ESS Cryogenic System Process Design

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Abstract. The European Spallation Source (ESS) is a neutron-scattering facility funded and supported in collaboration with 17 European countries in Lund, Sweden. Cryogenic cooling at ESS is vital particularly for the linear accelerator, the hydrogen target moderators, a test stand for cryomodules, the neutron instruments and their sample environments. The paper will focus on specific process design criteria, design decisions and their motivations for the helium cryoplants and auxiliary equipment. Key issues for all plants and their process concepts are energy efficiency, reliability, smooth turn-down behaviour and flexibility. The accelerator cryoplant (ACCP) and the target moderator cryoplant (TMCP) in particular need to be prepared for a range of refrigeration capacities due to the intrinsic uncertainties regarding heat load definitions. Furthermore the paper addresses questions regarding process arrangement, 2 K cooling methodology, LN2 pre-cooling, helium storage, helium purification and heat recovery.

1. System overview
The cryogenic system at ESS comprises three independent helium refrigeration plants: the Accelerator Cryoplant (ACCP), the Target Moderator Cryoplant (TMCP) and the Test and Instruments Cryoplant (TICP). Furthermore there will be an extensive cryogenic distribution system (CDS) connecting the cryoplants with their consumers. A block diagram of the ESS cryogenic system and functional descriptions have been published in numerous papers [1], [2], [3]. As the cryogenic consumers have very different technical requirements and schedule demands it was decided at an early stage to provide cryogenic cooling with three separate plants.

1.1. ACCP heat load and temperature requirements
The ACCP is the most complex and versatile of all cryoplants at ESS. The cryogenic load is dominated by 2 K refrigeration which translates into a supply of a supercritical 4.5 K flow and a return flow of sub-atmospheric vapor between 4.6 K and 6.0 K, depending on the operation mode. Every cryomodule (CM) or attached valvebox contains an economizer to limit the mass flow at sub-atmospheric pressure.

The other two cryogenic loads that the cryoplant has to supply, thermal shield cooling and liquefaction load for cooling the RF main power couplers, represent only 11% and 10% respectively of the plants total exergy. The maximal design load that the cryoplant potentially must provide is listed in table 1. However, the ACCP shall be designed for a number of additional operation modes for part load, liquefaction, 4.5 K refrigeration etc.
This load combination makes liquid nitrogen pre-cooling less attractive as performance boosting with LN2 pre-cooling is rather moderate. Another typical reason for applying liquid nitrogen pre-cooling is heavy cool-down duty. In our cryomodules the very thin walled cavities result in a relatively low cold mass of only 20 tons for the whole accelerator [4]. Hence cool-down is not a significant issue and LN2 support not required. Only expansion turbines will provide the cryogenic refrigeration in the ACCP, increasing reliability, capital cost saving and traffic reduction.

Table 1. ACCP loads and temperatures.

<table>
<thead>
<tr>
<th>Type</th>
<th>Static and dynamic load in CMs</th>
<th>Economizers and CDS load</th>
<th>Thermal shields</th>
<th>Coupler cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. range</td>
<td>2 K</td>
<td>2 – 4 K</td>
<td>33 – 53 K</td>
<td>4.5 – 300 K</td>
</tr>
<tr>
<td>Max. load</td>
<td>2230 W</td>
<td>830 W</td>
<td>11380 W</td>
<td>9.0 g/s</td>
</tr>
</tbody>
</table>

1.2. TMCP heat load and temperature requirements
The vast majority of the neutrons that are produced in the spallation source by the proton beam hitting the target wheel, are fast neutrons. A moderator-reflector system then transforms these fast neutrons into slow neutrons, which are the final form of useful radiation provided by the neutron source [5]. A key feature of the target system are the hydrogen moderators, which use supercritical cold H₂ to reduce the neutrons energy before they reach the instrument lines.

The characteristic load requirements for the TMCP is described relatively briefly. The plant must supply up to 32 kW refrigeration power at a temperature between 15 K supply and 20 K return. There is no pressure limitation on the helium flow cooling the circulating hydrogen; the helium pressure shall be as high as technically and economically feasible in order to have reasonable equipment sizes.

Almost 80% of this load is directly related to the beam power, as the neutrons deposit significant energy into the hydrogen. The rest of the load is caused by static load on the helium transfer lines to the hydrogen circulator coldbox (HCC), the hydrogen lines to the target moderators and the HCC itself which includes hydrogen circulators, an ortho-to-para hydrogen converter, piping, and controls.

