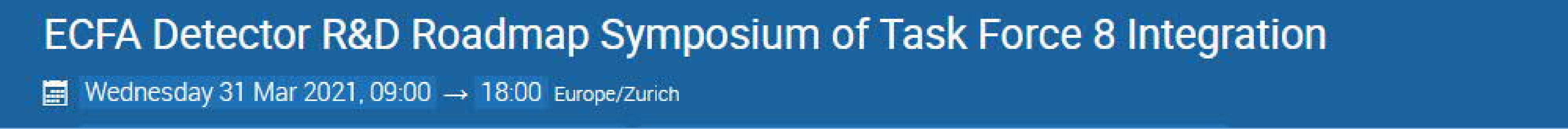


ECFA Detector R&D Roadmap Symposium of Task Force 8 Integration

Wednesday 31 Mar 2021, 09:00 → 18:00 Europe/Zurich

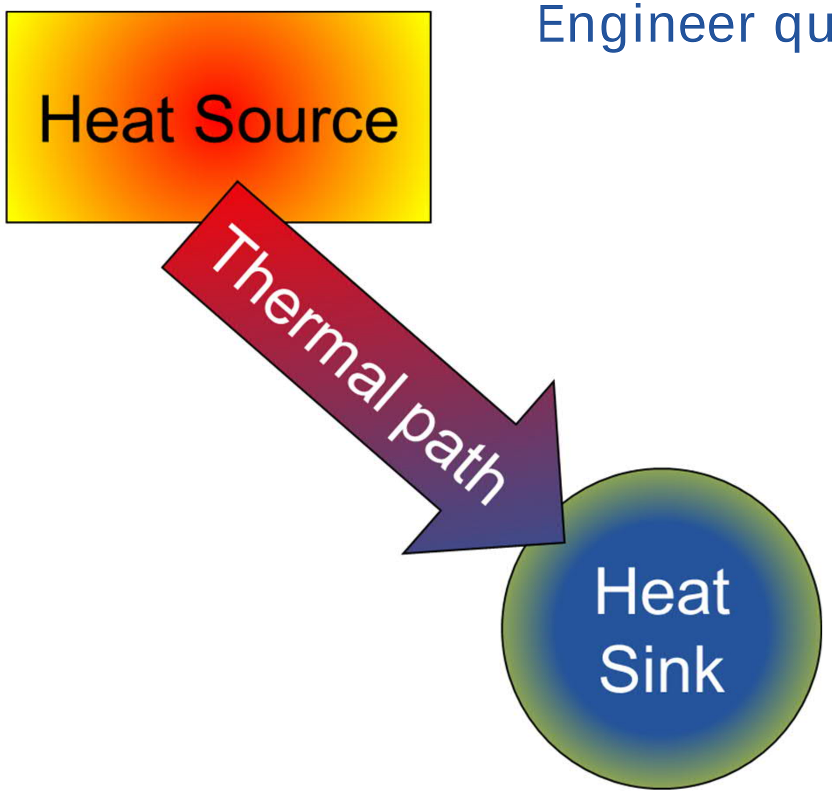
Local cooling

Paolo Petagna (CERN)
Marcel Vos (IFIC)

OUTLINE

- Basic concepts
- Future detector challenges
- R&D needs
- Final considerations

Thermal management of electronics

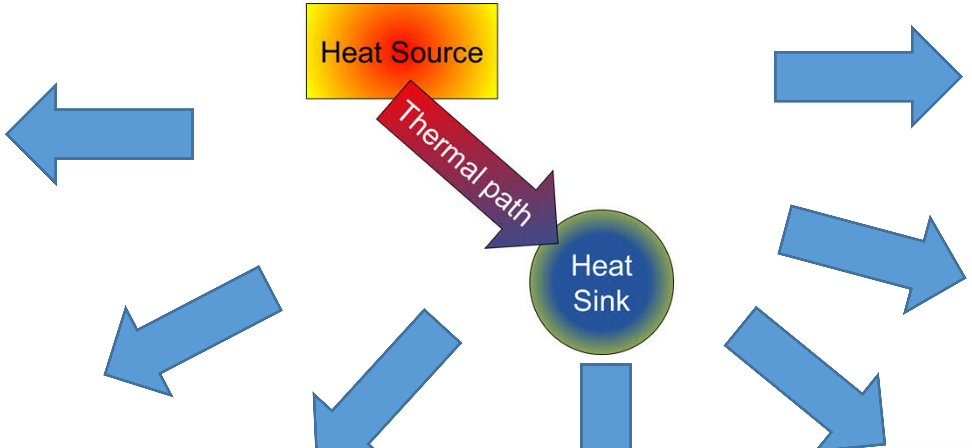


Engineer questions:

- Amount of heat produced by the Heat Source?
- Max temperature of the Heat Source?
- Uniformity requirements?
- Stability requirements?
- Temperature constraints on the Heat Sink?
- Position of the Heat Source?
- Heat Source / Heat Sink interface?
- Space available?
- Material issues (quantity & location)?
- Environmental issues?
- Cost issues?
- Reliability?
- Lifespan?

Thermal management of electronics

Based on the answers to the above questions, you can find different approaches to the thermal management of electronics (examples shown for high power computing chips, one of the most demanding applications in commercial electronics):


Heat Source

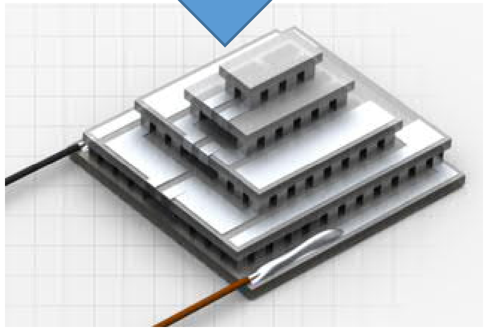
Thermal path

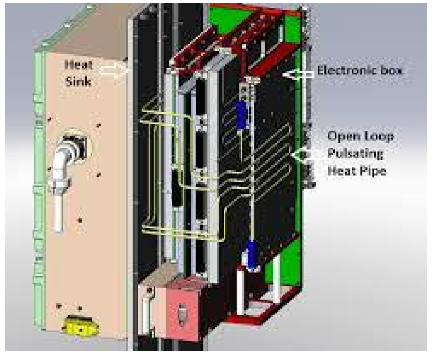
Heat Sink


Forced air cooling

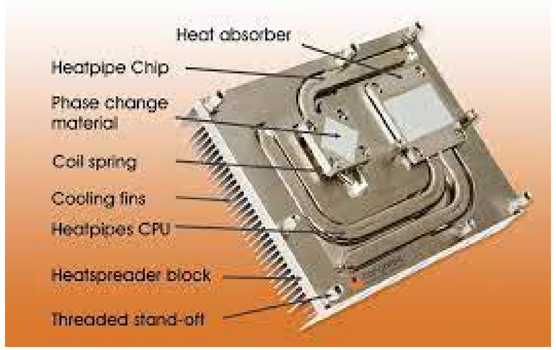

Liquid assisted air cooling


Mechanically pumped

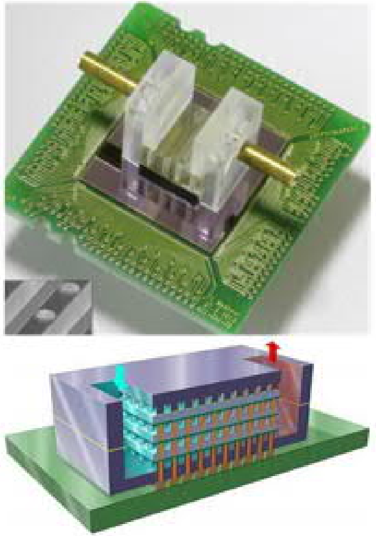

Thermoelectric



Pulsating heat pipe



Heat pipe


Multi-micro-channel

Peculiarities of detector cooling

- Low power density, but (usually) large surfaces
- Moderate to very high radiation
- Radiation length minimization
- Cold operation
- High uniformity in space
- High stability in time
- Magnetic field
- Extreme reliability
- Long lifetime

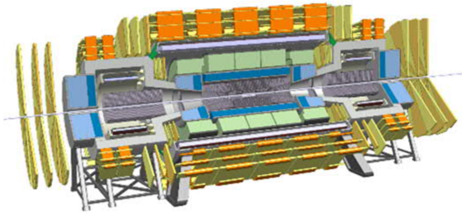
Two reference parameters (usually competing)

$$X_0 = \frac{716.4 \cdot A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}\ \mathrm{g\cdot cm^{-2}}$$

$$TFM = \frac{\Delta T_{sensors-fluid}}{Surface\ Power\ Density}$$

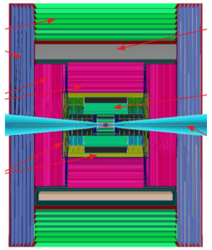
(Varying weight of each parameter depending on the specific application)

Future trends in cooling needs



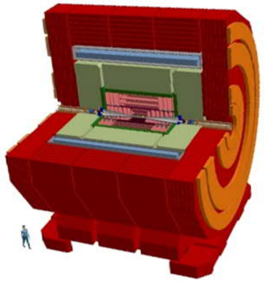
HL-LHC, HE-LHC, FCC-hh
(Rare decays: Kaons, Tau)

Tracker and Vertex: very cold and low TFM
ECAL: Lar? Digital Si/W? Analog Si/W?
Timing layers?



Muon colliders

Tracker and Vertex: a bit in-between
ECAL: Digital Si/W

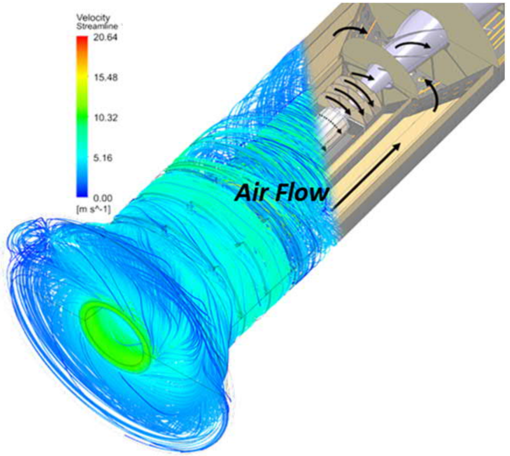


Strong interaction (fixed target or collider)
Linear e+e-, Circular e+e-
(Rare decays: Mu->e+e+e-, Mu->e-)

Tracker and Vertex: remove heat at minimum X_0
ECAL: Si? SciFi + SiPMs? Gaseous?
Timing layers?

