Cold cooling R&D developments

30 June 2021

Bart Verlaat, CERN

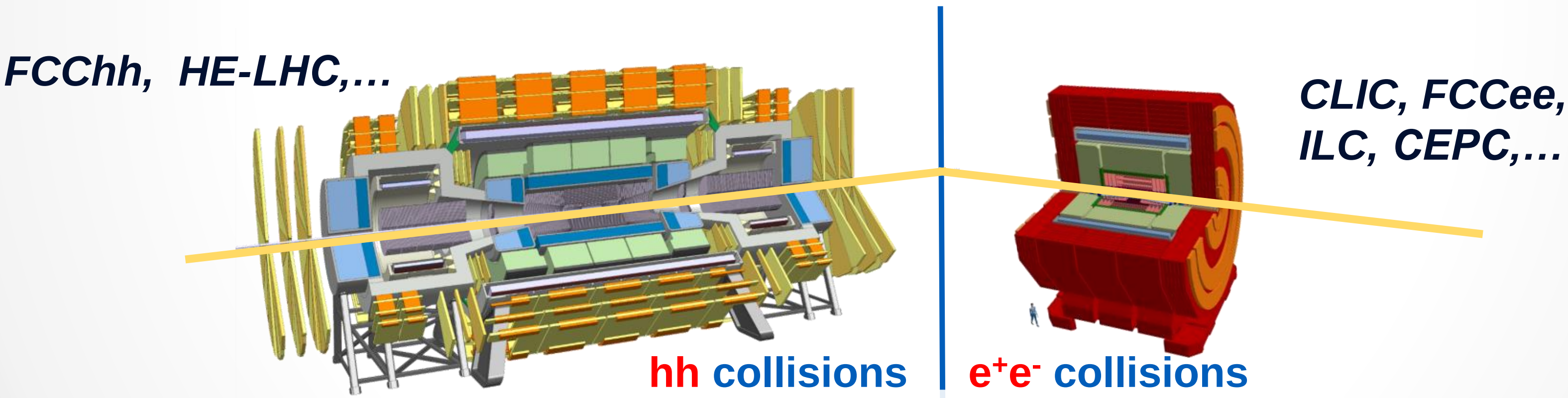
The cold future of CERN

- Triggered by LHCb-VELO3 EP-DT has looked into the options for colder cooling than the current CO2 technology can provide.
- Parametric studies have been done to explore the cold landscape to see which technologies and fluids would be candidates.
- The cold cooling R&D is adopted in future R&D programs as there is mutual interest of other future detectors
  - Part of ECFA –R&D roadmap
    - https://indico.cern.ch/e/ECFADetectorRDRoadmap
    - https://indico.cern.ch/event/957057/program
    - https://indico.cern.ch/event/999825/
  - Part of EP-DT R&D roadmap
    - https://indico.cern.ch/event/743661/
- A PhD project has started in collaboration with NTNU-Trondheim on cold cooling research

What are the cooling need trends for future?

Slides from ECFA talk

- Cooling demand input was given in the 2 input sessions
  - https://indico.cern.ch/event/994685/
  - https://indico.cern.ch/event/994687/
- Global tendency for future cooling needs:
  - **Lepton-Lepton, Lepton-Hadron and Ion colliders** all seems to have in common a warm temperature domain and relatively low heat load densities.
  - **Hadron-Hadron colliders**, have the tendency for a colder cooling at increased power densities.
  - Other presented experiments did not show extreme cooling demands requiring special long term R&D, exceptions to this statement are:
    - Silicon Photomultiplier detectors are considered as technology in many detectors and require very cold temperatures
    - The AMBER detector is considering a cryogenic tracker with temperatures below 1.8K



- *High radiation dose (~ 100 MGy/10years)*
- *Very high integrated dissipated power*
- *Low temperature*

- *Unprecedented spatial resolution (1-5 µm point resolution)*
- *Low dissipated power (<50mW/cm²)*
- *Room temperature*
- *Low material budget*

Cooling & Refrigeration versus Cryogenics

Slides from ECFA talk

- There are many differences in the definition and application of cooling versus cryogenics. For the future we are approaching the intermediate space requiring long term R&D.
- Cryogenics is often declared as temperatures below 120K / -153°C being referenced to liquid Krypton at atmospheric pressures
- The “Standard” Cooling / Refrigeration domain is above -60°C. Limited choice of industrial applications are present for colder temperatures, without using cryogenic technologies.
- Another very important difference between refrigeration and cryogenics:
    - Refrigeration has the goal is to remove large heat numbers at medium low temperatures using pressurized gasses in piping systems
    - Cryogenics has the goal to make very cold temperatures at reduced heat numbers often around atmospheric pressure systems in pool boiling cryostats.
- The widely used CO_2 cooling for detectors has an application range of 20°C / -40°C
- For future detector cooling we need to explore the unknown intermediate space (-150°C /-40°C) approaching cryogenic temperatures with relative large heat loads to cool.
    - We need to mix our Cooling and Cryogenic knowledge and experiences

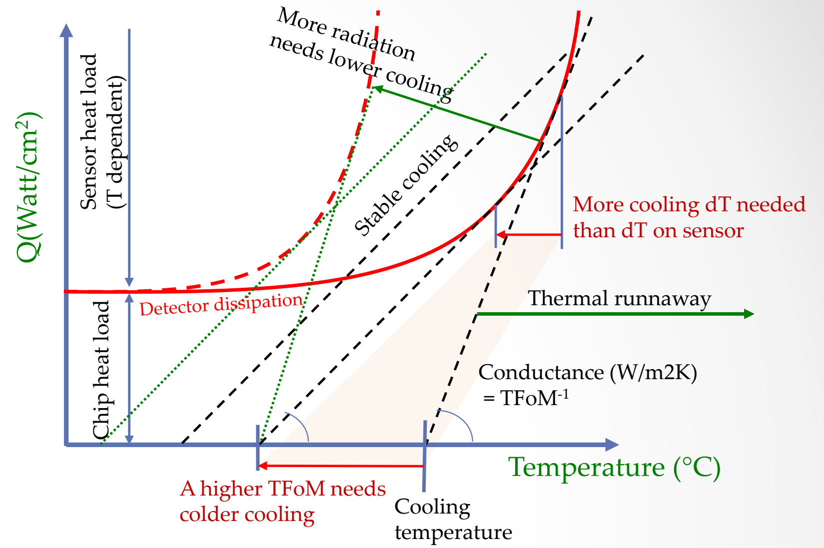
Fluid	Boiling point (K/°C)
Helium-3	3.19 / -269.96
Helium-4	4.214 / -268.936
Hydrogen	20.27 / -252.88
Neon	27.09 / -246.06
Nitrogen	77.09 / -196.06
Air	78.8 / -194.35
Fluorine	85.24 / -187.91
Argon	87.24 / -185.91
Oxygen	90.18 / -182.97
Methane	111.7 / -161.45
Krypton	119.75 / -153.4