The TMCP is a classical cold-end refrigerator where refrigeration power at higher temperatures than the load is only required to compensate for heat exchanger losses. Liquid nitrogen pre-cooling was never considered for this plant.

1.3. TICP heat load and temperature requirements
The TICP’s primary function is to provide the necessary refrigeration for the CM teststand. The TICP is by far the smallest of all three cryoplants. It is essentially a customized standard plant, more than twenty times smaller than the ACCP and can therefore not be treated like a small ACCP.

Like the ACCP, the TICP has to deliver supercritical 4.5 K helium for the 2 K circuit, 40 K refrigeration for thermal shield cooling and helium liquefaction for the coupler cooling. With very low 2 K heat loads cold sub-atmospheric compression is not feasible. Instead the returning vapor flow is heated up and compressed in process vacuum pumps to the low cycle pressure. Hence for the TICP the supercritical 4.5 K helium flow translates to constant level liquefaction of about 4 g/s. Furthermore the TICP shall provide refrigeration of about 390 W between 33 and 53 K for thermal shield cooling. It shall be noted that the TICP size is not impacted by the static load on the transfer line, interconnecting TICP coldbox and CM test stand, apart from the thermal shield. In fact the load on the transfer line is allowed to be be quite high and is only limited by the operational restrictions of the economizer in the CM.

Regarding LN2 pre-cooling for the TICP the picture looks quite different. When operating to supply the CM test stand the characteristic plant load is ideal for liquid nitrogen pre-cooling.

It was therefore decided to request a plant design using liquid nitrogen pre-cooling for the test stand service. This reduces the plant size significantly and cuts electrical power and cooling water consumption in half.
2. Adaption to change in heat loads

2.1. Load evolution

A high level goal of ESS is to shoot the first beam on target and produce neutrons, by 2019. This will be achieved with the minimum number of cryomodules required for an envisaged beam power of 1.43 MW. The accelerator will then be upgraded in several steps with more cryomodules to increase energy and beam power. To the first order the production rate of the cryomodules dictates the construction schedule, the beam power and eventually the cryogenic loads for ACCP and even more for TMCP. This is illustrated in figures 1 and 2. These figures show also the load curves with no safety margins applied, so a load range can be defined where the actual heat loads is likely to be. Both figures show clearly how important it is to design the cryoplants for very high rangeability not only during the stepwise upgrade but also with respect to turndown conditions and load uncertainties.

![Figure 1. ACCP 2K heat load vs. number of cryomodules.](image1)

![Figure 2. TMCP 15-20K heat load vs. beam power.](image2)
The TICP has to deal with load uncertainty as well but the load is expected to remain broadly constant when servicing the test stand.

2.2. ACCP and plant staging

The baseline of the lattice of the ESS proton accelerator is called Optimus+ and includes 13 spoke cryomodules, 9 medium beta cryomodules and 21 high beta cryomodules [6]. The tunnel, however, is prepared to accommodate 14 additional cryomodules in the contingency space in case the expected beam power is not achieved with the baseline configuration. The entire cryogenic infrastructure must be designed to serve the maximum load including contingency. As this contingency may eventually not be required and also the full safety margin may not be exploited, the motivation was high to call for special provisions to allow highly efficient heat load adjusting.

One fundamental decision was to mix cold and warm sub-atmospheric compression, as shown in figure 3.

For a cryoplant with a 2 K load in this range the use of cold sub-atmospheric compression is obvious. Taking the compression heat of the cold turbo compressors into account the refrigeration load relevant for the turbine cycles of the plant is between 4 K and 25 K, depending on the vapour return and number of cold compressor stages.

The number of cold compressors was carefully chosen. The lower limit was specified to be three in order to permit efficient heat transfer of the SP return flow in reasonably sized heat exchangers even under turn-down conditions. Four or more cold compressors were possible but did not allow for the very advantageous warm compressor set-up as described in section 4.2.

