CERN


12th Forum on Tracking Detector Mechanics

Purdue University, West Lafayette, USA
29-31 May 2024

MANCHESTER
1824
The University of Manchester

DRD8 WG3

Bart Verlaat and Oscar Augusto de Aguiar Francisco

On behalf of the DRD8 preparation group

Forum on Tracking Mechanics

29-31 May 2024

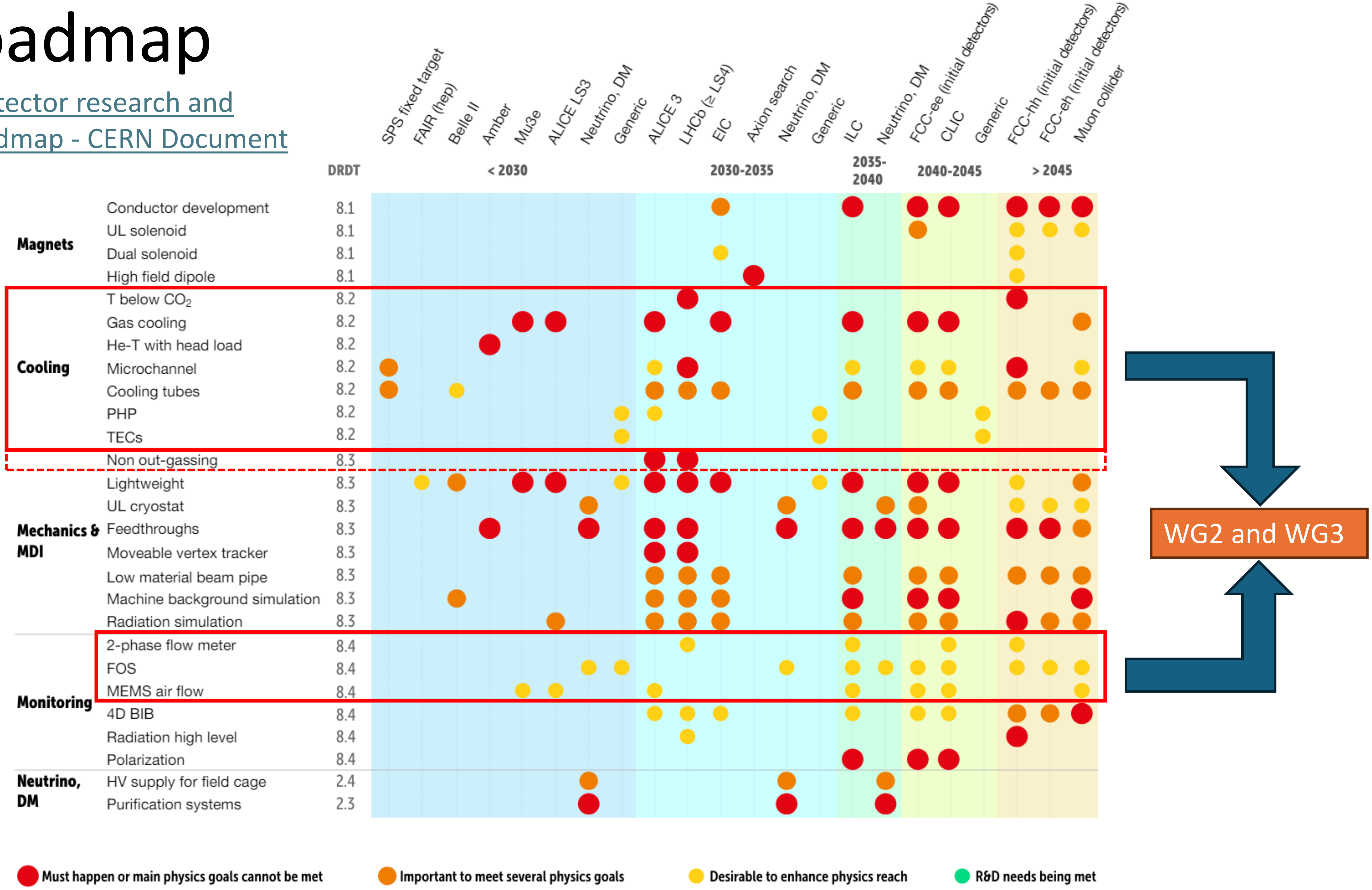
Purdue University, West Lafayette, USA

Goal of the DRD8 WG3

- To identify the development directions for cooling related topics.
- To find partner institutes to setup and define research
- To coordinate the activities and funding
- To indicate existing and available research facilities

ECFA roadmap

[The 2021 ECFA detector research and development roadmap - CERN Document Server]



		DRDT	< 2030								2030-2035						2035-2040		2040-2045			> 2045		
			SPS fixed target	FAIR (hep)	Belle II	Amber	Mu3e	ALICE LS3	Neutrino, DM	Generic	ALICE 3	LHCb (≥ LS4)	EIC	Axion search	Neutrino, DM	Generic	ILC	Neutrino, DM	FCC-ee (initial detectors)	CLIC	Generic	FCC-hh (initial detectors)	FCC-eh (initial detectors)	Muon collider
Magnets	Conductor development	8.1											🟠				🔴		🔴	🔴		🔴	🔴	🔴
	UL solenoid	8.1																	🟠			🟡	🟡	🟡
	Dual solenoid	8.1											🟡									🟡		
	High field dipole	8.1												🔴								🟡		
Cooling	T below CO_2	8.2										🔴										🔴		
	Gas cooling	8.2					🔴	🔴			🔴		🔴				🔴		🔴	🔴				🟠
	He-T with head load	8.2				🔴																		
	Microchannel	8.2	🟠								🟡	🔴					🟡		🟡	🟡		🔴		🟡
	Cooling tubes	8.2	🟠		🟡						🟠	🟠	🟠				🟠		🟠	🟠		🟠	🟠	🟠
	PHP	8.2								🟡	🟡					🟡					🟡			
	TECs	8.2								🟡						🟡					🟡			
Mechanics & MDI	Non out-gassing	8.3									🔴	🔴												
	Lightweight	8.3		🟡	🟠		🔴	🔴		🟡	🔴	🔴	🔴			🟡	🔴		🔴	🔴		🟡		🟠
	UL cryostat	8.3							🟠						🟠			🟠	🟠			🟡	🟡	🟡
	Feedthroughs	8.3				🔴			🔴		🔴	🔴			🔴		🔴	🔴	🔴	🔴		🔴	🔴	🟠
	Moveable vertex tracker	8.3									🔴	🔴												
	Low material beam pipe	8.3									🟠	🟠	🟠				🟠		🟠	🟠		🟠	🟠	🟠
	Machine background simulation	8.3			🟠						🟠	🟠	🟠				🔴		🔴	🔴				🔴
	Radiation simulation	8.3						🟠			🟠	🟠	🟠				🟠		🟠	🟠		🔴	🟠	🟠
Monitoring	2-phase flow meter	8.4										🟡					🟡			🟡		🟡		
	FOS	8.4							🟡	🟡					🟡		🟡	🟡	🟡	🟡		🟡	🟡	🟡
	MEMS air flow	8.4					🟡	🟡			🟡						🟡		🟡	🟡				🟡
	4D BIB	8.4									🟡	🟡	🟡				🟡		🟡	🟡		🟠	🟠	🔴
	Radiation high level	8.4										🟡										🔴		
	Polarization	8.4															🔴		🔴	🔴				
Neutrino, DM	HV supply for field cage	2.4							🟠						🟠			🟠						
	Purification systems	2.3							🔴						🔴			🔴						

🔴 Must happen or main physics goals cannot be met
🟠 Important to meet several physics goals
🟡 Desirable to enhance physics reach
🟢 R&D needs being met

WG2 and WG3

Boundary between WG3/2 from LOI

Current identified research topics

All red are directly cooling related

WG 8.2: Low Mass Mechanics and thermal management:

