# Commissioning of the Large-Scale 2 K Helium Refrigeration System at ESS

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**Abstract.** The European Spallation Source (ESS), built in Lund, Sweden, will provide long-pulsed neutron fluxes at very high brightness to the neutron research community. The ESS is driven by a 2.0 GeV proton linear accelerator (LINAC) comprising 43 cryomodules (CMs). The accelerator cryoplant (ACCP) provides the cooling for the CMs and the cryogenic distribution system (CDS) of the LINAC. To maintain the superconducting cavities operating at 2 K, the ACCP can provide a maximum refrigeration capacity of 3.0 kW at 2 K. The ACCP adopts a 3 stages cold compressors string combined with one warm compressor to achieve 31 mbar for the CMs cavity circuit. In a dedicated collaboration between the supplier of the refrigeration plant, Linde Kryotechnik, and ESS, the ACCP has been successfully commissioned and tested in different operating modes. This paper will cover the system design, commissioning experience, performance results and lessons learned. The new developed control logic will be discussed.

**Keywords:** Accelerator Cryoplant (ACCP) · 2 K Helium Refrigeration system · Cold compressors (CCs)

## 1 Introduction

As one of the world-class neutron science facilities, the European Spallation Source (ESS) will provide a 2.0 GeV proton Linac using superconducting RF cavities operating at 2 K, supporting the research range from material science, condensed matter and biomedical studies [1].

The Accelerator Cryoplant (ACCP) will supply super-critical helium to the cryomodules (CMs) in the Linear Accelerator (LINAC) through the Cryogenic Distribution System (CDS). According to the design specification [2], the ACCP has a cooling capacity of ~ 2.5 kW at 2 K, 4.5 K liquefaction rate of 6.8 g/s and 8.5 kW at 40~50 K in stage 1 and ~ 3.0 kW at 2 K, 4.5 K liquefaction rate of 9 g/s and 11.4 kW at 40~50 K in stage 2. In both stages, there are five operation modes, in which the stage 1 nominal design mode (S1ND) will be the most important operation mode in the coming years. In order to maintain the 2 K operation for CMs, three stages of cold compressors (CCs) and one sub-atmospheric warm compressor are adopted. In a collaboration between the supplier, Linde Kryotechnik (LKT), and ESS, the ACCP has been successfully commissioned and tested in different operating modes. The simplified ACCP process flow diagram with a test vessel and heaters are shown in Fig. 1.


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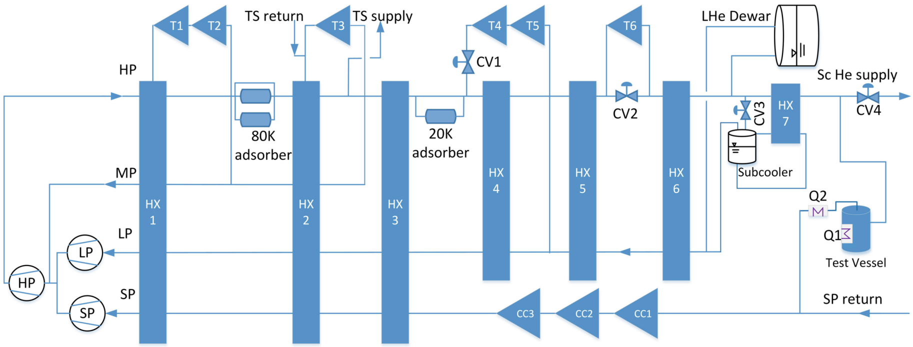



**Fig. 1.** The simplified ACCP process flow diagram with a test vessel ((heat exchangers: HX1 ~ HX7; Turbines: T1 ~ T6; different pressure stages: HP, MP, LP and SP; Heaters: Q1, Q2; Thermal shield (TS) [3])

After successful completion of the acceptance test and agreeing on the residual punch points, ACCP has been handed over to ESS in October, 2020. Subsequently, a variety of tests, including CCs off-design tests, ACCP-CDS new modes tests and ACCP envelope capacity tests have been performed, as well as trouble shooting, such as turbines damage and cold compressor speed sensor failure. In the following sections, the commissioning and performance of ACCP and some issues will be discussed.

