bverlaat@nikhef.nl

# Evaporative $CO_2$ cooling for thermal control of scientific equipments

**SLAC Advanced Instrumentation Seminars**

March 28, 2012, 1:30 PM, Kavli 3rd floor

Bart Verlaat

(Nikhef/CERN)

bverlaat@nikhef.nl

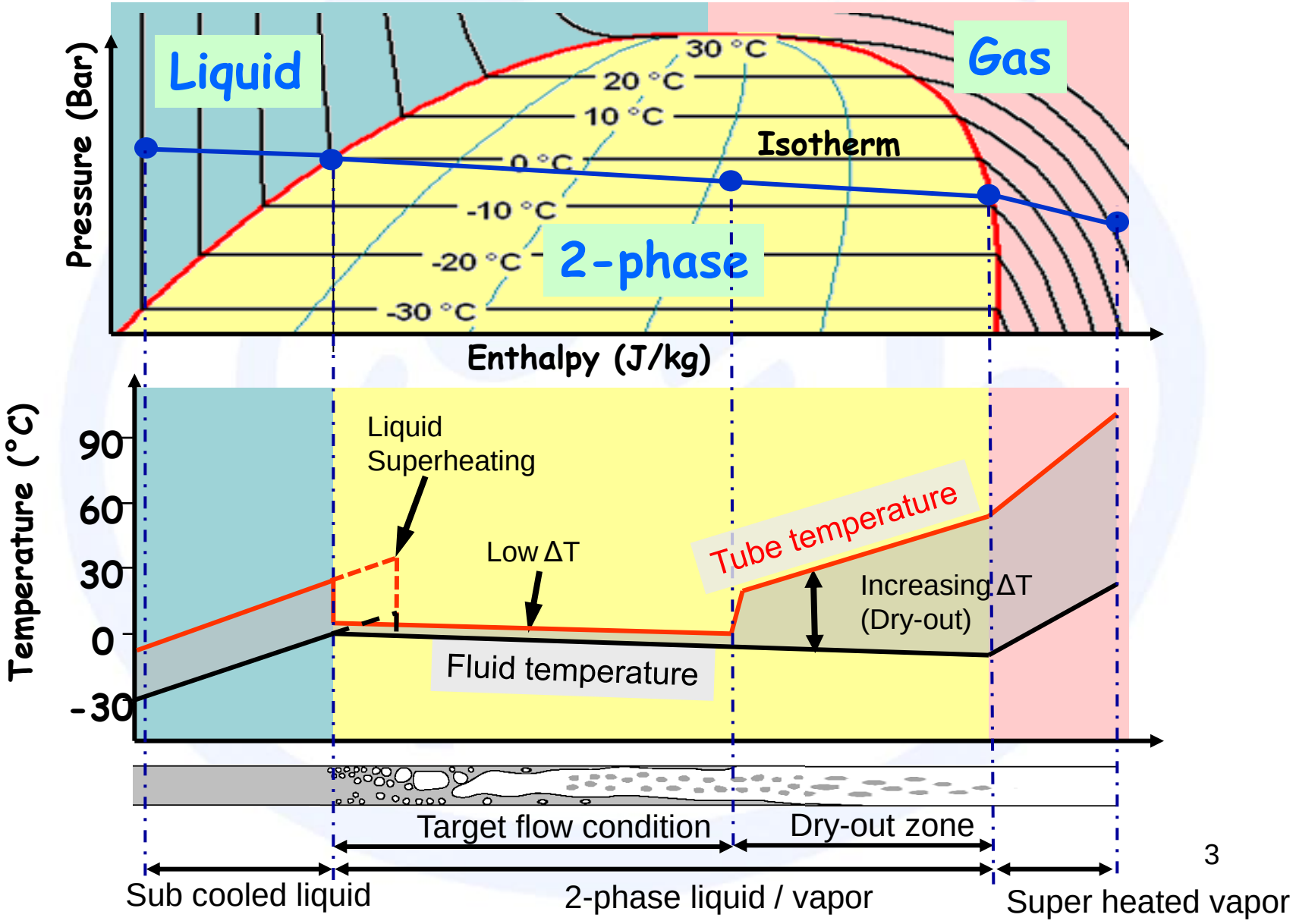
# $CO_2$ Cooling Seminar

- Introduction to 2phase cooling and fluid trade-off
- $CO_2$ cooling modeling
- Introduction to the 2PACL $CO_2$ circulation method.
- $CO_2$ cooling in the AMS-Experiment.
- $CO_2$ cooling in the LHCb Velo Detector
- Ongoing projects.
- Conclusions

bverlaat@nikhef.nl

# What happens inside a cooling tube?

## *Heating a flow from liquid to gas*



bverlaat@nikhef.nl

# Cooling efficiently scientific equipment.

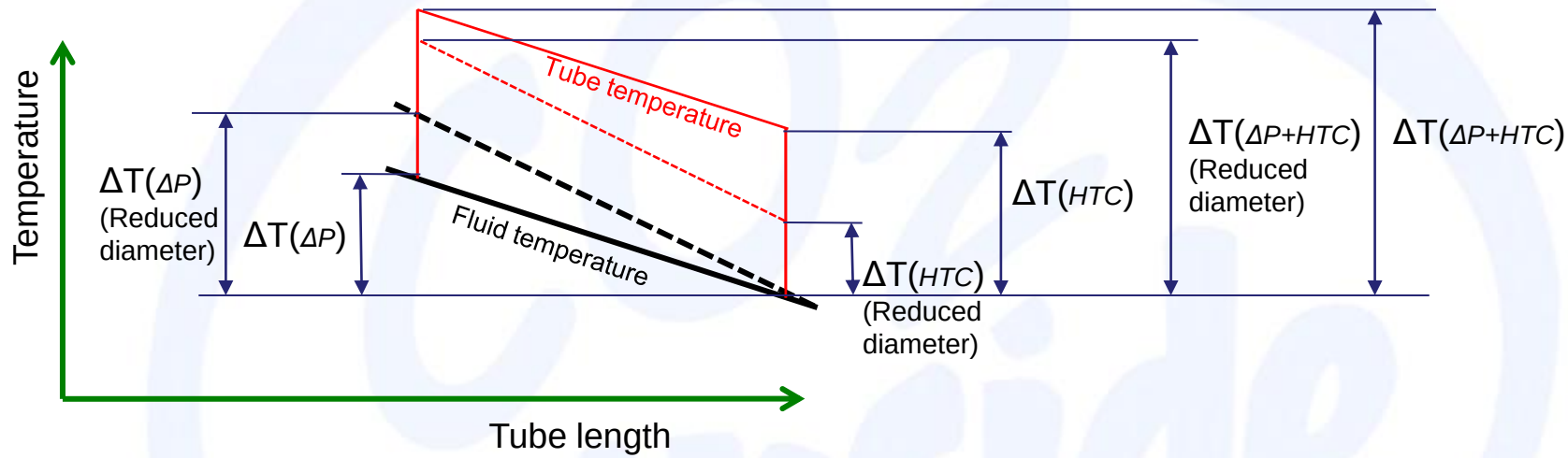
- What do we expect in general from a 2phase flow in scientific equipment?
  - Inside the equipment (Evaporator):
    - Small additional cooling hardware (small diameter tubing)
    - Large heat removal capacity
    - Low temperature gradients
      - Low gradient from tube wall to fluid
      - Low gradient over tube length (Isothermal)
  - Outside the equipment (Circulation system)
    - Stable temperature
    - Control over fluid condition in side evaporator

- Which fluid is most suitable?

bverlaat@nikhef.nl

# Temperature profiles

- To compare different fluids it must be understood which mechanism contributes to the thermal performance.




- For efficient heat transfer: $\Delta T(\Delta P+HTC)$ as small as possible
- For isothermal heat transfer: $\Delta T(\Delta P)$ as small as possible
- As in general small cooling tubes are preferred, so lets introduce a new property to distinguish the heat transfer relative to the needed volume

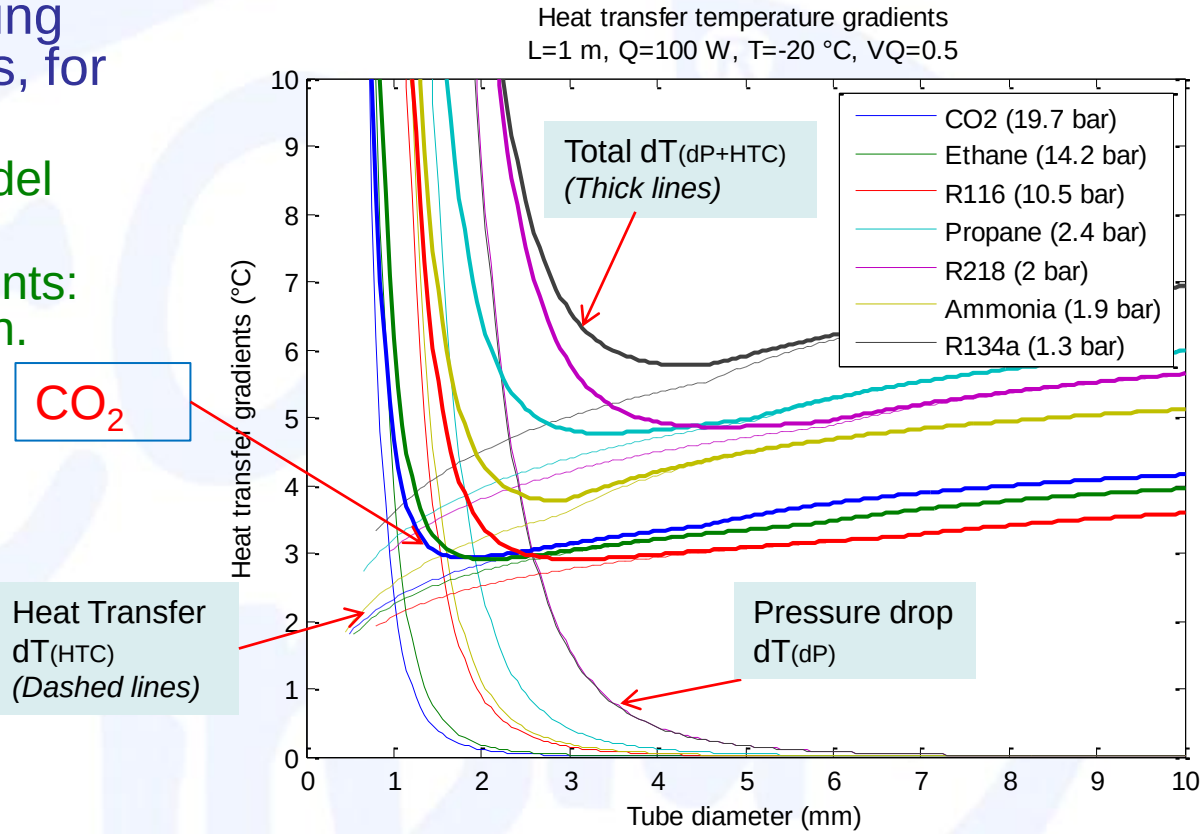
Overall Volumetric Heat Transfer Conduction (W/m³K): $\dfrac{Q}{V_{tube} * \Delta T(\Delta P+HTC))}$

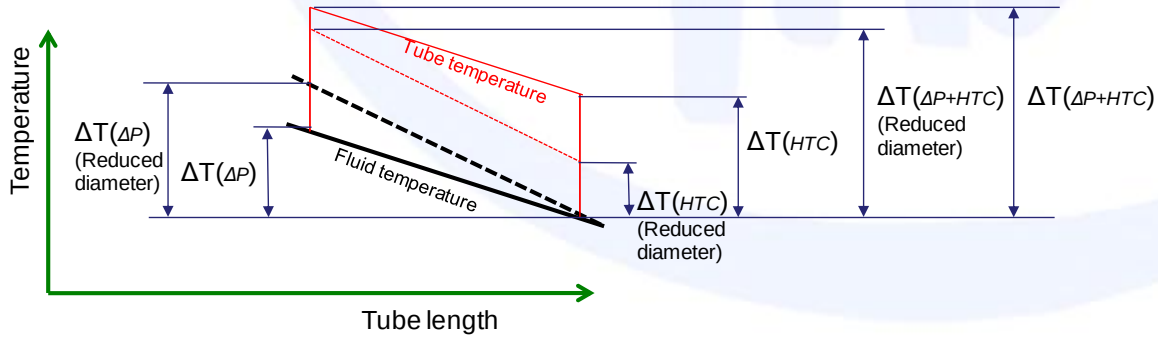
Isothermal Volumetric Heat Transfer Conduction (W/m³K): $\dfrac{Q}{V_{tube} * \Delta T(\Delta P))}$

bverlaat@nikhef.nl

# Fluid Trade-off (1)

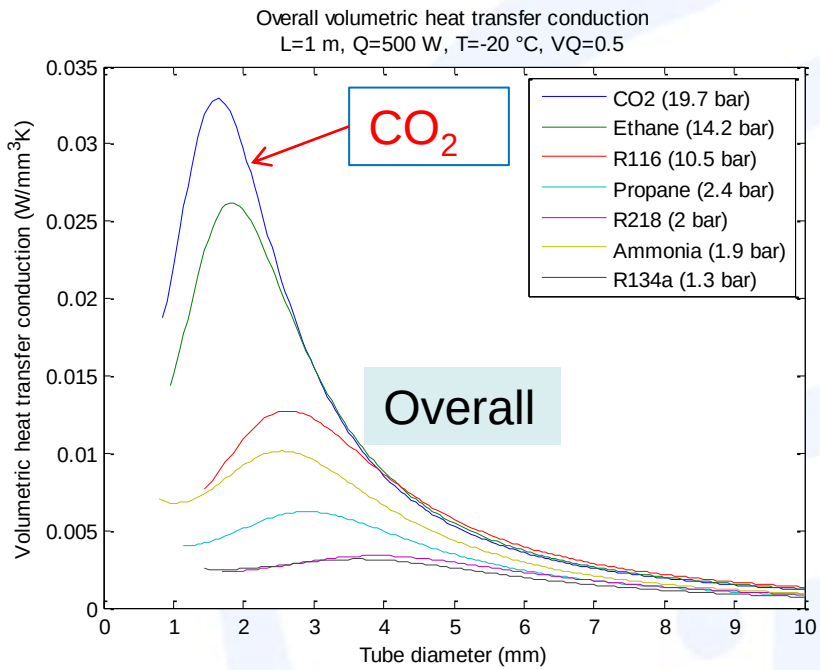
- Fluid trade-off regarding temperature gradients, for simplicity:
  - Pressure drop: Friedel correlation
  - Heat transfer gradients: Kandlikar correlation.

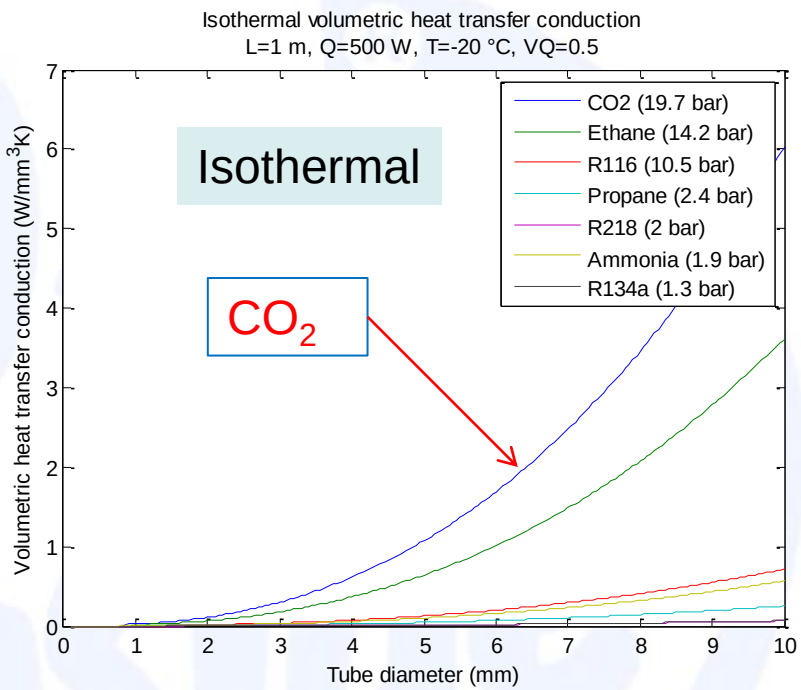


bverlaat@nikhef.nl

# Fluid Trade-off (2)




- Translating the temperature gradients to the volumetric heat transfer conductance
  - Clearly visible: $CO_2$ is a winner in both overall and isothermal.
  - Another interesting phenomena: The higher the pressure the more efficient. Is this maybe the simple answer to the perfect fluid?

bverlaat@nikhef.nl

# Is high pressure the answer to an efficient cooling fluid?

- In fact it is, the higher the pressure:
  - The more the vapor stays compressed
  - The smaller the needed volume
  - But as well: lower gas speeds mean lower pressure drop.
- Other properties are also important:
  - High latent heat (=less flow)
  - Low viscosity (=low pressure drop)
  - $CO_2$ is favorable for both properties.
- And on top of that pressure drop is less significant at high pressures as it doesn't effect the boiling pressure as it would do at low pressure fluids.

bverlaat@nikhef.nl

# $CO_2$ a perfect cooling fluid for scientific use

- As shown, $CO_2$ is a really good candidate cooling fluid if the following properties are required (In general for scientific and high-tech equipment):
  - Low mass and low volume cooling pipes
  - Isothermal behavior
  - High heat removal capacity

- The stability in time is a merit of the attached cooling plant, here fore the 2PACL principle was invented for particle detector cooling.
  - However high pressure fluids are less sensitive to pressure changes, so in fact they are as well beneficial for stable temperature systems.

bverlaat@nikhef.nl

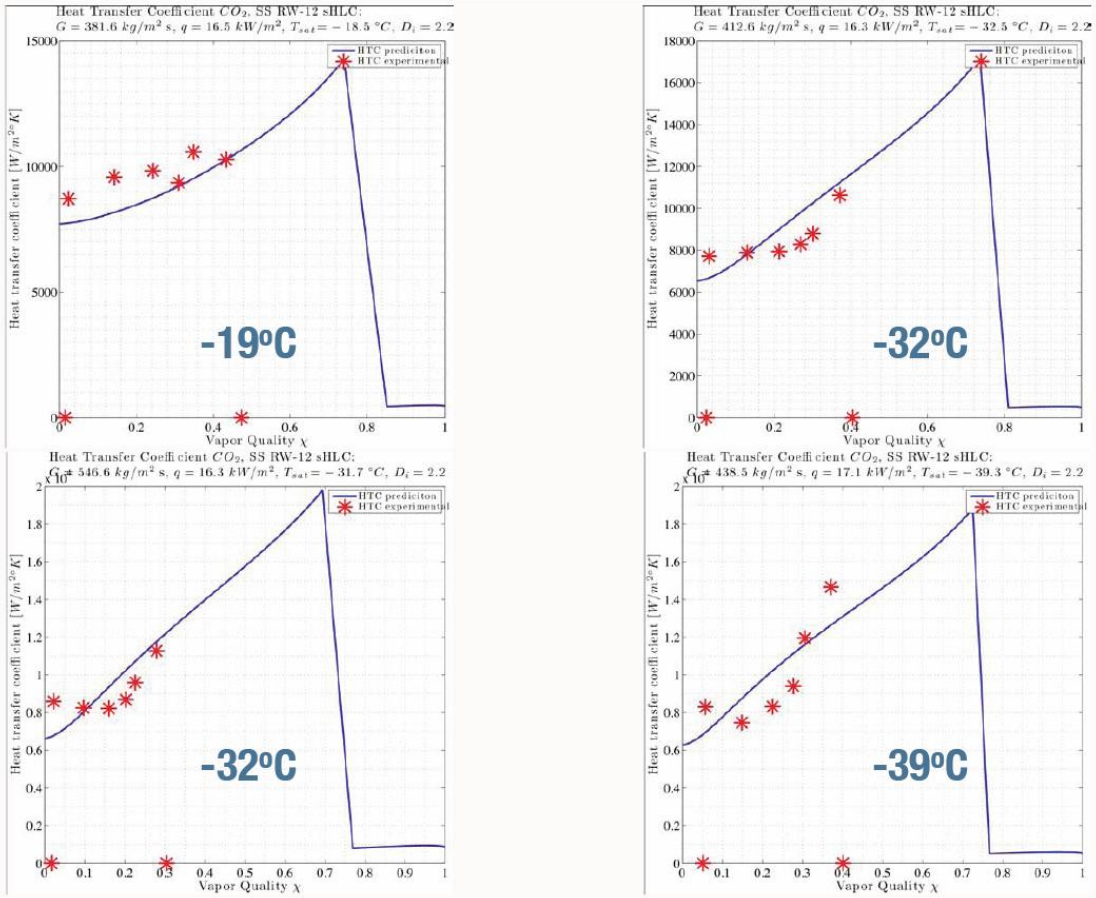
# $CO_2$ heat transfer and pressure drop modeling

- Nowadays good prediction models of $CO_2$ are available. Especially the models of J. Thome from EPFL Lausanne (Switzerland)
  - See SLAC's Advanced Instrumentation Seminar talk by J.Thome @ 9 feb 2011
- Models are flow pattern based and are reasonably well predicting the flow conditions and the related heat transfer and pressure drop.
- The Thome models are successfully used to predict the complex thermal behavior of particle detector cooling circuits.
- A simulation program called CoBra is developed to analyze full detector cooling branches.

bverlaat@nikhef.nl

# Experimental heat transfer data (measured at SLAC)

## ID2.16mm, HTC CO2 (Medium heat, 16kW/m$^2$)

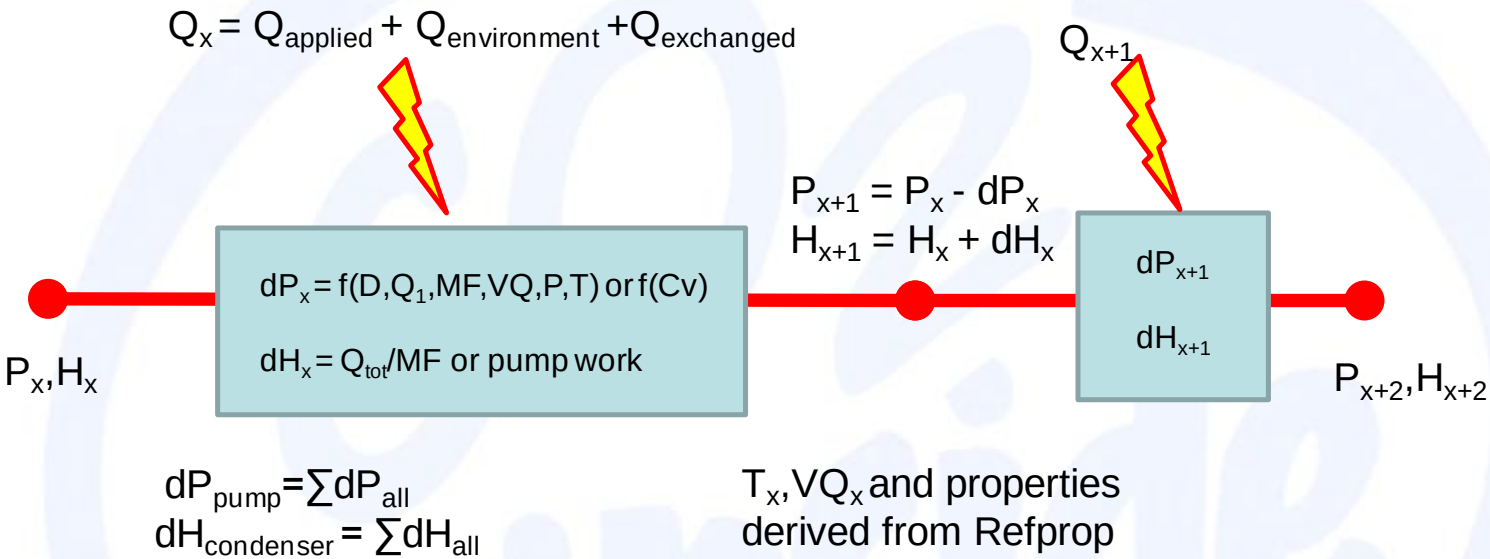



Interesting research on heat transfer is done at SLAC in a joint effort with Nikhef.
M. Oriunno (SLAC) & G. Hemmink (Nikhef)