EP-DT
Detector Technologies

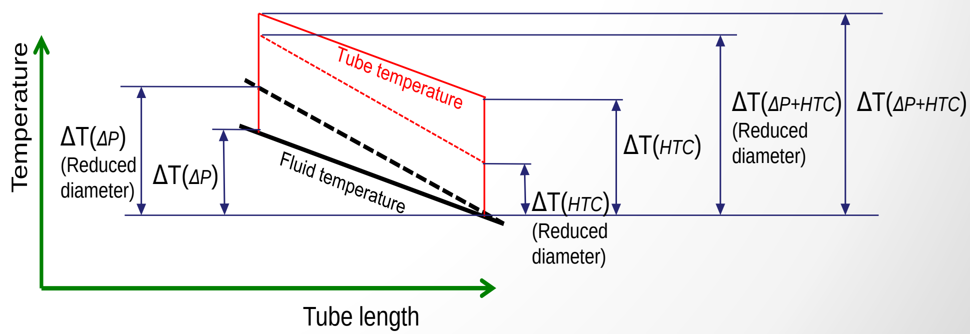
Detector cooling explained

Slides from ECFA talk

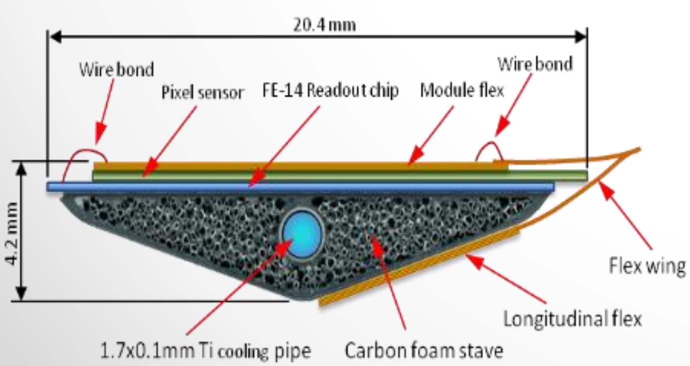
- To keep the detectors cold and away from thermal runaway, 2 things are important:
  - The cooling fluid low temperature
  - The Thermal Figure of Merit (cm^2*K/W),
    - TFoM = The thermal resistance from source to sink (sensor to cooling)
    - TFoM: A thermal resistance chain including: material conductance, interface resistance, fluid heat transfer coefficient and pressure drop (2-phase systems) or caloric heating (Single phase systems)
  - As the gradients are heat load depended a higher TFoM requires a colder fluid temperature. The relation is non-linear (An accelerating cold temperature is needed at a worse TFoM)
- The selection of the TFoM and hence cooling temperature is a mass saving optimization



