Design status of the ESS cryogenic moderator system

H Tatsumoto¹, D Lyngh¹, Y Beßler², M Klaus³, F Hanusch², P Arnold¹ and H Quack³

¹European Spallation Source (ESS) ERIC, Odarslovsvägen 113, Lund, Sweden.
²Forschungszentrum Jülich, ZEA-1, GmbH, 52425 Jülich, Germany.
³Technische Universität Dresden, Institute of Power Engineering, 01069 Dresden, Germany.

hideki.tatsumoto@esss.se

Abstract. The Cryogenic Moderator System (CMS) has been designed to cool high-energy neutrons down to cold neutrons in two cryogenic hydrogen moderators (four ones in the future) by forced flow of subcooled liquid hydrogen at 17 K and 1.0 MPa. At 5 MW proton beam power, an estimated nuclear heating of 6.7 kW (17.3 kW in the future) is generated in the moderators. The subcooled liquid hydrogen is circulated by two pumps arranged in series with a mass flow rate of 1 kg/s to maintain the average temperature rise over each moderator below 3 K and is cooled through a plate fin heat exchanger by a helium refrigerator with a cooling capacity of 30.3 kW at 15 K. The ESS moderator vessels are optimized for maximum cold neutron brightness and pure para-hydrogen, requiring a para concentration of > 99.5 %. An ortho-para-hydrogen convertor is integrated into the loop along with an online para-hydrogen measurement system. The pressure fluctuation caused by unpredictable abrupt changes of nuclear heating will be mitigated using a pressure control buffer with a volume of 65 l.

1. Introduction

The European Spallation Source (ESS) is going to provide long-pulsed cold and thermal neutron fluxes at very high brightness and is one of the world’s largest science and technology infrastructure projects being built on the outskirts of Lund, Sweden. 2 GeV protons (at nominal current of 62.5 mA) with an average beam power of 5 MW delivered by a superconducting linear proton accelerator are injected on a rotatory tungsten target at a pulsed repetition rate of 14 Hz [1]. Fast neutrons liberated via a nuclear spallation reaction slow down to thermal and cold neutrons using water and liquid para-hydrogen (p-H₂) as moderator materials, respectively [1, 2].

In the beginning, the ESS will install two hydrogen moderators above the target wheel and the current plan is to replace them with four (two above and two below, respectively) in the future. The design of a flat butterfly shaped hydrogen moderator vessel, which is made of a high-strength aluminum alloy (AL6061-T6), is optimized for a maximum neutron brightness under the condition of a p-H₂ concentration of more than 99.5% [2]. The calculated nuclear heating generated in the two hydrogen moderators will be 6.7 kW for the proton beam power of 5 MW, while for the four moderators it will be 17.2 kW [3]. A cryogenic moderator system (CMS) that continuously supplies subcooled liquid hydrogen with a temperature of 17 K and a p-H₂ concentration of more than 99.5% will remove the large nuclear heating in the moderators. The CMS has been designed in order to satisfy the ESS goals of providing high brightness cold neutrons for science. The CMS is cooled by a helium refrigeration plant.
with a maximum cooling power of 30.3 kW, which is called the Target Moderator Cryoplant (TMCP) [4, 5].

The ESS CMS has been designed by the ESS in-kind partner, Forschungszentrum Jülich GmbH (FZJ) in cooperation with Technische Universität Dresden, and is being fabricated in FZJ with a planned factory acceptance test in March 2020 according to the schedule. The installation into the ESS Target building is planned to start in October 2020 and the commissioning is planned to be completed by April 2022. The first beam-on-target is going to be realized in 2022.

2. Design of the ESS cryogenic moderator system (CMS)

2.1. System design

The ESS has selected subcooled liquid hydrogen at a pressure of 1.0 MPa and a temperature of around 17 K as the moderator fluid for cold neutrons. The ESS CMS is required for the following design conditions in order to satisfy the ESS goals of providing high brightness cold neutrons for science.

