Overview of the CO_2 cooling DEMO obtained results and a prediction of future system behaviour

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Challenges & Goals

Challenges for Phase 2

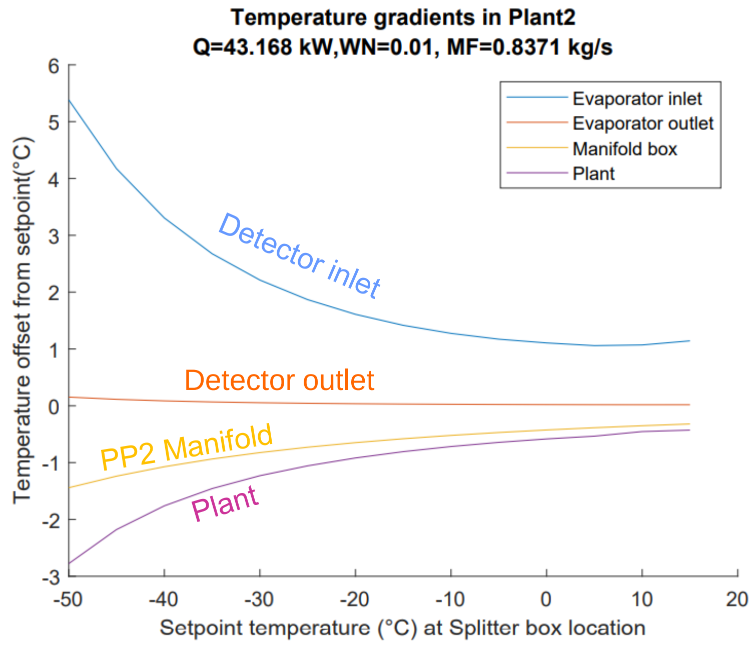
- **High cooling capacities required**
  - 300 kW for ATLAS → 7 plants, 6 accumulators
  - 550 kW for CMS → 9 plants, 8 accumulators
  - Redundancy important for continuous operation

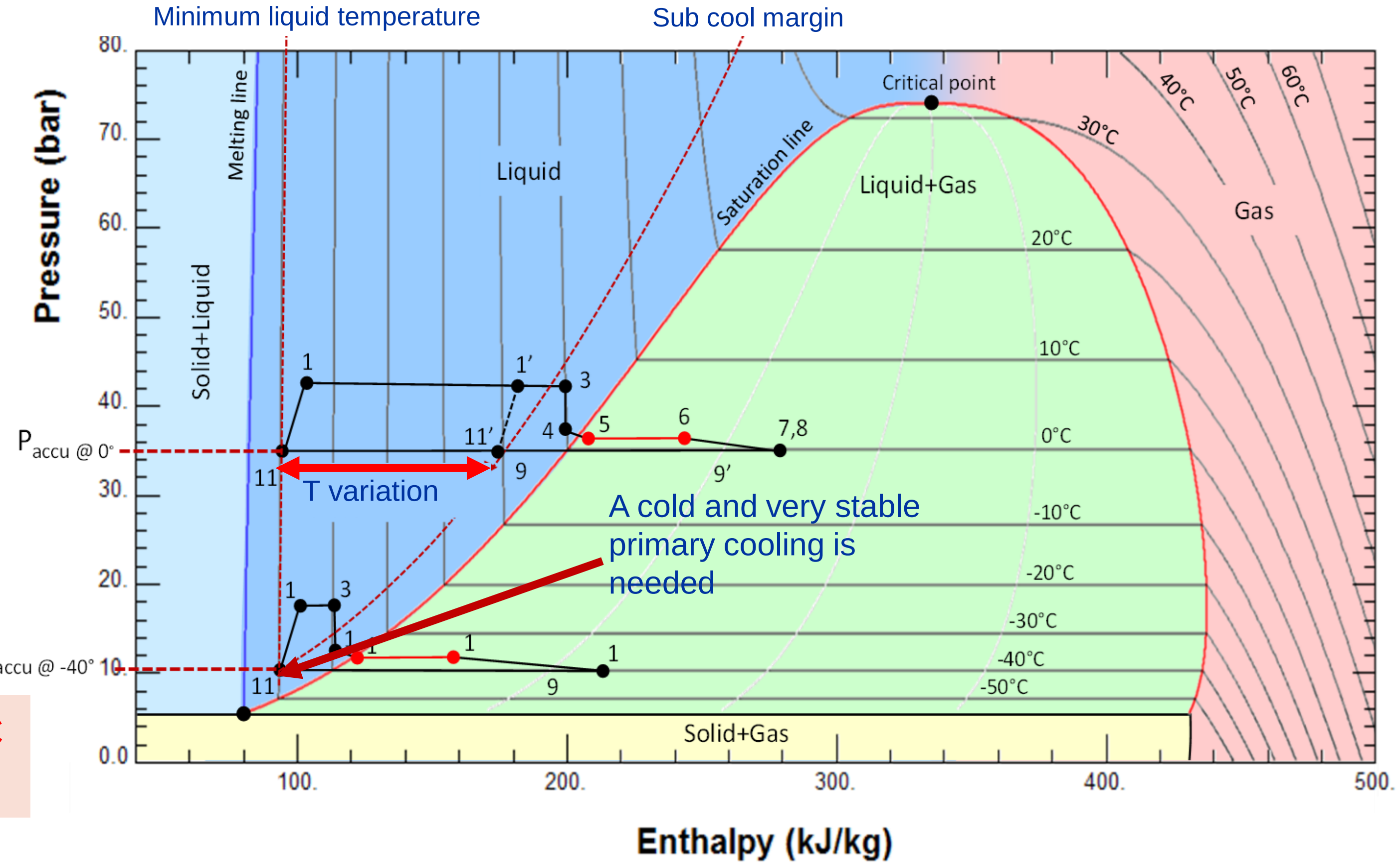
- **Operation temperatures down to -45°C**
  - -45°C close to CO_2 triple point
  - Increased gradients at lower temperatures
  - Stable primary cooling is required in limited range temperature zones

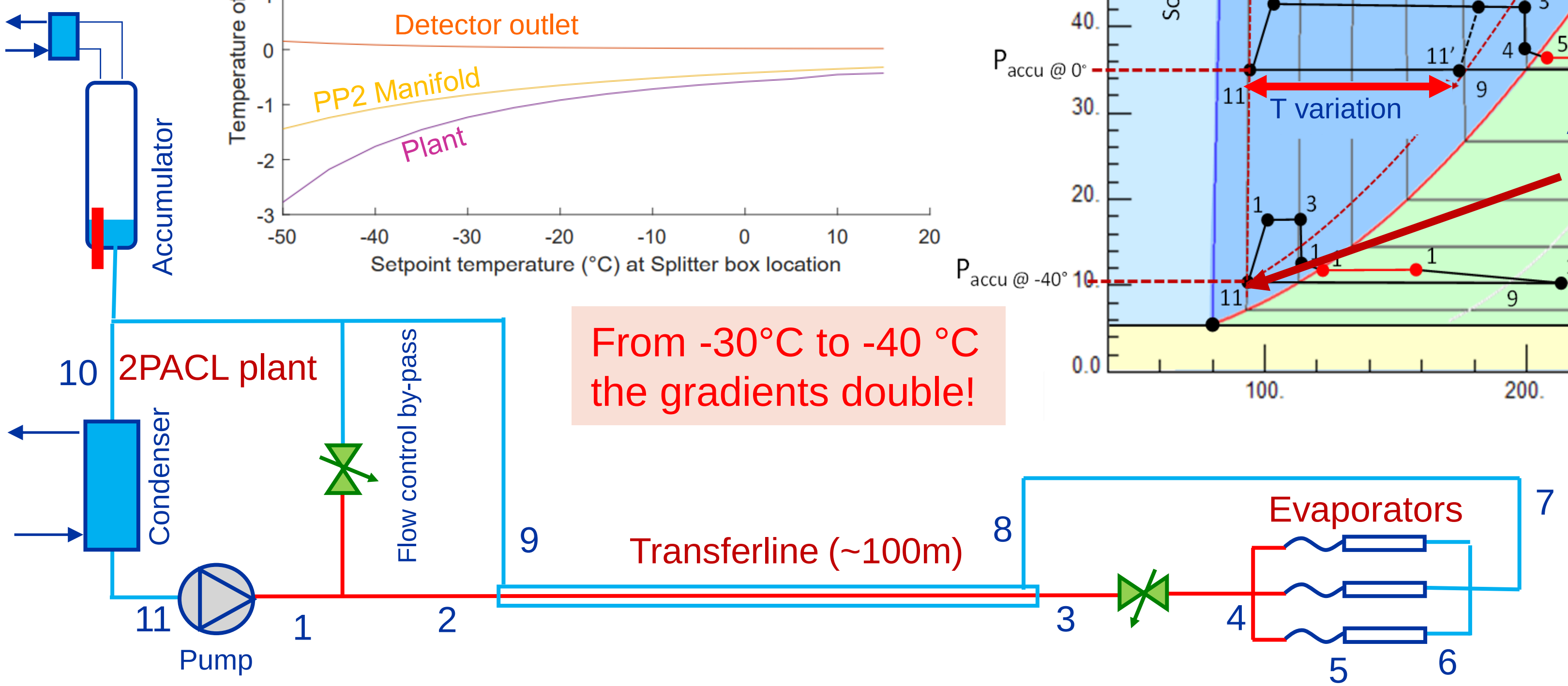
- **Need for surface facilities**
  - Smaller accumulators in cavern, therefore surface storage of CO2
  - Primary cooling system on surface, therefore large transferlines to service cavern

- **Energy efficiency considerations**
  - Improvement of energy efficiency with scaled up systems

The cold challenge



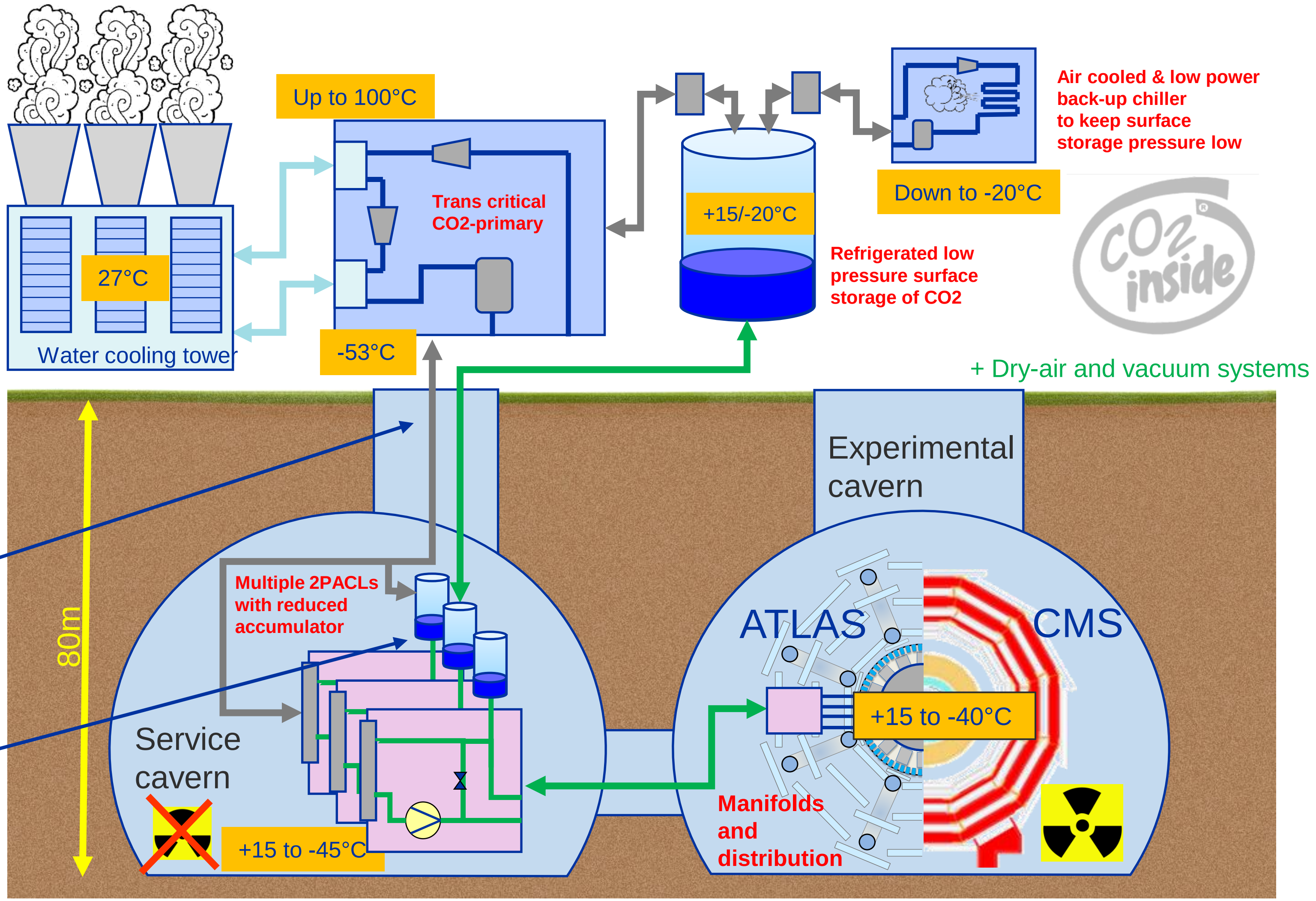




From -30°C to -40 °C the gradients double!

The surface challenge

- 2PACL cooling plants located in USA-15 / USC-55 underground
- Detector evaporator loops are connected via manifolds and concentric transfer lines to the 2PACL plants
- The 2PACL plants are cooled by the primary R744, which is located on the surface
- The primary R744 plants are cooled by water from the towers and air cooling
- Surface storage of CO2 to control the charges of the underground 2PACL plants

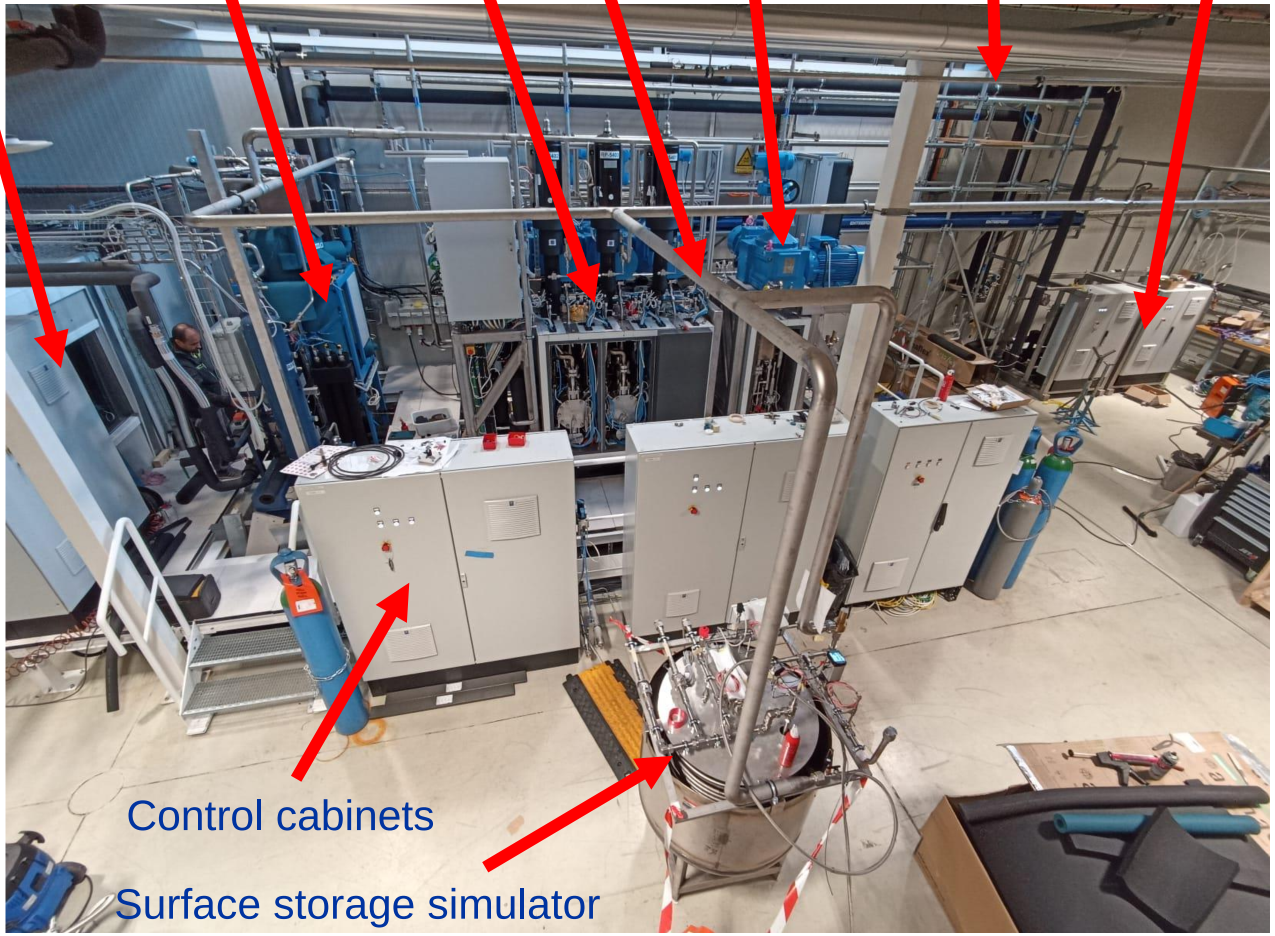


- **Uninsulated transfer lines**
  - Requires warm liquid supply and warm return gas to cavern to avoid condensation
- **Reduced accumulator sizes**
  - Good interaction required between cavern plants and surface storage

