The Evolution of the Cryogenic System of the European Spallation Source

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Abstract. The European Spallation Source (ESS) is an intergovernmental project building a multidisciplinary research laboratory based upon the world’s most powerful neutron source to be built in Lund, Sweden. The ESS will use a superconducting linear accelerator which will deliver protons with 5 MW of power to the target at 2.0 GeV with a nominal current of 62.5 mA. A cryomodule test stand will be supplied with helium for the site acceptance tests. The target will have two moderators using supercritical hydrogen to cool down the neutrons. The neutron instruments and the experiments’ sample environment will use liquid helium and liquid nitrogen to cool detectors and samples. The ESS cryogenic system is designed to deliver cryogenic cooling capacity to all three client system. A first concept of the ESS cryogenic system was developed in 2010 and 2011 with a limited amount of input from the clients as well as from site infrastructure (i.e. buildings and utilities). The design had to be flexible enough to accommodate future changes in scope, schedule and available infrastructure. Over the following years the design has evolved together with these parameters to achieve a maturity today which allowed us to order the accelerator cryoplant and to start procurement of many of the other parts of the ESS cryogenic system. This paper presents the evolution of the design throughout the years and the factors influencing certain design choices.

1. Introduction
The European Spallation Source (ESS) is a project which aims to build the world’s most powerful neutron source. ESS will use a 5 MW linear accelerator to deliver protons to the target at an energy of 2.0 GeV. The target consists of a rotating disc of tungsten, where the protons will liberate highly energetic neutrons through the process of spallation. Two moderators will cool down the neutrons to more suitable energies using supercritical hydrogen. In the 22 instruments that are located around the target, neutrons will be applied to a range of scientific questions, spanning the fields of physics, chemistry, geology, biology, archaeology and medicine.

In 2003 a design concept was adopted that set the course for delivery of ESS’s first neutrons by 2019. This concept did not definitely specify a superconducting accelerator, but it already included a cold hydrogen moderator.

After ESS’ technical organization had been established in 2009, a re-design saw the publication of the Conceptual Design Report [1] in 2012 and finished in 2013 with the publication of the Technical Design Report [2]. In the new design, both accelerator and target moderators represent significant customers of cryogenic cooling.

The design of the ESS cryogenic system has evolved from the first concept in 2011 to a fairly detailed design in 2015.
2. Overview of the ESS cryogenic system today
The ESS cryogenic system as it is planned today [3], has four major parts.

In the proton accelerator, most of the acceleration is carried out by three types of superconducting RF cavities. There are 13 double spoke cavity cryomodules, 9 medium beta elliptical cryomodules and 21 high beta elliptical cryomodules. There is also space in the accelerator lattice for an additional 14 high beta cryomodules. They can be used as contingency to produce a beam energy of 2 GeV, if the specified accelerating gradient of the cavities is not achieved. All the SRF cavities operate in saturated 2 K He II baths. Cooling to the accelerator will be supplied by the accelerator cryoplant (ACCP) [4].

The connection between the accelerator cryoplant and the cryomodules is assured by the cryogenic distribution system (CDS) as described in [5].

The supercritical hydrogen moderator receives a heat load of up to 24 kW from the neutrons. This heat is removed by a hydrogen – helium heat exchanger which is in turn cooled by a 15 K helium flow coming from the target moderator cryoplant (TMCP) described in [6].

The neutron instruments will require a significant amount of liquid helium and liquid nitrogen both for instruments and sample environments.

Another consumer of cryogenic cooling is the ESS cryomodule test stand. All cryomodules will be tested at operating temperatures and full RF power before being installed in the accelerator tunnel. The spoke cavity cryomodules will be tested at the FREIA facility in Uppsala University [7], while all the elliptical cavity cryomodules will be tested at the ESS site in Lund. The ESS cryomodule test stand requires enough cooling to test a single cryomodule at full power [8]. Cooling for the test stand and supply of liquid helium to the instruments will be assured by one test stand and instruments cryoplant (TICP).

3. First concept, May 2011
Before the establishment of the accelerator division’s cryogenics and vacuum group in 2010 there was no concept for the cryogenic system of ESS. The first step was therefore to define responsibilities inside the organization as well as the scope of work for the group. When the decision had been taken to centralize all cryogenic activities in accelerator’s cryo group, it was time to establish the needs and requirements for the different clients in the facility.