(1) Average temperature increase over the cold moderators caused by the nuclear heating shall be kept below 3 K

(2) p-H\textsubscript{2} concentration shall be more than 99.5 %

The liquid hydrogen circulation flow rates of 0.5 kg/s and 1.0 kg/s respectively are required for the two- and four-moderator arrangements to satisfy the p-H\textsubscript{2} concentration requirement. The ESS CMS needs an ortho-para-hydrogen (o-p-H\textsubscript{2}) converter, similar to that of the J-PARC [6].

Figure 1 shows an overview of the ESS CMS that consists of two turbo pumps in series, a pressure control buffer (PCB) in a bypass, an o-p-H\textsubscript{2} converter in a bypass and two different kinds of heat exchangers (HXs), a plate-fin type (HX-61100) [4] and a finned tube type (HX-61200) in a cold box, vacuum insulated cryogenic hydrogen transfer lines (HTL), a distribution box, an in-situ p-H\textsubscript{2} measurement system (p-H\textsubscript{2}MS) with a valve box, distribution lines (HDTL), moderator vessels (u.d.cM, u.u.cM, l.d.cM and l.u.cM) and a hydrogen vent line. The design pressure is 1.7 MPa, which is defined by the design limits of the cold moderator vessel. The main loop of the CMS is cooled via the heat exchanger, HX-61100, by the TMCP where the high pressure varies from 0.6 to 2.2 MPa and the feed flow rate is 0.12 to 0.97 kg/s at 15 K. The helium temperature leaving the HX-61100 is 20 K [4], while the hydrogen temperatures at both ends of it are 17 K and 20.5 K.

![Figure 1. Overview of the ESS cryogenic moderator system (CMS).](image-url)
Subcooled liquid hydrogen is supplied through the HTL with a length of 35 m and a diameter of 60.33 mm from the CMS cold box to the distribution box. It gets split into four HDTLs (of DN25 size) in order to ensure the feed temperature of 17.5 K and a p-H₂ of 99.5% at the inlet of each moderator. Removable U-shaped bayonets connect each HDTL with the pipe on the top of the moderator-reflector plug (MRP) because it needs to be replaced every year. The feed flow rate to each moderator is adjusted by a manual hand valve in the return HDTL. The p-H₂ MS is placed in a bypass from and to the distribution box and the o-p-H₂ fractions are continuously measured by Raman spectroscopy via a sapphire glass window at a flow of around 1 g/s.

There are six separate vacuum spaces (the CMS cold box, the HTL, the distribution box, the MRP, the valve box and the p-H₂ MS area). The vacuum spaces are operated under a high vacuum of approximately lower than 10⁻³ Pa, which is always being monitored, during cryogenic operation as static vacuum without continuous pump operation.

2.2. Liquid hydrogen pump

A ball-bearing type hydrogen pump is designed to circulate 1 kg/s at 17 K for the four-moderator arrangement, although the required flow rate is only 0.5 kg/s for the two moderators. The required pump heads are 156.3 kPa for 1 kg/s and 100.8 kPa for 0.5 kg/s to overcome the pressure drop as mentioned later in section 2.9. Two hydrogen pumps are placed in series because of redundancy and are operated at the same rotation speeds. If one pump fails, the other is ramped up to get the required flow rate. Figure 2 shows predicted pump performance at the nominal operation point for two-pump in series and single operation. For the two pumps, the required rotation speeds are 7,500 rpm and 10,000 rpm for the two- and four-moderator arrangements, respectively. It turns out from figure 2 (b) that, even if one pump fails, the revolution speed required for the remaining pump is lower than the maximum speed of 14,000 rpm.

