Conceptual design of S$^3$FEL cryogenic system

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Abstract. A new project called Shenzhen SRF Soft Free Electron Laser (S$^3$FEL) is under proposal phase at Institute of Advanced Science Facilities, Shenzhen (IASF), in China. The purpose is to produce high intensity coherent X-ray with laser properties. The S$^3$FEL accelerator is based on the TESLA technologies and will deliver electrons with the energies of up to 2.5GeV. The electrons will be accelerated by 1.3 GHz superconducting cavities cooled down to the 2 K level. The 2 K cryostat will be protected against heat radiation and conduction by means of one thermal shields at 40–80 K level and one thermal intercept at 4.5–8 K level.

The S$^3$FEL accelerator consists of twenty-six 1.3 GHz and two 3.9 GHz cryomodules, both operated in CW modes. Four independent cryoplants will be used for the S$^3$FEL project. A 500 W@2 K helium refrigerator will be used for the test facility including two vertical test benches (VTB) for cavities, one magnet test bench for the superconducting magnet (MTB) and three horizontal test benches (HTBs) for cryomodules. A 1 kW@2 K helium refrigerator will be used for the prototype machine for R&D purpose of the superconducting accelerator. Two cryogenic plants with 4 kW@2 K refrigeration capacity will be used for supporting the S$^3$FEL accelerator cryogenic cooling requirement. Ideally, one should have enough capacity to supply the cooling for the whole LINAC and the other is acting as a complete set of back up to keep the high availability. In addition, the second plant could compensate the cavity performance degradation due to the long term running or the unexpected cavity performance during the manufacture process. This paper describes the conceptual design of the S$^3$FEL cryogenic system. The performance of the cryogenic system and the project schedule are also described.

1. Introduction

Shenzhen Superconducting Soft x-ray Free Electron Laser (S$^3$FEL) is a 2.5 GeV continuous-wave (CW) superconducting electron linear accelerator, is to be constructed in the Institute of Advanced Science Facilities, Shenzhen (IASF), in China. The S$^3$FEL project uses superconducting RF cavities and cryomodules based on the TESLA technologies$^{[1]}$. The electrons will be accelerated by 1.3 GHz and 3.9 GHz superconducting cavities cooled down to the 2 K level. The 2 K cryostat will be protected against heat radiation and conduction by means of one thermal shields at 40–80 K level and one thermal intercept at 4.5–8 K level. The S$^3$FEL accelerator consists of twenty-six 1.3 GHz and two 3.9 GHz cryomodules, both operated in CW modes$^{[2]}$. Four independent cryoplants will be used for the S$^3$FEL project. A 500 W@2 K helium refrigerator will be used for the test facility including two vertical test benches (VTB) for cavities, one magnet test bench for the superconducting magnet (MTB) and three horizontal test benches (HTBs) for cryomodules. A 1 kW@2 K helium refrigerator will be
used for the prototype machine for R&D purpose of the superconducting accelerator. Two cryogenic plants with 4 kW@2 K refrigeration capacity will be used for supporting the S$^3$FEL accelerator cryogenic cooling requirement. Ideally, one should have enough capacity to supply the cooling for the whole LINAC and the other is acting as a complete set of back up to keep the high availability. In addition, the second plant could compensate the cavity performance degradation due to the long term running or the unexpected cavity performance during the manufacture process. Figure 1 shows the block diagram of S$^3$FEL cryogenic system. This paper describes the conceptual design of the S$^3$FEL accelerator cryogenic system. The performance of the cryogenic system and the project schedule are also described.

![Figure 1: S$^3$FEL cryogenic system block diagram](image)

2. Cryogenic system requirements

2.1. General Requirements
The S$^3$FEL cryomodules require cryogenic cooling for the super-conducting niobium cavities at 2.0 K, low temperature thermal intercept at 4.5 ~ 8 K and a thermal shield at 40 ~ 80 K. The low temperature thermal intercept can provide the necessary heat partition cold source for the module high power Coupler (FPC), high mode Coupler (HOM Coupler), Tuner (Tuner) and other components to reduce the heat leakage through the above components to the 2 K temperature region.