Traditionally heat loads are thought to be controlled by the so-called floating pressure process [7], whereby for matching higher heat loads is achieved by loading mass into the system and by increasing the pressure levels while the pressure ratio over the rotating machinery remains roughly constant. This strategy is limited by the restriction to keep the low pressure level (LP) stable. Still, this is very efficient for cryogenic loads above the 2-phase level that are not linked to a stable LP, and for liquefaction loads where the cryoplant has to deliver refrigeration over the whole temperature range from ambient to the 2-phase level [8], and a substantial part of this refrigeration is, in a three-pressure-process, not linked to a stable LP.

![Figure 3. Simplified flow scheme of the ACCP as proposed by Linde Kryotechnik AG.](image-url)
As the discharge pressure of a turbo compressor is a function of the mass flow, which in turn is a function of the heat load, the cryoplant and the warm compressor system must be able to cope with floating SP level as well.

For efficient heat load adaption of the ACCP however, the floating pressure strategy is not sufficient and needs to be supported by other means. Hence, another fundamental decision was to ask for modification possibilities for the ACCP in order to adjust to the actual heat load requirements in a stable and efficient way.

For the sake of clear plant specifications and acceptance test conditions two sets of configurations were defined which are called stage 1 and stage 2. The staging is realized on the one hand by means of two sets of flow parts for cold rotating equipment, turbine expanders and cold turbo compressors, and on the other hand by variable frequency drives for the cold turbo compressors, the SP-MP and the LP-MP compressors.

As shown in figure 1, the ACCP operates in more or less extreme part-load conditions for several years, which is easier to serve efficiently in stage 1 configuration than in stage 2. In principle one could think of yet another flow part modification for the time when it is clear how many cryomodules will be served and how much of the safety margin is actually required.

Several sets of flow parts provide, beside the load adjustment possibility, advantages in the spare strategy. The variable frequency control for the SP and LP machines and the cold compressors provide efficient plant adaption also in all intermediate modes.

2.3. TMCP and system pressures
As figure 2 indicates, the heat load requirements for the TMCP vary even more over time than the requirements for the ACCP. Particularly the difference between beam ON and beam OFF is substantial, translating to a TMCP heat load ratio of five and higher. Fortunately, the heat load temperatures are far above the 2-phase level, permitting very flexible and efficient use of the floating pressure control as described in section 2.2.

The duty for the TMCP is characterised by a large load and a rather small temperature difference between helium supply and return, which results in a large mass flow and a moderate pressure ratio for the rotating machinery. In order to permit reasonable equipment sizing to process the high flow also in warm conditions, the selection of a two-pressure process with quite high LP for the maximal design case is obvious. Properly selected warm compressors shall operate close to their maximal loading for essentially the entire performance range, keeping volumetric flows, pressure ratios and temperatures in the cold part constant. Variable frequency drives are not feasible due to the high power of the motors of the warm compressors.

All equipment such as oil removal systems and adsorbers must be designed to work at different pressure levels. A big challenge is to load helium to or, respectively, unload it from the cryoplant due to the mismatched pressures of system and tanks and due to inventory management, which is described in section 3.3.

Adapting the system pressures to match the cryogenic loads is only feasible for long term load changes. For the occasional beam trip and subsequent loss of 90% of the heat load, the TMCP will have to adopt a less elegant strategy. Traditionally, in this kind of system, an electrical heater would make up for the missing heat load, prevent the temperatures from dropping and causing the expansion turbines to trip. Due to the high refrigeration load, replacing 90% of the load with an electrical heater seems rather impractical. Instead, one could exploit the large enthalpy difference between cold and warm helium by taking ~20 g/s from the feed flow, heat it in an atmospheric heater to ambient temperature and mix it to the return flow, as also described in section 3.3.

2.4. TICP and operation scenarios
The test stand load can be translated into exergetically equivalent rising level liquefaction of ~130 l/h. This is much more than required later, when serving the liquid helium demands of the neutron instruments and their sample environments. For the normal TICP liquefaction operation in an
open loop there is hence the choice to precool with liquid nitrogen or not, depending on the specific needs at the time of operation.

The cryoplant specification includes an incentive to optimize the plant for rising level liquefaction without pre-cooling while operating the internal purifier. This helps to reduce the plant size and select the optimal expansion turbines.

When operating a helium liquefier that is actually too big for the helium consumption of the customers, sufficient high pressure buffer volume and liquid storage volume has to be foreseen. The TICP will presumably be switched on for 2-3 days only every week to fill the 5’000 liter storage tank.