In May 2011, a technical note [9] outlined the first concept of the ESS cryogenic system. The note describes the separation of the system into four sub-systems, namely:
- the accelerator cryoplant, supplying cooling to the superconducting RF cavities;
- the target cryoplant, a helium refrigerator that supplies cooling to the hydrogen system of the moderators;
- a helium liquefier, supplying liquid helium in mobile dewars to the neutron instruments, supplying cooling to the cryomodule test stand as well as collecting and purifying the helium returning from the instruments;
- a liquid nitrogen storage and distribution system, supplying liquid nitrogen from several storage tanks to the instruments via mobile dewars.

Building on this first assessment, the ESS cryogenic system has evolved since 2011 into a more advanced design. During 2015 two major parts of the system have been contracted out to industry (ACCP) respectively an In-Kind partner (CDS). Two more contracts for TMCP and TICP are expected to be signed before the end of the year, leaving only some auxiliary systems such as the interconnecting piping and the gas and liquid storage tanks to be procured later.

4. Evolution of heat loads and helium liquefaction capacity
The clients of the ACCP are the superconducting accelerating cavities of the proton linac which are housed in their cryomodules. They are described by Darve et al in [10]. The design of the cavities and the cryomodules has progressed significantly since the first concept, making the heat load predictions more and more accurate. The big changes in heat load between 2011 and 2015 are due to a redesign of the linac lattice, leading to a reduction in the number of cavities and cryomodules in the baseline
design and to the introduction of a contingency capacity of 14 cryomodules. Other changes include the
decision to have segmented cryomodules rather than a continuous cryostat, the adoption of the
CEBAF/SNS-style space frame design for the cryomodules and the reduction of the number of cavities
per cryomodule from eight to four. Whereas the heat load estimates in 2011 were only based on top-
down comparisons with existing machines, the newer numbers are based on bottom-up calculations
based on a proper design.
Similarly, the heat load introduced by the transfer and distribution lines has evolved from rough
estimates of 1 W/m to a sophisticated analysis of a concrete design, taking into account the
contributions of valve boxes, vacuum barriers and instrumentation.

Determining the heat loads on the target cryogenic system has always been less straightforward
than for the accelerator. This is due to two circumstances. Firstly, there are not many comparable
systems existing in the world today and secondly, small changes in the mechanical design of the target
moderators lead to over-proportionally big changes in heat load to the hydrogen circuits.
A redesign in 2014/2015 of the moderator shape resulted in a more than doubled neutron
production, but increased as well the heat load by a factor of 1.75. Because neutron production by
spallation as envisaged at ESS is still a field in it’s infancy and evolving rapidly, predictions of the
final heat load on the TMCP are coupled with high factors of uncertainty.

Predicting the instruments’ consumption of liquid helium and liquid nitrogen has initially been
based on an extrapolation from the numbers available at the ILL in Grenoble. The varying nature of
neutron experiments, advances in instrument design and the increase in use of so-called cryogen free
cryo coolers have made a reliable prediction of the demands for liquid cryogens very difficult. ESS’
strategy from the beginning has been to use the same cryoplant TICP for cooling cryomodules on the
test stand as well as for re-liquefying helium for the instruments, albeit not at the same time. Because
of the relatively high refrigeration load for CM testing, the capacity of the TICP is determined by this
mode of operation. In liquefaction mode, the same plant can deliver more than the foreseen maximum
demand for liquid helium and can be run part time only, buffering the helium in a 5000 liter storage
dewar. A more detailed prediction of liquid helium demand is therefore not necessary and potentially
increased demand in the future is at least partly covered.

5. Evolution of cryoplant layout from concept to design
From the beginning, the number of cryoplants to serve the four separate clients has been set to three.
The differences in client demands between the accelerator cryomodules, the target moderators and the
test stand and instruments do not allow the design of one cryoplant to reliably supply all the needed
refrigeration and liquefaction. Schedule considerations both during installation and operation do also
make separate plants more efficient and reliable.
Because of the variations in client heat loads, as described above, the planned cryoplant sizes, as
shown in Table 1, have also varied over the years. The basic cryogenic cycle of the ACCP hasn’t
changed much since the CDR in 2012. It is based on a Claude cycle with multiple expanders and a
complex flow distribution in the heat exchangers and a set of cold compressors with mixed cold and
warm sub-atmospheric compression.
The TMCP’s design has initially been very close to the SNS target cryoplant. It has since evolved
to take into account the specific requirements of ESS, including the large distance between helium
coldbox and hydrogen system as well as the increased heat load.
The safety factors applied to the estimated heat loads in order to determine the cryoplants’
specified capacities have also evolved over time. Before 2012, when the expected heat loads were not
known in detail, a general safety factor of 1.8 was applied.
Table 1: Evolution of cryoplant capacities and safety factors

