Chapter 6

Specialised Technical Services

Chapter abstract

Summary: This chapter describes three specialised technical systems: the cryogenic system, vacuum system and test stands. These systems support all three areas of the ESS facility: accelerator, target and experiments. The system designs are conservative and based on experience at other facilities such as CERN, SNS and CEA Saclay. Issues such as the determination of safety factors for the cryogenic system capacity as well as the availability and sustainability of the cryogenic system are also discussed.

The cryogenic system consists of: the linac cryoplant that provides cooling for cryomodules; the test and instruments cryoplant that provides cooling for test stands and liquid helium for instruments; the target cryoplant that provides 16 K helium cooling for the target hydrogen moderators, and the distribution system that connects the linac cryoplant to cryomodules. The linac cryoplant and test/instrument cryoplant share common gas management and storage systems. The target cryoplant system is completely separate due to potential for tritium contamination. The cryogenic systems have been designed to meet sustainability goals through measures such as He conservation and heat recovery.

The vacuum system provides vacuum for the linac beam line, target system and instrument lines. It uses well-established technology and procedures based on experience at similar facilities, including SNS, JLab, J-PARC and LHC, and has low technical risk.

Test stands provide testing and validation of both RF equipment (klystrons and modulators) and cryomodules. Cryogenic connection to cryomodules in the test stands will prototype similar connections in the linac tunnel. The test stand programme accommodates the unavoidable uncertainty in the ESS construction schedule by allowing for RF equipment testing in a temporary location if necessary. Cryomodule testing will be carried out at the ESS site. All cryomodules will be tested at nominal temperatures and RF power levels before tunnel installation. Cryomodule testing will take place at two locations. The Uppsala test stand will test prototype and series production spoke cryomodules. The Lund test stands will test all elliptical cryomodules, and will retain the capability to test spoke cryomodules.
6.1 Cryogenic systems

The cryogenic system is the largest of the specialised technical systems and can be further divided into four subsystems: the linac cryoplant, the target cryoplant, the test stand and instruments cryoplant and the distribution system. The linac cryoplant will provide all the cooling to the 59 cryomodules containing the superconducting RF cavities. The target cryoplant will provide cooling to the 20 K hydrogen in the moderators surrounding the target. The test stand and instruments cryoplant will serve two purposes. It will produce liquid helium (LHe) for distribution in transport Dewars to instruments along the experimental beam lines, and it will provide cryogenic refrigeration to the cryomodule test stands. The main distribution system will provide the cryogenic and warm gas connections between the linac cryoplant and the cryomodules. A smaller distribution system will connect the test stand and instruments cryoplant to the cryomodule test stand. ESS will build this smaller system first and it will serve as a prototype for the main distribution system. The linac cryoplant and test stand and instruments cryoplant will share a common helium recovery, purification and gas handling system. They will also share a common helium gas storage facility. Separate LHe storage Dewars will be provided for these two plants. Due to the possibility of tritium contamination and to allow operational stability of the quite distinct cryogenic processes, the target cryoplant will be completely separate from the other two cryoplants. It will contain its own gas storage system, and will be linked to the target by a separate distribution line. Figure 6.1 is a high-level block diagram showing the ESS cryogenic system and its connections to other ESS components.

The cryoplants and distribution system will be controlled by a programmable logic controller (PLC)-based system which, in turn, will communicate with an EPICS-based Human-Machine Interface. The EPICS system will link the PLCs of the cryoplants and distribution system and allow operator control, data logging, trending and alarms. The detailed accelerator control structure is still under development and lower level connections, in particular between the distribution system and linac cryoplant PLCs, may

Figure 6.1: Block diagram of the ESS cryogenic system.
be necessary. Outside cryoplant vendors will produce the cryoplant control systems, up to and including the PLC level. ESS will produce detailed technical specifications for these systems, including guidelines for the standardisation of PLC hardware and data structure. ESS-vendor contracts will require vendors to provide all documentation and source code for their control systems. The integrated controls system (ICS) project will specify the details of the interface between the vendor-supplied PLC systems and the ESS controls systems. The ICS will create the EPICS controls as well as the entire control system for the distribution system. Private industry will produce all three cryoplants and the cryogenic distribution system in accordance with ESS performance specifications. The installation and commissioning of these systems will be a shared responsibility between the vendors and ESS.

One of the unique aspects of the ESS project is the attention paid to energy conservation and sustainability. A number of aspects of the cryogenic system reflect this priority. Superconductivity makes ESS possible. Without the use of superconducting RF structures, the energy costs of accelerating the proton beam would be excessive. Superconducting systems require cooling to cryogenic temperatures, which in itself requires energy. ESS attempts to minimise the energy costs of the cryogenic system by: designing the system to minimise the amount of cryogenic cooling required; specifying efficient cryogenic refrigeration plants and recovering as much of the heat removed from the cryogenic system as practical. Techniques to minimise the amount of cooling required include: the use of welded pipe connections rather than more easily demountable but higher heat leak bayonet connections; and the selection of cryogenic plant options (such as a final stage of warm compression for the sub-atmospheric pressure helium lines) that allow easier reduction of cryoplant capacity and minimise the need for active heaters to keep the cryogenic load constant. The linac cryoplant will be specified to operate at about 26% Carnot efficiency, which is in the upper range of possible cryogenic plant efficiency.

The most innovative aspect of the ESS cryogenic system regarding sustainability is the recovery of the heat produced by the warm helium compressors for reuse in the Lund District Heating System. ESS uses a significant amount of helium gas, also a limited resource. The cryogenic systems are designed to be closed cycle, recovering and reusing most of the helium gas. Only in certain abnormal operating conditions will helium be vented to the atmosphere.

Availability refers to the fraction of time that the ESS cryogenics system is able to provide the cooling required. If the cryogenic system is not functioning properly, ESS cannot deliver neutrons to researchers. Thus, a very high availability for the cryogenic system is required. There is significant experience in the operation of large He II cryogenic systems. Properly designed and operated, such systems can achieve availabilities of greater than 98%. There are a number of features in the proposed cryogenic system design that are chosen to help increase availability. Availability is aided by the separation of the more dynamic test stand cryoplant from the linac cryoplant, which will operate at more constant loads. Thus, an unexpected event in the test cryoplant due to an R&D test won’t impact the linac operation. Availability of liquid helium for the instruments is increased by the planned LHe storage, which will allow the instruments to operate for a number of days with the target plant shut down. The availability at the individual cryoplant level is helped by the presence of backup helium compressors that can be brought on line quickly in the event of a compressor failure, as well as by the presence of backup control power and backup instrument air supplies. Given the large amount of power required, the primary compressor power won’t have a backup, so a site power outage will shut down the cryogenic systems. However, such outages are quite rare in the Lund area.

6.1.1 The linac cryoplant

The linac cryoplant is the largest of the cryoplants and provides cooling at three nominal temperature levels: 40 K to 50 K for the thermal shields of the cryomodules and distribution system; 4.5 K for the power coupler thermal intercepts and 2 K for the SRF cavities. The linac consists of 59 cryomodules operating at 352.21 MHz for the spoke cavities and 704.42 MHz for the elliptical ones. The ESS cryomodules are individual cryogenic units and are cooled in parallel by the cryogenic distribution line. Details of the cryomodule design may be found in Chapter 4. Figure 6.2 is a flow schematic showing typical flows and connections between the distribution line and a cryomodule. Applying lessons gleaned from the experience of other accelerators such as SNS [1], the cryoplant will supply 4.5 K helium at 0.3 MPa to the cryomodules. The actual production of saturated 2 K He II will occur at each individual cryomodule. This approach is thermodynamically more efficient (it minimises the heat leak to the 2 K level) and limits the possibility of two-phase flow in the distribution system.
To produce the 2 K temperature level in each cryomodule, incoming helium, at temperatures varying from 4.5 K to 5 K along the length of the distribution line and at a pressure of 0.3 MPa, will be pre-cooled by the subcooler to 2.2 K before entering the Joule-Thomson expansion valve. The remaining enthalpy difference by evaporation of helium will be 20 J/g. An overall heat load to the 2 K temperature level of 40 W results in a mass flow of 2 g/s. Choosing the optimum temperature for the cavity operation is essential for the overall efficiency of the cryogenic system. ESS needs to determine if it is true that a reduction in the temperature of the superfluid helium bath to 1.8 K would increase the $Q$-value of the superconducting cavities by a factor of around 1.5, which would more than compensate for the increased cryogenic effort of providing helium at 1.64 kPa instead of 3.1 kPa saturation conditions. A temperature below 1.9 K, which is the temperature at which superfluid helium reaches its peak heat transfer capability, would avoid thermal run-away at localised hot spots on the cavity surface [2,3].

