SYSTEM DESIGN CHALLENGES FOR CO_2 EVAPORATIVE COOLING IN TRACKING DETECTORS

P. Tropea - CERN EP-DT

OUTLINE

This is not a talk about ALL advanced cooling techniques

(Vertex2017 P. Petagna)

This is not a "publicity" talk about CO_2

(Vertex2011, H. Postema)

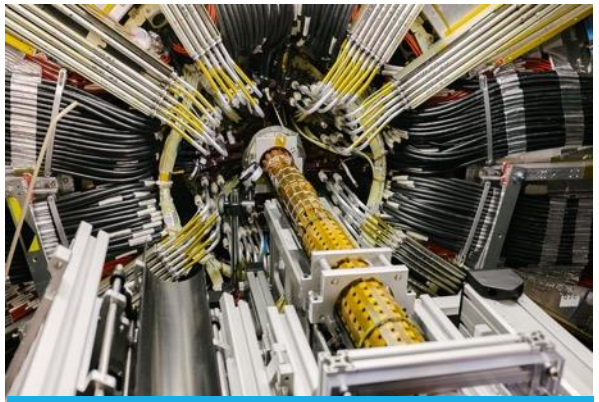
… but rather a collection of experiences & possible guidelines to get to a properly working CO_2 system

- Brief introduction to CO_2 cooling: the 2-PACL cycle
- The challenges in design phase
- Operational aspects
- Conclusions

WHERE?

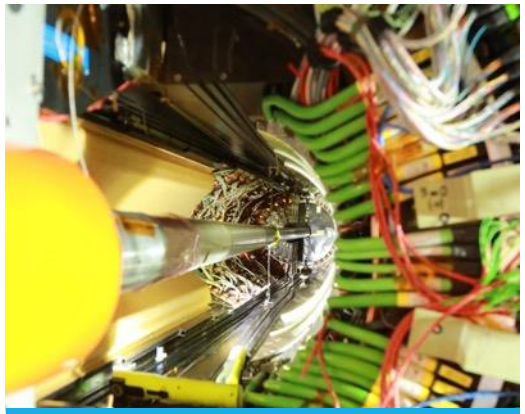
So far…

LHCb Velo 1.6 kW @ -25 C



ATLAS IBL 1.5 kW @ -35 C

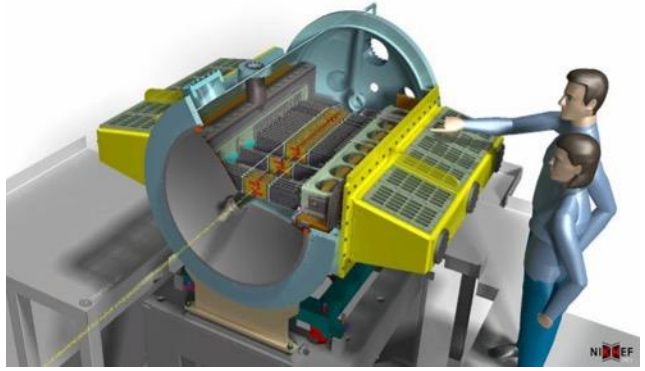
AMS Tracker 150 W @ -20 C



CMS Pix Phase I upgrade 7 kW @ -25 C

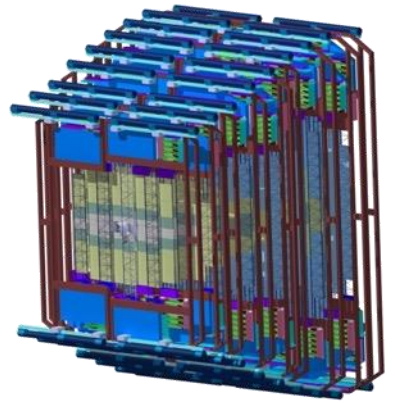
In the near future …

LHCb Velo Upgrade - 2 kW @ -35 C



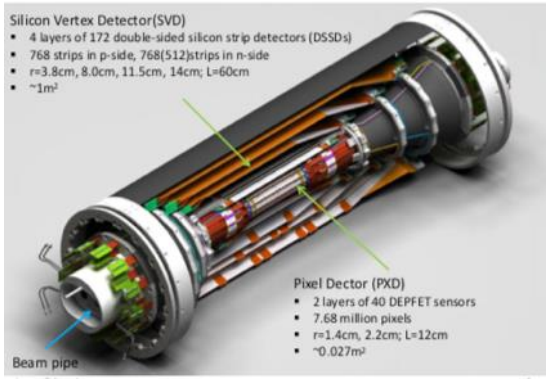
Source: The LHCb Collaboration, LHCb VELO Upgrade Technical Design Report, CERN/LHCC 2013-021, Nov 2013

CBM STS

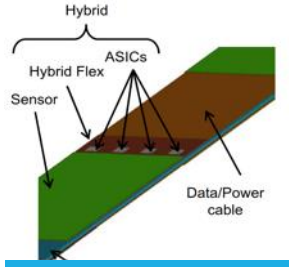


Source: A. Lymanets et al, "The Silicon Tracking System of the CBM at FAIR: detector development and system integration" TIPP 2014

BELLE II Vertex Detector



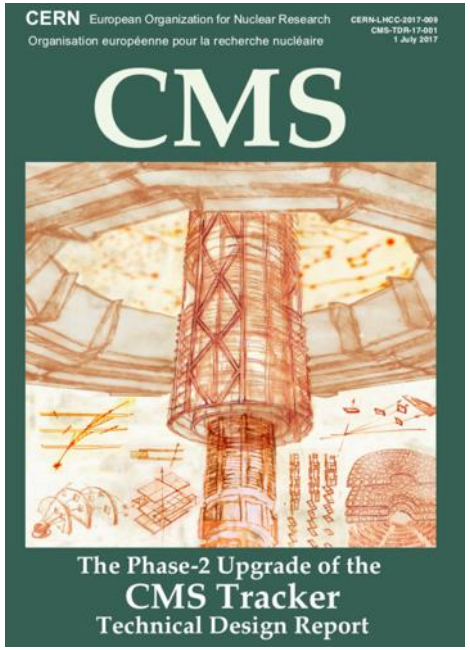
Source: H. Ye" Thermal Test and Monitoring of the Belle II Vertex Detector" Forum on Tracking Detector Mechanics 2016, Bonn

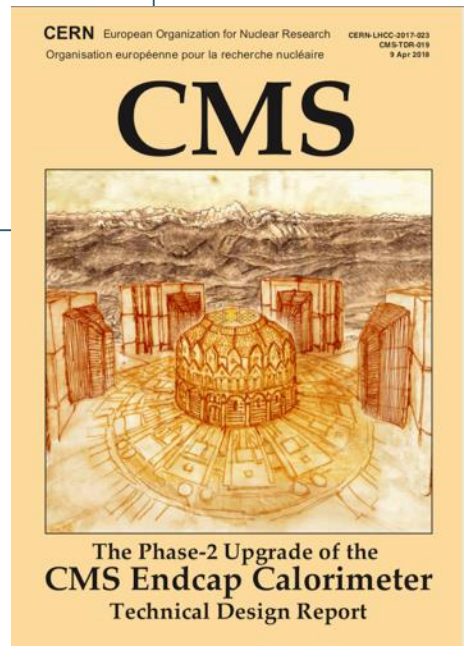


LHCb UT 5 kW @ -35 C

AND THEN? AT HL-LHC…

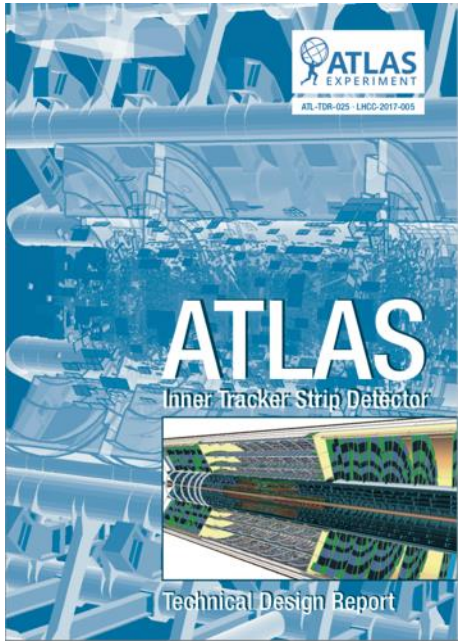
CMS

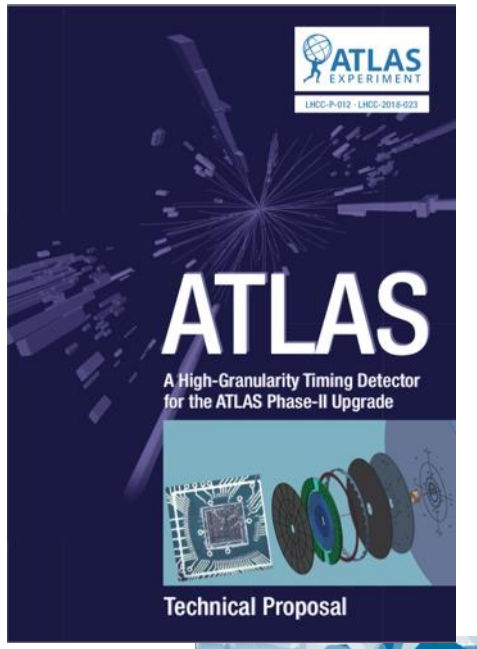


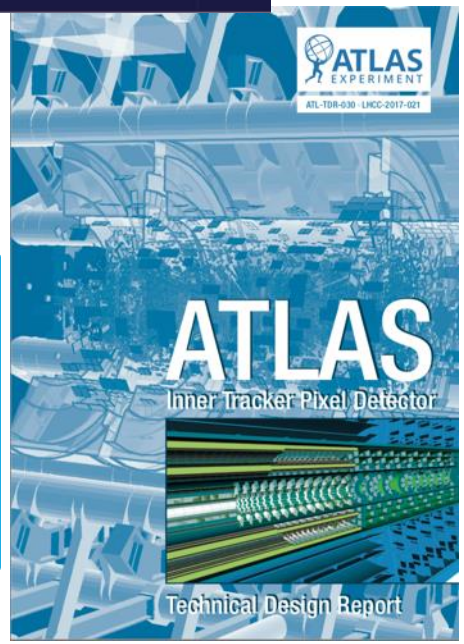


CMS	Evaporation T at the detector exit	Heat load of detector	Ambient pick up	Total heat
	ºC	kW	kW	kW
Outer Tracker	-35	102	11	113
Inner Tracker	-35	50	5	55
Barrel Timing Layer	-35	45	6.5	52
Calorimeter Endcap	-35	240	7	247
Endcap Timing Layer	-35	80	8.0	88
		517	37.5	555

ATLAS







ATLAS	Evaporation T at the detector exit	Heat load of detector	Ambient pick up	Total heat
	ºC	kW	kW	kW
Pixel Endcap	-30	26.2	2.6	113
Pixel Barrel	-35	55.1	5.5	60.61
Pixel Insertable	-45	20.6	2.1	23
Strip	-30	122.7	12.3	135
HGDT	-30	25	2.5	28
		249.6	24.96	359

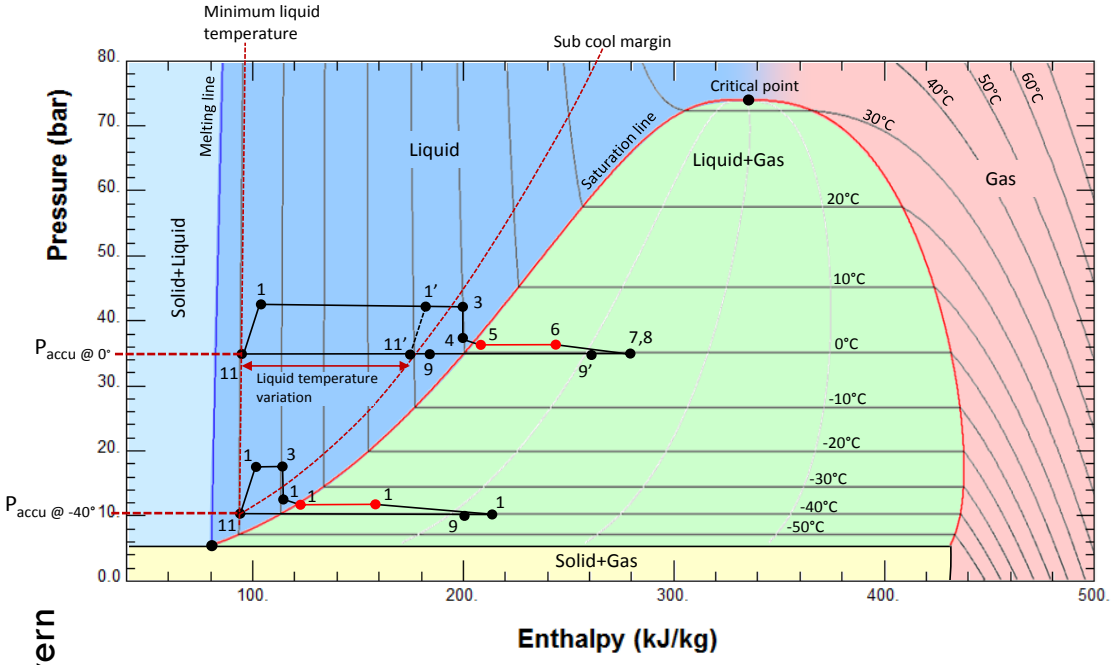
A good order of magnitude bigger & more complex than ever….

