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# Application of JLab 12GeV Helium Refrigeration System for the FRIB Accelerator at MSU

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***Abstract.*** The planned approach to have a turnkey helium refrigeration system for the MSU-FRIB accelerator system, encompassing the design, fabrication, installation and commissioning of the 4.5-K refrigerator cold box(es), cold compression system, warm compression system, gas management, oil removal and utility/ancillary systems, was found to be cost prohibitive. Following JLab's suggestion, MSU-FRIB accelerator management made a formal request to evaluate the applicability of the recently designed 12GeV JLab cryogenic system for this application. The following paper will outline the findings and the planned approach for the FRIB helium refrigeration system.

**Keywords:** Helium, refrigeration, 2 K process, sub-atmospheric process, cycles, efficiency, cryomodule design



## INTRODUCTION

The cryogenics group at Michigan State University – Facility for Rare Isotope Beams (MSU-FRIB) developed the specifications for the cryogenic system to support the accelerator cryogenic refrigeration requirements and requested a quote from industry in 2011 based upon the conceptual design in [1]. This turnkey approach for the design, fabrication, installation and commissioning of the 4.5-K refrigerator cold box(es), cold compression system, warm compression system, gas management, oil removal and utility/ancillary systems, was found to be cost prohibitive and created a risk for the viability of the entire FRIB project. To address the cryogenic system cost issues, the FRIB management requested advice from Jefferson Lab's (JLab's) cryogenic group for options. The 12 GeV upgrade cryogenic system (JLab CHL-2), based on Ganni Cycle Floating Pressure Technology [2, 3], is a balanced system design, capable of many modes of operation. With minor modifications, this cryogenic system can be easily adapted to different types of loads which have approximately the same total load exergy. The FRIB total load exergy requirement is expected to be of the same order or smaller than the 12 GeV cryogenic system. Based on JLab studies of 2-K process options [4] and experience with systems having a similar design philosophy [5, 6], it was decided to change the process from partial cold compression, as indirectly requested in the specifications, to complete cold compression similar to the JLab and SNS operating systems.

## REFRIGERATION PROCESS SPECIFICATIONS

The formal request sent to industry for quote in 2011 by the FRIB cryogenics group had the process requirements shown in Table 1 and included an unprecedented requirement of a 7:1 turn down in 2-K capacity. This turn down requirement may have influenced the design choice towards the partial cold compression process.

If a complete cold compression process, similar to JLab and SNS, is used, the 4.5-K refrigerator system capacity required for FRIB is shown in Table 2. The various process options for the 2-K process were evaluated and the complete cold compression process was selected, which has the advantages summarized in [4]. For this process, a higher 4.5-K capacity is required, relative to a cycle that uses partial cold compression, to eliminate the warm sub atmospheric compression power.

As is evident from Table 2 and 3, the specified cryogenic system capacity is larger than the JLab 12 GeV upgrade cryogenic system; which has a total refrigeration capacity of 1332 kW. In an effort to maintain project viability, MSU-FRIB agreed to a revised plan developed by JLab. This plan started with a cooperative JLab/FRIB comprehensive reassessment of cryomodule (CM) and distribution heat loads with a number of revised requirements

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**TABLE 1**. The FRIB system capacity as requested from industry in 2011

| *MSU FRIB: "Turnkey" Mode-1 as specified †* | | *Supply* | | *Return* | | | | |
|---|---|---|---|---|---|---|---|---|
| **Load Description** | *w* | p | T | p | T | q | $E_L$ | % $E_{L,tot}$ |
| | [g/s] | [bar] | [K] | [bar] | [K] | [kW] | [kW] | [-] |
| **Shield** | 190.9 | 5.07 | 38.00 | 4.05 | 55.00 | 16.98 | 120.7 | 8.9% |
| **4.5-K Refrigeration** | 266.1 | 3.04 | 4.45 | 1.27 | 4.55 | 5.00 | 348.0 | 25.5% |
| **4.5-K Liquefaction** | 9.0 | 3.04 | 4.45 | 1.27 | 300.00 | *N/A* | 60.3 | 4.4% |
| **Sub-atmospheric** | 216.3 | 3.04 | 4.45 | 0.0292 | 4.00 | 5.26 | 834.7 | 61.2% |
| | | | | | | | **1364** | |
| † *Saturation pressure at 4.55 K is 1.342 atm. Saturation temperature at 1.25 atm is 4.468 K* | | | | | | | | |