18

bverlaat@nikhef.nl

# CoBra Calculator
# (CO2 BRAnch Calculator)

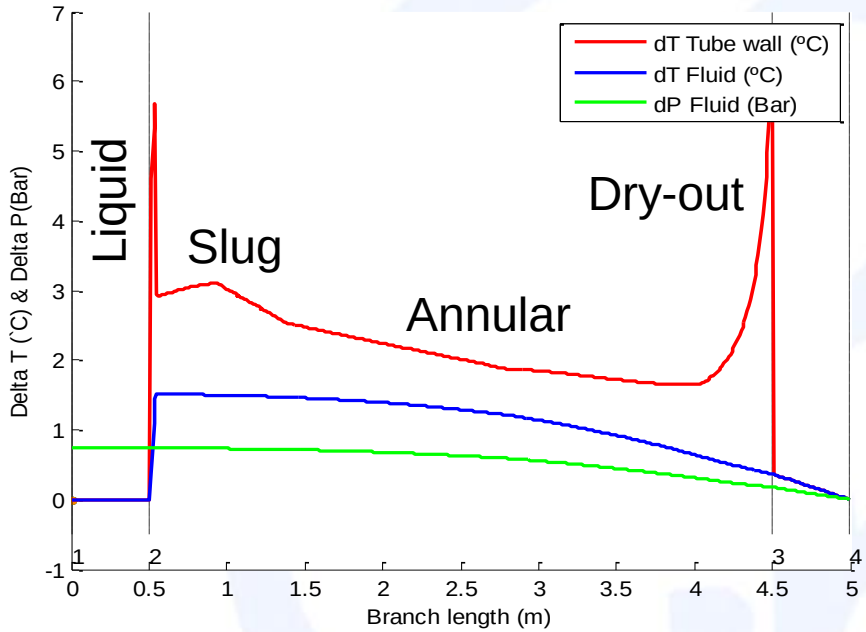


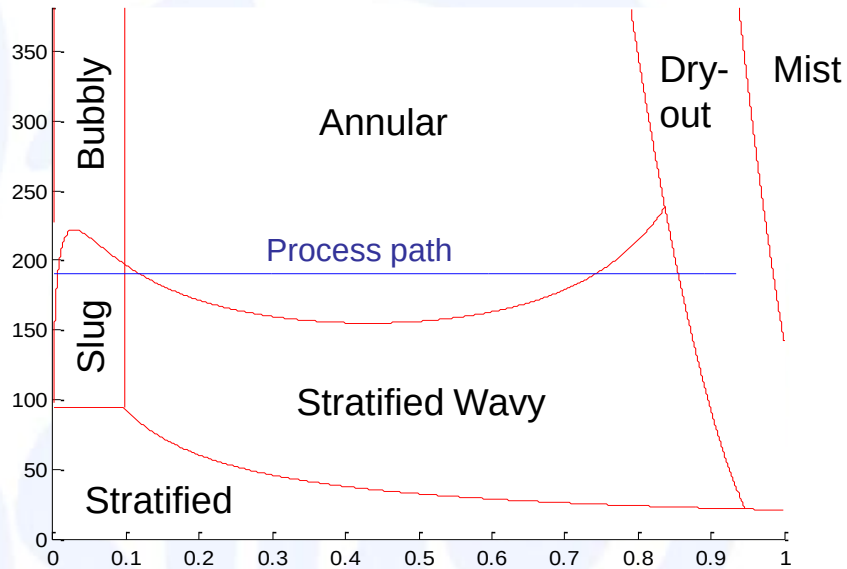

- Iterative method chopping a long line in small elements (~1mm).
- Model can read simple configuration files giving simple tube geometry
- Heat leak and internal heat exchange between elements can be taken into account.
- CoBra is a very helpful tool for predicting the complex behavior of 2-phase flow.

bverlaat@nikhef.nl

# CoBra example calculation

5mx1.5mmID tube (4m heated), Mass flow=0.3g/s, Q=90Watt , T=-30ºC




- CoBra is able to analyze complex thermal behavior of $CO_2$ in long tubes

bverlaat@nikhef.nl

# Internal heat exchange and ambient heating

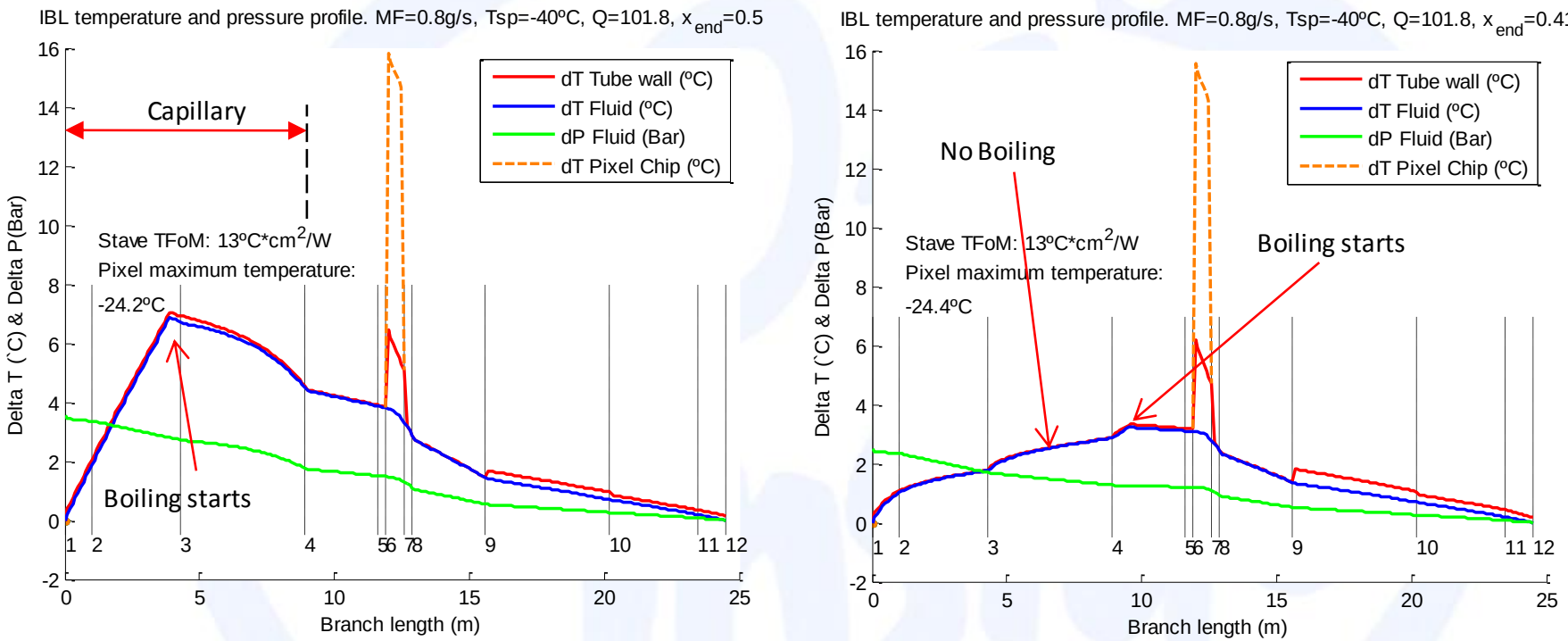


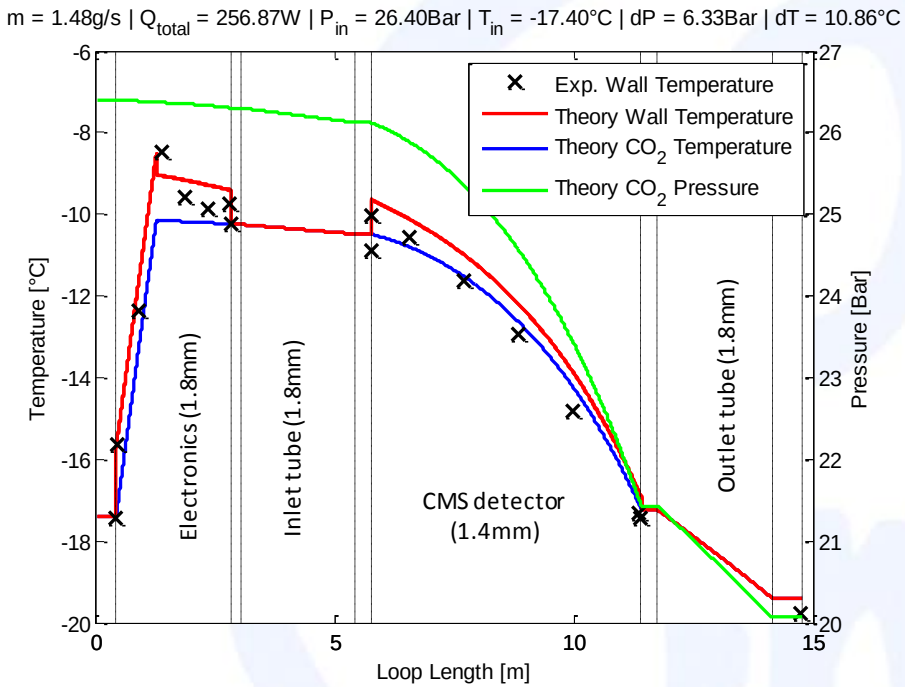

*Figure 7: CoBra calculation example of the IBL cooling tube. The branch has a 1mm inlet (1-4), a 1.5 mm cooling tube (4-8), a 2mm outlet (8-9) followed by a 3mm outlet (9-12). The dashed temperature profile is the actual sensor temperature taking into account the conductance of the support structure. The graph on the left has no internal heat exchange, the right graph takes internal heat exchange of the in and outlet tube into account.*

Figures from: DESIGN CONSIDERATIONS OF LONG LENGTH EVAPORATIVE CO2 COOLING LINES
Bart Verlaat and Joao Noite, GL-209, 10th IIF/IIR Gustav Lorentzen Conference on Natural Working Fluids, Delft, The Netherlands 2012

bverlaat@nikhef.nl

# Comparison to test results

## CMS-B-PIX




## Atlas-IBL

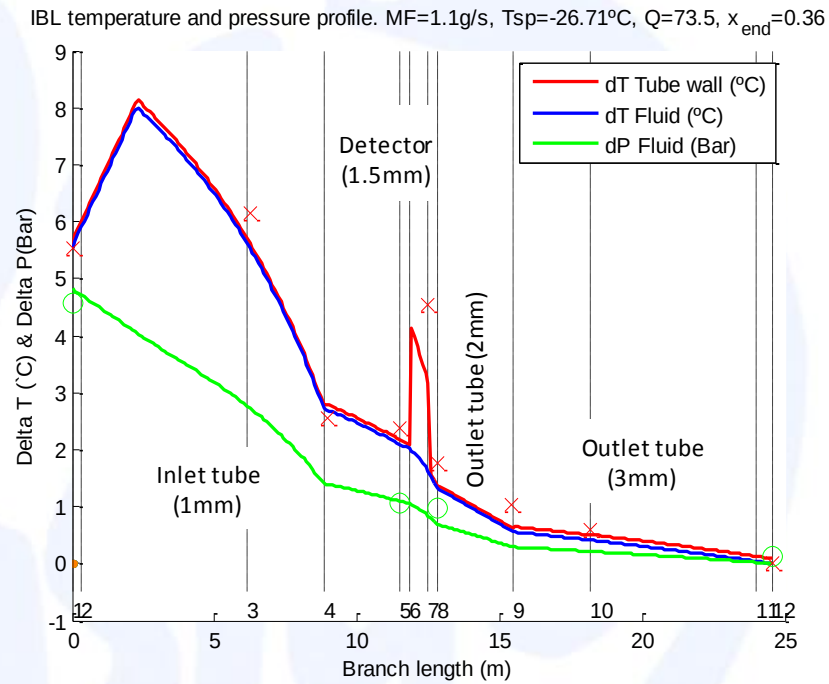
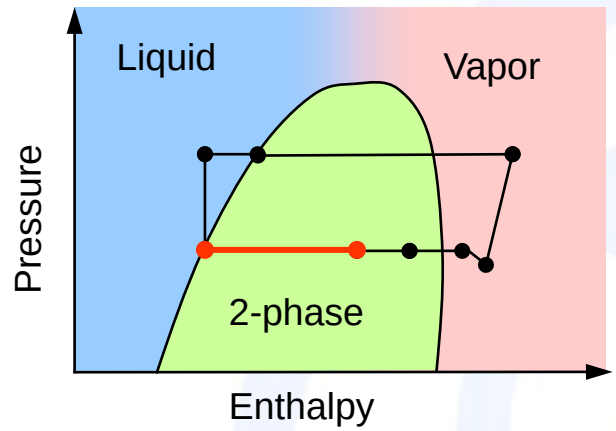



*Figure 8: Temperature and pressure test results of the CMS pixel upgrade cooling branch (left) and the Atlas IBL cooling branch (right). Comparison with the CoBra calculator showed that the calculator is a promising tool for predicting the temperature and pressure gradients over long length cooling branches.*

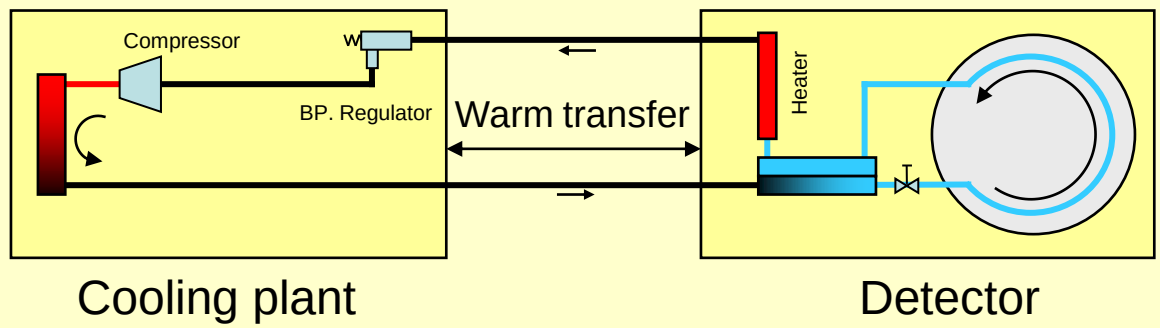
Figures from: DESIGN CONSIDERATIONS OF LONG LENGTH EVAPORATIVE CO2 COOLING LINES
Bart Verlaat and Joao Noite, GL-209, 10th IIF/IIR Gustav Lorentzen Conference on Natural Working Fluids, Delft, The Netherlands 2012

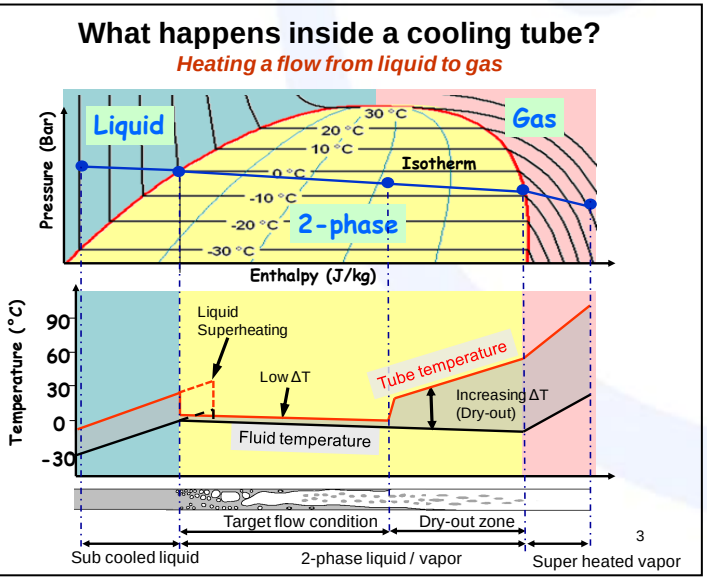
bverlaat@nikhef.nl

# What circulation method can we use?




## Refrigeration method: **Vapor compression system (Atlas)**



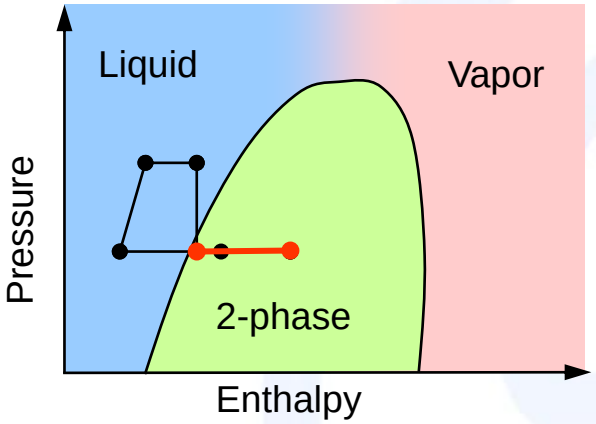

If we remember slide 3, we see that proper cooling takes place on the liquid side, while compressors need gas as input. It is better to invent a cycle staying on the liquid side.

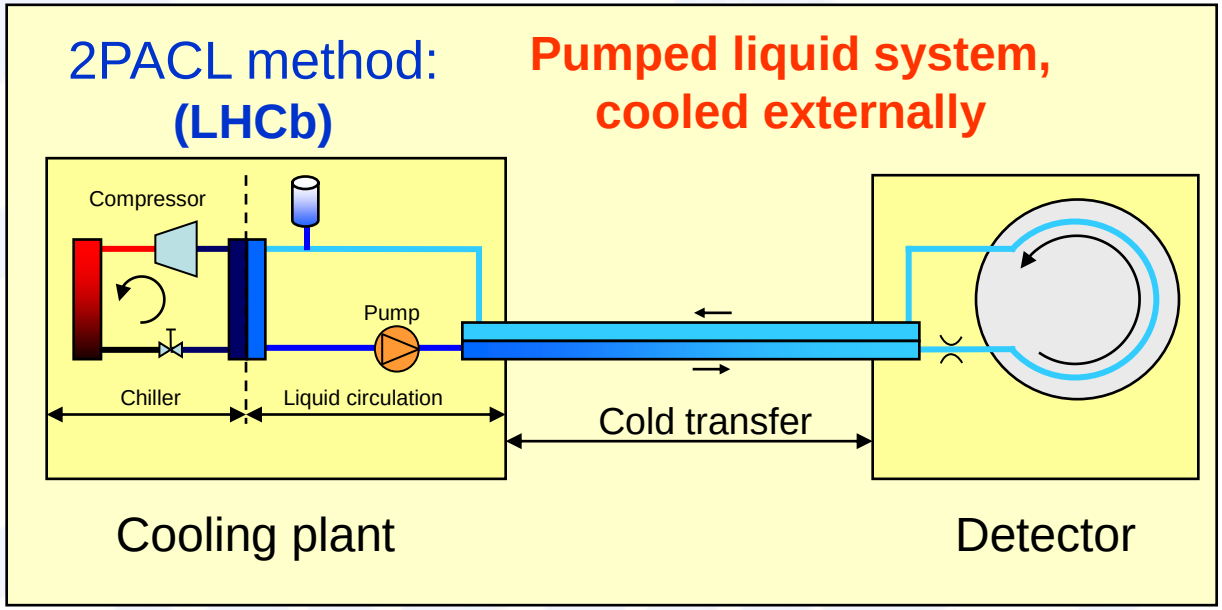
**=> externally cooled pump cycle.**

bverlaat@nikhef.nl

# New cycle for particle detectors: 2PACL

## (The 2-Phase Accumulator Controlled Loop )



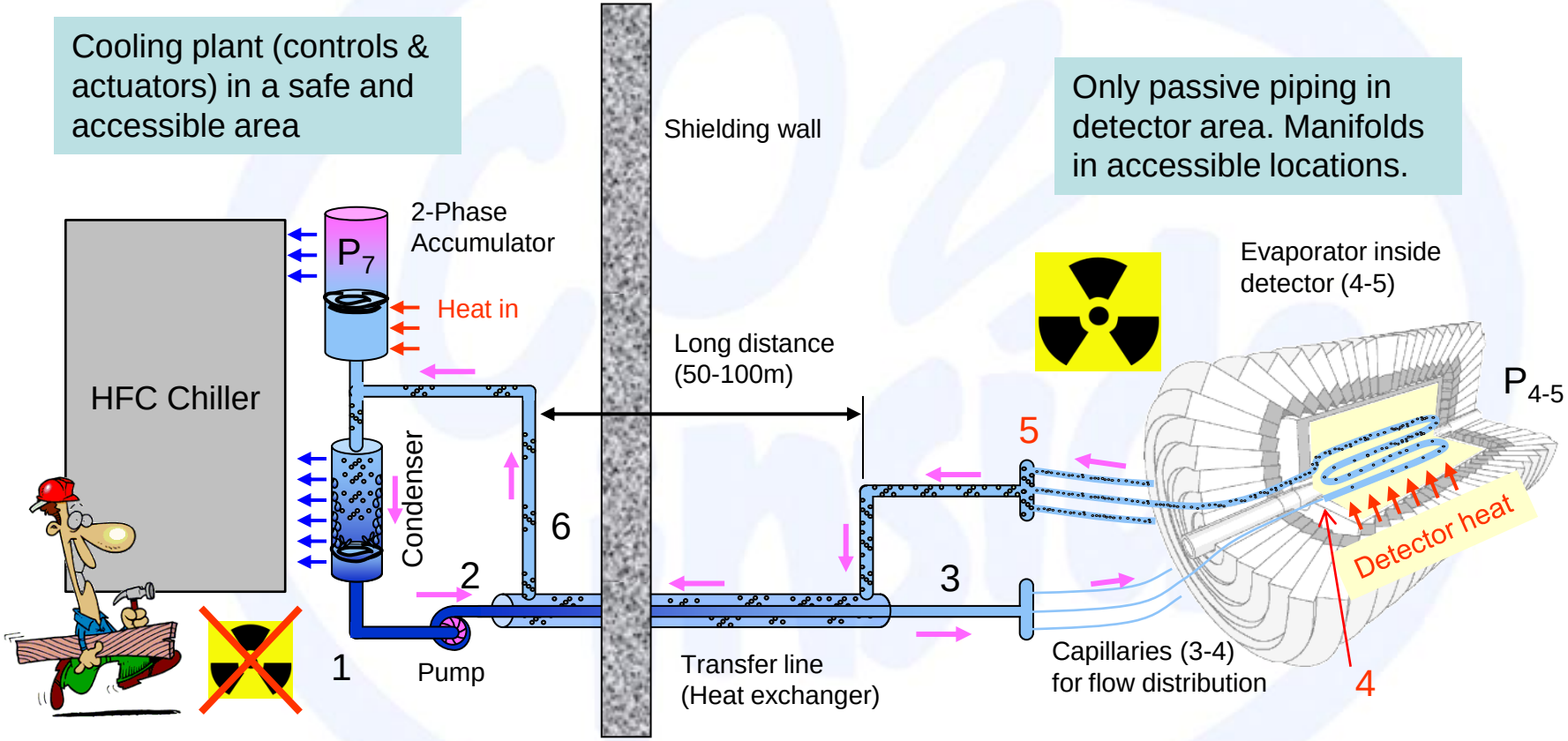

- The 2PACL has the following advantages:
  - Cycle stays on the liquid side, no heat required (experiment can be cooled unpowered and no control heaters required)
  - Evaporator pressure=(temperature) controlled with a 2-phase vessel away from the experiment. No local control nor sensing needed!
  - All control hardware in a distant accessible cooling plant
  - Primary cooling can be anything, no accurate temperature control needed as long as it is colder than the 2PACL 2-phase temperature.
  - Inlet fluid state defined by physics => saturated liquid.
  - Large temperature range (typical from room temperature down to -40°C)

bverlaat@nikhef.nl

# 2PACL application in a particle detector

Cooling plant (controls & actuators) in a safe and accessible area

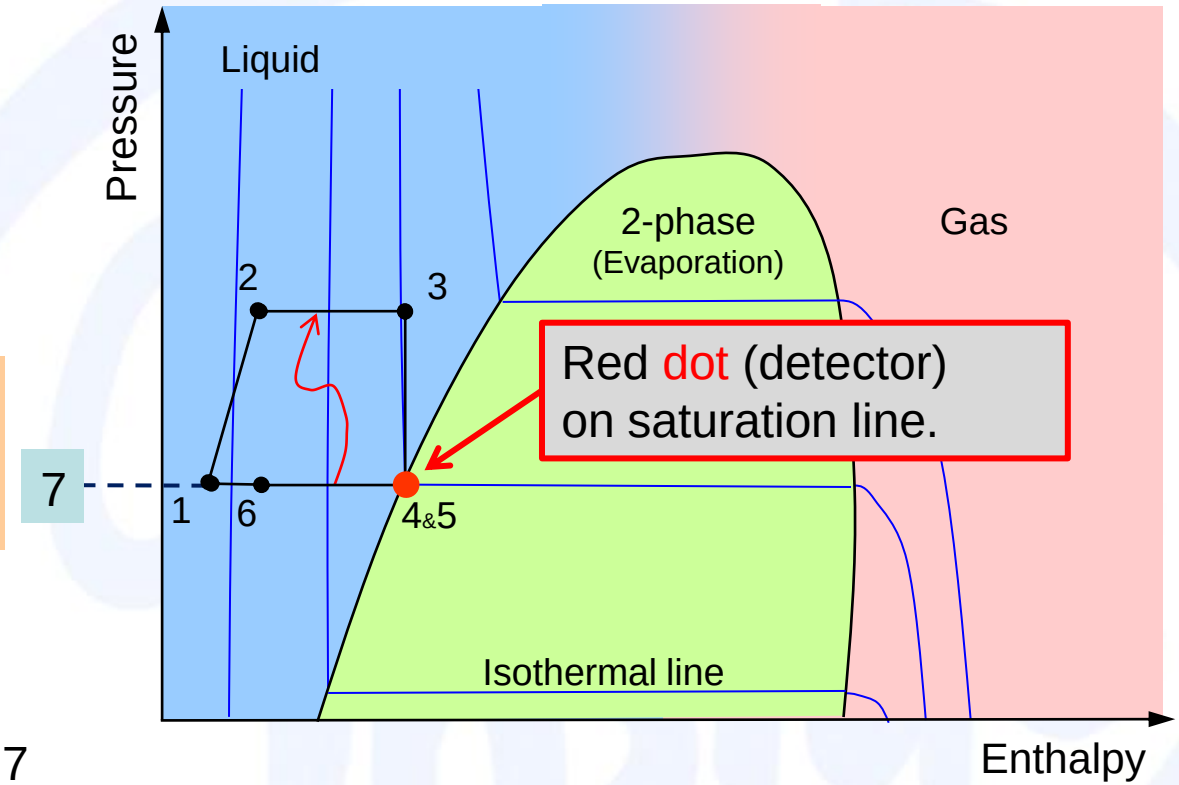
Only passive piping in detector area. Manifolds in accessible locations.