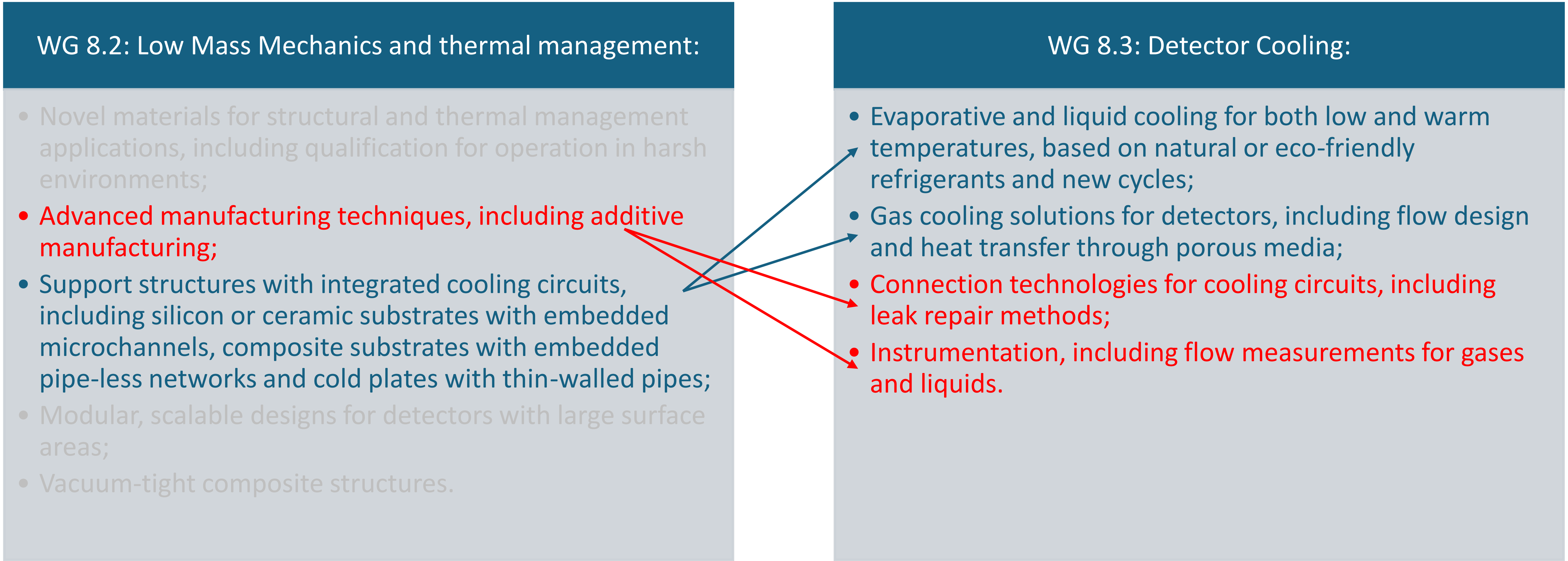
- Novel materials for structural and thermal management applications, including qualification for operation in harsh environments;
- Advanced manufacturing techniques, including additive manufacturing;
- Support structures with integrated cooling circuits, including silicon or ceramic substrates with embedded microchannels, composite substrates with embedded pipe-less networks and cold plates with thin-walled pipes;
- Modular, scalable designs for detectors with large surface areas;
- Vacuum-tight composite structures.

WG 8.3: Detector Cooling:

- Evaporative and liquid cooling for both low and warm temperatures, based on natural or eco-friendly refrigerants and new cycles;
- Gas cooling solutions for detectors, including flow design and heat transfer through porous media;
- Connection technologies for cooling circuits, including leak repair methods;
- Instrumentation, including flow measurements for gases and liquids.

These two groups cannot be disentangled in many aspects
(coolant – cooling plate, integration-local cooling plate, coolant-material compatibility, scalability-integration, …)

Similarities between WG3/2



WG 8.2: Low Mass Mechanics and thermal management:

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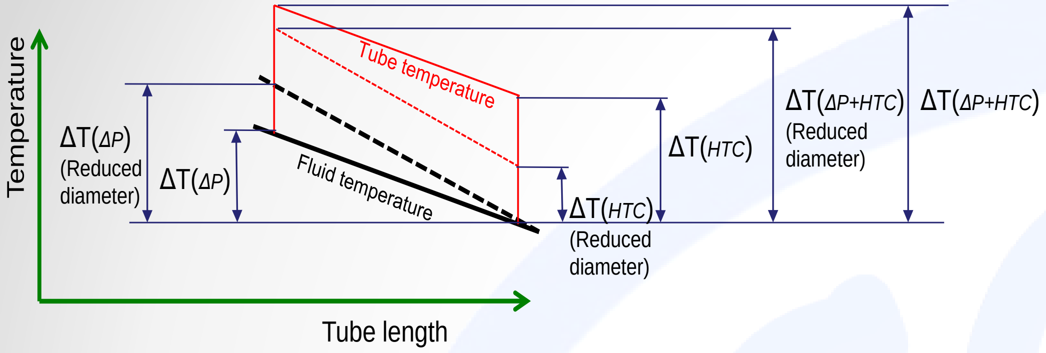
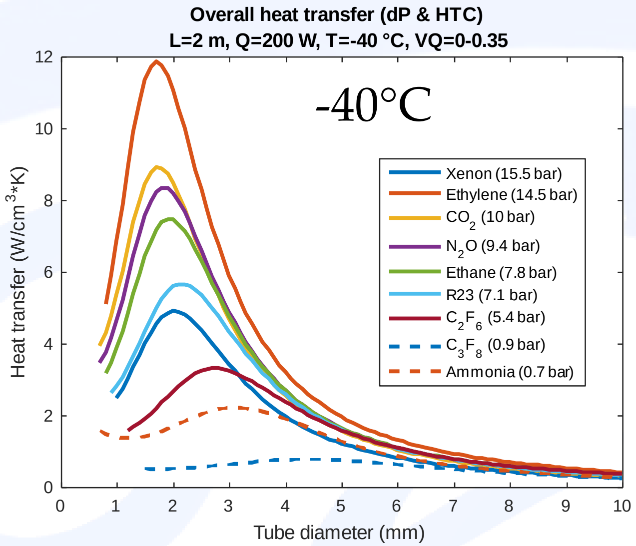
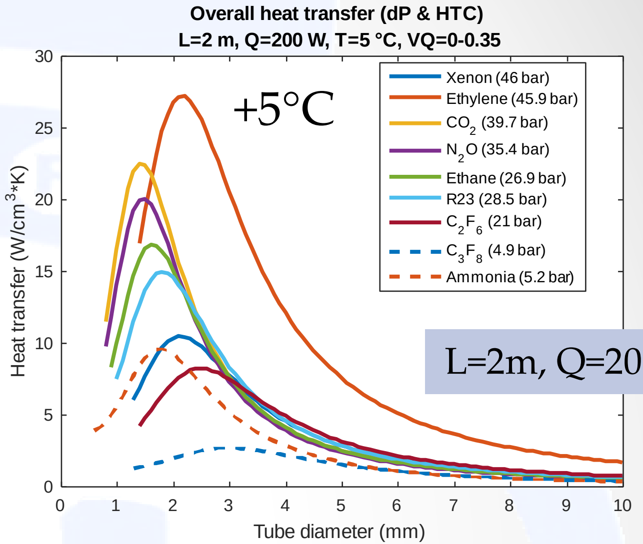
You cannot separate the same colors from each other. Developing integrated cooling means you need to integrate the right geometry for best heat transfer, not just integrate a channel .
Connection methods and new instrumentation are often based on additive manufacturing