Scaled-up DEMO system

DEMO

- Full scale system containing all system elements
- Real size plant and accumulator
- Short low-capacity transferline
- 100 kW dummy load to simulate detector heat
- Able to circulate 1.58 kg/s of CO2
- Includes one-head back-up plant for redundancy swap
- Surface Storage Simulator unit



Challenges for Phase 2

- **High cooling capacities required**
  - 300 kW for ATLAS → 7 plants, 6 accumulators
  - 550 kW for CMS → 9 plants, 8 accumulators
  - Redundancy important for continuous operation

- Demonstrate operation with 100 kW cooling power at -45°C at the plant
- Demonstrate automatic procedures

- **Operation temperatures down to -45°C**
  - -45°C close to CO_2 triple point
  - Increased gradients at lower temperatures
  - Stable primary cooling is required in limited range temperature zones

- Demonstrate stable operation in all conditions, especially at cold temperatures

- **Need for surface facilities**
  - Smaller accumulators in cavern, therefore surface storage of CO2
  - Primary cooling system on surface, therefore large transferlines to service cavern

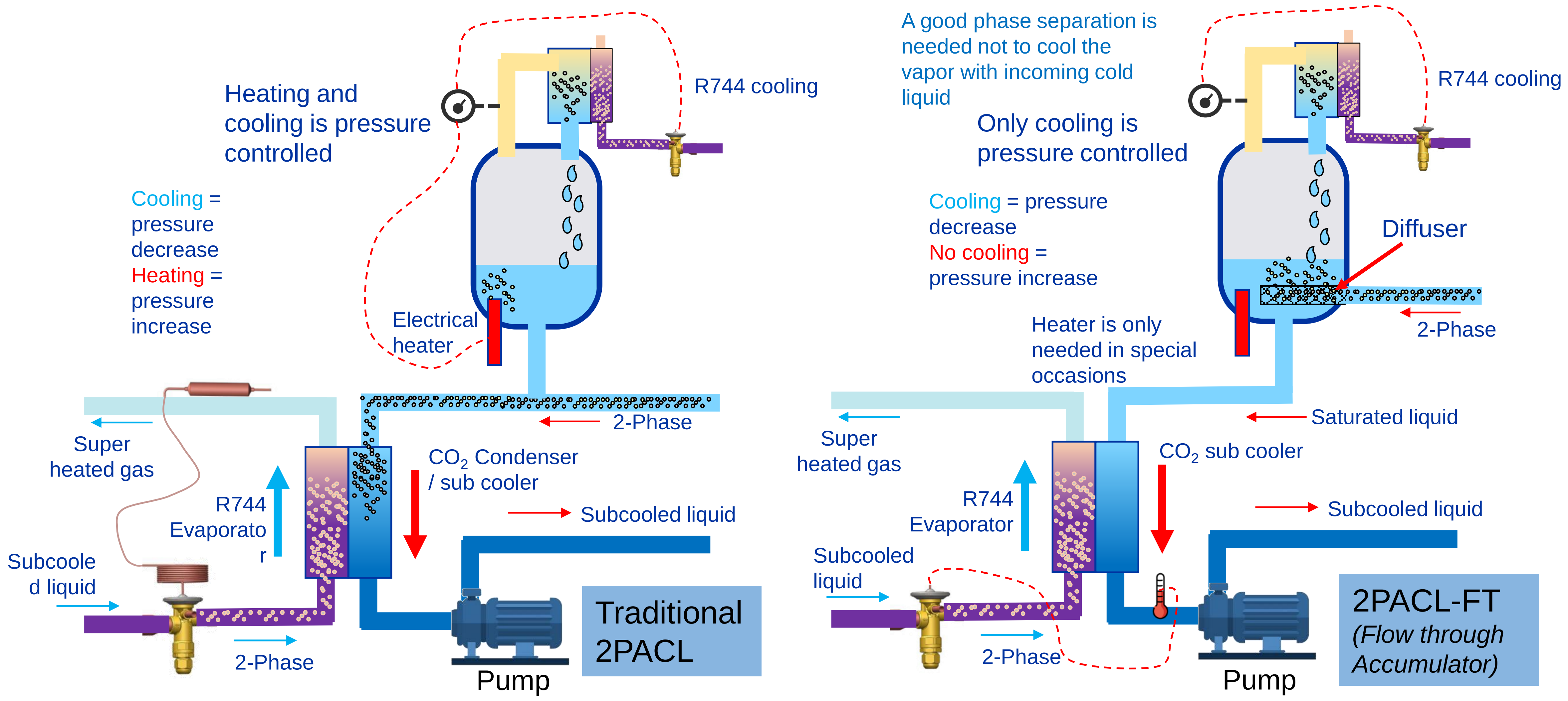
- Demonstrate specific design updates
  - Surface storage interaction
  - A reliable accumulator level control
- Demonstrate the warm return of the R744 gas (R744 transfer is without insulation)

- **Energy efficiency considerations**
  - Improvement of energy efficiency with scaled up systems

- Demonstrate the new method of accumulator flow-through (2PACL-FT)

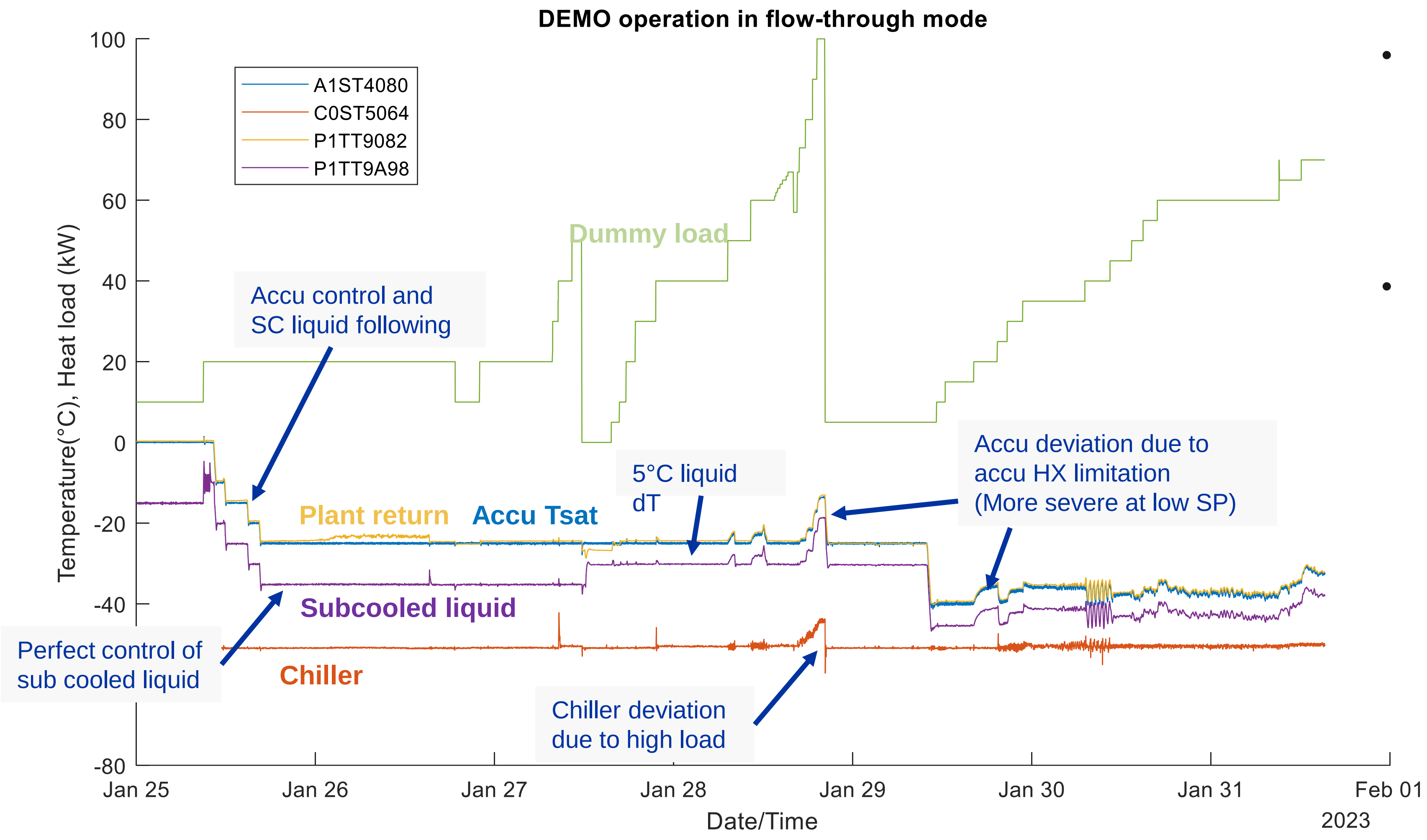
Operation and Performance

Flow-through vs. non-flow-through



Schematic by Bart Verlaat

Typical system behavior in 2PACL-FT mode

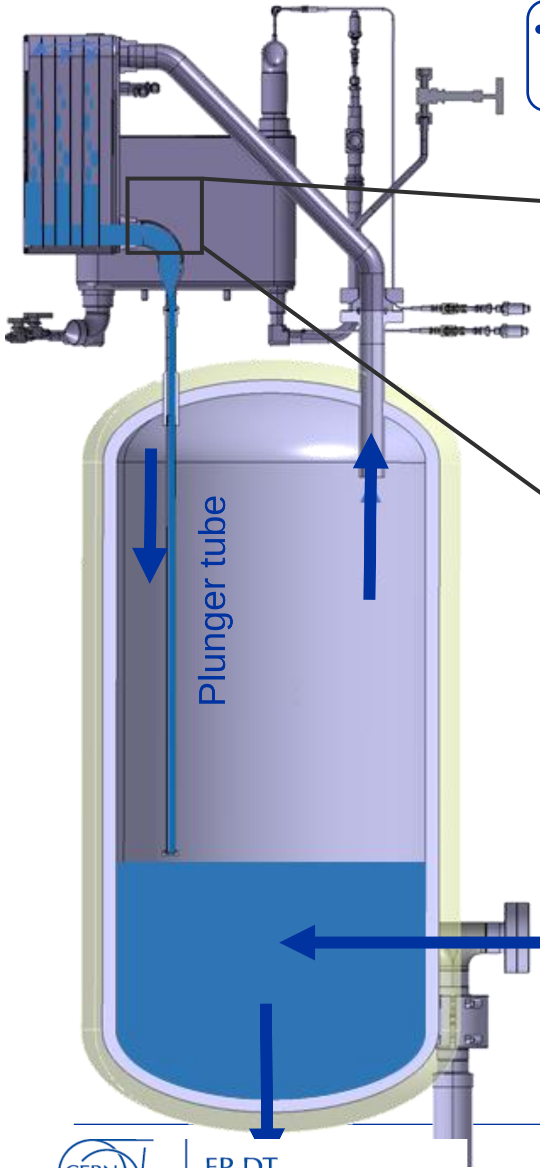


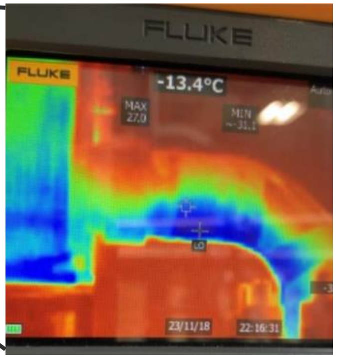
- **2PACL-FT mode shows a very stable and easy to control system**
- **It has a very good liquid temperature controllability so that at high temperature set-points there is no risk of cold drift anymore**
  - Very good experience with a liquid dT of only 5°C
- **No need to condense pump flow to -50°C, as a few degrees subcooling is sufficient**

Accumulator Redesign

- Installation of a Q-pipe in heat exchanger to improve flow distribution in the heat exchanger

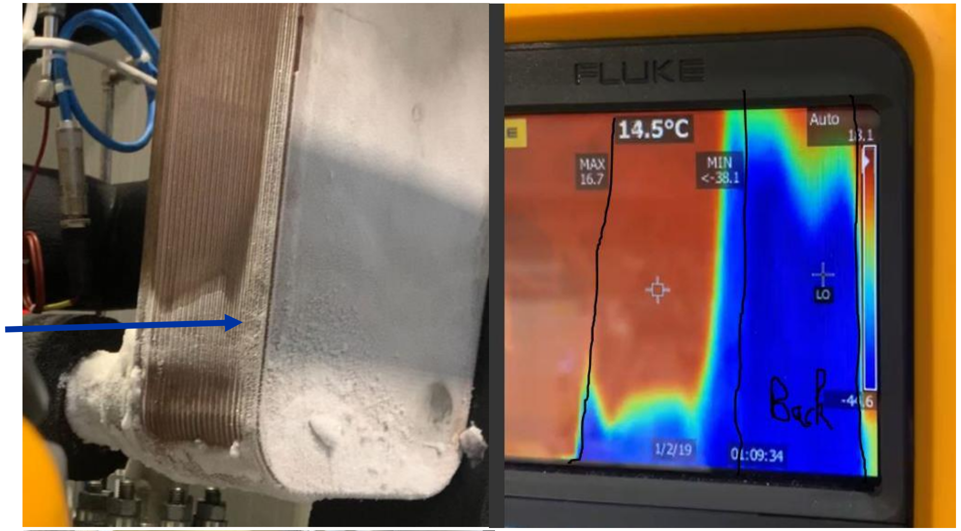
- Addition of a plunger tube to keep heat exchanger flooded



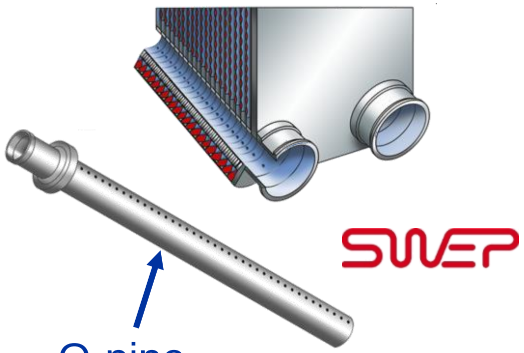


Too little convective flow without a plunger tube

No Q-pipe shows liquid flowing through the back



Flow distribution much better with Q-pipe

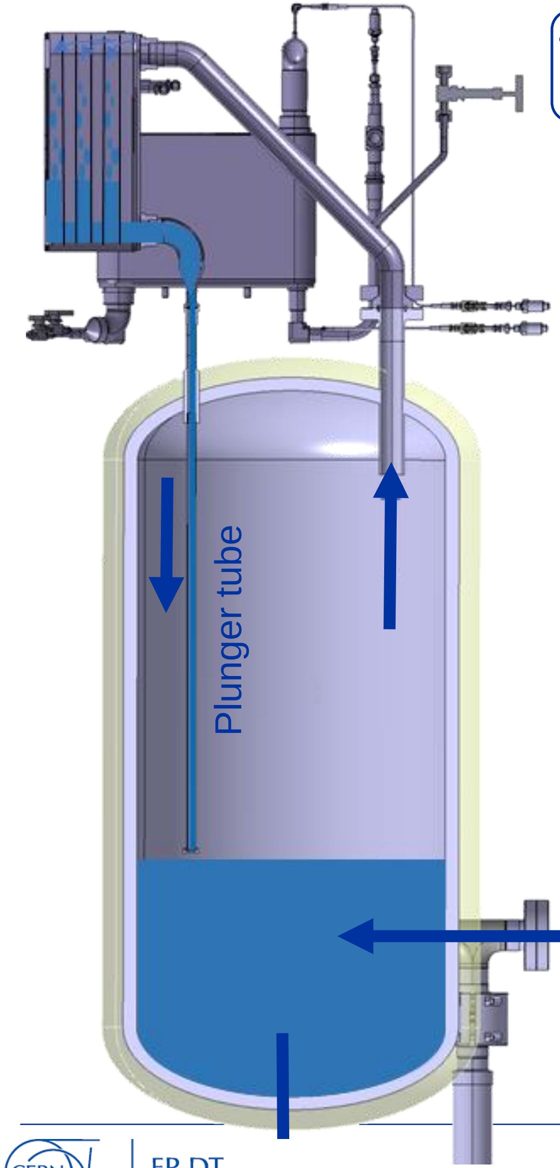


Q-pipe

Schematics by Yann Herpin

Plunger and Q-pipe have increased cooling capacity from 15 kW at -35°C to 50 kW at -45°C

