Operational experience from the use of a 90 metre thermosiphon cooling plant for C_3F_8 evaporative cooling of the ATLAS silicon tracker

M. Battistin, S. Berry, P. Bonneau, C. Bortolin, F. Corbaz, O. Crespo-Lopez, C. Deterre, C. Degeorge, B. DiGirolamo, M . Doubek, G. Favre, G. Hallewell, S. Katunin, D. Lefils, D. Lombard, A. Madsen, S. McMahon, K. Nagai, C.Rossi, A. O'Rourke, B. Pearson, D. Robinson, A. Rozanov, E. Stanecka, V. Vacek, L. Zwalinski

Forum on Tracking Detector Mechanics 2017
Marseille, 3 – 5 July 2017

Outline

Cooling of ATLAS detector

The thermosiphon evaporative cooling system

60 kW dummy load commissioning

Swap tests

Conclusion and what's next

Cooling of the ATLAS detectors

Thermal requirements:

- Detector temp -15°C, corresponding to target evap temp of -25 °C to cope with radiation exposure over 10 years
- Temperature uniformity better than 2°C along the evaporators
- Total power to be removed 62.4 kW (204 parallel cooling loops)

Attree et al. "The evaporative cooling system for the ATLAS inner detector" JINST 3.07 (2008): P07003

Advantages of the evaporative cooling system:

- Min extra material into Si trackers = min background particles
- Wide range of operating temperature
- Good thermal uniformity
- Mass flow 10-20 times less than in mono-phase liquid cooling system (smaller pipes)

Cooling of the ATLAS detectors

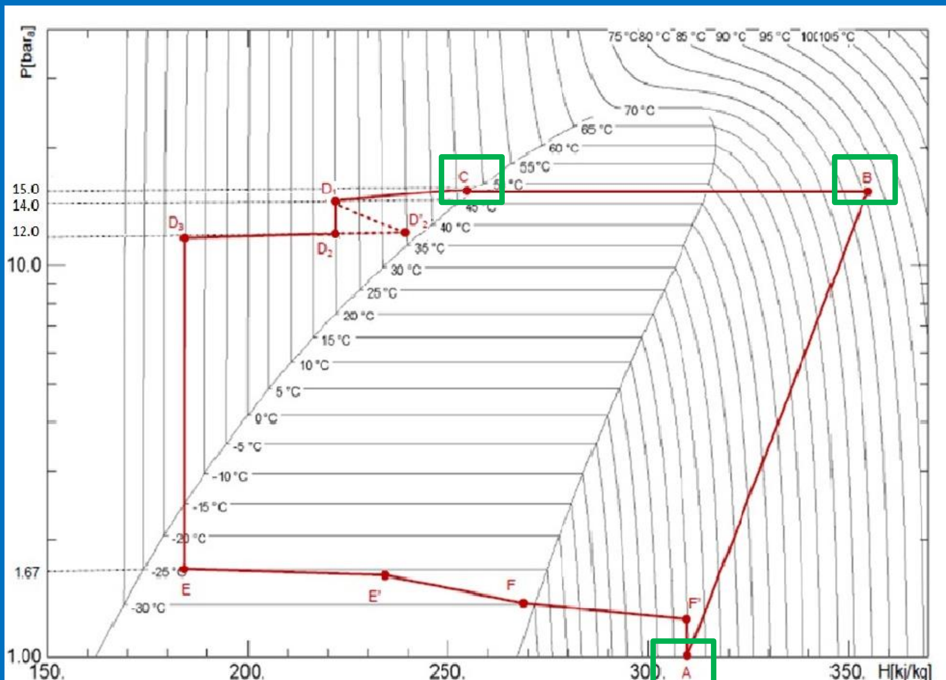
Cooling of ATLAS detector is done by mean of a fluorocarbon evaporative cooling system

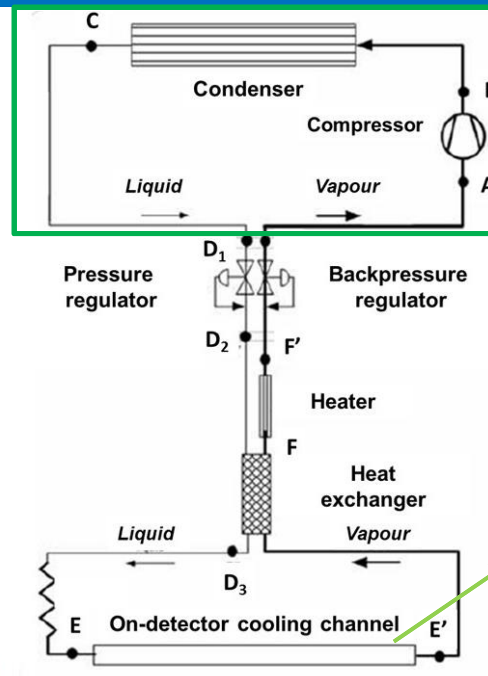
System based on a compression-condensation cycle similar to standard industrial direct expansion cooling plant.

Actually the external part of the evaporative cooling system is made of 7 oil free compressors working in parallel

Cooling of the ATLAS detectors

Evaporative cooling system divided into two main parts separated by distribution /collection racks equipped with PRs and BPRs





EXTERNAL PART
7 compressors working in parallel and a condenser

Target evaporation temperature in the on-detector cooling pipes **-25°C** (corresponding to a **saturation pressure** of **1.67 bar$_{abs}$** with C_3F_8 coolant)

High radiation environment → Oil free compressor to prevent accidental mixing of activated coolant and lubricating oil

Especially modified to satisfy the very demanding compression ratio
(*max p_out =15 bar$_{abs}$; min p_aspirating=1 bar$_{abs}$*) *Haug model QTOGX-160/80 (P_{max}=17 bar$_{abs}$; P_{min}=0.8 bar$_{abs}$)*

Compressors were improved and are presently working satisfactorily but still represent the weakest component of the system and need frequent preventive and corrective maintenance (frequent filter change because of carbon dust from piston segments)

Increase of fluid activation due to increase of beam luminosity. RP risk related to the development of leaks on alternative vibrating machines

⇩

Need of a more reliable plant

⇩

Need of a more leak-tight circuit

⇩

Thermosiphon plant (TS)

Any active component is eliminated from the primary loop.
The plant takes advantage of the great height difference (~100 m) between the underground cavern housing the experiment and the surface

→

natural circulation of the coolant

Description of the TS

Overview of the TS lay-out:

Water circuit

Low T chiller
(3 ton C_6F_{14})

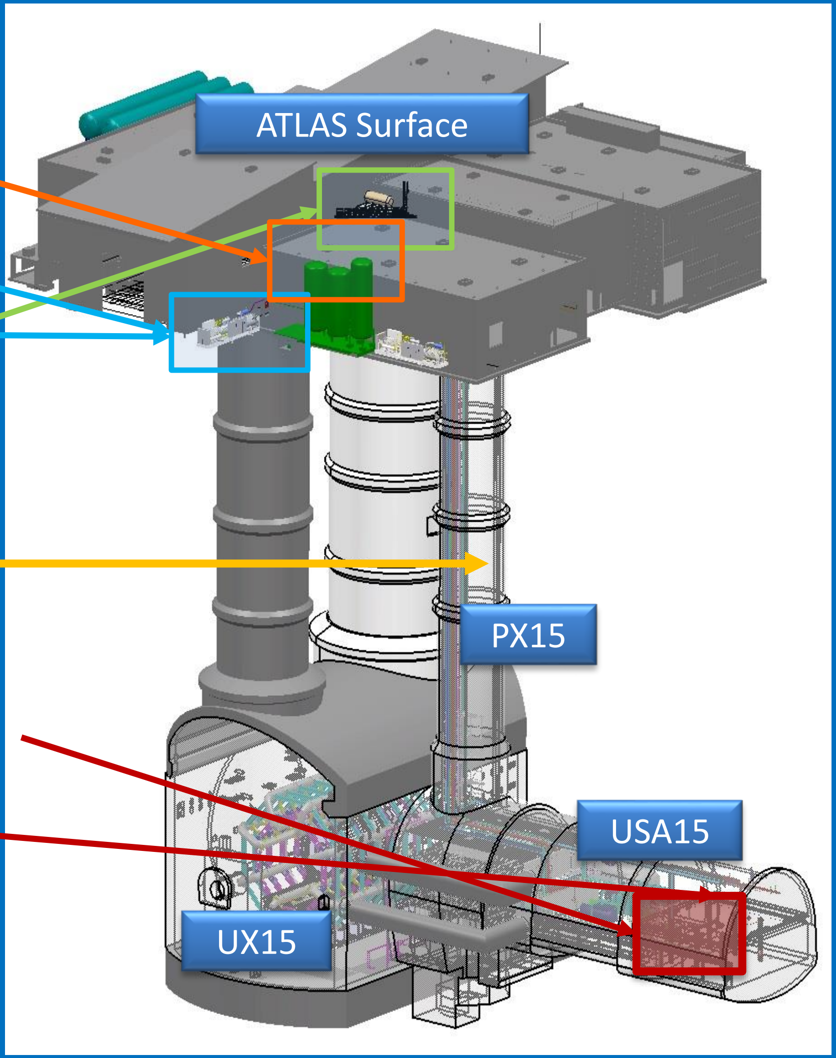
Brine circuit

Condenser

C_3F_8 piping
(1.5 ton C_3F_8)