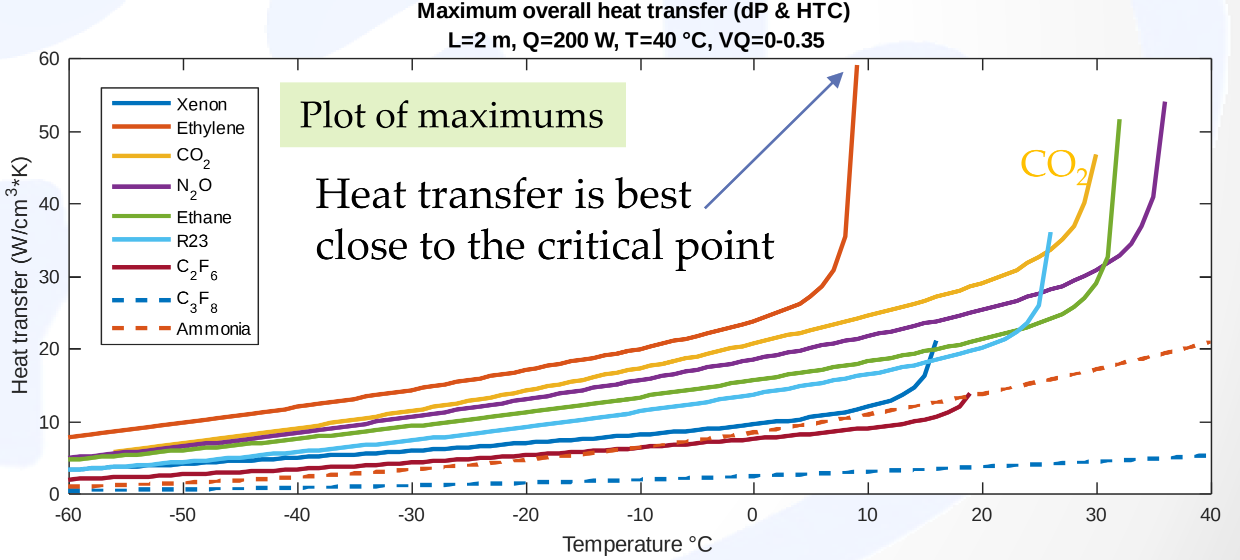
Fluid comparison and temperature performance




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

L=2m, Q=200Watt


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

Plot of maximums

Heat transfer is best close to the critical point

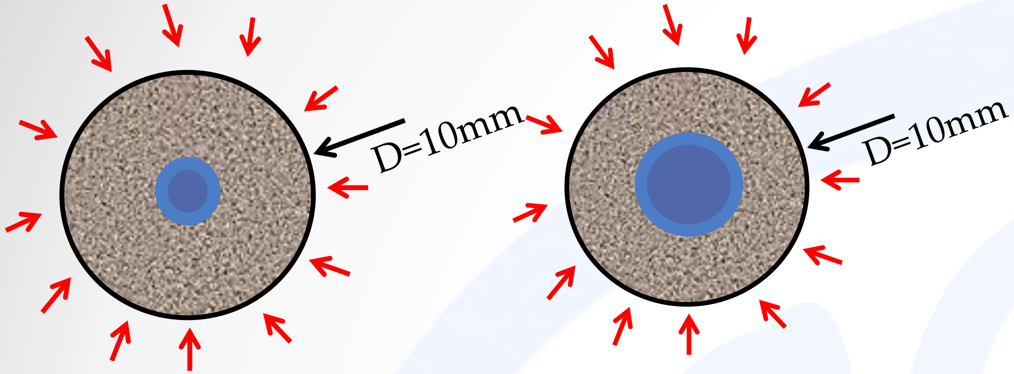
Slides from FCC workshop 2020

https://indico.cern.ch/event/932973/contributions/4102407/attachments/2142143/3609779/CoolingTalkFCCworkshop10nov20.pdf

What about this mysterious critical point?

- The cooling optimization fluid comparison is explained in detail at:
  - Slides of the 2013 Forum in Oxford (UK), https://indico.cern.ch/event/233332/contributions/1546088/attachments/388971/540971/ForumSlides18jun2013.pdf
- In the Encyclopaedia of Two-Phase Heat Transfer and Flow:
  - P. Petagna, B. Verlaat, A. Francescon, “Two-Phase Thermal Management of Silicon Detectors for High Energy Physics”, in J.R. Thome (Ed), Encyclopaedia of Two-Phase Heat Transfer and Flow III, World Scientific, 2018, pp. 335-412

Optimize design for the detector



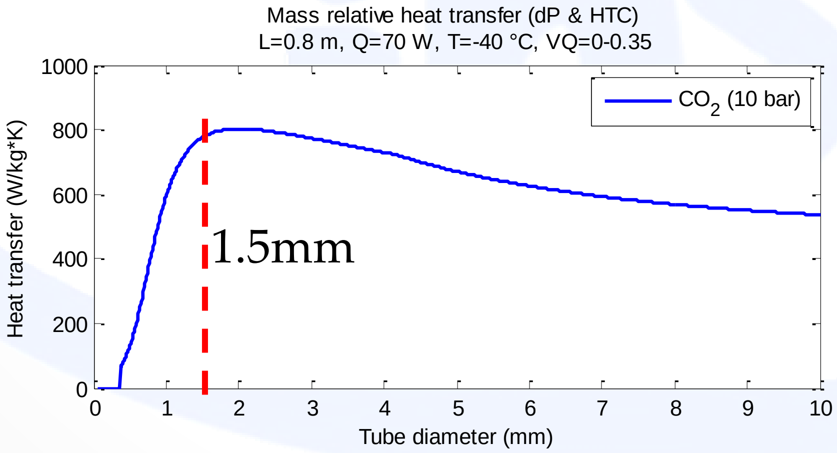
- Minimize the cooling pipe only is not necessary the optimum.
- A small pipe makes the cooling hardware light but depending on the design it can be replaced by other material.
- The pipe interface becomes smaller and hence temperature gradients can increase over this interface
  - Glued pipes are critical for small glue surfaces
- A full conductance picture must be included in the analyses for optimization

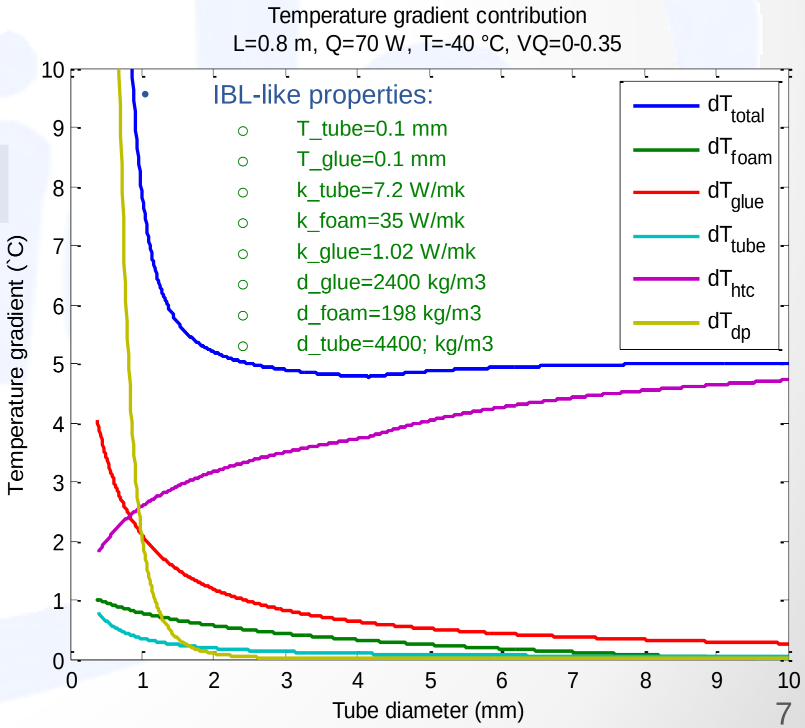
This combined cooling pipe/detector conductive path optimization is needed and is a combined WG2 and WG3 activity

