SiPM cooling: requirements, challenges, options

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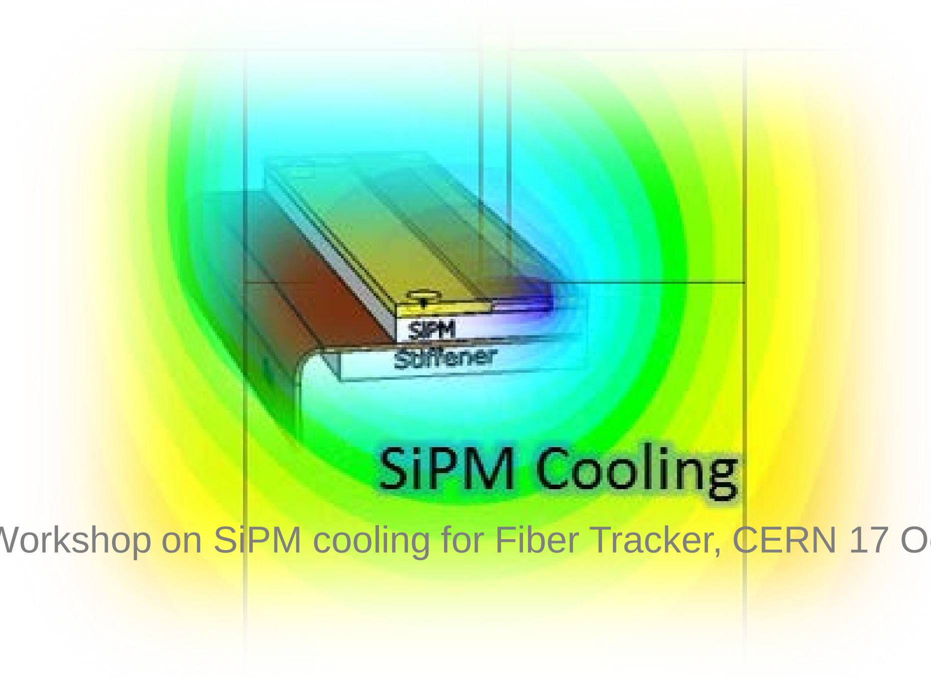
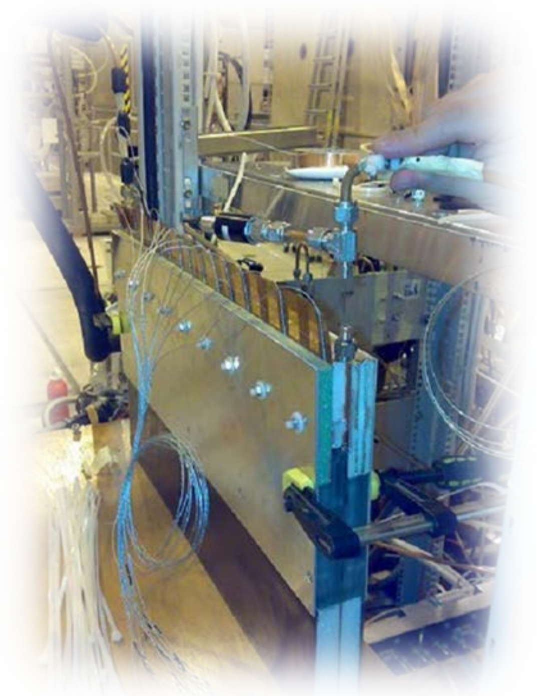


1st Workshop on SiPM cooling for Fiber Tracker, CERN 17 October 2013

Current status

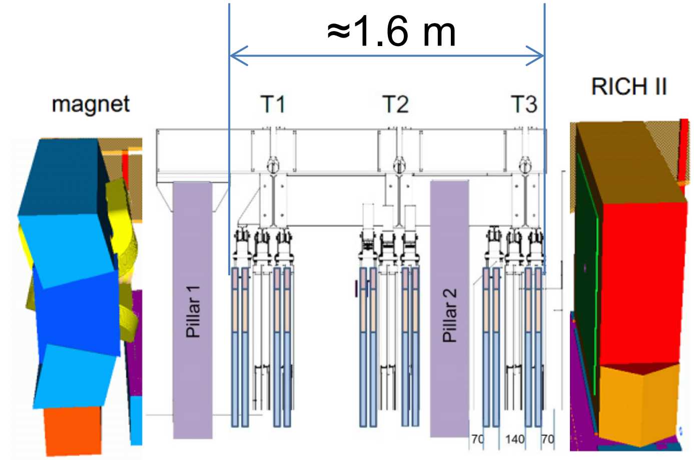
- Requirements (see the attached "Draft Specs…"): stable
- Thermal simulation project with EN-CV-PJ (E. Da Riva): ongoing since March 2013
- Cooperation with the CTU (Prague) group led by V. Vacek: summer 2013 tests of the chilled air and 2-phase (C_3F_8) cooling options with the FT end-cap mockups
- Participation in end cap design (consultancy)
- Two full-scale end cap mockups were made
- Contacts with the industry: Ferrotec NORD (RU), ITE (UA), Thermacore (UK), Korund Albion Ltd (UK), HYDRO Aluminum (DK)
- Initial liquid (C_6F_{14}) cooling test with the "mockup#2"