“Balcony” by-pass unit

Evaporative connection



12 m Condenser - Surface

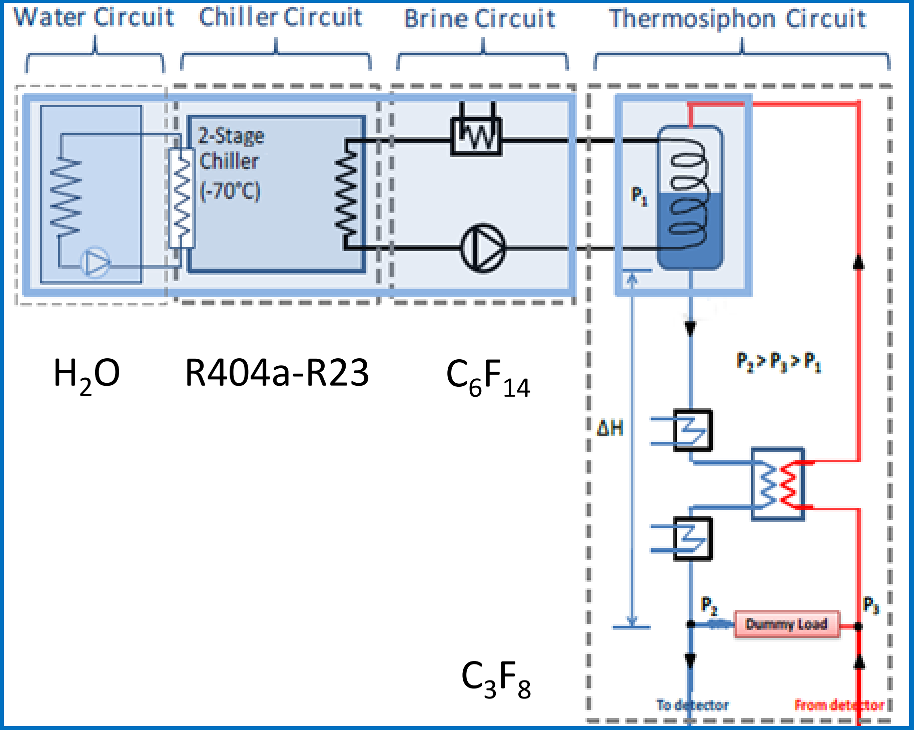
92 m Surface - Balcony room

102 m Surface - beam line

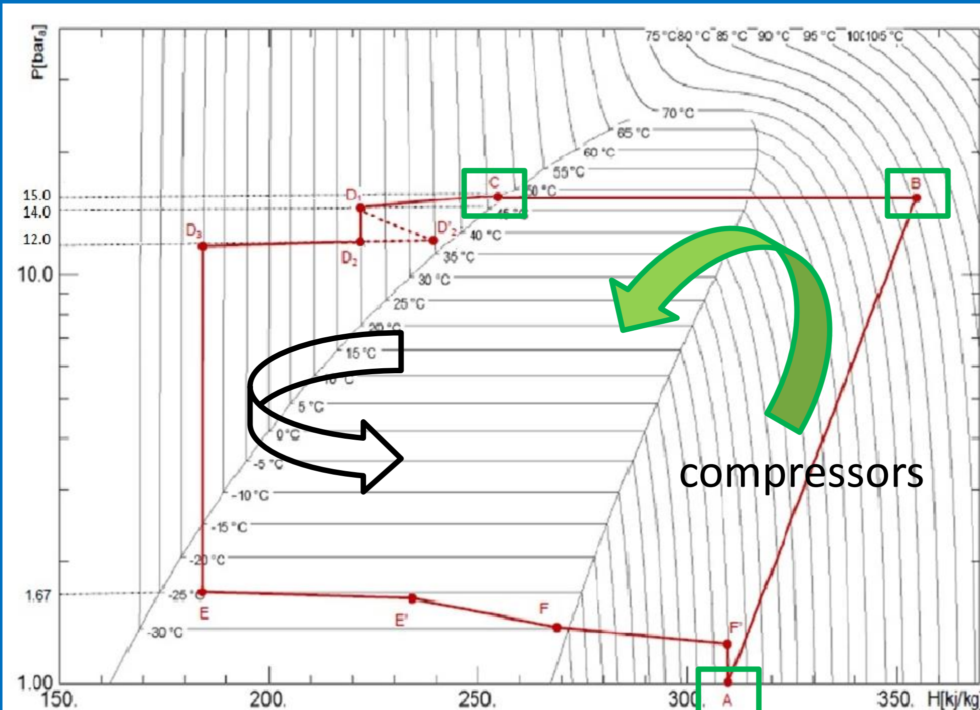
Let’s see how the system works……

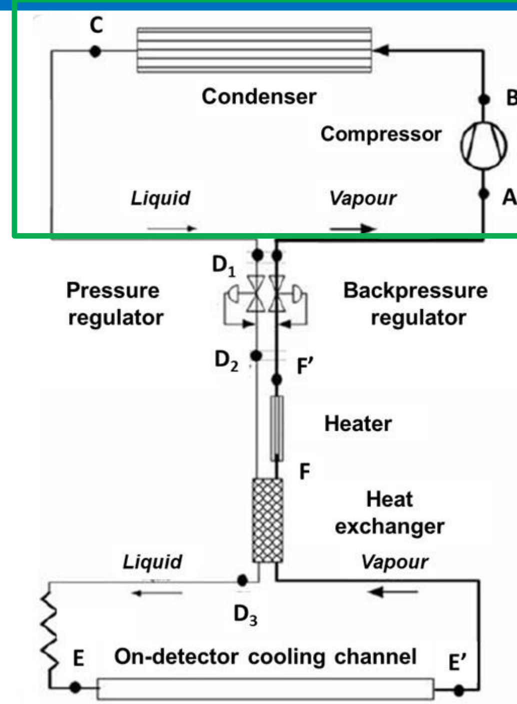
Description of the TS

The thermosiphon is composed of 4 separated circuits:



1. **Water circuit**: cooling the first stage of the chiller circuit: water from cooling towers at ~25°C:
2. **Chiller circuit**: two stage compression cycle to cool down perfluorohexane (C_6F_{14}) "brine" heat transfer liquid to -70°C. The chiller operates in cascade: the fist stage using R404a and the second stage R23;
3. **Brine circuit**: C_6F_{14} closed loop used to condense the C_3F_8 through heat exchange across the tubes in the condenser. C_6F_{14} is used as a transfer fluid mainly for its chemical similarity to C_3F_8;
4. **Thermosiphon primary circuit**: condensing C_3F_8 at surface to produce a liquid column from surface to cavern (exit pressure → hydrostatic column of fluid). Liquid evaporates in the unchanged on-detector cooling channels and returns to surface as vapour by differential pressure. System must supply high pressure liquid to on-detector components, while guaranteeing the required evaporation pressure.





Compressor driven evaporative system (A-C)

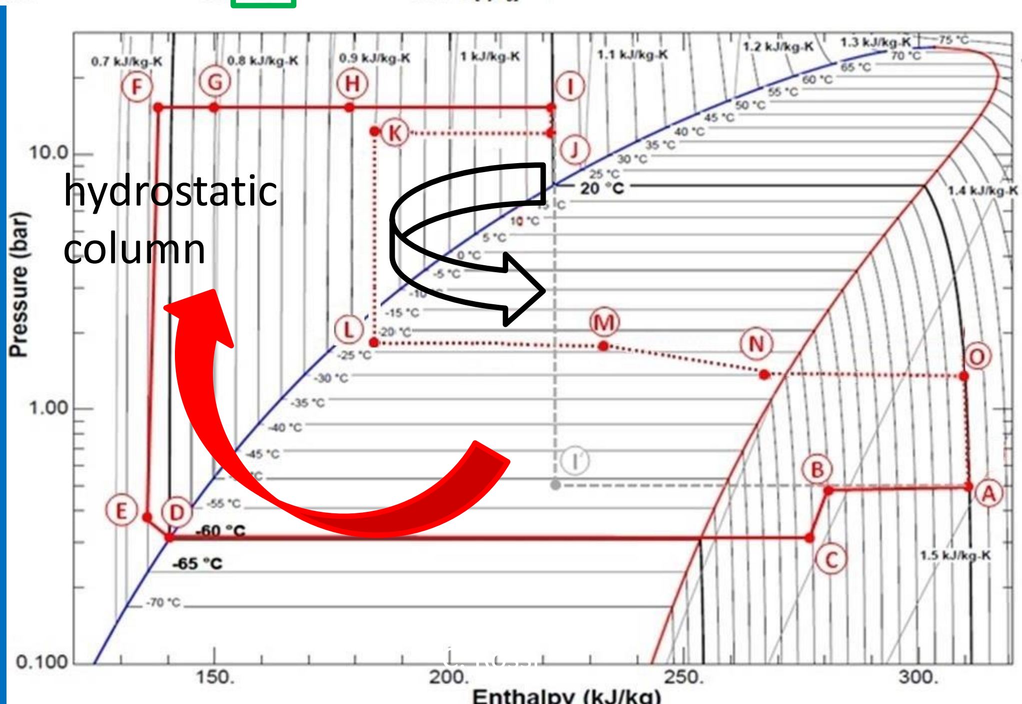
Internal circuit (D1 – F')

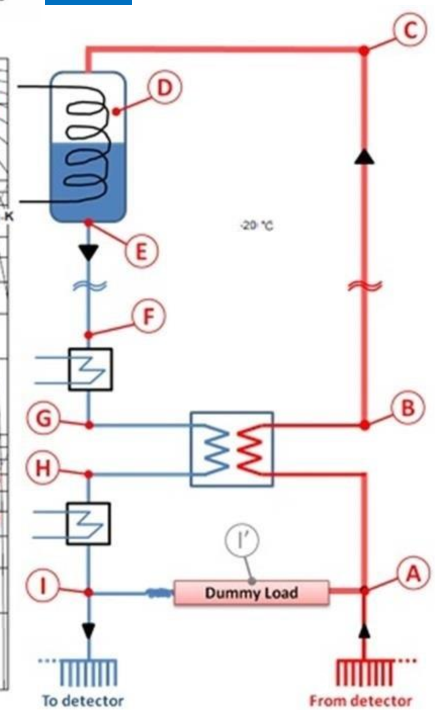
EDMS 1083852

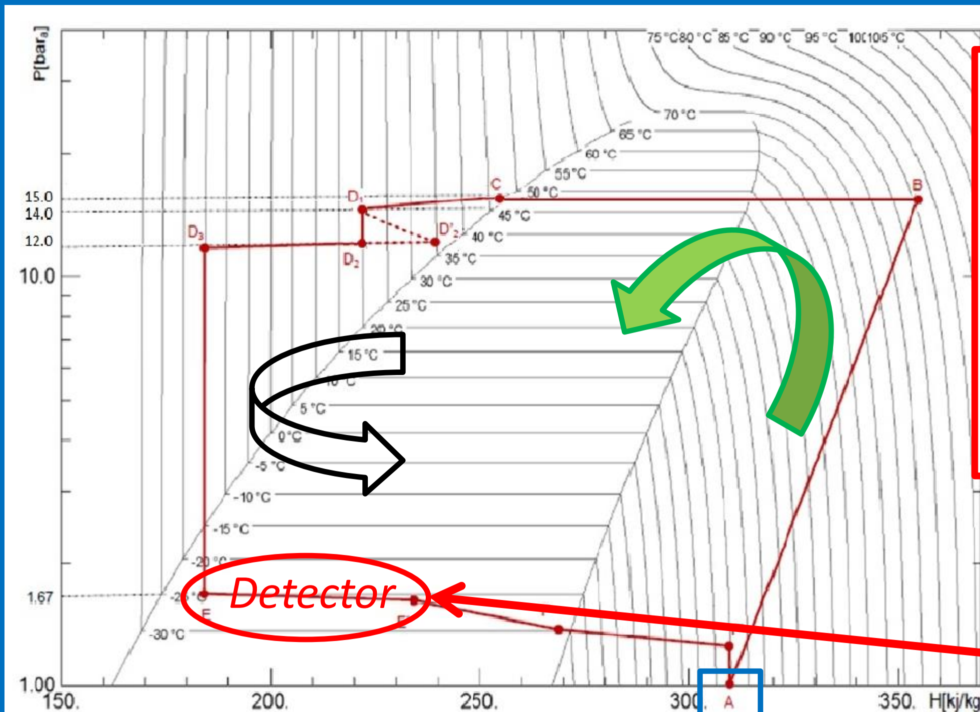
Thermosiphon circuit (A-I)

Internal circuit (J – O)

