Conceptual design of DALS test facility cryogenic system

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Abstract. Dalian advanced light source (DALS) is a new project proposed by Dalian Institute of Chemical Physics (DICP) aiming to produce high-quality electron beam with repetition rate up to 100 kHz and the project is subject to central government approval. The cryomodules and superconducting cavities need to be tested before assembled in the real accelerator so the test facility is necessary. The Accelerator module test facility (AMTF) project has been funded by Dalian local government and is currently under construction as the pre-research project for DALS, it consists of four testbenches, one Horizontal testbench (HTB) for cryomodule test, one Vertical testbench (VTB) for cavity test, one Cryogenic testbench (CTB) for cryogenic test and one Injector testbench (ITB) for beam test. A Test facility cryoplant (TFCP) with capacity of 370 W@2 K will be used for cooling testbenches. This paper presents the design and current progress of the TFCP system, which includes the refrigerators, helium compressors, process vacuum pump system (PVPS), gas storage system, recovery and purification system.

Keywords: Light source, test facility, cryogenic system, helium refrigerator

1. Introduction

Light sources are playing an increasingly important role in frontier science and have wide applications in physics, chemistry, biology and basic energy sciences. DICP already has an ambient temperature Free electron laser (FEL) user facility called Dalian Coherent Light Source (DCLS), as the first user facility in China and has been officially opened to users since July 2017[1]. In order to obtain higher repetition rate and energy DICP has proposed a new project called Dalian Advanced Light Source (DALS) and is still subject to central government approval, it is a high repetition rate EUV FEL based on CW SRF accelerator technology. As the pre-research project of DALS, Accelerator Module Test Facility (AMTF) has been funded by Dalian local government since 2018, a dedicated cryoplant, called Test Facility Cryoplant (TFCP) will provide cooling for the AMTF.

This paper presents the current status of the TFCP system, review the heat load, cryogenic requirements, process design and main components, in the end, preliminary layout is detailed.

2. Cryogenic system status

After a year of technical and commercial communication, the contract between DICP and Linde for the purchase of TFCP refrigerator was signed in October 2020. The Basic design review of the refrigerator was completed in May 2021, now the project is in its detailed design phase. The fabrication will be completed in June 2022, the final acceptance is planned in April 2023 considering 6 months for installation and commissioning on site.
For the status of other components, the tender for the process vacuum pump system has been completed in June 2021. The design of cryogenic distribution system has been completed, the next plan is to conduct the tender for the valves and instrumentations.

3. Cryogenic system architecture
The system architecture is presented in the TFCP block diagram of the Figure 1. 2 K helium gas from four testbenches is heated to 300 K by an electrical heater and then enters the Process vacuum pump system (PVPS) where it is compressed from Very low pressure (VLP) to atmospheric pressure (LP), then compressed to high pressure (HP) by the compressor system. The helium storage system is connected with compressor system for HP helium supply, and the helium purification system connected with it for helium recovery and purification. In the cold box, the HP helium from compressors is pre-cooled by the Liquid Nitrogen (LN2) system, and through a modified Brayton cycle 4.5 K liquid helium is supplied from the cold box to Test facility distribution box (TFDB) for distribution to different testbenches and Liquid helium Dewar for storage.

![TFCP block diagram](image)

**Figure 1.** TFCP block diagram

4. Heat load analysis
In order to assess the required cooling capacity of a large helium cryogenic system, it is necessary to know the heat load of the entire system. The module structure of the DALS project is mainly based on the LCLS II module design, which can be internally divided into 300 K, 40-50 K, 5-8 K, and 2 K by temperature zones. 300 K is the outermost module shell temperature, 40-50 K is the thermal radiation shield temperature used to shield the thermal radiation from the shell, 4.5-8 K is the thermal intercept temperature used to intercept the heat conduction from 40-50 K and provide heat sink for various components.