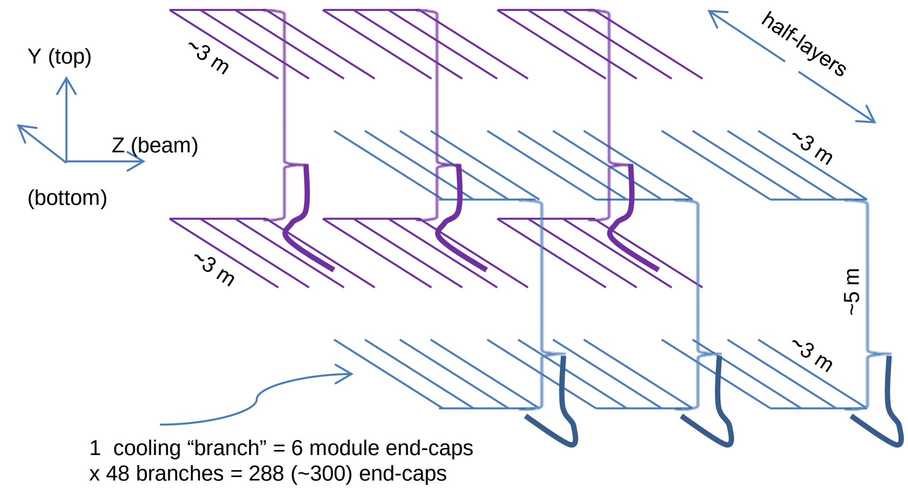


The activity is supported by CERN PH-LBO, but no LHCb groups assumed a commitment, yet…

What's to be cooled?

- 3 stations (with half-stations moving apart); station = 4 layers; 1 layer = 12 modules
- 12 * 12 = 144 modules * 2 (top/bottom) = 288 end caps;
- 1 end cap: 53 cm (X) x 20 cm (Y) x 4 cm (Z); contains an array of 16 SiPMs
- Total length of SiPM arrays: ≈150 m
- 1 cooling "branch" = 6 consecutive end caps (≈ 3 m); 48 branches
- No encapsulating gas volumes! End caps are exposed to the cavern ambient air (nominal: T=20C, dew point 10-12C)
- Heat load: O(10W/module) , dominated by parasitic heat influx (w/o heat pick-up in all lines!). Total: 3 kW …. 6 kW + 20…25% (lines)





Big extent, no encapsulation

Requirements (I)

- **-40°C…-50°C** : SiPM dark noise!
  - increases 50…100 fold upon neutron irradiation (50 fb^{-1})
  - decreases 2-fold at every 10°C of cooling, thus +20°C -> -40°C by the end of lifetime
  - Most important for inner modules (|x|<1 m)
  - A design margin (down to -50°C) is required, too
- **Temperature uniformity in space** : SiPM gain adjustability
  - SiPM as a whole: common gain adjustment, broad range;
  - channel-by-channel within SiPM: no adjustment -> ±0.5 °C / 33 mm
  - A gradient of up to 10°C over 3 m is tolerable (but cool inner modules first!)
- **Condensation, frost formation**
  - Keep all external surfaces above a local dew point
  - Internal spaces (SiPM enclosure) : flushing with dry (pre-cooled?) gas
  - consider external gas envelope around end caps?
- **Modularity**
  - Every end cap has its own cooling structure (e.g., no common cooling pipe for 6 modules)
  - SiPMs should be accessible for maintenance

Requirements (II)

