Cooling Supply for the STS Detector: Lessons Learned for the Future

Engineering Design Report

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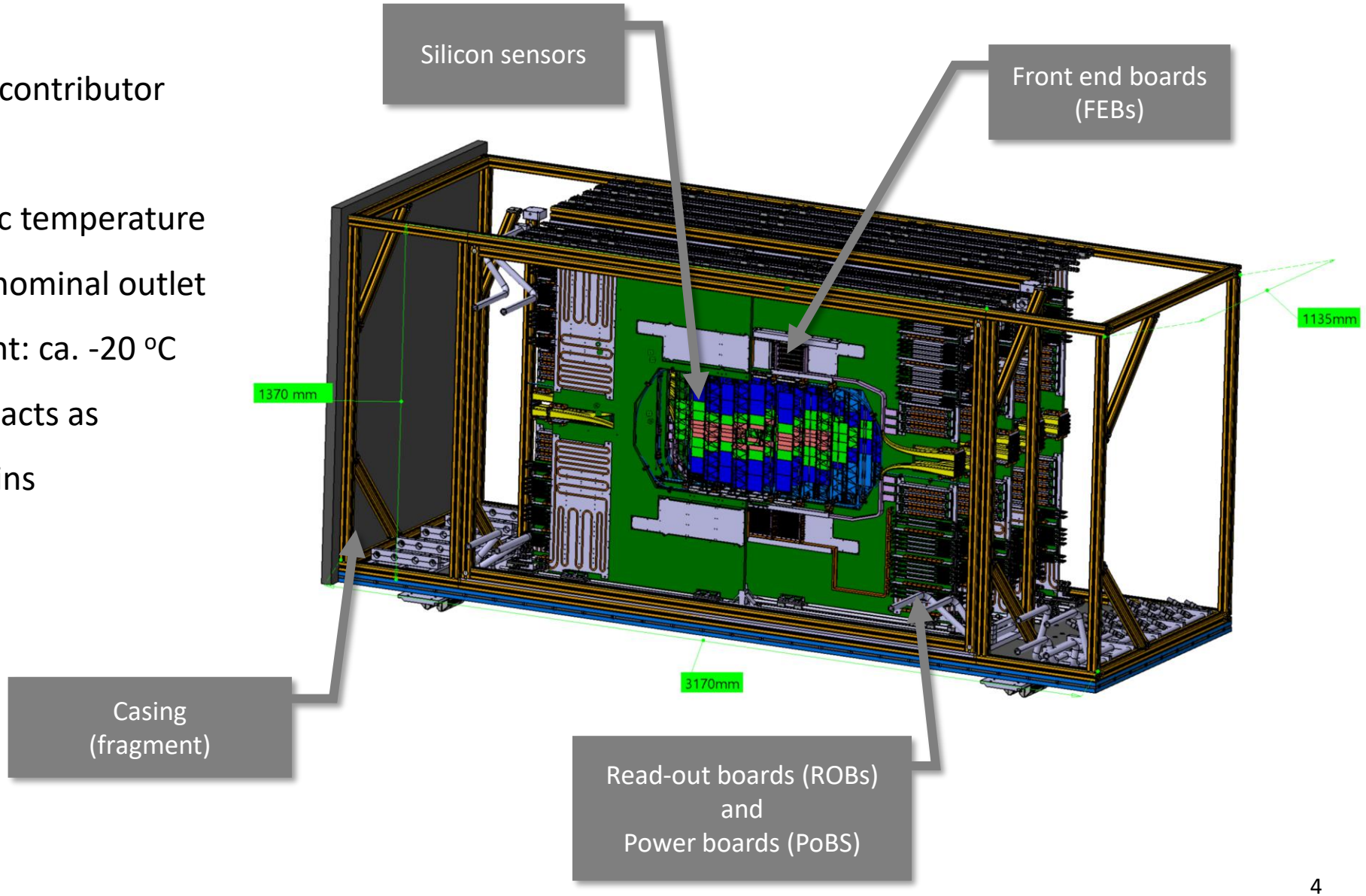
Agenda

1. The final vision on the cooling supply for STS detector
   - power dissipation and heat gains
   - installation layout
   - specs for the final cooling plant
2. The pilot cooling supply system
   - introduction to the set-up
   - trial-run results
3. Details on 3M NOVEC 649 usage as a coolant
   - is there a problem with acidity?
   - dealing with precipitation due to solubility falling w/ temperature
   - NOVEC production discontinuation

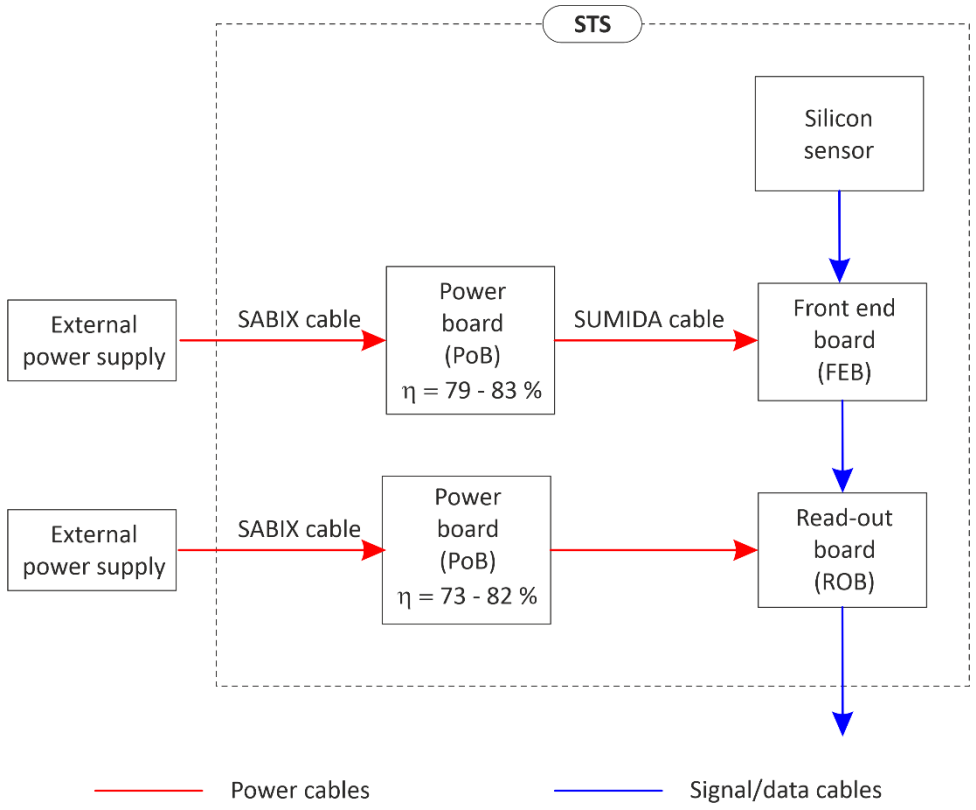
The final vision on cooling supply for STS detector