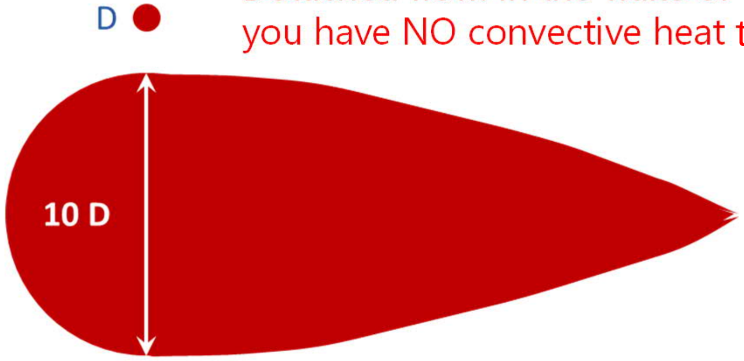
Air cooling: fears of a former aerodynamicist

Any fluid-structure interaction it's "work" and dissipates energy
(also) Fluids try to minimise work if they can



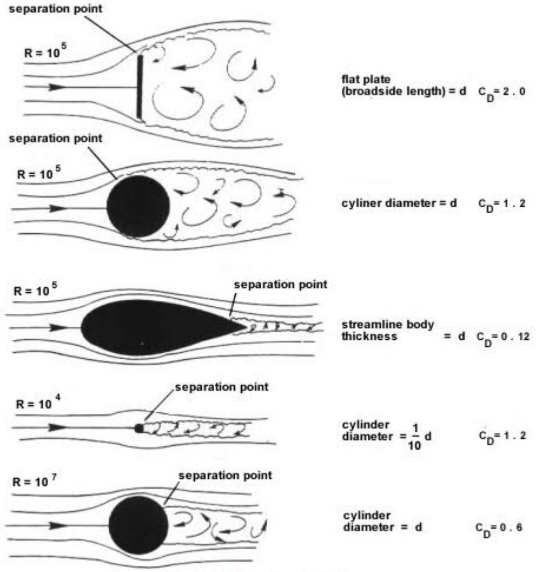
- In "internal" (or "confined") flows, the fluid is guided and constrained within a structure: a duct, a channel, a pipe: its only possible revenge is to "lose pressure" and force you (or your pump) to work more;
- In "external" (or "free") flows, the fluid is constrained by a structure on one side only and is free to decide what it wants to do: you must be gentle and smart and guide it where you want.

EXAMPLE: THESE TWO CYLINDERS HAVE THE SAME DRAG COEFFICIENT



Detached flow: in the wake of this cylinder you have NO convective heat transfer

Attached flow: in the wake of this cylinder you may still have a decent convective heat transfer



Drag coefficients of various bodies.

Air cooling: fears of a former aerodynamicist

- In order to have an effective air cooling the geometrical design of the structure must be entirely finalized to this goal from the beginning
- The air path must always be guided to avoid that small changes from “as design” to “as built” may have unforeseeable, potentially catastrophic and likely unrecoverable consequences on the performance
- Additional challenge: bringing large quantities of air in well controlled condition of temperature and velocity distribution may prove to be more tricky and space consuming than one could imagine

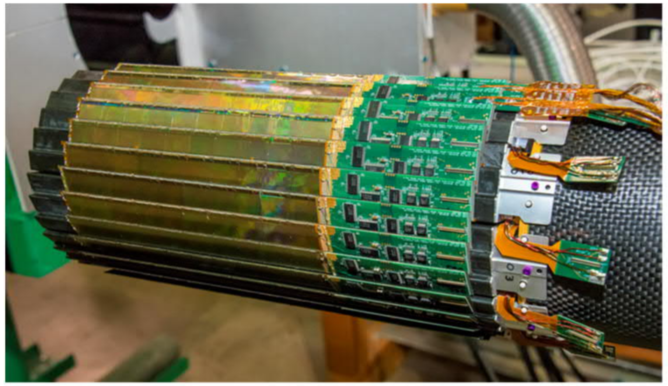
I am not saying – nor I want to say – that “it will not work”, rather than it may very well prove to be way more difficult and risky than what many people think now: the concept must be well conceived in all details and fully integrated in the detector design from the beginning.

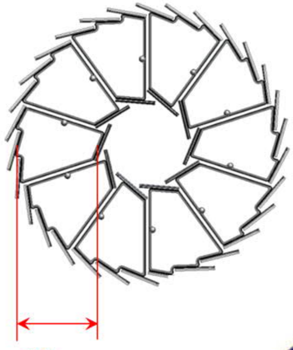
Push on R&D on realistic smaller scale cases now for hopes of success in the future!

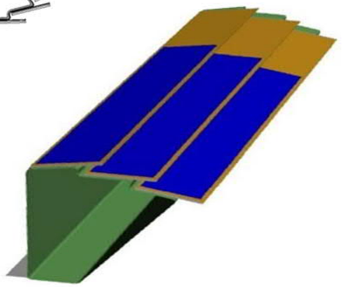
Air cooling: the STAR case

The PXL subdtetector of the STAR HFT @ RHIC is the first silicon detector operating on a collider successfully cooled by air…
But there are very specific conditions for this to work (e.g. studies on the ALICE ITS upgrade failed to provide satisfactory performance).

Details: G. Contin et al., *The STAR MAPS-based PiXeL detector*, NIM A907, 60-80 (2018)







- CMOS MAPS technology
- Goal X/X_0 = 0.37% per layer
- Room temperature operation
- Max T on sensor = 40 ˚C
- Radiation tolerance up to 90 kRad/year
- Fluence $2x10^{11}$ to 10^{12} 1MeV n_{eq}/cm^2
- 1st to 2nd layer gap: <u>50 mm</u> (!)

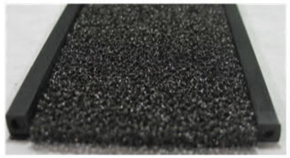
- Chip dissipation = 0.17 W/cm^2
- Total power ~350 W (chips + drivers)
- Air flow T = 23 ±1 ˚C
- Air speed = 10.1 m/s
- DT air-detector = 12 - 13 ˚C

TFM ~70 K cm^2/W

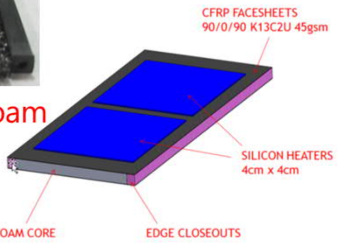
Air cooling: porous carbon foam as interface

Interesting studies at LBNL on the combination of air cooling with micro-fluidics through carbon foams:

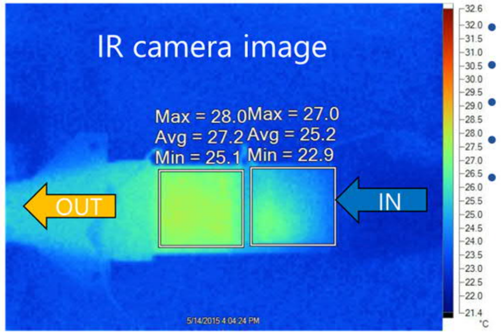
"Advanced Materials and Tools Research" (E. Anderssen et al.)
Forum on Tracking Detector Mechanics 2015 (Amsterdam, NL)
https://indico.cern.ch/event/363327/contribution/34



Allcomp carbon foam (CVD)



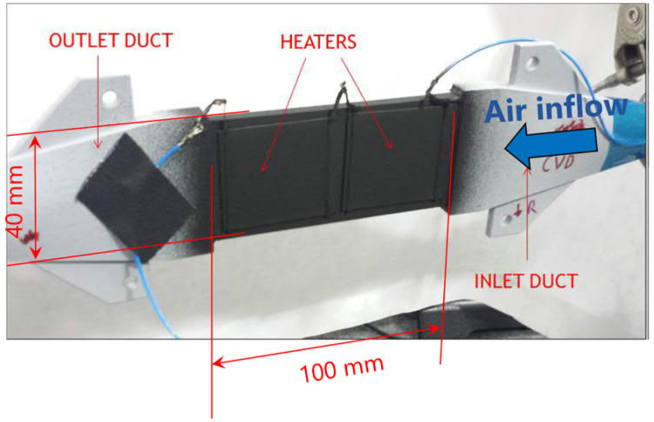
Test "stavelet"

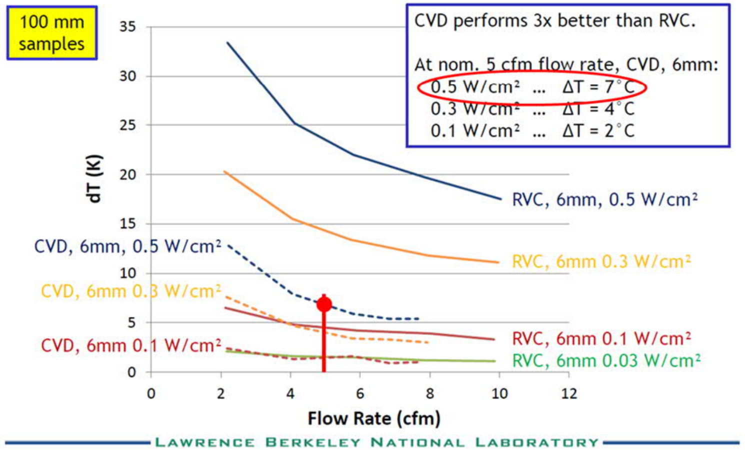


- Room temperature
- Air flow rate = 0.14 m³/min (5 cfm)
- Air speed ~ 10 m/s
- Foam thickness = 6 mm
- Power density = 0.5 W/cm²

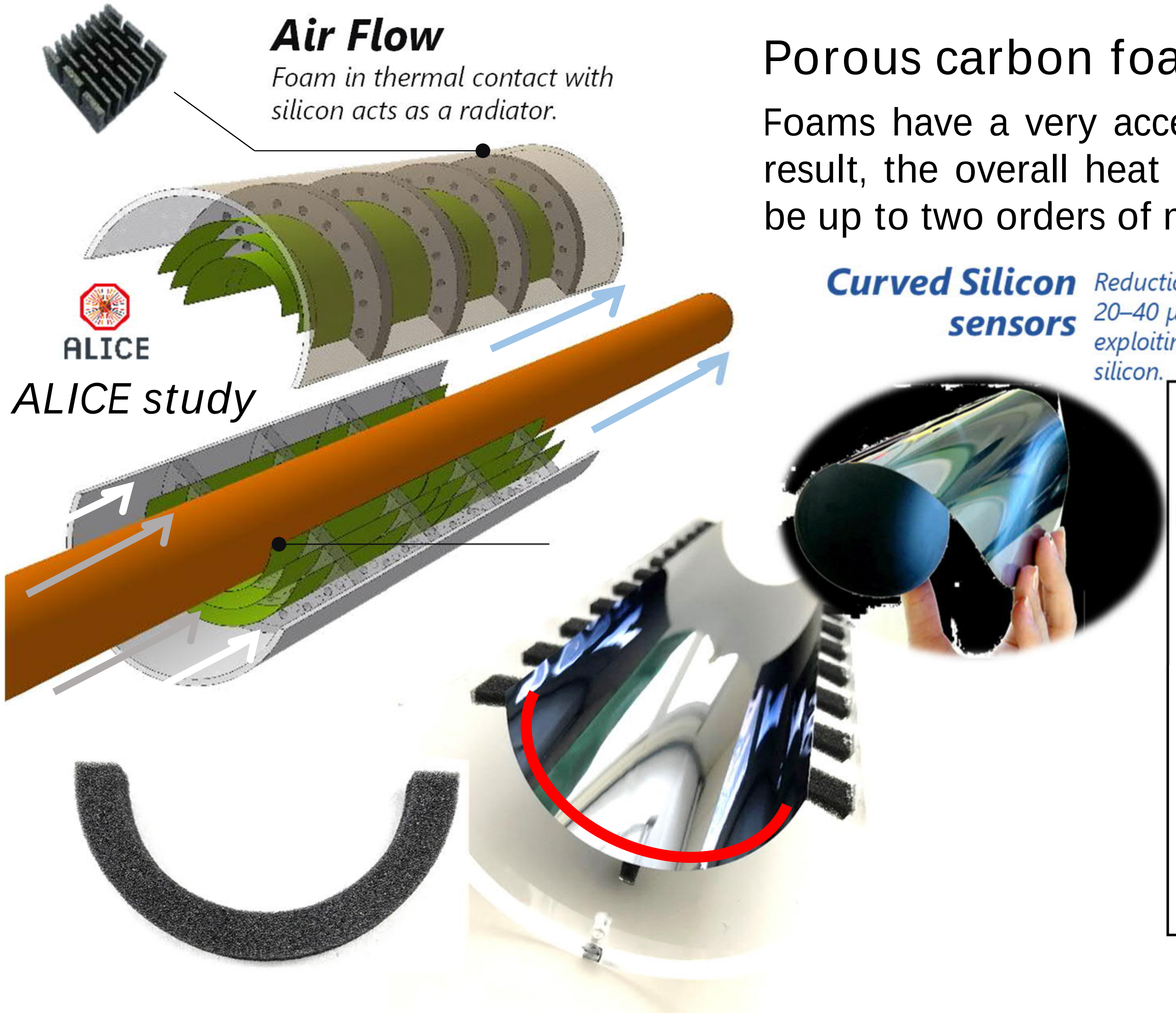
TFM = 14 [K·cm²/W]
(on a 100 mm length)

Length limitation!





