Lecture 4 of 4
(13:1)

(5.7) Examples from cooling silicon tracking detectors in particle physics (ATLAS, CMS, LHCb)

We've seen some examples from the present running of ATLAS:

- **Saturated Fluorocarbons of the form $C_nF_{(2n+2)}$**
  like C_3F_8 (current use in most of the ATLAS Silicon tracker)
  and C_6F_{14} (current use as liquid coolant in parts of the CMS Silicon tracker)
  which have respective GWP_{20} of around 5890 & 6640 x CO_2.

- **New upgraded trackers are however being built**
  for the High Luminosity phase of LHC to run from 2029-2041

- **A core aim in these detectors is to use low Global Warming Potential coolants**

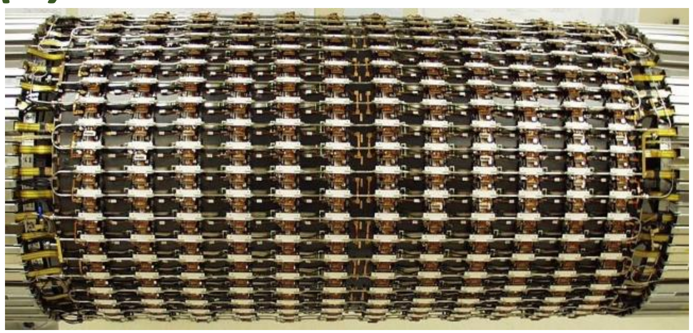
- **Any coolant must be non-flammable, non-toxic, non-oxone depleting,**
  (electrically) non-conductive, radiation resistant and have low or zero GWP

- **CO_2 cooling is being pushed hard at CERN but has problems of high operating pressure and a limiting evaporating temperature of -56 °C (triple point temperature where 3 phases of CO_2 co-exist (liquid, vapor, solid CO_2 'snow')**

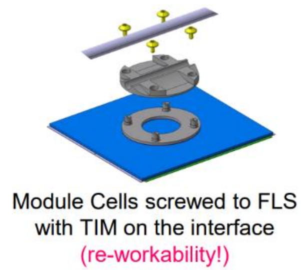
(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

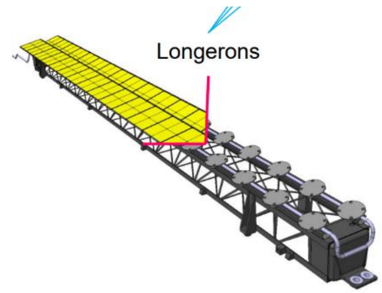
Two distinct types of detector cooling geometry at HL-LHC:

(1) Tube and block 'DNA'



ATLAS barrel SCT (present)



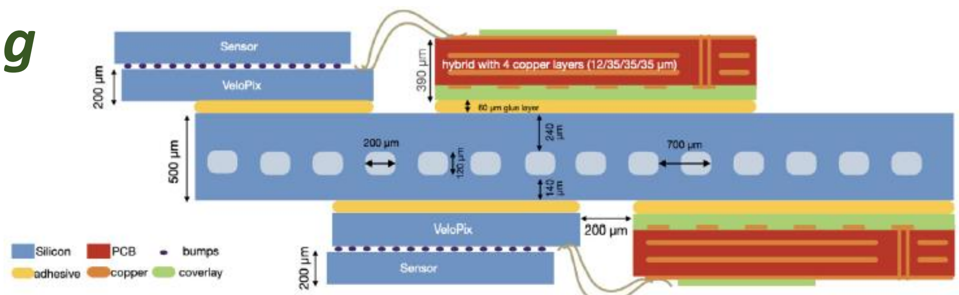


ATLAS ITK Barrel longerons and Si module block attachment (future HL-LHC)

Disadvantages: long(er) heat conduction path (more interfaces) Si → cold(er) coolant

(2) Micro-channel cooling

LHCb VELO upgrade



Advantages: shortest heat conduction path to coolant: coolant can be warmer:

Disadvantages: fraglity issues: channels etched in silicon and cover plate attached

(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

Micro-channel cooling: more on the LHCb VELO upgrade

Nuclear Inst. and Methods in Physics Research, A 1039 (2022) 166874

Contents lists available at ScienceDirect

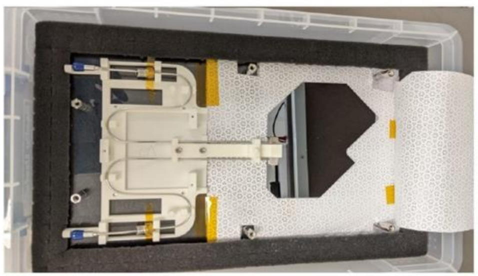
Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Microchannel cooling for the LHCb VELO Upgrade I

