IOP Conf. Series: Materials Science and Engineering **278** (2017) 012094 doi:10.1088/1757-899X/278/1/012094

Commissioning and Testing of a new 4.5K Cold Box for JLab Cryogenic Test Facility

T. Wijeratne[1], N. Hasan[1], M. Wright[1], V. Ganni[1], K. Dixon[1], J. Creel[1] and P. Knudsen[1]

[1] Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

E-mail: thilan@jlab.org

Abstract. A new 4.5K cold box at Jefferson Lab (JLab) Cryogenic Test Facility (CTF) was recently installed and commissioned to upgrade the existing 4.5 K refrigeration system and work in parallel with the existing 4.5 K cold box. This new 4.5 K cold box is equipped with two turbo-expanders and, at its maximum capacity condition, it is expected to support at least 6.6 g/s of helium liquefaction or 650 W of refrigeration at 4.5 K. It can also handle up to 10 g/s 30 K return flow for 2 K refrigeration recovery that supports cryo-module and superconducting cavity testing. Performances of the cold box at its maximum capacity conditions as well as several other operating modes were tested for acceptance. We will briefly review the new 4.5 K cold box design features and discuss the commissioning and performance testing results.

1. Background

The Cryogenic Test Facility (CTF) at Jefferson Lab (JLab) was commissioned in 1988. It mainly consisted of a 35 K shield refrigerator (CB1), a 4.5 K refrigerator (CB2), three Mycom warm helium compressors and a 10,000 liter liquid helium (LHe) dewar. The CTF warm gas management system consisting of the three Mycom rotary screw compressors, can support up to 110 g/s of flow (*i.e.* 55 g/s per compressor with the third one as stand-by) to the cold box at 16.0 bar. The existing 4.5 K refrigerator at CTF is a CTI M2200 cold box with two expansion engines that supports cryo-module and superconducting radio frequency (SRF) cavity testing. The cold box primary supply (4.5 K, 3.0 bar) is used to fill either test dewars for SRF cavity testing (intermittent load) or to support a fully assembled cryo-module at 2.0 K (continuous load when installed). The cryogenic system also has a refrigeration recovery heat exchanger that recovers capacity from the 2.0 K load and re-injects it back to the 4.5 K cold box. Since it's commissioning, CB2 has supported CTF for more than 225,000 hours of continuous operation. However, owing to the expansion engines, this cold box requires very high maintenance to keep up with the capacity requirement from the loads. The new 4.5 K cold box (CB3) was installed in the spring of 2017 to supplement (and replace, in the long run) the existing 4.5 K cold box (CB2). It is a Linde L280 cold box consisting of two turbo-expanders, liquid nitrogen pre-cooler and five heat exchangers core. The cold box mainly has two process streams - one for high pressure supply and the other for low pressure return flow. The expansion stream uses the two turbines in series with a heat exchanger in between them. The cold box also has a third stream with injection ports back into the low pressure stream at various temperature levels to support 2.0 K loads. A simplified flow diagram and physical arrangement of CB3 is shown in figure 1.