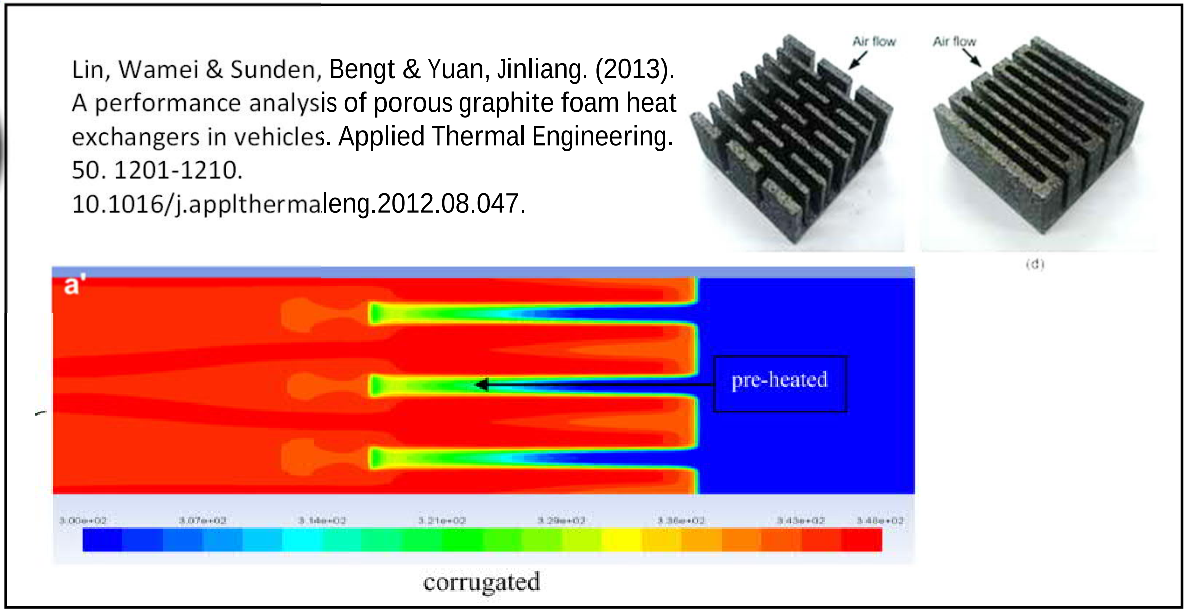
Air cooling: porous carbon foam as radiator



ALICE study

Porous carbon foam structures as air cooling radiators

Foams have a very accessible surface area (> 4 m2/g) and are open celled. As result, the overall heat transfer coefficients of foam-based heat exchangers can be up to two orders of magnitude greater than conventional air heat exchangers.



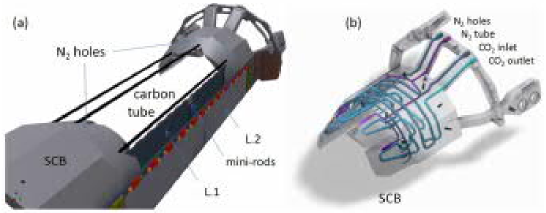
Lin, Wamei & Sunden, Bengt & Yuan, Jinliang. (2013). A performance analysis of porous graphite foam heat exchangers in vehicles. Applied Thermal Engineering. 50. 1201-1210. 10.1016/j.applthermaleng.2012.08.047.

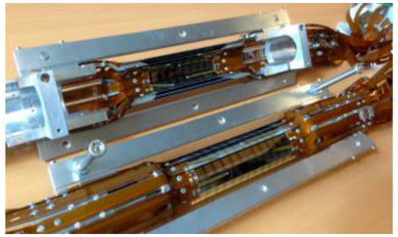
Slide courtesy of C. Gargiulo

Liquid assisted air cooling

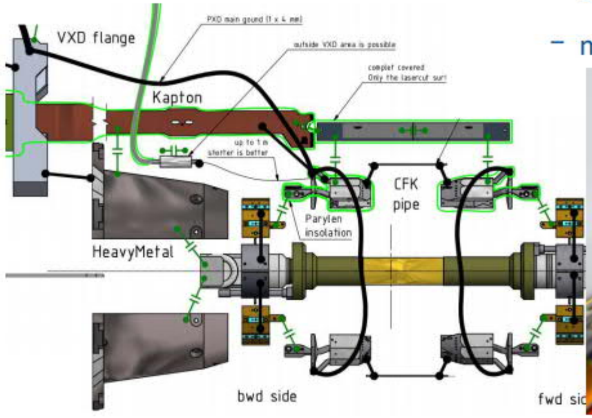
Cold fluid (CO_2 or Novec) for the thermal management of the electronics, air for the sensors (easier for detector with limited acceptance)

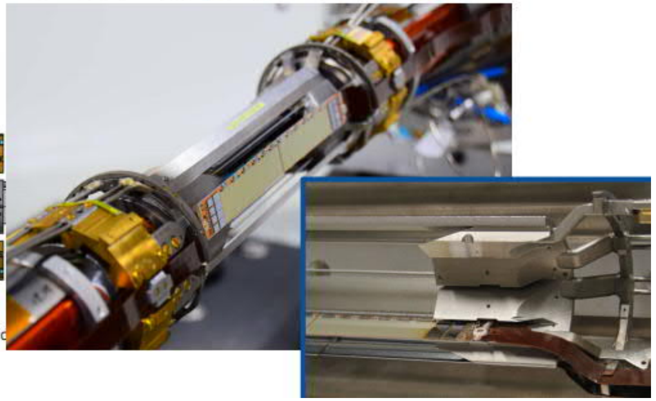
Belle II PXD @ KEK





- 3D printed metal support cooling blocks (SCB)
- mounted directly onto the beam pipe

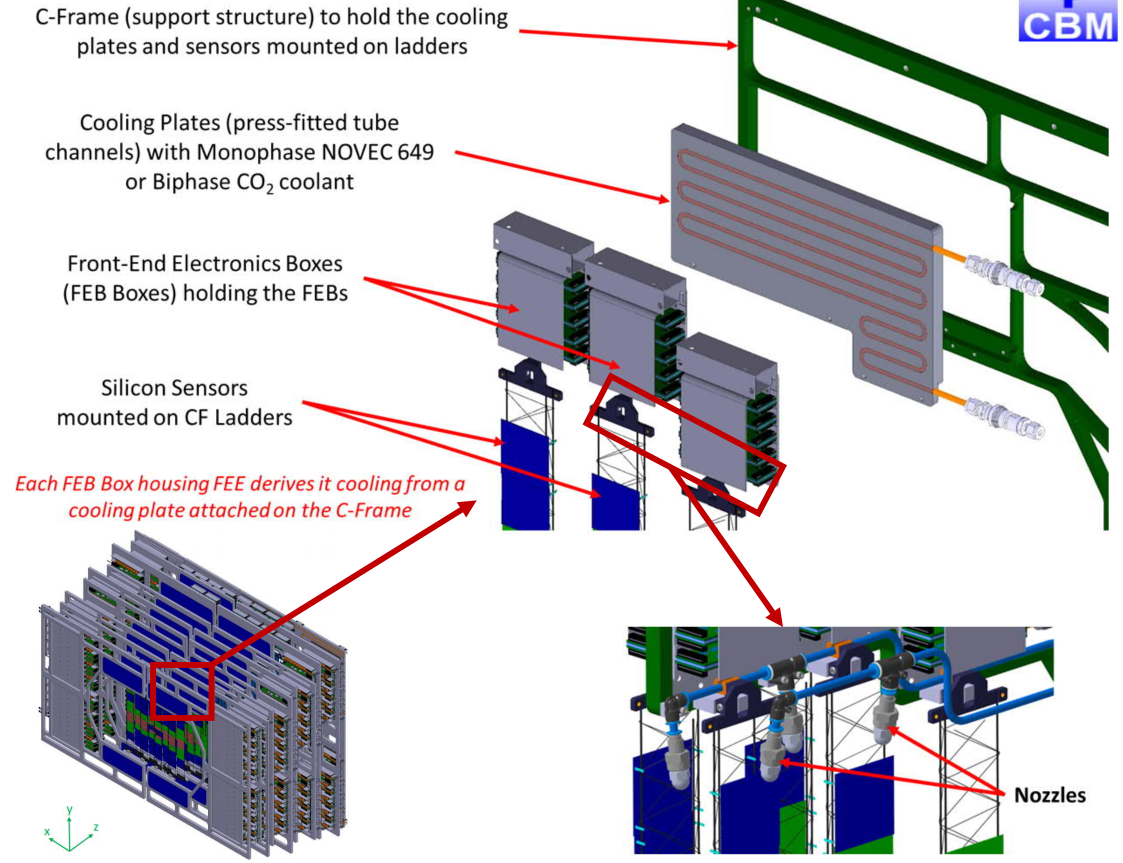




H. Ye et al., NIM A, Volume 896, 11 July 2018, Pages 82-89

B. Paschen, Vienna Conference of Instrumentation 2019

CBM STS @ FAIR



C-Frame (support structure) to hold the cooling plates and sensors mounted on ladders

Cooling Plates (press-fitted tube channels) with Monophase NOVEC 649 or Biphase CO_2 coolant

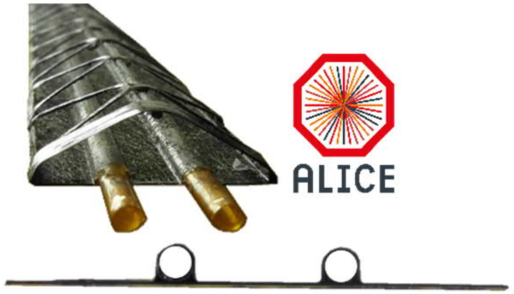
Front-End Electronics Boxes (FEB Boxes) holding the FEBs

Silicon Sensors mounted on CF Ladders

Each FEB Box housing FEE derives it cooling from a cooling plate attached on the C-Frame

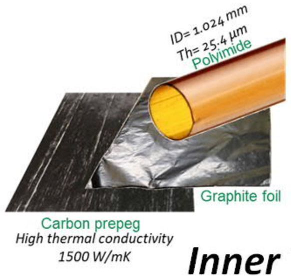
K. Agarwal, Forum on Tracking Detector Mechanics 2019

