R&D for a colder future in HEP
https://indico.cern.ch/event/775863/contributions/3413707/

19 June 2019

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Abstract

• CO2 cooling has been the ideal cooling technology for detectors since its introduction for the LHCb-VELO cooling in the beginning of the millennium. The target operational temperatures for silicon detectors have been lowered over the years stretching the CO2 cooling technology to its limits. Detector cooling typically having small tubes need a high pressure evaporative fluid to be able to remove the detector heat in an efficient way. CO2 cooling has proven to work efficiently at high pressure close to the critical point and is reducing its favorable properties by going colder. The current targets for CO2 cooling is below -40°C. CO2 cooling performs still well compared to other cooling fluids, but is loosing efficiency fast. CO2 cooling is also hitting a real hard boundary which is the triple point, where the liquid CO2 freezes to dry-ice at -56°C.

• Some future detectors are considering colder cooling temperatures. If efficient cooling with small tubes is required a different fluid is needed with a lower critical point than CO2. R&D on the heat transfer behaviour of other fluids either sub or super critical is needed. Systems with lower critical points also need a different way of operating than the current operation of the CO2 systems. A super critical cool down is needed to cool down the detector in a gentle way. This new system approach and new fluid applications needs R&D to explore the possible cooling technology for the colder future.

Beside investigating the use of fluid (or mixture of fluids) with lower critical point, the other obvious way to cope with requests for lower temperature of the sensors is to work on thermal management design approaches minimizing the temperature difference between the sensor and the cooling fluid. The most effective solutions in this sense come from the integration of micro-structured cold plates in the detector supports, where tremendous progresses have been recently made. However, today the most developed approach relies on the application of MEMS-derived processes to the micro-fabrication of silicon devices, which prove to be extremely effective, but very expensive and difficult to integrate.

Promising developments with high potential come from the extension of additive manufacturing techniques to ceramic materials and from the introduction of innovative processes for silicon microstructuring. These subjects certainly call for active R&D.
The challenges for a future with larger radiation

\[ \text{Conductance (W/m}^2\text{K)} = \frac{1}{\text{TFoM}} \]

- More radiation needs lower cooling
- A higher TFoM needs colder cooling
- More cooling \(dT\) needed than \(dT\) on sensor
- Detector dissipation
- Thermal runaway

**Going colder or increase the heat transfer!**

**Note:** Going colder with the cooling means that the detector will become that cold when the power is switched off!
Optimization of the heat transfer to the cooling fluid

- The next slides present the status of a typical detector like cooling tube:
  - Length: 2m
  - Heat load 200 Watt
- The cooling optimization fluid comparison is explained in detail at:
  - Slides of the 2013 Forum in Oxford (UK)
- In the Encyclopaedia of Two-Phase Heat Transfer and Flow:
Fluid comparison

Overall heat transfer (dP & HTC)
L=2 m, Q=200 W, T=-40 °C, VQ=0-0.35

Overall heat transfer (dP & HTC)
L=2 m, Q=200 W, T=5 °C, VQ=0-0.35

Maximum overall heat transfer (dP & HTC)
L=2 m, Q=200 W, T=40 °C, VQ=0-0.35

Heat transfer is best close to the critical point
Cooling fluids for cold use

Overall heat transfer (dP & HTC)
L=2 m, Q=200 W, VQ=0-0.35

Heat transfer (W/cm³*K)

- Methane
- Krypton
- CF₄
- CO₂
- Xenon
- Ethylene
- N₂O
- Ethane
- R23

Practical limit of CO₂

Methane
Krypton
CF₄
Ethylene
N₂O
CO₂
If we want to go significantly colder than -40°C (CO₂ practical limit):
  - Use N₂O, similar behaviour as CO₂ but a lower freezing point (but has a reduced efficiency at low T)
  - Change to CF₄ or Krypton
  - Use flammable fluids like Ethylene

Maximum overall heat transfer (dP & HTC)
L=2 m, Q=200 W, T=-80 °C, VQ=0-0.35

![Diagram showing heat transfer performance of different fluids](image-url)
For those who see a WARM future (Paolo’s favourite)

CO₂ is Supercritical above 73.8 bars and 31.1 °C

Very high HTC in single-phase (with very low viscosity)

And it looks like Paolo is not the only crazy guy thinking about it
Note: The values in this table are from a quick internet search and should therefore be read globally to get a rough comparative idea….remember this talk is meant to initiate R&D on this topic….rather than a report on R&D.

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• Low temperature fluids with low critical point need a special system principle
• Especially start-up is challenging
  o Avoid thermal shocks
  o Trans critical cool down?
Not only the TFM of a microchannel cold plate is much lower than TFM of any other technology, but it stays basically constant with $T_{\text{sat}}$ (i.e. in this case HTC is much less dependent on $T_{\text{sat}}$).
µ-channels: TFM insensitive to $T_{\text{sat}}$?

"Macro" zoom at position 1
Images: 90 000 fps
Flow rate = 0.3 g/s
Chip power = 3 W/cm²
$T = +5\, ^\circ C$

Traces of boiling onset already in the capillary: saturation attained

Stable nucleate boiling with high interactions at walls immediately triggered

Backward facing step induces flash boiling and prevent backflow

Nice feature made possible by the use of a high pressure refrigerant and (for the time being...) silicon as material
μ-channels: TFM insensitive to $T_{\text{sat}}$?

"Macro" zoom at position 2
Images: 61 200 fps
Flow rate = 0.3 g/s
Chip power = 3 W/cm$^2$
$T = +15 \, ^\circ\text{C}$

Some flow pulsation visible
Good for HTC enhancement
Induces vibrational forces appear negligible... but maybe we can get some measurements made at Georg’s!? 

Bends enhance the mixing and extract energy from the flow locking and increasing boiling.
μ-channels: TFM insensitive to $T_{sat}$?

Inlet/outlet comparison
Images: 67 500 fps
Flow rate = 0.3 g/s
Chip power = 3 W/cm$^2$

TOP: $T = + 15 \, ^\circ\text{C}$
BOT: $T = -25 \, ^\circ\text{C}$

Due to the high confinement (?) and to the design, the boiling pattern is very much dependent on $T$ at start, but MUCH LESS once developed.
Silicon μ-channels: pros & cons

- Same CTE than sensors and chips
- Well managed MEMS processes allow for μ-level features
- Highly thermally conductive material
- Naturally very planar cold plate
- Maximum size limited by wafer size and sensible surface use
- Hydraulic connections and interconnections still problematic
- Cold plate geometry limited to (almost) flat configurations
- Pretty expensive production costs
- For high pressure refrigerant Si-Si bonding must be almost perfect on the whole wafer surface

AIDA 2020
Lots of progresses in many aspects
See previous talk by Marcel
Do $\mu$-channels NEED to be in Si?

Let’s not miss the AM train!

polymer fluidic channels 3D printed on the back of a working CMOS chip

Lots of polymers (including epoxies and PI) + dopant
Several ceramics (with ~25% polymer)

3D printed polymer micro-valves (can be actuated)

Today printable: Ti, SS, Al, several custom alloys…
3D-printed dreaming

Conductive heat spreader + PIX

Ceramic 3D printed "complex" tubes
CO₂ inside
Simplified System P&ID

A 2-Stage CO$_2$ transcritical refrigeration cycle
Primary CO$_2$ cooling cycle: A transcritical cycle

Transcritical R744 cycle of 1 slice
- $p_c = 76.4$ bar, $T_{evap} = -49 ^\circ$C, $Q_{evap} = 49$ kW, COP = 0.94