Evap	TS
D1	I
D2	J
D3	K
E	L
E'	M
F	N
F'	O







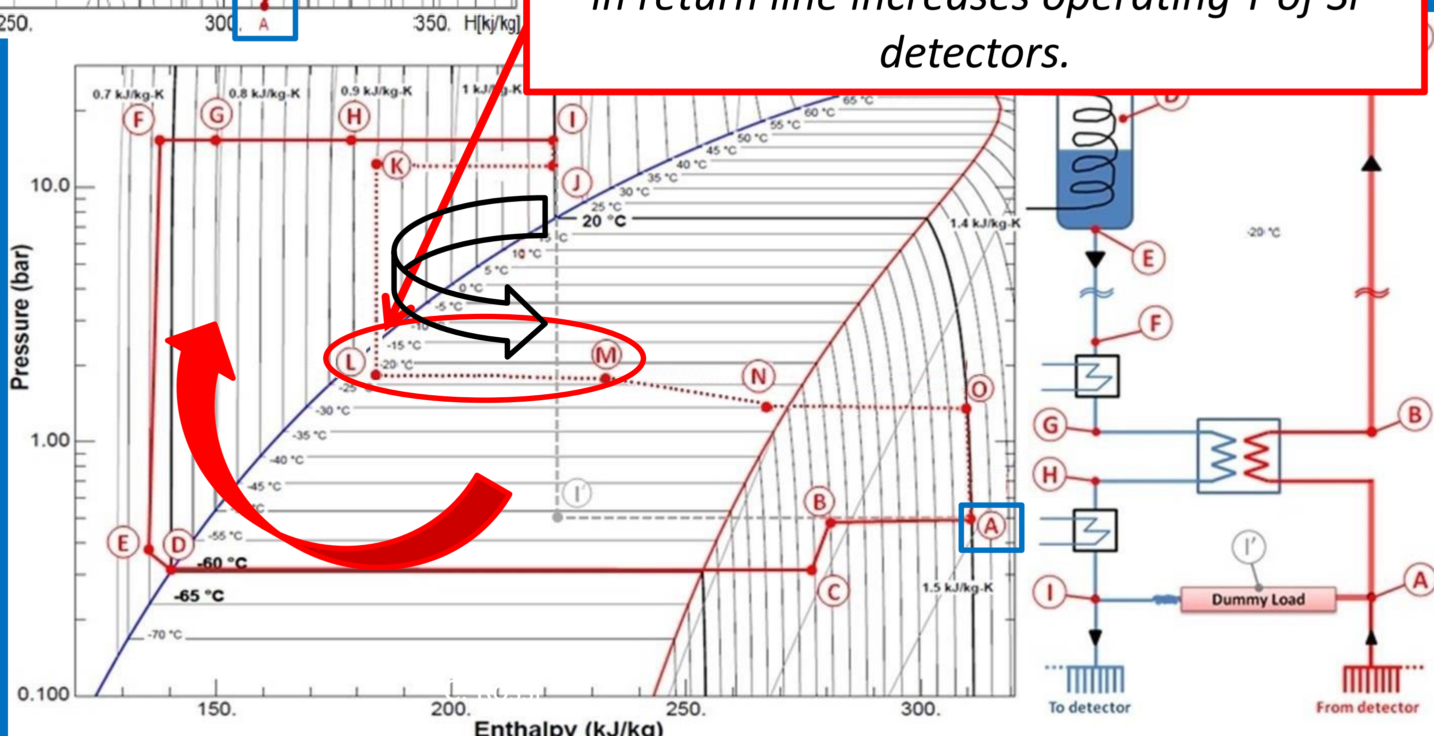
Compressors reliability 1st reason for TS
→but also higher margin on required p/T@detector.
Baseline pressures:
Compressor-driven→ = 1 bar$_{abs}$;
TS→ = 500 mbar$_{abs}$
→ Required evaporation p easier to achieve

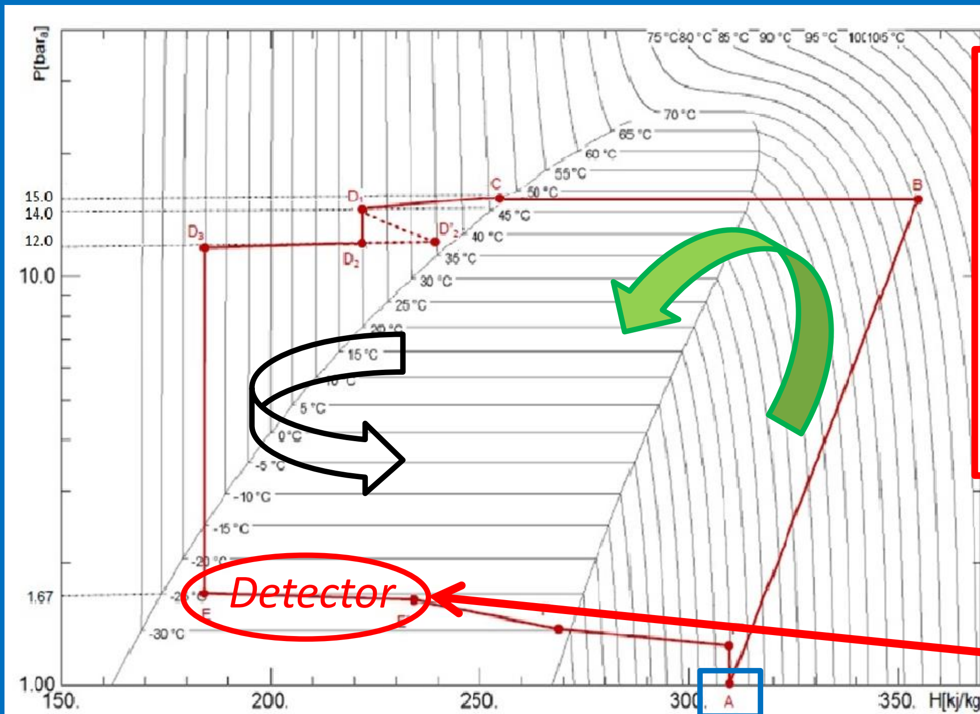
Target pressure specified at end of on-detector cooling channels → Pressure drop in return line increases operating T of Si detectors.

Thermosiphon circuit (A-I)

Internal circuit (J – O)

Evap	TS
D1	I
D2	J
D3	K
E	L
E'	M
F	N
F'	O





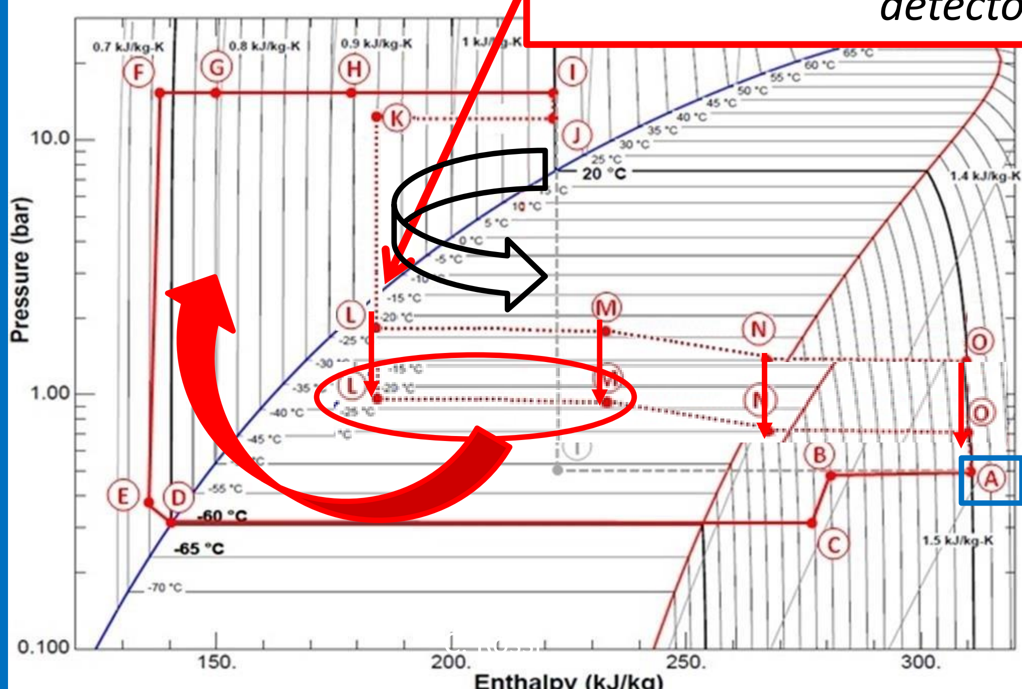
Compressors reliability 1st reason for TS
→but also higher margin on required p/T@detector.
Baseline pressures:
Compressor-driven→ = 1 bar_{abs} ;
TS→ = 500 $mbar_{abs}$
→ **Required evaporation p easier to achieve**

Target pressure specified at end of on-detector cooling channels → Pressure drop in return line increases operating T of Si detectors.

Thermosiphon circuit (A-I)

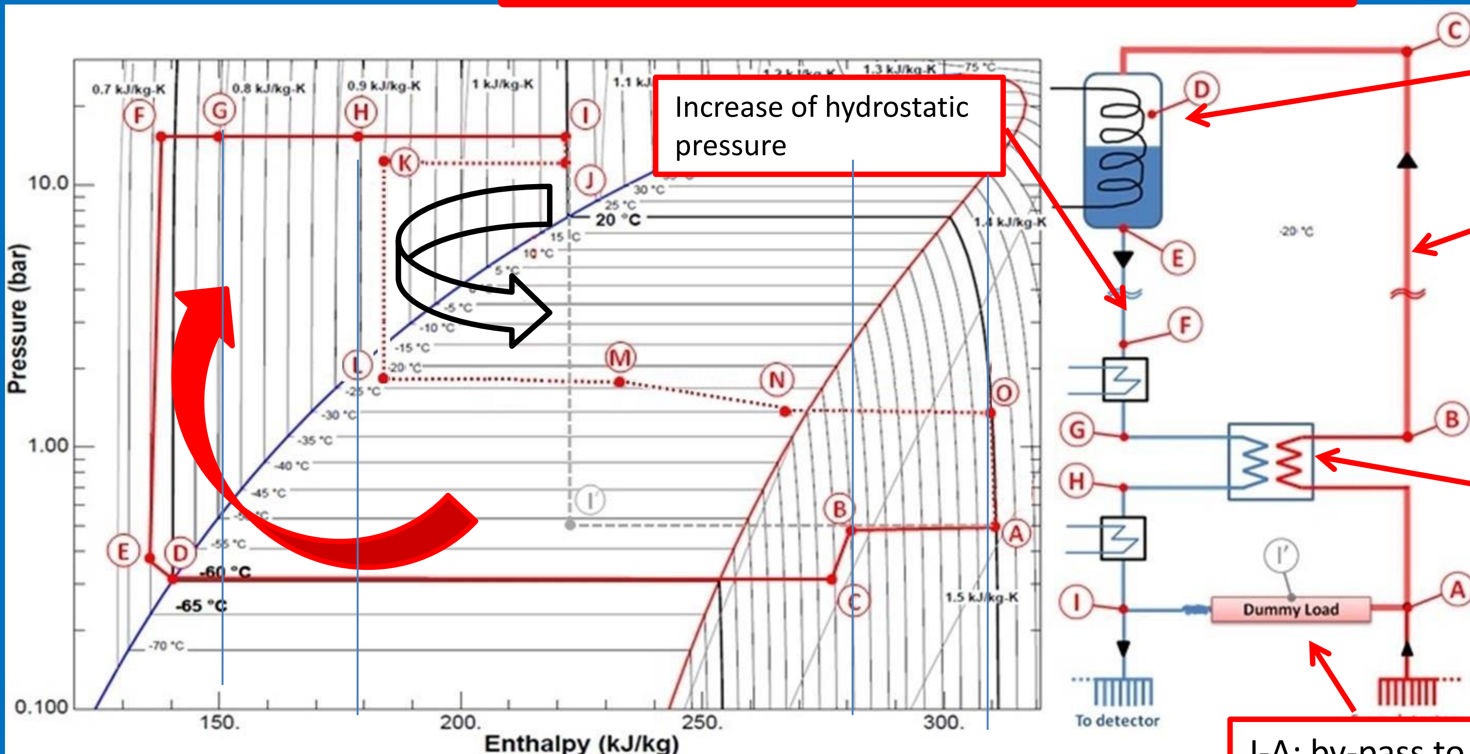
Internal circuit (J – O)

Evap	TS
D1	I
D2	J
D3	K
E	L
E'	M
F	N
F'	O



In TS baselime pressure (A) is lower → by regulating BPR we can lower O and therefore have a lower p/T @detector

Description of the TS



condenser and subcooling. storage when system is stopped.

pressure drop along vapour return line (vapour column weight and frictional pressure drop)

counter flow heat exchanger

I-A: by-pass to rapidly ramp down at start-up. Stable performance even when SCT and Pixel trackers are off (minimum thermal load).

