TWEPP-2008

Topical Workshop on Electronics for Particle Physics

CO_2 Cooling for HEP experiments

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Amsterdam, The Netherlands

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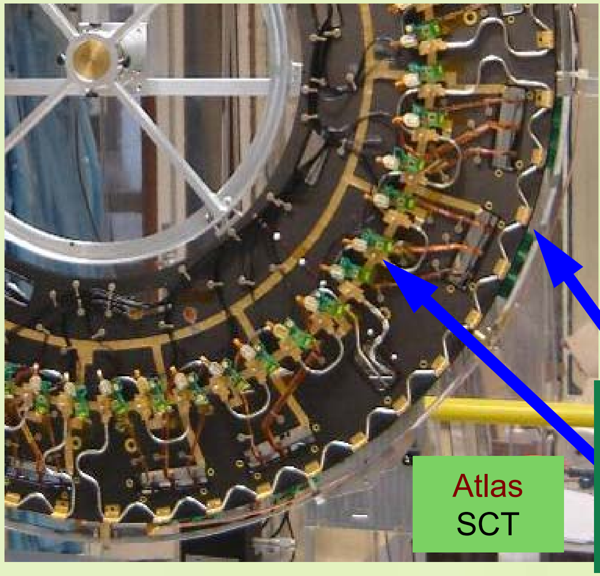
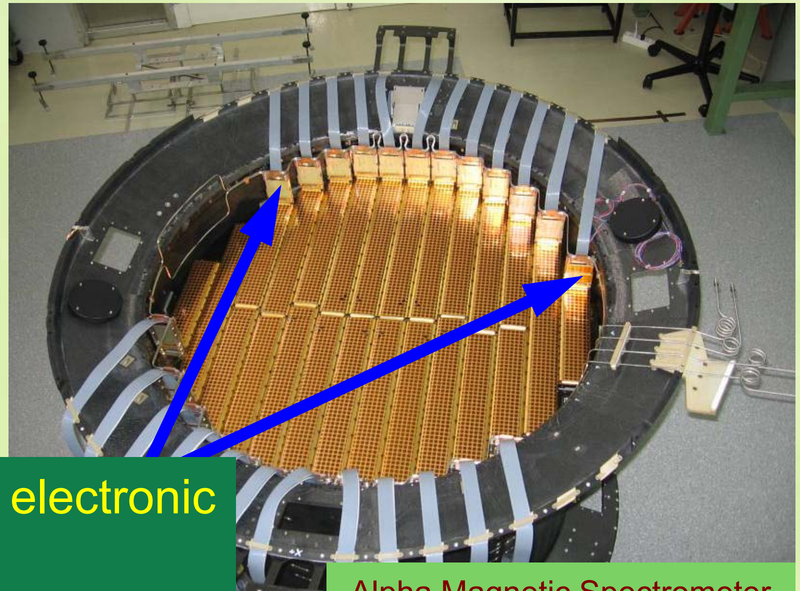
(Silicon) Particle Detectors and Cooling

- (Silicon) Particle detectors have specific needs for thermal control:
  - **Many distributed heat sources over large volumes.**
  - **Low temperature gradients between these sources.**
  - **Permanent cooling**
    - *To avoid thermal runaway of the irradiated silicon*
  - **Cooling pipes should have low mass inside detectors**
  - **Cooling pipes should have low structural impact**
  - **Radiation resistant cooling fluid**





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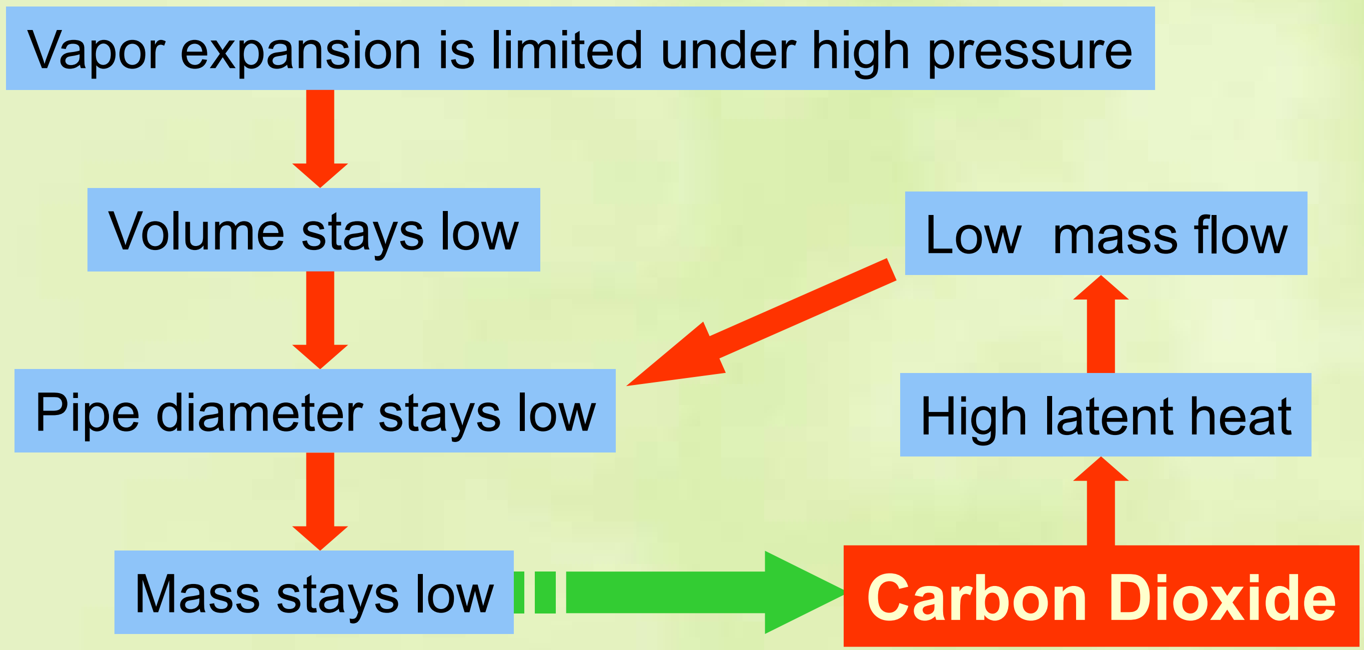
Why Evaporative CO_2 Cooling?

The lightest way of cooling is:

Evaporate at high pressure!

Why?



Later on in this presentation this will be illustrated by calculations

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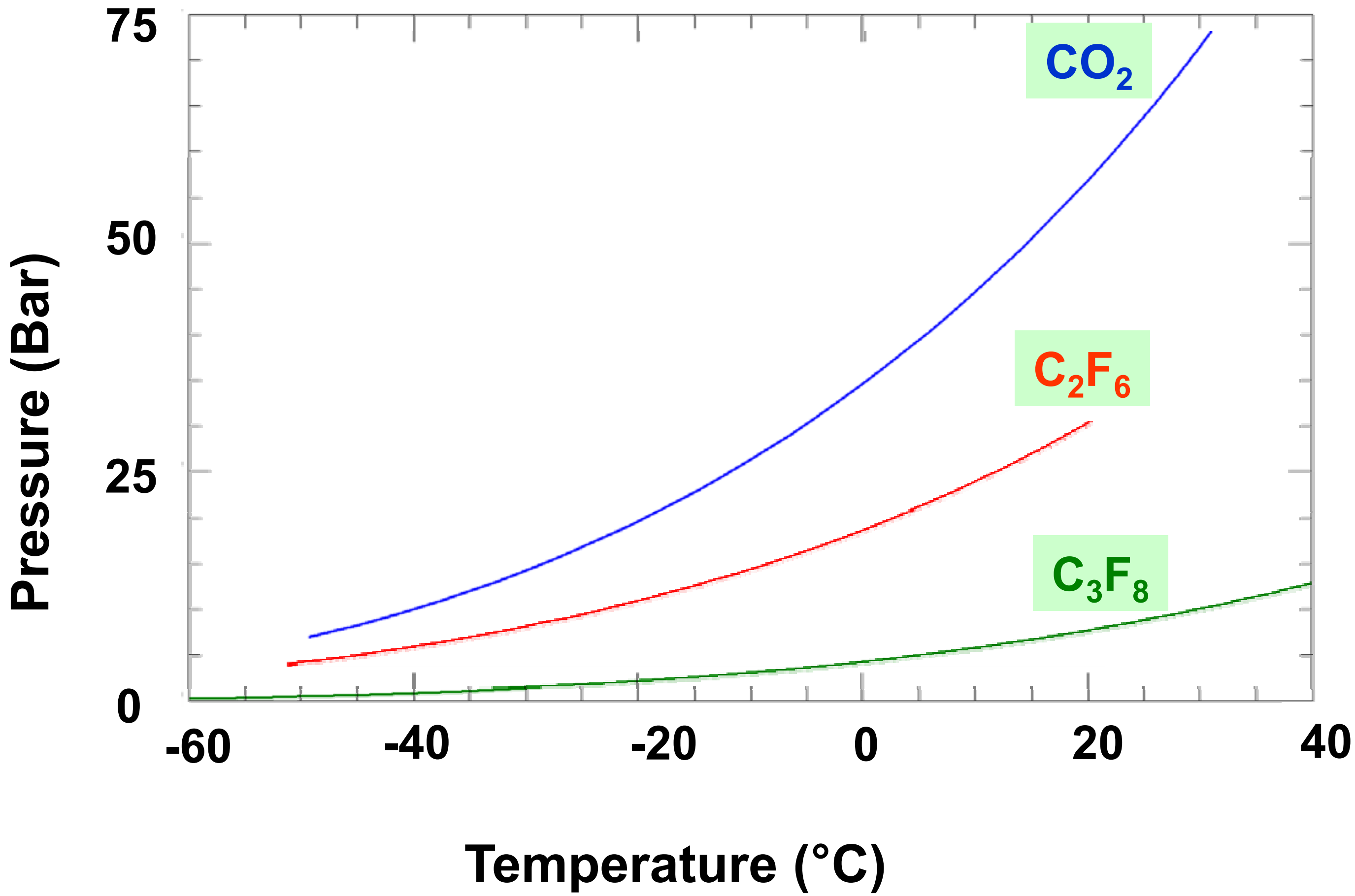
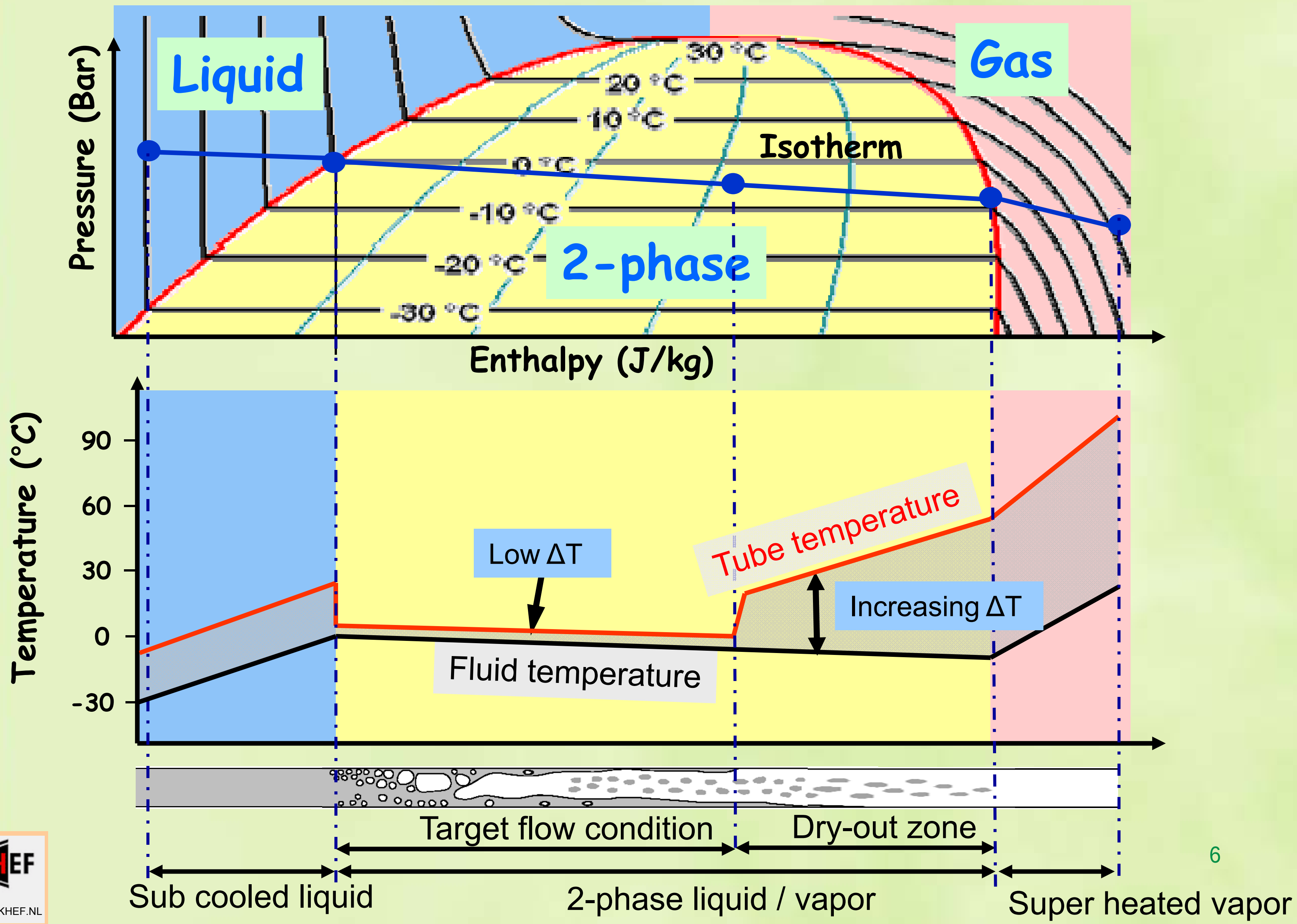
Saturation curves in the PT Diagram for CO_2, C_2F_6 & C_3F_8

(3 used or considered refrigerants at CERN)



What happens inside a cooling tube?

