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Cryogenics at the European Spallation Source

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Abstract

Cryogenics plays an important role at the European Spallation Source, a world class neutron science center, currently under construction in Lund, Sweden. Three principal applications of cryogenics are found at ESS. The SRF cryomodules of the ESS proton linac require cooling at 2 K, 4.5 K and 40 K; the hydrogen moderator surrounding the target that produces neutrons, requires cooling via 16.5 K helium and LHe is required for many of the scientific instruments. These needs will be met by a set of three cryogenic refrigeration/liquefaction plants and an extensive cryogenic distribution system. Significant progress has been made on the ESS cryogenic system in preparation for the expected first beam on target in 2019. This work includes: funding of industry studies for the accelerator cryoplant, preliminary design of the cryogenic distribution system, investigation of possible in kind contributors and release of the invitation to tender for the accelerator cryoplant. This paper describes the requirements, design solutions and current status of the ESS cryogenic system. The planned recovery of waste heat from the cryogenic plants, a unique aspect of ESS, is described. The procurement of the cryogenic system, expected to be done via a combination of purchase via competitive bids and in kind contributions is also discussed.

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Keywords: ESS; refrigeration;He II; distribution system; hydrogen moderator; neutron science

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1. Introduction

The European Spallation Source (ESS) is a world class neutron science facility currently under construction in Lund, Sweden Peggs (2013). Upon completion, it will be the most powerful neutron source in the world. ESS is driven by linear accelerator that produces a 5 MW beam of 2 GeV protons. The bulk of the acceleration is carried out by superconducting RF cavities operating at 2 K. The protons strike a rotating tungsten target, producing neutrons via the spallation process. These neutrons pass through a supercritical hydrogen moderator operating at 17.5 K before spreading out to a suite of up to 22 neutron science instruments. Initial operation is expected in 2019 using a 570 MeV proton beam and 7 instruments. Full operation with a 2 GeV proton beam and 22 instruments is planned for 2023. The total project cost for ESS is 1843 Million Euros (2013 Euros). ESS is funded by 17 European nations and a feature of the project is that a significant amount of the funding comes in the form of in-kind contributions of equipment and expertise.

2. Cryogenics at ESS

2.1. Requirements

Cryogenics plays a key role in the ESS project. In the accelerator, the bulk of the acceleration is carried out by 3 types of superconducting RF (SRF) cavities. Darve et al. (2014). There are a 13 double spoke cavity cryomodules, 9 medium beta elliptical cryomodules and 21 high beta elliptical cryomodules. There is also room in the accelerator lattice for an additional 14 high beta cryomodules in the event that they are required to produce a beam energy of 2 GeV. All the SRF cavities operate in saturated 2 K He II baths. Each of the cryomodules also contains a 40 K thermal shield and requires helium cooling of the RF power couplers. The power coupler cooling returns the helium at ambient temperature and thus is a liquefaction load. There are currently no superconducting magnets in the ESS accelerator.

The supercritical hydrogen moderator absorbs up to 20 kW from the neutrons. This heat is removed by a hydrogen – helium heat exchanger which is in turn cooled by a 16.5 K supercritical helium flow. The hydrogen moderator system is further described in Gallimore et al. (2014).

The neutron instruments will also require a significant amount of liquid helium and nitrogen both for instrument components and sample environments. The current requirement is a maximum of 7500 liters a month of LHe for the instruments.

An additional cryogenic requirement is the ESS cryomodule test stand. All cryomodules will be tested at operating temperatures and full RF power prior to installation in the ESS tunnel. The spoke cavity cryomodules will be tested at the FREIA facility in Uppsala University, Ruber et al. (2014) while all the elliptical cavity cryomodules will be tested at the ESS site. The ESS cryomodule test stand requires sufficient cooling at 2 K, 40 K and 4.2 K liquefaction to test a single cryomodule at full power, Hees et al. (2014).

