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Specification of the ESS accelerator cryoplant

Xilong Wang*, Philipp Arnold, Jaroslaw Fydrych, Wolfgang Hees, John M. Jurns, Daniel Piso, John Weisend II

European Spallation Source ESS AB, P.O Box 176, Lund and SE-22100, Sweden

Abstract

The European Spallation Source (ESS) is a neutron-scattering facility being built with extensive international collaboration at Lund, Sweden. The ESS accelerator will deliver protons with 5 MW of power to the target at 2.0 GeV, with a nominal current of 62.5 mA. The superconducting part of the accelerator is about 300 meters long and contains 43 cryomodules. The ESS accelerator cryoplant will provide the cooling for the cryomodules and the cryogenic distribution system interconnecting cryoplant and cryomodules. The cryoplant will cover three cryogenic circuits: bath cooling for the cavities at 2 K, the thermal shields at around 40-50 K and 4.5 K forced helium cooling for the power couplers. This paper describes project stages, the cryogenic architecture and the design basis including cooling capacity, operation modes and interfaces. The important design choices comprising no liquid nitrogen pre-cooling, one integrated cold box, waste heat recovery and process control system strategy as well as the principles of evaluation are presented. All the topics above are implemented and addressed in the technical specification, which has been finished and issued in June 2014. That is a very important step in the development of the ESS cryogenics system.

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1. Introduction

The European Spallation Source (ESS) is a multi-disciplinary research center based on the world's most powerful neutron source, currently under construction at Lund, Sweden (Peggs [1]). The ESS accelerator will deliver protons

* *Corresponding author. Tel.:* +46-72-179-2123.
E-mail address: xilong.wang@ess.se

with 5 MW of power to the target at 2.0 GeV with a nominal current of 62.5 mA. The ESS accelerator cryoplant (ACCP) will serve the superconducting section of the accelerator, which consists of 43 cryomodules (CMs) (Darve et al. [2]) and cryogenic distribution system (Fydrych et al. [3]) with a length of about 300 m at current optimum design scenario.

There is a possibility to install 14 additional CMs in the future as design contingency. The ACCP will provide the cooling capacities at three temperature levels: 2 K bath cooling for cavities, 4.5 K forced helium flow for the power couplers and 40-50 K helium flow for thermal shield (TS).

The initial concepts of the ACCP were developed and described in earlier papers: Wang et al. [4], Weisend et al. [5] and Wang et al. [6]. Since then much practical R&D work, especially two industry studies, has been performed and the engineering design has progressed considerably.

The design basis and important design choices are well known and the ACCP performances and technical requirements are well defined. All of them are implemented and addressed in the technical specification and tender documents, which have been issued in June 2014.

2. Project stages

From the cooling capacity supply point of view, the ESS project will be divided into two stages.

Stage 1 between 2019 and 2023: with reference to the current optimum design, the superconducting section of the accelerator consists of 13 Spoke CMs with two cavities in each, 9 medium beta and 21 high beta elliptical CMs with four cavities in each.

There are 146 SRF cavities and 43 CMs in total and the length of the cold accelerator is about 300 meters. Commissioning of the ESS accelerator will start in 2019 and proceed until it reaches the full beam power of 5 MW at 2.0 GeV with a nominal current of 62.5 mA in 2023. In this period, different groups of CMs, i.e. spoke CMs, spoke CMs + medium beta CMs and spoke CMs + medium beta CMs + high beta CMs, will be installed in the tunnel and will, one after another, require cryogenic cooling.

Stage 2 from 2023 onward: in the case of lower than anticipated performance of the cavities, additional 14 high beta CMs are considered as design contingency and can be installed in the tunnel from 2023 onwards in order to reach the ESS nominal design values. In this case, the relevant static and dynamic heat loads of the superconducting accelerator will increase. As a result, the cryogenic requirements under the current optimum design plus contingency will represent the maximum heat loads for the ACCP.