The cryogenic system is the important support system of S$^3$FEL machine. In order to meet the cooling requirements of the accelerator cryomodule and the heat load requirement of S$^3$FEL in different operating modes, the system is required to perform in an array of operating modes: cool down, fast cool down, nominal operations, 2 K stand-by mode (all components at operating temperatures but with no RF power to the SRF cavities), 4.5 K stand by (all cavities and magnets at 4.5 K with no RF power), maximum liquefaction mode and fault response mode. Operating costs are also important and results in a requirement that the cryogenics plant operates efficiently under all operating modes including the nominal turn-down cases.
2.2. Heat loads

In order to properly specify the cooling capacity of the helium refrigerator system, it is necessary to understand the expected heat loads at the various operating temperatures. The approaches of combining literature investigation and engineering experience summary is adopted to evaluate the static and dynamic thermal loads with a certain design margin\[3\]. The static heat loads come from the cryogenic pipeline, distribution valve box, feedcap, endcap and cryomodule itself\[4\]. The dynamic thermal loads come from the heat load generated by the application of RF power to the superconducting cavity, specifically including the dynamic heat loss of the superconducting cavity, the heat dissipation generated by each power source component and the high-order mode radiant heat absorbed by each component\[5-8\]. The results are shown in table 1 below.

| Table 1. Heat load budget of S\bar{F}EL cryogenic system |
|-----------------------------------------------|
| Section | CM No. | 40-80 K | 4.5-8 K | 2 K |
|---|---|---|---|---|
| Single 9cell | | | | |
| 2 | Static | 60.4 | 8.3 | 3.54 |
| 1 | Dynamic | 17.7 | 1.7 | 0.88 |
| 1.3 GHz | | | | |
| 26 | Static | 3198 | 442 | 187.2 |
| 25 | Dynamic | 3900 | 394 | 2710 |
| 3.9 GHz | | | | |
| 2 | Static | 246 | 34 | 14 |
| | Dynamic | 297 | 27 | 344 |
| CM | Predict in total (W) | Static | 3504 | 484 | 205 |
| | | Dynamic | 4233 | 425 | 3056 |
| CDS | Predict in total (W) | Static | 5039 | 392 | 297 |
| | | Static | 8543 | 876 | 502 |
| CM+CDS | Predict in total (W) | | | | |
| | | Static | 11036 | 1179 | 651 |
| | | Dynamic | 4657 | 467 | 3056 |
| CM+CDS | With Safe factors | Static | 16000 | 1700 | 4000 |
| | | Dynamic x1.5 @40K,5K | 1.02 | 1.03 | 1.08 |
| Note: CM: cryomodule, CDS: cryogenic distribution system |

Considering the safety factor, the heat loads at 2 K, 5-8 K and 40-80 K are 3707 W, 1646 W and 15693 W respectively. Relative to the estimated value, the cryogenic system needs to provide 4 kW@2 K, 1700 W@4.5 K-8 K and 16000 W@40-80 K, and the corresponding overall system safety factors are 107.9%, 103.3% and 101.7% respectively.
3. Conceptual design

3.1. Overview
A few design choices have been made that influence the conceptual design of S$^3$FEL accelerator cryogenic system. These include:

a) Use the two same cryoplants for the S$^3$FEL accelerator and equipped VFD for VLP, LP stages and rotary machines.
b) No liquid nitrogen pre-cooling.
c) Cold compressor shall be the preferred solution for ACCP.
d) The whole cryogenic system can be operation in full automatically.
e) The design and construction of all components of the ACCP shall consider an operation lifetime at least 25 years.

In the normal operation mode, a helium refrigerator can meet the thermal demand of the upstream and downstream modules. The design interface parameters of cold box need to calculate the mass flow rate of each loop. The specific results are shown in table 2. The isothermal heat load is 3363.9 W at 2 K level, which directly affects the superfluid helium. The non-isothermal heat load between the J-T heat exchanger and cryomodule affects the liquid yield efficiency. In order to simplify the calculation, it is assumed that the supply flow temperature is 2.75 K and 3 bar. The average temperature of the helium bath is 1.99 K, the calculated liquid rate is 80.2 %, and the calculated mass flow rate is 179.2 g/s. Considering the safety factor of the system, the return flow rate of cold box is 198.9 g/s.

The heat load is 1645.7 W at 4.5 – 8 K level. Assuming the supply flow temperature and pressure is 4.5 K and 3 bar, and the return flow temperature is 8 K and 2.5 bar, the total mass flow rate is calculated to be 43.5 g/s at 4.5 K. Considering the system safety factor, the return flow rate of the loop is 43.5 g/s. The total 4.5 K cold box outlet flow rate is 242.4 g/s.