ATLAS IBL optimization

Slides from FCC workshop 2020

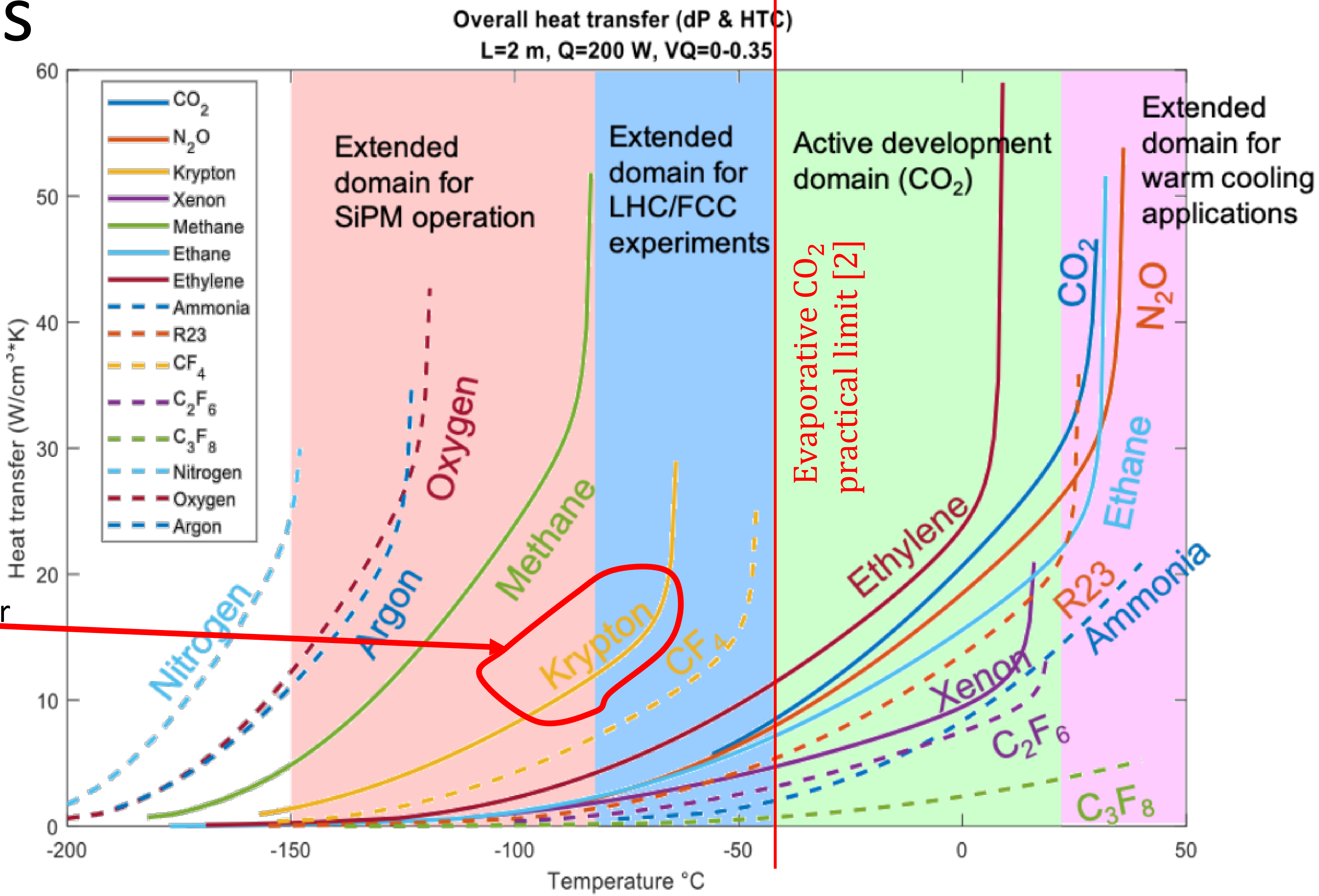
https://indico.cern.ch/event/932973/contributions/4102407/attachments/2142143/3609779/CoolingTalkFCCworkshop10nov20.pdf





- IBL-like properties:
  - T_tube=0.1 mm
  - T_glue=0.1 mm
  - k_tube=7.2 W/mk
  - k_foam=35 W/mk
  - k_glue=1.02 W/mk
  - d_glue=2400 kg/m3
  - d_foam=198 kg/m3
  - d_tube=4400; kg/m3

Coolants



Interesting candidate fluid for temperatures below CO2

- No R&D is advised for any fluorocarbon or other greenhouse cooling liquid. (roadmap)

Next generation of synthetic refrigerants?

The use of F-gasses in the past decades has a severe impact on humans and the environment:

- Depletion of the ozone layer (CFCs)
- Global warming (CFCs, HCFs, HFCs) Fluorocarbons @ CERN
- Poisonous decomposition products in new HFO class (PFAS*) NOVEC @ CERN
  - Acidification of our waters by TFA
  - New "allowed" HFO-1234yf is a serious treat to the environment
  - See warning report: https://atmosphere.cool/hfo-tfa-report/

*PFAS (Per- and polyfluorinated alkyl substances), also known as the **Forever Chemicals.**
Large chemical family of over 9,000 highly persistent chemicals that don't occur in nature.

Investigations by NIST (M. McLinden @ ICR2019) show that by theoretical analyses of all possible molecule combinations that the options for the use of efficient cooling fluids without the risk of a future ban by regulations are **the use of natural refrigerants only**. Any other chemical fluid will sooner or later be banned by regulations.

NTNU
Slides: Armin Hafner

CERN and the Environment (12-13 October 2022): Overview · Indico

Operating field (simplified)

Sc=Super critical
2ph=2-phase
l=Liquid
G=gas

RED= R&D needed

Power density (W/cm^2)	$T < -45^\circ C$	$-45^\circ C < T < 15^\circ C$	$15^\circ C < T$
> 1	Krypton (2phKr, scKr)	2phCO_2	2phCO_2, scCO_2
$0.15 - 1$		2phCO_2 (Common)	2phCO_2 , scCO_2
< 0.15	Krypton, 2phN_2O N_2O/CO_2 mix Sublimation CO_2 (~~Novec~~*) or gN2	2phCO_2 or Liquid (~~Novec~~*)	2phCO2, scCO2 Liquid Air Special gas

Future cooling should only focus on natural refrigerants (CO_2, N_2O, Kr, Air, Water)
What about flammable gasses? There are some thermally very good candidates (Methane, Ethylene)

*Fluorocarbon-based coolants are not recommended, and if approved the European Chemical Agency Restriction draft will limit their usage even more (Annex XV, June Status Update EDMS) => GWP & PFAS regulations

Pre-DRD8 discussion

Indico page link

IPHC interest for R&D on low-mass pixel detection modules — *Jerome Baudot*
40/S2-D01 - Salle Dirac, CERN 14:20 - 14:40

University of Sheffield, ATLAS and beyond !! — *Paul Neil Kemp-Russell*
40/S2-D01 - Salle Dirac, CERN 14:40 - 15:00

CONTRIBUTION FROM THE CMS GROUP OF PERUGIA — *Dr Cristiano Turrioni*
40/S2-D01 - Salle Dirac, CERN 15:00 - 15:20

Investigating mechanical and cooling structures for future trackers (University of Manchester)
Oscar Augusto De Aguiar Francisco

Seamless Integration of Lightweight Mechanics in the Silicon Tracking System for the CBM Experiment at FAIR
Maksym Teklishyn

Ferrara's BESIII Group: Current Activities, Research Interests, Facilities — *Stefano Gramigna*
40/S2-D01 - Salle Dirac, CERN 16:00 - 16:20

Coffee break
40/S2-D01 - Salle Dirac, CERN 16:20 - 16:40

Composites for Tracking Detectors — *Laura Rhian Pickard*
40/S2-D01 - Salle Dirac, CERN 16:40 - 17:00