## 2 ACCP Commissioning and Performance

### 2.1 The Commissioning of ACCP

After one and a half years' commissioning and operation, ACCP runs in a very efficient and stable condition. The commissioning experience includes:

- Before the cooldown, the impurities of the system are removed by a small flow circulation among ACCP, pure helium tanks and Helium recovery system until the impurity condensation is below 10 ppm.
- During the cold box cooldown, the opening of the third turbine string inlet valve is controlled to make sure that the Mach number of turbines T4 and T5 is less than 1 in order to avoid the turbine damage. The adsorbers should start earlier to make sure the impurities adsorbed.
- The capacity of the HP compressor is regulated by the slide valve, which will affect the efficiency of HP compressor. Normally, the opening of the HP slide valve should make sure the opening around 20% ~ 30% of the two HP-MP bypass valves in order to keep the MP pressure stable.

## 2.2 The Performance of CCs

In ACCP, the 3 CCs string combined with a sub-atmospheric pressure (SP) compressor are used to keep all CMs in the LINAC at 2 K. The suction pressure of SP compressor could range from 0.3 bara to 1.05 bara, which will compensate the flow variation for CCs during the pump down or in off-design conditions. The flow scheme for the 2 K part is presented in Fig. 2. The bypass valves CV34998 and CV33801 are used to regulate the CC mass flow (FC34905) and CC1 suction temperature (TC34650). The set point of FC34905 is based upon the SP suction pressure, which means the mass flow set point is regulated by setting the SP suction pressure. The CC1 suction pressure can be set in auto mode. If the CCs haven't reached the maximum working capacity, the CC1 suction pressure will reach the setpoint.

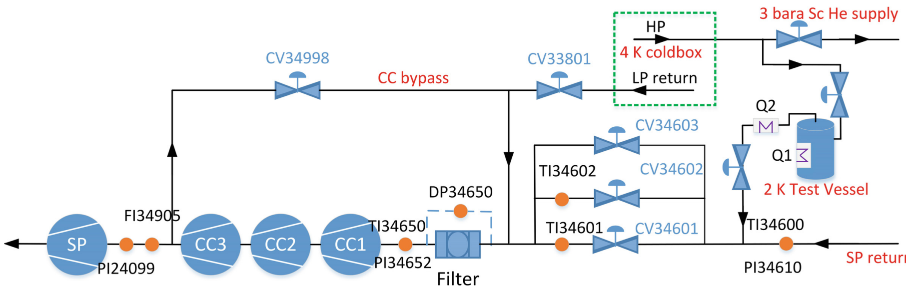



**Fig. 2.** The flow scheme of CCs and SP compressor

In S1ND mode, the measured parameters of CCs are shown in table 1. With the CC1 suction pressure of 25.93 mbar and the suction temperature of 4.5 K, the mass flow of CCs is stabilized at 95.3 g/s and the isentropic efficiencies of all the CCs are > 72%. The CCs map is presented in Fig. 3, which shows the pressure ratios of CC2 and CC3 are better than the design (S1D). The performance of CCs met the expectation in S1ND.

**Table 1.** The measured parameters of CCs in S1ND mode

| | CC1 | CC2 | CC3 |
|---|---|---|---|
| $T_{inlet}$, K | 4.5 | 8.9 | 15.7 |
| $P_{inlet}$, mbar/bara | 25.93 mbar | 0.10 bar | 0.30 bar |
| $T_{outlet}$, K | 8.9 | 15.7 | 22.7 |
| $P_{outlet}$, bara | 0.10 | 0.30 | 0.62 |
| mass flow, g/s | 95.3 | 95.3 | 95.3 |
| Polytropic efficiency, % | 79.1% | 75.7% | 81.5% |
| Isentropic efficiency, % | 73.1% | 72.1% | 75.5% |