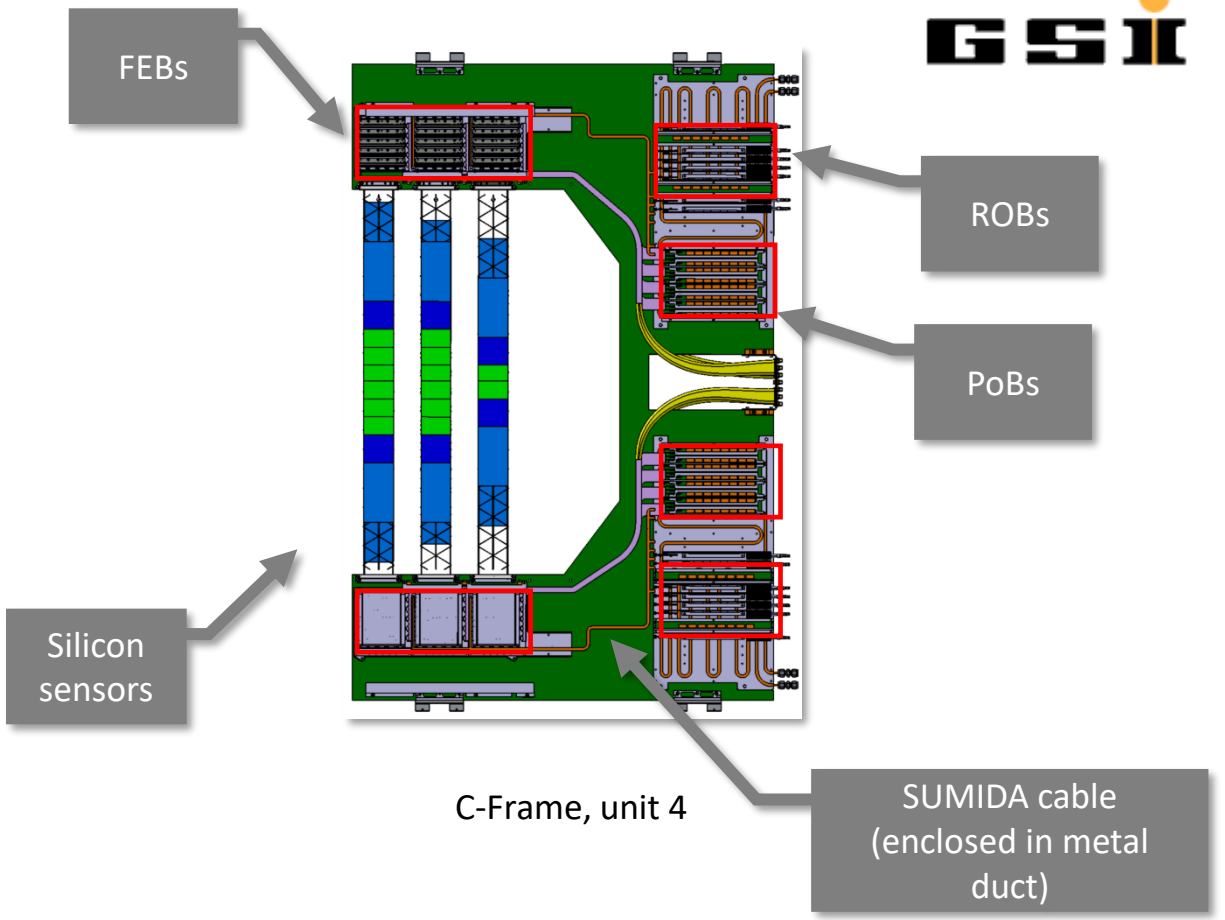
STS Detector Overview

- Electronic boards are the main contributor to the power dissipation
- Silicon sensors require a specific temperature to operate, which is related to nominal outlet temperature of the cooling plant: ca. -20 °C
- The casing (thermal enclosure) acts as an additional source of heat gains



