CEC 2023 IOP Publishing
IOP Conf. Series: Materials Science and Engineering **1301** (2024) 012084 doi:10.1088/1757-899X/1301/1/012084

Commissioning of the cryogenic distribution system of the ESS superconducting linac

P Arnold [1,5], E Asensi [1], N Elias [1], J Fydrych [1], P Nilsson [1] , J Zhang [1], J Polinski [2], P Duthil [3], A Petersson [4]

[1] ESS ERIC, Lund, SE-22100, Sweden
[2] Wrocław University of Science and Technology, Wrocław, Poland
[3] Irène Joliot-Curie Laboratory (IJCLab), Orsay, France
[4] Lunds Tekniska Högskola (LTH), Lund, Sweden

Email: philipp.arnold@ess.eu

Abstract. The European Spallation Source (ESS) is a neutron-scattering facility being built with extensive international collaboration in Lund, Sweden. An essential part of the project is the linear 2.0 GeV proton accelerator. Its superconducting part is designed to comprise 13 spoke and 30 elliptical cryomodules that are cooled at 2K. The cryogenic distribution system (CDS) connects the refrigeration plant with the cryomodules via multi-transfer lines, individual valveboxes for every cryomodule and an endbox. It is designed, manufactured and installed under the responsibility of two ESS in-kind partners. The CDS for the spoke cryomodules (CDS-SL) is supplied by IJCLab, France, the CDS for the elliptical cryomodules (CDS-EL) is supplied by WUST, Poland. Pre-commissioning, commissioning and operation is done by ESS whereby IFJ PAN contributed with valuable advice. Pre-commissioning activities like loop checks, temperature curve validation, pressure sensor calibration or valve initialization and leak tightness tests followed after mechanical or electrical completion of the respective CDS parts and started in summer 2022. Eventually, the system was ready for commissioning and a first cooldown was performed in December 2022. Goal of this commissioning was to acceptance test and check off the system before pilot cryomodule installation in the tunnel started in March 2023. The paper describes diverse challenges regarding TAO and cryo operation. Test results, lessons learnt, and required modifications are discussed as well as preliminary results of retesting and an outlook.

1. Introduction

The superconducting linac (SCL) including its utilities and connected subsystems consist of equipment provided by a large number of different in-kind partners and industrial suppliers [1].

A central part of the SCL is the CDS as schematically shown in figure 1. After design, manufacturing and installation the combined CDS needed to be commissioned and tested together with the Accelerator Cryoplant (ACCP) to verify the static CDS heat load and detect potential flaws before cryomodule installation and subsequent beam commissioning. Also, the ACCP with its cold compressors, acceptance tested in 2019 on test loads, needed to be verified to operate in the combined system including at off-design conditions with much reduced heat loads.

Unfortunately, a large number of flaws were detected, heat load verification was not fully possible and ACCP operation at 2K was also limited due to issues that are described in the following sections.

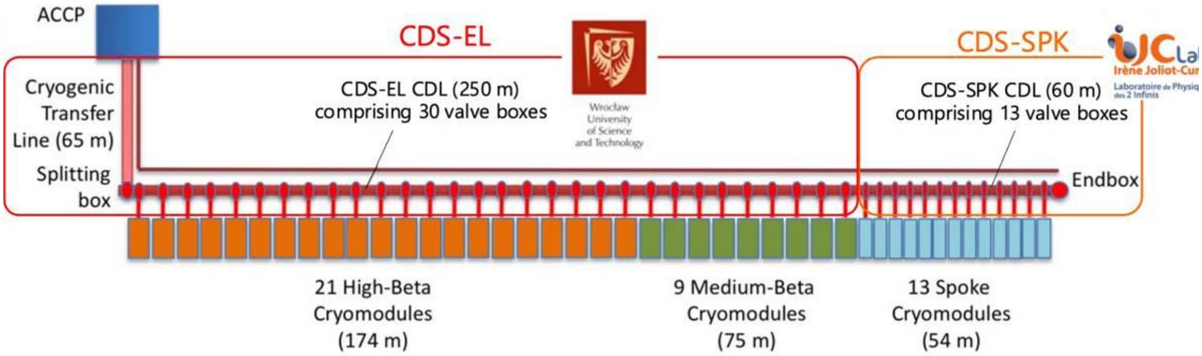


Figure 1. Simplified schematic of the CDS.