The low pressure He gas must be pumped away from the 2 K saturated baths surrounding the cavities and returned to the cryoplant. In plants of this size, there are two options for such a pumping system. One relies solely on cold compressors; the other employs a set of cold compressors followed by a final stage of warm compression. The cryogenic heat load at 2 K in the ESS accelerator will be roughly two-thirds dynamic, resulting from cavity and beam heating, and one-third static heat leak from warmer temperatures. Thus, it is desirable for ESS to use the pumping system that makes it easiest to reduce the 2 K plant capacity when the dynamic load is reduced. The alternative approach of using electric heaters to mimic the dynamic load for a significant length of time is counter to the ESS project goals of energy...
6.1. CRYOGENIC SYSTEMS

efficiency and sustainability. The 2 K capacity may be more easily reduced using a mixture of cold and warm compression for the low pressure He pumping system and this is the approach selected for the linac cryoplant. This approach, which CERN uses in the LHC plants [4], also allows for an easier restart of the 2 K system after a system upset.

Each cavity is equipped with an RF power coupler whose outer conductor is flanged to the 2 K cavity surface. The power couplers need to be cooled by a controlled flow of supercritical helium that warms up from 5 K to around 150 K towards the warm end of the power coupler and returns back as ambient-temperature gas to the linac cryoplant. The appropriate mass flow is regulated at ambient temperature with a flow controller in the return connection at each power coupler. The distribution system will deliver He to the cryomodules for coupler cooling at 0.3 MPa. The current coupler design calls for an operating pressure of 0.14 MPa. That reduction in pressure must be accomplished inside the cryomodules.

Helium gas will be used at supply conditions of 1.95 MPa at 40 K to cool the thermal radiation screens. It will return to the cryoplant at 1.9 MPa and 50 K. This thermal shield will act as a heat sink at 40-50 K for instrumentation wires and support structures as well. Lowering the temperature of the thermal screen from typical values of 50-80 K to the average temperature level of 45 K makes possible a simplified design of the cryomodule without a separate 5 K thermal radiation screen [5]. The ESS Cryogenics Group will further optimise the temperature and pressure specifications for the shield circuit helium as part of the development of the specification of the overall linac cryoplant.

A cool-down line connected at the cryomodule connection box to the 4.5 K helium supply line will achieve the cool down of the whole cryomodule. To guarantee the required temperature gradient along a cryomodule and the required time-temperature history of the cold mass itself, a specified flow rate will be mixed in the valve box, using the cold helium supply on the one hand and the ambient temperature helium gas from the warm-up line on the other hand. For an effective cool-down procedure, this cool-down line will be connected to the bottom of each cavity enclosure. The same line will be able to conduct a warm-up procedure for the whole linac in a fast and uniform way with a helium gas flow of increasing temperature. Because part of the cavity cooling circuit operates at sub-atmospheric pressures, a guard system is required to protect against leakage of outside air into the pure helium gas system from the outside. Therefore all seals of safety relief devices in these circuits, as well as the shaft sealing of cryogenic valves, will be connected to a helium guard system, which will surround these non-welded connections with a pure helium gas atmosphere. The saturation pressure for a 2 K superfluid helium bath is 3.13 kPa. The adjustable J-T valve will create the pressure step and regulate the level in the two-phase pipe. For a given heat load to the 2 K cold mass, the appropriate helium flow rate will be set in this circuit. The return part of this circuit will start with the low-pressure pipe connected to the two-phase pipe in the cryomodule. The overall drop in pressure in the vapour low pressure (VLP) return part of the cavity cooling circuit, including the heat exchanger in the cryomodule, will have to be smaller than 0.25 kPa.

The specific cryoplant cycle design will be produced by the vendor ESS selects to provide the plant. Nonetheless, Figure 6.3 shows a generic schematic of the major components of the linac cryoplant. Determining the capacity of the linac cryoplant requires a detailed analysis of all the possible heat loads. The dynamic and static heat loads have been estimated for the cryomodules described in Chapter 4, and for the distribution system. These estimates are based on current understanding of the designs and on the expected performance of cavities and couplers. The dynamic loads (RF and beam loss) have a built in safety factor as they assume conservative performance of the cavities and the maximum acceptable beam load. During 2013, these estimates will be reﬁned as the designs are developed. By September of 2013, formal technical notes on the cryomodule heat load and the distribution heat load will be prepared by the responsible groups. These will serve as an input into the final sizing of the Linac cryoplant. Both the heat load analysis and the proposed plant sizing will be peer reviewed by external experts in September 2013. This approach will provide plant sizing information in sufﬁcient time for the speciﬁcation of the Linac cryoplant in 2014. A current estimate, sufﬁcient for costing and planning, is 1724 W at 2 K, 1223 W at 5 to 8 K and 7872 W at 40 K. There is also expected to be an 7.2 g/s liquefaction load at 4.5 K for coupler cooling. These numbers do not include any safety factor except for those associated with the cavity dynamic loads and with beam heating. The determination of the appropriate safety factors is discussed in Section 6.1.5. A cryoplant of this size is similar to those used at the JLab 12 Gev Upgrade [6] and at the LHC [4]. Such a cryoplant, while certainly a custom order, is well within the current state of the art.

The inventory of liquid helium for the cold part of the linac, including the distribution system, will be 12,000 l. Gaseous helium storage at ambient temperature will keep the helium inventory at the discharge pressure of the cryoplant compressors, which is 2 MPa. Seven cylindrical gas tanks with a diameter of
3.7 m and a length of 10 m will be sufficient to store the necessary amount of helium gas, since one of these tanks can store an equivalent amount of 1,750 l liquid helium. The exact size and number of tanks will be determined by ESS in consultation with potential vendors. Additionally, a liquid helium storage tank of 20 m$^3$ will be installed to store helium for a second fill and to compensate for helium losses during operation. The Linac Cryoplant will share gas storage and management with the Test Stand and Instruments Cryoplant.
6.1.2 Test stand and instruments cryoplant

This cryoplant will serve two functions. During ESS operations, the test stand and instruments cryoplant will provide liquid helium to the various instruments along the neutron beam lines. The number, type and position of the instruments requiring LHe will change over the lifetime of ESS. This feature, along with the relatively small LHe requirements for a single experiment, has led the ESS Cryogenics Group to select delivery of LHe via portable Dewars rather than through a dedicated distribution system. There will be a dedicated room temperature return header along all the neutron beam lines to collect the He gas from the instruments. This gas will be returned from the instruments to the cryogenics building, where it will be purified and returned to gas storage. This system will reduce helium losses during normal operations to the absolute minimum.

Estimates have shown that the nominal instrument requirements for LHe is 17 l/h with an expected peak rate of 35 l/h. In order to allow for uncertainties in instrument LHe needs, and to compensate for possible degraded operation of the plant, the test stand and instruments cryoplant will be sized to liquefy at least 50 l/h. This cryoplant will also include a 5000 litre LHe storage tank that will create a buffer volume to compensate for unexpected plant shut downs and to supply unexpected peak needs. The instruments are also expected to require up to 200 l/h of liquid nitrogen (LN$_2$). This will be provided by on-site storage filled by an external vendor on a regular basis. In order to limit the number of refills, a total of 50 m$^3$ of LN$_2$ storage, divided among several Dewars, will be provided. Once used by the instruments, the nitrogen gas will be safely vented into the outside air.

The second function of this cryoplant is to provide cryogenic cooling for the cryomodule test stands. Each of the 59 cryomodules will be tested under full RF and cryogenic operating conditions prior to installation in the ESS tunnel. Based on the current ESS schedule and cryomodule production rates, the Cryogenics Group has determined that three test stands will be required: one dedicated to the spoke cryomodule testing and two dedicated to the medium-$\beta$ and high-$\beta$ cryomodules. In order for the results of the testing to be unambiguous, the cryoplant should provide refrigeration at the same temperature levels as will be used in the operating linac. Thus, the cryoplant must provide cooling at 40 K, 4.5 K and 2 K. As in the case of the linac cryogenic system, the cryoplant will provide helium at 4.5 K and 0.3 MPa to the cryomodules and the conversion to 2 K saturated He II will take place inside the cryomodule. The connections to the cryomodules on the test stands will have the same design as those in the linac tunnel. This will allow early validation and experience with the linac distribution line design. One issue that is yet to be resolved is the method by which the sub-atmospheric-pressure helium is pumped off the He II bath in the cryomodules under test. This may be accomplished by a set of cold compressors or by a set of room temperature vacuum pumps. The final choice will be made during the design and specification phase scheduled for completion by mid 2013. Regardless of the choice made, all helium pumped off the 2 K baths will be recovered, purified and reused.

The refrigeration capacity of this plant at the various temperature levels is based on the worst-case assumption that ESS will have to operate all three test stands simultaneously under full RF power. The resulting plant has a 4.5 K equivalent capacity of 500 W to 600 W. A plant with this refrigeration capacity can easily be designed to operate as a liquefier producing the 50 l/h required. Even after ESS begins operating, there will still be a need for some cryomodule testing to support both the repair of cryomodules and the development of upgraded cryomodules. The test stand and instruments cryoplant will be designed to meet both this need and the instrument liquid helium needs. The test stand and instruments cryoplant will be located in the cryogenics buildings, along with the linac and target cryoplants and adjacent to the cryomodule test stand area. The instrumentation and test cryoplant will be the first of the ESS cryoplants to be procured, installed and commissioned. As such, it will provide valuable experience and training for the ESS cryogenics team.