There are two types of thermal load in cryomodule, dynamic thermal loads and static thermal loads. The static heat load comes from the transfer lines, distribution box, feedcap, endcap and cryomodule itself. The static heat loads of the distribution box and transfer lines are calculated with reference to the empirical engineering values, and the static heat loads of the cryomodule are mainly refers to some literature measurement results [2,3]. The dynamic heat loads are derived from the heat load generated by the RF power applied to the superconducting cavities, including: RF heat load, Coupler heat load, HOM coupler heat load, HOM and wakefield heat load and current lead heat load. This part of the heat load is calculated with reference to some literatures [3-6]. In order to weaken the various uncertainties that may exist in the process of heat load estimation, the safety factor is generally used to enlarge the predicted heat load value of the module and distribution system. Here we take safety factor of 1.5 for all static heat load and for dynamic heat in 40-50 K, 5-8 K temperature zone safety factor of 1.5 is also taken. But for 2 K dynamic heat load no safety factor is used because a conservative cavity performance
Q0 of $1.5 \times 10^{10}$ is chosen for calculation of RF heat load. Here the assumption is mainly based on the test results of LCLS-II [7,8].

Table 1. Calculated 1.3 GHz cryomodule heat load breakdown

| Temperature level | 1.3 GHz Cryomodule Heat Load (W) |
|-------------------|----------------------------------|
|                   | 40 K | 5 K | 2 K |
| CM Static heat load | 123 | 17 | 7.2 |
| RF                | -    | -   | 145 |
| Coupler           | 112  | 11.2 | 1.6 |
| CM Dynamic heat load | HOM coupler cables | 1 | 0.4 | 0.17 |
|                   | Wakefield heating | 0 | 0 | 0 |
|                   | Current leads | 5.35 | 2.73 | 0.37 |
| Per CM            | 242  | 31  | 155 |

The total heat load of the cryomodule is shown in Table 1, and the overall heat load is shown in Table 2. According to the heat load estimate and considering some margin the requirements for helium refrigerator is listed in Table 3. We also need the refrigerator with fast cooldown mode to obtain a higher quality factor for superconducting cavities.

Table 2. Overall heat load budget

| Section | No. | Heat load budget of TFCP (W) | | |
|---------|-----|-----------------------------|---|---|
|         |     | Static                      | 40 K | 5 K | 2 K |
| HTB     | 1   |                            | 123  | 17  | 7.2 |
|         |     | Dynamic                     | 117  | 14  | 145 |
| ITB     | 1   | Static                      | 123  | 17  | 7.2 |
|         |     | Dynamic                     | 132  | 16  | 155 |
| VTB     | 1   | Static                      | 50   | 0   | 10  |
|         |     | Dynamic                     | 0    | 0   | 30  |
| CDS     |     | Static                      | 892  | 154 | 15  |
| CM+CDS  | Without safety factor | Static | 1188 | 188 | 24 |
|         |     | Dynamic                     | 249  | 30  | 330 |
| CM+CDS  | With safety factor | Static | 1782 | 282 | 40 |
|         |     | Dynamic                     | 374  | 45  | 330 |
| Installed Total | | | 2156 | 327 | 370 |
| Refrigerator Capability | | | 2500 | 400 | 370 |

Table 3. TFCP heat load and mass flow requirements

| Loops | Heat load (W) | Mass flow (g/s) | Pressure (bar) | Temperature (K) |
|-------|---------------|-----------------|----------------|-----------------|
|       | Supply Return | Supply Return   | Supply Return  | Supply Return   |
| 2 K   | 370 29 19     | >=3 and <=3.5   | <=4.6          | 300             |
| 4.5-8 K | 400 10       | >=3 and <=1.3   | <=4.6          | <=8             |
| 40-50 K | 2500 42 42    | 13.4 12.9       | 40 80          |