2. Commissioning preparation

Before actual cooldown and operation at cold temperatures could start a number of tests and preparations on the system had to be conducted.

It is by far easier to conduct most tests and qualify the CDS before the cryomodules (CMs) were connected. Instead of CMs there were endcaps connected at the valvebox (VBX) jumpers as schematically illustrated in figures 2 and 3 for the elliptical and spoke VBXs, respectively.

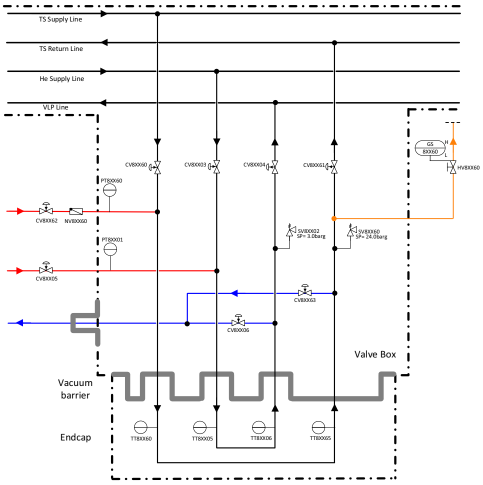


Figure 2. Simplified schematic elliptical VBX

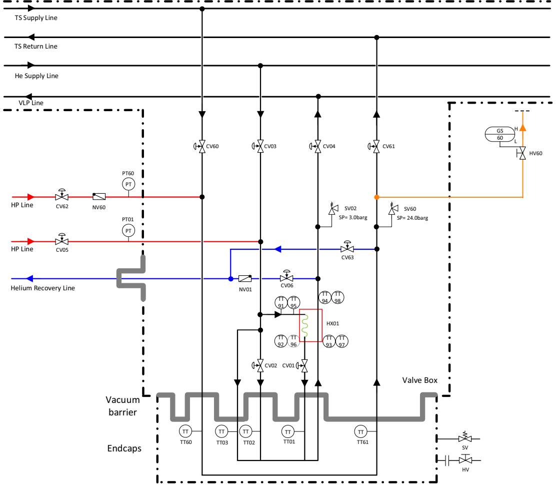


Figure 3. Simplified schematic spoke VBX

pressures stable. After ~5 days, a purity of <10 ppm, **based on readings of H_2O and N_2,** permitted starting One type of these tests were measurements of the control valves seat leaks which are quicker and easier if done with a small test volume of the U-tubes instead of a full cryomodule attached. Many leaks were detected predominantly in the elliptical part of the CDS which still need to be completely understood and rectified.

Before that, the pressure transmitters had to be calibrated by first pumping the system down for adjusting the zero and then pressurising for the full operation span. Both, lowest pressure at pumpdown and stability of the high pressure, can be used to get an idea of the overall system leak tightness to air or to the helium recovery system. Several leaks were identified before we could deem the system good enough for further operation.

Another activity was verifying the individual curve and wire connection for each of the CERNOX sensors in the CDS. A number of issues were detected as uploading the wrong calibration curve or mixing up, wrongly connected wires or short circuits.