Oscar Augusto de Aguiar Francisco [a,b,*], Wiktor Byczynski [a,b,**], Kazu Akiba [c], Claudia Bertella [a,b], Alexander Bitadze [b], Matthew Brock [d], Bartosz Bulat [a], Guillaume Button [a], Jan Buytaert [a], Stefano De Capua [b], Riccardo Callegari [a], Christine Castellana [i], Andrea Catinaccio [a], Catherine Charrier [i], Colette Charvet [a], Victor Coco [a], Paula Collins [a], Jordan Degrange [a],

O.A. de Aguiar Francisco, W. Byczynski, K. Akiba et al.



O.A. de Aguiar Francisco, W. Byczynski, K. Akiba et al.

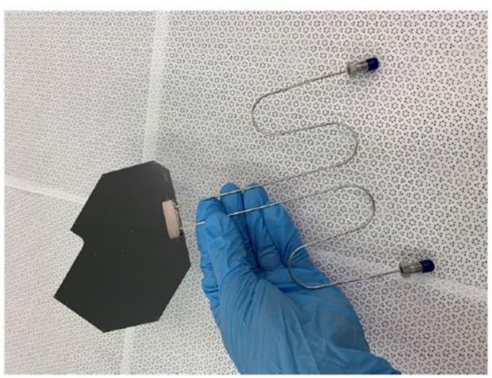
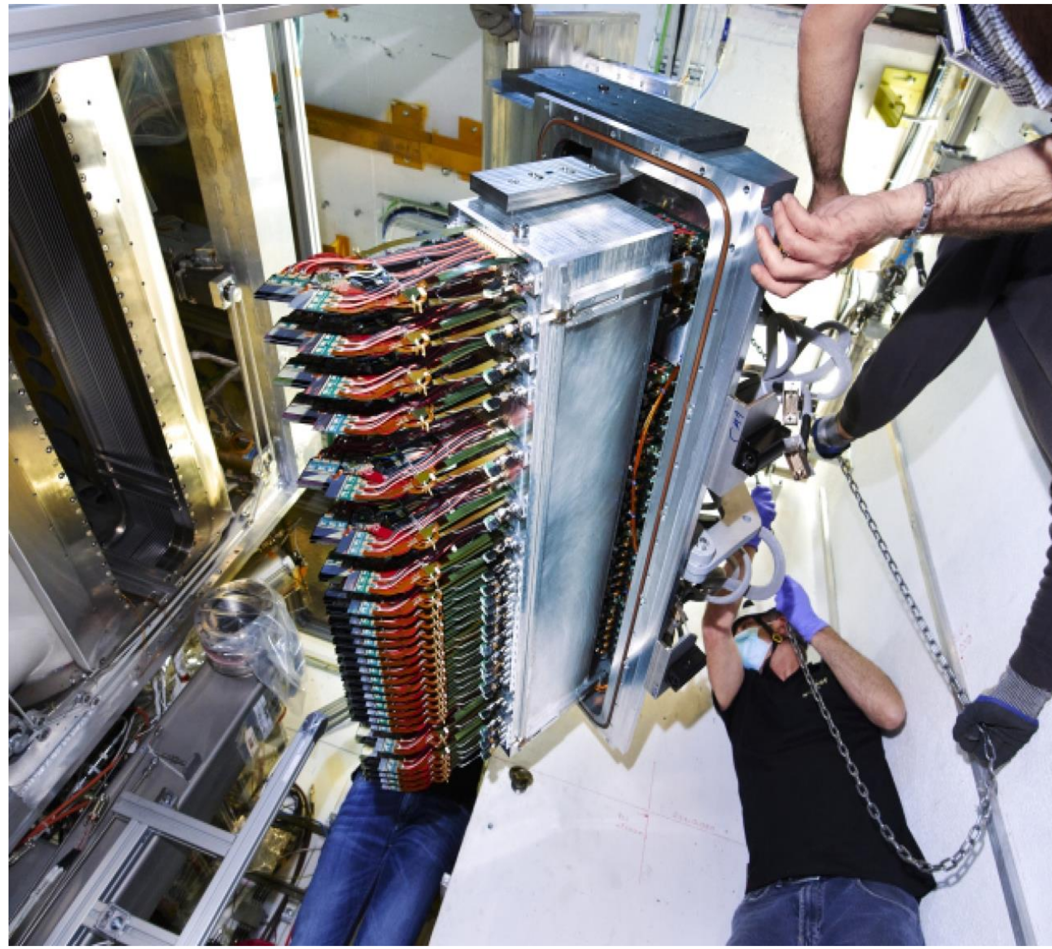


