Compressed Baryonic Matter Experiment

CBM-TN-230xx v1.0
July 4, 2023

The final and pilot cooling plant for the STS detector

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Abstract

A cooling supply concept with 3M NOVEC 649 as a coolant is presented for the STS detector. The requirements for the final cooling plant have been established, in particular power dissipation and heat gain.

The final cooling concept is based on the experience gained during designing, building, and testing pilot cooling supply at GSI — a down scaled version of the cooling supply system for the STS detector. The main components of the pilot cooling supply have been described: the pilot cooling plant, cooling test rig, drainage system.

This version of the technical note is a prelude of the cooling mechanics for the CBM-STS Cooling Engineering Design Review (July 07, 2023) - `https://indico.gsi.de/event/17904/`

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1 Power dissipation and heat gain for the STS detector

The main source of power dissipation in the STS detector are electronic boards. A diagram showing interactions between the electronic boards and their power flow is shown in fig. 1. A front end board (FEB) detects signals from the silicon sensors. After the signal is processed, it is transferred to read-out board (ROB) as data. The FEBs and ROBs are powered through power boards (PoB), which include DC-DC converters. External power supplies provide power to the power boards. In addition, power cables: SABIX and SUMIDA dissipate power inside the detector.

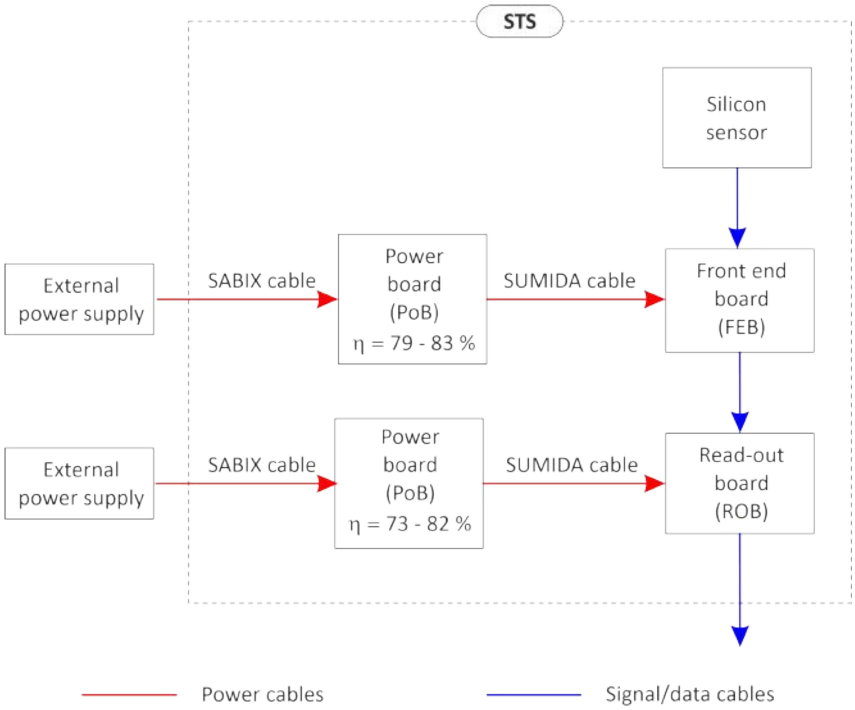

Figure 1: Electronic boards interactions and power flow

In terms of heat gains, the largest share belongs to heat gains from pipelines between the cooling plant and the front wall of the detector (see fig. 2), heat gains through the STS casing(thermal enclosure), and energy loss in the circulation pump.

The overall power dissipation and heat gain are given in table 1.

Table 1: Power dissipation and heat gain

Source	Dissipated power or heat gain [W]
Front end boards (FEBs)	25756
Read-out boards (ROBs)	2817
SUMIDA cables	2250
Power boards (PoBs)	6770
SABIX cables	688
Casing	943
Coolant pipelines	1672
Pump	634
Total:	**41530**