Accordingly, the ACCP will be designed and manufactured to ultimately fulfill the requirements at Stage 2. However, in order to optimize the plant operation and efficiency in the first years of operation, the respective Stage 1 configuration will be fulfilled as well.

The staging requires the followings:

- The warm compression from sub-atmospheric (SP) to low pressure (LP) or medium pressure (MP) is equipped with variable frequency drive (VFD) so that at least 25% of the stage 2 SP flow can be regulated;
- The warm compression from LP to MP is equipped with VFD so that at least 25% of the Stage 2 LP flow can be regulated continuously;
- All the cold compressor drives are equipped with VFD;
- Each cold compressor has a spare cartridge comprising flow parts optimized for Stage 1 operation that can easily be adapted with flow parts optimized for Stage 2 operation;
- As many expansion turbine spare cartridges as deemed optimal by the contractor in view of capital and operational cost are equipped with flow parts optimized for Stage 1 operation easily to be adapted with flow parts optimized for Stage 2 operation;
- The initial installation, commissioning and acceptance testing will be performed with all equipment optimized for Stage 2 operation;
- After successful acceptance testing the equipment will be exchanged for equipment optimized for Stage 1 operation, which will then be commissioned and acceptance tested;
- The cartridges with flow parts optimized for Stage 2 operations will be adapted with spare parts for Stage 1 operation and the Stage 2 flow parts to be stored for later use.

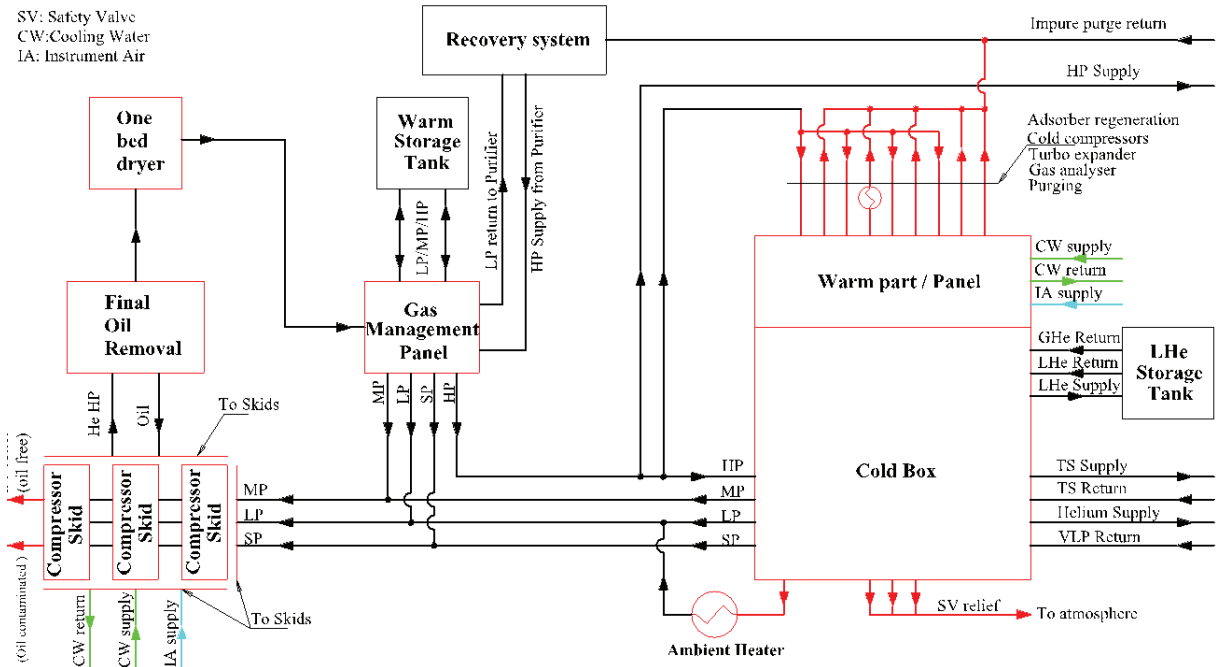


Fig. 1. Simplified block diagram of the ACCP.