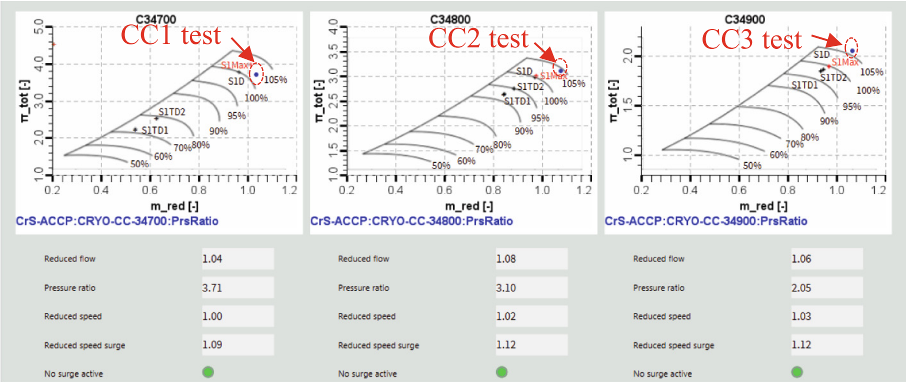



**Fig. 3.** The CCs map in S1ND

### 2.3 The Performance of ACCP

The parameters comparison among the measurements, ESS requirements and the Design of ACCP in S1ND is listed in Table 2. All the measurements exceed the ESS requirements. The design parameters have a 5% margin than the requirements. Using the exergy efficiency with the definition as same as in [4], the measured WCS and the Cold Box (CBx) exergy efficiencies are 48.5% and 54.0%, respectively. The measured system exergy efficiency is 26.2%, which is 1.4% higher than the Design. The performance of ACCP is better than the expectations.

**Table 2.** The parameters comparison between measurement and design in S1ND

| | Measurements | Requirements | Design*Note |
|---|---|---|---|
| 2 K heat load, W | 2519 | 2478 | 2603 |
| 4.5 K coupler cooling, g/s | 6.9 | 6.8 | 7.14 |
| TS heat load, W | 8962 | 8551 | 8979 |
| 2 K mass flow, g/s | 95.3 | 92.5 | 97.0 |
| CC1 suction pressure, mbar | 25.93 | $\leq$ 27.00 | 26.00 |
| 4.5 K equivalent heat load, W | 7585 | 7292 | 7670 |
| WCS input Power, kW | 1900 | / | 2034 |
| WCS exergy efficiency, % | 48.5 | / | 45.1 |
| CBx exergy efficiency, % | 54.0 | / | 55.0 |
| System exergy efficiency, % | 26.2 | / | 24.8 |

* Note: The ACCP design parameters have a 5% margin compared with the requirements of ESS

Based on the test results in different operating conditions, the HP pressure in Gas Management Panel (GMP) and the system efficiency are shown in Fig. 4, in which the HP pressure has a linear correlation with the 4.5 K equivalent heat load. Generally, the system efficiency increases with the 4.5 K equivalent heat load increase. When ACCP operates in the floating mode, i.e. the GMP load/unload valves are closed, LHe Dewar is used to balance the system capacity. The slide valve in HP compressor could control the bypass flow from HP to MP, which affects the WCS efficiency. The HP pressure could be set according to the 4.5 K heat load to fine tune the system stability before operating in the floating mode.