Thermodynamic cycle of the thermosiphon circuit and corresponding schematic. Thermosiphon circuit (A-I). Beyond these points C_3F_8 enters the internal cooling circuits. Fluid exits the detectors at point M point (E' in the previous compressor evaporative cycle)

Operating point	Pressure [bar_{abs}]	Temperature [°C]	Physical State
A	0.5	20	Superheated vapour
B	0.495	-20	Superheated vapour
C	0.309	-25	Superheated vapour
D	0.309	-60	Saturated liquid
E	0.4	-65	Sub-cooled liquid
F	16.1	-62	Sub-cooled liquid
G	16.1	-51	Sub-cooled liquid
H	16	-20	Sub-cooled liquid
I	16	20	Sub-cooled liquid
I'	0.5	-51	Two-phase x=0.6

Designed parameter EDMS 1083852

Description of the TS


TS Condenser: 12m above ground level


Brine and Chiller circuit: Ground level


Connection to existing system: 92m underground


Water circuit: Ground level

Tests with dummy load

Several preliminary tests were done running the TS on the 60kW dummy load from February 2016.

Aim:

- Tune set points of the system
- Improve reliability and performance
- Define an automatic procedure for the TS start and pull down
- Verify TS stability and possibility of swap between the two systems

Tests:

Start-up of the system
run at warm conditions
run at normal conditions

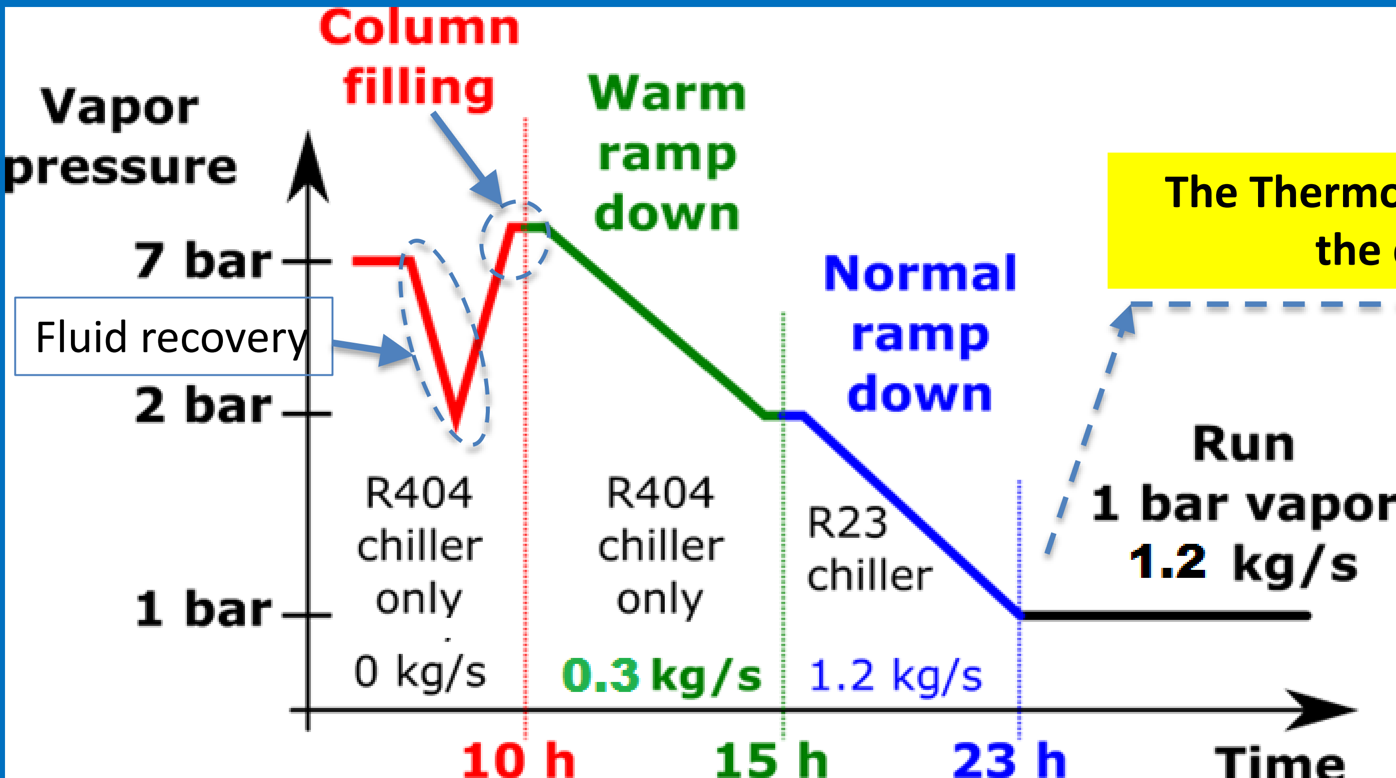
Warm conditions:
Temperature in condenser -20 °C
Vapour pressure 2 bar_a
C_3F_8 mass flow 0.3 kg/s

Normal conditions:
Temperature in condenser -40 °C
Vapour pressure 1.3 bar_a
C_3F_8 mass flow 1.2 kg/s

Tests with dummy load

Start-up of the system:

1. Circulation starts after liquid column is filled at condenser temp = -15 °C
2. Slow temperature (0.2°C/min) ramp-down to warm mode
3. Warm mode circulation through dummy load (only R404a chiller)
4. Slow temperature (0.2°C/min) ramp-down to normal mode
5. Set points are achieved



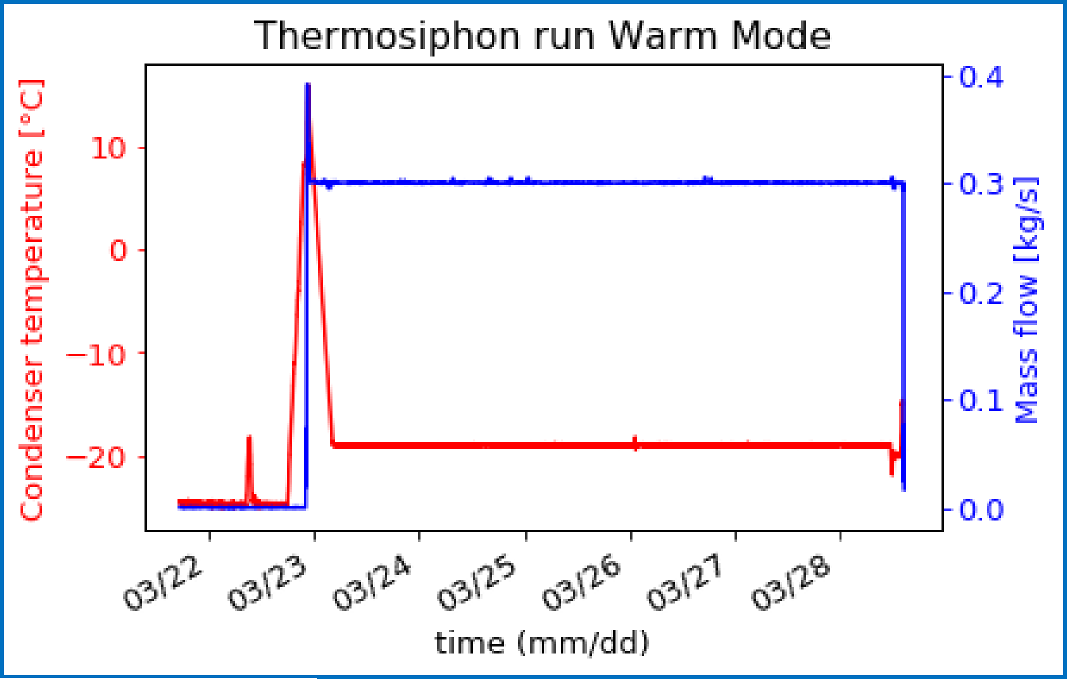
The Thermosiphon can cool the detector

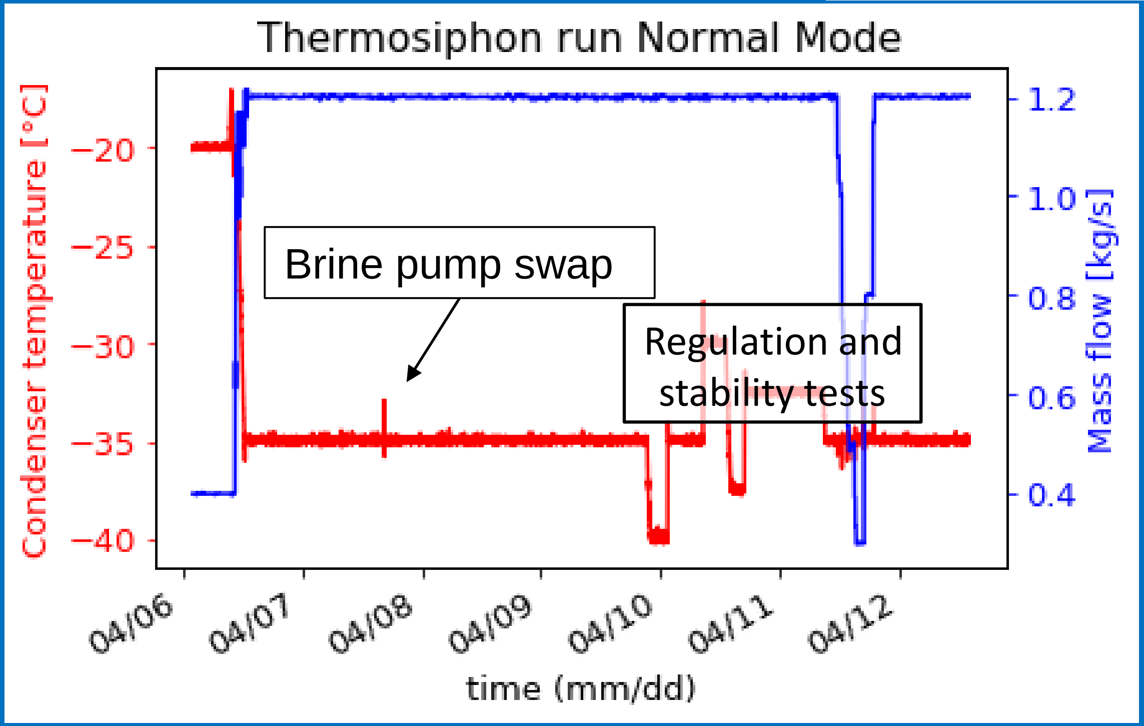
From Martin Doubek

On dummy load - Connection valves closed

Run at warm and normal mode:

The stability of the system is verified





EDMS 1791134

Tests with dummy load

Results:

- It takes approx. 24 hours to start the Thermosiphon from stand still (empty liquid pipes)
- The thermosiphon can match the parameters of the current compressor plant (C_3F_8 mass flow 1.2 kg/s, vapor pressure ~1.3 bar_a and liquid pressure ~15 bar_a at compressor room level)
- Up to 20-day long run have been carried out, proving that stable circulation and pressure can be maintained through the dummy load
- During commissioning it was also proven that TS can run as low as 0.4 bar_a in the condenser at full mass flow of 1.2 kg/s