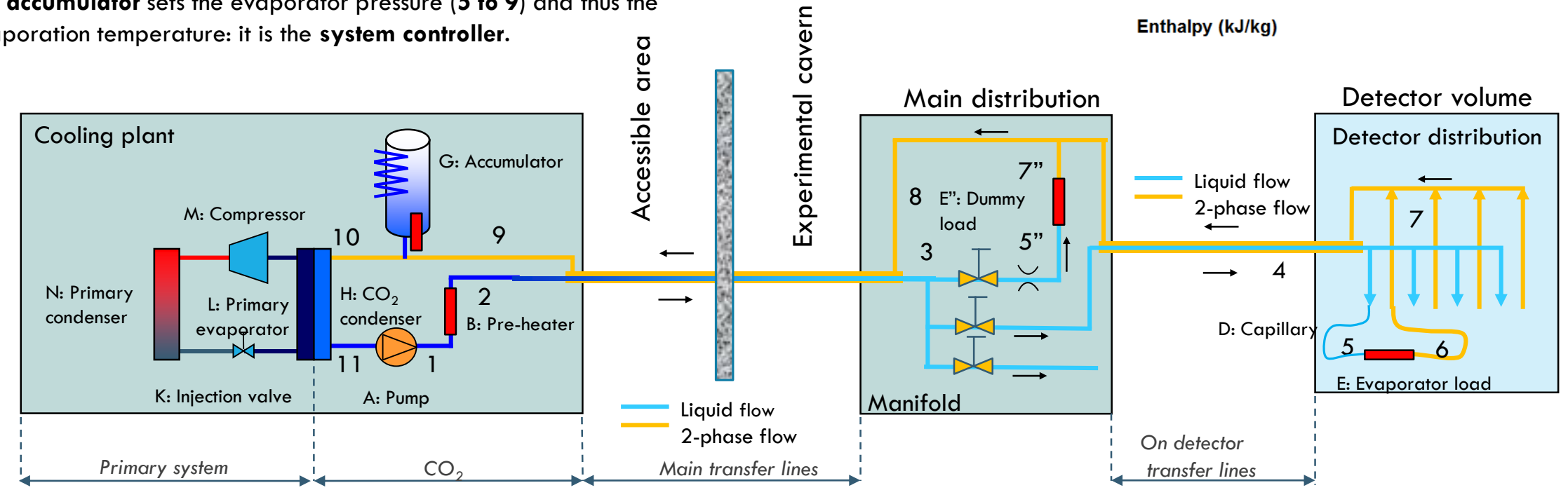
PAOLA.TROPEA@CERN.CH

THE CO2 2 PACL CYCLE

11-1: Subcooled liquid CO_2 is circulated using a membrane pump. **1-3:** Cold refrigerant passes through an internal heat exchanger where it exchanges heat with the return fluid and gets heated to the evaporator temperature. **3-5:** adiabatic + diabatic expansion. **5-6:** Saturated liquid now enters the **evaporator** where it cools the detectors. **8-9:** The return line forms the internal heat exchanger, and heats up the cold supply-side refrigerant to the evaporator temperature. **9-11:** The absorbed heat is dumped into the primary external chiller system (conventional vapour compression system) in the condenser, and subcooled liquid CO_2 is fed back to the pump.

The **accumulator** sets the evaporator pressure (**5 to 9**) and thus the evaporation temperature: it is the **system controller.**

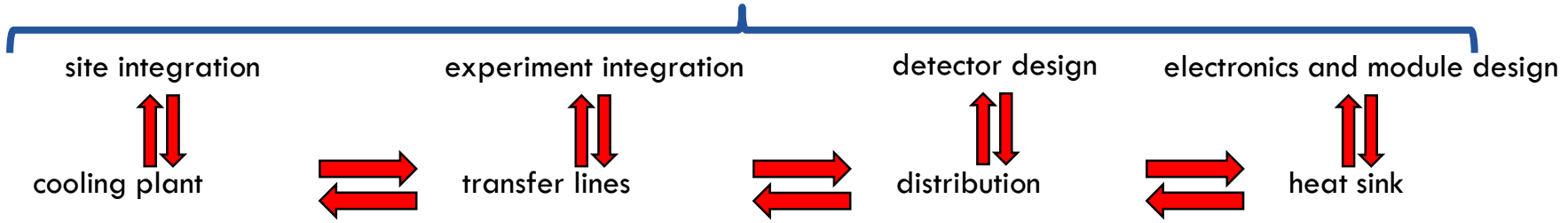




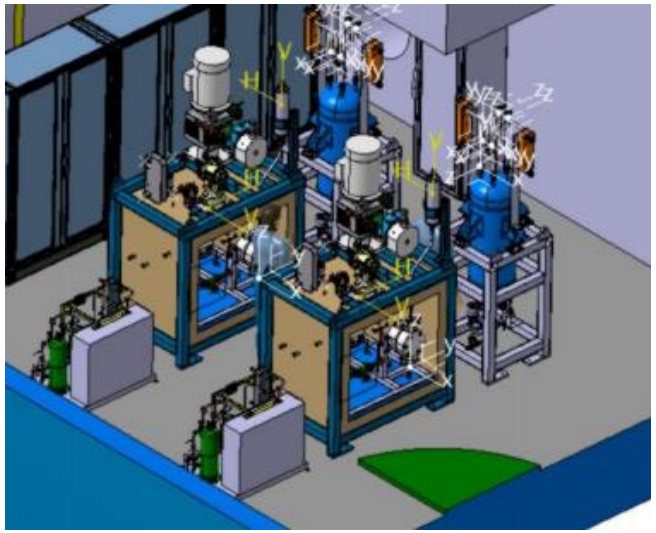
Verlaat B., Controlling a Two-Phase CO_2 Loop Using a Two-Phase Accumulator, ICR07-B2-1565, International Conference of Refrigeration, Beijing, China, 2007

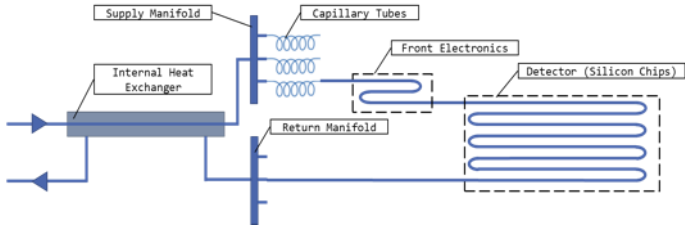
THE DESIGN CHAIN

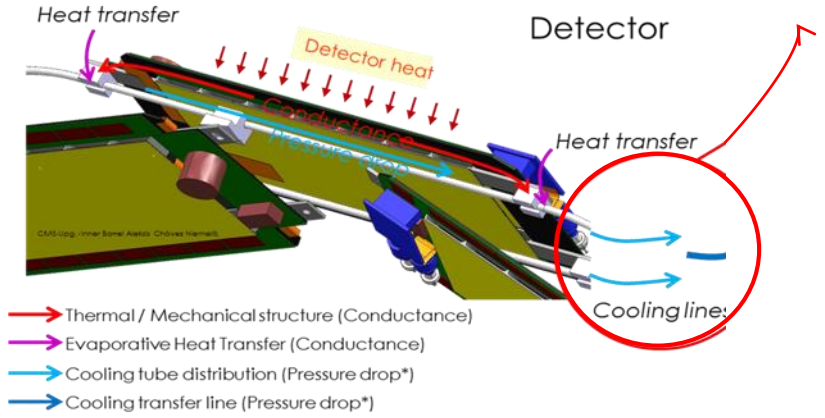
The complexity of an evaporative system: each design modification on a components would influence the behaviour of the full system: how?



Thermal contact not treated in this talk
See next talk from Georg + references at the end of this presentation







FROM REQUIREMENTS TO SPECS TO SYSTEM DESIGN (1)

Detector requirements: **power** & **inlet temperature** are not enough

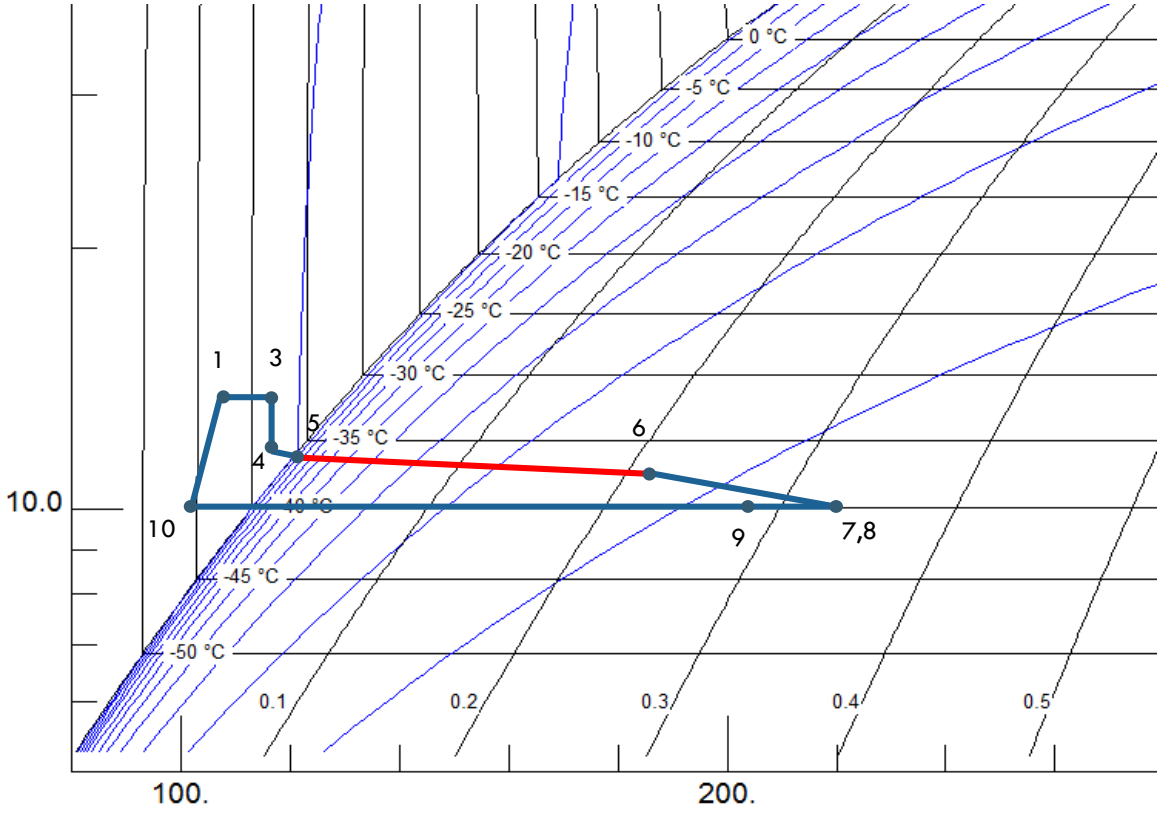
The temperature

The system controls T in 9, i.e. in order to specify the T of evaporation inside the detector, one need to know the Δp across the detector (5-6) & the return pipes (6-7,8)+ transfer lines (8-9) : in 2-phase, Δp= ΔT

Specs to system design:
- T @ accumulator
- Δp from 5 to 9: detector & all return lines

CO_2 operational limits: -47°C @ accumulator

L. Zwalinski https://doi.org/10.1016/j.nima.2018.09.093

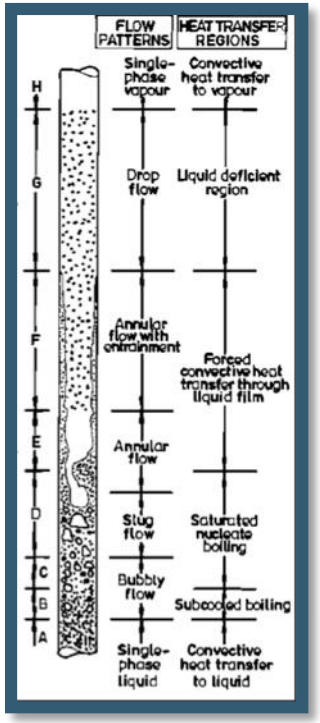


1) DETECTOR EVAPORATOR DESIGN

2) TRANSFER LINE DESIGN

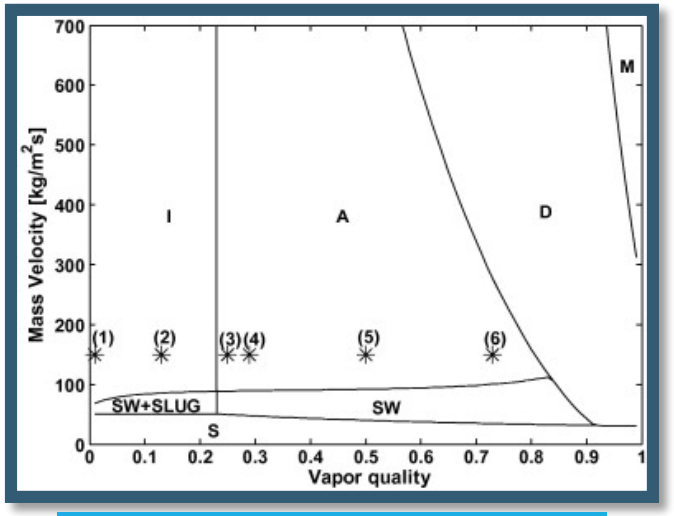
Need reliable models to predict Δp & Heat transfer coefficient (HTC) in boiling CO_2

THE CO_2 2-PHASE FLOW DP & HTC MODELS



Vertical pipe

Horizontal pipe



Cheng - CO_2 flow pattern map (2008)

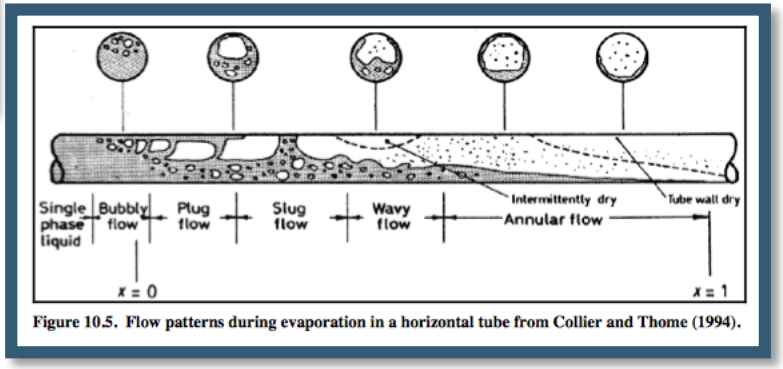
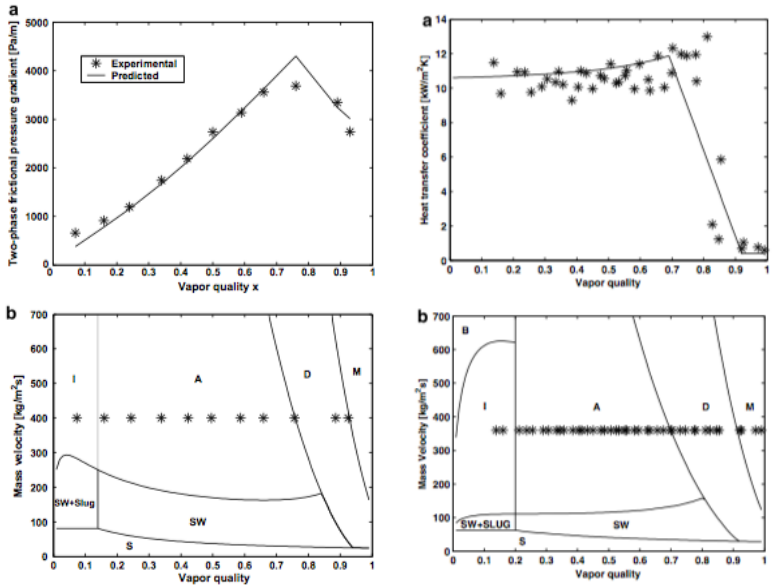


Figure 10.5. Flow patterns during evaporation in a horizontal tube from Collier and Thome (1994).