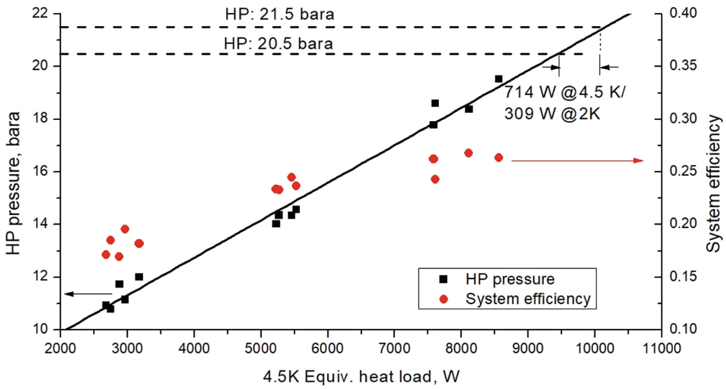



**Fig. 4.** HP pressure in GMP and system efficiency versus 4.5 K equiv. Heat load for ACCP

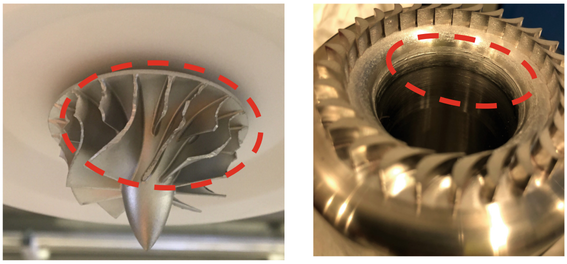
# 3 Issues and Improvements

## 3.1 Turbines Damage

In the third turbine string, there are two serial turbines, Turbine 4 (T4) and Turbine (T5). Both T4 and T5 were damaged during the commissioning. In June 14$^{th}$, 2021, the T5 expansion wheel and the nozzle were found with damage after the ACCP had a performance degradation for several months, shown in Fig. 5. After LKT's investigation, the reason for T5 damage is the Mach shock during the cooldown process. To make sure T4/T5 Mach number $< 1$ during cooldown, a new control logic was implemented in the PLC which controls the opening of T4 inlet valve according to the T4 inlet temperature and T4/T5 pressure ratio.

T4 occurred a bearing damage and inlet filter deformation after a power outage in Sepember 30th, 2021. With LKT's inspection, the reason for T4 bearing damage might be T4 incorrectly assembled in LKT workshop and the deformed filter might be caused by very high debris load. Then the spare T4 was installed.

The repair was still under warranty and the damaged turbines were swiftly carried out by LKT. Now both T4 and T5 have nominal performance again.



(1) Expansion wheel (2) Nozzle

**Fig. 5.** The damaged expansion wheel and nozzle in T5

### 3.2 CC2 Speed Sensor Failure

In October 22nd, 2021, the CC2 speed sensor was broken and sent back to LKT for replacement. During the future operation of LINAC it might happen that we need to replace one CC and keep the rest of the cryogenic system and CMs working at 4.5 K. Therefore, we arranged the test to warm-up the CCs string under the condition of the the CBx in cold. The process includes CCs string warm-up, CC spare replacement, CCs string cool-down and CCs string pump-down, which presented in Fig. 6. It took 24 h to warm up the CCs, 1.2 h to cool down the CCs string and 0.6 h to pump down the CCs string. According to our experience, around 6 h are required to replace the CC spare. Therefore, 32 h in total are needed to replace one CC with CBx cold. In the future, we will further investigate and work on to minimize the downtime caused by one CC replacement after the CDS and CMs are connected with the ACCP.

