Sumitomo Variable Speed Helium Compressor Study

[ALMA-40.00.00.00-3010-A-REP]

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Version	Date	Author	Affected Section(s)	Reason
1	2023-04-24	D. Urbain	All	Initial Draft
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2.1	2025-04-24	T. Anderson	All	Template Formatting and Copy Edits

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1 Acknowledgment

I would like to thank individuals at Sumitomo SHI Allentown, mainly Paul Mattiola and William Worley, for supporting this project. On multiple occasions, I reached out to them with questions, and they always did their best to answer them and found the time to meet on Zoom.

At NRAO, I want to recognize Mike Leblanc for developing the test software and Raul Lower for building the second Cryo-test-cart. His second flowmeter assembly is a welding masterpiece.

In Chile, Takeshi Okuda and Mark Gallilee's help was invaluable. They coordinated the installation inside the ESO container and the technical support at the AOS. Over the three-year project, we had to overcome several setbacks, from test instrumentation failure to a cyber attack.

It has been a privilege and a pleasure to collaborate with the Chilean staff members on this project for the ALMA observatory.

2 Introduction

The ALMA observatory has been in operation for over ten years, and the helium compressor (CNA-61D) has revealed some limitations during extremely cold weather at the high site. In these conditions, a compressor shut down for maintenance or due to a power outage can take up to ten hours before it can be restarted safely. Sumitomo (SHI) has engineered a new model (FA-70H) that addresses the cold start problem and replaces the now-discontinued ALMA model.

The observatory has started to buy replacement compressors every year to build a stock of spares in anticipation of obsolescence and future failures. Due to ALMA's remote location, all energy needs must be provided on-site. The cryogenic system is a major contributor to the overall energy consumption.

Reducing the compressor's power consumption could help reduce the operation cost, and it must be investigated as this could offset the purchase cost in the long term.

2.1 *Purpose*

The helium compressor can be fitted with an inverter to adjust the operating frequency and reduce power consumption. NRAO has been exploring this type of variable-frequency operation for the new ngVLA project, aiming to lower operating costs and enhance reliability.

As ALMA has begun acquiring new compressors to establish a stock of spares, the study seeks to ascertain whether an inverter-driven compressor should be considered in place of the standard model.

2.2 *Scope*

The variable frequency compressor is a prototype unit that takes the standard FA-70H model and adds a commercial inverter. Sumitomo did the integration of the inverter because some electrical and mechanical modifications were required. The inverter replaced the adsorber inside the Indoor Control Unit (ICU), and a new enclosure was built for it. The initial evaluation of the compressor alone was done at Sumitomo in Allentown, then shipped to Socorro. While the compressor was being built and tested, a duplicate of the cryo-test cart was assembled. A test cryostat, a 3-stage ALMA coldhead, and a Helium buffer tank were ordered from Sumitomo SHI Japan.

Mike Leblanc developed the LabVIEW test software to take unattended measurements and plot the results. Taking cryogenic data can be extremely time-consuming because after any change, one must wait for the thermal equilibrium to be restored, and averaging is necessary to eliminate the thermal fluctuations inherent to the Gifford-McMahon (GM) cryocoolers.

The tests done in Socorro aim to characterize the impact of the compressor speed on the 3-stage cryocooler's performance and power consumption. When applying the right heat load to each stage, the test cryostat can emulate the ALMA front end.

Once in Chile, the compressor and test instrumentation were installed inside a refurbished shipping container, allowing the testing to proceed at the Operations Support Facility (OSF) and then at the Array Operations Site (AOS). Having access to a spare ALMA Front End was essential to confirm the validity of the tests done in Socorro. Running the compressor in the container at the AOS is the closest one can get to the actual operating conditions without using an antenna. The AOS test focuses on reliability and not performance, testing the effects of the altitude and the ambient temperatures on the equipment.

Task	Description	Duration
Build a duplicate of the ngVLA cryo-test cart	- Purchase of test instrumentation - Fabrication of the cryo-test cart - Fabrication of a flowmeter - Assembly of the Sumitomo test cryostat	8 months
Develop test software	Write LabVIEW test software to do load maps.	8 months
Build a prototype Sumitomo variable frequency compressor FA-70V	Modify the production compressor to accept an inverter and keep the same size enclosures	8 months
Evaluation of the prototype compressor at Sumitomo	Test the compressor by measuring: - Power consumption - Pressures (supply and return) - Flow	2 months
Evaluation of the compressor in Socorro	Test the compressor with a 3-stage cold head - Power consumption - Pressures (supply and return) - Flow - Cold head load maps - RFI testing	5 months
Shipping equipment to Chile	Crate and ship compressor, test cryostat, 3-stage cold head, cryo-test cart, and test instrumentation	3 months
Installation of equipment in a container at the OSF	Install - Two compressor, standard FA-70H and prototype FA-70V - The compressor's indoor and outdoor units are inside their respective enclosure on top of the shipping container. - Cable and helium lines. - Two air conditioning units - Spare ALMA Front End - Cryo-test cart (secure to the wall)	3 weeks
Testing of the compressor at the OSF	Test the compressor with - Test cryostat - Spare Alma Front End	2 weeks
Move the container to the AOS.	Load the container on a flatbed truck and drive to the AOS. Set down the container near the AOS building and establish power and network connections.	2 days
Testing of the compressor at the AOS	Run the compressor with the test cryostat, set the inverter frequency and the three heat loads, and collect 100 samples	One year

Task	Description	Duration
	averaging the data for extended periods(several days or weeks)	
Documentation	Writing the final report	2 months

Table 1: Project Timeline

3 Related Documents and Drawings

3.1 *Applicable Documents*

The following documents may not be directly referenced herein, but provide necessary context or supporting material.

Ref. No.	Document Title	Rev/Doc. No.
AD01	Development Upgrades of the Atacama Large Millimeter/submillimeter Array (ALMA) Sumitomo Variable Speed Helium Compressor Analysis Principal Investigator: Ephraim Ford	Revised 02/06/2020
AD02	Sumitomo (SHI) cryogenics of America, Inc. FA=70H Helium Compressor Operating manual	
AD03	LakeShore Cryotronics, Inc. User's Manual Model 224 Temperature Monitor	
AD04	Nidec Control User Guide Commander C200/C300	
AD05	Nidec User Guide SM-Ethernet	
AD06	Teledyne Hastings Instruments HVG-2020B Instruction Manual	
AD07	Teledyne Hastings Instruments THCD-401 Instruction Manual	
AD08	Teledyne Hastings Instruments 200/202 Series Flowmeters/controllers Instruction Manual	
AD09	B&K Precision Model 9174B Programmable DC Power Supply User Manual	
AD10	ASHCROFT Model T2 Pressure Transducer Datasheet	
AD11	Moxa EDS-205A/208A Series	

	Hardware Installation Guide	

3.2 *Reference Documents*

The following documents are referenced within this text:

Ref. No.	Document Title	Rev/Doc. No.
RD01		
RD02		
RD03		

3.3 *Acronyms*

Below is a list of acronyms and abbreviations used within this document. For a complete set of acronyms and abbreviations, please go to the ESO - ALMA Acronyms webpage.