5. Helium Refrigerator
In response to our requirements, Linde provided us the standard model LR700-3T. In refrigeration mode, there is an expected cooling capacity of 370 W at 2 K, 420 W at 5 K and 2600 W at 40 K, the corresponding 2 K mass flow is 19.9 g/s. In fast cooldown mode, the 2 K mass flow is 57.7 g/s. In liquefaction mode, it has a liquefaction rate of 30.4 g/s with LN2 precooling, and 12.8 g/s without LN2 precooling.
The process of the refrigerator is presented in the process flow diagram of the Figure 2. The helium gas compressed from compressors at ambient temperature enters the cold box through high pressure (HP) line and cooled in the first heat exchanger by LN2 precooling. After the first heat exchanger there are two switchable full-flow 80 K adsorber for protecting the plant from contamination even if one adsorber needed to be regenerated. The helium stream after the adsorber is cooled further in the second heat exchanger and then separated into the turbine and J-T stream. A large fraction of helium gas flow into the turbine string and expanded to low pressure (LP), joining the return stream to precool the J-T stream. A port at 13 bar and 40 K is set after the second heat exchanger for the gas to be used for shield cooling, the return of this shield is directed to the inlet of the first turbine. The remaining portion of the helium gas is further cooled in heat exchangers by low pressure return flow and passes a 20 K adsorber that removes neon and hydrogen. Downstream the 20 K adsorber the helium gas is cooled further in a heat exchanger and expanded in a J-T turbine to supercritical pressure. Part of the stream is expanded in a J-T valve and liquefied into a sub-cooler, this works in combination with a heat exchanger, cooling the J-T stream and delivering it to the cryomodules. Part of the delivered stream returns at a temperature of 8 K and low pressure after cooling the thermal shield. The rest enters the J-T heat exchanger and expanded in the J-T valve for 2 K cooling of the cavities. The 2 K gas is then returned to compressors at ambient temperature and a pressure of 1.05 bar.

Figure 2. General process diagram of cold box

In the case of reduced thermal load, the helium stream can be liquefied into the 5000 L Dewar. In Fast cool down (FCD) mode, the liquid in the sub-cooler is supplied directly from the 5000 L Dewar and the mass flow from the J-T turbine is lead to the sub-cooler, the expected 4.5 K supply mass flow is about 57 g/s.

For FCD mode, cooldown and warmup mode, there is an additional CD/WU return line within the cold box, depending on the return temperature, this line redirects the return flow to the corresponding heat exchanger at 10 K, 15 K, 80 K and 300 K.

6. Helium compressor system
The compressor system is also part of Linde’s scope, it consists of helium recycle compressors and the oil removal system (ORS)/gas management panel (GMP).

The helium recycle compressors are standard Kaeser compressors, multiple compressors can be operated in parallel to generate the required mass flow rate. The suction pressure is controlled slightly above atmospheric pressure to avoid contamination of air, a nominal discharge pressure of 14.5 bar is selected. Here one FSD575 with variable frequency drive (VFD) and two ESD375 are selected. The
FSD575 with VFD can continuously regulate the mass flow from 35 g/s to 101.7 g/s. The nominal mass flow of ESD375 is 62.15 g/s, it can be switched on or off to add or subtract each 62.15 g/s when the cold box is not running, so the regulation of the mass flow from 35 g/s to 226 g/s can be handled. For the FSD575 compressor and ESD375 compressor the motor rated power are 315 kW and 200 kW respectively.

The process of the compressor system is shown in Figure 3. The oil and helium have to be separated completely after the compressors. In the first step, the oil is removed from the helium at the first coalescer located in the bulk oil separator of the compressor. Then the helium enters the second and third coalescer vessel located on the separate ORS/GMP skid, the oil content after the second coalescer is lower to 0.5 ppm. The final removal of oil takes place in the oil adsorber, the remaining liquid impurities from the helium are removed to a final concentration of less than 10 ppb by weight. Considering that the testbenches will frequently disconnect from distribution box for testing, which may introduce the water, a full-flow dryer is added after the oil adsorber to prevent the water from entering the system.

![Figure 3. General process diagram of compressor system](image)

7. **Process vacuum pump system**

We have accomplished the tender for the PVPS system, Leybold won the bidding and this system is based on Leybold oil-sealed pumps, which the similar models are already used and proven in a lot of projects such as IHEP, CERN [9,10]. The process vacuum pump system is located downstream of the compressor system, it consists of 3 groups of independent units, each independent unit contains 4 unit of modules, each module contains 1 WS2001FU roots pump and 1 SV750BF mechanical vacuum pump. The PVPS system has the capability of compressing 19.6 g/s helium to 1.05-1.2 bar with the suction pressure of 21-30 mbar.