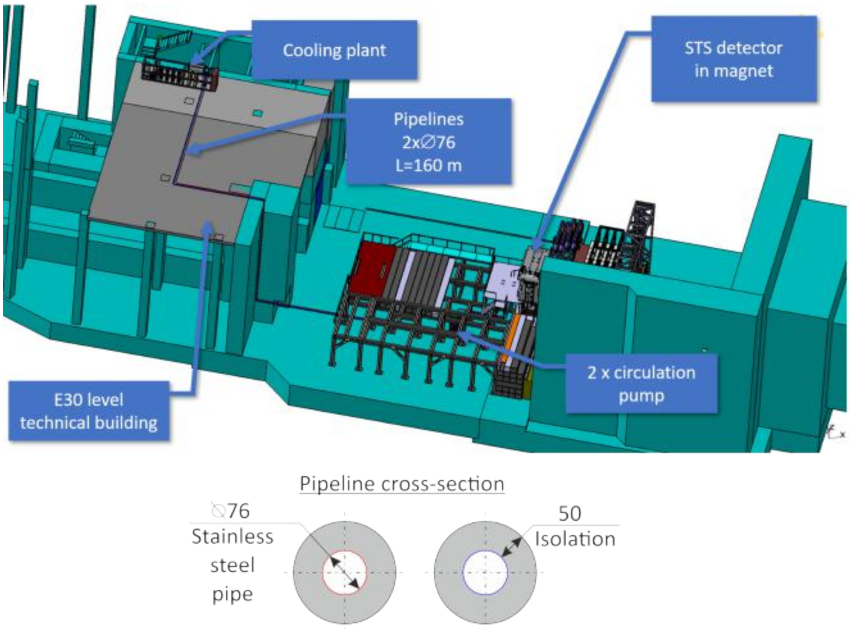

Figure 2: Coolant pipelines layout

2 The final cooling plant requirements

The basic requirements for the cooling plant are listed in table 2.

Table 2: The final cooling plant basic requirements

Parameters	Units	Value	Note
Nominal cooling capacity	kW	50	+20% design safety factor
Partial cooling capacity	kW	23	-20% design safety factor
Nominal balancing heater power	kW	50	
Primary side refrigerant	-	CO2	
Secondary side coolant	-	3M NOVEC 649	
Nominal outlet coolant temperature	oC	-22,5	-2,5 K design safety margin
Nominal inlet coolant temperature	oC	-11,5	+2,5 K design safety margin
Nominal flowrate	m3/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 oC
Static pressure on the secondary side at the plant's level at nominal operation	bar	0,2	

The following considerations were made when choosing the refrigerant and coolant:

- 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 CO2 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, and being easy to use.
- The STS cooling supply makes use of CO2 and NOVEC 649 simultaneously to take advantage of the both.

A basic process flow diagram of the STS cooling supply is shown in fig. 3. The CO2 refrigeration system cools down NOVEC 649 on the secondary side of the heat exchanger (evaporator). The fluid on the secondary side is driven by a centrifugal pump, which is located in irradiated area down in the cave. To maintain smooth outlet temperature transition, the coolant flows through a tank-accumulator that, in turn, connected to an expansion tank pressurized with nitrogen to maintain static pressure within the acceptable range.

Another important component on the secondary side is a filter-dryer with desiccant to absorb water from NOVEC 649 to avoid acid formation during the start-up due to the hydrolysis reaction between precipitated water and NOVEC. Potentially, a combined water and acid absorption filter can be used instead to provide additional reliability.

