Cooling R&D needs for future detectors

ECFA-WG8, 31 March 2021

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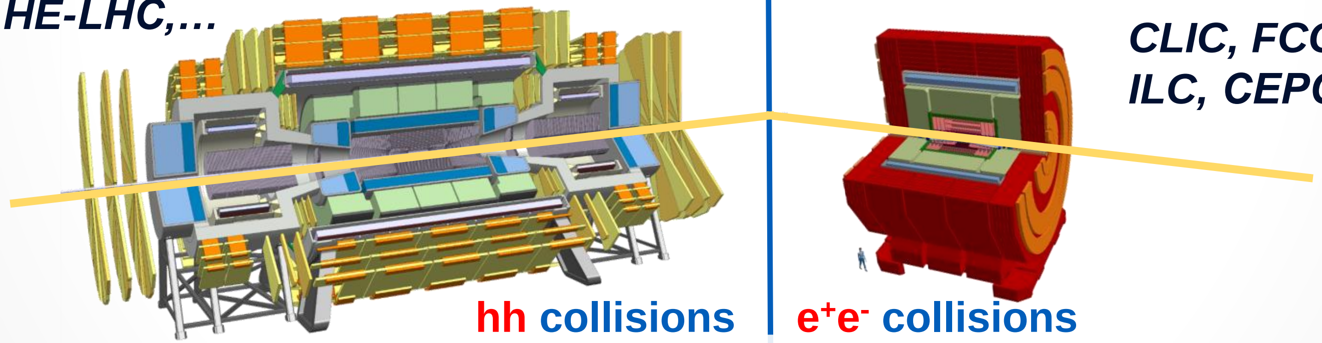
What are the cooling need trends for future?

- 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

FCChh, HE-LHC,…

CLIC, FCCee, ILC, CEPC,…



hh collisions | **e^+e^- collisions**

- *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/cm^2)*
- *Room temperature*
- *Low material budget*

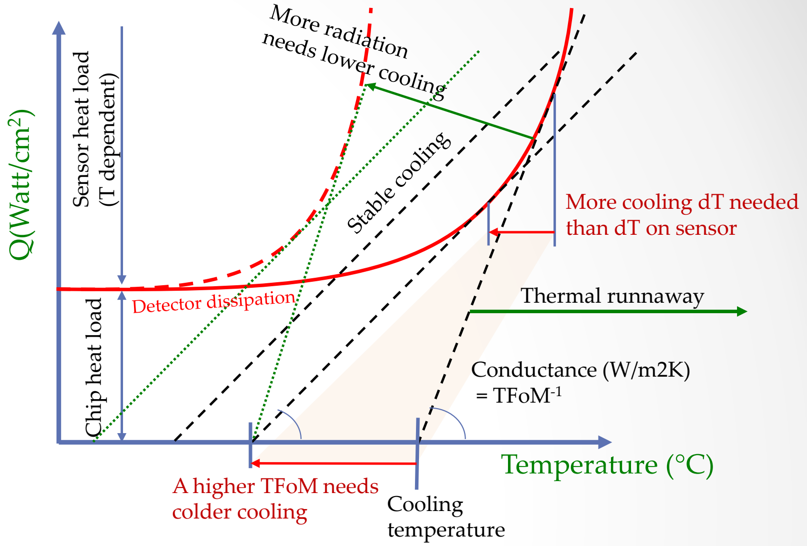
Cooling & Refrigeration versus Cryogenics

- 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.
    - With 1 very challenging application: The AMBER experiment, <1.8 K with 10Watt dissipation!

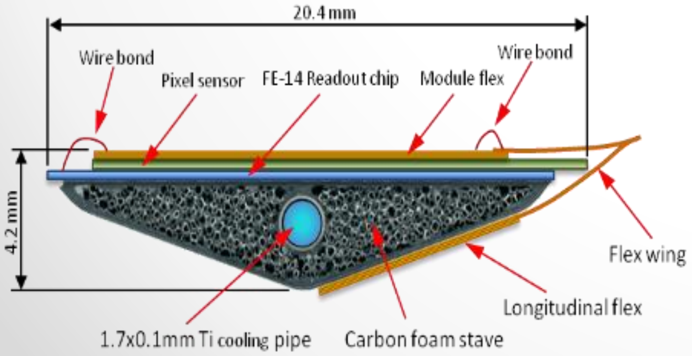
Fluid	Boiling point (K/°C)
Helium-3	3.19 / -269.96
Helium-4	4.214 / -268.936
Hydrogen	20.27 / -252.88
Neon	27.09 / -246.06
Nitrogen	77.09 / -196.06
Air	78.8 / -194.35
Fluorine	85.24 / -187.91
Argon	87.24 / -185.91
Oxygen	90.18 / -182.97
Methane	111.7 / -161.45
Krypton	119.75 / -153.4