Electronic Boards Power Dissipation

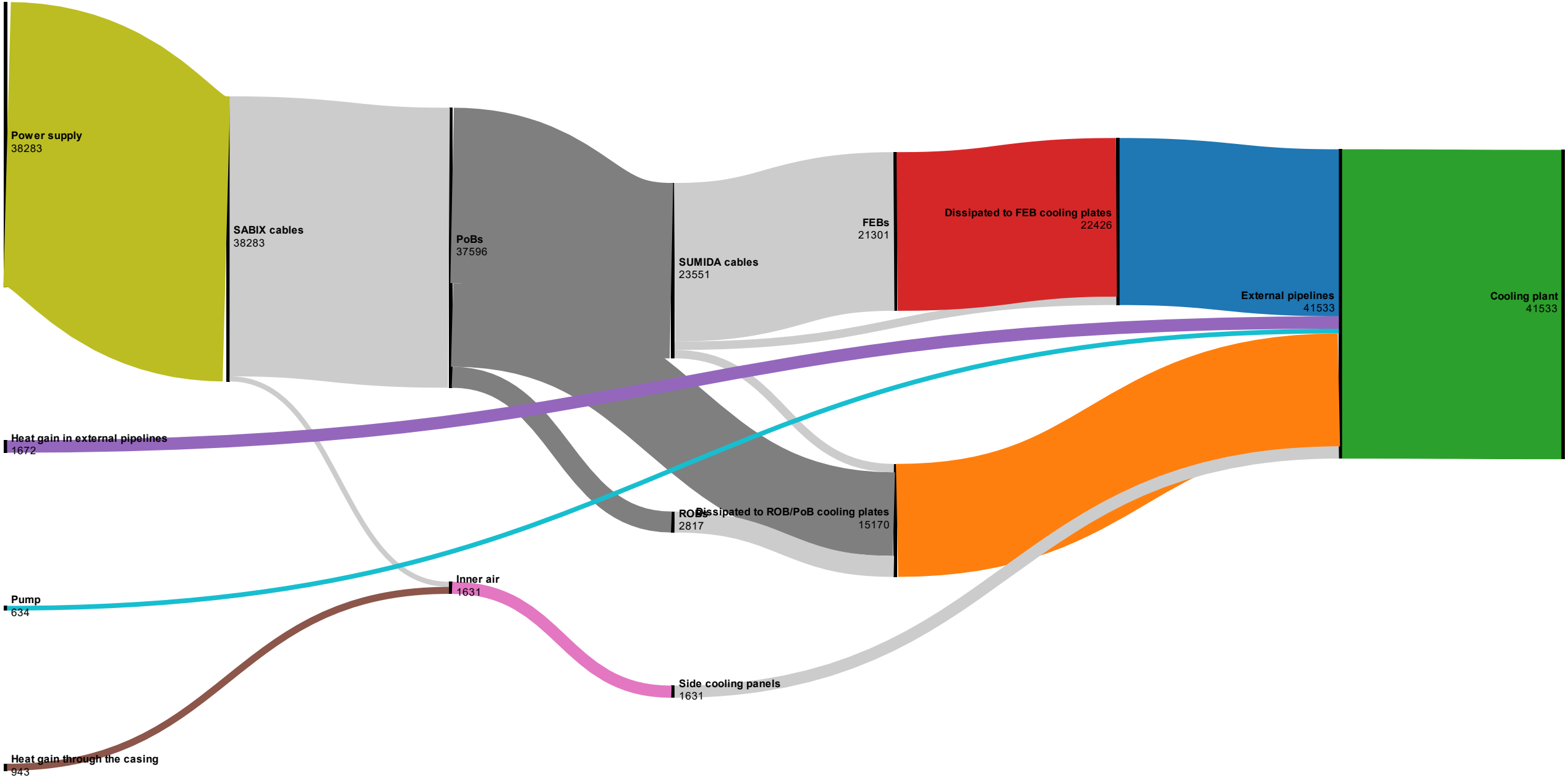




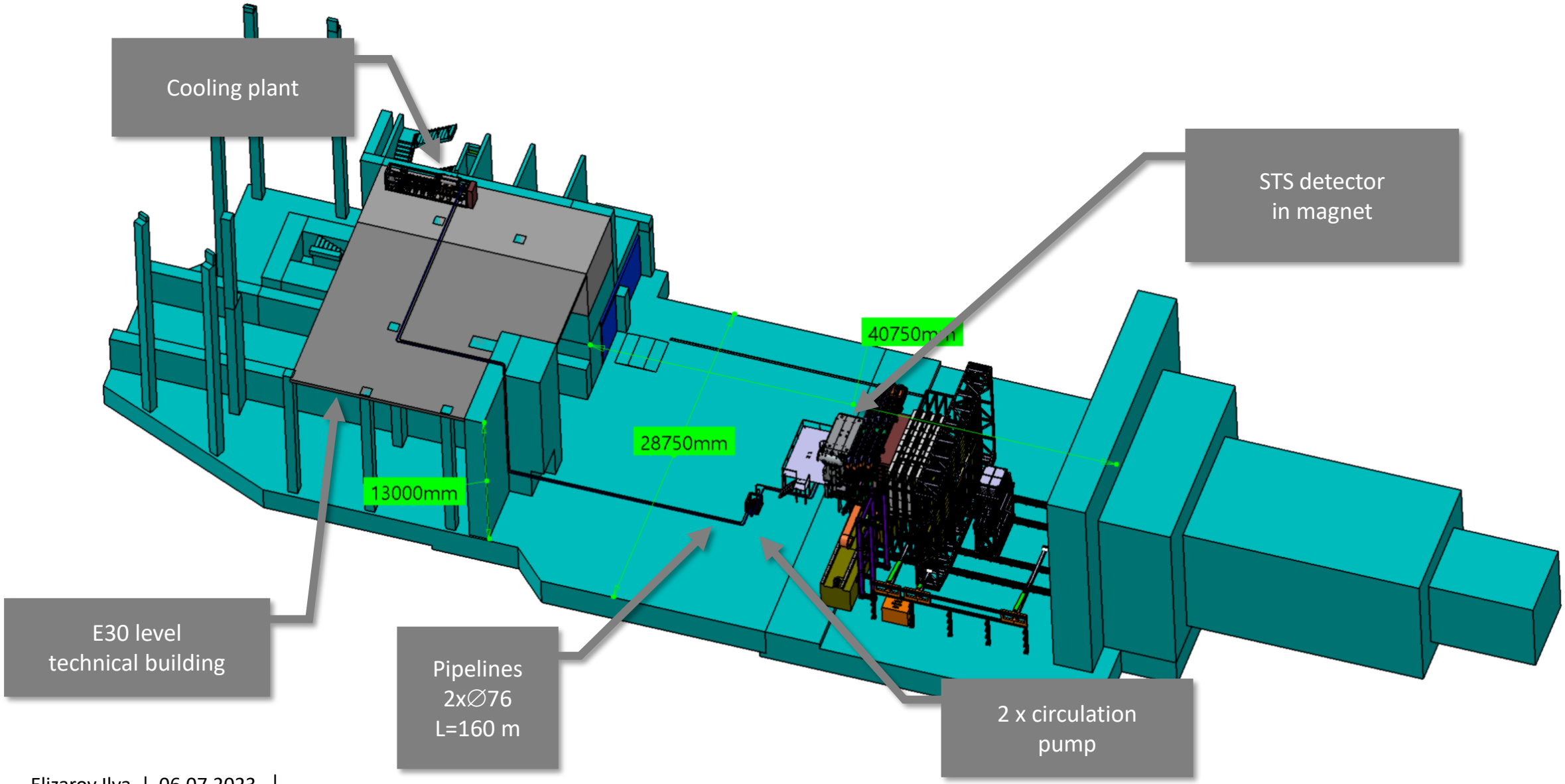
Electronic boards power dissipation per type

FEB 8 ASICS + 4 LDO	ROB 3 FPGA	FPoB per FEB 16 FEAST	RPoB per ROB	SUMIDA cable for one FEB, L=1,6 m
12,20 W	4,89 W	5,75 W	2,04 W	1,28 W

Power Flow Summary

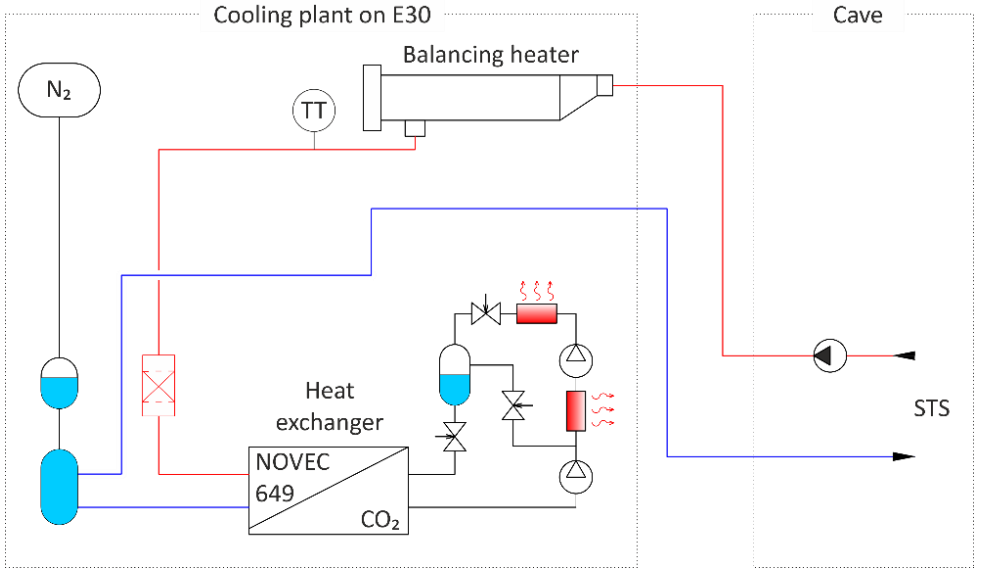


Cooling Supply Installation Layout



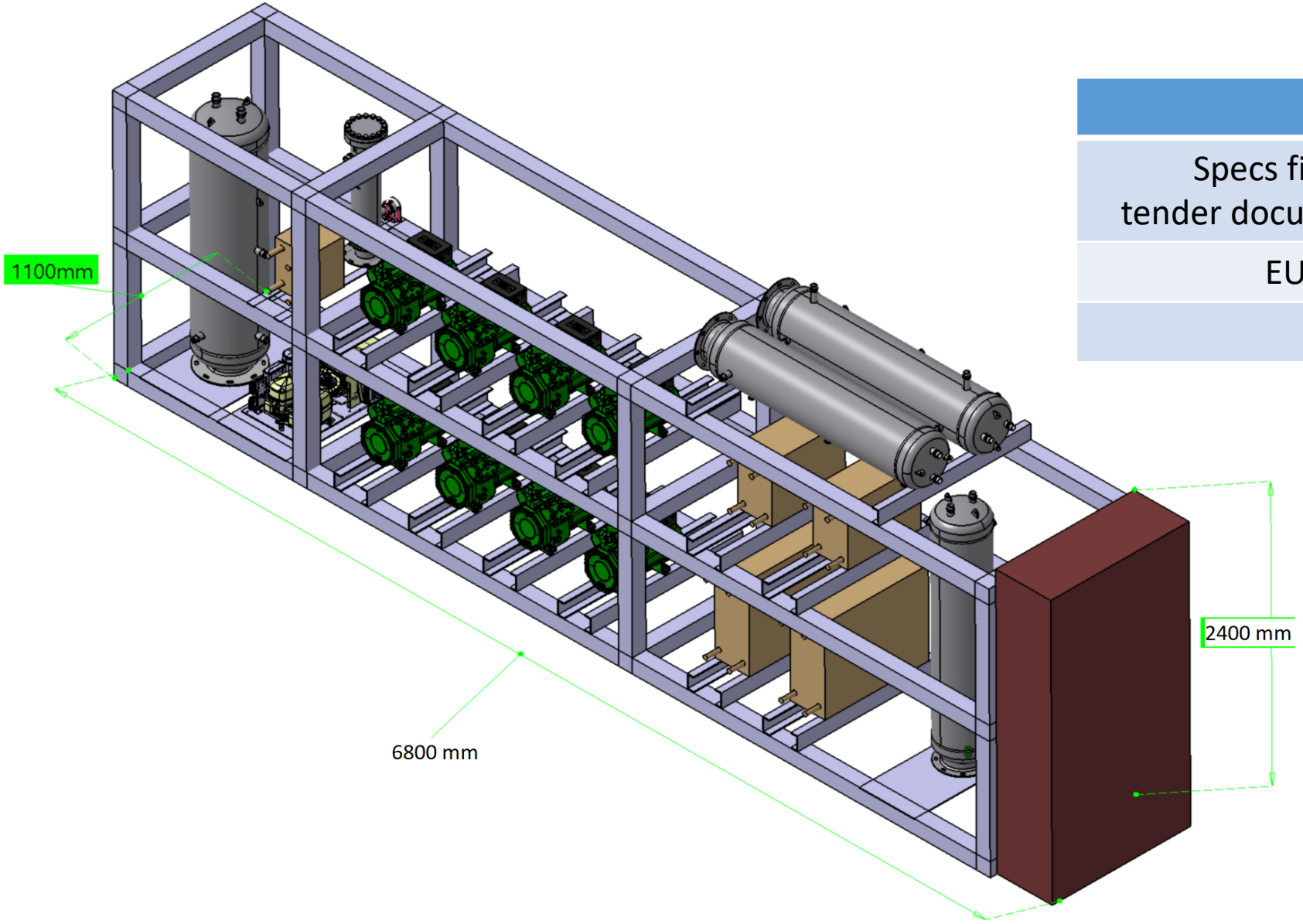
The Final Cooling Plant Specs

Parameters	Units	Value	Note
Nominal cooling capacity	kW	50	+20% design safety factor
Partial cooling capacity	kW	23	-20% design safety factor
Nominal power of balancing heater	kW	50	
Primary side refrigerant	-	CO_2	
Secondary side coolant	-	3M NOVEC 649	
Nominal outlet coolant temperature	°C	-22,5	-2,5 K design safety margin
Nominal inlet coolant temperature	°C	-11,5	+2,5 K design safety margin
Nominal flowrate	m^3/h	20	+10% design safety factor
Nominal pressure difference	bar	2,7	+20% safety design factor
Static pressure on the secondary side at the plant's level in stand-by mode	bar	0,9	at 23 °C
Static pressure on the secondary side at the plant's level at nominal operation	bar	0,2	