Ultra-lightweight liquid cooling



Water leakless cooling

High conductivity carbon plate with embedded Kapton pipes

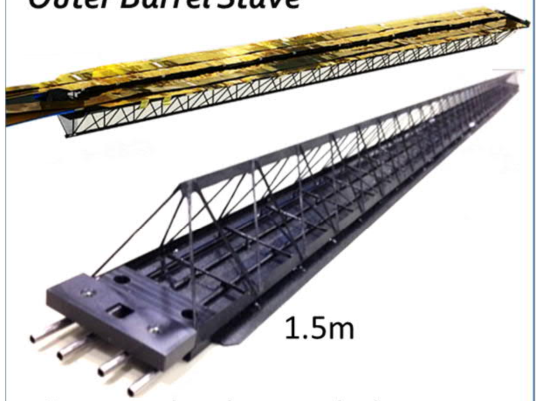


ALICE ITS
Inner Barrel Stave

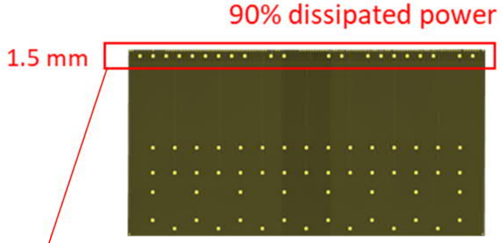
***Inner** Tracking System*
Active area: 9.4 m^2
N chips: 24120
Chips heat flux: 40 mW/cm^2

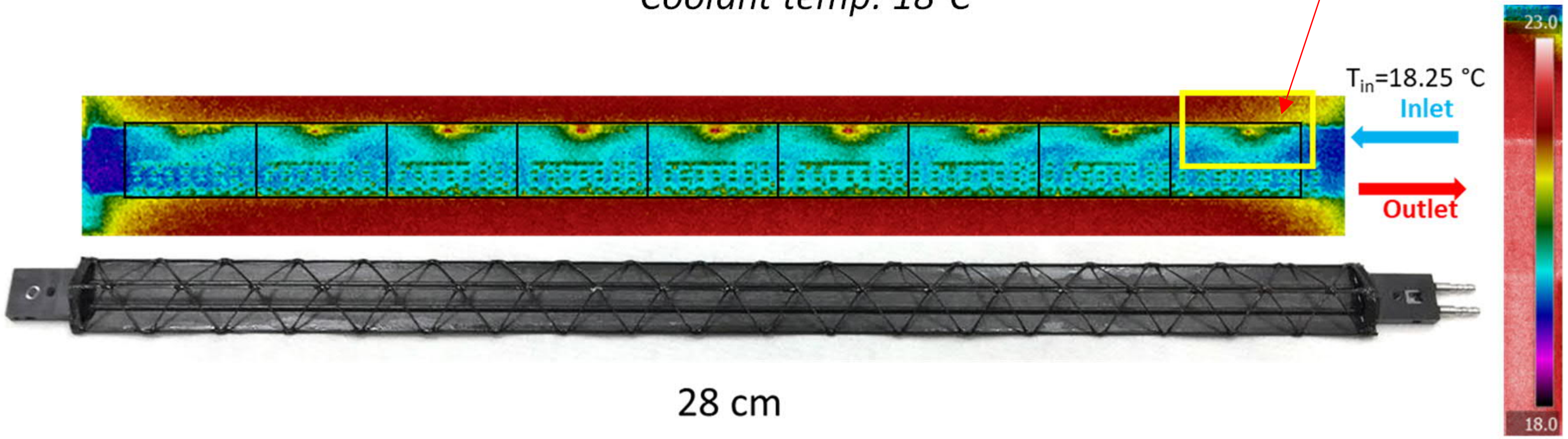
Total Power: ~5 kW
NIEL: 1.7x10^{12} 1MeV neq/cm2
Working temperature ~ 23°C
Fluid: Water (leak-less) ~ 0.6 l/h
Coolant temp: 18°C

ALICE ITS
Outer Barrel Stave



Same technology scaled up to for ITS outer layers



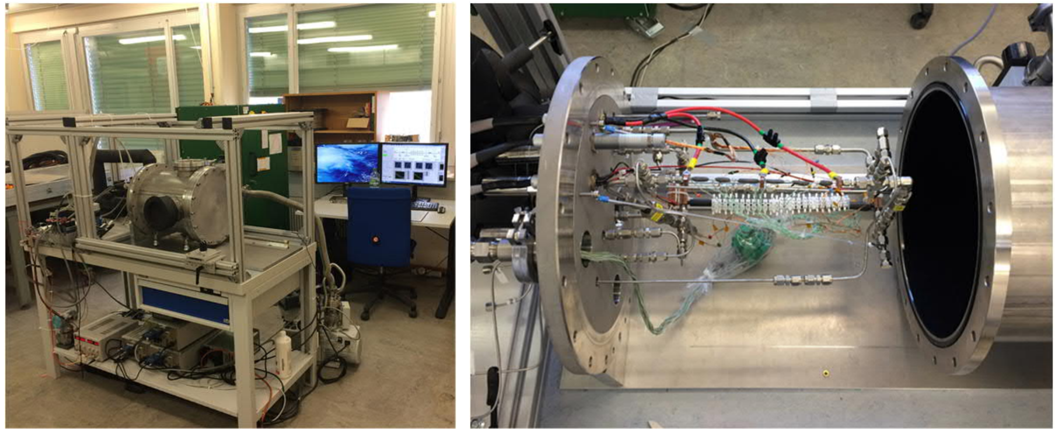


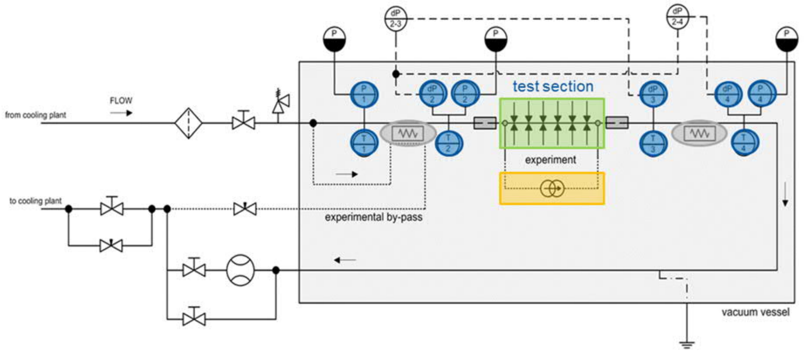
TFM > 100 K·cm^2/W
On digital chip area

TFM ~ 50 K·cm^2/W
On sensor area

Slide courtesy of C. Gargiulo

Can this approach be used for cold CO2?

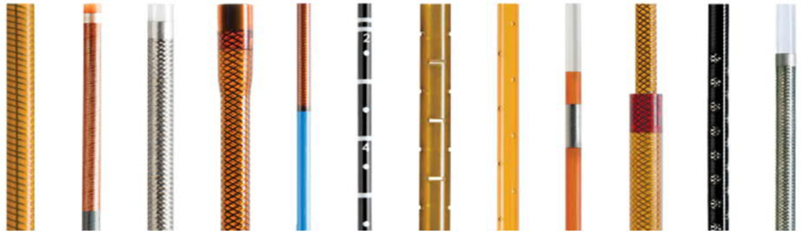




pressure and temperature sensors before and after the experiment

temperature sensors on the experiment

Planned 2021

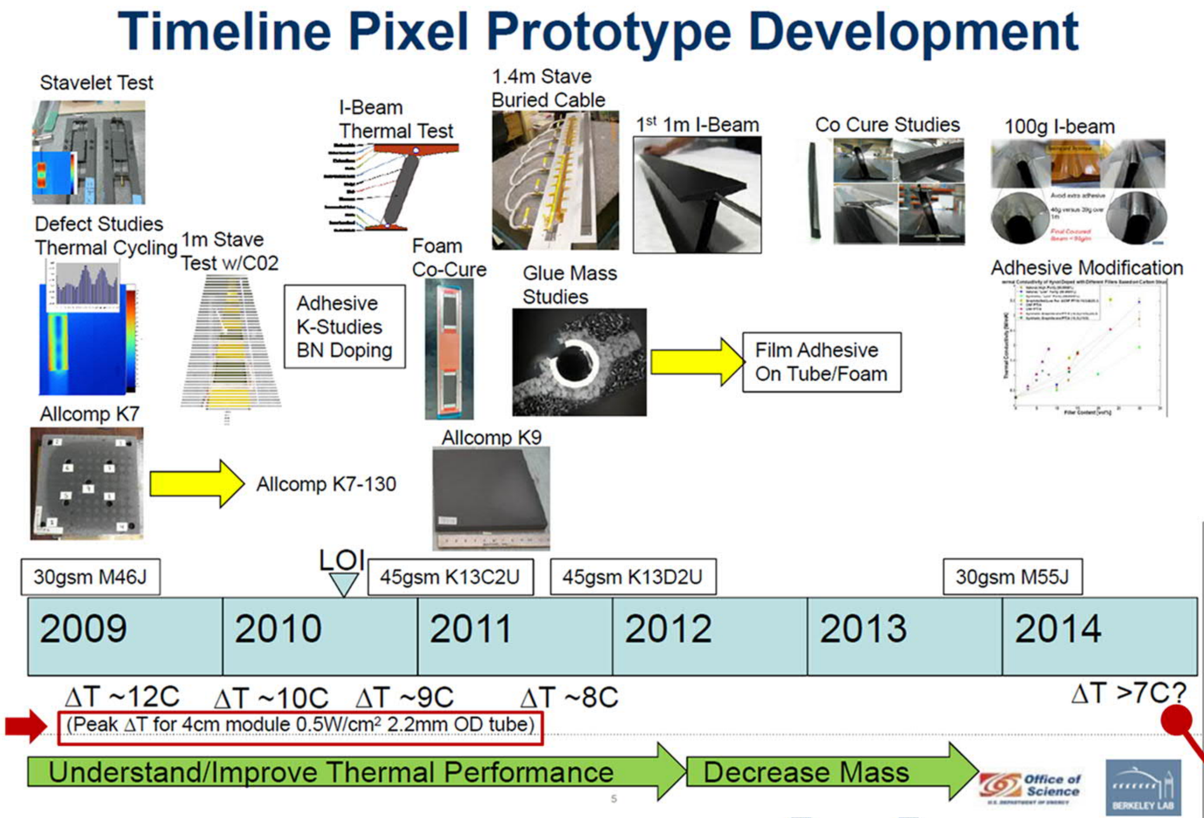


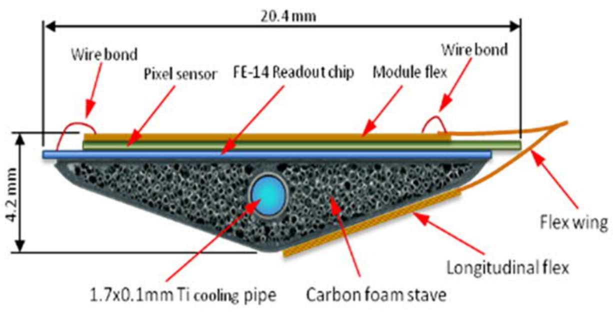
Ø$_i$ [mm]	Min Th. [mm]	Max Th [mm]	P$_{max}$[Bar] @th.min	P$_{max}$[Bar] @th. max
0.051	0.00635	0.0127	169.8	339.6
1.024	0.0254	0.1778	36.8 (50*)	257.3
2.052	0.032	0.1778	23.2(25*)	128.9

**used in ALICE ITS – MFT and tested*

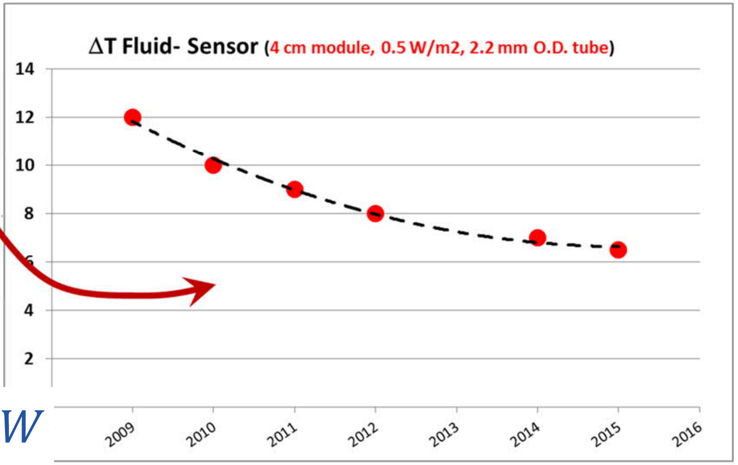
- Hydraulic connections (cycling)
- Deformation under pressure
- Heat Transfer Coefficient
- Wall thermal resistance

Low T cooling: why “colder than CO_2”?





