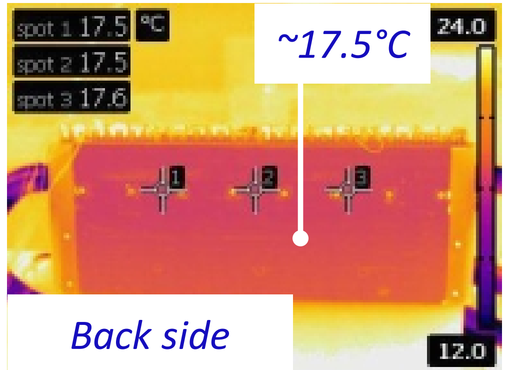
Mock-up tests, single module results

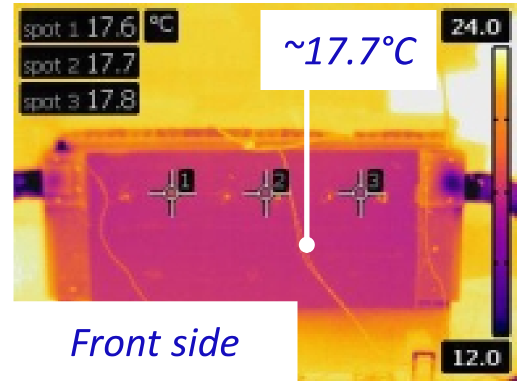
- In agreement with simulations, at v > 1.0 m/s (>20 g/s), the flow becomes largely turbulent (Re > 2300, secures a high HTC and small ΔT)
- “Inlet/outlet effect” … still compatible with 1°C /sub-array requirement
- ΔP(in-out) and ΔT(out-in) per module agree with simulation: ΔP = 0.2 bar and ΔT ≤ 0.3°C, at -40°C and 1.5 m/s
- Thermal load is largely compatible with 10…13 W/module. Measurements with 3…6 serially connected modules will provide a more accurate estimate



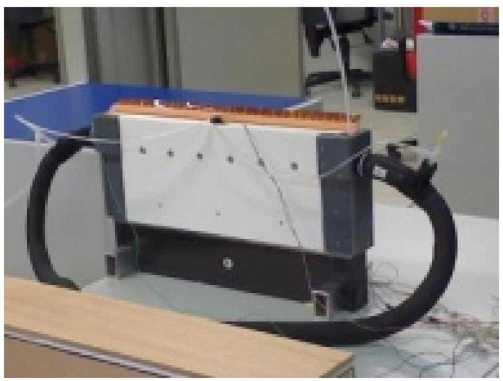
Preliminary design values: v=1.5 m/s, ΔP≈1.2 bar/branch, thermal load =20 W/module

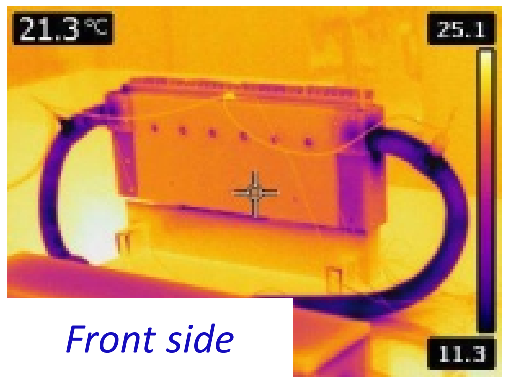
IR images of the module, at T_{fluid} = -50C (T_{room} = 23C)

