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Commissioning of a replacement subatmospheric cold box for Jefferson Lab's Central Helium Liquefier

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Abstract. Jefferson Lab's Cryogenics Department has designed, fabricated, installed, and commissioned a new subatmospheric cold box to replace one of the two existing units within our Central Helium Liquefier (CHL). The replacement cold box, dubbed SC1R, pumps saturated helium vapor at 0.0385 atm from Jefferson Lab's continuous electron beam accelerator facility (CEBAF) cryomodules to maintain an operating temperature of nominally 2.1 K. This is accomplished using a five-stage cryogenic centrifugal compressor (cold compressor) system and a brazed aluminum plate-fin heat exchanger operating between 2.1 K and 4.5 K. In this paper we will describe our experience commissioning the SC1R cold box. We will discuss pump-down of the system to 2.1 K and steady-state operation at the cold compressor design flow rates of 170, 200, and 250 g/s. Performance of the heat exchanger and cold compressors has been mapped across a range of flow rates and optimized for CEBAF operations. This commissioning data will be used to monitor future performance and adapt to changing load requirements.

1. Introduction

The Central Helium Liquefier (CHL) at Thomas Jefferson National Accelerator Facility (Jefferson Lab) provides liquid helium for its Continuous Electron Beam Accelerator Facility (CEBAF). CEBAF is comprised of two superconducting linear accelerators (LINACs) joined by 180° magnetic steering arcs, allowing the electron beam to make multiple passes through each LINAC and obtain energies up to 12 GeV. Each LINAC consists of 25 cryomodules which house superconducting radio frequency (SRF) cavities immersed in saturated liquid helium baths. Near the center of each LINAC a nominal bath temperature of 2.08 K is maintained by regulating the vapor pressure at 0.0385 atm, but pressures and temperatures rise slightly towards each end.

The CHL complex contains two plants that each have a nominal refrigeration capacity equivalent to 18 kW at 4.5 K. They consist of warm compressor systems and main cold boxes, or 4 K cold boxes, which contain the heat exchangers and turbo-expanders that operate below ambient temperature and produce nominally 4.5 K liquid. A separate subatmospheric cold box, or 2 K cold box, contains a five-stage cryogenic centrifugal compressor (cold compressor or CC) train with an additional heat exchanger located at the first stage compressor suction. The cold compressors pump on the cryomodule helium baths to maintain subatmospheric conditions, while the heat exchanger takes advantage of the cold vapor returning at nominally 2.1 K to subcool the supply to the LINAC from 4.5 K to 3.0 K. An overview of the cryogenic system is shown in Fig. 1.

Nearly 30 years have passed since the older of the two plants, CHL1, was fully commissioned [1]. The 4 K component of the other plant, CHL2, is still fairly new [2, 3], but it uses a 2 K cold box that was constructed over 20 years ago as a redundant system for CHL1 [4]. Over time both subatmospheric cold boxes had become a significant risk to 12 GeV accelerator operations because the cold compressor

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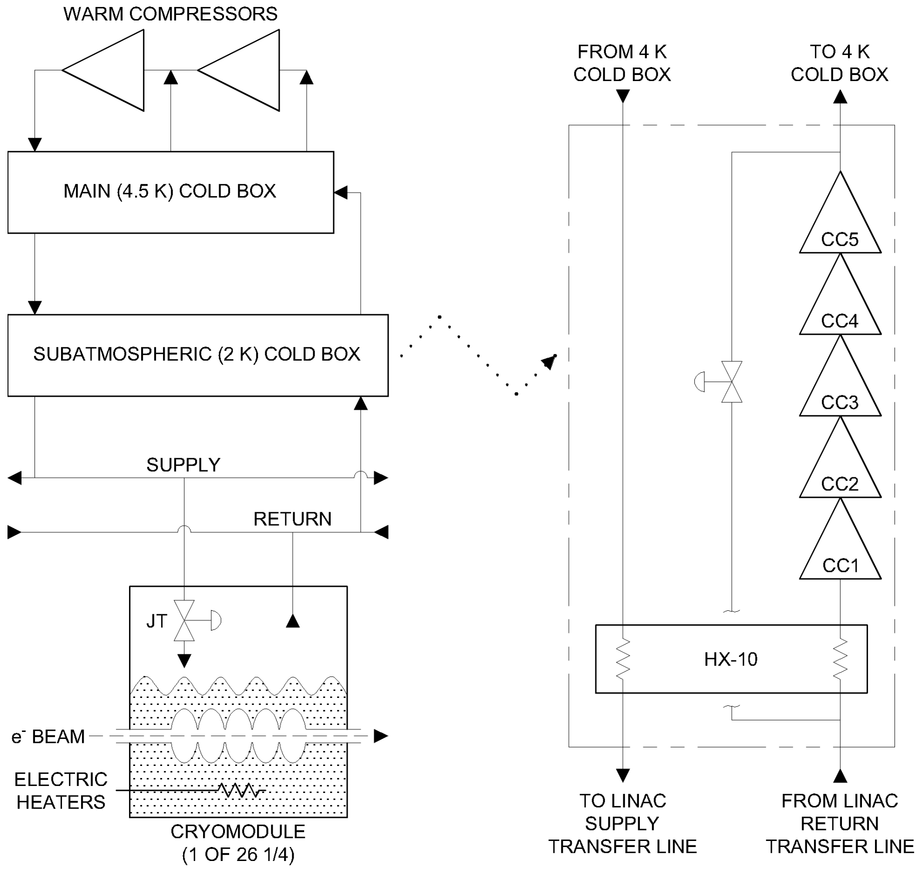

