

4.5-K Refrigerator Cold Box System for the 12 GeV Upgrade at JLab

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In September 2009 Linde Cryogenics, a division of Linde Process Plants, Tulsa, Oklahoma, was awarded the contract to deliver an 18 kW 4.5-K equivalent refrigerator system to JLab in Newport News, Virginia. This system includes upper (300 to 60-K) and lower (60 to 4.5-K) cold boxes, interconnecting transfer lines and auxiliary equipment. Linde Kryotechnik AG will supply seven large dynamic gas bearing expansion turbines and the engineering design for this refrigerator. In conjunction with JLab's second 2.1-K cold box, this refrigerator system will allow JLab to double its current 2.1-K refrigeration capacity of 4600 W as part of the accelerator upgrade to 12 GeV.

BACKGROUND

As shown in Figure 1, the present Central Helium Liquefier (CHL-1) at JLab supports 22-1/4 cryomodules (using SRF Niobium cavities) in a 'north' LINAC, 20 in a 'south' LINAC and 3-1/4 at the Free-Electron Laser (FEL). The CHL-1 operates in conjunction with a 2.1-K cold box which houses five stages of centrifugal cold compressors [1]. The new 4.5-K cold box (CHL-2) will operate with a duplicate 2.1-K cold box. In the 12 GeV configuration, five new style cryomodules will be added to the north and five to the south LINAC, doubling the total LINAC load [2]. Both new and old 4.5-K and 2.1-K cold boxes will have approximately the same capacity, with one supporting the north LINAC and the other the south LINAC and the FEL [3].

DESIGN BASIS AND PERFORMANCE DATA

Table 1 presents an abbreviated summary of JLab's specification for the cold box design basis. It consists of six different operational (design) modes defined to promote a balanced design by ensuring a proper selection of the expanders and heat exchangers thereby avoiding in the design unnecessary performance limitations and plant inefficiencies at off-design mode and/or load operation. However, the utility of the

design modes is limited to the design phase. For commissioning and operation a ‘mode’ concept will not be implemented since the plant will find its optimal working point for the applied load automatically [4]. Rather, by using the floating pressure – Ganni cycle (licensed to Linde) in cooperation with the Linde dynamic gas bearing turbines and the presented flexibility of the plant, a high overall system efficiency can be maintained automatically (i.e., without manual intervention, except for intentional shut-down of equipment in extreme capacity reduction cases) and in a very simple manner for any potential ‘modes’ and loads.

Table 1 Design modes (abbreviated) per customer specification [5]

#	Design Mode	Load @ 2 K [g/s] *	Load @ 4.5 K [kW]	Liquefaction [g/s]	Load @ 30 K [kW]
1	Maximum capacity (CBX supporting maximum cold compressor operation)	>238	0	>15	>12
2	Nominal capacity (CBX supporting nominal cold compressor operation)	>200	0	0	>7.5
3	Maximum 4.5-K liquefaction	0	0	>150	>7.5
4	Maximum 4.5-K refrigeration	0	>10.5	0	>12
5	Maximum fill (of Linac cryo-modules)	>200	0	>35	>12
6	Stand-by 4.5-K refrigeration**	0	>2.5	0	>12

* Load at 2.1 K means supply flow at 3.2 bar 4.5 K, with return flow at 1.2 bar 30 K