Fig. 20. Microchannel assembly, consisting of a microchannel cooler soldered to a fluidic connector, ready to be equipped with VELO module components.



https://www.youtube.com/watch?v=RmIQwLdfFZg

(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

Micro-channel cooling: more on the LHCb VELO upgrade

Recent mastery of evaporative CO_2 cooling in microchannels

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New insights on boiling carbon dioxide flow in mini- and micro-channels for optimal silicon detector cooling

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Micro-channel
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ABSTRACT

Whilst the thermal management needs of future silicon detectors are increasing, the required mass and volume minimization of all detector ancillaries gets more demanding. This requires highly effective active cooling in very small channels. In the context of the AIDA-2020 project, a new test stand has been developed to characterize, with unprecedented level of accuracy, boiling flows of CO_2 in mini- and micro-channels with hydraulic diameter ranging from 2 down to 0.1 mm. The heat transfer coefficient and pressure drop behaviour in stainless steel tubular evaporators for saturation temperatures from +20 to −25 ° C, mass fluxes from 1200 to 100 kg m^{-2} s^{-1} and heat fluxes from 0.5 to 3.5 W/cm^2 are discussed for one diameter. In addition, high speed camera observations of CO_2 flow patterns recorded on micro-structured silicon cold plates are used to help with the interpretation of the heat transfer coefficient and pressure drop trends reported.

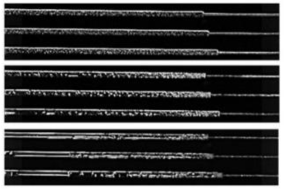
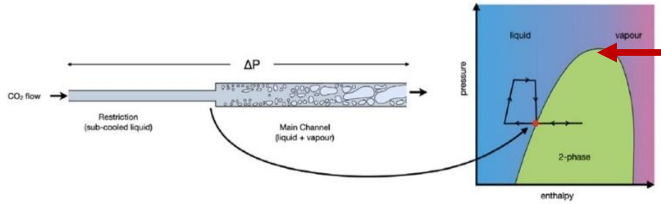


Fig. 7. Boiling CO_2 in micro-channels: upper to lower: 15 °C, 5 °C, −25 °C.

Fig. 8. Boiling CO_2 in micro-channels: left to right: 15 °C, 5 °C, −25 °C.

Fig. 9. Boiling CO_2 in micro-channels at 5 °C: boiling enhancement at inlet restrictions.

Fig. 10. Boiling CO_2 in micro-channels at 10 °C: film behaviour in the channels: homogeneous and smooth (left), inhomogeneous and wavy (right).



High CO_2 evaporation pressure

(~70 bar at room temp.)

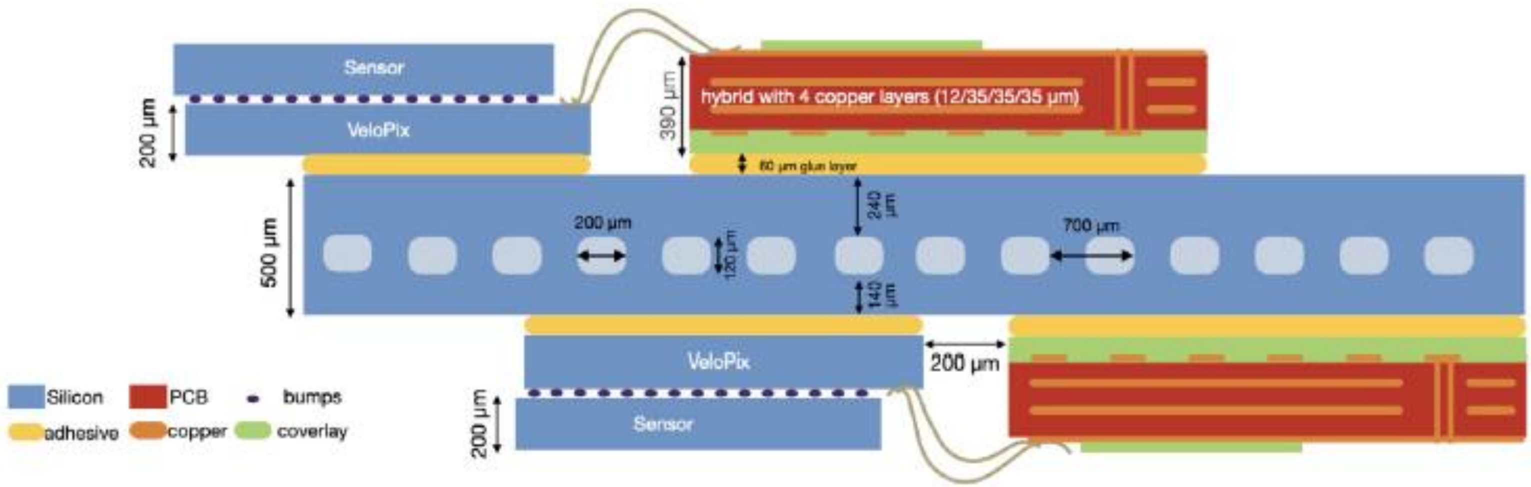
Fig. 2. The left side of the figures shows the typical channel shape for the bi-phase CO_2 microchannel cooling implementation. The pressure drop at the point where the channel expands should bring the coolant to the saturation point as it enters the region of the detector to be cooled. The diagram on the right illustrates the principle of the Two-Phase Accumulator Controlled Loop (2PACL) cooling concept used in LHCb [6].