based on JLab and SNS experiences. These include bayonet type disconnects between the CM and the distribution system, as well as, valves required for process control, cool down and warm up of CM 4.5-K and 2-K components. The additional process valves reflect the MSU-FRIB requirement for independent warm up and cool down of the magnets in the CM's for degaussing. It has been recognized that additional refrigeration capacity will be required to implement these changes, but the operational benefits outweigh the importance of the increased heat load. The heat stationing of the support structure and the other components were also revised to minimize the total load exergy required for the CM. In addition, a decision was made to incorporate a 4 to 2-K heat exchanger for each CM. The CM flow diagram, shown in Figure 1, has been developed based on the studies done by JLab [7, 8].

Based on this proposed revised configuration and CM design and on JLab and SNS experience for similar cryogenic distribution systems [9], the cryogenic load requirements were revised, which are given without any margin added as shown in Table 4. The distribution system load estimates were comparison checked with respect to the measured values at JLab and SNS to provide confidence in these estimates.

The FRIB load size and types are different from the 12 GeV cryogenic system. The main differences are that the FRIB cryogenic system must handle a 4.5-K magnet load and a 50% larger shield load as compared to the 12 GeV cryogenic system. However, the 12 GeV cryogenic system design was based on a balanced system design, capable of efficiently adjusting to varying capacity and load characteristics using the Ganni Cycle Floating pressure process [2, 3]. JLab conducted all the process studies required to evaluate if the recently designed 12 GeV cryogenic system could be adopted for the FRIB application.

The calculated (no margin added) loads for FRIB at various temperatures are summarized in Table 4. The 4.5-K, ~1 bar return distribution heat loads are shown under '5-K Sensible' column and the 2-K, ~0.03 bar return distribution heat loads, after the 2 to 4-K heat exchanger in the CM's, are shown under '4-K Sensible' column in the Table 4. The distribution system heat load to the sub atmospheric flow (4-K Sensible) is absorbed into the cold compressor (CC) inlet flow, thus raising the CC inlet temperature but not contributing to increased 2-K mass flow rate. The refrigeration demand at the design loads on the 4.5-K system is given in Table 5. Although the primary goal is to reduce the cryogenic systems costs by adopting the 12 GeV cryogenic systems, the desire to have a 50% capacity margin based on the estimated loads is also an important consideration. The refrigeration capacity margin is intended for the uncertainties in the load estimates, performance deficiencies in the system components, and future upgrades for the FRIB accelerator system.

**TABLE 2:** 4.5-K system capacity required if complete cold compression is used

| *MSU FRIB: "Turnkey" Mode-1 on 4.5-K CBX* | | *Supply* | | *Return* | | | | |
|---|---|---|---|---|---|---|---|---|
| **Load Description** | *w* | p | T | p | T | q | $E_L$ | % $E_{L,tot}$ |
| | [g/s] | [bar] | [K] | [bar] | [K] | [kW] | [kW] | [-] |
| **Shield** | 190.9 | 5.07 | 38.00 | 4.05 | 55.00 | 16.98 | 120.7 | 7.9% |
| **4.5-K Refrigeration** | 270.3 | 3.04 | 4.55 | 1.25 | 4.45 | 5.00 | 357.3 | 23.5% |
| **4.5-K Liquefaction** | 9.0 | 3.04 | 4.55 | 1.06 | 300.00 | *N/A* | 61.0 | 4.0% |
| **Cold Compressor** | 216.3 | 3.04 | 4.55 | 1.17 | 30.00 | 33.91 | 981.4 | 64.5% |
| | | | | | | | **1520** | |