![Figure 2. Predicted hydrogen pump performance at nominal conditions (17K and 1.0 MPa).](image_url)

2.3. Pressure Control Buffer (PCB)

The CMS forms a closed loop, which is filled with subcooled liquid hydrogen that behaves like an incompressible fluid. The slight temperature changes in the return line from the cold moderators to the HX-61100 caused by the nuclear heating at the moderators would result in a severe pressure rise. The travel time of the hydrogen from the moderators to the HX is 11.5 s at the circulation flow rate of 1 kg/s. The pressure control buffer (PCB) vessel is designed to mitigate the pressure fluctuation by the vapor phase in it, which is called “passive pressure control” [7]. This is the biggest advantage of selecting subcooled liquid hydrogen unlike supercritical hydrogen in J-PARC [6] and SNS [8]. The vessel with a volume of 65 l and a diameter of 323.9 mm is mounted vertically in the cold box. The PCB is connected to the main piping downstream of the hydrogen pump and holds a liquid fraction in its lower part (20 l) at around 17.5 K. The vapor released by a control valve (CV-62029) placed on the top of it is liquefied
by HX-61200 mentioned later in section 2.4. The hydrogen gets its equilibrium p-H$_2$ concentration passing through the o-p-H$_2$ converter and then comes back to the suction side of the pumps. The slight bypass flow would make the liquid and vapor temperatures maintained at around 17.5 K at the bottom and 30 K at the surface of the liquid. The upper two third of the PCB is not insulated with multilayer insulation (MLI) to the outside to get an intended heat leak of 0.2 kW in it, which leads to an evaporation of 0.33 g/s.

When the proton beam is on the target, hydrogen density gets lower in the return line and then a small amount of liquid hydrogen will flow into the PCB. If the vapor corresponding to the liquid volume change is released by CV-62029 and condensed via the HX-61200, the CMS pressure would still be maintained at 1.0 MPa. This is called an “active pressure control” [7]. The released vapor flow rate via CV-62029 is estimated to be 3.09 g/s, which includes the evaporation flow due to the static heat load, just for 11.5 s for the 5-MW proton beam. On the other hand, the pressure would fall after a proton beam trip. To keep the same pressure, CV-62029 should be temporary closed and the vapor of 2.76 g/s at 45 K should be generated by the electrical heater of 1.66 kW and the static heat load of 0.2 kW.

The liquid hydrogen level in the PCB is detected in two ways: a hydrostatic head of liquid hydrogen and temperature sensors placed vertically at six different altitudes corresponding to the liquid volume of 3%, 11%, 21%, 29%, 36% and 43%. Electrical heaters are utilized to boil liquid hydrogen to adjust the liquid level, which leads to the pressure control of the CMS. Four heater elements made of Ni-Cr wire are wound around the vessel between the level of 11% and 43%, where the heat flux is 11.2 kW/m$^2$, and have a maximum capacity of 2 kW.

2.4. Heat exchangers

There are two heat exchangers. One is a plate fin heat exchanger (L500 x W250 x H228 mm) placed in the main CMS loop in order to remove the heat load in the CMS and maintain the feed hydrogen temperature at 17 K [4]. The other is a finned tube type heat exchanger, HX-61200, which has the function of condensing the vapor released from the PCB to maintain the CMS pressure at around 1.0 MPa. For the nominal operation, the evaporated gas of 0.33 g/s should be condensed and cool it to 22 K via the HX-61200. The removal heat load required for the HX-61200 is 0.2 kW. This is because the helium stream comes into it after passing through HX-61100 and the feed helium temperature is around 20 K. For the active pressure control at the maximum beam power mentioned in 2.3, the flow rate through the HX-61200 is 3.09 g/s and the removal heat load is estimated to be 1.96 kW.

The fin tube is coiled helically around a central mandrel and is housed in a surrounding stainless steel vessel. The length and the diameter of the copper finned tube where hydrogen is flowing have been determined to be 12 m and 16.5 mm to meet the requirements, while the length of the annular space through which helium is passing as cross flow is set 0.33 m. A CFD analysis shows that the pressure drop of the helium flow is 0.8 kPa under the conditions of 1 kg/s, 20 K and 2.1 MPa and satisfies the design criteria of maximally 3 kPa.

