Development and verification of a steady-state operating methodology for wide-range operation of 2 K cold compressor system

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Abstract. Superconducting radio frequency (SRF) cavities used in modern particle accelerators require operation at 2 K with superfluid helium. For large-scale systems, the most practical approach is to use multi-stage cryogenic centrifugal compressors (cold compressors or CCs) to compress the sub-atmospheric helium returning from the load to positive pressure with a pressure ratio in the order of 40. The mass flow rate through the compressor train is typically controlled with a primary compressor, while the remaining compressors are coupled to the primary compressor through electronic speed ratios. Historically, the steady-state system parameters (*e.g.* speed ratios) for a specific operating point were obtained empirically from extensive testing. Hence, the operating regime for these systems remained limited regardless of the actual 2 K load requirement. However, stable operation of the cold compressor system over a wide range of (mass flow) capacities to match the actual 2 K load is a major factor to meet the accelerator goals. In an event where the required 2 K load flow is lower than the design, overall cryogenic system operational cost savings from turning down the CC flow (a challenging task) can significantly outweigh the inefficiencies due to operation of the cold compressor system outside of its peak efficiency regime. Each g/s of reduction in CC mass flow can result in a 15 – 20 kW reduction of input power at the main 4 K refrigerator compressor system. A steady-state operating algorithm has been developed to improve 2 K system reliability and stability over a wide range of steady-state operational conditions. An in-house mean-line centrifugal compressor characterization model is used in conjunction with the developed algorithm to estimate the selection of electronic speed ratios for optimal stability under a given load (flow). Functionality and validity of the developed steady-state methodology is tested using the FRIB cold compressor system up to a 2:1 turn-down capacity range. Excellent agreement between the model predictions and the FRIB cold compressor system response is observed and presented.

1. Introduction

1.1 FRIB 2 K System

The Facility for Rare Isotope Beams (FRIB) employs a sub-atmospheric cryogenic system which enables cooling capabilities below the normal boiling point (NBP) of helium (~ 4.2 K). This system is critical for operation of the linear accelerator (linac), which utilizes superconducting radio frequency (SRF) cavities requiring helium bath temperatures near 2 K. The sub-atmospheric system lowers the helium bath temperature below the NBP of helium by reducing the cryostat pressure, thereby decreasing the corresponding saturation temperature until reaching the target operational temperature.

Evacuation of the helium vapor (*i.e.* reduction of the cryostat pressure) is achieved at FRIB exclusively using cryogenic centrifugal compressors (cold compressors, or CCs). The FRIB sub-atmospheric system consists of five cold compressors which are operated in series, producing an overall pressure ratio of approximately 40. Helium vapor returning at a pressure of 30 millibar (corresponding to a saturation temperature of ~ 2 K) is compressed by the CC train to above atmospheric pressure, and the flow is subsequently injected back into the main 4 K refrigeration system. A simplified schematic of the FRIB cryogenic system is provided in Figure 1. The benefits of full cold-compression sub-atmospheric systems are discussed in detail within [1, 2].