Frictional pressure drop (I) & HTC (II) prediction based on flow pattern maps



CO_2 two-phase pressure drops prediction methods

Method	Percentage of Predicted Points within ±30 %	Mean Error	Standard Deviation
Chisholm (1973)	56.1 %	48.6 %	73.8 %
Friedel (1979)	71.1 %	30.9 %	55.8 %
Grönnerud (1972)	30.2 %	75 %	113.1 %
Müller-Steinhagen and Heck (1986)	55.8 %	33.3 %	44.3 %
Modified Chisholm by Yoon et al. (2004)	47 %	34.7%	93.7%
Moreno Quibén and Thome (2007a, 2007b)	42.4 %	50.1%%	90.6%
Cheng et al. (2008a)	74.7 %	28.6%	44.3%

- *Thome J., 2009,"Wolverine Engineering Data Book III"*
- *Cheng L, Ribatski G, Quiben J, Thome J, 2008,"New prediction methods for CO2 evaporation inside tubes: Part I – A two-phase flow pattern map and a flow pattern based phenomenological model for two-phase flow frictional pressure drops", International Journal of Heat and Mass Transfer, vol 51, p111-124*
- *Cheng L, Ribatski G, Thome J, 2008,"New prediction methods for CO2 evaporation inside tubes: Part II– An updated general flow boiling heat transfer model based on flow patterns", International Journal of Heat and Mass Transfer, vol 51, p111-124*

Any calculation needs proper testing!

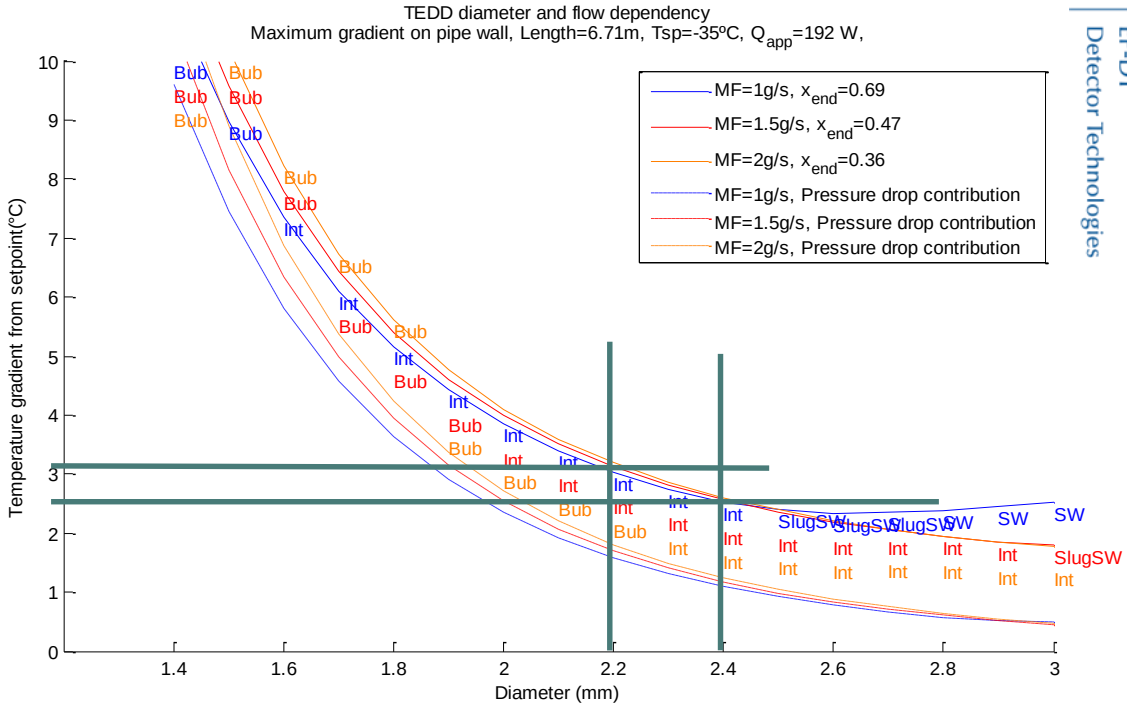
DETECTOR EVAPORATOR DESIGN

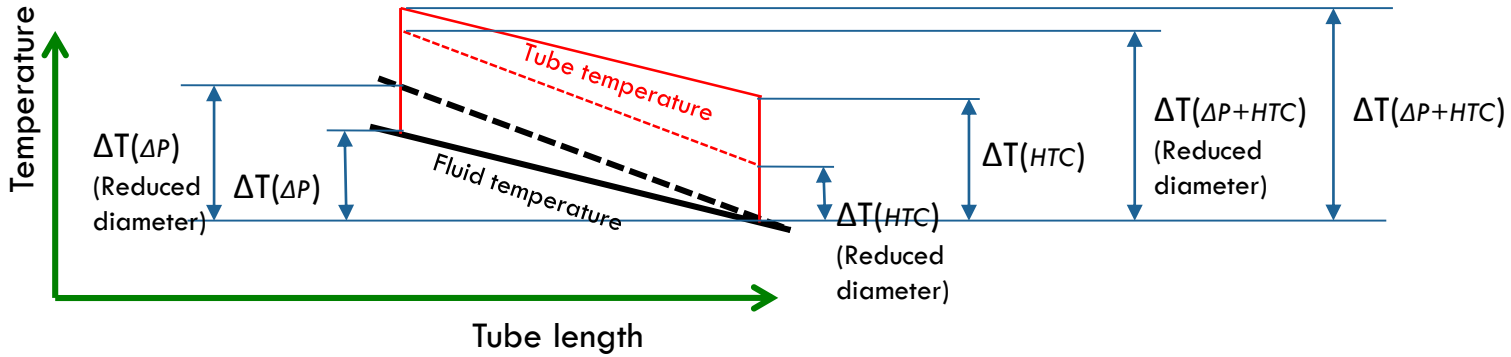
1) Low mass -> small pipe diameter, small wall thickness
2) Enhanced heat transfer coefficient -> small pipes!

BUT…

ΔT along detector increase with pressure drops (Δp) and reduced pipe diameter

The pipe size needs to be determined optimizing the combined ΔT(Δp+HTC)





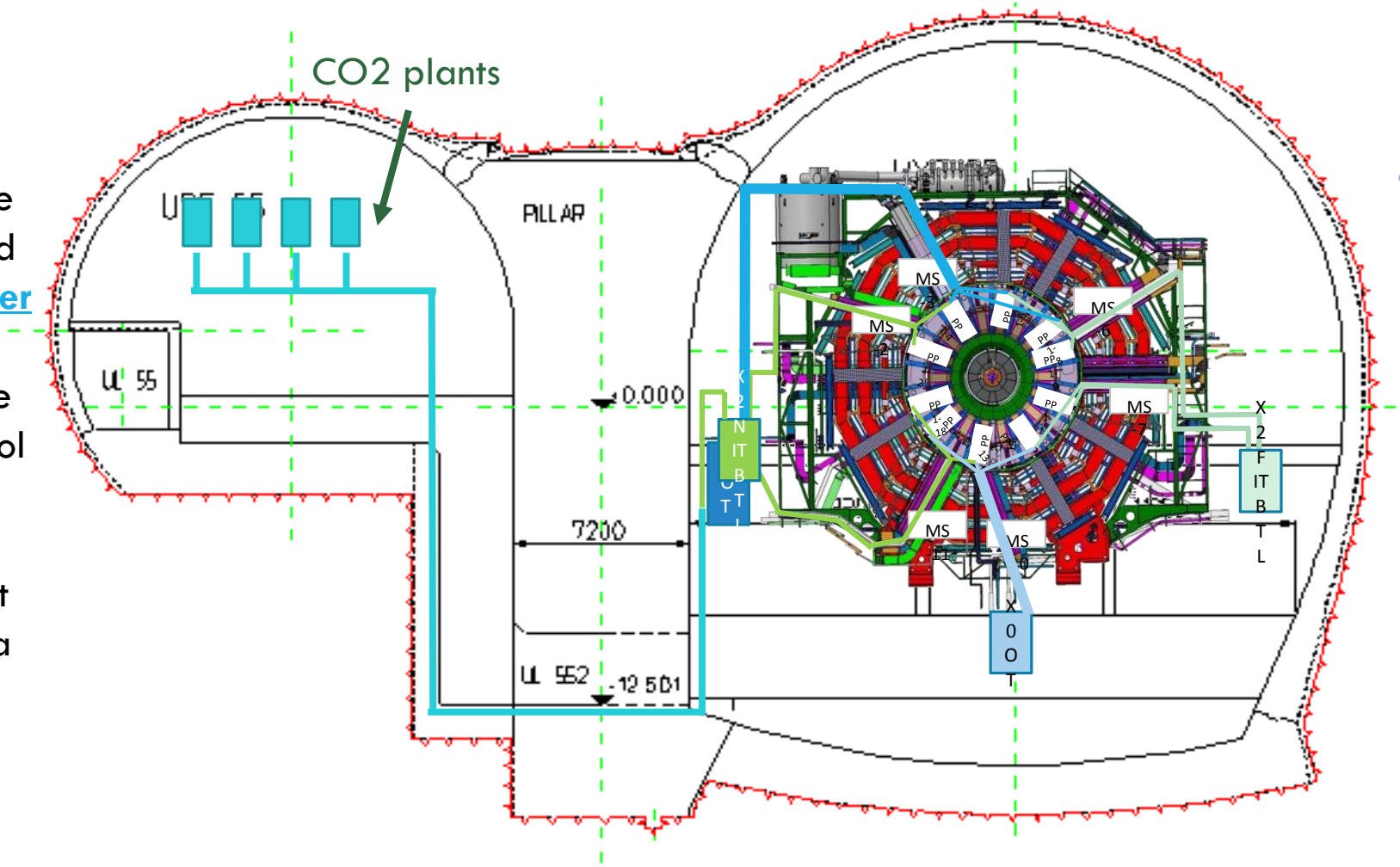
TESTING OF THE CHOSEN GEOMETRY IS MANDATORY to DEFINE REAL PRESSURE DROPS

Verlaat B., Dimensioning of CO2 cooling pipes in detector structures I, Forum on Tracking Detector Mechanics, Oxford, 2013

TRANSFER LINE DESIGN

1. Limit the pressure drops in order to reduce as much as possible the ΔT between the detector exit and the regulation accumulator: **proper sizing**
2. Ensure saturated conditions at the detector inlet (temperature control & stability): **concentric**
3. Transfer cold fluid with no impact on the rest of the experiment in a reliable way: **vacuum insulated**

CMS underground premises cross section

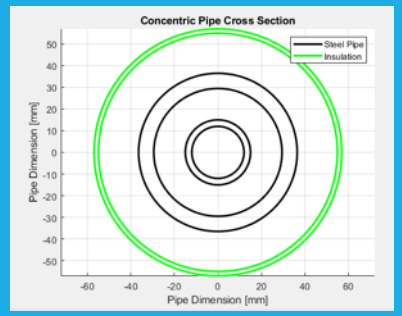


Forum on Tracking detector mechanics

- *2014 http://indico.cern.ch/event/287285/contributions/1640696/attachments/534388/736812/140630_TransferLines.pdf*
- *2015 https://indico.cern.ch/event/363327/contributions/860744/attachments/722740/991990/ForumNikhef2015.pdf*
- *2016: https://indico.cern.ch/event/469996/contributions/2148165/attachments/1278563/1898196/Forum2016_TransferLines_Tropea.pdf*

PRESSURE DROPS IN 2 PHASE FLOW

Plant to Manifold Run



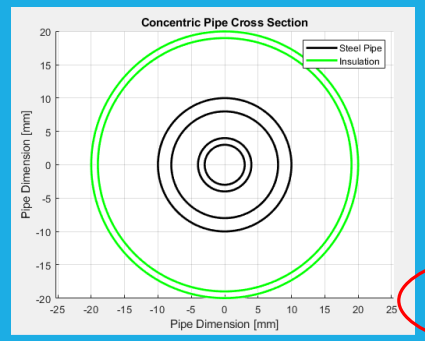
Largest Transfer Line

Preliminary Cross Section

Vac jacket: ⌀ 114 mm
Return: ⌀ 90 x 10 mm
Supply: ⌀ 30 x 3 mm

Worst Case Friction Losses*
dP = 0.21 bar ~> dT = 0.6 °C

Manifold to Detector Run



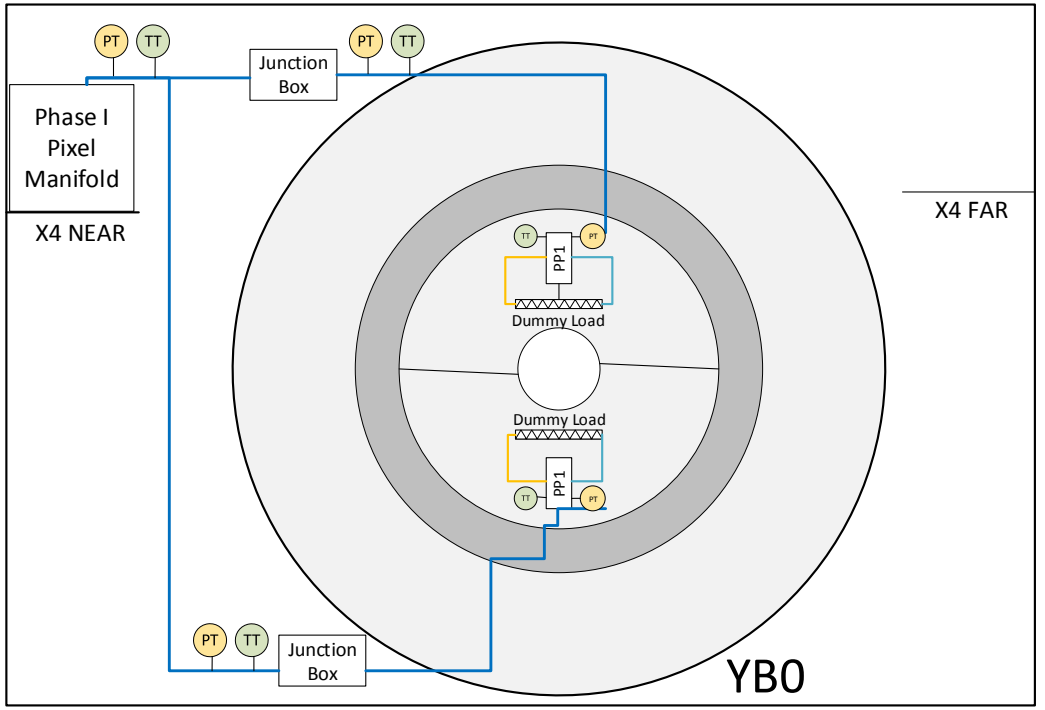
IT Transfer Lines

Preliminary Cross Section

Vac jacket: ⌀ 40 mm
Return: ⌀ 20 x 2 mm
Supply: ⌀ 8 x 1 mm

Worst Case Friction Losses*
dP = 0.2 bar ~> dT = 0.5 °C

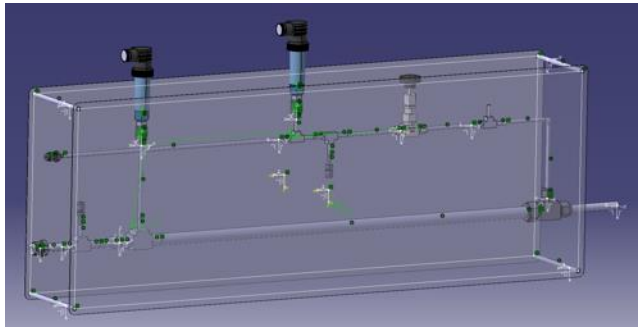
Ex: 1.1 °C due to frictional p drops OUTSIDE the detector



Experiment	US to UX Transfer line	Length
CMS	Total length, m	75
	Accumulated return upward length, m	**21.5**
	Accumulated return downward length, m	**12**
ATLAS	Total length, m	126
	Accumulated return upward length, m	0
	Accumulated return downward length, m	**6**

Understanding the effect of gravity on return lines pressure drops: what is the contribution?