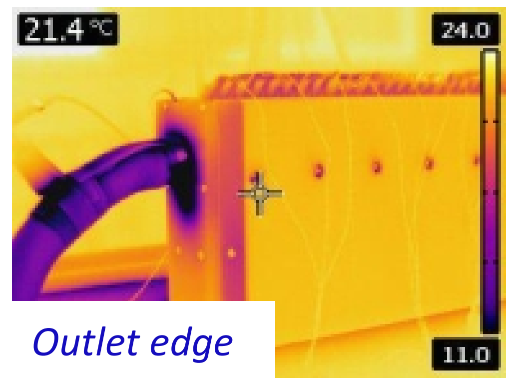




No outer insulation (bare Alu sheets





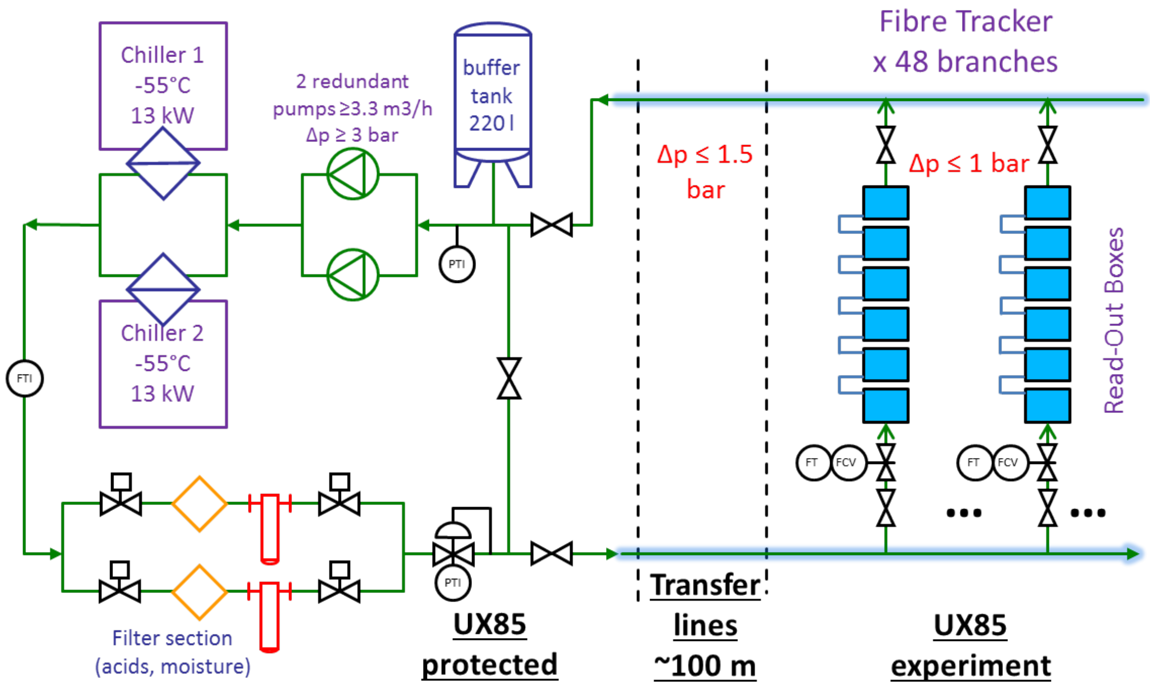


With extra outer Rohacell insulation sheets

Conclusions

- Outer Alu heat spreader is effective, the surface T is well above dew point (≈10°C in cavern)
- Extra outer insulation gives 10-15% reduction in heat load
- Expected cold spots: module edges and lids having no internal insulation

Conceptual system design

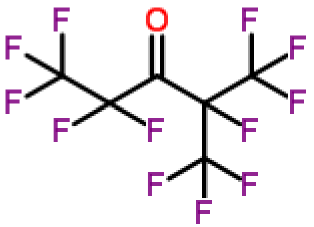


Main cooling system design specifications (see TDR for more details):

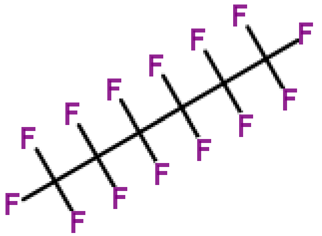
- Industrial chiller: cooling power ≥13 kW at -55°C, working T(fluid) ≤ -50°C
- Refrigerant mass: 330 kg (~210 l at +40°C)
- Pump: ΔP ≥ 3 bar, flow rate ≥ 3.3 m3/h
- Transfer lines: ΔT = O(1°C), each way
- Estimated cost (infrastructure only): 290-350 kCHF

Refrigerant

- **Baseline choice:** 3M^{TM} NOVEC 649 thermal management fluid
  - fluoro-ketone, $C_6F_{12}O$
  - thermophysical properties similar to C_6F_{14}
  - volatile, dielectric, low viscosity
  - inflammable
  - low toxicity (widely used as a clean fire extinguishing agent in occupied spaces, e.g. data centers)
  - GWP=1
  - Reactive with liquid water (not important for our application)
  - 3M positions Novec fluids as a replacement for pFC



- **Backup:** C_6F_{14} (3M^{TM} FC-72)
  - very well studied, used in 13 LHC systems
  - deprecated, GWP=7400