6.1.3 Target cryoplant

A key feature of the ESS target will be the hydrogen moderators, which will use hydrogen at 20 K and 1.5 MPa to reduce the energy of the neutrons before they reach the instrument lines. The neutrons will deposit significant amounts of energy into the hydrogen that will have to be removed to maintain the hydrogen at its nominal operating temperature of 20 K. The target cryoplant will provide the cooling for the hydrogen moderators. The heat deposited into the hydrogen will be removed via a heat exchanger that will transfer the heat from the hydrogen circuit to a gaseous He circuit operating at 16 K which is
connected to the target cryoplant. Both the helium and hydrogen circuits will be closed loops and will be separated from each other. Only heat will transfer between them. This approach is similar to that used for the LH2 moderators at SNS [7] and J-PARC [8] as well as in larger hydrogen target experiments [9]. The design and procurement of the hydrogen moderators and associated hydrogen circulation loops, including the helium/hydrogen heat exchanger, is provided as part of the target system described in Chapter 3. Current analysis shows that the required capacity of the target cryoplant is 25 kW at 16 K, without including a safety factor [10]. Due to the helium circuits proximity to the target, there is the possibility of tritium contamination in the target cryoplant. ESS will manage this risk in two ways. First, the target cryoplant will be completely separate from the other cryogenic systems, with its own He gas management and storage systems. In addition, the target cryogenic plant will be designed to prevent the automatic venting of helium at warm-up.

### 6.1.4 Distribution system

Figure 6.4 shows how the linac cryogenic distribution system starts at the connection boxes of the linac superconducting RF cryomodules and moves out through the cryogenic transfer line (CTL) to the linac refrigeration plant, hosted in a common cryoplant facility at the high-energy end of the linac. Key design features of the distribution system are:

- All cryogenic supply and return lines will be placed in one common, vacuum-jacketed cryogenic transfer line, the diameter of which will mainly be determined by the VLP helium return pipe.

- An intermediate temperature thermal shield, operating at the same temperature as the cryomodule shields (40 K/50 K), will be included in the CTL, valve box and jumper sections.

- Each cryomodule will be connected to the cryogenic transfer line via jumper connections with a U-shape design. Cryogenic valves situated in a vacuum-insulated valve box will allow the separation of single cryomodules from the cryogenic transfer line.

- The jumper sections will be welded connections within a common vacuum jacket rather than separate bayonet connections.

- The system will allow individual warm up and cool down of a cryomodule, while keeping the rest of the system at cryogenic temperatures.

- A vacuum barrier in the jumper connection will separate the vacuum of the transfer line and the individual cryogenic insulation vacuum of the cryomodules.

- High-pressure helium gas will cool the thermal radiation shields. This temperature level additionally serves as a first level of heat interception.

- Supercritical helium will be supplied in a second circuit feeding the superfluid helium cooling of the superconducting cavities. The supercritical helium flow will be pre-cooled in a 2 K subcooler at each cryomodule. A cool-down line, bypassing the precoring heat exchanger, will connect to the supercritical supply line as well.

![Figure 6.4: Schematic of the linac cryogenic distribution system.](image-url)
- The pressure drop in the precooling heat exchanger in each cryomodule should be smaller than 0.1 kPa at the low-pressure vapour side, while sub-cooling the incoming helium flow to a temperature below 2.2 K.

- The acceptable pressure drop in the VLP line mainly determines the pipe dimension of the cryogenic transfer line. The maximum allowable pressure drop in the vapour helium return system at the 3.1 kPa pressure level is 0.25 kPa over the whole length of the 450 m VLP line.

- A part of the supplied supercritical helium will be used for cooling the RF power couplers. The flow will warm up to 150 K cooling the power coupler and will return to the cryoplant at ambient temperature.

The design of the CTL assumes that all cryogenic elements in the linac will be cooled using one cryogenic plant, which will be located at the high power end of the linac. The schematic of the CTL in Figure 6.2 shows the interconnection of the CTL with a typical cryomodule. The allowable pressure drop for the heat exchanger on the vapour return side is 0.1 kPa. This sets the limit for the pressure drop of the VLP return pipe and the jumper connection to less than 0.15 kPa. The major influencing parameter of the cryogenic transfer line is the necessary diameter of the VLP return pipe. On one hand, there is a cross section restriction on this big-diameter pipe that determines the vacuum enclosure pipe that finally needs to fit in the tunnel layout. On the other hand, there is a limited margin of permissible pressure drop for the 450 m long cryogenic transfer line on the order of $\Delta p < 0.15$ kPa. Figure 6.5 shows the accumulated heat load versus length of the gas return pipe starting from the spoke cryomodules towards the cryoplant.

The heat load to the 2 K cavity circuit is 1.9 kW directly in the cryomodules. Additionally, there is a heat load to the supply helium in the CTL and to the jumper connection and interconnection boxes. The CTL heat load is reduced as much as possible by introducing an 8 K return line, which lifts the majority of the heat load to the 5 to 8 K temperature level. Therefore the accumulated heat load at the cryoplant side of the CTL adds up to 2.1 kW, as shown in Figure 6.5. A pressure drop calculation of the sub-atmospheric pressure vapour flow determines the overall pressure drop to be 0.1 kPa for an inner pipe diameter of 260 mm, for example. At each cryomodule connection, the flow coming from the cryomodule

![Figure 6.5: Cumulative heat load and resulting pressure drop in the VLP return line starting at the spoke cryomodules of the Linac and moving towards the cryoplant. Also see Figure 6.4. The inner pipe diameter for this example is 260 mm. No safety factor for heat loads is applied in this calculation.](image-url)
mixes with the flow of the VLP return pipe. A straight drift section after each T-intersection adds a heat load of 0.2 W/m to the VLP pipe that increases the flow temperature up to 4.3 K within the cryogenic transfer line.

Figure 6.6 shows the pressure drop and temperature change along the full length of the gas return pipe as a function of the pipe diameter. The pressure drop decreases with increasing pipe diameter, reaching the specified limit of 0.1 kPa at a diameter of 260 mm. This pressure difference along the gas return pipe causes a change of saturated vapour pressure in the two-phase pipe for different cryomodules along the Linac. Figure 6.6 also shows the maximum temperature difference caused by the change in saturated vapour pressure along the cryogenic transfer line plotted against the gas return pipe diameter (blue diamonds). For a given temperature of the helium bath in the first spokes, the resulting temperature difference at the last cryomodule is about 10 mK for a pipe diameter of 260 mm. The design of the distribution system is ongoing. The Cryogenics Group is still studying a number of issues, such as the number, type and location of safety valves; the number of warm helium lines; the design of the cool-down line and the final line sizes. ESS will finalise these design decisions in 2013.

6.1.5 Safety factors for cryoplant capacities

In large scientific facilities such as ESS, the precise determination of the cryoplant cooling capacities is complicated. This results from a number of factors. At this stage of the project, prior to significant prototype testing, the static and dynamic heat loads of the cryogenic components have been calculated, but are not yet verified. Even after all prototypes are complete, subsequent degradation of cryogenic component performance may lead to higher heat loads. Additionally, over time the performance of the cryoplant may be reduced due to equipment failures. Another complication is that the amount of uncertainty will vary between temperature levels and in the case of ESS, from cryoplant to cryoplant. For example the 40 K to 50 K shield heat load, which is mostly independent of cavity performance, can be determined with less uncertainty than the 2 K heat load. Similarly, the 16 K heat load for the target cryoplant has
been determined by well-understood neutronics calculations, and is thus predicted with a high degree of confidence. One approach for dealing with this uncertainty is to multiply the expected cryogenic loads by a safety factor to determine the final capacity of the cryoplants. There are hazards in this approach. One has to be careful not to apply safety factors on top of safety factors, resulting in an overly conservative and costly system. Alternatively, being overly optimistic and applying too small a safety factor can result in a cryoplant that is too small to meet actual operating requirements. These hazards are best avoided by being very explicit and clear about the definition and size of the safety factors used.

