Testing and analysis of stand-by operating modes for FRIB helium refrigeration system

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Abstract. The main helium refrigeration system at FRIB is designed for a maximum capacity of 180 g/s (30K, 1.16 bar) cold compressor return flow, 14.0 g/s of 4.5 K liquefaction load, 4.0 kW 4.5 K refrigeration load and a 20.0 kW (35 – 55 K) thermal shield load. The helium refrigeration system operates using the Ganni Floating Pressure process and can adjust to a range of variable cryogenic load conditions without any artificial loads. It is designed considering long-term 24/7 support for the loads (cryostats and superconducting magnets) maintained at 4.5 K, without the need for a complete warm-up to room temperature. A number of maintenance, repair and outage scenarios, and the corresponding stand-by operating modes for the refrigeration system with the base-line cryogenic load have been considered, tested and analysed. This paper reports an overview of these stand-by modes and the associated analysis.

1. Introduction

The superconducting radio frequency (SRF) linear accelerator (LINAC) at the Facility for Rare Isotope Beams (FRIB) at Michigan State University is designed to provide up to 400 kW for all beams [1]. The cryogenic loads for the LINAC and its’ associated experimental system are due to 46 cryo-modules (comprised of superconducting solenoids and SRF Niobium resonator cavities), 4 superconducting dipoles and 14 other large superconducting dipole and quadrupole magnets [2-4]. The SRF cavities are designed to be operated at sub-atmospheric pressure (nominally at 2.0 K, or 30 mbar-absolute, accomplished using cryogenic compression process), while the rest of the loads are to be supported at 4.5 K. A helium cooled thermal shield (around 55 K) is used in all these loads for intercepting heat in-leak from thermal radiation. In total, the FRIB helium refrigeration system is required to support the following type of loads during accelerator operations – (a) the return from the cryogenic (cold) compressors (at around 30 K), (b) 4.5 K refrigeration, (c) 4.5 K liquefaction and (d) 35-55 K helium thermal shield [5].

The FRIB helium refrigeration system was commissioned in late 2017 and is designed based on the Ganni Floating Pressure cycle and offers a wide range of operational flexibility. The testing for the design-operating modes and performance mapping was completed in early 2018 [5]. In the present paper, testing, and analysis of the stand-by operating modes for the FRIB helium refrigeration system is discussed. The refrigerator system may need be operated in a stand-by mode (i.e. 4.5 K refrigeration with thermal shield) under various circumstances. These could be during – accelerator / cryogenic system maintenance, reduced utility (electrical power or liquid nitrogen) operation during natural calamities, or equipment failure (e.g., turbo-expander). Testing the system operability under these ‘off-design’ modes is very important. Maintaining the system operability during these conditions would
reduce thermal cycles on the critical components (i.e., superconducting magnets, SRF cavities) and the cryogenic system, preserve the helium inventory during maintenance, minimize down-time for accelerator operations, and improve availability of the cryogenic system.

For each of these ‘off-design’ modes, the exergy supplied to the refrigeration system is calculated based on the process measurements and are then compared. The insights obtained from the observations during the testing period and their corresponding analyses are utilized for developing procedures for system operation and maintenance.

2. FRIB helium refrigeration system

![Simplified schematic diagram of the FRIB 4.5 K refrigerator lower cold box (turbo-expander segment only).](image)

The FRIB helium refrigeration system has available a total of 6 warm compressors - 3 low pressure stages, 1 medium pressure stage, 1 high pressure stage, and 1 swing (i.e., low to high, or medium to high) stage. Details regarding the compressors and their performance testing can be found in [6].