- **Temperature uniformity in time** :
  - SiPM gain affects the detection efficiency (should be constant at 98-99%)
  - Different for G(T) for Hamamatsu and KETEC SiPMs
  - HAMAMATSU: ±1°C between calibrations (LHC fills?)
- **Cooling power: 3…6 kW (+20…25% for lines)**
  - Dominant heat load: parasitic influx through end cap insulation, flex PCB and fibres
  - Simulation: O(10W) per end cap, without in/out lines
  - tests (with loose in/out insulation) indicated <20W
  - 20 W*300 end caps = 6 kW, plus heat pick up in tranfer/commenctions
- **(some) radiation hardness: ~50 Gy, ~10^{12} neutrons/cm^2 (1 MeV)**
  - Peltier modules (?)
  - Refrigerants beyond traditional pFC? Candidate: HFC (e.g. R125, C2F5H)
- **Anti-requirement: no concerns about material budget**
  - Unlike with IDs, can use materials like copper, steel, PC

Requirements (III, see the “Specs”)

- Thermal expansion matching (CTE: PC=70 ppm, Alu=23 ppm)
- No rigid cooling/SiPM junctions (only sliding or elastic)
- No “dirty”, non-volatile, non-dielectric fluids (Si oils, brines…)
- No interference with r/o electronics (connections at the end cap sides)
- Remote cooling plant/power supplies: ~70 m away
- No electro-mechanical appliances near the detector (fans, pumps etc)
- 6 “caterpillar” sections
- SiPM cooling should be insensitive to 3…5° inclination (U-/V- layers)
- Cooling/annealing cycling (heating up to +40°C should be foreseen)
- Preferences (apart from **low cost**):
  - Environmentally-friendly solution
  - Warm (above dew point) connections only
  - Maximal use of existing infrastructures (mixed/chilled water, C6F14 transfer lines)

Challenges

- Operating a 150 m long SiPM array, at -40°C or below, within 40 mm enclosures, without external dry gas volume
- Upgraded OT should fit into the space envelope of the existing tracker, not intended for sub-zero cooling (tight gaps!)
- Distribution/manifolding: 300x2 = 600 inlets and outlets, over twelve 5x6 m2 planes
- "Elastic" insulation of the module edges
- Long-term stability of the thermal interfaces between SiPMs and the cooling structures (silicone thermal pads? metal foams?)
- Cost

Cooling technologies, options (I)

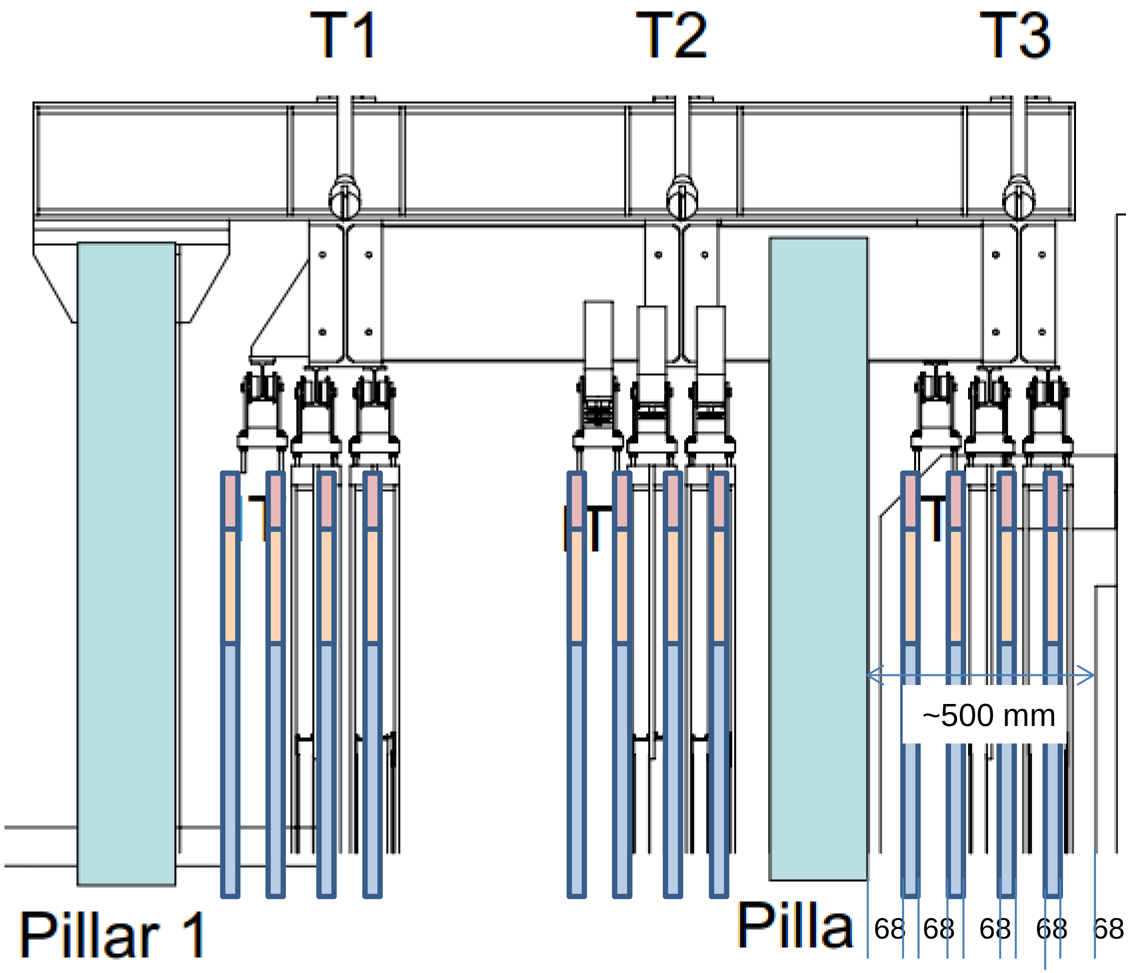
- Plain mono-phase liquid cooling (see Enrico's talk)
  - So far baseline choice, widely used at CERN, established technology, COTC components
  - Big reserve in cooling power, permits serial module connection
  - Naturally permits annealing by warming-up
  - In clash with the requirements of low-occupancy, preferred warm connections
  - >600 potential leaks
  - C6F14 (a usual choice): expensive, high GWP, oil-free pump
  - Low-loss transfer lines can be expensive (70 m, two-way)
- 2-phase (evaporative) cooling (Vic, Greg, Bart)
  - Established technology, widely used at CERN,
  - Enormous reserve in cooling power, permits serial connections
  - Potentially permits warm-only connections (with local vapor heaters)
  - Possibly, can use commercial "green" refrigerants (e.g., HFC-125)
  - -40…-50 °C – too low for refrigerants commonly used at CERN (C3F6, CO2)
  - More difficult to control and equalize temperature ("Ferrari with breaks only")
  - For annealing, an extra heater will be needed
  - More stuff inside end caps (in case of local pre-cooling and heating)