2.5. Ortho-para-hydrogen (o-p-H$_2$) converter

The natural conversion mechanism during and after the cool down below 20 K is rather slow, taking actually months to enrich the p-H$_2$ to a level higher than 99.5%. Ortho-hydrogen (o-H$_2$) could decrease the moderation performance significantly, absorbing neutrons instead of slowing them down and letting them pass. Iverson and Carpenter [9] predicts that a neutron irradiation induces conversion of 0.003% of the p-H$_2$ volume to o-H$_2$ per pulse. Based on this, a p-H$_2$ of 0.0114% via the moderators would convert to o-H$_2$ for the ESS proton beam at 14 Hz. For 99.5% of the p-H$_2$ concentration at the inlet of the moderators, it decreases to 99.488% downstream of the moderator.

The o-p-H$_2$ converter with a diameter of 273.05 mm has been designed and is filled with a commercial catalyst IONEX® Type OP with an average grain size of 0.5 mm. The catalyst bed size is designed to be 35 l. The o-p-H$_2$ converter is arranged in a bypass of the loop in order to convert quickly and keep the p-H$_2$ concentration requirement to more than 99.5%, because the pressure drop over the o-p-H$_2$ converter would get large, for example, 127 kPa at 1 kg/s. At the nominal operation, the o-p-H$_2$
converter is kept at a temperature of 17.3 K where the equilibrium p-H₂ concentration is 99.96%. Assuming a conversion efficiency, $\eta_p$, of 80%, the o-p-H₂ converter would give 99.868% of the p-H₂ if the concentration is 99.5% at the inlet of it. Considering the mass balance at the connection of the converter bypass and the main flow, it turns out that a bypass flow rate of 31.5 g/s is needed and then the pressure drop over the bypass line can be calculated to be 24.6 kPa, which is quite small in comparison with the whole CMS pressure drop mentioned later in section 2.9. The space velocity, $SV$, is calculated using the following equation [10]

$$SV = \frac{k}{\ln(1 - \eta_p)}$$  \hspace{1cm} (1)

where $k$ is a rate constant for o-H₂ to p-H₂.

The space velocity is calculated to be 2174 for $\eta_p = 0.8$ $k = 3500$ [10, 11]. The catalyst bed size of 9.6 l would be sufficient at the nominal operation. It is therefore confirmed that the catalyst bed size of 35 l is chosen conservatively.

2.6. In-situ Para-hydrogen Measurement System (p-H₂MS)

The ESS plan is to measure the p-H₂ concentration of the feed hydrogen as well as that of the return flows of the cold moderators in situ, using Raman spectroscopy through a small sapphire glass window to ensure the 99.5% of p-H₂ requirement. The online p-H₂ measurement system (p-H₂MS) has been designed to be placed in bypass as shown in figure 1. The piping with a size of 21.34 mm is routed from the return HDTLs and the feed HTL back to the return HTL in the distribution box. The total length of the bypass lines is around 25 m. There are a feed control valve (Kv= 0.5), a return valve (Kv= 0.5) and a release valve for each bypass line in the valve box. The hydrogen inventory of the piping with a glass window between the valves is reduced to 0.6 l. The pressure drop over the bypass is calculated to be 1.47 kPa at the required flow rate of 1 g/s, while those of the return lines running in parallel along it is calculated to be 5.24 kPa at a circulation flow rate of 1 kg/s for the four-moderator configuration and 3.94 kPa at 0.5 kg/s for two-moderator configuration. The total heat load is estimated to be 0.01 kW, which corresponds to a temperature rise of 1 K for 1 g/s.