A variable frequency drive for the recycle compressor helps to cope with the different load scenarios and will be considered.

3. Helium management

3.1. Helium inventory and storage

The ESS cryogenic system will contain substantial amounts of helium. During nominal operation about 3 tons of cold helium will be circulating between the cryoplants and their loads, not counting the helium in the second fill liquid helium storage tank attached to the ACCP.

The majority, roughly two third, of this helium is filled in the cryomodules and distribution system of the cold linac. Before the pump-down to 2 K, when being filled with liquid helium, the linac and cryodistribution systems require about 130 kg more helium than during nominal operation. This is due to the large 2 K vapour return line, which is filled with 25 times denser vapour at 4.5 K compared to the gas at nominal conditions. The density increase of the liquid helium during pump-down has a slightly lower impact and affects only the cryomodules, not the CDS.

A significant portion of the helium is deposited in the long transfer lines connecting the TMCP and its load, the hydrogen circulator coldbox (HCC) in the target building. The cryoplant has to load and cool down about 350 kg of helium from warm to operating conditions.

When the TICP is serving the cryomodule test stand it operates in a closed loop. The helium to fill the connected test cryomodule must be stored in a warm buffer tank. The amount needed is not significant compared to the amount required for the bigger cryoplants. However, when serving the liquid helium demands of the neutron instruments and their sample environments the TICP operates in an open loop.

About 7’500 liters of liquid helium is the expected monthly consumption of the neutron instruments and related facilities. Liquid helium is transferred to mobile dewars and returns warm at a more or less constant flow rate to the central helium recovery system where it is pressurized and stored. It is purified in the internal purifier of the TICP coldbox when the liquefier is switched on, so the high pressure buffer volume has to store the returning helium of about one week at least.

3.2. Purification

The different cryoplants have different purification needs.

The TMCP, circulating helium in a closed loop mostly at pressures well above atmospheric, is expected to see the least amount of impurities. Only an adsorber at 20 K level is foreseen to collect the last traces of impurities and provide early indication of potential hydrogen leakage in the helium / hydrogen heat exchanger.

The ACCP, circulating helium in a vast distribution system with a good portion at sub-atmospheric and slightly over-atmospheric pressure, is expected to be exposed to higher impurity intake. Therefore, dual adsorbers at 80 K and one single adsorber at 20 K are foreseen. Furthermore a full flow dryer is placed downstream of the systems oil adsorber that shall adsorb all moisture in the system during commissioning and after longer shut-downs.

The TICP will certainly be the system seeing the highest levels of impurities. When operating for the test stand in a closed loop the helium has to pass an 80 K adsorber and a 20 K adsorber in a setup similar to the ACCP. When operating to provide liquid helium in an open loop the liquid nitrogen pre-
cooling may be switched off most of the time. In this case the 80 K adsorber is not at the right temperature level anymore and has to be bypassed. The feed helium from the recovery system however has to pass an internal freeze-out purifier first before it enters the main process cycle.

As the entire ESS facility is designed for minimal helium losses there is a strive to recover as much helium as possible, e.g static boil of from the 20'000 litre liquid helium tank, usable gas from adsorber regeneration and purge processes and some safety valves. In order to prevent all this helium ending up in the TICP system in the long run, as well as for redundancy purposes, another adsorber based, LN2 cooled, stand-alone helium purifier will be installed on site.

3.3. Loading and unloading

Whereas the loading and unloading is rather straightforward for ACCP and TICP it is not a trivial issue for the TMCP where the process pressures change drastically as a function of the required refrigeration performance. While the low pressure can be as high as 5 bar(a) at maximum refrigeration, the high pressure can be as low as 10 bar(a) or lower during turndown operation. To use this range, minus the transfer pressure losses, as the operation window for the gas buffers in a classical concept is not acceptable for the large helium mass to be stored.

Figure 4. Simplified flow scheme of the TMCP as proposed by ESS in the technical specification to potential suppliers.

First a so-called “low pressure buffer volume” (LPB) and a “high pressure buffer volume” (HPB) are defined. The system can also be divided in a high pressure region, basically comprising the transfer lines and the HPB, and in a low pressure region, the rest of the TMCP and the LPB.