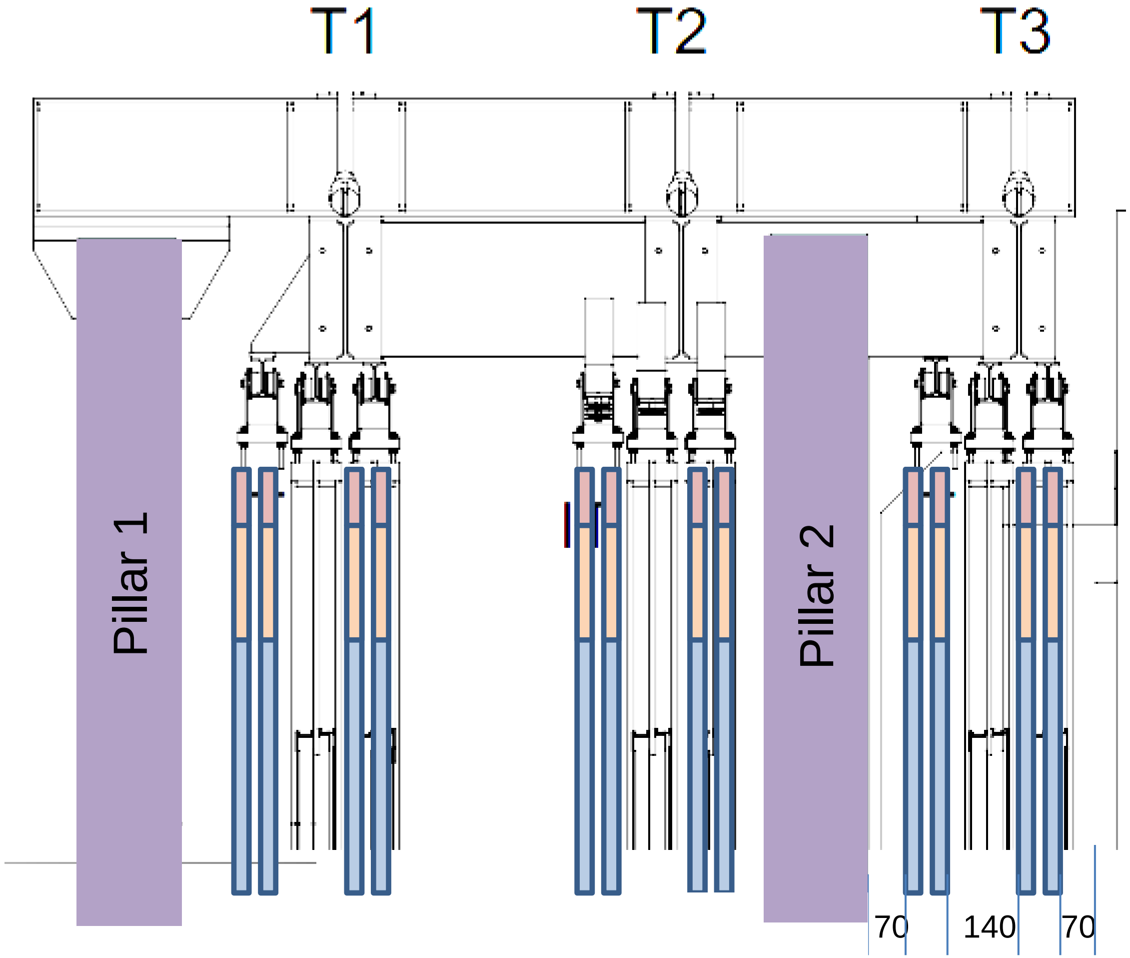
Cooling technologies, options (II)