Heating a flow from liquid to gas



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How to design a cooling tube?

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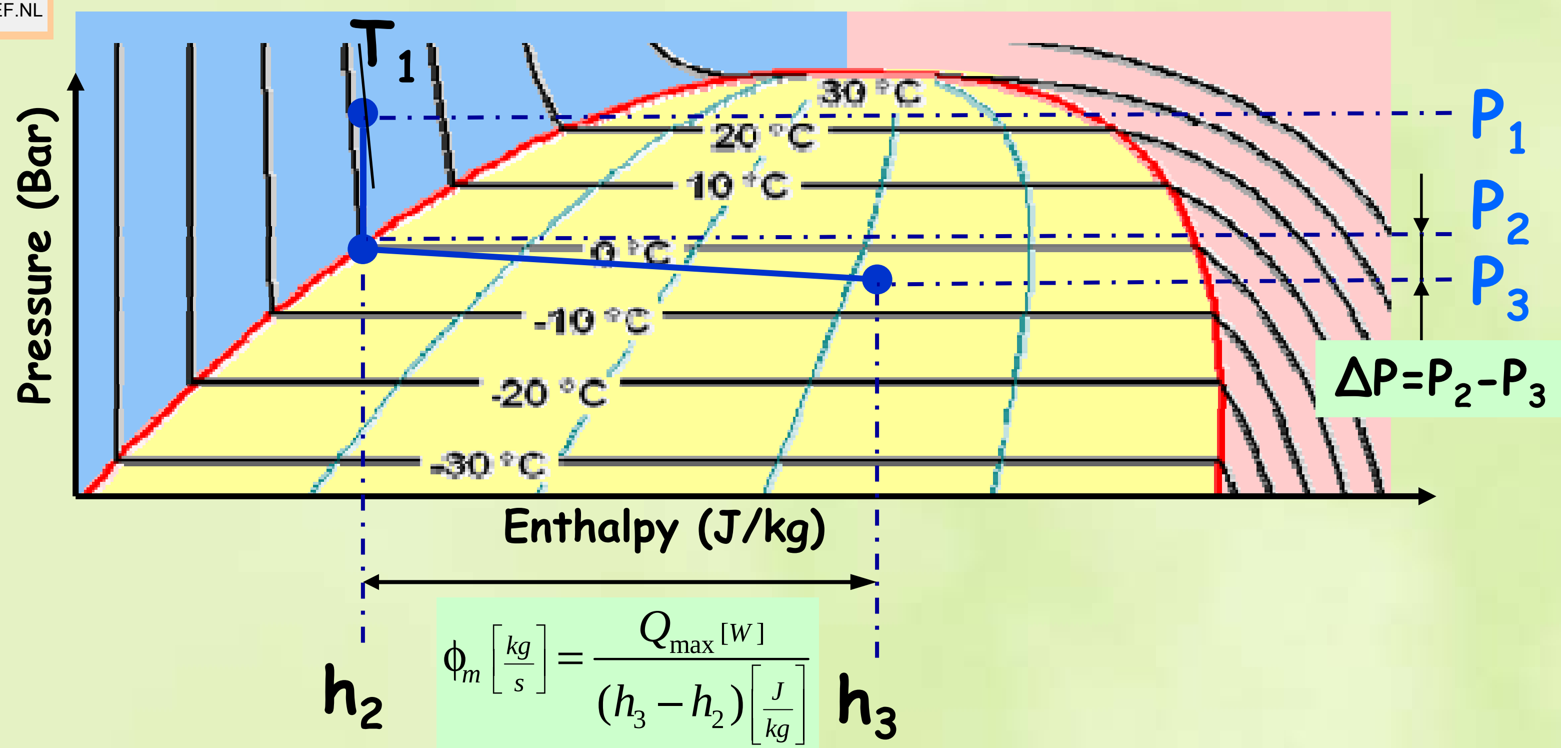

$$\phi_m\left[\frac{kg}{s}\right] = \frac{Q_{max}[W]}{(h_3 - h_2)\left[\frac{J}{kg}\right]}$$

For evaporative cooling 5 items are important:

- Controlling inlet enthalpy (h_2) by expanding from liquid (P_1,T_1)
- Setting mass flow ($\varnothing_m$) as function of maximum heat load (Q_{max})
- Controlling outlet pressure (P_3)
- Minimize pressure drop (ΔP)
- Optimize heat transfer (α) with contact area.

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2-Phase flow prediction

2-phase flow theory =

Well understood single phase flow theory

x

Magic empirical correlations in a black box

Pressure drop: $$\Delta P_{2-Phase} = \Delta P_{Liquid} * \frac{E + 3.24 * F * H}{Fr^{0.045} * We^{0.035}}$$

For example: Friedel Correlation

Heat transfer: $$\alpha_{2-Phase} = \alpha_{Liquid} * (C_1 * Co^{C_2} * (25 * Fr_{LO})^{C_5} + C_3 * Bo^{C_4} * F_{fl})$$

For example: Kandlikar Correlation

2-Phase coëfficiënt order 1~10

How to get the ideal 2-phase flow in the detector?

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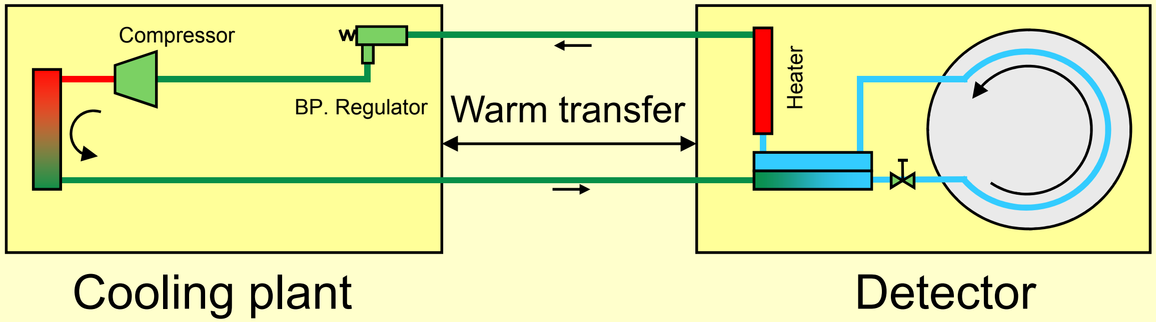
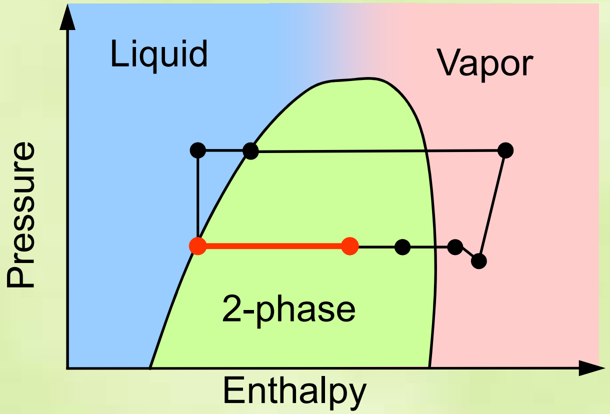
Traditional method: **Vapor compression system**

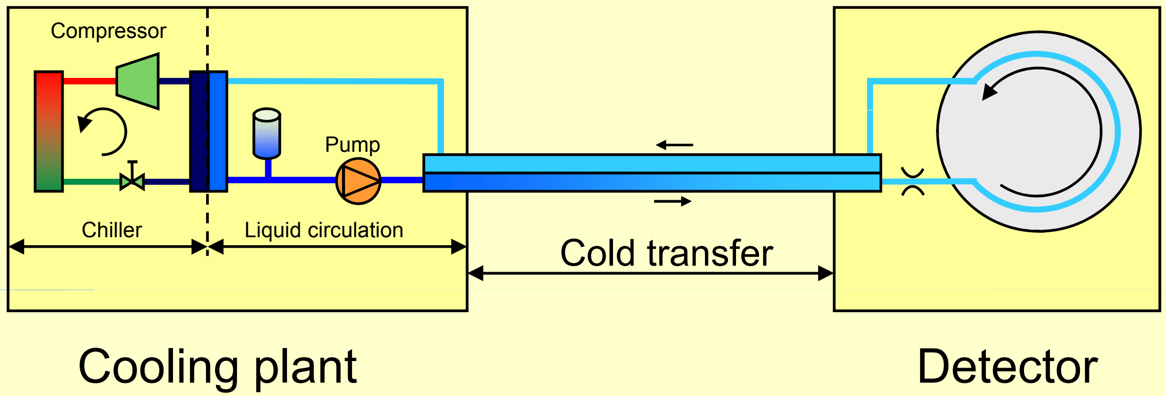
(Atlas)

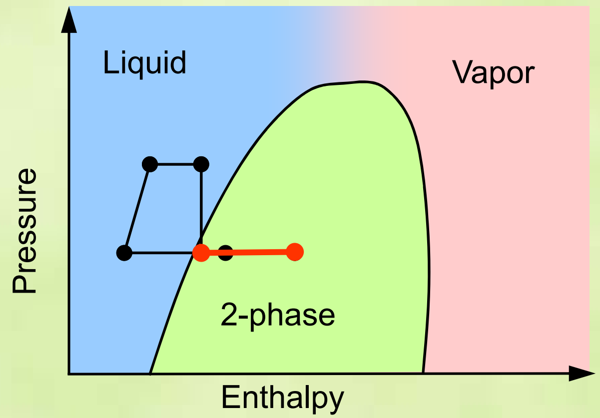




2PACL method: **Pumped liquid system**

(LHCb)