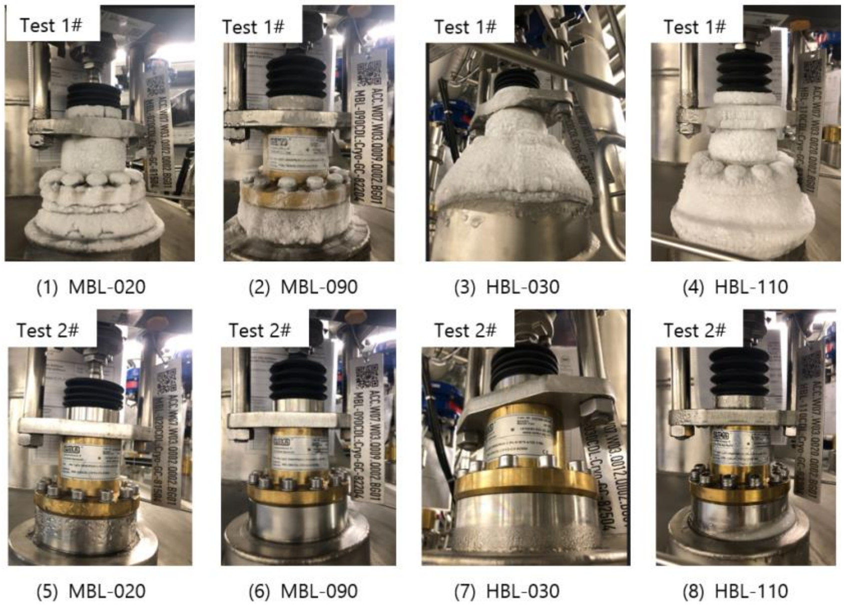
Finally, the CDS was pumped and purged before being connected to the cryoplant process circuits. From the cryoplant we bled a small flow to the helium recovery system comprising gasbag, high pressure compression, storing and purification [3] while feeding clean helium of the same amount to keep the cooldown.

3. 1st Cooldown and discovery of issues on control valves

In December 2022 the first cooldown of the ACCP simultaneously with the CDS was performed in roughly 1.5 days including a night of temperature stabilization, from ambient to the target feed temperature of 8K. The feed at 8K without LHe Dewar and phase separator sub-cooler is a special operations mode that had been developed with the cryoplant supplier Linde Kryotechnik before the testing started [4].

A first inspection after temperature stabilization but before cooldown completion did not reveal severe cold spots or moisture formation on the long cryoline, however some cold spots on valveboxes due to heat conduction. However, by reaching target temperatures and operating for a longer time a number of issues became obvious:

- Vibration and noise development in most of the CDS-EL valve boxes
- Ice formation at the top of nearly all CDS-EL VLP (vapour low pressure) return valves, see figure 4
- Ice formation downstream several safety relief valves in CDS-EL, indicating leak over the seat of those valves
- Ice formation downstream several control valves connecting cold to warm circuits in both, CDS-EL and CDS-SL, indicating leak over the seat of those valves as well



(1) MBL-020 (2) MBL-090 (3) HBL-030 (4) HBL-110

(5) MBL-020 (6) MBL-090 (7) HBL-030 (8) HBL-110

Figure 4. Ice formation on CDS-EL VLP return valves at 20% open 4K supply valves (Test 1#) and at 3% open 4K supply valves (Test 2#)

Other operation conditions as valve openings, temperature and pressure have been kept stable, indicating that the ice forming is connected to flow conditions rather than heat conduction.

By tuning valve openings, we could minimize most vibration and noise development but of course this entails a systems operation limitation that is not acceptable.

It soon became obvious that the ice formation on the VLP return valves is due to thermo-acoustic oscillations (TAO), a phenomenon well known in cryogenic installations and described in many publications as for instance in [6]. In case of the ESS is that the CDS-EL VLP return valves are relatively large with a gap between valve body and valve insert of 2 mm that for this DN50 valve results in a residual cross section of ~500 mm^2, the equivalent of a DN 20 tube, for the gas to travel between the cold and the warm end. Despite that the valve has a thermal intercept ring for anchoring the valve body to the thermal shield, this is unfortunately not used and was missed in design reviews. The resulting large temperature ratio between warm and cold ends and free possible gas flow, are considered to be the root causes of this TAO. This is unacceptable and needed to be rectified.

The helium leaking over the safety valves and some control valves did fortunately not constitute direct losses of this precious gas. The control valves are all part of closed loop circuits, the safety relief valves discharge in a line that is connected to the side-wide helium recovery system, as also described in [3]. This setup has advantages but makes leaks nearly impossible to detect before cool-down. Nevertheless, rectifying these leaks was an add-on for the to-do list after system warmup.