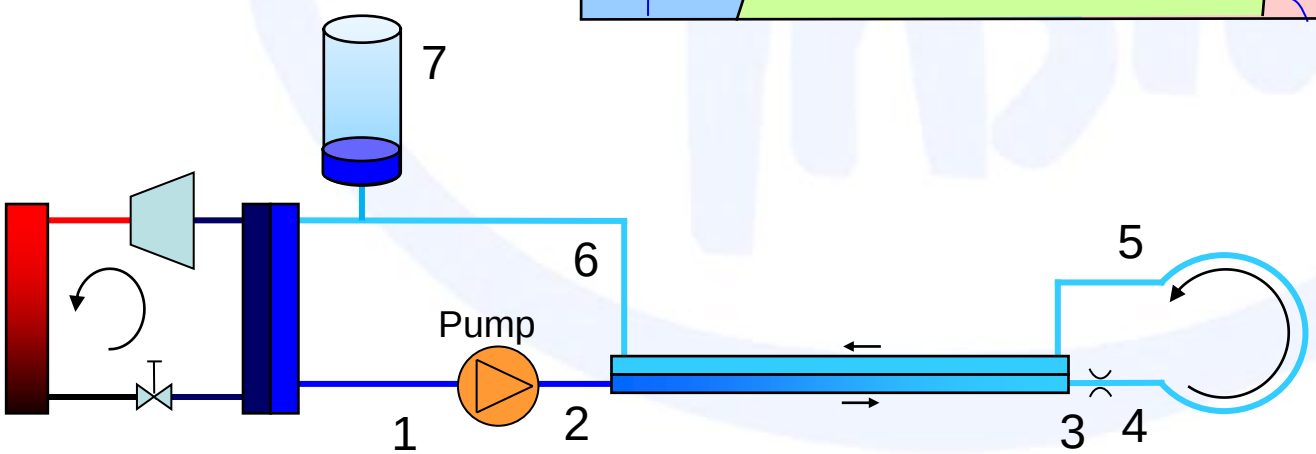


bverlaat@nikhef.nl

# 2-Phase Accumulator Controlled Loop (2PACL)

Pressure control with accumulator. Change set-point.

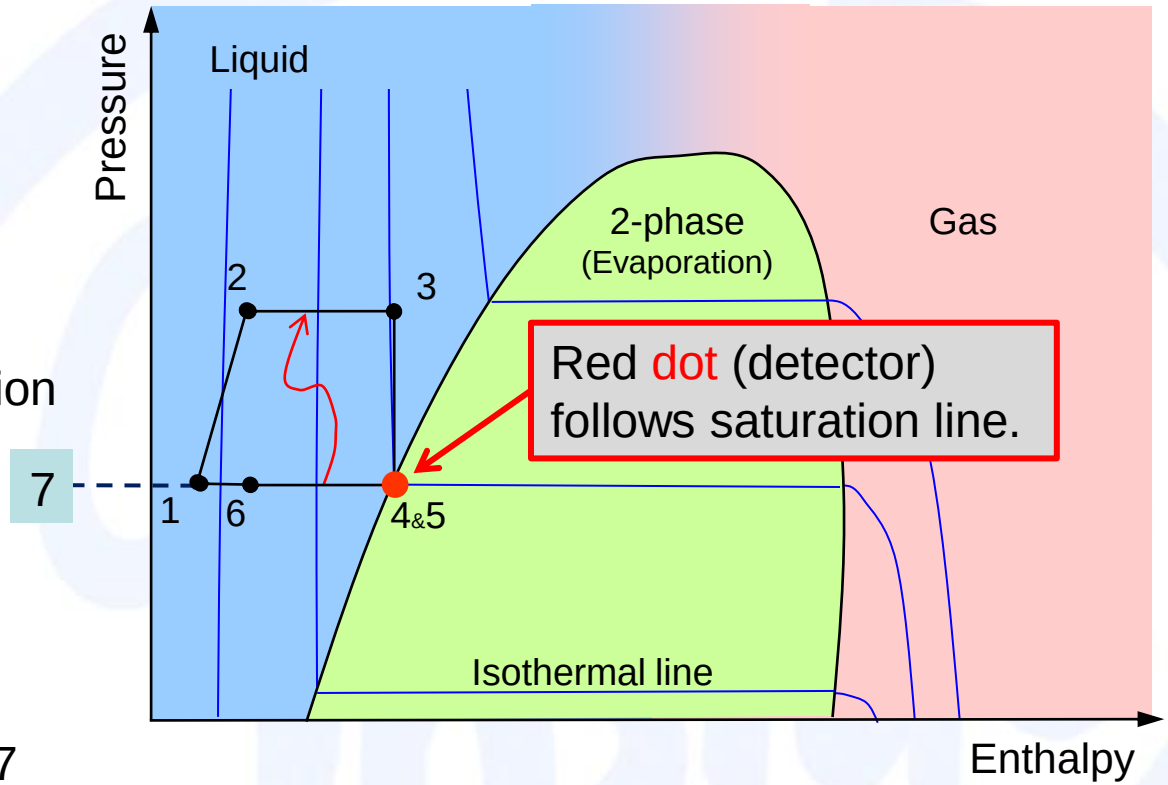


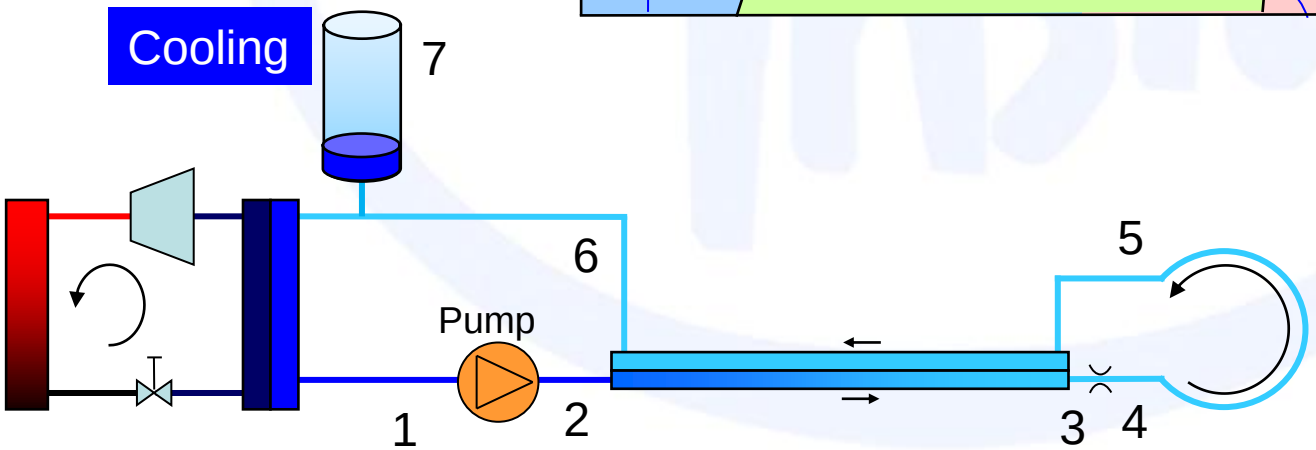



bverlaat@nikhef.nl

# 2-Phase Accumulator Controlled Loop (2PACL)

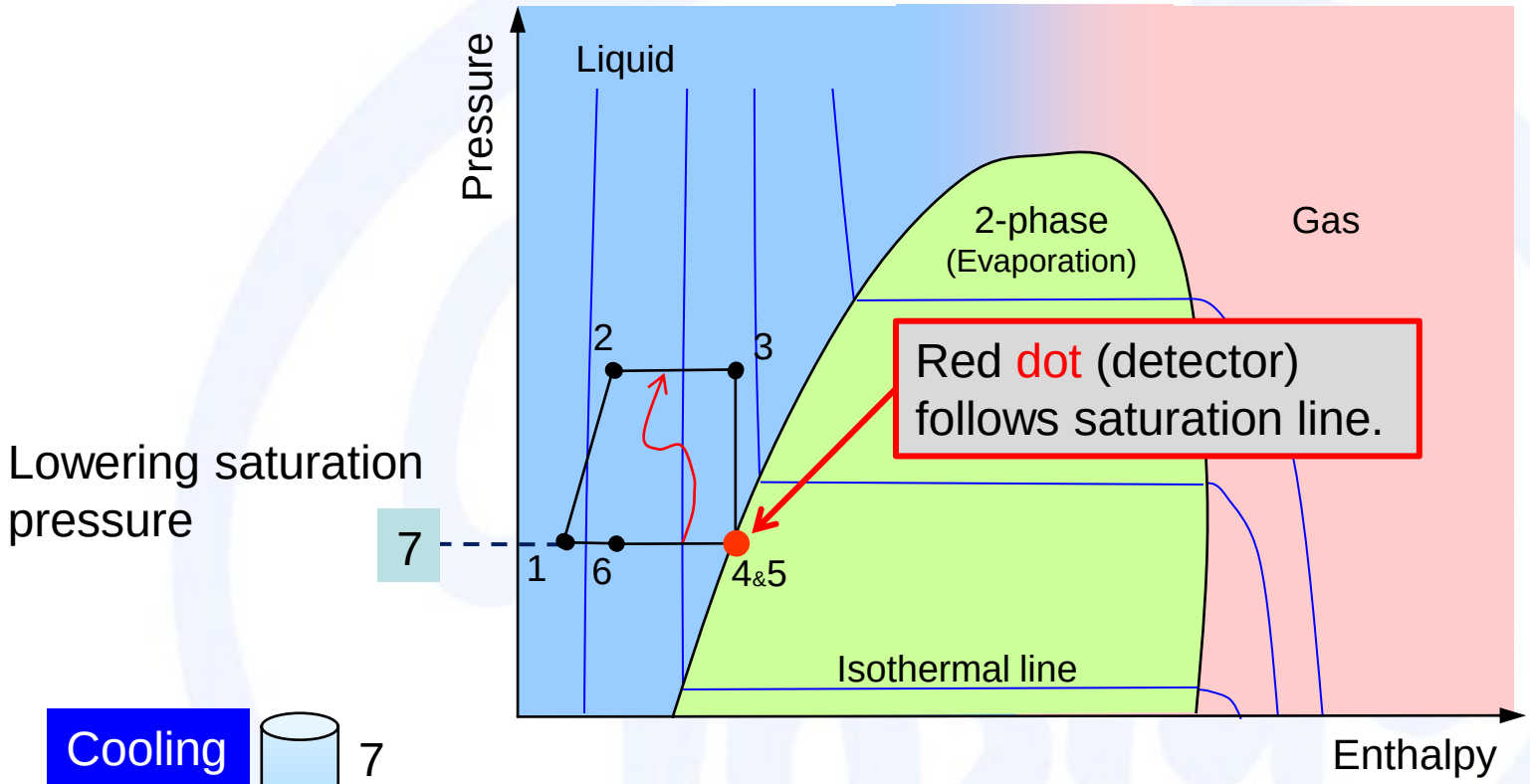
Lowering saturation pressure

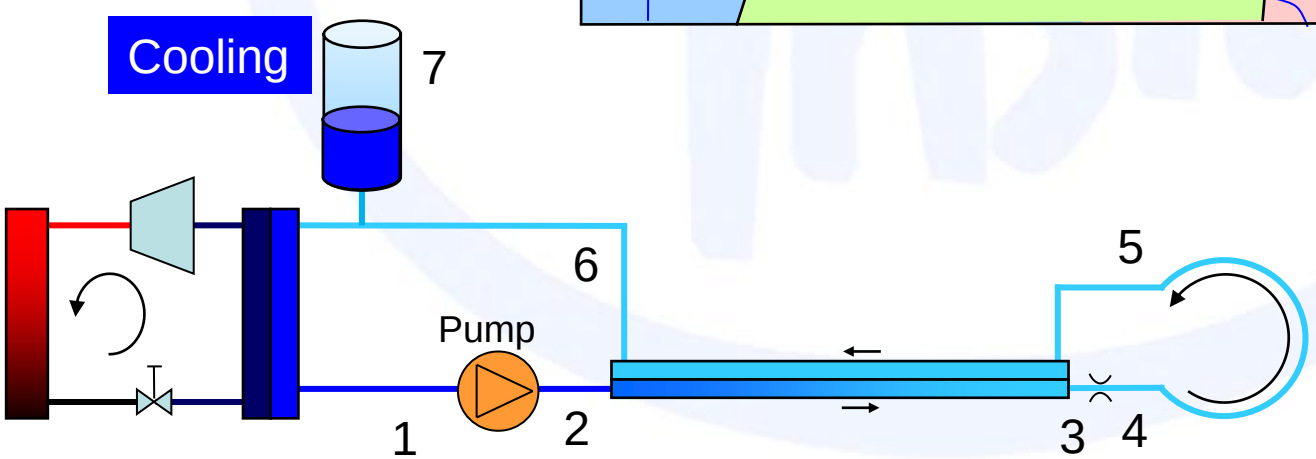


bverlaat@nikhef.nl

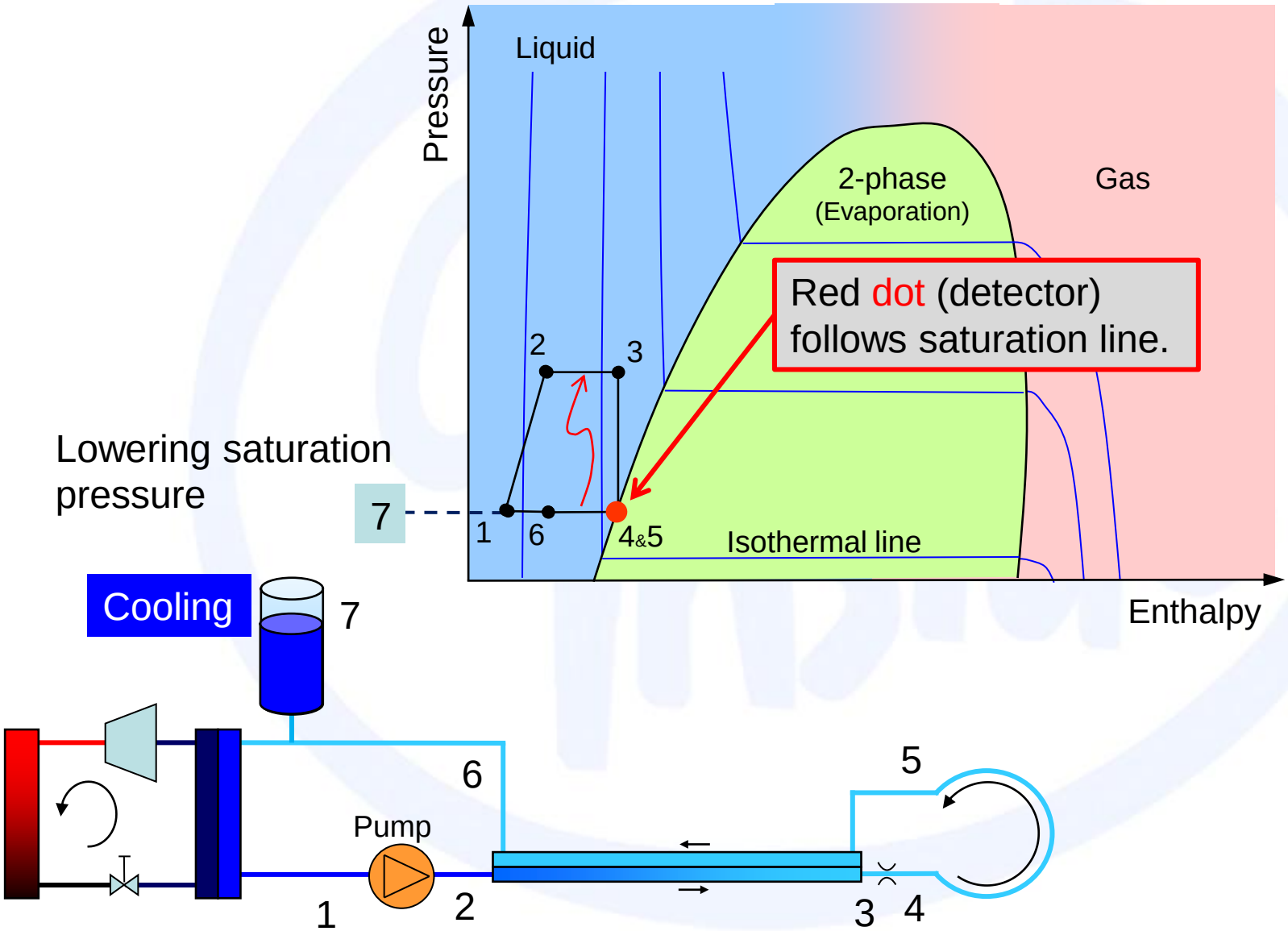
# 2-Phase Accumulator Controlled Loop (2PACL)



bverlaat@nikhef.nl

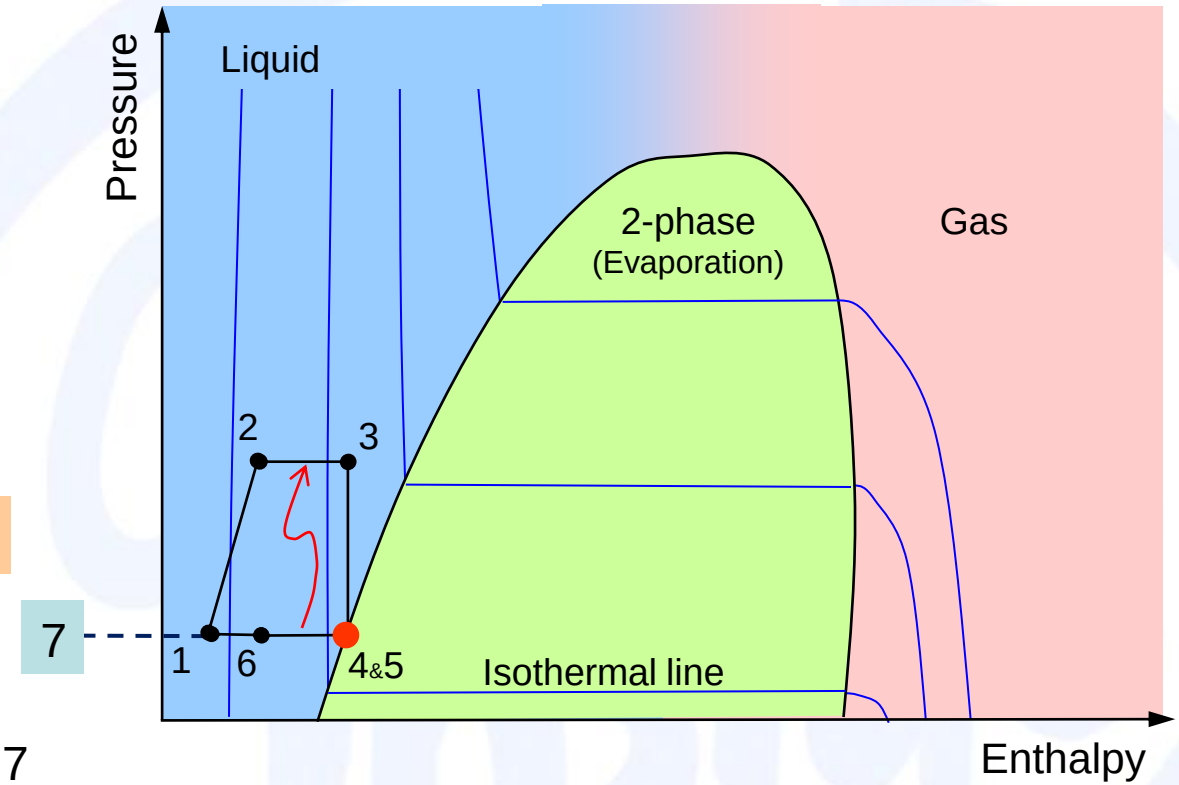
# 2-Phase Accumulator Controlled Loop (2PACL)