LHCb Detector Overview

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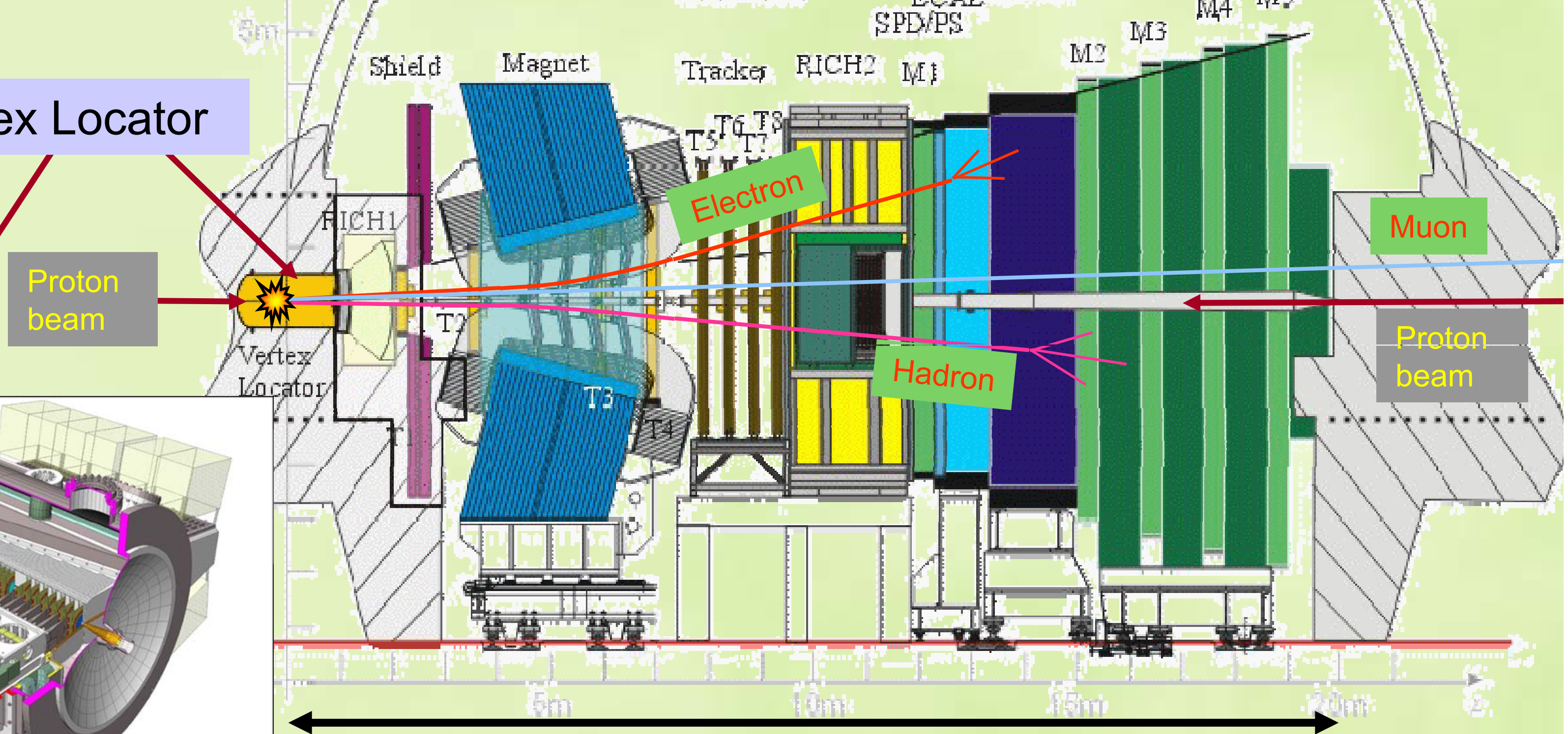
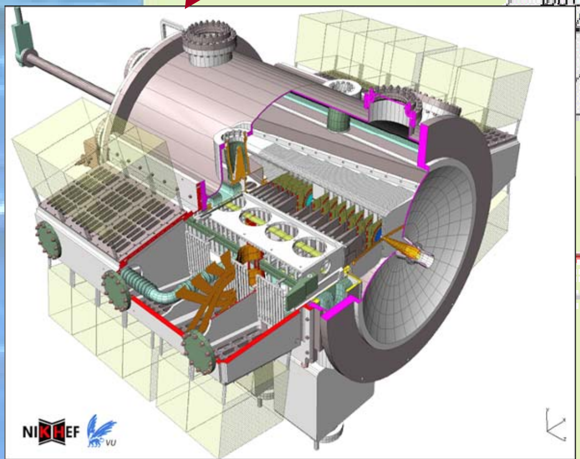
Goals of LHCb:
Studying the decay of B-mesons to find evidence of CP-violation
(Why is there more matter around than antimatter?)

LHCb Cross section

Vertex Locator





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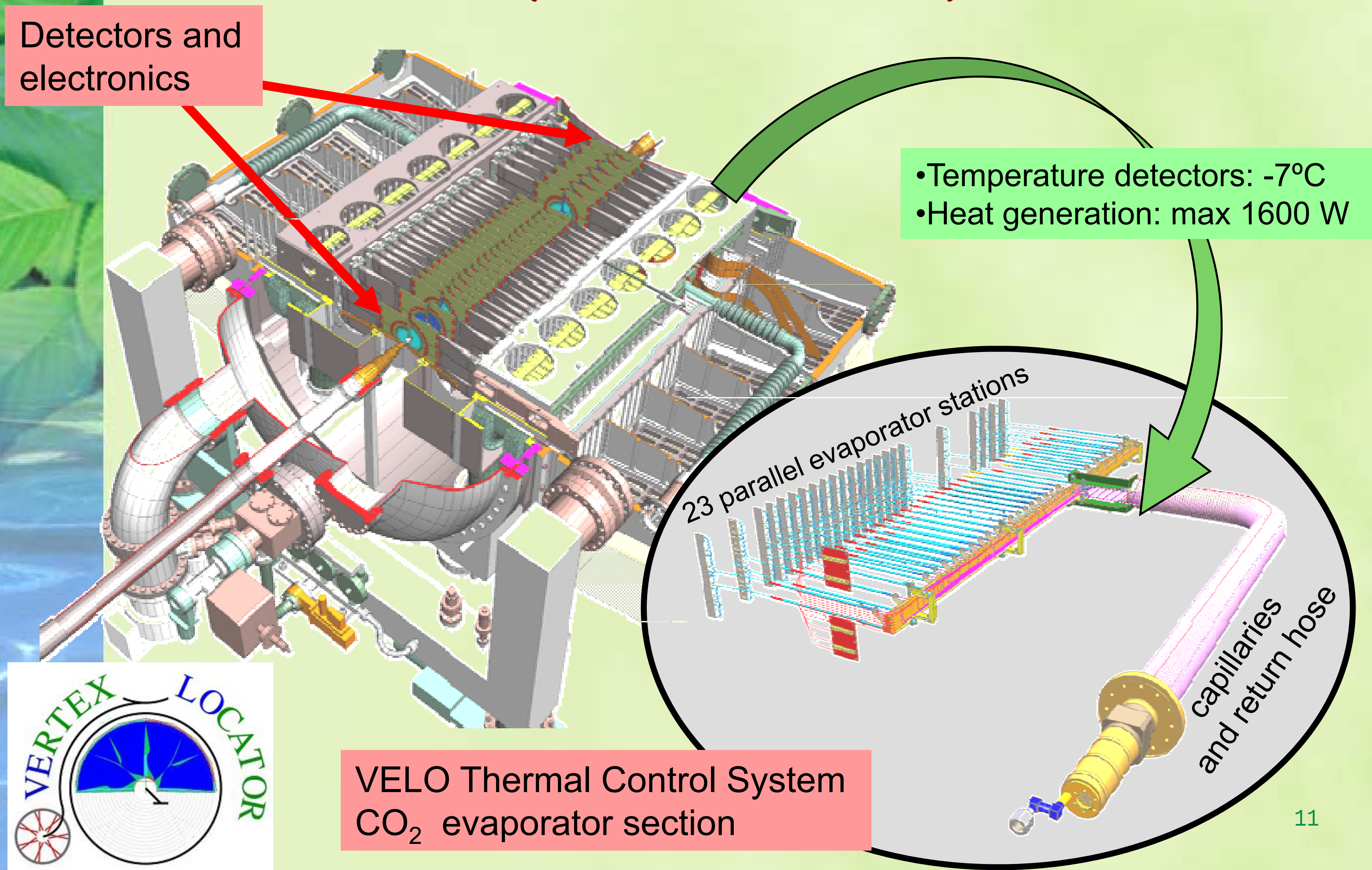
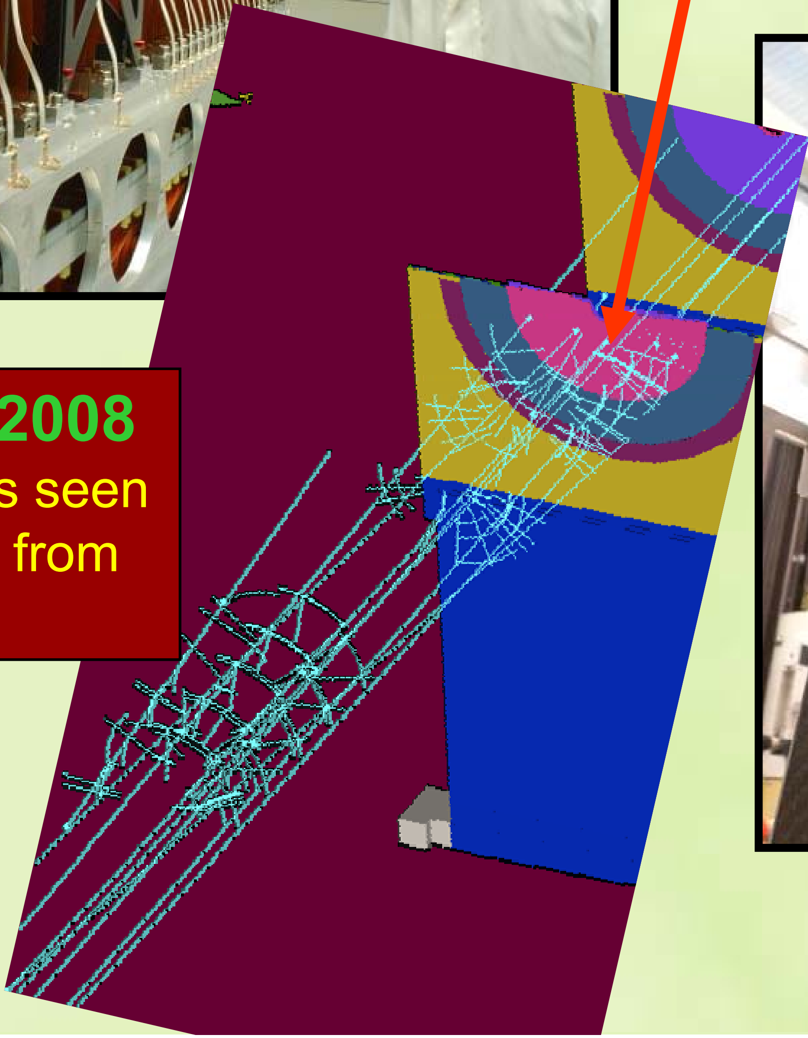
The LHCb-VELO Detector

(VErtex Locator)

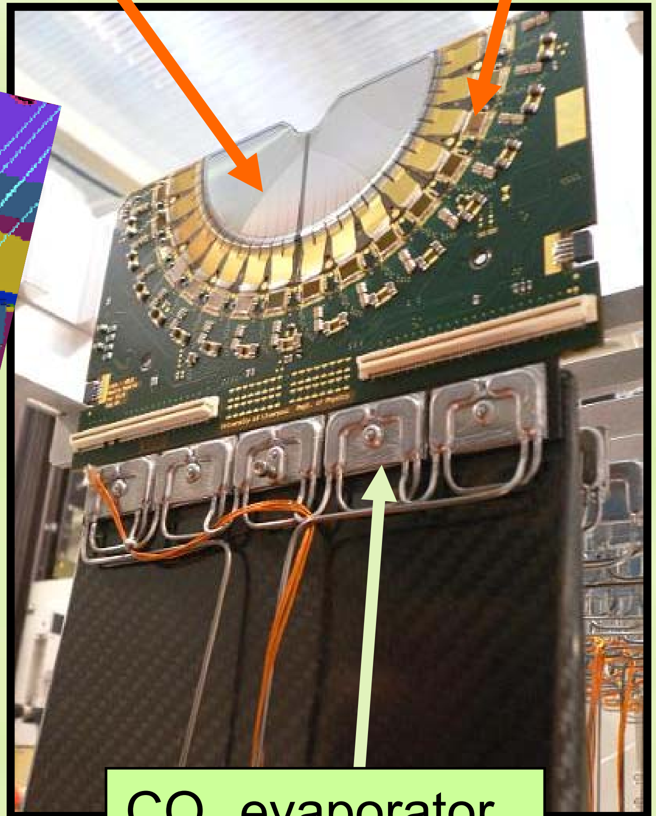


The Velo Detector



Detection Silicon

Heat producing electronics



22 August 2008
The VELO has seen particle tracks from an LHC test!

CO_2 evaporator
(Stainless steel tube casted in aluminum)

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VELO Cooling Challenges

- VELO electronics must be cooled in vacuum.
  - Good conductive connection
  - Absolute leak free
- Maximum power of the electronics: 1.6 kW
- Silicon sensors must stay below -7°C at all times (on or off).
  - To avoid thermal runaway of the irradiated silicon
- Adjustable temperature for commissioning.
- Maintenance free in inaccessible detector area

