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LCLS-II LINAC 2.0 K COMMISSIONING

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Abstract. In 2023, SLAC commissioned a continuous-wave superconducting linear accelerator (CW SCRF Linac) to support its new Linac Coherent Light Source (LCLS-II). The LCLS-II Linac comprises 37 cryomodules, each equipped with superconducting niobium cavities. These cryomodules hold helium bath operating at 2.0 K for the electron beam. Achieving the 2.0 K temperature in the Linac involves reducing the liquid helium saturation pressure to 31 mbar using a series of centrifugal compressors. This paper presents the results of the commissioning of the 2K system at SLAC.

1. Introduction

SLAC National Accelerator Laboratory, managed by Stanford University for the U.S. Department of Energy's Office of Science, has commissioned a state-of-the-art continuous-wave superconducting accelerator to support LCLS-II (Linac Coherent Light Source). Housed in one-third of SLAC's original 2-mile-long linear accelerator, LCLS-II is designed to produce an X-ray beam at 4 GeV, with the support of a powerful Helium refrigeration system (HRS) capable of providing 4 kW of cooling capacity at 2.0 K [1].

1.1 2K Cold Compressor System

The 2K system at SLAC employs a series of five cold compressors (CC) in series to lower the linac pressure to 31 mbar, achieving a temperature of 2.0 K in the cavities. This system also incorporates a plate and fin heat exchanger (4K-2K heat exchanger) within the distribution box to recover cooling capacity from the 2K return (Line B) and cool-down the 4K supply (Line A) to reduce the flash across the JT valves (Figure 1). The exhaust from the CC, at a pressure of 1.22 bara and 23 K, is re-injected in the cryoplant.

The 2K system was commissioned with linac connected and the controls [2] as shown in Figure 1 are briefly described below

1. Flow controller controls the flow by regulating the speed of all five CC
2. Pressure controller computes the heat required to maintain the linac pressure and distributes it equally to 37 cryomodule heaters
3. Level in the cryomodules are maintained by the JT valves
4. CC suction temperature is controlled by regulating the heat exchanged between 4K supply and 2K return

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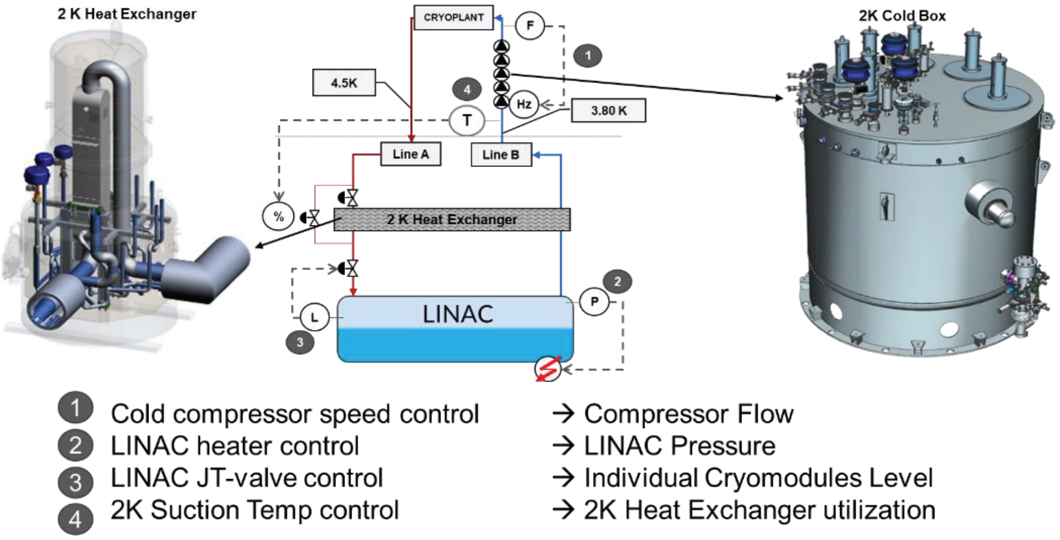

Figure 1. SLAC 2K Cold Compressor System

2. Commissioning Timeline

Before starting the CC, helium refrigeration system (HRS) was fully commissioned and tested using electric heaters to simulate the LINAC and the 2K CC equivalent heat loads [3]. The linac was cooled down successfully in March 2022 and reached the target temperature of 4.5 K within a week [4]. This was followed by 5 weeks of careful planning and preparation for the commissioning of CC. Preparation involved collaborating with the vendor to establish the pump-down path and included a thorough review of procedures, process control narratives, the designation of interlock and trip conditions, and the development of HMI and PLC code [2]. This thorough preparation and system review was instrumental in commissioning the 2K system within 15 days.