Figure 1. Simplified overview of a Jefferson Lab central helium plant.

technology had become obsolete and replacement parts were no longer available [5]. We have therefore replaced the original CHL1 2 K cold box, SCM, with a new 2 K cold box, SC1R, built from entirely new components including state-of-the-art cold compressor technology. In this paper we will briefly review the design, fabrication, and installation of the SC1R cold box (Sect. 2), share our experience commissioning the system (Sect. 3), and discuss its performance during the commissioning period (Sect. 4).

2. Design, Fabrication, and Installation

The mechanical design and fabrication for the SC1R 2 K cold box have been presented and published on IOP Conf. Series: Materials Science and Engineering **755** (2020) 012120 [5]. This section is to briefly review the design and fabrication and to discuss the installation of the new cold box.

Central to the SC1R system are the five cold compressors designed and manufactured by Air Liquide [6]. Compressor wheels are magnetically levitated on a digitally controlled five-axis active magnetic bearing system and driven by a high-speed synchronous motor. The motor assembly mounts to a casing, which contains the diffuser and volute and is integrated into the cold box vacuum shell. Since the motor units reside on the ambient side of the vacuum shell, they can be easily serviced from an access platform constructed around the top of the cold box.

The cold box vacuum vessel was designed and fabricated in accordance with American Society of Mechanical Engineers (ASME) Boiler & Pressure Vessel Code, Section VIII, Division 1 [7]. It was fabricated from SA516 G70N carbon steel and a torispherical head was used to reduce wall thickness and cost. All of the piping that was not considered part of the vacuum vessel pressure boundary was designed, fabricated, examined, tested, and inspected according to ASME B31.3 [8]. Dual-rated A312 TP304/304L seamless austenitic stainless steel was used for the piping systems in this project. Since most of the cold mass is not protected by liquid nitrogen-cooled shielding, twenty layers of multi-layer insulation (MLI) were applied to the internal surfaces of the vacuum shell. It was challenging to insulate the areas near the cold compressor casings, because the gaps between the inner surface of the head and the top surfaces of CC3–CC5 casings are particularly small.

A nationally recognized lifting and transport organization was subcontracted to safely remove the existing SCM cold box, transport the new cold box from our workshop, and install it inside the CHL. The subcontractor was involved even in the design stage. The outline dimensions of the completed cold box were limited to 11’9-1/2” wide × 17’11-3/4” tall so that the completed assembly, plus 10-ton machine skates that were used to move it out of the workshop (see the left panel of Fig. 2), would fit through the 12’ wide × 20’ high workshop rollup door. A 60-ton capacity forklift was used to place the new cold box inside the CHL. To accommodate the height of the cold box assembly and forklift, the existing 12’ wide × 20’ high CHL rollup door was replaced with a 12’ wide × 24’ high door (see the right panel of Fig. 2).

Figure 2. Left: Moving the SC1R 2 K Cold Box assembly out of the workshop on 10 ton machine skates. Right: Moving the cold box into the CHL building using the 60 ton forklift.