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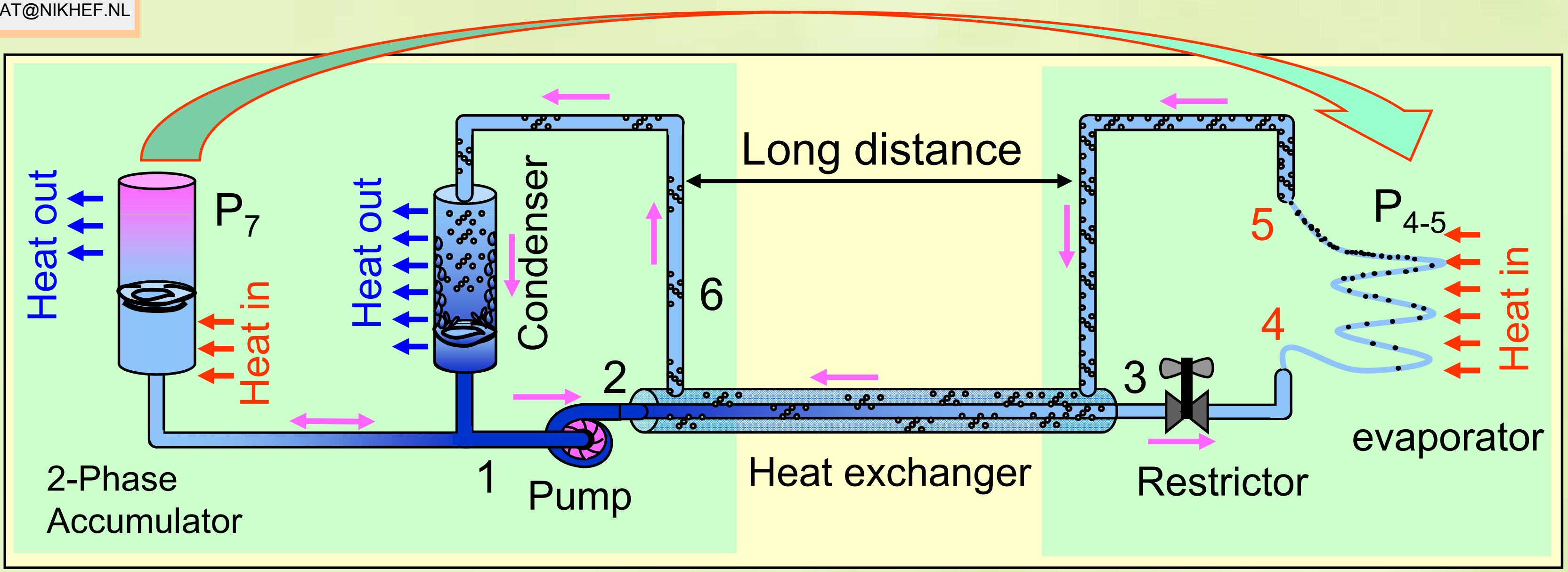
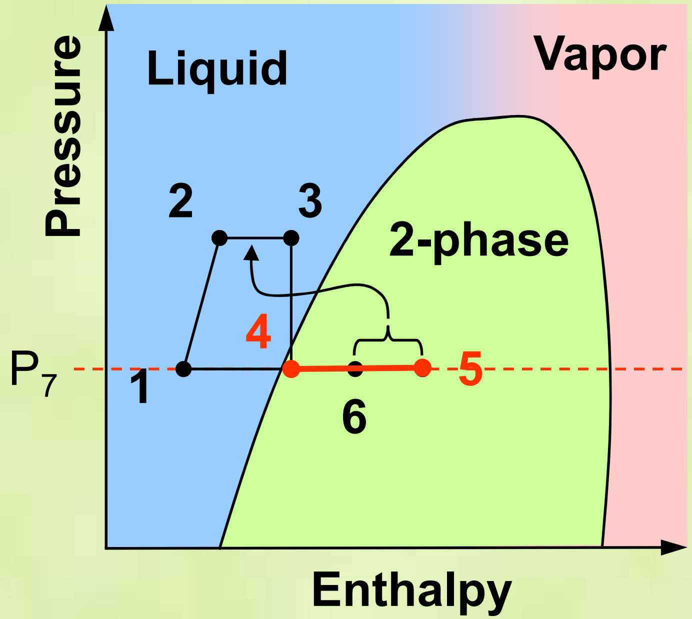
The 2-Phase Accumulator Controlled Loop (2PACL)



2PACL principle ideal for detector cooling:

- Liquid overflow => no mass flow control
- Low vapor quality => good heat transfer
- No local evaporator control, evaporator is passive in detector.
- Very stable evaporator temperature control at a distance ($P_{4\text{-}5} = P_7$)



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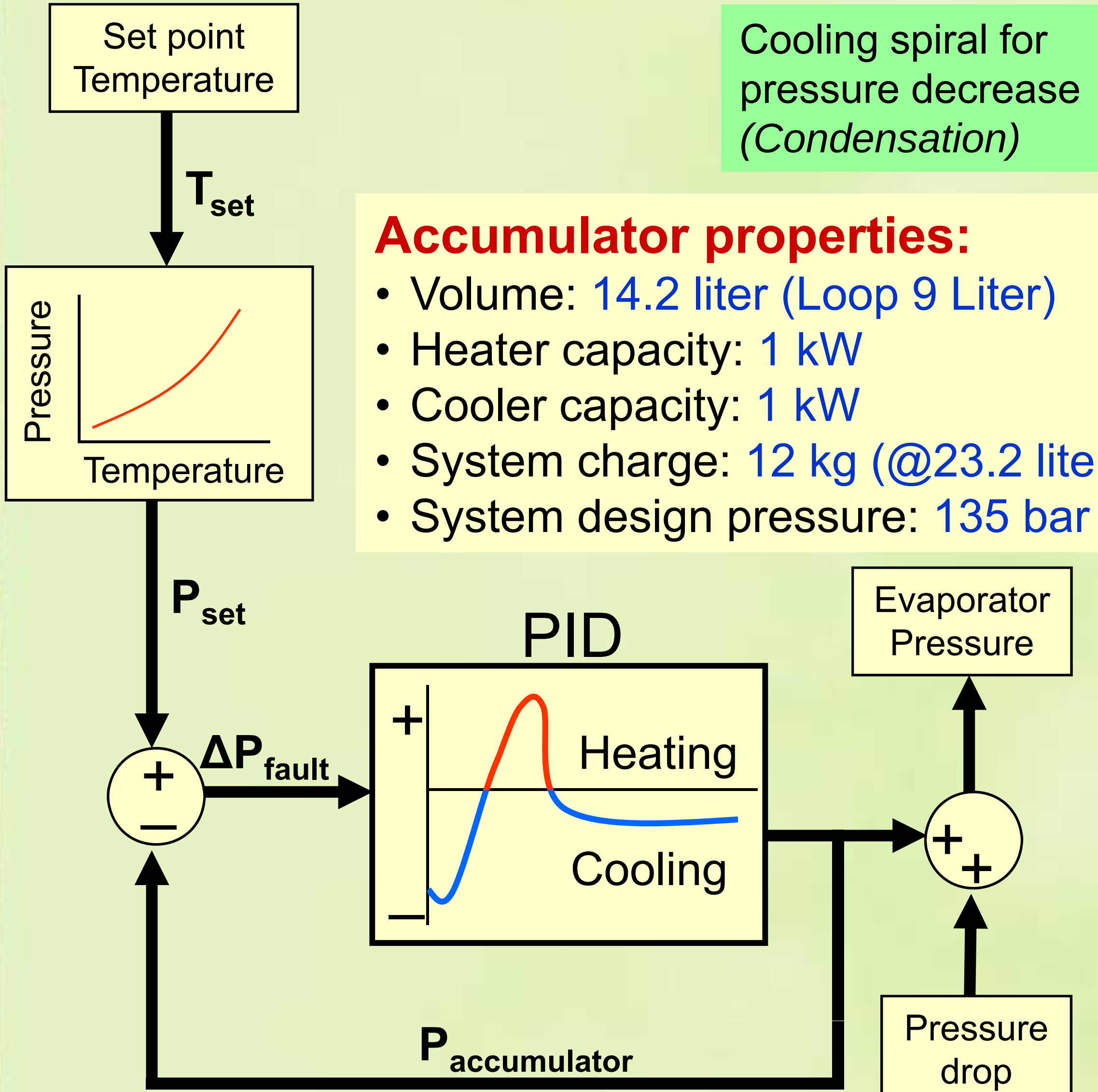
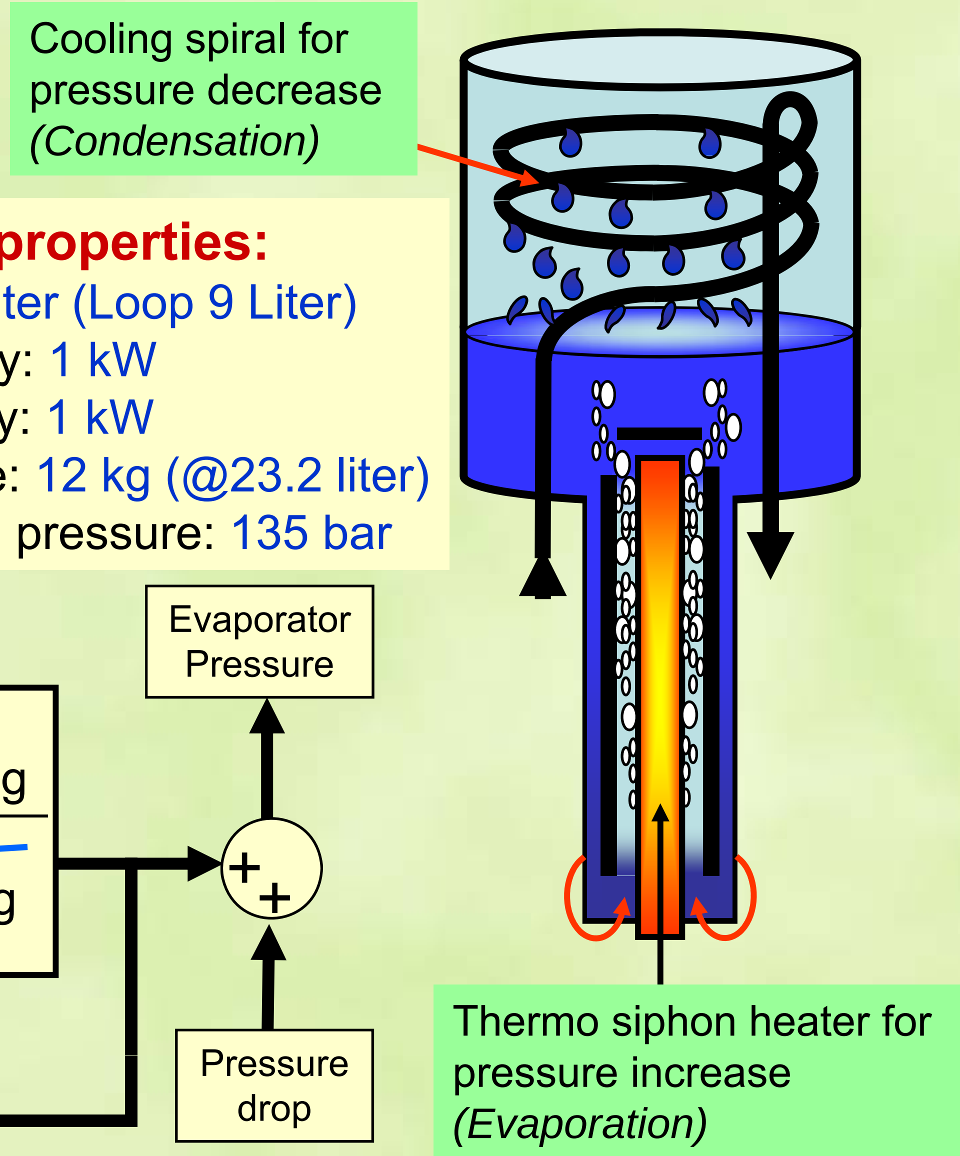
VTCS Accumulator Control



Accumulator properties:

- Volume: 14.2 liter (Loop 9 Liter)
- Heater capacity: 1 kW
- Cooler capacity: 1 kW
- System charge: 12 kg (@23.2 liter)
- System design pressure: 135 bar