4. Static heat load determination

Even though the detected issues, particularly the valve TAO, were substantial, we proceeded with heat load determination to find out more about the system, it's capabilities and limitations.

To determine the overall heat load of the CDS without CMs and its liquid helium vessels, we operated the system at 8K, making sure to have one phase and sensible heat to deal with only. Also, we wanted to test in a temperature range yielding moderate specific heat capacity gradients and consequently better resolution of the temperature measurements.

We tested according to a method described in [4] which aims to minimize the impact of systematic measurement errors and produces robust results.

The applied CDS mass flow was modulated in the endbox. The heat loads were calculated using flow measurements, feed and return pressures and temperatures from the ACCP. We found a strong dependency of the TAO in the VLP return valves to the opening of the 4.5K supply valves in the respective valve boxes and consequently the heat load. Heat loads were determined between 424 W and 900 W whereby the lower values correlate with lower opening of the 4.5K supply valves, see figure 5.

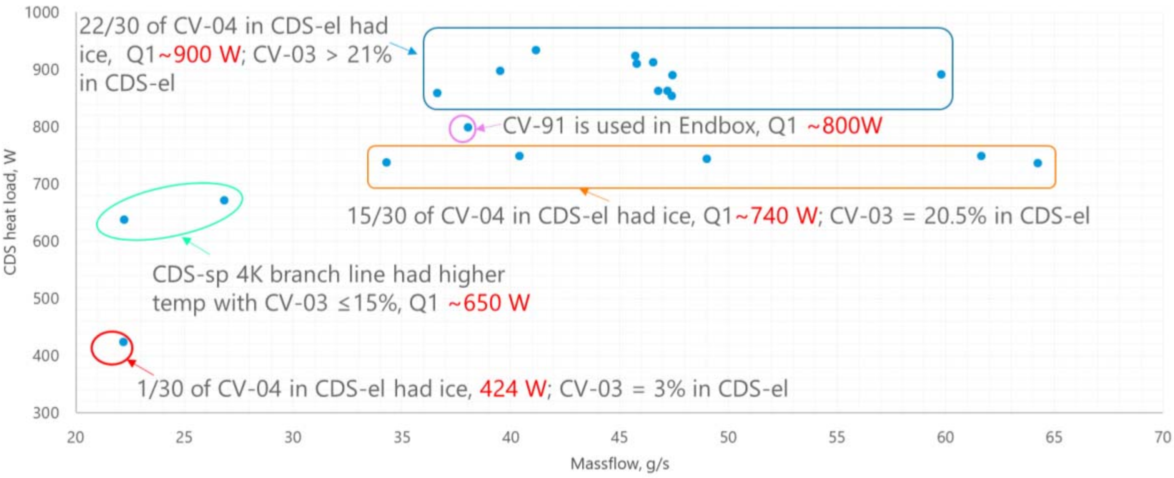


Figure 5. Determined heat loads of the CDS in function of 4.5K supply valve opening.

The lowest determined value is very close to the design value of 317W for CDS-EL and 102W for CDS-SL [1]. The CDS overall heat load at ~4K is dominated by the non-isothermal part in the VLP return circuit. According to [2] the ACCP has a specified heat load performance of 627W in our current configuration (with possibility to increase) and in [5] it is shown that the measured ACCP loads do even exceed this value. We have reasons to believe that the combined heat load of the CDS is adequate to support the SCL once the TAO have been removed.

5. Pump down and TAO on endbox

Following the heat load testing at 8K we intended to reduce the feed temperature to 6.0K and then to pump down the system to the 2K equivalent pressure which would be ~27mbar at the inlet of the first cold compressor in the ACCP coldbox. This way we could maintain one phase flow at all locations, yet at the same expected return temperature of 4.0 K as in design conditions. The system was pumped down successfully deploying first the sub-atmospheric warm compressor down to 400 mbar and subsequently the three cryogenic turbo compressors down to the target pressure of 27 mbar at the ACCP coldbox inlet. The cold compressors are kept within their operation limits between surge and choke line by tightly controlling flow and temperature with bypass and cooling valves, see figure 6. However, as we operated at elevated supply temperature to the CDS, the cold compressor temperature controls were dysfunctional and the system easily tripped upon the slightest deviations.