AC	Alternating Current
ALMA	Atacama Large Millimeter/sub-millimeter Array
AMG	Array Maintenance Group
AOS	Array Operations Site (16,400ft or 5000m)
CCA	Cold Cartridge Assemblies
DSOC	Domenici Science Operations Center
ESO	European Southern Observatory
GM	Gifford McMahon
GUI	Graphical User Interface
ICU	Indoor Compressor Unit
IRV	Internal Relief Valve
NRAO	National Radio Astronomy Observatory
OCU	Outdoor Compressor Unit
OSF	Operations Support Facility (9,500ft or 2900m)
PPI	Periodic Pressure Instability
scfm	standard cubic feet per minute
SIS	Superconductor-Insulator-Superconductor mixer
VLA	Very Large Array

3.4 *Verb Conventions*

“Must” for an obligation; “must not” for a prohibition.

“May” for a discretionary action; “should” for a recommendation.

“Will” is used to indicate a future happening/action.

4 Test Instrumentation

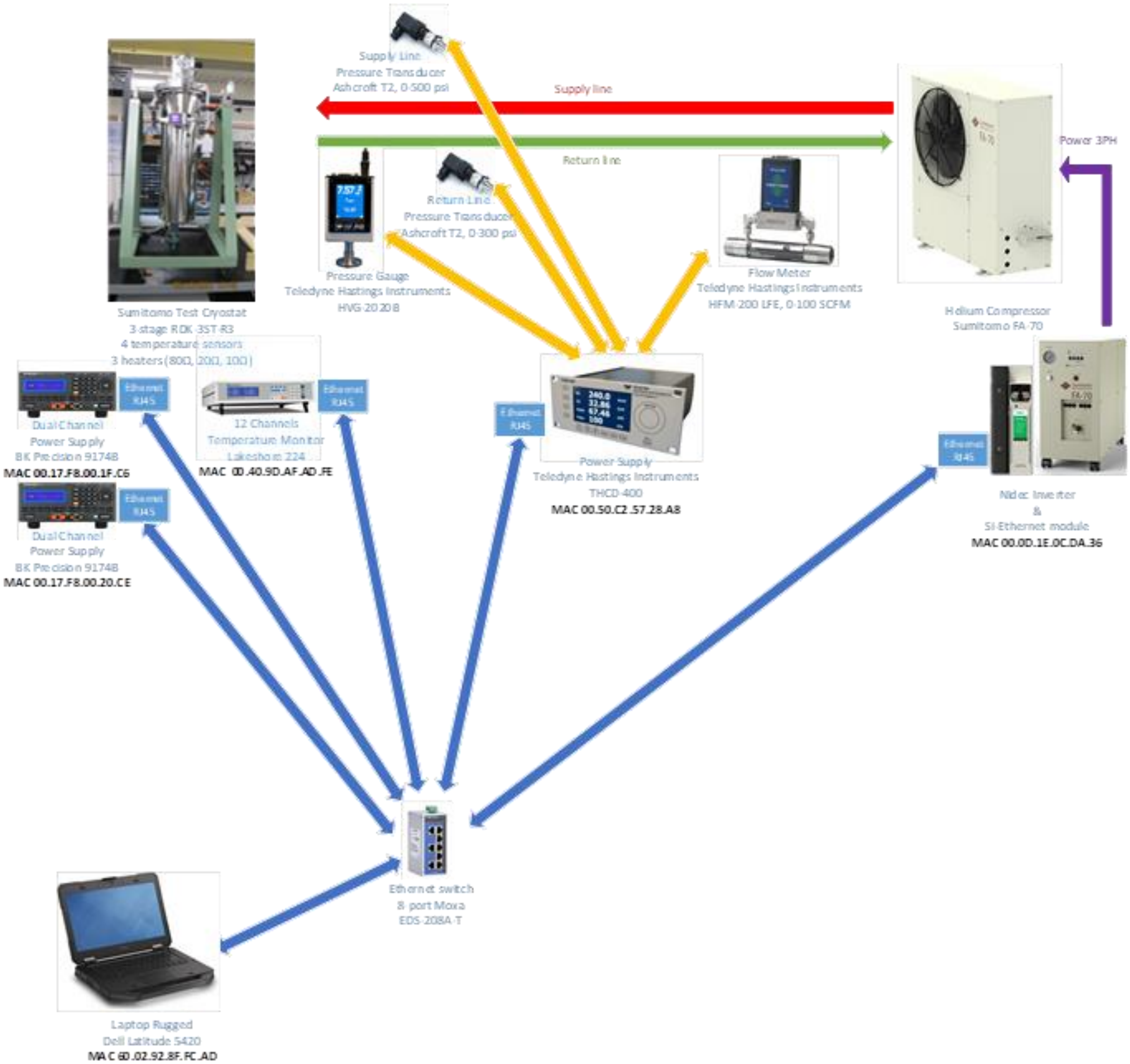


Figure 1: Compressor study test instrumentation

4.1 *Cryo-Test Cart*

The cryo-test cart capitalized on the design work done for the ngVLA project; it used the same hardware but was updated. For example, the flow meter was a fully welded assembly to eliminate the expensive and heavy flanges, and the charcoal trap was replaced with the same model as the FA-70 compressor to guarantee availability in

Chile. The test instrumentation was the same, except for the updated Teledyne THCD-400 power supply with an Ethernet interface and the new pressure gauge HVG-2020B with a broader range.

4.1.1 Power Supply

The two programmable dual-channel power supplies power the heaters placed on the three stages of the test cryostat, which represent the thermal loads of the ALMA Front-End Cryostat.

4.1.1.1 BK Precision 9174B

The BK Precision 9144B dual-channel power supply has two voltage ranges: 0 to 35VDC at 3A and 0-70VDC at 1.5A.

Picture 1: BK Precision 9174B

The power supply is equipped with a GPIB/LAN interface card to allow remote configuration and control using SCPI commands. Because the Sumitomo cryocooler for ALMA has three stages, two power supplies are needed to apply the heat loads.

Picture 2: Interface Card LAN/GPOB

The 4th channel powers the Moxa Serial-to-Ethernet converter. The converter takes the Sumitomo serial interface (RS232 protocol on RS385 Physical layer) and converts it to Ethernet.