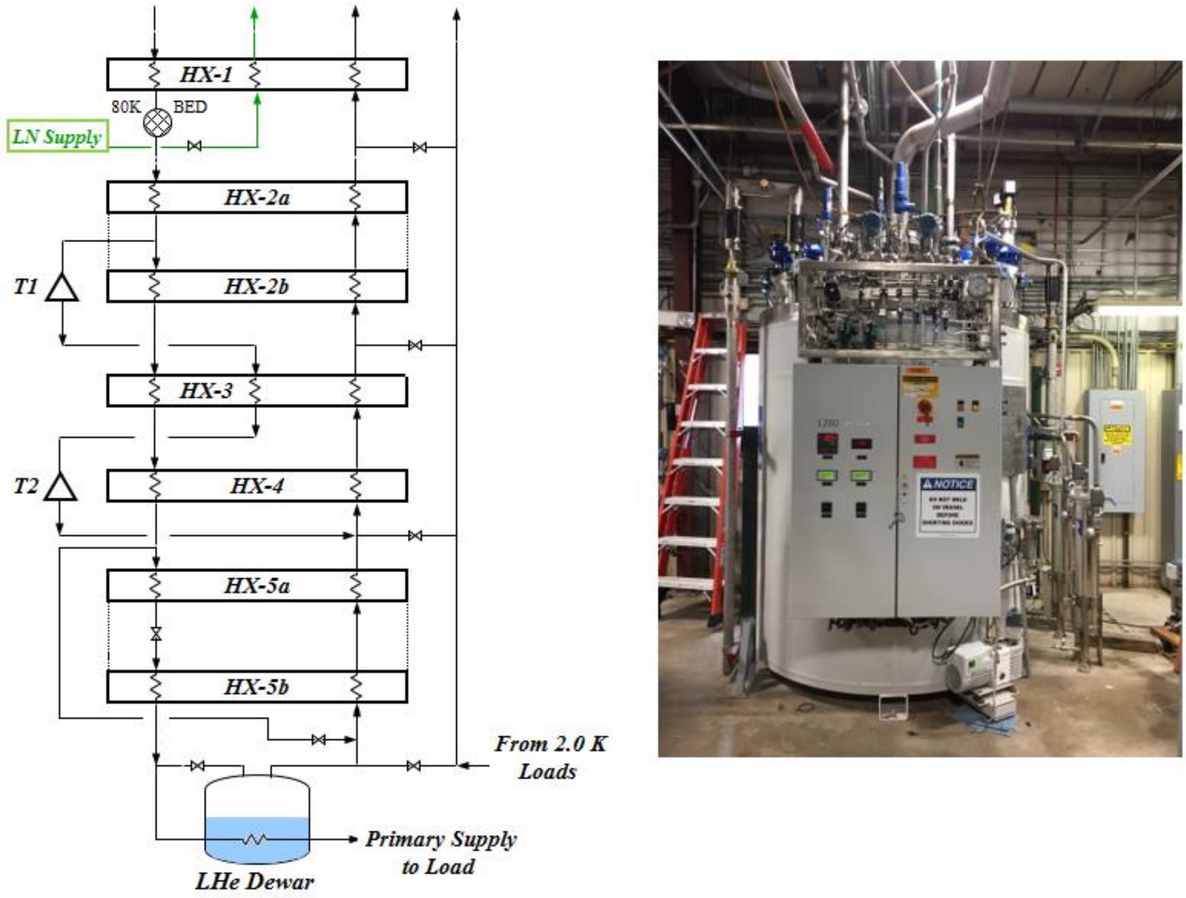

Figure 1. Simplified Flow Diagram (left) and Physical Arrangement (right) of the new CTF Cold Box (CB3)

In the present study, the cold box performance parameters are compared to the contract specification and the design for different modes of operation – including the maximum and minimum 4.5 K liquefaction modes. The new 4.5 K cold box (CB3) capacity measurements at various cold box supply pressures are also discussed. The effects of various cold box features on the performance of the cold box are described in detail.

2. Set-up and Commissioning

Several modifications were made to the CTF cryogenic system in order to connect the new 4.5 K cold box (CB3) to the existing system. Besides installing the warm process piping and utilities for CB3 (such as instrument air, turbine brake cooling water), modifications to the existing cryogenic transfer lines to the LHe dewar were made. In order to retain redundancy, cryogenic transfer lines to / from both cold boxes (CB2 and CB3) were made available to the load and the LHe dewar.

During the commissioning of the new 4.5 K cold box, the entire cryogenic system was thoroughly examined. This included - checking installed process piping to match with the design, checking electrical wiring of the control system, calibration of the temperature and pressure instrumentation, cycling control valves etc. The loads were completely disconnected from system in order to eliminate any uncertainty from the capacity measurements. Test heaters were installed in the LHe dewar to impose an artificial load on the cryogenic system. At the end of the inspection, the cold box was cooled to 4.5 K using the turbo-expanders only (*i.e.* without the LN pre-cooling).

