Sub-atmospheric re-pressurization analysis of FRIB linac segment 2 cryogenic distribution system

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Abstract. The continuous wave heavy ion beam linear accelerator at FRIB consists of 46 cryo-modules, housing 324 superconducting radio-frequency (SRF) resonators and 69 superconducting solenoids. The three linear accelerator (Linac) segments, designated LS1 to LS3, are arranged in the shape of a paper clip, with 4 superconducting dipole magnets in the curved segments. The SRF resonators are operated at 2 K, requiring a sub-atmospheric helium pressure, and the superconducting magnets are operated at 4.5 K. The design of the cryogenic transfer-lines for these Linac segments is complex and contains multiple process lines. Namely, these are the primary (4.5 K) supply, and return, sub-atmospheric return, 35 K shield supply and 55 K shield return. The shield return encloses the other process lines, thermally intercepting the ambient temperature heat load. Testing was conducted on the re-pressurization and liquid levels of the 24 cryo-modules of LS2’s 2 K system. System models were developed and then compared to the test data to characterize the static heat in-leak to the cryo-modules. Reasonable agreement was found between the validated models and preliminary measurements.

1. Introduction

1.1. Background and Motivation

To reach temperatures below 4.5 K that are required for linear accelerator (Linac) SRF resonator operation, the pressure of the helium system is reduced using several stages of cryogenic (colloquially, “cold”) centrifugal compressors, thereby lowering the boiling temperature of the fluid. The motivation behind the presented experiment was to gather information on the re-pressurization rate of the sub-atmospheric system when the cold compressor system discontinues operation, known as a “trip” (intentional or not). The re-pressurization experiment was conducted on the 24 cryo-modules of LS2’s 2 K system starting from an operational 2 K pressure of approximately 30 mbar up to atmospheric conditions (around 1 bar).

To gain a deeper understanding of the process, system models were developed and then compared to the experimental data obtained during this testing and from previous system testing on the sub-atmospheric system and cryo-modules. The model developed for the current work utilizes real fluid properties and estimates the pressure changes as heat is added to the Linac and return transfer line. The intention for the model is to allow users to estimate the re-pressurization rates of systems with known heat in-leak values and/or to estimate the heat in-leak of an existing system from the measured re-pressurization rates. The former has great value for helium inventory management, operational and maintenance planning, and the latter can allow proper characterization of an existing system.
1.2. FRIB Distribution System
The Linac at FRIB has three segments, designated as LS1, LS2 and LS3, which are arranged in the shape of a paper clip. The curved portions interconnecting the straight segments have 4 superconducting dipole magnets. Each Linac segment has its own shaft transfer-line, which transports the cryogen from the helium refrigeration plant down to the Linac cryo-modules and returns the fluid to the cryo-plant. These transfer lines contain multiple process lines; namely, the primary 4.5 K supply and return, 4 K 30 mbar sub-atmospheric return (i.e., return to cold compressors), 35 K shield supply, and 55 K shield return lines. The shield return encloses the other process lines, thermally intercepting the ambient temperature heat load. A schematic of the FRIB distribution system can be seen in Figure 1.

![Figure 1: FRIB distribution system and shaft transfer line cross section](image)

2. Experimental Testing
The LS2 re-pressurization profile of SRF resonators helium vapor space and sub-atmospheric return transfer-line due to heat in-leak was experimentally obtained in March of 2021. For this testing, the sub-atmospheric system was isolated by closing the cryo-module JT (Joule-Thompson) valves to the liquid volume enclosing the SRF resonators and by closing the discharge of the cold compressors to the main cold box. Additionally, electric heat to the SRF resonator liquid volume was turned off during the testing period to ensure that the heat added to the system was exclusively due to heat in-leak.

The results captured during this experiment included the helium vapor/gas pressure of the SRF resonator liquid volume within the cryo-modules and sub-atmospheric return transfer-line and the temperature measurements of the return transfer-line process piping. The trends observed for both the pressure and temperatures can be seen below in Figures 2 and 3. Total time required to reach atmospheric conditions was approximately 5.5 hours, with a slope transition region in the curve just before 1.5 hours.