https://www.youtube.com/watch?v=hsLXi9QTxUo

A film narrated by LHCb physicist Paula Collins

(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

Despite these evident successes, the coolant is not directly passing through the detector chips, just through a heat collector plates onto which they are bonded which contain 200 x 120 micron etched microchannels .



So the silicon pixel detectors and their readout electronics are *almost directly* cooled by fluid evaporating in microchannels.

We can therefore ask:

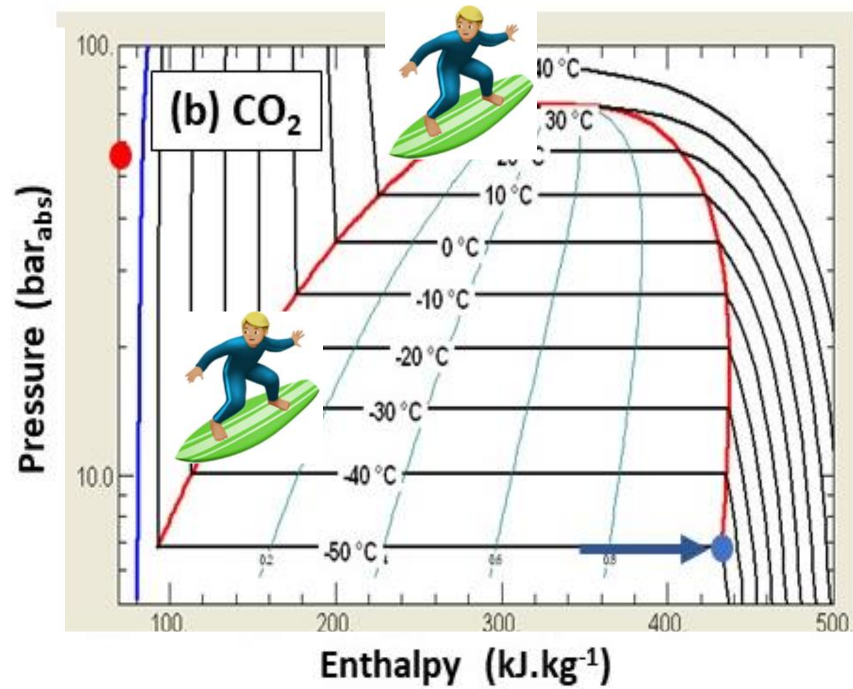
- **will processor chips ever have microchannels etched into them for direct coolant flow?**
- **will this coolant be liquid, or evaporative for reduced mass flow?**
- **how would the cooling pipes be connected?**
- **what would the (necessarily electrically non-conductive) fluid be: a fluorocarbon, CO_2 or a new low GWP fluid, for example from the 3M "NOVEC" range?**

(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

The CO_2 problems:

(1) High evaporation pressure at room temperature (60-70 bar)
the detector has to 'surf ' down the saturated liquid line to the operating evaporation temperature of -30 → -40 °C (pressure around 12 - 18 bars):
fatigue cycling an issue in microchannels..?

(2) The high triple point temperature of -56 °C
limits the lowest temperature attainable in the tubes of a tube & block cooling system:
may not be cold enough for operation of Si detectors after years of irradiation in the LHC High Luminosity program (2029-41)



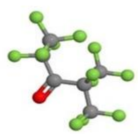
Low GWP Alternatives to CO_2:

(1) Noble gases like Xenon and Krypton

- *Very expensive and in very short supply, particularly since the war in Ukraine.*
- *Complex transcritical circulation for Krypton (outside the scope of this unit);*
- *Xenon probably just squeaks in (~50 bar @ 15 C) but still has relatively high pressure evaporation at room temp, but no triple point problem (-112 ˚C)*