The ESS cryogenics team will use the following formula to determine each cryoplants cooling capacity at a given temperature [11]:

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

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 (i.e. those associated with RF cavities and couplers)
- \( F_{us} \) 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 operational safety factor \( F_o \) takes into account the desirability of having some operating space in which to control the plant. It also allows some margin for seasonal temperature variations, and degraded plant performance due to minor maintenance issues. \( F_{us} \) and \( F_{ud} \) take into account the uncertainty in predicting the exact static and dynamic heat loads. Table 6.1 lists the ESS safety factors for each cryoplant and each temperature level. The clarity of this approach allows for straightforward reviews. The value of \( F_o = 1.15 \) is an estimate based on industry experience. The lowest safety factor (1.3) is associated with 40 K to 50 K static loads and the dynamic loads associated with the target, as these loads have been calculated with the highest degree of confidence. The safety factors associated with both the cavity dynamic heat load and the beam heating are set to 1.0. This results from the baseline estimates of these values already containing safety margin. The operational safety factor is still applied to these values as well. The safety factors may be adjusted as the project continues and additional design and performance data becomes available. The plant capacities and safety factors must be firmly determined before the plant specification is released for

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Table 6.1: Cryoplant safety factors for each cryoplant and each temperature level.
bidding by industry. At the earliest, this will occur in the first quarter of 2014 for the test stands and instruments cryoplant.

Experience shows that maintaining a high purity of the helium gas is key to cryoplant availability [12]. ESS will use well-established operating procedures along with helium purification systems and monitoring of the helium gas purity to address this issue.

6.2 Vacuum systems

6.2.1 Accelerator vacuum systems

Front end systems

The front-end systems comprise the Ion Source (IS), Low Energy Beam Transport (LEBT), Radio Frequency Quadrupole (RFQ) and Medium Energy Beam Transport (MEBT). With the exception of the MEBT, these systems will be designed to handle the high hydrogen gas loads needed for ion source operation. While the vacuum systems will be suitably sized to manage these loads, the pump exhaust will also be handled in an appropriate manner to eliminate the potential for the formation of explosive mixtures. Safety considerations will be addressed in the design and the design will comply with applicable codes and standards for the handling of hydrogen.

Since beam energy levels in the front end systems are relatively low, no specific actions will need to be taken to reduce vacuum levels below those dictated by beam transport requirements in order to allow hands-on maintenance. The radiation levels anticipated will not impact the selection of vacuum equipment. The use of elastomers, such as EDP or Viton, for sealing is well-accepted, but ESS will use metal seals and CF-style flanges where possible. The use of TMPs (turbomolecular pumps) is appropriate for the continuous pumping of the high hydrogen gas flows that will need to be pumped from the IS and LEBT sections. Dry scroll pumps will also be used for initial evacuation and will back these TMPs. The use of closed cycle cryo-pumps is also an option, however, hydrogen inventory and the impact of routine regeneration will need to be considered if ESS decides to use this type of pump.

The greatest risk when pumping hydrogen is the formation of an explosive mixture at hydrogen concentrations in the air as low as 4.5%. Even with the low flow rates anticipated, it is prudent to dilute the hydrogen concentration below the explosive limit by gas ballasting the scroll pumps with nitrogen to produce an exhaust stream below the critical concentration. This will eliminate the potential for explosive mixtures forming in the vicinity of the pump's electric motor, switches or other electrical equipment. ESS will use this strategy no matter which type of primary pump it decides to use. Due to the potential for hydrogen explosions, ESS will not use hot filament gauges. Emergency power is not essential for these systems if TMPs are used, since the run down time will allow an orderly shut down of the systems and extensive precondition of the systems will not be required to bring them back on line. If cryo-pumps are used, consideration will need to be given to the provision of emergency power to prevent the unscheduled warm up of the pumps. Vacuum gauging and manual vent valves to bring the systems up to atmospheric pressure will be fitted.

Pumping will be distributed along the length of the RFQ and will be designed to provide sufficient pumping speed to maintain RFQ pressure at an operational level and to minimise gas flow into the MEBT. The use of TMPs for the RFQ has several advantages: commonality with the pumping systems used for the ion source and LEBT; reducing the need for spares; providing continuous operation by avoiding the need for periodic regeneration, which will extend machine availability unless redundant pumps are used; and improving operational safety since hydrogen inventory will not be accumulated in the pumps. The optional use of cryo-pumps has the same disadvantages as delineated in the previous section, and the exhausted gas stream would be handled in a similar way. Pneumatically operated gate valves will be provided at both the entrance and exit of the RFQ to allow preconditioning of the LEBT and isolate the MEBT during RFQ maintenance and conditioning. The valves will be sized to have sufficient aperture to ensure that the gate seal is outside the tails of the beam profile. The valve between the RFQ and MEBT will be a normally closed (NC) valve (power to open) which will isolate the RFQ from the MEBT in the event of power failure or loss of vacuum. Each TMP (or cryo-pump) will be equipped with inlet gate valves to allow individual pumps to be isolated from the system. The comments regarding emergency power in the previous section also apply in this case. The RFQ will be fitted with vacuum gauging and a manual vent
valve to bring the RFQ up to atmospheric pressure. Again, the use of elastomers, either EDP or Viton, for sealing is considered acceptable but ESS will use metal seals and CF style flanges where possible.

Since the gas loads associated with the MEBT will be primarily due to outgassing, the use of ion pumps will be a suitable choice for this application. Noble ion pumps are preferred to suppress any tendency for argon instability. RF screens will be required at the inlet to each ion pump to prevent the regurgitation of gas from the ion pumps into the systems as a result of the RF power. A fixed mechanical pumping system using a TMP backed by a scroll pump is preferred for the initial evacuation of the MEBT prior to bring the ion pumps online. An NC gate valve (one that closes automatically upon loss of power or vacuum) will be installed between the MEBT and warm linac to isolate the system in the event of power failure or loss of vacuum. Emergency power will be considered to maintain MEBT vacuum during a power outage, eliminating the need to bring the mechanical pumping system online in order to restart the ion pumps. The MEBT will be fitted with vacuum gauging and a manual vent valve to bring the system up to atmospheric pressure.

**Drift tube linac**

As is the case with the MEBT, the gas loads associated with the drift tube linac DTL tanks will be primarily due to outgassing and the use of ion pumps will be a suitable choice for this application. Noble ion pumps will be used to suppress any tendency for argon instability. RF screens will be required at the inlet to each ion pump to prevent the regurgitation of gas from the ion pumps into the systems as a result of the RF power. The ion pumps will be connected directly to the DTL tanks. Initial evacuation of each DTL tank will be accomplished using a mobile pump cart prior to bringing the ion pumps online. This connection will be made via a gate valve fitted to the DTL tank. This valve will be interlocked with the pump cart via an electrical connector, which will connect the gate valve to the pump cart. Tank and pump cart pressures will be used as valve interlock commands. It is anticipated that it will be possible to use elastomers or the sealing of drift tubes, post couplers, slug tuners, etc. Silver coated “C” seals or a similar approach will be used in these sealing areas to maintain RF coupling between components. NC gate valves will be installed between individual DTL tanks and the low energy differential pumping section to isolate individual tanks in the event of power failure or loss of vacuum. RF heating of the valve seals may be an issue with the higher energy tanks and will need to be investigated before valve selection is finalised, especially if a minimum aperture beam line is used. This could require the use of valves which provide RF resistance in the opened position by providing electrical contact between the flanges.

Emergency power will be required to maintain the DTL tanks under vacuum during a power outage, which will eliminate the need to reconnect a mobile pump cart prior to bringing the ion pumps back online due to a loss of tank vacuum (> $10^{-4}$ mbar). Each tank will be fitted with vacuum gauging and a manual vent valve to bring the tank up to atmospheric pressure. To provide the maximum possible pumping speed in a limited space, it is anticipated that a getter pump will be used to provide the pumping between the RF window and iris. The getter pump will be provided with an isolation gate valve to allow the getter to be reactivated when heated. A TMP backed by a scroll pump would be used to pump out the gas released during this reactivation. Emergency power will be optional for the RF window pumping system, since the pumps of the DTL tank will be available during a power outage to pump the RF window cavity through the iris. Each RF window will be fitted with vacuum gauging. The RF window will be vented through the iris into the DTL tank. Once more, the use of elastomers for sealing is considered acceptable, but ESS will use metal seals and CF style flanges where possible. The windows will use a brazed assembly. In addition to providing for the location of the between-tank isolation valves, tank interconnections will also be used to accommodate beam instrumentation as needed. The diameter of the tank interconnecting beam line will be minimised within the limits required to accommodate the tails of the beam to limit heating. While elastomers would be acceptable, ESS will use metal seals and CF style flanges where possible.

**Low energy differential pumping section**

The low energy differential pumping section (LEDP) provides a pressure reduction between the last DTL tank and the first spoke cavity in order to limit the flow of gas from the warm section of the machine into the cold section. The LEDP will have distributed ion pumps and a beam tube that will provide the minimum conductance possible in order to generate the maximum pressure gradient within the physical constraints dictated by physics and the installation. This section will also include beam instrumentation.
and a fast closing valve to protect the first spoke cavity from an inrush of gas that may result from a loss-of-vacuum event occurring in the warm section of the machine. Emergency power will maintain the LEDP under vacuum during a power outage in order to protect the cold section of the machine. The LEDP will be fitted with vacuum gauging, fast valve sensor and a manual vent valve with micron filter to bring this section up to atmospheric pressure. With the limited beam aperture, metal seals and CF style flanges will be used where possible. Valve sealing will be limited to the use of elastomers (EDP or Viton). Following fabrication of the LEDP beam pipe, it and other components will be extensively cleaned prior to assembly in a class 10/100 clean room to minimise the potential for contamination of the cold section of the machine during and following installation.