2 setups being prepared – controlled lab conditions in CERN EP-DT & real scale CMS during LS2 (T. Pakulski)



Courtesy of T. Pakulski, CERN EP-DT

FROM REQUIREMENTS TO SPECS TO SYSTEM DESIGN(2)

The power & the mass flow rate

Power capacity for a given mass flow varies @ different T

“Warm” operation to be well defined in scope in design phase: checkout? Annealing? Detector on/off?

Ex: detector power = 165 kW @ -45C

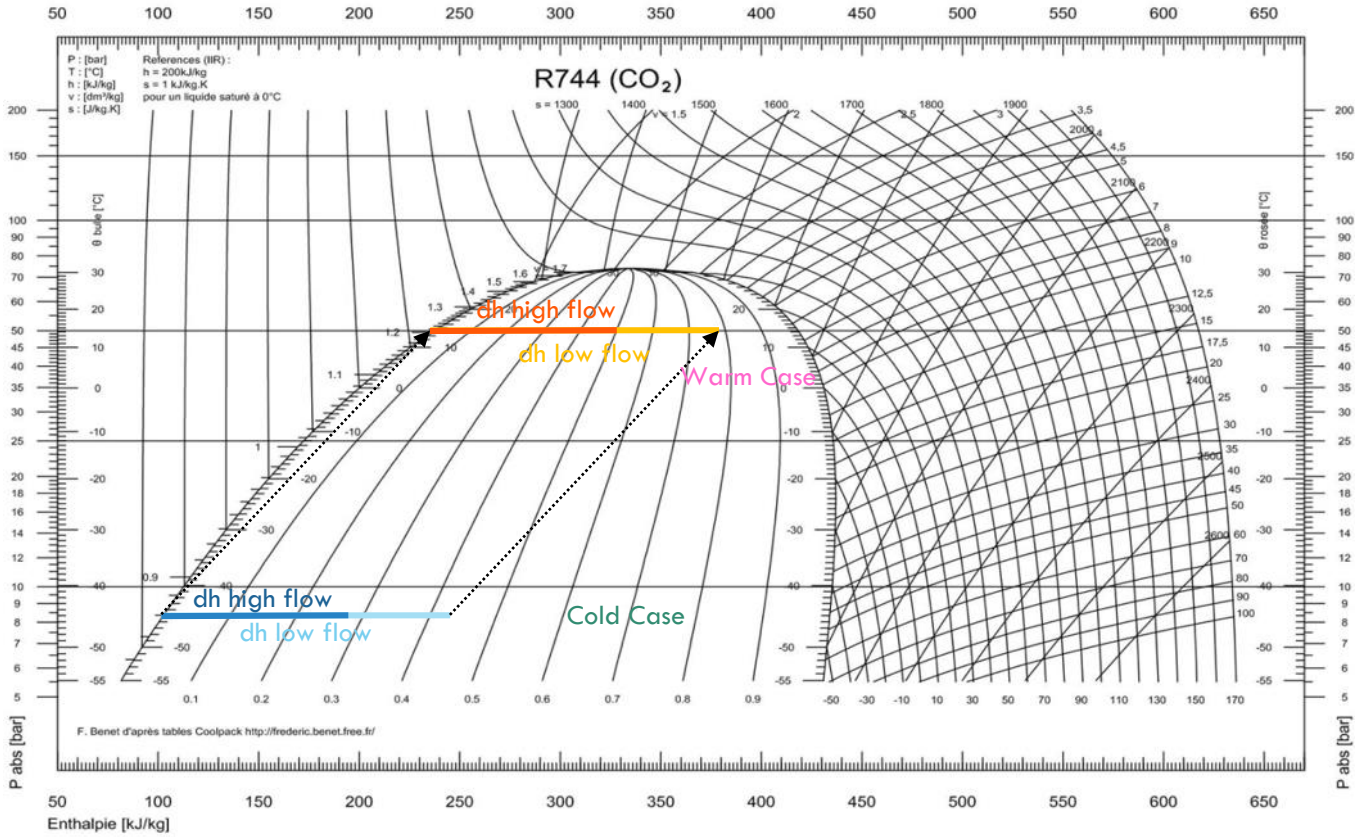
Cold Case: Accumulator Tsat = -45’ C

Design VQ	Required Coolant Flow
33%	1.51 kg/s
42%	1.19 kg/s

Warm Up

Coolant Flow	Resulting Quality
1.51 kg/s	58.8%
1.19 kg/s	**75.7%**

Warm Case: Accumulator Tsat = +15 ‘C



1.19 kg/s, X = 60% - >127 kW cooling capacity @ 15C

AND THEN?

Power & temperature requirements are defined, can be sent as input to plant design!

…what else is missing to have a complete specification set?

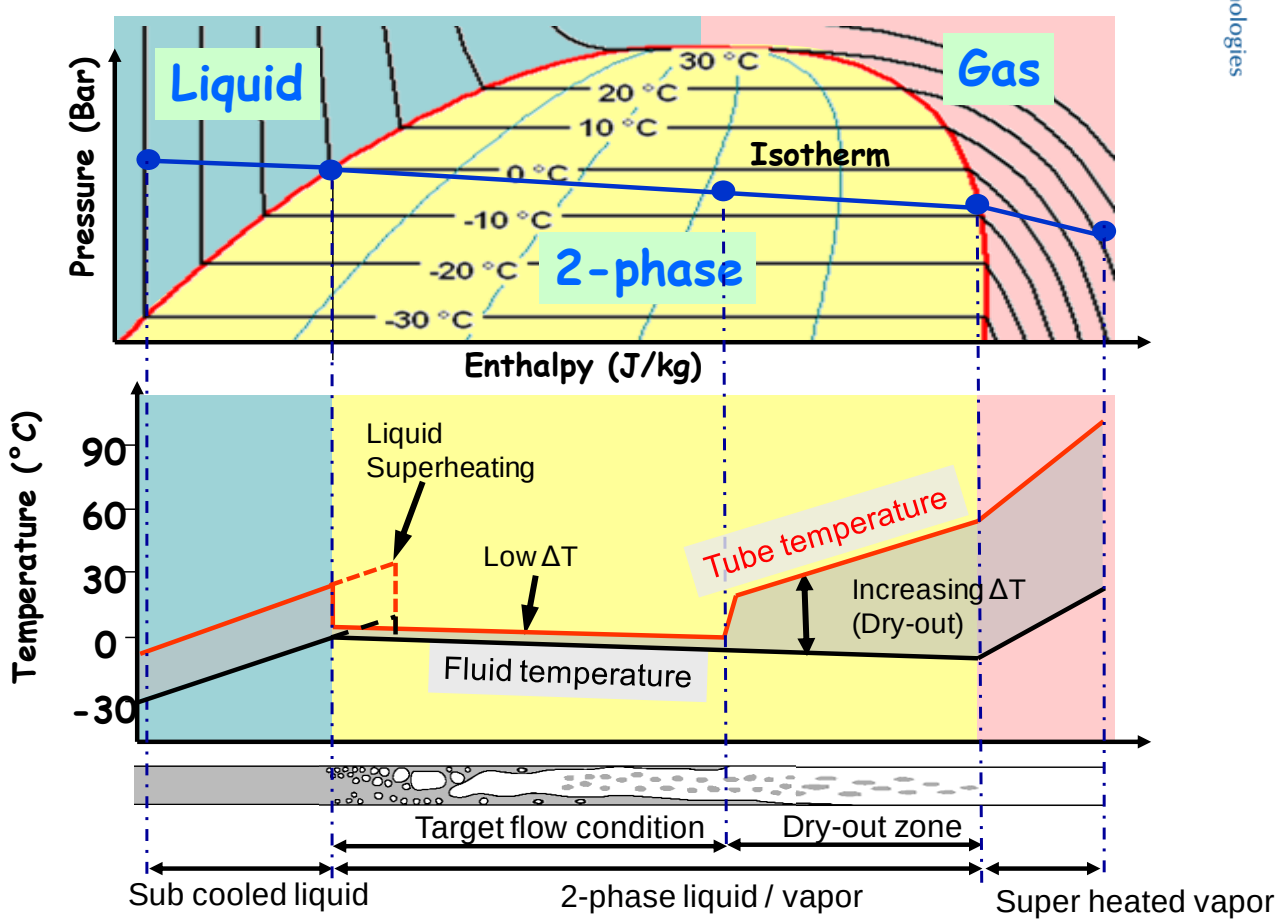
1. Make sure evaporation happens in the good place
2. Balancing of parallel loops
3. Think about operation

ONSET OF EVAPORATION (& SUPERHEATED LIQUID ISSUES)

HTC dramatically change between liquid and two-phase, thus the need to make sure that evaporation starts at the active detector inlet.

1) Make sure that liquid is not subcooled
2) Make sure that no liquid superheating happens

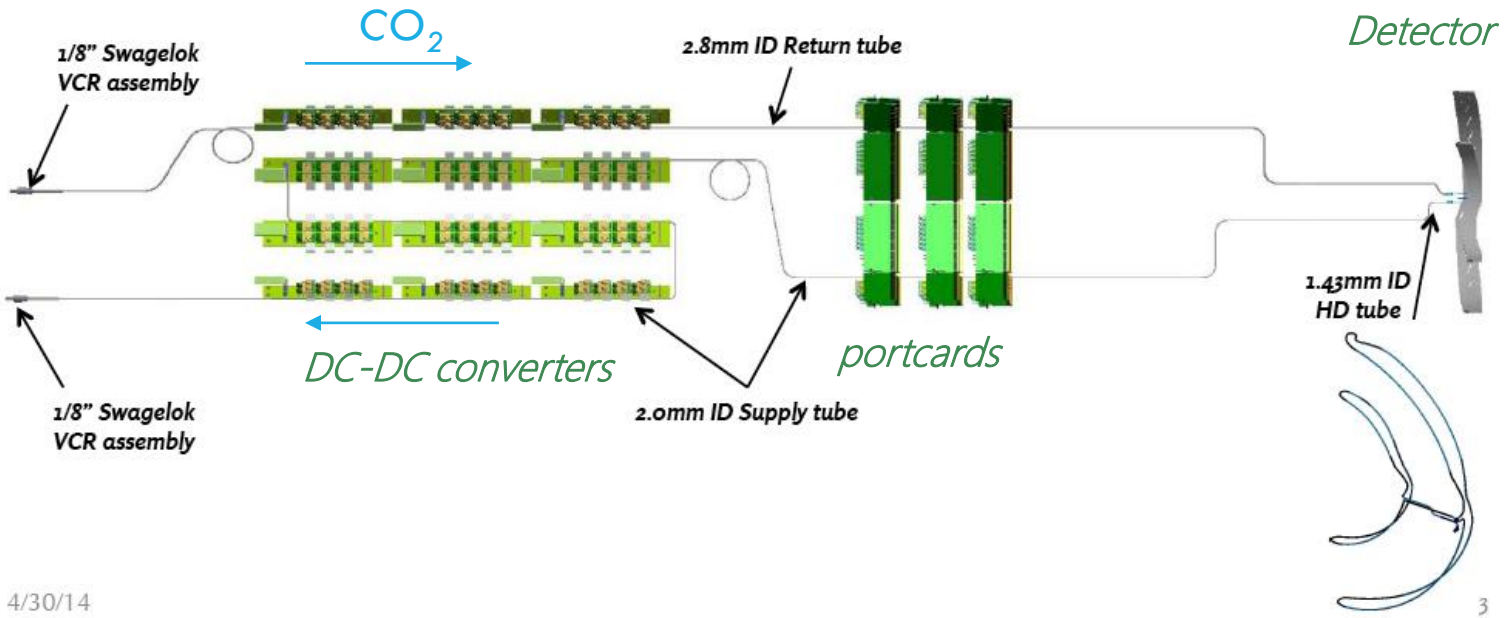
Liquid superheating = Heating of a substance above the temperature at which a change of state would ordinarily take place without such a change of state occurring, for example, the heating of a liquid above its boiling point without boiling taking place; this results in a metastable state.