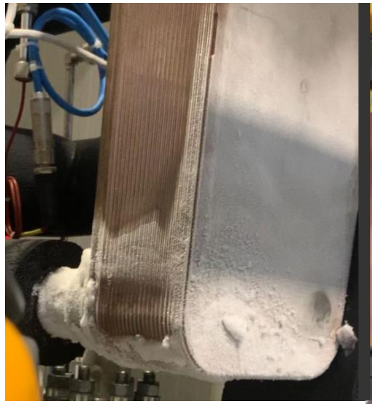
Accumulator Redesign

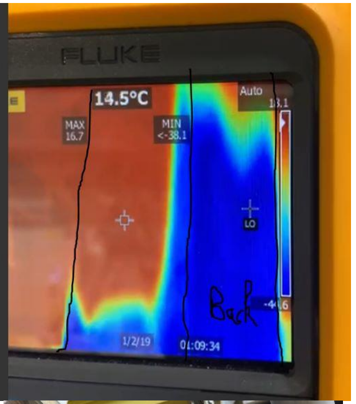


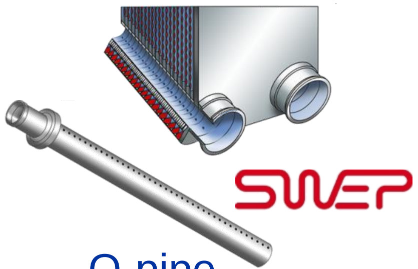
- Addition of a plunger tube to keep heat exchanger flooded

- Installation of a Q-pipe in heat exchanger to improve flow distribution in the heat exchanger

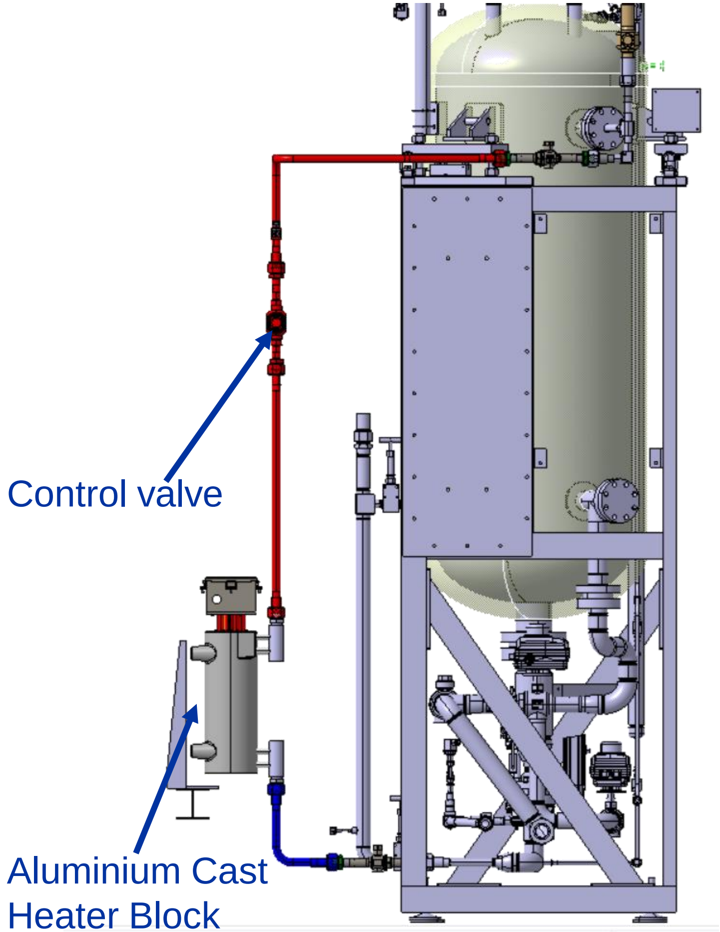
- Cast heater block temperature is kept constant and flow is regulated with a control valve
- This concept keeps the heater surface warm and hence reduces moisture problems