When the TMCP operates at full load the majority of the helium, about 350 kg, fills the transfer lines between TMCP and HCC. The last molecules of helium have to be transferred from the HPB at a pressure above the low cycle pressure to the TMCP, say at 6 bar(a) in the buffer. Hence the HPB cannot get emptied below 6 bar(a). When the entire system is warm and depressurized the majority of the helium rests in the warm helium buffers, which are hence at high pressure. Yet there must be at least one tank at an intermediate pressure between the cycles low and high pressure for the next system start.
An arrangement and control concept has to be found for different loading and unloading scenarios such as refrigeration ramping, cool-down and warm-up or intrinsic system safety without helium loss in a longer power shutdown.

Another vital piece of equipment for the TMCP and transfer line helium management is an ambient heater as shown in figure 4. The heater fulfills four functions:

1) It enables acceptance tests of the TMCP without bulky electrical heaters by bleeding a fraction of the 15 K supply flow over the ambient heater into the return, which, as a result, warms up to 20 K.
2) During beam trips it replaces the missing heat load at the HCC by bleeding a fraction of the 15 K supply flow over the ambient heater into the return line at the HCC interface. This way the temperature in the return line, its density and inventory remain constant.
3) It permits unloading the transfer line to the HPB in case of a longer power shutdown. The rest of the TMCP system is isolated from the transfer line and connected to the LPB in this case.
4) It helps to warm up the system by “driving coldness out of the system” through the ambient heater to the LPB.

The helium mass in the transfer line is only about 10% in warm condition at the highest system pressure compared to full operation conditions. So when the transfer line has to be warmed up it unloads to the HPB before the system pressures turn down. The same applies in case there is no beam for a long time but the system has to be kept cold. The transfer line pressures are lowered, decreasing the helium inventory to approximately half while the rest of the system maintains the high pressure for the duration of the transfer line unloading. When the transfer line has reached the desired operation pressure the TMCP system pressures can turn down as well.

4. Reliability and Availability

4.1. Background

The users of the ESS facility have specific requirements on reliability and availability, which translates to a figure of permitted failures per duration, as listed in table 2. At ESS reliability is defined as “the probability of fulfilling the major design function (MDF) of the system…for a predefined period of time” [7]. \( R(t) = e^{-\lambda t} \), where \( R \) is the reliability, \( \lambda \) the failure rate and \( t \) the mission time. So the actual reachable reliability figure depends very much on the predefined mission time, in the order of one hour or one day.

<table>
<thead>
<tr>
<th>Downtime duration</th>
<th>Accelerator</th>
<th>Target</th>
<th>ICS</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 second - 6 seconds</td>
<td>120 per day</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6 seconds - 1 minute</td>
<td>40 per day</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1 minute - 6 minutes</td>
<td>4.8 per day</td>
<td>-</td>
<td>40 per year</td>
<td>-</td>
</tr>
<tr>
<td>6 minutes - 20 minutes</td>
<td>1.7 per day</td>
<td>-</td>
<td>10 per year</td>
<td>-</td>
</tr>
<tr>
<td>20 minutes - 1 hour</td>
<td>90 per year</td>
<td>2 per year</td>
<td>4 per year</td>
<td>3 per year</td>
</tr>
<tr>
<td>1 hour - 3 hours</td>
<td>29 per year</td>
<td>1 per year</td>
<td>2 per year</td>
<td>1 every 2 years</td>
</tr>
<tr>
<td>3 hours - 8 hours</td>
<td>15 per year</td>
<td>1 every 2 years</td>
<td>1 every 2 years</td>
<td>1 every 2 years</td>
</tr>
<tr>
<td>8 hours - 1 day</td>
<td>5.5 per year</td>
<td>1 every 2 years</td>
<td>1 every 5 years</td>
<td>1 every 3 years</td>
</tr>
<tr>
<td>1 day - 3 days</td>
<td>2.3 per year</td>
<td>1 every 2 years</td>
<td>-</td>
<td>1 every 10 years</td>
</tr>
<tr>
<td>3 days - 10 days</td>
<td>1 every 5 years</td>
<td>1 every 20 years</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>more than 10 days</td>
<td>3 every 40 years</td>
<td>1 every 40 years</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Availability is defined as “the probability to find the machine fulfilling its MDF, when it is claimed to be in operation”. [7] \( A(t) = \frac{MTBF}{MTBF + MDT} \), where \( A \) is the availability, \( MTBF \) is the mean time between failures and \( MDT \) is the mean downtime. The availability can only be determined
for an extended operation time in the order of several years. Depending on the type of neutron beam experiments, kinetic or integrated-flux, different requirements on beam power and time were formulated.