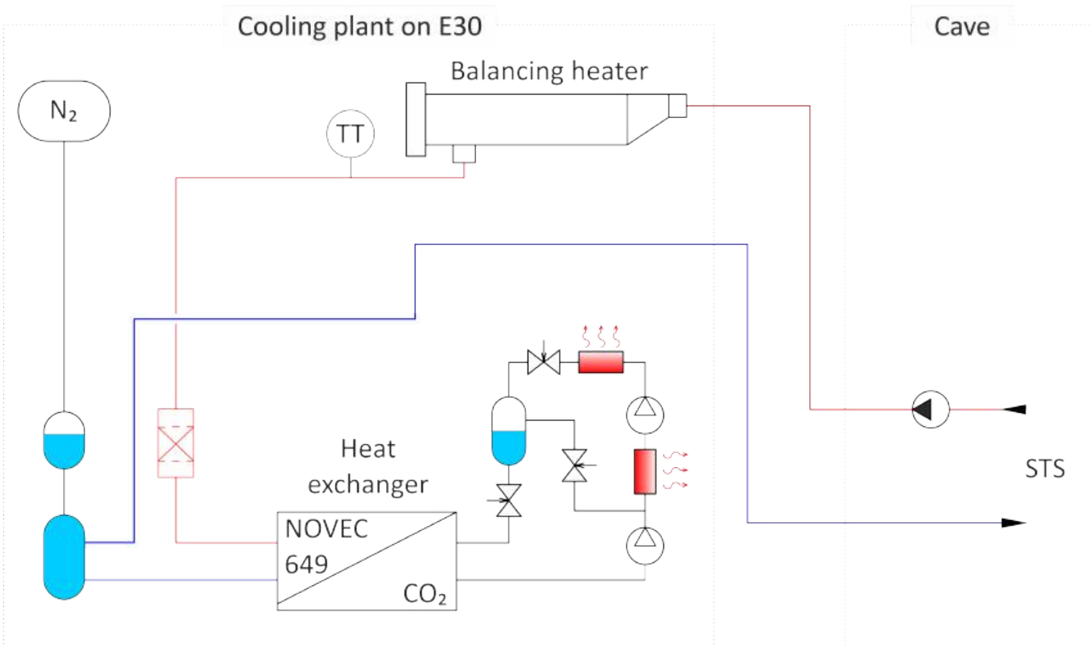

Figure 3: Basic process flow diagram of the STS cooling supply

A balancing heater is required to assure steady-state coolant temperature during power up of the detector; otherwise, power boards can experience not tested temperature fluctuations during the start-up. For this case, a plot of electric power and coolant temperature are given in fig. 4.

A 3D image of the final cooling plant for STS detector is shown in fig. 5.

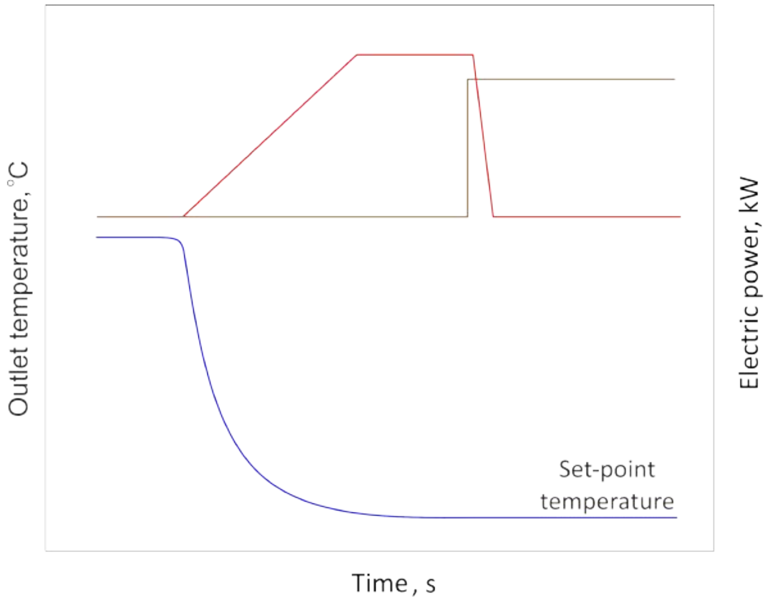

Figure 4: Plot of electric power and coolant temperature during power up of the detector