A vacuum space including the glass window is physically isolated from those of the valve box and the distribution box. If a hydrogen leak occurs due to a failure of the glass window, the p-H₂MS can be completely isolated by the control valves from the main CMS loop. The remaining liquid hydrogen in the bypass piping is released and depressurized by a release control valve or a safety relief valve, while the hydrogen leaked in the vacuum space is released being maintained below 150 kPa by a vacuum safety device. The glass windows are planned to be replaced every year as a safety precaution. We are developing the sapphire glass window for use in LH₂ temperature range and a high pressure of 1.7 MPa.

2.7. Hydrogen vent line

All the relief devices and active control release valves are connected to the hydrogen vent line with total length of 40 m. The pipe is routed from the A2T triangle room to the roof top of the Target building as shown in figure 1. The hydrogen vent line is always maintained by helium environment at positive pressure by a check valve with a cracking pressure of 10 kPa. All of the hydrogen is released to the outside via this hydrogen vent line.

2.8. CMS hydrogen inventory

Table 1 describes a summary of the CMS hydrogen inventory for two- and four-moderator arrangements. The overall volumes of the CMS are estimated to 387.6 l and 441.6 l, respectively. The volumes where liquid hydrogen exists are 321.8 l and 375.8 l, although it is dependent on a liquid level in the PCB.

2.9. Pressure drop

The pressure drop over the main liquid hydrogen circuit is estimated at the nominal operation condition for both the two- and four-moderators arrangements. Fluid properties of p-H₂ at 17 K and 1.0 MPa given
by GASPAK [12] have been used. The friction factor of a pipe is calculated using the Colebrook equation [13], where a surface roughness of 0.05 mm is used. The pressure drops of the moderators are calculated by a CFD simulation [3]. The feed control valve (Kv=65) and the return manual control valve (Kv=30) are set opened by 95% and 90%, respectively. There are two check valves which have a flow resistance given by Kv=100. The cracking pressure is also considered. HX-61100 has been specified for a pressure drop of 10 kPa at 1 kg/s. The summary of the pressure drop calculation is described in Table 2, where the pressure drops for not only the piping but also equipment like a valve, an orifice flow meter and a filter are included. The circulation flow rates required for the two- and four-moderator arrangements are 0.5 kg/s and 1.0 kg/s, respectively, and the calculated pressure drops are 100.8 kPa and 156.4 kPa under the nominal operation condition. The effects of the mass flow rate on the pressure drop at 17 K and 1.0 MPa are also shown in Figure 2. As mentioned in section 2.2, that the hydrogen pump performances satisfy the operational conditions not only for two pumps in series but also for a single operation.

**Table 1. CMS hydrogen inventory.**

| Component                                | LH$_2$ (l) | GH$_2$ (l) |
|------------------------------------------|------------|------------|
| Two-moderator                           |            |            |
| (Four-moderator)                         |            |            |
| HX-61100 (plate fin)                     | 30.0       | -          |
| Piping from HX outlet to Moderators      | 139.1      | (162.2)    |
| Moderator vessels                        | 1.3        | (3.8)      |
| Piping from Moderators to HX             | 120.9      | (149.3)    |
| O-p-H$_2$                                | 15.5       |            |
| PCB (liquid/vapor)                       | 15.0       | 45.0       |
| Bypass and auxiliary piping              | -          | 18.1       |
| HX-61200                                 | -          | 2.7        |
| Total                                    | 321.8      | (375.8)    | 65.8 |

**Table 2. Pressure drop over the main liquid hydrogen circuit at a nominal operation condition.**

| Component                                      | Two-moderator | Four-moderator |
|------------------------------------------------|---------------|----------------|
|                                               | $m$ (kg/s) | $\Delta P$ (kPa) | $m$ (kg/s) | $\Delta P$ (kPa) |
| Feed piping in the cold box                   | 0.50        | 6.0            | 1.00        | 16.7            |
| Main feed transfer line (HTL)                 | 0.50        | 6.6            | 1.00        | 24.7            |
| Feed and return distribution lines (HDTLs)    |              |                |             |                 |
| via bayonet and moderators                    | Upper u.d.cM | 0.24           | 71.0        | 0.24            | 71.0            |
|                                               | Lower l.d.cM | -              | -           | 0.26            | 78.2            |
|                                               | l.u.cM       | -              | -           | 0.26            | 78.7            |
| Main return transfer line (HTL)               | 0.50        | 5.0            | 1.00        | 16.7            |
| Return piping in cold box including HX-61100  | 0.50        | 4.9            | 1.00        | 19.5            |
| Total pressure drop                           | 100.8       |                | 156.4       |                 |