The step change in slope corresponds with the lambda transition line of helium. The lambda line for helium is the point at which the second order phase transition from helium-I to helium-II occurs. Below
2.1768 K, a portion of the helium exists as helium-II, which has superfluid properties. When the pressure rises above 50.418 mbar, the saturation temperature becomes greater than the lambda line temperature, and therefore the only fluid present is helium-I, which behaves as a classical fluid.

Figure 2: LS2 sub-atmospheric transfer-line re-pressurization - pressure profile over the duration of the experiment
3. Model Development

The present mathematical model for the re-pressurization process was intended to be a simple one-dimensional description of the process, using real fluid properties obtained using HEPAK® [1,2]. From energy conservation, neglecting the kinetic and potential energies and since there is no work performed (either shaft work or a change in the control volume boundary), the change in the total energy of a system can be described by,

$$\Delta E = \Delta U = m(u_2 - u_1) = Q$$  \hspace{1cm} (1)

Where, $E$, is the total energy [J], $m$, is the total fluid mass [kg] (liquid-gas-vapor); $u_1$, and, $u_2$, are the initial and final mass specific internal energies [J/kg]; and, $Q$, is the total heat input [J].

Using finite differences, the governing equation becomes,

$$m_h(u_{t+\Delta t} - u_t) = q \cdot \Delta t$$ \hspace{1cm} (2)

The initial overall ratio of vapor mass to total mass (i.e., a kind of overall ‘quality’ factor) for the control volume was found as,

$$x_o = \left[ \frac{\nu_{r,o}}{(1-\nu_{r,o})\rho_r} + 1 \right]^{-1}$$ \hspace{1cm} (3)
Where, the initial vapor to liquid density ratio \((\rho_v)\) and the initial liquid to total volume \((V_{r,0})\) are defined respectively as the ratio between the saturated vapor and saturated liquid densities at the initial pressure, \(\rho_v\) and \(\rho_l\), and the ratio between the saturated liquid volume and the total volume, \(V_l\) and \(V_{total}\),

\[
\rho_r = \frac{\rho_v(V_{r,0})}{\rho_l(V_{r,0})} \quad \text{and} \quad V_{r,0} = \frac{V_l}{V_{total}}
\]

The initial average fluid density \([\text{kg/m}^3]\) in the control volume is found as,

\[
\rho_o = \left[ \frac{1-x_o}{\rho_l} + \frac{x_o}{\rho_v} \right]^{-1}
\]

Then, using HEPAK®, the initial specific internal energy of the system is found from the initial pressure and density; i.e.,

\[
u_o = u(p_o, \rho_o)
\]

To assess the influence of the return transfer line piping mass, the model was modified accordingly. The total transfer line mass of the system is,

\[
m_{TL} = V_{TL} \cdot \rho_{TL}
\]

Where, \(V_{TL}\) is the return transfer-line pipe metal volume \([\text{m}^3]\); and, \(\rho_{TL}\) is the pipe metal density \([\text{kg/m}^3]\), which was assumed to be constant. Using the transfer-line mass \([\text{kg}]\) and specific heat \([\text{J/kg-K}]\), the heat absorbed \([\text{J}]\) by the metal for a given temperature difference is,

\[
Q_{TL} = m_{TL} \left( \frac{c_p_{TL} + c_p_{TLT}}{2} \right) (T_{TL,T+\Delta t} - T_{TL,T})
\]

Since the specific heat of materials can vary significantly at low temperature, the transfer-line specific heat was calculated using a NIST curve fit for 304 stainless steel [3]:

\[
C_p = 10^a + b \log_{10} T + c (\log_{10} T)^2 + d (\log_{10} T)^3 + e (\log_{10} T)^4 + f (\log_{10} T)^5 + g (\log_{10} T)^6 + h (\log_{10} T)^7 + i (\log_{10} T)^8
\]

Where, the coefficients (‘a’ to ‘i’) are as found in [3].