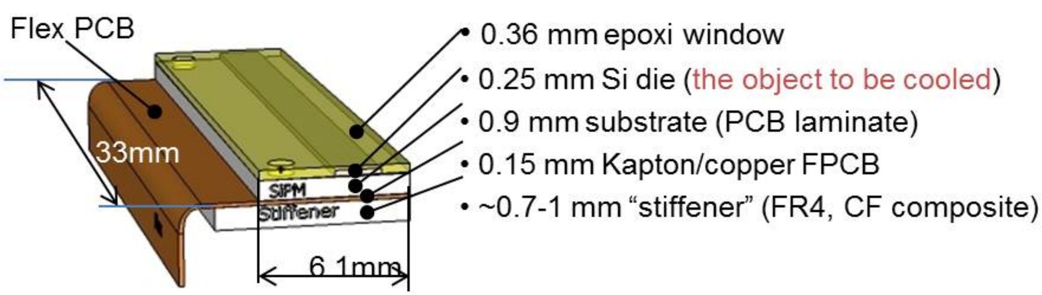
Summary

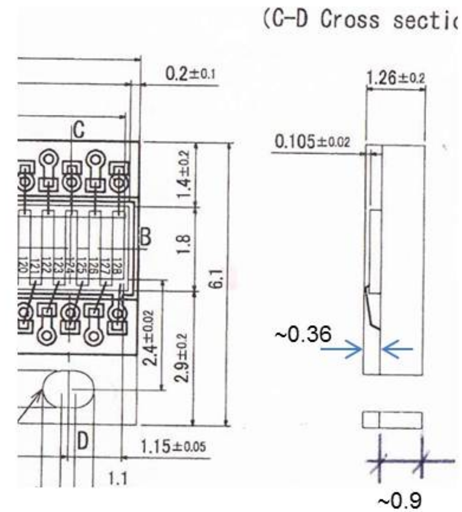
- Cooled SiPMs, in ~0.53 m arrays, T down to -40°C, combined L≈150 m
- Mono-phase liquid cooling system, use of environment-friendly refrigerants
- Design cooling power ~13 kW, dominated by heat leaks
- Thermal mock-up tests (ongoing): general agreement with simulation

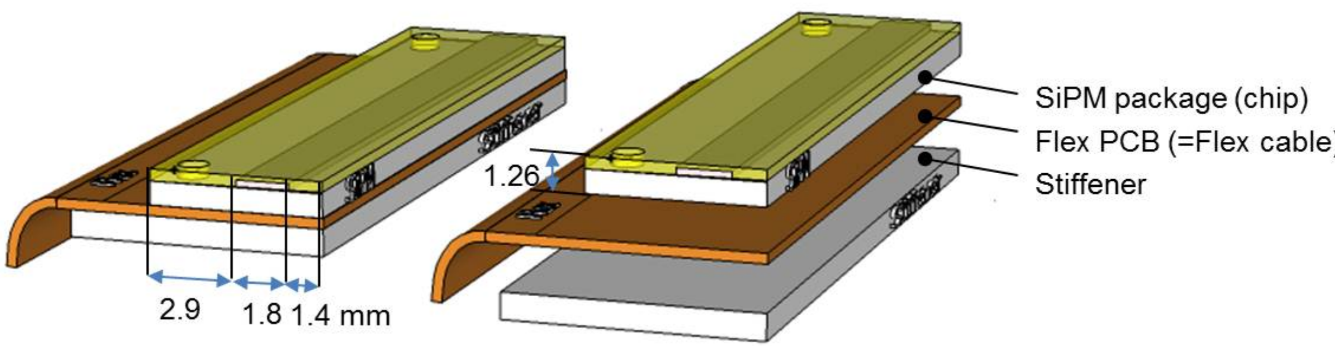
- Issues to be further investigated:
  - NOVEC 649 validation
  - ROB edge insulation
  - Effect of warm electronics
  - Vapour barriers
  - Low-loss (flexible) interconnections

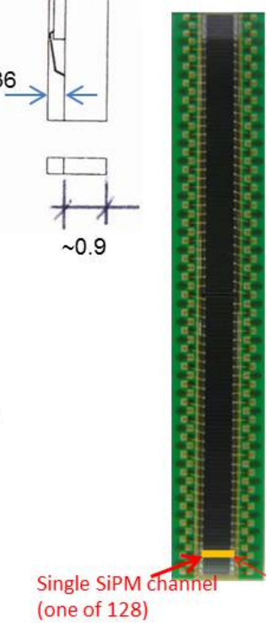
Backup slides

SiPM details (see also Zhirui Xu's talk)