2.10. Heat load

All the cryogenic equipment is insulated by high vacuum and partially is covered with 20 layers of MLI, where the thermal radiation heat load between 300 and 20 K is considered to be 1.3 W/m$^2$ on the cold surface. However, the piping in the MRP is not covered with MLI because of the irradiation damage. The heat load is calculated using the well-known radiation heat transfer correlation with the Boltzmann constant [14]. The heat load of a pump, $Q_p$, is calculated using the pump head, $\Delta P$, in Table 2 as follows.
The heat load can be simplified model and the

detectors are connected to the hydrogen vent line. All the
2014/68/EU (PED) for pressure equipment. Double safety devices (a combination of a spring-load safety relief valve and a rupture disk) are applied for redundancy and higher safety.

The region of space around the CMS within a radius of 1 m is defined as ATEX (Directive 2014/34/EU) zone 2 because leak rates from valves are considered low and all safety and relief valves are connected to the hydrogen vent line. All the CMS equipment get grounded and electrical equipment certified for the ATEX zone 1 is used within the restricted zone defined here. Stationary hydrogen leak detectors are planned to be placed in ATEX zone 2. In case a hydrogen leak is detected, the CMS shall be immediately stopped and be depressurized by releasing all the hydrogen to atmosphere through the vent line.

2.12. Pressure and temperature fluctuation due to turning the proton beam on or off

The temperature in the return line from the moderator to the main HX is warmed up from 17.5 K to 19.6 K caused by the nuclear heating of 17.2 kW at the flow rate of 1 kg/s. The pressure fluctuations, $\Delta P_f$, and the LH$_2$ volumes coming into the PCB, $\Delta V$, are estimated for the passive pressure control using a simplified model shown in figure 3, where the conservation of the hydrogen mass is considered and the heat load can be completely removed by the HX. The effect of the initial LH$_2$ volume in the PCB, $V_3$, on $\Delta P_f$ and $\Delta V$ are shown in figure 4. It turns out that the pressure rise for the two-moderator arrangement is much lower than the allowable one of 0.1 MPa just by the passive control. For the four-moderator arrangement, the calculated pressure rise is 93 kPa, which is slightly lower than the criteria. It would be possible to get a higher pressure rise than 100 kPa if a temperature fluctuation appears downstream of the HX. Therefore, it is expected that a combination of the passive and active control

\[
Q_p = \frac{\dot{V} \Delta P}{\eta_p}
\]

where $\dot{V}$ is the volumetric flow rate and $\eta_p$ is the isentropic efficiency, which is set to be the design value of 0.72.

Table 3 updates the heat loads for the two- and four-moderator arrangements [4]. The heat loads of the pumps account for around 50% of all the static heat load in both cases. It turns out that, for the 5-MW proton beam, the total heat loads of the CMS are 8.6 kW and 21.9 kW respectively, which is 27% lower than the maximum TMCP cooling power of 30.3 kW. When the active pressure control is used just after the proton beam injection described in section 2.3, the heat load of 1.96 kW via HX-61200 is added and that of the whole CMS results in 23.8 kW temporarily. In this case, it turns out that the TMCP can also absorb the heat load.