Cold linac

The accelerating cavities of the spoke, medium-β and high-β cryomodules will be cooled with helium at cryogenic temperatures and as a result will be self-pumping. Each unit will be fitted with vacuum gauging and a manual vent valve with micron filter to allow each section to be brought up to atmospheric pressure. The cavities will be conditioned prior to installation in the tunnel and connection to the warm sections. This connection will be made under clean room conditions using portable clean rooms to minimise the potential for particulate contamination of the cavities. Following connection and evacuation of the warm sections, the interconnecting valves to adjacent cryomodules will be opened. As each warm section is installed, the vacuum jackets of cryomodules adjacent to it will be evacuated using a portable pump cart. Once the vacuum jackets are under vacuum, the cryomodule will be ready for cool down. The pump cart can be removed once the cryomodule has been cooled down, since this will provide self-pumping of the vacuum jacket due to the cold surfaces. Beam line connections will be made using metal seals and CF style flanges where possible.

The linac warm units will provide the beam line connection between individual spoke cavity modules and cryomodules. These sections will have a centrally located ion pump, beam instrumentation, vacuum gauging and manual vent valve with micron filter to allow them to be brought up to atmospheric pressure. The warm sections will be isolated from the cryomodules during installation by isolation gate valves located on the end of each adjacent cryomodule. While elastomers would be acceptable for sealing, ESS will use metal seals and CF style flanges where possible. Emergency power will be provided to maintain the warm sections under vacuum during a power outage to minimise the flow of gas into the cold sections of the machine. Following fabrication of the warm beam pipe, this and other components will be extensively cleaned prior to assembly in a class 10/100 clean room to minimise the potential for contamination of the cold sections of the machine during installation.

High energy differential pumping section

The high energy differential pumping section (HEDP) will provide a controlled pressure increase between the last high-β cryomodule and the HEBT in order to limit the flow of gas from the warm section of the machine into the cold section. The HEDP will have distributed ion pumps and a beam tube providing the minimum conductance possible in order to generate the maximum pressure gradient within the physical constraints dictated by physics and the installation. This section will also include beam instrumentation and a fast closing valve to protect the final cryomodule from an inrush of gas from the HEBT into the cold sections of the machine in the event of a loss of vacuum in the HEBT. Emergency power will be provided to maintain the HEDP under vacuum during a power outage in order to protect the cold section of the machine. The HEDP will be fitted with vacuum gauging, fast valve sensor and a manual vent valve with micron filter to bring this section up to atmospheric pressure. With the limited beam aperture, metal seals and CF style flanges will be used where possible. Valve sealing will be limited to the use of elastomers (EDP or Viton). Following fabrication of the HEDP beam pipe, this and other components will be extensively cleaned prior to assembly in a class 10/100 clean room to minimise the potential for contamination of the cold section of the machine during and following installation.

High energy beam transport

The high energy beam transport (HEBT) beamline runs from the HEDP to the target and tuning beam dump windows, with the allowable pressure rising to about $10^{-6}$ mbar as the beam line approaches the
target and tuning beam dump windows. The pressure in the proximity of the HEDP must be lower than this to minimise the flow of gas into the last cryomodule.

The size of the beamline will expand rapidly as it moves from the vicinity of the collimator to the target and tuning beam dump windows. Since this area will be activated, special precautions will be required for maintenance, in particular, the use of shielding and long-handled tools or remote handling techniques. These requirements and the larger beamline pose challenges in the selection of the appropriate metal seal design for the beam line flanges and in provisions to allow remote leak testing. For hands-on maintenance upstream of the collimator, a gamma blocker will be rotated into the beamline to block the back-streaming of radiation from the target, tuning beam dump or collimator. Radiation hard components will be used when available and these components will need to exhibit a high level of reliability. Local shielding and a strategy using redundancy of components needs to be considered in the vacuum design for these radiation areas.

Ion pumps will be used for the pumping of the HEBT. They are the most suitable option because they have no on-board electronics and controllers can be located remotely. Vacuum instrumentation will be of concern in the radiation areas and will require careful consideration and selection of equipment during the design process. Valves will be metal sealed where possible. Corrosion as a result of nitrous oxide forming from the irradiation of the air will also be a consideration, especially if bellows are used. It is currently planned to install a fast valve upstream of the collimator to protect the upstream beam line in the event of a break in the target. A similar fast valve will be implemented upstream of the tuning beam dump window to protect the linac in case of its rupture. Emergency power will be provided so that access is not required to re-evacuate the beamline using mobile pump carts to restart ion pumps in case of a power outage. The interface with the target will be at the “safety isolation valve”, which is a part of the second confinement safety barrier of the target station, on the upstream side of the valve. The Target Division will be responsible for the proton beamline downstream of this valve up to and including the target window. This will be a radiation area and a design will be developed that will provide for the disconnection and reconnection of the proton beamline from the safety isolation valve using long-handled tools or remote handling techniques. Remote leak testing after the connection has been reestablished will also be required. The design adopted will be integrated into the maintenance strategy for the safety isolation valve and window. Corrosion as a result of nitrous oxide will also be a consideration if bellows are used.

The proton beam line will terminate at the window in front of, but not connected to, the tuning beam dump. The window design has yet to be completed although it is currently anticipated that it will be water-cooled. This will be a radiation area and the design will be compatible with replacement by the use of long-handled tools or remote handling techniques. One option for the vacuum connection would be the use of a clamshell-style clamp, with metal seal, that could be opened and closed using long-handled tools. After release from the clamp, the flanges could be opened using a double bellows arrangement that would be installed in the final section of the beam line. The bellows assembly would be evacuated to open the flange connection to the window, allowing its replacement, and pressurised to close the connection. The capability to leak test the connection after mating will also be required. With the level of radiation that can be anticipated, consideration must be given in the design to the potential for corrosion of the bellows as a result of the production of nitrous oxide. The type of connections adopted for the water connections to the window is outside the scope of responsibility of the vacuum group.

Target systems

The vacuum group will assist in designing the vacuum interface and proton beam window, the target safety valve located in the proton beam line and the interconnecting beam line between these two components. Since the area will be activated, the design developed will be compatible with replacement by the use of long-handled tools and/or remote handling techniques. Since these components form part of the beam line, helium leak testing will be required. Although the HEBT will operate at a relatively high pressure, on the order of $10^{-6}$ mbar, a reasonable level of leak tightness will need to be achieved following the change out of components to minimise the gas load to which the HEBT ion pumps will be exposed so as to limit maintenance requiring the change out of pumps due to saturation. The vacuum group will also provide assistance in the design of embedded vacuum system within the He target cooling circuit and the He monolith circuit.
6.2.2 Instruments and neutron beam lines

The vacuum group will provide support during the development of instruments and neutron beam lines; providing guidelines for the design of vacuum chambers and components, and selection of vacuum components and equipment; conducting material testing, such as outgassing studies on materials to be installed in a vacuum environment; providing advice and review during the design of instrument chambers and components from a vacuum prospective, for example, concerning weld design and material selection; inspecting fabricated components and chambers for vacuum compatibility; witnessing vacuum testing at vendor premises and providing for the testing and start up of the various vacuum systems following installation. The vacuum group also will provide support on vacuum-related issues during the design and installation of the initial suite of instruments. Ongoing discussions will be held with the scientists responsible for the design of these instruments and with those responsible for other vacuum tasks that may be required. Vacuum resources will be adjusted as required to accommodate the needs of instrument design and installation. Approximately 2900 m of neutron guide will be installed to support the full suite of instruments. It is anticipated that vacuum pumps will be required at about 20 m intervals along the neutron guides and that they will need to provide an operating pressure in the $10^{-4}$ to $10^{-5}$ mbar range.

The vacuum group will assist in the vacuum design of the neutron guides and interfacing components, such as choppers, and will design, procure, fabricate and install the vacuum pumping equipment needed to support this activity. It is anticipated that the neutron guides will be pumped with mobile pumping units allowing the ready exchange of units for servicing. It is estimated that 30 to 40 mobile pumping units will be required for the neutron guides needed to support the initial suite of instruments.

Vacuum facilities will be provided to support both construction and pre-operation activities. These facilities will include: outgassing test chambers for the investigations of materials and components; general purpose bake-out and drying ovens for the preparation of equipment prior to installation; support equipment including pump carts, leak detectors etc.; class 10/100 cleaning area and washing area for the preparation of warm sections and other critical components prior to installation; pump carts, leak detectors and other equipment specifically needed for “clean” cryomodule vacuum assembly such as making and breaking beamline connections in the cold linac; portable clean rooms to support the making of “clean” beamline connections; and provision of limited spares-holding to support vacuum operations through pre-operational activities. Pump carts, leak detectors, cold traps and other equipment needed to support vacuum operations on activated and/or contaminated circuits will also be provided.