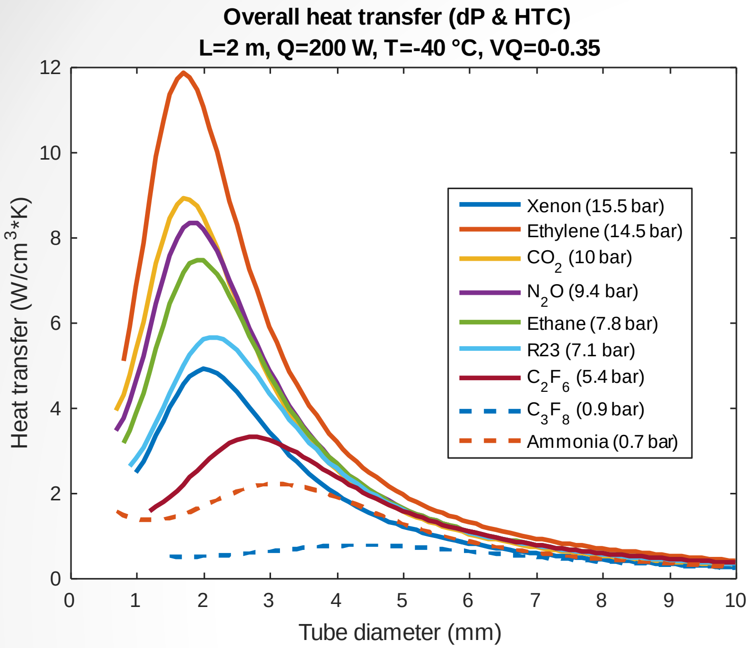
TFoM and cooling temperature

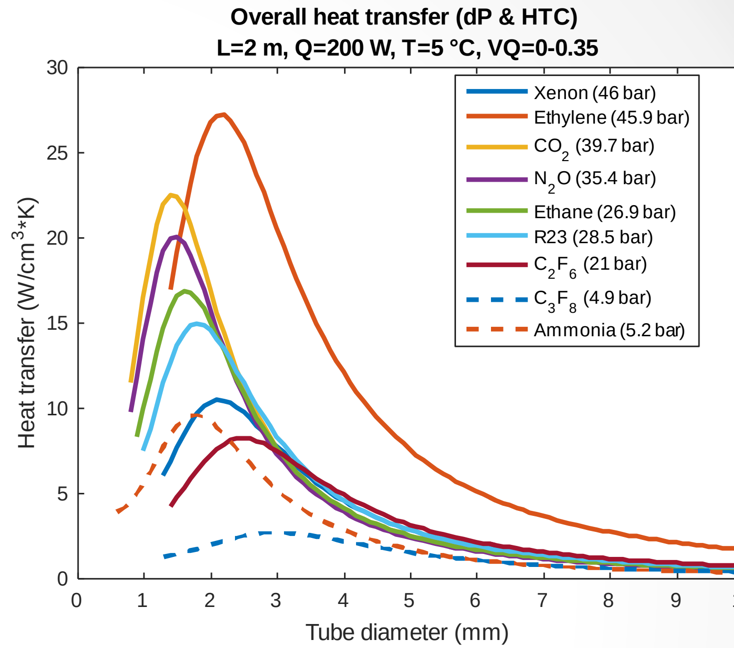


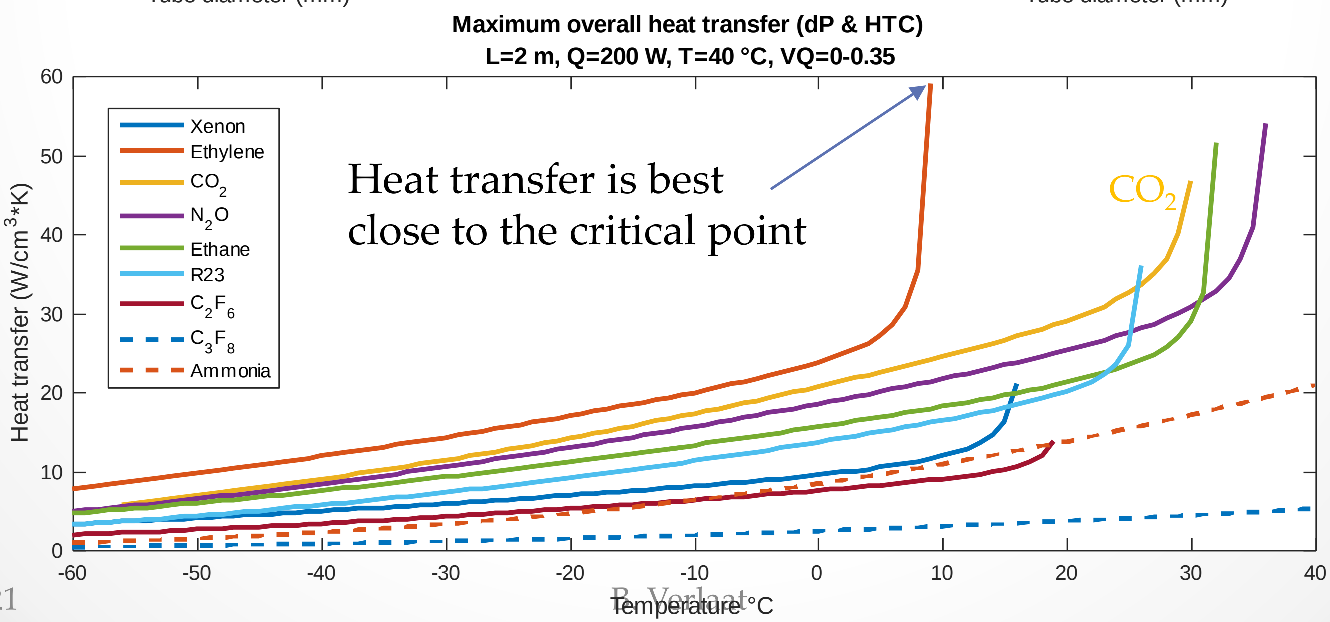
Cooling system gradients



Fluid comparison



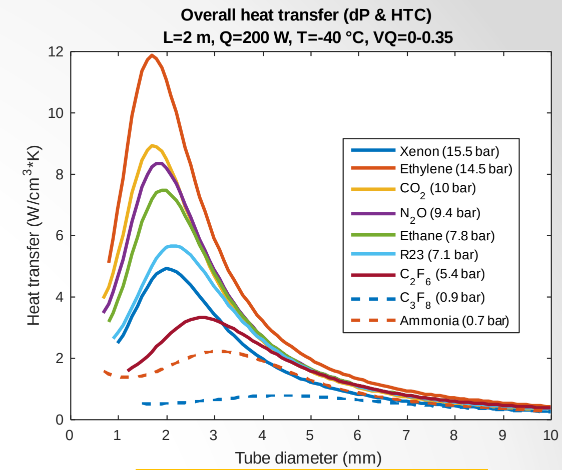




EP-DT
Detector Technologies

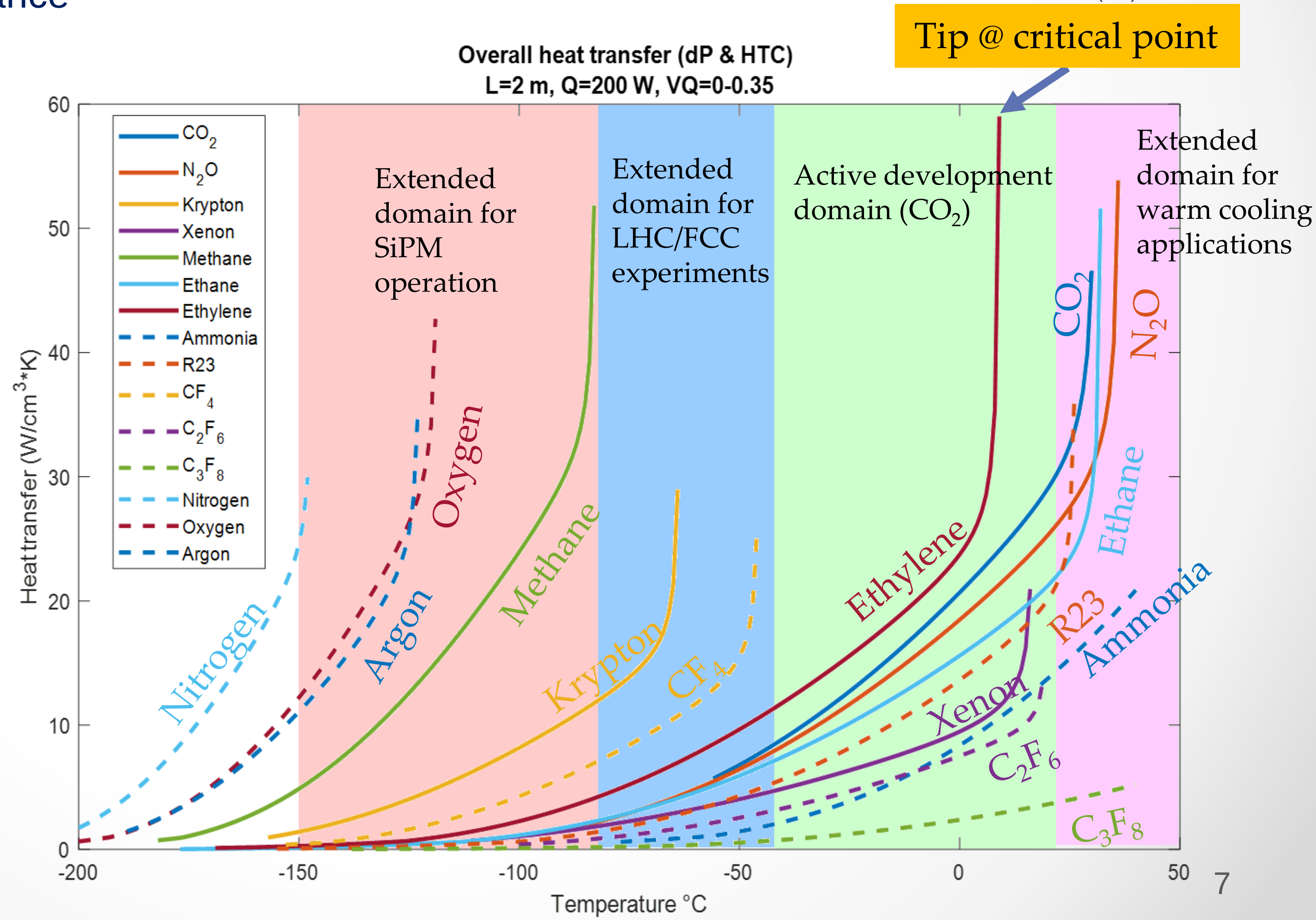
Cooling fluid choices

Slides from ECFA talk



- A good method to compare different fluids at different operational temperatures is to plot the optimal pipe volume per achieved conductance (Volumetric heat transfer in W/cm^{3}K).
- The volumetric heat transfer takes the losses by pressure drop and convective heat transfer into account
- This approach shows that the closer you are to the critical point, the better the performance

- High heat load density cooling (>0.3 W/cm^2)