Detector mechanics, cooling and integration at DESY — *Andreas Mussgiller et al.*
40/S2-D01 - Salle Dirac, CERN 17:00 - 17:20

Carbon fiber composites structures: R&D goals at Purdue University for future detectors — *Sushrut Rajendra Karmarkar*
40/S2-D01 - Salle Dirac, CERN 17:20 - 17:40

Overview of the Work package on Mechanics in the CERN EP-R&D — *Corrado Gargiulo*
40/S2-D01 - Salle Dirac, CERN 17:40 - 18:00

Future detector cooling R&D lines at CERN — *Paolo Petagna*
40/S2-D01 - Salle Dirac, CERN 18:00 - 18:20

At 6 December 2023, groups have expressed their interests and available facilities for the different research topics.

https://indico.cern.ch/event/1344395\

- We will contact the groups to discuss their whishes and ideas.
- If you were not yet involved but interested in joining some related RnD let me know
- If you are at forum its good forum coffee talk

- Please contact me or Oscar:
  - "Bart Verlaat" <Bart.Verlaat@cern.ch>
  - "Oscar Augusto De Aguiar Francisco" <oscar.augusto@cern.ch>

Pre-DRD8 discussion

WG 8.2: Low Mass Mechanics and thermal management:

1. Novel materials for structural and thermal management applications, including qualification for operation in harsh environments;
2. Advanced manufacturing techniques, including additive manufacturing; (4x, Sheffield, Manchester, GSI, CERN)
3. Support structures with integrated cooling circuits, including silicon or ceramic substrates with embedded microchannels, composite substrates with embedded pipe-less networks and cold plates with thin-walled pipes; (7x, Strasbourg, Perugia, Manchester, GSI, DESY, Perdue, CERN)
4. Modular, scalable designs for detectors with large surface areas;
5. Vacuum-tight composite structures.

WG 8.3: Detector Cooling:

1. Evaporative and liquid cooling for both low and warm temperatures, based on natural or eco-friendly refrigerants and new cycles; (4x, Perugia, Manchester, DESY, CERN)
2. Gas cooling solutions for detectors, including flow design and heat transfer through porous media; (4x, Strasbourg, Perugia, DESY, CERN)
3. Connection technologies for cooling circuits, including leak repair methods; (2x, Sheffield, Manchester)
4. Instrumentation, including flow measurements for gases and liquids. (1x, CERN)

We will contact you soon to discuss your ideas for input. If you are at the forum, lets have a coffee…

Cooling system cycle and fluid research at CERN

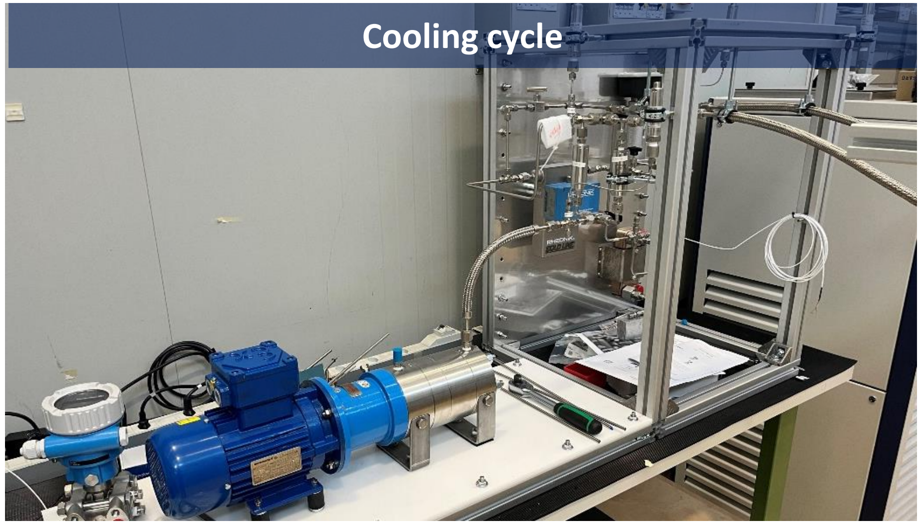
Supercritical CO2 for warm applications

In the range +32 C to + 40 C

(C. Pedano)

Advantages:

- Simplicity of a single-phase cooling-like
  - Hydraulic pressure drop➔ gas-like
- Better heat and mass transfer properties than water.
- Dielectric fluid, Natural refrigerant



Cooling cycle

- Experimental setup almost completed @CERN,
- Start of experimental activity planned for June (after setup commissioning and calibration)

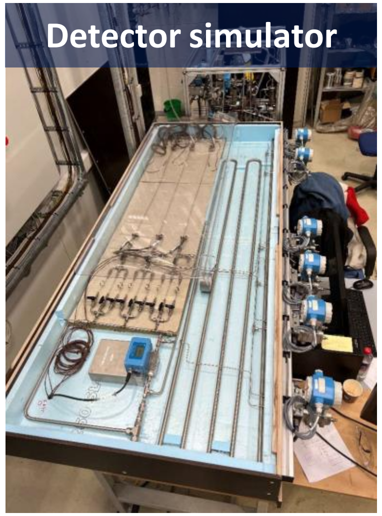
Super and subcritical Kr for cold applications

As low as -90C

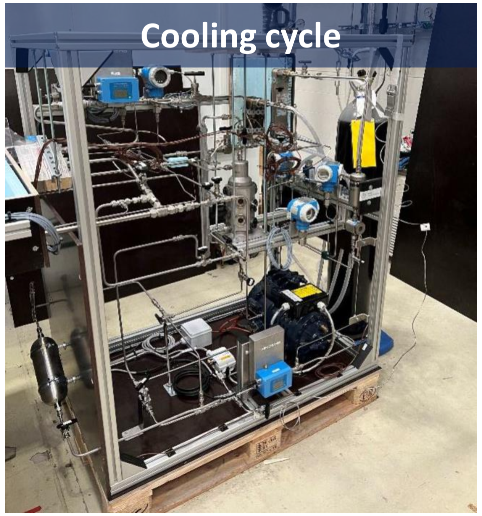
(L. Contiero)

Advantages:

- Expected similar behaviour as CO2 but then at cold. (The CO2 of the cold)
- New cycle in development, also applicable to other fluids.
- Dielectric fluid, Natural refrigerant



Detector simulator



Cooling cycle

- Experimental setup completed @NTNU, transfer at CERN planned for June
- Commissioning and calibration planned with CO_2

External partners

Hochschule Offenburg
offenburg.university

KIT
Karlsruher Institut für Technologie

Collaboration with

NTNU

AIDA innova

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA no 101004761.