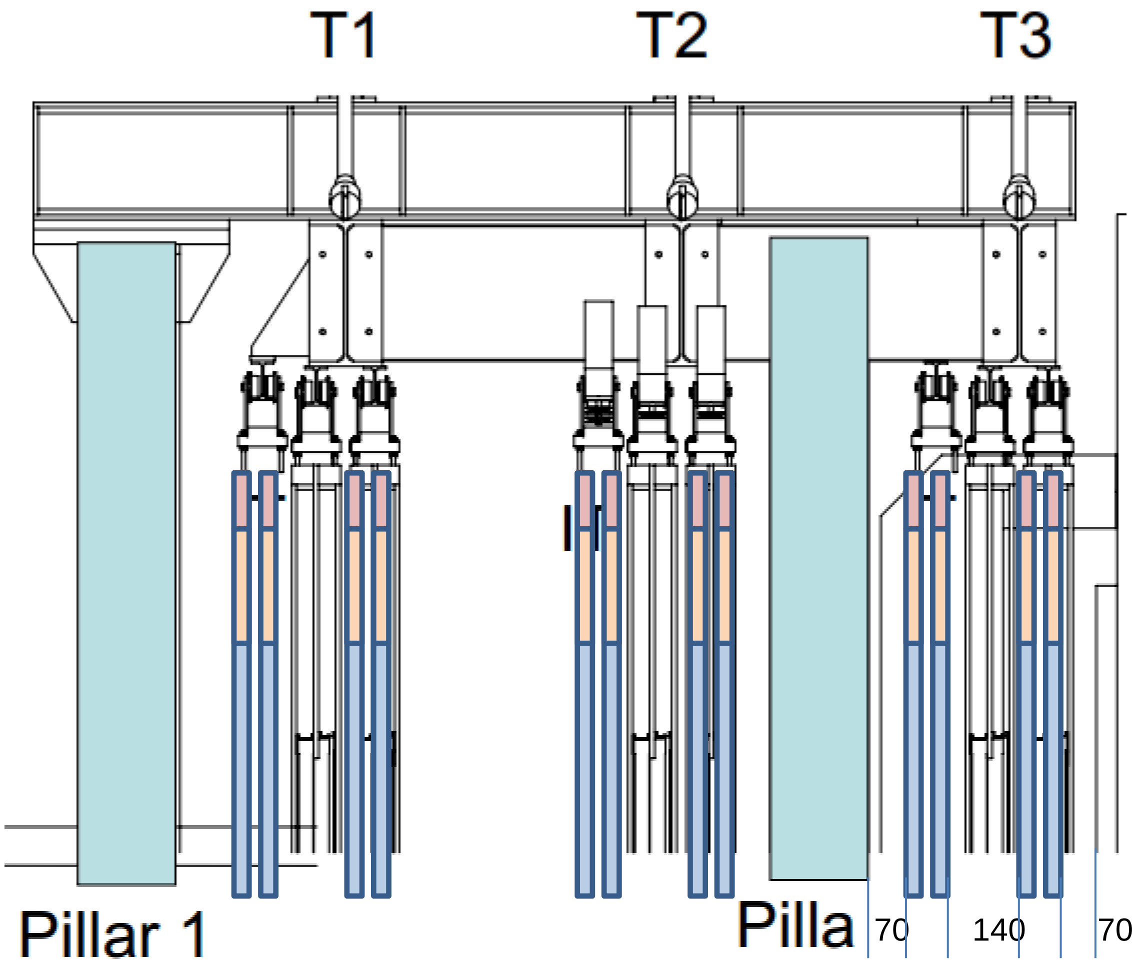
- Chilled air (Vic)
  - Demonstrated to work with SciFi mockups; 100% non-polluting
  - Naturally permits annealing by warming-up
  - Potentially, voids the problem of thermal interface (radiators can be glued to SiPMs)
  - no reserve in cooling power
  - Steep temperature gradient, serial connections are impossible
  - Attractive only if the cooler (vortex tube) is integrated in the end cap
  - Not as "green" as it looks: requires enormous amount of dry compressed air, O(10^4 m^3/h) for 300 end caps (efficiency: <20%)
- Thermo-electric or hybrid (Petr)
  - Historically the earliest proposed option
  - Widely used for compact cooling systems (a single end cap?)
  - Ideal modular solution, with "warm-only" connections
  - Stability under neutron irradiation??
  - Low efficiency for high ΔT (at best ~10% for ΔT of 70 °C) – require 30…60kW w/cooling
  - Can be expensive (linear floating power supplies, ~1200 ~30W channels)
  - Hybrid solutions (e.g., with low-T heat pipes) require R&D