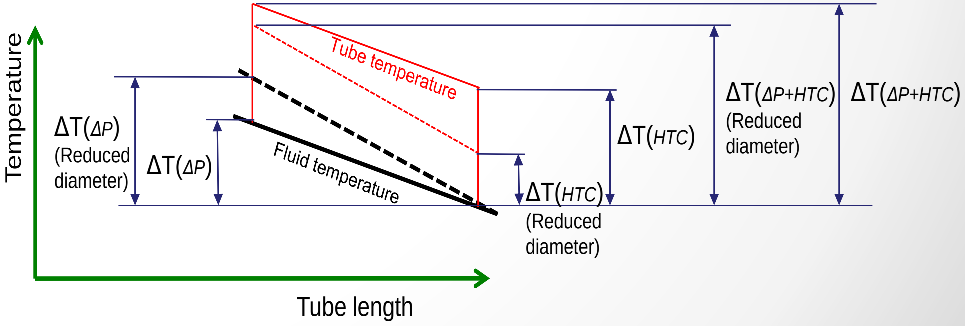
Detector cooling explained

- 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



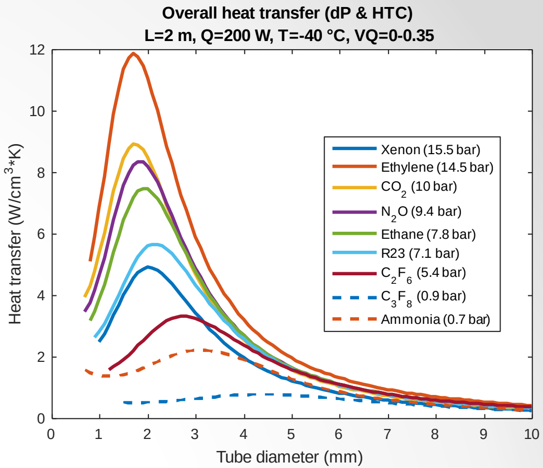
TFoM and cooling temperature





Cooling system gradients

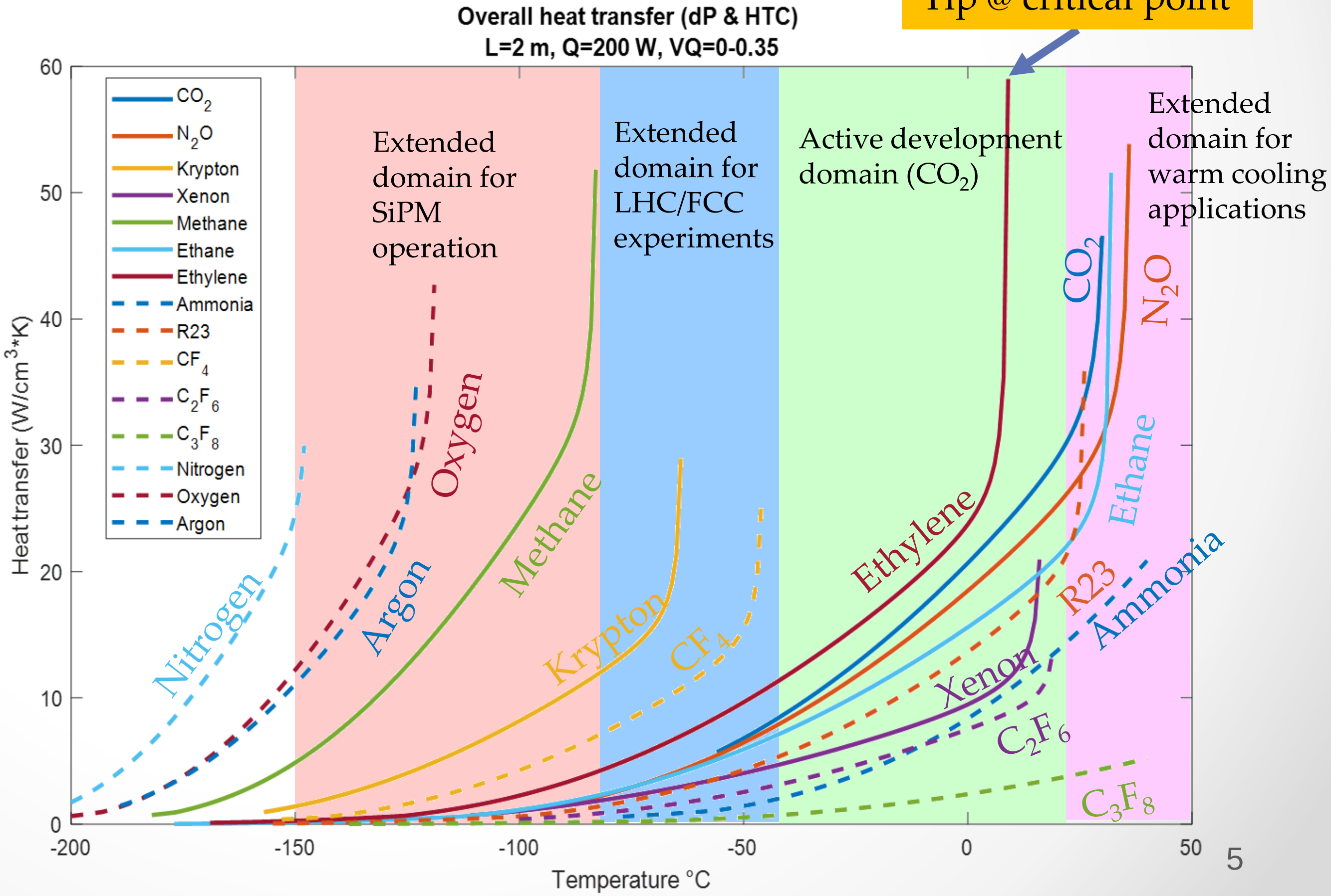
Cooling fluid choices



- 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

Tip @ critical point



Extended domain for SiPM operation

Extended domain for LHC/FCC experiments

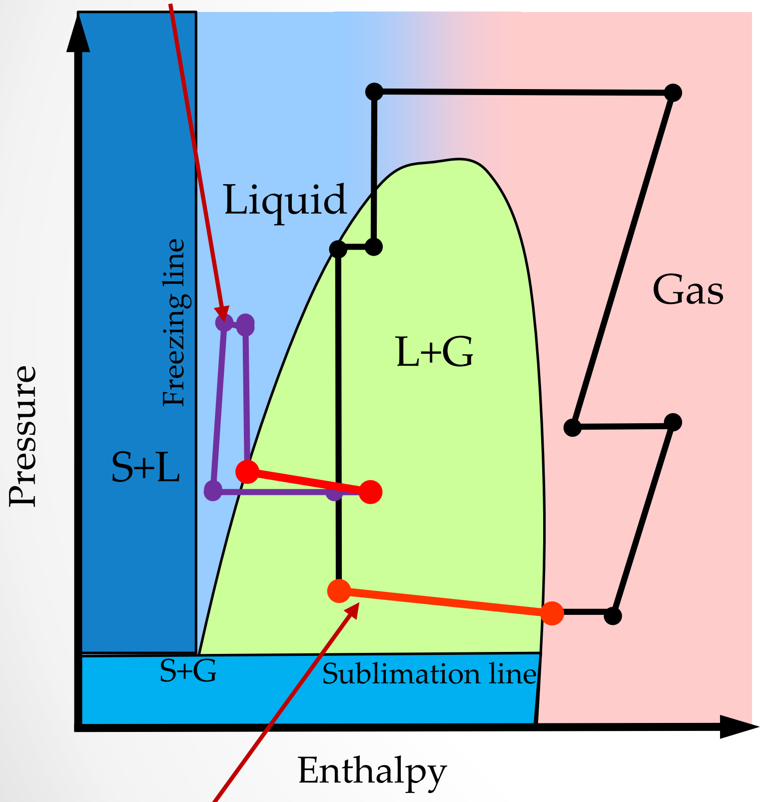