Picture 3: Moxa P5150A-T Serial RS-485 to Ethernet converter

4.1.2 Temperature Monitor

To track the performance of the cryocooler, the test cryostat is equipped with temperature sensors and heaters on every stage. The temperature sensors are selected for their temperature range and accuracy. Most of the temperature sensors sold by LakeShore Cryotronics have their calibration curve already programmed into the 224 monitor. The other sensors will have their calibration curve entered by the user. LakeShore offers a free download software called "Curve Handler" to program the 224.

4.1.2.1 LackShore Cryotronics Model 224

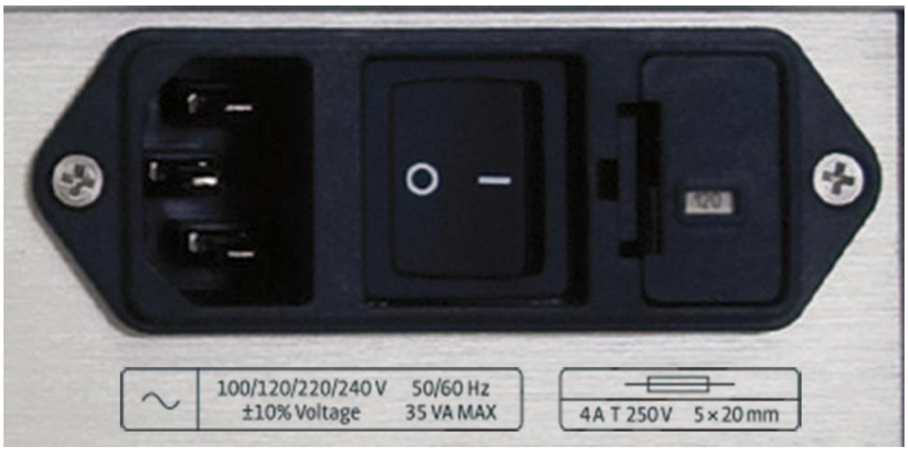
The temperature monitor model 224 offers 12 channels configurable for different sensor types. Each channel can be labeled and programmed with the sensor's calibration curve for optimal resolution.

Picture 4: LakeShore 224 Temperature Monitor

The temperature monitor connects to the laptop via Ethernet and has an RJ45 connector on the back panel.

Picture 5: LakeShore 224 Rear Panel

The twelve temperature channels are grouped into three groups of four. Each group of four corresponds to a separate board inside the instrument; inputs A, B, C, and D are on the motherboard, while channels C2, C3, C4, and C5 and channels D2, D3, D4, and D5 are on two identical plug-in boards.



Picture 6: Configurable AC Line Input Assembly

The line input assembly is configurable to allow the instrument to be used with different AC powers with frequencies of 50Hz and 60Hz.

Nominal	Minimum	Maximum
100V	90V	110V
120V	108V	132V
220V	198V	242V
240V	216V	264V

Table 2: Line Voltage Configuration

The fuse must be selected according to the line voltage, rated for 4 Amps, and of the slow-blow type, as the letter "T" indicates.

4.1.3 Pressure & Flow Monitor

To fully characterize the cryogenic subsystem, in addition to the thermal loads and temperature of the three stages of the cryocooler, the vacuum pressure of the test cryostat, the helium pressure of the supply and return lines, and the flow of helium gas are needed.

4.1.3.1 Teledyne Hastings' THCD-401 Four-Channel Power Supply and Display

Picture 7: THCD-401 Four Channel Power Supply & Display

The THCD-401 accepts line voltage between 90-250 VAC and frequencies between 50 and 60 Hz. It has four channels that can be configured to power and monitor different sensor types.

Ch1	Helium flow (scfm)
Ch2	Test cryostat vacuum pressure (Torr)
Ch3	Helium Return Pressure (psi)
CH4	Helium Supply Pressure (psi)

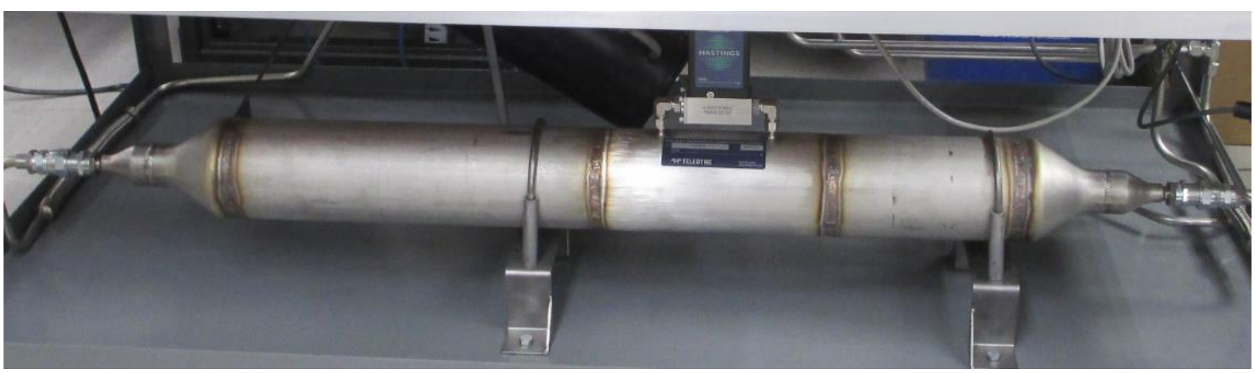
Table 3: THCD0401 Channel Allocation

4.1.3.2 Teledyne Hastings' HFM-200 LFE

The HFM-200 LFE mass flow meter is calibrated for helium. It has a working pressure of 500 psi and a maximum flow of 100 SCFM (2500 SLM). The tube diameter is four inches, which is important because it dictates the overall length of the assembly.

Picture 8: HFM 200 LFE Mass Flow Meter

To accurately measure the flow, Teledyne recommends adding sufficient conductance before entering and after exiting the LFE sensor to allow a laminar flow to develop fully with minimum turbulence. The rule of thumb is to add a tube five times the LFE sensor diameter in length upstream of the sensor and a second tube at least one time the diameter downstream. Conical sections can reduce the size of tubing required to establish the laminar flow; our flow meter was built following Teledyne's recommendations and information provided by Sumitomo USA.



Picture 9: Complete Flow Meter Assembly

4.1.3.3 Teledyne Hastings' HVG 2020B Vacuum Sensor

The vacuum sensor measures the pressure inside the test cryostat to determine when it is safe to turn on the Sumitomo cryocooler. If the pressure is too high, ice will form on the cold surfaces, and the thermal transfer by convection might overcome the cooling power of the cryocooler, preventing the desired cold temperatures from being achieved.