6.3 Test stands

Test stands for the cryomodules and RF systems will be employed in both Uppsala and in Lund.

6.3.1 Uppsala test stand

The FREIA laboratory at Uppsala University serves as a Facility for Research Instrumentation and Accelerator Development [13]. The construction of the 1000 m$^2$ FREIA laboratory hall will be completed in July 2013. The hall will have separate areas for three RF test bunkers, for RF power generation equipment, for a helium liquefier and cryogenic storage facility, for a vertical cryostat, for equipment mounting, for a control room, for a small workshop, for equipment storage and for offices (located at a mezzanine) and contain general laboratory infrastructure like power and fluid distribution systems. A sketch of the inside of the hall is shown in Figure 6.7. A helium cryogenic facility and a general purpose test cryostat will be delivered in December 2013 and commissioned by May 2014. The bunkers will be built up during 2013 using steel loaded concrete blocks.

The first project for which the FREIA Laboratory will be used is the development and prototyping of the RF system for the ESS superconducting spoke cavities, to be followed by the high power testing of the first prototype ESS spoke cryomodule. In a first phase, the functionality of the tetrode-based RF power system will be demonstrated in tests in which one power system is used to power a single spoke cavity. In a second phase, the prototype spoke cryomodule containing two superconducting spoke cavities will be tested at high power, requiring the simultaneous operation of two complete RF systems. Testing of the 14 production spoke cryomodules will also be carried out in the Uppsala test facility. The first RF power source with control and distribution equipment is scheduled to arrive before December 2013. The RF source will first be commissioned and tested using a water cooled load. The first prototype spoke cavity
is expected to arrive in May 2014. It will be installed in the horizontal test cryostat and tested with an RF source during the second half of 2014. The prototype spoke cryomodule is scheduled to arrive in mid 2015. It will be tested at high power during the second half of 2015 and the first half of 2016. Thereafter, FREIA can be used for acceptance testing of the series spoke cryomodules as they are delivered from the production line.

Three major components are required for the ESS test program in Uppsala; RF equipment, cryogenics and the test stand infrastructure.

### RF equipment

Reliable development of an energy efficient and resource effective RF system requires testing of the individual components and the complete RF system in a realistic environment. Thus an RF test facility is required with which the different concepts, topologies and elements of the RF system can be investigated in an in-depth test program. The RF test facility requires a complete RF system consisting of an LLRF system, high power RF amplifier, RF distribution system and spoke cavity, as shown in Figure 6.8. The LLRF system will generate the low power RF signal and adjust the individual amplitude and phase to the spoke cavities. The LLRF will also measure the field in the cavities and tune the cavity frequency to adjust for so-called Lorentz force detuning caused when the high power RF pulse starts filling the cavity volume. The spoke cavities will require an RF power of 350 kW at 352.21 MHz with 3.5 ms pulse length and 14 Hz repetition rate. Tetrode type vacuum tubes will be used as the high power RF amplifiers in combination with solid state pre-amplifiers. The layout of the proposed RF sources is described in detail in Section 4.8.6. For commissioning and initial testing, the high power amplifiers will be connected to a water cooled RF load. Thereafter, they will be connected to the superconducting spoke cavities. Prototype testing of the spoke cryomodules requires the addition of a second RF power amplifier and distribution chain. This will make it possible to power both cavities in a cryomodule simultaneously. The second chain
Figure 6.8: Possible configuration of RF equipment to power a superconducting spoke cavity in FREIA.

will be modelled on the first chain, with improvements based on lessons gained from experience.

Cryogenics

Figure 6.9 shows the layout of the FREIA cryogenic facility, including a helium liquefier, liquid and gas helium storage, liquid helium distribution valve box, impure helium gas recovery system and a liquid nitrogen distribution system. The capacity of the cryogenic facility is designed to provide 30 W cooling power at 2 K to a superconducting cavity or other device in the cryostat. The helium liquefier will provide a 2-phase mixture of gas and liquid helium at 4.4 K, 0.13 MPa at the output of its cold box into a liquid helium storage Dewar. From this Dewar the liquid helium will be distributed to external users and cryostats connected to the distribution valve box. The temperature of the liquid helium can be decrease additionally in the 2 K cold box of the cryostat to cool superconducting cavities. A sub-atmospheric pumping system will be used to decrease the helium pressure as required to keep the liquid bath temperature at 2 K. The helium liquefier plant will consist of a 4 K cold box, a helium cycle compressor (1.3 MPa output pressure) as well as high and medium pressure helium gas storage. An oil removal system to clean the helium gas leaving the compressor, a high pressure gas distribution panel and automatic control system will also be included but are not shown in Figure 6.9. In addition, a liquid nitrogen storage tank and distribution system will be used for pre-cooling of the liquefier cold box in order to increase its liquefaction capacity. Liquid nitrogen will also be used for the thermal shield cooling of the test cryostat.

The combination of storage Dewar and distribution valve box provides the possibility to deliver liquid helium both to the test cryostat and to other users. This ensures upgrade possibilities to add other test cryostats as well as the filling of liquid helium transport Dewars for external experiments. The large volume storage Dewar can serve as a buffer supply of liquid helium when the required liquid helium flow exceeds the flow directly from the liquefier. This makes it possible to run experiments in the test cryostat with feed boxes required cooling power exceeding the liquefier power, as well as enhancing the filling speed for transport Dewars. The 2 K liquid helium flow will be created inside the test cryostat. To provide 30 W cooling power requires a 1.5 g/s 2 K liquid helium flow. Including losses and accounting for gas helium in the 2-phase flow, we estimate that this requires a 2 times larger 2-phase flow from the 2 K cold box and 1.5 times larger 2-phase flow from the 4 K liquefier cold box. The required liquefaction capacity is therefore 4.6 g/s at 4.4 K which is equivalent to 140 l/h. The actual liquefier capacity will be in the order of 120 l/h. The 2000 l volume of the liquid helium storage Dewar serves as buffer to provide the additional required flow during full dynamic thermal load operation in the test cryostat (i.e. with full RF power on two spoke cavities). The storage Dewar will be refilled during intermediate breaks when there is only static thermal load in the test cryostat.

Test stand infrastructure

The test stand infrastructure consists of a versatile horizontal cryostat and a concrete bunker for radiation protection purposes. Initially the test stand will contain a single 2 K type cryostat with a horizontal vacuum tank. The cryostat will have a direct connection to the cryogenic facility and a vacuum pumping system.
Figure 6.9: Layout of the FREIA test stand cryogenic facility including horizontal and vertical test cryostats.
The facility will be designed such that other cryostats, with either horizontal or vertical vacuum tanks, can be added later on. The design of the initial test cryostat will be adopted from the CHECHIA cryostat at DESY, CryHoLab at CEA Saclay and the BESSY HoBiCaT facility [14–17], with small improvements. These cryostats have been designed for horizontal testing of superconducting cavities at temperatures between 1.8 and 4.2 K with help of an integrated cryogenic feed box. The thermal radiation shield is typically cooled with liquid nitrogen. The HoBiCaT cryostat is shown in Figure 6.10. This cryostat has an internal volume that is sufficiently large for the installation of two superconducting cavities. It has doors at both ends to allow easy access to the interior volume of 1.1 m diameter by 3.5 m length. The cavities slide into the cryostat on a rolling table. Power couplers can penetrate the vacuum vessel through feedthroughs on the side. Diagnostic ports are provided for additional instrumentation. The FREIA cryostat will be installed inside a bunker with 80 cm thick walls of iron ore concrete (4.0 kg/dm$^3$), a common Swedish alternative to barite concrete. The bunker will have an internal volume 4 m wide by 9.6 m long and 4.8 m high. This will enable simultaneous installation of both the horizontal test cryostat and the prototype spoke cryomodule.

During the ESS construction phase the FREIA facility is available for test of the complete spoke cryomodules. Testing of the prototype spoke cryomodule has already prepared the facility for the acceptance testing: RF systems have been extensively tested, staff is familiar with installation and testing of a spoke cryomodule. The bunker is designed such that a cryomodule can be installed simultaneous with the horizontal cryostat leaving the possibility open to continue tests on RF systems or a cavity. Cryomodules can enter the FREIA hall through the access door and work space between bunker and cryogenic plant. The bunker wall on that side can be opened to install the cryomodule.