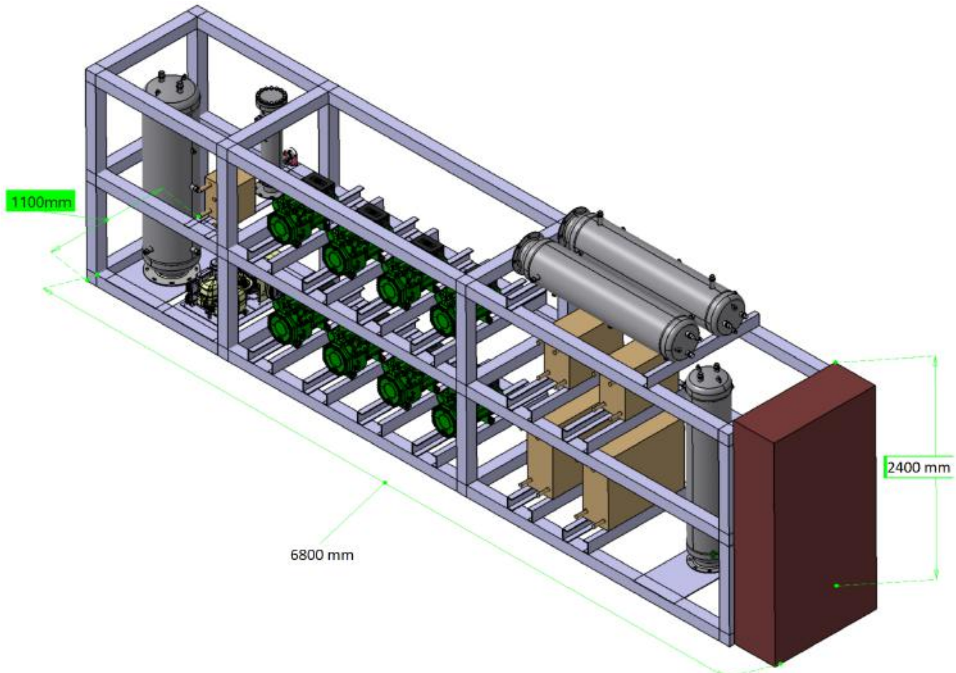

Figure 5: 3D render of the final cooling plant

3 The pilot cooling supply

To verify the cooling supply concept for the STS detector, a pilot cooling supply system was built at GSI. A process flow diagram of this system is given in fig. 6. 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 partial cooling capacity 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.

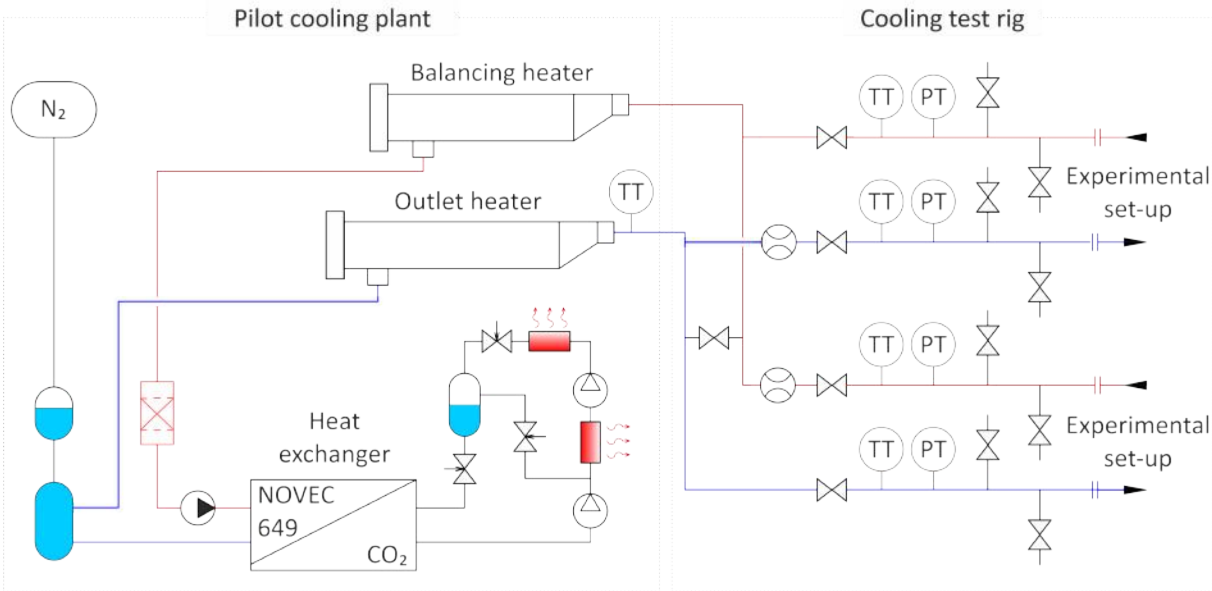

Figure 6: Plot of electric power and coolant temperature during power up of the detector

3.1 The pilot cooling plant

The pilot cooling plant specs are shown in the table 3. Despite announced outlet temperature range -40 ... -30 °C, the latter set-point is maintained only with fluctuations due to the chosen control strategy.

Table 3: The pilot cooling plant basic specs

Parameters	Units	Value	Note
Nominal cooling capacity	kW	15	
Partial cooling capacity	kW	6,4	
Primary side refrigerant	-	CO2	
Secondary side coolant	-	3M NOVEC 649	
Nominal outlet temperature of the coolant	oC	-40 ... -30	
Outlet coolant temperature with the outlet heater	oC	-30 ... 10	
Flowrate range	m3/h	1,2 ... 2,8	at -40 oC
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	

The details on the CO2 refrigeration cycle physical parameters can be found in p-H diagram in fig. 7.