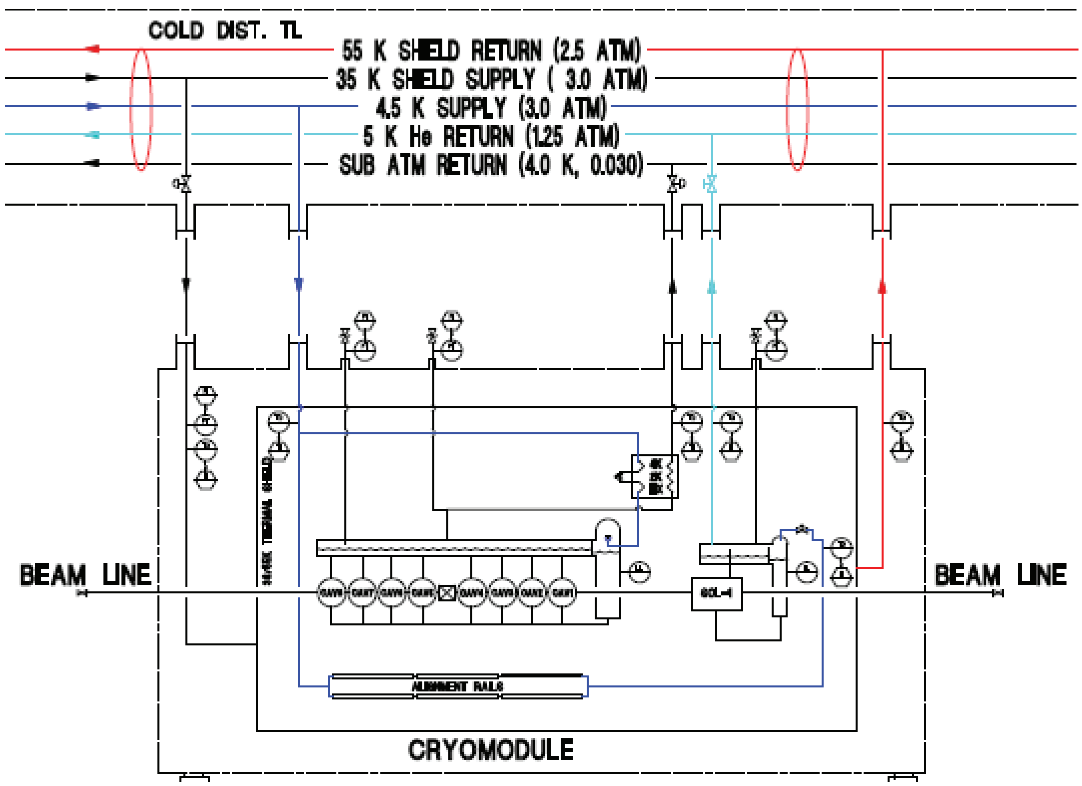


**FIGURE 1**. The CM flow diagram and the interface to the cold distribution

**TABLE 3.** Planned 4.5-K system capacity for the JLab 12GeV system

| *JLab 12GeV Mode-1: Max. Capacity* | | ***Supply*** | | ***Return*** | | | | |
|---|---|---|---|---|---|---|---|---|
| **Load Description** | *w* | **p** | **T** | **p** | **T** | **q** | **E$_L$** | **% E$_{L,tot}$** |
| | **[g/s]** | **[bar]** | **[K]** | **[bar]** | **[K]** | **[kW]** | **[kW]** | **[-]** |
| **Shield** | 131.3 | 3.17 | 34.99 | 2.67 | 53.37 | 12.6 | 88.5 | 6.6% |
| **4.5-K Refrigeration** | 0.0 | 3.25 | 4.55 | 1.25 | 4.45 | 0.0 | 0.0 | 0.0% |
| **4.5-K Liquefaction** | 15.8 | 3.25 | 4.55 | 1.07 | 308.50 | *N/A* | 107.2 | 8.0% |
| **Cold Compressor** | 250.0 | 3.25 | 4.55 | 1.16 | 30.00 | 39.7 | 1136.8 | 85.3% |
| | | | | | | | **1332** | |

**TABLE 4**. Estimated heat loads for FRIB

| ***FRIB Design Loads*** | | | | | | |
|---|---|---|---|---|---|---|
| **Component** | **40 K Shield [kW]** | **4.5-K Refrigeration [kW]** | **4.5-K Liquefaction [g/s]** | **5-K Sensible [kW]** | **2-K Refrigeration [kW]** | **4-K Sensible [kW]** |
| Distribution Total | 4.62 | 0.18 | | 0.27 | | 0.51 |
| Cryomodule Static | 7.92 | 1.68 | 1.8 | | 0.41 | |
| Cryomodule Dynamic | 0.77 | 0.47 | 1.4 | | 2.09 | |
| **Predicted Loads** | **13.31** | **2.33** | **3.2** | **0.27** | **2.50** | **0.51** |