The platform components, such as beams, columns, gratings, guardrails, and stairs, were all prefabricated to save installation time. These components would have to be perfectly aligned with the newly installed cold box, which itself would have to be perfectly aligned with the existing 2 K return header in the CHL building. In order to accurately position the cold box, an as-built survey of the cold box was conducted to determine the required location of anchor bolts with respect to existing building infrastructure. The anchor bolts were then pre-installed to guide the installation of the cold box. Shims were placed under the cold box to control the elevation of eight plates that support the platform, and levelness was gauged from the CC1 and CC2 casing top flanges. The installation was successful: not one prefabricated component of the platform required modification, and the 2 K return header on the cold box aligned well with the header in the building.

Field connections of the mechanical and electrical utilities, such as instrument air, electrical controls, cooling water, vacuum, and helium purge and recovery, were executed by our technical staff. As the installation was performed during the global Covid-19 pandemic, these tasks were re-evaluated and

Figure 3. Panoramic photograph of the SC1R subatmospheric cold box installation showing the top of the cold box and cold compressors (left) and variable frequency drives and active magnetic bearing controllers (right).

work practices and schedules were adjusted. As a result, the SCM demolition and SC1R installation were safely completed on schedule. The picture in Fig. 3 shows the installed SC1R 2 K Cold Box system as seen from the platform.

3. Commissioning

Initial commissioning efforts were devoted to successful pumpdown, the process of speeding up cold compressors to reduce the LINAC pressure to the normal operating point. Once repeatable pumpdown was achieved, efforts were turned to stable operation under steady state conditions.

3.1. Pumpdown

Pumpdown refers to the process of speeding up cold compressors from idle to operating speed, thereby reducing cryomodule helium bath pressure and temperature along the saturation line from nominally 1 atm to normal operating conditions (0.0385 atm, 2.08 K). This is an automated process during which the speed of CC3 is adjusted to maintain a desired mass flow rate, while the other speeds are held at constant ratios relative to CC3. We selected CC3 for flow control because it is the fastest compressor that does not reach maximum speed during pumpdown. The control system also manipulates the mass flow setpoint, various valve positions, speed ratios, cryomodule electric heaters, and other machine parameters to complete the automatic pumpdown as quickly as possible [9]. Cold compressor speed progression and the corresponding reduction of suction pressure is shown for a typical SC1R pumpdown in Fig. 4.

Our first several pumpdown attempts were terminated early by cold compressor trips, or automated shutdowns, initiated primarily by flow surge and less commonly by apparent loss of communication between the control system and cold compressor variable frequency drives (VFDs). Upon investigation we discovered issues with the digital communication as well as the pumpdown path, or the progression of cold compressor operating points throughout the pumpdown process.

The VFDs communicate with our programmable logic controller (PLC) via combination of ethernet and controller area network (CAN) bus. We discovered that occasionally incomplete commands were received over the communications network. Incomplete speed request commands would cause one of the compressors to suddenly and drastically slow down, resulting in a trip due to flow surge, and incomplete watchdog signals would cause emergency shutdowns due to erroneous communication timeout. These issues were resolved by a VFD firmware update that implemented a checksum to disallow execution of incomplete digital commands.

Separate from any digital communication issues, the cold compressors repeatedly tripped due to flow surge when the suction pressure reached approximately 0.25 atm. Several factors contributed to the