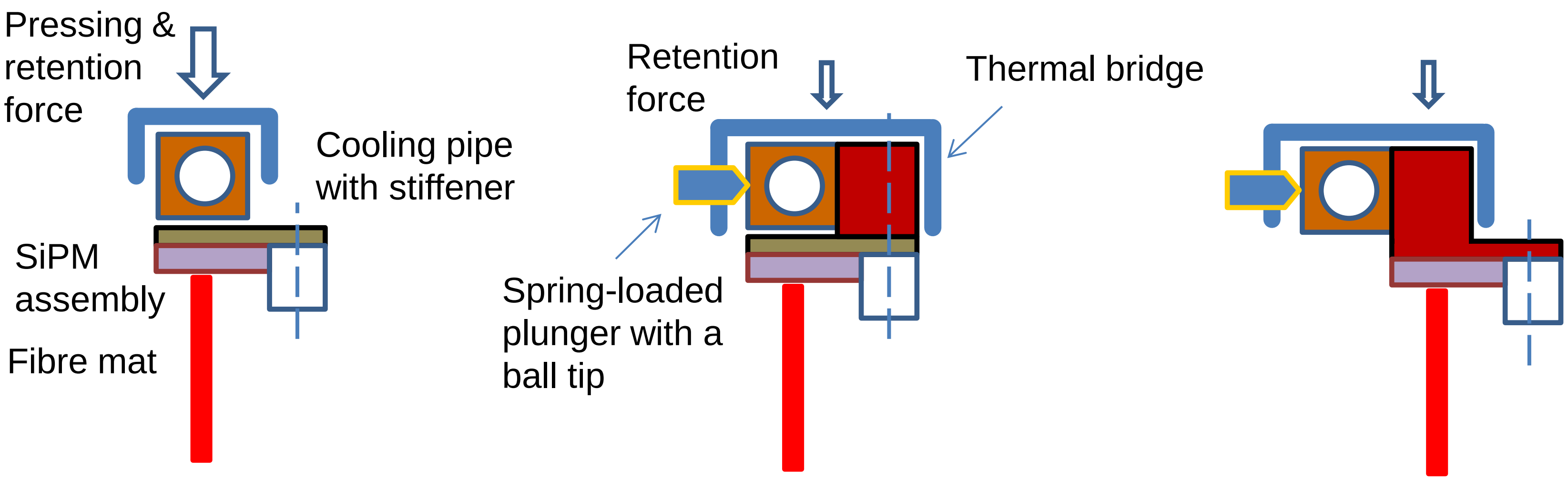


Why not "2-phase" (vapor compression)?

Property	Mono-phase	Vapor compression
Well-tested, experience at CERN	Yes	Yes
Temperature uniformity	4-5K / branch	<1K / branch
Refrigerant mass @ detector	Heavy (C_6F_{14})	Light (C_2F_6, half-vapour)
System pressure	Low (2 – 4 bar max)	High (>30 bar)
Reversibility (cooling-heating)	Yes	No
Thermal inertia	Slow, easy to control	Fast, more difficult to control
Transfer lines	Cold	Warm
(Inter-)connections at detector	Cold	Warm (in) / Cold (inter, out)
Local equipment, apart from cooling pipes (per branch)	Only on-off valves	On-off, capillaries, HEX
Cooling plant equipment	Commercial chiller + pump	Oil-free compressor, condenser
Sensitivity to refrigerant choice	Low	Refrigerant is pre-defined
Estimated infrastructure cost	290-350 kHF	300 KCHF + manifolding, capillaries, HEX = >400 CHF

Cooling pipe fixation

- Two basic designs for cooling pipe fixation (“vertical”≈ TDR and “horizontal”)
- “Horizontal” design is better adopted for serial modules interconnection and servicing SiPMs, potentially permits to decouple the cooling and SiPM structures



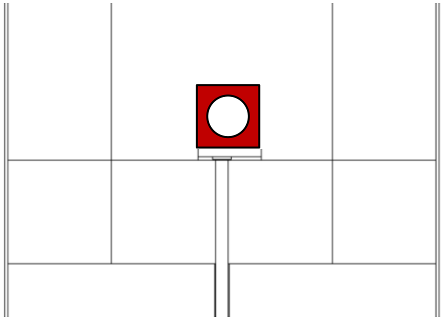
Vertical inlet/outlet
(“TDR design”)