| Component                                      | Two-moderator (kW) | Four moderator (kW) |
|------------------------------------------------|--------------------|---------------------|
| Two liquid hydrogen pumps                      | 0.935              | 2.909               |
| PCB, HXs, o-p-H$_2$ converter                  | 0.037              | 0.037               |
| Piping, valves and auxiliary pipes in Cold box | 0.015              | 0.015               |
| Feed and return HTLs with valves               | 0.126              | 0.126               |
| Feed and return HDTLs, valves and auxiliary pipe | 0.118           | 0.231               |
| Moderator vessels and their pipes without MLI | 0.227              | 0.454               |
| Spacers in MRP                                 | 0.421              | 0.850               |
| Total static heat load                         | 1.879              | 4.622               |
| Dynamic heat load: Nuclear heating at moderators| 6.696              | 17.248              |
| Total static + dynamic heat load               | 8.575              | 21.870              |
would enable to mitigate such an excess pressure fluctuation caused by the dynamic nuclear heating to a value below 100 kPa.

3. Conclusions
The ESS cryogenic moderator system (CMS) has been designed. The required circulation flow rates of subcooled liquid hydrogen are 0.5 and 1 kg/s at 17 K and 1.0 MPa given by two hydrogen pumps in series, respectively. An o-p-H$_2$ converter is installed to secure a p-H$_2$ concentration of more than 99.5% in a bypass and an in-situ p-H$_2$ measurement system in another bypass is also designed to meet this moderator design requirement. A pressure control buffer is installed in a bypass to mitigate a pressure fluctuation caused by turning on and off an abrupt dynamic heat load below 0.1 MPa. The design ensures that the pressure drop, the heat load and the pressure fluctuation meet the design requirement.

4. References
[1] Garoby R and Danared H et al 2018 Phys. Scr. 93 014001
[2] Andersen K, Bertelsen M, Zanini L, Klinkby E B, Schönfeldt T, Bentley P M and Saroun J 2018 J. Appl. Cryst. 51 pp264-281
[3] Bessler Y, Henkes C, Hanusch F, Schumacher P, Natour G, Butzek M, Klaus M, Lyngh D and Kickules M 2017 IOP Conf. Ser: Materials Science and Engineering 171 012131
[4] Jurns J, Ringner J, Quack H, Arnold P, Weisend II J G and Lyngh D 2015 IOP Conf. Ser: Materials Science and Engineering 101 012082
[5] Arnold P, Hess W, Jurns J, Su X T, Wang X L and Weisend II J G 2015 IOP Conf. Ser: Materials Science and Engineering 101 012011
[6] Tatsumoto H, Ohtsu K, Aso T, Kawakami Y, Teshigawara M 2014 Adv. Cryo. Eng. 66 pp 66-73.
[7] Klaus M, Eisenhut S, Quack H, Haberstroh Ch and Bessler Y 2015 IOP Conf. Ser.: Mater. Sci. Eng. 101 012050
[8] Crabtree J A 2005 Proc. Int. Collaboration. Adv. Neutron Source (ICANS-XVII) pp306-314.
[9] Iverson E B, Carpenter J M 2003 Proc. Int. Collaboration. Adv. Neutron Source (ICANS-XVI) pp707-718
[10] Sakamoto S 2012 Technical Design Report of Spallation Neutron Source Facility in J-PARC, Japan Atomic Energy Agency Report (JAEA-Technology) 2011-035 pp129-131
[11] Klaus M, Schwab A, Haberstroh Ch, Eckhardt K, Beckler Y, Baggemann J and Cronert T 2019 J. Conf. Series: Materials Science and Engineering 502 012161
[12] GASPAK user's guide 1998 Cryodata
[13] Colebrook C F 1939 J. Institution of Civil Engineers. 11 (4) pp133–156
[14] Van Sciver S W 1986 Helium Cryogenics (New York: Plenum Press) pp328-333

![Figure 3. Simplified CMS loop model.](image1)

![Figure 4. Predicted pressure rise and LH$_2$ volume change for the 5 MW proton beam.](image2)