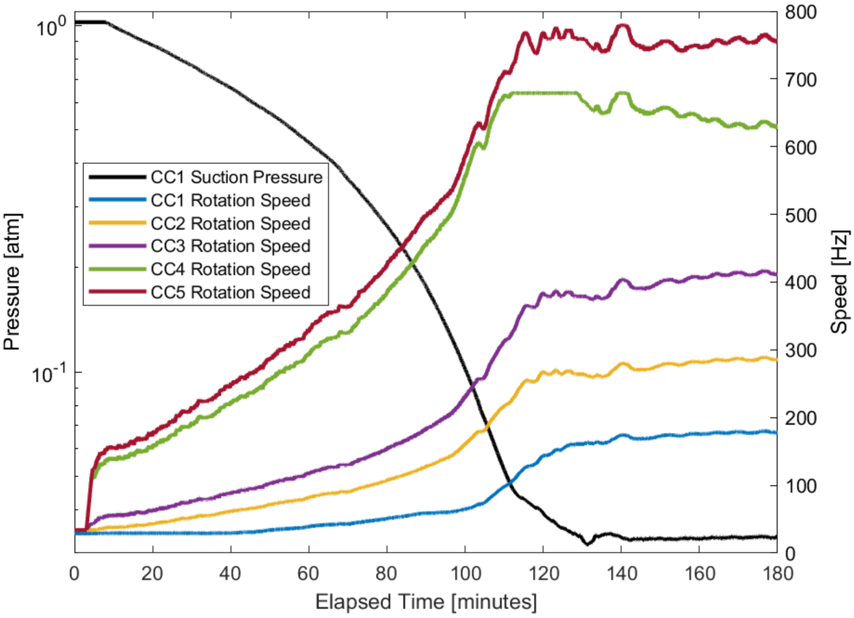

Figure 4. Cold compressor train suction pressure (left axis) and individual rotation speeds (right axis) during a typical pumpdown. Automatic speed ratio adjustment during the transition between pumpdown and steady-state operation can be seen towards the end of the pumpdown, where CC4 slows down and the others speed up to compensate.

deviation of CC4 and CC5 away from the intended pumpdown path and toward surge conditions. The overall pressure ratio was higher than expected due to backpressure imposed by the main cold box. We also found the cold compressor efficiency to be higher than predicted by the design, lowering the suction temperature (and by extension volumetric flow) of each stage for a given pressure ratio.

Several minor changes were made to the pumpdown path that allowed us to reliably reach operating pressure without tripping. Mass flow to the main cold box was reduced and the CC4 and CC5 speed ratios were reduced to compensate for the excess pressure ratio. We simultaneously increased flow through the cold compressor train by recycling roughly 100 g/s through the cold compressor bypass valve (see Fig. 1) until the suction density becomes sufficiently low. The bypass valve was used in this manner for SCM, but was not initially implemented for SC1R because it was not called for by the design pumpdown path. The effect of these adjustments can be seen on the cold compressor performance maps of Fig. 5. These show the pressure ratio for each stage as a function of its reduced (non-dimensional) flow rate X. Magenta dotted lines show the design pumpdown path and surge lines appear in solid red. When the only flow passing through the cold compressor train is that originating from the LINAC, operating points follow the pumpdown path shown by the lighter grey trace. By recycling flow through the bypass valve while maintaining the same flow rate from the LINAC, the pumpdown path moves farther away from the surge line, as indicated by the darker black trace. Despite the excess pressure ratio, which prevents the actual pumpdown path from following the design path, the extra flow allows the process to be completed reliably and repeatedly.

3.2. Steady-State Operation

Steady-state operations were short lived at first because periodic pressure spikes in the supercritical supply from the main cold box would destabilize the cold compressors enough to cause a flow surge. This affected the SC1R cold box at lower flow rates, when the compressors operate closer to surge