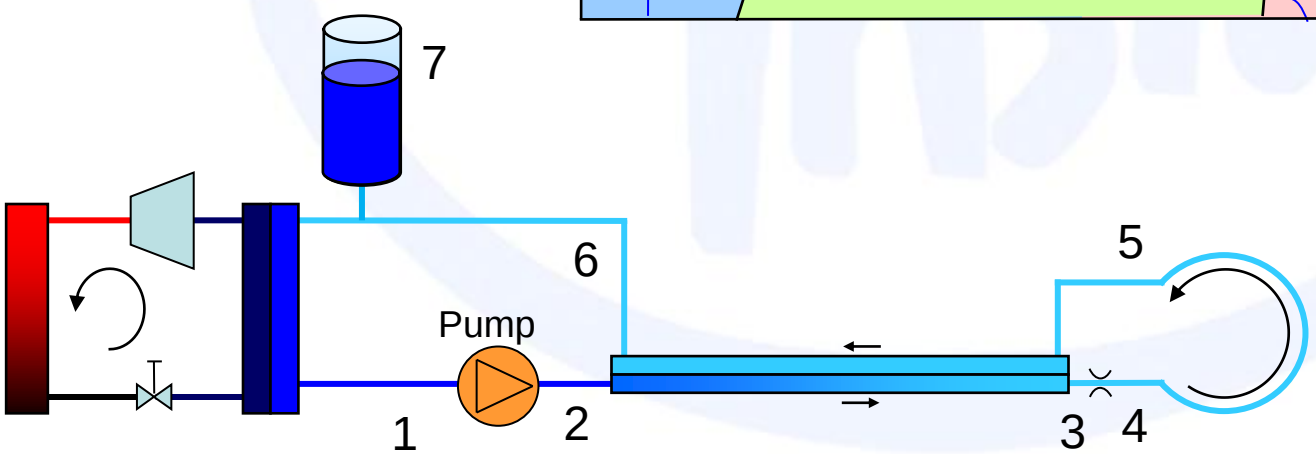


bverlaat@nikhef.nl

# 2-Phase Accumulator Controlled Loop (2PACL)

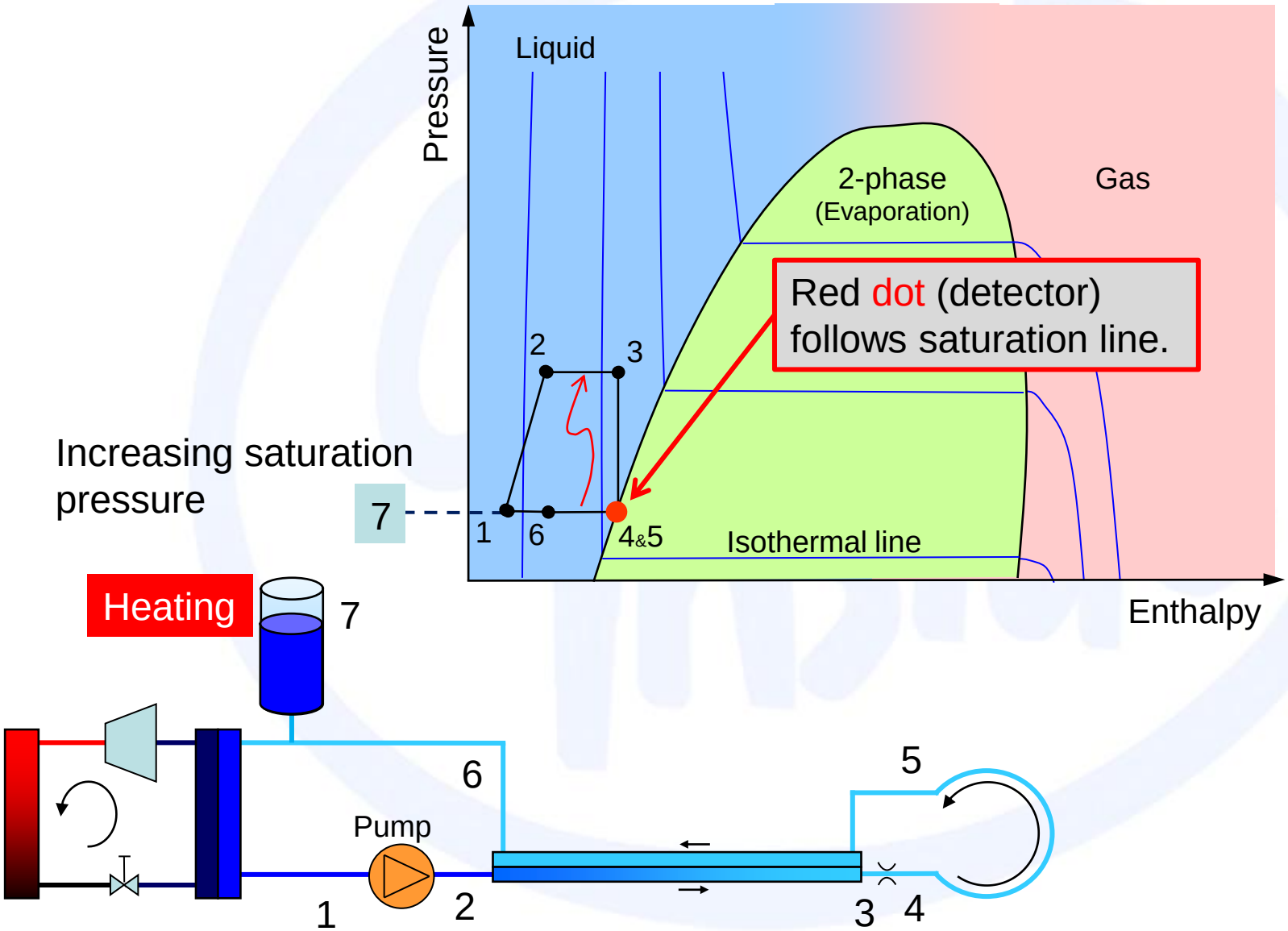
Set point reached



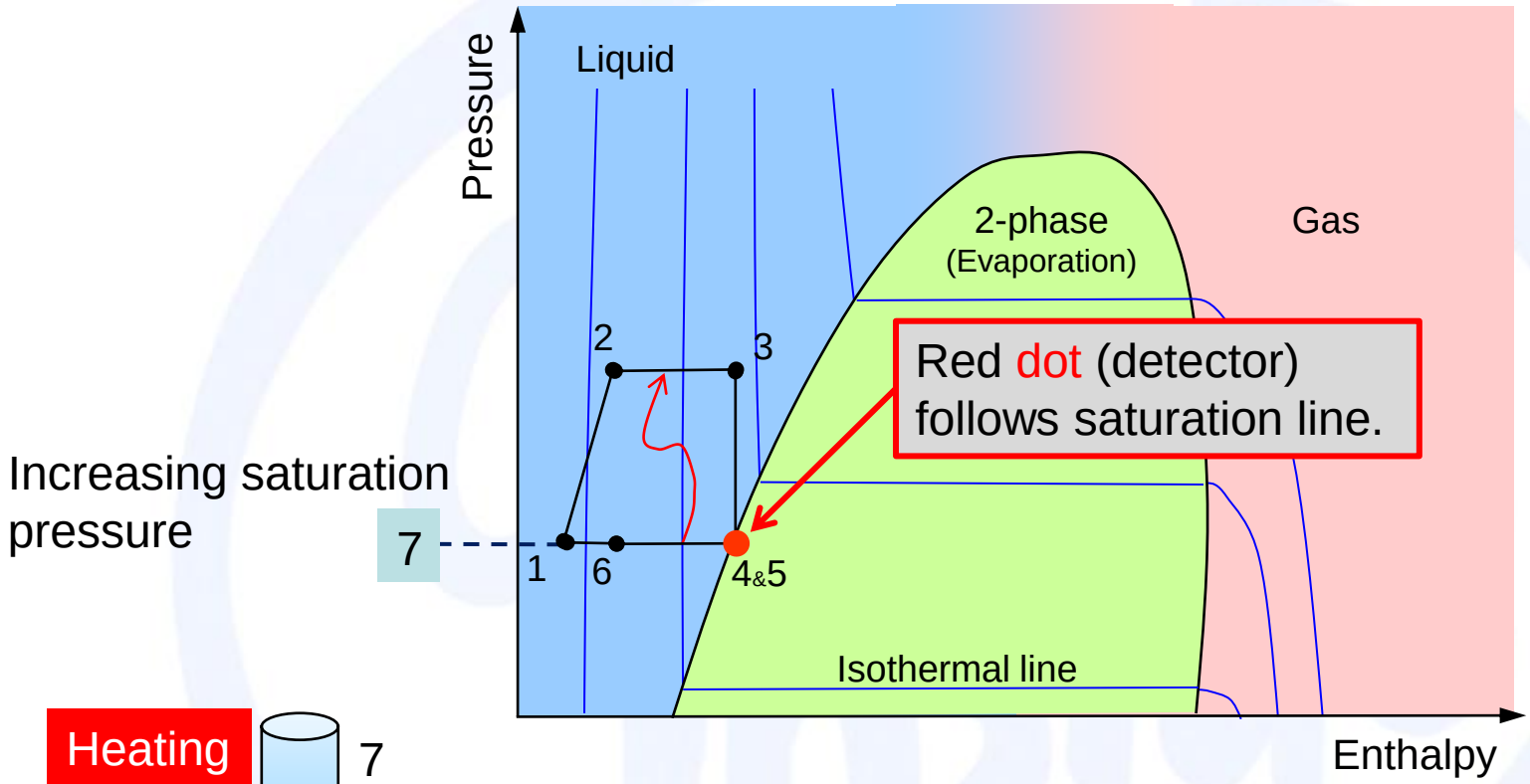
bverlaat@nikhef.nl

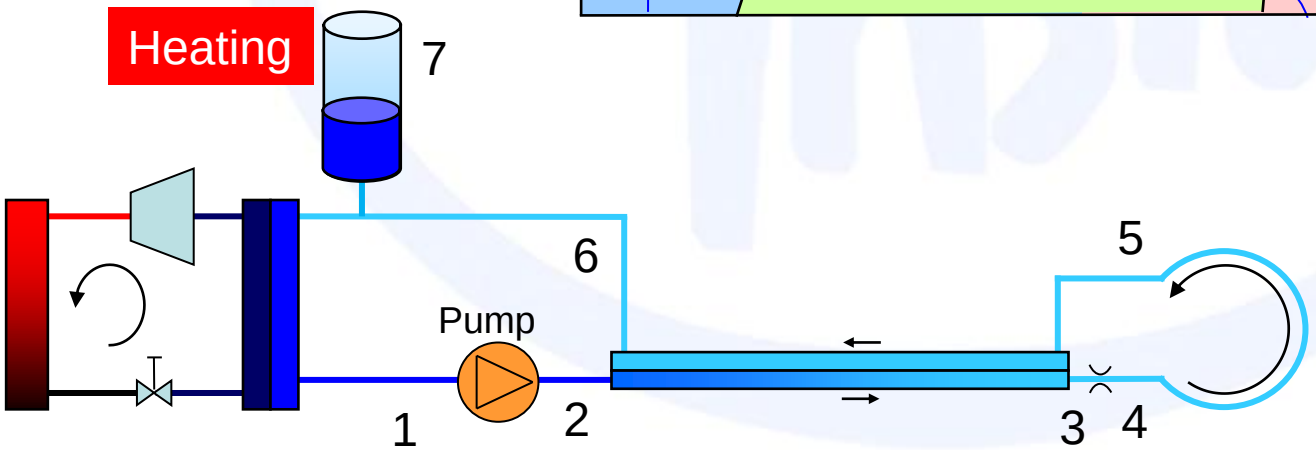
# 2-Phase Accumulator Controlled Loop (2PACL)



bverlaat@nikhef.nl

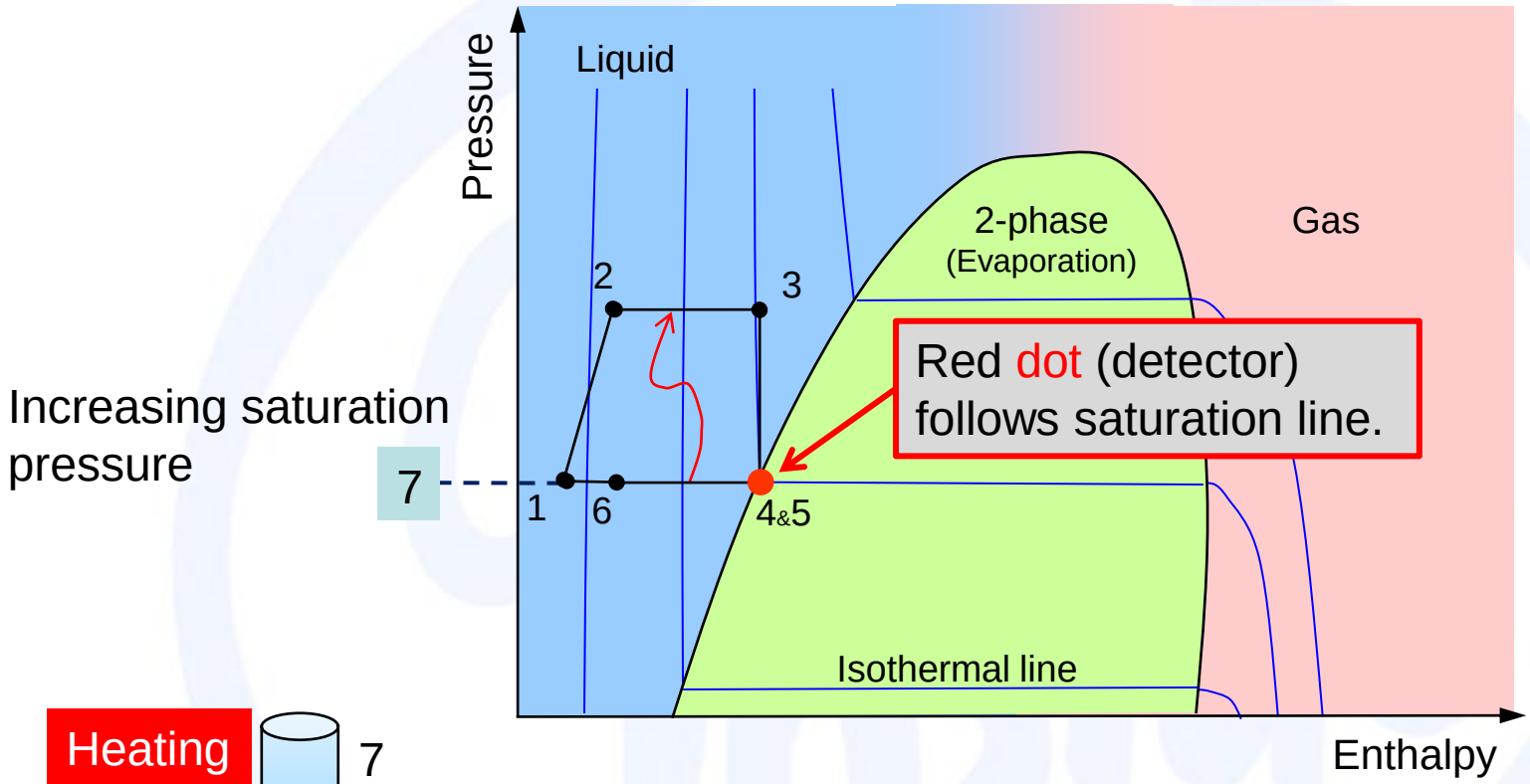
# 2-Phase Accumulator Controlled Loop (2PACL)