**TABLE 5**. 4.5-K system capacity required for FRIB with no margin

| *MSU-FRIB Design Loads* § ‡ | | ***Supply*** | | ***Return*** | | | | |
|---|---|---|---|---|---|---|---|---|
| **Load Description** | ***w*** | **p** | **T** | **p** | **T** | **q** | **E$_L$** | **% E$_{L,tot}$** |
| | **[g/s]** | **[bar]** | **[K]** | **[bar]** | **[K]** | **[kW]** | **[kW]** | **[-]** |
| **Shield** | 127.5 | 3.00 | 35.00 | 2.50 | 55.00 | 13.3 | 91.5 | 10.6% |
| **4.5-K Refrigeration** | 140.9 | 3.25 | 4.55 | 1.25 | 4.45 | 2.6 | 187.3 | 21.6% |
| **4.5-K Liquefaction** | 3.2 | 3.25 | 4.55 | 1.10 | 300.00 | | 21.7 | 2.5% |
| **Cold Compressor** | 125.0 | 3.25 | 4.55 | 1.20 | 30.00 | 19.8 | 565.7 | 65.3% |
| | | | | | | | **866** | |
| *§ Assumed 20 J/g for 2-K load effective latent heat; i.e., 2500 W / 20 J/g = 125 g/s.* | | | | | | | | |
| *‡ 4-K sensible heat affects cold compressor discharge temperature, not the flow requirement to the 2-K load.* | | | | | | | | |

Although the overall margin of the 4.5-K refrigerator capacity to total load exergy requirement is maintained at greater than 50% (1339 kW 4.5-K plant capacity vs. 866 kW for the calculated load; Table 6 to 5), the individual margins are somewhat biased towards the more uncertain loads like 4.5-K refrigeration and liquefaction. These loads are associated with the magnets and the heat leaks to the supports in the CM and distribution system. The margins are biased less towards the cold compressor flow, due to turn down considerations. Additional margin is allocated for 4.5-K liquefaction since this can be used very effectively by the floating pressure process for any load, especially magnet lead cooling and the cold compressor load. With these considerations in mind, the cryogenic system capacity requirements developed for the FRIB refrigeration system are shown in Table 6.

Once the applicability of the 12 GeV cryogenic system to the FRIB accelerator was recognized, FRIB management was ready to deal with the commercial aspect of the procurement, since it will reduce the cost, technical risk and schedule. JLab has also calculated the FRIB cryogenic system capacity for other modes of operation, similar to those of 12 GeV. Then the process analysis with required modifications to the turbine flow coefficients and other changes were provided to Linde Kryotechnik (LKT), who provided the process design for the 12 GeV cold boxes. LKT confirmed the applicability of the 12GeV cold box to the FRIB cryogenic system and its ability, with modified turbine capacities, to meet FRIB load. Figure 2 shows the load exergy comparison for each mode between 12 GeV and FRIB. As a result of this analysis, FRIB management decided to select this 4.5-K refrigerator.

The cryogenic system is planned to be designed for independent commissioning of the 4.5-K refrigeration system (i.e., independent of the Linacs), similar to SNS and JLab CHL-2. The 2-K system is planned to be commissioned with very few CM's in the Linac, also similar to SNS. This independent commissioning will provide the flexibility required for planning and scheduling the installation of the refrigeration system. This allows the commissioning activities of the overall system, including the various sections of the Linac, to be, more flexible. The distribution system [9] is planned to provide independent operation of the three Linacs at 4.5-K and 2-K. This will facilitate the commissioning support of the CM's .

**TABLE 6**. Planned 4.5-K system capacity for FRIB with margin

| *MSU-FRIB Mode-1: Max. Capacity* | | ***Supply*** | | ***Return*** | | | | |
|---|---|---|---|---|---|---|---|---|
| **Load Description** | ***w*** | **p** | **T** | **p** | **T** | **q** | **E$_L$** | **% E$_{L,tot}$** |
| | **[g/s]** | **[bar]** | **[K]** | **[bar]** | **[K]** | **[kW]** | **[kW]** | **[-]** |
| **Shield** | 192.5 | 2.88 | 35.00 | 2.63 | 54.90 | 20.0 | 126.8 | 9.5% |
| **4.5-K Refrigeration** | 227.6 | 3.25 | 4.55 | 1.25 | 4.45 | 4.2 | 302.5 | 22.6% |
| **4.5-K Liquefaction** | 14.0 | 3.25 | 4.55 | 1.08 | 307.80 | *N/A* | 94.9 | 7.1% |
| **Cold Compressor** | 180.0 | 3.25 | 4.55 | 1.20 | 30.00 | 28.6 | 814.7 | 60.8% |
| | | | | | | | **1339** | |