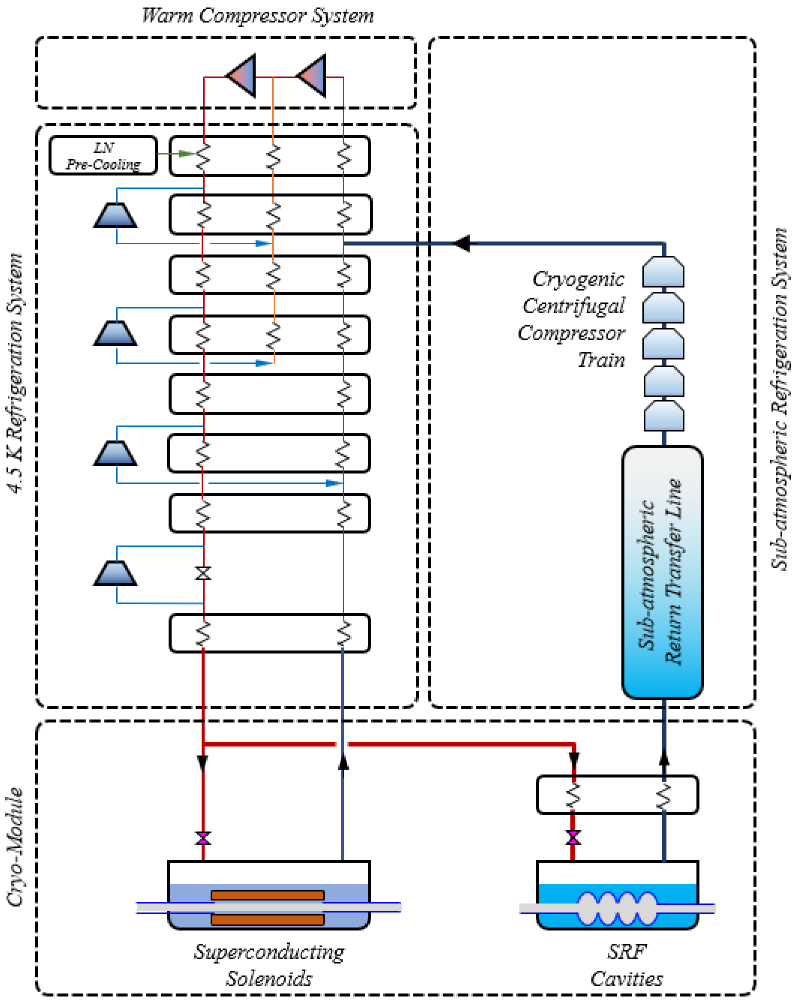

Figure 1. Simplified schematic of the FRIB cryogenic system

1.2 Historical Operation Methodology

The sub-atmospheric system for the Continuous Electron Beam Accelerator Facility (CEBAF, Jefferson National Lab) was the first large-scale system which exclusively used cold-compressors to achieve 2 K operational conditions [3]. The original system consisted of four cold compressors operated in series, with a fifth compressor stage later being added to improve overall system stability. The operating methodology developed during the commissioning of this system was pioneering, being adopted at future facilities which implemented full cold-compression systems (*i.e.* SNS, FRIB, and additional systems at JLAB) [1, 3, 4].

The operational methodology developed for these systems includes the selection of a "primary" compressor, which is actively controlled to satisfy a target mass flow rate through the compressor train. This primary compressor is typically the final compression stage, as this compressor has the smallest wheel size and subsequently the highest rotational speed, allowing for more precise control. The remaining compressors on the train are "secondary" compressors, which are tied to the primary compressor through electronically implemented speed ratios.

During steady-state operations, the speed ratios of the secondary compressor are typically chosen such that each compressor operates in a stable region. Traditionally, the selection of the speed ratios was conducted empirically, based on experimental (*i.e.* trial and error) observations of the system during steady-state operation. Therefore, if the operational region of interest for the sub-atmospheric system was altered, the user would slowly manipulate the speed ratios to reach the target operational region while maintaining adequate stability along the compressor train.

2. Developed Operation Methodology

2.1 Stability Region

The objective when operating the cold compressor train is to maintain reasonable stability margin of the individual cold compressors while minimizing the mass flow rate (and therefore load) through the compressor train. Minimizing the mass flow through the compressor train reduces the input power required by the main 4 K refrigerator compressor system but inherently shifts the performance of each cold compressor towards the low flow stability limitation of the respective compressor. Therefore, a system control balance between minimizing cold compressor mass flow while maintaining stability is necessary.

Estimation of the stability limits for the cold compressors is integral when choosing control parameters which satisfy the operating objective discussed. A numerical mean-line model was developed which predicts the performance of a cold compressor (given selected compressor geometry parameters and system process conditions), and estimates the stability limitations (surge and choke lines) of the compressor [2, 5]. This model was modified to include the geometrical features of the cold compressors installed in the FRIB sub-atmospheric system, allowing for characterization of the individual cold compressors [6]. Characterization includes estimation of the stability limitations over a wide range of operation conditions, *i.e.* development of a compressor performance map (operational envelope).

2.2 Speed Ratio Selection

Once the compressor performance maps have been developed using the mean-line model, these performance maps can then be utilized in the selection of compressor speed ratios to establish the stability margin under prescribed operational conditions. Due to the differences between the compressor stages and the increased sensitivity of the earlier compression stages to process perturbations, an algorithm was developed to estimate "optimal" speed ratios. The optimization parameter during the speed ratio selection is the RMS weighted surge margin, as defined in equation (1). This definition includes a weighting parameter, ω, which is used to capture the greater sensitivity of the early compressor stages. Here, the surge margin is defined as the difference between the normalized volumetric flow rate at the operational point and at the surge line for a given pressure ratio. The total (RMS weighted) surge margin captures the stability limits of all the compressors in the compressor train.