Active development domain (CO_2)

Extended domain for warm cooling applications

System Cycles

2PACL cycle

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

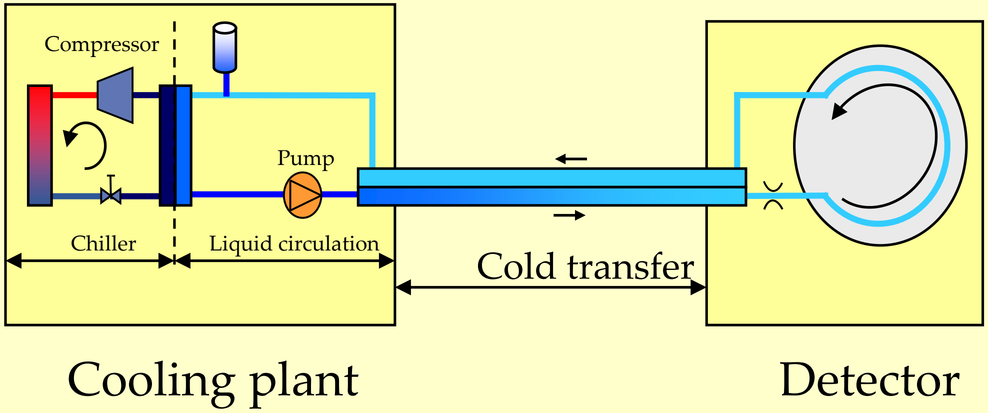


Vapor compression cycle

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

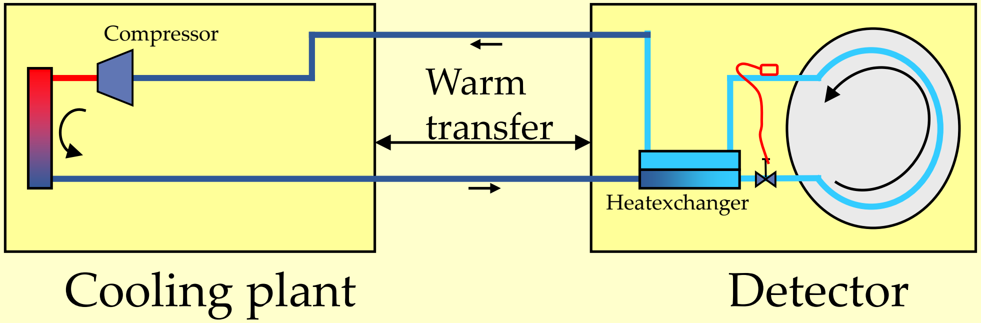
2PACL method: **Pumped liquid system, cooled externally**

(LHCb, ATLAS, CMS)



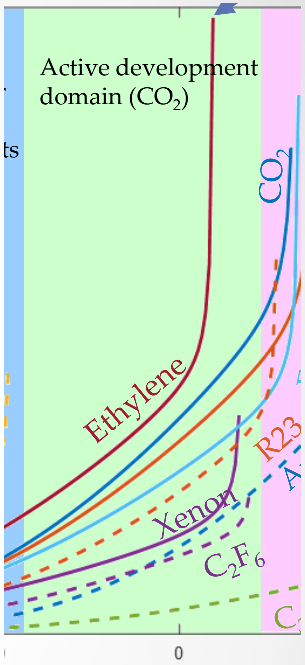
Refrigeration method: **Vapor compression system**