At 40 – 80 K (high temperature shield), the heat load is 15727.2 W. Assuming the supply flow temperature and pressure is 40 K and 19.5 bar, and the return temperature and pressure is 80 K and 19 bar, the total mass flow rate is calculated to be 74.6 g/s. Considering the system safety factor, the return flow rate is 75.5 g/s.

Table 2. ACCP mass flow requirements

| Loops      | Heat load (W) | Mass flow (g/s) | Pressure (bara) | Temperature (K) |
|------------|---------------|-----------------|-----------------|-----------------|
|            |               | Supply          | Return          | Supply          | Return          | Supply          | Return          |
| 2 K        | 4000          | 198.9           | 8               | 3               | 0.027           | 4.5             | 3               | 3.5             |
|            |               | 242.4           |                 |                 |                 |                 |                 |                 |
| 4.5- 8 K   | 1700          | 43.5            | 8               | 3               | >= 2.5          | 4.5             | 8               |                 |
| 40-80 K    | 16000         | 75.5            | 19.5            | 19              | 40              | 80              |                 |                 |

3.2. Helium refrigeration system
The cryogenics plant for S$^3$FEL accelerator system is known as the Helium Refrigeration System (HRS). The refrigeration cycle of a 4 kW@2 K refrigerator is shown in figure 2. It adopts a reverse Claude refrigeration cycle without liquid nitrogen pre-cooling. There are five cooling stages including...
of series turbine cooling stage, J-T cooling stage and 2 K cooling stage. The refrigerator needs eight heat exchangers to complete the cycle. Turbine expanders T1, T2, and T3 are all expanded from high pressure back to medium pressure to cool the mainstream helium circuit. Turbine T4 is used to produce supercritical helium. Two sets of nitrogen and oxygen adsorbers with 80 K level are built-in, which can be switched to regenerate each other. A set of 20 K adsorbers are used to absorb neon, hydrogen and other components in helium. The 2 K cooling stage is achieved by cold compressor, reducing the pressure of the SRF cavities to 30 mbar, and cooling the helium bath to 2 K. Figure 2 is a preliminary Process Flow Diagram (PFD) of the HRS. Final details will be depended on the chosen vendor’s design.

![Figure 2. PFD of the accelerator refrigerator](image)

3.3. Distribution system

The Cryogenic Distribution System (CDS) includes distribution boxes, interface box, cryogenic transfer line, feedcaps, and endcaps. A simplified schematic of the LINAC is shown in figure 3. The CDS supports two independents cryogenic LINAC strings with twelve 1.3 GHz Cryomodules (CM) and two 3.9 GHz CMs on the upstream and thirteen 1.3 GHz CMs on the downstream. There are two operation modes.

- Normal operation with only ACCP1 operating. In this mode, ACCP1 can cool down the upstream accelerator by upstream cryogenic distribution box (UCDB) and cool down the downstream accelerator by interface box (IB) and downstream cryogenic distribution box (DCDB). If the ACCP2 is not installed, the transfer line to ACCP2 shall be blanked.
- Normal operation with ACCP1 and ACCP2 both operating. In this mode, upstream heat load is transferred by ACCP1 and downstream heat load is transferred by ACCP2. The connection valves in IB will be closed to stop the flow between downstream and upstream.
Figure 3. S³FEL accelerator cryogenic system overview

Figure 4. Layout of S³FEL cryogenic system

3.4. Cryogenic system layout

Early specification of the space and layout for the cryogenic system is very important. The cryogenics group must ensure that enough space and utilities exist to meet the function needs of the cryogenic system[9]. To ensure that appropriate space is allocated, a model of the cryogenic plant space is shown in figure 4. In this layout, the coldbox hall is closed to the S³FEL tunnel. The cold box, LHe dewar, UCDB, DCDDB IB will place in the coldbox hall. The distance is about 182 m between compressor hall and coldbox hall. The warm compressor and removal oil system will be placed in the compressor hall. The recovery storage and purify system is beside the compressor hall. All transfer lines are connected
by bridge. The preliminary design of system layouts is finished, and now effort will proceed into civil engineering design.

4. Summary
Cryogenic system plays a vital role in the S3FEL project. The conceptual design of the cryogenic system is complete and ACCP specifications are well underway. It is expected that the order for ACCP will be the beginning of 2022 and the detailed design of the cryogenic distribution system will also start this year. The S3FEL cryogenic system will be ready to use by January 2026.

5. References
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