In addition to the compressor system, the refrigeration system is comprised of a 4.5 K refrigerator cold box and a sub-atmospheric cold box. The 4.5 K refrigerator cold box is physically separated into an upper cold box (300 to 60 K) and a lower cold box (60 to 4.5 K) and has three process streams – high pressure (HP), medium pressure (MP), and low pressure (LP). The upper cold box has not turbo-expanders, and uses liquid nitrogen (LN) pre-cooling (along with refrigeration recovery from MP and LP streams) to cool the HP stream to 80 K. The lower cold box houses seven (7) turbo-expanders configured in four (4) expansion stages. These turbine stages (or strings) are turbine T1/T2, T3/T4, T5/T6 and T7. The exhaust flow from the first two stages returns to the MP stream, while the exhaust from the third returns to the LP stream. The fourth stage (T7) is a JT-turbo-expander. A simplified schematic of the FRIB 4.5 K refrigerator (lower) cold box is shown in figure 1. The thermal shield would normally be supplied from the outlet of the first turbine stage and return to the MP stream at a temperature level in between these turbines (T1 and T2). However, there are other options possible for supplying helium shield flow to the loads (referring to figure 1). A bypass valve in parallel to the JT-expander (T7) is utilized during initial system cool-down or if the JT-expander is shutdown, in order to supply helium to the load. A 10,000-liter liquid helium dewar and a 2000-liter sub-cooler are downstream of the JT-expander stage. Supercritical helium flow (nominally at 3.2 bar) is supplied to these vessels. Flow to the LINAC cryo-stats (i.e., cryo-modules and folding segment dipoles) are
supplied as liquid at 1.6 bara from the 10,000-liter helium dewar. However, the experimental system superconducting magnets are supported with the supercritical helium flow from the JT-expander. A wide range of cold box performance testing (including LN usage and cold box efficiency characterization) was done earlier and is discussed in [5]. The performance testing has demonstrated that the FRIB refrigerator has good efficiency for a wide capacity range and load type. The natural load following process of the Ganni Floating Pressure cycle allowed for an efficient cryogenic system operation anywhere from a 6.0 to 21.0 bar supply pressure automatically, without operator intervention, throttling of turbines, or introducing artificial loads, while minimizing utility usage.

### 3. Testing and analysis methodology

During the stand-by operating mode testing period, the FRIB cryogenic refrigeration system supported the cryogenic loads from the accelerator and the experimental system (e.g., target and fragment separator magnet loads). Due to the folded construction of the LINAC, the cryogenic distribution is divided into three segments – LS1, LS2 and LS3. LS1 distribution supports 15 cryo-modules, LS2 distribution supports 24 cryo-modules and a superconducting dipole on the folding segment, and LS3 distribution supports 7 cryo-modules and 3 superconducting dipoles on the folding segment [2]. All these thermal loads were maintained at 4.5 K. The experimental system cryogenic distribution system had recently been commissioned and was supporting only 2 superconducting magnets; since, the remaining 12 superconducting magnets were not commissioned yet [3]. The thermal load from all these cryo-stats (and associated distribution) is estimated as presented in table 1.

| Type of Load                     | Heat Load |
|----------------------------------|-----------|
| Refrigeration (4.5 K)            | 4000 W    |
| Liquefaction (4.5 K)             | 3.0 g/s   |
| Thermal Shield (35-55 K)         | 12600 W   |

Testing data was recorded using FRIB’s data archiver system. Sufficient time to reach steady state was provided before changing between each of the stand-by modes of operation. Flow rates at the cold box interface and each turbo-expander string inlet were measured using venturi elements and corrected using real gas properties. Based on operational experience and observations during 4.5 K refrigerator performance testing [5, 7, 8], the expander efficiencies remain fairly constant over a wide operating range. The expander outlet temperatures are assumed to be accurate, and the inlet temperatures are calculated (and corrected) based on the refrigerator vendor provided expander efficiency and measured pressure ratio. This inlet temperature is then utilized to calculate the mass flow based on the venturi differential pressure and using the real gas properties (for density and isentropic exponent). This flow rate was compared with the flow rate calculated from the nozzle flow coefficient.

An overall mass balance calculation around the 4.5 K refrigerator cold box was performed to check for errors. But an overall energy balance was not done in this analysis. Input exergy to the 4.5 K refrigerator cold box was calculated from the measured process conditions, i.e.,

\[
E_{\text{input}} = \varepsilon_{HP} \dot{m}_{HP} - \varepsilon_{MP} \dot{m}_{MP} - \varepsilon_{LP} \dot{m}_{LP} \quad \text{... (3.1)}
\]

Electrical power input to the warm compressor system was also measured.

