Commissioning plan for LCLS II 2 K cold box

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Abstract. Commissioning of the LCLS II cryogenic plant has been planned with respect to electrical and mechanical systems checkout, equipment cleanup, cool-down, and individual performance evaluation. This plant consists of warm and cold storage, helium compressors, 4.5 K and 2 K cold boxes, and all auxiliaries typical for helium refrigeration processes. The 2 K cold box, consisting of five cold compressors in series to produce the flow and pressures necessary for 2K operation, will be the last equipment installed and, along with an additional 10,000 L helium dewar, will allow the entire plant to be commissioned as a single entity. The pre-commissioning stages, commissioning plan for 2 K cold box without connecting to the LCLS II LINAC, additional test equipment needed to simulate the loads, all process studies and associated results are described herein.

1. Introduction

Two cryogenic plants with 2.0 K Cold Boxes are required for the Linac Coherent Light Source II (LCLS-II) project, which is under installation phase at SLAC National Accelerator Laboratory, Menlo Park. A total of thirty-five 1.3 GHz and two 3.9 GHz superconducting cryomodules in LCLS II Linac are required to be operated with 2.0 K helium at superfluid condition in the SLAC tunnel. The cryogenic plant [1], part of responsibility of Thomas Jefferson National Accelerator Facility consists of: a main compressor system, an oil removal system, a 4.5 K Cold Box, a 2.0 K Cold Box, a helium recovery system with purifier, an Interface Box, a main transferline, liquid helium main dewar, liquid nitrogen tank, gaseous helium storage tanks and utility systems.

In previous work, overall system design and engineering [2] have been completed for the cryogenic plant, which is similar to the existing cryogenic system [3] at Thomas Jefferson National Accelerator Facility. Manufacturing of most of the equipment for both the cryogenic plants is now complete and has been delivered to SLAC National Accelerator Laboratory. Commissioning of the entire cryogenic plant is now the upcoming activity for the LCLS II project. The commissioning of 2.0 K cold box has been identified as the most challenging part. The 2.0 K cold box consists of six cold compressors, of which only five will be running in series, along with control valves. The commissioning plan has been developed and detailed out in the present work.

2. Commissioning of 2.0 K Cold Box

The commissioning of the 2.0 K cold box involves the following stages after the completion of installation activities.

(i). Checkout of electrical installation
(ii). Verification of mechanical installation
(iii). Control and signal checkout
(iv). Verification of shutdowns
(v). System cleanup with flushing and purge-filling processes
(vi). System cool-down 300 K to 4.5 K temperature level along with control logic verification
(vii). Pump-down with cold compressors into the test volume
(viii). Acceptance testing of cold compressors by verification of minimum, nominal and maximum capacity condition

The prerequisite for the commissioning of 2.0 K cold box is the completion of acceptance testing of 4.5 K cold box and liquid helium main dewar with the test loads.

2.1. Objectives and Purpose
The main objective of the present work is to develop a complete commissioning plan for the 2.0 K cold box including all required commissioning equipment. In particular,

(i). Develop the process flow diagram for the complete test scheme
(ii). Define the commissioning equipment
(iii). Develop a process simulation model for 2.0 K cold box commissioning and acceptance testing
(iv). Prepare the pump-down and acceptance test plan with the commissioning equipment

The purpose of the commissioning plan is to develop the expected pump down path for the cold compressors involving the commissioning equipment. Further, the expected performance of each of the five cold compressors has been prepared to support the actual on-site commissioning work.

2.2. Inputs and Assumptions
In order to achieve the high mass flow configuration in 2.0 K cold box, the first five out of six cold compressors are designed and configured to operate at the sub-atmospheric inlet condition as in Table 1. A provision to use cold compressors 2 through 6 is available as a ‘low mass flow configuration’, which requires a future piping modification to bypass cold compressor 1. A commissioning test scenario has been developed with isolating the LCLS II superconducting linac at the Interface Box by removing the necessary u-tubes. It is assumed to perform the commissioning testing, one at a time, for the two 2.0 K cold boxes using only one set of commissioning equipment. It has been further assumed that each 4.5 K cold box is capable to support the varying heat load profile during the entire startup and pump down process.

