The ESS Test and Instruments Cryoplant – First test results and operation experiences

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Abstract. The European Spallation Source (ESS) is a neutron-scattering facility being built with extensive international collaboration in Lund, Sweden. The world’s most powerful linear proton accelerator shoots protons against a rotating tungsten target where neutrons are knocked off (“spallate”) and are guided to the neutron instrument suites. Three cryogenic plants and a vast cryogenic distribution system serve the cooling needs of the superconducting RF cavities in the accelerator, the cold hydrogen moderators in the target, a cryomodule test stand and the sample environments for neutron instruments. The project’s demand of schedule and economic feasibility requires a high degree of parallel work for installation and commissioning of the cryogenic and auxiliary systems. The first of the three plants, the Test and Instrumentation Cryoplant (TICP) has been installed, commissioned and acceptance tested in 2018 by Air Liquide Advanced Technologies (ALAT). The plant consists not only of a standard compressor system and coldbox but also of a process vacuum system for 2K operation, internal and external helium purifiers, liquid helium tank, filling and boil of station and a helium recovery system. It is heavily integrated in the overall cryogenic installations at ESS. The paper describes some project challenges, acceptance test results and first operation experience.

1. System overview
The overall cryogenic set-up at the ESS has been described already in [1] and [2]. Each of the three cryogenic helium plants at ESS consists of an individual compressor system, coldbox system and cryogenic distribution to its clients. But the plants are also heavily integrated as they share connections to pure helium storage tanks, cooling water, instrument air, nitrogen supply, safety relief manifolds and a common helium recovery and purification system.

This approach has both, advantages and disadvantages. It saves equipment and installation cost, allows for an all integrated approach, high consistency, and very flexible use of all sub-systems (e.g. warm tanks and purifiers). However, there are substantial challenges during parallel installation and commissioning activities and unexpected interface issues as explained in more detail in [4].

1.1. TICP specification and requirements
As already described in [3], the thermal requirements of the TICP main coldbox and recycle compressor system are derived from the requirements of the cryomodule test stand and the corresponding cryogenic distribution system. The coldbox is designed for a constant level liquefaction load of 4.0 g/s and a simultaneous thermal shield load of 390 W between 33 and 53 K. This performance falls well in the standard range of the typical suppliers of helium liquefiers. As the cold helium shall be supplied in supercritical state at 4.5 K and the plant’s capacity shall be capable of being boosted temporarily, a helium subcooler emerged in a phase separator vessel and an additional liquid helium return line from the liquid helium storage tank needs to be part of the coldbox system as shown in figure 1. Air Liquide designed a cryoplant based on the HELIAL ML™ helium refrigerator with a Kaeser DSDX 305 SFC used as recycle compressor, operated at 14.5 bar and a maximum flow rate of 56 g/s.
Together with the thermal shield supply and return and the special multi-channel transfer line interface for the cryodistribution to the test stand, the TICP contains some non-standard features.

Most of the supplied helium at 3 bar and 4.5 K subsequently has to be pumped to generate 2 K in the test stand. A dedicated Process Vacuum Pump System (PVPS), consisting of three parallel trains of a root blower – rotary vane pump – assembly, pumps the returning helium with 25 mbar at the pump inlet.

The second main operating scenario of the TICP coldbox and recycle compressor system is rising LHe dewar level liquefaction in combination with operation of the internal freeze-out purifier.

Liquid helium is not only required for the ESS neutron instruments sample environment but for all major liquid helium users in Lund including our neighbour, the next-generation synchrotron MAX IV, that ESS supplies through a collaboration agreement with Lund University. Hence, the TICP has also a 5’000 l liquid helium tank, a semi-automatic liquid helium filling station with weight scale and a mobile dewar boil-off station.

Finally the TICP comprises not only coldbox and a recycle compressor systems, but a helium recovery system consisting of a 100 m$^3$ gasbag, two high pressure compressors, high pressure storage bundles, a high pressure valve distribution panel and an independent liquid nitrogen cooled adsorption purifier.

1.2. TICP system integration and scope split

The TICP Coldbox system including liquid helium infrastructure is located in the Coldbox Hall of the ESS Klystron gallery building. The warm compressor system, recovery system and external purifier are located in one of the compressor halls in the ESS Compressor building and the pure helium storage tank farm is located outside the Compressor building as shown in figures 2 and 3.