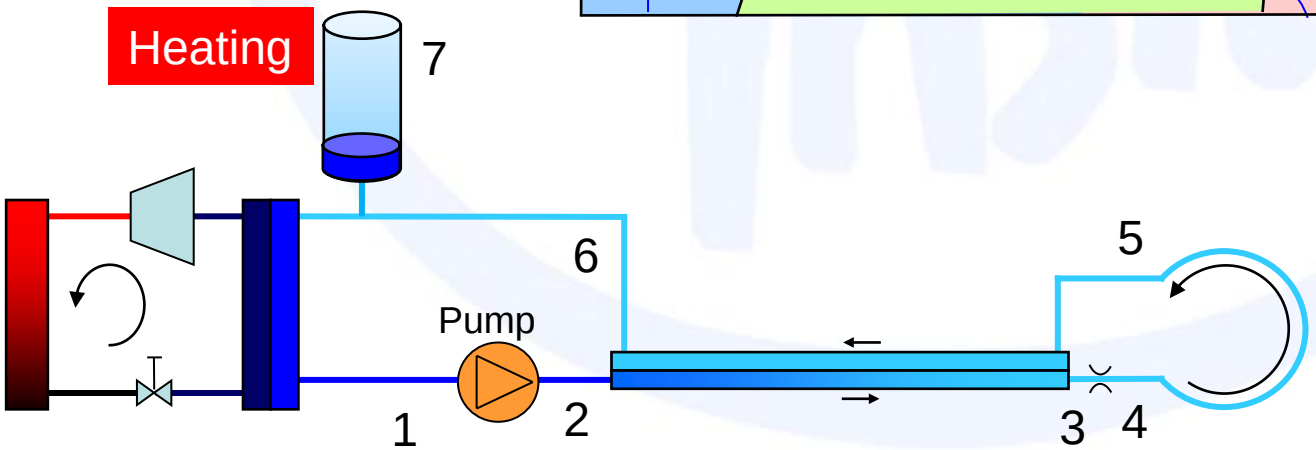


bverlaat@nikhef.nl

# 2-Phase Accumulator Controlled Loop (2PACL)

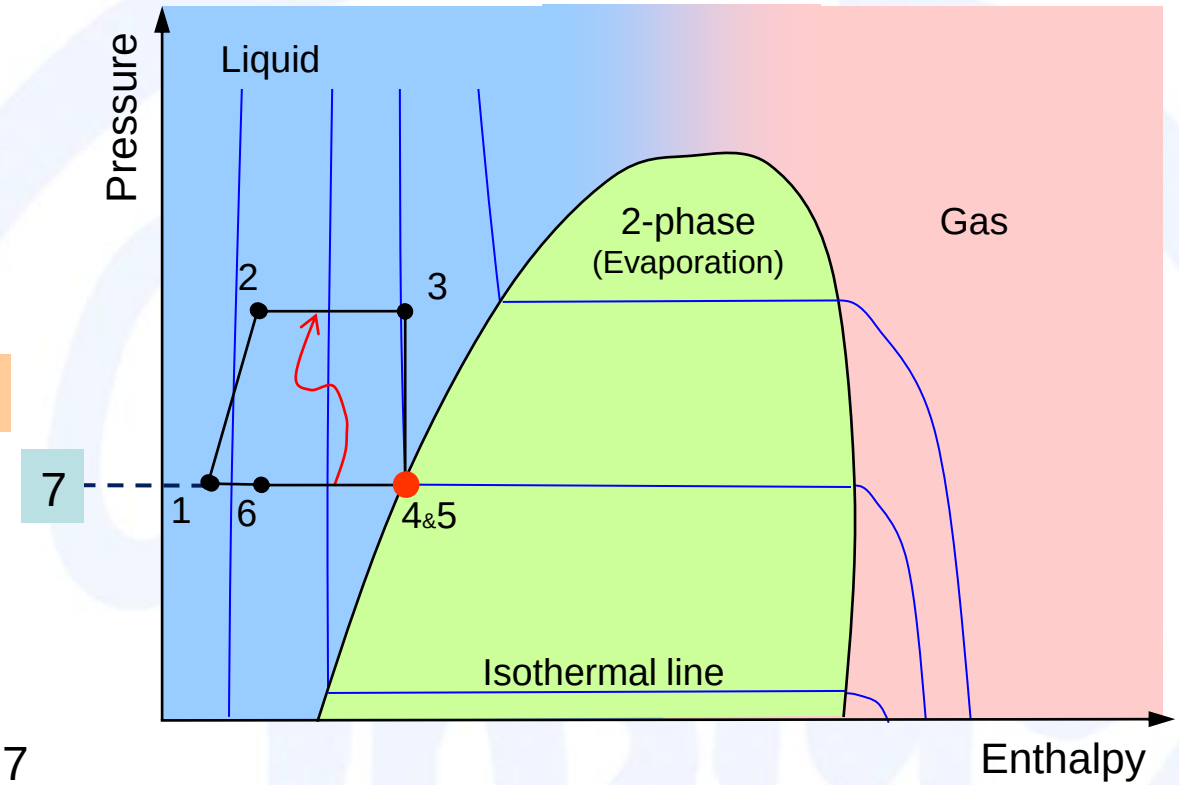


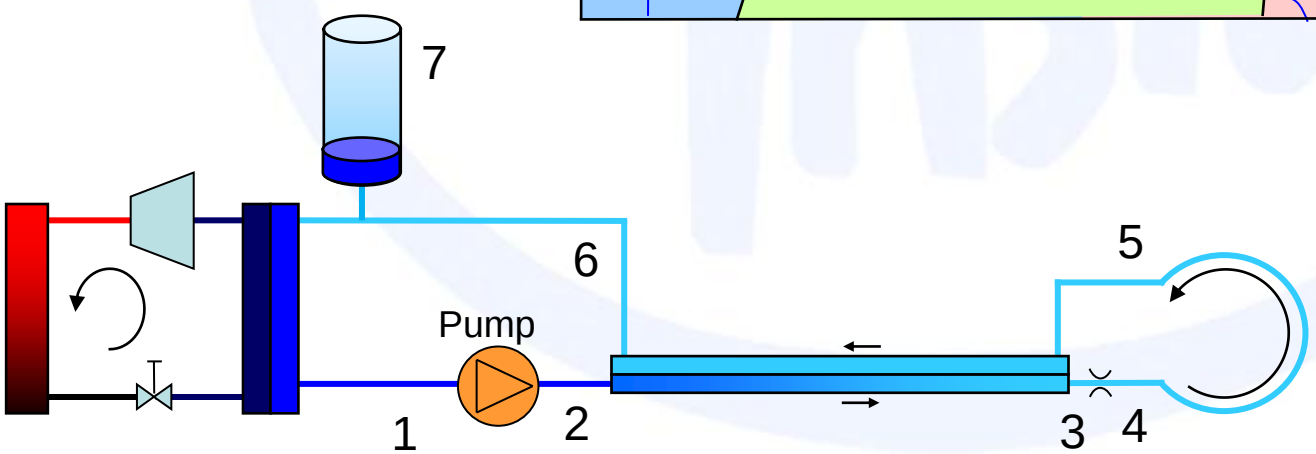



bverlaat@nikhef.nl

# 2-Phase Accumulator Controlled Loop (2PACL)

Set point reached

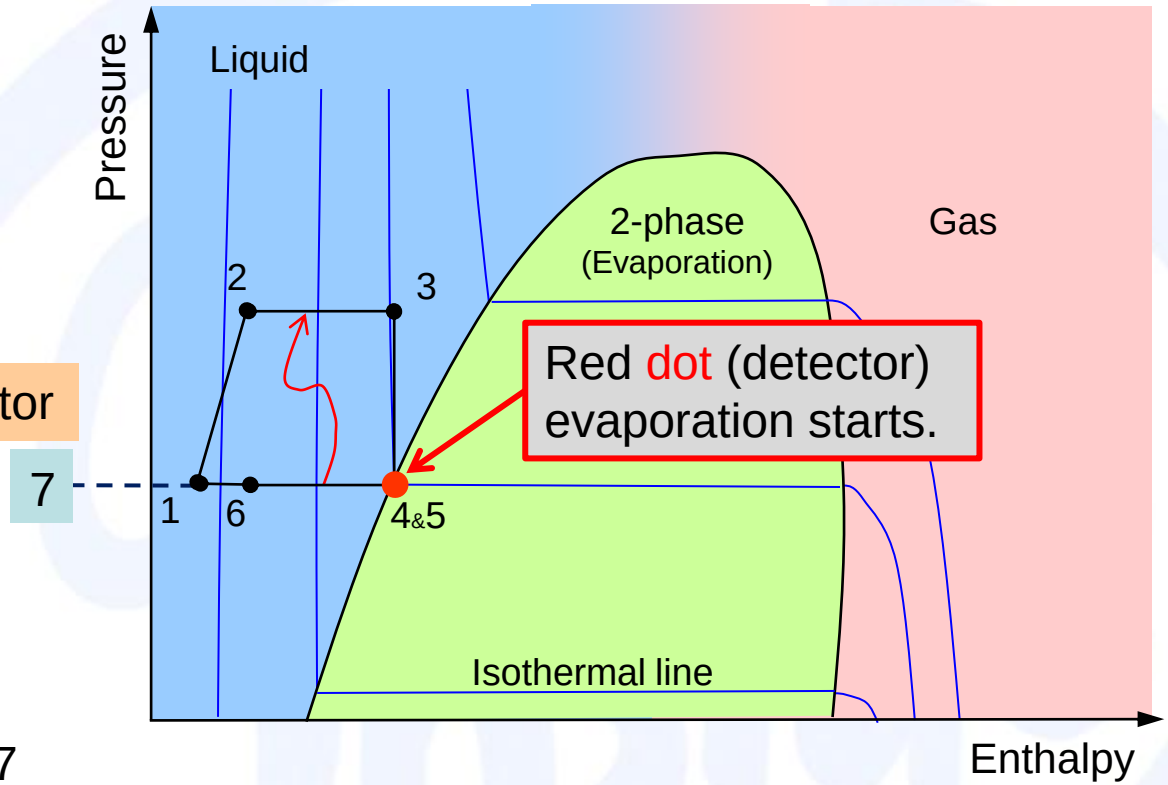


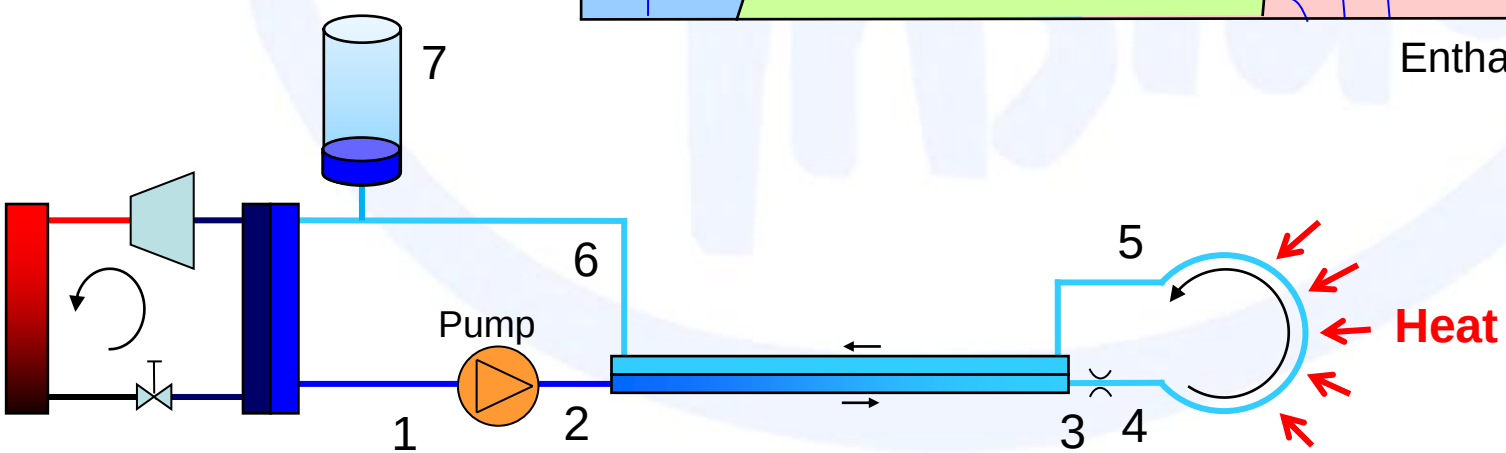



bverlaat@nikhef.nl

# 2-Phase Accumulator Controlled Loop (2PACL)

Switching on detector

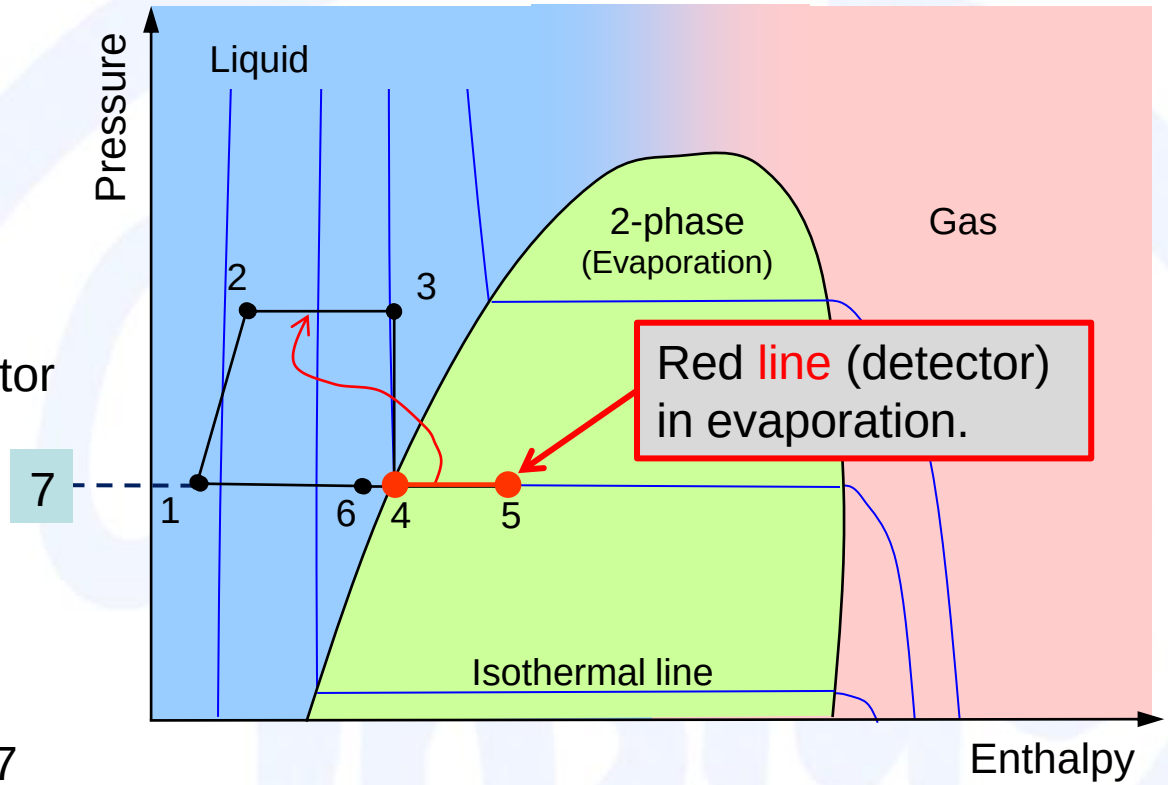


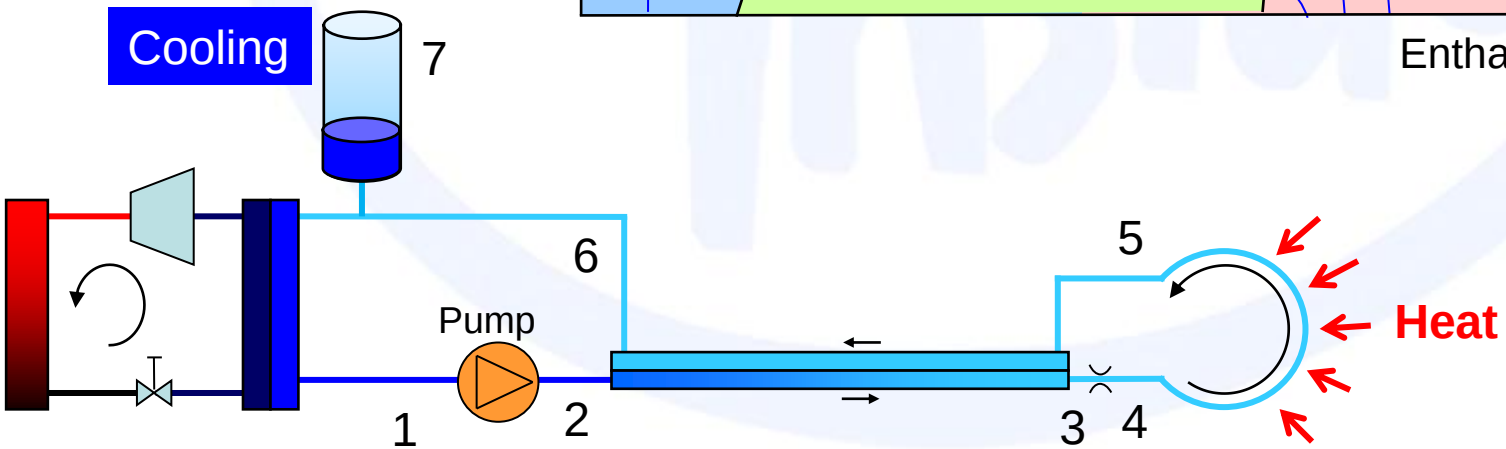



bverlaat@nikhef.nl

# 2-Phase Accumulator Controlled Loop (2PACL)

Powering detector

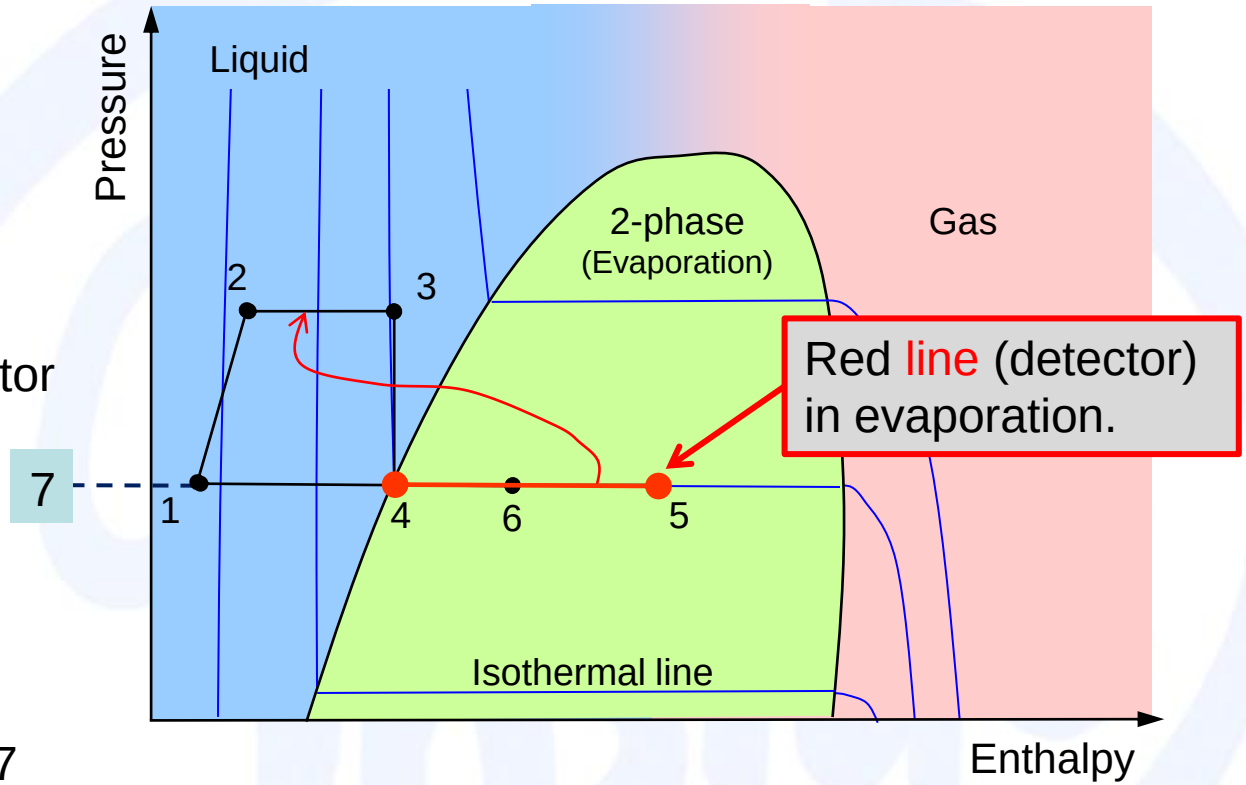


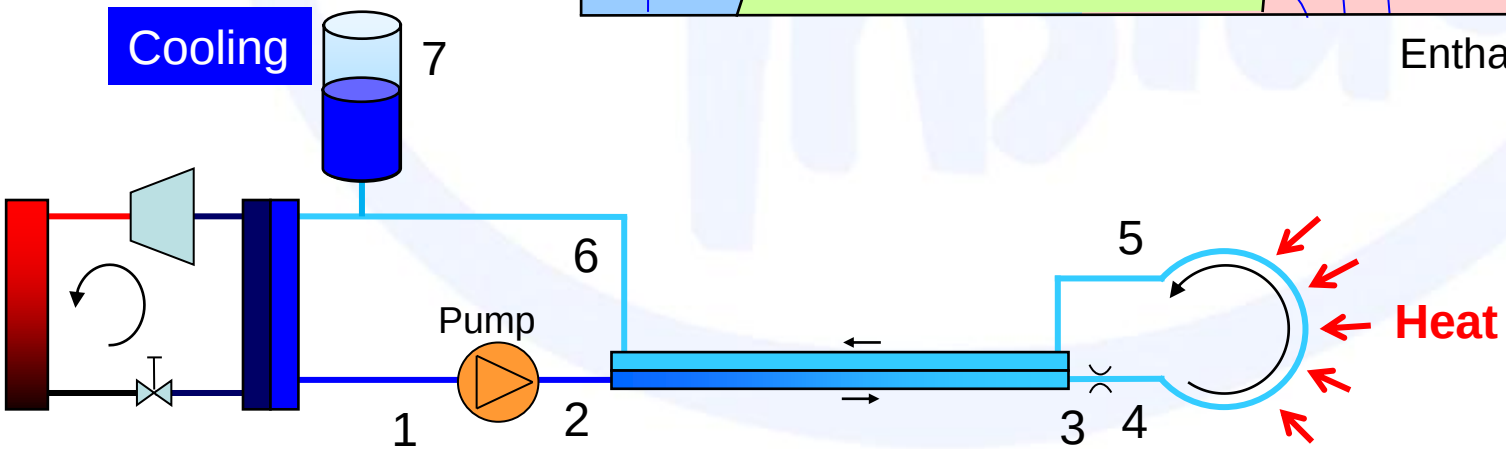



bverlaat@nikhef.nl

# 2-Phase Accumulator Controlled Loop (2PACL)

Powering detector

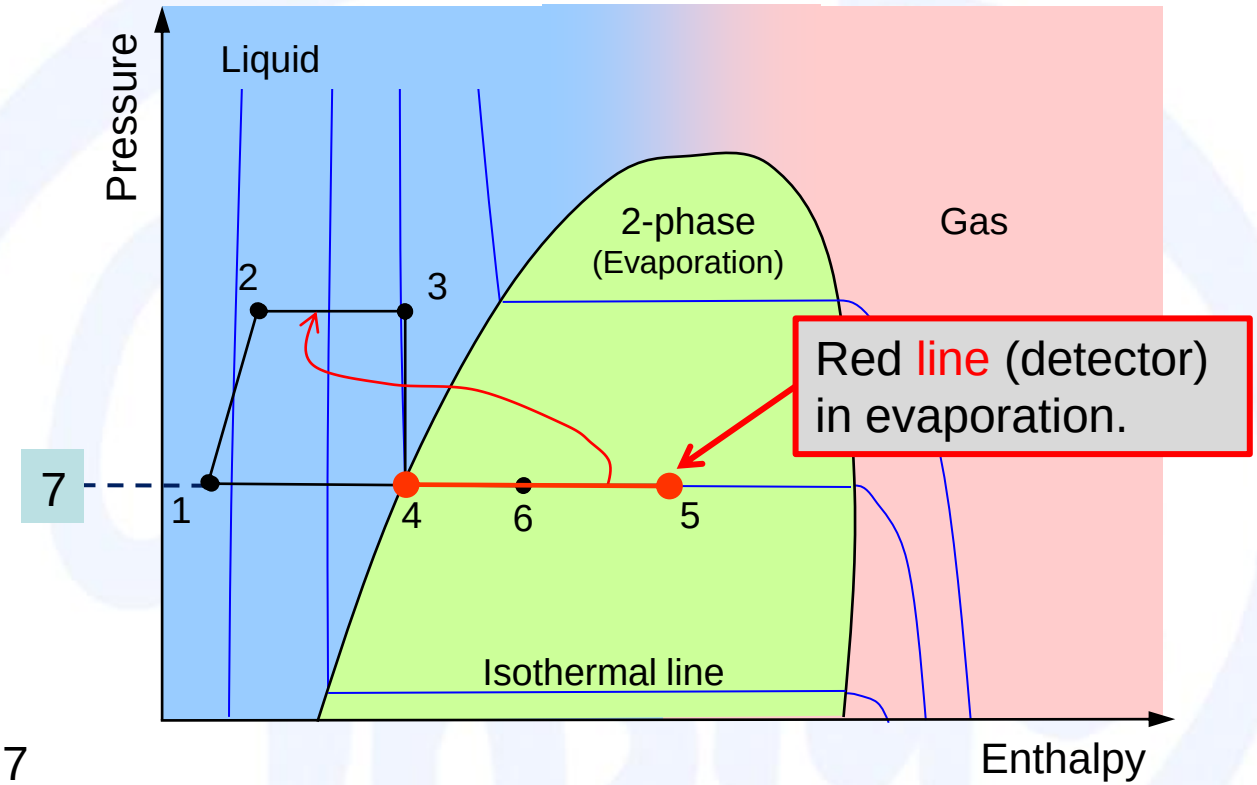


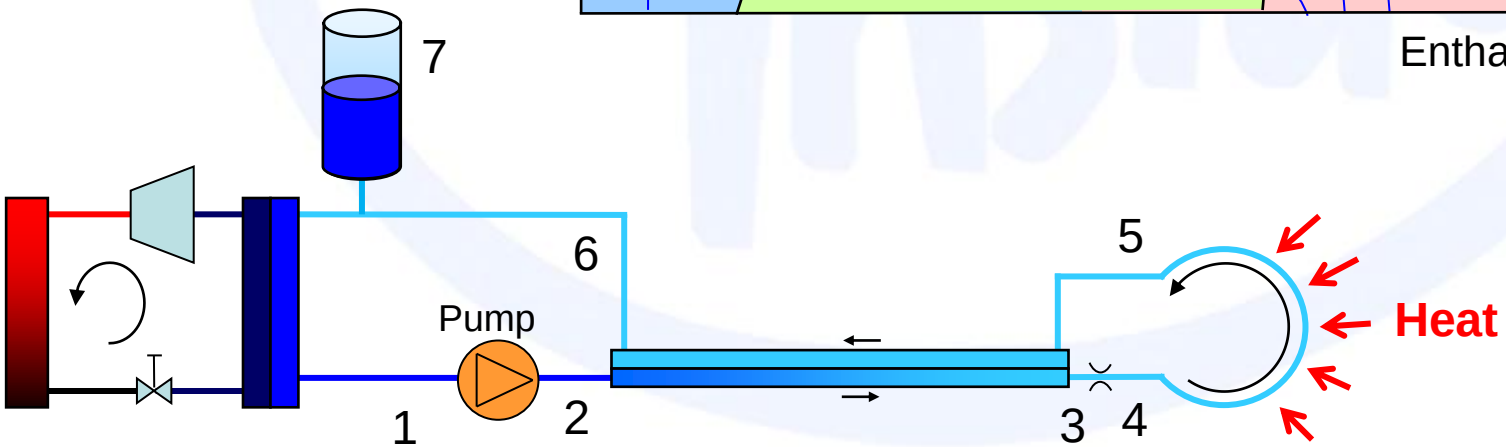
bverlaat@nikhef.nl

# 2-Phase Accumulator Controlled Loop (2PACL)

Detector is on



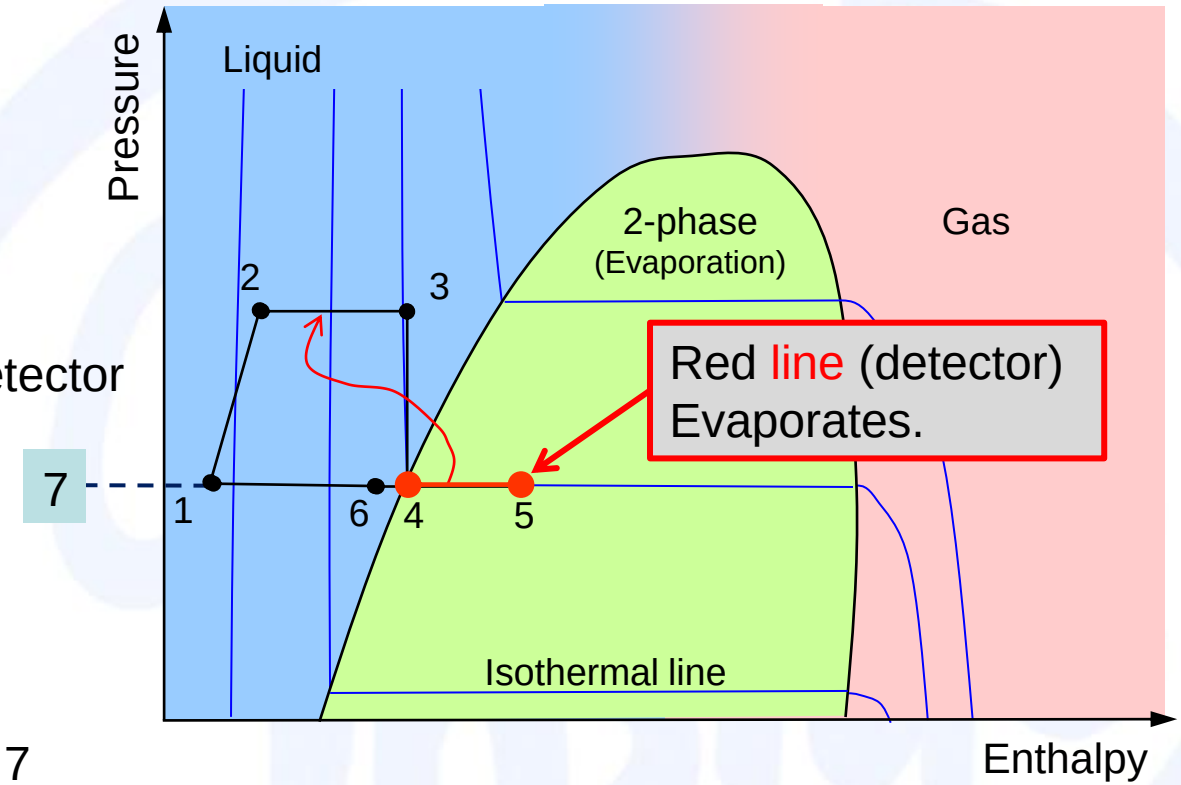

Red line (detector) in evaporation.

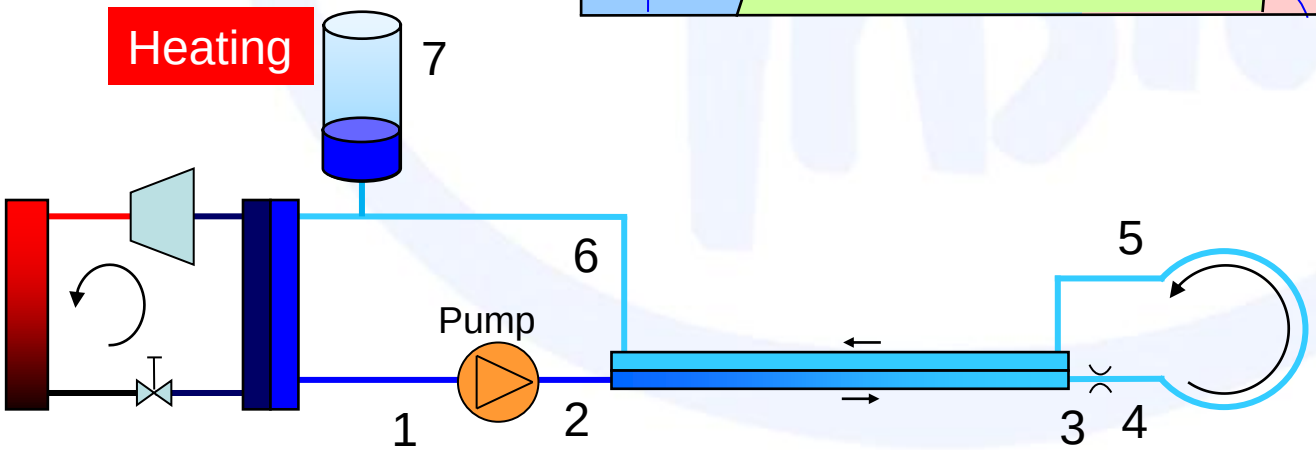


bverlaat@nikhef.nl

# 2-Phase Accumulator Controlled Loop (2PACL)

Unpowering detector

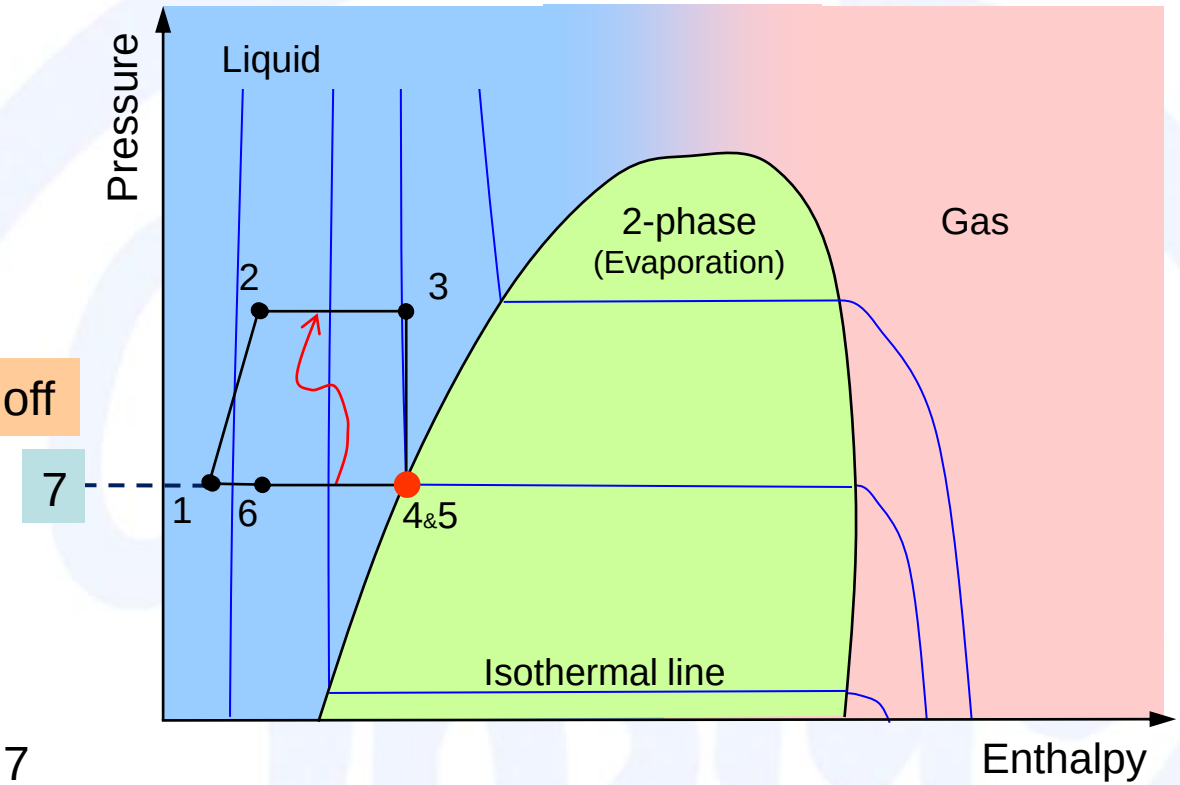


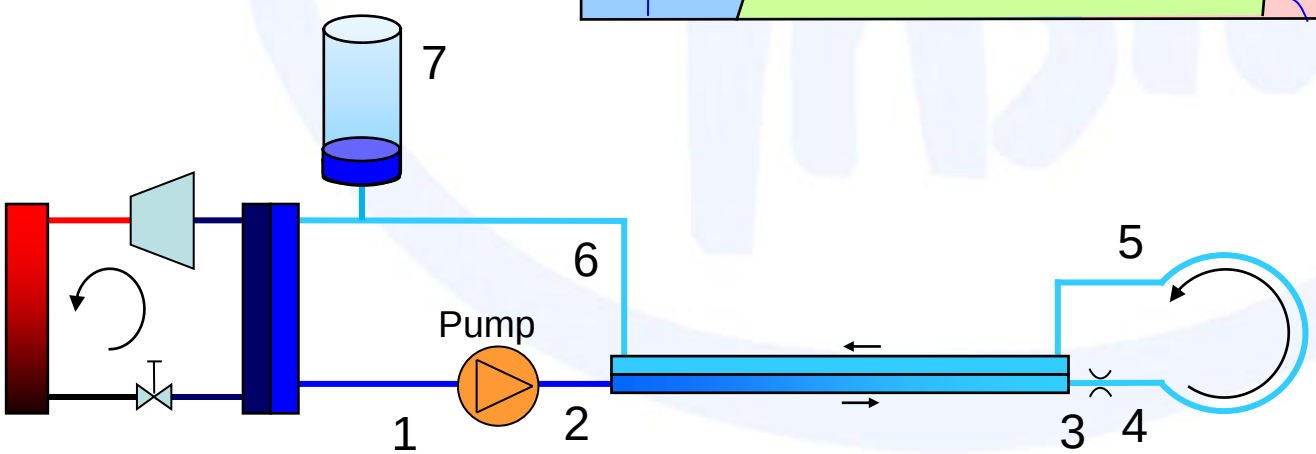



bverlaat@nikhef.nl

# 2-Phase Accumulator Controlled Loop (2PACL)

Detector power is off



bverlaat@nikhef.nl

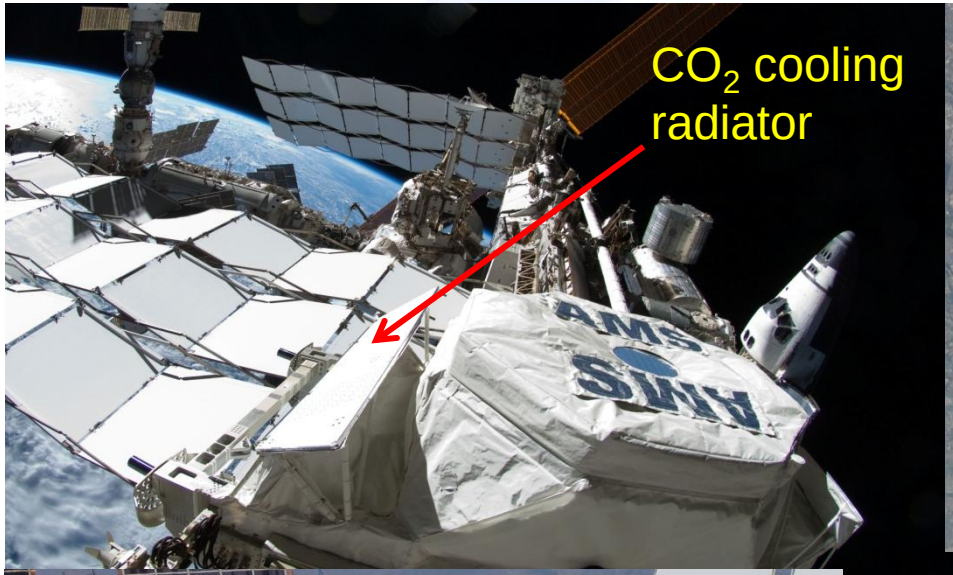
# $CO_2$ cooling projects in particle physics