ESS has a commitment to be a sustainable research facility. Towards that end, the heat removed by the cryogenic systems will be recovered and transferred to the Lund District Heating System as opposed being deposited in cooling towers or ponds. This adds additional requirements on the cryogenic system. See section 3 below.

An early design choice at ESS, based on both reliability and schedule concerns, is to meet the cryogenic requirements of ESS with 3 separate optimized cryogenic refrigeration plants sharing a near common recovery, purification and storage system. The 3 plants are the Accelerator Cryoplant (ACCP), the Target Moderator Cryoplant (TMCP) and the Test and Instrumentation Cryoplant (TICP). Table 1 shows the high level capacities of these plants. Fig. 1 is a block diagram of the integrated ESS cryogenics system.

2.2. Accelerator cryoplant (ACCP)

The ACCP is the largest and most complicated of the ESS cryoplants. It also requires the longest time to design build, install and commission. The ACCP must be able to adapt to two operating configurations: Stage 1 in which the nominal 43 cryomodules are cooled and Stage 2 in which the additional 14 high beta cryomodules have been added and require cooling. Thus, turn down capability is a significant requirement of the plant design.

Table 1. ESS cryoplant capacities by temperature level.

Cryoplant	2 K	4.2 K Liquefaction	16.5 K	40 K
ACCP	3 kW	270 l/h	-	11 kW
TMCP	-	-	20 kW	-
TICP	76 W	6 l/h	-	420 W

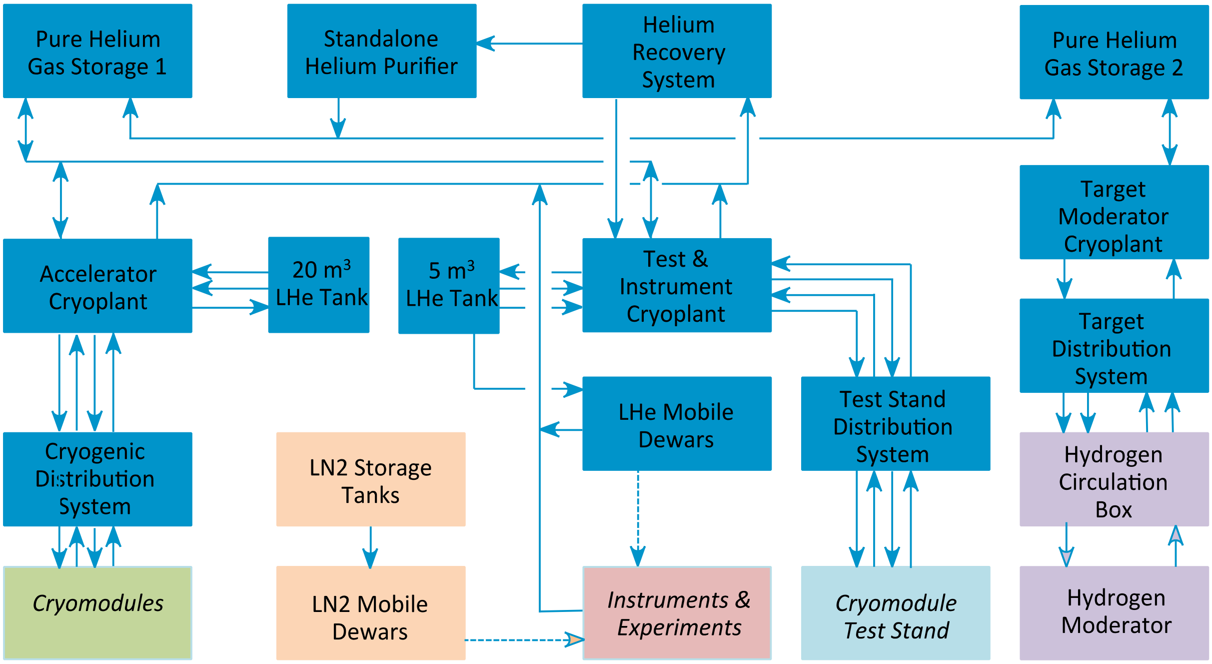

Fig. 1. Block diagram of the ESS cryogenic system.