In order to have effective cold compressor bypass and temperature control we had to reduce the feed temperature and to operate with 2-phase helium via the endbox and the ACCP internal 2K test vessel.

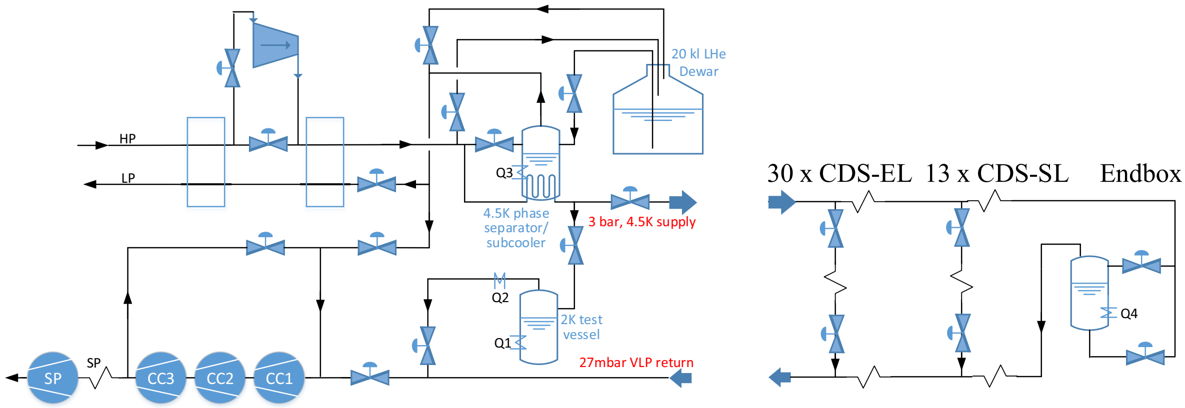


Figure 6. Simplified schematic of ACCP cold end and CDS loops.

Unfortunately, another TAO phenomenon was identified at the endbox, preventing us from using the cold compressors again.

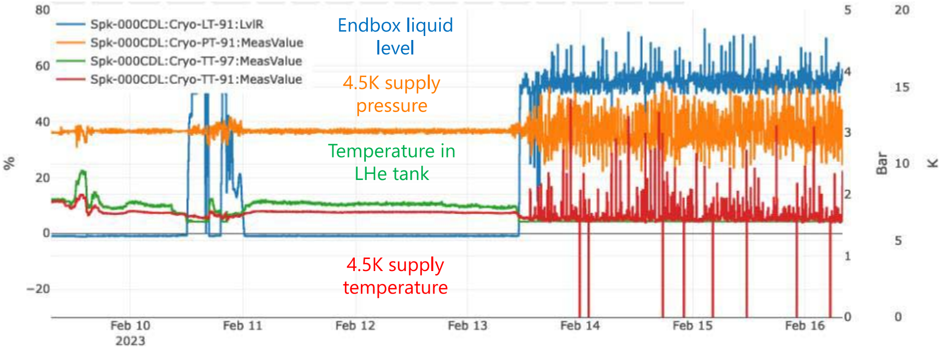


Figure 7. Relevant process variables at the endbox.

Figure 8: Endbox 3d model.

It could be shown that the appearance of TAO (oscillations in 4.5K supply pressure shown in orange in figure 7) are directly linked to reducing the 4.5K supply temperature (shown in red in figure 7) and not to other system variables like liquid helium level in the endbox phase separator, tank temperature, valve openings or alike. Also, no pressure oscillations have been observed in the previous operation phases. The dominant oscillation frequency detected with our pressure sensors and data acquisition chain was 0.2 Hz but also other, much smaller frequencies appeared in the ACCP.