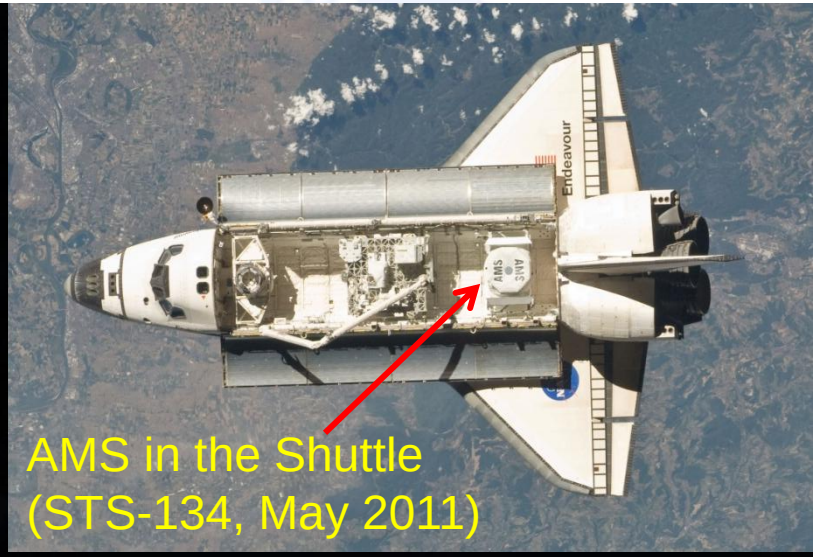
- 2 $CO_2$ cooling systems have successfully been built for particle detectors
  - AMS-Tracker experiment on the International Space Station
  - LHCb-Velo experiment for the Large Hadron Collider at CERN
- Many future $CO_2$ cooling systems are under design:
  - Atlas Inner B-layer @ CERN
  - CMS upgrade pixel @ CERN
  - Belle-2 @ KEKb (Japan)
- Some are foreseen for the far future:
  - CMS upgrade tracker @ CERN
  - Atlas upgrade pixel and tracker @ CERN
  - LC-TPC for the future Linear Collider

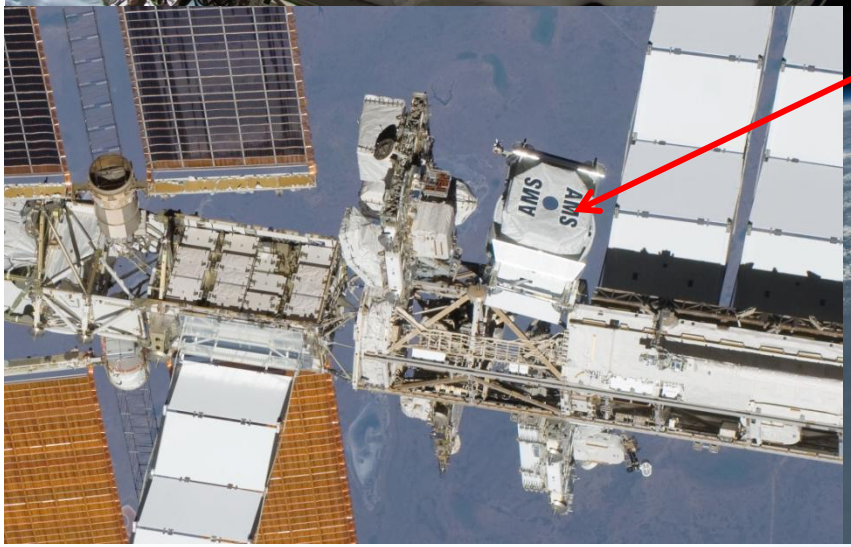
bverlaat@nikhef.nl

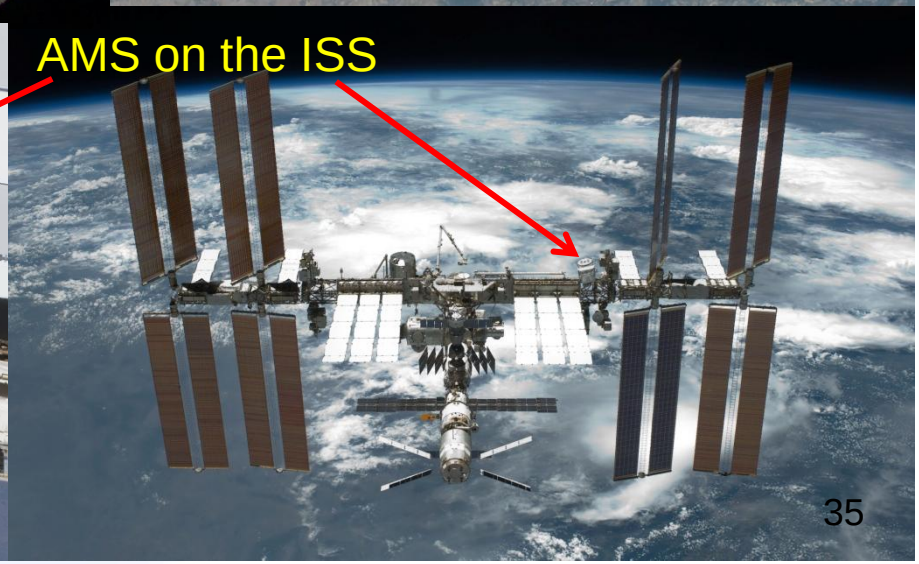
# The 1st $CO_2$ cooling system in Space!

A $CO_2$ cooling system for Alpha Magnetic Spectrometer (AMS) Tracker Detector on the International Space station (ISS)