Generally, the contractual scope split between ESS and ALAT can be put in quite simple terms: ALAT provides the pieces of TICP equipment and connects these amongst each other. ESS provides civil infrastructure, utilities, pure helium storage tank farm, connections to the cryomodule teststand and the recovery system, optical fiber network connections, and the long interconnection piping between the Coldbox Hall, Compressor hall and storage tank. Looking more into detail such as where exactly the
interface points are located, which pipe supports can be used by whom, who provides which part of strength calculation etc. the scope split turned out not to be quite as simple as projected.

Figure 2. Overview ESS construction site.  

Figure 3. Cryo Compressor and Coldbox Building.

2. Challenges during project execution

2.1. Installation and Commissioning

The installation and commissioning phase for the TICP took substantially longer than what was foreseen in the bidding phase, which was caused also to some extent by ESS being a green field construction site with parallel installation and commissioning activities for the other cryoplants and other subsystems. One of the biggest contributors to the delay was perhaps an insufficient interconnecting pipe support concept from ALATs sub-supplier before installation start and a lacking stress calculation, particularly with respect to the interface points to the ESS supplied piping.

One crucial challenge was the correct support for the ambient heater for the returning sub-atmospheric flow from the CM teststand, also being used for the acceptance testing, shown in figures 4 and 5. This ambient heater consists of four welded finned tube segments with an inner swirl, each of four segments turned 45° with respect to the previous one to ensure proper turbulence in the pipe and avoiding a cold inner jet. The entire ambient heater is more than 18 m long and shrinks when in use, which needs to be carefully considered when supporting this pipe and its interconnecting pieces.

Another challenge of the ambient heater was liquefied air collecting on the drip tray and causing a lot of condensate to rain down from the drip tray. So, a secondary drip tray acting as additional fins that enhances thermal exchange with ambient air and provides a gap to the primary drip tray was

Figure 4. Finned tube.  

Figure 5. Ambient heater for 4 K sub-atmospheric return flow from CM teststand, consisting of 4 welded finned tubes.
installed. An even more effective measure was putting up a fan, connected to a perforated tube above the finned tube, which increases the heat transfer coefficient by providing forced flow over the fins.

Another source of difficulties was the pressure safety relief valve of the gasbag, which is basically an oil bucket that was connected to the gas bag on the upstream side and to the safety relief header on the downstream side with a plastic flexible hose. More details are provided in [5].

2.2. Acceptance testing
Acceptance testing is a main requirement for hand-over and finalising the commissioning phase, so the general acceptance test strategy had already been defined at the procurement stage of the plant. Further details have been developed during preliminary and detail design by Air Liquide, including definition of sensors to be used and measurement failure analysis. Three main operation scenarios have been tested thoroughly.

2.2.1. Helium purification by means of the external purifier. The duty specification of the stand-alone purifier was to purify an average flow of at least 5 g/s with up to 2,000 ppm air impurities or 1.7 g/s average flow at up to 10,000 ppm air impurities, whereby the average flow was defined as the total purified helium mass divided by the cycle time, comprising all steps from operation, regeneration, purging, cool-down and to resuming operation.

Air Liquide provided a liquid nitrogen cooled purifier, based on the ULTRAL™ design with 7 cold adsorber beds and a standard upstream dryer.

Although specification and equipment design seem quite straightforward, correct acceptance testing is not as easy. We decided to test the 10,000 ppm case using dry nitrogen. Topping up clean helium gas bundles with nitrogen would not work due to insufficient homogeneity of the mixture within limited time. In order to achieve a more homogenous and time-constant gas mixture over a long time, i.e. for at least one entire purifier cycle, a simultaneous feed of helium and nitrogen had to be ensured. After several failed attempts to feed nitrogen at the high-pressure valve panel spare connection and to feed nitrogen upstream the gasbag, finally the best place was found directly upstream the purifier itself very close to the inlet impurity measurement. Estimating the correct gas flow rates of helium and nitrogen based on pressure indicators or even weight scale proved to be too inaccurate or instable over time. Adjusting the flow manually as a function of the on-line impurity measurement gave the most reliable results.

The enforced acceptance testing of this stand-alone purifier, often a bit underestimated, led to several control logic adjustments and some limited hardware modifications based on sub-optimal initial result. However, at the end we can report that the purifier performed at 180% of the guaranteed capacity which is an excellent final result. Switching to regeneration is still triggered based on time but is now primarily triggered as a function of outlet impurity at the 5o out of 7 adsorber beds (where the impurity measurement tap is located). The time constant is, within limits, adjustable and used now only as secondary regeneration trigger.

2.2.2. Helium liquefaction including coldbox internal purifier. As explained in [3] the liquefaction capacity of the TICP coldbox is secondary to its performance to supply refrigeration to the cryomodule test stand at ESS. During the procurement phase, the bidders were to give the maximum expected liquefaction rates, both with and without liquid nitrogen pre-cooling and with a helium feed including 1% air impurities that their proposed cryoplant, designed for test stand operation, would provide. These values then had to be guaranteed and constitute the baseline of the acceptance tests in this scenario.