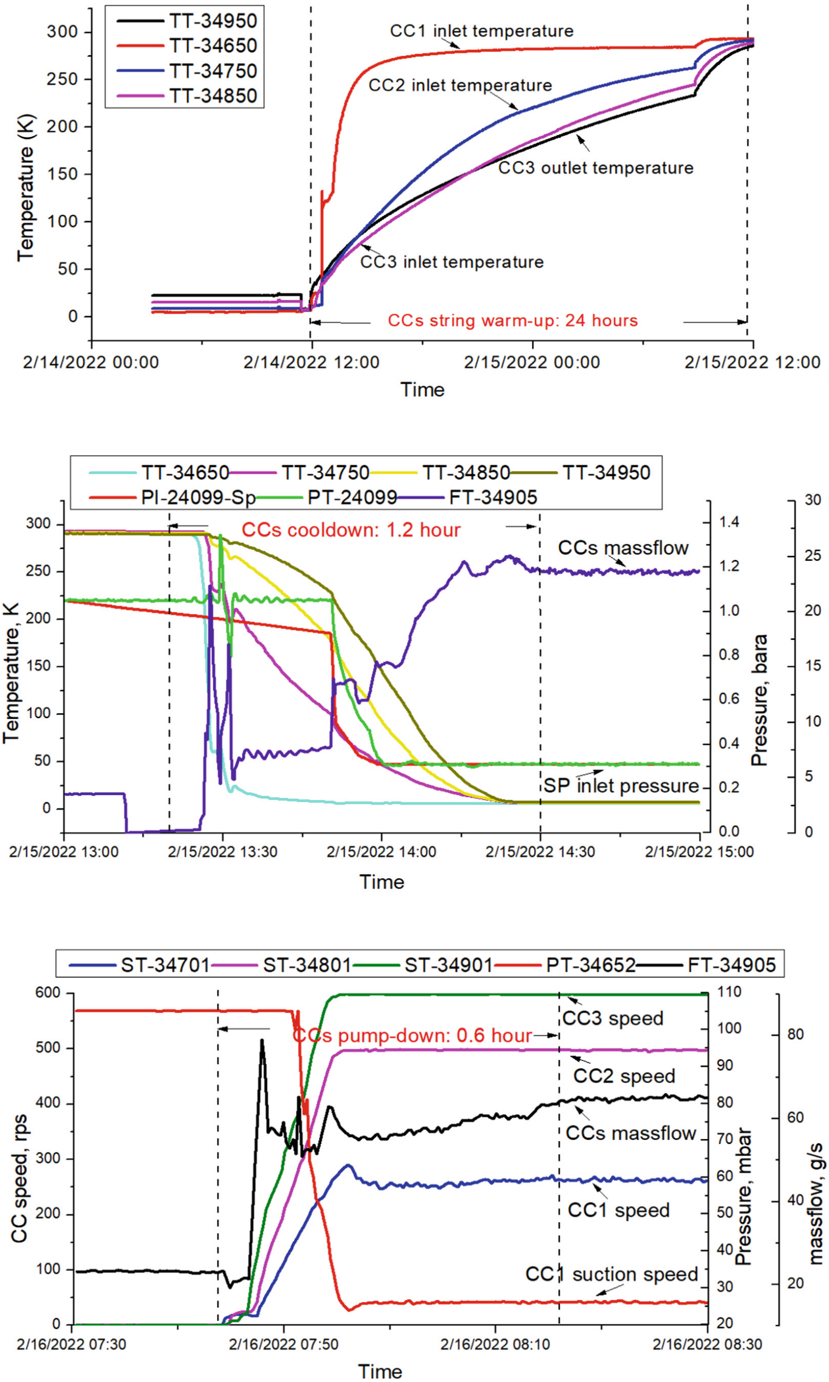



**Fig. 6.** **(1)** The trends for CCs string warm-up, **(2)** The trends for CCs cooldown, **(3)** The trends for CCs pump-down

## 4 Conclusion

ACCP had the site acceptance test successfully and fulfilled the expectations in July, 2020. Then we had ~ 1.5 years ACCP fine tuning and operation. The ACCP performance are studied, such as CCs off-design and ACCP different heat loads tests. With the issues occurring during the commissioning, the operation process is optimized and more experience has been achieved. After ACCP and CDS connected, ACCP-CDS integrated test will be carried out in Q4, 2022.

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## References

1. Weisend II, J.G., et al.: Status of the ESS cryogenic system. In: AIP Conference Proceedings, vol. 1573, no. 1, pp. 633–638. American Institute of Physics, January 2014
2. Wang, X., et al.: Specification of the ESS accelerator cryoplant. Phys. Procedia **67**, 89–94 (2015)
3. Wang, X.L., Arnold, P., Hees, W., Hildenbeutel, J., Weisend, J.G.: ESS accelerator cryoplant process design. In: IOP Conference Series: Materials Science and Engineering, vol. 101, no. 1, p. 012012. IOP Publishing, November 2015
4. Arnold, P., et al.: Large scale refrigeration plant for ground testing the james webb telescope at NASA johnson space center. In: AIP Conference Proceedings, vol. 1218, no. 1, pp. 1080–1086. American Institute of Physics, April 2010