Asymptotic trend of ΔT



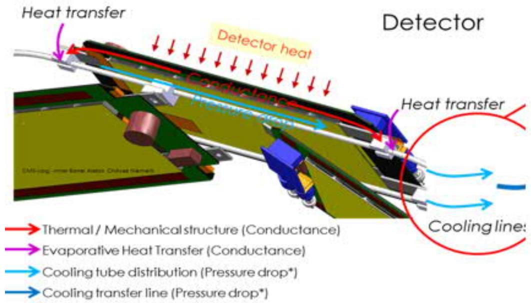
e.g. for a power dissipation of 1 W/cm² if you look for T_{MAX} <-30 °C on your sensor, the saturation temperature in the evaporator must be T_{Sat} <-42 °C (maybe -40 if an optimal design for CO_2 allows for higher HTC)

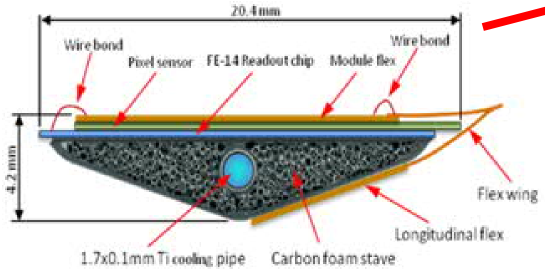
“Thermal Figure of Merit”: $TFM = \frac{T_{hot} - T_{sat}}{Q/S}$

Apparent asymptotic behaviour: $TFM_{min} \sim 12\, K\, cm^2/W$

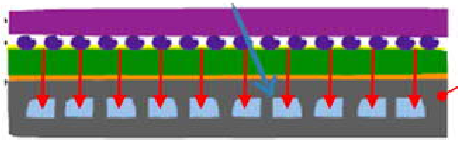
How to get minimal TFM with very low X_0?

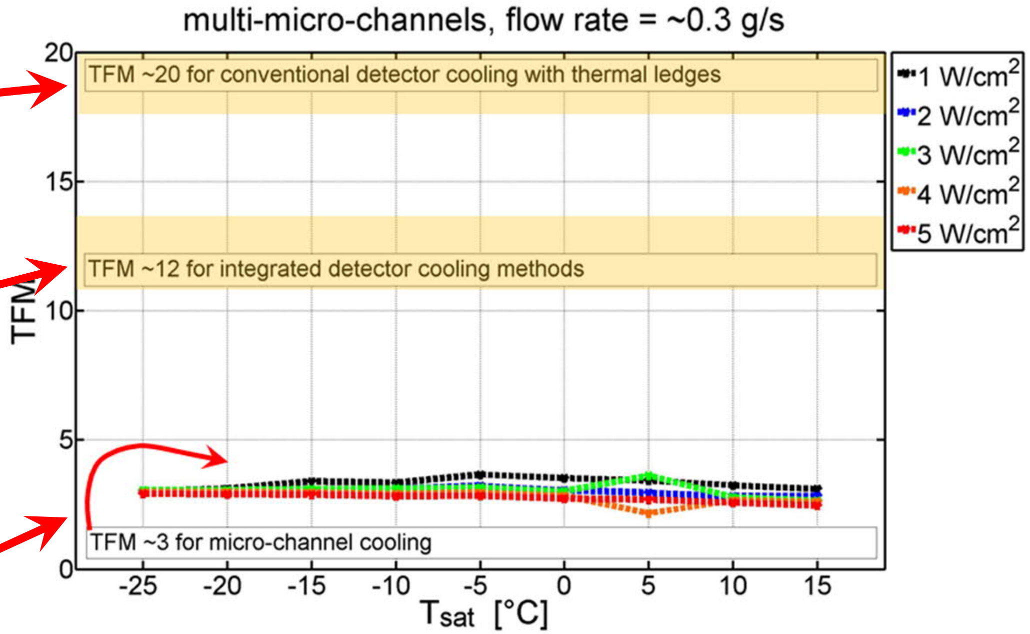
Going colder is not the only way…





Micro-channel device





Plot from D. Hellenshmidt et al. *New insights on boiling carbon dioxide flow in mini- and micro-channels for optimal silicon detector cooling, NIM A Volume 958, 1 April 2020, 162535*

Not only the TFM of a microchannel cold plate is much lower than TFM of any other technology, but it stays relatively constant with T_{sat} (i.e. the HTC is not largely dependent on T_{sat})

How to get minimal TFM with very low X_0?

Original idea (liquid H_2O)

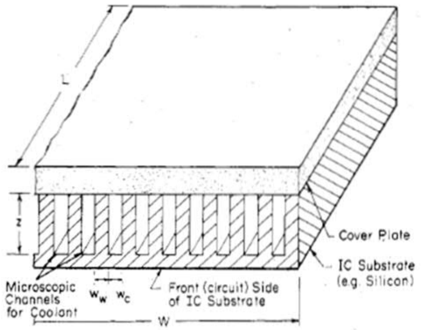
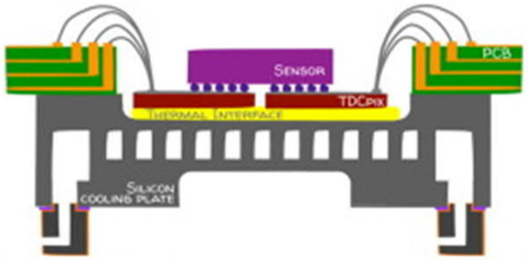
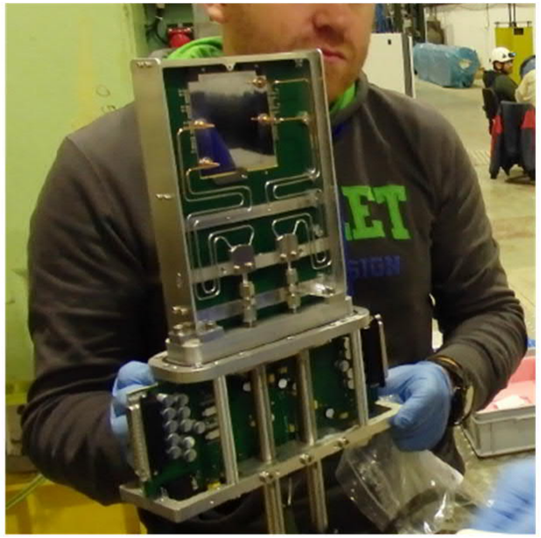


Fig. 1. Schematic view of the compact heat sink incorporated into an integrated circuit chip. For a 1 cm^2 silicon IC using a water coolant, the optimum dimensions are approximately $w_w = w_c$ 57 μm and $z = 365$ μm.

D.B.Tuckerman, R.F.W.Pease: *High-performance heat sinking for VLSI*, IEEE Electron Device Letters Vol.2, Issue 5, pages 126–129, **1981**

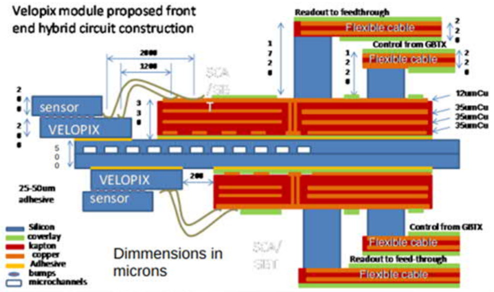
NA62-GTK (liquid FC72)

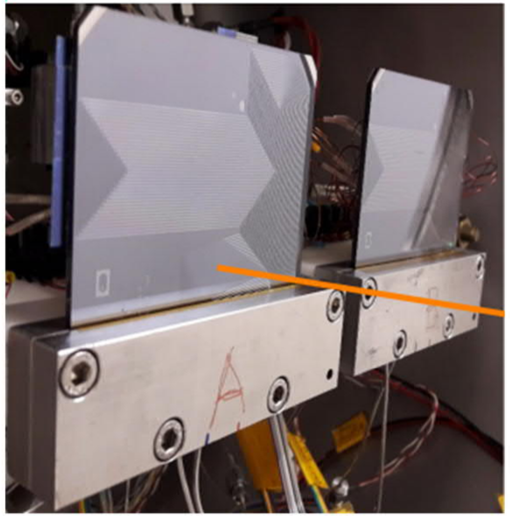




G.Romagnoli et al: *Silicon micro-fluidic cooling for NA62 GTK pixel detectors*, Microelectronic Engineering, Vol.145, pages 133-137, **2015**

LHCb-Velo (Boiling CO_2)

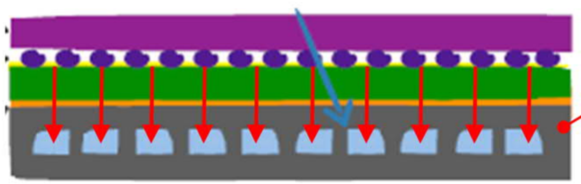




O. Augusto (on behalf of LHCb VELO Upgrade and CERN EP-DT groups) *Microchannel cooling techniques for the LHCb VELO Upgrade*, 26th International Workshop on Vertex Detectors, Las Caldas, Spain, 12 Sep **2017**

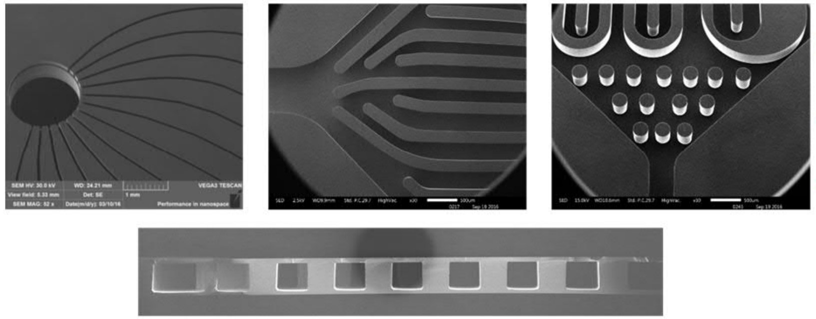
Si microchannels: present limitations

- Good thermal conductivity (>150 W/mK)
- Same CTE of chip and sensor



Wafer-level etching + fusion bonding:

- Si-Si (hydrophobic bonding)
- Si-O-Si (hydrophilic bonding)