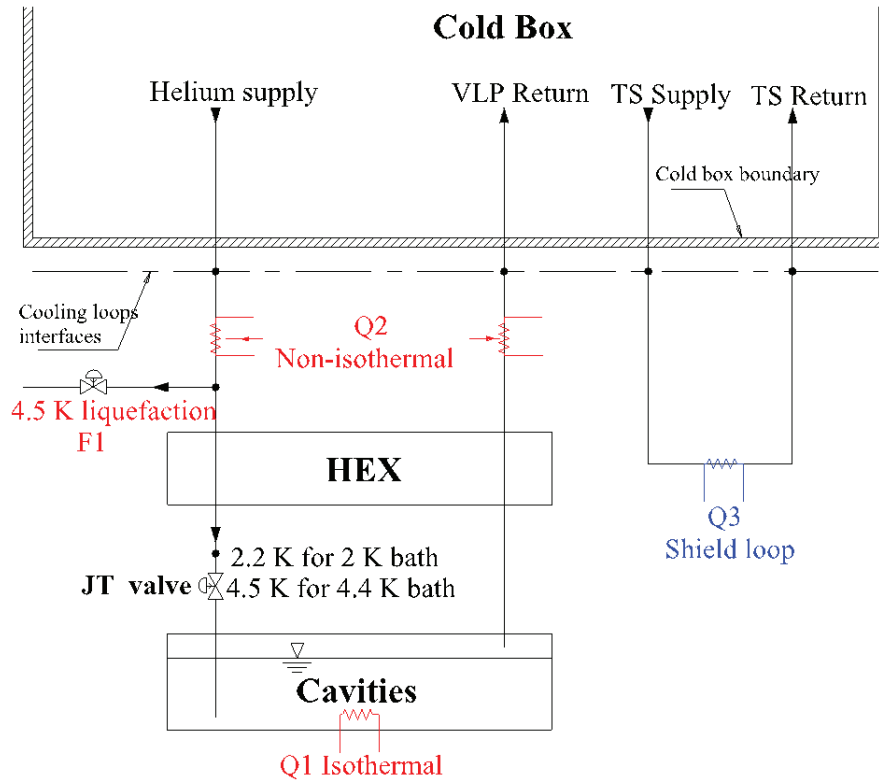


Fig. 2. ACCP cooling loop interfaces.

3. Cryogenic architecture

A simplified block diagram of the ACCP is shown in Fig. 1. The ACCP consists of the main components:

- The warm compressor station (WCS) circulating helium at the flows and pressures required to achieve the performance of the ACCP. All warm compressors with a suction pressure above the atmospheric pressure will be oil-lubricated screw compressors and designed for a pressure from 0 bar (vacuum) to 25 bar abs. The warm compressor station includes three compression stages compressing helium from SP to LP or MP depending on the actual process design, from the LP to MP and from the MP to high pressure (HP). The ACCP vendor can define the number of compressors in each stage. The compressor station is assembled on skids with the grouping defined by the vendor. For the screw compressors/process vacuum pump system (if applicable), a technology referenced with good experience and successful operation for helium service under similar sub-atmospheric conditions is mandatory. The type, choice and arrangements are based on a technically safe and cost-effective operation;
- Final oil removal system (FOR) consisting of a set of coalescing filters for the continuous separation of oil mist from the helium and a charcoal adsorber to adsorb oil aerosols;
- A one-bed dryer downstream of the FOR in order to adsorb the water vapour molecules under the full flow conditions;
- Gas management panel (GMP) including valves and pipe terminals for the process control;
- One cold box with all equipment to achieve the required performance, mainly consisting of heat exchangers, expansion turbines, cold compressor system, adsorbers, phase separator and sub-cooler, instrumentation, valves and piping work, corresponding electrical cabinets, a working platform, etc.;
- One ambient heater for the cool-down/warm-up of the ACCP alone or the ACCP with the whole accelerator.