3. Testing Methods

The following tests were performed to ensure that the capacity of the cold box met the specifications and to understand the performance of the cold box at varying load conditions –

- Maximum 4.5 K liquefaction capacity
- Maximum 4.5 K refrigeration capacity
- Minimum 4.5 K liquefaction capacity
- 4.5 K Liquefaction capacity at different cold box supply pressures (7.2 – 15.0 bar)

Maximum 4.5 K liquefaction capacity of the cold box was measured in two different ways – measuring the rate of rise in the LHe dewar and using the ambient vaporizer (measuring the vaporizer flow). LN consumption (mass flow) was also measured to make sure it met the specification. For the maximum refrigeration mode, electric heat was added into the LHe dewar to impose an artificial refrigeration load. Finally, a turndown capacity test (*i.e.* minimum liquefaction) of the cold box was performed by lowering the supply pressure to the cold box to 7.2 bar and imposing a 4.5 K liquefaction load to stabilize the cryo-plant. The liquefaction capacity of the cold box for various discharge pressures ranging from 7.2 bar to 15.0 bar was also measured. Although, these were not a part of the acceptance test for the cold box but were performed to understand the performance of the cold box at different loading conditions.

4. Results and Discussion

Comparison between the specification, design and test data for the two major modes of operation (Maximum 4.5 K liquefaction and 4.5 K refrigeration) are shown in table 1. As observed from the data, the actual 4.5 K liquefaction capacity is about 44% greater than the expected performance (design). As a result of this, the LN consumption at this mode was also found to be greater than the specification. However, the calculated cold box efficiency (32.3%) was found to be greater than the design cold box efficiency (30.5%) in this mode. This increased cold box capacity is possibly a result of larger turbine flow coefficient than the design. Since the primary load on the cold box is 4.5 K liquefaction or a combination of 4.5 K liquefaction and 2.0 K load, this increased liquefaction capacity than the design is definitely beneficial for CTF. This (possibly) increased turbine flow coefficient also affected the performance of the cold box in 4.5 K refrigeration mode, resulting in a higher than expected supply flow to the cold box. However, it is important to consider that the major operating modes of the cold box are either a pure 4.5 K liquefaction or a combination of 4.5 K liquefaction and 2.0 K load, and a higher than expected cold box supply flow in the 4.5 K refrigeration mode should not affect the performance of the cryogenic system in the long run.

Table 1. Comparison between specification, design and test performance parameters for maximum 4.5 K liquefaction and 4.5 K refrigeration modes

	4.5 K Liquefaction			4.5 K Refrigeration		
	Specification	Design	Test	Specification	Design	Test
Liquefaction (g/s)	≥ 6.6	7.0	9.5	--	--	--
Refrigeration (W)	--	--	--	≥ 650	682.5	700
LN Consumption (g/s)	≤ 30	25.3	33.4	N/A	11	11.8
HP inlet flow (g/s)	N/A	68.7	97.3	≤ 90	82.9	100.6
HP inlet pressure (bar)	14	14	13.8	N/A	10.85	10.9

The T-s diagram for the cold box operating at a maximum 4.5 K liquefaction load of 9.5 g/s is shown in figure 2. The temperature profiles across each of the heat exchangers can be seen from this figure. A supply flow of 97.3 g/s is required to sustain this load, which means operating two of the three warm compressors of the gas management system. Out of this 97.3 g/s, about 65.8 g/s was recycled by the turbo-expanders. The rest of the 31.5 g/s was required to support the load (LHe dewar). The calculated isentropic efficiency of the turbo-expanders T1 and T2 are 72.5% and 81.5% respectively at this mode. A LN consumption rate of 33.4 g/s was observed at the maximum 4.5 K liquefaction mode.