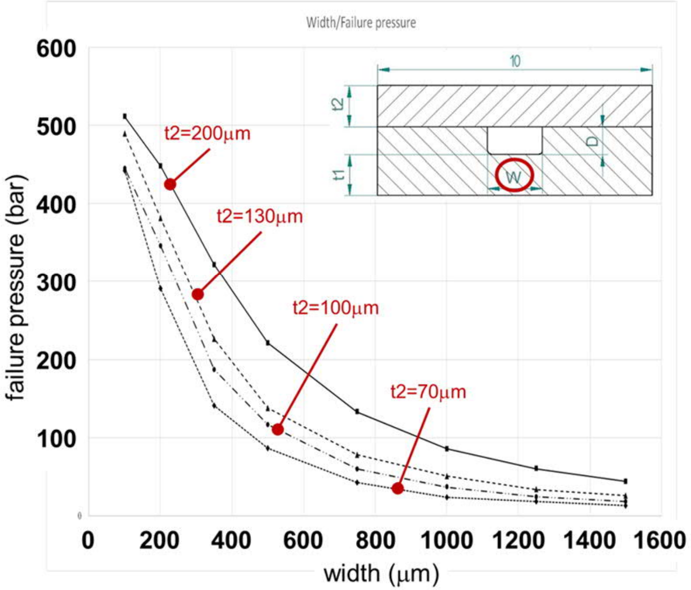


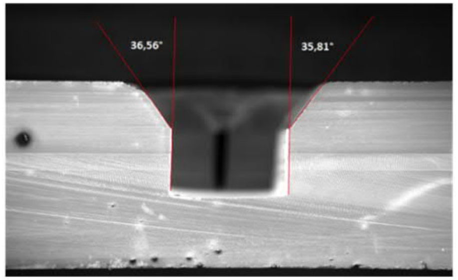
- Well established MEMS technology
- Extreme geometrical accuracy
- Complex shapes

- High mechanical resistance
- Pure elastic material (no fatigue)
- Very thin cold plates possible

Drawbacks:

- expensive process
- brittle fracture
- size limitation

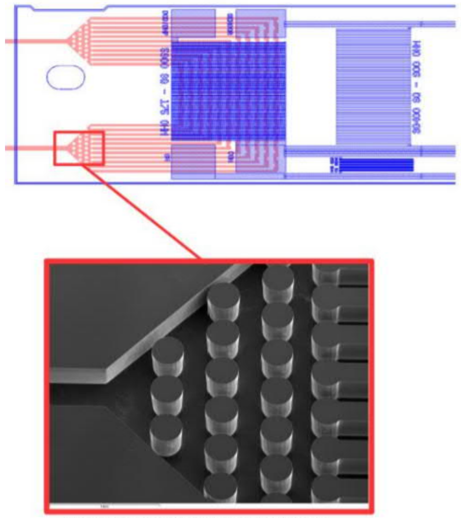




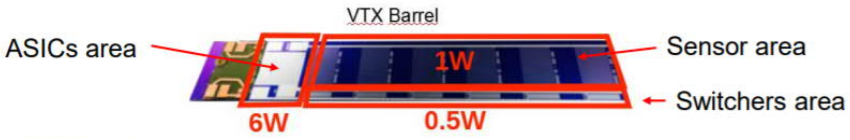
Microchannels: status from AIDA2020

European Union's Horizon 2020 Research and Innovation programme Grant Agreement no.654168

Microchannels integrated in active DEPFET sensor

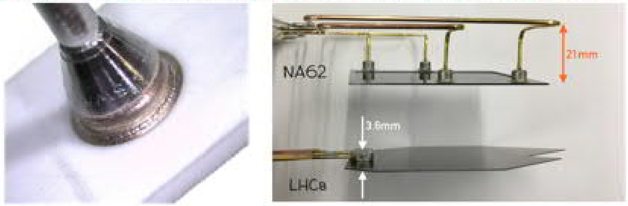


Micro-channel pattern in handle wafer



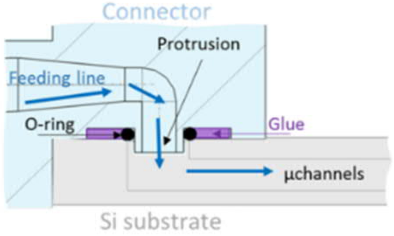
Progress on micro hydraulic connectors

metal connectors soldered (Ti/Ni/Au) on silicon and ceramic



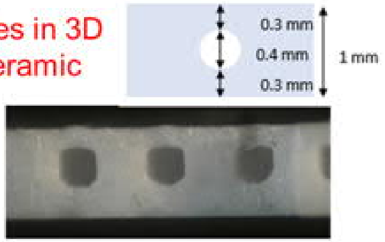
3D printed polymer glued on silicon

3D printed ceramic soldering?

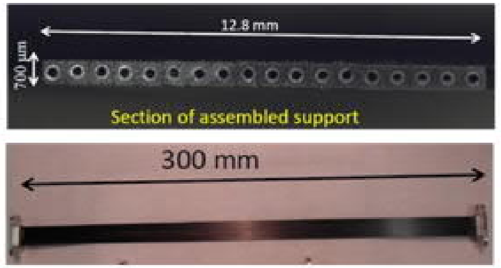


Alternative productions

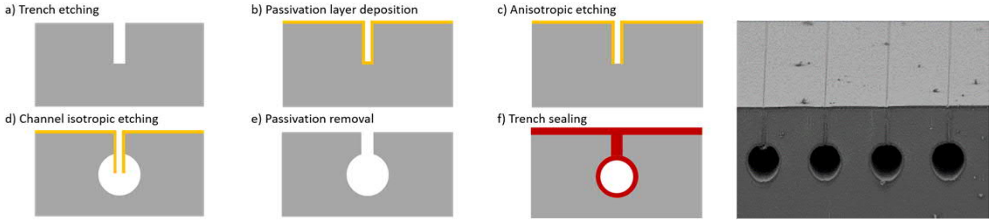
Cold plates in 3D printed ceramic



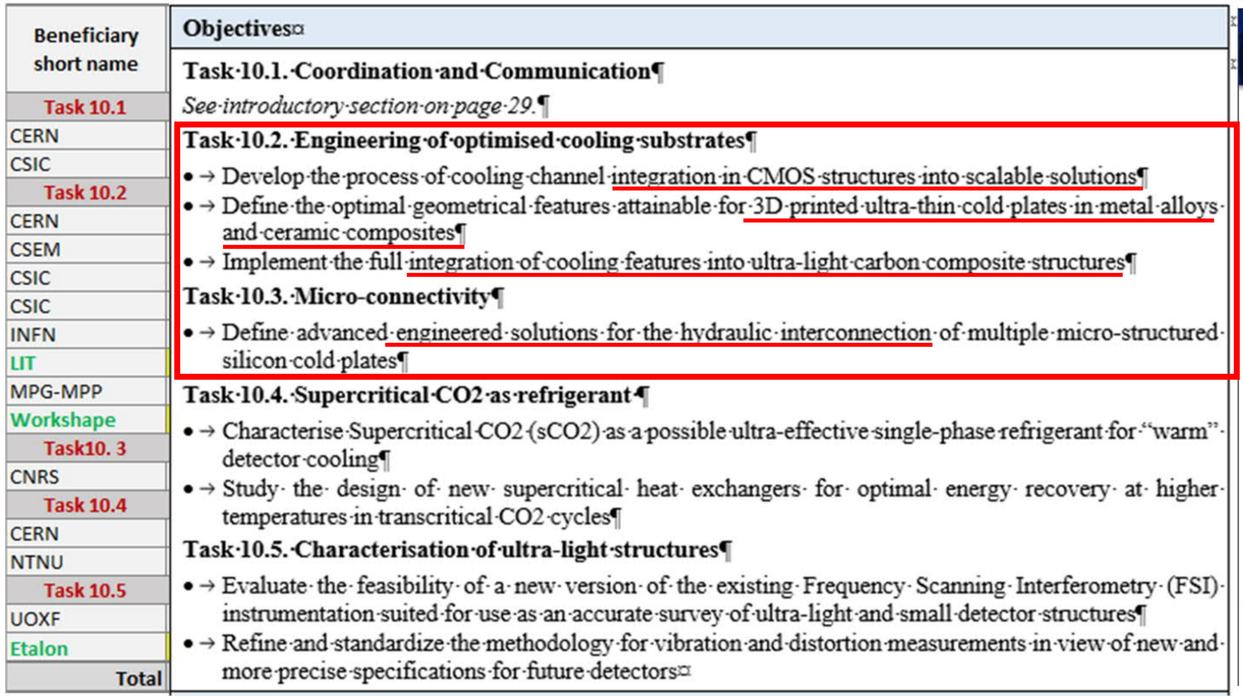
Ultra-thin polymer pipes in carbon/graphite matrices



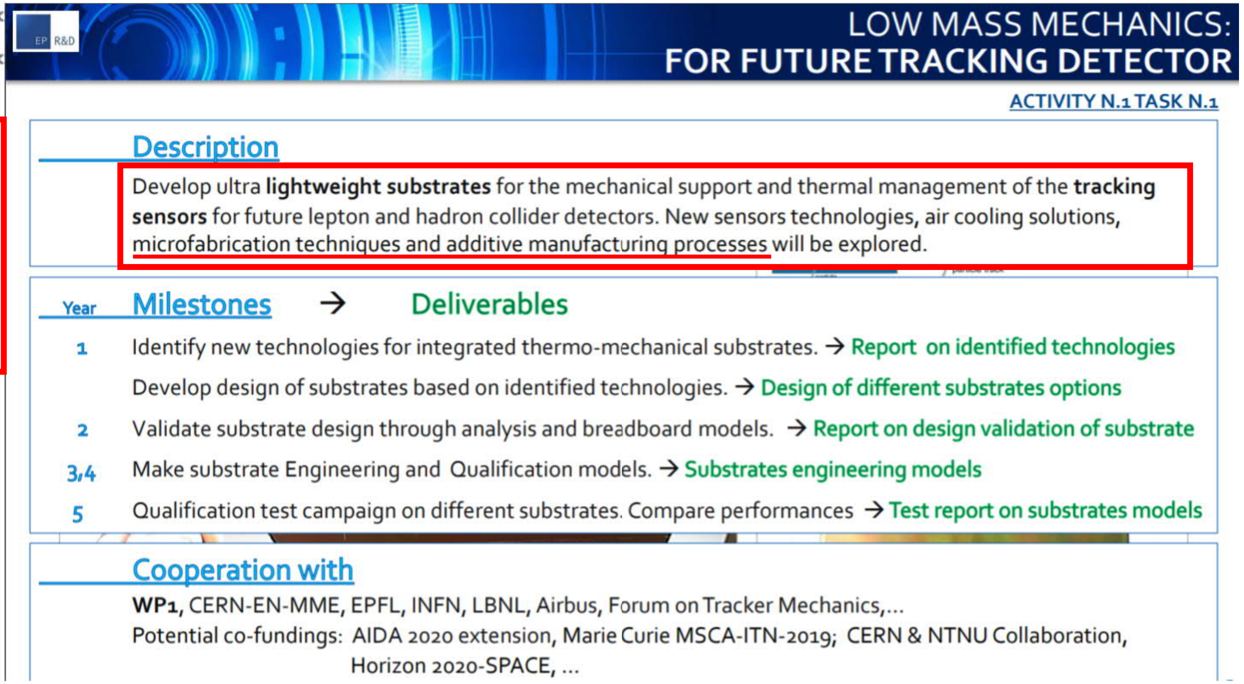
CMOS-compatible process to embed channels in Si



Microchannels: AIDAInnova and EP-RDT



Beneficiary short name	Objectives
Task 10.1 CERN CSIC Task 10.2 CERN CSEM CSIC CSIC INFN LIT MPG-MPP Workshop Task10. 3 CNRS Task 10.4 CERN NTNU Task 10.5 UOXF Etalon Total	**Task 10.1. Coordination and Communication** *See introductory section on page 29.* **Task 10.2. Engineering of optimised cooling substrates** • → Develop the process of cooling channel integration in CMOS structures into scalable solutions • → Define the optimal geometrical features attainable for 3D printed ultra-thin cold plates in metal alloys and ceramic composites • → Implement the full integration of cooling features into ultra-light carbon composite structures **Task 10.3. Micro-connectivity** • → Define advanced engineered solutions for the hydraulic interconnection of multiple micro-structured silicon cold plates **Task 10.4. Supercritical CO2 as refrigerant** • → Characterise Supercritical CO2 (sCO2) as a possible ultra-effective single-phase refrigerant for "warm" detector cooling • → Study the design of new supercritical heat exchangers for optimal energy recovery at higher temperatures in transcritical CO2 cycles **Task 10.5. Characterisation of ultra-light structures** • → Evaluate the feasibility of a new version of the existing Frequency Scanning Interferometry (FSI) instrumentation suited for use as an accurate survey of ultra-light and small detector structures • → Refine and standardize the methodology for vibration and distortion measurements in view of new and more precise specifications for future detectors