All other equipment, not mentioned above, will be separately ordered, not being in the baseline scope of the ACCP tender. This includes warm helium storage tanks, LHe storage tank, recovery system and the warm interconnecting pipes between warm compressor hall and the cold box building.

4. Cooling loop interfaces

Fig. 2 shows the conceptual cooling loops for the ESS accelerator interfacing with the cold box of the ACCP. The 2 K heat loads consists of the isothermal load (Q1), which is applied to the liquid helium bath enfolding the cavities and the non-isothermal load (Q2) affecting the 2 K vapour return. The temperatures of 2.2 K downstream the heat exchanger (HEX) and upstream the Joule-Thomson valve supplying the 2 K bath is used to determine the mass flow rate. F1 represents the 4.5 K liquefaction rate required for the coupler cooling and Q3 is the thermal shield heat load. It should be noted that the vendor would take responsibility for the inlet temperature (see Table 1) regulation of the cold compressor system through a by-pass connection in the cold box.

5. Cooling requirements and steady state operation modes

The thermal performance of the ACCP clients, including CMs and cryogenic distribution system, are the key element to determine the heat load budget, the required capacity and the cost, as well as to guarantee the ACCP efficient operation. Detailed studies and analyses have been performed to estimate the heat load imposed on the CMs, cryogenic distribution system and that due to beam losses and have been addressed in several internal technical notes by Duthil [7], Olivier [8], Molloy et al. [9], Jarosz [10] and Fydrych [11]. The updated heat loads including operational and uncertainty margins (Weisend et al. [5]) and the operation parameters are listed in Table 1, where the bold values listed is strictly guaranteed and the italic values may be taken into account as reference for the process design.

The main steady state operation modes include the nominal design comprising both beam and RF operational and the nominal turndown with both beam and RF non operational. The former mode features the highest cooling capacity needed in both stages. In the latter, the total heat deposited into the 2 K circuit comprises only the static load; The 2 K refrigeration cycle will be able to efficiently handle the dynamic heat load range. Two standby

operation modes include 4.5 K standby for several-days interruptions of the RF power and beam and thermal shield (TS) standby for the scheduled machine maintenance lasting 90 days per year (approximate 60 days in summer and 30 days in winter). In addition, the maximum 4.5 K liquefaction capacity of the designed system, which is required for cool-down and CM re-filling operation, is determined by the vendor in the design phase and shall be demonstrated during the final acceptance test. The installed cooling capacities of the ACCP are about 3 kW at 2 K, 9 g/s liquefaction rate at 4.5 K & 3 bar and 11 kW at 40-50 K.

Table 1. Heat loads and operation parameters for main steady state operation modes.

Operation modes	Level	Heat load, W	Mass flow, g/s		Pressure, bar		Temperature, K		
			Supply	Return	Supply	Return	Supply	Return	
Stage 1 (2019- 2023)	Nominal design	2 K	2478	99.3	92.5	≥ 3	≤ 0.027	4.5	4.5
		4.5 K Liqu.	-		6.8	≥ 3	1.05	4.5	300
		TS	8551	79.3	79.3	15-19.5	Ps- ΔP^*	$\geq 33^*$	$\leq 53^*$
	Nominal turndown	2 K	1472	49.0	42.2	≥ 3	≤ 0.027	4.5	6.1
		4.5 K Liqu.	-		6.8	≥ 3	1.05	4.5	300
		TS	8551	79.3	79.3	≥ 11.5	Ps- ΔP^*	$\geq 33^*$	$\leq 53^*$
Stage 2 (2023-)	Nominal design	2 K	3050	120.2	111.2	≥ 3	≤ 0.027	4.5	4.6
		4.5 K Liqu.	-		9.0	≥ 3	1.05	4.5	300
		TS	11380	105.5	105.5	15-19.5	Ps- ΔP^*	$\geq 33^*$	$\leq 53^*$
	Nominal turndown	2 K	1990	67.3	58.3	≥ 3	≤ 0.027	4.5	5.9
		4.5 K Liqu.	-		9.0	≥ 3	1.05	4.5	300
		TS	11380	105.5	105.5	≥ 11.5	Ps- ΔP^*	$\geq 33^*$	$\leq 53^*$