Picture 10: HVG-2020B Wide Range Vacuum Sensor

The vacuum sensor has an integrated display and covers the 0.1 mTorr to 1000 mTorr pressure range. Before starting the cryocooler, it is recommended that the vacuum pressure drop below one mTorr.

4.1.3.4 Ashcroft T27M0210D2300#G and T27M0210D2500#G Pressure Transducer

The supply line exits the compressor and goes to the cryocooler, while the return line leaves the cryocooler and returns to the compressor. The pressure of both lines must be monitored to confirm that the compressor operates appropriately.

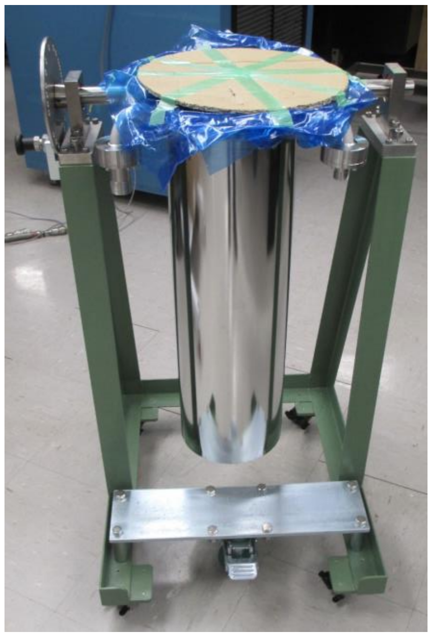
Picture 11: Ashcroft Pressure Transducer

The sensor for the supply line has a maximum pressure of 500 psi (T27M0210D2500#G), while the return line sensor has a maximum pressure of 300 psi (T27M0210D2300#G).

The ALMA receiver uses a 3-stage Gifford McMahon cryocooler to cool its sensitive electronics below 4K, which is required for the SIS mixer's operation. To test the influence of the compressor operating frequency on the cryocooler's cooling performance, an ALMA cryocooler was purchased with a test cryostat designed for it. This is the same cryostat used in Chile to test a cryocooler's capacity after service.

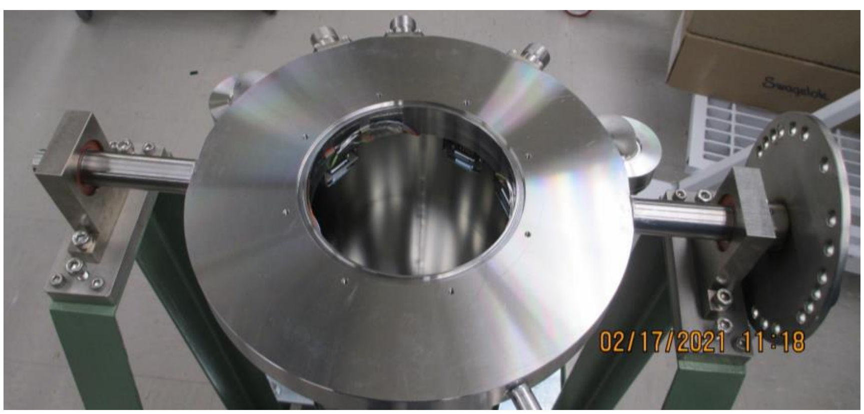
4.1.4 Cryostat Test Description

A metal frame with lockable caster wheels supports the test cryostat.



Picture 12: Frame Supporting the Test Cryostat

The cryostat outer cylinder is welded to a large flange supported by an axle mounted to the frame with bearings, allowing the cryostat to rotate to facilitate the assembly.



Picture 13: Cryostat Supporting Flange with Rotation Axle

4.1.5 Sumitomo 3-State GM Cryocooler

The Sumitomo GM cryocooler has three stages; to my knowledge, it is the only model on the market. The third stage temperature needs to drop below 5K to allow SIS junctions to operate as mixers for the frequency bands three and higher.

RDK-3ST-R3	**50/60 Hz**
1st stage cooling capacity	33 Watts @ 80K
2nd stage cooling capacity	16 Watts @ 16K
3rd stage cooling capacity	1 Watt @ 4K

Table 4: Sumitomo 3-Stage Nominal Cooling Capacities

Picture 14: Sumitomo 3-State GM Cryocooler

4.1.6 Instrumentation

The test cryostat is equipped with temperature sensors and heaters on every stage to apply specific heat loads and monitor the temperature response.

	1st stage	2nd stage	3rd stage
Heater	80Ω heating blanket	20Ω heating blanket	10Ω heating blanket
Temperature sensor	T_1: R800-7 Platinum/cobalt resistance thermometer (15K to 375K)	T_2: R800-6 Platinum/Cobalt resistance thermometer (4K to 375K)	T_3: RD42ZT0578EQ/RuO T_4: DT500 (diode)

Table 5: Heater & Temperature Sensors per Stage

The third stage has two temperature sensors: one (T_3) has accuracy below 10K but no resolution above 150K, and the second (T_4) covers the full range down to 4K but has limited resolution and accuracy below 10 K.

Heaters are wrapped around each stage to apply heat evenly and conform to the cylindrical shape.

Picture 15: Installation of Temperature Sensors & Headers

The temperature sensors use a four-wire measurement for better accuracy, eliminating the error that the resistance of the wire carrying the bias current will introduce if only two wires are used. Each sensor comes out of the cryostat on a separate connector and connects directly to the LakeShore 224 temperature monitor.