In 2013, ESS funded two industry studies for this plant. The results of those studies, along with internal ESS analysis, have led to the following design choices for the ACCP:

- No LN_2 precooling in the upper stages of the plant. This choice simplifies logistics and reduces operating costs at an increase of capital costs. Such a choice also reduces site truck traffic;
- Optimize the plant to operate in both operating configurations (stage 1 and stage 2) by procuring two sets of flow parts for cold rotating equipment and installing variable frequency drives on some warm compressors;
- Cold compressors are used to provide the subatmospheric pumping required to produce 2 K helium but suppliers can propose a final stage of warm compression if such a solution aids in turn down capability and rapid recovery from plant trips;
- In addition to purging, warm up and cool down operations, the ACCP will be designed to operate in 4 modes: Nominal (2 K and RF power and beam on), Standby (2 K but no RF power or beam on), 4.5 K standby and 40 K standby;
- The ACCP will be procured by competitive bid (or possibly in-kind-contribution) covering the cycle design, compressors and cold box, controls and commissioning. Installation and procurement of liquid and gaseous Helium storage will be separate contracts or possibly optional additions to the primary ACCP contract.

The ACCP requirements and specifications have been developed in concert with the cryogenic design of the cryomodules and cryogenic distribution system. An area of particular attention has been the determination of the required capacity of the ACCP in all modes and in both operating configurations. Table 2 shows the plant capacities for different operating modes and stages. These numbers include a safety factor which works out to 1.5 times the nominal requirements.

A detailed technical specification and statement of work for the ACCP have been written and a formal Invitation to Tender was released in June 2014. Vendor responses are expected in November 2014 and the ACCP order should be placed in February 2015. The plant is expected to be installed and fully commissioned in June 2018. Further details of the ACCP may be found in Wang et al. (2014).

Table 2. ACCP plant capacities by operating scenarios and mode.

Operation modes		**2 K Load, W**			**4.5 K Load**		**40-50 K, W**
		Isothermal	**Non-isothermal**	**Total**	**4.5 K, W Total**	**Liquefaction, g/s**	**Total**
Stage 1 2019-2023	Nominal	1860	627	2478		6.8	8140
	Turndown	845	627	1472		6.8	8140
	Standby				1472	6.8	8140
	TS Standby	-	-	-	-	-	8140
	Maximal Liquefaction	Loads in standby mode plus maximum liquefaction rate at rising level into the storage tank					
Stage 2 2023-…	Nominal	2226	824	3050		9.0	10819
	Turndown	1166	824	1990		9.0	10819
	Standby				1990	9.0	10819
	TS Standby	-	-	-	-		10819
	Maximal Liquefaction	Loads in standby mode plus maximum liquefaction rate at rising level into the storage tank					

2.3. Cryogenic distribution system (CDS)

The cryogenic distribution system connects the ACCP to the cryomodules in the ESS tunnel. The cryomodules are connected in parallel to the distribution line and each cryomodule has its own isolation vacuum. Vacuum barriers separate each cryomodule's isolation vacuum from that of the distribution line. In the distribution line, at each cryomodule, is a valve box. Each cryomodule is connected to its corresponding valve box via a vacuum insulated jumper connection. The process pipes in the jumper are welded while the vacuum sleeve has a flanged connection.

As in the case of the Spallation Neutron Source (SNS) and the JLab 12 GeV upgrade, the 2 K He II is created at each individual cryomodule. The cryogenic distribution line supplies 4.5 K, 3 bar helium which is passed through a precooling heat exchanger and then expanded via a Joule-Thompson valve into the 2 K bath surrounding the SRF cavities. Sub-atmospheric vapor pumped off the 2 K space passes back through the precooling heat exchanger and is returned to the ACCP. In the case of the elliptical cryomodules, the heat exchanger and JT valve are part of the cryomodules. In the case of the spoke cavity cryomodules, the heat exchanger and JT valves are part of the valve box due to space and ease of assembly considerations.