(CO_2 primary / Atlas ID)



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

- 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

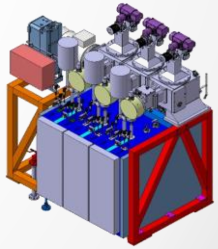
ATLAS-IBL
2014-

CMS-Pixel
2015-

Traci
2011-2015

Lucasz
2016-

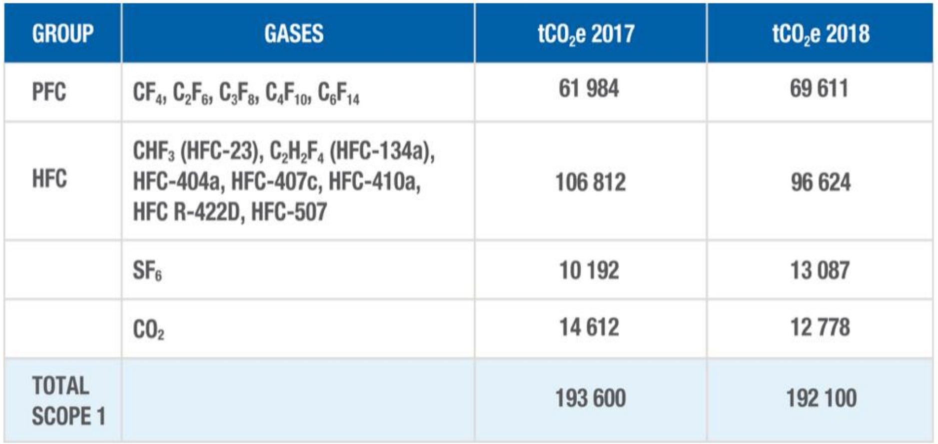
LHCb-Mauve
2019-



ATLAS & CMS Ph2
Upgrade (2025)

CERN official environment Report

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



GROUP	GASES	tCO$_2$e 2017	tCO$_2$e 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

«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 **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**."

Cooling fluids used at CERN

(with room temperature reference)

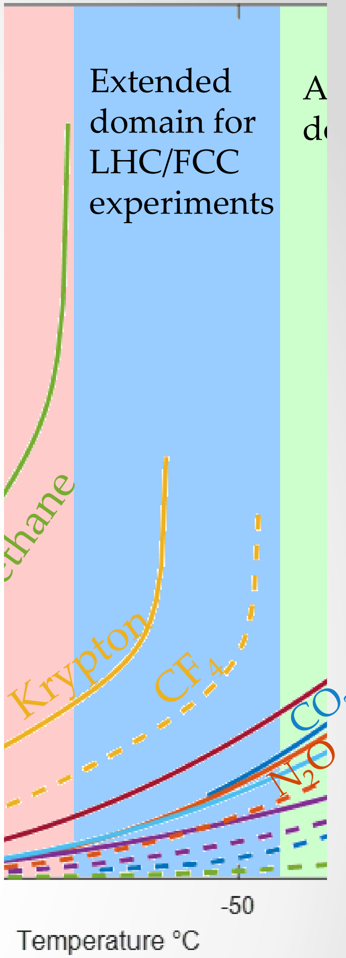
No future

	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

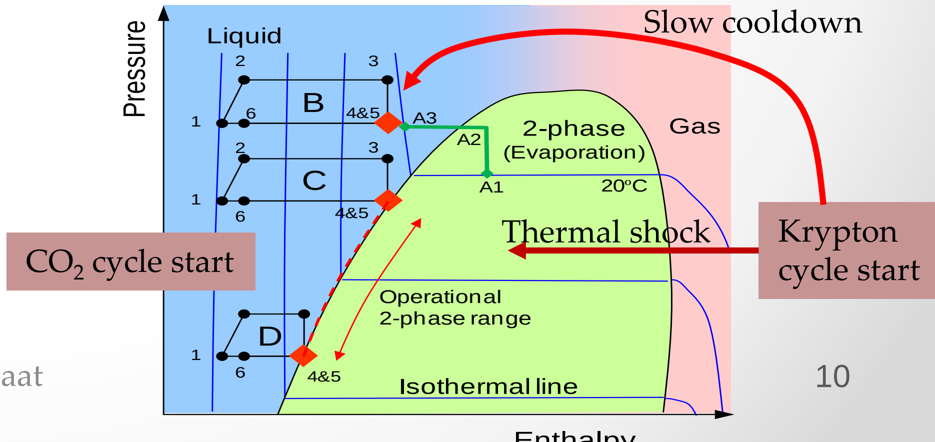
[1] Not well understood radiation and material compatibly issues