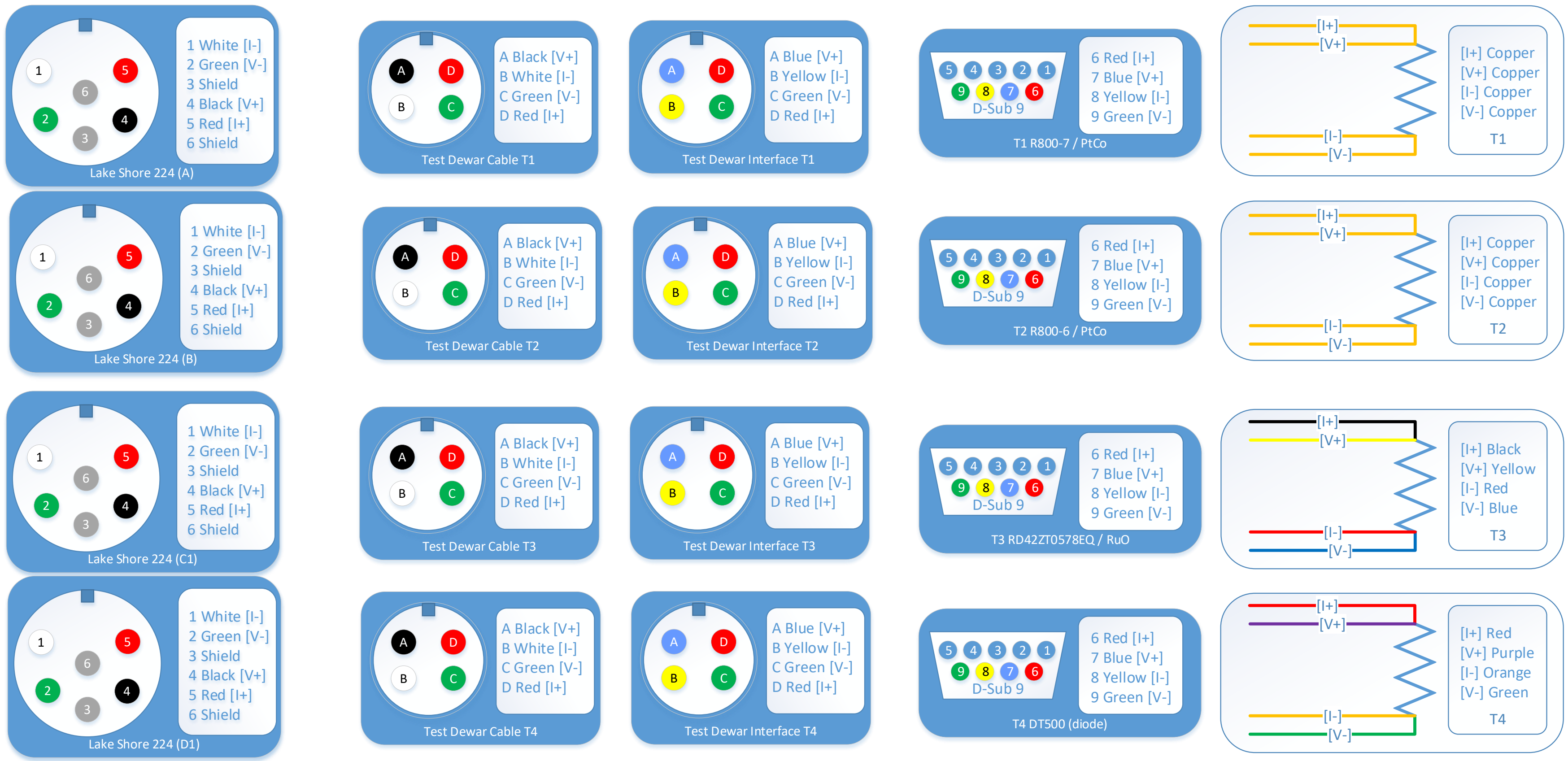


Figure 2: Wiring Diagram of Test Cryostat Temperature Sensors

The three heaters exit the test cryostat on a single connector, which is then split into three cables to connect to the two dual-channel power supplies.

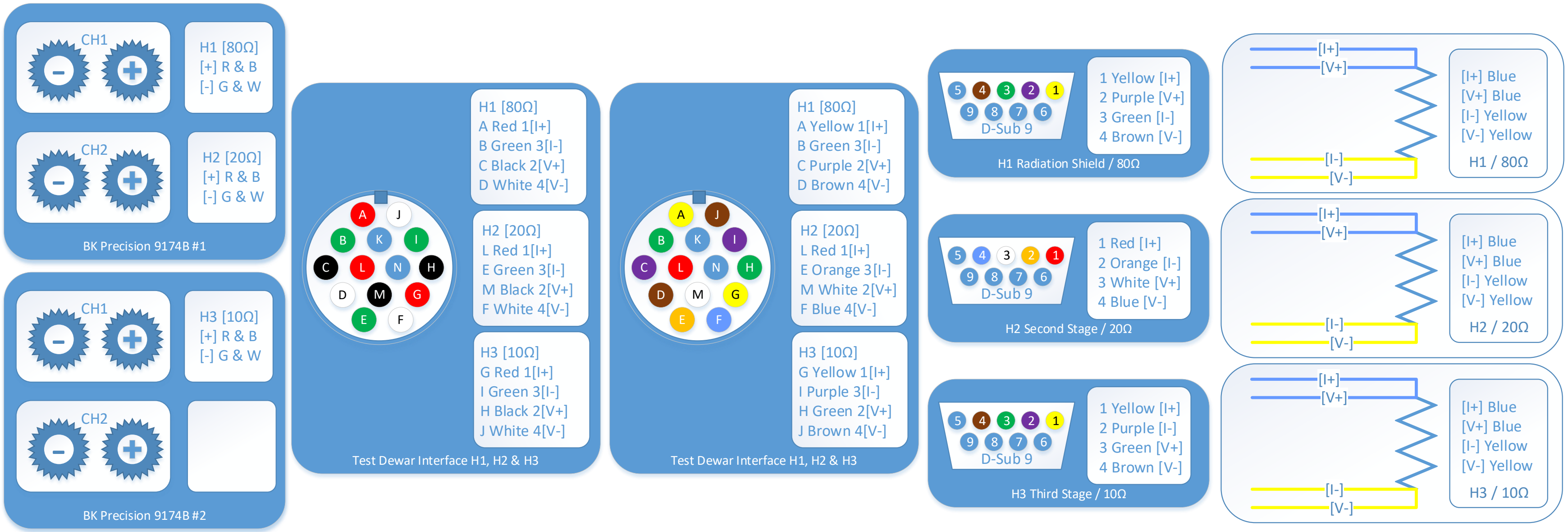
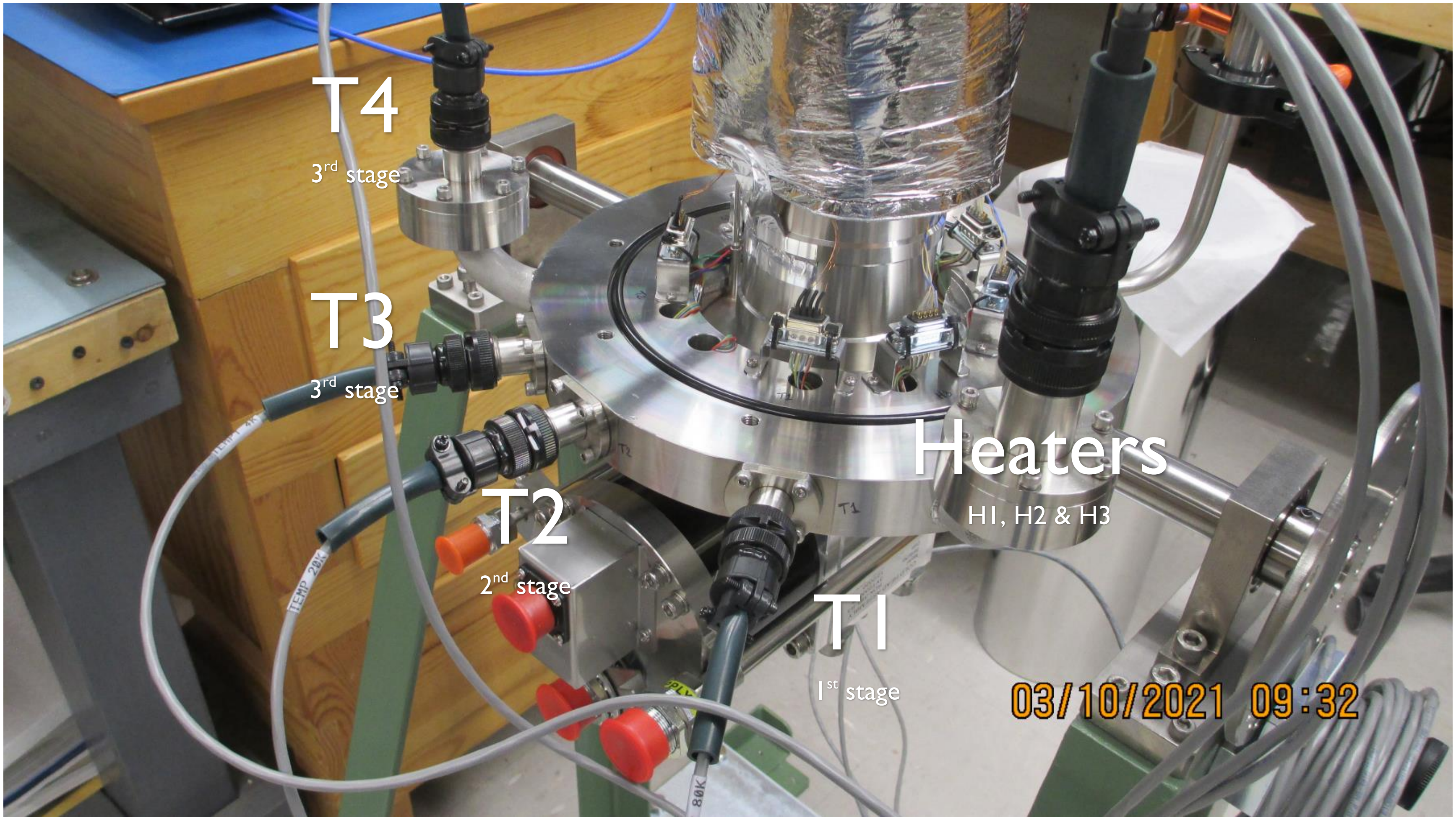