LOW MASS MECHANICS:
FOR FUTURE TRACKING DETECTOR

ACTIVITY N.1 TASK N.1

Description

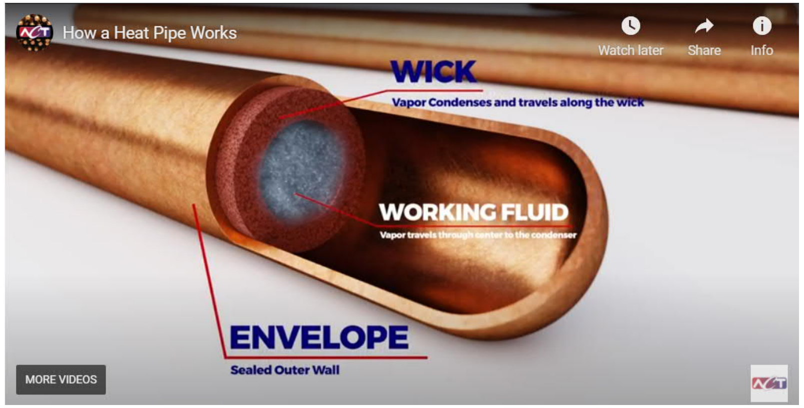
Develop ultra **lightweight substrates** for the mechanical support and thermal management of the **tracking sensors** for future lepton and hadron collider detectors. New sensors technologies, air cooling solutions, microfabrication techniques and additive manufacturing processes will be explored.

Year	Milestones →	Deliverables
1	Identify new technologies for integrated thermo-mechanical substrates. →	Report on identified technologies
	Develop design of substrates based on identified technologies. →	Design of different substrates options
2	Validate substrate design through analysis and breadboard models. →	Report on design validation of substrate
3,4	Make substrate Engineering and Qualification models. →	Substrates engineering models
5	Qualification test campaign on different substrates. Compare performances →	Test report on substrates models

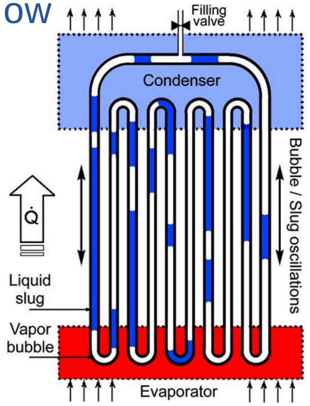
Cooperation with

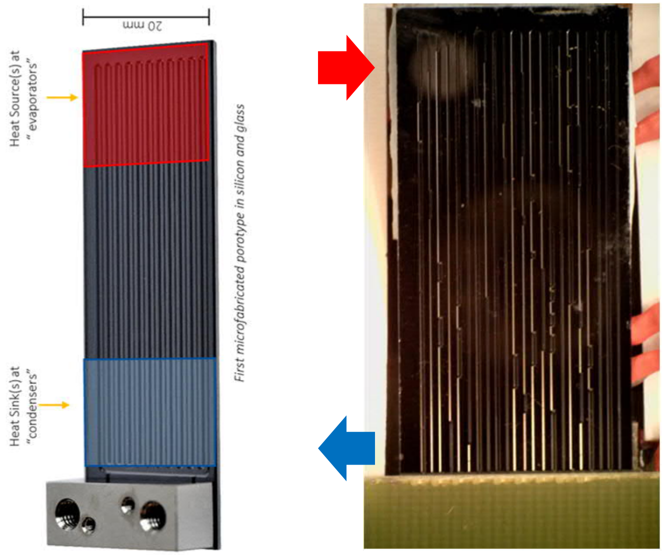
WP1, CERN-EN-MME, EPFL, INFN, LBNL, Airbus, Forum on Tracker Mechanics,...
Potential co-fundings: AIDA 2020 extension, Marie Curie MSCA-ITN-2019; CERN & NTNU Collaboration, Horizon 2020-SPACE, ...

Microchannels: micro-Pulsating Heat Pipes?

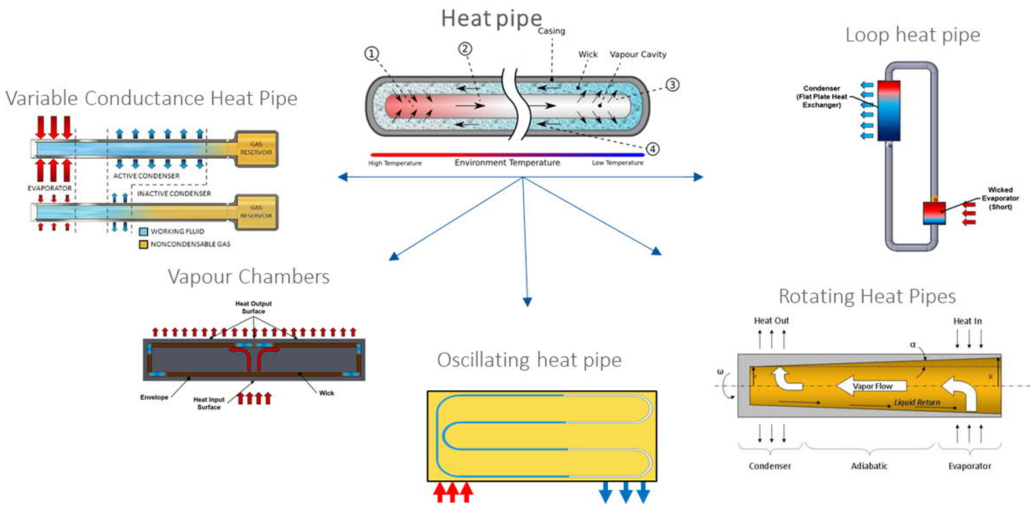


PHP: no need of wick/capillary for the return flow





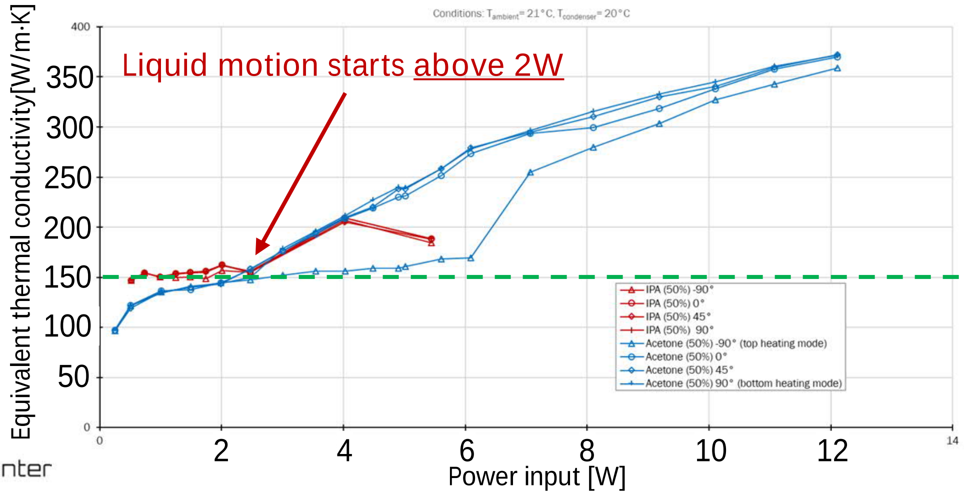
Thermal performance of dual-diameter μOHP (400um - 225um) charged with Acetone



Si Micro-Oscillating (Pulsating) Heat Pipe

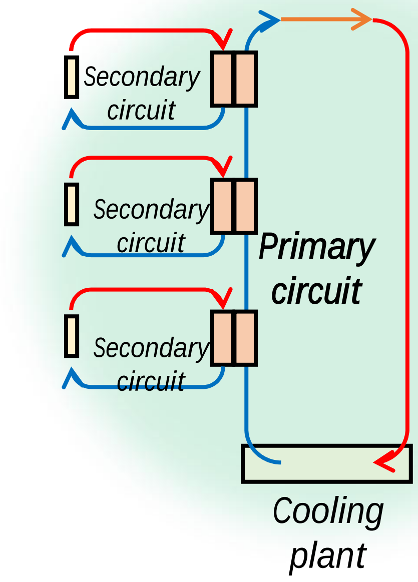
ISSUE: requires power

Reducing power may not always be beneficial…

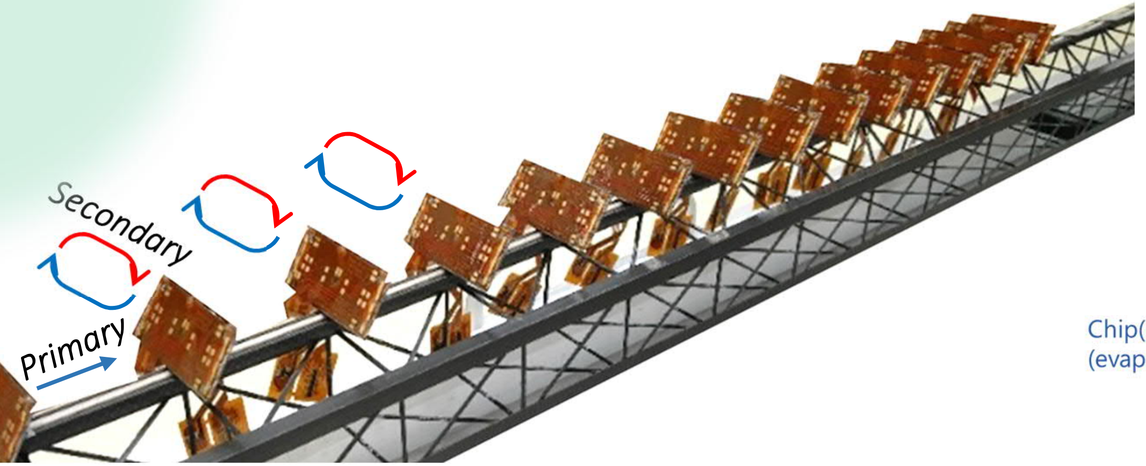


T. Frei, AIDA2020 Annual Meeting, WP9 session 2019

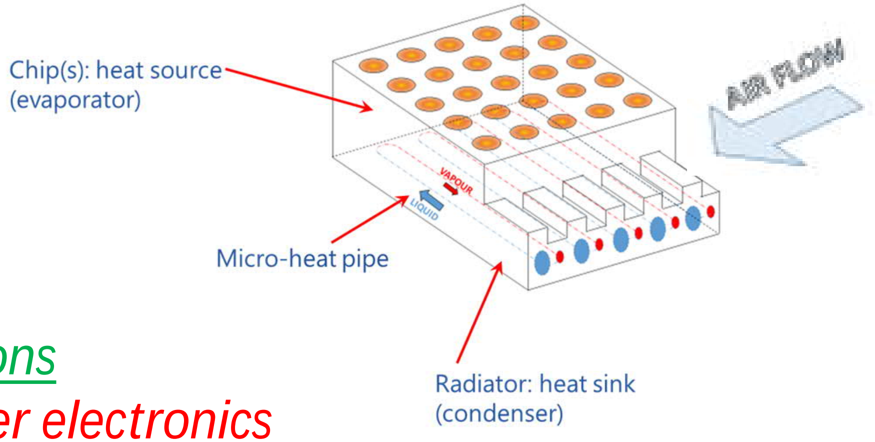
Microchannels: PHP potential



Multiple “Quad size” PHP cold plates (not necessarily in Si: can be 3D printed) thermally connected to a common cooling line connected to the primary heat sink, all pre-integrated in a ultra-light support structure



The primary heat sink might also be an air flow?