$$S_T = \sqrt{\frac{\sum_i^N \omega_i S_i^2}{N}} \tag{1}$$

When the operational conditions are specified (*i.e.* the suction conditions and mass flow rate), the maximum RMS weighted surge margin can be calculated. This procedure estimates the individual compressor speeds, which can then be used to calculate the secondary compressor speed ratios. In addition to the surge margin, other constraints must be recognized when running this algorithm. These include the maximum rotational speeds of the compressor, $N_{i,max}$, the choke stability limit, $\dot{m}_{i,choke}$, and the total target pressure ratio required across the compressor train, $P_{R,Total}$. These conditions are described in equations (2) through (4) and must be satisfied for the algorithm to produce a valid solution.

$$N_i \leq N_{i,max} \tag{2}$$

$$\dot{m} \leq (1 - \delta_i)\dot{m}_{i,choke} \tag{3}$$

$$\prod_i^N P_{R,i} = P_{R,Total} \tag{4}$$

The proposed algorithm for finding the "optimal" steady-state secondary compressor speed ratios can be used for both steady-state conditions and to give insight on the transition from one steady-state region to another. When transitioning to a new steady-state region, several points can be established between the initial and final steady-state points, and the speed ratios can be determined along this path. This will provide additional information on stability while transitioning to another steady-state operational region of interest.

3. Results and Discussion

3.1 Validation of Methodology

Extensive data has been collected through experimental operation of the FRIB sub-atmospheric cold compressor train. The measured data from actual operation was used in the validation of the developed methodology and ranged from minimum flow to maximum flow capabilities of the compressor train. Prior to the use of the mean-line model for speed ratio calculation, the stability limit estimations were validated against all the current experimental measured data available from the FRIB system. Figure 2 shows the resulting stability limit estimations for the first two FRIB cold compressor stages. From the figure, it is evident that the mean-line model successfully captures all collected experimental data, including the high pressure ratio data region of CC1. It should be noted that the criteria used to signify the stability limitations (for both surge and choke) were held consistent when executing performance analysis across different compression stages.

Accurate estimation of the stability limitations for each cold compressor stage enables the estimation of speed ratios using the speed ratio selection algorithm presented. Testing of the algorithm was completed by performing a mass flow sweep from a minimum CC flow of 120 g/s to a maximum CC flow of 210 g/s. The process path along the mass flow sweep for CC1 and CC2 are provided in Figure 3. The entirety of the mass flow sweep was completed within a singular day, with additional cryogenic plant loading maintained approximately constant.

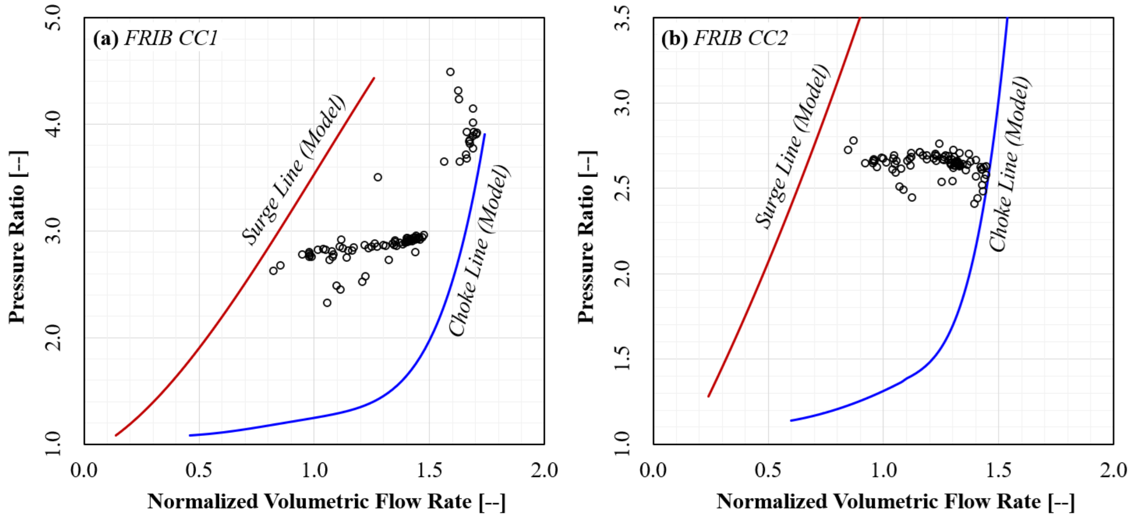

Figure 2. Stability limit estimation compared to measured data for FRIB CC1 and CC2, with solid lines being the surge and choke lines (as labelled) and the open symbols being measured FRIB test data