Due to high availability requirements, the cryomodules are designed so that likely equipment failures (e.g. tuner motors) can be fixed without needing to remove the cryomodule from the beam line. The cryogenic distribution system contains sufficient valves and pipes (both cold and warm) to allow individual warm up and cold down of one or more cryomodules while keeping the rest of them at operating temperatures. This feature, along with the separate cryomodule isolation vacuums, facilitates in situ repairs.

Conceptual design of the CDS is well advanced, including determining the number and sizes of pipes, valve sizing, thermal insulation design, structural design and expected heat leak. Similar to the cryomodules, the CDS contains a 40 – 50 K thermal shield. Figure 2 is a view of part of the CDS showing a valve box, distribution line and jumper connection.

The CDS will almost certainly be an in kind contribution from one or more institutions. Detailed design of the CDS at one of these institutions is expected to begin in mid 2014 with commissioning of the CDS to be completed in January 2019. Additional details of the CDS may be found in Fydrych et al. (2014).

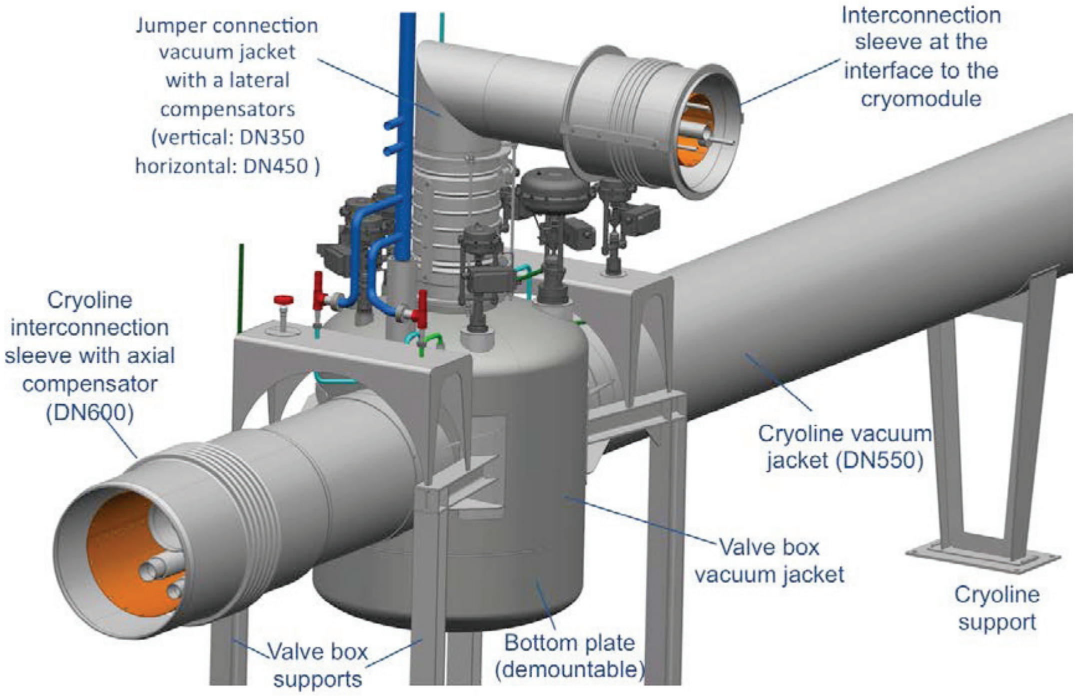

Fig. 2. Conceptual design of the cryogenic distribution line and valve box for the elliptical cavity cryomodule.