| source                  | date       | accelerator cryoplant capacity | target cryoplant capacity | liquid helium yield | contingency / safety factor |
|-------------------------|------------|-------------------------------|---------------------------|--------------------|-----------------------------|
| technical note          | May 2011   | 13.4 kW @4.5Keq.              | 11 kW @4.5Kq.             | 31 l/h             | 1.8                         |
| CDR                     | Feb. 2012  | 14.0 kW @4.5Keq.              | -                         | 45 l/h             | 1.8                         |
| TDR                     | Apr. 2013  | 1.7 kW @ 2 K                  | 25 kW @ 16 K (no contingency) | 50 l/h             | safety factor equation for acc. plant with factors between 1.15 and 1.5 |
|                         |            | + 1.2 kW @ 5-8 K              |                           |                    |                             |
|                         |            | + 7.9 kW @ 40 K               |                           |                    |                             |
|                         |            | + 7.2 g/s liquefaction        |                           |                    |                             |
| technical specifications| Jun. 2015  | 2.23 kW @ 2 K                 | 32 kW @ 15 K              | 50 l/h             | same as for TDR, above      |
|                         |            | + 0.83 kW @ 2-4 K             |                           |                    |                             |
|                         |            | + 11.4 kW @ 33-53 K          |                           |                    |                             |
|                         |            | + 9.0 g/s liquefaction        |                           |                    |                             |

In an effort to establish an unambiguous formula for determining the cryoplant capacities using a set of well defined safety factors for different heat load sources and temperature levels, Equation 1 (based on work by Tom Peterson of Fermilab) was given in 2013 by Weisend et al [11].

\[
C = F_o (F_{ud} Q_d + Q_b + F_{us} Q_s) \tag{1}
\]

where:
- C is the total cooling capacity of cryoplant at a given temperature
- \(F_o\) is the operational safety factor
- \(F_{ud}\) is the uncertainty factor on the dynamic heat loads
- \(F_{us}\) is the uncertainty factor on static heat loads
- \(Q_d\) is the predicted dynamic heat load
- \(Q_b\) is the predicted beam heat load
- \(Q_s\) is the predicted static heat load

The layout, size and utility demands of the buildings that house the cryoplants needed to be determined at an early stage so as to allow the Conventional Facilities Division to start designing the buildings and associated utility supply units. The early safety factor of 1.8 meant for the ACCP that the sum of expected heat loads of 7.5 kW (7 kW for the cryomodules and 0.5 kW for the transfer line) translated to a projected cryoplant capacity of 13.4 kW. This value was used together with an assumed coefficient of performance of 270 to arrive at the estimated electrical power consumption of 3.6 MW.

This value, in turn, was used to determine the cooling water demand, assuming as a first approximation that the heat introduced by the electrical power needs to be extracted by cooling water. The HVAC system for the compressor buildings was sized using a factor of 5% of heat to air. In 2015 this factor was increased to 10% following discussions with the manufacturer of the ACCP, leading to a re-design of the HVAC system. The real value is expected to lie somewhere between 5% and 10% and only tests on the installed plants will tell.

An important decision when designing a cryoplant concerns the use of liquid nitrogen precooling. Arguments for precooling include reduced electricity consumption and a guaranteed stable adsorber temperature. Arguments against include increased reliance on frequent deliveries of LN2 by truck and increased plant costs. ESS took the decision not to use precooling for the ACCP and TMCP after carefully weighing the arguments. The fact that operating plants without precooling gives a greater degree of autonomy from gas supplies was one of the determining arguments, as the cost implications
of both solutions were almost equal. Another reason not to use pre-cooling in the refrigerator is the maldistribution in the heat exchangers caused by an unbalanced flow in different pressure circuits HP, MP, LP and SP, resulting in cold return flow and increased liquid nitrogen consumption. The arguments are discussed in detail in [12].

The TICP will operate with precooling when in CM testing mode.

Starting with the 2013 layout, helium storage was designed to hold two times the amount needed to run the accelerator for a combination of factors. The low maximum allowable working pressure (MAWP) of the niobium cavities make it impossible to hold much of the total helium inventory in case of a total power failure. The time it takes from a compressor trip until enough helium has been lost to prevent subsequent cooldown of the accelerator has been calculated to be around four hours. A power cut of this length has a low but still relevant probability. The presence of a diesel backup powered recovery compressor only partly mitigates this risk. Another potential cause for loss of large quantities of helium is the breaking of one or more burst disks. Even though the cavities are protected by safety relief valves, the fairly low MAWP of the cavities and subsequent low set point of the safety devices, increases the risk of a blow-off. Although this risk of losing a large percentage of the helium to atmosphere has a generally low probability, the consequences are potentially disastrous because of the uncertain delivery times for large quantities of helium from suppliers.