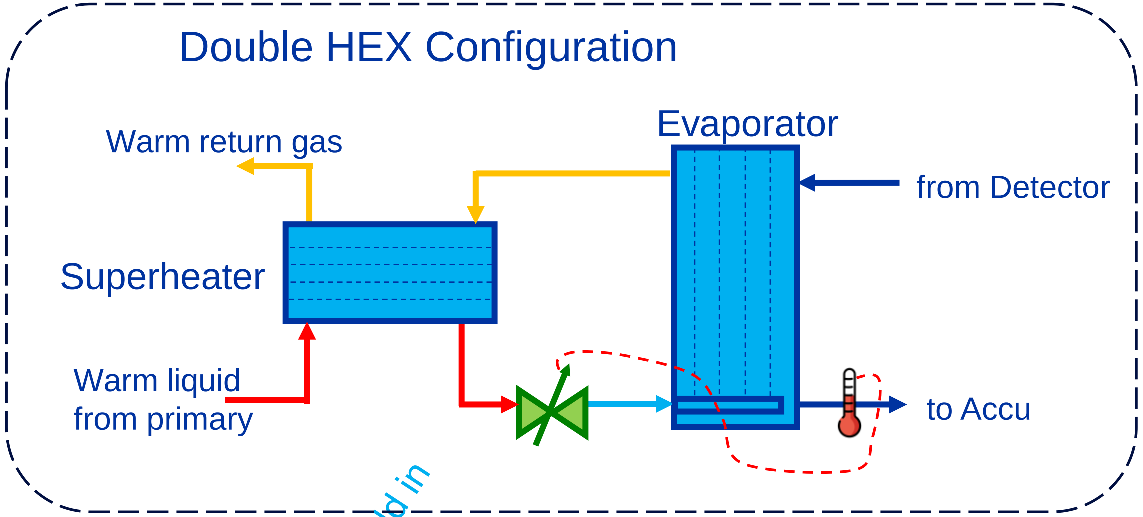


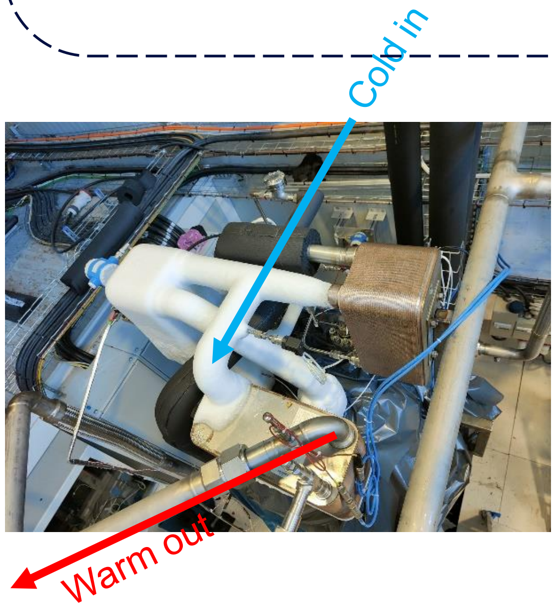
Q-pipe

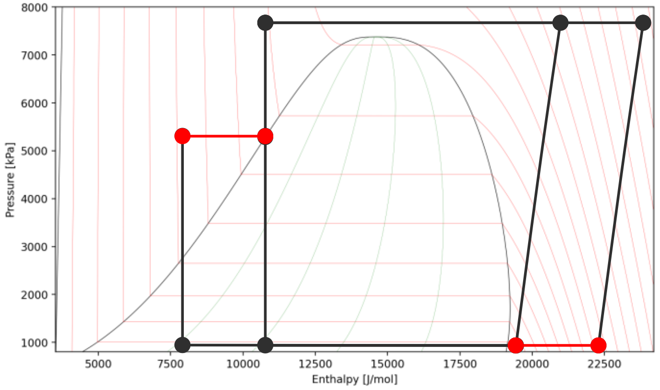


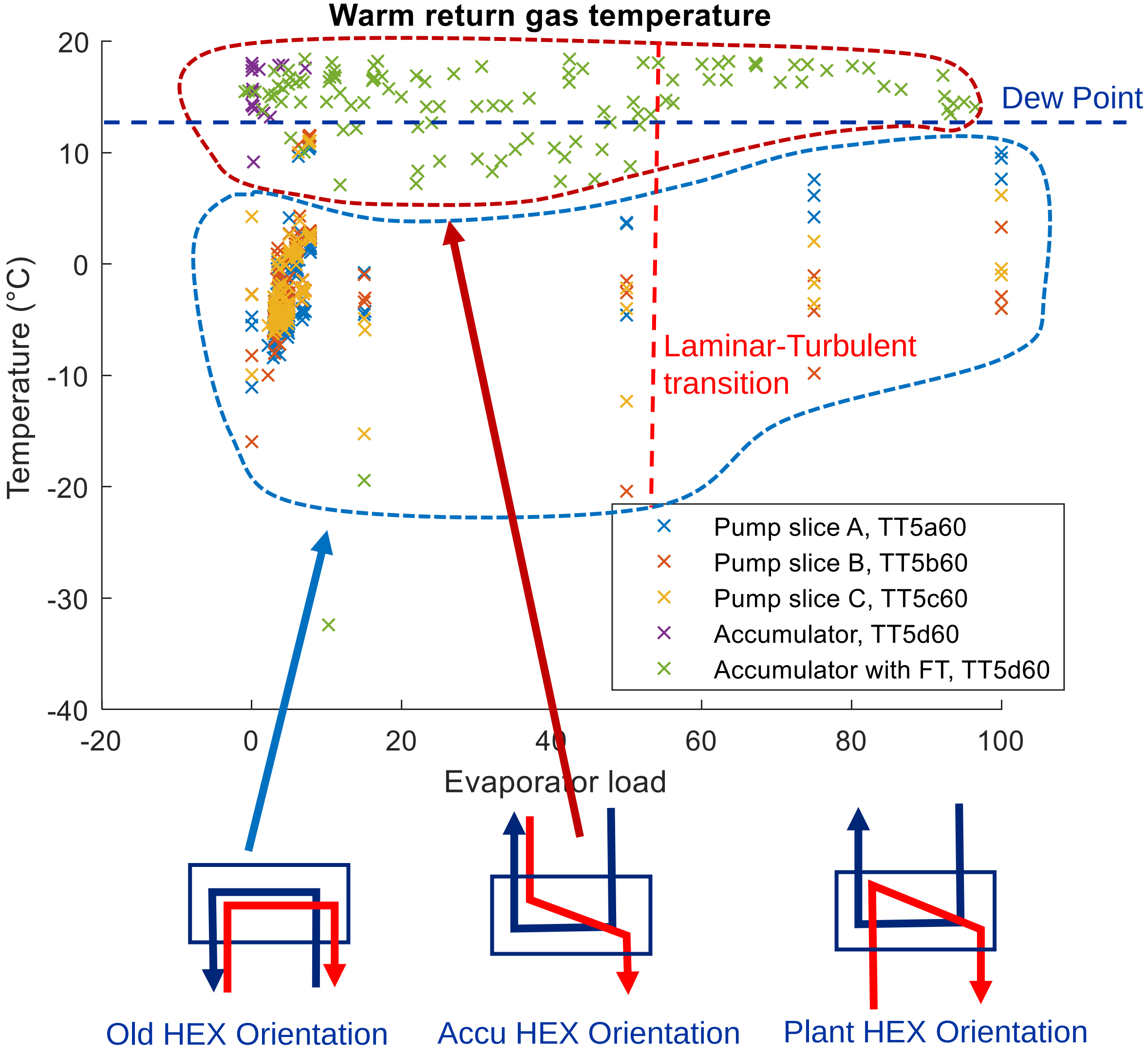
Schematics by Yann Herpin

Heat Exchanger Configuration

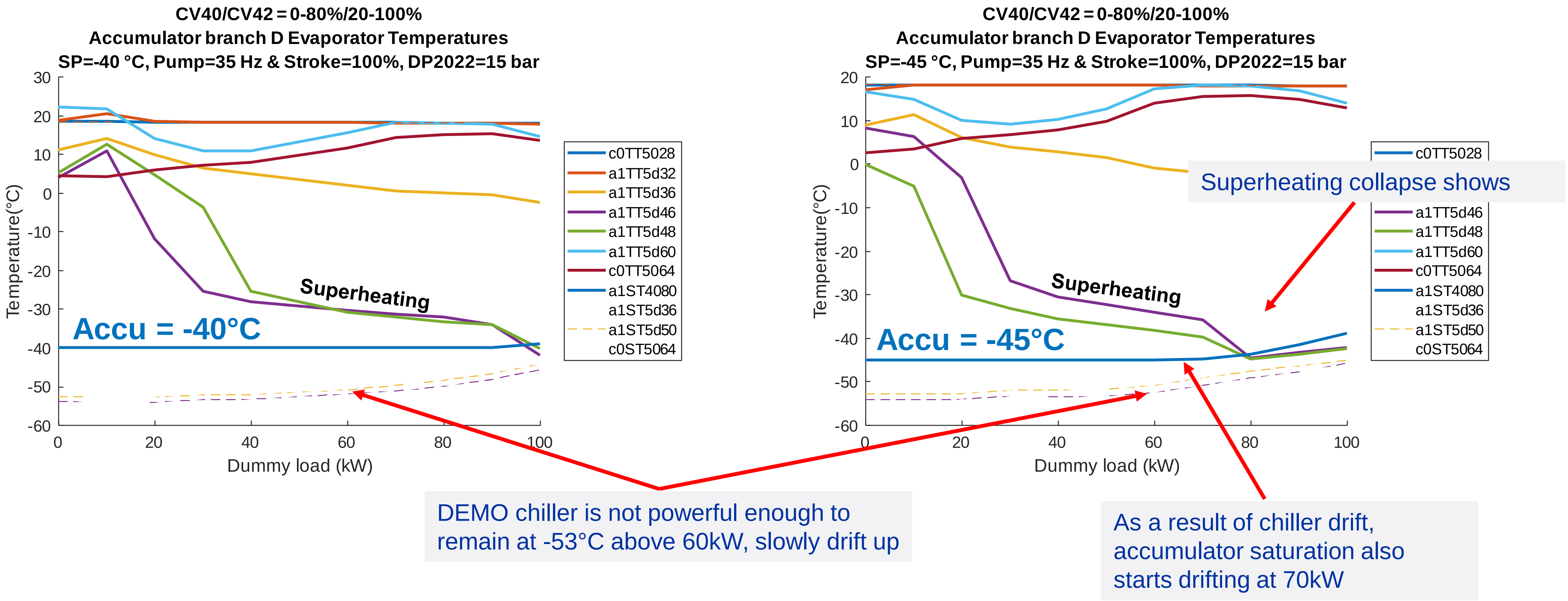






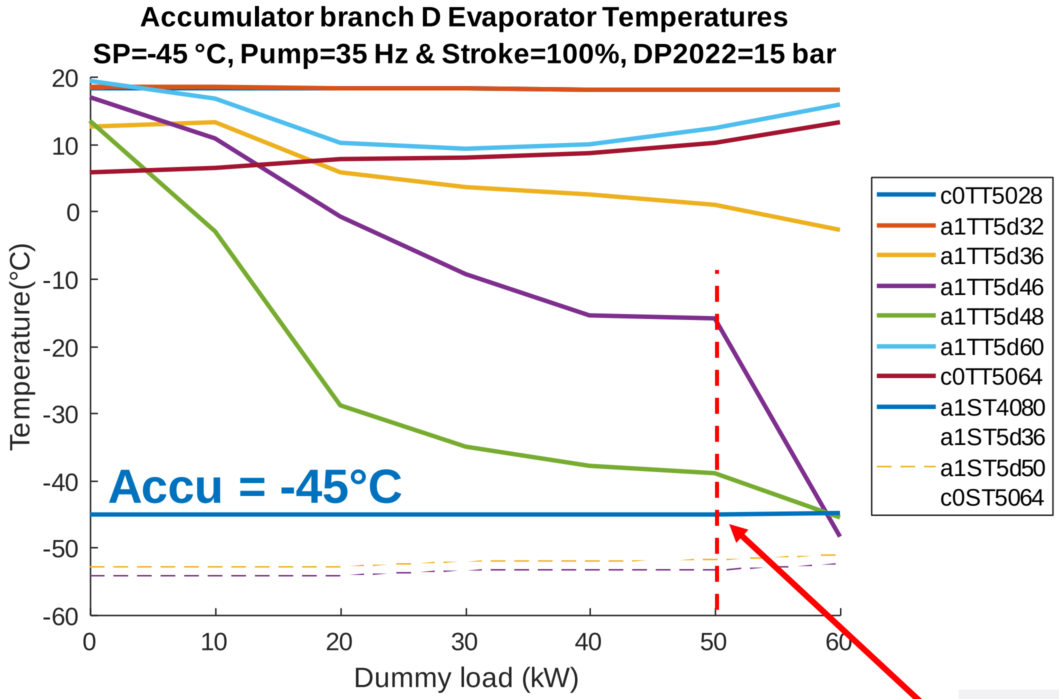


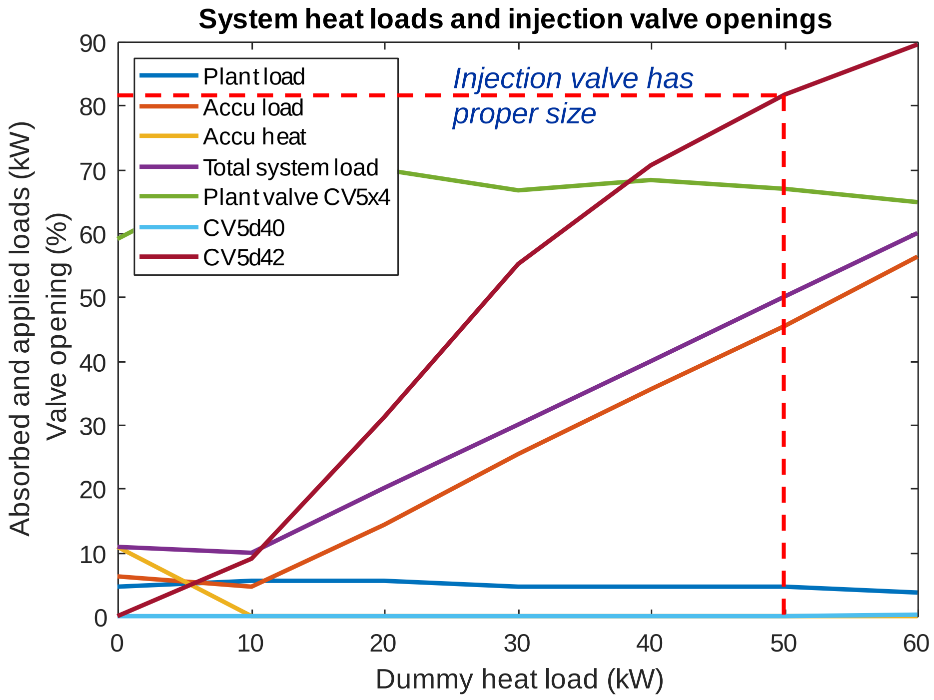
Our performance goal: 100kW @ -45°C



The DEMO R744 chiller is not powerful enough to maintain -53°C above 60kW, a drift to -45 °C is observed at 100kW, and is therefore not able to cool down the accumulator sufficiently

Our performance goal: 100kW @ -45°C

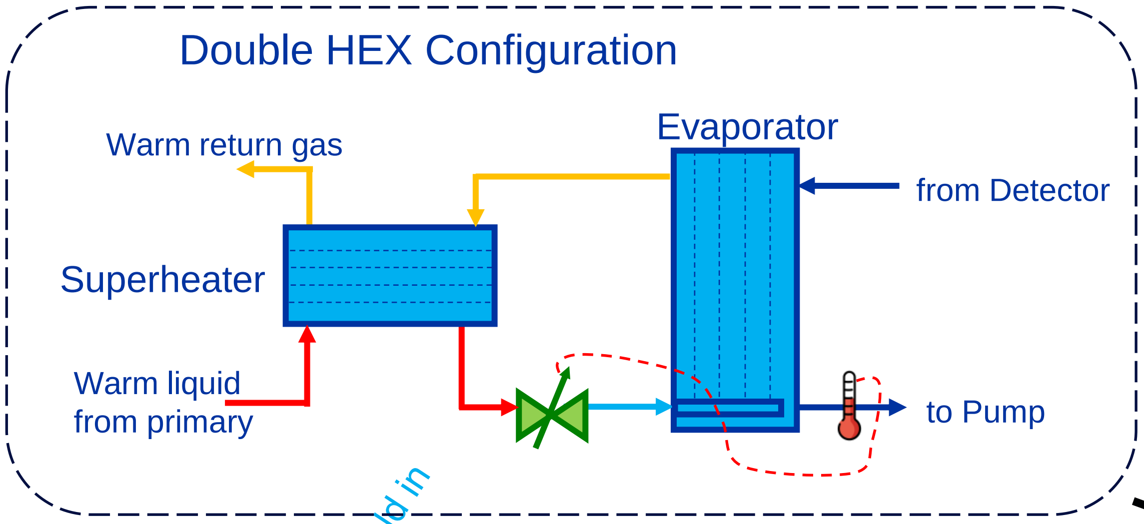


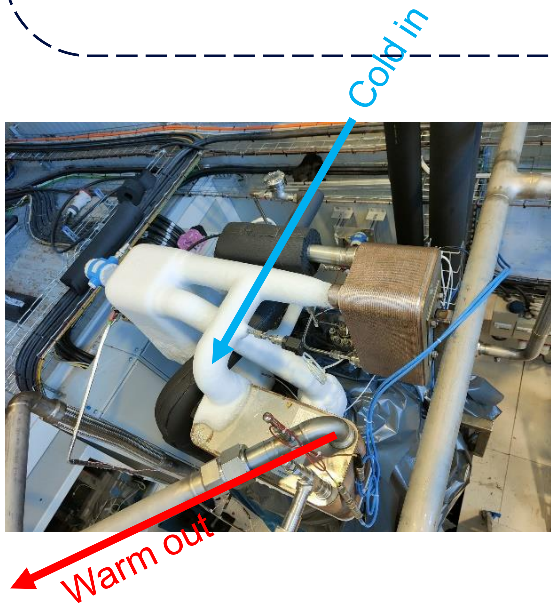


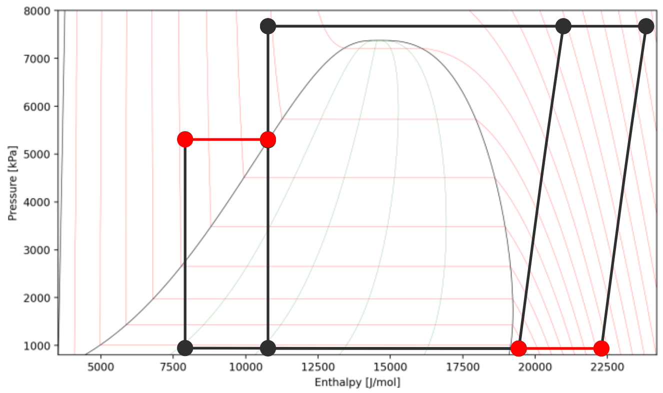
Accumulator heat exchanger reaches 50 kW at -45°C

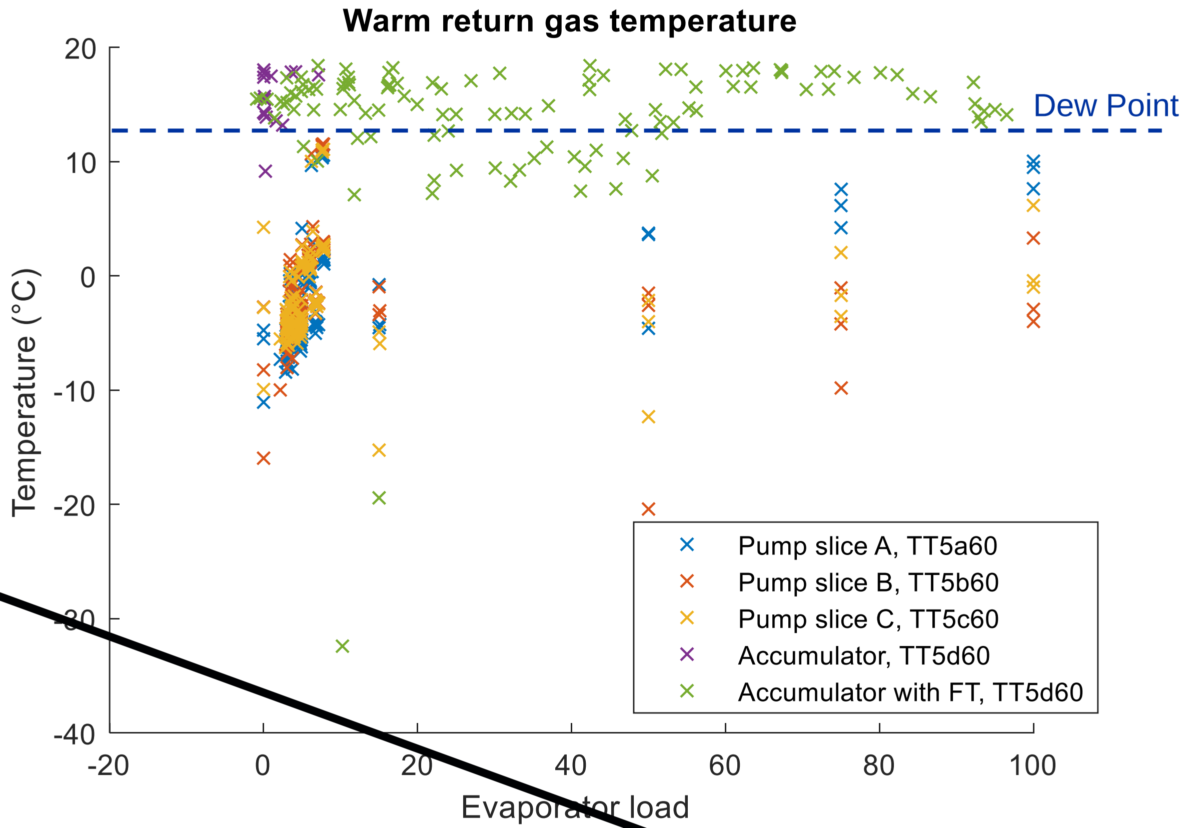
- We have two heat exchangers operated in parallel on the accumulator
- -45°C was kept at 50kW on a single heat exchanger!
- With two heat exchangers, our goal of 100 kW at -45°C would be reached!
- ATLAS maximum systems power: 60 kW; CMS maximum systems power: 90 kW

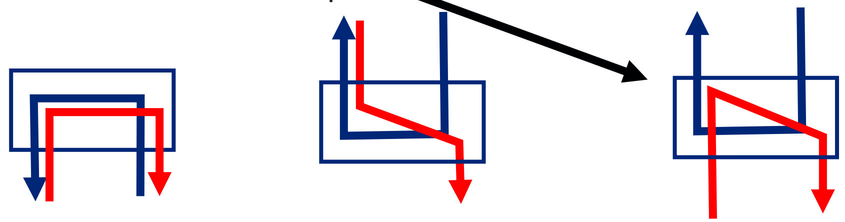
Heat Exchanger Configuration







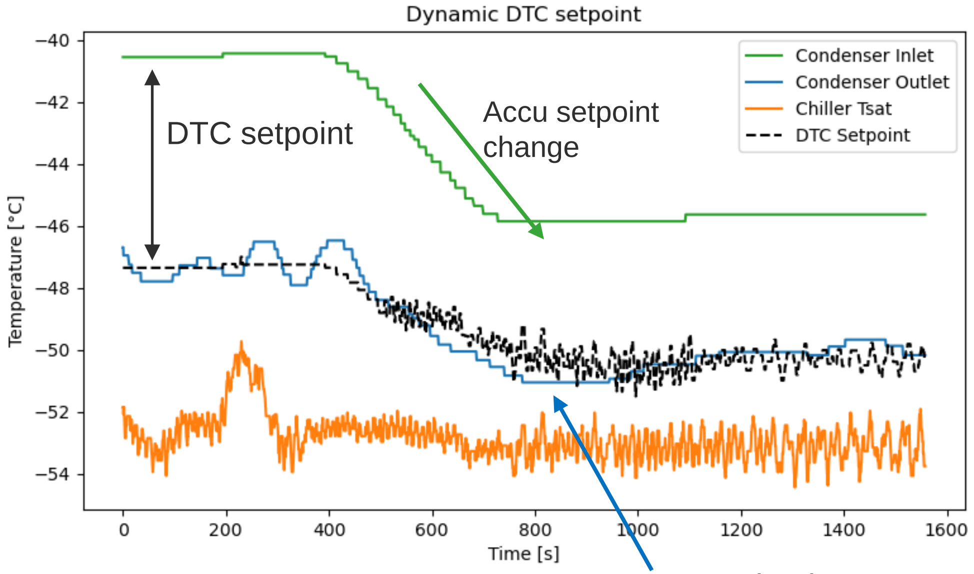




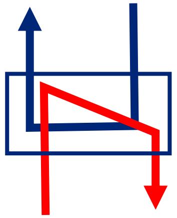
Old HEX Orientation | Accu HEX Orientation | Plant HEX Orientation

Operation of the Condenser/Subcooler

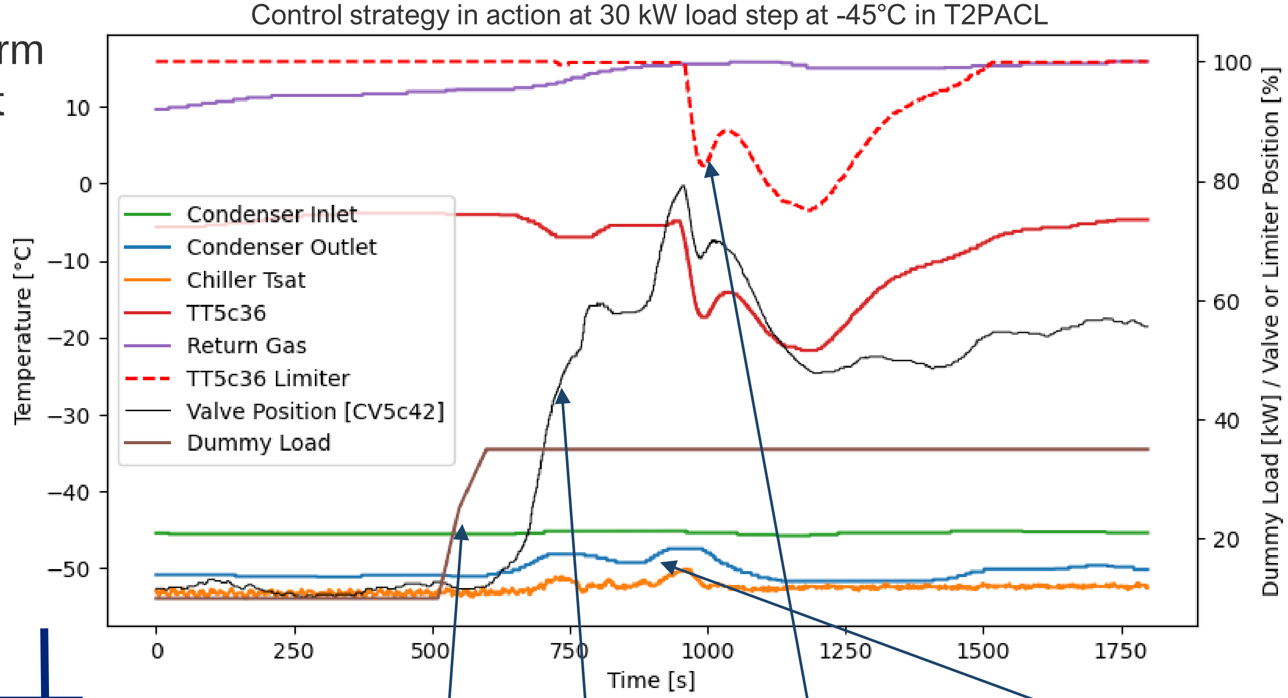
- Recently implemented new control strategy ensures sufficient pump subcooling at -45°C at high and low load cases
  - Dynamic dT setpoint only requests no more than what the chiller can provide in cooling
  - Output high limiter on the valve to keep return gas warm
  - 'Boost mode' implemented to speed up valve action at low subcooling



DTC setpoint decreases with available temperature differential



Plant HEX Orientation



Step of 30 kW induced

Valve opens quickly due to a 'boost mode'