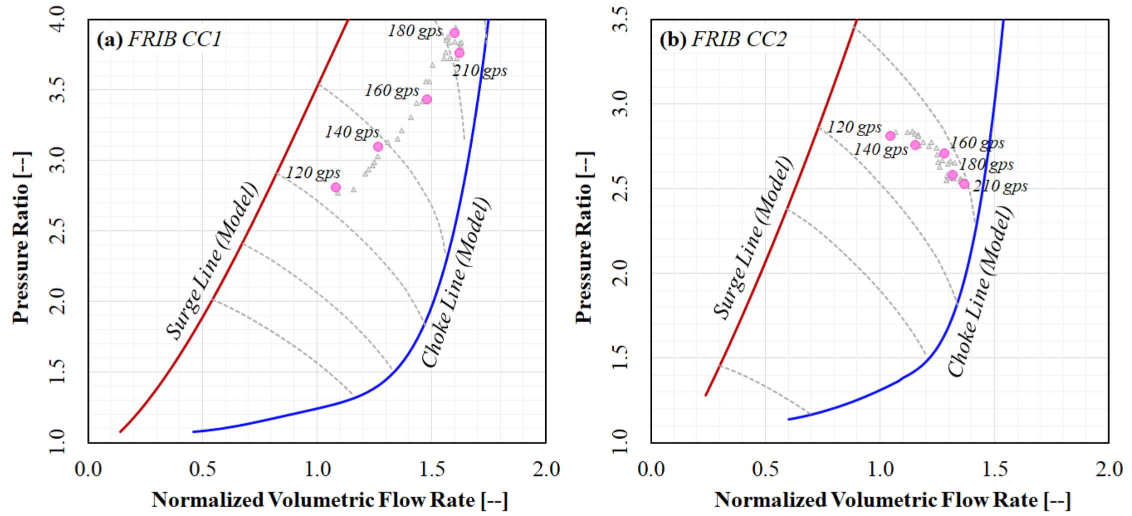

Figure 3. Performance maps for CC1 and CC2 during the mass flow sweep, with magenta circles indicating steady-state points of interest and grey triangles indicating the transient process path

Differences in process path behavior between CC1 and CC2 are due to the fundamental behavior of dynamic, continuous-flow compressors. While the mass flow rate is increased, the rotational speed (and subsequently the pressure ratio) of the first stage must increase to raise the volumetric flow rate through the machine (as suction temperature and pressure are nearly invariant). Since the overall pressure ratio of the compressor train remain constant, the other compressor stages (*i.e.* CC2 – CC5) must reduce their pressure ratios to maintain the overall pressure ratio. This behavior is evident when comparing the CC1 and CC2 process paths.

Prior to the mass flow sweep testing, the speed ratios were estimated using the mean-line compressor performance model in conjunction with the speed ratio selection algorithm. This provided a starting point for cold compressor operation, and the speed ratios were adjusted during testing based on the real-time compressor performance map locations. Table 1 provides a comparison between the estimated speed ratios (shown in parentheses) and the actual speed ratios (shown above the estimated).

Table 1. Speed ratio selection for mass flow sweep testing, with estimated values in parentheses below actual values used during testing

CC #	Speed Ratios				
	120 [g/s]	*140* [g/s]	*160* [g/s]	*180* [g/s]	*210* [g/s]
1	0.309 *(0.309)*	0.330 *(0.307)*	0.351 *(0.345)*	0.379 *(0.387)*	0.379 *(0.382)*
2	0.609 *(0.616)*	0.620 *(0.633)*	0.631 *(0.658)*	0.637 *(0.666)*	0.637 *(0.642)*
3	0.840 *(0.831)*	0.840 *(0.849)*	0.840 *(0.838)*	0.860 *(0.851)*	0.870 *(0.879)*
4	1.000 *(1.000)*	1.000 *(1.000)*	1.000 *(1.000)*	1.000 *(1.000)*	1.000 *(1.000)*

Results from the mass flow rate sweep testing indicate that the estimations determined using the mean-line model and speed ratio algorithm establish practical preliminary speed ratio selections. Over the mass flow rate span, the critical locations for accurate speed ratio estimations are the lowest and highest mass flow regions. Under these conditions, the operation of the cold compressor approaches stability limitations. Across the intermediate mass flow rate points, the stability criteria are somewhat more ambiguous, as the compressors are operating well within their respective operational envelopes. From Table 1, the estimations at minimum and maximum experimental flow rates show excellent agreement with the values implemented during testing, which is especially valuable under these operating conditions.