- From 2022, the last EU legislation imposes global warming potential (GWP) limit of 150 on multipack refrigeration with a capacity of 40 kW, except for cascade systems.
- The refrigeration industry is shifting towards usage of low GWP refrigerants, one of which is CO_2 itself.
- CO2 has disadvantage of high expansion coefficient, high operation pressure, toxicity, and requires qualified personell for the maintenance.
- 3M NOVEC 649 or perfluoro(2-methyl-3-pentanone) has advantage of low operating pressure, non-toxicity, low GWP (equals one), and being easy to use.
- The STS cooling supply makes use of CO2 and NOVEC 649 simultaneously to take advantage of the both.

The Final Cooling Plant Render

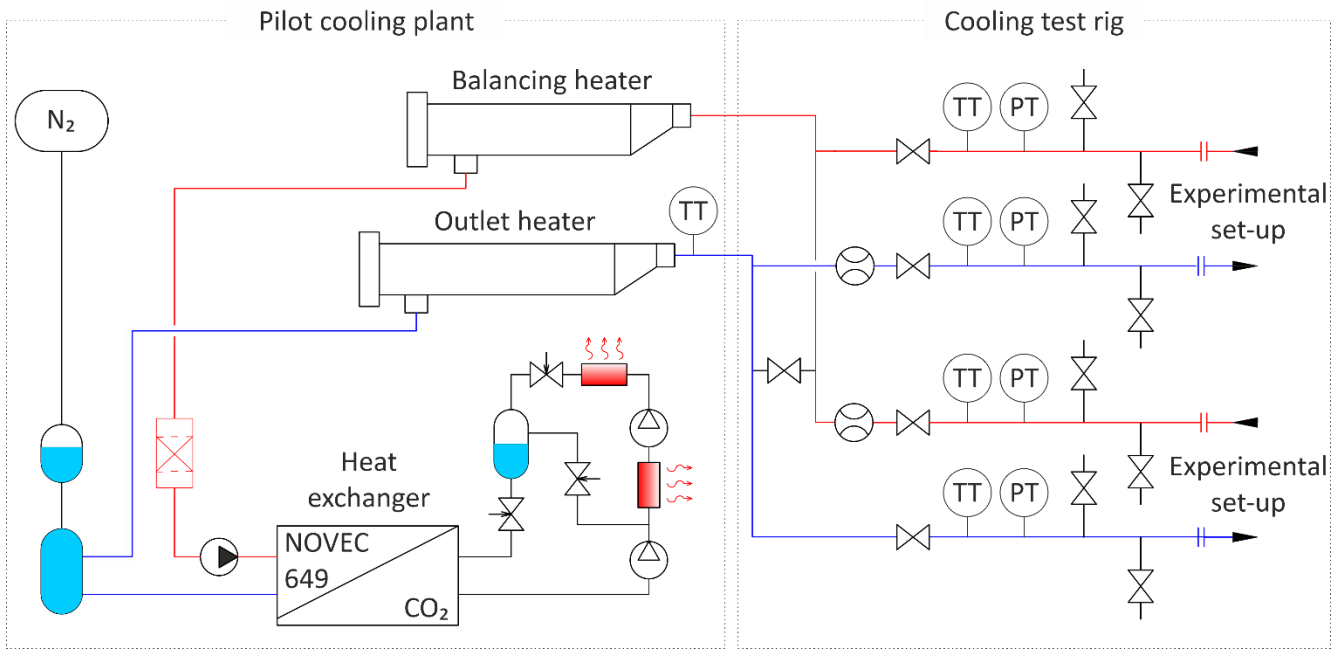


Outlook	
Specs finalization, tender documentation	Ready by Sep, 2023
EU tendering	Sep, 2023 – Feb, 2024
Ordering	Mar, 2024

The pilot cooling supply system

The pilot cooling supply

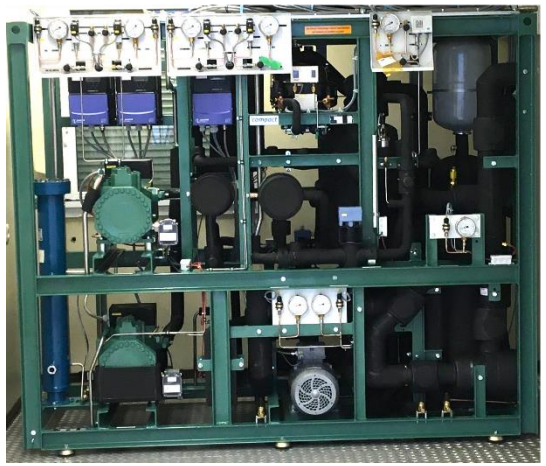
A pilot cooling supply system has been built at GSI to verify its suitability for the STS detector electronics cooling.

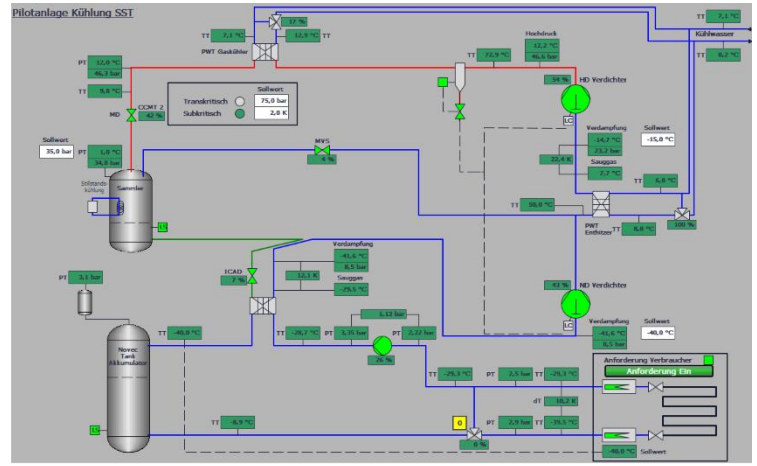


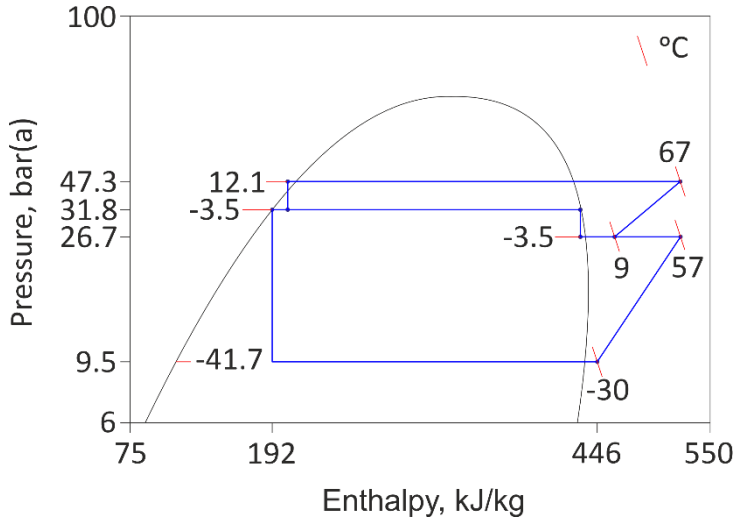
- The pilot cooling is a booster-type CO2 refrigeration system that extracts heat from the secondary side coolant through a heat exchanger (evaporator).
- Outlet heater extends temperature range of the pilot cooling plant.
- Balancing heater covers the mismatch between the minimum cooling demand of the plant and experimental set-ups.
- With the cooling test rig, various experimental set-ups and the drainage system can be connected to the cooling supply.