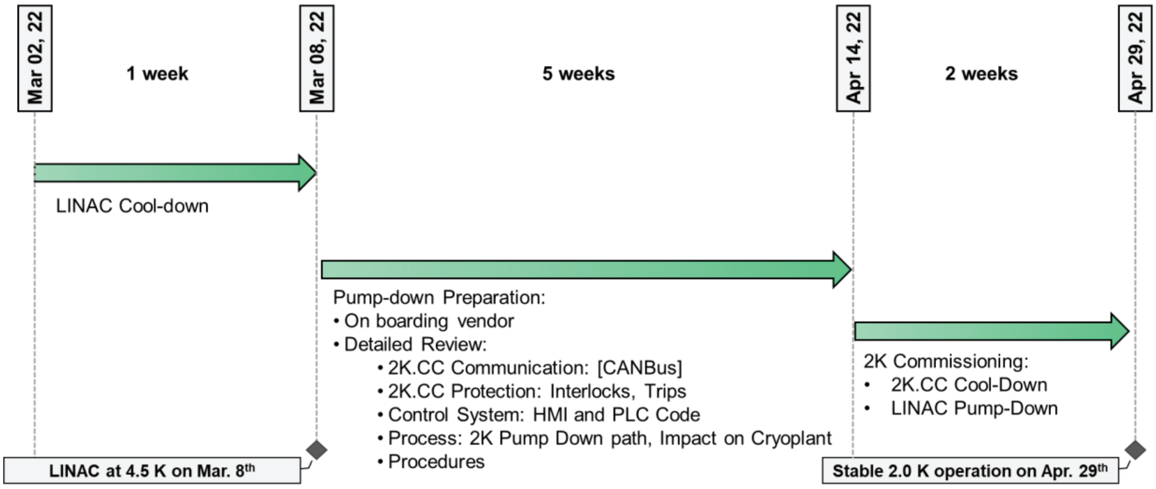

Figure 2. 2K System commissioning timeline

The first successful pump-down was achieved on April 29, 2022, taking 2.5 hours. Subsequent code improvements have significantly reduced the pump-down time to 1.5 hours.

3. 2K System Performance

3.1 Cold Compressor tests

A comprehensive series of tests was conducted to establish the CC operational thresholds. These tests included maximum flow capacity tests, minimum flow capacity tests and optimization of the heat exchanged at 4K-2K Heat exchangers. The goal was to determine the optimal process parameters within which the system operates efficiently and safely.

LCLS-II CC were designed to deliver a specified capacity of 215 g/s at suction conditions of 27 mbar pressure and 3.5 K temperature. During the test, the system exceeded this specification, achieving a maximum flow rate of 260 g/s which is 20% higher than the specified flow (Table 1). However, due to the limitations in the HRS, particularly the capacity of low-pressure compressor (LP), the cryoplant cannot operate stably at this higher flowrate.

Table 1. Cold Compressor Maximum capacity test

Parameters	Specified	Maximum
Flow	215 g/s	260 g/s
Suction Pressure	27 mbar	26 mbar
Suction Temperature	3.5 K	3.4 K
Density at suction	0.38 kg/m^3	0.38 kg/m^3
Discharge Pressure	1.2 bara	1.3 bara
Discharge Temperature	25 K	20 K
Isentropic Efficiency	58%	74%

Further tests were carried out to analyse and determine optimal CC flow that can be sustained by the HRS. These tests indicated that the HRS operation is stable for a CC flow range of 225 g/s to 235 g/s. Consequently, the CC flow was set to 230 g/s. Next, the minimum flow capacity of the CC was explored to determine its operational limits at reduced flowrate. A stable turn-down flow capacity of 180 g/s was achieved. Test results are shown in Table 2.