Satisfying results of the dummy load tests
(stable operation, comparative cooling performance of compressor system)

↓

Swap tests

During the swap tests (18.04.17 – 24.04.17) the external part of the evaporative cooling system (7 // compressors) was replaced by the thermosiphon

↓

Thermosiphon was the primary cooling system for ID

↓

Several swap tests between the two systems

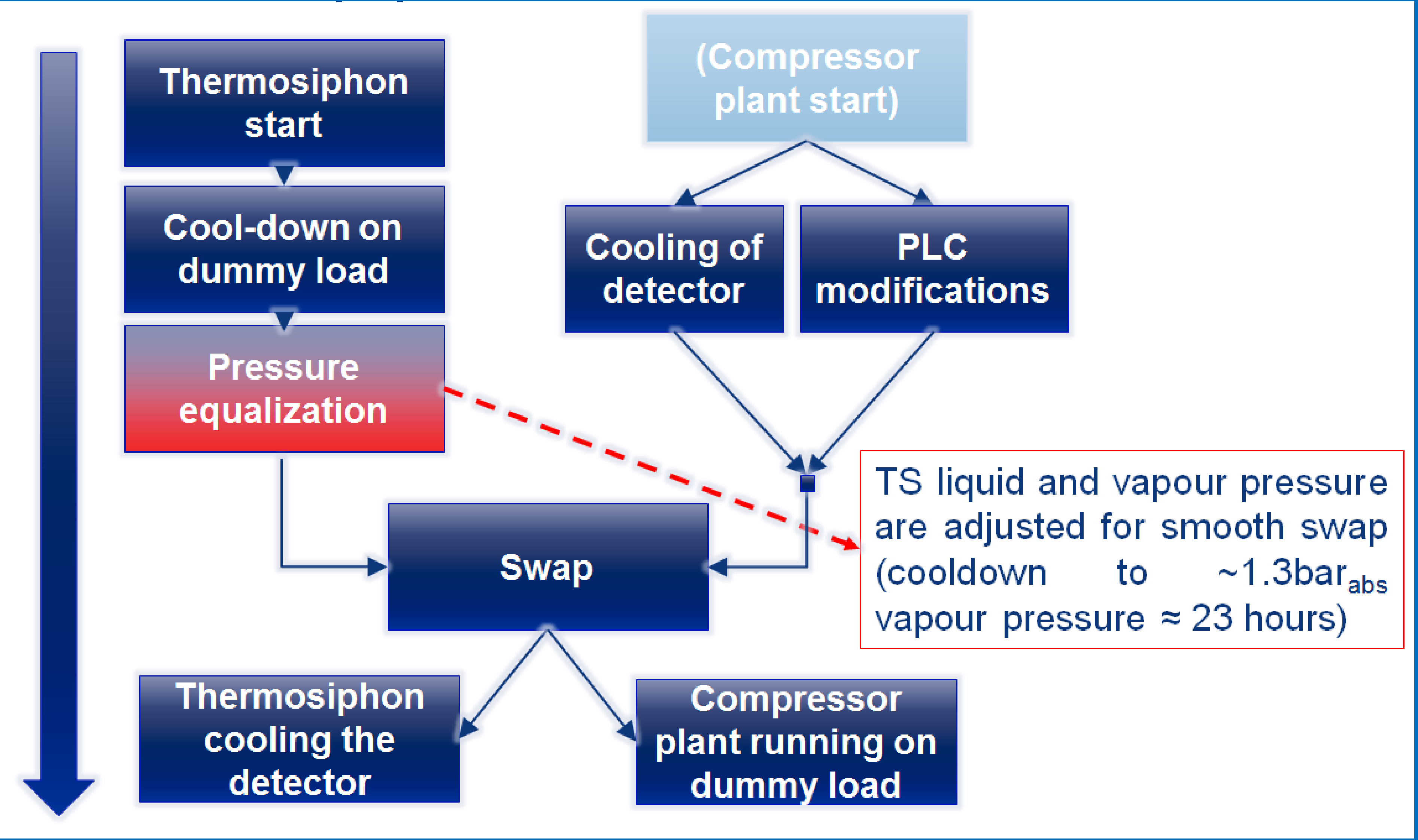
Swap tests

Aim:

- Validate swap between compressor plant and Thermosiphon (back and forth)
- Optimize some Thermosiphon set points for the detector cooling
- Evaluate various pressures (delivered liquid…) and pressure drops (vapor return, liquid line…)
- Maintain stable cooling of the detector for few days.

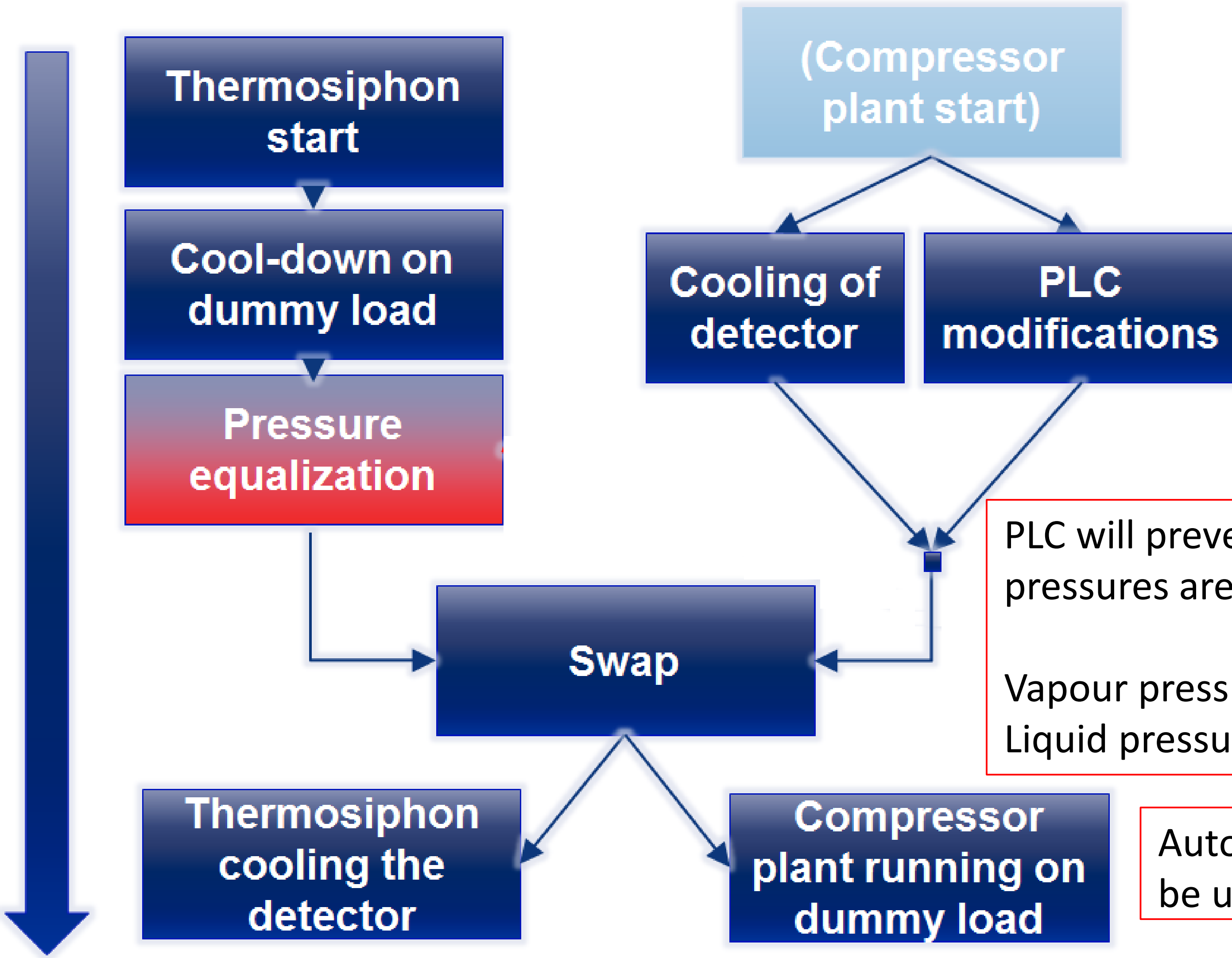
Swap tests

Swap procedure flow chart



Swap tests

Swap procedure flow chart



The valves between the two systems are controlled by compressor plant PLC

Opening/Closing done by PLC **on request** when pressure conditions are met.

PLC will prevent the swap when the pressures are not within limits.

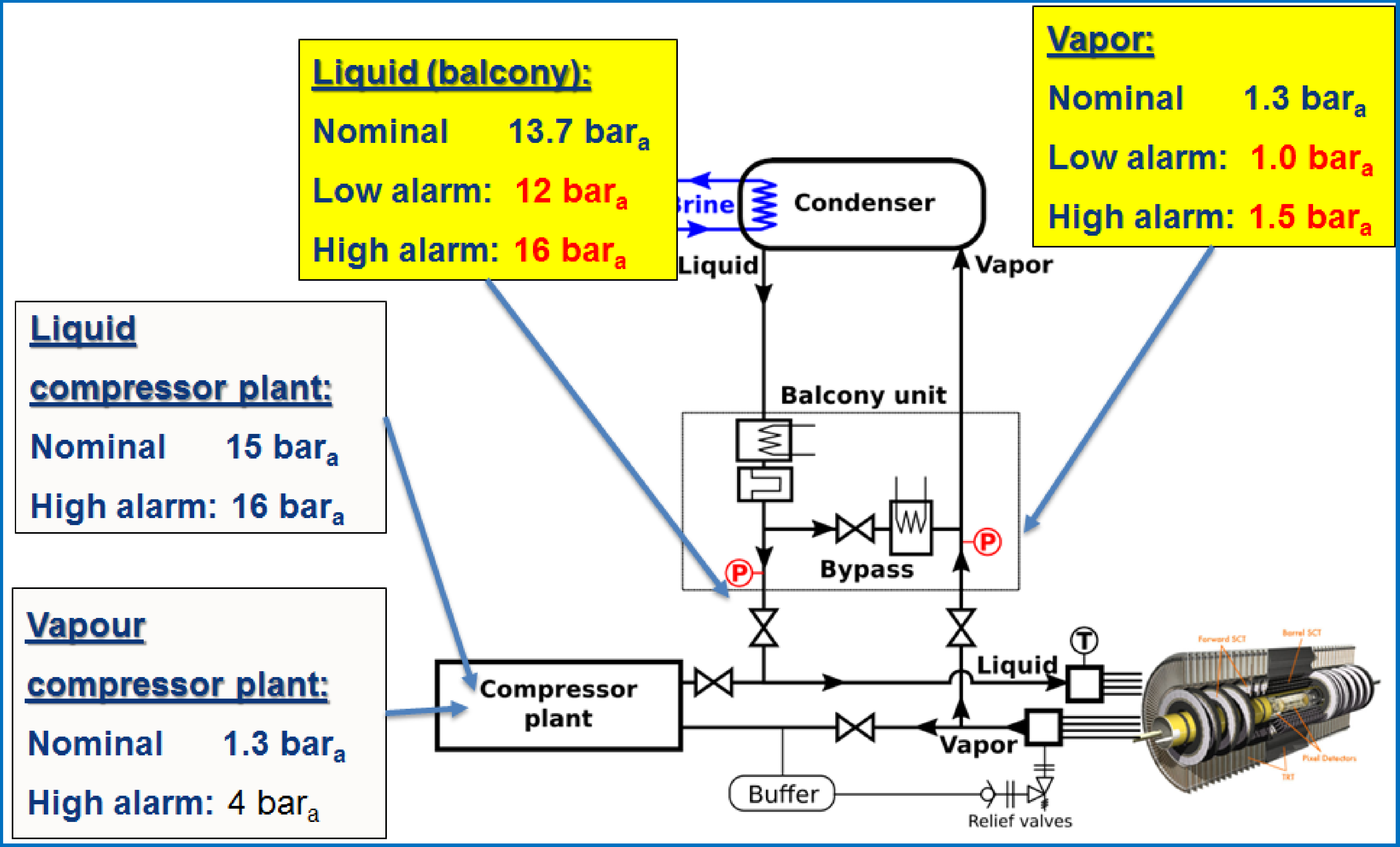
Vapour pressure limits = 1 ÷1.5 bar_a
Liquid pressure limits = 12 ÷16 bar_a