Valve opening is limited to ensure warm return gas

Subcooling is ensured and does not drop too low

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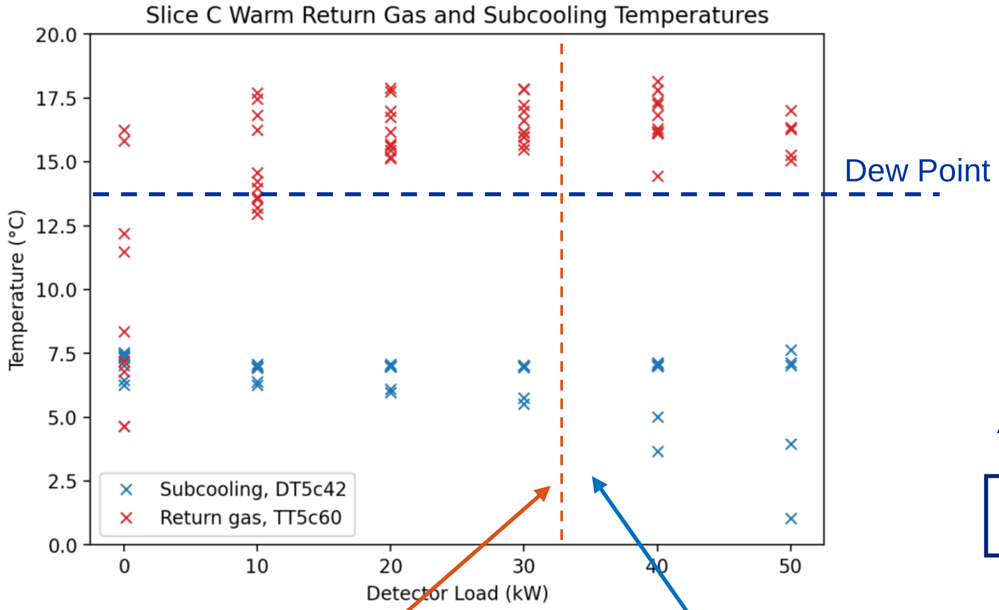
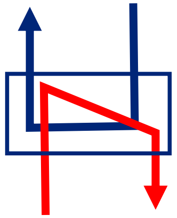
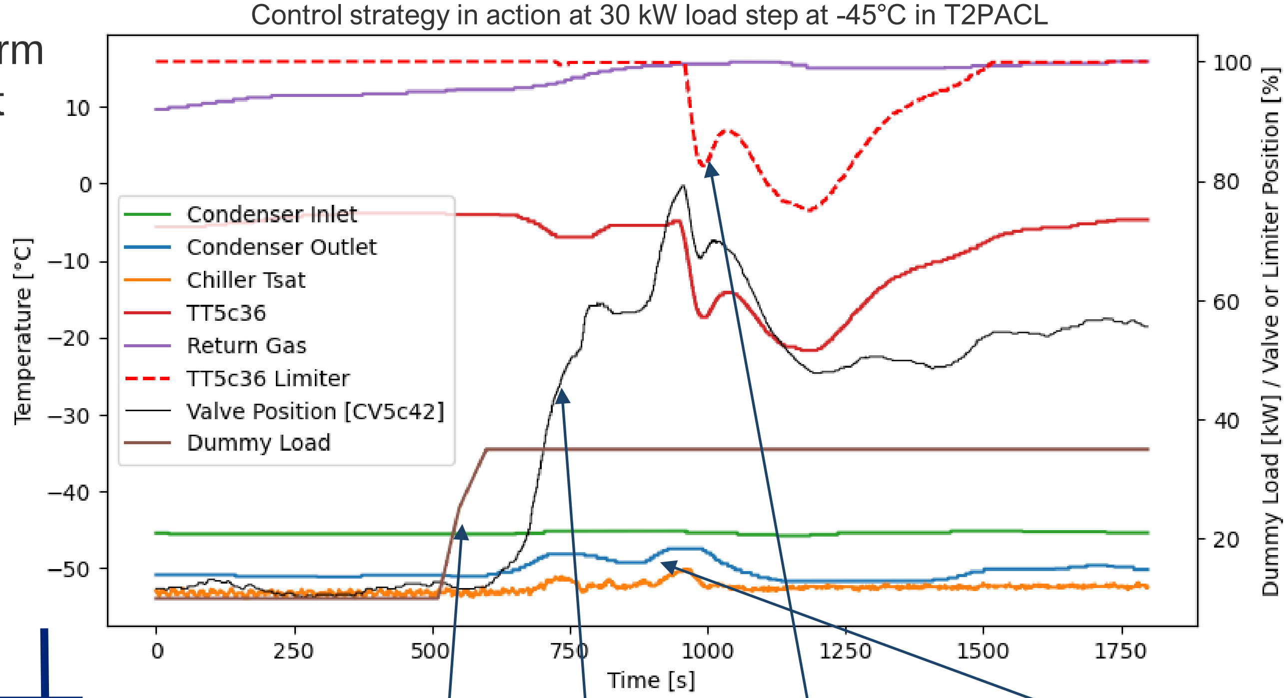


HEX slice target

Subcooling ensured in all detector cases !!



Plant HEX Orientation



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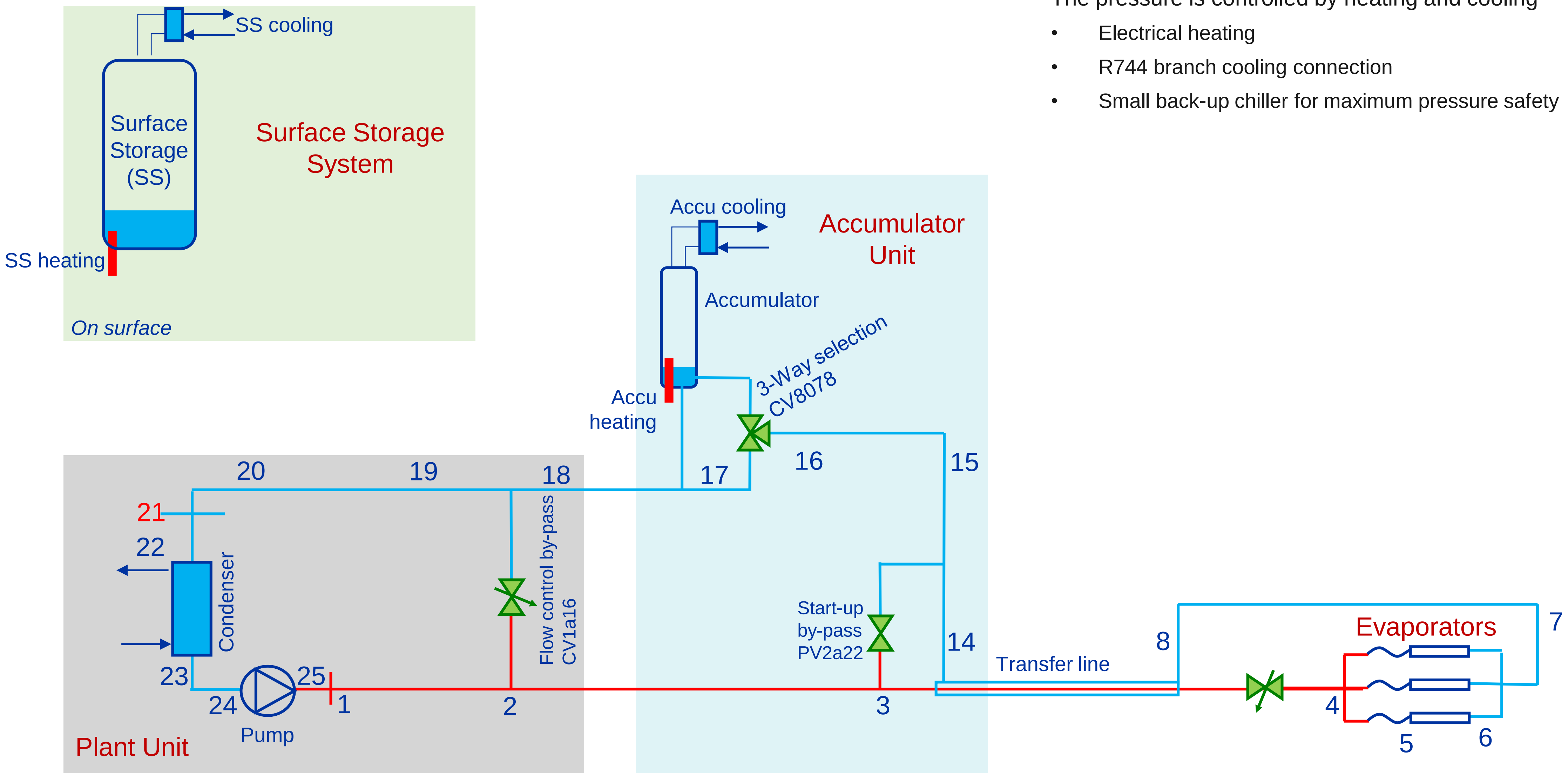
Surface Storage

Surface Storage Concept

The surface storage is in fact 1 large common accumulator for all systems

The pressure is controlled by heating and cooling

- Electrical heating
- R744 branch cooling connection
- Small back-up chiller for maximum pressure safety



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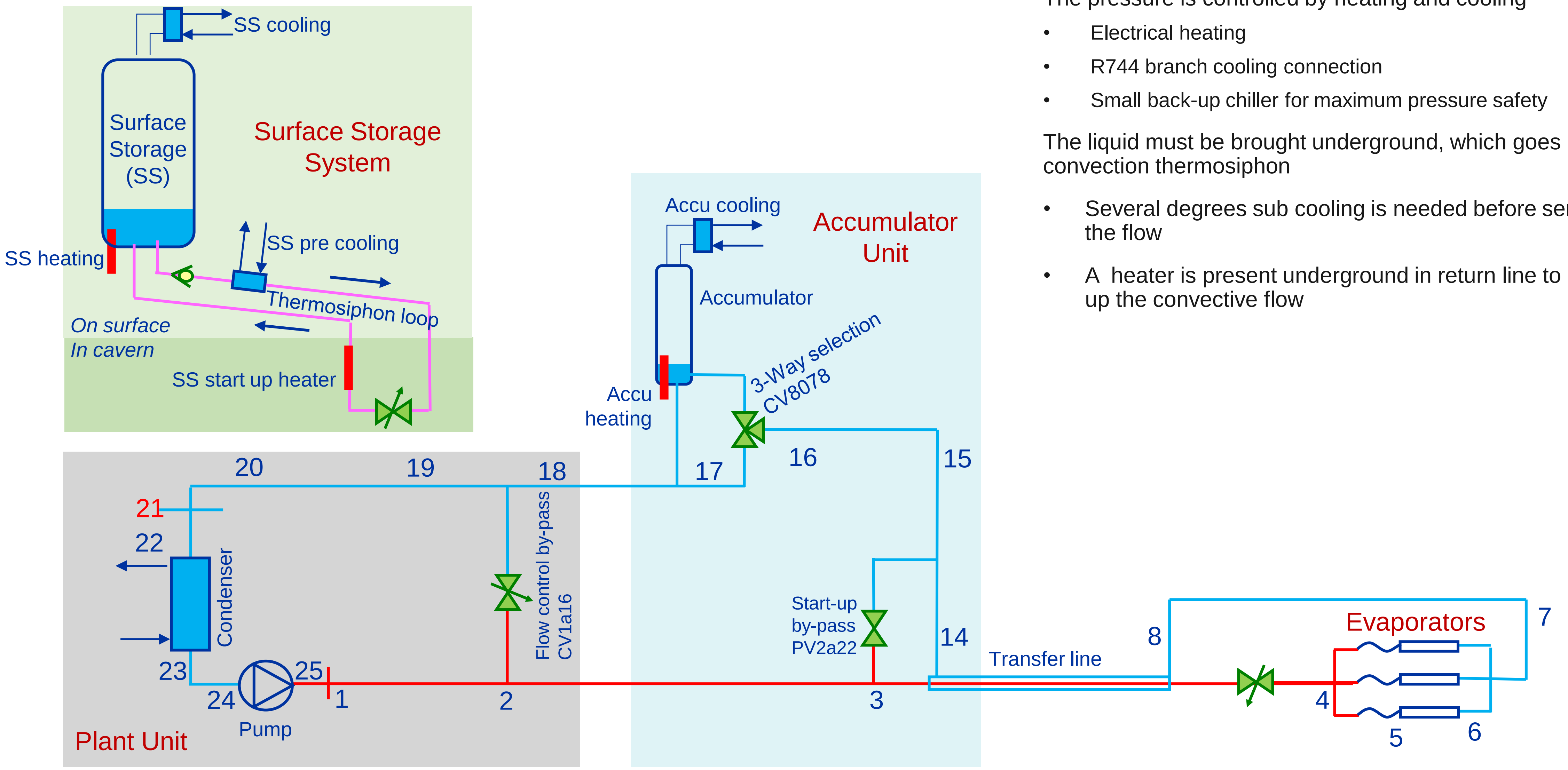

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The liquid must be brought underground, which goes by a natural convection thermosiphon

- Several degrees sub cooling is needed before sending down the flow
- A heater is present underground in return line to help start-up the convective flow

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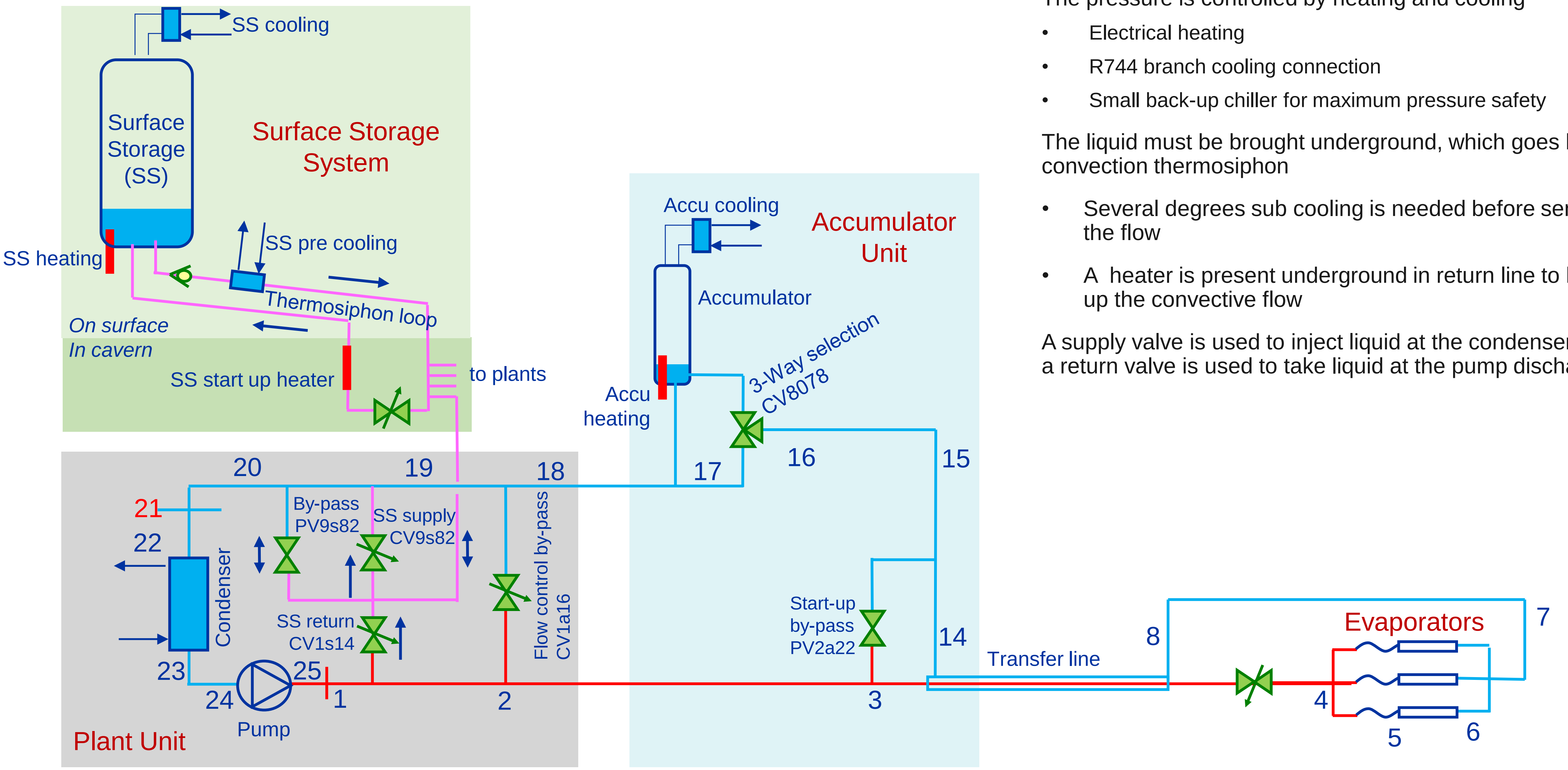