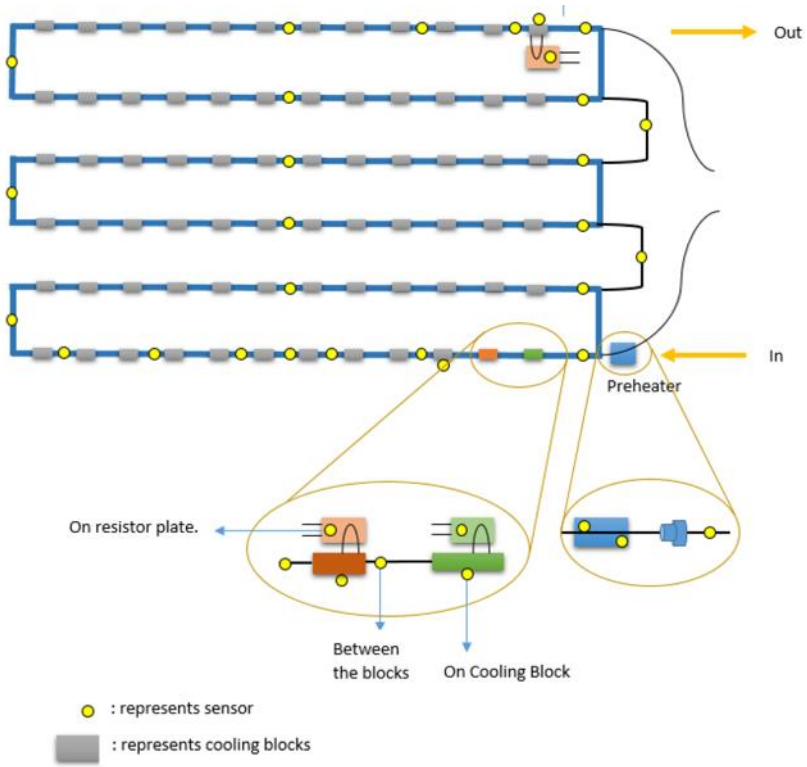


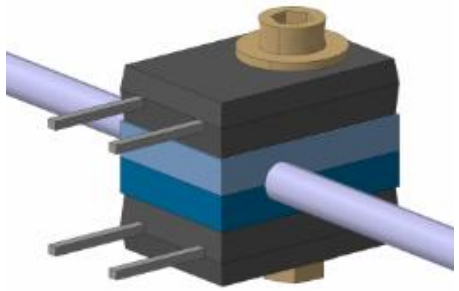
Two approaches under study:
- pre-heaters (CMS)
- "warm nose" (ATLAS)

PREHEATER SOLUTION

CMS Phase I Pixel (Forward Pixel cooling scheme)







Pre-heater concept tested
(2x10W resistors clamped to pipe)

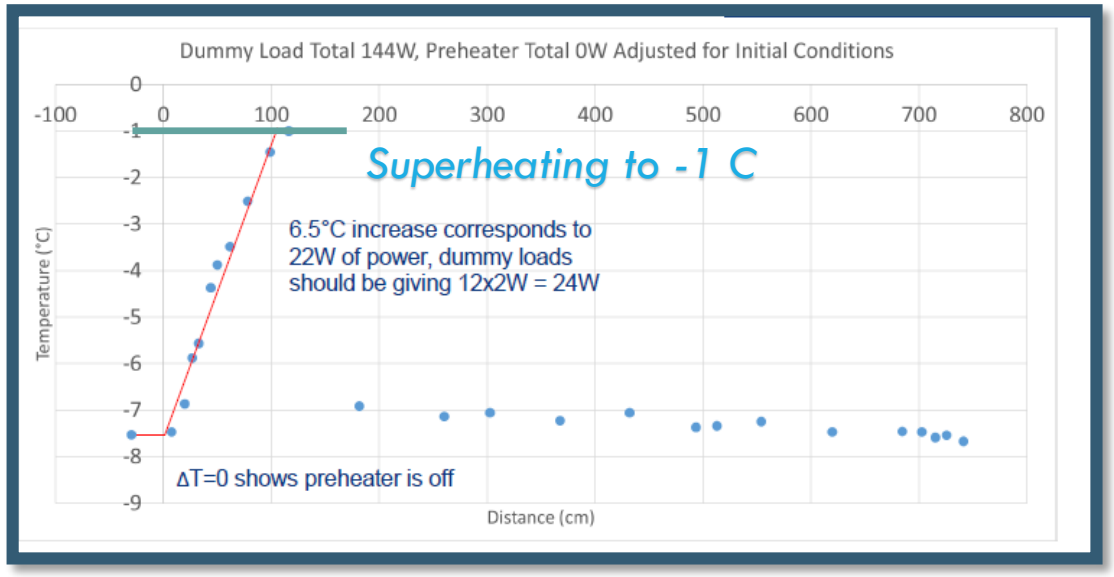
CMS Tracker upgrade

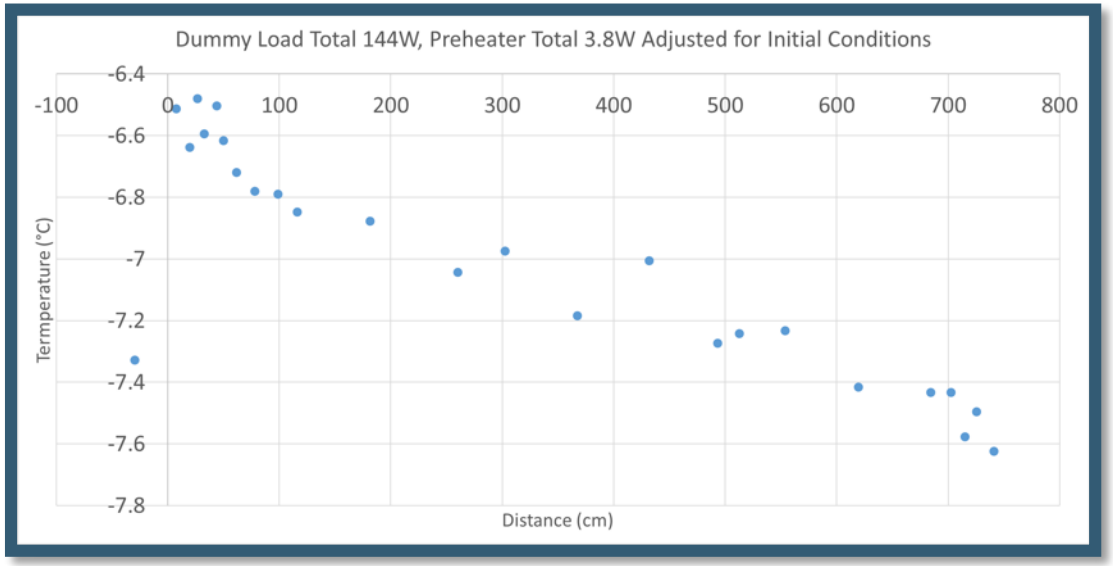
"give a kick" to evaporation with a high heat flux load at the detector entrance

Courtesy of T. French CERN EP-CMX

PREHEATER TESTING

CO2 Set Point	28 bar (-8 °C)
Dummy Load Power	144 W
Preheater Power	0/3.8 W
Flow	1.44 g/s



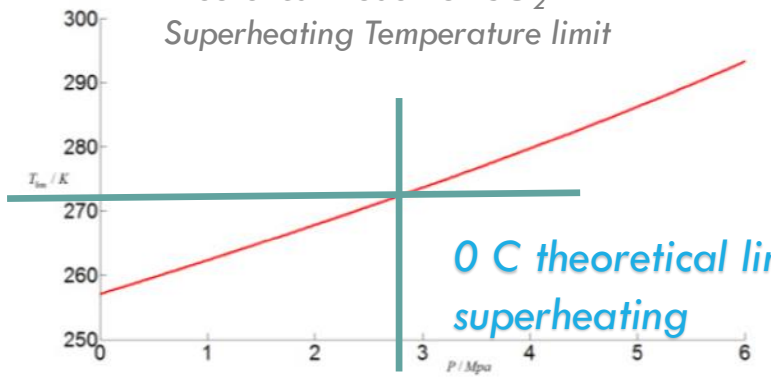


Further development:

- Verification of behaviour at different operating T, with detector power cycles
- Strategy on powering scheme to be validated
- Full detector sub-structure model mock-up

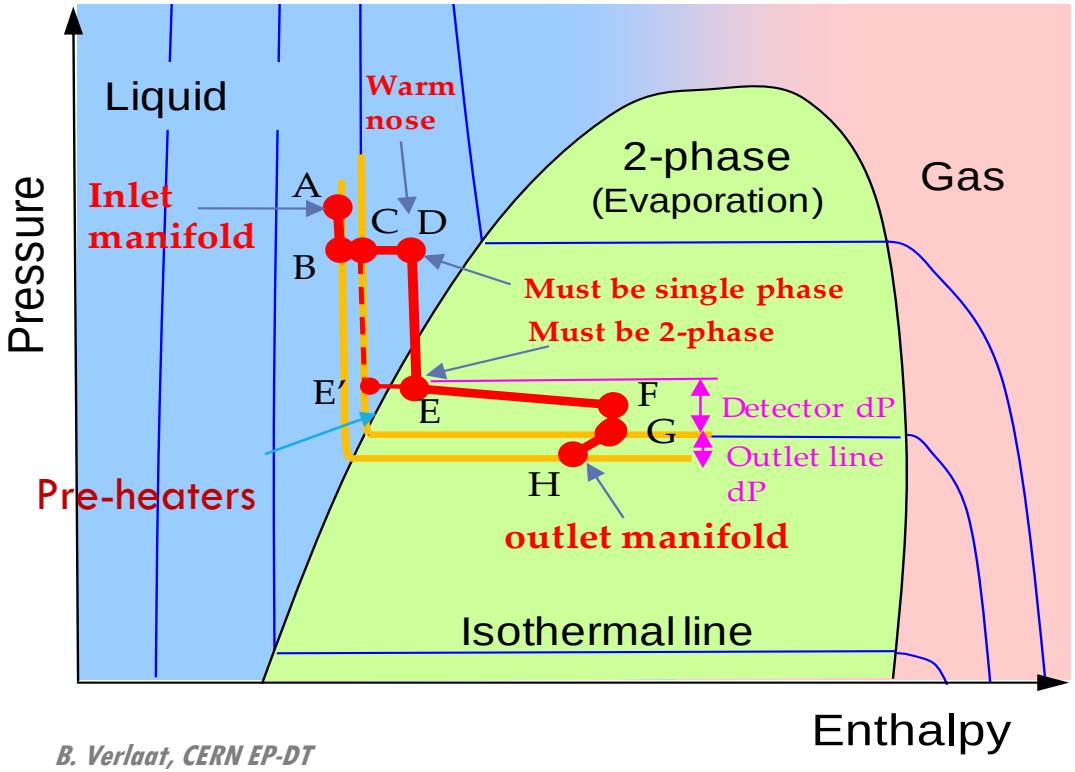
Courtesy of T. French CERN EP-CMX & G. Baldinelli , University of Perugia, IT

Theoretical model for CO_2 Superheating Temperature limit

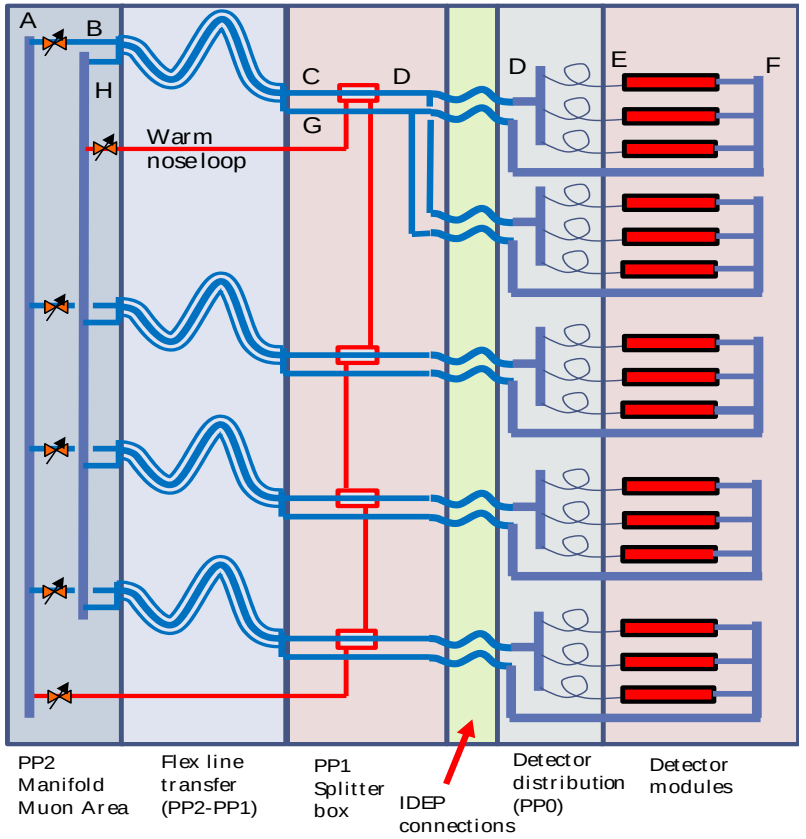


Qian Huang et al, "Study on Mechanisms of CO2 BLEVE Based on the Cusp-catastrophe Model", https://doi.org/10.1016/j.egypro.2014.12.123

WARM NOSE SOLUTION



B. Verlaat, CERN EP-DT



Δp verification done & prototypes produces

Further development:

- Full verification of concept on CO_2 setup

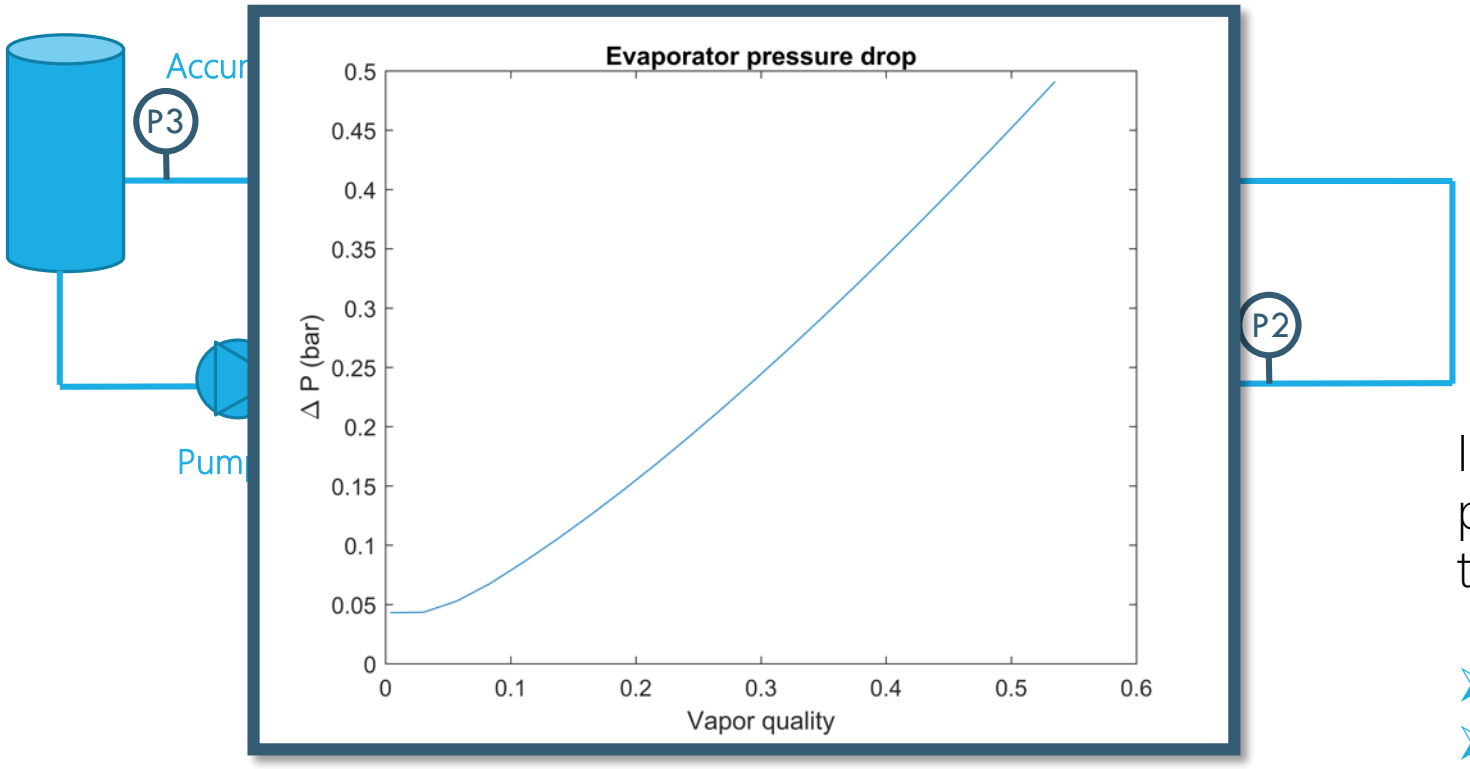
C. Rossi, INFN Genova

Courtesy of B. Verlaat, CERN EP-DT

BALANCING PARALLEL LOOPS (1)

Why? Parallel loops share the same pressure drop & the mass flow in each loop shall be tuned to the specific loop power & geometrical characteristics in order to properly function.

Typical hydraulic circuit balancing works…but:



Δp vs Vapor quality for a sample evaporator
ID 2mm, 3.4m long , massflow1.2 g/s, power 0-200 W

1. Manifolding is typically in non accessible areas
2. Pressure drops in the evaporator change dramatically when in liquid or two phase (power on-off)

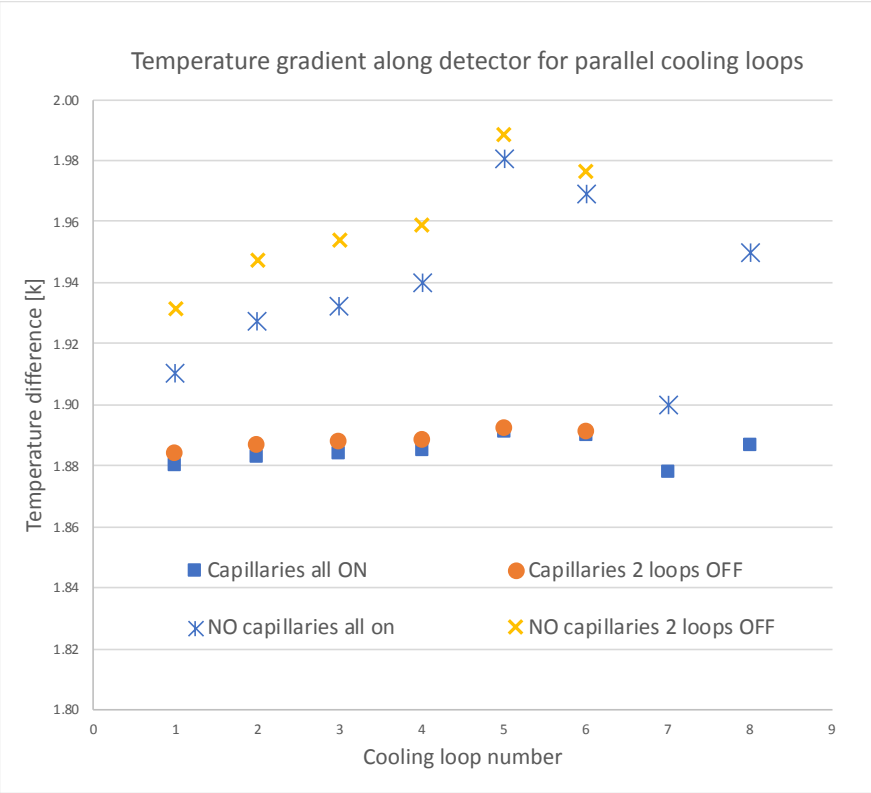
Introduce fixed pressure drop on liquid phase which is predominant with respect to detector one

- *Small object*
- *Totally passive*

Capillaries or calibrated orifices

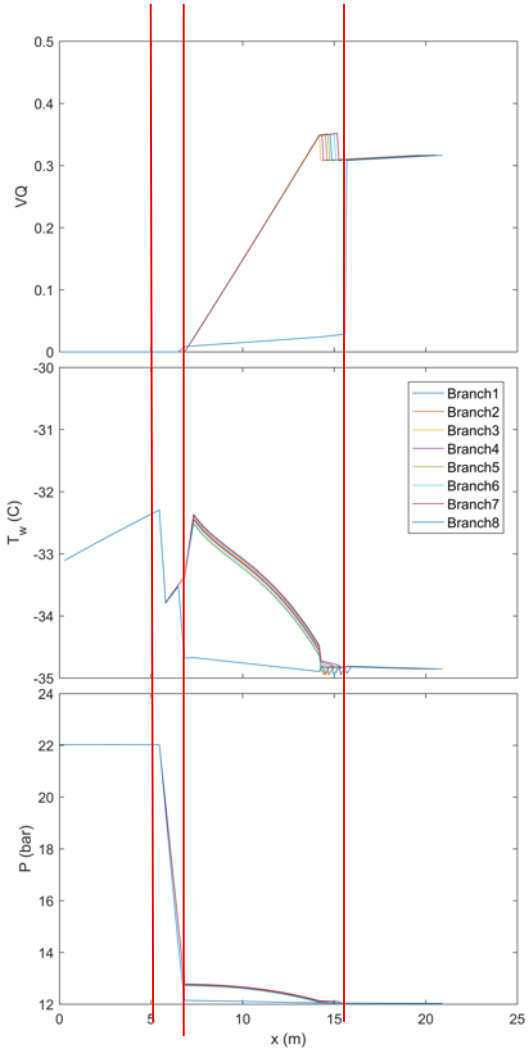
DESIGN OF BALANCING TOOLS

Typical restriction sizing:
1) $\Delta P|_{restriction} > 4\Delta P|_{detector}$
2) $\Delta P|_{capillary+detector} = 10$ bar



The tool for parallel loop calculations, based on empirical correlations for Δp in two-phase. Results of a simulation with 8 parallel loops of CMS TB2S.

capillaries
return manifold
Inlet manifold
evaporator



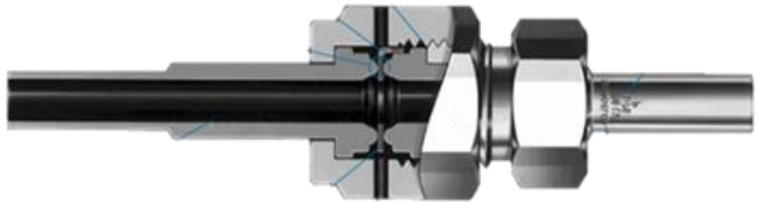
R. Puente, University of Cantabria & CERN EP-DT

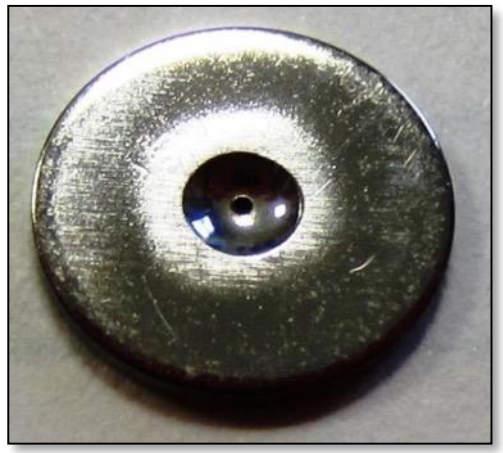
EP-DT Detector Technologies

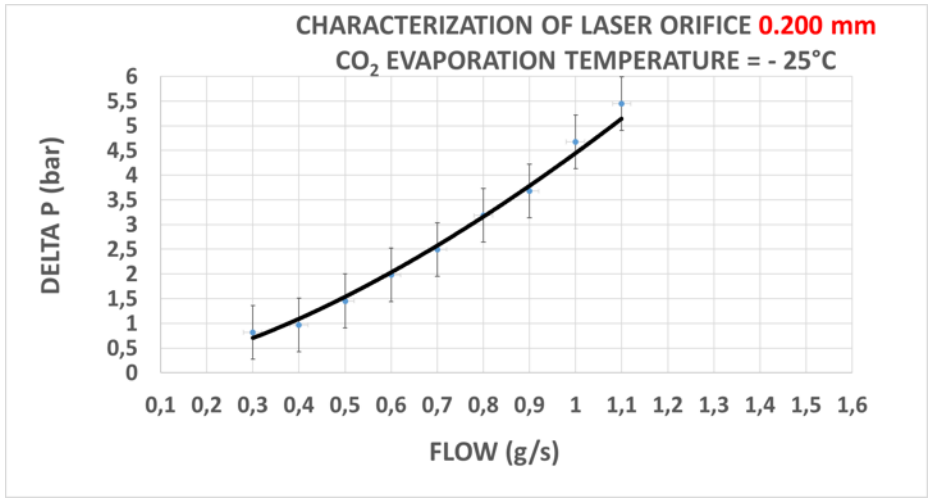
ORIFICE SOLUTION

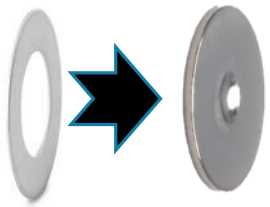
LHCb UT

1/8 INCH VCR GASKET (6 mm)
250 µm hole









Laser orifices on VCR blind gaskets

S. Coelli, "Calibrated orifices for CO_2 cooled detectors", Forum on Tracking Detector Mechanics, Valencia, 2018

\+ Super for small places, just one connector

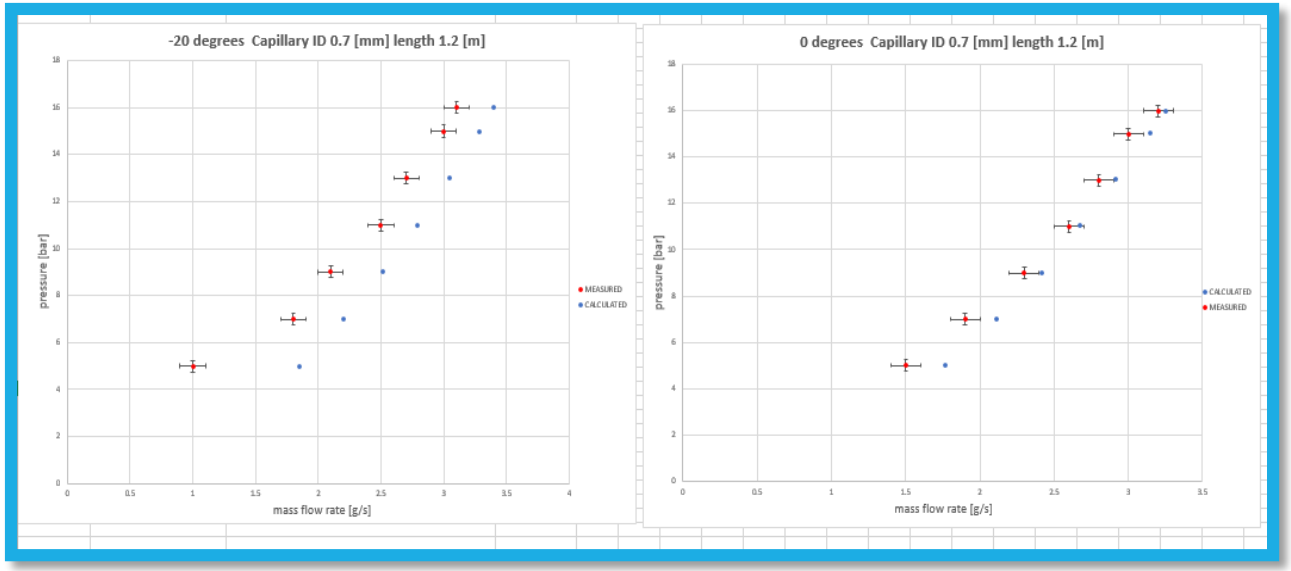
\- Attention: proper filtering to be put in place, typical hole sizes ½ of capillaries ID

NOT FOR NON ACCESSIBLE AREAS

CAPILLARIES

- Can typically have “big” diameters (>0.4 mm less risk of clogging)
- Can be used as standard pipes and be routed along detector volume (ex bulkhead to CMS Outer tracker in present design)
- Need calibration (mostly to take into account real pipe rugosity)

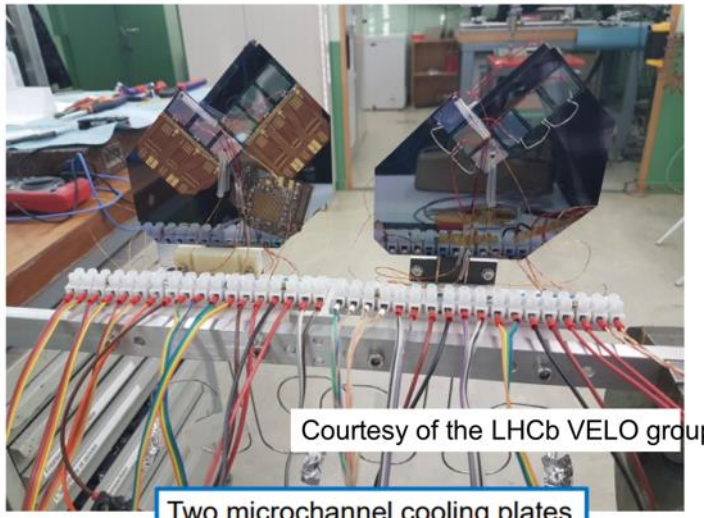
CMS Pixel PP0: Courtesy of J.Daguin CERN EP-DT