NTNU – Trondheim
Norwegian University of Science and Technology

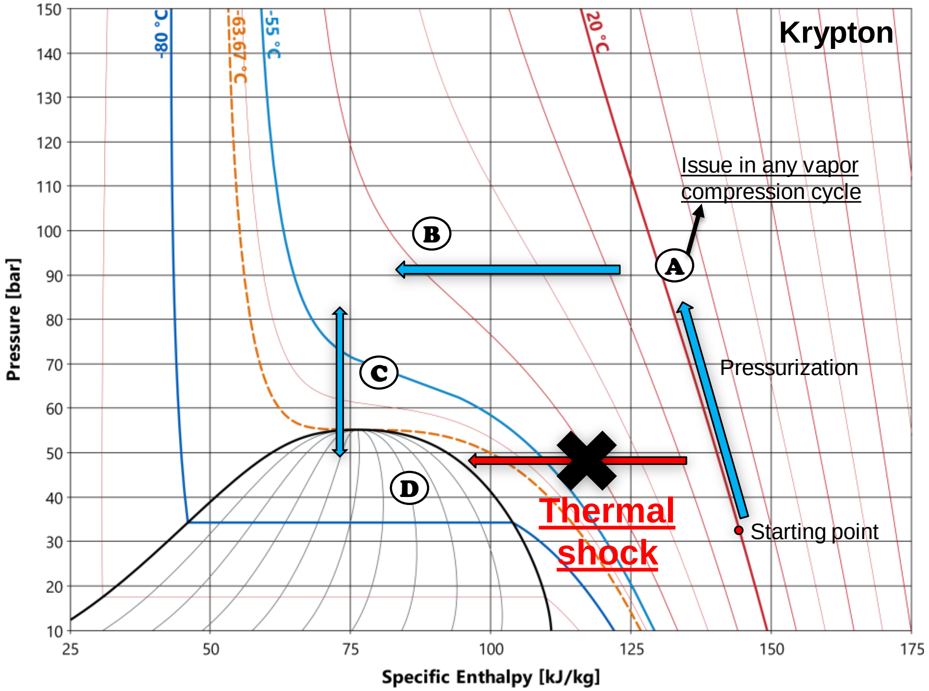
CERN
EP-DT
Detector Technologies

From -40°C to -70 °C and below
=> from R744 to R784

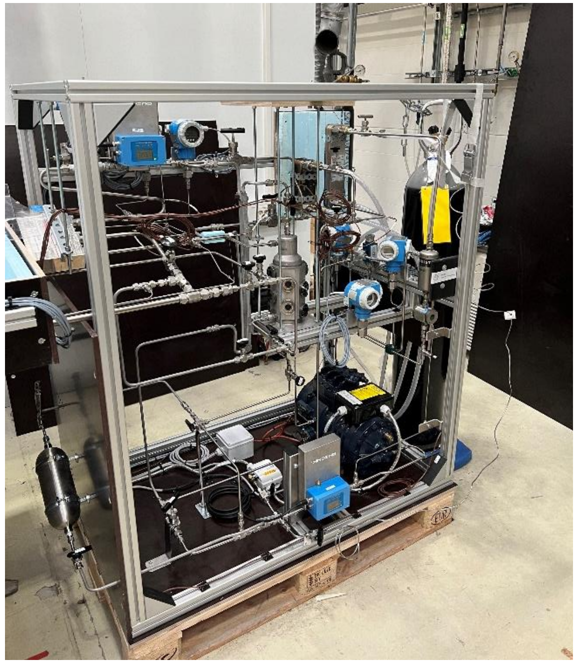
Is Krypton the CO_2 for colder temperatures?

Development of a new cycle with a new coolant
An ejector driven cycle with potential also for other fluids (Full control, no thermal chocks)

Maneuvering through the PH-diagram



Prototype ready at NTNU



A PhD project by Luca Contiero
1st paper published

https://doi.org/10.1016/j.nima.2024.169420

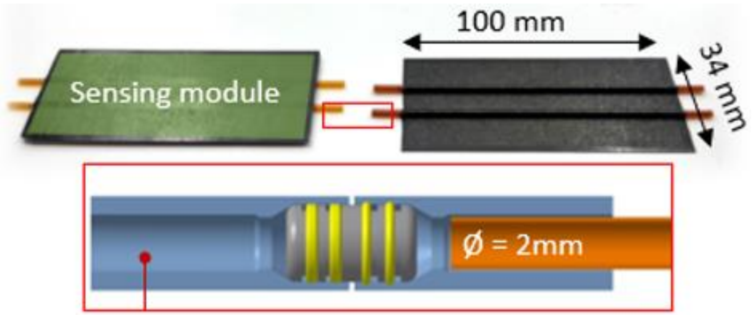
A new cold cooling system using krypton for the future upgrade of the LHC after the long shutdown 4 (LS4)

Future silicon detectors for High Energy Physics Experiments will require operation at lower temperatures to cope with radiation damage of the sensors…

doi.org

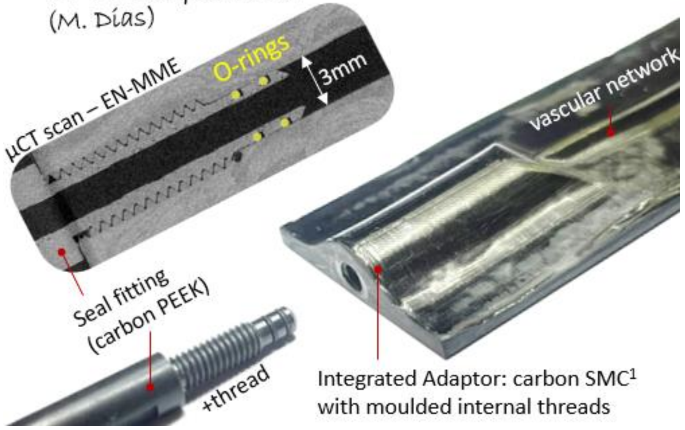
Interconnections

CERN C. Gargiulo (EP-DT day)



Adaptor: carbon PEEK machined

- Connection to the feedline
  EP-DT Composite Lab
  (M. Dias)



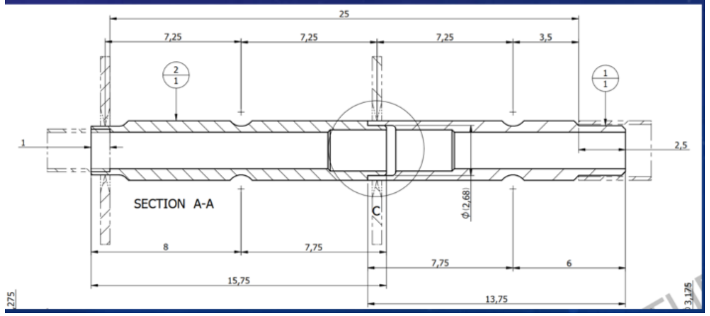
Integrated Adaptor: carbon SMC[1]
with moulded internal threads

University of Sheffield

Custom-made removable connection
(welding)

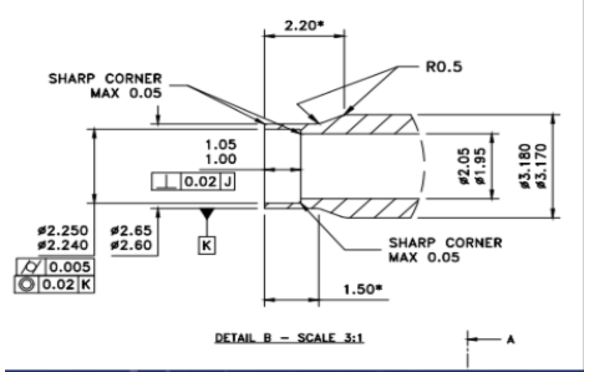
“fred”on Wiglet assembly

Details of socket/spigot integration joint
@1/8 “ on exhaust side. 0.5mm wt at joint



Experience with electrically
Insulating with ceramics

Detail of the 2.27mm sleeve
with 1 mm deep sleeve portion

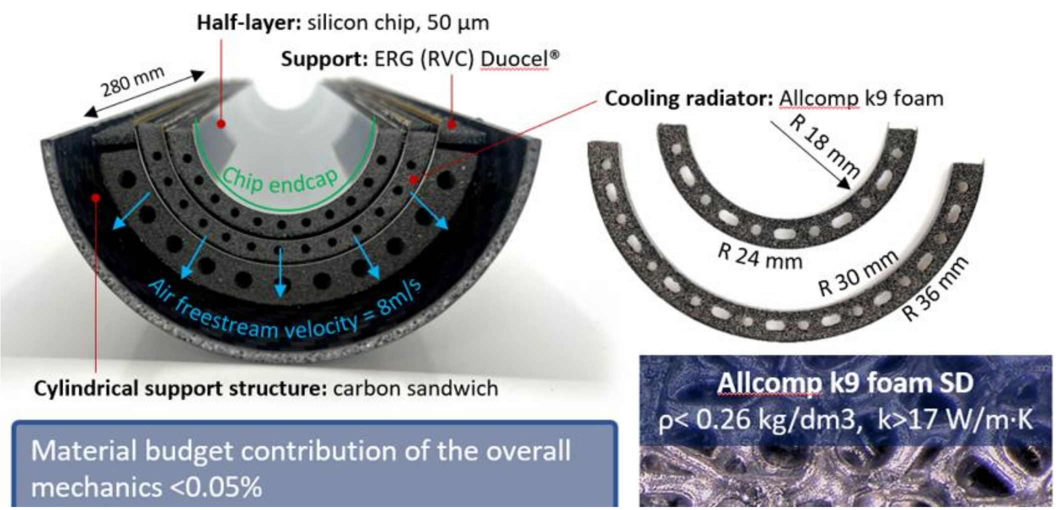


Gas Cooling for warm low power detectors (Typical e-e coliders)