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A supply valve is used to inject liquid at the condenser inlet, while a return valve is used to take liquid at the pump discharge

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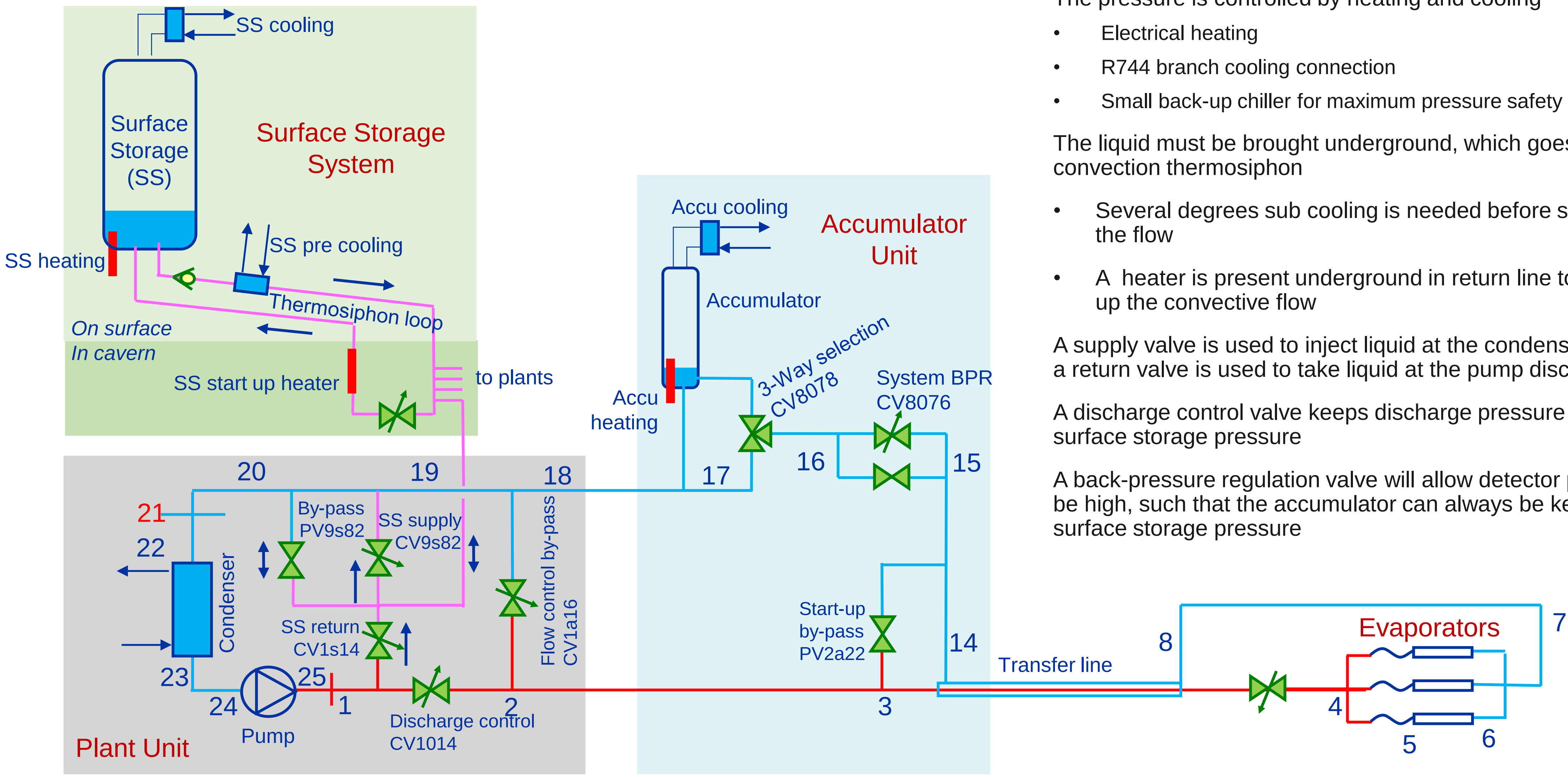

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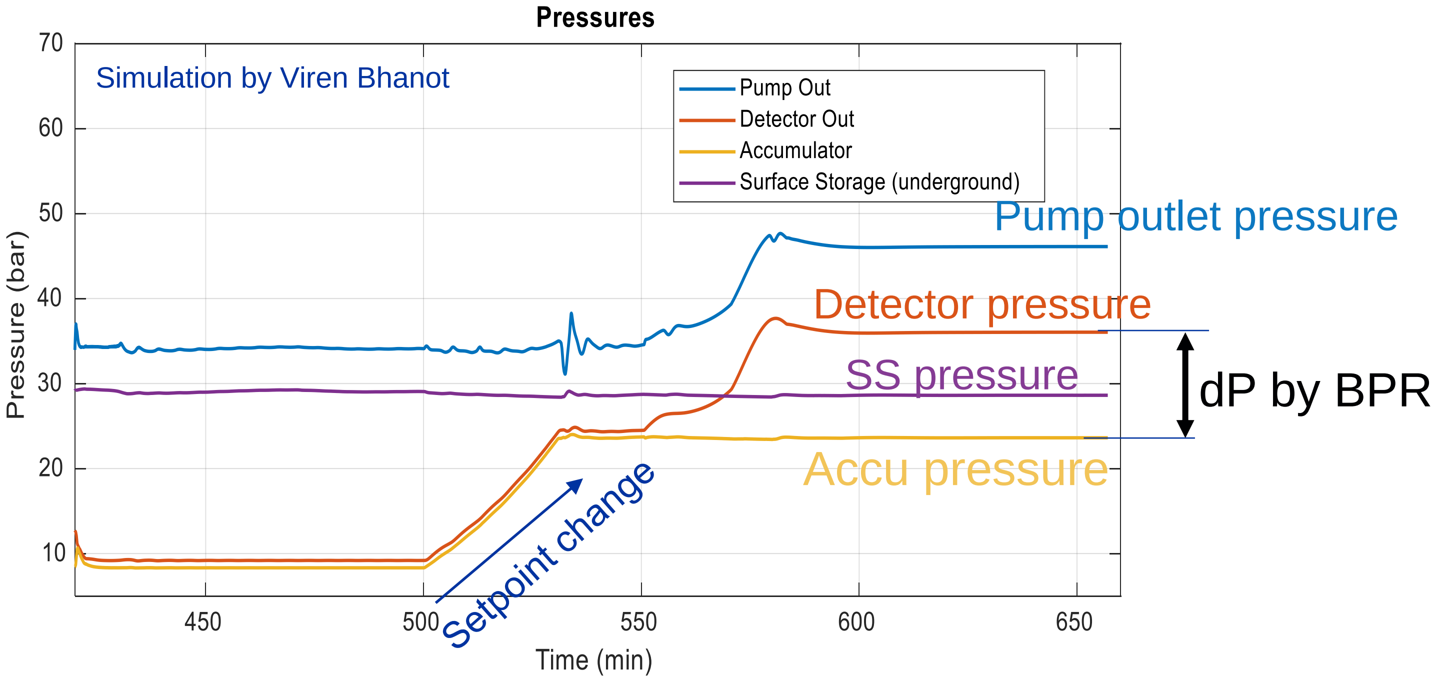
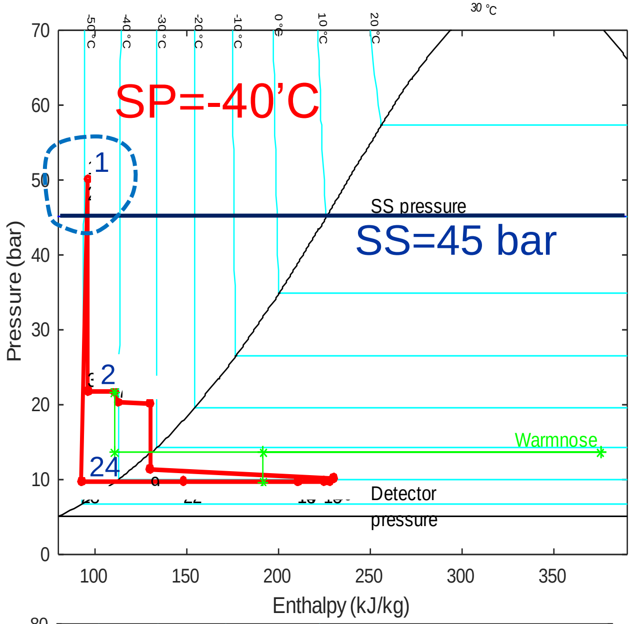
A discharge control valve keeps discharge pressure above surface storage pressure

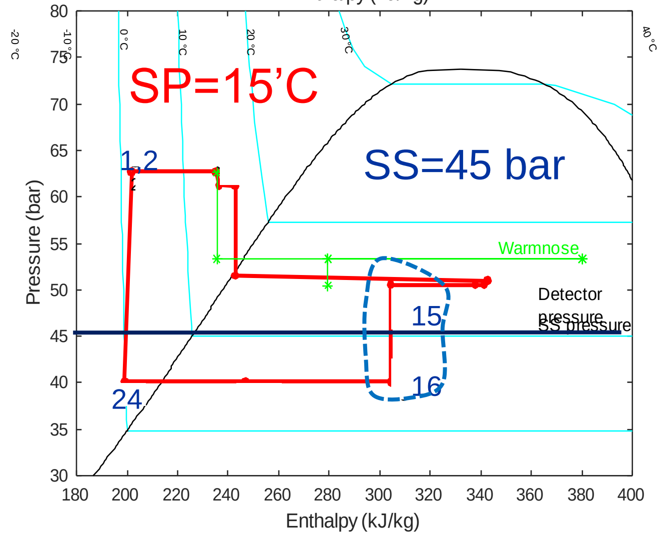
A back-pressure regulation valve will allow detector pressure to be high, such that the accumulator can always be kept below surface storage pressure

Surface Storage 2PACL Operation

- The Surface storage pressure underground is foreseen to work between 20 bar and 56 bar (~14-51 bar in SS-tank)
- Discharge valve will keep discharge pressure 5 bar above surface storage setpoint, such that emptying will always be possible
- Back pressure regulator (BPR) will be able to keep detector pressure at higher setpoints than surface storage setpoint, allowing us to keep the accumulator below surface storage setpoint
    - This will allow us to always be able to fill
- Surface storage and accumulator setpoints will be aligned as much as possible, but with multiple plants, BPR will be required in some cases



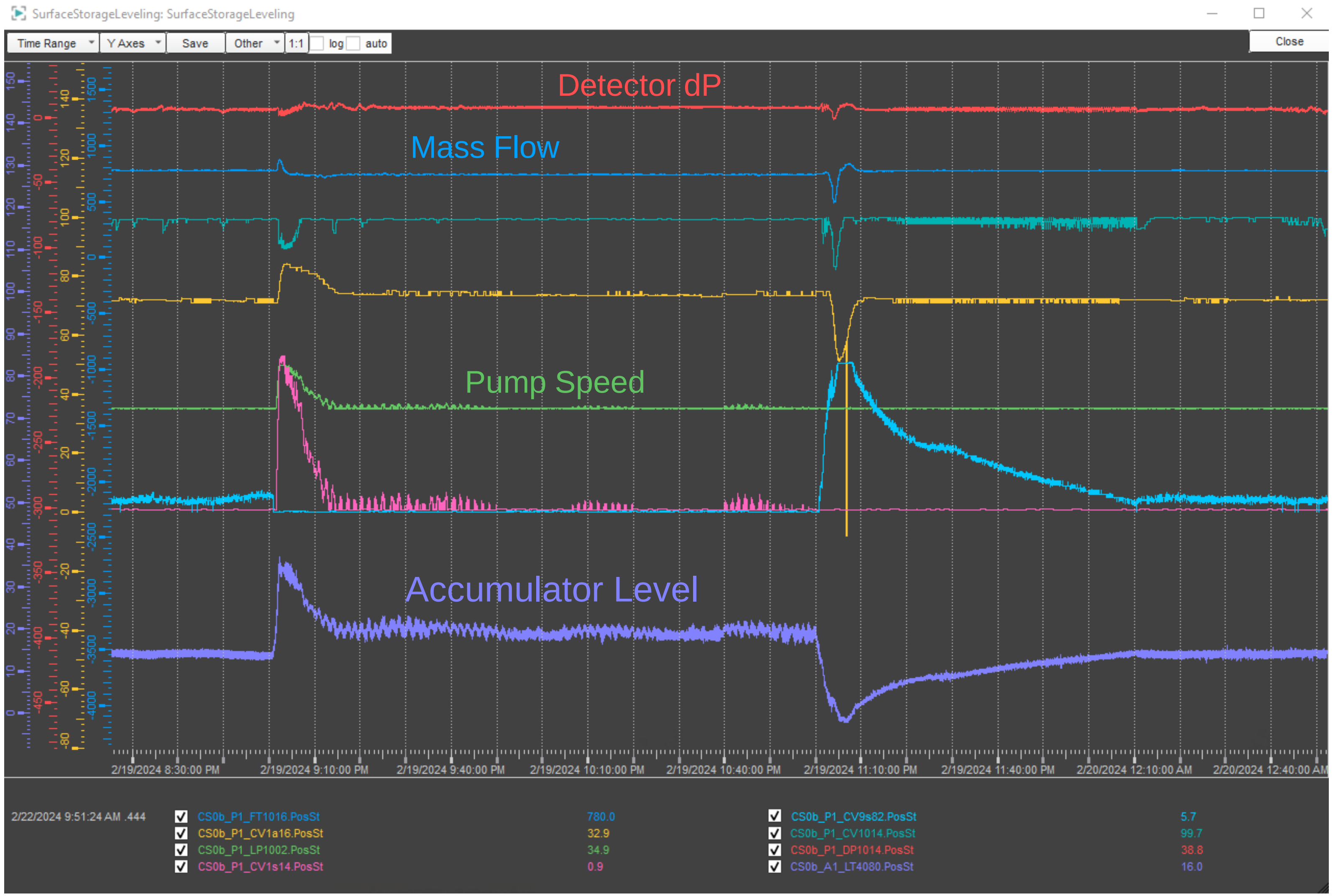




Accumulator Level Control

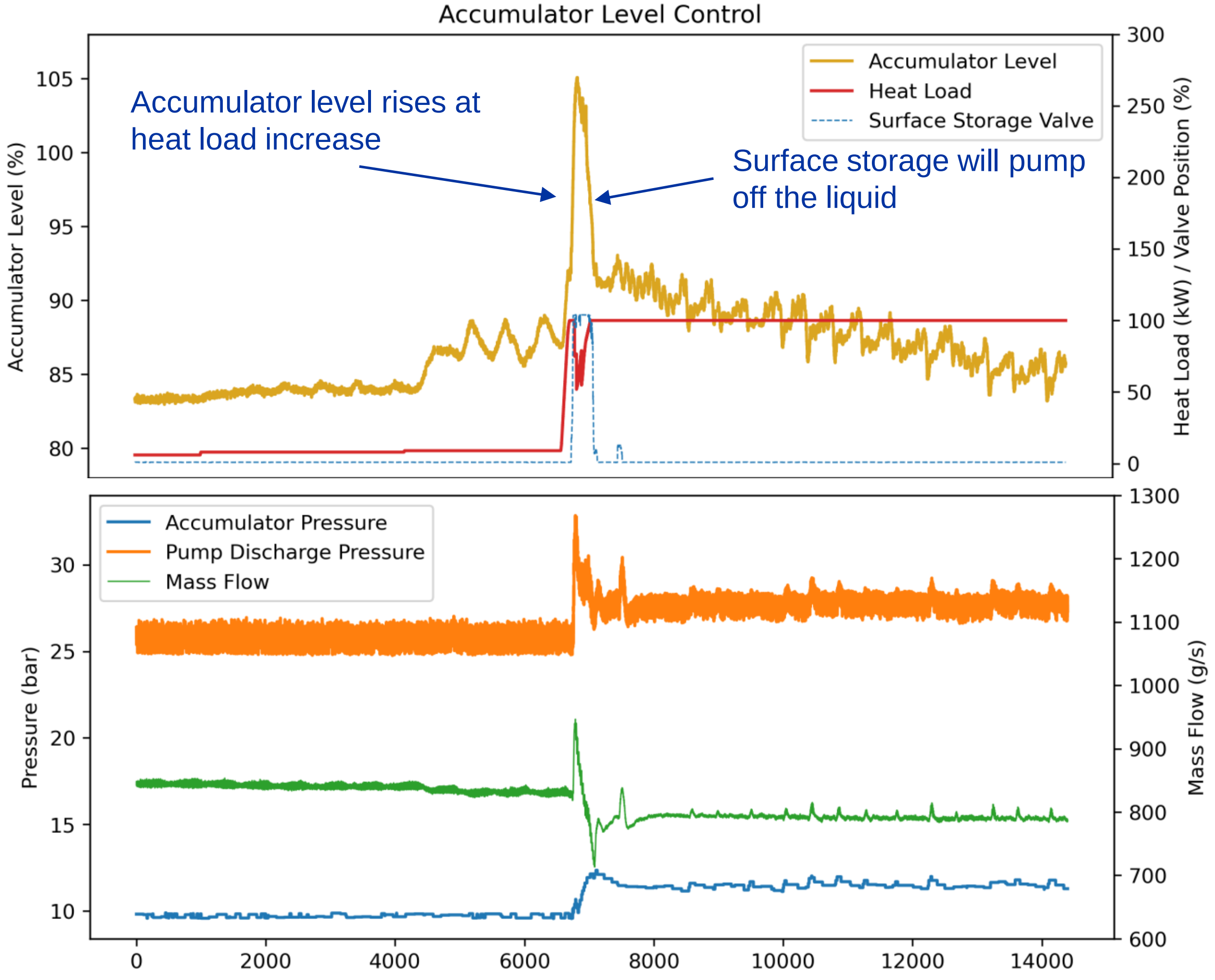
- Implementation of level control will of the accumulator will keep the liquid level of the accumulator always in a specified range
- If level is low, surface storage valves will open to fill the plant until accumulator reaches the desired level
- Vice versa, if the accumulator level is high, surface storage emptying valve will regulate until level setpoint is reached
- Pump speed will be boosted during emptying to keep detector flow steady