Automatic swap back can be used in case of alarms

Swap tests

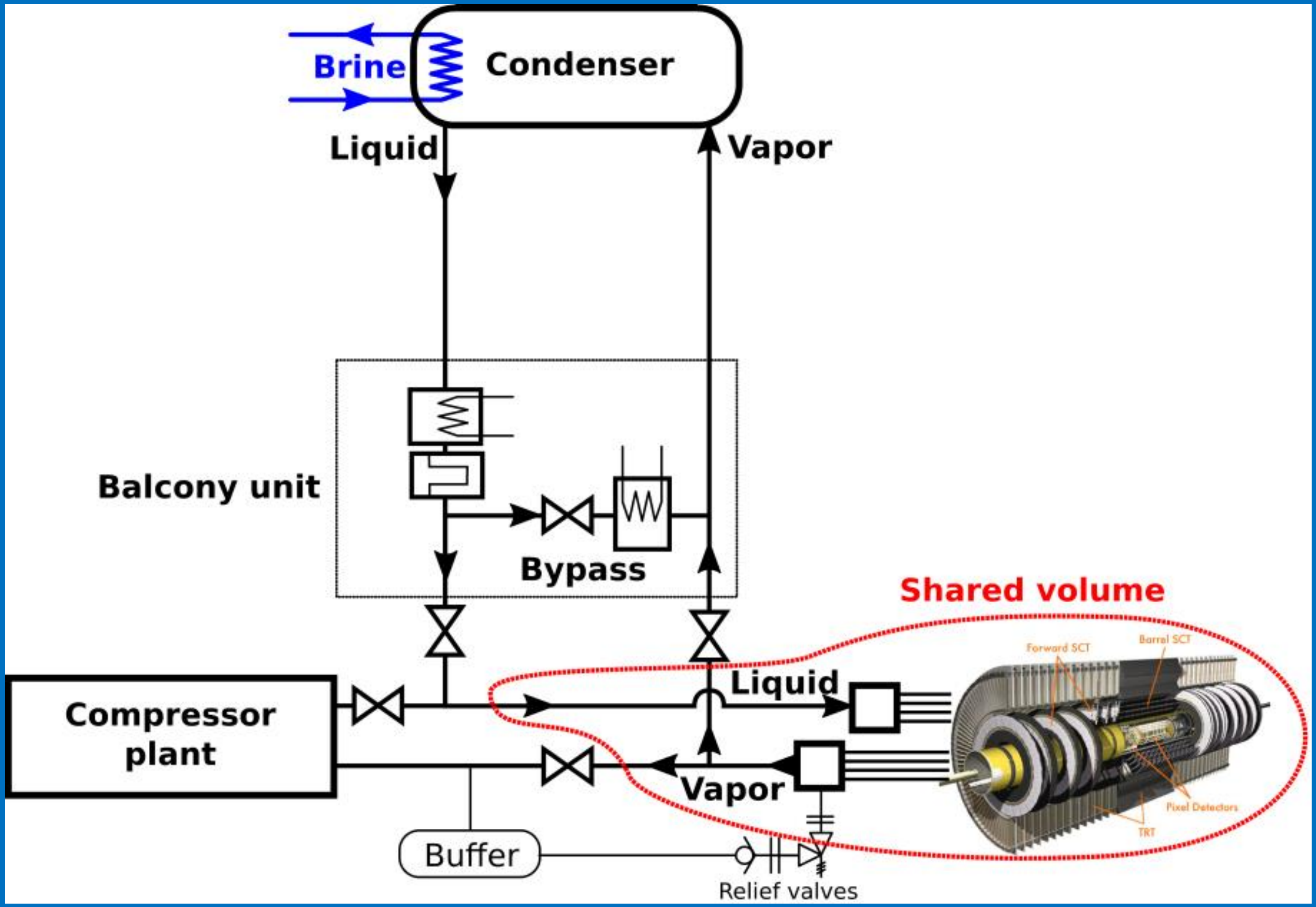
Alarms:

Dedicated pressure alarms are installed in the balcony unit and connected to the compressor plant PLC which controls all the valves involved in the swap.



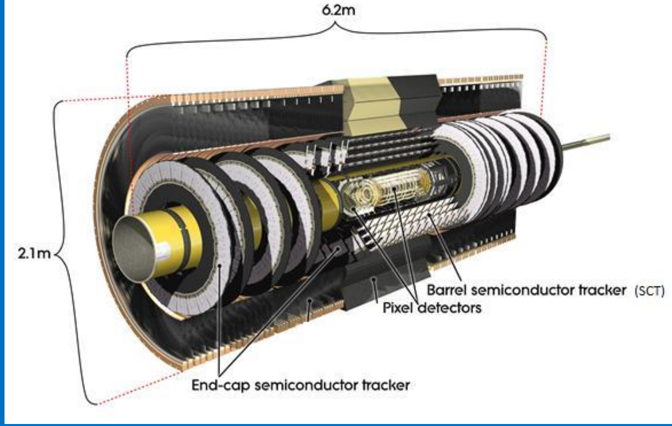
Swap tests

Buffer:



The 8 m^3 vapour expansion tank will be permanently connected to compressor plant only, ready at 1.3 bar_a to take care of the vapour in case of problems. (TS vapour volume = 7 m^3)

Swap tests



Tests:

Cooling steps:

1)	"Dry" swaps	- all detector loops closed	0.00 kg/s
2)	"33%" swaps	- SCT END-CAPS only	0.34 kg/s
3)	"70%" swaps	- SCT (END-CAPS + BARREL)	0.74 kg/s
4)	"100%" swaps	- SCT + PIXEL	1.03 kg/s

Mass flow increased while involving different cooling loops.

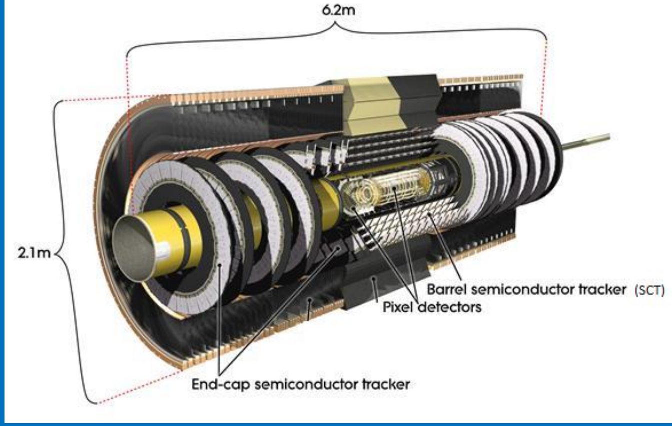
Nominal pressure kept in all the tests

Normal conditions:
Compressor room level:
Vapour pressure 1.3 bar_a
Liquid pressure 13.7 – 15.7 bar_a
Liquid temperature 20 °C

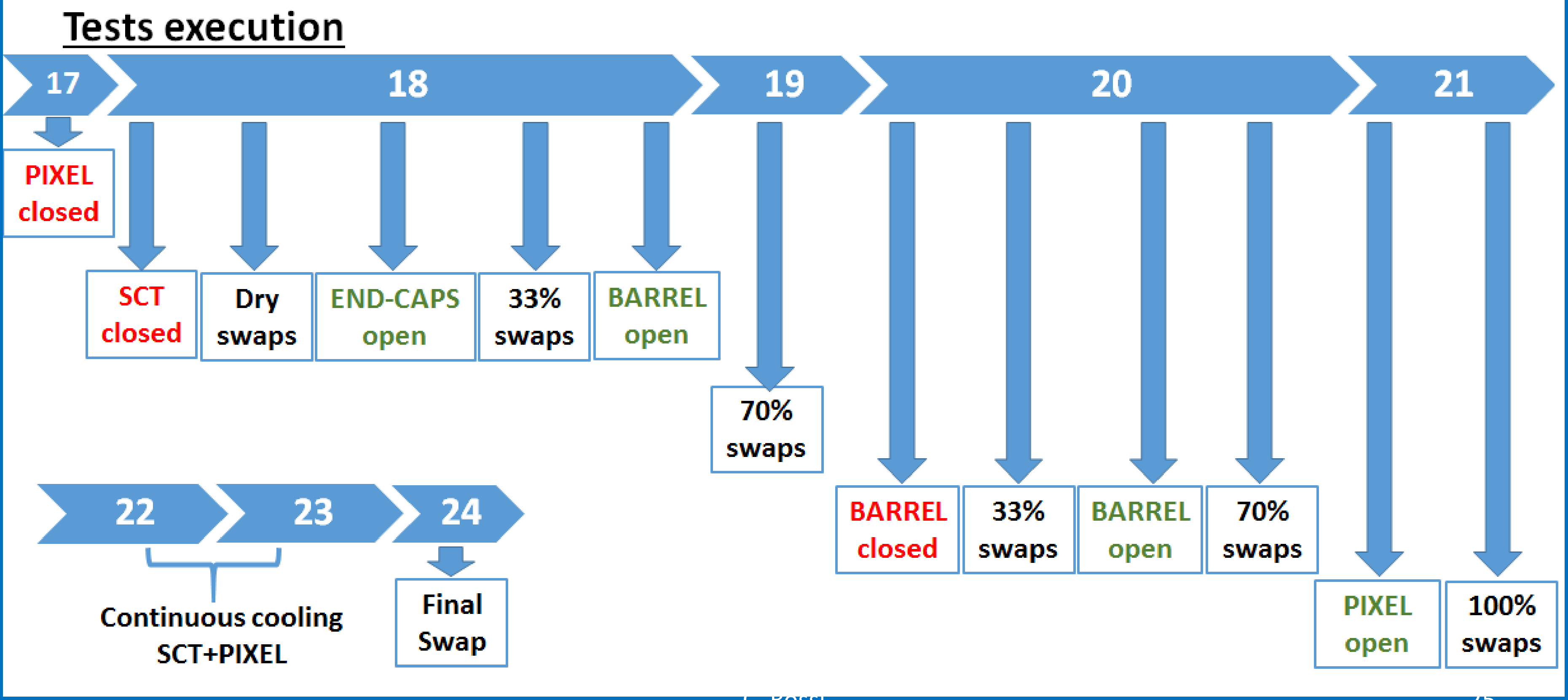
C_3F_8 mass flow 1.15 kg/s
Condenser Temperature ≈ -40 °C