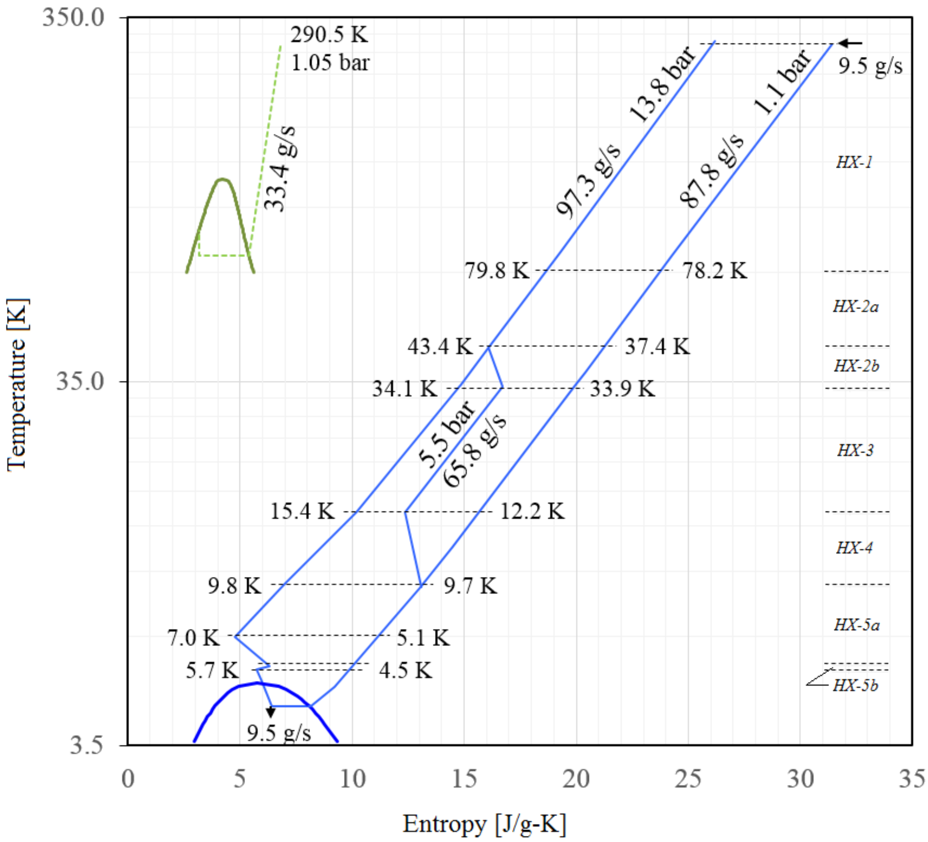

Figure 2. Cold box T-s diagram for the maximum 4.5 K liquefaction mode (Test).

Figure 3 shows the efficiency of the cold box as well as a breakdown of the available exergy for the maximum liquefaction, maximum refrigeration, and minimum liquefaction modes (at 4.5 K). As seen, the cold box is most efficient in the maximum 4.5 K liquefaction mode with an efficiency of about 32.3%. This is expected as the cold box is designed to serve primarily as a liquefier. The maximum 4.5 K refrigeration mode is able to use less of the exergy from the helium though the input exergy is about the same as the liquefaction mode. This plot also helps to show the importance of the turndown mode (*i.e.* minimum 4.5 K liquefaction) to the CTF Cryogenic system even though the cold box is not very efficient in this mode. Although the cold box can operate with supply pressures as low as 7.0 bar, the existing gas management system (warm compressors and oil removal system) is required to operate at a pressure of at least 12.0 bar (due to effective oil removal). Hence, a back-pressure regulator was installed at the cold box supply piping prior to the commissioning of the new 4.5 K cold box. Though reducing the supply pressure to the cold box does not save power directly due to the back-pressure regulator, it does lower the LN consumption in the minimum 4.5 K liquefaction mode as shown in figure 3. The reduced supply flow through the cold box (at minimum 4.5 K liquefaction mode) also allows the plant to operate with only one warm compressor instead of two.

