Commissioning of the Warm Compressor System for the ESS Accelerator Cryoplant

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Abstract. The accelerator cryoplant (ACCP) providing the cooling for the cryomodules and the cryogenic distribution system for the cold part of the ESS proton linac is being built and commissioned at the European Spallation Source (ESS) in Lund, Sweden. The ACCP warm compressor system (WCS) consists of several compression stages. The sub-atmospheric pressure stage (SP) is used to compress helium coming from the cold compressors directly to middle pressure (MP) level. The low pressure stage (LP) compresses the helium from LP level to the same MP level, being merged with additional flow from the cold box and the flow from the SP stage. The total flow is compressed in a single compression stage (HP) from MP to HP. The oil-flooded screw compressors are chosen in a way that the flow in each stage SP, LP and MP is compressed by a single screw compressor. Both, SP and LP compressors are equipped with a variable frequency drive (VFD) to adapt the compressor capacities to the various load cases. The ACCP had been contracted to Linde Kryotechnik AG in 2015 and all compressors are made by the Aerzener Maschinenfabrik GmbH, Germany. Following successful installation and commissioning in 2018, the final 100 hours test run at maximum nominal design condition and the part load tests under various ACCP operation modes were carried out at the beginning of 2019. The key parameters, including mass flow, power consumption, isothermal and volumetric efficiencies, are well fulfilled with the design data. The paper describes the system features, project challenges, lessons learned and acceptance test results.

1. Introduction
The European Spallation Source (ESS) is a world-class neutron science facility, funded by at least 13 European countries, currently under construction in Lund, Sweden [1]. One dedicated cryoplant, with installed cooling capacities of 3050 W @ 2 K, 9 g/s @ 4.5 K and 11380 W @ 40-50 K, is used to serve the accelerator superconducting section. The cooling requirements, process choices, design features and parameters, system configuration, machine concept and layout have been developed and improved over the years [2-11]. The ACCP had been contracted to Linde Kryotechnik AG (LKT) in 2015 and all warm oil injected screw compressors are made by Aerzener Maschinenfabrik GmbH, Germany (Aerzen). All components had been delivered to the ESS site since July 2017 and the successful performance tests were carried out at the beginning of 2019.

2. Design and system features
The ACCP warm compressor system (WCS) consists of three oil injected helium screw compressors and related bulk oil separators (BOS), oil and helium coolers manufactured by Aerzen, the final oil removal system (FOR), a dryer to adsorb moisture and the gas management panel (GMP) to control the pressure levels in the plant. The FOR, dryer and GMP are separately ordered by LKT from their sub-contractors. The schematic of ACCP WCS and the overview of assemblies are shown in Figure 1 and 2.

![Figure 1. The Schematic of ESS ACCP Warm Compressor System](image)

The sub-atmospheric (SP) compressor generates the compressor station’s lowest pressure on the intake side, which directly comes back from the cold compressors in the cold box. The helium gas is compressed to a middle pressure. The SP compressor can be operated with the same process data as the low-pressure (LP) compressor. The LP compressor generates the pressure on the intake side that is slightly above the atmospheric pressure and compresses the gas to the same middle pressure as the SP compressor. Both SP and LP compressors are supplied with oil by a common oil and gas skid, which also separates the gas-oil mixture coming from the compressors and cools the process gas by means of a gas cooler. The process gas from the oil and gas skid of the SP and LP compressors flows through a line to the intake side of the high pressure (HP) compressor. Additional helium coming back from the cold box is fed into this line; the HP compressor then compresses the entire gas volume to a high-pressure level and then release it into the system on the discharge side. The MP is consistently regulated by the operation conditions. The adaption of the MP ensures operation of the turbines and screw compressors at highest efficiencies during all operation modes. SP and LP compressors are equipped with a variable frequency drive (VFD) for each to adapt the capacity of the compressor to the load case. The HP compressor runs with fixed speed as load adaption by adjustment of the middle pressure makes a VFD unnecessary.

A guard system has been installed to prevent the entry of air into areas of the SP compressor that are constantly under sub-atmospheric condition during the normal operations. This system consists of double seals whose intermediate space is pressurized to a level above the ambient pressure. This means that the only leaks that could occur are those resulting from intermediate pressure or guard pressure in the direction of the environment or the process system, and the entry of air is prevented, even in case of leaks. All flanges and instruments for the SP compressor under sub-atmospheric condition are guarded.