Figure 3: Wiring Diagram of Test Cryostat Heaters



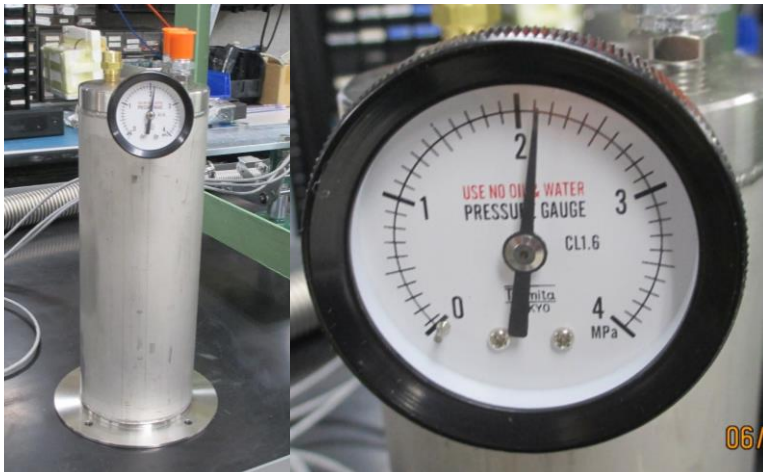
Picture 16: Sumitomo Test Cryostat Cabling

4.2 *Helium Buffer Tank*

The ALMA Front End has a stringent temperature stability requirement that cannot be met without temperature stabilization. Active temperature control is not recommended because the required heaters will add thermal load to the already heavily loaded third stage. Sumitomo used a passive temperature stabilization based on helium gas liquefaction at 4K. A small volume of liquid helium acts as a thermal capacitor, damping the small temperature oscillations introduced by the GM thermal cycle.

4.2.1 Hardware

The helium temperature stabilization circuit comprises a buffer tank connected by capillary tubing to a small reservoir attached to the third stage of the cryocooler. When the temperature of the third stage drops below 4.2K, the helium gas starts to condense and liquefy in the small reservoir. Because helium in liquid form has 1/750 the volume of helium gas, the pressure in the buffer tanks drops quickly. The buffer tank has a charge pressure of 2.1 MPa at room temperature to maintain positive pressure. It is essential to maintain a positive pressure to avoid the ingression of other gases that will freeze and block the capillary tubing and could cause its rupture during the warm-up phase.



Picture 17: Helium Buffer Tank 3rd Stage Temperature Stabilization Circuit

4.3 *Cryo-Test-Cart*

The cryo-test cart was designed to measure the flow of a compressor; it allows the supply line from the compressor to be connected to up to two cryocoolers or to go through an adjustable needle valve. After the cryocooler and the valve, the circuits are recombined by a Tee junction and fed to a charcoal trap to eliminate oil contamination before entering the flow meter. The quarter-turn valve allows the user to direct the flow toward the two cryocooler supply connections or the needle valve.