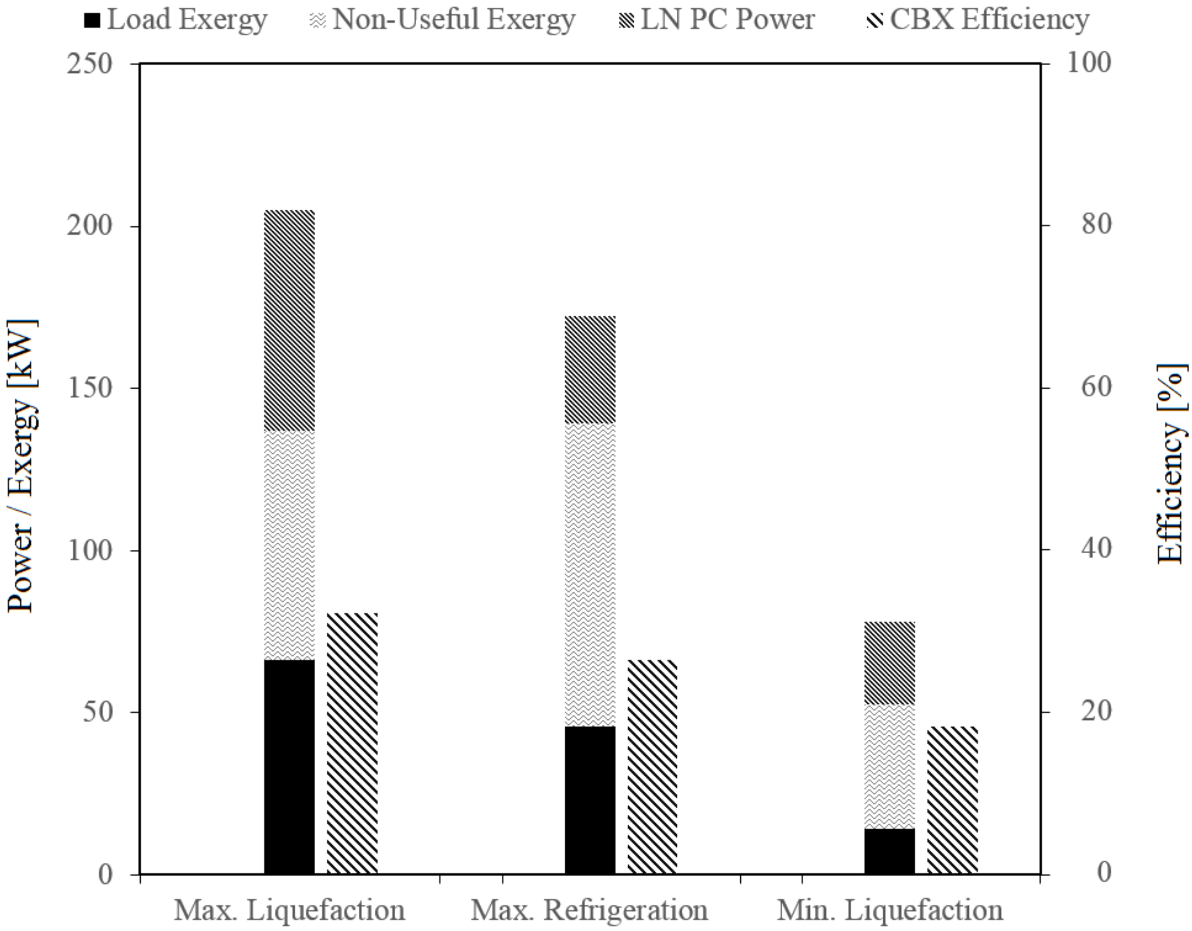

Figure 3. Cold box performance parameters at different modes of operation.

Variation of 4.5 K liquefaction capacity at different cold box supply pressures ranging from 7.0 bar to 15.0 bar is shown in figure 4. It is observed that the 4.5 K liquefaction rate increases with the increase in supply pressure until it reaches a maximum liquefaction rate at approximately 14.0 bar. At supply pressures greater than 14.0 bar, no significant change in the 4.5 K liquefaction rate was observed. This is possibly due to the limitations of the cold box (heat exchanger, turbo-expanders etc.). It is important to understand the performance of the cryo-plant at different supply pressures – to match the capacity during times of lower demand. It is to be noted that the data shown in figure 4 is based on operating two warm compressors. For energy saving in the long term, it is also important to learn the cold box performance (capacity) with flow from only one warm compressor and at different cold box supply pressures. However, tests at this configuration could not be performed yet due to scheduling constraints.