** Mode 6 requires a minimum amount of rotating equipment while supporting the LINAC loads at 4.5-K.

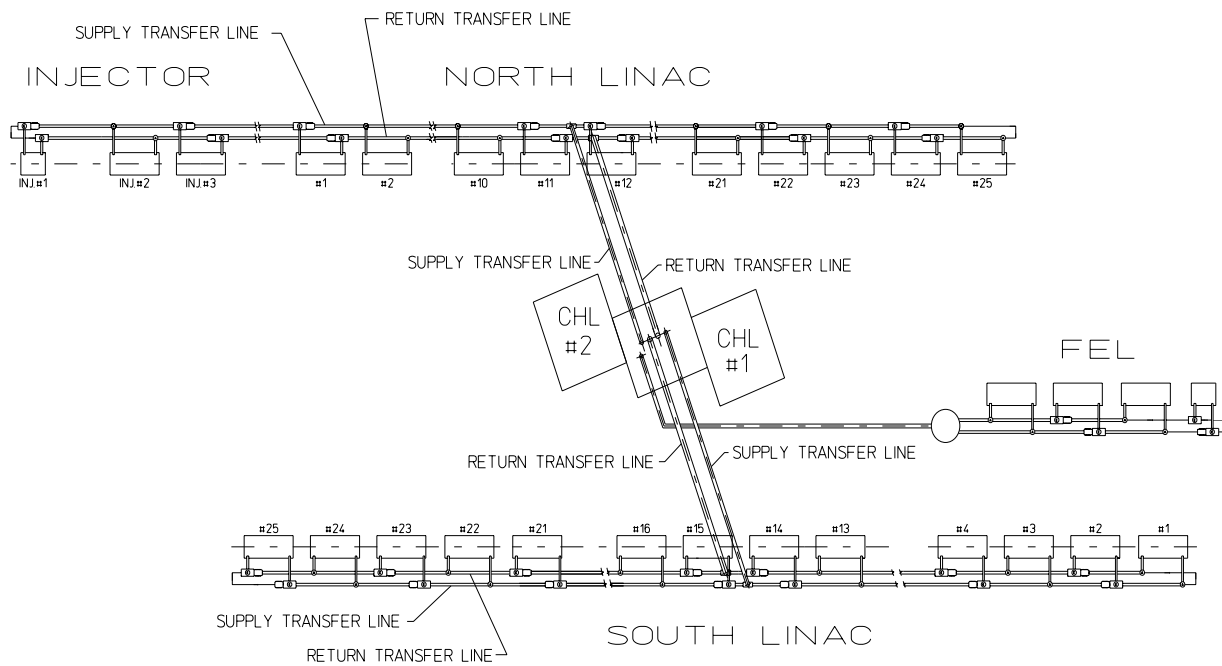


Figure 1 Installation of new refrigeration plant at JLAB

As required by the JLab specification [5], the objective of the CBX design was to achieve a maximum total 4.5-K plant exergetic efficiency for all design modes by using a minimum number of compressors from a specified set of compressor frame sizes and operating with a specified set of isothermal and volumetric efficiencies that are a function of the stage (low or high) and the pressure ratio (similar to [6]). Also, estimate motor efficiencies were specified and it was required that all compressors in each stage utilize the same frame size. Since the CBX uses LN pre-cooling, the equivalent input power

for this utility was determined from the exergy provided by the LN and a (assumed) production efficiency of 35%. So, although the compressor system was not within Linde’s scope of work, the CBX design compelled its selection in a manner that would optimize the total 4.5-K plant efficiency. In Figure 2 the design modes are ordered by total load exergy and plotted together with the expected exergetic efficiencies of the cold box (CBX) and total 4.5-K plant (i.e., CBX, LN and compressor system) efficiency.