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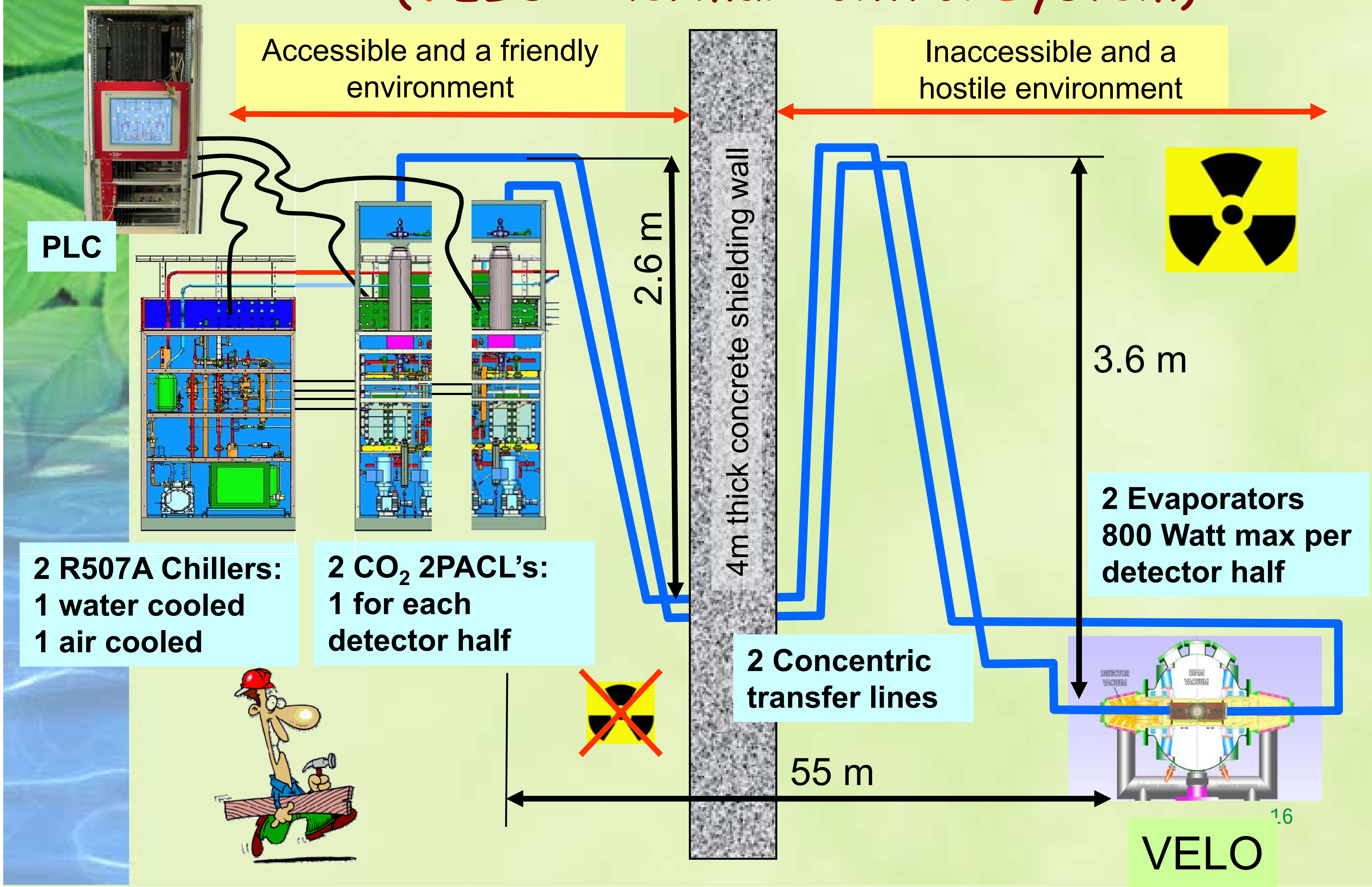
LHCb-VTCS Overview (VELO Thermal Control System)



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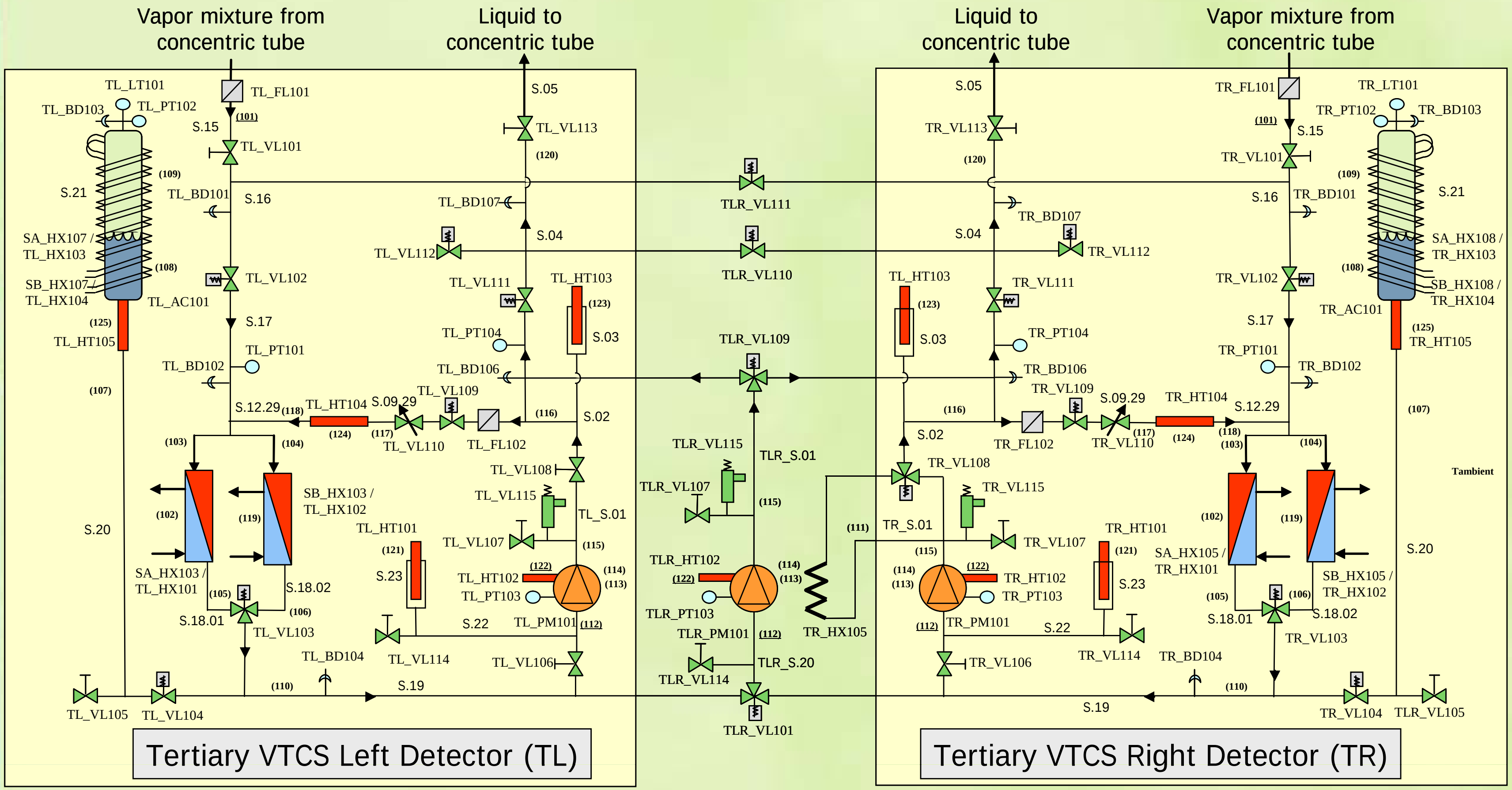
VTCS Schematics

2x CO_2 2PACL's connected to 2 R507A chillers (Redundancy)

Lots of sensors and valves



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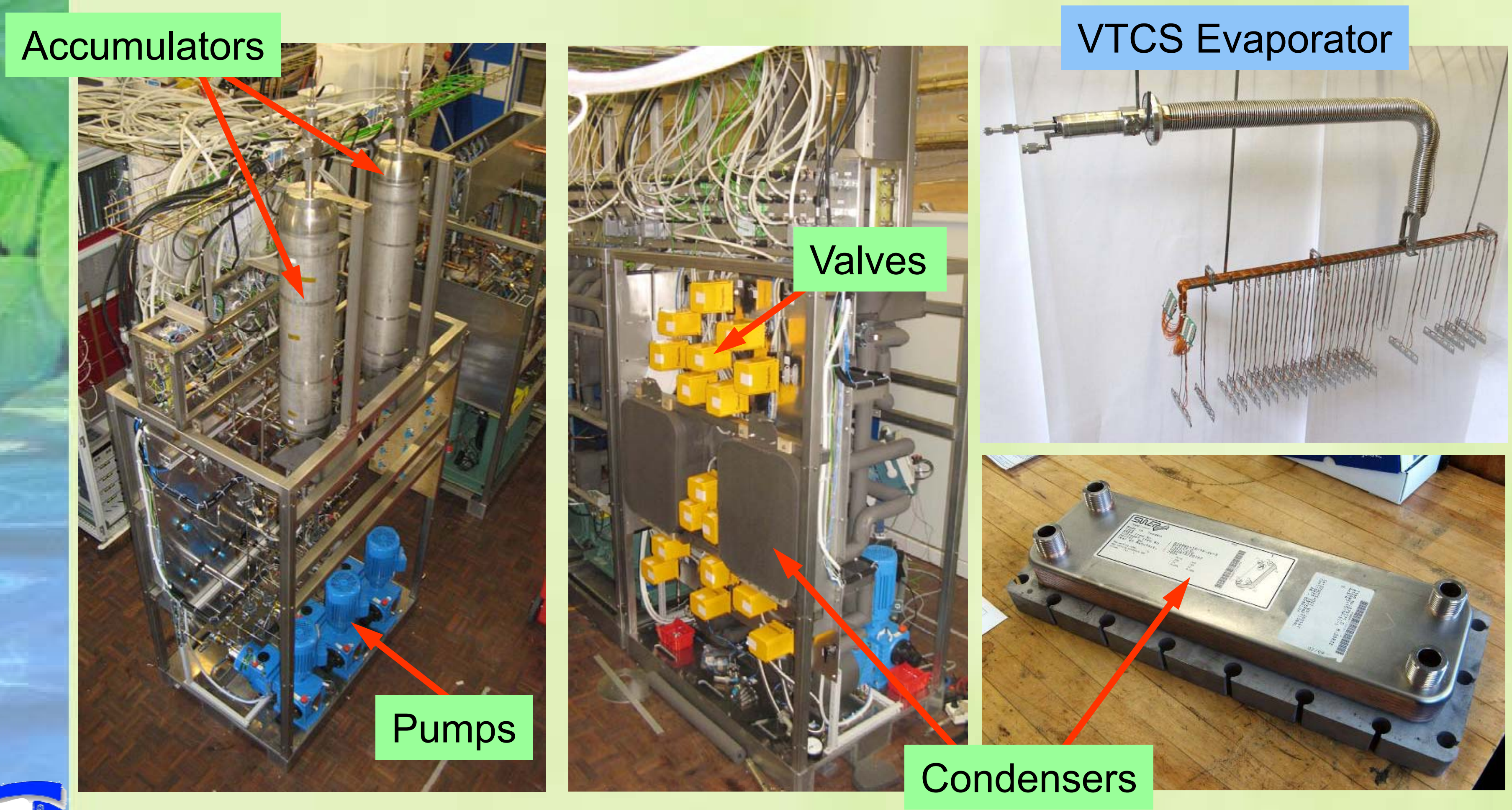
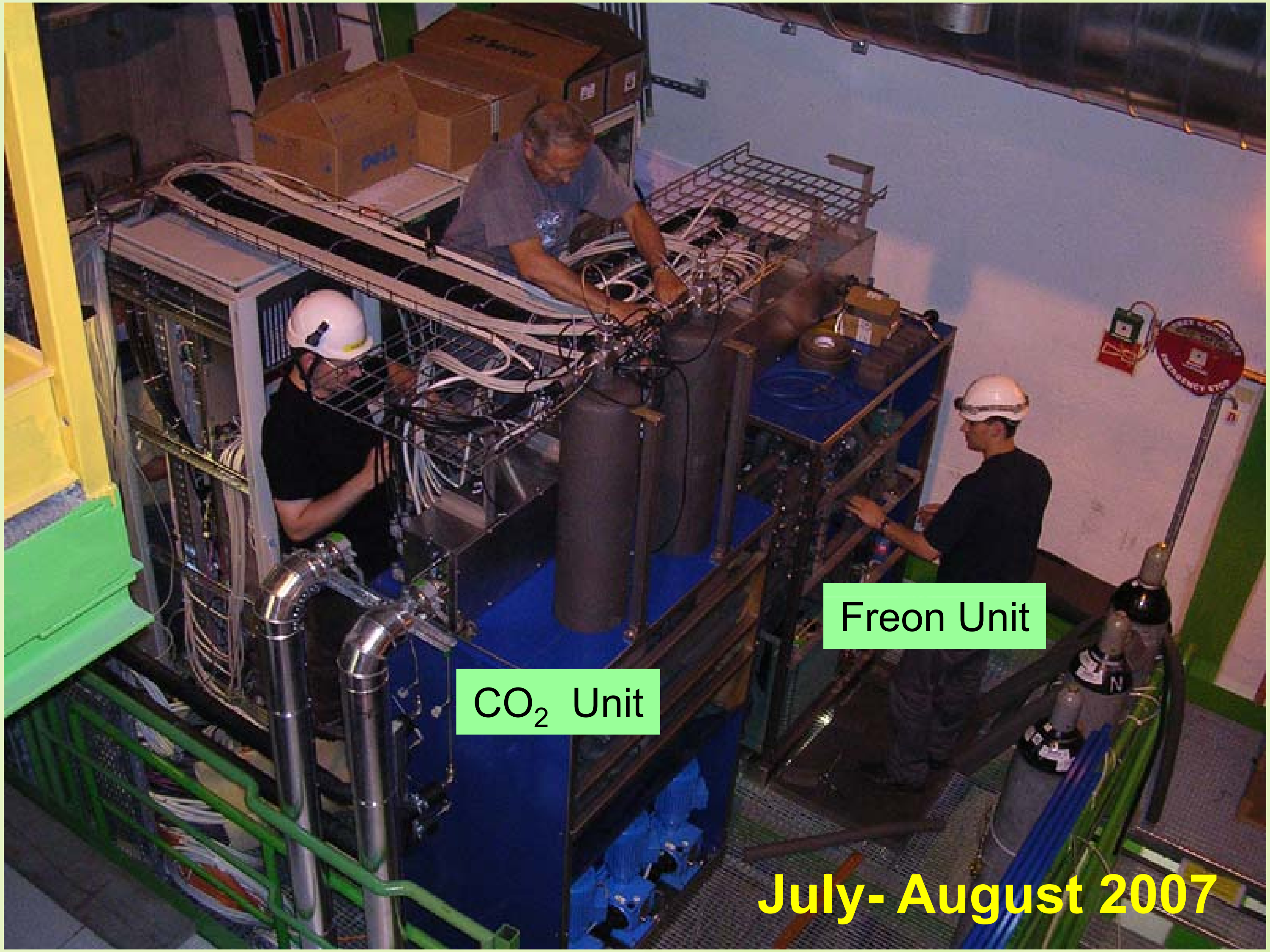
LHCb-VTCS Cooling Components