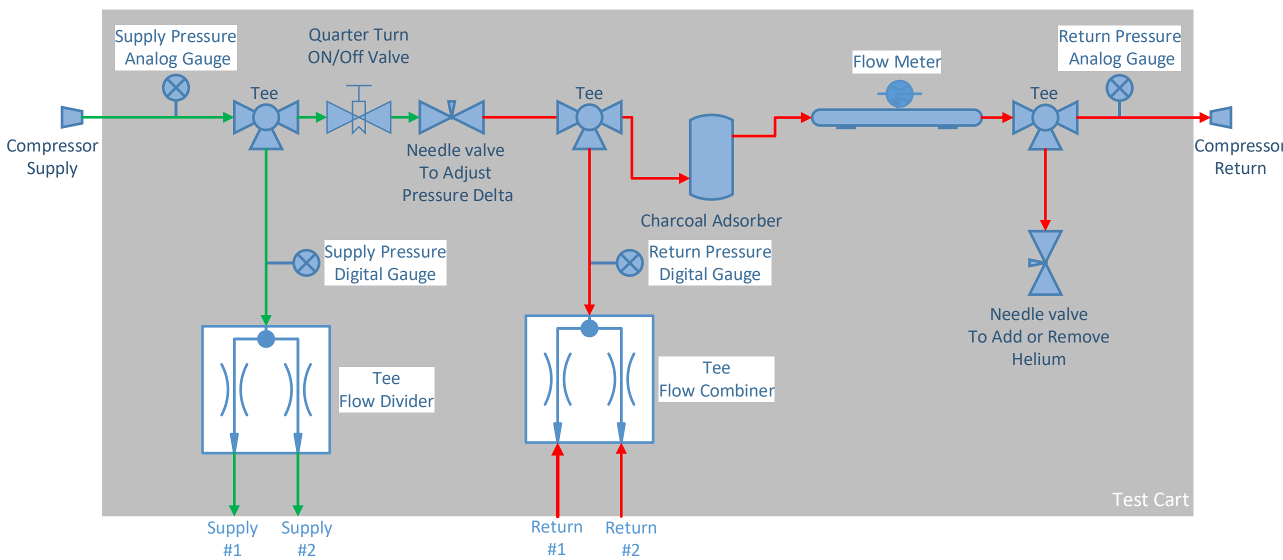
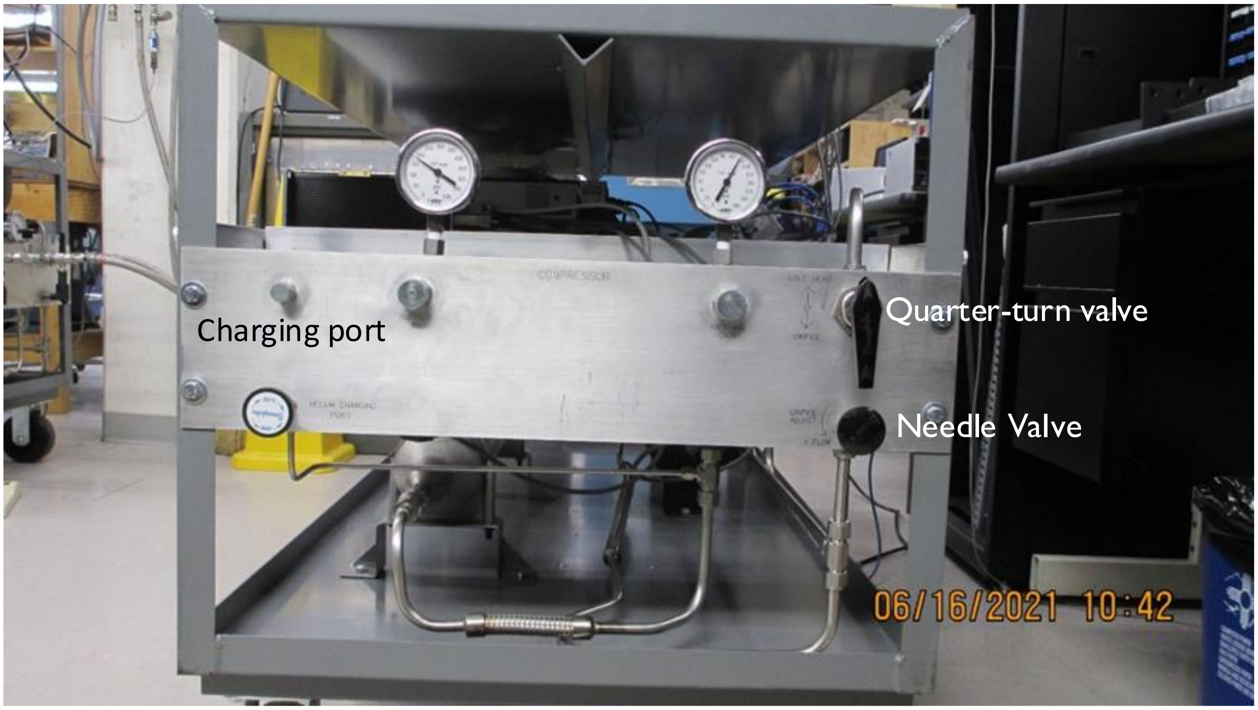


Figure 4: Cryo-Test-Cart Block Diagram

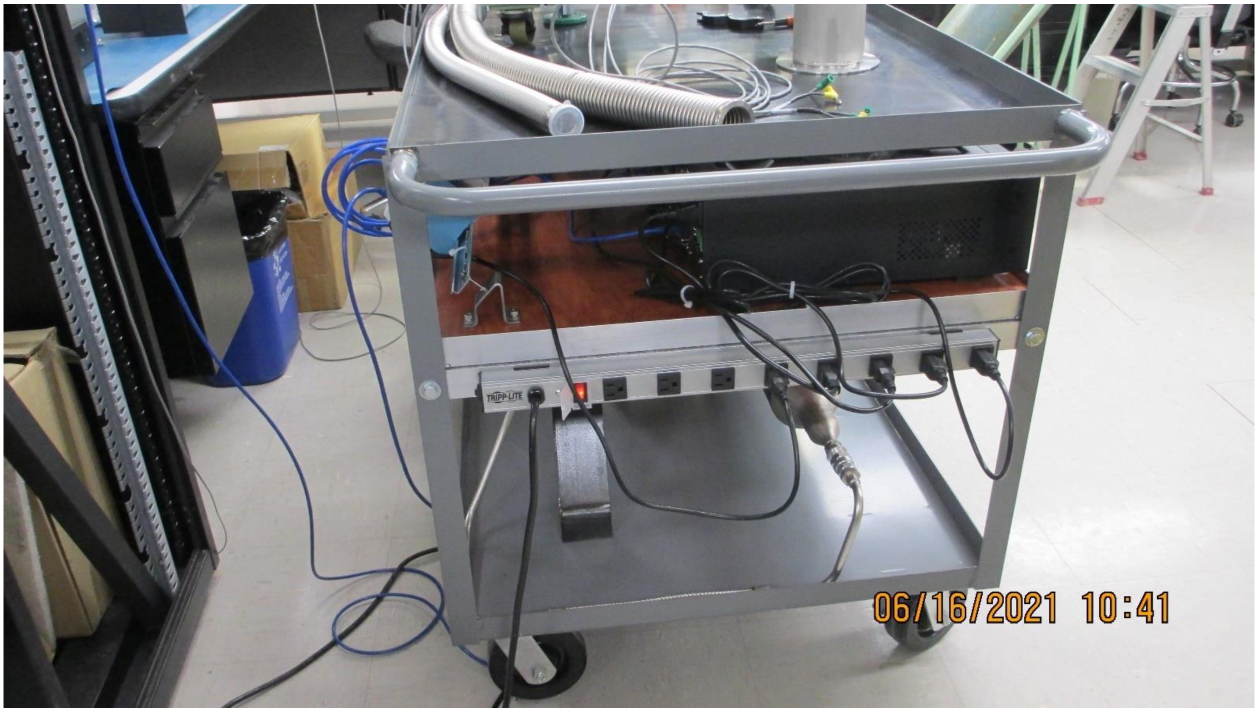
Picture 18: Complete Cryo-Test Cart

4.3.1 Cryo-Test Cart Assembly

The cryo-test-cart's helium circuit is built with Swagelok tubing and fittings and mounted on a cart purchased from McMaster-Carr. The Aeroquip connectors allow regular helium lines to be connected. The sturdy upper shelf can support the Sumitomo test cryostat, reducing the test assembly's overall footprint.