The Pilot Cooling Plant Specs

Parameters	Units	Value	Note
Nominal cooling capacity	kW	15	
Partial cooling capacity	kW	6,4	
Primary side refrigerant	-	CO_2	
Secondary side coolant	-	3M NOVEC 649	
Nominal outlet temperature of the coolant	°C	-40 ... -30	
Outlet coolant temperature with the outlet heater	°C	-30 ... 10	
Flowrate range	m^3/h	1,2 ... 2,8	at -40 °C
Pressure difference range	bar	0,5 ... 2,5	
Refrigeration cycle coefficient of performance (COP)	-	2,05	
Static pressure on the secondary side in stand-by mode	bar	3,1	
Static pressure on the secondary side in operation	bar	3,4	
Electric power range of the balancing heater	kW	0 ... 11	
Electric power range of the outlet heater	kW	0 ... 24	

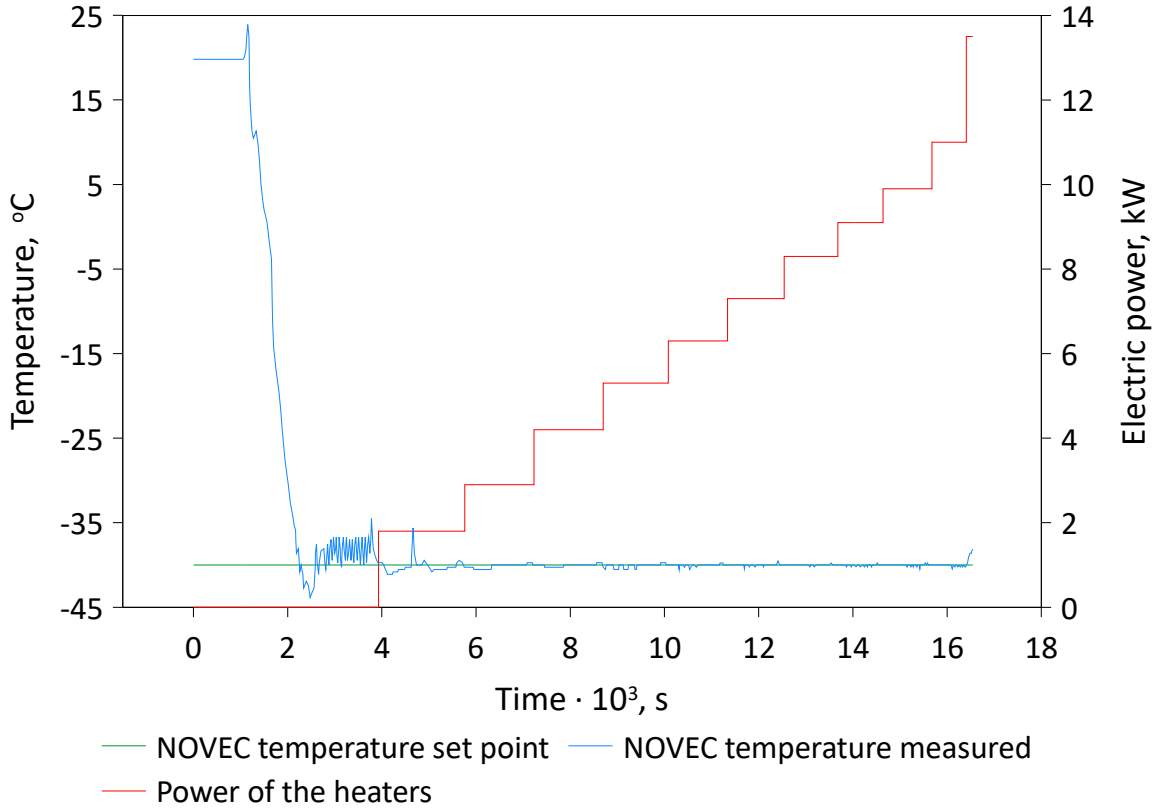






Pilot Cooling Plant: Trial-Run

A trial-run was performed to test the performance of the pilot cooling plant: electric power of the heaters was increased in steps to check if the plant can keep up the temperature set-point -40 °C.



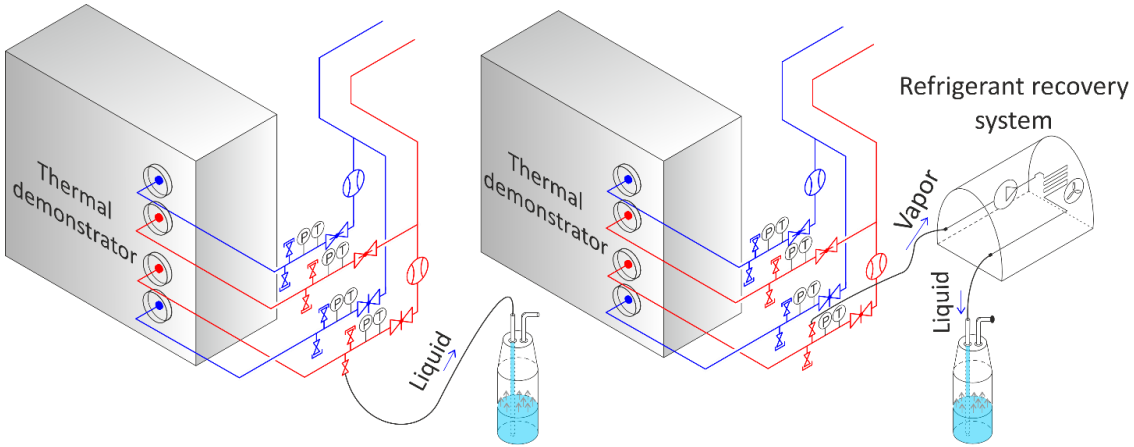
- Steady-state operation is only possible with the heat gain equal to partial cooling capacity of the plant
- The set-point can be maintained with maximum heat gain from the heaters of 11 kW - nominal capacity was achieved

Cooling Test Rig

- The cooling test rig was built to allow connecting various experimental set-ups, including the thermal demonstrator, for testing cooling concept for the STS detector
- Supports standard DN 25 flange connection
- The STS detector can be connected for testing without a beam
- Monitors flow parameters:
  - flow rate;
  - inlet and outlet temperature;
  - inlet and outlet pressure.
- Supports connecting the drainage system

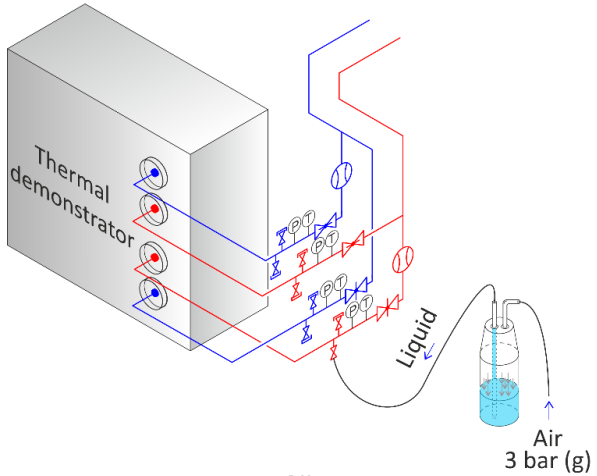
Drainage System

The drainage system allows for draining and refilling experimental set-ups with NOVEC 649 without losing the liquid.