(2) Fluoroketone ($C_nF_{2n}O$) replacements for saturated fluorocarbons ($C_nF_{(2n+2)}$)

- *The substitution of two fluorine atoms with an oxygen atom can reduce the GWP to zero: if the oxygen atom is on the end or on a side-arm of the molecule (see next slides);*



NOVEC 649 $C_6F_{12}O$
(GWP_{20} = ≤ 1)
$CF_3CF_2C(O)CF(CF_3)_2$

C_6F_{14}
(GWP_{20} = 5890)

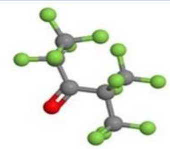
- *Ultraviolet scission of the fluoroketone molecules in the upper atmosphere does not create long-lived debris molecules (references given in unit support notes);*
- *($C_nF_{2n}O$) molecules with the same number of carbons as their ($C_nF_{(2n+2)}$) partners will have similar thermodynamics (molecular weight difference = 22 units);*
- *3M NOVEC 649 ($C_6F_{12}O$) authorised for use as a C_6F_{14} replacement at CERN (liquid cooling)*

(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

A Fluoroketone ($C_nF_{2n}O$) replacement for a saturated flurorcarbon ($C_nF_{(2n+2)}$)

Thermophysical Properties of NOVEC 649 ($C_6F_{12}O$) & C_6F_{14} (at 25°C except where noted: after [7.15])

Fluid thermophysical property	NOVEC 649: $C_2F_5C(O)CF(CF_3)_2$ Perfluoro-2-methyl-3-pentanone ($C_6F_{12}O$ fluoro-ketone)	C_6F_{14} (Perfluorohexane, Saturated fluorocarbon)
Boiling temp @ 1 atm (˚C)	49	56
Critical Temp (˚C)	169	178
Critical Pressure (MPa)	1.87	1.89
Freezing temperatre (˚C)	< -100	< -100
Specific heat ($J.kg^{-1}K^{-1}$)	1103	1050
Density ($kg.m^{-3}$)	1610	1680
Kinematic viscosity (cSt)	0.42	0.4
Latent Heat ($J.kg^{-1}$)	88	88
Vapour Pressure @ 25 ˚C (kPa)	40.4	30.9
Vapour Pressure @ 100 ˚C (kPa)	441	350
Water solubility (ppm_w)	21	10

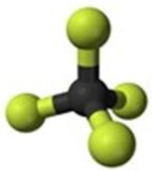


NOVEC 649 $C_6F_{12}O$ (GWP_{20} = ≤ 1) $CF_3CF_2C(O)CF(CF_3)_2$

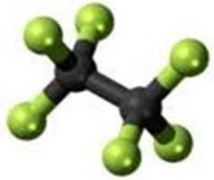
C_6F_{14} (GWP_{20} = 5890)

(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

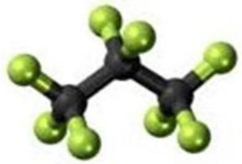
Saturated fluorocarbons ($C_nF_{(2n+2)}$) and their Spurred fluoroketone ($C_nF_{2n}O$) analogs (with 20 year Global Warming Potentials, where measured)



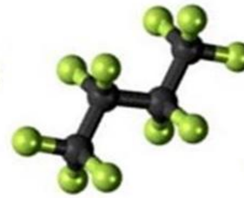
CF_4 (GWP_{20} = 4880)



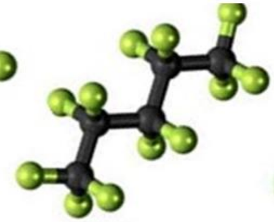
C_2F_6 (GWP_{20} = 8210)



C_3F_8 (GWP_{20} = 6640)

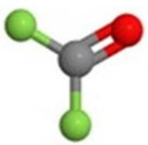


C_4F_{10} (GWP_{20} = 6870)

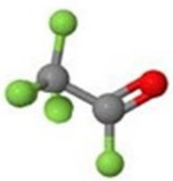


C_5F_{12} (GWP_{20} = 6350)

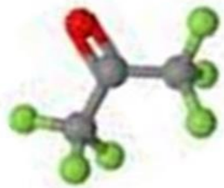
C_6F_{14} (GWP_{20} = 5890)



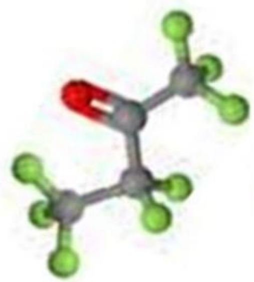
CF_2O (GWP_{20} = ?)