### 6.3.2 Lund test stand phase I: RF equipment tests

The Lund test stand will serve two distinct purposes: during phase I, the main RF equipment prototypes – the modulators and the klystrons – will be acceptance-tested. In phase II, the series production cryomodules will be acceptance-tested. The test bench for phase I will consist mainly of a hall equipped with
6.3. TEST STANDS

The RF equipment test stand will be placed in an industrial hall (factory or large lab space) that will provide standard 3-phase electrical power for both modulator and klystron soak tests. It will be equipped with electrical grounding that allows high power/high voltage equipment to be operated safely and free of power disturbances. It will also be equipped with primary cooling water and a secondary deionised water loop to evacuate most of the heat generated by the tests. Finally, it will have sufficient ventilation to keep the temperature in the hall at $24 \pm 3^\circ C$, in order to create a stable environment for reproducible tests. The test stand will be equipped with all auxiliary services necessary for the tests, such as access control, fire safety, lighting, offices, control room, rest rooms, workshops and logistics areas (storage and handling spaces). Special care will be taken to avoid pollution by oil spills from the RF equipment. This can include oil barriers and oil separators in the drain sumps on top of the precautions mentioned in the discussion about oil leakage in Section 4.8.5. During the soak tests the RF equipment should ideally be set up in its final configuration (i.e. similarly to how the series production will be installed in the klystron gallery). See also the discussion about reception tests at the end of Section 4.8.5. A schematic of the test setup is shown in Figure 6.11. The actual physical setup of the test equipment has not yet been decided and depends on the available surface. The requirements for utilities are listed in [18], with a summary of the most important points in Table 6.2.

The baseline location for the test stand is the upgrade space of the klystron gallery on the ESS site, because it is explicitly designed for housing the RF equipment in question. The availability of both civil engineering structures and utilities at the projected start date can not, however, be guaranteed. Therefore, using an existing industrial facility in Lund as a fallback solution during an initial period is being studied. The small number of pieces of equipment to be tested makes the logistics of phase I relatively simple,

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total installed power</td>
<td>kVA</td>
<td>1300</td>
</tr>
<tr>
<td>Deionised cooling water resistivity</td>
<td>MΩ</td>
<td>$&gt; 10$</td>
</tr>
<tr>
<td>Dissipated cooling power</td>
<td>kW</td>
<td>1200</td>
</tr>
<tr>
<td>HVAC temperature</td>
<td>°C</td>
<td>$24 \pm 3$</td>
</tr>
</tbody>
</table>

Table 6.2: RF equipment test stand building and utilities requirements.
compared to phase II. Nonetheless, ESS will carry out detailed planning to ensure that delivery and
installation of the testing equipment, auxiliary equipment and RF equipment goes as smoothly as possible.
The RF equipment to be tested will arrive from a number of different manufacturers. The modulators will
be supplied by at least three different companies and the klystrons by three or four different companies. The
test stand will provide of enough storage space to accommodate the successive or simultaneous installation
of all equipment, taking into account the challenges of coordinating delivery schedules across multiple
manufacturers.

ESS will select manufacturers of klystrons and modulators based on the results of equipment testing.
Thus, it is of key importance to ensure the comparability of test results across manufacturers. The
modulator soak tests are foreseen to take place over 12 months. All modulators will be tested in parallel
under identical conditions, to allow a fair comparison of the different models. The klystron soak tests are
foreseen to take place over six months. Klystrons also will be tested in parallel under identical conditions.
The modulators will first be tested without any of the other RF equipment attached, i.e. without the
klystrons. After an initial period of testing lasting roughly six months, the modulators fitness will be
evaluated individually. If enough of the modulators are deemed fit to serve as power sources for the
klystron tests, these tests will begin. During this second period of testing, the klystron tests will overlap
with the remaining modulator tests, saving time in the overall testing schedule. For the klystron tests, all
RF equipment must be installed, including waveguides, circulators, dummy loads and LLRF systems, as
described in Section 4.8.2. If the individual modulator tests determine that there is an inadequate number
of modulators that are fit to serve as power sources for the Klystron tests, the start of the klystron tests
will be postponed until testing has identified an adequate number of reliable modulators.

If the phase I tests are conducted off the ESS site, this part of the test stand will be decommissioned
after termination of the RF equipment tests. The building will be prepared for return to the owners. The
tested RF equipment will be transferred to the klystron gallery upgrade space on the ESS site, where it
will be used to provide power for the cryomodule testing program in phase II. If the phase I tests have
been conducted in the klystron gallery upgrade space on the ESS site, this part of the test stand will be
transformed and expanded to serve as the test stand for phase II.

6.3.3 Lund test stand phase II: elliptical cryomodule acceptance tests

In phase II, the series production elliptical cavity cryomodules will be acceptance-tested, while testing of the
spoke cavity cryomodules series production remains an option. Detailed descriptions of the cryomodules
can be found in Section 4.4. The main purpose of the cryomodule site acceptance tests is to verify
the proper functioning of the series production cryomodules. Both cryogenic and RF operability will be
evaluated. Another goal is to measure key parameters of the cryomodules subsystems, such as heat loads
of the cryogenic components and resonant efficiencies of the RF components. Another important part of
the testing process is the in situ conditioning of the main RF power coupler. In phase II, the test stand will
need substantial operational support from the test stand personnel. This support will include operation of
the cryoplant, supervision of the automated operation of utilities and occasional maintenance interventions.
The tests themselves will be run by RF testing personnel, cryomodule testing personnel and mechanical
and instrumentation installation crews. There will be a permanent test stand operator presence during
all testing hours. Cryomodule site acceptance tests require full RF power to the cavities, which produces
x-ray emissions from the cryomodules. Therefore, the cryomodule tests have to be conducted in concrete
bunkers, which shield the surroundings from this radiation. The tests also require a constant flow of cold
helium in order to maintain the cryomodules at their operating temperature, which makes the proximity
of the test stand to a correctly dimensioned helium cryoplant indispensable.

The cryomodule test stand will have three bunkers, two for the elliptical cavity cryomodules (both
medium beta and high beta) and one for the spoke cavity cryomodules. Each bunker will be fully equipped
with wave guides, cryogenic transfer line, valve boxes and jumper connections, as well as assorted ancillary
equipment. The RF power supplies, i.e. the moderators and klystrons, will be located outside the bunkers,
and the waveguides will be fed from the power supplies into the bunkers through suitable chicanes. The
bunkers have to be big enough to allow easy and rapid installation and disconnection of the cryomodules
in order to minimise turn-around times. ESS will equip the test stand with all auxiliary services necessary
for the tests, such as access control, fire safety, lighting, offices, control room, rest rooms, workshops and
logistics areas (storage and handling spaces).

During ESS construction, this test stand is not intended for cryomodule prototype R&D and testing,
nor for cavity testing. There will be limited space in the test stand area for staging of the cryomodules, but not for long term storage. At a later stage of the ESS project, more test facilities and associated spaces will become necessary, e.g. a clean room suite for cryomodule assembly and repair as well as a vertical cavity test stand. Ideally, the test bunkers will have the same cross section as the accelerator tunnel, so as to create a realistic test bench not only for testing the main functions of the cryomodules, but also for testing many other parts of the accelerator installation process. While space and cost considerations may not permit this, at least one of the bunkers must be comparable in size to the linac tunnel, and the other two must be adequately sized to allow rapid installation and disconnection of testing equipment. The length of the bunkers should allow easy manoeuvring around the installed cryomodules. At least one of the bunkers should be long enough so that both warm inter-module sections could be installed with the cryomodule, if combined tests or space verifications should be desired. The total length will include space for personnel access (chicanes), and the total width will include space for the wave guide chicanes.

Tables 6.3 and 6.4 show the bunker lengths and widths, based on the lengths of the different types of cryomodules, the desired additional space to install warm sections, space for passage around the modules, an assumed wall thickness of 1 meter and space needed for access chicanes. The actual physical setup of the bunkers and the test equipment has not been finalised as this Technical Design Report goes to press. It will depend on the available surface and the positioning of the utility headers. A preliminary layout is shown in Figure 6.12, and a block diagram of the test setup is shown in Figure 6.13.

<table>
<thead>
<tr>
<th>Bunker</th>
<th>Modules Warm</th>
<th>Inner Wall Chicanes Outer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[m] [m] [m]</td>
<td>[m] [m] [m]</td>
</tr>
<tr>
<td>Elliptical</td>
<td>7 2 11 1 + 1 2 15</td>
<td></td>
</tr>
<tr>
<td>Elliptical</td>
<td>7 1 8 1 + 1 2 11</td>
<td></td>
</tr>
<tr>
<td>Spoke</td>
<td>4 1 5 1 + 1 2 9</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.3: Lund test stand bunker lengths.

| Bunker Inner Wall thickness Chicanes Outer |
|--------------|-----------------|-----------------|
| [m] [m] [m]  |                 |
| All          | 5.5 1 + 1 1.5 9 |                 |

Table 6.4: Lund test stand bunker widths.

Figure 6.12: Preliminary layout of the cryomodule site acceptance test stand in phase II.
Cryogenics

The cryoplant providing cryogenic cooling for the cryomodule test stand will be located in the cryogenics buildings alongside the klystron gallery upgrade space. The cryoplant will supply refrigeration at conditions which are very similar to the conditions in the accelerator, as discussed in Section 6.1. The worst-case scenario is the simultaneous testing of three cryomodules with full RF power. The cryoplant and distribution system will be dimensioned to adequately supply cooling for this scenario. Tables 6.5 and 6.6 show the heat load contributions and the installed heat load capacities for the three test bunkers and the distribution system [19]. The expected installed (4.5 K equivalent) capacity of the test and instrumentation cryoplant is seen to be 437 W. However, to provide adequate capacity to produce 50 l/hr of liquid helium and to operate one test stand at the same time, the plant will be sized to be between 500 W and 600 W.