VTCS Units Installed @ CERN



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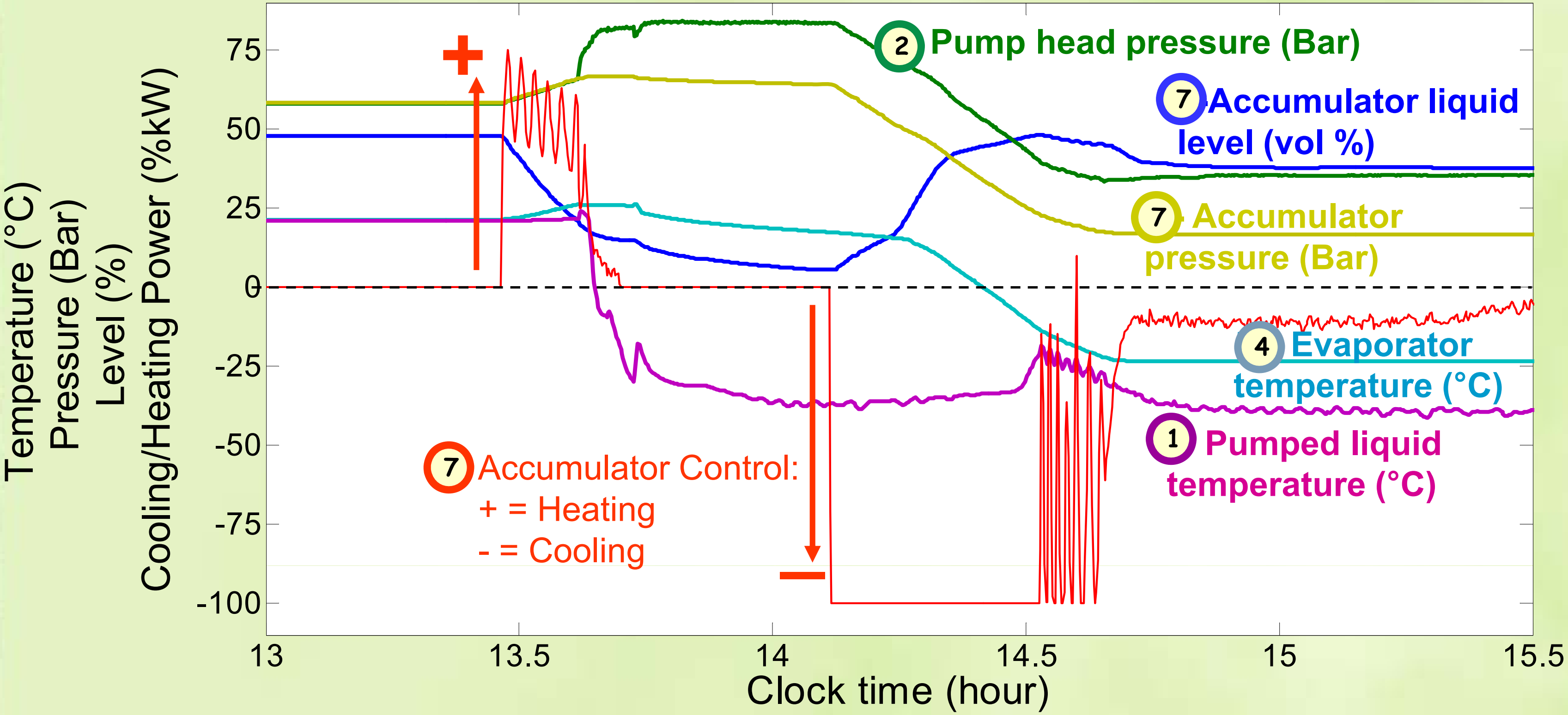
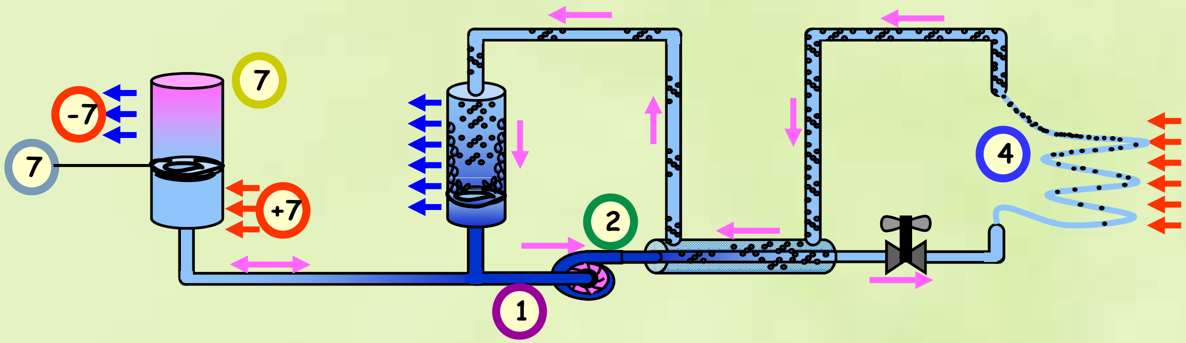
VTCS 2PACL Operation

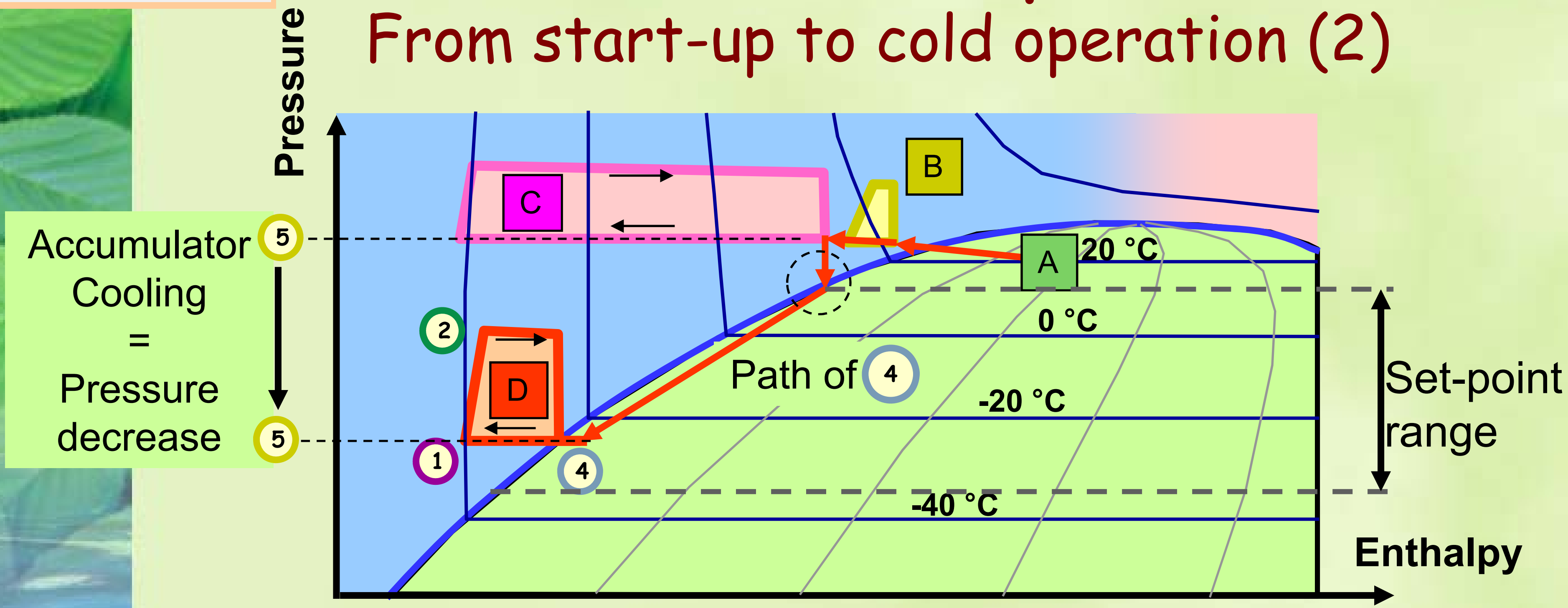
From start-up to cold operation (1)

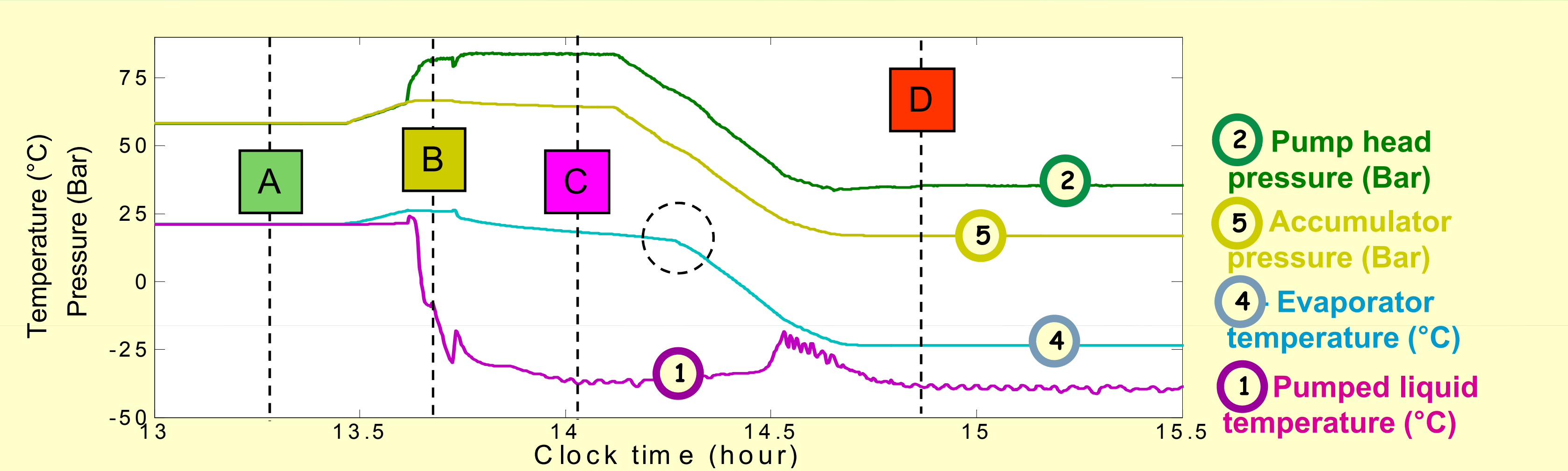




VTCS 2PACL Operation

From start-up to cold operation (2)