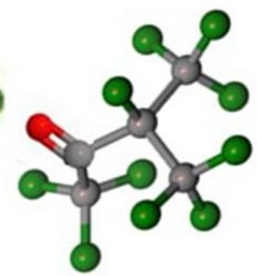
C_2F_4O (GWP_{20} = ?) $CF_3C(O)F$



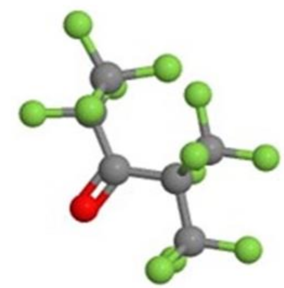
C_3F_6O (GWP_{20} = ?) $CF_3C(O)CF_3$



C_4F_8O (GWP_{20} = ?) $CF_3CF_2C\ (O)CF_3$



NOVEC 5110 $C_5F_{10}O$ (GWP_{20} = ≤ 1) $CF_3C(O)CF(CF_3)_2$



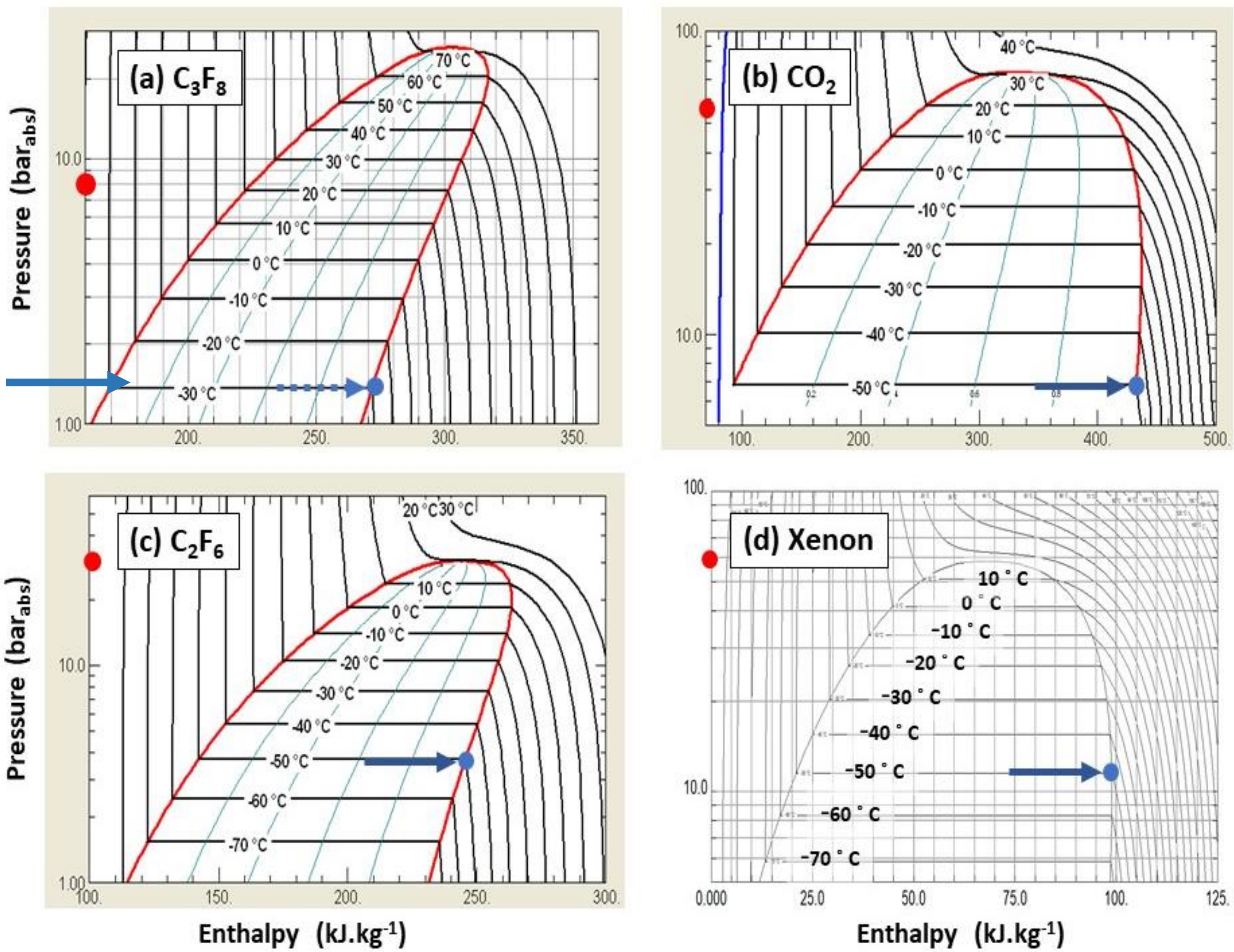
NOVEC 649 $C_6F_{12}O$ (GWP_{20} = ≤ 1) $CF_3CF_2C(O)CF(CF_3)_2$