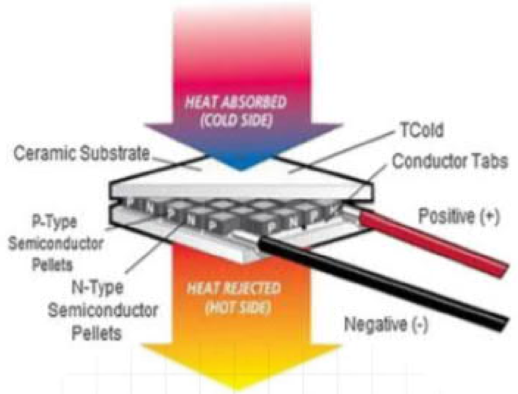


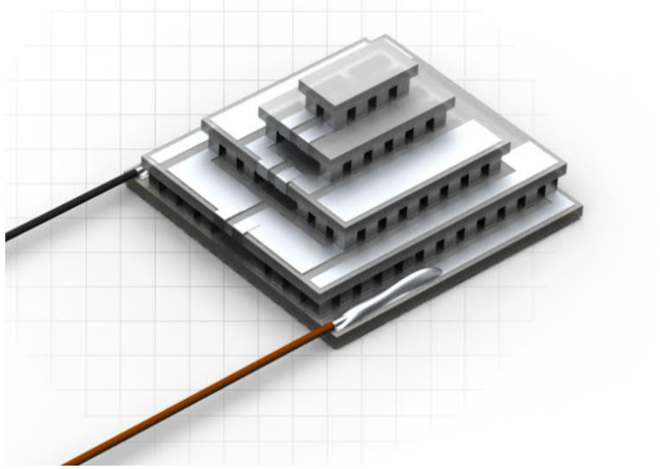
+ *Might eliminate the problem of multiple micro-hydraulic connections*

- *Might require a minimum power input incompatible with low power electronics*

Thermoelectric coolers

Mainly bismuth tellurium compounds since 60 years

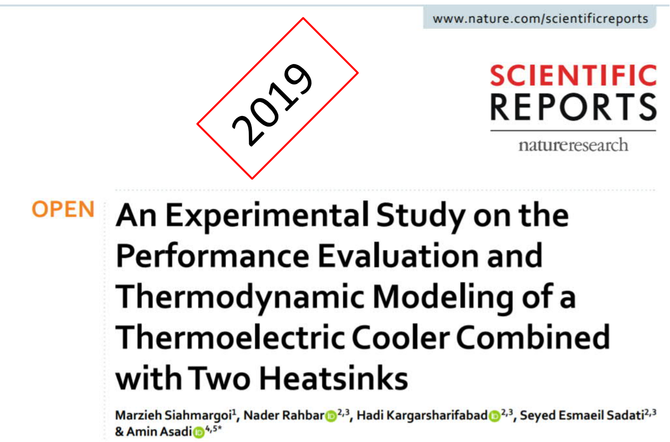




Termoelectric Coolers (TECs)

- + No moving parts
- + Compact size
- + No maintenance
- + High temperature stability
- + Precise temperature control

- \- Poor efficiency (10-15%)
- \- Limited DT (requires pile-up)
- \- High X0
- \- Still require a heat sink


2019

www.nature.com/scientificreports

SCIENTIFIC REPORTS

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An Experimental Study on the Performance Evaluation and Thermodynamic Modeling of a Thermoelectric Cooler Combined with Two Heatsinks

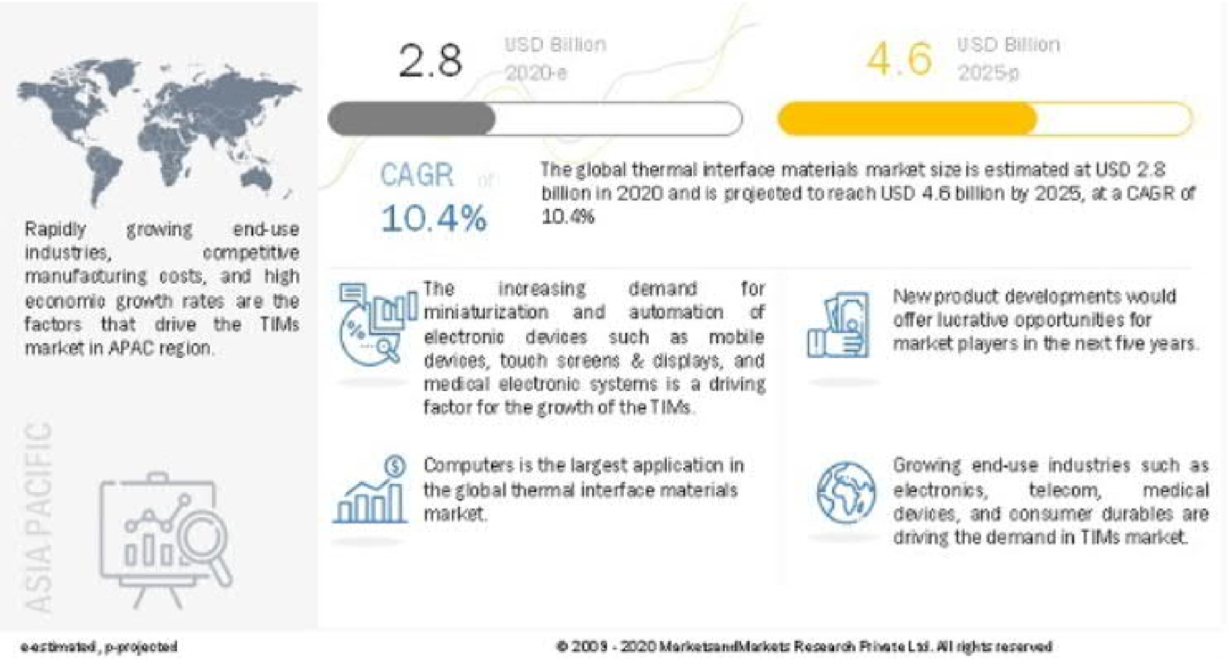
Marzieh Siahmargoi[1], Nader Rahbar[2,3], Hadi Kargarsharifabad[2,3], Seyed Esmaeil Sadati[2,3] & Amin Asadi[4,5*]

R&D Indications

- Optimal voltage for selected T
- Radiation resistance

Thermal Interface Materials

A MARKET IN RAPID EXPANSION



The global thermal interface materials market size is estimated at USD 2.8 billion in 2020 and is projected to reach USD 4.6 billion by 2025, at a CAGR of 10.4%

Rapidly growing end-use industries, competitive manufacturing costs, and high economic growth rates are the factors that drive the TIMs market in APAC region.

The increasing demand for miniaturization and automation of electronic devices such as mobile devices, touch screens & displays, and medical electronic systems is a driving factor for the growth of the TIMs.

New product developments would offer lucrative opportunities for market players in the next five years.

Computers is the largest application in the global thermal interface materials market.

Growing end-use industries such as electronics, telecom, medical devices, and consumer durables are driving the demand in TIMs market.

e-estimated, p-projected

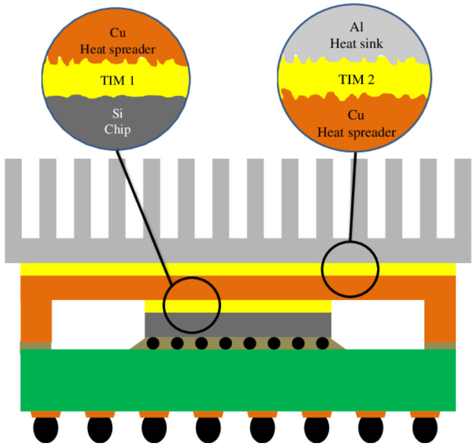
Recent Developments

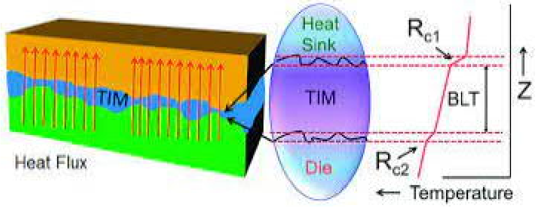
- In September 2020, Parker Hannifin Corporation launched THERM-A-GAP GEL 37, new single component, thermally conductive dispensable materials.
- In July 2020, Dow Corning Corporation launched a new product DOWSIL TC-3065 thermal gel. It is a thermally conductive gel used to dissipate heat from electronic components.
- In June 2020, Dow Corning Corporation launched a new TIMs, DOWSIL TC-4040. This gap filler is easy to dispense, possess high thermal conductivity, and resist slumping.
- In June 2020, Henkel AG & Co. KGaA launched new TIM Bergquist Gap Filler TGF 7000. It is used for various applications, such as automotive ADAS systems, power conversion systems, electric pumps, and others.
- In April 2020, Henkel AG & Co. KGaA launched Loctite EA 9536 magnet bonding tape, which provides high materials expansion for electric motors. This epoxy-based adhesive film can fix the magnet securely in position, fill gaps, and compensate for manufacturing tolerances in the electric motor.
- In August 2020, Henkel AG & Co. KGaA established a new facility at Salisbury, North Carolina, for the production of UV-curable acrylic pressure-sensitive adhesives (PSA).
- In February 2020, Henkel AG & Co. KGaA started a new production facility in Pune, India.
- In May 2019, 3M signed a definitive agreement to acquire Acelity Inc. (US) and its subsidiaries.

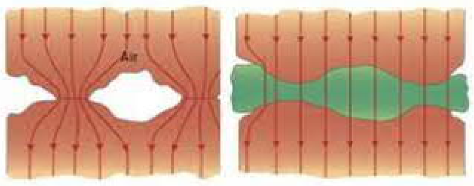
SOURCE: MARKETSANDMARKETS

Thermal Interface Materials

NEED FOR SYSTEMATIC CHARACTERIZAZION: ORPHAN R&D!!!







a) Interstitial air *b) Thermal interface material*

Thermal pads
Thermal greases
Thermal adhesives
Phase Change Materials

Typical subjects:
- Doping: type / quantity
- Optimum temperature range
- Aging
- Radiation resistance
- Applicability / flowability
- Gap filling capacity
- Carbon nanotubes?

Creation of a shared database?

Final considerations

- No single thermal management scheme is by definition better suited than the others for all configurations: careful analysis of the design parameters and of priorities (the "engineer questions") must guide towards the optimal choice

- While the goals and challenges for the next future (say, 2026) are relatively clear and on target, the longer terms perspectives are very quite diverging for detectors conceived for *hh* collisions or for e^+e^- collisions. The others lay somewhat in-between

- Direction #1: need to start from challenging, possibly small-size, concrete cases: solving the problems of the "small ones" now brings to maturity the technology for the "big ones" in the future

- Direction #2: both "ultra-lightweight" and "highly integrated" cooling are key techniques that require focused R&D, appropriately funded and coordinated among the different experiments. It makes no sense to try and solve the same problem several times on isolated little islands. The CERN R&D program and AIDAInnova can help, but wouldn't be wise to think (again) about a dedicated R&D collaboration?