The warm line connecting the 4.5K supply line to its safety valve SV91 (marked blue in figure 8 with the green safety valve) at the endbox was soon covered in ice, meaning that large heat transport took place there. The pressure oscillations reached easily an amplitude of >10% of the absolute pressure, making a new attempt to deploy the ACCP cryogenic turbo compressors impossible.

6. Rectification and system modifications

The cooldown and cryogenic operation of the CDS was an important milestone that revealed several issues that needed to be rectified and retested before the serial CM installation took place. In a short window of opportunity, during the pilot CM installation where one spoke and one elliptical CM only where installed, modifications and repairs on the CDS were planned and conducted. First and foremost, the TAO needed to be eliminated, both on the VLP return valves in CDS-EL and at the endbox. Also, the spring load on several leaky safety valves in CDS-EL needed to be readjusted. Mind, that leaks were detected operating just above atmospheric pressure by identifying cold spots downstream the 4.5K supply valves, much lower than the nominal 3 bara at these locations once the CMs are connected.

Inspired by [6] we looked into attaching convection brakes, so called wipers, along the valve stems of the VLP return valves. Anchoring the valves properly to the thermal shield would require opening of all fully welded CDS-EL VBXs and not guarantee the complete elimination of TAO. As time was of the essence, the steal rings to keep the wipers made of PE in place were manufactured and tack-welded to the valve inserts in the ESS workshop. Only the wipers themselves were delivered by the valve manufacturer WEKA after testing with ESS made valves and own designs failed. Positioning of the rings was done with the goal to minimise temperature ratios (the driving force of TAO) along the shaft. A typical VLP return valve insert is shown in figure 9.

Figure 9. VLP return valve insert with wipers as convection brakes against TAO

This was repeated for all 30 CDS-EL VBXs which, including dismounting, remounting, re-initialisation and commissioning, was quite a large job.

Figure 10: Update on 3d model of endbox.

Figure 11: Added RLC components

Figure 12: As-built endbox with modifications

The TAO on the endbox was analysed by ESS and in-kind partner IJCLab. As modifications in the cold part of the endbox are impractical and attempting to block the flow in the chimney to the safety valve would impair the systems safety, it was decided to change the acoustic impedance on the warm side of the thermo-acoustic resonating system.

The warm inlet line to the safety valve was significantly shortened (figure 10). Using electro-acoustic analogy [7] three elements of an "RLC" system were added to be able to detune the acoustic resonator and damp TAO: a fine control needle valve as resistor (R), a flexible hose as inductor (L) and a warm damper vessel as capacitor (C), see figure 11. The as-built result is shown in figure 12.

7. 2nd cooldown, preliminary results and outlook

The 2nd cooldown started in June 2023 with the main objectives to show successful elimination of the TAO on the VLP return valves and on the endbox, meaningful operation of the ACCP cold compressors including the two pilot cryomodules that have now been installed, repeat the static heat load determination and tackle a couple of more issues related to leaks, sensors and controls.

First it has to be stated that connecting the two pilot cryomodules to the CDS elevates the complexity of the interconnected system to a new level, particularly regarding secondary circuits like coupler cooling return, purge lines etc. but also in terms of safety and controls complexity.

Cooling down the CDS with the pilot cryomodules, filling with liquid helium and pumping down to 2 K with the ACCP warm and cold compressors works after first start up difficulties smoothly and stable.

The TAO on the endbox could effectively be damped a great deal only by replacing the safety valve and a little further by connecting the damper vessel with fine tuning valve, illustrated in figure 13. There are still oscillations at ~52 Hz which cannot be damped with our system but overall, the result seems acceptable.