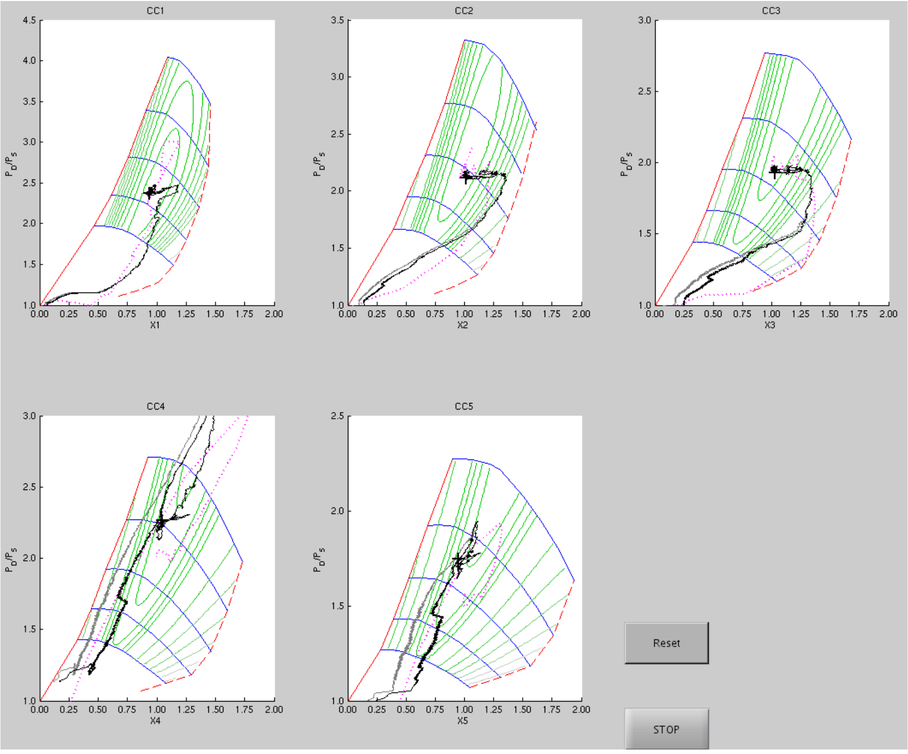

Figure 5. SC1R cold compressor performance plots showing the successful pumpdown path.

conditions. We discovered that the main cold box wet expander bypass valve, a pneumatic valve which should remain closed, would unseat and re-seat in sync with the plant's instrument air compressor duty cycle. Isolating the valve's air supply caused it to remain closed and removed the supply pressure spikes.

After stabilizing the 4 K supply pressure we demonstrated the ability to run at steady state across a range of mass flow rates with the LINAC pressure held constant at 0.0385 atm. The SC1R ran satisfactorily at the design mass flow rates of 170 g/s, 200 g/s, and 250 g/s as well as several intermediate flow rates enumerated in Fig. 6. We did not encounter any further issues during the steady-state testing phase.

4. Performance

Stability and reliability are the most important aspects of cold compressor performance for accelerator operations. Since flow surge is the most commonly observed process-related cause for cold compressor trips, we use surge margin to gauge stability. We have defined surge margin as $(X - X_S) / (X_C - X_S)$ where X denotes the reduced flow rate at a given operating point, and X_S and X_C denote reduced flow at surge and choke conditions, respectively, for the same blade tip Mach number as the operating point. As shown in the left panel of Fig. 7, surge margin exceeds 20% for all cold compressors at all flow rates tested, except for CC4 at 170 g/s. This can be easily remedied if desired by adjusting the cold compressor speed ratios. Twenty percent surge margin is plenty to keep the compressors running in the absence of severe process upsets.

In terms of efficiency, the SC1R cold compressors outperform the SCM cold compressors as well as their own design. Taking SC1R as a load on the 4 K plant, the center panel of Fig. 7 shows the Carnot work required to support it across the range of mass flow rates tested during commissioning. This is obtained from the exergy lost between the supply to SC1R from the main cold box and the return to the main cold box from SC1R. For comparison, the Carnot work requirement predicted by the

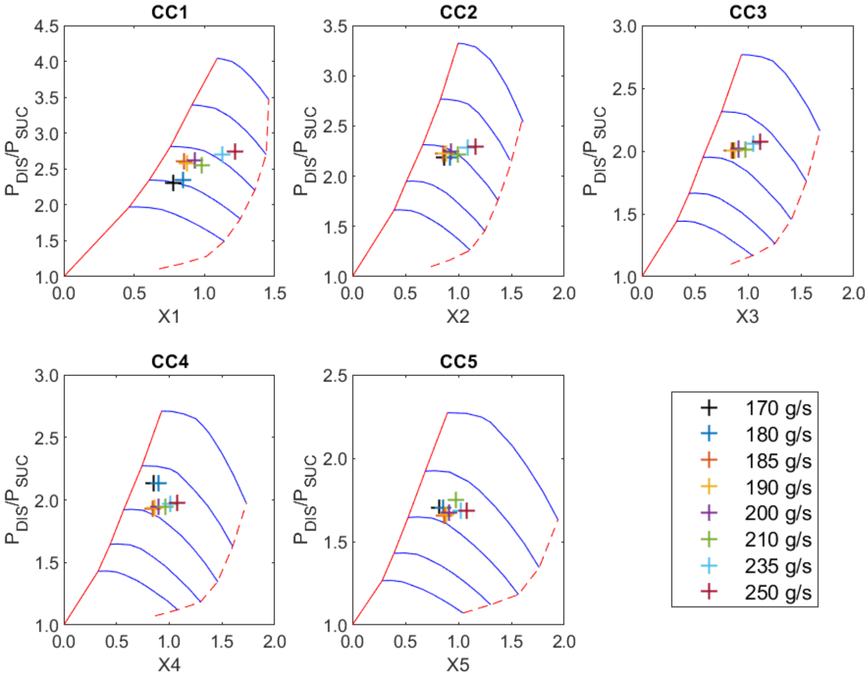

Figure 6. SC1R cold compressor performance maps showing the steady-state operating point at several flow rates.

cold compressor design, as well as for the SCM cold box, are also shown. SC1R provides a Carnot work reduction of nearly 8% at the nominal operating point of 200 g/s when compared to SCM. The improvement as compared to the cold compressor design is also substantial. While this can be attributed to better-than-expected efficiency, it is artificially inflated because the design discharge pressure is lower than measured in the field.