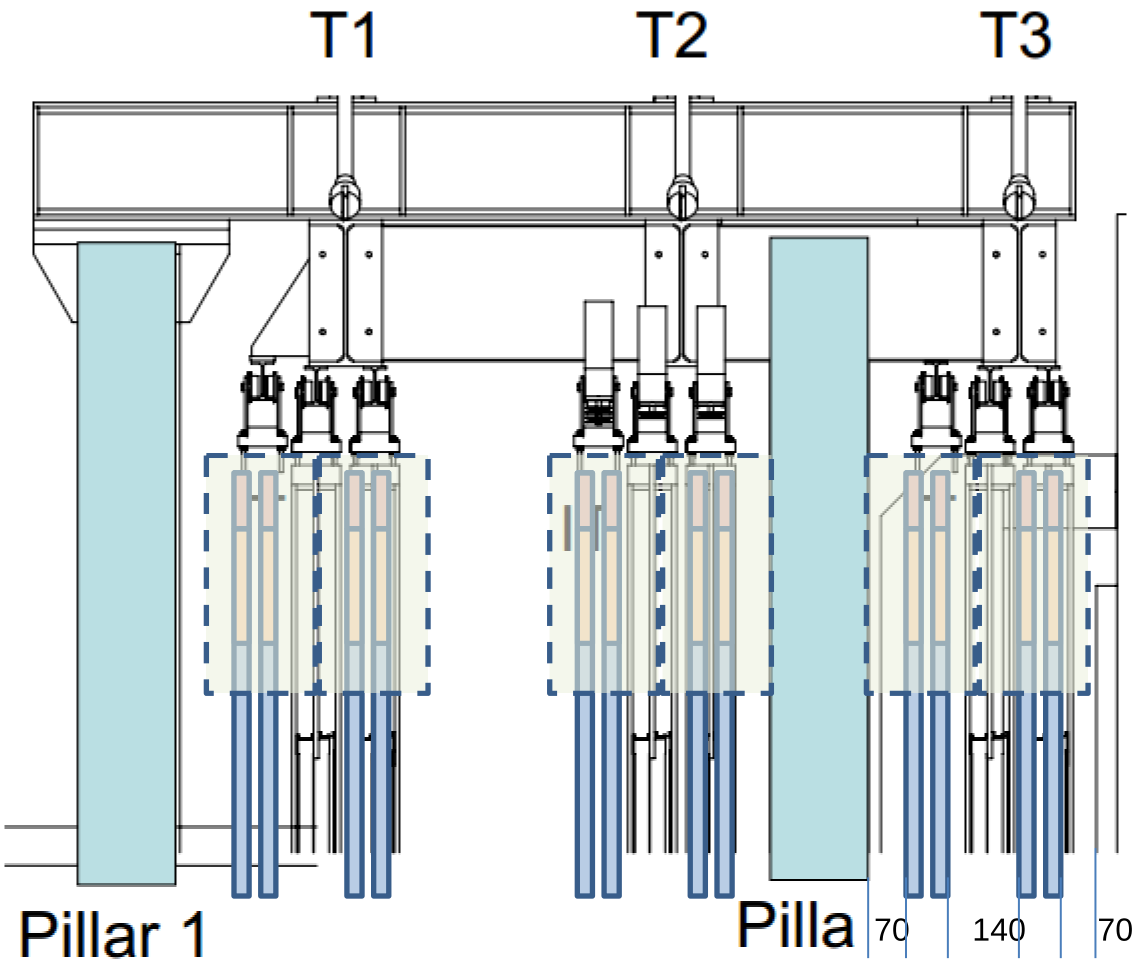
Summary

- No cooling solution wins in all categories, so some more constraints are needed to make the choice…
- A non-scientific wisdom: *the simple things in life are best!...* So, maybe the missing bit is just make it as simple as possible…
- …but not simpler.

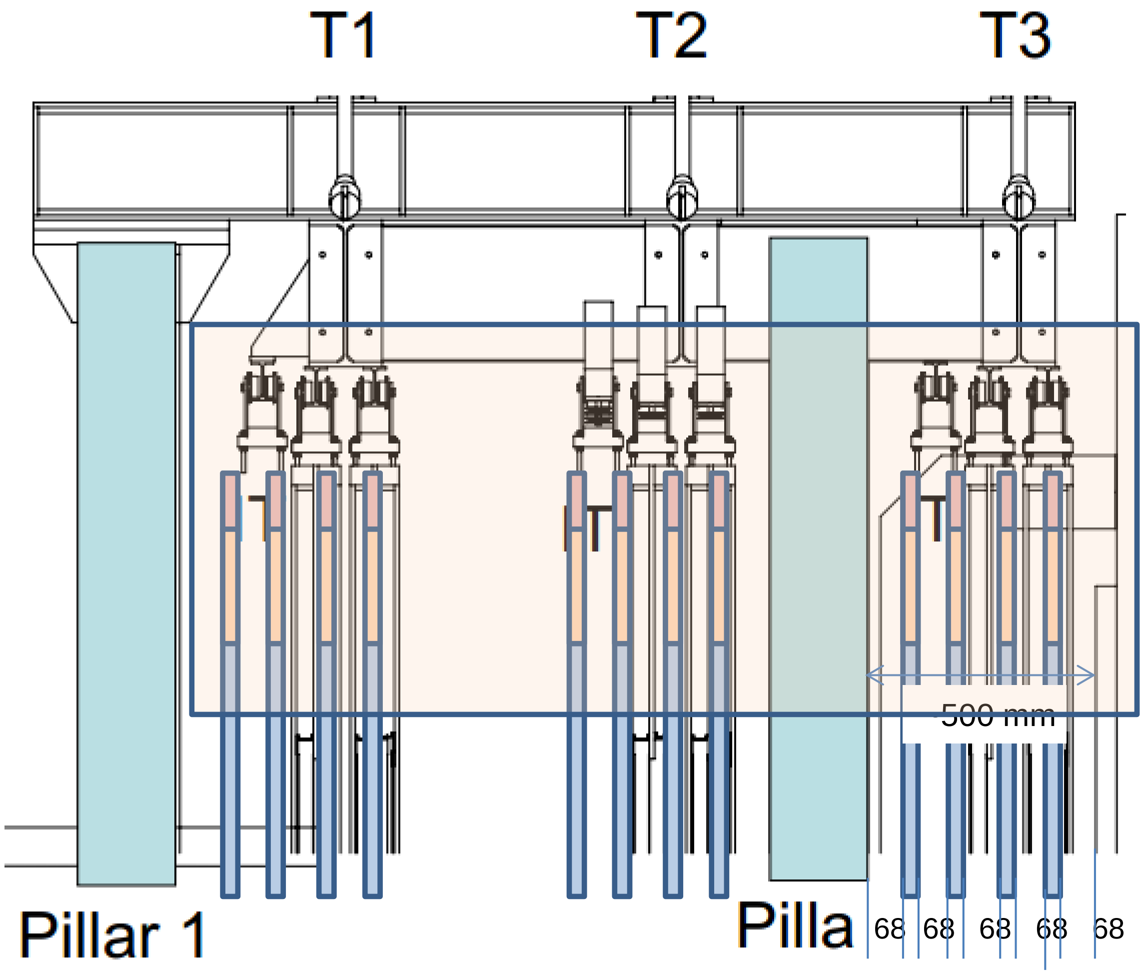

T1
T2
T3
~500 mm
Pillar 1
Pilla
68
68
68
68
68


T1
T2
T3
Pillar 1
Pillar 2
70
140
70


T1
T2
T3
Pillar 1
Pilla
70
140
70



Ideally, there should be "gas envelopes" flushed with dry gas around the end caps, like with all deep-cooled detectors. This would be a radical solution to a humidity condensation and the edge insulation problems. Real-life solutions should represent <u>approximations</u> to this approach.