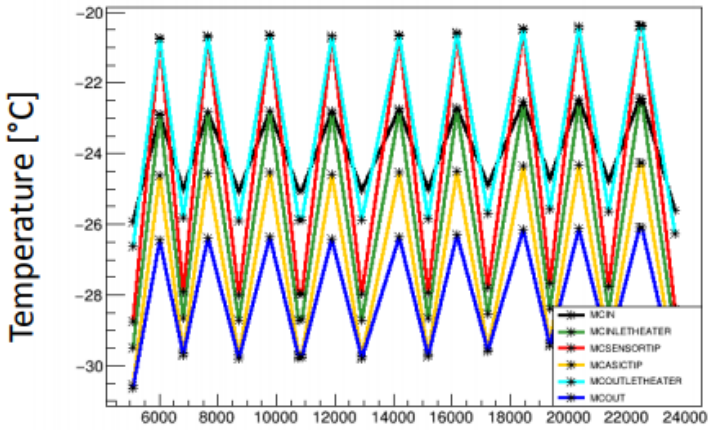
CMS Pixel capillary integration & calibration : courtesy of K. Rapacz CERN EP-DT

LHCB VELO UPGRADE – ORIFICES & CAPILLARIES

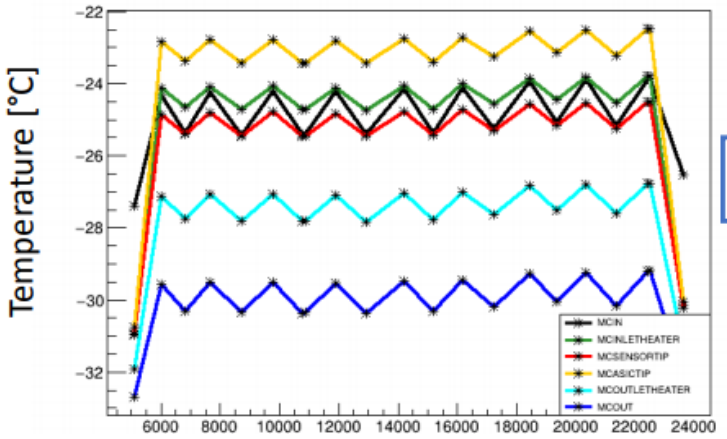
A complex and advanced design: Si microchannels



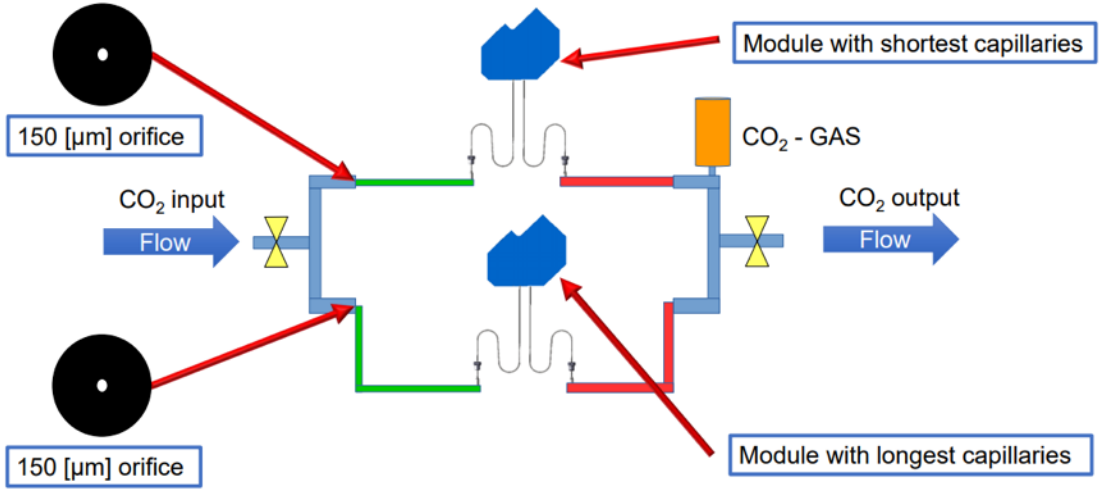
Two microchannel cooling plates



MC1



MC2



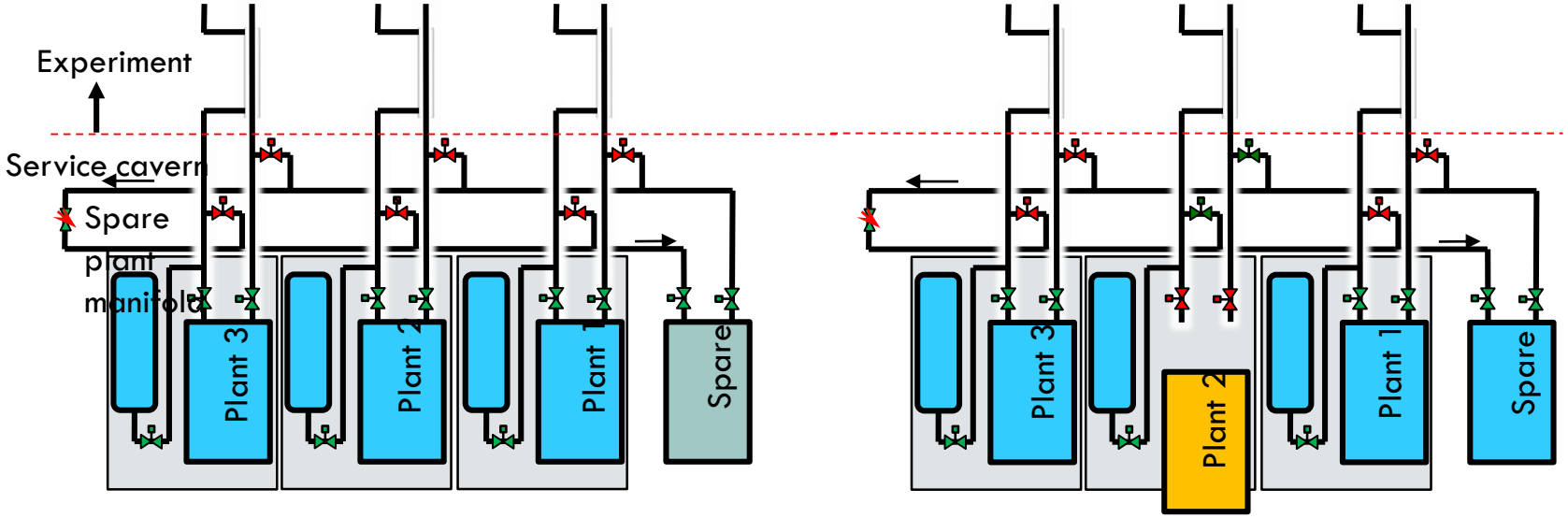
Courtesy of the LHCb VELO group

OPERATION

Cooling rate: determines the size of plant/primary

Warming rate: ATTENTION - EVAPORATIVE SYSTEM CANNOT BE USED TO WARM UP THE DETECTOR VOLUME if no power applied

Redundancy: same Δp for all detectors fed by same plant, common backup or not?
Need to operate cold during maintenance periods/power cuts/shut-downs



Spare plant runs cold over the spare manifold for direct kick-in (IBL method)

Spare plant replaces any of the other units, which can be dismounted for maintenance or repair

OPERATION – PLANT CONTROLS & DETECTOR MONITORING

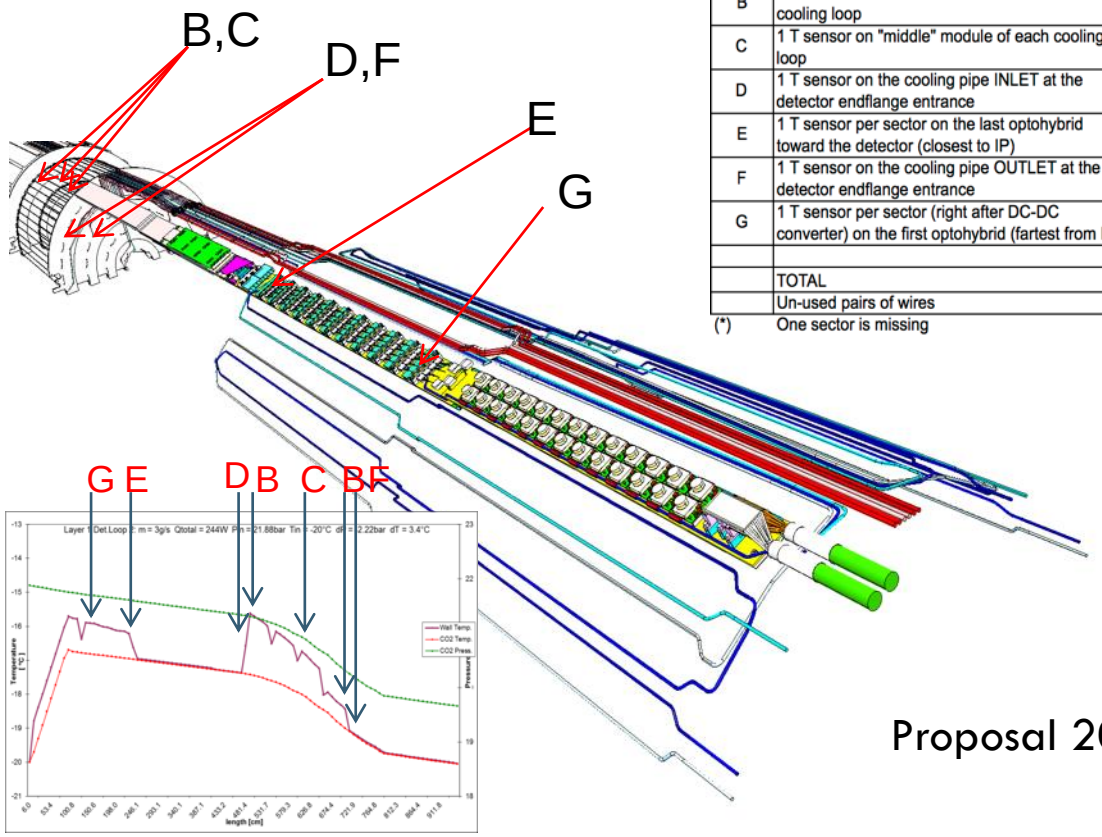
Ad-hoc temperature monitoring needed to assess the system behaviour: info at the level of the plant are not enough!

See:

- *Evaporation onset on IBL – K. Sliwa, Forum on Tracking Detector Mechanics 2017*

- *CMS Pix recent flow tuning operations (private comm.)*

For plant operation: a temperature value of the detector is needed at startup to avoid any thermal shock, should be available also when detector is OFF



BPIX

		OPTION A	OPTION B
		Pair of wires	Pair of wires
A	1 T sensor on Air and 1 HMX sensor	3	3
B	1 T sensors on first and last module of each cooling loop	12	12
C	1 T sensor on "middle" module of each cooling loop	6	6
D	1 T sensor on the cooling pipe INLET at the detector endflange entrance	6	
E	1 T sensor per sector on the last optohybrid toward the detector (closest to IP)		8
F	1 T sensor on the cooling pipe OUTLET at the detector endflange entrance	6	
G	1 T sensor per sector (right after DC-DC converter) on the first optohybrid (fartest from IP)		7(*)
	TOTAL	**33**	**36**
	Un-used pairs of wires	3	

(*) One sector is missing

Proposal 2015

GOLDEN RULES SUMMARY

Design Temperature : Si sensor T - ΔT(Thermal contact)- ΔT(Δp across detector evaporator) - ΔT(Δp across return transfer lines (frictional and static) = Accumulator set point: must be achievable! -47 °C is the min so far…

Power dissipation: The optimum design for the cooling system needs a tuning to a certain flow rate (transfer lines & Δp, hydraulic component size, etc) – Flow rate & vapor quality (the margin to overheating in the detector) determine cooling power = f (T). An optimised system for -35 °C will not provide full cooling power @ +15 °C with the same safety margin to dryout.

Design of on-detector evaporators: Find the optimum pipe size looking at the best compromise between material budget and ΔT (ΔP+HTC), define operation scenarios to do calculations! TEST all that you size
Include studies on evaporation onset (and a monitoring system that allows you to detect if something is going wrong)

Operation of parallel circuits: Make your choice of balancing system and make sure you have margin with respect to all operational cases (included running with other subsystems).

Prepare for operation: choice of backup method, design for proper monitoring system, communication btwn plant & detector of relevant parameters (a mandatory one = "detector temperature").

On-detector design & operation teams + cooling teams

CONCLUSIONS

The size of CO_2 cooling systems for the next generation of detectors (up to >100 kW per system) makes the design & construction challenge bigger than in any evaporative CO_2 system developed so far for HEP.

Several parallel loops from multiple subdetector will need to be operated in parallel & the design of all of them need to be “synchronised”.

A comprehensive approach shall be adopted, where detector design, integration, operation & cooling team must exchange information: the design of each part of the CO_2 system strongly influences the rest – ITERATION to converge to an optimized solution is mandatory

The common development for both ATLAS & CMS allows for intrinsic easier exchange of experience, but the challenge remains!

FURTHER READING

WHY CO_2?