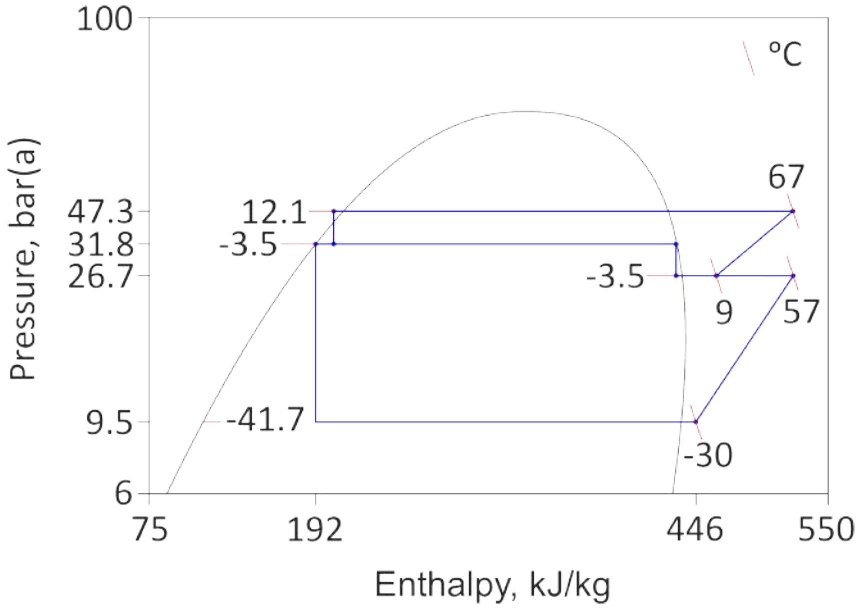

Figure 7: p-H diagram of the CO2 refrigeration cycle for -40 °C secondary side coolant temperature set-point

A photo of the pilot cooling plant and human-machine interface (HMI) are show in in fig. 8. The heaters and their control cabinet with Siemens LOGO! TDE control panel are shown in fig. 9.

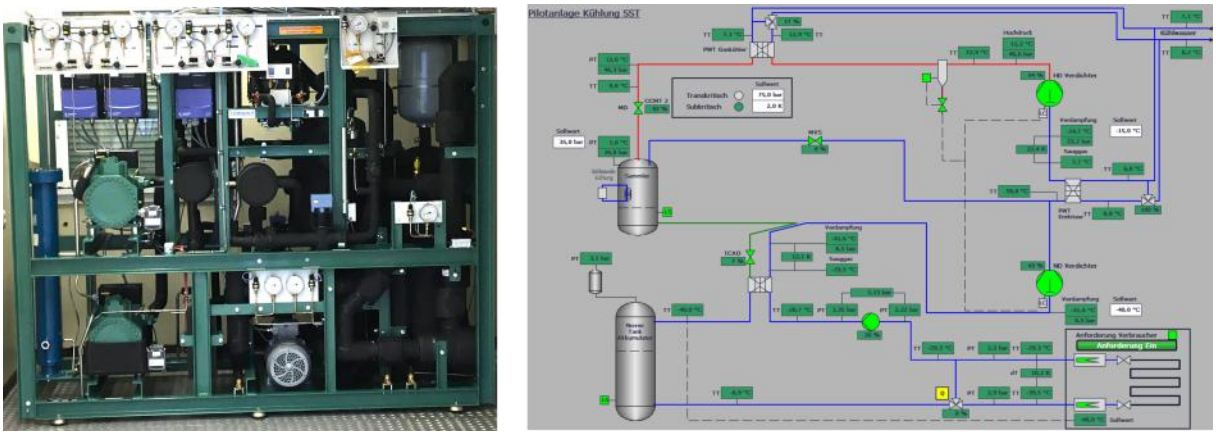

Figure 8: Photo of the pilot cooling plant (left), human-machine interface (HMI) (right)