3.1 Implications of Methodology

The proposed methodology for the selection of speed ratios is particularly useful for stable turn-down of the cold compressor train. Turn-down refers to lowering of the mass flow rate through the compressor train, with the turn-down ratio defined as the maximum stable operational flow divided by the minimum stable operating flow. The cold compressor flow is directly coupled to the required 2 K loading of the accompanying accelerator, and if this load is reduced, the mass flow rate can be lowered through the sub-atmospheric system. Sub-atmospheric mass flow rate reduction can lead to operational cost savings, specifically within the main 4 K compressor system.

Reduction of the mass flow naturally shifts the individual compressor operational points towards their respective surge line stability limitations. When approaching the surge region, speed ratio selection becomes critical for maintaining the reliability of the cold compressor train. If any transient events propagate towards the compressor train, proper speed ratio selection can reduce the likelihood of compressor shut down (due to breaching the instability region and triggering surge conditions).

To demonstrate the benefits of turning down the cold compressor system (with a permitting 2 K load), a case study was developed using cryogenic system data from cold compressor experimental testing. Assumptions applied for the case study include:

- Super-critical helium is supplied to the cryostat at 3 bar and 4.5 K
- Cold compressor train suction is 0.0285 bar and 4.45 K
- Cold compressor train discharge pressure at 1.20 bar
- Equivalent 4 K refrigeration is calculated at 1.20 bar

Isentropic efficiency of the overall cold compressor train was estimated by curve fitting the measured experimental data along the mass flow rate ramp. This curve fit was developed using the mass flow rate as the independent variable.

Selecting the mass flow rate through the cold compressor train, the partial liquefaction load exergy can be calculated using the return temperature estimated from the compressor train efficiency. The partial liquefaction load exergy can then be translated into an equivalent 4 K refrigeration load. From previous experimental test data, the discharge pressure of the main 4 K compressor system can then be estimated [7]. Finally, from experimental measurements of the inverse coefficient of performance (COP^{-1}, with respect to discharge pressure), the input power can be estimated. Results from this case study are provided in Figure 4. From this plot, it is evident that although the compressor train may not be under peak isentropic efficiency conditions, the reduction in mass flow rate through the train produces input power savings at the main compressors. For instance, if the mass flow rate is reduced from ~160 g/s to ~110 g/s, the estimated main 4 K compressor system power consumption decreases by approximately 750 kW.

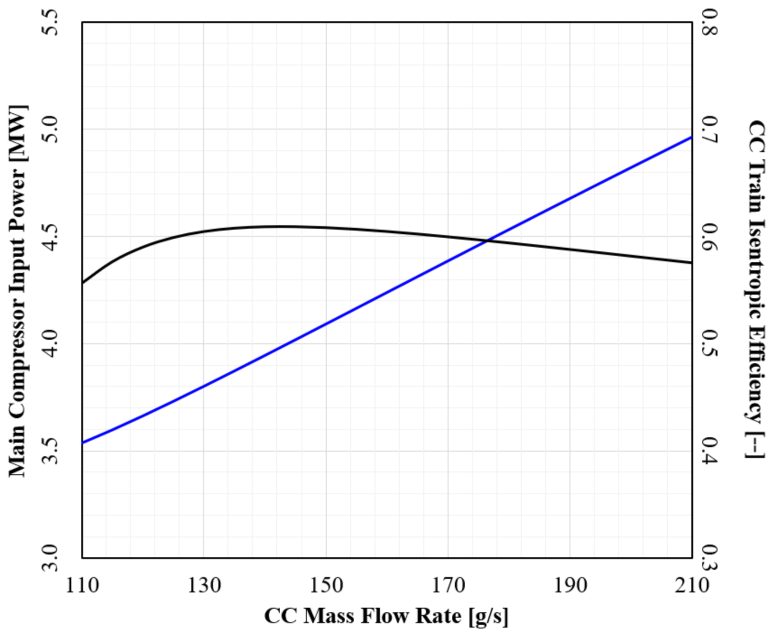

Figure 4. Reduction of main compressor input power for CC loading when reducing CC mass flow rate, where blue is the input power and black is the train isentropic efficiency

While this case study demonstrates the benefits of turning down the cold compressor system, it should be noted that the cost savings will only be realized based on the operation of the main 4 K refrigerator. Cost savings are contingent on the 4 K refrigerator also being capable of turning down. Operation of the 4 K refrigerator using the Ganni Cycle Floating-Pressure Process [8] allows for the 4 K refrigeration plant to have variable loading while maintaining a nearly constant exergetic efficiency, enabling savings to be achieved from turning down the 2 K system.