Pressure drop across each of the two heat exchanger streams is shown as a function of mass flow rate in the right panel of Fig. 7. As expected, both streams exhibit a slight increase in pressure loss with increasing flow rate. The return stream pressure drop is satisfactory compared to that allowed by the

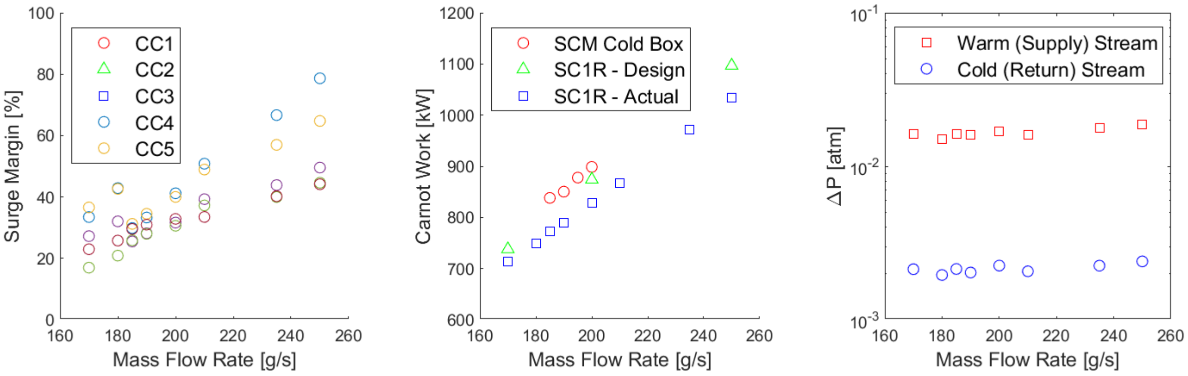

Figure 7. Left: Surge margin for the cold compressors across the tested range of mass flow rates. Center: Carnot work requirement for the SC1R cold box compared to the design and SCM cold box. Right: SC1R HX-10 pressure drop as a function of mass flow rate through the cold compressor train.

design specification. Pressure loss on the supply side appears to be higher, but this can be attributed to the presence of a flow control valve and substantial length of piping in between the pressure measurement taps. This information is useful for detecting and diagnosing operational issues such as contamination of the subatmospheric helium system, which can appear as excessive pressure drop over the return stream.

Thermal performance of the heat exchanger (e.g., heat transfer effectiveness) is also of interest, but we do not have a complete set of temperature measurements to use for characterization. Both the primary and redundant temperature diode at the return stream inlet developed a short to ground during installation of the cold box. Supplementary temperature diodes were surface mounted to the outside of the return piping, and while these provided valuable qualitative information during commissioning, the measurement accuracy is not sufficient to characterize heat exchanger performance. We have designed a method for obtaining temperature measurements from the shorted diode, but were not able to implement it for commissioning due to parts availability.

We have selected 180 g/s as the cold compressor mass flow rate for the initial period of operations. This is slightly higher than the rate that helium is vaporized due to SRF cavity power dissipation, leaving some margin for electric heaters to stabilize cryomodule pressure but reducing the refrigeration capacity wasted on electric heat. In the future, we will determine the optimal balance between operational stability and cold compressor efficiency at the selected flow rate and adjust speed ratios accordingly [10].

5. Conclusions

The SC1R subatmospheric cold box has been designed, fabricated, and installed by Jefferson Lab's Cryogenics Department to replace the aging technology of the original system. Despite some initial digital communications and process issues, we commissioned the system by demonstrating that it can repeatably and reliably pumpdown the LINAC and operate stably across a range of mass flow rates between 170 g/s up to 250 g/s. During the commissioning period we found all aspects of the SC1R performance to be satisfactory. In particular, the increased efficiency offered by the new cold compressor technology demands less overall cryogenic plant power to support 2 K accelerator operations.

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