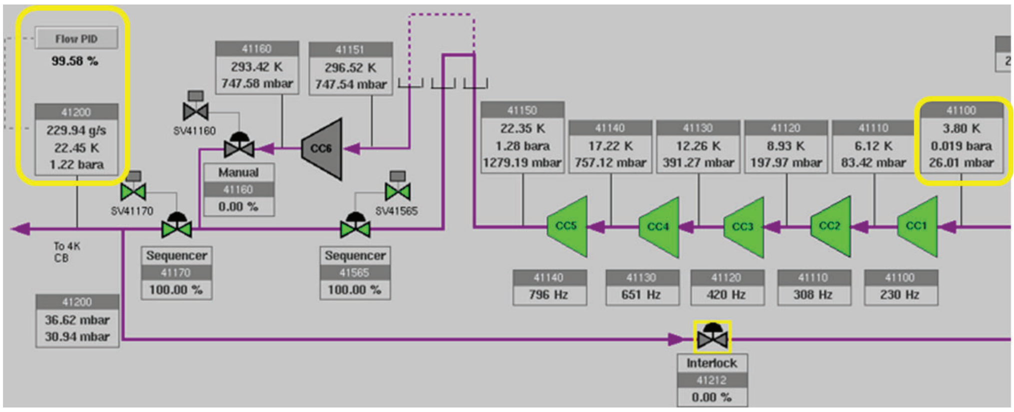

Figure 3. CC at optimum flow capacity of 230 g/s

Table 2. Cold Compressor optimum and Minimum flow capacity test

Parameters	Optimum	Minimum
Flow	230 g/s	180 g/s
Suction Pressure	26 mbar	27 mbar
Suction Temperature	3.8 K	3.8 K
Density at suction	0.33 kg/m^3	0.34 kg/m^3
Discharge Pressure	1.22 bara	1.22 bara
Discharge Temperature	22.6 K	22.5 K

These tests established the stable operating range for the CC, showing that with a nominal flow of 230 g/s, the CC capacity can be turned down by 25%.

Additional tests were conducted to optimize the utilization of 4K-2K heat exchanger in the distribution box. The flow controller was set to 230 g/s while gradually increasing the flow through the heat exchanger, which allowed 4K supply to cool down further and 2K return to warm up. The CC tripped due to flow surge at a suction temperature of 4.0 K (Figure 4). This helped to determine the suction temperature limit of the CC.

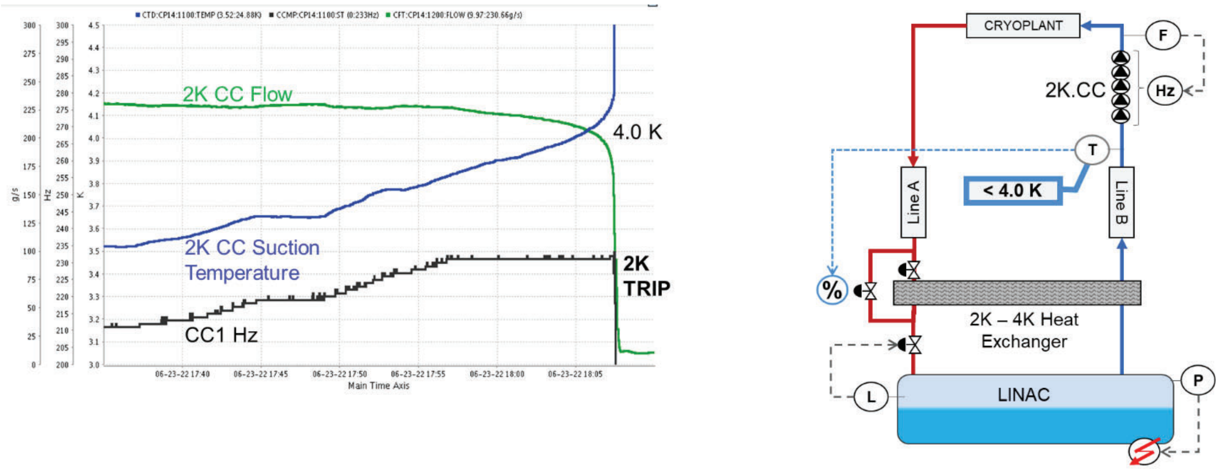

Figure 4. CC at maximum suction temperature of 4.0 K

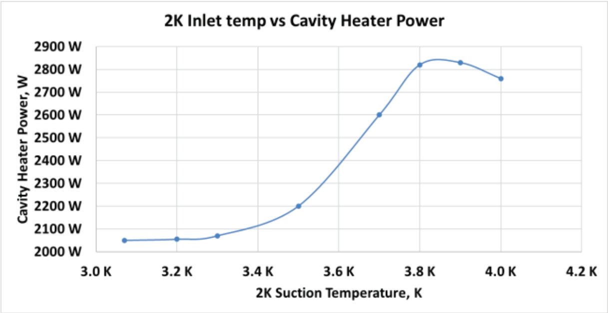

Figure 5. CC suction temperature vs dynamic power

Adjusting the flow split at the 4K-2K heat exchanger to increase the CC suction temperature decreases the 4K supply temperature, which reduces the flash across the JT and enhances the achievable dynamic power (cryomodule heater power) in the linac. However, higher CC suction temperatures also reduce CC flow, potentially decreasing the dynamic power. It was observed that CC suction temperature above 3.8 K leads to reduction in CC flow that offsets the benefits of increased dynamic power gained by lower JT inlet temperature (Figure 5). Thus, the optimal operating parameters for the CC were determined to be a flow of 230 g/s at a suction pressure of 27 mbar and a suction temperature of 3.8 K