  - A fluid with a high volumetric heat transfer is needed to maintain a low contribution to the TFoM.
  - Preferred choice is 2-phase evaporative cooling, with relative high pressure
- Low heat load density cooling (<0.3 W/cm^2)
  - Volumetric heat transfer less of an issue, more fluids can be considered for practical reasons
  - Single phase and air cooling can be considered



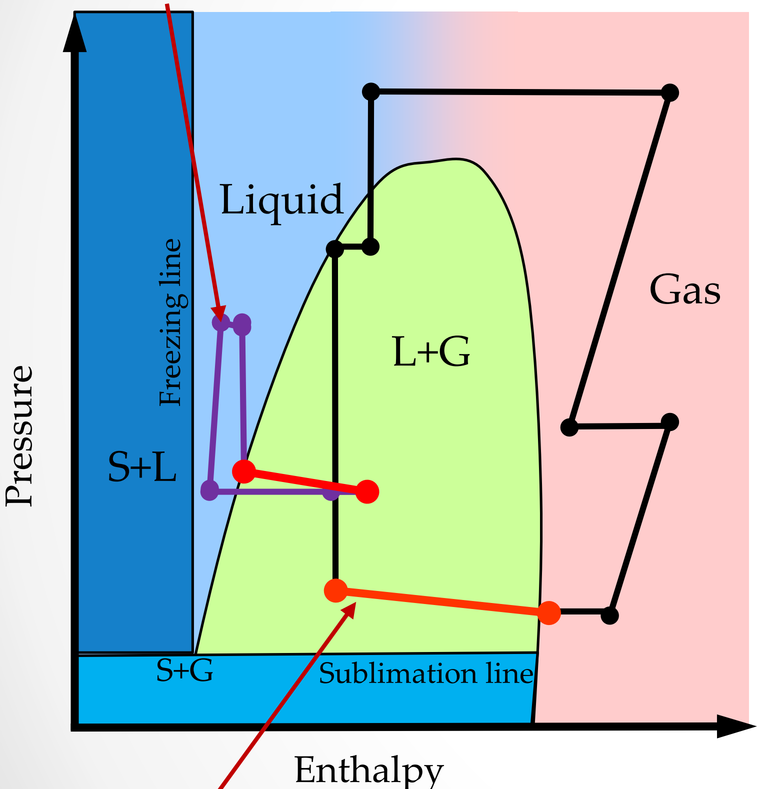
EP-DT
Detector Technologies

Slides from ECFA talk

System Cycles

<u>2PACL cycle</u>

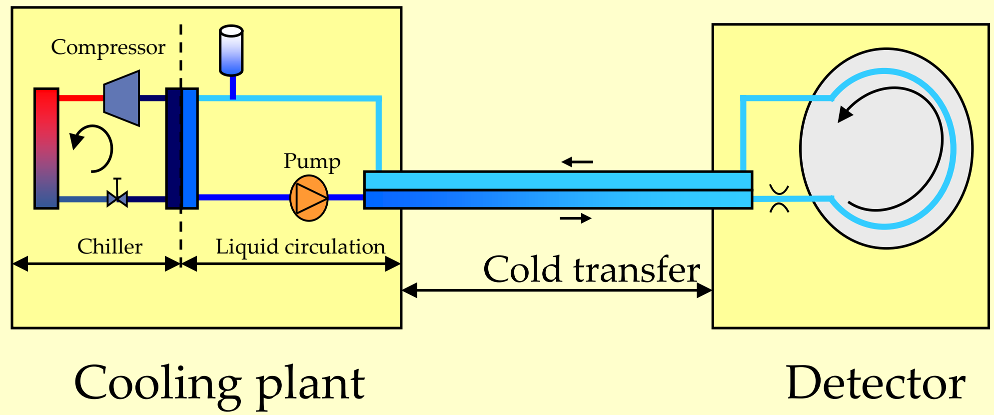
- Good heat transfer due to low vapor quality
- Limited cold use due to liquid freezing (>-40°C)
- Cold transfer lines



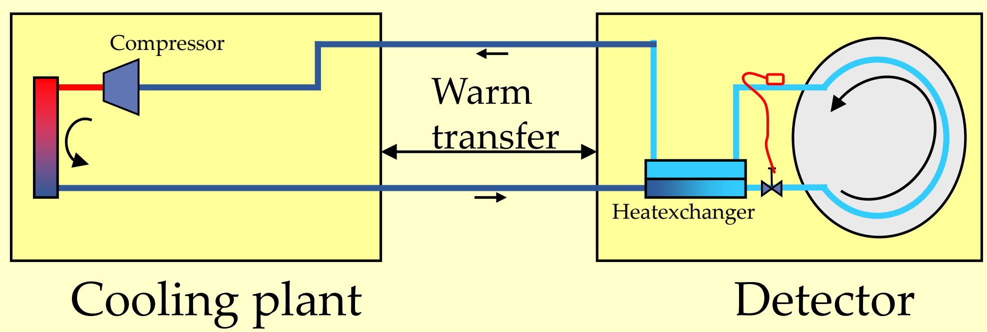
<u>Vapor compression cycle</u>

- Reduced heat transfer due to high vapor quality
- Can run colder than 2PACL (-53°C)
- Can have warm transfer lines (Integration benefit)