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

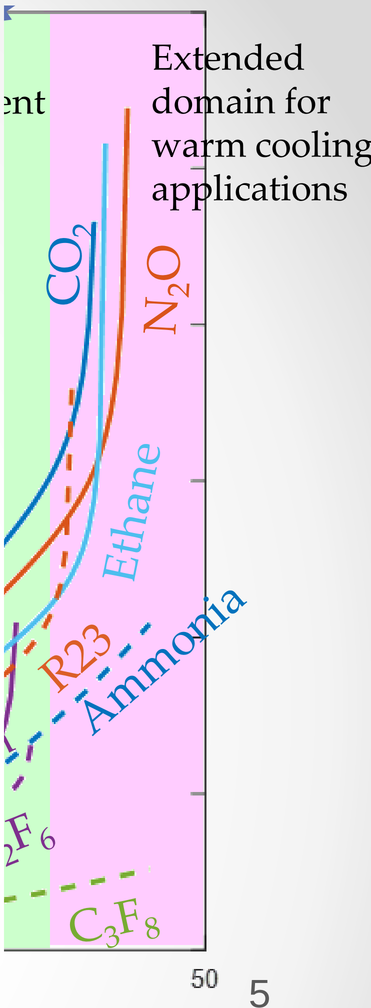
- Future detectors with increased radiation doses require colder cooling beyond the current CO_2 capacities (<-40°C)
- There are not many existing technologies in this temperature domain
- Serious R&D is needed in this temperature domain exploring new technologies
- Candidate fluids and cycle technologies:
  - 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



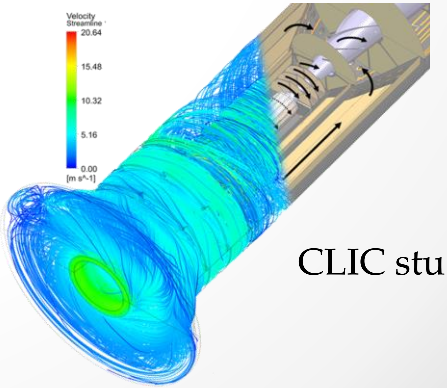
Warm cooling domain
(Room temperature and above)



- Lepton and Ion collider experiments require ultra light detectors which can be cooled at room temperature.
- Candidate technologies:
  - Direct air cooling using an air draft through the detector,
    - Special designed layout to facilitate convective air flow
    - Considered for Alice upgrade
  - Water or Novec cooling (Novec if dielectric fluids are needed)
    - Low pressure solution for ultra thin plastic piping
  - Warm evaporative or super critical CO_2
    - In case very small cooling channels are needed (eg. micro channels)
    - Good solution for services cooling like cables and DAQ boxes in the detector vicinity

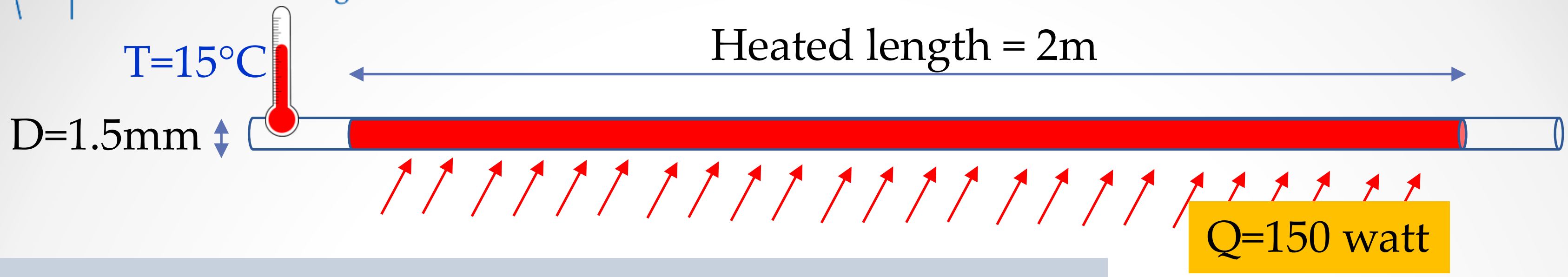
Air-cooling example PXL/STAR HFT @ RHIC
0.17 W/cm^2, dT=13°C, Wind speed: 10.1 m/s
(Windforce 5 Beaufort)
Thermal figure of merit: 70 K*cm^2/W