Swap tests

DRY	3 swaps
SCT END CAPS	3 swaps
SCT (EC + Barrel)	6 swaps
SCT+ PIXEL	3 swaps



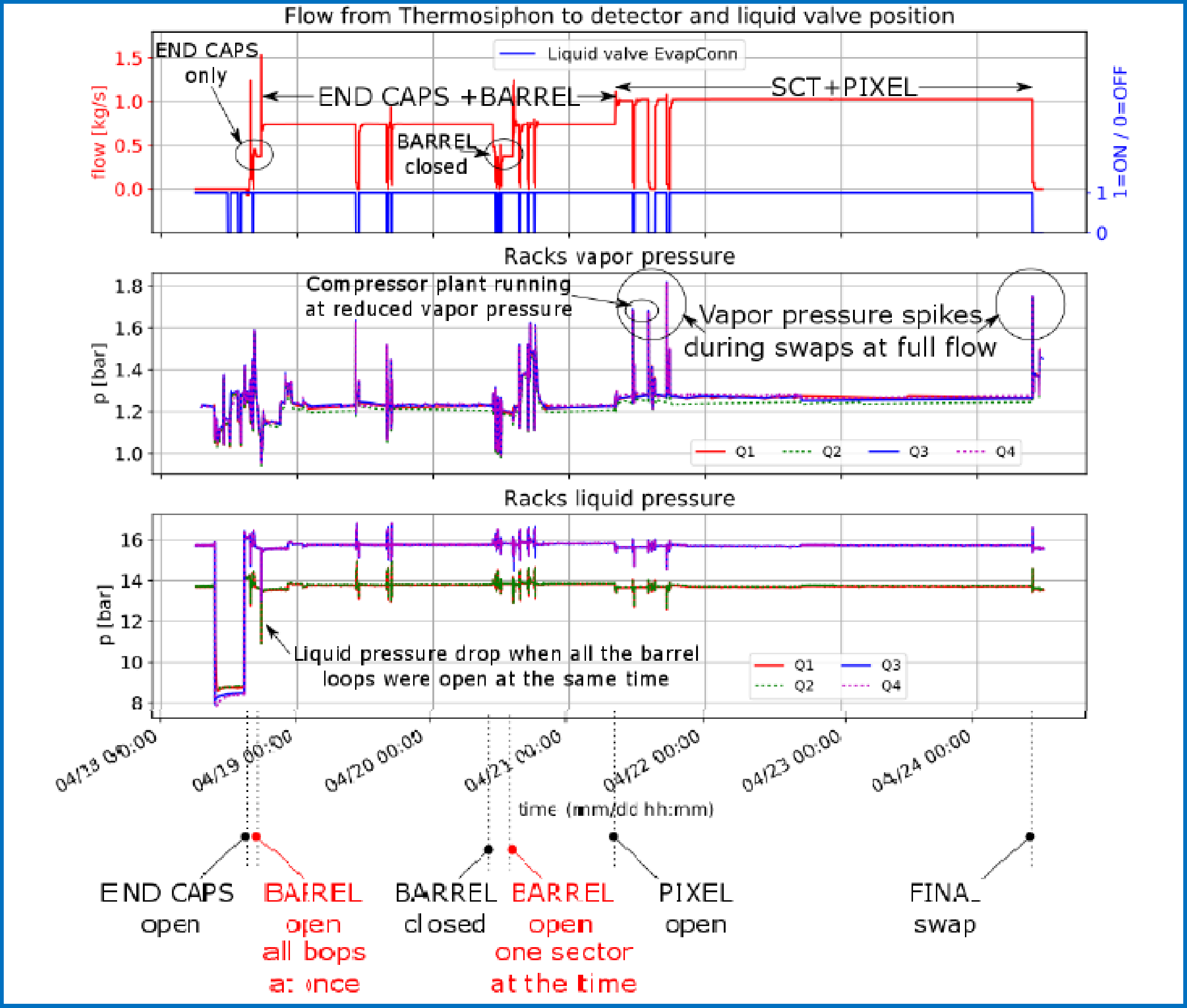
From EDMS N. 1801926



Swap tests

Results:

✓ Liquid and vapour pressure measured at balcony level were stable



Swap tests

Results:

- ✓ Vapour and liquid pressure in the distribution rack delivered by TS very close to the nominal pressure of the compressor plant

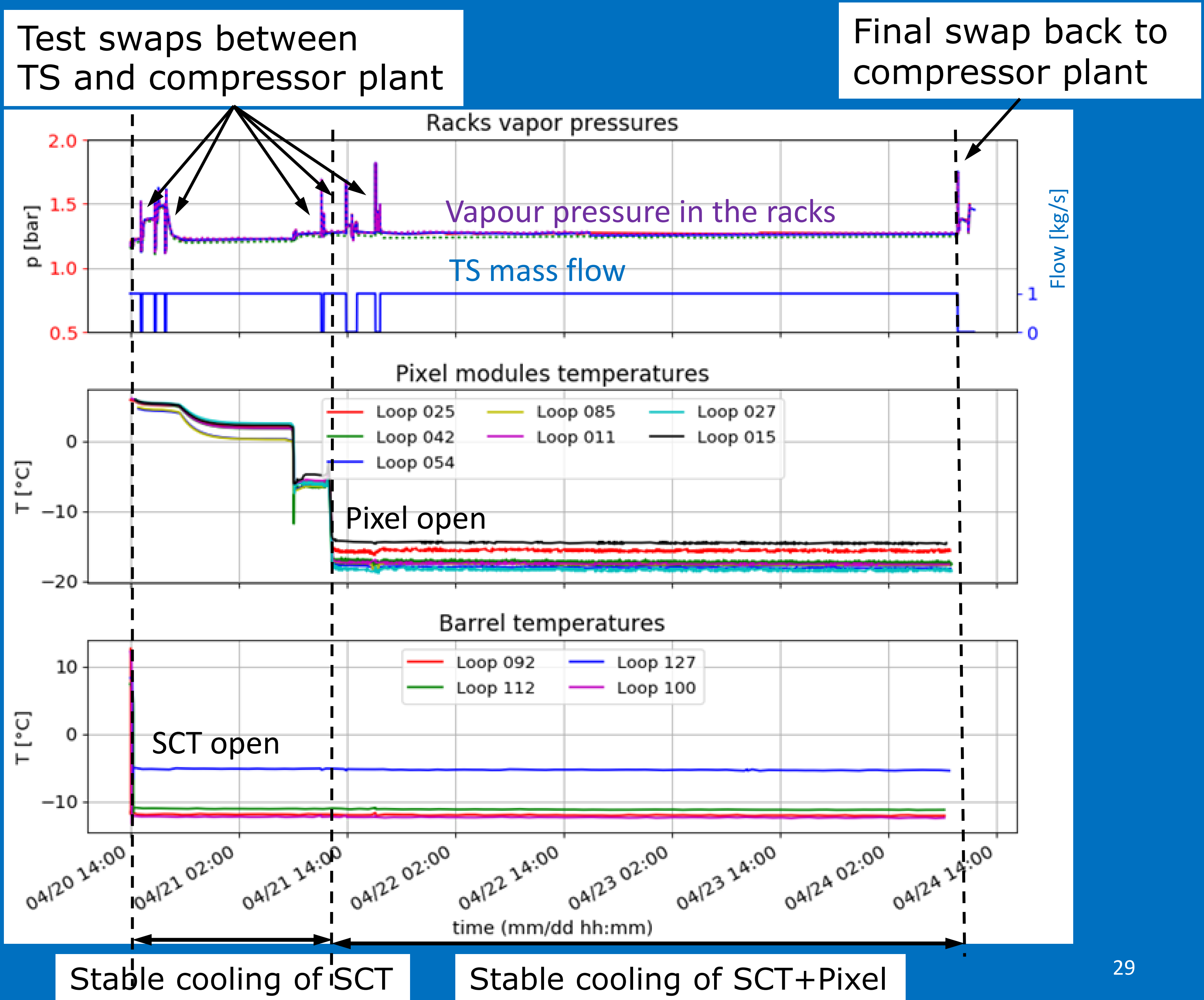
Table 4 - Distribution racks pressures

	Q1	Q2	Q3	Q4
Compressor plant (SCT+PIXEL)				
Liquid pressures [bar_a]	13.55	13.57	15.56	15.56
Vapour pressures [bar_a]	1.44	1.43	1.44	1.44
Thermosiphon (SCT+PIXEL)				
Liquid pressures [bar_a]	13.72	13.75	15.71	15.71
Vapour pressures [bar_a]	1.26	1.25	1.26	1.28

Swap tests

Results:

- ✓ Detector module temperature remained stable during the swaps (max fluctuation of temperature approximately 2-3 °C with the lowest back pressure settings



Test swaps between TS and compressor plant
Final swap back to compressor plant
Racks vapor pressures
Vapour pressure in the racks
TS mass flow
p [bar]
Flow [kg/s]
Pixel modules temperatures
Loop 025
Loop 085
Loop 027
Loop 042
Loop 011
Loop 015
Loop 054
Pixel open
T [°C]
Barrel temperatures
Loop 092
Loop 127
Loop 112
Loop 100
SCT open
04/20 14:00
04/21 02:00
04/21 14:00
04/22 02:00
04/22 14:00
04/23 02:00
04/23 14:00
04/24 02:00
04/24 14:00
time (mm/dd hh:mm)
Stable cooling of SCT
Stable cooling of SCT+Pixel

Swap tests

Results:

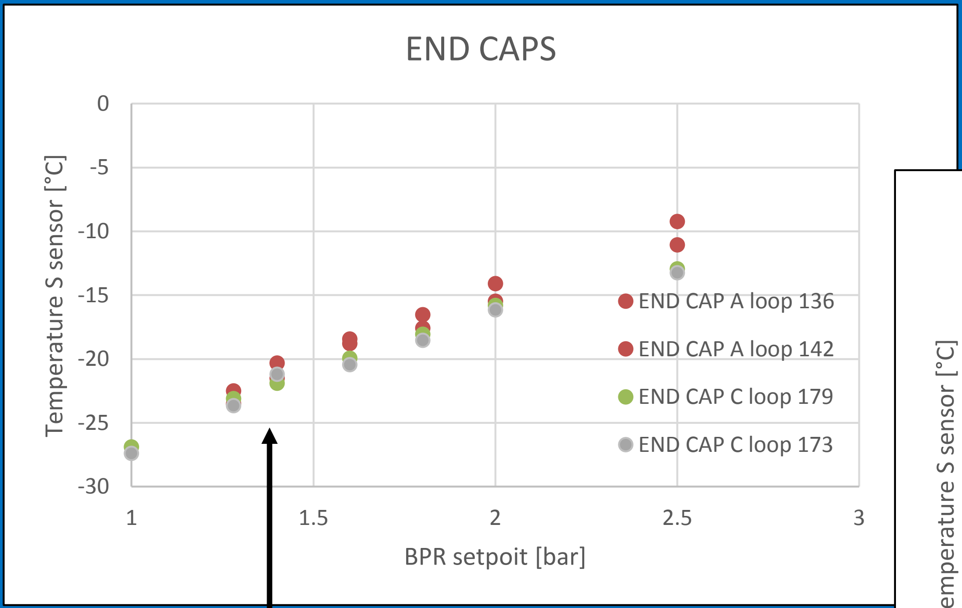
- ✓ Liquid and vapour pressure measured at the balcony level were stable
- ✓ Vapour and liquid pressure in the distribution rack delivered by TS very close to nominal pressure of compressor plant
- ✓ Detector module temperature remained stable during the swaps (max fluctuation of temperature approximately 2-3 °C)
- ✓ TS had been continuously cooling the Inner Detector
- ✓ The Inner Detector temperature was stable