2PACL method: Pumped liquid system, cooled externally
(LHCb, ATLAS, CMS)



Refrigeration method: Vapor compression system
(CO_2 primary / Atlas ID)

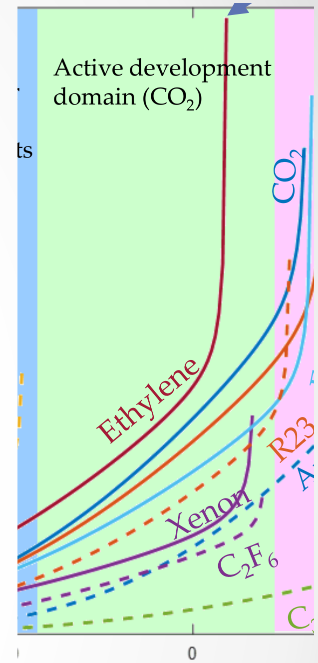


EP-DT
Detector Technologies

Currently active cooling domain (-40°C / +20°C)

Slides from ECFA talk

- In this temperature domain the leading choice is evaporative CO_2 cooling using the 2PACL cycle technology
- Well known technology, still R&D needed in specific domains
  - Larger heat flux domains (>1W/cm^2 sensor flux)
  - By use in complex evaporator geometries like micro-channels or 3D print heatsinks.
  - Warm cooling behaviour for services cooling
- Alternative fluid candidates are single phase Novec or water (+°C)
- Fluorocarbons (single or 2-phase are not being considered for future use due to their bad environmental properties and their potential ban by future regulations)
- CO_2 is used at CERN in the following applications:




AMS@ISS 2011-


LHCb-Velo 2008-2018

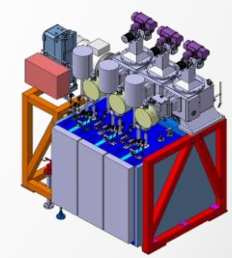

ATLAS-IBL 2014-


CMS-Pixel 2015-


Traci 2011-2015


Lucasz 2016-


LHCb-Mauve 2019-


ATLAS & CMS Ph2 Upgrade (2025)

CERN official environment Report

Slides from ECFA talk

«CERN's emissions are equal to a large cruise liner»
https://physicsworld.com/a/cerns-emissions-equal-to-a-large-cruise-liner-says-report/

«Greenhouse gas emissions at CERN arise from the operation of the Laboratory's research facilities. The majority of emissions come from CERN's core experiments and more than 78% are **fluorinated gases**. With climate change a growing concern, the

GROUP	GASES	tCO_2e 2017	tCO_2e 2018
PFC	CF_4, C_2F_6, C_3F_8, C_4F_{10}, C_6F_{14}	61 984	69 611
HFC	CHF_3 (HFC-23), $C_2H_2F_4$ (HFC-134a), HFC-404a, HFC-407c, HFC-410a, HFC R-422D, HFC-507	106 812	96 624
	SF_6	10 192	13 087
	CO_2	14 612	12 778
TOTAL SCOPE 1		193 600	192 100

Organization is committed to reducing its direct greenhouse gas emissions.»
https://hse.cern/environment-report-2017-2018/emissions

CERN management accepted and financed an objective to reduce CERN's direct greenhouse gas emissions by 28% by the end of 2024. Among the actions being taken to achieve this, **CERN has for several years been developing environmentally-friendly cooling systems that have potential for applications in other domains**."

Slides from ECFA talk

Cooling fluids used at CERN *(with room temperature reference)*

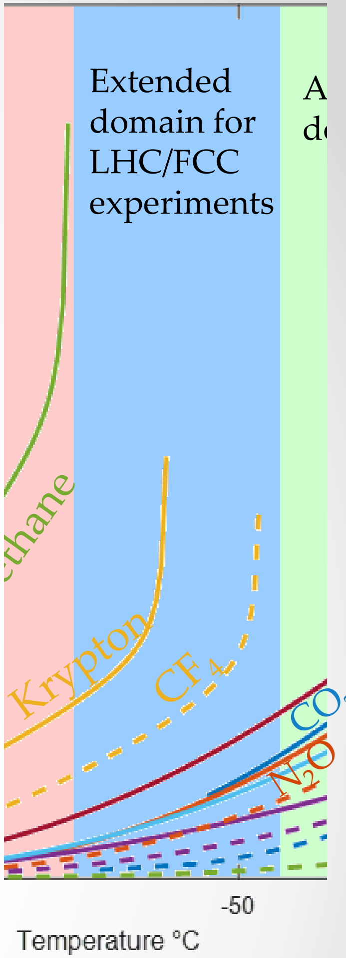
	Normal boiling conditions P=1atm or T=20 °C		2-Phase properties at 20°C	Critical point		Properties at normal conditions T=20 °C, P=1atm or normal boiling pressure in case of liquefied gas			Other properties	
Fluid	Boiling temperature (°C)	Boiling pressure (bar)	Latent heat (kJ/kg)	Critical temperature (°C)	Critical pressure (bar)	Density (kg/m3)	Heat capacity (kJ/kg*K)	Viscosity (µPa*s)	GWP	Prize €/kg
Water	100	0.023	2453	373.9	220.6	998	4.18	1001.6	-	0
Novec 649 [1]	49.1	0.326	96.2	168.7	18.7	1617	1.10	756.6	1	47,-
C6F14	56.9	0.236	94.0	175.9	18.3	1703	1.03		9300	30,-
C5F12	29.8	0.695	95.0	147.4	20.5	1632	1.07	497.6	9160	
C4F10	-2.2	2.29	88.9	113.2	23.2	1516	1.07	230.9	9200	138,-
C3F8	-36.8	7.56	79.1	71.9	26.4	1352	1.15	180.6	8900	38,-
C2F6	-78.1	Super critical		19.88	30.5	Super critical			11100	100,-
CO2	-78.4	57.29	152.0	30.97	73.8	773.4	4.3	66.1	1	0.015