A 20’000 liter dewar directly connected to the ACCP has two advantages. With it’s low boil-off rate, it can hold a second fill of helium for the accelerator which allows it to start up even after a major helium loss coinciding with a prolonged stand still. It also allows the ACCP to use the cold capacity of the stored helium to improve cooldown times and transient operation.

The TMCP, on the other hand, only operates with gaseous helium and does not contain parts with maximum allowable operating pressures below 20 bar. This makes it possible to design the plant and it’s associated medium pressure tanks to hold all helium in gaseous form, even in the event of a prolonged power cut.

6. Evolution of the CDS concept/layout/design/specification

From the moment when it was decided to have segmented cryomodules with an external distribution line, the basic concept of the transfer and distribution system was fairly obvious. Table 2 shows that the number of cryomodules and to a certain extent their length was still subject to change. Yet, the distribution system could be designed to easily adapt to these changes. Decisions that needed to be taken early on concerned the number and location of vacuum barriers, the placement of the 2 K heat exchangers and JT valves as well as the concept for allowing an upgrade of the accelerator with 14 contingency cryomodules.

| source                      | date     | size of cryoplant buildings + outdoors space | electrical consumption of all cryoplants | length of acc. CDS / length of cold linac | number of SRF cavities in the cold linac |
|-----------------------------|----------|---------------------------------------------|----------------------------------------|-------------------------------------------|------------------------------------------|
| technical note              | May 2011 | 1750 m² + 1000 m²                           | 6.6 MW                                 | 450 m / 370 m                            | ~ 200                                    |
| CDR                         | Feb. 2012| N/A                                         | N/A                                    | 450 m / 390 m                            | 212                                      |
| TDR                         | Apr. 2013| N/A                                         | N/A                                    | 450 m / 390 m                            | 208                                      |
| technical specifications    | Jun. 2015| 1650 m² + 450 m²                            | 5.5 MW                                 | 385 m / 310 m + 120 m (cont.)            | 146 + 56 (cont.)                         |
A lot of effort was put into a preliminary sizing of the cryogenic distribution system. Because of space constraints in the accelerator tunnel and the CTL gallery that connects the coldbox hall to the tunnel, it was important to reserve the correct space envelope for the transfer line. It allowed the tunnel integration team to attribute the parts of the tunnel adjacent to the transfer line to other equipment without the risk of having to change the tunnel cross section when the transfer line design was finalized.

7. Evolution of buildings and utilities
Based on the requirements on the cryoplants and the estimates of their sizes and utility consumptions, a sizing of the buildings housing the cryoplants and their utilities was done in 2011 and kept up-to-date throughout the design process, as shown in Table 2. The 2011 note includes an example installation concept, showing a possible layout, positioning and sizing of the cryo buildings as shown in Figure 1. The concept is loosely based on experience from CERN’s LHC cryoplants and their buildings, as well as input from SNS and DESY. The buildings were estimated to have an area of 1750 m², with an additional 1000 m² of outdoors space for gas storage.

The 2015 detailed design of the cryo buildings has 1650 m² indoors and 450 m² outdoors. The total electrical power consumption of all cryoplants was estimated at 6.6 MW, whereas it is assumed to be 5.5 MW in 2015. These relatively small variations show that the initial estimates were fairly realistic, including the applied safety margins which were improved and reduced over the course of the years. The building that has undergone most scrutiny during the design process is the compressor building. It is divided into two big halls, one for ACCP the other for TMCP, TICP, the recovery compressors and the external helium purifier. A separate section is used by the HVAC station and the cooling water pumping units. The separation into different rooms has been done to reduce disturbances from one system to the other, especially concerning noise. It should be possible to run one plant while performing maintenance on the other in a comfortable environment.
The sizing follows exactly the dimensions of CERN’s LHC compressor buildings with a length of 40 m, a width of 15 m and a free height of 7 m. The difference lies in the arrangement of utility spaces. ESS has eliminated underground galleries in order to save building costs. All pipes, cables and ducts have to be routed inside the halls themselves. This, however, introduced a number of problems with the compressor layout inside the building. In retrospect, it would have been wiser to equip the compressor building with galleries for easy routing of utilities.