CERN

C. Gargiulo
(EP-DT day)

- **Carbon foam** (EP R&D & ALICE team)

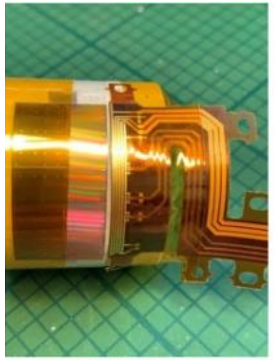


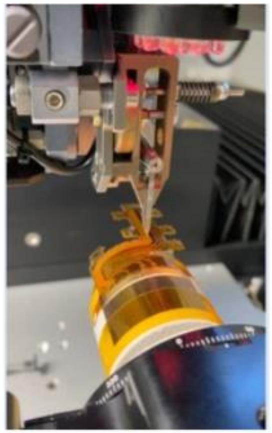
Material budget contribution of the overall mechanics <0.05%

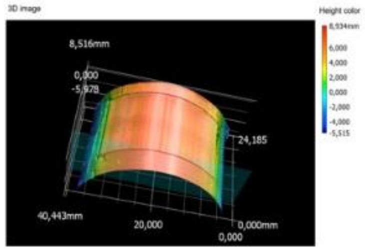
Allcomp k9 foam SD
ρ< 0.26 kg/dm3, k>17 W/m·K

IPHC/ CNRS/ University Strasbourg, J. Baudot

Sensor bending (Goal: reduce radius down to 1-3 cm)

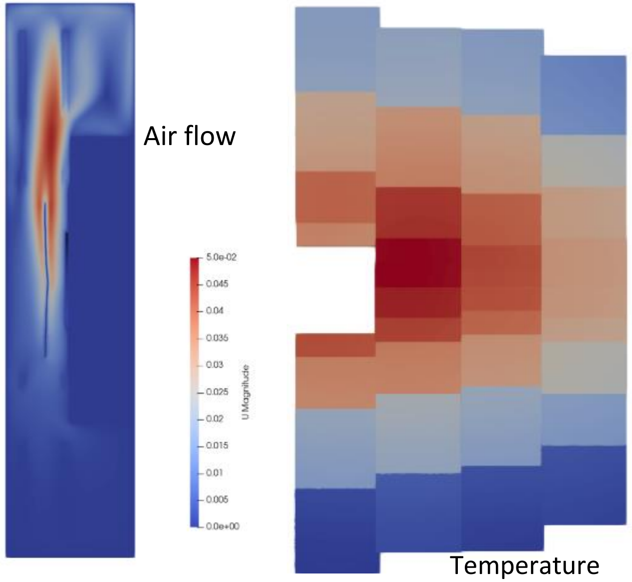






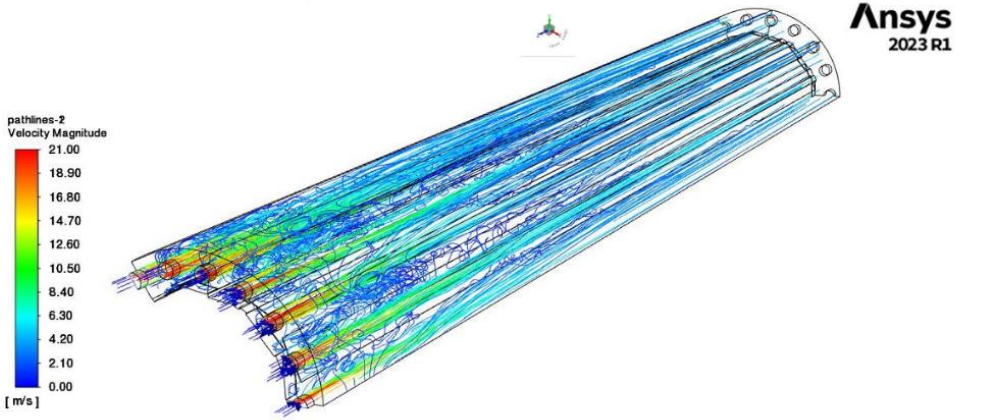
Curvature reached
(@ IPHC) 18 mm

Open source Air flow simulation(OpenFoam)
GSI-Darmstadt, M. Teklishyn



INFN Perugia, C. Turrioni

Air flow cooling simulation



Some talks were shown on the forum

Monitoring In combination with additive manufacturing

In-line temperature sensor

C. Manoli et al (Attract final report)

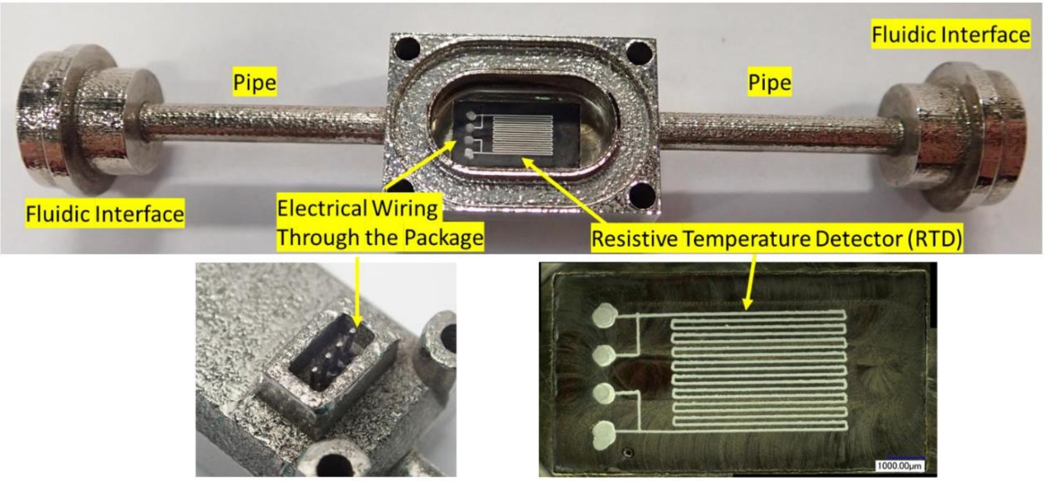


Fig. 1. AM constructed pipe from SLM with AJP patterned RTD embedded.