The oil and helium mixed after the compressor have to be separated completely in an oil removal system located downstream of the compressor. In a first step, the oil is removed from the helium in the
first coalescer located in each BOS skid (internal coalescer). Downstream the BOS the oil content of the helium is below 100 ppm. Three external coalescers are located downstream of HP BOS and the oil content after the first of these coalescers is lower than 0.5 ppm. The first and second coalescers are equipped with a level switch to control drains for automatic return of the accumulated oil back to the compressor suction. While the third coalesce has only a manual valve as no aerosol oil collection is expected at this stage. The final removal of the oil vapor takes place in the charcoal adsorber vessel. It is designed for an operation time of more than 18’000 hours. Within the adsorber, both the vapor-phase and the remaining liquid impurities are removed from the helium to a final concentration of less than 10 ppb by weight. A full flow dryer is located downstream of the ORS and to control the moisture level lower than 0.1 ppm by volume.

Table 1. ACCP WCS parameters at the nominal design conditions.

| Stage                  | SP         | LP         | HP         |
|------------------------|------------|------------|------------|
| No. Units              | 1          | 1          | 1          |
| Compressor type        | Aerzener Screw Compressor VMY 536 H |
| Internal Volume Ratio, Vi | 4.0        | 2.6        | 2.6        |
| Intake pressure, bar a | 0.607      | 1.05       | 4.05       |
| Intake temperature, °C | 33         | 33         | 40         |
| Intake volume flow, m3/h | 4550        | 6345       | 4272       |
| Mass flow, g/s         | 117        | 287        | 735        |
| Discharge pressure, bar a | 4.25       | 4.25       | 20.5       |
| Discharge temperature, °C | 71         | 83         | 83         |
| Motor speed, rpm       | 2670       | 3600       | 2950       |
| Compressor capacity at motor speed, % | 100 | 100 | 85 |
| Shaft power consumption, kW | 303 | 516 | 1383 |
| Equipped with VFD     | Yes        | Yes        | No         |
| Impurity removal       | Oil        | BOS (1000 ppm) - Coalescer in skid (100 ppm) - FOR (0.5 ppm Aerosols and 10 ppb Vapour) | Water One bed on line dryer (0.1 ppmV) |

Figure 2. Overview of warm compressor system assemblies.
All valves and related piping terminals for the process control in the compressor station are grouped together as much as possible and be installed into one common panel, called as gas management panel (GMP), which is used to control the pressure levels in the plant and for loading and unloading of the helium to/from the pure helium buffer vessels.

The design parameters for the ACCP warm compressor station at the nominal design conditions are shown in Table 1.

3. General test procedures
The warm compressor station had been ordered by LKT in September 2015 and delivered to ESS site in July 2017 almost exactly on schedule. It took about 10 months to finish the installation in May 2018 and additional 9 months to complete the commissioning and the final performance tests in January 2019, which is a big deviation from the original project schedule. The delay was caused by several unexpected issues, which will be discussed in the later of this paper.

Each compressor had been function tested as well as pressure and leak checked before shipment to ESS takes place. The functional tests had been performed at the workshop with ambient air in the Aerzen test bench for a minimum of 2 hours. A thermodynamic equivalent operation of the compressor is not possible due to restrictions of the test bench setup and of test motor capacities. These tests proved, however, that the compressors operate within their design limits.

After the installation on site, a series of inspections and reviews had been performed together by LKT, Aerzen and ESS staff, including the completions of mechanical and electrical installations, control loop checks, and documentation checks. A continuous action list of open points was established to keep track all the issues found and to implement a plan to work on these issues. The compressor system was allowed to start up when all show-stoppers were removed.