Horizontal inlet/outlet pipe is better positioned; can use thermal grease

SiPM s/modules can be removed without dismounting the pipe

Flow regime with round ID=4 mm pipe

- Pipe dimensions: 4 mm i.d. (round)
- Refrigerant temperature: -50°C
- Cooling load per module: 10 W
- Fluid: NOVEC 649
- Density: 1.7-2.9T(°C) g/cm^3 (~1.8 at -50°C)
- Viscosity: ~1.3 cSt, Thermal conductivity: ~0.075 W/mK (both at -50°C)

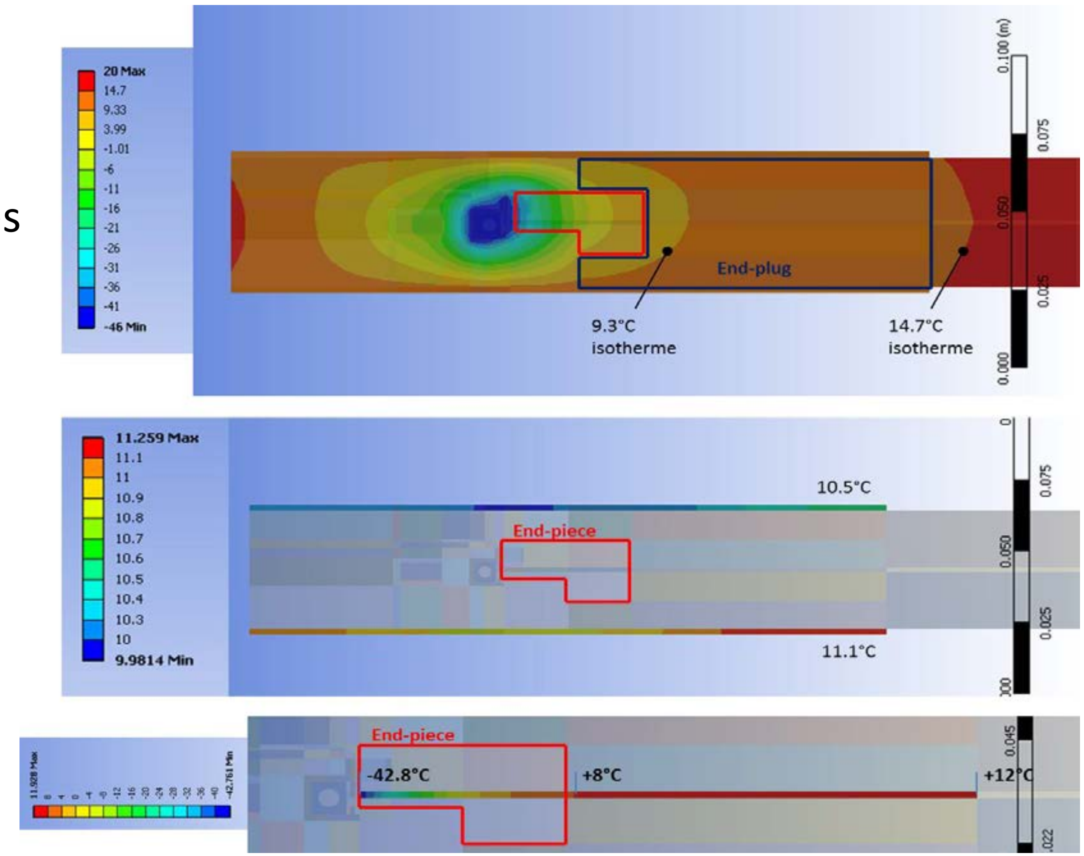


Velocity [m s^{-1}]	Re [-]	$\Delta T_{wall-ref}$ [K]	HTC [W m^{-2} K^{-1}]	$\Delta T\ ref_{out-in}$ (6 modules) [K]	Δp (6 mod & bends) [bar]	Flow Rate (all system) [m^{3}h^{-1}]
0.25	655	10.9	129	9.7	0.06	0.5
0.50	1310	8.6	178	4.8	0.14	1.1
1	2600	3.2	477	2.4	0.5	2.2
1.5	4000	1.6	937	1.6	1.1	3.3

- Laminar flow (Re < 2300, v < 0.9 m s^{-1}) is to be avoided;
- Re ~ 3000 (v ~ 1.15 m s^{-1}) could be risky: turbulent flow may not be achieved;