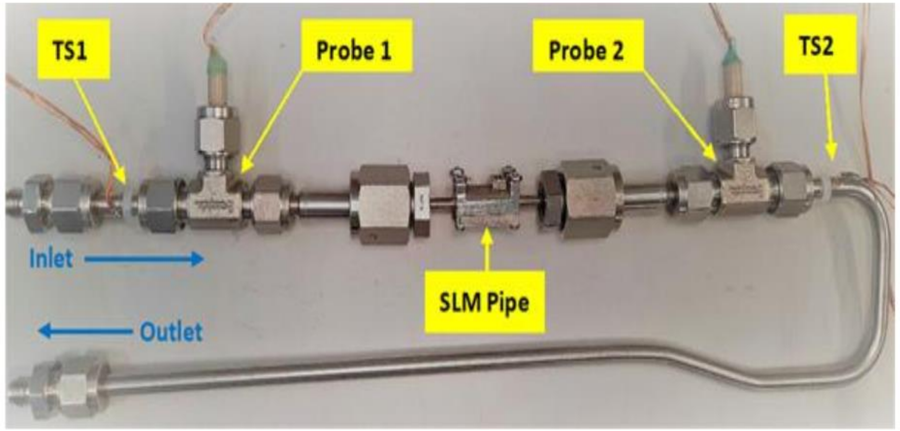
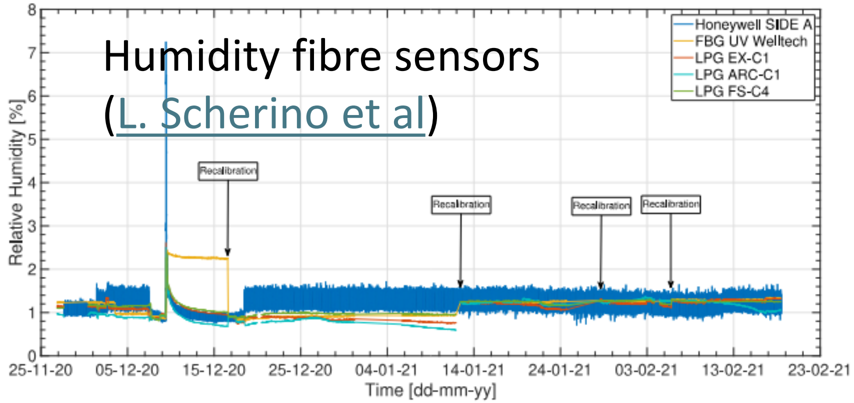


Fig. 3. Hydraulic circuit incorporating SLM pipe with RTD sensors.



Humidity fibre sensors
(L. Scherino et al)

New potential contributions not mentioned in the pre-DRD8 meeting(?)
- More contributions welcomed

New monitoring applications with fibers?
Large volume temperature mapping, integrated flow and pressure measurements?

Backup slides

DRD8 letter of intent

Because of the dependence on design choices for sensors, front-end electronics, and electrical and readout services, the work on mechanics and cooling is highly reliant on the system specifications. To enable targeted and collaborative R&D work in our field, we propose to focus on solutions within two application frameworks.

- Low intensity (LI): In this framework the mechanics and cooling will support sensors and electronics that have been designed for low power densities, possibly involving pulsed powering. The number and cross-section of electrical services will be small. Radiation damage levels will be low, and thus there will be no need to operate these systems cold (< 15 °C). Where possible, gas cooling will be an appealing solution. Radiation hardness levels of materials will be moderate. This will be the framework that will target, although not exclusively, experiments at future lepton colliders.

- High intensity (HI): Detector systems within this framework will have to cope with high particle densities of signal and background particles. The high channel density and complexity of the front-end electronics will result in high power densities, which will need to be supplied (likely by advanced powering systems like serial powering or DC-DC conversion), and removed by potent evaporative cooling systems. Significant radiation damage will require cold (< -35 °C) operation to keep leakage currents under control. Materials will need to be qualified for the high radiation environment. This will be the framework that will aim for experiments at future hadron machines.

Material minimisation and a good thermal connection between local heat sources and sinks will be major goals in both cases, but the optimisation will be different. Nevertheless, we do expect that some of the solutions we will develop will be of benefit for both frameworks.
To verify and benchmark the performance of the solutions developed in this R&D effort, and as physical deliverables, we propose the construction of demonstrators which take into account the specifications defined in the context of other DRD efforts like DRD3 or DRD7. These demonstrators should be exercised in realistic environments, in a test-beam and/or real physics experiments, where possible.

DRD8 letter of intent

- Mechanics is highly reliant on the system specifications

- Two potential optimization paths:

Low intensity	High intensity
low power	high power
low radiation	high radiation
$T < 15^\circ\mathrm{C}$	$T < -35^\circ\mathrm{C}$
targeting future lepton colliders	evaporative systems preferred
Liquid and gas cooling can be considered	targeting future hadron colliders

- Within the DRD8 framework, the proposal is to construct demonstrators defined in the context of DRD efforts like DRD3 and DRD7 to be tested in realistic environments (testbeam or physics experiments)

Timeline

Suggestion:

- To have the DRD8 Proposal ready for submission in autumn, we must start now nominating a team of people preparing and collecting the contents of the proposed R&D for each WG.
    - ➢ **We should create mailing lists for each WG and a general mailing list for DRD8.**
    - ➢ **It would be good to have one contact person per institute and WG to facilitate the collection of information.**
    - ➢ **We should nominate WG conveners asap, ideally 2-3 per WG.**
- We certainly need at least one more DRD8 meeting after the summer before submission of the Proposal.
    - **Boundaries of WG2 and WG3 should be discussed.**
    - **We need an overall editorial team, which could be the Steering Committee.**

Presented interest in cooling related matters (1)

- IPHC/ CNRS/ University Strasbourg, J. Baudot
  - 8.2.3 Integrated support structure and cooling
  - 8.3.2 Direct sensor air cooling

- University of Sheffield/ Lancaster University/ RAL/ QMUL, Paul Kemp-Russel
  - 8.2.2 Additive manufacturing
  - 8.3.3 Connection technologies

- INFN Perugia, C. Turrioni
  - 8.2.3 Integrated support structure and cooling
  - 8.3.1 Evaporative cooling and thermodynamics
  - 8.3.2 Direct sensor air cooling

- University of Manchester, O. Augusto de Aguiar Francisco
  - **Included in the “Microchannels cooling plates” at Forum on Tracking Mechanics 2024**
  - 8.2.2 Additive manufacturing
  - 8.2.3 Integrated support structure and cooling
  - 8.3.1 Evaporative cooling and thermodynamics
  - 8.3.3 Connection technologies

Presented interest in cooling related matters (2)

- GSI-Darmstadt, M. Teklishyn
  - 8.2.2 Additive manufacturing
  - 8.2.3 Integrated support structure and cooling

- Desy-Hamburg, A. Mussgiller
  - 8.2.3 Integrated support structure and cooling
  - 8.3.1 Evaporative cooling and thermodynamics
  - 8.3.2 Direct sensor air cooling

- Perdue University, S. Karmarkar
  - 8.2.3 Integrated support structure and cooling

- CERN, C. Gargiulo, P. Petagna, B.Verlaat
  - 8.2.1 Novel materials
  - 8.2.2 Additive manufacturing
  - 8.2.3 Integrated support structure and cooling
  - 8.3.1 Evaporative cooling and thermodynamics
  - 8.3.2 Direct sensor air cooling
  - 8.3.4 Instrumentation

Country/Institute	**Contr.WG1**	**Contr.WG2**	**Contr.WG3**	**Contr.WG4**	**Total**
France					
IPHC Strasbourg	1.5				1.5
CPPM Marseille		0.25	0.25		0.5
LPNHE Paris		0.4	0.3		0.7
Germany					
DESY	0.5	1.5	0.5		2.5
GSI Darmstadt		0.25		0.25	0.5
Italy					
INFN Pisa	0.2	0.2			0.4
INFN Perugia		0.25	0.25	0.5	1
Spain					
CNM Barcelona		0.5			0.5
IFIC Valencia	0.2	0.6	0.2		1
Switzerland					
CERN	1	2	1	1	5
Univ. of Geneva	0.25	0.5	0.25		1
United Kingdom					
UKRI-STFC RAL		0.25			0.25
University of Bristol		0.5			0.5
Bristol Comp. Inst.		1.5	0.25		1.75
Nat. Comp. Centre	0.25	2		1	3.25
Univ. of Manchester		1	1		2
Univ. of Oxford		0.75			0.75
Univ. of Sheffield			0.1		0.1
Univ. of Liverpool	0.4	0.8	0.2		1.4
USA					
Purdue University	1	2	2	1	6
Fermilab		0.5	0.5		1
LBNL and SLAC		0.5	0.5		1
Grand Total	**5.3**	**16.0**	**7.3**	**3.8**	**32.4**