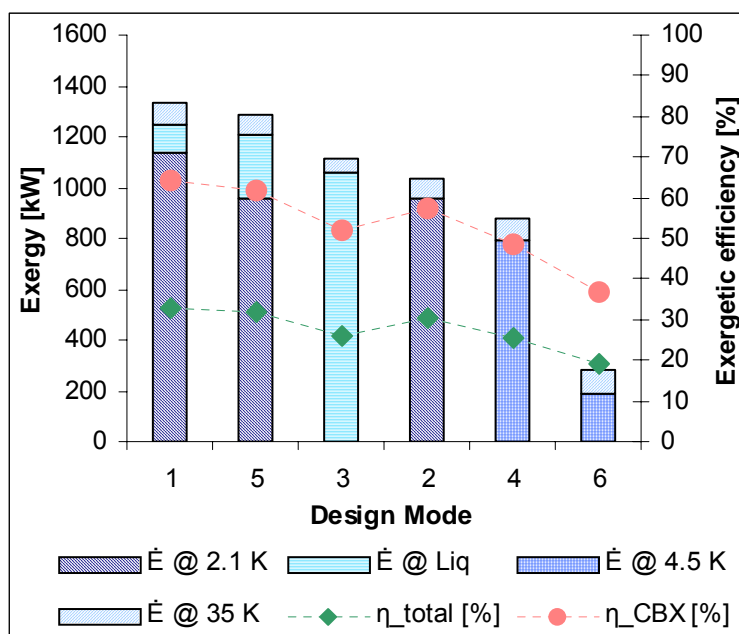


Figure 2 Load exergies and expected efficiencies

FURTHER DESIGN CONSIDERATIONS AND SELECTED FEATURES

The refrigerator consists of two CBX’s, one “upper” CBX for the temperature range of 300 to 60-K and one “lower” CBX for the range of 60 to 4.5-K (see Figure 3). By separating the refrigerator into two CBX’s, existing site space allocation constraints are eased, on-site installation cost and complexity is greatly reduced, the long heat exchangers (HX’s) in the upper CBX can be oriented vertically in a single core and the expansion turbines in the lower cold box can be located indoors inside a horizontal cold box facilitating access for maintenance. All HX’s in the upper and lower CBX’s will be installed vertically with the warm-end upwards; an ideal situation that is often inhibited by site constraints. The upper CBX utilizes LN pre-cooling in the configuration of a thermo-siphon and is arranged to ensure proper phase-separation thereby allowing minimal LN usage [7]. The 300 to 80-K helium-helium HX is quite long and separate from the 300 to 80-K high-pressure helium-nitrogen HX. In conjunction with flow balancing valves this will also promote minimal LN usage [7]. Although, for process reasons it is preferable to split the upper and lower CBX’s at the 80-K temperature level to allow the interconnecting transfer-line heat leak to be adsorbed by the LN, the 80 to 60-K HX could not be reasonably fit into the required lower CBX prescribed size constraints. For mode 1, the HX’s have 54.5 total NTU’s between 300 to 80-K, 50.6 total NTU’s between 80 to 30-K and 43.1 total NTU’s between 30 to 4.5-K. Per the customer’s specification [5], HX lengths were kept to (approximately) less than 10 NTU’s per meter (of effective

length) and pressure drop ratio's between (a) core to distributors and (b) core plus distributors to headers plus nozzles to (approximately) at least a factor of three. This is intended counter any flow maldistribution as a result of unintended manufacture peculiarities and/or reduced flow at a capacity turn-down condition (to approximately 30%).