Table 1. Mode-wise process condition for the cold compressors in high mass flow configuration

| Modes             | Mass Flow | Suction Condition | Discharge Condition |
|-------------------|-----------|-------------------|---------------------|
| Maximum Capacity  | ≥ 215 g/s | 3.5 K, 27 mbar    | < 30 K, 1.2 bara    |
| Nominal Capacity  | ≥157 g/s  | 3.6 K, 28 mbar    |                     |
| Minimum Capacity  | ≤150 g/s  | 3.6 K, 28 mbar    |                     |

3. System Description
The overall system involves a fully operational 4.5 K cold box along with its associated liquid helium main dewar. Figure 1 shows the complete process flow diagram for the 2.0 K cold box commissioning. The cold end of the 4.5 K cold box has been represented for simplification. The 2.0 K cold box is connected to the 4.5 K cold box using a main transferline with interconnecting u-tubes. Lines C and D
within main transferline represent the closed loop for the cold shield whereas lines E and F depicts the flow path to warm shield of the LCLS II superconducting linac. A small amount of flow has been provided to the C-D and E-F loops with the help of two bypass u-tubes in order to keep the main transferline cold. Lines A and B of main transferline are connected to the 2.0 K test dewar in order to simulate the part of LCLS II superconducting linac pump down volume.

**Figure 1.** Process flow diagram for the 2.0 K cold box commissioning [TT: temperature transmitter, PT: pressure transmitter, FT: flow transmitter, LT: level transmitter, ST: speed transmitter and ETHR: electrical heater]

**Figure 2.** System model including major equipment and connections for the CP1 2.0 K test
Cold compressors (CC) 1 through 5 are arranged in series and a 6th cold compressor is isolated by removing the inlet u-tube providing the high flow configuration for the commissioning test. Figure 2 shows the entire 3D model of the 2.0 K test configuration with verification of space availability for the test dewar as well as the interfacing connections during the commissioning phase.

4. Process Design and Calculation

The process modeling and simulation [4] has been developed using Microsoft® Office Excel. Separate analysis has been performed as per the modes shown in Table 1. Figure 3 shows the developed process model for the 2.0 K cold box including cold end of the 4.5 K cold box, main dewar, test dewar and associated inter-connections. Further, the process model shows the simulation results for the maximum capacity of 215 g/s mass flow through the series of cold compressors. Similar simulation has been performed for nominal capacity as well as minimal capacity mode. The electrical heater (ETHR31000), shown inside the main dewar in Figure 1, is used to generate the majority of the mass flow for the operation of the series of cold compressors. Electrical heater (ETHR41521-24) is used to raise the inlet temperature of CC1 to 3.5 K in order to simulate the actual operating condition.

**Figure 3.** Process model for the 2.0 K cold box commissioning for maximum capacity mode
4.1. Pump down simulation
The entire pump down from atmospheric to sub-atmospheric pressure has been simulated by dividing the process into ten discrete points. Each of the points has been simulated to evaluate the operation of all five cold compressors. Two different pump down paths have been simulated for the present work and comparison between two paths has been analyzed for better understanding. The two pump down paths have been defined as follows
(i). Pump down – 1
(ii). Pump down – 2
In case of pump down – 1, the dominant mass flow has been originated from the test dewar. The ratio between the mass flow originated from test dewar to the mass flow originated from the main dewar is given as 29:1.
However, pump down – 2 has been defined as the dominant flow originated from the main dewar whereas the test dewar provides the makeup flow. The ratio between the mass flow originated from test dewar to the mass flow originated from the main dewar is given as 0.46:1.
Lower temperature at the inlet of CC1 than Table 1 is expected for the pump down – 1 due to the absence of electrical heater in the mass flow path originated from test dewar. In case of pump down – 2, the electrical heater (ETHR41521-24) as in Figure 1 has been activated to achieve the correct inlet temperature of CC1 as in Table 1. It is assumed that the liquid helium level in the test dewar needs to be around 20 % in order to sub-merge the electrical heater (ETHR42100) as in Figure 1. This would help to get at least 8.0 m³ of saturated vapor volume inside the test dewar for a stable pump down process. The isentropic efficiencies at each stage of pump down was a non-constant in order to calculate accurate discharge temperatures.