2.4. Target moderator cryoplant (TMCP)

The target moderator cryoplant provides the cooling for the 17.5 K supercritical hydrogen moderators that surround the target. These moderators reduce the energy of the neutrons to values more interesting to researchers. Heat deposited in the moderators is absorbed by a hydrogen cooling loop which is in turn connected via a heat exchanger to a 16.5 K helium flow from the TMCP. Thus, the TMCP is the heat sink for the heat deposited in the moderator. The moderators and hydrogen loop and heat exchanger are the responsibility of the ESS Target Division. An early design of this loop in given in Gallimore et al. (2014).

Recently, an innovative moderator design has been developed that is both smaller and results in higher neutron brightness. The impact of this change on the TMCP requirements is still being finalized. Currently, the expected 16.5 K capacity of the TCMP is estimated to be 20 kW. The TCMP will be ordered in August of 2015 and is expected to be fully commissioned in June of 2018. Further details of this plant may be found in Jurns et al. (2014). One option for the plant design is described in Klaus et al. (2014).

2.5. Test and instruments cryoplant (TICP)

The third and smallest of the ESS cryoplants is the Test and Instruments Cryoplant. This plant has 2 roles. During initial ESS construction, it provides cooling to the elliptical cryomodule test stand at the ESS site. During operations, the TICP will provide up to 7500 liters per month of LHe to the scientific instruments as well as providing cooling for the occasional cryomodule test. Based on these requirements, the cryoplant is sized to provide 76 W at 2 K, 420 W at 40 K and 6 l/hr of liquefaction when run in mixed refrigeration/liquefaction load. Such a plant will provide well over the required 7500 liters per month when operated in pure liquefaction load. Due to the small 2 K load, pumping of the sub-atmospheric helium from the cryomodule will be done by warm vacuum pumps rather than cold compressors. All helium pumped off will be recovered, purified and reused.

The TICP will be ordered in August of 2015 and fully commissioned in July of 2017 in time for the first cryomodule tests.

2.6. Helium recovery and storage

One of the goals of the ESS cryogenic system is to recover and reuse all the helium in the system. The ACCP and TICP cryoplants share a common gas storage system. The TMCP has separate gas storage that can be cross connected to the ACCP and TICP storage. A helium recovery system is under design that will recover 300 K helium gas from the science instruments and return to the cryogenic system for purification, storage and re-liquefaction.

The helium recovery and storage system will include a cryogenic purifier to remove contaminates as well as sensors to monitor helium purity. The bulk of the gas storage will occur at 20 bar with a smaller amount at 200 bar to store the helium gas returning from the instruments. Gas storage at ESS will be sized to allow storage of all the inventory in accelerator and instruments as gas. A compressor, powered by a back-up diesel generator will be available to recover helium during site wide power failures. One of our goals is to limit the venting of helium into the atmosphere to a few, rare failure modes.

A significant amount of storage in liquid form is also planned. A 5 m^3 dewer is connected to the TICP to allow us to continue to supply LHe to the instruments in the event of an unscheduled stoppage of the plant. A 20 m^3 dewar will be connected to the ACCP. This storage allows both management of the system inventory and the possibility of a rapid refill of the accelerator cryogenic system in the case of a sudden loss of the accelerator inventory. Table 3 summarizes the gas and liquid storage plans for ESS. The components of the recovery, storage and purification systems will be acquired by separate procurement or as in kind contributions.

Table 3. Helium storage at ESS.

LHe	GHe (20 Bar)	GHe (200 Bar)
5 m^3 (instruments backup) 20 m^3 (accelerator)	900 m^3	12 m^3

3. Heat recovery

A unique aspect of ESS is the project's commitment building a sustainable research facility. Part of the sustainability plan for ESS is to recover as much waste heat as possible and supply it to the District Heating System in Lund. In the case of the ESS cryogenics system, this means that the heat deposited in the oil and helium coolers of the warm compressors as well as in the compressor motors (if water cooled) will be recovered Jurns et al., (2014). To ensure the high return temperature required for useful heat recovery, the cryogenic plant design will require high efficiency heat exchangers as well as active control of the water flow rates to both maintain proper equipment cooling and high return water temperatures in all cryoplant operating modes. The higher capital costs of such systems are viewed as worthwhile if the systems contribute to the sustainability goals. Figure 3 is an example of energy recovery in the ACCP compressors with similar systems planned for the other two ESS cryoplants