### 4. Stand-by operating modes

Six different stand-by modes of operation were tested. These include a baseline-reference case (Mode 0), a case with no LN pre-cooling (Mode 1), and 4 cases each with a turbo-expander string shutdown (Modes 2 to 5). All of these six stand-by modes of operation are detailed in table 2. The thermal loads provided in table 1 were kept constant during the testing.
Table 2. Estimated thermal load supported by 4.5 K refrigerator cold box during testing

| Mode No. | Description                                      |
|----------|--------------------------------------------------|
| Mode 0   | LN Pre-Cooling Active, All Expander Strings Operating |
| Mode 1   | No LN Pre-Cooling, All Expander Strings Operating |
| Mode 2   | LN Pre-Cooling Active, T1/T2 Expander String Shutdown |
| Mode 3   | LN Pre-Cooling Active, T3/T4 Expander String Shutdown |
| Mode 4   | LN Pre-Cooling Active, T5/T6 Expander String Shutdown |
| Mode 5   | LN Pre-Cooling Active, T7 Expander String Shutdown |

4.1. Mode 1 – No LN pre-cooling

![Figure 2. FRIB 4.5 K refrigerator process parameters (temperature, pressure, and mass flow) during Mode 1 testing.](image)

The FRIB cryogenic system operation without LN assisted pre-cooling is an important operational state to investigate due to the possibility of LN unavailability caused by severe weather or supply shortages. Under normal conditions, the FRIB 4.5 K refrigerator cold box uses LN to help cool the high-pressure stream from ambient temperature to approximately 80 K. This test was performed by shutting off the LN supply to the refrigerator cold box and allowing sufficient time for heat exchangers to redistribute their temperature profiles.

As shown in Figure 2, the 4.5 K refrigerator cold box required substantial time to reach steady state without LN pre-cooling. During this time, heat exchanger temperatures and turbine temperatures increased from normal operational conditions to compensate for the elimination of the pre-cooling provided by the LN. From figure 3, it is seen that the temperature downstream of the LN pre-cooler heat exchanger warmed up to 170 K, and the T1-T2 turbo-expander string inlet warmed up to 85 K from 55 K (in Mode 0). There were slight increases in inlet temperatures for the rest of the turbo-expander strings, as well as the HP supply pressure to the cold box. The shield circuit supply and return temperatures were affected as well. However, the shield return temperature from the loads stayed below 85 K.
4.2. Mode 2-5 – Operation without specific turbo-expander strings
As listed in table 2, stand-by operating modes 2-5 each have one of the turbo-expander strings shutdown to simulate a failure (or inoperability during maintenance). And the LN pre-cooling was used as normal (mode 0) for each of these modes.

Mode 2 has turbo-expander string T1-T2 shutdown. In this mode, the thermal shield flow is supplied to the loads from the HP stream (T1-T2 inlet) and returned at an elevated temperature level to the MP stream (refer to figure 1). Mode 5 had turbo-expander string T7 shutdown with the flow to the loads supplied using the T7 bypass valve.

5. Results and discussion
Figure 4 shows the temperature distribution within the 4.5 K refrigerator cold box for each of the modes of operation tested. It shows only the temperature distribution within the turbo-expander section in the lower cold box (i.e., downstream of the LN pre-cooler section). Note that the temperature scale (y-axis) of the plot is logarithmic. The temperature distribution shows a break in the curve when a turbo-expander string is shutdown in modes 2-5. For each expansion-stage shut-down, the corresponding ‘cooling step’ profile vanishes, and the temperature profile re-distributes. As observed from figure 3, with an isothermal refrigeration dominated load, such as the modes tested, the ‘cooling step’ profile becomes less prominent towards the colder end of the refrigerator.

Figure 3. Temperature distribution within the expander section of the FRIB 4.5 K refrigerator cold box for each of the stand-by modes of operation.