No future (C6F14, C5F12, C4F10, C3F8, C2F6)

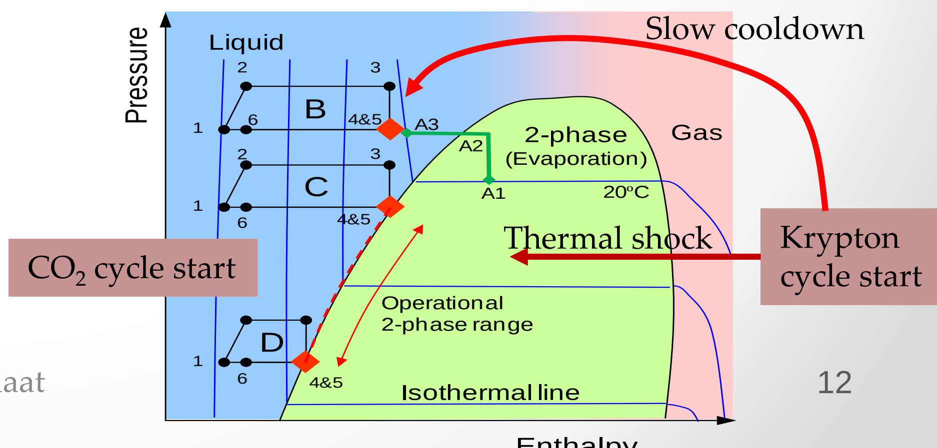
[1] Not well understood radiation and material compatibly issues

Extended domain for Hadron collider experiments (-80°C / -40°C)

- Future detectors with increased radiation doses require colder cooling beyond the current CO_2 capacities (<-40°C)
- There are not many existing technologies in this temperature domain
- Serious R&D is needed in this temperature domain exploring new technologies
- Candidate fluids and cycle technologies:
  - Krypton (evaporative and super critical),
    - A new cycle technology is needed as cooldown from ambient starts in the gas phase
    - Trans-critical cooldown needed to avoid thermal shocks
  - Carbon Tetrafluoride (CF4)
    - The only fluorocarbon candidate which could be considered due to the limited choice of candidates in the high temperature area of this domain
    - Same cycle challenges as Krypton
  - N_2O/CO_2 mixtures (100% CO_2 > -55°C / 100% N_2O @ -90°C)
    - N_2O has nearly the same properties as CO_2, but a much lower freezing temperature. Can be used as a mix with CO_2 acting as an anti-freeze or pure if ultra low temperatures are needed (>-90°C)
    - Due to the lower efficiency at cold temperatures, N_2O/CO_2 mixtures are best to be considered for low heat flux applications like SiPM cooling.
  - Ethane or Ethylene would be good thermal candidates, but not preferred because of their flammable properties.



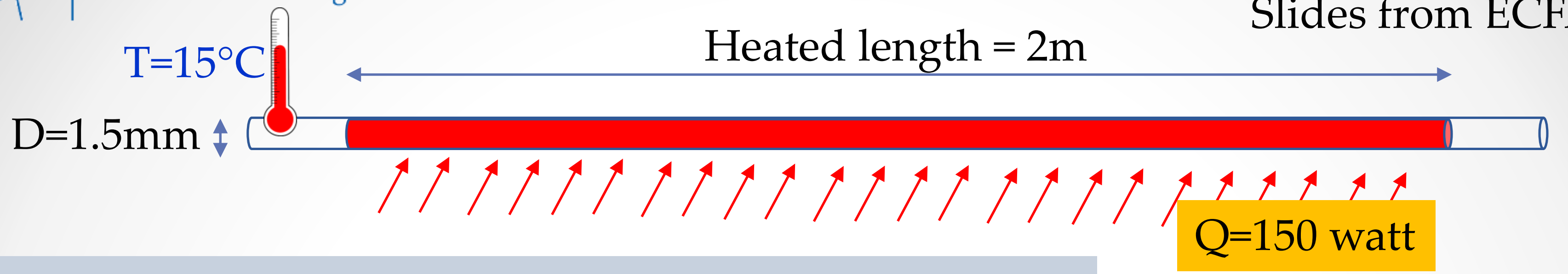
- Currently VELO-3 is seriously looking into this temperature domain
- Future high radiation experiments (eg. FCC) are expected to need colder cooling than the current CO_2 range