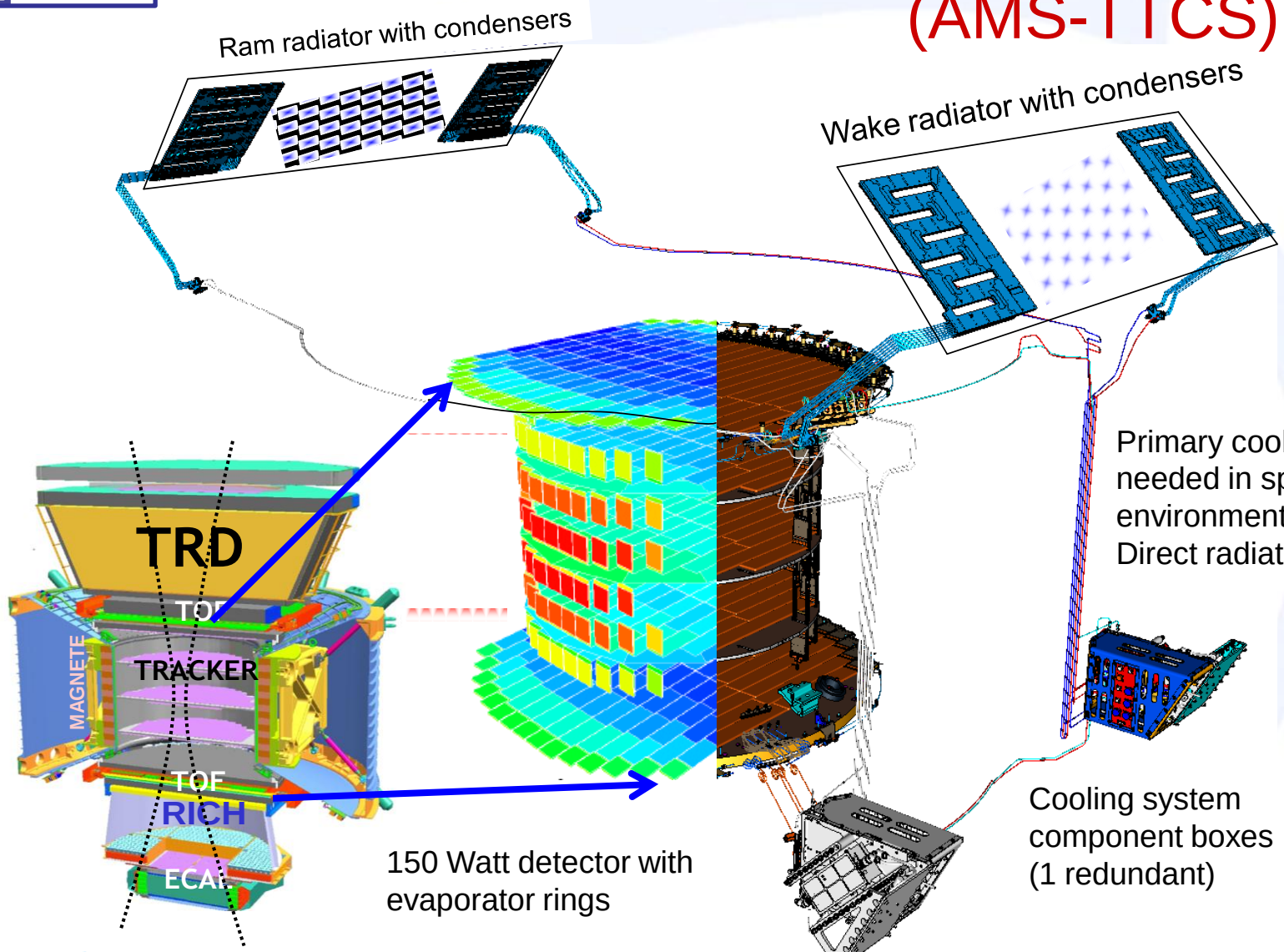



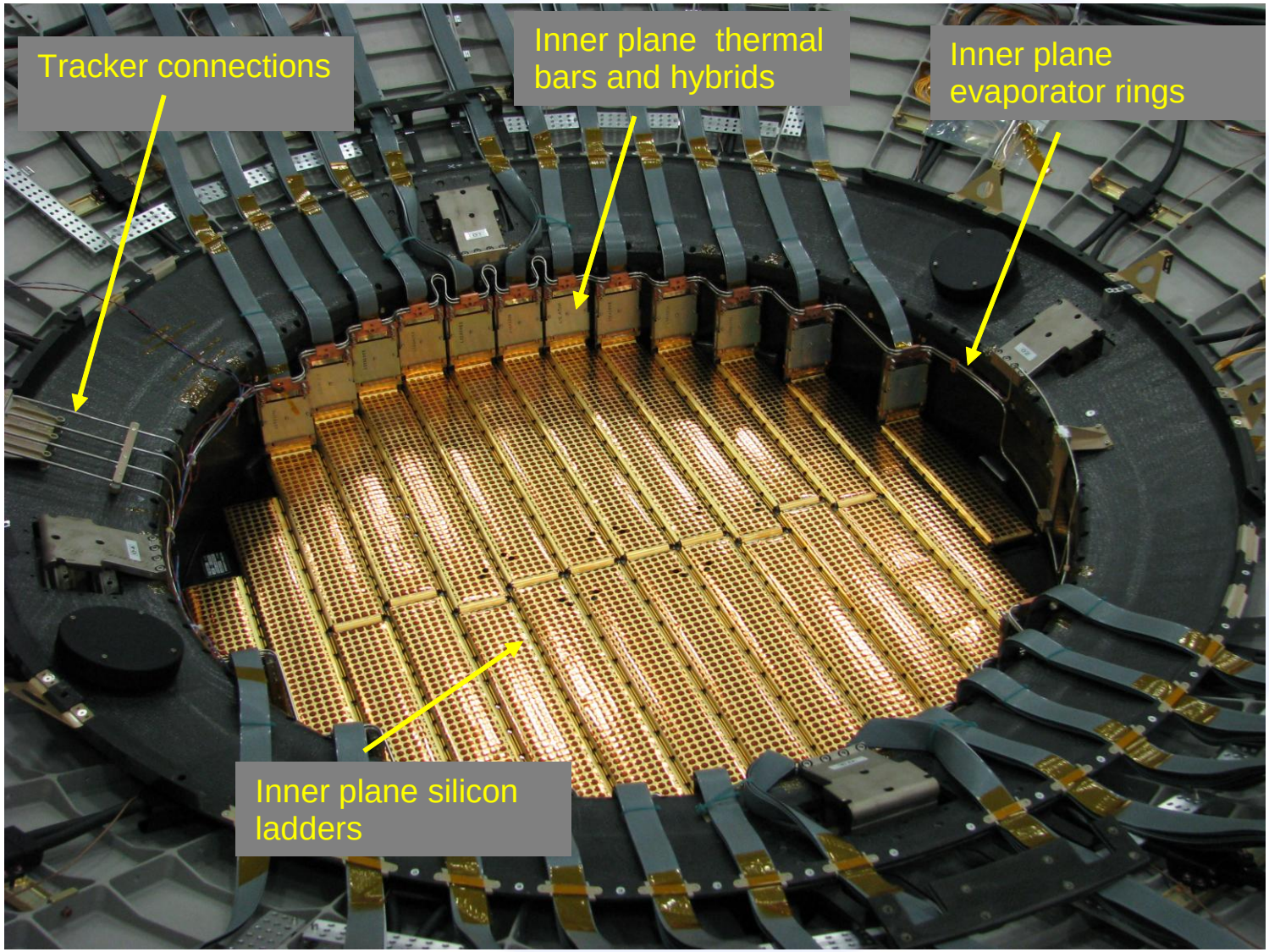
bverlaat@nikhef.nl

# AMS-Tracker Thermal Control System (AMS-TTCS)



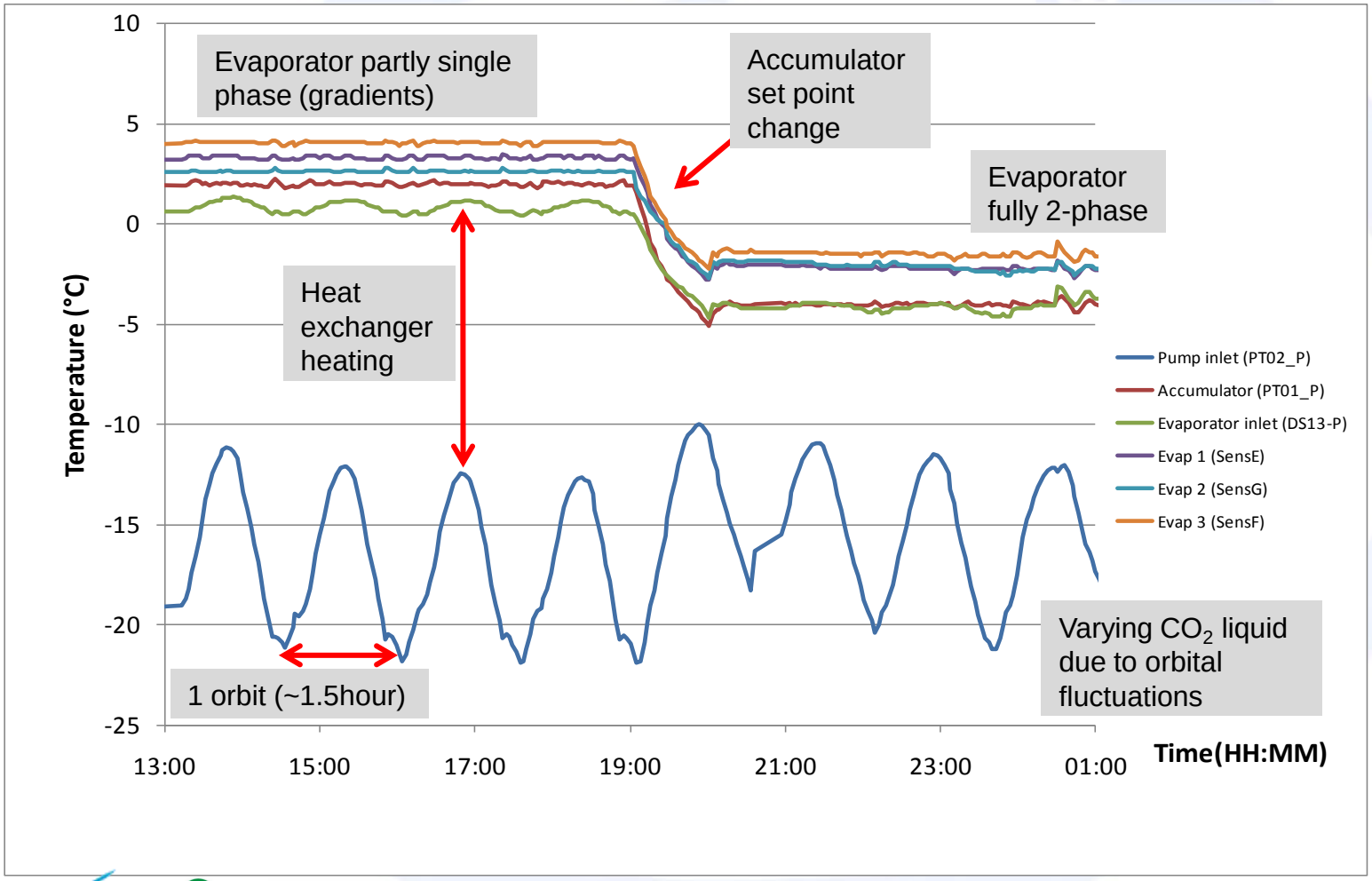
bverlaat@nikhef.nl

# AMS-Tracker with $CO_2$ cooling rings.



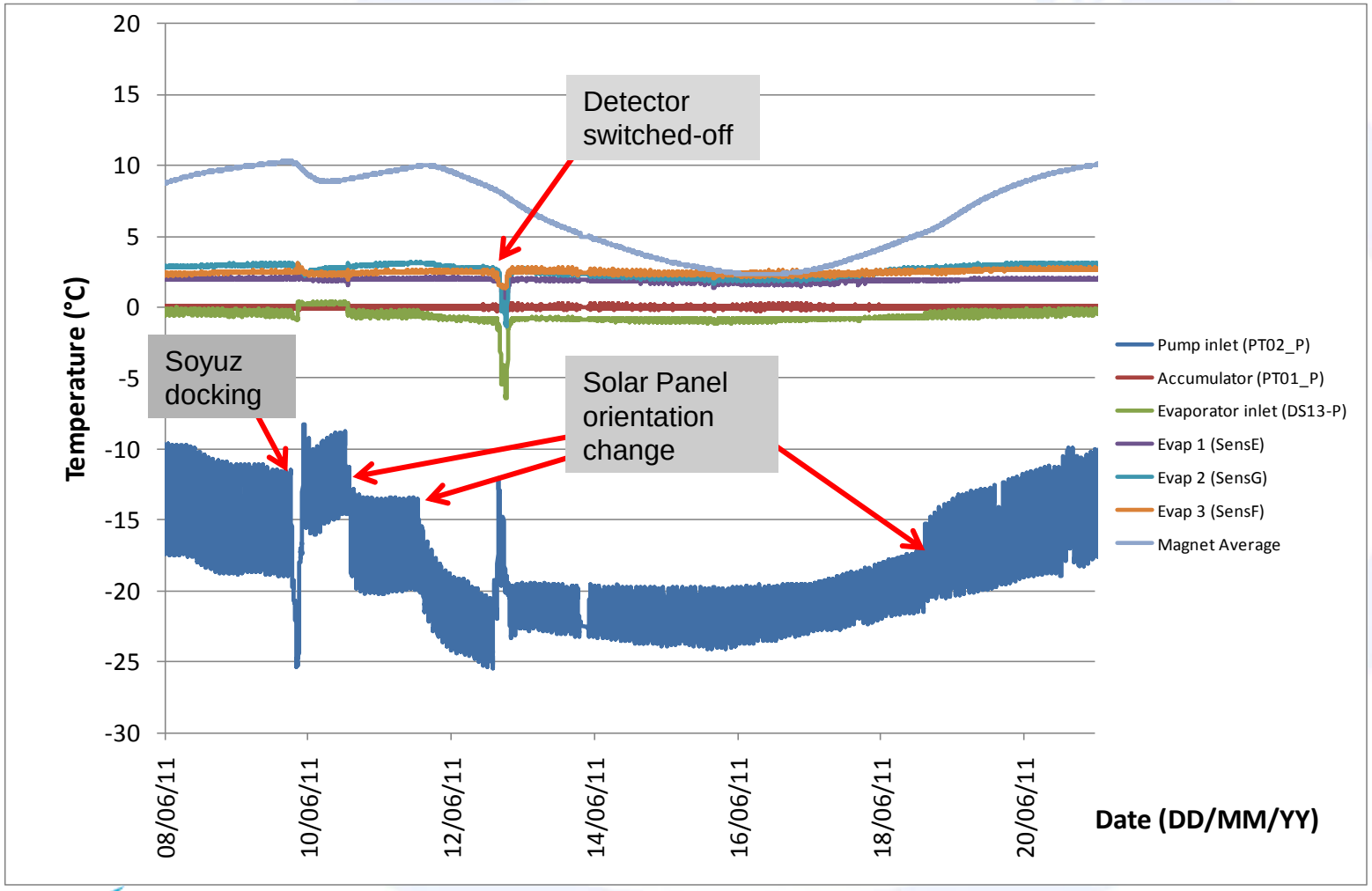
bverlaat@nikhef.nl

# AMS TTCS Cooling performance in space (1)



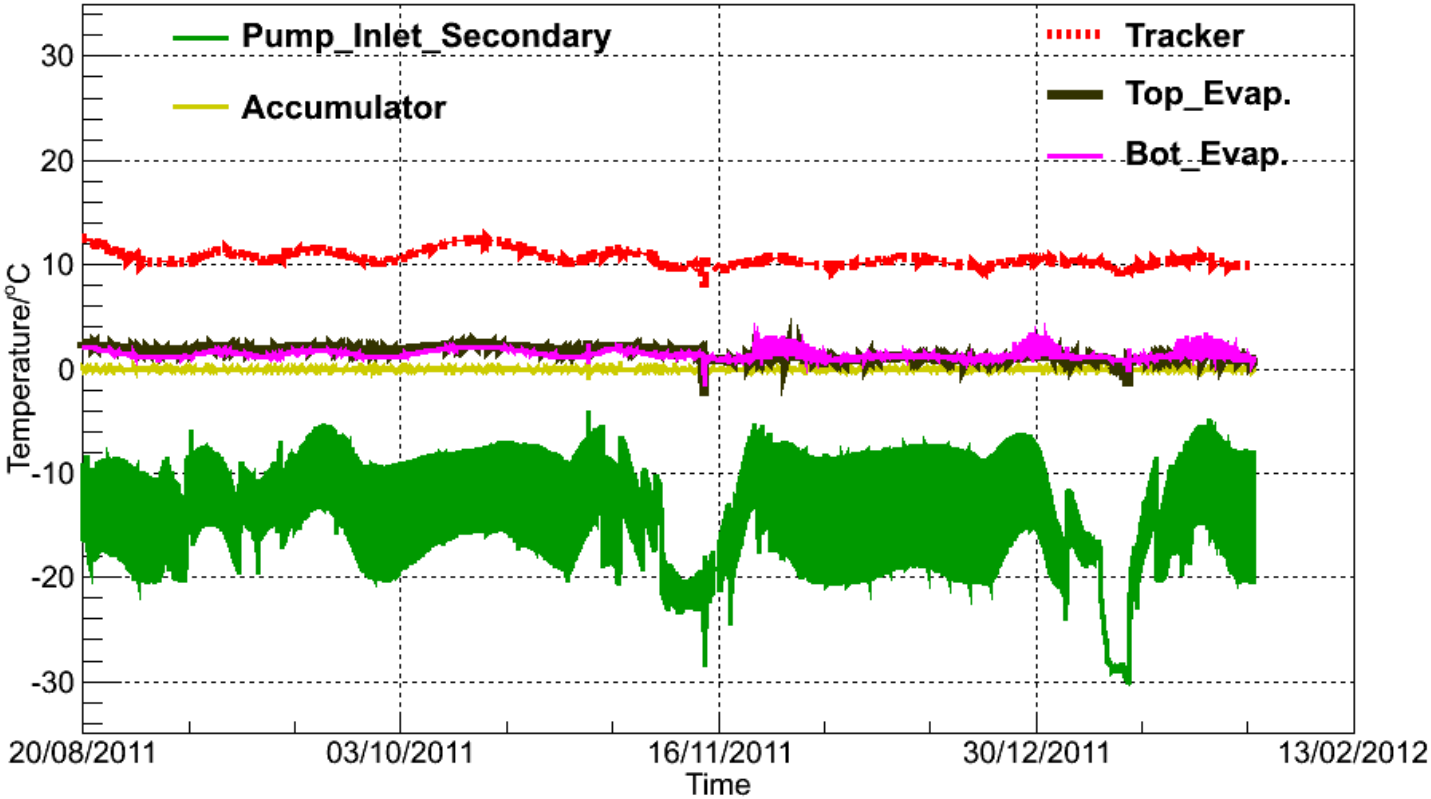
bverlaat@nikhef.nl

# AMS TTCS Cooling performance in space (2)



bverlaat@nikhef.nl

# AMS TTCS Cooling performance in space (3)

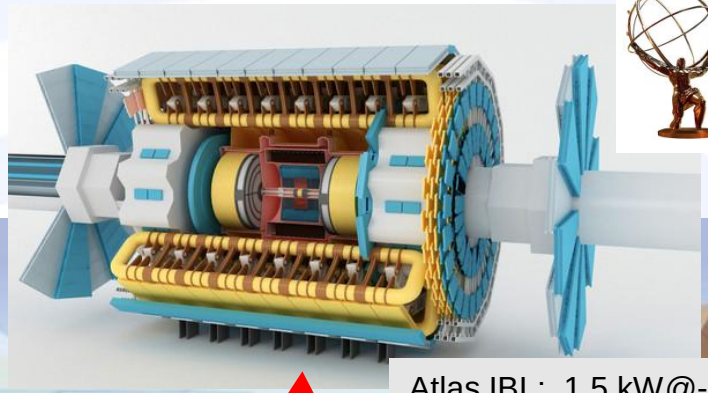



6 month stable at 0°C despite cold low beta periods

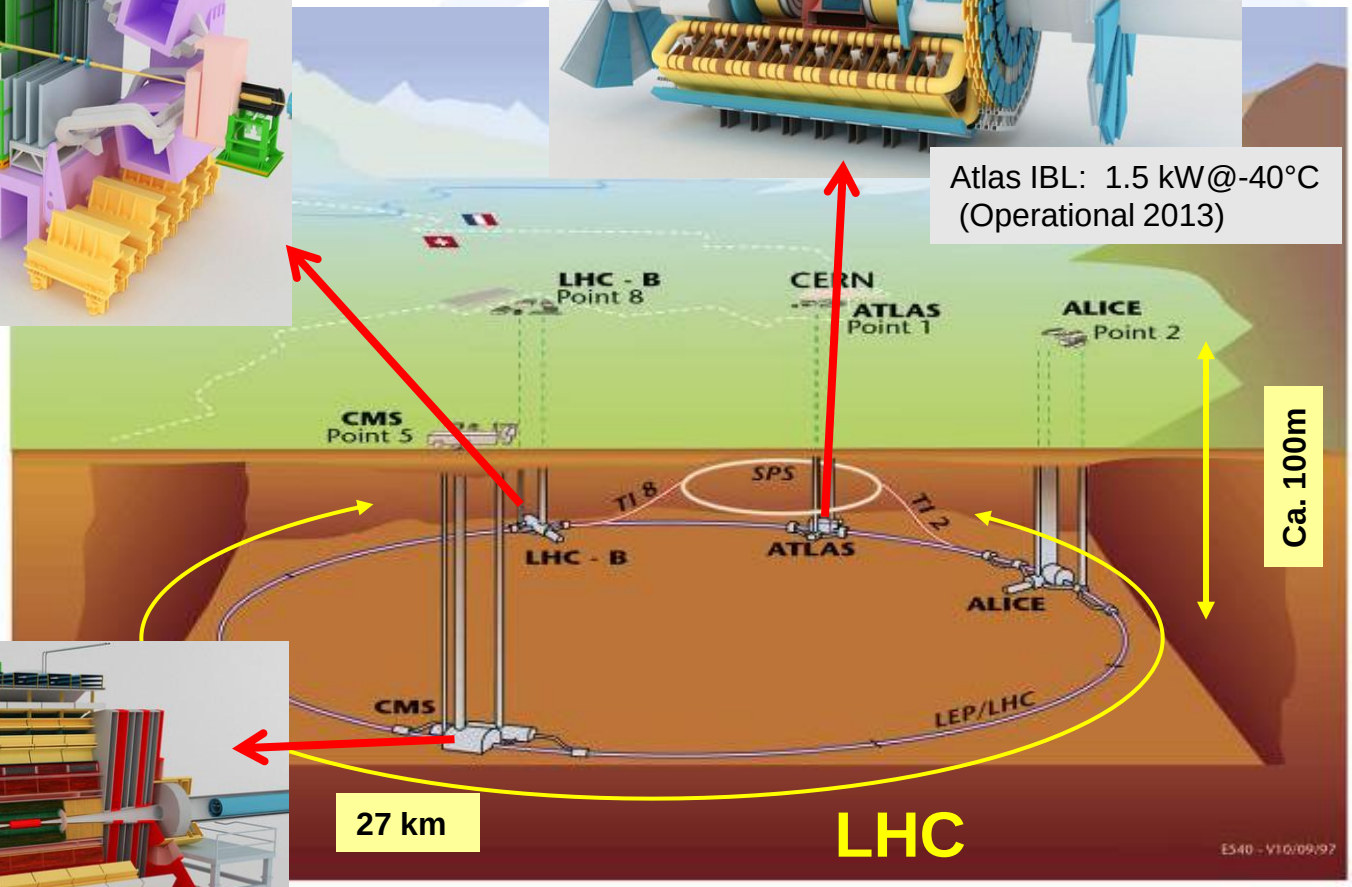
bverlaat@nikhef.nl

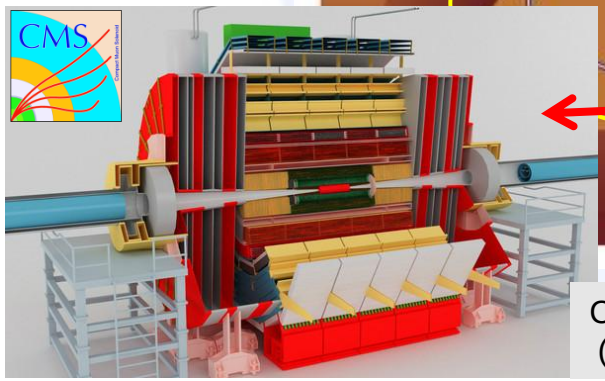
# $CO_2$ cooling projects in LHC

VELO detector: 1.5 kW@-30°C
(Running successfully since 2007)



Atlas IBL: 1.5 kW@-40°C
(Operational 2013)

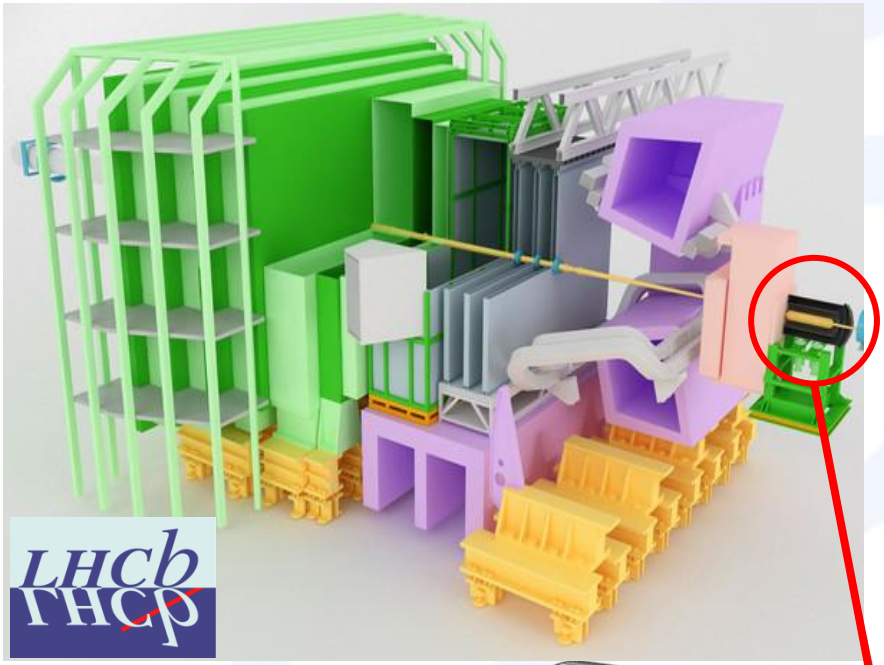


CMS pixel: 15 kW@-20°C
(Operational 2014)

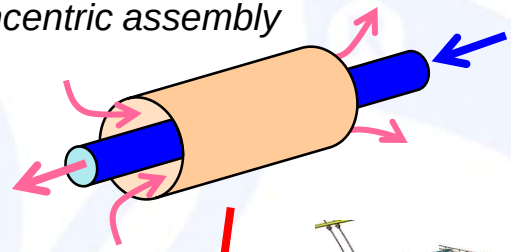
bverlaat@nikhef.nl

# LHCb-Velo Thermal Control System (LHCb-VTCS)



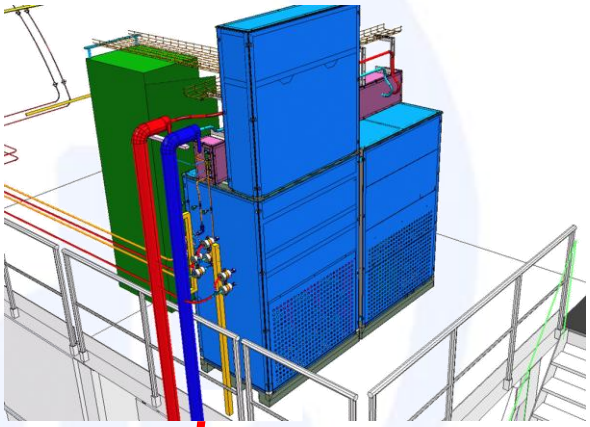

**Transfer tube**

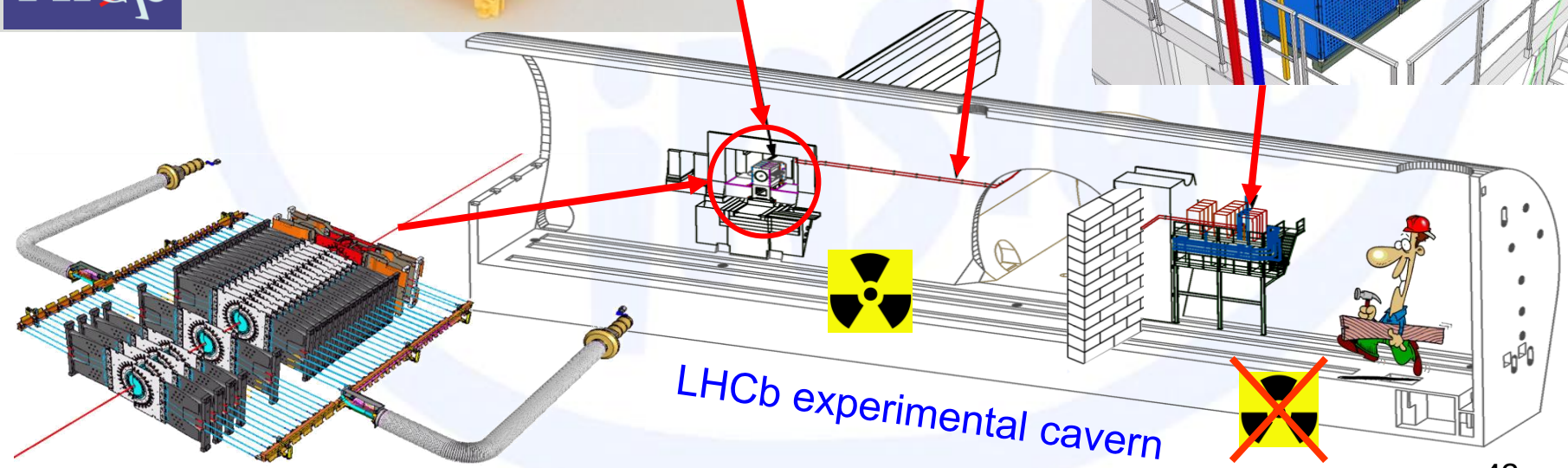
*Concentric assembly*



**Cooling Plant**

*All active hardware*

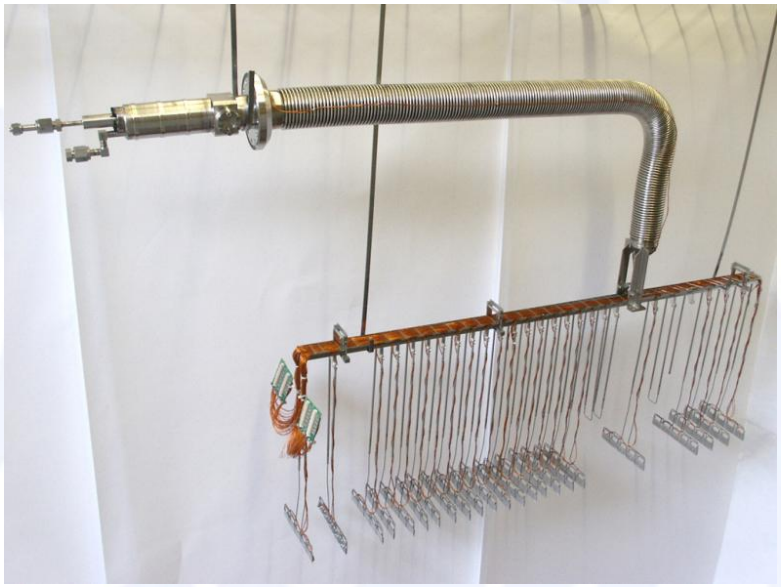


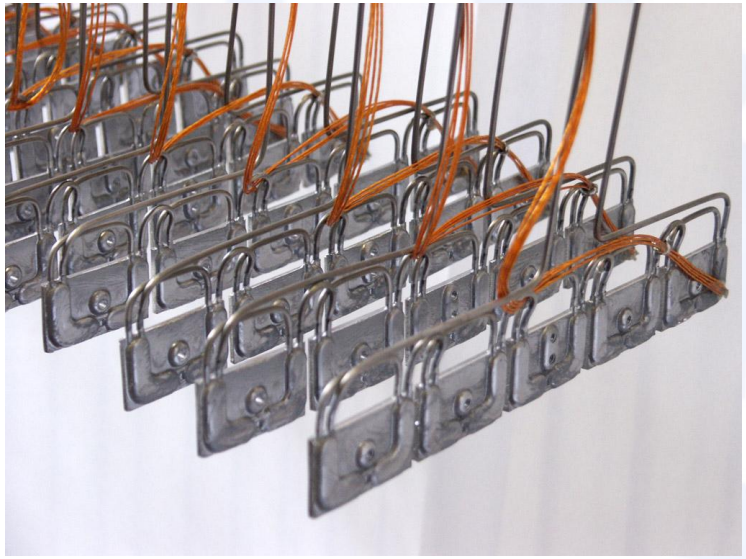


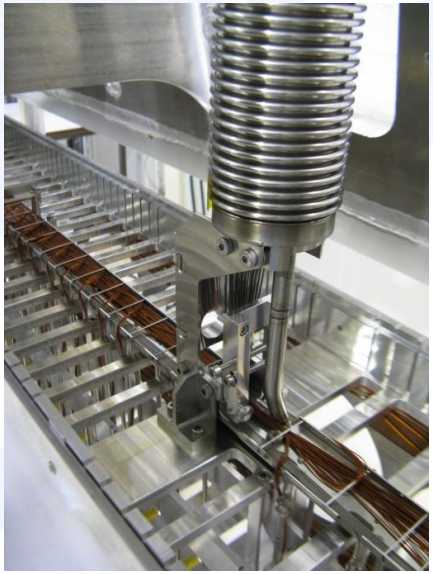

Cooling capacity: 1.5 kW@-30°C

bverlaat@nikhef.nl

# VTCS Evaporator





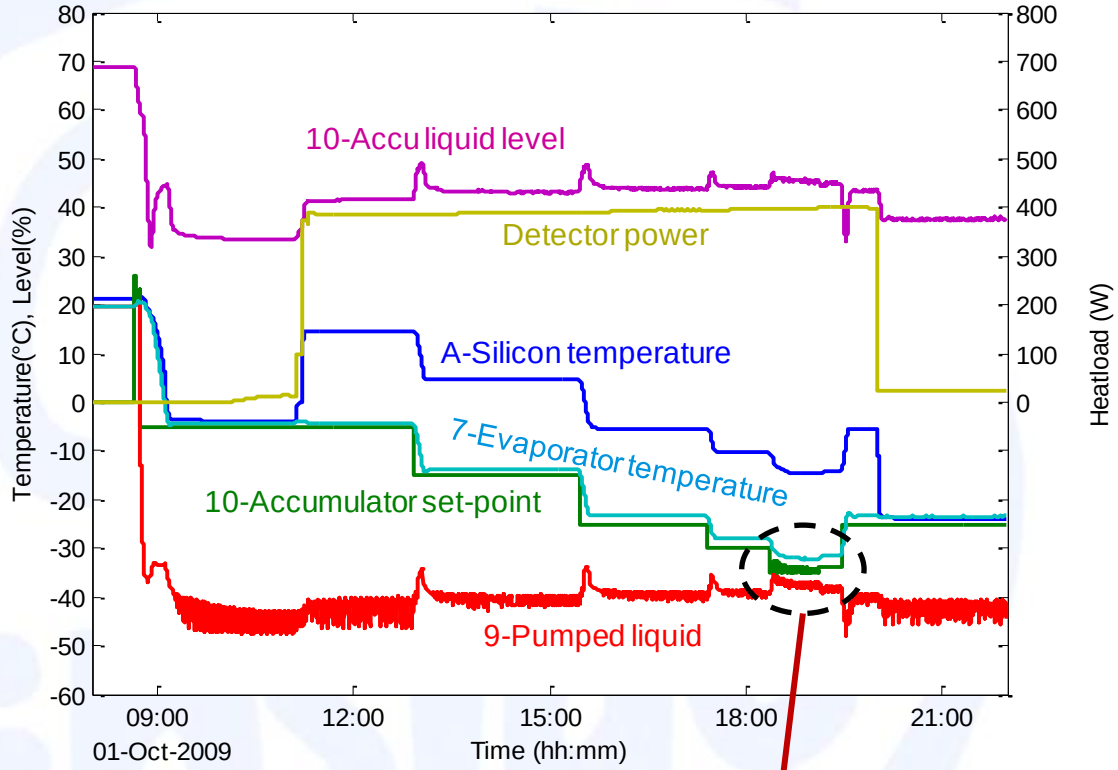


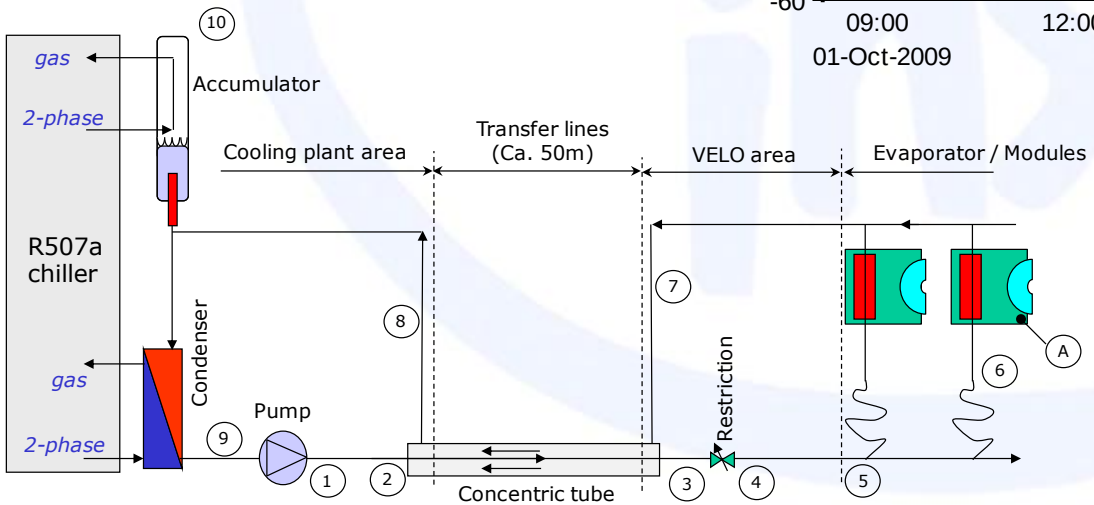
bverlaat@nikhef.nl

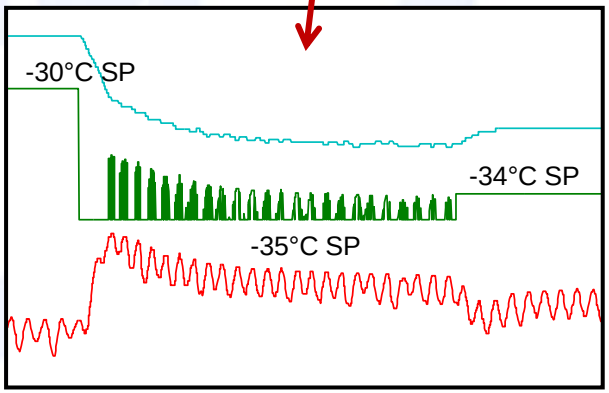
# VTCS Commissioning results:
# Start-up and operation

Start–up of the VTCS during October 2009 commissioning:

8:40 - Start-up with set-point -5°C
11:10 - Detector switched on
12:50 – Set point to -15°C
15:30 - Set point to -25°C
17:10 - Set point to -30°C
18:20 - Set point to -35°C (System Limit)
19:10 - Set point to -34°C
19:30 - Set point to -25°C
20:00 - Detector Switched off

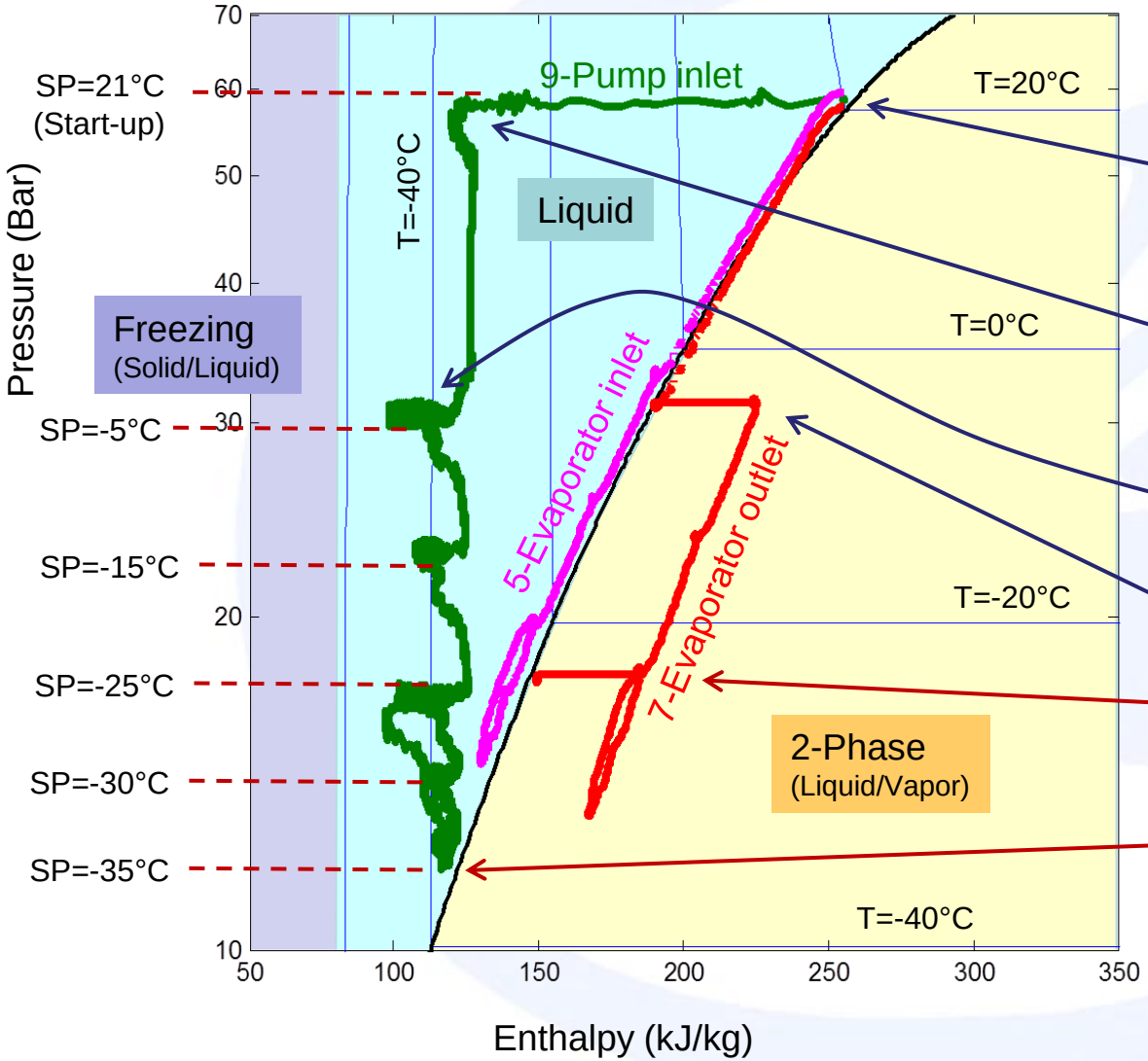


bverlaat@nikhef.nl

# VTCS Commissioning results:
# Start-up and operation in the PH-diagram




## Start-up sequence

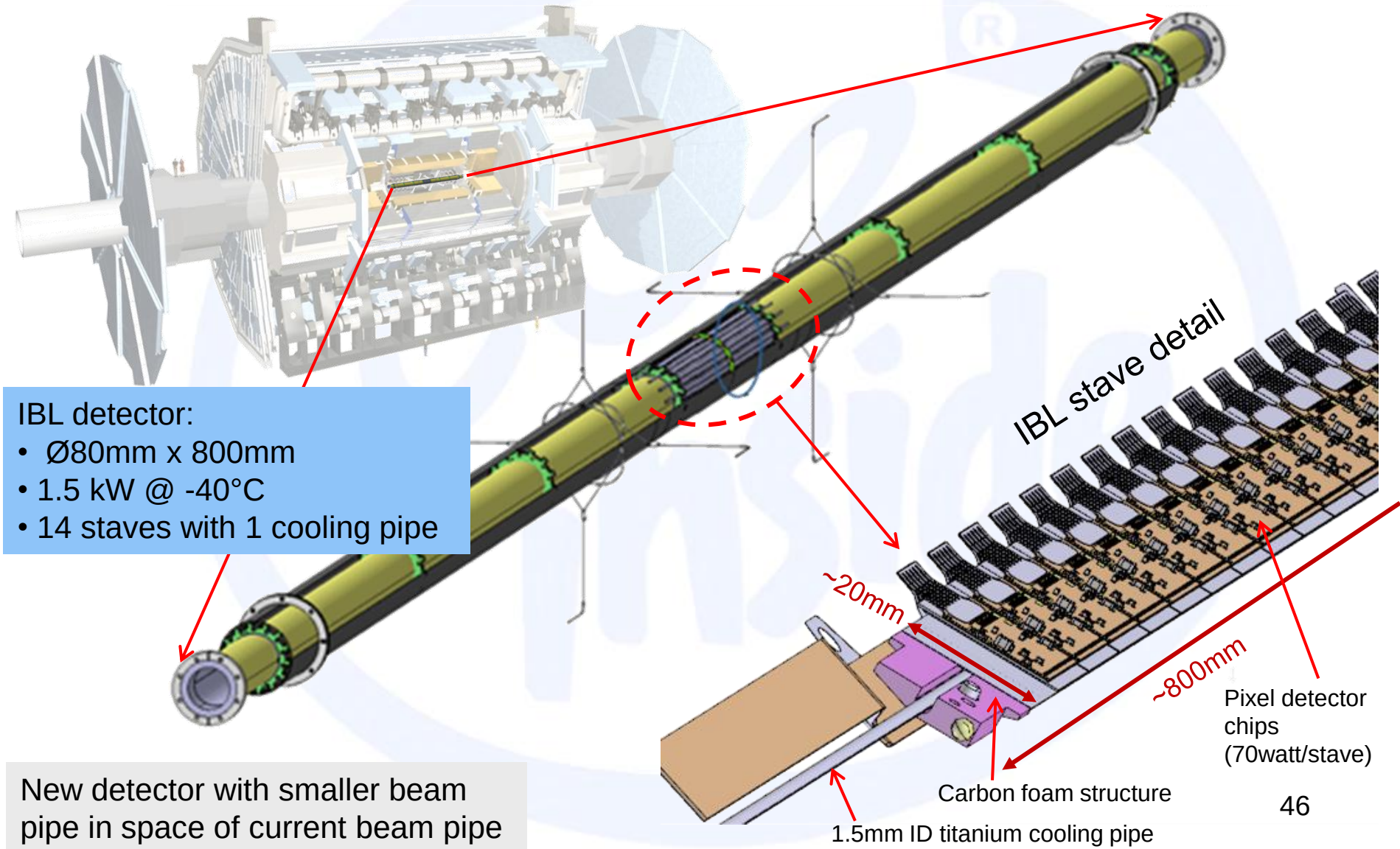
1. Increase pressure to make liquid.
2. Pump at high pressure and cool down in liquid mode
3. Lower pressure to desired set-point
4. Power-up detector