Several areas for improvement were identified during the commissioning and acceptance testing of the cold box. As shown earlier, the liquid nitrogen (LN) is directly injected into the pre-cooler heat exchanger. This configuration of the pre-cooler makes it harder to control the LN flow through the heat exchanger (due to two-phase heat exchange in the piping) [2]. During the commissioning, the LN supply valve was found to oscillate between its minimum and maximum positions, which created minor oscillations in the cold temperatures. Tuning the PID control loop for the LN supply valve dampened the oscillations to some extent. Some of the conditions for the cold box shut-down and restart (stable supply and return pressure from cold box, low pre-cooler temperature, etc.) were found to be too constrictive. These were relaxed after detailed discussion with the manufacturer. The control signal for the cooldown bypass valve (between HX-5a supply upstream to HX-5b return downstream) was found to be erroneous. This resulted in several cold box shut downs during the commissioning period (and later) due to improper capacity control. It was set to operate on the turbo-expander 1 inlet temperature for better capacity control of the cold box.

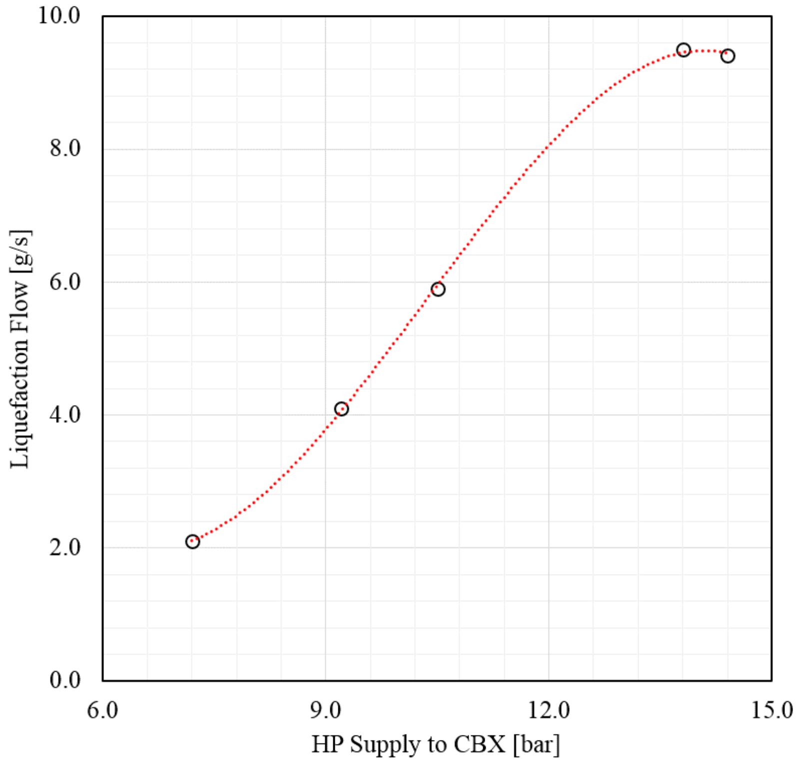

Figure 4. 4.5 K liquefaction capacity at different cold box supply pressures.

5. Conclusion

The new 4.5 K cold box at CTF was installed in spring 2017 and the commissioning and performance testing was completed by early summer of 2017. As the cold box exceeds the expected liquefaction capabilities, it will greatly improve the capacity of the CTF cryogenic system. The work accomplished for the new 4.5 K cold box will benefit developing and testing cryo-modules for the LCLS-II project at SLAC and for other cryo-modules in the future. In the near future, the new 4.5 K cold box will be further tuned to operate efficiently with the existing cryogenic system at CTF.

6. References

[1] Ganni V and Knudsen P 2009 Optimal design and operation of helium refrigeration systems using the Ganni cycle *AIP Conference Proceedings* **1218** 1057-71.

[2] Knudsen P and Ganni V 2009 Helium refrigerator liquid nitrogen pre-cooler component parameter sensitivity analysis *AIP Conference Proceedings* **1218** 215-22.

Acknowledgments

The authors would like to express their appreciation and thanks to the TJNAF management and to their colleagues for their support. This work was supported by the U.S. Department of Energy under contract no. DE-AC05-06OR23177.