T1
T2
T3
500 mm
Pillar 1
Pilla
68
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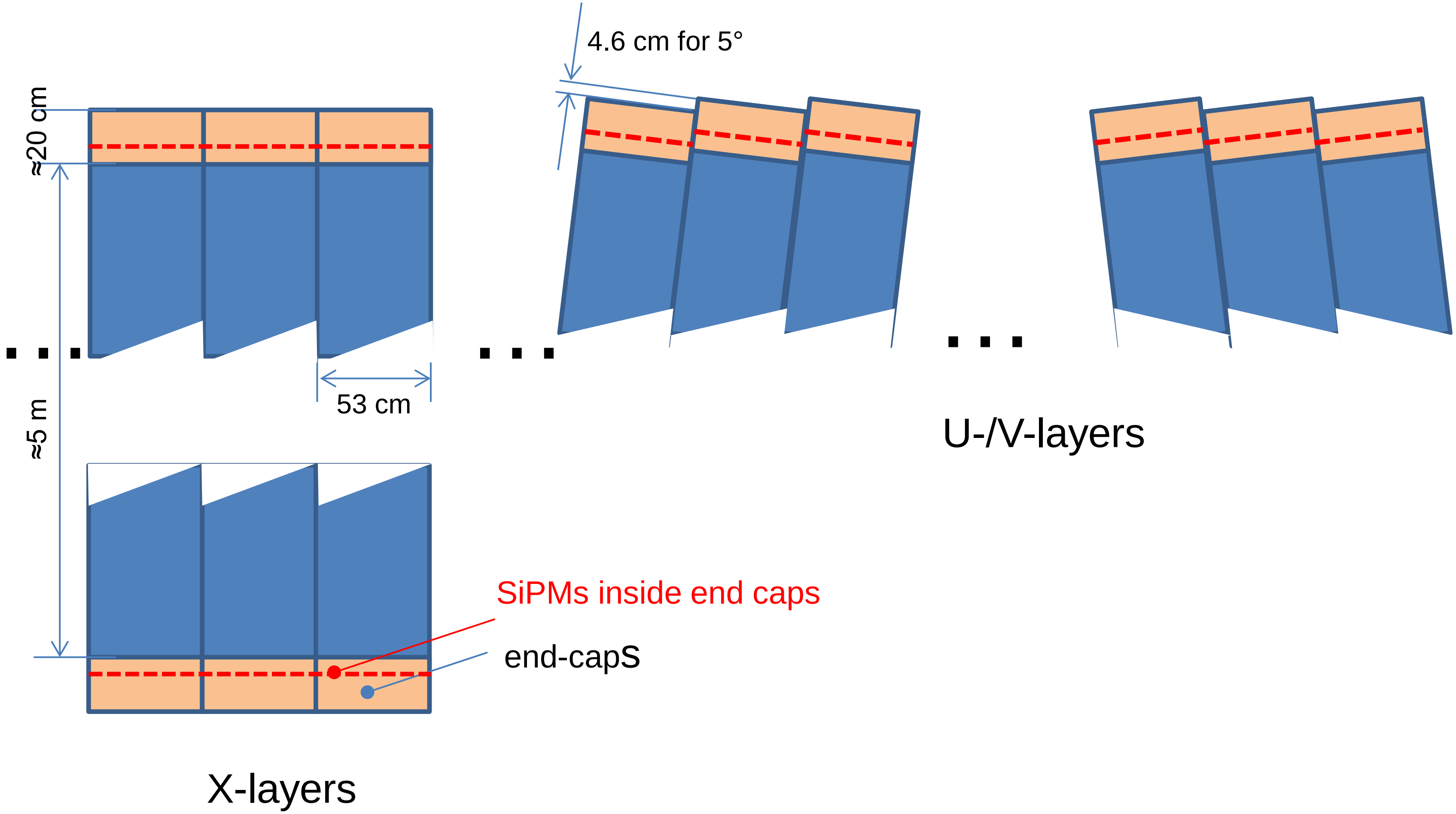
4.6 cm for 5°
≈20 cm
≈5 m
53 cm
U-/V-layers
SiPMs inside end caps
end-capS
X-layers