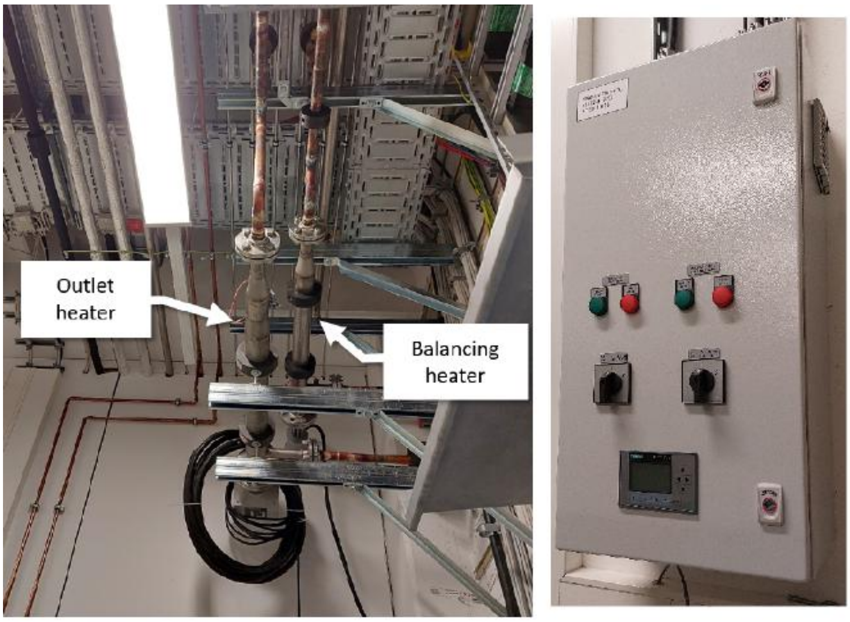

Figure 9: Photo of the outlet and balancing heaters (left), control cabinet for the heaters (right)

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 (see fig. 10). Steady-state operation was reached with delivering electric power of 1,8 kW from the balancing heater to achieve partial cooling capacity. When the heaters delivered 13,5 kW of electric power, the nominal cooling capacity was exceeded.

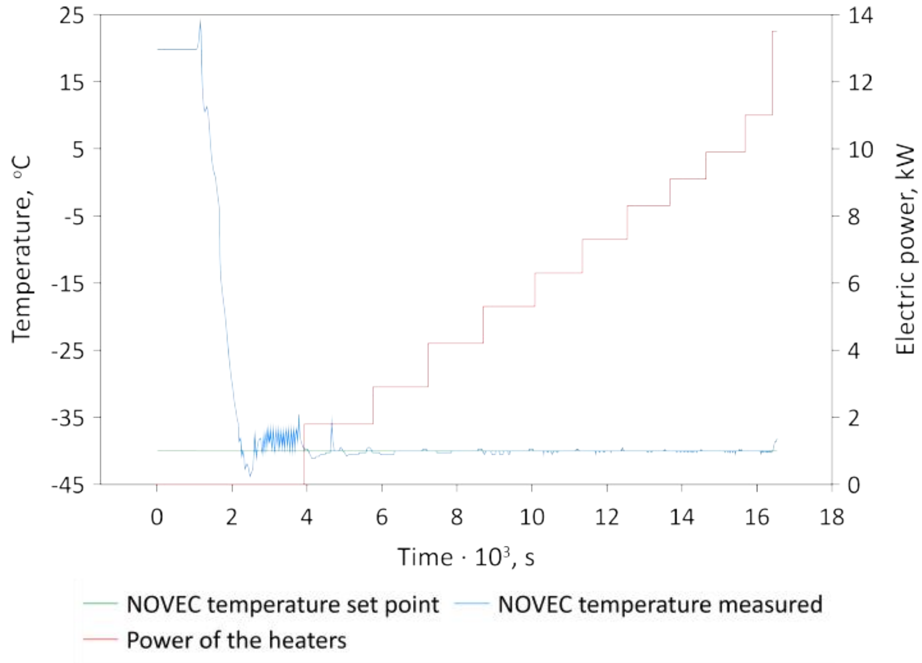

Figure 10: Testing pilot cooling plant performace

3.2 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 through standard flange connection DN25 (see fig. 11).

Figure 11: The cooling test rig

The cooling test rig monitors parameters of the liquid coolant during the tests (flow rate, inlet, and outlet temperature and pressure). In addition, it supports connecting the drainage system.

3.3 The drainage system

NOVEC 649^{TM} cooling agent needs to be collected from the devices that no longer undergo tests. This is due to the requirements of industrial waste treatment, the price and long delivery times of the cooling agent. The drainage system allows for draining and refilling experimental set-ups with NOVEC 649 without losing this liquid.