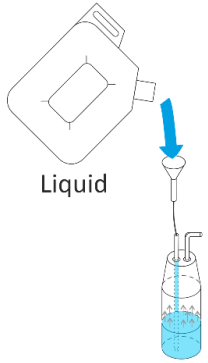


Draining: liquid stage

Draining: vapor stage



Refilling



Coolant storage

The drainage system connected to the cooling test rig

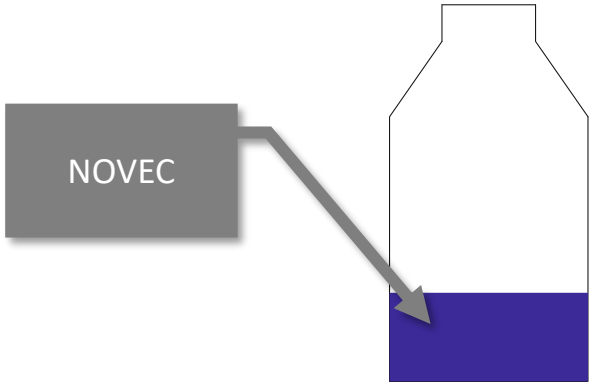
Details on NOVEC 649 usage in the cooling supply system

Acid Formation Mechanism

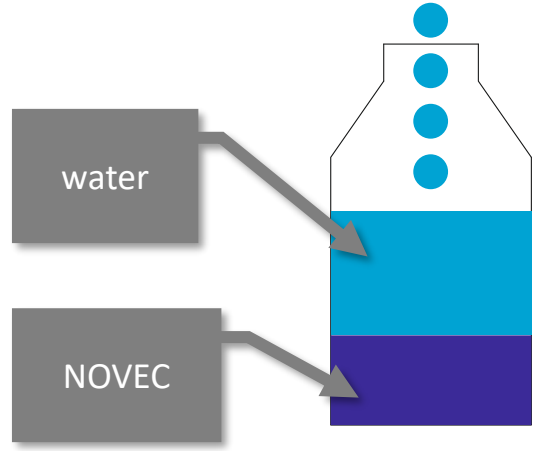
NOVEC undergoes a hydrolysis reaction with dissolved in it water:

$$\underset{\text{NOVEC}}{C_6F_{12}O} + H_2O \rightleftharpoons \underset{\text{PFPrA}}{C_3F_5O(OH)} + \underset{\text{HFC-227ea}}{C_3F_7H}$$

The consequence of the reaction depends whether water is added to NOVEC from an external source:



Reaction without excess of water

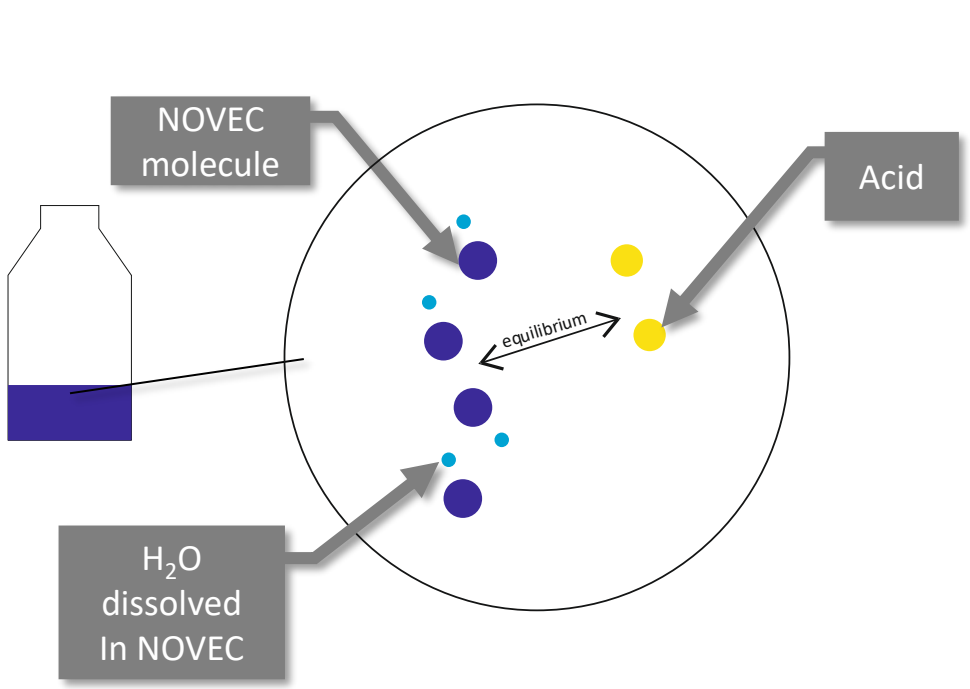


Reaction with excess of water
(two separate phases are formed due to poor solubility)

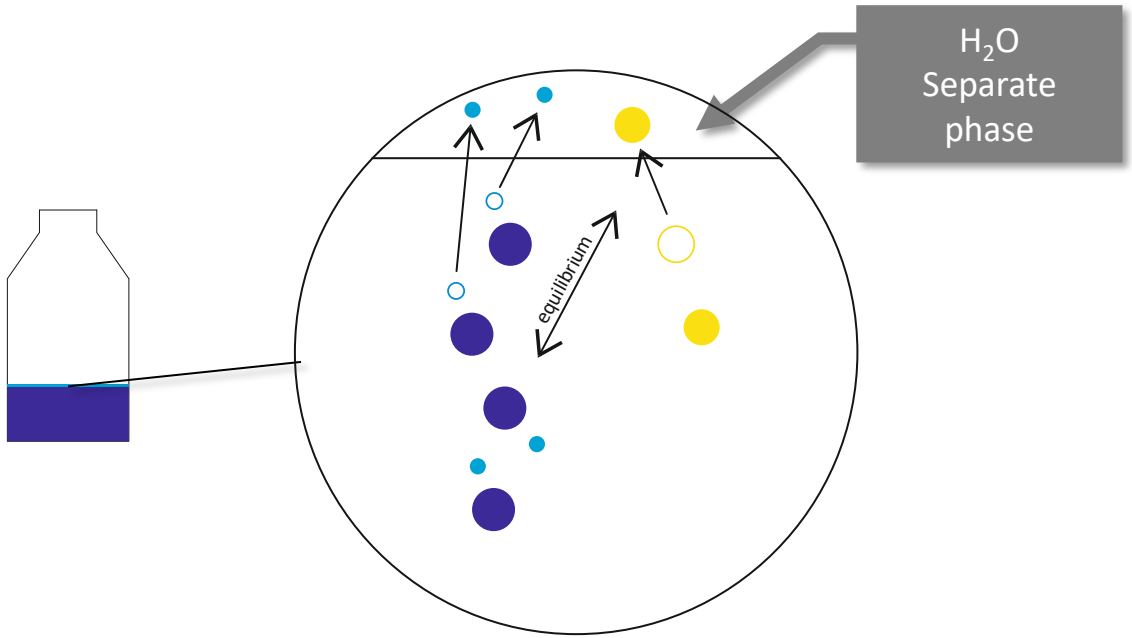
- Some acid can be present from off-the-shelf NOVEC, up to 3 mg/kg according to the datasheet - cannot cause corrosion
- Water solubility in NOVEC is poor 10 mg/kg at 25 ^{o}C