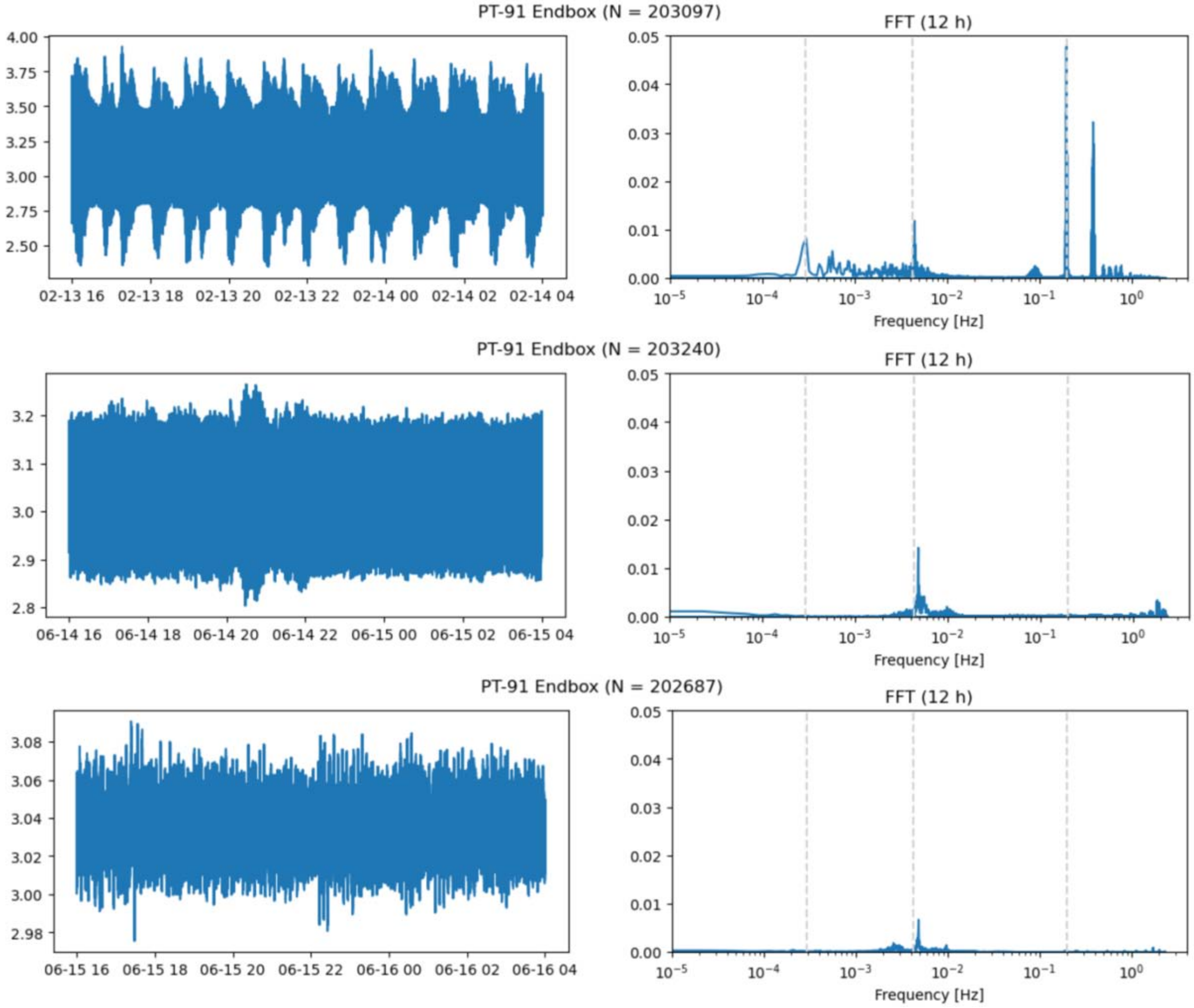


Figure 13. 4.5K supply pressure before (top), after SV replacing (middle) and after damper tuning (bottom) with pressure oscillations (left) and Fast Fourier Transform (FFT) (right) showing dominant frequencies

The TAO on the VLP return valves can be considered as eliminated. When reproducing the same operation conditions as during the 1st cooldown and as shown in figure 4, noise and vibrations are no longer detectable. No ice formation has been observed. The overall heat load of the entire system from ACCP supply to return at 8 K feed temperature has been determined with high accuracy by the method as described in [4] to 458 W, as shown in figure 14. Deducting an assumed heat load of 40 W for both connected CMs, as previously tested on teststands, the resulting heat load of the CDS including interface with vacuum barrier to the ACCP is 418 W, i.e. almost precisely the design heat load of CDS-EL and CDS-SP of 419W combined.