(5.7) Examples from cooling particle physics Si trackers (ATLAS, CMS, LHCb)

Some Thermodynamic comparisons two convenient SFCs, CO_2, Xe

(F-K thermodynamics should be similar to same carbon order SFCs)

C_3F_8 probably won't go cold enough for HL-LHC operation



(5.7) SWOT analysis of cooling fluids HL-LHC

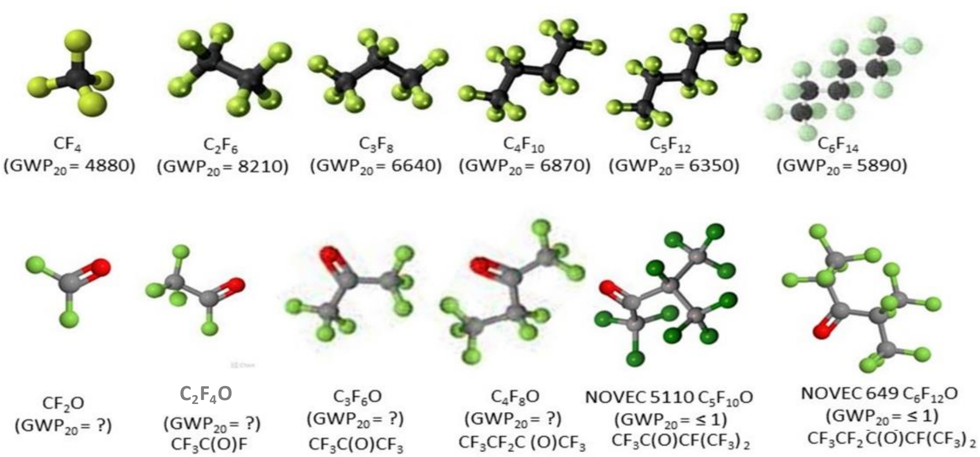
Strengths CO_2	Weaknesses CO_2
Non-flammable, non-toxic, electrical insulator, non-ozone-depleting, radiation resistant, GWP=1	High pressure circulation (60 bar) at ambient temp before cooldown to operating temp High triple point (-56°C)
Threats CO_2	**Opportunities CO_2**
High triple point may make Si tracker operation problematic: less thermal 'headroom' after heavy irradiaton ('thermal runaway' phenomenon)	Extensive R&D program at CERN Evaporative coolant of choice for ATLAS, CMS for start of HL-LHC program

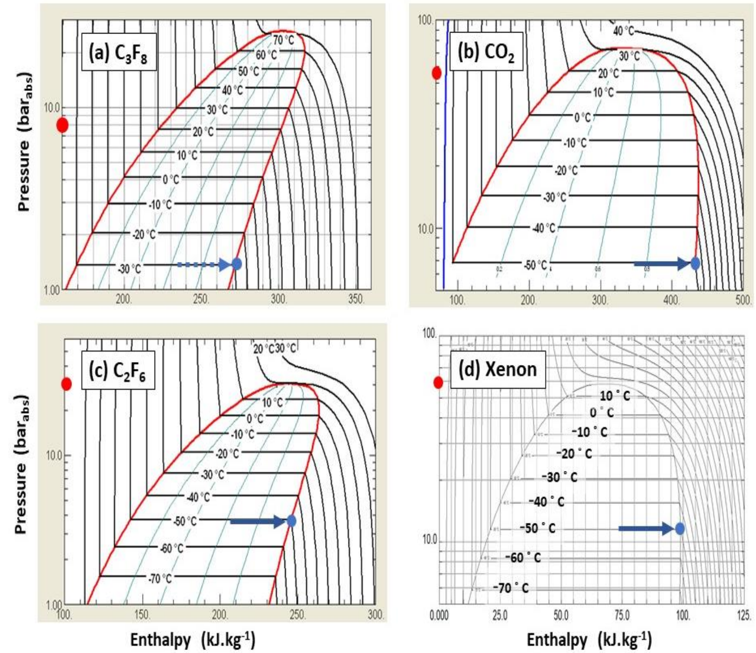
Strengths C_2F_6	Weaknesses C_2F_6
Non-flammable, non-toxic, electrical insulator, non-ozone-depleting, radiation resistant	Very high GWP (around 6000 x CO_2)
Threats C_2F_6	**Opportunities C_2F_6**
Production will be phased out unless a strong motivation from semiconductor manufacture industry	Proved to decrease the operating temp of an ATLAS SCT thermal model in blend with 75% C_3F_8