Although the temperature of the return transfer-line varies along its length, there are only a few temperature measurements installed. One of these was selected and assumed to reflect the overall temperature (in an average sense). Since this data was collected during the test, at a given time it was possible to interpolate the temperature of the return transfer-line (for that measurement location).

With the modification to the energy conservation to include the return transfer-line metal mass, the increase in the fluid internal energy at the next time step is,

\[
u_t + \Delta t = u_t + \frac{(n_{CM} q_{CM} + q_{TL})(\Delta t)}{m_h} - \frac{m_{TL}(c_p_{TL} + c_p_{TLT})}{m_h} (T_{TL,T+\Delta t} - T_{TL,T})
\]

\[
p_t + \Delta t = f(\rho_o, u_t + \Delta t)
\]

Where, \(n_{CM}\), are the number of cryo-modules; \(q_{CM}\), is the heat in-leak [W] to the cryo-module SRF resonator liquid volume; and, \(q_{TL}\), is the return transfer-line heat in-leak [W]. Subscripts TL and h signify the parameters associated with the transfer-line and the helium, respectively.
The model was developed into three cases:

1. Heat in-leak absorbed by the fluid (helium) only
2. Heat in-leak absorbed by both the fluid and the return transfer-line piping metal, based on measured pipe (wall) temperatures
3. Heat in-leak absorbed by both the fluid and the return transfer-line piping metal; with the return transfer-line wall temperature adjusted to match measured pressure rise

For #3, the adjustment was implemented using a factor \( \tau_{adj} \) multiplying the measured return transfer-line temperature change between each time-step.

\[
(\Delta T)_{adj} = \tau_{adj} (T_{TLt+\Delta t} - T_{TLt})
\]  

(11)

It was found that, \( \tau_{adj} = 0.86 \) met the criteria for the current model.

4. Model Results and Discussion

Specifying a sufficiently small time interval \( \Delta t \), the re-pressurization curve was integrated from 30 mbar to 1 bar for each case. The resulting re-pressurization curves are shown in figure 4, along with the baseline (“measured”) curve obtained from the experiment.

![Figure 4: LS2 sub-atmospheric transfer-line re-pressurization - comparing the results from each model case to the experimental data](image)

Figure 4: LS2 sub-atmospheric transfer-line re-pressurization - comparing the results from each model case to the experimental data
Overall, the model matches the observed behavior exhibited by the experimental data. Case 1 under-predicts the re-pressurization time, resulting in the pressure reaching atmospheric conditions 1.5 hours earlier than the experimental measurement. Case 2 over-predicts the re-pressurization time, resulting in the pressure reaching atmospheric conditions 5 hours later than the experimental measurement. With the correction factor of 0.86, case 3 can be matched to the experimentally measured data.

These results could indicate that the measured heat in-leak into the cryo-modules and/or the return transfer-line is incorrect. However, it is important to recall that the model assumes the helium remains a saturated fluid. That is, there is no super-heating of the vapor within the return transfer-line, although it is known that in reality it is superheated.

The lack of a sharp lambda transition predicted by cases 2 and 3, as compared to the measured pressure profile and case 1, indicate that the amount of heat absorbed by the return transfer-line piping metal is much less than calculated for cases 2 and 3, and the remaining heat in-leak is in fact absorbed into the gas.

5. Conclusion
The one-dimensional model developed to characterize the Linac sub-atmospheric return transfer-line re-pressurization rate has a reasonable behavior compared with experimental measurement. The present model has discrepancies near the lambda transition point, and a more sophisticated model is currently being developed to capture the physics of the actual process more accurately.

Additional re-pressurization testing is planned for Linac segments 1 and 3. These tests on LS1 and LS3 will be followed by a similar evaluation and analysis to LS2, allowing for further verification of the developed model. By estimating the re-pressurization rates for three distinct systems, the fidelity of the model can be checked and adjusted as necessary.

It is anticipated that the modelling tools developed from this study and future studies will provide a practical tool for the characterization of large-scale sub-atmospheric helium systems. Characterizing the re-pressurization rates and heat in-leak of these systems is valuable for system operation and maintenance planning and provides important information on the maximum allowable operator response time to a shutdown of the cold compressor system.

6. References
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