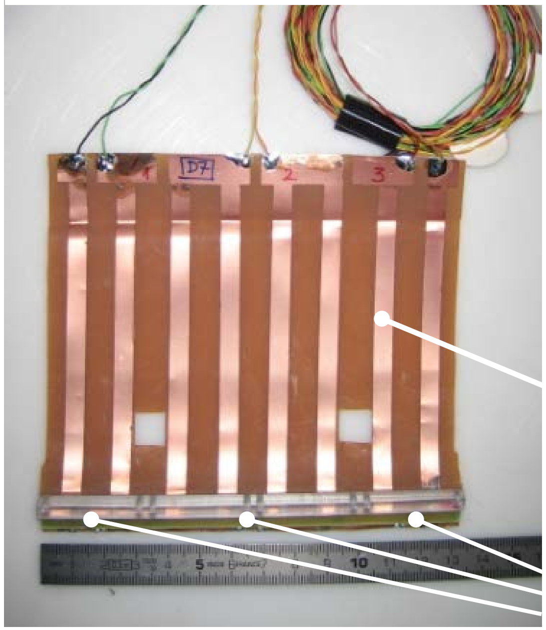
CFD simulation

- Simulation: joint project with CERN EN-CV: “CFD studies for SiPM cooling”
  - Different module geometries and heat transfer options
  - **Heat load: < 10 W** per ROB, excluding connections



CFD simulation for liquid cooling option

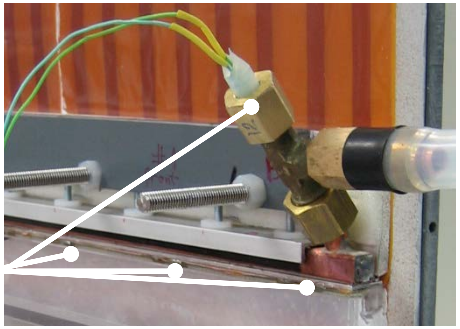
Dummy SiPM sub-array with T-sensors at Si dye level

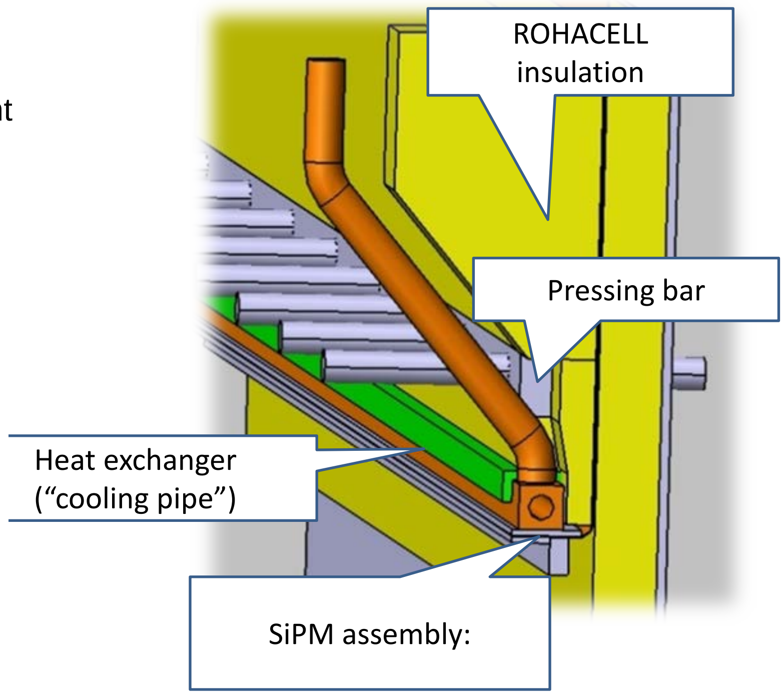


Dummy flex PCB, with correct amount of copper

Calibrated PT1000 sensors

PT1000s





SiPM temperature range	–40°C...+40°C
Heat load per ROB	10–20 W at –40°C
Pump capacity	$\Delta p \geq 3$ bar; $\geq 3.3\,\mathrm{m}^3/\mathrm{h}$
Chiller power	≥ 13 kW at –55°C
Temperature accuracy	±0.1K
Total coolant mass/volume	min. 330 kg/213 l (Novec 649 at 40°C)
Transfer lines	DN32, ≈100+100 m; $\Delta T <$ (1K + 1K)
Heat pick-up in pipes	transfer: ≤2.4 kW; distribution: ≤2.5 kW
Manifolding scheme	1(transfer):12(flex):2(up-down):2(x-u/v)