Conclusion and What’s next

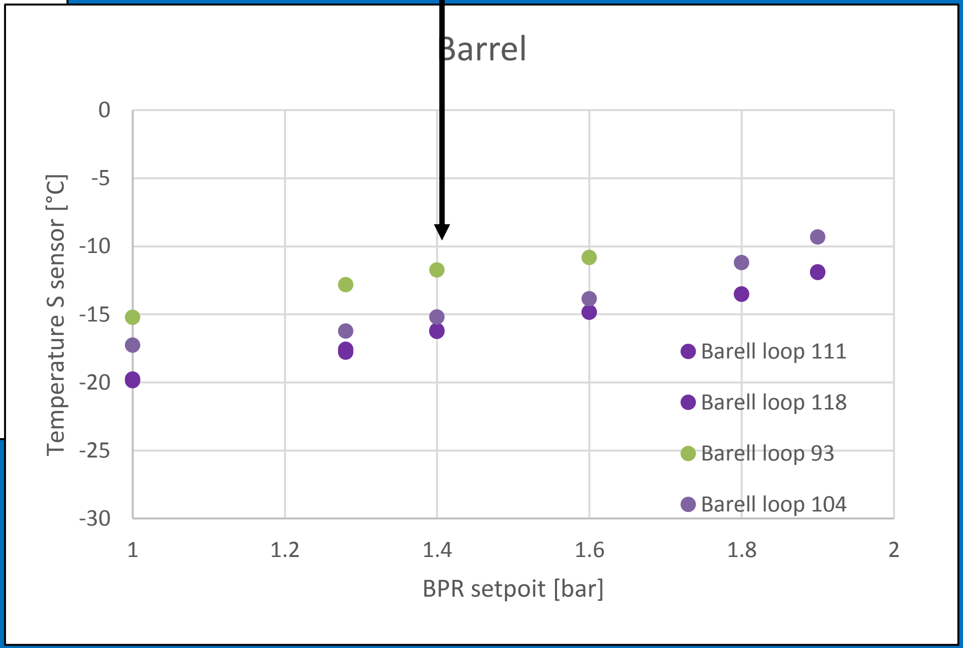
- Transient occurring during the swaps are safely within alarm limits → automatic swap can be implemented

- New condenser is approved and will be produce by the December 2017 → new more reliable design, subcooling power doubled to shorten the ramp down, levelmeter added

Latest TS runs (July 3 2017: exploiting thermosiphon « headroom » by further reducing pressure (in SCT endcap and barrel cooling circuits: preliminary)



Best achievable with compressors



Best achievable with compressors

BPR at 1 bar_a - 27 ^oC in SCT end-cap, -20 ^oC in SCT barrel

Present limitation is the minimal back pressure setting on the dome-loaded back pressure regulators: will need a sub-atmospheric dome pressure system to run lower with C_3F_8, but C_2F_6/ C_3F_8 blends would not require this

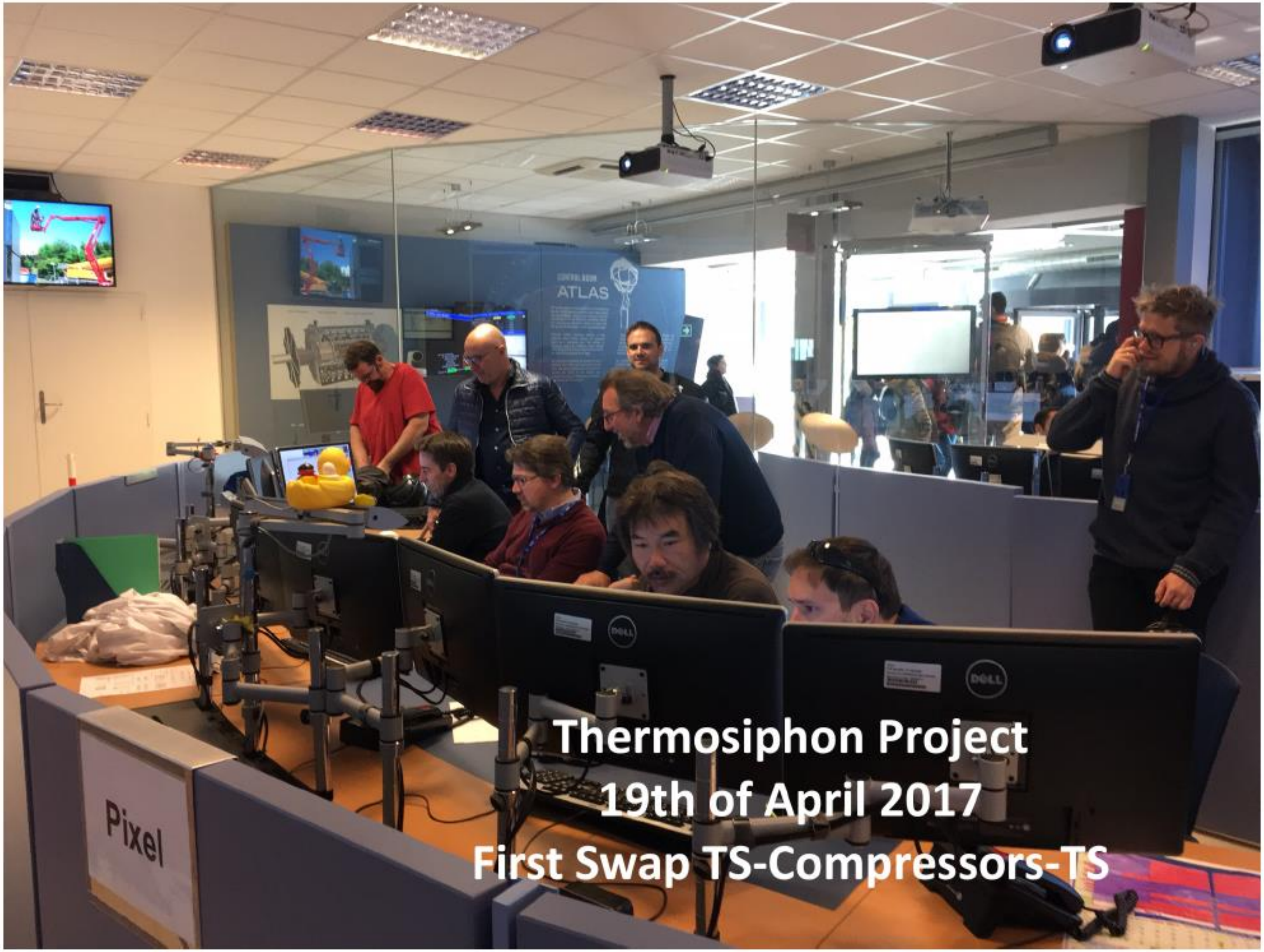
Conclusion and What's next

- 3/7/17 low vapour pressure tests (below 1 bar) to verify the minimum temperature reachable with TS. The first results highlight than we can gain 8 ^{o}C on Barrel modules and 13 ^{o}C on End-caps ones.

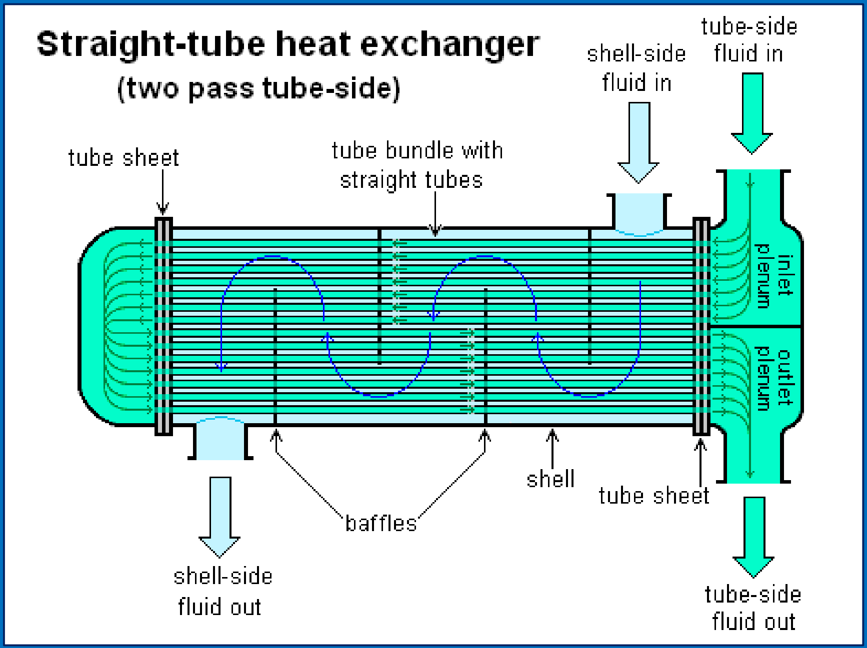
- C_3F_8 / C_2F_6 blends can offer further temperature reductions (~9^{o} C) in the present through-detector and on-detector services – see talk by G. Hallewell

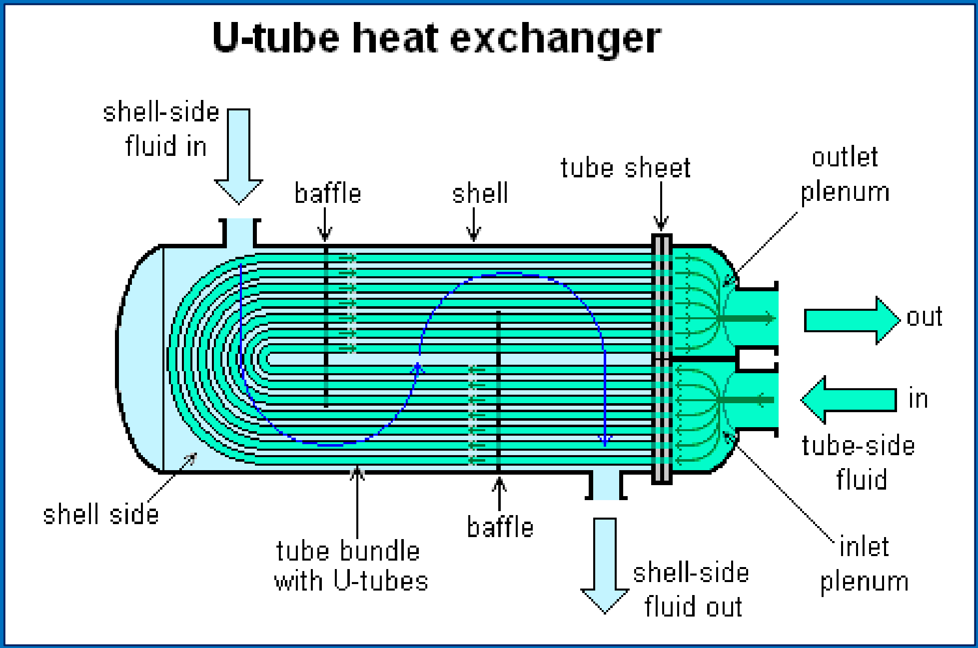
Thank you for you attention

cecilia.rossi@cern.ch


ATLAS
Pixel
Thermosiphon Project
19th of April 2017
First Swap TS-Compressors-TS

New condenser: modification of the mechanical design





- Reduction of number of welds (1110 -> 370)
- Reduction of thermal stress

Swap tests

<u>Results</u>:

✓ Liquid and vapour pressure measured at balcony level were stable