3.2 Linac heat loads observation

- Cryomodule Static heat load

Static heat load measurement was conducted by quantifying the boil-off for all the 37 cryomodules. During this test, cryomodule JT valves were closed individually to prevent liquid helium filling, thereby eliminating the effect of flash. The change in the level was recorded for 0 W to 80 W heater power. This level change was then converted into the boil-off rate and heat load for the cavity geometry. The measurement of the change in the level was verified by plotting it linearly against the heater power. The expected static heat load was 330 W however, the current observed total static heat load for 37 cryomodules is 500 W.

- Non-isothermal heat load on Line B

The anticipated non-isothermal heat loads for LCLS-II was 400 W. However, a much higher cumulative non-isothermal heat load of 1,200 W is observed on 2K return line, which includes 2K return line within the cryomodules, and the cryo distribution system.

Using available heat leak data from the literature can result into underestimation of the actual heat load. Therefore, a more conservative approach should be considered. Additionally, it is important to install sufficient reliable instrumentations at various locations to aid in accurate diagnosis.

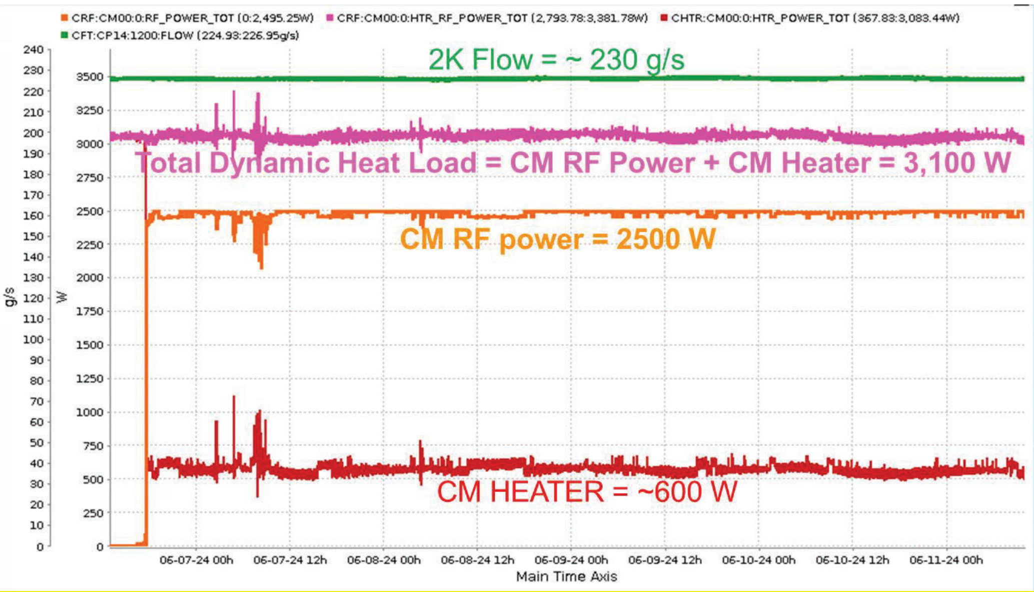

Figure 6. LCLS-II Observed Dynamic Heat load

- Dynamic Heat load (Figure 6)

Currently, at SLAC we have achieved the dynamic heat load of 2,500 W at 3.5 GeV beam operation

4. Conclusion

The commissioning of 2K system at LCLS-II involved a series of tests to establish operational thresholds and optimize system performance. These tests demonstrated excellent performance and high efficiency of the cold compressors. The results emphasize the importance meticulous planning and thorough testing.

The cold compressors exceeded their specified flow capacity, achieving a maximum of 260 g/s, though operational stability was limited by the low-pressure compressor capacity, leading to a stable flow setting of 230 g/s. Further testing confirmed that the system operates reliably within a flow range of 225 g/s to 235 g/s and established a stable turn-down flow capacity of 180 g/s. Additional tests determined that the optimal operating parameters for the cold compressors are a flow of 230 g/s at a suction pressure of 27 mbar and a suction temperature of 3.8 K.

The discrepancy between the expected and observed heat loads highlights the need for a conservative approach and emphasizes the importance of instrumentation accuracy for precise heat load assessments.

5. References

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Acknowledgments

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