Switch-off detector

Lowest possible set-point (liquid approaches saturation line)

bverlaat@nikhef.nl

# Atlas IBL-cooling system (1)

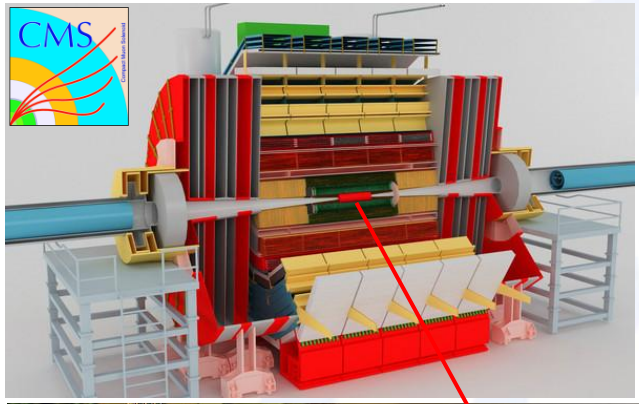


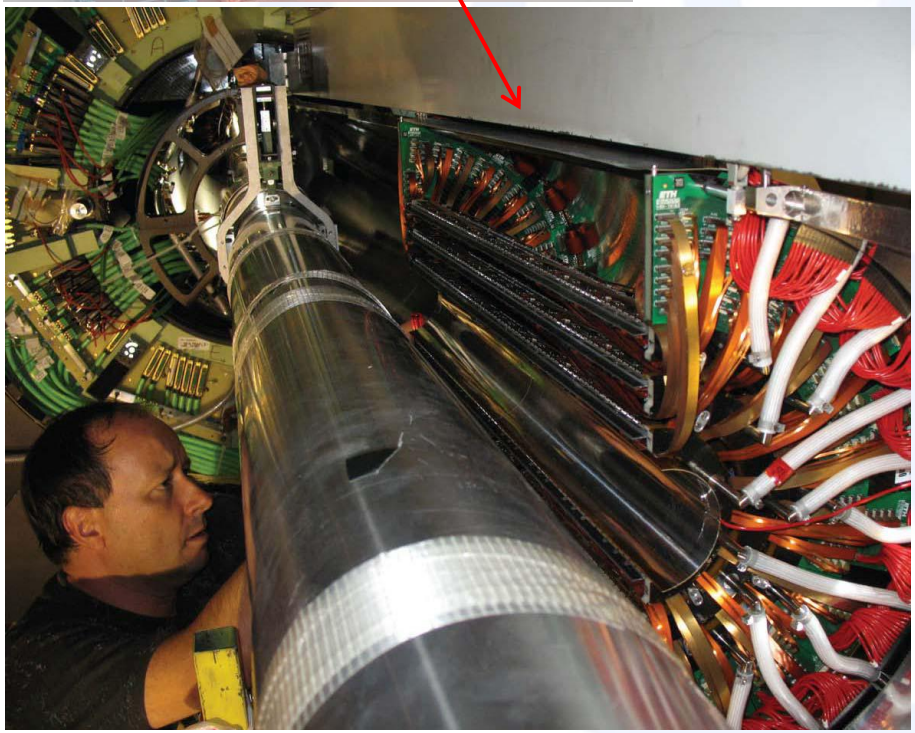

IBL detector:
- Ø80mm x 800mm
- 1.5 kW @ -40°C
- 14 staves with 1 cooling pipe

New detector with smaller beam pipe in space of current beam pipe

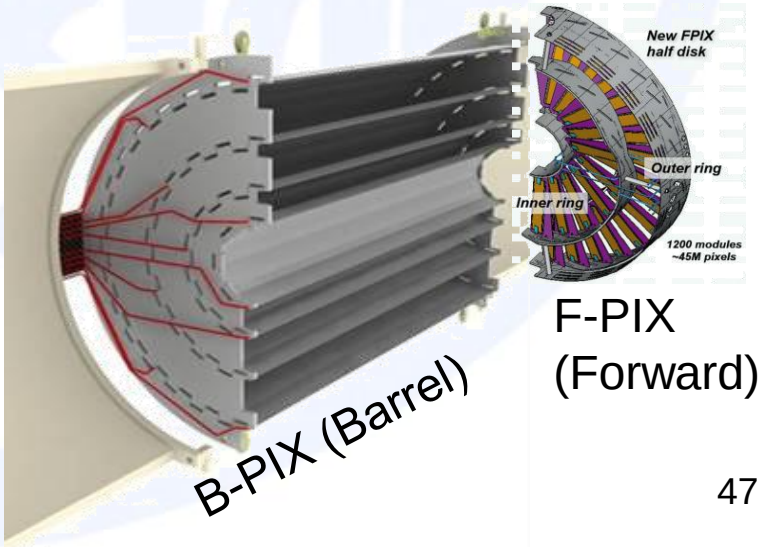
bverlaat@nikhef.nl

# CMS upgrade pixel cooling system



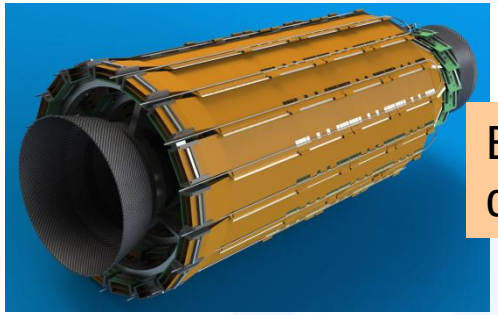
- Replacement and upgrade of current pixel detector
- 15kW @ -20°C
- Very long serial lines with relative high heat flux



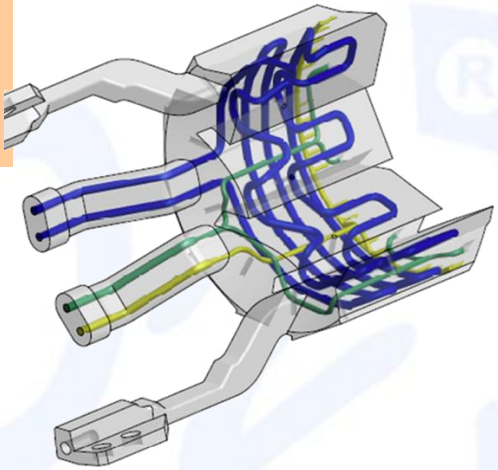
bverlaat@nikhef.nl

# KEK Belle-2 SVD and PXD

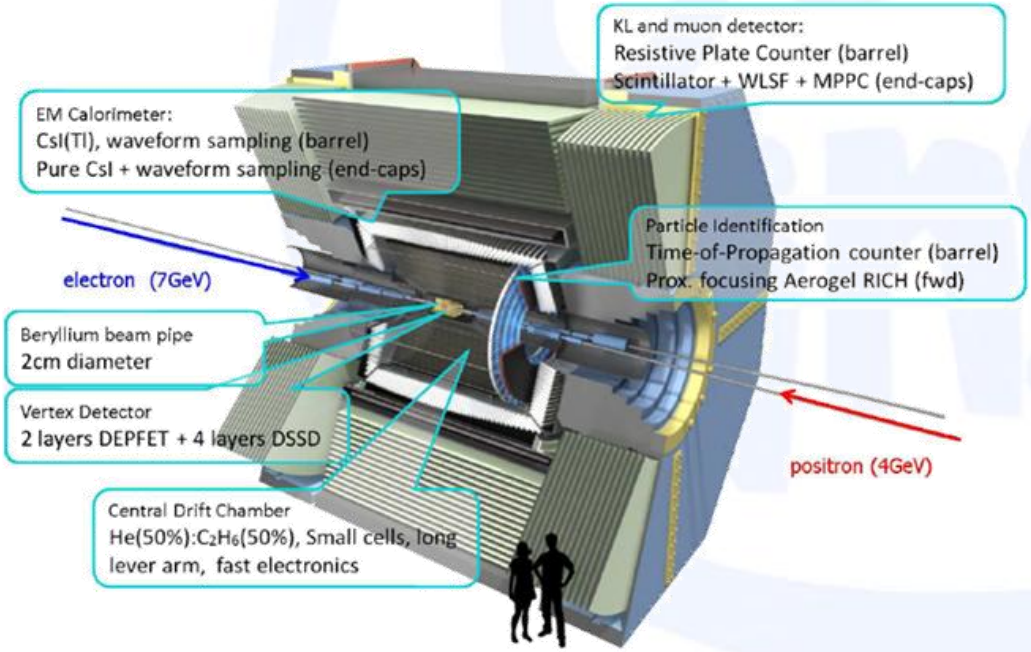
Belle-2 PXD and SVD, 1.5 kW@-30ºC
Common $CO_2$ cooling plant
development with Atlas IBL



Belle-II SVD detector



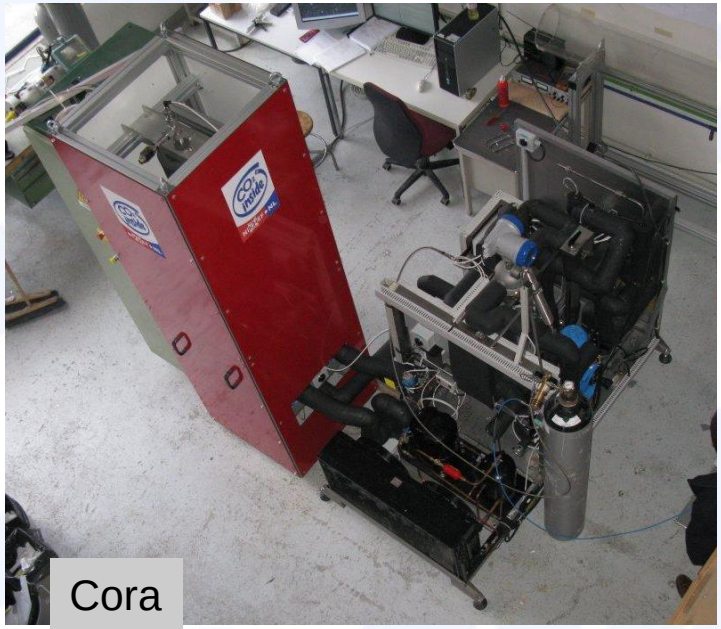
Belle-II pixel detector
*(Rapid Prototyping heat sink)*



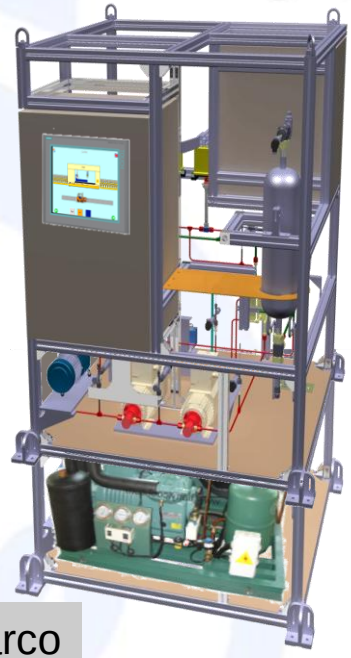

bverlaat@nikhef.nl

# $CO_2$ cooling support

Traci



Cora



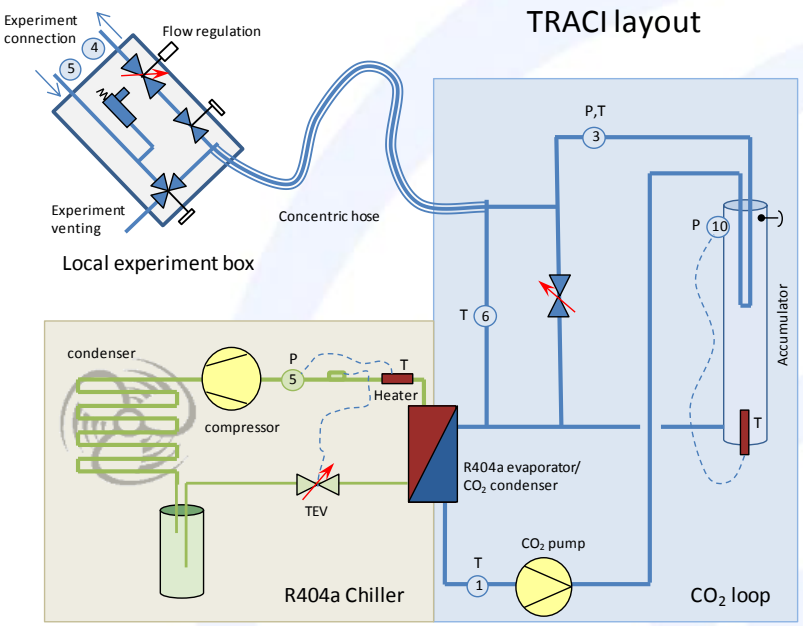
Marco

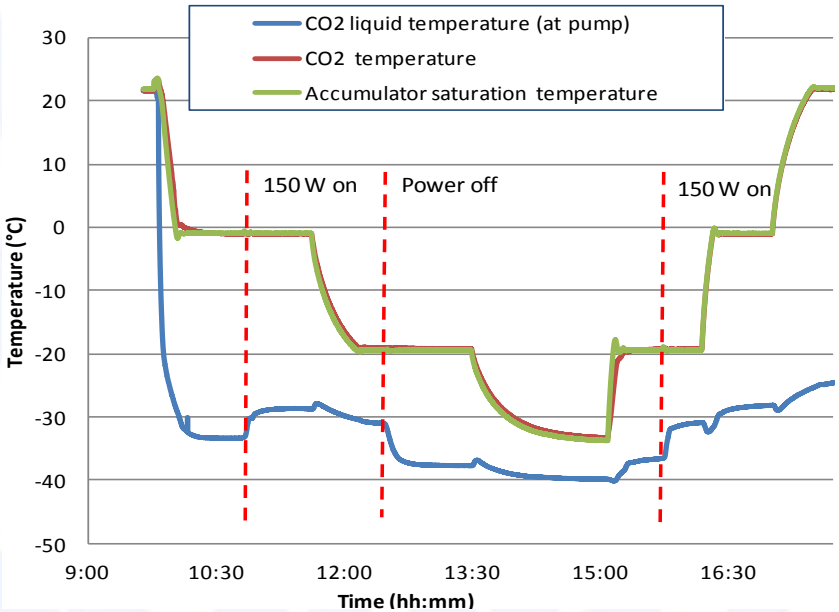
- To support the $CO_2$ cooling projects in particle physics several test systems are under development:
- Cora ($CO_2$ Research Apparatus)
  - Fixed test plant for CERN based research (0-2kW, +20 to -35ºC)
- Marco (Multipurpose Apparatus for Research on $CO_2$
  - Fully automatic (User friendly) $CO_2$ test system for general use (0-2kW, +20 to -45ºC)
  - Base design for future on detector cooling plants (Atlas IBL, Belle-2)
- Traci (Transportable Refrigeration Apparatus for $CO_2$ Investigation)
  - Small test system for laboratory use
  - New simplified 2PACL concept to reduce cost and complexity (0-350W, +20 to -40ºC)

bverlaat@nikhef.nl

# TRACI

## Transportable Refrigeration Apparatus for $Co_2$ Investigation




- TRACI: A simplified new concept for providing a conditioned $CO_2$ flow for cooling research.
- 2PACL principle simplified (few functions have been integrated)
  - Integrated 2PACL (I-2PACL )
  - Patent of I-2PACL concept filed
- Goal: An easy to (mass) produce user friendly system
  - Operational from +25$^0$C to -40 $^0$C
  - Initial cooling power up to 350 Watt (depending on minimum temperature)

bverlaat@nikhef.nl

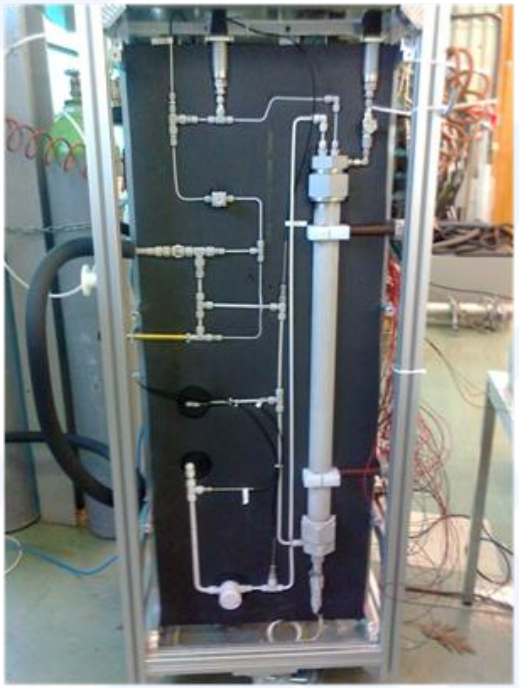
# The TRACI factory

- Prototypes are already “mass produced”
  - 2 have been build (Atlas & LHCb)
  - 3 under construction (Atlas, CMS & Nikhef/AIDA for development)
  - Investigating a start-up company for real production

bverlaat@nikhef.nl

# TRACI a modular design

Commercial chiller



$CO_2$ piping in a 2D-foambox

Control: Simple conditioner and relay logic

User interface:

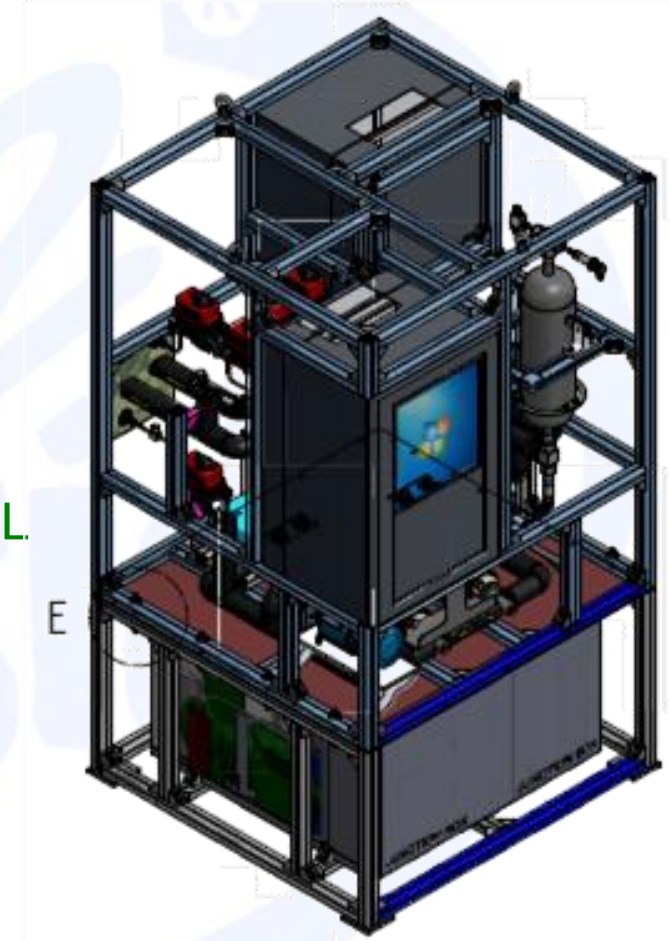
- *On/off and reset buttons*
- *Error indication*
- *Pressure controller*

bverlaat@nikhef.nl

# MARCO

## Multipurpose Apparatus for Research on $CO_2$

- MARCO is prototype $CO_2$ 2PACL system for multipurpose use.
- User friendly
  - Automatic experiment connection
  - Automatic filling
- Designed according to CERN experiment standards.
  - Baseline concept for the detectors IBL (CERN) and Belle-2 (KEK), common development with MPI-Munich.
  - PVSS-Unicos control interface
- Low temperature design
  - 2kW@-45ºC
  - Frequency controlled 2-stage chiller



bverlaat@nikhef.nl

# MARCO production

A $CO_2$ 2PACL build in MPI

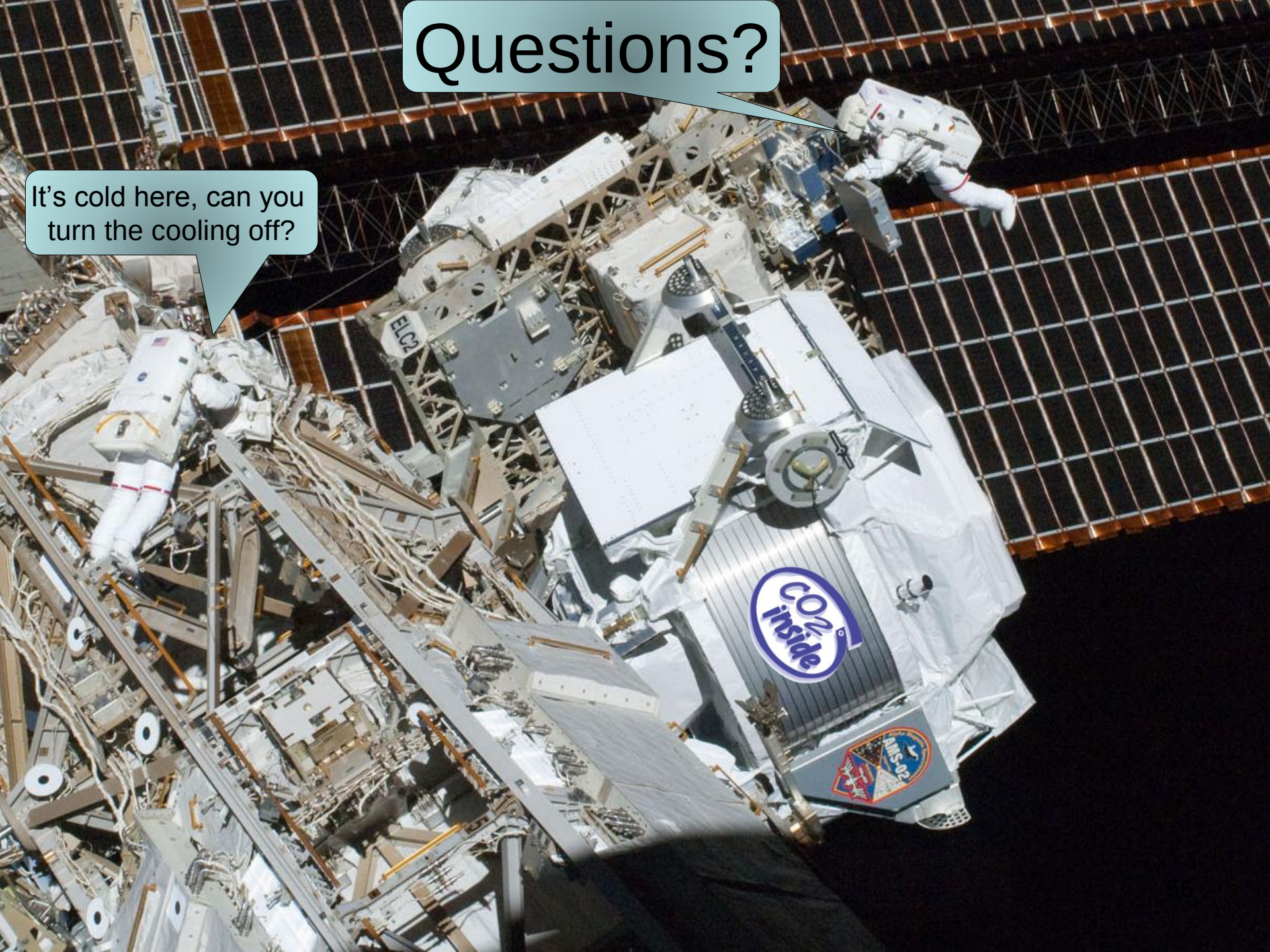
Controls build at CERN-DT

2-stage chiller for IBL temperatures from ECR-Nederland

bverlaat@nikhef.nl

# Conclusions

- $CO_2$ is a very good candidate fluid for applications were limited cooling space is available or limited additional mass is allowed.
- $CO_2$ cooling is a good candidate if high power densities are present and an isothermal heat sink is required
- $CO_2$ cooling is widely accepted in Particle Physics community as the future cooling method for the inner silicon detectors.
- The 2PACL concept has proven to be a good method for controlling evaporation conditions in distant set-ups
- 2 $CO_2$ systems are operational in particle physics and perform well.
- Several new systems are under development including systems for testing


Questions?
It's cold here, can you turn the cooling off?
ELC2
CO2 inside
STS-102