Kinetic experiments: “A reliability of at least 90% should be provided for the duration of the measurement. The measurement will be considered failed when the beam power is reduced to less than 50% of the scheduled power for more than 1/10th of the measurement length” [8].

Integrated-flux experiments: “For the duration of the experiment at least 90% of the experiments should have at least 85% of beam availability and on average more than 80% of the scheduled beam power. The beam will be considered unavailable when its power is less than 50% of its scheduled power for more than one minute” [8].

Although these statements do not sound particularly tough they put demanding requirements on the cryogenic systems. Due to the nature of cryogenics it makes only sense to define a relatively high mission time for the reliability, as failures preventing a cryogenic plant from operation inevitably lead to very long downtime for the entire machine, e.g. the accelerator. If failures in the cryogenic system cause downtime the duration is rather in the range of hours or days than below.

4.2. ACCP compressor set-up
Experience from other labs has shown that, besides utility failures, failures in the compressor system belong to the most frequent and severe ones to cause plant downtime. Once the cryoplant is shut down it usually takes between several hours and a whole working day until the entire system is up and running again, depending on the duration of the maintenance action and resulting needs to re-cool down.

The cryoplant vendor’s compressor concept is advantageous as only three compressor blocks with two oil systems are used, which saves space. All machines are of the same type and size. Even the motors of the SP and the LP machine have the same rating, only the HP machine’s motor is different.

Although the SP compressor motor requires less power than the LP motor, the same model was chosen. This saves spare parts and enables both machines to act as spare for each other. This means that 4.5 K cooling is possible even if one of the two machines is not operating. Furthermore some internal margin is provided for the LP machine as some LP flow could be directed to the SP compressor in case the LP compressor turns out to be insufficient in an operation mode.

Not only is unplanned downtime an issue but also scheduled downtime related to preventive maintenance of the compressors as this may result in warming up the cryomodules. This is particularly the case for the HP compressor that cannot be replaced by the SP or LP machines and is indispensable for the cryoplant operation.

To reduce this risk, ESS and its cryoplant vendor are looking into possibilities to provide a backup compressor system. Besides being able to keep the system cold during an HP compressor failure, a backup compressor significantly increases the degree of freedom for scheduling maintenance and reduces the risk of quick fixes and half solved problems due to time constraints.

The most attractive backup solution seems to be a system that is able to replace every stage. Figure 3 illustrates the basic principle, which of course is a simplification of the actual challenge to realize this concept with regard to oil distribution, system control and automation etc.

4.3. TMCP parallel strings
The large refrigeration capacity of the TMCP, resulting in big equipment sizes, makes it more difficult to defend a backup system such as for the ACCP as these backup systems are quite costly items.

The requested refrigeration performance is so high, that two parallel recycle compressors are adequate for the plant. This together with the stepwise performance increase as shown in figure 2 drive the natural decision to design the cryoplant with two parallel expansion turbines at the cold end. This provides not only another very efficient part-load control strategy but also full redundancy for the first years of operation and at least partial redundancy in the long run. A compressor failure would then force the accelerator to reduce beam power, which decreases the neutron production in the target. On
the other hand the system will not have to be shut down immediately but maintain part load operation, providing useful neutrons that can still serve a number of neutron instruments.

4.4. **TICP and auxiliary systems support**
One of the worst case scenarios in view of the cryogenic system at ESS is a long power shut down, causing the helium in the cryomodules to evaporate due to the static heat load. In this case the evaporating helium flows eventually into the main low pressure line of the ACCP that is connected to the equivalent main low pressure line of the TICP. The TICP recycle compressor, that receives power from a backup system, will be able to compress the evaporating helium and shift it to the warm medium pressure storage tanks. So at least a major loss of helium due to longer power outage can be avoided.

Depending on the actual market situation it can be difficult to replace helium that was lost to the atmosphere, e.g. due to break of one or more bursting disks that protect the helium tanks around the cavities in the cryomodules at quite low pressure. In order to avoid a situation when the accelerator has to reduce beam power or cannot operate at all because there is not enough helium on site, a substantial amount of helium shall also be stored in the 20’000 litre liquid helium storage tank.

**References**

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