Level plot at -40°C accumulator setpoint and 20 bar surface storage pressure

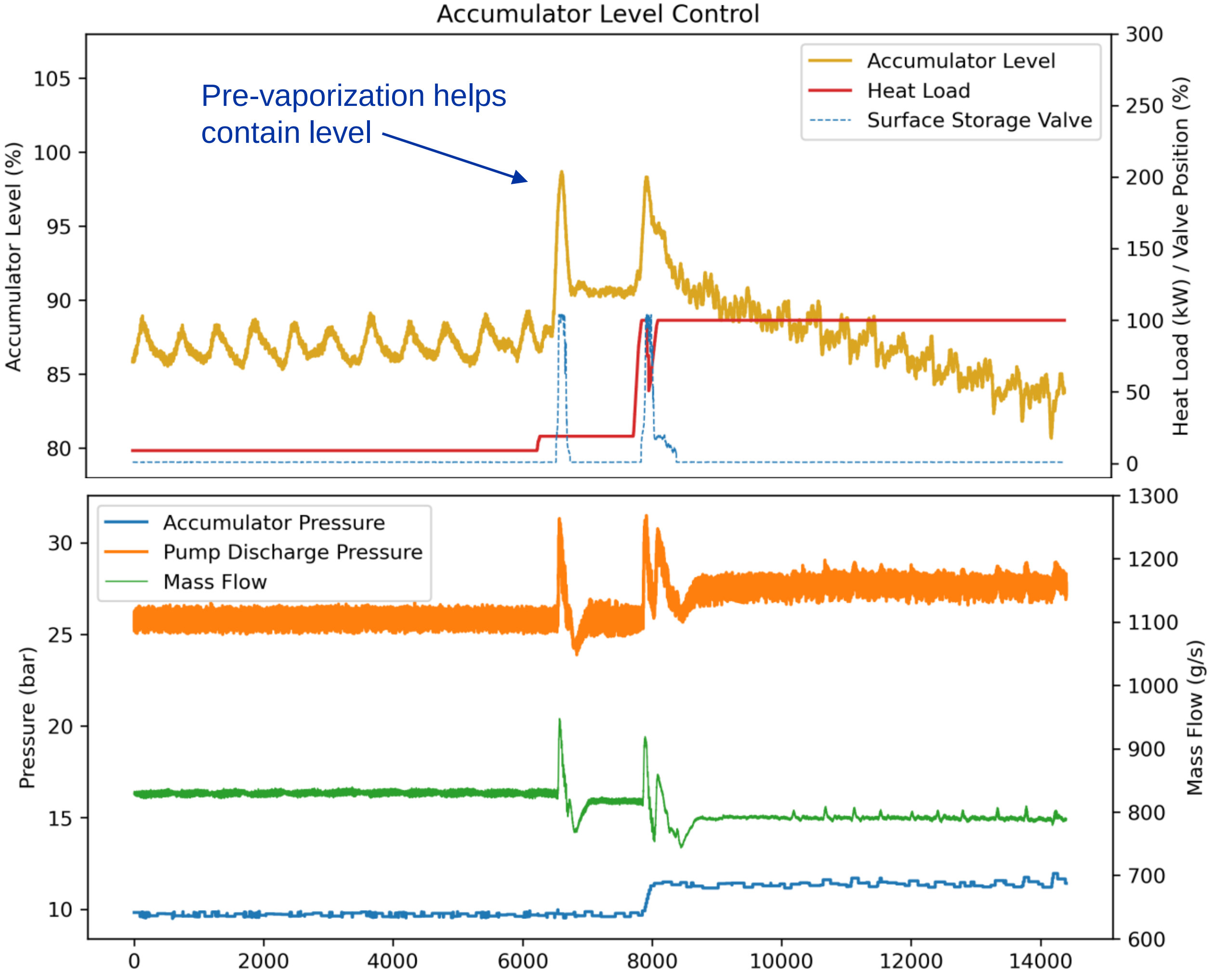


Pre-vaporization

Without Pre-vaporization



With Pre-vaporization



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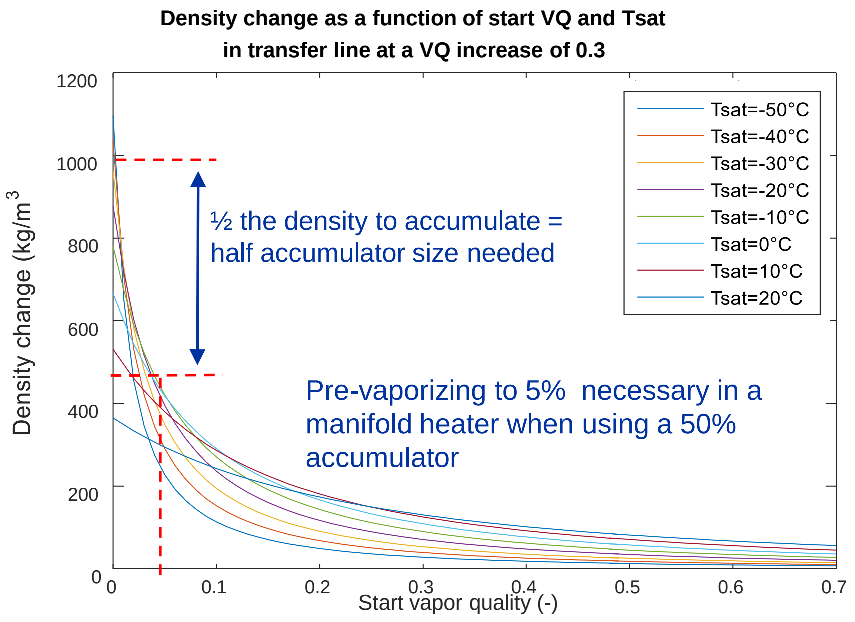
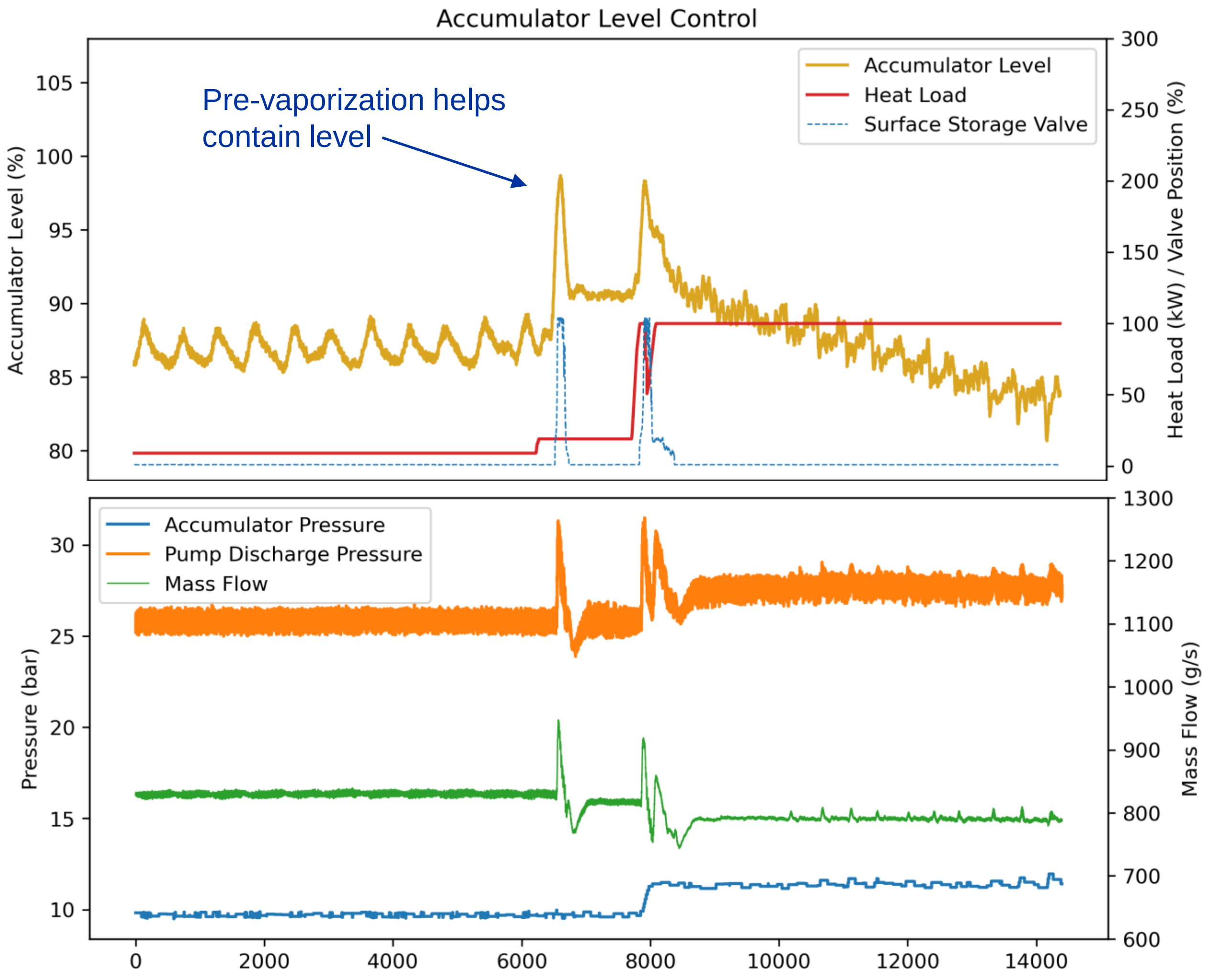


With Pre-vaporization



- Pre-vaporizing of the transfer line helps a lot, 5% VQ reduces the vapor volume with 50%
- Accumulator charge reduction after pre vaporization and detector powering
- With pre vaporization a power cycle will require less accumulator volume

Plant and Accumulator start-up

Traditional Start-up Procedure

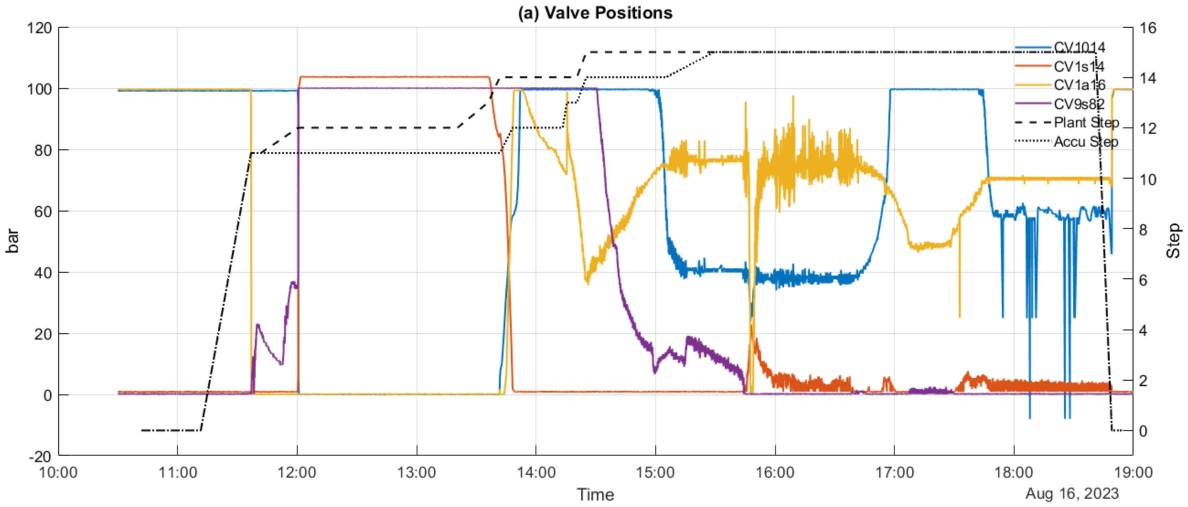
- Detector Liquification
- Detector Circulation
- Accumulator Control
- Operation

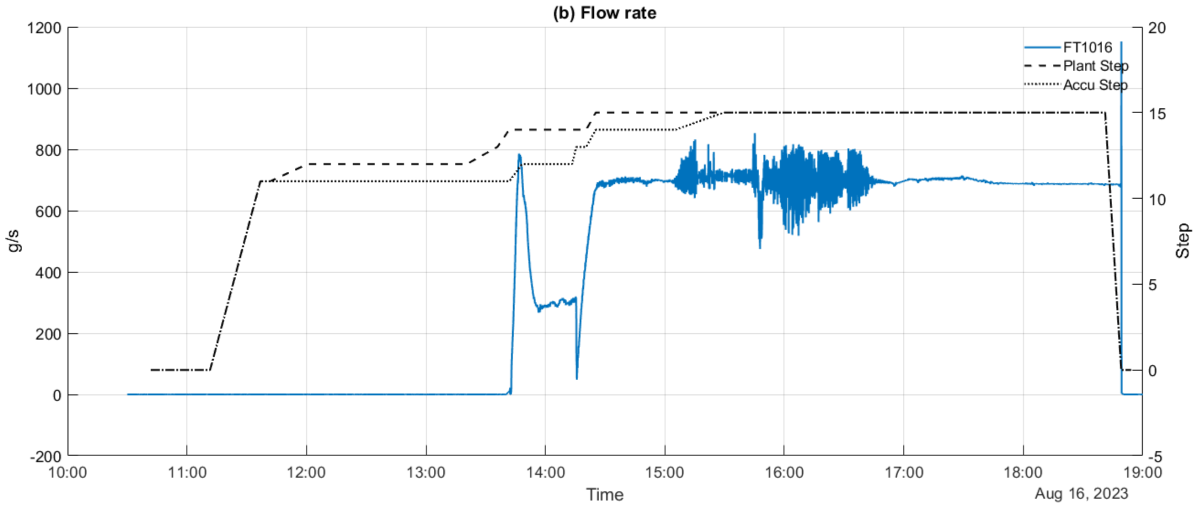
Start-up Procedure with Surface Storage

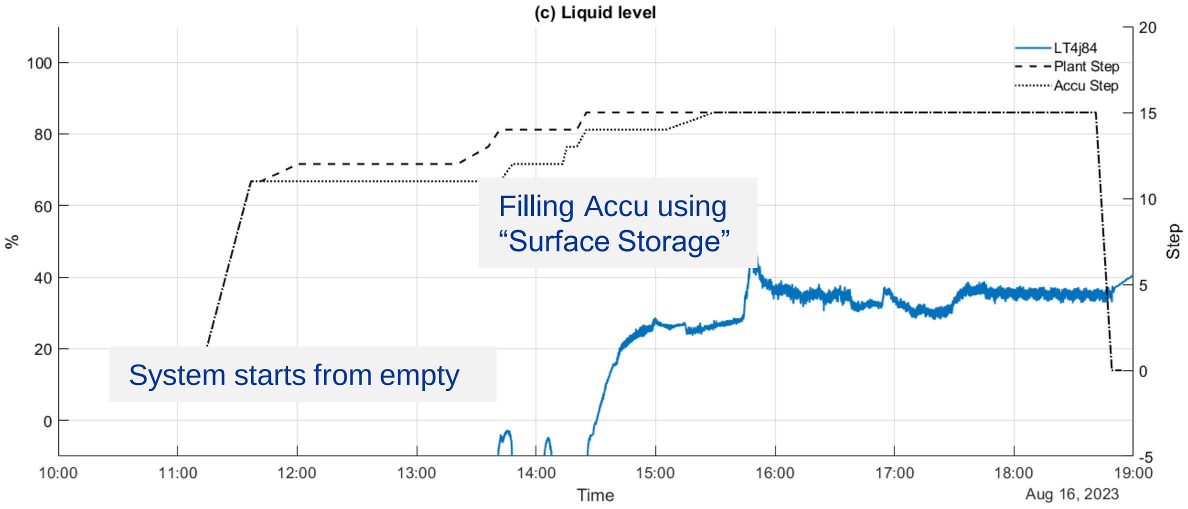
Plant Start-up	Accumulator Start-up
Surface Storage Pressure Equalization	Detector Liquification (by BPR)
Pump Liquification	Detector Circulation
Plant Circulation	Accumulator Control
Accumulator Skid Circulation	Operation