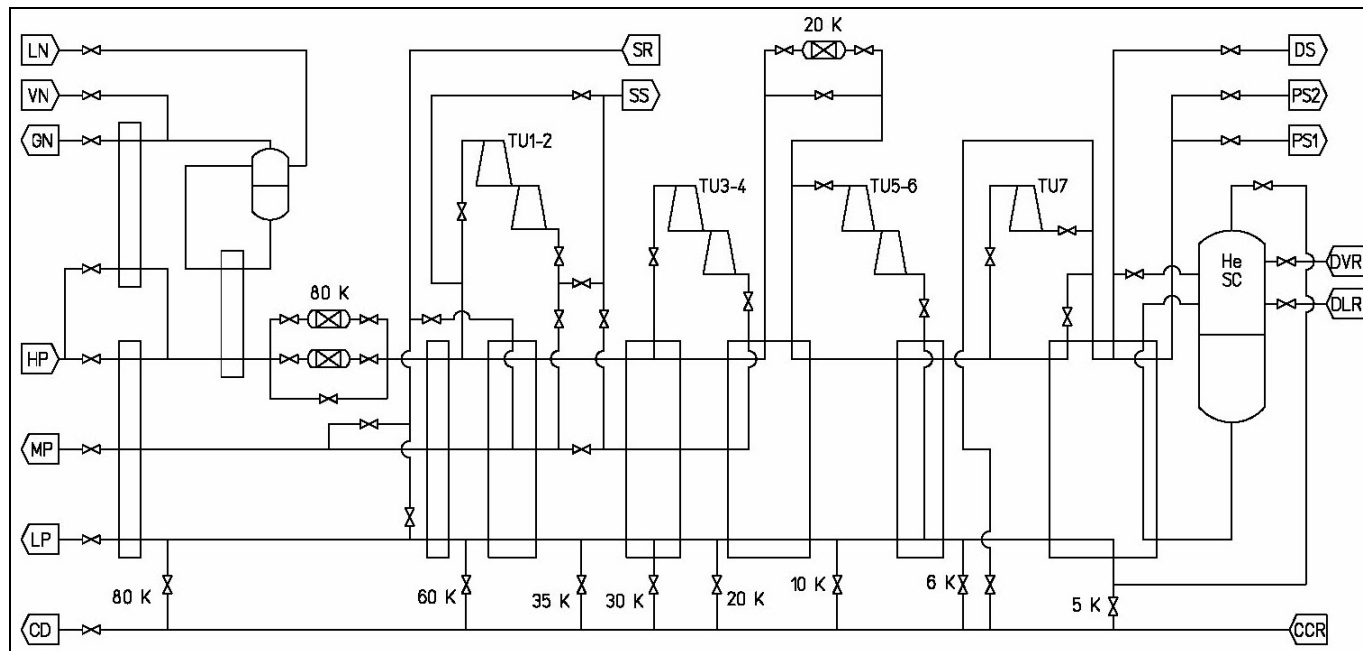


Figure 3 Process flow diagram

To ensure maximum efficiency, for modes 1 and 2 (the primary design modes) the temperature ratio of the expansion stages below 30-K (the cold compressor return temperature) were selected to result in roughly equal turbine (string) mass flows [8]. Of course, since compressor displacements are not a continuous variable, some slight adjustments are necessary to accommodate the selected compressor frame sizes. Although sophisticated process analysis was employed (due to non-ideal fluid properties and component complexities) to select the cycle and analyze component requirements necessary for an optimal design, in fact, a simple ‘Carnot Step’ analysis [8] can predict the optimum expansion stage flows and temperature ratios quite reasonably. In Figure 4, the design modes are ordered by the supply pressure to the CBX which is the same order as by total load exergy in Figure 2. Apart from the first turbine flow which is principally used to cool the thermal shield between 35 and 55 K, in load cases that consist primarily of the 2.1-K load and/or 4.5-K liquefaction, the turbine flows are close to each other for each temperature stage. Load cases that consist primarily of 4.5-K refrigeration, such as modes 4 and 6, exhibit more unequal expansion stage mass flows (and temperature ratios) since this type of load does not inherently require an imbalance [9] and the non-ideal fluid properties contribute a much larger fraction of the availability supplied to the CBX. As indicated in Figure 4, for a compressor capacity based upon mode 1, it is advantageous to utilize the JT turbine (TU7) bypass in other modes for optimal efficiency (for a given compressor capacity).

Table 2 summarizes the flexibilities built into the refrigerator to provide robustness and an ability to operate over a wide range load conditions and diverse kinds of modes.

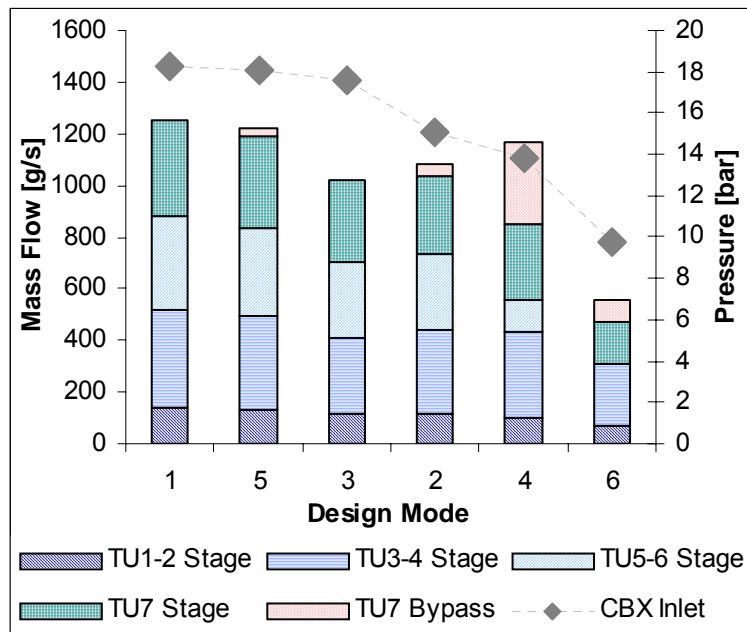


Figure 4 Turbine mass flows and Supply Pressure to CBX

Table 2 Refrigerator flexibilities

Refrigeration of each turbine string can be modulated while maintaining near optimal speed without adjusting the inlet valve by adjusting the system charge. Inlet valves will only operate under greatly reduced capacity conditions, 4.5 K refrigeration or for turbine protection.
Each turbine string can be independently shut-down, isolated, cleaned or replaced, then brought back on-line.
To assist in capacity when required, the JT expander can be bypassed by any amount with minimal perturbation to the supply with the incorporation of an upstream HX (located upstream of the bypass valve to achieve a more optimal cooling curve).
Three configurations for thermal shield cooling are possible (see Figure 3). The thermal shield may be cooled by way of the first turbine string (TU1-2), the second turbine string (TU3-4) or the LN pre-cooling stage.
Refrigerator can continue to operate, although at a reduced capacity, if there is a LN utility failure.
LN pre-cooler can utilize the sensible nitrogen vapor from the 2.1-K CBX cold compressor motors.
Dual 80-K adsorber beds can be independently isolated, regenerated and then brought back on-line. Also, both beds can be bypassed if necessary.
20-K adsorber bed can be bypassed while being isolated, regenerated and then brought back on-line.

SUMMARY

An extended process analysis at the beginning of the project for the various design modes has allowed the development of a plant with high efficiency for all design modes and considerable robustness and flexibility for diverse kinds of modes and a wide range of load adaptation. Presently, the refrigerator is scheduled to be delivered the fall of 2011. This collaboration between JLab, Linde Cryogenics and Linde Kryotechnik AG has proven to be quite successful to date.

ACKNOWLEDGMENTS

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