The structure of the PVPS system can be seen in Figure 4, three testbenches are connected to 3 independent units to ensure the flexibility of complex test conditions, so that each testbench can be tested independently without being affected by the cooldown or warmup process of other testbenches. Each unit has a variable range flowmeter for monitoring the outlet mass flow which could be used for module static or dynamic heat load test.
8. Warm helium storage and recovery & purification system

8.1. Warm helium storage system
The total helium inventory in cryogenic system during normal operation is calculated considering 50% helium loss per year, the total helium storage (4.2 K) is 5347 L, and 8021 L including the helium loss. Considering some unforeseen circumstances such as power outage or refrigerator shutdown and the need to balance helium shortages in the market, the total storage capacity of 10000 L is chosen, which is equivalent to 6 pure helium storage tanks (100 m$^3$ at 14 bar).

8.2. Recovery & Purification system
The helium purification has to be considered if a system needs to operate with a long time period and a high availability. The recovery and purification system mainly consists of a gasbag, recovery compressor, impure helium cylinders, and purifier. The gasbag is designed for a size of 130 m$^3$, the impure helium from the system can be transferred to the gasbag for temporary storage, and the recovery compressors is turned on when the gasbag reaches a certain level and the impure helium will be compressed into the high-pressure impure helium cylinders. The inlet pressure of the recovery compressor is 1-1.2 bar, and the outlet pressure is 200 bar which is the storage pressure of impure helium cylinders. The volume of impure helium cylinders is chosen here as 5700 L so that all helium in the system can be stored if the whole system is contaminated. The purifier is designed with two towers with a combined maximum mass flow rate of 220 Nm$^3$/h, the purifier can operate continuously for 8 hours and purify 1760 Nm$^3$ of helium. Assuming the cryogenic system is fully contaminated, as mentioned before, total helium volume in the cryogenic system is 5347 L which is about 4000 Nm$^3$ helium, the time to purify all contaminated helium is less than 3 days.

9. Preliminary layout and arrangement
The 3D layout of the project is shown in Figure 5, there are three buildings: Cryogenic hall, Module testbench hall and Injector testbench hall. The cryogenic systems are mainly placed in cryogenic hall and module testbench hall. The compressors and cold box are separated in two buildings, which can reduce the impact of compressor vibration on the cryomodule, shorten the length of cryogenic transfer line, and improve the efficiency.
The cryogenic hall has a total length of 50 m and a width of 19 m, covering an area of 950 m², including equipment area, assembly area and work area. The detailed layout can be seen in Figure 6. Equipment area is the main area of the cryogenic hall and used for the installation and operation of cryogenic equipment, including compressors, oil removal system and PVPS system. The assembly area is for loading, unloading and transportation when the equipment arrives. The work area is used for a variety of operational needs during the construction and maintenance of the hall. The whole cryogenic hall is equipped with cranes, with a minimum distance of 7 m from the ground under the crane hook. It is used to place compressor system, PVPS system and recovery & purification system. A storage area of approximately 50 m long and 10 m wide is reserved outside the cryogenic hall.
The layout of the module testbench hall can be seen in Figure 7, it is also a single-story building with a total area of 3682 m² and a height of 9 m under the crane hook. The function areas such as vertical testbench, horizontal testbench, module assembly area, cavity assembly area and assembly clean room are positioned in this hall. The internal space is 105 meters long and 30 meters wide, a traveling crane with a load of 20 tons is covered the whole building. The hall has a roll-up door of 5 meters in height and width for entry and exit of equipment.

10. Conclusion
The cryogenic system of the DALS test facility project has a cooling capacity of 370 W at 2 K to provide cooling for all test benches. The refrigerator cold box is the Linde standard model LR700-3T with liquid nitrogen pre-cooling and three turbines. Three Kaeser standard screw compressors are used with a discharge pressure of 14.5 bar. The contract between DICP and Linde Kryotechnik AG was signed and the detailed design phase is ongoing. The project is progressing well and the refrigerator is expected to be delivered to the site in July 2022. The PVPS system is capable of compressing 19.6 g/s helium from suction pressure of 21-30 mbar to discharge of 1.05-1.2 bar and the bidding was completed. Six 100 m³ warm helium storage tanks of 14 bar are chosen, the purification system has a maximum processing flow rate of 220 Nm³/h. There will be a lot going on in this project in the next two years and the whole cryogenic system is expected to be ready in August 2023.

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