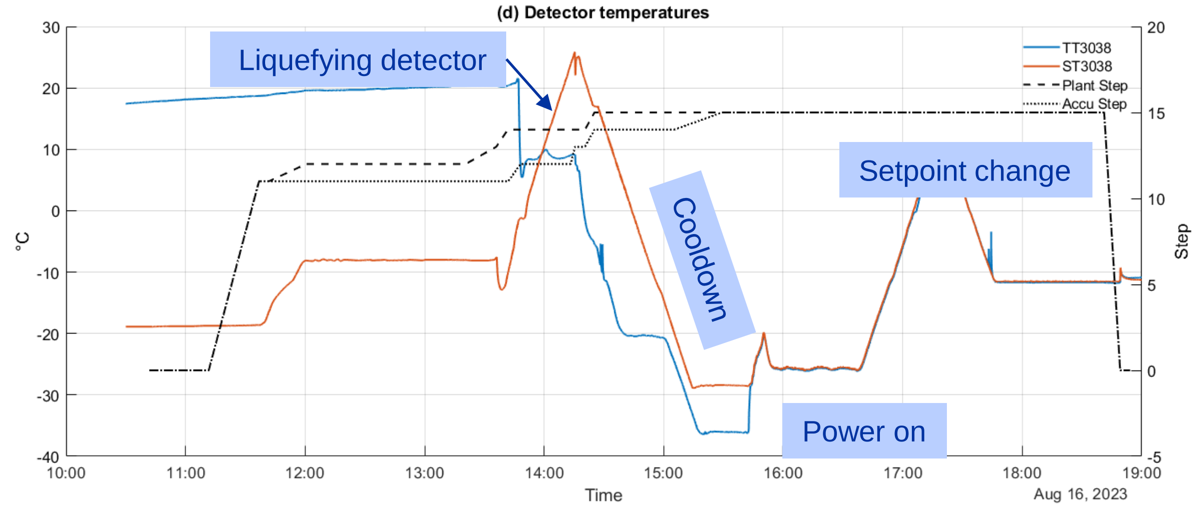
Start-up with surface storage starts from plant vapour state

Plant and Accumulator start-up



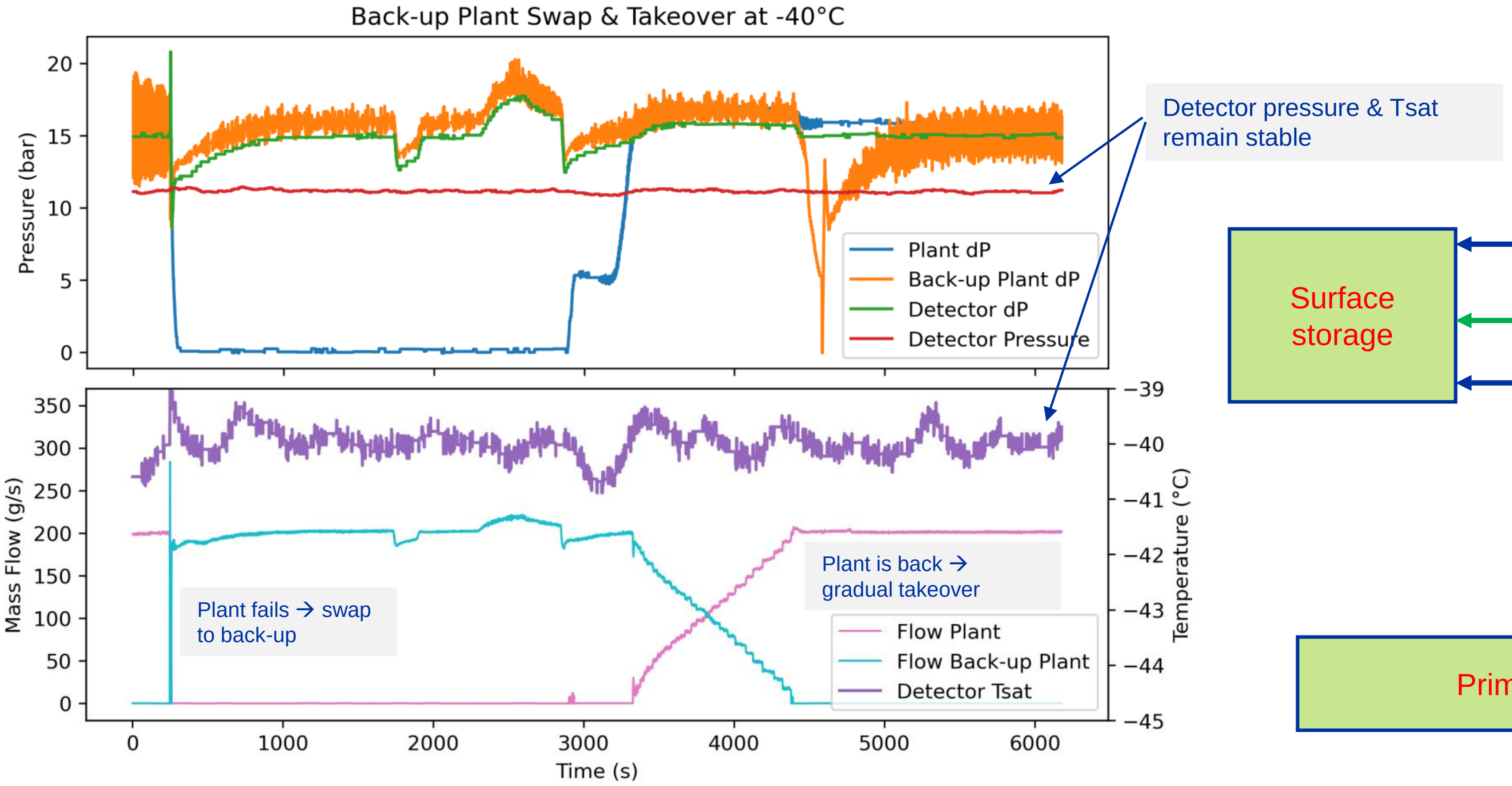


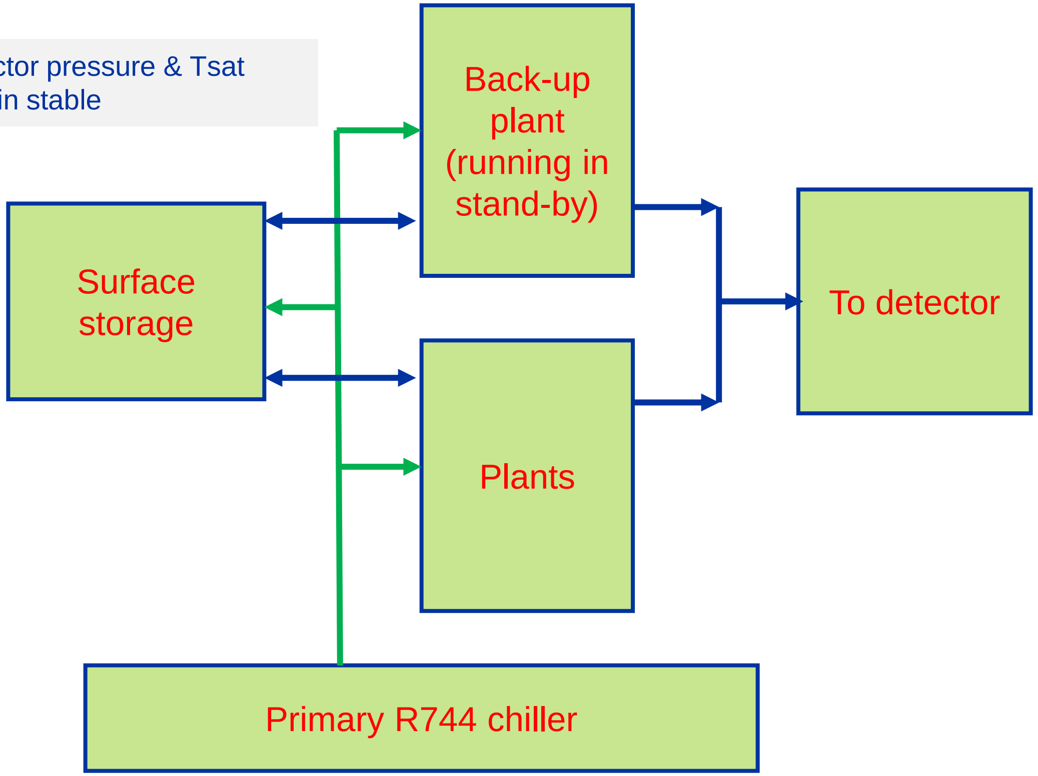




Back-up Plant Functionality

- Back-up plant is circulating in standby instantly kicks in and starts sending liquid to detector in case of main plant failure
- A temporary high flow is given due to the discharging of the higher pressurized back-up plant
- Pressure differential is maintained, and flow has not dipped to interlock values. Therefore, detector continues running during a swap
- Once the main plant is restarted, a swap takeover is performed in return, and the back-up plant returns to standby





Summary & Conclusions

Summary & Conclusions

The DEMO has successfully been operated full time since October 2022

- Including some technical stops for upgrades

Many aspects of DEMO operation have been thoroughly tested

- Design load of 100 kW at -45°C is attainable
  - Both in flow-through and traditional mode
- Stable performance at different heat loads at -45°C has been achieved
  - Heat exchanger performance considerably improved
  - Flow-through mode tested and applied successfully as baseline operation
  - Good control strategies for stable detector cooling at ultimate conditions
  - Also good temperature control when in liquid
- Surface storage interaction
  - Accurate accumulator level control has turned out to be possible
  - New start-up procedures have been run through using surface storage interactions
- Back-up plant functionality has successfully been tested at different temperature setpoints and configurations

Predictions for the Final Systems

- Stable operation at temperatures from +15°C to -40°C at the detectors is expected from DEMO operation, irrespective of the load
- Performance of DEMO meets foreseen detector heat loads, and the system is expected to handle heat load deviations and other perturbations well
- With thorough commissioning campaign, good performance is expected throughout the final system lifetime

Thank you!!

On behalf of the EP-DT team!

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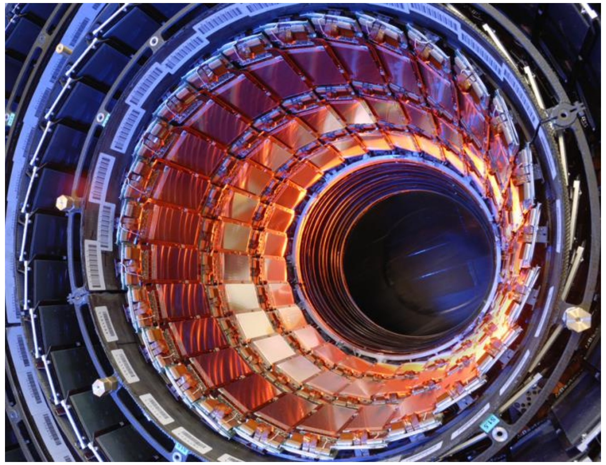
The basic concept: 2PACL

Two-Phase Accumulator Controlled Loop → 2PACL
Low vapor quality cooling for best heat transfer in small tubes
Large temperature range
- +20°C / -45°C
- Independent to applied heat load

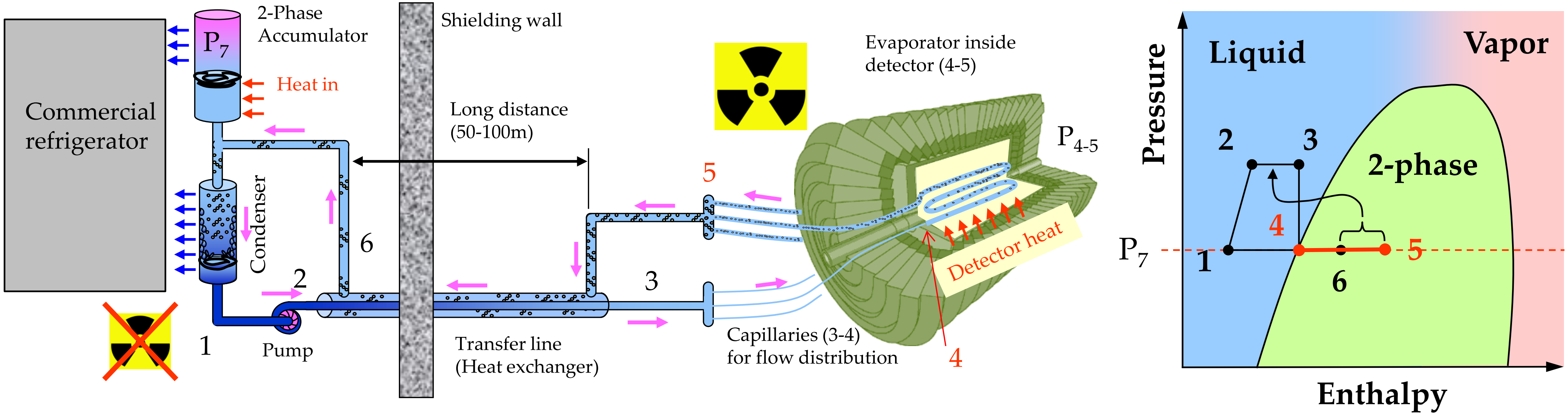
Liquid loop start-up
- No thermal shocks

Very stable evaporator temperature control at a distance
- Detector Pressure ≈ Accumulator Pressure

All active control in distant plant in an accessible area



Successful in first LHCb Velo detector and Velo upgrades, CMS Pixel detector and ATLAS IBL



Detector Specifications

Detector type			Evaporator set point (°C)	Detector design load (kW)	Ambient Pick-up (kW)	Pre-heaters or Warm-nose(kW)	Maximum load for cooling plant (kW)	# of units	# of pump heads	Load per unit (kW)	Load per head (kW)	Design VQ @ cold	Detector flow(g/s)	Flow incl.MTFL By-pass (10%)	Flow Incl. plant by-pass (10%)	Cooling plant name
CMS	OT		-35°C	114,9	0	0,0	163,4	2	3	81,7	27,2	0,42	621	683	752	P1, P2
	IT			48,5	0	0,0										
	BTL		-35°C	36,1	6,5	1,2	43,8	1	2	43,8	21,9	0,33	424	466	513	P3
	CE		-35°C	242	15	0,0	257	4	2	64,3	32,1	0,42	488	537	591	P4, P5, P6, P7
	ETL		-35°C	69,5	2	3,0	74,5	1	2	74,5	37,3	0,42	566	623	685	P8
ATLAS	HGTD	Nominal	-40°C	35,2	2,5	0,0	39,3	1	2	39,3	19,7	0,33	369	406	447	P1
		Maximal		36,8												
	SBR	Nominal	-37°C	45,1	10,2	8,6	102,9	2	2	51,4	25,7	0,33	492	541	595	P2, P3
		Maximal		54,1												
	SEC	Nominal		26,1												
		Maximal		30,0												
	POB	Nominal	-40°C	50,6	9,2	9,4	112,7	2	2	56,4	28,2	0,33	530	583	641	P4, P5
		Maximal		60,7												
	PEC	Nominal		27,8												
		Maximal		33,4												
	PXI	Nominal	-40°C	20,1	2,7	3,0	29,8	1	1	29,8	29,8	0,33	280	308	339	P6
		Maximal		24,1												