PXL/STAR



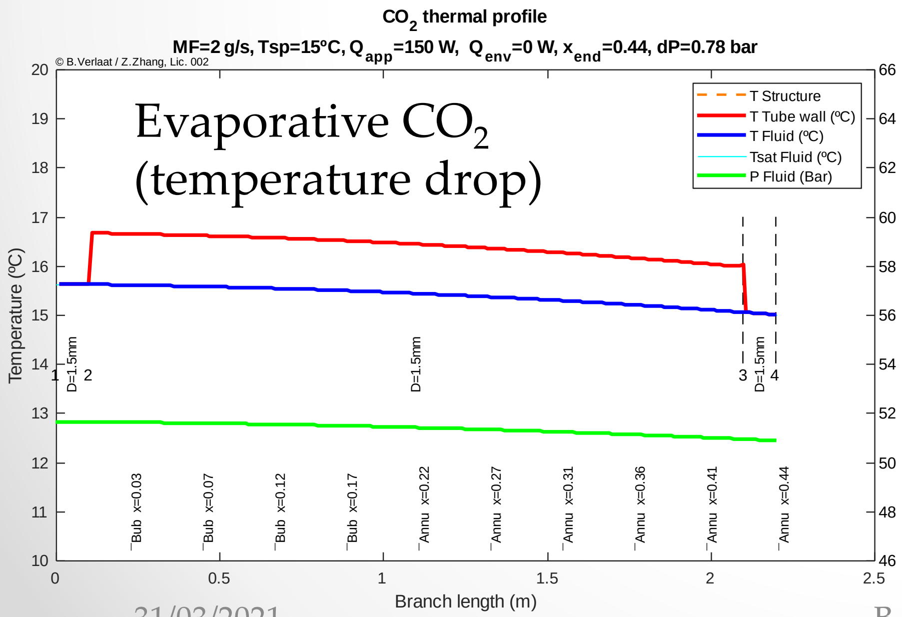
CLIC study

Evaporative CO_2 vs Water and Novec649



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


CO_2 thermal profile

MF=2 g/s, Tsp=15°C, Q_{app}=150 W, Q_{env}=0 W, x_{end}=0.44, dP=0.78 bar

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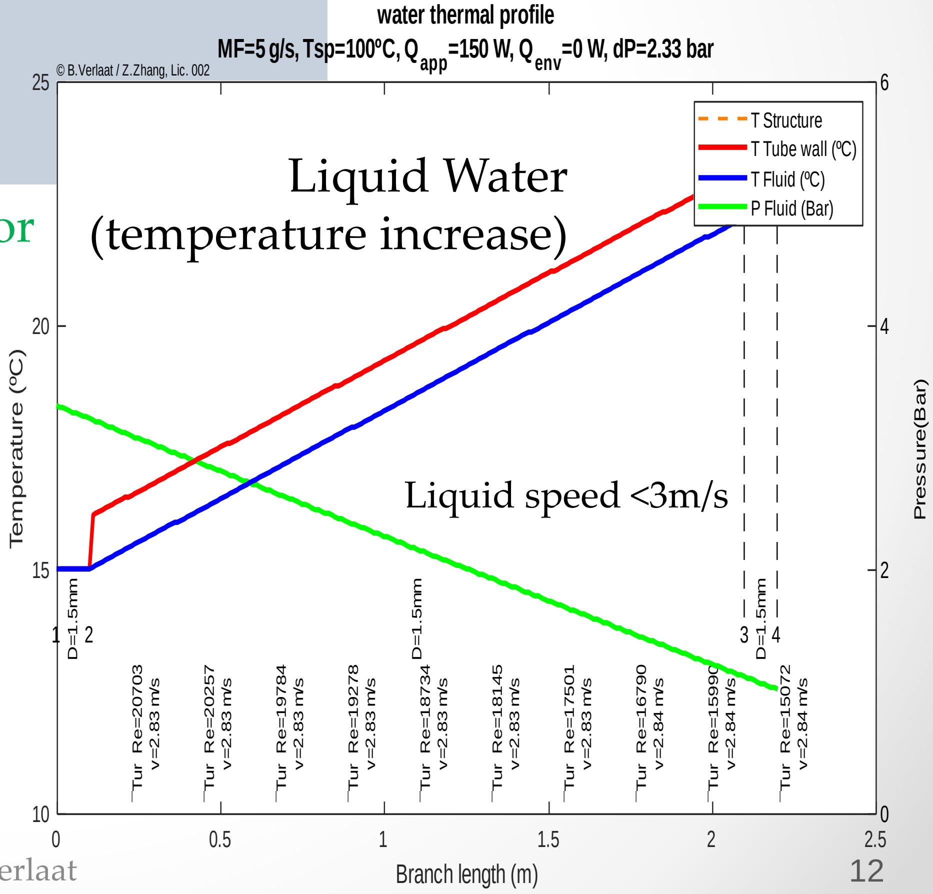
Evaporative CO_2
(temperature drop)


water thermal profile

MF=5 g/s, Tsp=100°C, Q_{app}=150 W, Q_{env}=0 W, dP=2.33 bar

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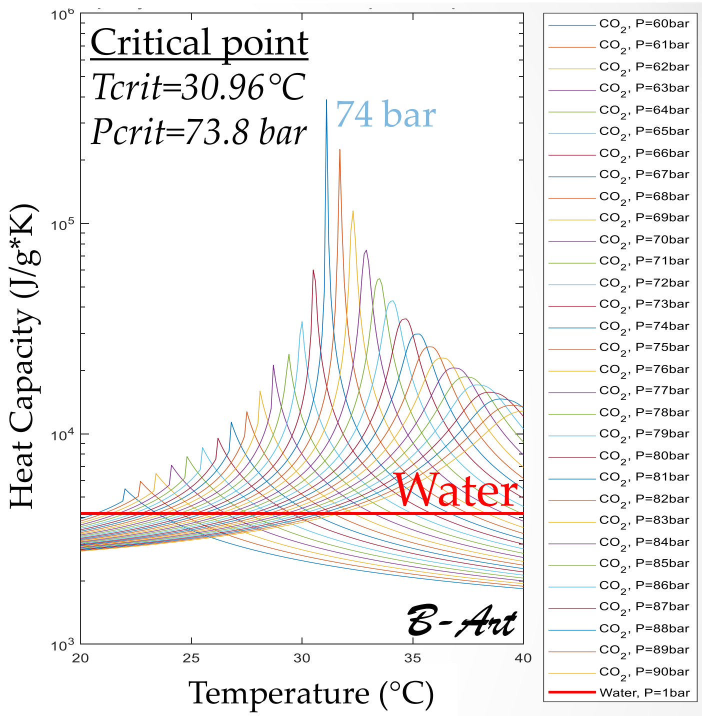
Liquid Water
(temperature increase)