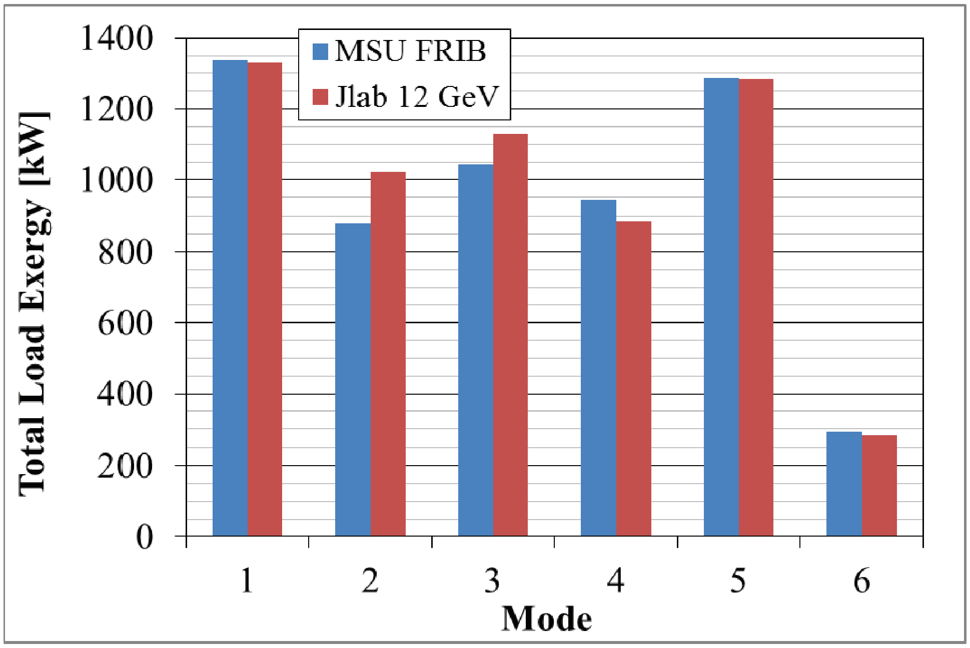


**FIGURE 2**. Refrigeration capacity comparison for various modes between 12 GeV vs FRIB. Mode-1 is maximum capacity. Mode-2 is the nominal capacity. Mode-3 is maximum liquefaction. Mode-4 is maximum refrigeration. Mode-5 is the maximum fill (i.e., nominal capacity plus liquefaction). Mode-6 is the stand-by capacity.

FRIB presently plans to procure all other applicable sub systems based on the 12 GeV and SNS designs developed by JLab. Most of these sub systems were designed by JLab and procured as build to print designs on a competitive basis from various vendors. In addition, the support systems needed (e.g., electric power, cooling water etc.) for the helium refrigeration system have also been reduced to less than half from the previous plans.



## COMMENTS ABOUT CRYOGENIC SYSTEM PROCUREMENT

"Turnkey" approaches appear attractive and easier for users wanting to transfer most of the work to industry. However, "turnkey" large-scale, non-standard systems, different from a manufacturer's standard product line, can be very expensive. Especially when many of the required subsystems are not the "turnkey" supplier's primary expertise; e.g., compressor skids from a refrigerator manufacturer, or vice versa. Flexible system design is also very important in operating the system at maximum efficiency since the everyday actual loads are typically somewhat different from the ***estimates*** which may also include unplanned loads and various margins in the planning. For a system integrator it is also critical to understand the strengths and limitations demonstrated by various suppliers. These statements on integration activities are equally true of the non-specialized equipment, that is, infrastructure and utilities, such as cooling water systems, motor control centers, power distribution systems, etc. As a consequence of these factors substantial project risks and increase cost can be incurred with the "turnkey" approach.

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