Strengths xenon	Weaknesses xenon
Non-flammable, non-toxic, electrical insulator, non-ozone-depleting, radiation resistant, GWP=0	High pressure circulation (50 bar) at ambient temp before cooldown to operating temp (amost transcritical) Extremely expensive
Threats xenon	**Opportunities xenon**
Very difficult future procurement (war in Ukraine) (10^{-8} atmospheric content.)	Could find expertise In particle physics community for fabrication of circulators: already used in dark matter experiments

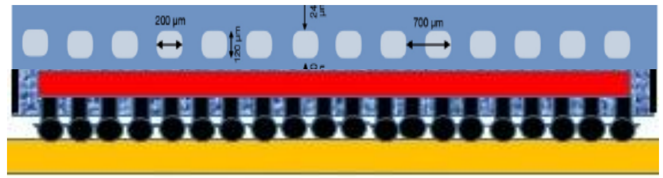
Strengths $C_nF_{2n}O$	Weaknesses $C_nF_{2n}O$
Non-flammable, non-toxic, electrical insulator, non-ozone-depleting, radiation resistant, GWP=0	
Threats $C_nF_{2n}O$	**Opportunities $C_nF_{2n}O$**
Large scale industrial production may depend on the phasing-out of SFCs, needs of semiconductor manufacture industry: Material compatibility needs further study.	Expertise in particle physics community for 3M NOVEC 649 ($C_6F_{12}O$)

- ***Last problem (6): See separate sheet – one for the sleuth***:
- while a new fluid C_3F_6O would have all the advantages of C_3F_8, but with zero GWP, the thermodynamics of C_3F_8 and presumably of C_3F_6O (which differs in molecular weight by 22 units) is not perfect for cooling a processor chip at room temperature. What fluid in the $C_nF_{2n}O$ spectrum might be better, and why?
- **Hint:** the figures below may help in this.



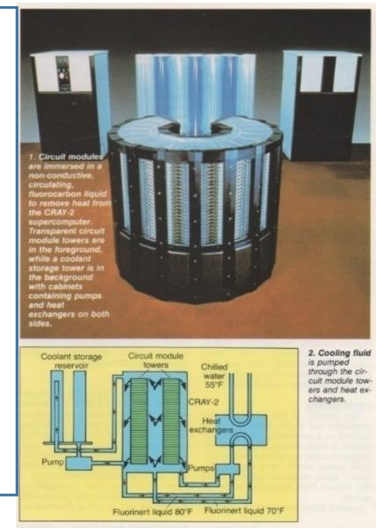


So where does this leave the option of immersion cooling of processors, or the cooling of processor chips themselves thru microchannels?

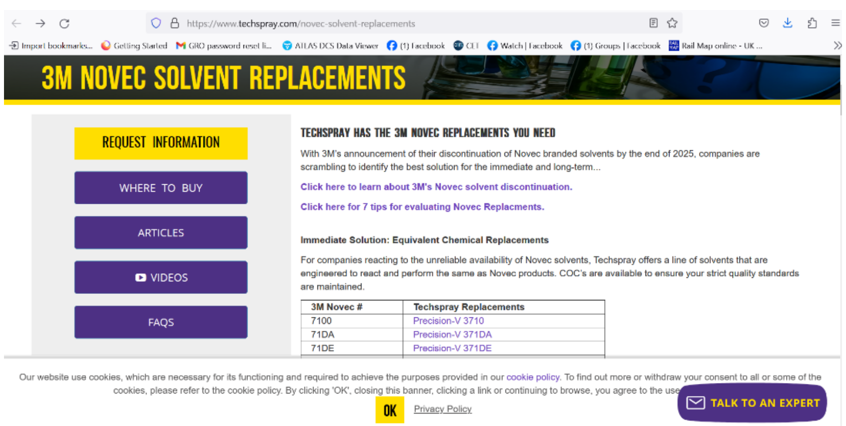


Electrical connections
to computer mother board

Will processor chips ever look like this?
Can semiconductor lithography, implantation, microchannel etch, sealing and connectivity be achievable in one final device?



3M seem to have lost enthusiasm to produce any more fluorinated fluids after 2025, but companies like F2 Chemicals (Preston, UK), Astor (Ru), Synquest (FL), Techspray (GA) continue (probably many others: e.g.China)



Note *Some 3M `NOVEC' fluids are HFCs with GWPs in the ranges of hundreds:
****Better to concentrate on $C_nF_{2n}O$ molecules over the full carbon spectrum with GWP = 0.**
But the needs of the semiconductor & electronics industries will be determinant...