5. Cold Compressor Simulation Results
The most important area of interest is to simulate and understand the operational behavior of all five cold compressors with the help of process design model. During the commissioning test configuration, pump down – 1 and pump down – 2 have been simulated in details as per the work objective. The results from CC1 through CC5 are analyzed with plots of pressure ratios to the non-dimensional flow rates calculated based on the nominal volumetric flow rate and inlet process condition.
Figure 4 - 8 show the performance plots of CC 1 – 5. The performance characteristics of all five cold compressors include the operational limits for better assessment. The plots as in Figure 4 through Figure 8 show the simulated results for maximum, nominal and minimal capacity modes as defined in Table 1. In case of pump down – 1, the performance characteristics of cold compressors 1 is very close to the operational limits with higher pressure ratio for a particular non-dimensional flow. It has also been observed from the plots that the pump down – 2 is better compared to the pump down – 1 path with respect to the larger surge margin.

![Figure 4. Cold Compressor – 1 Performance Plot](image-url)
Figure 5. Cold Compressor – 2 Performance Plot

Figure 6. Cold Compressor – 3 Performance Plot

Figure 7. Cold Compressor – 4 Performance Plot
Figure 9 shows the varying heat load profile (Qtotal) to the cryogenic plant during the entire pump down stages for both the pump down paths. This figure also describes the combined heat load profile (Qcc) originated from all five cold compressors. It has been observed that larger total heat loads as well as combined cold compressor heat loads resulted for the pump down – 2 as compared to the pump down – 1. This is because of the high inlet temperature operation of the CC1.

Further, it has been observed that the peak heat loads from both pump down scenarios are within 31.75 kW, the maximum sub-atmospheric capacity of each cryogenic plant.

6. Manufacturing Status of 2.0 K Cold Box
The manufacturing of two 2.0 K cold boxes was earlier awarded to two independent sub-contractors in order to mitigate the schedule risk of delay during the construction. Cold casings of the cold compressors were integrated in to the cold box piping at the supplier facilities.

The factory acceptance tests have been successfully completed for both the 2.0 K cold box manufacturing efforts. Figure 10 shows the internal piping and the outer vacuum jackets of first 2.0 K cold box at the supplier facility during the manufacturing stages. Similarly, Figure 11 illustrates the second 2.0 K cold box at the second supplier site. Both the manufacturing of cold boxes has been successfully completed along with all the manufacturing inspections.
Currently, the test dewar is under fabrication at the supplier site. The design activities related to the test dewar neck-can and associated 2.0 K cold box test interconnecting u-tubes are complete.

7. Conclusion
A detailed commissioning plan for the 2.0 K Cold Boxes including cold compressors have been developed including acceptance testing. The process model has been developed to verify the operation of the cold compressors against the operational limits of each one and to develop the pump down paths. Details of two pump down paths have been assessed and the second pump down path has been selected for better stability of all the cold compressors within the operational limits. Even though the second pump down path was analyzed as a more demanding scenario in terms of total sub-atmospheric heat load capacity requirement out of the cryogenic plant, the required capacity is well within the maximum sub-atmospheric capacity of cryogenic plant in the maximum operating mode. Both the 2.0 K cold boxes have been delivered to SLAC National Accelerator Facility, Menlo Park, USA for subsequent on-site assembly and installation activities. Commissioning of 2.0 K cold box is expected to be performed at SLAC; one-by-one starting in summer of 2020.

8. References
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