EP-DT
Detector Technologies

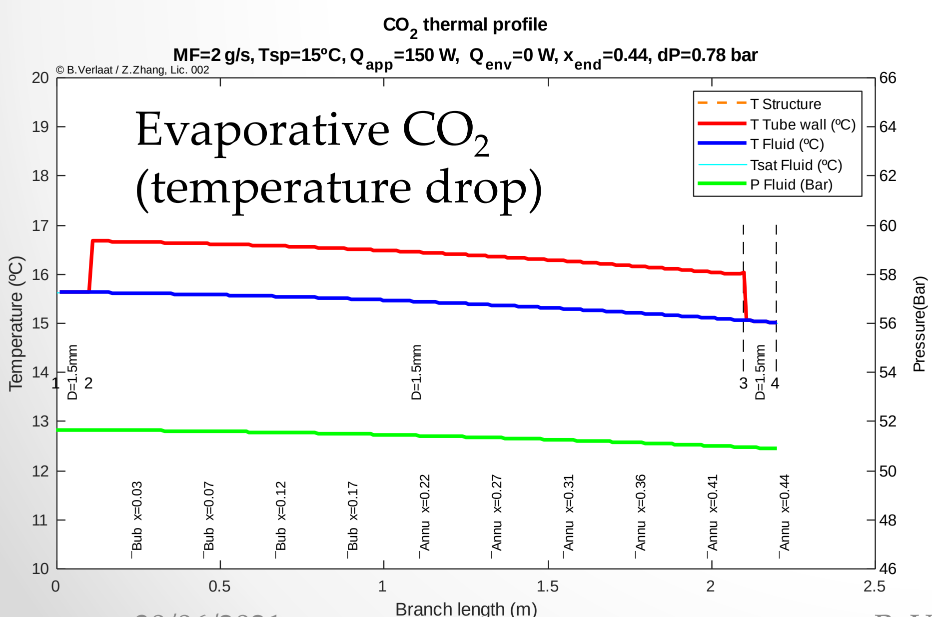
Evaporative CO_2 vs Water and Novec649

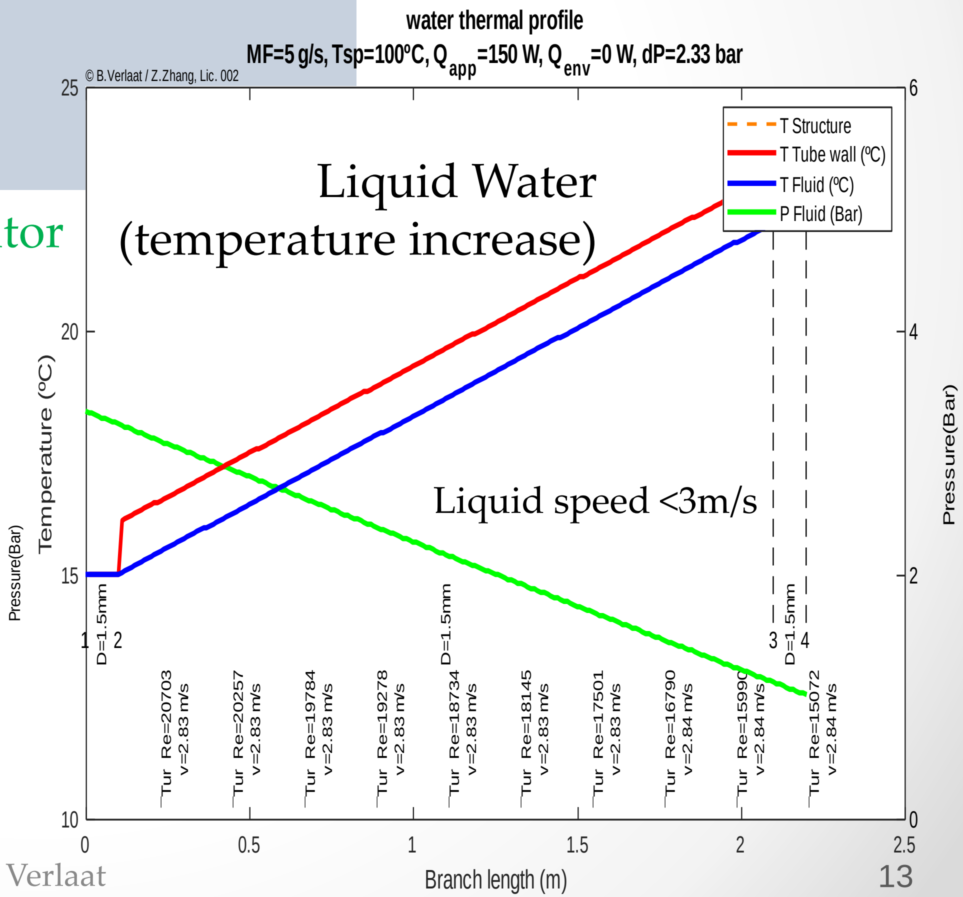
Slides from ECFA talk



2-phase CO_2	Liquid Water	Liquid Novec (graph not shown)
MF=2g/s	MF=5 g/s	MF=7.5g/s
dP=0.8 bar	dP=2.3 bar	dP=2.6 bar
dT_{fluid}=0.6°C	dT_{fluid}=7.2°C	dT_{fluid}=18.2°C
dT_{total}=1.6°C	dT_{total}=8.2°C	dT_{total}=22.1°C

CoBra calculator





Slides from ECFA talk

Supercritical cooling, a special mono-phase cooling case

- The super critical region is a mono-phase region with very favourable properties for heat and mass transfer
  - Very high heat capacity, Cp=J/kg*K
  - Very low viscosity, μ=Pa*s
- High heat transfer capability
- SC-CO_2 is interesting to explore for warm cooling applications (31°C / 45°C)
- For cold temperature applications the use of super critical Krypton cooling (SC-Kr) can be considered (-63°C / -50°C)

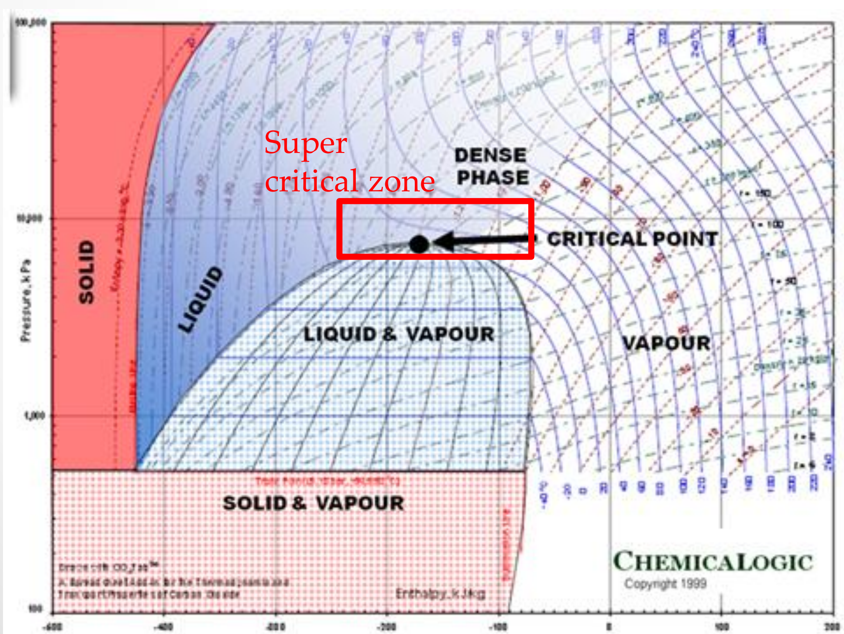
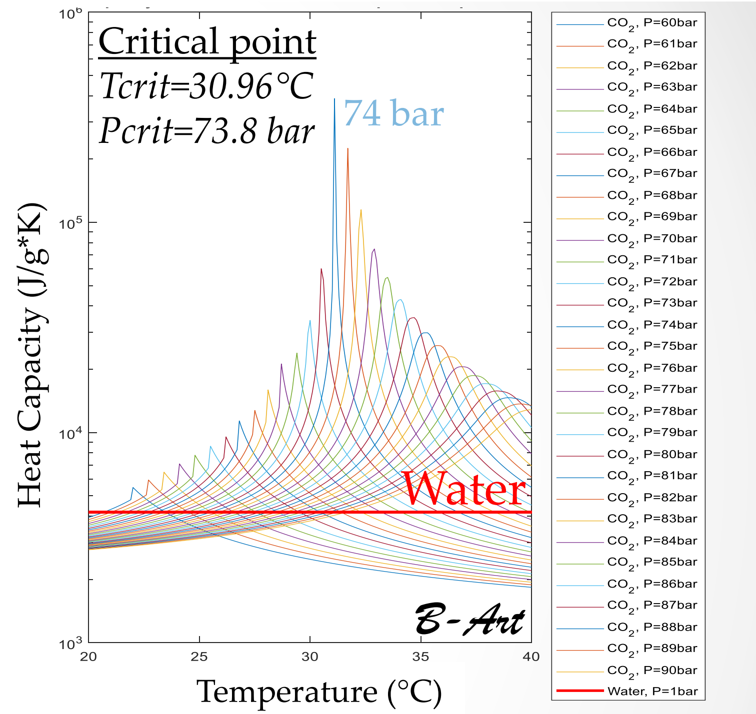