Further test conditions were a rising level in the liquid helium storage dewar and a constant level, over time average, of the pure helium gas buffer tank, i.e. the internal purifier performance needs to match the liquefier performance. To verify this apparently trivial condition is in practice quite time consuming, yet indispensable to enforce controller tuning for good plant performance. The helium flow cycle established to validate these requirements is illustrated in figure 6.
Figure 6. Test set-up of the liquefaction and internal purifier operation.

By connecting more pure helium storage tanks as feed for the internal purifier, a long test duration could be ensured. Furthermore, this set-up permits precise helium mass balances to double-check the level measurement in the liquid helium storage tank.

Air Liquide guaranteed in their proposal a helium liquefaction rate of 137 l/h consuming 18 g/s liquid nitrogen and a rate of 40.7 l/h without liquid nitrogen pre-cooling, but with 2% impurity. After discussions between ALAT and ESS during commissioning, it was decided to relax the impurity content from 2% to 1% in order to optimize the purifier for a more relevant use case, to be consistent with the ESS specified external purifier requirements, and to ease the acceptance testing itself. The nitrogen feeding was done in a similar way then for the external purifier tests. We implemented our lessons learned and used the well-proven set-up with the same impurity measurement, that was specifically mounted on the line dryer upstream the coldbox internal purifier.

Figure 7. Liquefaction w/ LN2 pre-cooling and internal purifier operation.

As with the external purifier several control logic adjustments and substantial controller fine-tuning were necessary before an ultimately successful acceptance test could be conducted. The plant reached a liquefaction performance of 138.7 l/h with LN2 pre-cooling at 1% N2 feed impurity, see figure 7, whereby it has to be noted that the internal phase separator level was decreasing during the test, meaning the net liquefaction is slightly lower than shown in the trendline. Without LN2 pre-cooling the liquefaction rate was measured as 54.5 l/h at 1% N2 feed impurity. The LN2 pre-cooled operation mode has passed the test with very little margin only and could possibly have failed had we tested with the...
original 2% feed impurity. Different from the external purifier, the internal purifier consumes refrigeration power from the expansion turbines, which reduces the liquefaction performance. Also, the purified helium is discharged to the low pressure side of the recycle compressor, i.e. it has to be compressed again. However, the liquefaction rate is more than sufficient for its purpose at ESS.

A point of concern was the apparently very high liquid nitrogen consumption, which however could not be measured precisely during acceptance testing. Data collected during operation now indicate a more reasonable consumption rate that is furthermore being monitored by ESS operators.

2.2.3. Cryomodule (CM) teststand operation and Process Vacuum Pump System (PVPS). Test stand operation is the main design case of the plant and the performance guaranteed by ALAT matches the requested 4 g/s "constant level liquefaction" with LN2 pre-cooling (14 g/s) plus 387 W thermal shield load at <40 K supply temperature. Of the supplied 4 g/s a returning still cold vapour flow of 3.8 g/s shall be warmed up and returned to the cycle at 27 mbar via a vacuum pump system, whereas 0.2 g/s are cool the power couplers and return at ambient pressure and temperature to the coldbox.

The thermal shield load was tested by a simple bypass with electrical test heater, continuously switched on during all performance testing with the bypass valve simulating the specified maximal pressure drop of 500 mbar. In order to test the plant performance without extra equipment such as a 2 K phase separator and an electrical heater, we decoupled the coldbox test and the PVPS test. This also helped to verify the different process margins of the liquefier and the PVPS.

The 3 bar, 4.5 K supply helium from the internal sub-cooler of the phase separator vessel was warmed-up in an innovative ambient heater mounted on the wall of the coldbox hall as shown in figures 4 and 5. In a first approach we tried to control this helium flow such that the liquid helium level of the 5’000 l dewar was kept constant in order to find out the maximum rate supported by the plant. Setting the correct control parameters turned out to be unfeasible due to the slow level change. Instead, we decided to set a stable flow, using the flow meter downstream the PVPS, by a constant position of the supply valve and allow a slight dewar level rise, indicating some margin on the plant.

This test was successful and a 4.5 K supply mass flow of 4.1 g/s was achieved, simultaneously to the specified 387 W thermal shield load and a nearly constant liquid level in the LHe Dewar.