Liquid speed <3m/s

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)

Super critical heat capacity of CO_2 compared to water



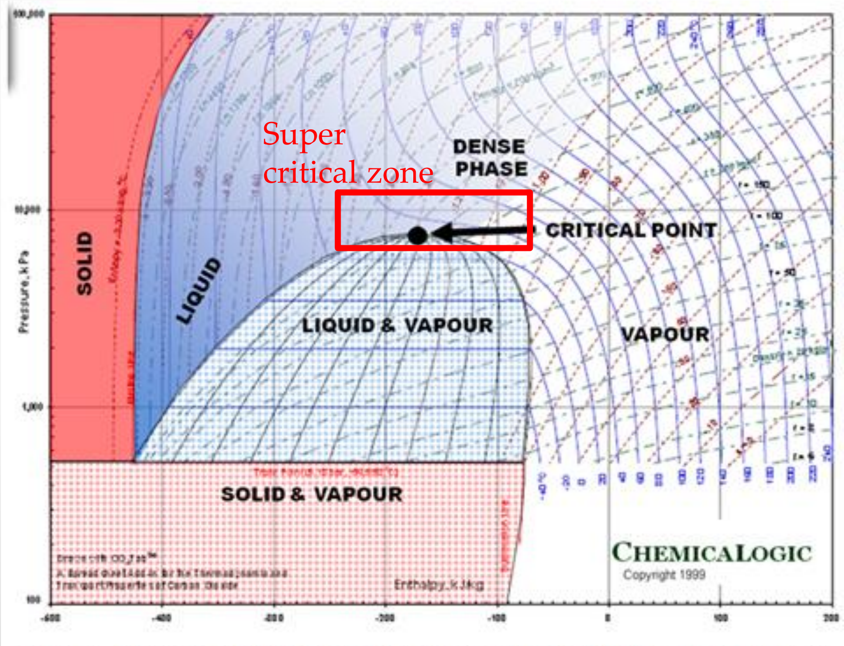


Figure 1. Pressure-enthalpy diagram for carbon dioxide identifying different phases

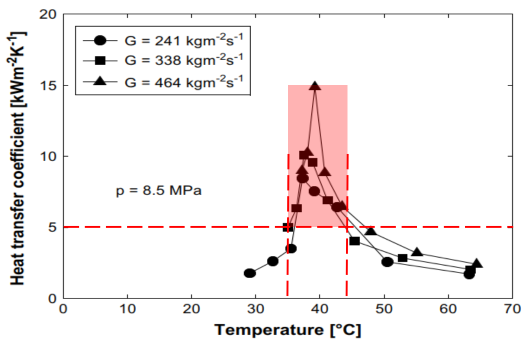
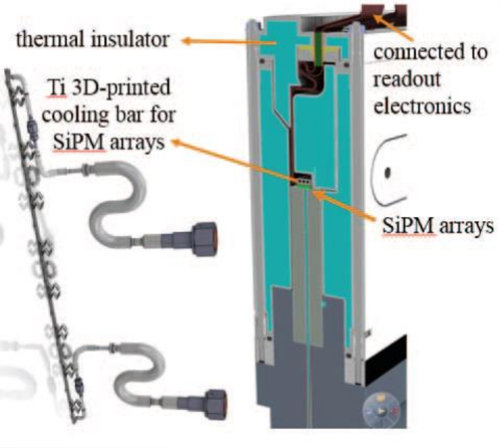
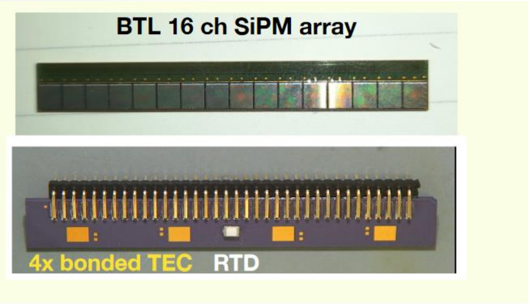


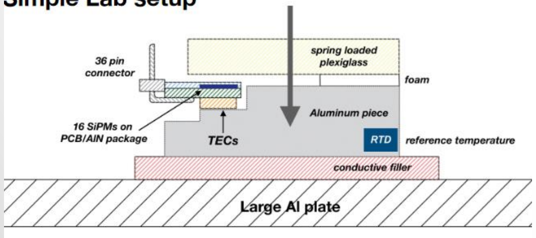
Fig. 3 – Heat transfer coefficient versus bulk temperature for different mass fluxes by Yoon et al. (2003).