Figure 1. Pressure-enthalpy diagram for carbon dioxide identifying different phases

Super critical heat capacity of CO_2 compared to water



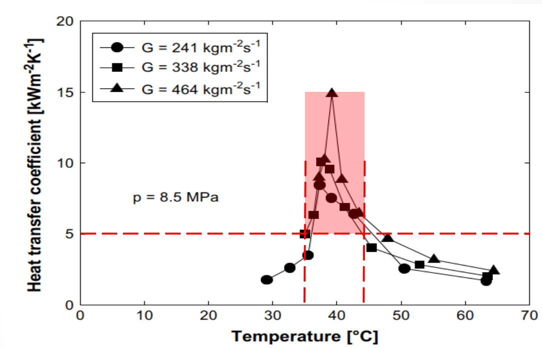
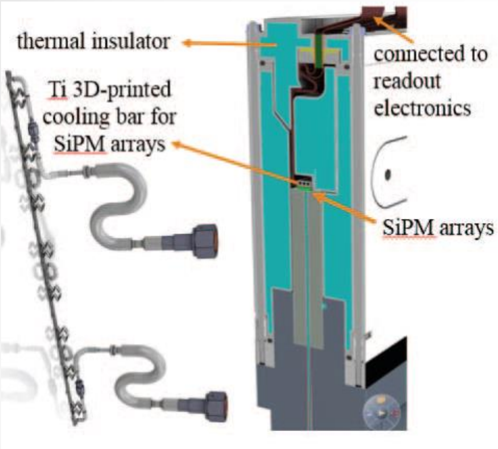
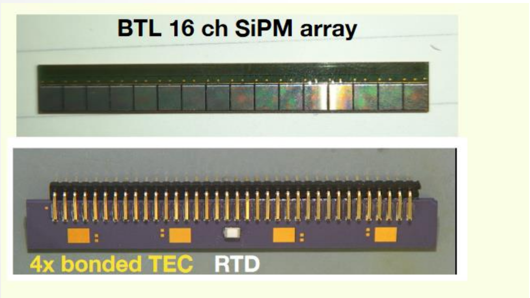


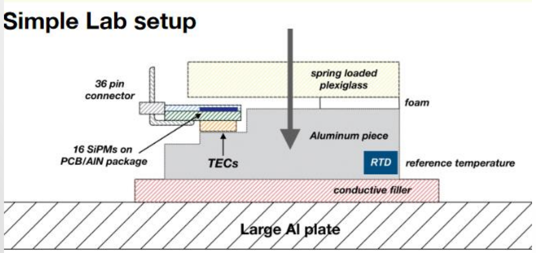
Fig. 3 – Heat transfer coefficient versus bulk temperature for different mass fluxes by Yoon et al. (2003).

Silicon Photomultipliers (SiPM)

Slides from ECFA talk







CMS SiPM with TEC cooling

- Many future detectors are considering SiPM detectors.
  - Current : LHCb-SciFi, CMS-EC upgrade
  - Future : Calorimeters, scintillator trackers
- Cooling temperature depends on noise allowance and radiation level
- Temperatures in the range of -50°C to -150°C are being considered
- SiPM have a low heat dissipations
- Main contribution for cooling system is heat leak due to the difficulty to make good insulation (Direct mounting on scintillator material)
- The wish for cryogenic temperatures have a large challenge as the detectors are not suitable to fit in standard cryostats.
- Cooling method candidates:
  - Integrated Thermal Electric Cooler (TEC or Peltier) with CO_2 or Novec cooling
  - CO_2/N_2O mixtures in a vapor compression cycle potentially with warm in and outlet lines (ATLAS ID cooling concept)
  - Pressurized 2-phase Krypton based cooling like slide 10
  - Pressurized 2-phase Argon or LN2 for colder temperatures
- R&D involves:
  - Cooling fluid use
  - Cooling cycle
  - Insulation / mechanical structure design concept

Summary

- Some summary points from ECFA talk:
  - For future detector cooling the following R&D areas have been localized:
    - High heat density cooling in the temperature domain below CO_2 (-40°C / -80°C)
      - Super and sub critical Krypton cooling using a trans critical cool down cycle
      - CF_4 is a non-green back-up solution
    - Low heat density cooling in the temperature domain below CO_2 (-40°C / -80°C)
      - CO_2/N_2O mixtures (or pure N_2O) in an oil free vapor compression cycle (With warm transfer lines) or 2PACL cycle
  - A special attention to the following specific detectors is needed
    - SiPM cooling including thermal housing design (-40°C / -150°C), using technologies mentioned above

LN2 saturation

	Temperature (°C)	Pressure (bar)
1	-200.00	0.59842
2	-195.00	1.1117
3	-190.00	1.9067
4	-185.00	3.0660
5	-180.00	4.6767
6	-175.00	6.8299
7	-170.00	9.6198
8	-165.00	13.146
9	-160.00	17.516
10	-155.00	22.854
11	-150.00	29.329

- For future LHCb, similar activities for cold cooling are done in the general R&D domain
  - For VELO, high power density cold cooling is an option
    - Krypton, CF_4 with a new cycle (T=-150/-60'C)
    - Pressurized liquid nitrogen an option (T<150'C) for colder cooling
  - For SciFi low power density cold cooling
    - Extended CO_2/N_20 in a vapour compression cycle (>-90'C)
    - Colder than -90'C pressurized liquid Krypton, Argon or N2 would work