4. Summary

The design of the ESS cryogenic system is well advanced. Basic decisions on the system configuration have been made, detailed heat loads and required capacities have been determined. Industry studies for the largest of the cryoplants (the ACCP) have been completed. A detailed technical specification and statement of work for the ACCP have been created and the invitation to tender for this plant has been released.

A detailed preliminary design of the cryogenic distribution system has been created and in kind partners for this system have been identified. Orders for all 3 cryoplants will be placed in 2015.

The requirements for the buildings containing the ESS cryogenic systems have been determined and agreed with the ESS Conventional Facilities Division. These buildings are currently under detailed design. Fig. 4 shows a conceptual layout of cryogenic equipment in the ESS cold box room. A separate building will contain the warm compressors.

A high level schedule for the ESS cryogenic system is shown in Fig. 5. The schedule is consistent with the ESS project goal of having first beams on target in 2019.

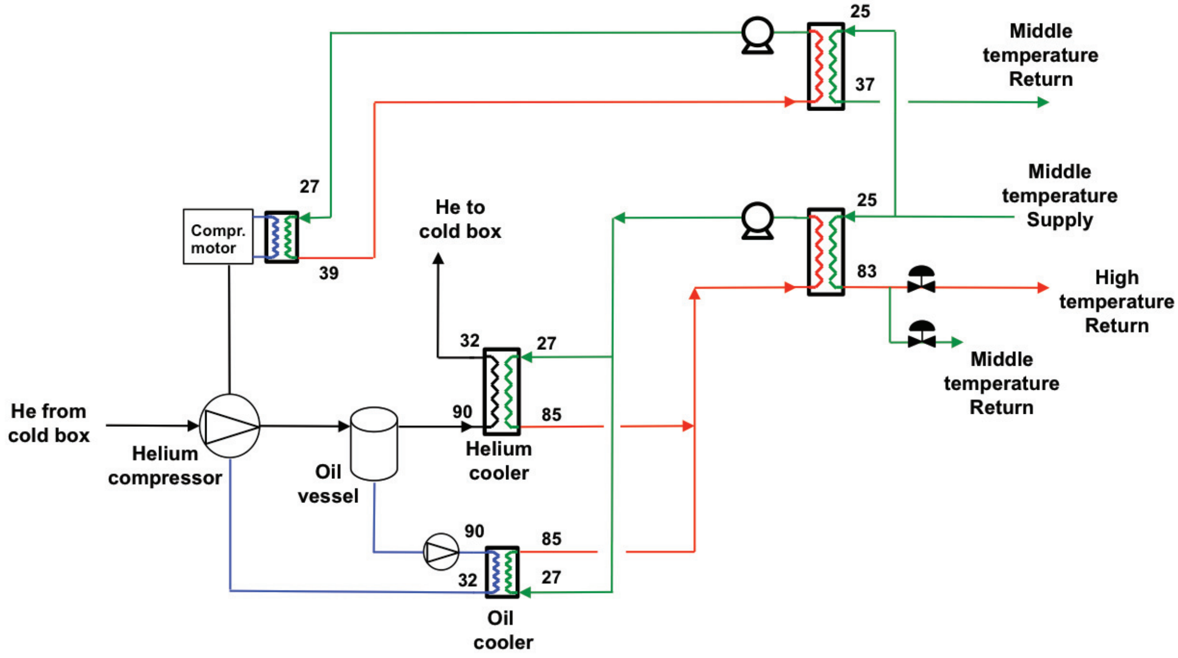

Fig. 3. Energy recovery from ACCP compressors (all temperatures in degrees C).