For draining an experimental set-up, shut-valves need to be closed, and a dip-tube tank must be connected to a draining valve (see fig. 12). When the draining valve is opened, the liquid flows to the dip-tube tank under pressure from the system. The remaining liquid can be extracted with a refrigerant recovery system by turning the coolant into vapor under vacuum. Afterwards,the vapor flows through oil less compressor and a condenser to undergo phase transition back to liquid.

For refilling an experimental set-up, vacuum must be applied first to avoid air bubble formation inside the set-up (see fig. 13).

Next, the liquid from the tank flows back to the system under air pressure. For storing, NOVEC 649 is poured to the dip-tube tank through a funnel.

A photo of the drainage system prepared for vapor stage draining is shown in fig. 14.

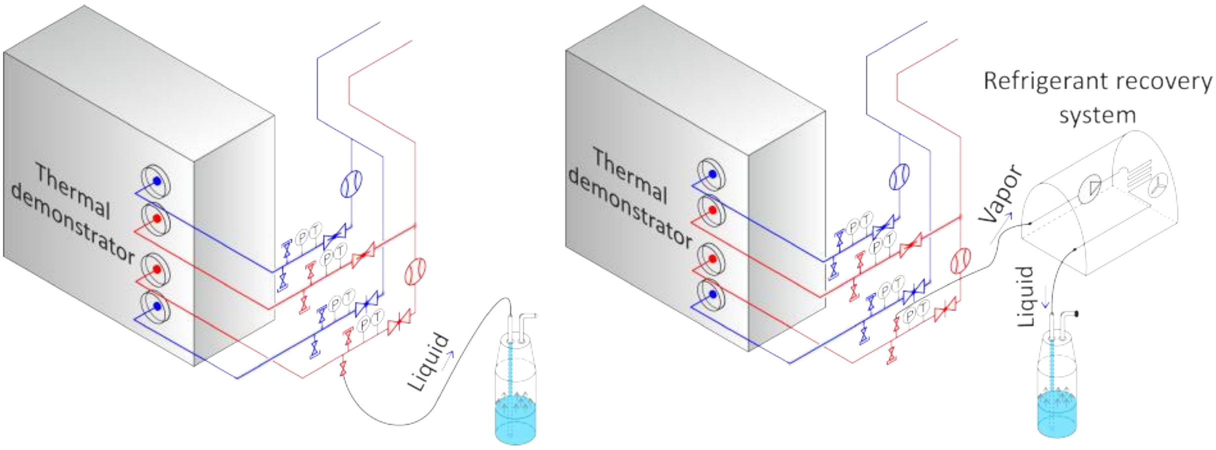

Figure 12: Draining sequence of the drainage system: liquid stage (left), vapor stage (right)

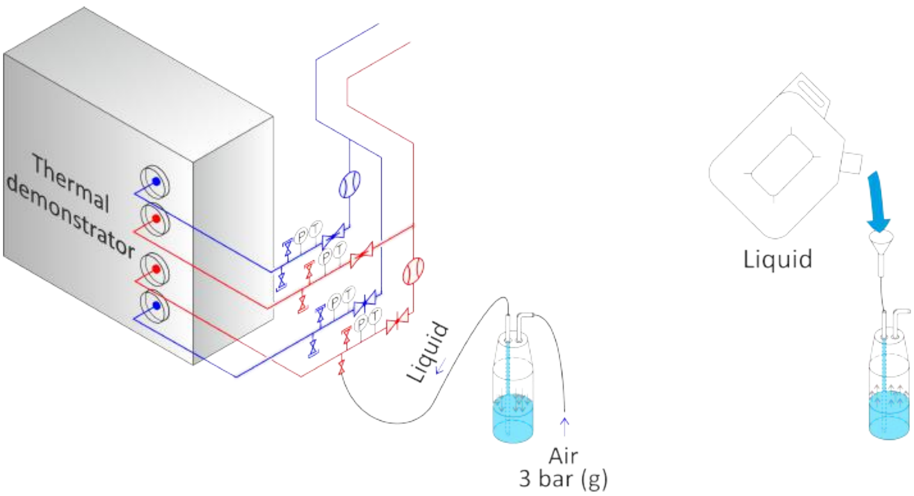

Figure 13: Draining sequence of the drainage system: refilling (left), storage of the coolant (right)

Figure 14: The drainage system connected to the cooling test rig