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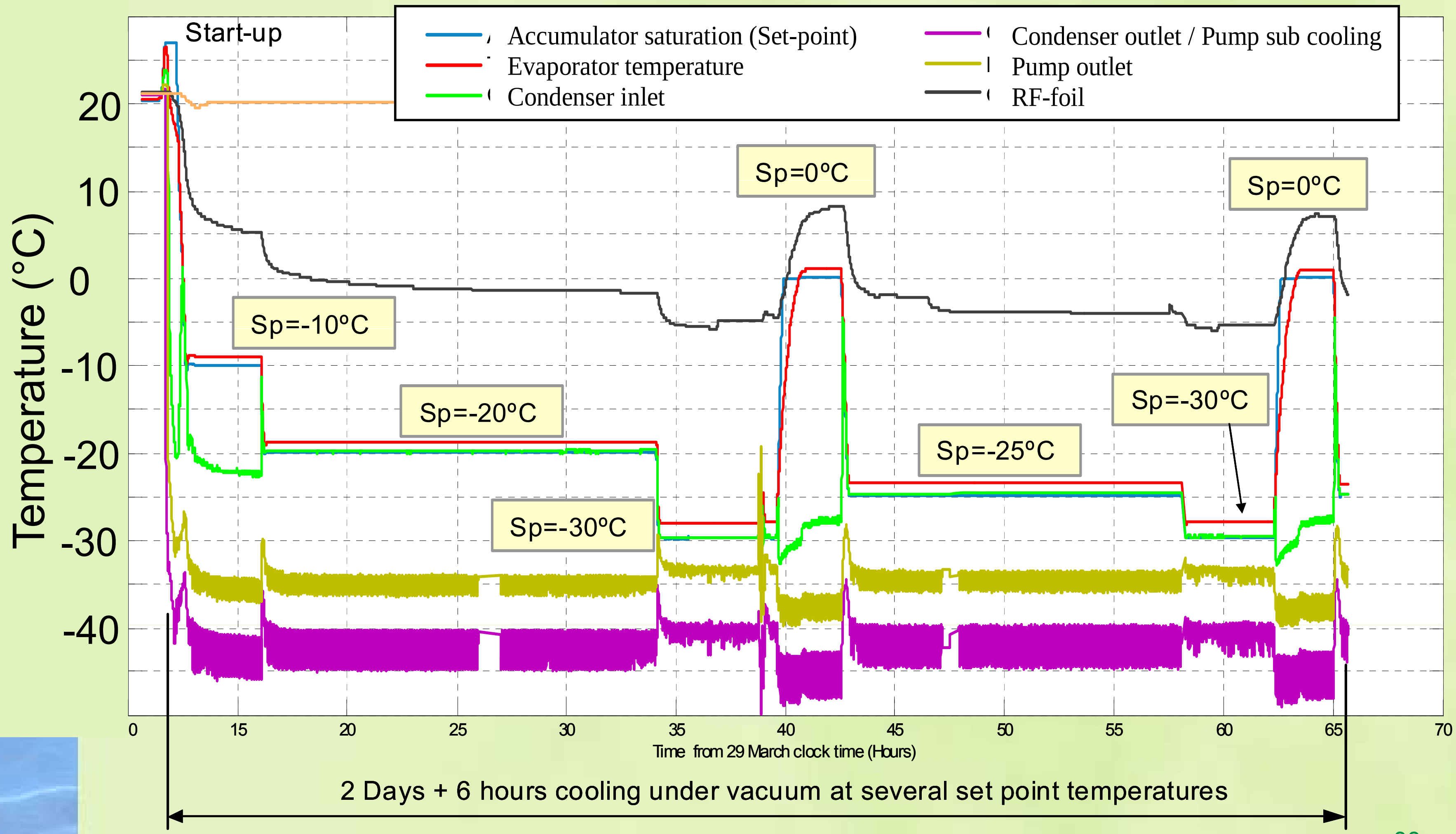
March '08: Commissioning of the VTCS

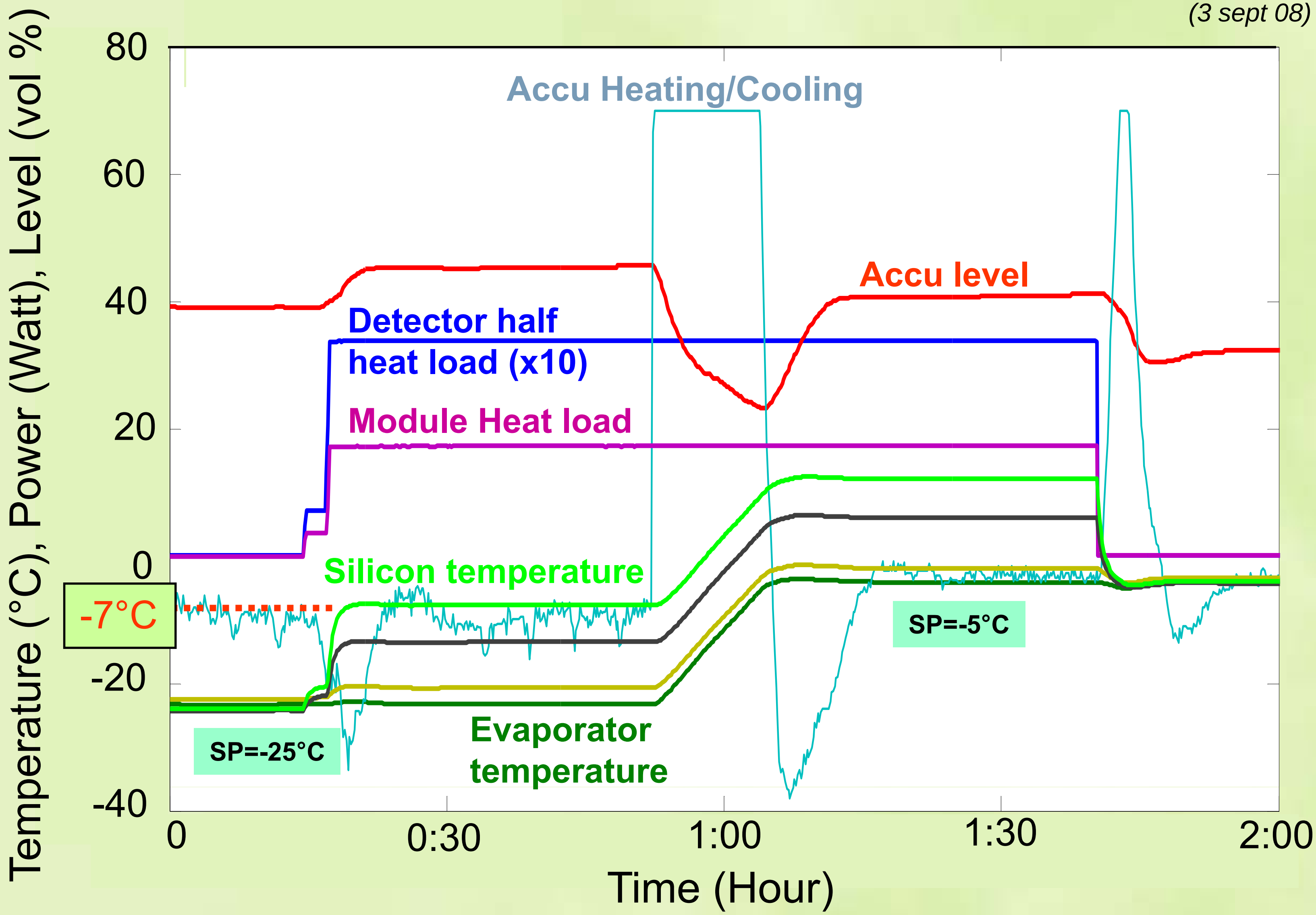
Detector under vacuum and unpowered



24 June '08: After a succesful commisioning of the detector at -25°C, the setpoint is increased to -5°C.

And has been running since then smoothly!

(3 sept 08)



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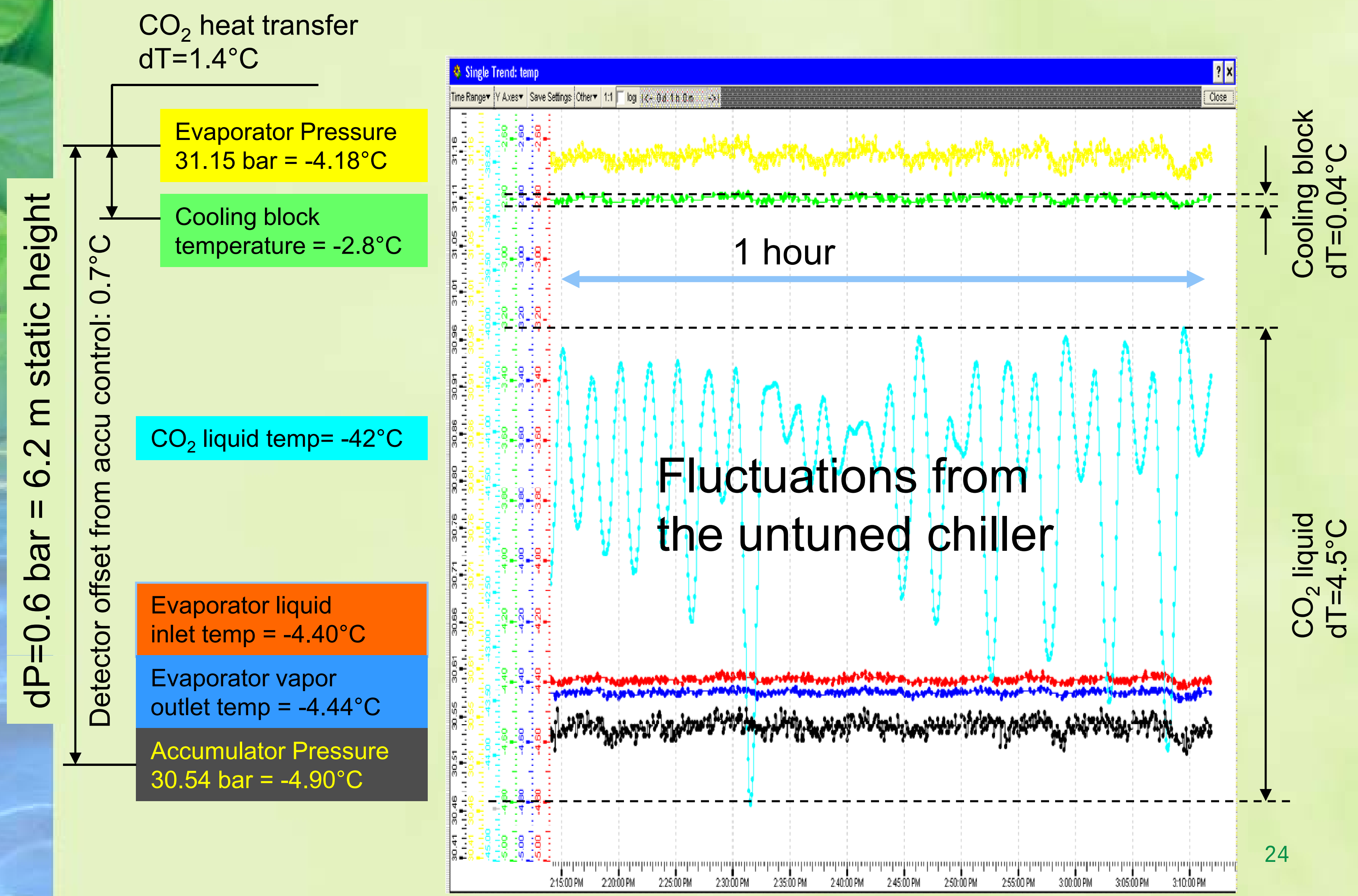
VTCS performance overview for a set point of -5°C (Detector switched on, fully powered)



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VTCS Summary

- The installation at CERN started in July 2007.
- The VTCS has successfully passed the 1st commissioning phase between march and June '08 and is ready to be used in the experiment
- Operational temperature range is between 0°C and -30°C set point (+10°C with the back-up chiller)
- It has run for 2½months continuously without any problem (only 3 interruption due to power or cooling water failures)
- It behaves very stable (<0.1°C fluctuation), with the chiller still to be tuned.
- The silicon temperature is below the required -7°C @ -25°C set point temperature. (This is consistent with the prediction)

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Some Lessons Learned

- The accumulator sometimes gives the pump a 2-phase mixture => cavitation. Problem is solved by connecting the accumulator to the inlet of the condenser instead of the outlet where it is now.
- Operational temperature range of the evaporator is larger than expected. This is due to the "Duck Foot Cooling[1]" principle of the transfer line.
- The main pressure drop of 2-phase flow in the return line was not caused by friction but by the heights of the upward columns combined. Minimization of the upward columns is more important in the design. Were CO_2 gives only about 1°C/bar (≈0.1°C/m), the use of other fluids will make upward 2-phase flow impossible without a big temperature penalty.