4. Summary and Conclusion

An operating methodology was developed using cold compressor performance maps, which can be generated using a mean-line centrifugal compressor performance estimation model. This mean-line model was developed in-house by the FRIB cryogenic staff and provides an estimation for the surge and choke stability margins as well as the overall performance (pressure ratio and temperature ratio) of the cold compressor system. The compressor performance maps were validated based on experimental measurements of the FRIB sub-atmospheric system [6]. An algorithm was developed which uses results from the mean-line model to estimate optimal speed ratio selections across the compressor train. This optimization was based on maximizing stability while maintaining the operational limits of the individual compressors and the coupled main 4 K cryogenic system. To validate the speed ratio selections, experimental measurements were taken from the FRIB cold compressor system during a mass flow sweep from 120 g/s to 210 g/s.

Through case study calculations, it was shown that approximately 15 – 20 kW of main 4 K compressor input power can be saved per g/s of cold compressor mass flow rate reduction. The implications of the developed methodology are evident when considering this reduction in mass flow since appropriate speed ratio selection for minimal compressor train flow rates is essential for maintaining cold compressor stability. Reduction of CC mass flow (when permitted by accelerator operations) can lead to significant operational cost savings when coupled with a 4 K cryogenic system which is being controlled using the Ganni Cycle Floating-Pressure Process.

Overall, the developed steady-state control methodology has improved the stability of the FRIB cold compressor train and sub-atmospheric system. Likewise, the control methodology has enabled greater turn-down of the sub-atmospheric system, increasing cost savings associated with main 4 K compressor input power reduction. Potential advancements include mean-line model accuracy improvement and integration of the optimal speed ratio algorithm into the model.

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References

[1] P. Knudsen, V. Ganni, F. Casagrande, A. Fila, N. Hasan, M. Wright, G. Vargas, N. Joseph, Design, Fabrication, Commissioning and Testing of FRIB 2 K Cold Compressor System, in: IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2020, pp. 012092.

[2] J.W. Howard, Characterization of a Cryogenic Centrifugal Compressor Train for Reliable Wide-Range Operation of Helium Sub-Atmospheric Systems, Ph.D., Michigan State University, United States -- Michigan, 2024.

[3] V. Ganni, D. Arenius, B. Bevins, W. Chronis, J. Creel, J. Wilson Jr, Design, Fabrication, Commissioning, and Testing of a 250 g/s, 2-K Helium Cold Compressor System, in: AIP Conference Proceedings, American Institute of Physics, 2002, pp. 288-304.

[4] F. Casagrande, P. Gurd, D. Hatfield, M. Howell, W. Strong, D. Arenius, J. Creel, V. Ganni, P. Knudsen, SNS 2.1 K Cold Box Turn-down Studies, Thomas Jefferson National Accelerator Facility (TJNAF), Newport News, VA …, 2006.

[5] J. Howard, P. Knudsen, A. Engeda, Empirical Loss Model Optimization for the Prediction of Centrifugal Compressor Off-Design Performance, in: ASME Turbo Expo 2023: Turbomachinery Technical Conference and Exposition, 2023.

[6] J. Howard, A. Engeda, P. Knudsen, N. Hasan, V. Ganni, Characterization of centrifugal compressors operating in FRIB's sub-atmospheric compression system, IOP Conference Series: Materials Science and Engineering, 1301(1) (2024) 012105.

[7] P. Knudsen, V. Ganni, N. Hasan, M. Wright, F. Casagrande, G. Vargas, N. Joseph, FRIB Helium Refrigeration System Commissioning and Performance Test Results, in: IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2020, pp. 012090.

[8] V. Ganni, P. Knudsen, Optimal Design and Operation of Helium Refrigeration Systems Using the Ganni Cycle, AIP Conference Proceedings, 1218(1) (2010) 1057-1071.