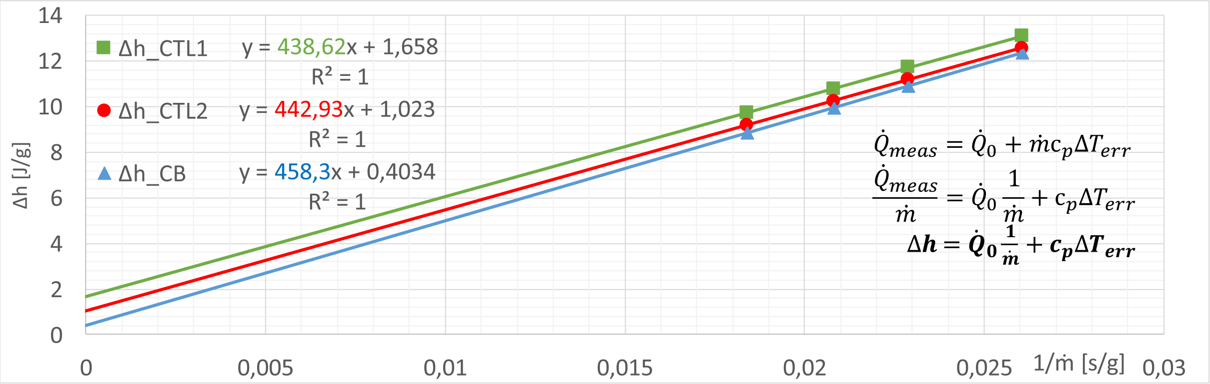


Figure 14. Heat loads $\dot{Q}_0$determined at 4 different mass flow rates using supply and return temperature at the Cryo Transfer Line (CTL) interface (green, red) and of the ACCP coldbox (blue), showing then somewhat higher heat load due to the vacuum barrier

The safety valves do not show signs of leakage anymore. Regarding leaks over valve seats the results are mixed. There is an improvement on many leaks while others need continued attention.

The primary goals have been achieved and the system is in a satisfactory state to allow series CM installation to start directly after warm-up and depressurization. Secondary goals have partly been achieved and do still need more work, particularly regarding valve seat leaks.

8. References

[1] Fydrych J, Arnold P, Hees W, Tereszkowski P, Wang X W and Weisend II J G 2015 Cryogenic distribution system for the ESS superconducting proton linac. *Physics Procedia* **67** 828-833.

[2] Wang X L, Arnold P, Hees W, Hildenbeutel J and Weisend J G 2015 ESS accelerator cryoplant process design *IOP Conference Series: Materials Science and Engineering* **101** 012012

[3] Arnold P, Hees W, Jurns J, Su X T, Wang X L and Weisend J G 2015 ESS cryogenic system process design *IOP Conference Series: Materials Science and Engineering* **101** 01201

[4] Zhang J, Arnold P, Fydrych J, Weisend II JG 2022 Preparation of the Integrated test of the Accelerator cryoplant and the Cryogenic distribution system at ESS to be published in *Proceedings of the 28th International Cryogenic Engineering Conference and International Cryogenic Materials Conference 2022 - ICEC28-ICMC 2022, Hangzhou, China*

[5] Zhang J, Arnold P, Kolev N 2022 Commissioning of the Large-Scale 2K Helium Refrigeration system at ESS to be published in *Proceedings of the 28th International Cryogenic Engineering Conference and International Cryogenic Materials Conference 2022 - ICEC28-ICMC 2022, Hangzhou, China*

[6] Hansen, B J, et al. 2017 Effects of thermal acoustic oscillations on LCLS-II cryomodule testing *IOP Conference Series: Materials Science and Engineering* **278** 012188

[7] Ghribi A. et al. 2022 Cryogenic thermoacoustics in the SPIRAL2 LINAC *Cryogenics* **124** 103487.