Silicon Photomultipliers (SiPM)





Simple Lab setup



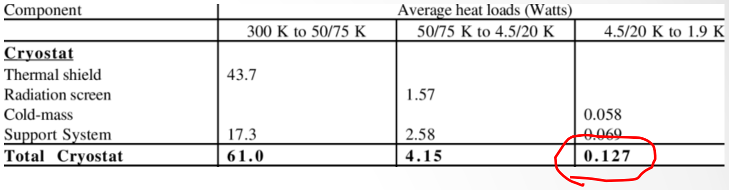
CMS SiPM with TEC cooling

- 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)
  - Krypton based cooling like slide 10
- R&D involves:
  - Cooling fluid use
  - Cooling cycle
  - Insulation / mechanical structure design concept

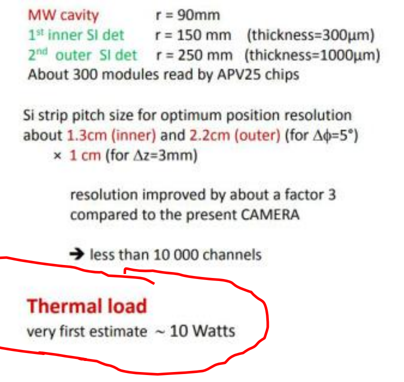
Cryogenic detectors

- The central tracker of AMBER has very challenging cryogenic requirements.
  - It needs to be cooled below 1.8K with significant heat loads.
    - 10 Watt in a Ø500mm*630mm volume
    - Comparison: LHC magnet is 0.13 Watt
  - According cryo-experts this is unprecedented
  - Very serious R&D is needed to cool in this temperature and heat load domain
- Nobel liquid detectors with embedded electronics
  - Calorimeters (See Martin Aleksa talk)
  - Neutrino experiments
  - Needs better understanding or this is challenging cryogenic technologies

LHC magnet loads



Component	Average heat loads (Watts)		
	300 K to 50/75 K	50/75 K to 4.5/20 K	4.5/20 K to 1.9 K
Cryostat			
Thermal shield	43.7		
Radiation screen		1.57	
Cold-mass			0.058
Support System	17.3	2.58	0.069
Total Cryostat	**61.0**	**4.15**	**0.127**



MW cavity r = 90mm
1st inner SI det r = 150 mm (thickness=300µm)
2nd outer SI det r = 250 mm (thickness=1000µm)
About 300 modules read by APV25 chips

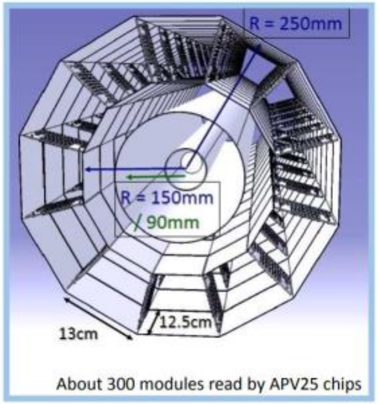
Si strip pitch size for optimum position resolution about 1.3cm (inner) and 2.2cm (outer) (for Δϕ=5°) × 1 cm (for Δz=3mm)

resolution improved by about a factor 3 compared to the present CAMERA

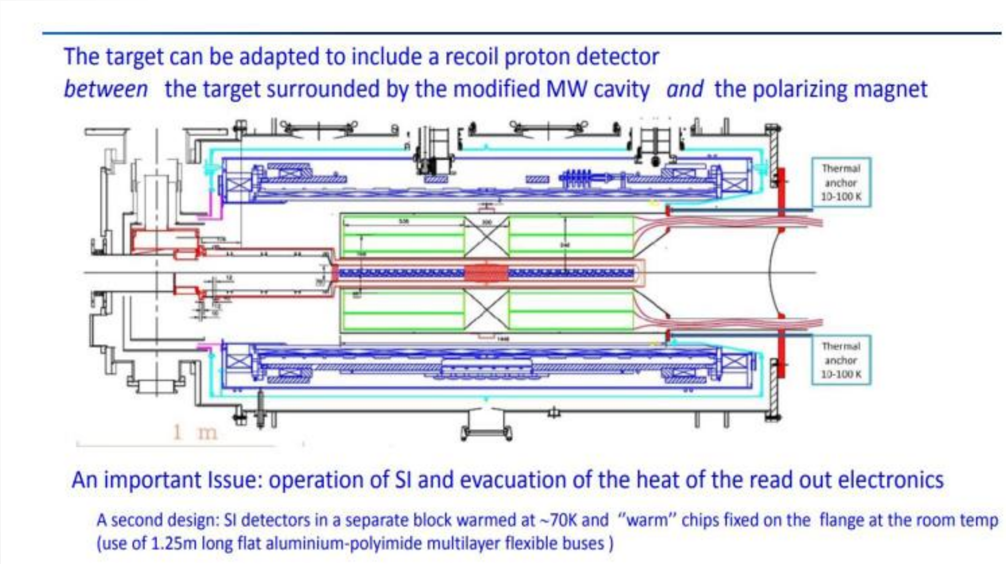
➔ less than 10 000 channels

Thermal load

very first estimate ~ 10 Watts



About 300 modules read by APV25 chips



The target can be adapted to include a recoil proton detector *between* the target surrounded by the modified MW cavity *and* the polarizing magnet

An important Issue: operation of SI and evacuation of the heat of the read out electronics

A second design: SI detectors in a separate block warmed at ~70K and "warm" chips fixed on the flange at the room temp (use of 1.25m long flat aluminium-polyimide multilayer flexible buses)

Summary

- 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
  - High heat density warm cooling applications (15°C / 35°C)
    - Super and sub critical CO_2 cooling
  - Low heat density warm cooling applications (15°C / 35°C)
    - Super and sub critical CO_2 cooling
    - Water and Novec single phase cooling
    - Direct air cooling solutions
- A special attention to the following specific detectors is needed
  - SiPM cooling including thermal housing design (-40°C / -150°C), using technologies mentioned above
  - Cryogenic AMBER tracker using very low temperatures with relative large heat dissipation