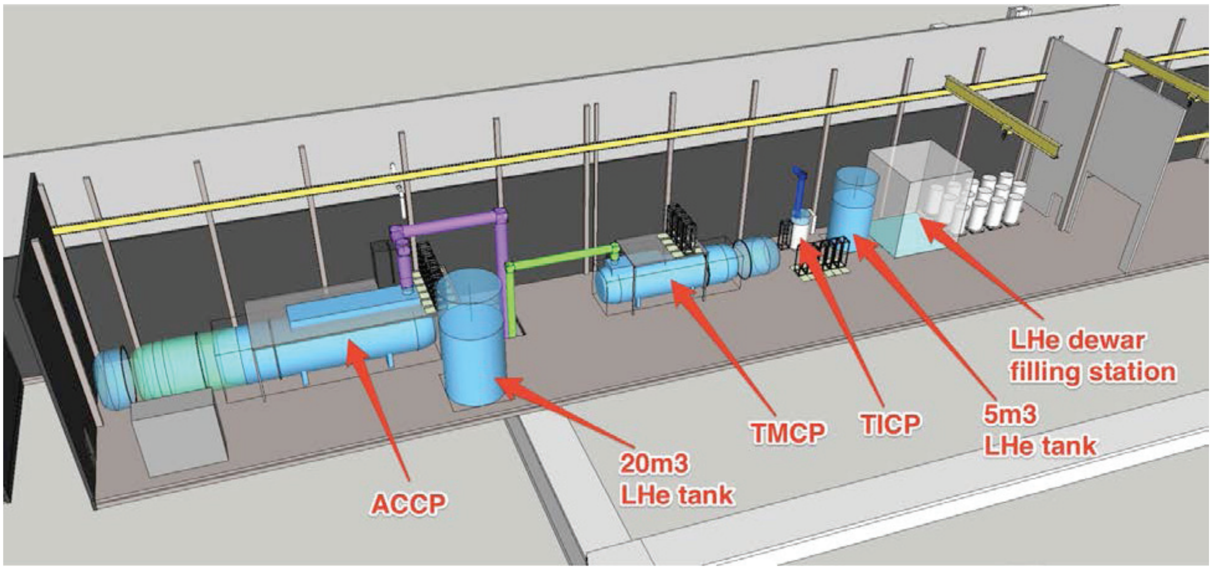

Fig. 4. Conceptual layout of equipment in ESS cold box room.