Acceptance testing of the PVPS was done using a bypass valve in the gas management panel, which regulates the flow of high pressure helium from the Kaeser compressor to the suction of the PVPS. This arrangement is not shown in the overview in figure 1. The upstream pressure of the PVPS can be controlled very precisely by this small bypass valve and by variable speed control of the roots blowers. In the test we achieved a maximal flow of 5.4 g/s at 25 mbar suction pressure and ±0.1 mbar pressure stability. Furthermore, special care has been taken to ensure very low disturbances should a pump train be switched off or on to accommodate long term load adjustments by using the large bypass valve. Fast load fluctuations at the test stand shall be regulated by means of heaters in the cryomodules.

3. Operation experiences and continuous improvement

3.1. Preparation of cryoline and test stand operation

The commissioning and acceptance testing of the TICP was performed without the cryogenic distribution system and CM teststand in place. In order to be able to test the cryoline to the teststand, i.e. basically its heat load, some adjustments were necessary.

To measure a temperature difference between supply to and return from the cryoline the helium, normally leaving the subcooler of the phase separator vessel at 4.5 K, is controlled to feed helium at a higher temperature. We need to make sure that also the flow downstream the expansion valve in the valve box returns in purely gaseous form and not in the 2-phase area. A stable feed temperature setting of 7 K was achieved by a combination of valve settings at the cold end and attenuation of the expander turbines in order to produce less refrigeration.

Another task was estimating the heat load on the thermal shield of the cryoline. Different to the main 4.5 K supply and sub-atmospheric return circuit, in the shield circuit there are neither flow meters nor
sufficiently precise temperature measurements. The one really accurate measurement we have is the electrical power of the shield test heater. The possibility of different shield bypass valve settings allowed us to do a parameter study in order to help deduce the shield mass flow from its bypass valve settings.

3.2. Modifications and finetuning

An issue asking for optimisation is the rather long cool-down and warm-up times of the TICP Coldbox. During the bidding phase ALAT estimated cool-down times of less than 3.5 hours (with LN2 pre-cooling) and warm-up of less than 8 hours which is certainly possible as theoretical calculations show. During commissioning, however, the various cool-downs took about 8 hours and the warm-ups about 24 hours. We concentrated first on reducing the warm-up time due to the larger potential time reduction.

![Figure 8](image)

**Figure 8.** Essential coldbox temperatures for warm-up. Different colours indicate different test dates and the red horizontal line indicates the warm-up end temperature definition that of 278 K for all temperature measurement locations.

Four temperatures are regarded for defining the end of the warm-up: the cold end temperatures of the warmest and the coldest heat exchangers and the top and bottom temperature of the phase separator.

An important role for the warm-up plays the phase separator with its internal sub-cooler. Flow through the sub-cooler coil like during CM acceptance testing means a high heat load for the cryoplant and an elegant way to bring heat to the coldest part of the coldbox. This means, however, that the phase separator has to be in use (mode enabled) for the warm-up which is not naturally intuitive when the phase separator was not used during nominal operation when the plant was e.g. only used as liquefier.
As the curves in figure 8 indicate, the warm-up times could successfully be shortened but there is still room for further improvement, particularly with respect to the phase separator. Its top temperature does currently limit the total warm-up time to about 11 hours.

Additional small modifications of the TICP include an automated mechanism to empty impure HP bundles into the gasbag once the pressure is lower than accepted by either the internal or external purifier. ESS fine-tuned automation and parametrisation of a second unloading valve in the gas management panel that is used during helium recovery of the Accelerator Cryoplant’s (ACCP) inventory when ACCP and TICP low pressure circuits are connected. Furthermore, ESS integrated the possibility for remote switching on and off the gas analyser and connecting this functionality to the operation of the recycle compressor to avoid situations of the gas analyser running without helium feed, which can potentially damage the analyser cell.

4. Summary

Following smooth engineering, procurement and manufacturing phases, a lot of issues on both ALAT and ESS side have led to substantial delays during the installation and commissioning phases. After successful acceptance testing, the TICP has been handed from ALAT to ESS in December 2018. The plant fulfills its key performance parameters and even overperforms in certain areas, particularly the external purifier and the PVPS. Minor performance parameters like LN2 consumption, warm-up and cool-down times did not meet the initial design estimations but are being finetuned at ESS as the operating experience is building up amongst the cryogenic team. The cryoplant is operated almost weekly to liquefy helium for Lund University’s different institutes including MAX IV and to support other cryogenic operations at ESS, such as helium recovery and purification for the other plants. It has also been used to test the cryo-distribution system for the CM test stand. The very near future will show how smooth the operation with the test stand works and how further finetuning can improve the plants performance to reduce operating cost and possible operator failures by improved automation.

References

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