* The thermal shield flow and temperatures within the limits is mandatory and the average shield temperature shall be ≤ 43 K. Referred to the maximum supply pressure of 19.5 bar ($P_s=19.5$ bar), the acceptable pressure drop of the thermal shield is less than 0.5 bar. For any other supply pressure, this pressure drop shall be approached via the scale of the corresponding pressure and temperatures.

6. Important design choices

Design choices to address important issues have been well studied and fixed. The key items are listed below:

- No liquid nitrogen (LN_2) pre-cooling: The ACCP shall be designed for the refrigeration performance without using LN_2 precooling. One basic advantage of the refrigeration system with LN_2 pre-cooling is to boost the cool-down process in term of the massive cold masses, i.e. in a magnitude of thousand tons at LHC, CERN. The ESS accelerator has a total cold mass of around 20 tons, which could be cooled down within a reasonable time. The other fact is that LN_2 is used to boost and increase LHe production capacity in 4.5 K liquefaction systems. It is noted from Table 1 that the 2 K circuit dominates the ACCP heat loads. The industry studies results confirm that in a large 2 K helium refrigeration system the boosting effect of LN_2 is not as big as in a 4.5 K liquefier and the efficiency saving is relatively small. Other positive effects, such as increased reliability due to less utility interfaces, operating cost saving due to the Swedish electricity cost, traffic reduction and environment protection, are all pointing towards a process without LN_2 pre-cooling;
- One integrated cold box: All ACCP cold components including expansion turbines, cold compressor system, heat exchangers etc. shall be integrated into one unique cold box. This solution brings advantages such as space saving, and low investment cost;
- Waste heat recovery: ESS has committed to an energy management strategy to recover a maximum of waste heat at the highest temperatures possible and to minimize the cooling water flow (Jurns et al. [12]). The recovery energy will be recycled from ESS to the city of Lund district heating system and other possible users. To accomplish this in the ACCP, for the oil and helium coolers in the warm compressor system, the warm end

temperature difference between oil/helium inlet and cooling water outlet shall be controlled to less than 10 K in normal operations;

- Process control system strategy: the ACCP control system will be based on Experimental Physics and Industrial Control System (EPICS) in order to provide monitoring and operational capabilities. Configuration tools and operator applications shall be implemented as plugins of the Control System Studio (CSS) framework following the ESS standards. The vendor shall provide the ACCP control system including hardware and software from PLCs to Human Machine Interface (HMI) level.

7. Principles of evaluation

The contract award shall be decided on the most economically advantageous tender presented. ESS will evaluate the bids based on three criteria: capital cost for the entire scope of supply (CAPEX), operation cost for the offered ACCP, taking into account the electrical power consumptions for the warm compressor system in specified operation scenarios (OPEX), and qualitative aspects such as completeness of proposal, simplicity and feasibility, availability, recovery time from a trip of rotating machinery, liquefaction capacity, etc. Within the maximum score of 100, an amount of 30 for CAPEX, 30 for OPEX and 40 for qualitative aspects will be counted.

8. Conclusion

The technical specification and other tender documents for the ESS accelerator cryogenic plant have been issued in June 2014. The contract award is expected to take place in the beginning of 2015. Potential vendors are motivated and engaged to give solutions and proposals in terms of efficient and reliable equipment.

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