The sizes of the compressor halls have not changed, although the heat loads have varied. Especially the increase in size of the TMCP has made space allocation in the respective compressor hall very difficult. It has also lead to an increase in size of both the HVAC and cooling water stations, which in turn required more space in the building. Close collaboration with the Conventional Facilities Division allowed us to find compromises and solutions that kept cost at a minimum.

One example is the required air temperature inside the compressor halls. Initially the requirement was set to “normal comfortable working environment” as in many of the other buildings. This resulted, however, in an exceptionally big and expensive HVAC system that was designed to keep air temperatures below 27°C at all times, even in the rare event of a hot summer in Sweden. Close scrutiny of the requirements and a relaxation of the allowable temperature range allowed the HVAC system to be significantly reduced in size and cost. As a trade off, there is a risk that the air temperature inside the compressor halls rises above 40°C. This risk is manageable, as most of the equipment can tolerate these temperatures and the parts that can’t will be spot cooled by dedicated ventilation outlets.

8. Compromises
One of the fundamental dilemmas of a new facility such as ESS is the need for parallel design of cryo buildings and cryoplants. Theoretically, the buildings and utilities should only be designed when the cryoplant engineering is done so as to base them on final and approved numbers. But as it takes years for the actual construction of the buildings, the cryoplant manufacturer would have to stop work during much of this interval. This not only unrealistic and costly, but also adds years to the process. Therefore the design of the cryogenic system and the design of the buildings has to proceed in parallel. This results in many points of friction, uncertainties and finally also mistakes and errors. The ESS cryogenics team minimized problems stemming from this parallel design in two ways.

The most important countermeasure is clear, direct and constant communication between all parties involved. Frequent meetings - both scheduled and ad hoc - between the cryo group and the engineers of the Conventional Facilities Division provided a safety net for cases when communication by mail or through requirement spread sheets was not enough. The few cases where bigger problems appeared can be directly attributed to misses in communication.

The second, almost equally important measure to allow a successful parallel design is the inclusion of reasonable margins in the initial design and the defense of these margins throughout the process. In projects of the size and complexity of ESS cost saving measures are as unwelcome as they are necessary. If they are enforced in a global, uncontrolled way without taking into account the complexities of a cryogenic system, they can result either in very costly retrofitting activities or in underperforming plants. Both of these outcomes are more costly in the end than e.g. a slightly bigger building. The key is to introduce small margins in the sizing and layout of the buildings and utilities as well as in the design of the plants themselves. These margins need to be placed strategically so as to enable the different pieces and parts to work together even though they themselves or their neighbours have changed. The experience from ESS shows that all buildings are filled to the brim although they have been designed in the beginning with a healthy amount of free space.

9. Lessons learned
The progress in the endeavor to build ESS’ cryogenic system has built on the dedication of a small team to manage a big and complex project. A number of decisions have in retrospect, however, turned out to be sub-optimal.
The location of the TMCP coldbox at a long distance from the He-H₂ heat exchanger and the hydrogen system presents a problem for the control and helium management of the TMCP. The long helium transfer line creates long response times and presents a large cold volume, resulting in large amounts of helium to be loaded or unloaded during changes in operation modes. When this issue was raised, the building layout was already frozen and a change no longer possible.

Responsibility for the hydrogen part of the target cryogenic system has been left with the Target Division, because of the extremely complex integration of the hydrogen moderators into the target system. This has created unnecessary interfaces between parts of the cryogenic system that are intricately linked.

Procurement of the ACCP could have been done by competitive dialogue instead of the open call for tender procedure. The competitive dialog allows more communication with the bidders and is well suited in a process where there are a number of issues in the technical specification that can be clarified easily with potential suppliers. The open call for tender, however, has very limited possibilities to clarify technical issues during the bidding process.

The specification of the cryo buildings has been a long process and a dialog with the Conventional Facilities engineers. A number of parameters - such as building footprint, location and orientation - had been established very early. In some cases, such as the placement of dewars, the exclusion of utility galleries and the width of the coldbox hall, a stronger insistence on the requests from the cryogenics team would have lead to better buildings.

10. Conclusion
The past five years have seen the ESS cryogenic system to evolve from nothing more than the realization that there needs to be one, to a well specified and detailed system being on the brink of procurement. Starting with one cryogenics engineer in 2010, the team has now almost 10 people working on aspects from process design through pipe routing and project management to building coordination. As the design of the entire ESS facility moved from concept to an impressive amount of detail, the design of the cryogenic system kept up with all changes and matured to a point where the path to actual construction, commissioning and operation is established.

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