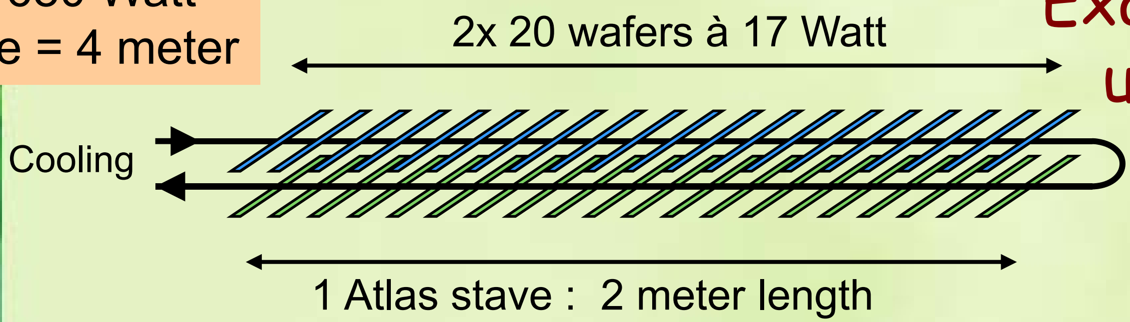
[1] The way a duck can have cold feet without loosing body heat, by exchanging heat between the in- and outlet bloodstream.

Outlook

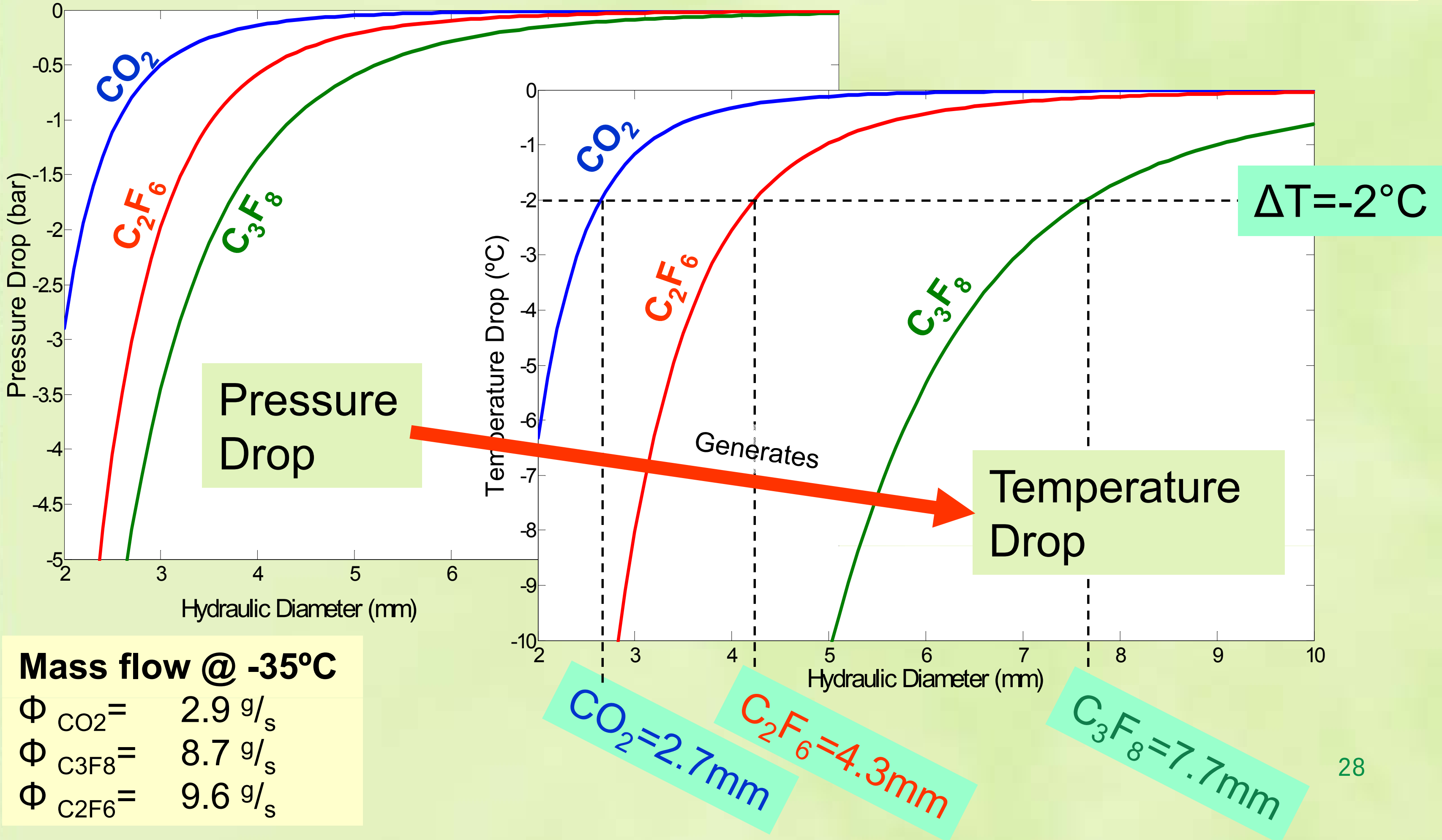
- The VTCS is not yet finished, some things have to be done:
  - **Implementing automatic back-up procedure.**
  - **Changing the accumulator connection.**
  - **Tuning the chiller.**
  - **Analyze data for publication.**
- Construction of a mini desktop 2PACL CO_2 circulator for general purpose laboratory use.
- Other CERN detectors (Atlas/CMS) have shown interest in the VTCS for their inner tracker upgrades.
  - **Challenge: Scaling of the 1.6kW VTCS to a 100kW system.**
  - **An example of fluid trade-off is given in an Atlas upgrade stave calculation example.**

Example of and Atlas upgrade stave (1)

Q = 680 Watt
Tube = 4 meter



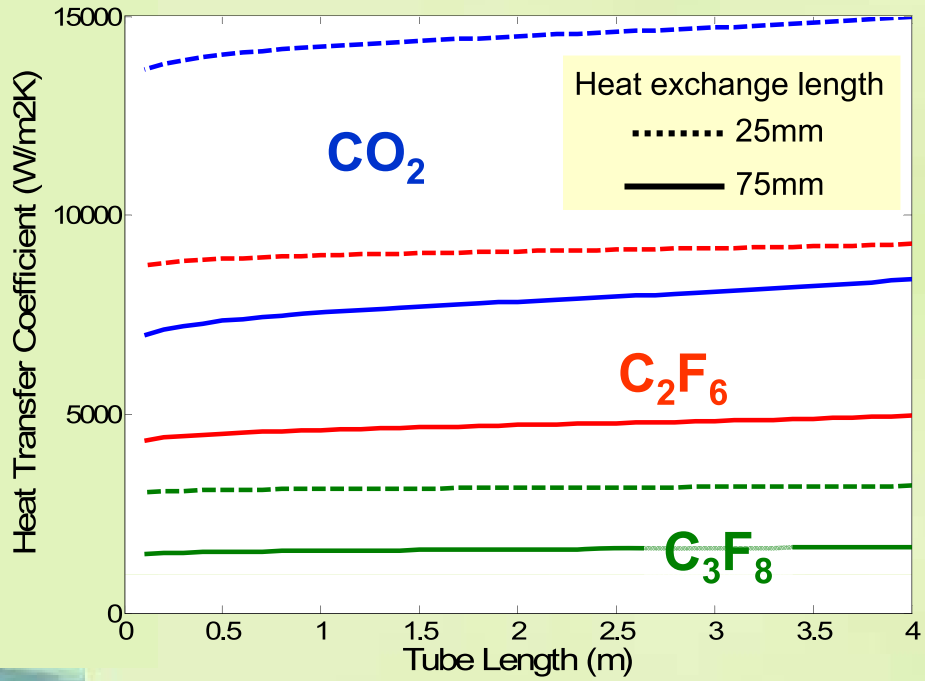
Calculations based on -35°C and 75% vapor quality at exit



Mass flow @ -35ºC

Φ_{CO2} = 2.9 g/s
Φ_{C3F8} = 8.7 g/s
Φ_{C2F6} = 9.6 g/s

Example of and Atlas upgrade stave (2)



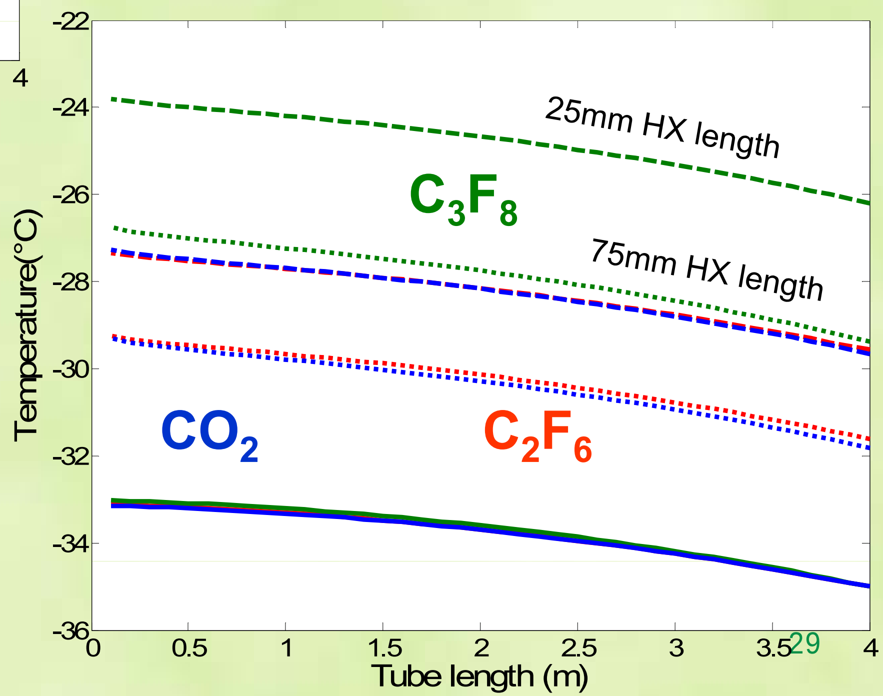
D4.3mm x L25mm = 50337 W/m²

D2.7mm x L75mm = 26722 W/m²

D4.3mm x L75mm = 16779 W/m²

D7.7mm x L25mm = 28110 W/m²

D7.7mm x L75mm = 9370 W/m²



Mass flux @ -35ºC

Φ'_{CO2} = 506 $^{kg}/_{m^2s}$

Φ'_{C3F8} = 661 $^{kg}/_{m^2s}$

Φ'_{C2F6} = 186 $^{kg}/_{m^2s}$

Critical Heat Flux (Bowring/Ahmad):
$CHF(CO_2)$ = 313 kW/m², x=1.1

Thank you for your attention:

Questions?