Reaction without Excess of Water

No acid is formed during water precipitation when NOVEC is cooled



Cooling
to 0 °C

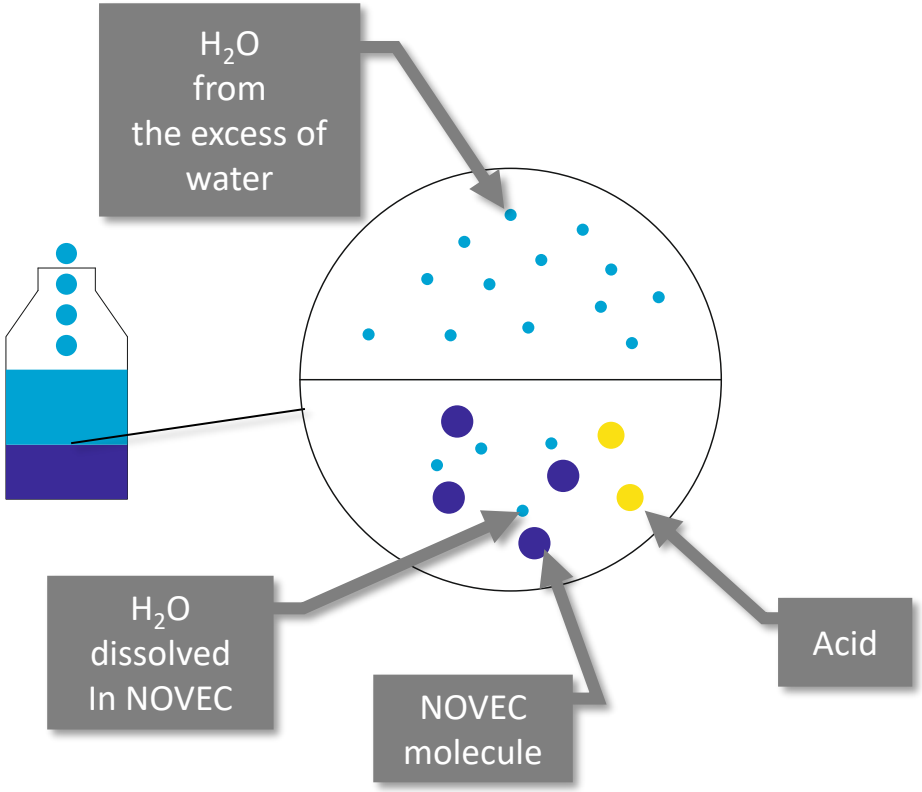


Miniscule acid concentration in NOVEC is **in equilibrium** with dissolved water

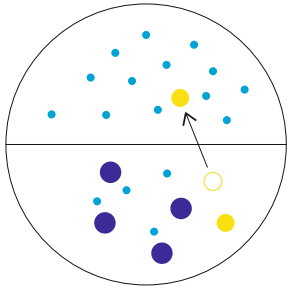
Due to the decrease in water solubility in NOVEC, water molecules start to leave NOVEC solution forming a separate water phase into which acid can migrate. NOVEC, water and acid concentration are kept **in equilibrium**.

Reaction with Excess of Water

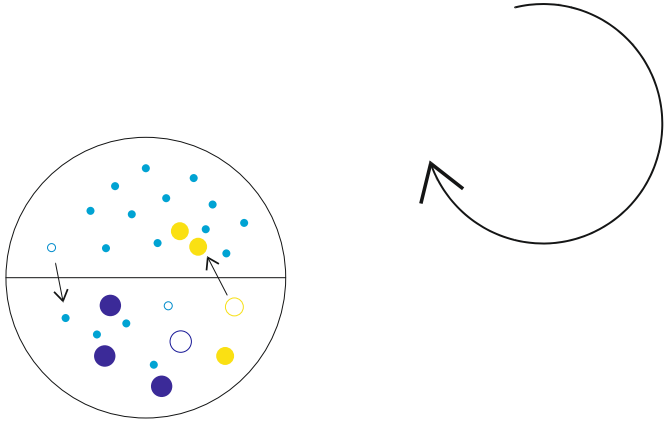
Acid is only created in presence of water excess from external source



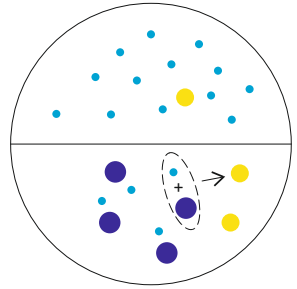
When excess of water is added to NOVEC, the equilibrium of hydrolysis reaction is broken



Acid migrates into water

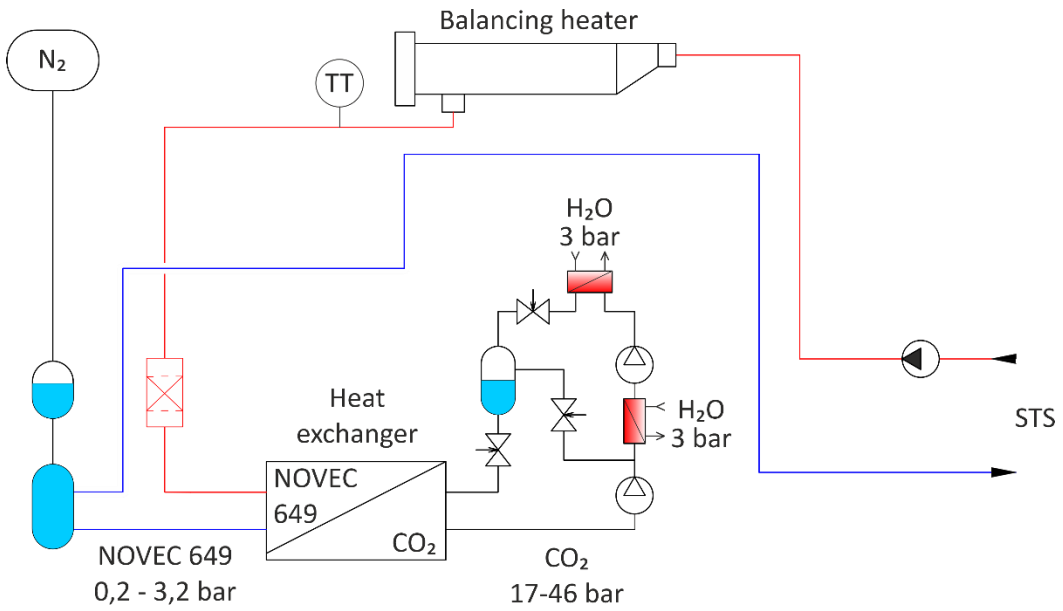


Used water molecules are replaced with those from the excess of water. Acidity of water is increased.



More NOVEC molecules are subjected to hydrolysis

Acid Formation Mechanism: Conclusion



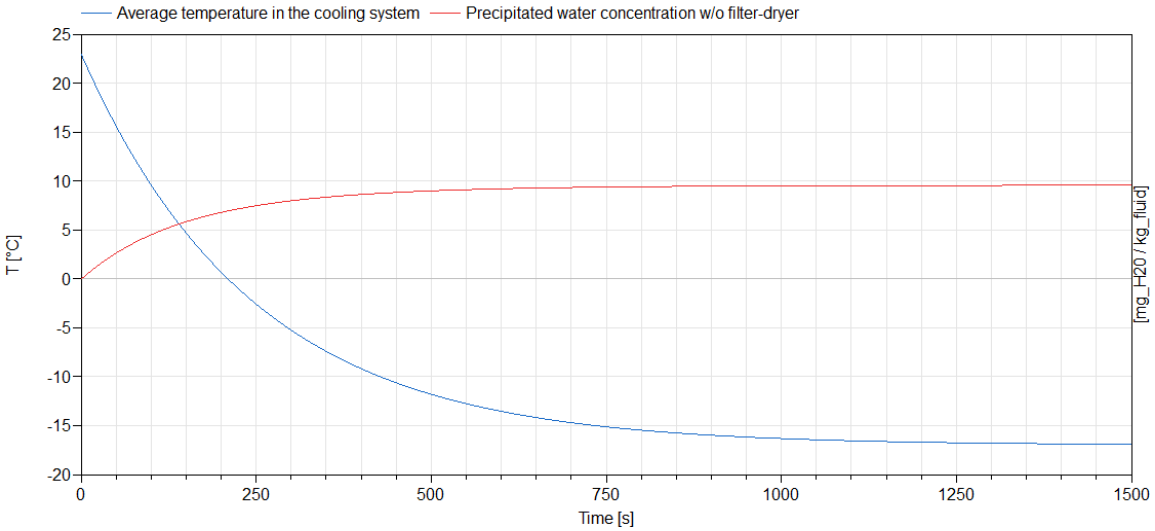
The piping system of CO_2 cooling plant is at the pressures that prevent water to enter CO_2 circuit even if evaporator and desuperheater started to leak.
In case of noticeable CO_2 pressure loss, a controller will inform about this failure and stop the plant.
This is true under assumption
if the heat exchanger is leaking as well.