The acceptance tests at ESS for the WCS include functional tests and capacity tests with the helium. During these tests, the WCS remained isolated from the cold box. The functional tests consist of measuring the pressure and temperatures of helium, oil and cooling water, checking the performance of the oil removal system, testing the control software and interlocks for all modes of operation and simulated failures, measuring of main characteristics such as helium flow rates, pressures, temperatures, and power consumptions. The capacity tests had been undertaken when all the partial tests described above have been successfully completed. For each compressor a 100-hours, full load, steady-state run at the conditions necessary to run the ACCP in the nominal design conditions defined in Table 1 had been performed and additional 2-hours run at various plant operation modes described in [10] had been tested.

![Figure 3. Commissioning and test runs of ACCP WCS.](image-url)
4. Final acceptance test results

The commissioning takes much longer time than the planned two months due to some issues, abnormal conditions and trouble-shootings. The commissioning and test runs indicated by the compressor mass flows are shown in the Figure 3. The compressors had experienced six test runs in total, two or three weeks for each time, and had to be stopped in between to solve the problems. However, the 100-hours test run carried out from 10-15 Jan 2019 had been went smoothly and successfully. All parameters are according to the design data and the expectations of mass flow and power consumption of all three stages are well fulfilled.

Volumetric and isothermal efficiency are the fundamental performance parameters commonly used for performance evaluation and comparisons of oil-flooded screw compressors [12-15]. Volumetric efficiency is the ratio of the actual (measured) mass flow rate to the theoretical mass flow rate calculated using the swept volume (displacement) at the measured inlet process conditions. Isothermal efficiency is the ratio of the theoretical input power to isothermally compress the actual mass flow rate to the “measured” shaft power being delivered to the compressor.

![Figure 4](image-url)

**Figure 4.** Isothermal and volumetric efficiencies of three compressors (the efficiencies at the normal design condition are shown for comparison with the actual measured results and S2D condition experienced 100 hours and the rest have about two hours test run).

Figure 4 shows the behaviour of the volumetric and isothermal efficiencies with respect to the pressure ratios (various operation conditions). The shaft power is given by the measured output power from the switchgear with accuracy of 1% and corrected by the VFD and motor efficiencies, which is specified by the manufactures. The mass flow rates are measured by the orifice flow meters with expected error of 1.3%, which are installed in the GMP and calibrated before in use. The temperatures with the accuracy of 1% and the pressures with the accuracy of 0.2% are measured directly at the suction and discharge side of each compressor. Besides the stage two design conditions (S2D) shown in Figure 4, the other points include various actual operation conditions, such as stage two turn down, stage one design, stage one turn down and stage two maximum liquefaction. Under the S2D conditions, the
Isothermal efficiencies show the HP of 59.1%, the LP of 58.4% and the SP of 53.9% and the volumetric efficiencies indicate the HP of 76.9%, the LP of 92.5 and the SP of 93.1%, which all reach the state of the art compressor performance and are in advance of the guaranteed values. It should be noted that the HP compressor has the rather low volumetric efficiency since only 81% of HP capacity is used to perform the work and its slide valves keeps at the fixed position of 95%. For LP and SP compressors, the VFDs are used to drive the motors. The slide valves keep open at 100% during nominal operation, resulting in much better volumetric efficiencies. In addition, at various operation modes, all compressors show rather good performance. As a result of the 100 hours acceptance tests, the overall performance of each of the compressors and the overall compressor system, including the GMP and process control, met all goals set for ESS ACCP operations and had been handed over to LKT for future commissioning together with the cold box.

5. Issues and improvements during commissioning
During commissioning several major issues have been encountered and improvements were incorporated rapidly, and they are listed as below:

- ESS site work coordination and conflicting schedule, as well as the unexpected long civil engineering preparation (specifically the concrete blocks) used as foundation for the compressor skids) caused about four months delay of the compressor system reception at ESS site.
- The escape paths and space requirement in case of fire was introduced into the equipment layout in the compressor building towards the end of the design phase, which caused some extra efforts to place the components and piping routing re-design.
- After assembling into the skid and compressor test run at Aerzen workshop, a leak between oil and water in the HP oil cooler was detected. After delivered to ESS site, the surface corrosion also in the SP/LP oil cooler was found by an endoscope inspection. The replacement of these two heat exchangers by a new manufacturer, fabrication and installation caused at least five months delay.
- During the compressor start-up the oil is still cold and under certain circumstances, the discharge pressure of the oil pump is higher enough to trigger the external safety valve in the oil discharge line, causing the safety valves to become leaky. To prevent that, a mechanical over flow valve with lower set pressure than that of the safety valve was implemented into each of oil pump internally.
- It was found that about one litre of oil was collected at the bottom of the gas cooler after several days of continuous run. In order to minimize the helium bypass, a sight glass with manual isolating valves and the related piping were installed at the lowest point of each gas cooler to allow a local visual check and send the collected oil back to the compressor if necessary.
- For a long while (test run 1-4 in Figure 3), the LP compressor shows ~20% less mass flow rate with ~10% less power consumption. It comes out eventually that the LP mass flow is bypassed in the GMP. After closing the HP-LP bypass in GMP, cross-checking the mass flow with a venturi flow meter through the cold box and oil injection optimization, the design mass flow was obtained and confirmed with a 10% less power consumption. It means that the LP performance is much better than the design.
- Oil leakage across LP compressor shaft seal of ~12-15 ml/h is much higher than ESS requirement of 5 ml /h. The shaft seal has already been replaced without effect. Further investigation is in progress.
- Wrongly size non-return valve and resulting extreme vibration. A non-return valve is installed at the suction side of the HP compressor to prevent the oil-rich helium flow back to the pipe line in case the compressor is switched off. It was found out during the commissioning that this valve is oversized and flapping continuously in certain operation cases, causing severe vibration to the surrounding equipment and piping. A correctly sized valve has been ordered, is being delivered and the installation scheduled.
- In order to keep the cold box LP and Linac SP pressures smooth and below acceptable limits even during compressor malfunction or during transition cases, check valves used as backpressure
regulator valves for each LP and SP compressor are installed to prevent the over pressure in these lines and release the helium to the gas bag. It turns out that the flow capacity of both check valves combined is almost doubled than the gas bag safety relief valve capacity (~100 g/s), imposing a substantial risk for the gas bag. The implementations to restrict the check valves flow had been carried out right after this was known.

- It is difficult to disassemble some parts of the skids such as oil pumps or suction strainers due to obstructed access, resulting in higher efforts for further maintenance. Special procedures have to be developed and plenty of spare gaskets to be held on stock.
- The cooling ducts for the VFDs were pointing horizontally towards to the stairway, which is risky to the personal in case of an incident blowing up the VFDs. The ducts had been modified now to point vertically up to the roof.
- The helium guard box for the SP compressor has not been pressure tested in the workshop. The vessel had to be tested and certified by the notified body on site.
- The compressor document package is, more than two years after compressor delivery, not fulfilling minimum requirements under the consideration of the complexity, completeness and clearness. It is being worked on by the supplier though.
- There was an incident resulting in compressor damage, caused mostly by missing interlocks. It happened when the LKT and Aezen PLC communication got lost, both suction and discharge line valves upstream and downstream the HP compressor unit were closed, but the compressor kept in operating conditions. The suction pressure dropped to nearly 0.05 bar abs and the oil supply increased due to the low suction pressure. The oil between the female rotor and discharge side plate was pressurized so much that it pushed the pressed-in radial bearing to the outer side of the side plate. The movement of the bearing sheared off the bearing temperature sensor, causing the compressor finally to trip as the suction pressure and vibration signals were not foreseen as trip initiations. After the compressor shut down, a high oil flow flushed backwards to the suction strainer, causing the damage of the suction strainer. The dust and particles collected in the suction strainer drooped into the compressor during the equalization process, finally causing the scratches at the rotors. The damaged compressor had been disassembled at the workshop and the root causes had been identified. New trip signals as low suction pressure, both vibration sensors over-range and PLC communication loss have been implemented as a result. The investigation to re-use the damaged compressor will be necessary repair or replace with a complete new one is on-going.

6. Conclusion
The ESS ACCP compressor system had been commissioned and successfully passed the final 100 hours acceptance tests at the beginning of 2019. To reach the design mass flow, both LP and SP only consume 90% of the electrical power. The compressor performances are beyond the guaranteed ones. They have allowed a very wide range of operation and keep the reasonably good isothermal and volumetric efficiencies at various modes. After about 2000 hours of operation for each compressor, they have proven to be efficient, reliable and possibly maintained.

7. References
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