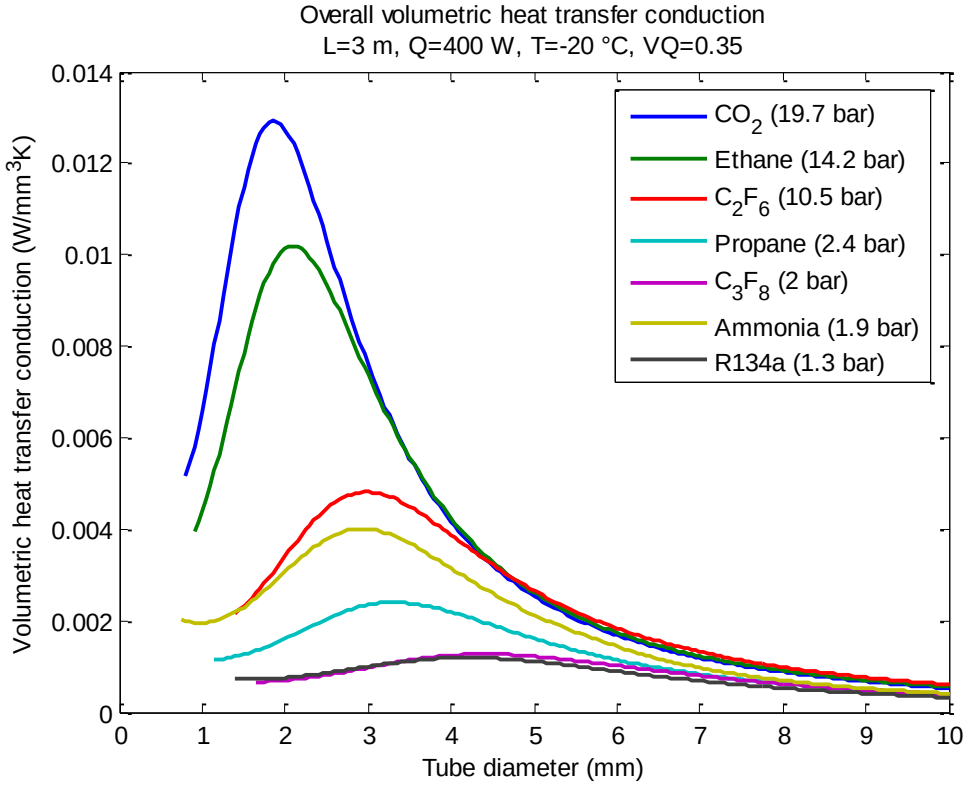
- **Significant saving of cooling hardware** (material budget) into the detector due to the physical properties:
  - large latent heat of evaporation
  - low liquid viscosity
  - high heat transfer coefficient
  - high thermal stability due to the high pressure
- Very practical fluid to work (environmental friendly, not activated)
- Practical range of the detector application -45^{0}C to +25^{0}C

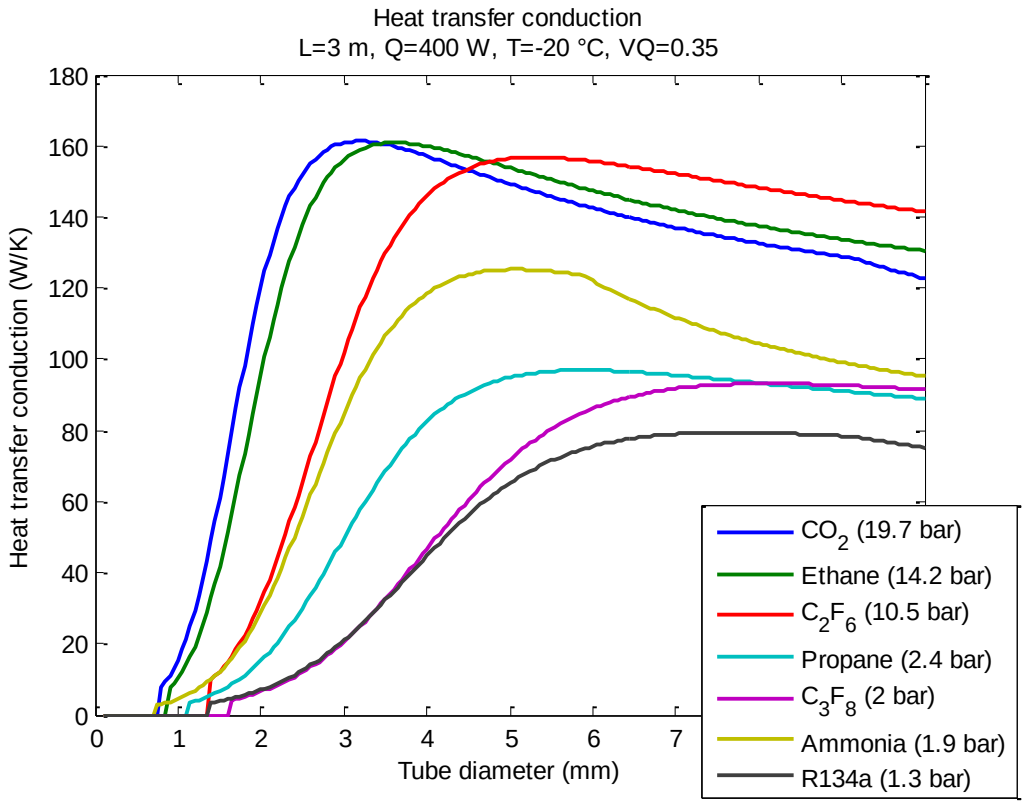
Models used: HTC-Kandlikar and dP-Friedel

CO_2 AGAINST OTHER COOLANTS

Volumetric heat transfer is also a good method to compare different fluids.

- How can we put as much heat into a small as possible cooling tube??





Models used: HTC-Kandlikar and dP-Friedel

Verlaat B., Dimensioning of CO2 cooling pipes in detector structures I, Forum on Tracking Detector Mechanics, Oxford, 2013

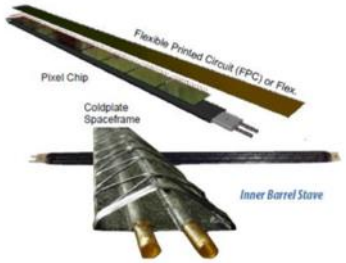
ABOUT ON-DETECTOR THERMAL CONTACTS

Cooling & Structure Optimization

Great attention to early design and integration of optimized support structures and thermal management solutions is **mandatory** for the present and the coming generation of Vertex detectors: not surprisingly all "classes of approach" are represented!

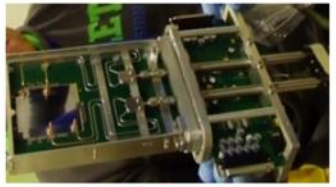
ATLAS IBL

ATLAS PIXEL upgrade (study)

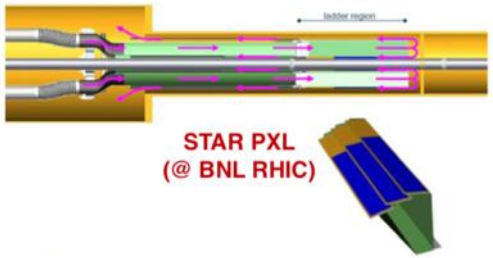


ALICE ITS upgrade

CMS PIX upgrade



NA62 GTK



STAR PXL (@ BNL RHIC)

P. Petagna, Vertex207
https://indico.cern.ch/event/627245/contributions/2676709/attachments/1521433/2376939/VERTEX_2017_2017Sep12_Advanced_Cooling.pdf

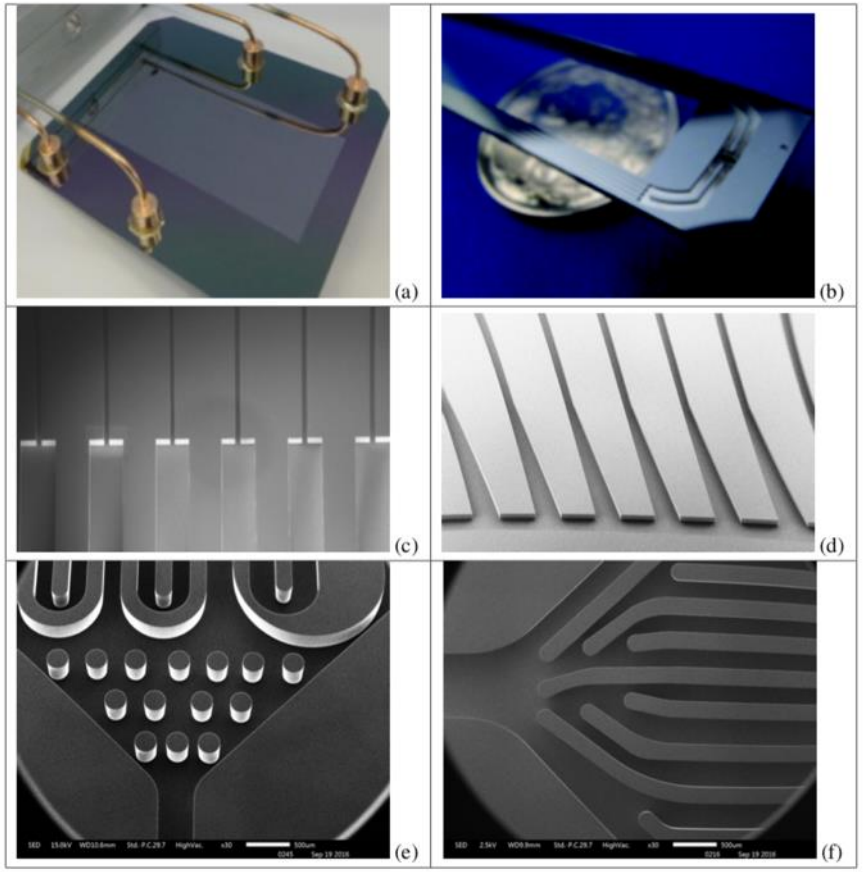
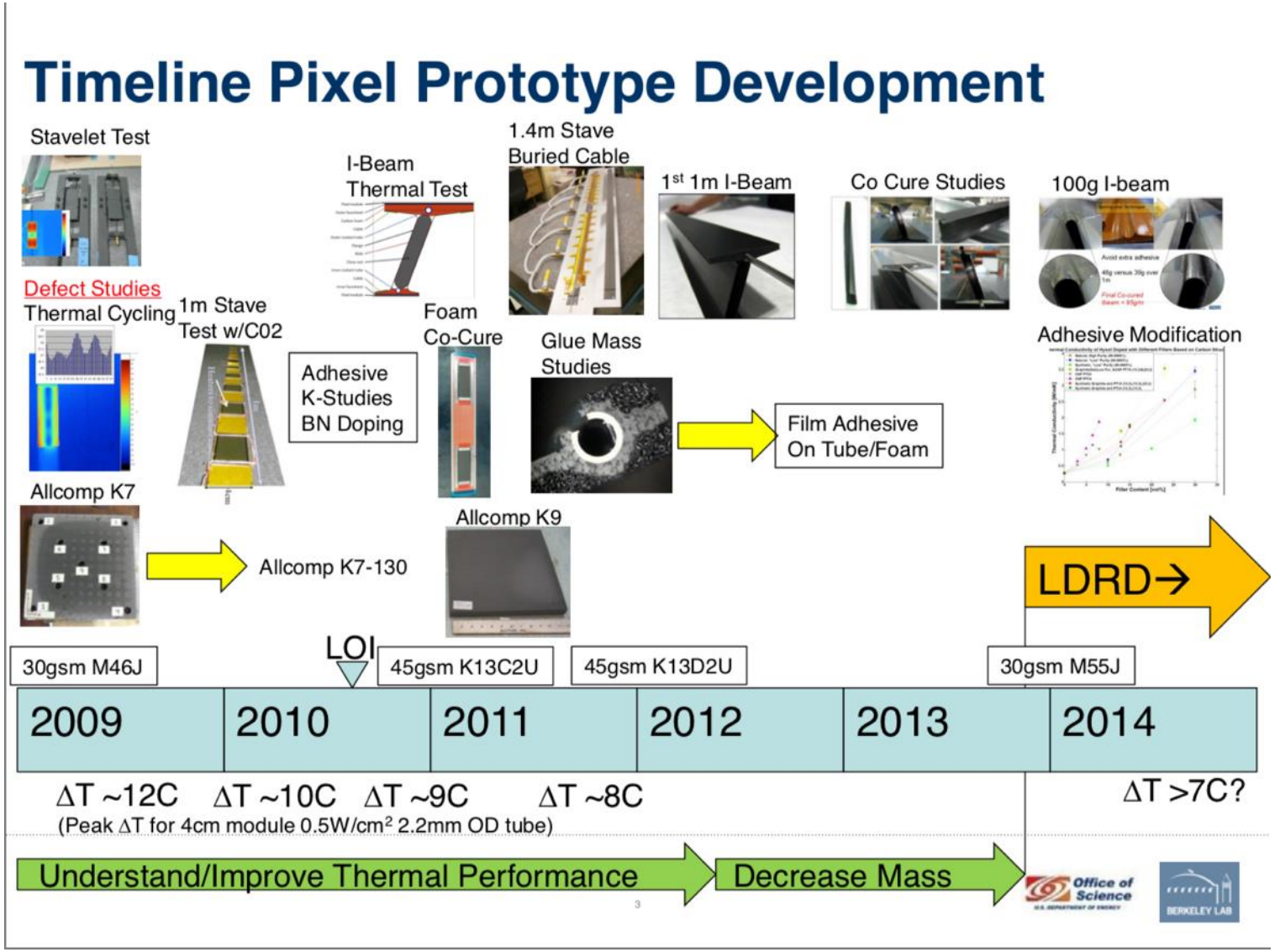


Figure 2: Photograph of the NA62 cooling plate [1] (a), photograph of a prototype structure for the ALICE-ITS [10] (b), X-ray image of the high-impedance, restricted-width structures where the liquid CO_2 evaporates in the LHCb VELO cold plate [7] (c), electron microscopy image of the broadening channels produced by CNM [11] (d), X-ray images of the structures integrated in detector-grade silicon by HLL [12] (e,f).

M. Vos, Vertex2016 , https://pos.sissa.it/287/037/pdf

ABOUT ON-DETECTOR THERMAL CONTACTS

E. Anderssen et al., *Advanced Materials and Tools Research*, Forum on Tracking Detector Mechanics 2015 (Amsterdam, NL): https://indico.cern.ch/event/363327/contribution/34



ABOUT PERFORMANCES OF CO_2 COOLING SYSTEMS

[1] B. Verlaat, et al., *CO_2 cooling for the LHCb-Velo experiment at CERN*, In: Proceedings of the 8th IIR Gustav Lorentzen Conference, Copenhagen, Denmark, 2008.

[2] Zwalinski L. et al, *The Control System for the CO_2 cooling plants for Physics experiments*, 2013, in proceedings of *14th International Conference on Accelerator and Large Experimental Physics Control Systems, San Francisco USA, 2013*

[2] L. Zwalinski, et al., *CO_2 cooling system for Insertable B Layer detector into the ATLAS experiment*, In: PoS (TIPP-2014) 224, 2014.

[3] P. Tropea, et al., *Design, construction and commissioning of a 15 kW CO_2 evaporative cooling system for particle physics detectors: lessons learnt and perspectives for further development*, In: PoS (TIPP-2014) 223, 2014.

[4] Daguin, J. et al, *CO_2 cooling for particle detectors: experiences from the CMS and ATLAS detector systems at the LHC and prospects for future upgrades,* Proceedings of the 24th IIR International Congress of Refrigeration - Yokohama, Japan, 2015

ABOUT PIPES & CONNECTORS

Workshop on pipe joining techniques for the ATLAS & CMS Tracker Upgrades

https://indico.cern.ch/event/721360/timetable/#20180518