The different turbo-expander flow rates for each of the stand-by modes of operation is shown in figure 4. This figure provides an idea of the relative distribution of the cooling provided by the FRIB 4.5 K refrigerator turbo-expanders. A slight increase in T7 (the JT-expander) flow rate is observed as the other expander cooling stages are shutdown from the warmer end to the cooler end. With a constant thermal load on the 4.5 K refrigerator, the load supply flow must be increased as the supercritical load (dewar and sub-cooler) supply temperature warms up slightly. For the rest of the turbo-expander stages, the flow rate is a function of inlet temperature and pressure since the expander flow coefficients are essentially constant. Significant changes in T1-T2 and T3-T4 expander flows were observed for modes
3 and 4 since the overall load is shared by these turbo-expanders. During normal operating conditions (e.g., mode 0), the T7 expander by-pass valve will open if the supercritical supply pressure drops in order to maintain a steady flow to the loads. However, this valve remained closed during the stand-by mode 2 to 4 testing. For Mode 5, it was used to supply flow to the loads.

![Figure 4. Turbo-expander flow rates for each of the stand-by modes of operation for the FRIB 4.5 K refrigerator cold box.](image)

Figure 5 shows the measured (HP) supply pressure and flow rate to the 4.5 K refrigerator cold box, and the calculated exergy provided to cold box. All of the tested stand-by modes have a noticeable effect on the cold box (HP) supply pressure. However, as compared to mode 0, modes 3 and 4 have the most significant effect on the cold box supply pressure, while mode 5 has the least effect. This indicates that the refrigeration provided by the JT-expander (T7), for an isothermal refrigeration dominated load is not substantial.

It is also observed that the cold box (HP) supply flow rate is the lowest for mode 3. All stand-by modes except mode 3 exhibit an increase in cold supply exergy compared to mode 0. Mode 3 indicated an increase in cold box supply (HP) pressure but overall reduction in supply flow. The FRIB 4.5 K refrigerator is designed for a liquefaction dominated load [5, 8, 9], where major share of the thermal load exergy is the cold compressor flow, which can be up to 180 g/s, supplied at 4.5 and returned at 30 K. The turbo-expander nozzle flow coefficients are selected based on this load. For an isothermal refrigeration dominated load (as is the case in these tests), the T3-T4 turbo-expander string recycles more flow than is optimal, due to the fixed flow coefficient of the turbo-expander nozzles, resulting in a colder operating range. So as compared to mode 0 from an energy conservation aspect it would seem to be more efficient to operate the FRIB 4.5 K refrigerator with the T3-T4 turbo-expander string shutdown (i.e., mode 3). However, the energy savings is minimal, and for practical purposes it is better to operate as in mode 0 to avoid starting and stopping the turbines unless there is an extended period of
stand-by operations with a constant thermal load. The cold box input exergy in Mode 5 was observed to be similar to that for Mode 0. As mentioned in Sec. 2, T7 by-pass valve (JT expansion) was used in this mode to supply the refrigeration flow to the loads. The refrigeration produced by the JT expansion valve with concurrent heat exchange (in a refrigeration dominated loading) was found to be comparable to that from a JT expander (T7) stage [10]. Hence, no overall impact on the cold box supply exergy was observed.

Figure 5. Measured 4.5 K refrigerator cold box supply (HP) pressure, flow rates and calculated supply exergy for the different stand-by modes of operation.

6. Summary and conclusion
The FRIB refrigeration system was able to support the specified stand-by modes in a stable manner. During testing, the 4.5 K refrigerator provided high operational flexibility at high efficiency for all stand-by operating modes. Data collected during the testing is useful for developing operational procedures and for system maintenance planning.

It was observed that stand-by mode 5 (i.e., JT-expander shutdown) does not appear to have a significant influence on the overall refrigerator efficiency for an isothermal refrigeration dominated load. The testing also indicated the influence of each expansion stage on the refrigerator overall energy consumption in a stand-by mode. For example, operating the T3-T4 expander string with the specified loads may not be the most efficient mode of stand-by operation. Detailed process cycle models for the 4.5 K refrigerator, and associated sub-systems are being developed to better understand the behaviour of the system in these ‘off design’ operating modes. With the data collected during the stand-by operating mode testing, the overall cryogenic system can be optimized and better prepared for any needed maintenance.
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