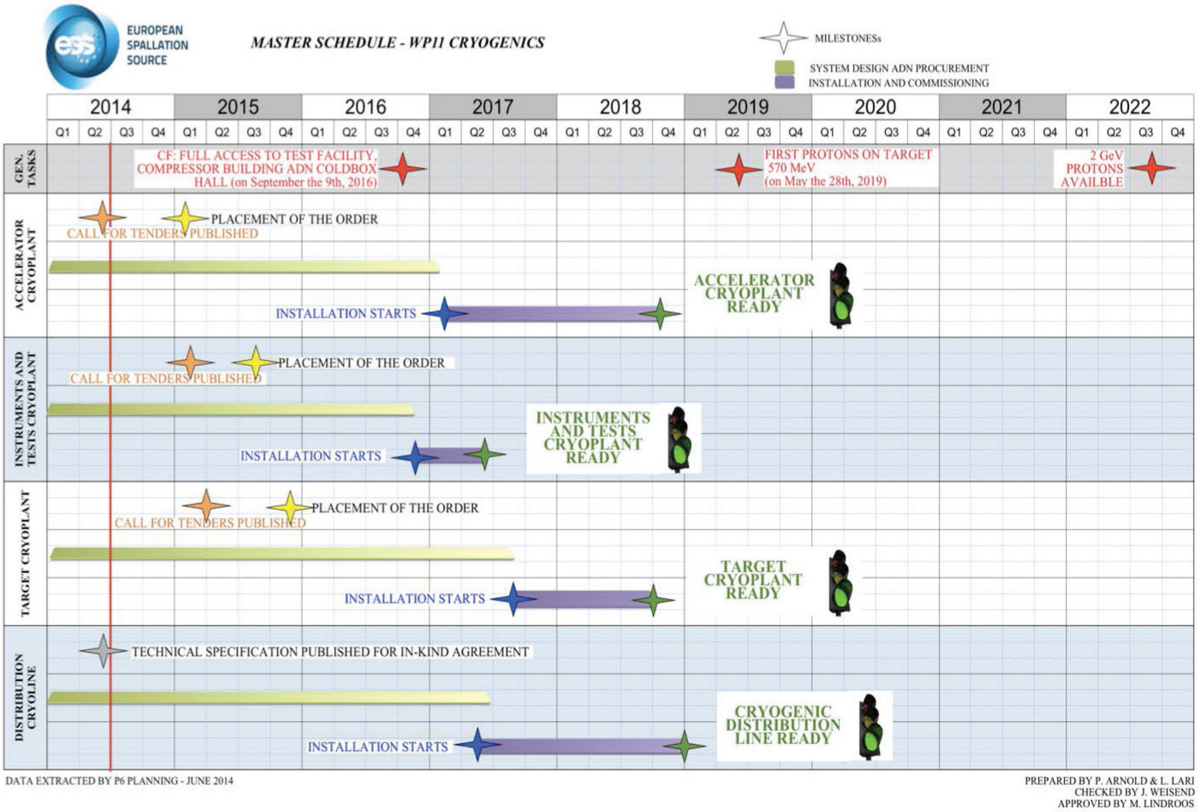

Fig. 5. ESS cryogenic system schedule.

References

Darve C., Elias N., Molloy S., Bosland P., Oliver G., Renard B., Duthil P., Bousson S., Reynet D., Thermeau J.P., The ESS superconducting RF cavity and cryomodule processes, 2014 ICEC, Enschede, the Netherlands, July 7-11 2014.

Fydrych J., Arnold P., Hees W., Tereszkowski P., Wand X.L., Weisend II J.G., Cryogenic distribution system for the ESS superconducting proton linac, ICEC25, Enschede, the Netherlands, July 7-11 2014.

Gallimore S., Nilsson P., Sabbagh P., Takibayev A., Weisend II J.G., Beßler Y., Klaus M., Challenges and design solutions of the liquid hydrogen circuit at the European Spallation Source, *Adv. Cryo. Engr.* Vol. 59, 659 (2014).

Hees W., Wang X.L., Fydrych J., Arnold P., Weisend II J.G., Spoelstra H., The ESS cryomodule test stand, 2014 ICEC, Enschede, the Netherlands, July 7-11 2014.

Jurns J.M., Arnold P., Weisend II J.G., Linander R., Cryogenic cooling of the cold neutron source at ESS, 2014 ICEC, Enschede, the Netherlands, July 7-11 2014.

Jurns J.M., Baeck H., Gierow M., Waste heat recovery from the European Spallation Source cryogenic helium plants – implications for system design. *Adv. Cryo. Engr.* Vol 59, 647 (2014).

Klaus M., Haberstroh C., Quack H., Beßler Y., Butzek M., Conceptual design of liquid hydrogen moderator cooling circuit for the European Spallation Source, 2014 ICEC, Enschede, the Netherlands, July 7-11 2014.

Peggs S. ESS technical design report. http://europeanspallationsource.se/documentation.tdr.pdf, ISBN 978-91-980173-2-8, April 23, 2013, European Spallation Source ESS AB, Lund, Sweden.

Ruber R., et al. The new FREIA laboratory for accelerator development, Proc. IPAC 2014, Dresden (2014).

Wang, X.L., Arnold, P., Fydrych J., Hees E., Jurns J.M., Piso D., Weisend II J.G., Specification of the ESS accelerator cryoplant, 2014 ICEC, Enschede, the Netherlands, July 7-11 2014.