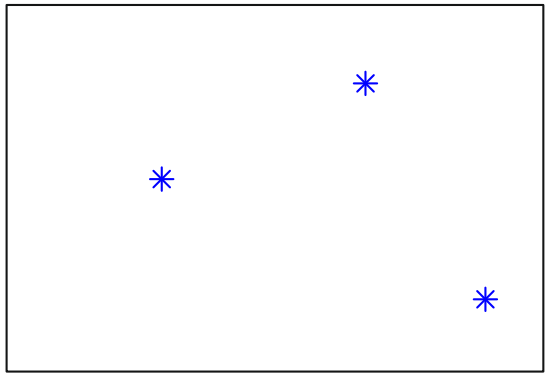
- Since our cooling supply system has no possibility for water to be added inside the system from an external source, no acid formation will occur in the system under any circumstances or operational modes
- The maximum acid concentration off-the-shelf NOVEC is 3 mg/kg, no more will be synthesized inside the cooling supply system
- The acidity of 3 mg/kg is equivalent to weight share $3 \cdot 10^{-6}$, which is so miniscule, that it cannot case any noticeable corrosion inside the piping system

As a result, measures against acid formation **are not required** for our cooling supply system, e.g. acid concentration monitoring, acid absorption devices

Precipitated Water Freezing

While the NOVEC temperature is reaching the nominal set-point -22,5 °C at the cooling plant, water from NOVEC will principate and freeze. The amount of frozen water is extremely low due to the poor solubility in NOVEC.





10 mg/kg solid water concentration is approximate equal to three snowflakes per liter

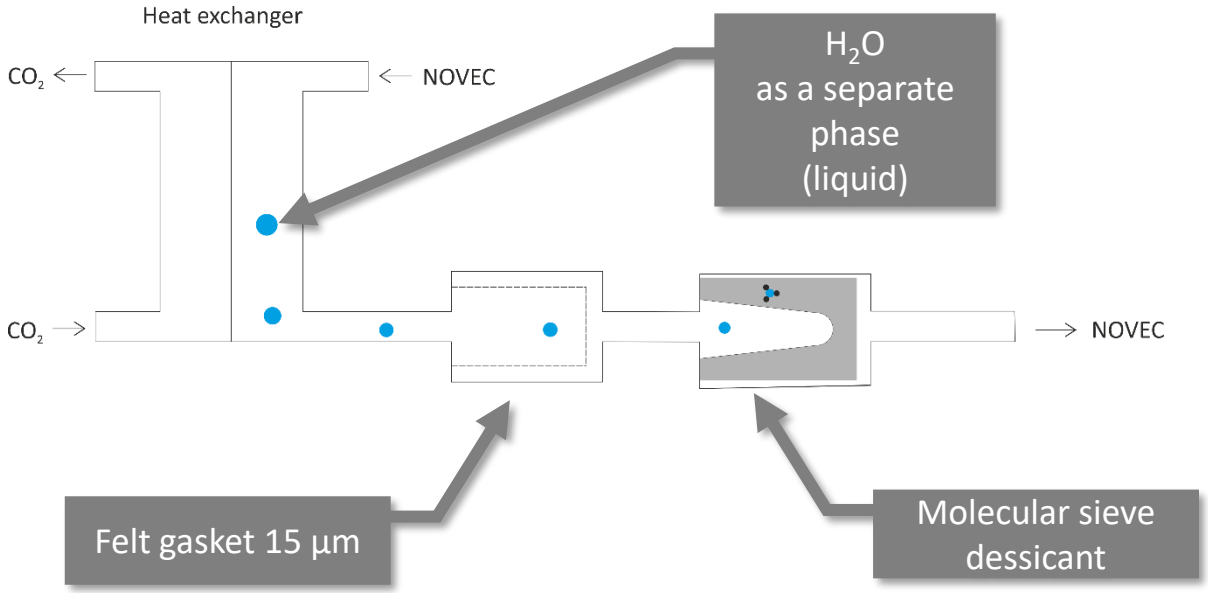
The minimum solid water sediments size is 500 µm

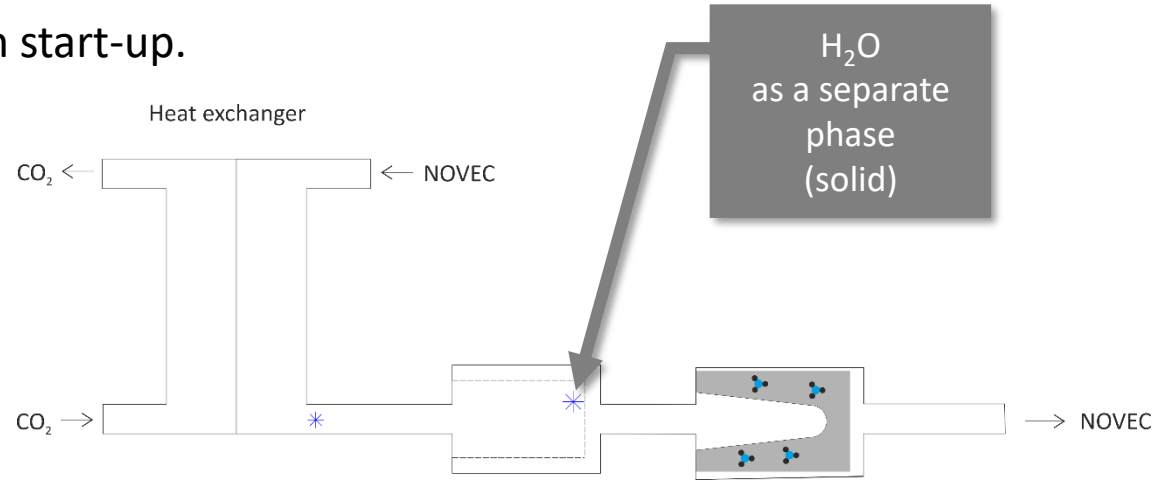
Forming precipitates can be eliminated **during formation** process by drying and filtered

The share of water content that can be extracted in liquid phase is 78%

Eliminating Precipitated Water

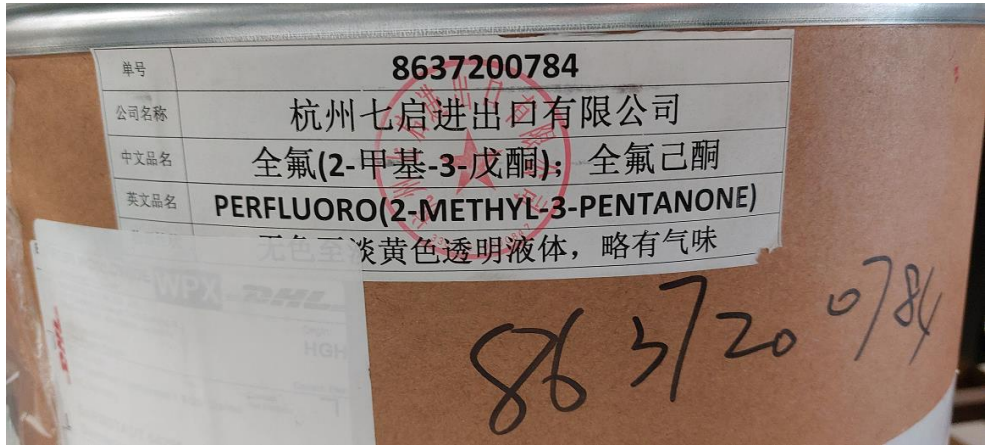
- Drying NOVEC at room temperatures trying to extract dissolved in it water is ineffective with molecular sieve filter dryers (99% share of industrial refrigeration). However, molecular sieve driers are very effective for absorbing water **as a separate phase.**
- As a result, for an effective drying process NOVEC must be brought to 0 °C, when most of the water content precipitates as water. After most of the water is absorbed, a 15 µm filtering material remaining solid water particles. No precipitations are left after the cooling plant – the piping system of the detector cannot be clogged.
- This method is highly reliable and, thus, does not require humidity monitoring system.
- Water elimination in this way naturally occurs during the system start-up.





NOVEC Substitution

- 3M corporation announced that it plans to discontinue per- and polyfluoroalkyl substance (PFAS), including include NOVEC 649 and its variation for fire-extinguishing application NOVEC 1230, by the end of 2025
- NOVEC 649 is a trademark for perfluor(2-methyl-3-pentanon)
- An extensive search for alternative suppliers that can provide us with industrial quantities and acceptable purity 99,9% was made
- After careful considerations, one company was selected, and a trial purchase of 35 kg was made



Thank you for your attention