<table>
<thead>
<tr>
<th></th>
<th>Static</th>
<th>2 K</th>
<th>Dynamic</th>
<th>5 K</th>
<th>50 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spoke CM</td>
<td>3.5</td>
<td>1.5</td>
<td>5.0</td>
<td>2.0</td>
<td>2.9</td>
</tr>
<tr>
<td>Medium-β CM</td>
<td>5.2</td>
<td>1.5</td>
<td>6.7</td>
<td>4.0</td>
<td>5.6</td>
</tr>
<tr>
<td>High-β CM</td>
<td>6.0</td>
<td>1.5</td>
<td>7.5</td>
<td>4.0</td>
<td>6.7</td>
</tr>
</tbody>
</table>

Table 6.5: Cryomodule heat load estimates.

<table>
<thead>
<tr>
<th></th>
<th>2 K static</th>
<th>2 K dynamic</th>
<th>5 K</th>
<th>4.5 K liquid</th>
<th>40 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryomodule prediction</td>
<td>19.2 [W]</td>
<td>45.2 [W]</td>
<td>3 [W]</td>
<td>0.32 [g/s]</td>
<td>186</td>
</tr>
<tr>
<td>Distribution line prediction</td>
<td>77 [W]</td>
<td></td>
<td></td>
<td></td>
<td>252</td>
</tr>
<tr>
<td>Total prediction</td>
<td>19.2 [W]</td>
<td>45.2 [W]</td>
<td>80</td>
<td>0.32 [g/s]</td>
<td>438</td>
</tr>
<tr>
<td>Installed power</td>
<td>33.1 [W]</td>
<td>52.0 [W]</td>
<td>137</td>
<td>32 [W]</td>
<td>654</td>
</tr>
</tbody>
</table>

Table 6.6: Summary of heat loads and installed capacity for the test and instruments cryoplant.

Figure 6.13: Block diagram of the cryomodule site acceptance test stand in phase II.
Figure 6.14: Schematic of the Lund test stand cryoplant, distribution line and test bunkers.

(4.5 K equivalent). All heat loads and capacities mentioned rely on preliminary heat load estimates for the cryomodules and have to be revised once more accurate values are known.

A schematic view of the cryoplant, the transfer line, the valve boxes and the cryomodule bunkers is shown in Figure 6.14. The distribution system, i.e. the transfer line and the valve boxes, will be as close to the final design of the linac system as possible, as discussed in Section 6.1.4. They need to differ in one aspect, however: simultaneous and independent operation of the three bunkers calls for a separate low pressure vapour return line for each of the cryomodules. This is needed to allow 2 K operation of some of the cryomodules while others are cooling down. Three independent vapour return lines will comfortably fit into the space of the full-sized vapour return line as needed for the tunnel. Therefore, the overall design and sizing of the test stand transfer line will be very close to the linac transfer line. The same is true for the valve boxes and jumper connections linking the transfer line to the cryomodules. The requirements for space and utilities are listed in Table 6.7. The cryomodule tests have to be performed as close to the final installation site (i.e. the accelerator tunnel) as possible in order to avoid damage to the modules during transport. An ideal location is the upgrade space in the klystron gallery. It has the required size, comes already prepared for the RF power equipment and is located very close to the cryogenics buildings. Figure 6.15 shows the location of the klystron gallery upgrade space and the cryogenics buildings. The klystron gallery upgrade space, the cryogenics buildings and the necessary utilities will be available in good time according to the main construction schedule.

Phase II planning, logistics, schedules and sequencing

The test stand is designed to be able to process three cryomodules in parallel: one spoke cryomodule and two elliptical cryomodules. Medium and high beta cavities have different lengths, which makes the routing of the RF wave guides from the klystrons to the power couplers different for these two types of cryomodule. The bunkers will have to have enough flexibility to adapt to either of the wave guide layouts, but re-routing is time consuming and should not be attempted more than once during the main test run. According to the construction project planning, the cryomodules will be arriving from the manufacturers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total installed power</td>
<td>kVA</td>
<td>1800</td>
</tr>
<tr>
<td>Dissipated cooling power</td>
<td>kW</td>
<td>1700</td>
</tr>
<tr>
<td>HVAC temperature</td>
<td>°C</td>
<td>24 ± 3</td>
</tr>
</tbody>
</table>

Table 6.7: Lund test stand phase II building and utility requirements.
Accelerator tunnel  
Klystron gallery  
Cryoplant buildings  
Target building  
Neutron lines  
Instruments

Figure 6.15: Location of the cryomodule test stand (red circle) among the ESS surface buildings.

over a long period. The 14 spoke cryomodules will arrive over a period of 14 months, the 15 medium beta cryomodules over a period of 14 months and the high beta cryomodules over a period of 28 months.

Some of the main pieces of equipment will be manufactured by suppliers and have a non-negligible lead and manufacturing time. This concerns mainly the cryogenic equipment such as the test and instruments cryoplant, the transfer line, valve boxes and jumper connections. Installation and commissioning of all equipment in the test stand area can start when Conventional Facilities hands over the klystron gallery upgrade space and relevant cryogenics buildings. It needs to be finished by the time the first cryomodules arrive. Main pieces of equipment are the RF power sources (modulators, klystrons), wave guides, bunkers, cryogenic transfer line, valve boxes and jumper connections. The test stand, including bunkers and RF power equipment will remain in place until a potential upgrade of the linac calls for their removal. This upgrade is not yet planned, but can be expected to happen many years after completion of the ESS facility. Therefore no plans are being made for the decommissioning or relocation of the test stand at this stage. There are 59 cryomodules of three different types to be tested in total: 14 spoke cryomodules, 15 medium beta cryomodules and 30 high beta cryomodules. Cryomodules are expected to arrive from the manufacturer with an average cadence of one cryomodule every month per type of cryomodule. This means that each bunker needs to process one cryomodule per month. Experience from other testing facilities, such as the XFEL Accelerator Module Test Facility [20], has shown that testing of a cryomodule takes at least two weeks, including installation and disconnection. An extra burden to the ESS test stand is the necessity to condition the RF main power couplers when installed in the cryomodules, adding around one week per cryomodule to the length of the test. Turnaround time for one cryomodule in the test stand is estimated at between three and four weeks, once the test stand is up and running at full speed.

After a cryomodule is tested on the test stand, it will be prepared for tunnel installation. This preparation can be done in the logistics part of the test stand area, where a space of around 200 m² is reserved for this purpose. However, there are no significant storage spaces included in the test stand, only buffering spaces for logistical purposes. If there is any delay in cryomodule installation, additional storage will have to be provided elsewhere.

Risk assessment and crucial interdependencies

The test stand will provide a service to other projects within the ESS programme and its planning, installation and operation are very closely linked to a number of other projects. These include cryomodules, RF equipment, cryoplant and conventional facilities, to name but the most important. Other minor interdependencies might become more significant over time, and project planning and execution must always remain flexible enough to respond to the changing circumstances. The cryomodule testing program will be one of the first major technical activities on site. As such it provides opportunities for prototyping other systems such as the Integrated Control System (ICS), vacuum systems, machine protection systems etc. It also will afford the opportunity for training cryogenic and RF operations staff. The complexity of the cryomodule test stand facility and its importance in meeting the project schedule means that significant planning and careful oversight will be required.

The biggest uncertainty is the production schedule of the cryomodules. Any delay will have implications for the test stand operation, which will either need to be delayed and/or sped up to recover lost time.
Availability of tested and accepted RF equipment is absolutely necessary. If not enough of the modulator or klystron prototypes qualify in phase I for operation of phase II, the two elliptical cryomodule bunkers can not be run in parallel and testing of cryomodules will be delayed. In the unlikely case that not even half of the RF equipment qualifies, no elliptical cryomodule can be tested as planned. A detailed risk assessment is necessary and will be performed during the course of the project preparation.

The test stand and instruments cryoplant will be the first cryoplant to be procured, installed and operated by the ESS Cryogenics Group. Availability is therefore not obvious. Tight integration between the test stand team and the cryoplant team will be implemented to mitigate this risk. The test stand will be one of the - if not the - first major activity in the buildings on the ESS site. Availability of buildings and utilities at the promised date can not be taken for granted and progress needs to be closely monitored. The integrated control systems (ICS) project will provide the control system for the test stand. Its personnel will use part of this effort to run a vertical integration test of all of their subsystems. This might create delays in the installation and commissioning of the test stand. A machine protection system (MPS) is not necessary for the test stand, but the test stand could be used as a test bench for parts of the MPS, if this does not disrupt the tests.
Bibliography