Picture 19: Cryo-Test-Cart Front Panel



Picture 20: Cryo-Test-Cart Power Strip

Picture 21: Cry-Test-Cart Loaded with Instrumentation & Flow Meter

Network Information

In Chile, the test instrumentation is installed in a refurbished shipping container at the high site (5000 m) and connected to an ALMA subnet. The IP addresses are listed in the table below.

Instrumentation	Manufacturer	Model	Interface	Host Name	MAC address (Media Access Controller)	TCP Port	IP address	DNS (Domain Name System)
Laptop	Dell	Latitude 5420 Rugged	USB / Ehternet	ALPACA	60:02:92:8F:FC:AD		10.197.198.11	alma-alpaca.aos.alma.cl
Power Supply Dual Channel	BK Precision	9174B (sn 503K17155)	USB / Ehternet	ALMA-TB-PS1	00:17:F8:00:1F:C6	5025	10.197.198.12	alma-tb-ps1.aos.alma.cl
Power Supply Dual Channel	BK Precision	9174B (sn 503K17164)	USB / Ehternet	ALMA-TB-PS2	00:17:F8:00:20:CE	5025	10.197.198.13	alma-tb-ps2.aos.alma.cl
Temperature Monitor	Lakeshore	224	Ethernet	ALMA-TEMP-MON	00:40:9D:AF:AD:FE	7777	10.197.198.14	alma-temp-mon.aos.alma.cl
Power Quality Logger	AEMC	PEL 105	USB / Ehternet	ALMA-PWR-MON			10.197.198.15	alma-pwr-mon.aos.alma.cl
Power Supply Four Channels	Teledyne Hastings Instruments	TCHD-400	USB / Ehternet	ALMA-PVF-MON	00:50:C2:57:28:A8	101	10.197.198.16	alma-pvf-mon.aos.alma.cl
Pressure Transducer	Ashcroft	T2 , 0-500 psi		ALMA-COMP-SUP				
Pressure Transducer	Ashcroft	T2 , 0-300 psi		ALMA-COMP-RET				
Vaccum Controller	Teledyne Hastings Instruments	DAVC-6-04	0-10V	ALMA-DEWAR-VAC				
Flow Meter	Teledyne Hastings Instruments	HFM-200 LFE 0-100 scfm		ALMA-COMP-FLOW				
Inverter	Emerson	Unidrive M200	Ethernet	ALMA-COMP-VFD	00:0D:1E:0C:DA:36	502	10.197.198.17	alma-comp-vfd.aos.alma.cl
Helium Compressor	Sumitomo	FA-70	RS 232	ALMA-COMP-FA40				
Serial to Ethernet Adapter	Moxa	P5150A-T	Ethernet	ALMA-ADAPT1	???	4001	10.197.198.18	alma-adapt1.aos.alma.cl
FA-70H	Laptop	?	Ethernet	FA70H-TEST	?	?	10.197.198.19	fa70h-test.aos.alma.cl

Table 6: Mac & IP Addresses for Test Instrumentation AOS Chile

5 Sumitomo Variable Speed Compressor FA 70V

The development work done on cryogenics for ngVLA indicates that operating a compressor at variable speed can reduce power consumption by adjusting the helium flow to the demand from the GM cryocooler. Because of the high energy cost at the ALMA site and the obsolescence of the current compressor model, a variable Frequency Drive (VFD) compressor can be a viable solution.

5.1 *Compressor Modification*

5.1.1 Hardware

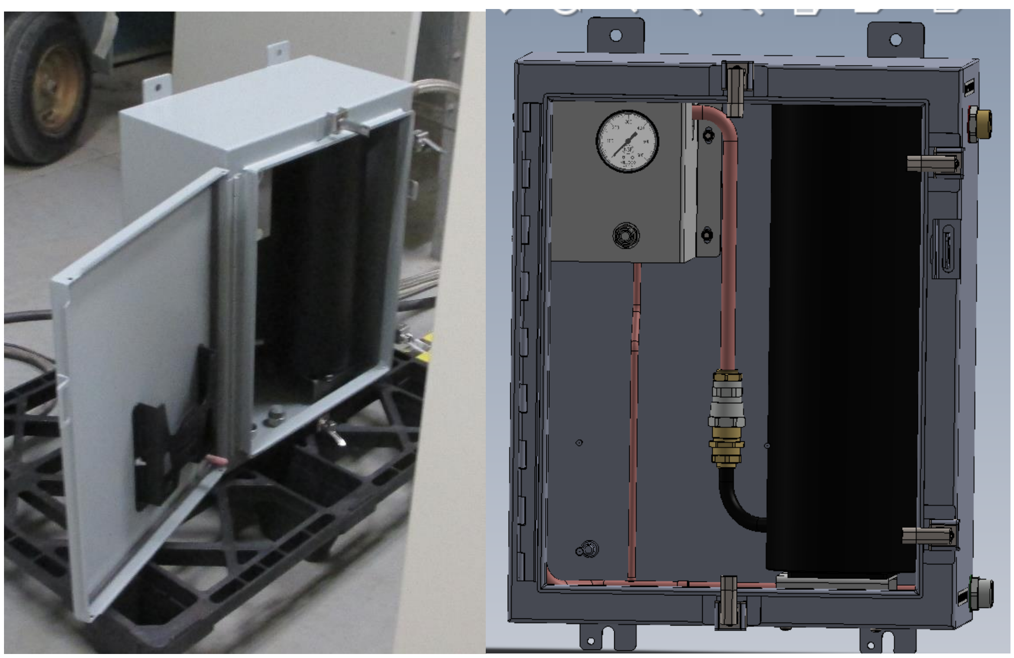
The operation of the helium compressor at variable frequencies requires the power to go through an inverter, a commercial unit selected based on the load power requirement. Sumitomo replaced the charcoal trap inside the indoor unit with the inverter to keep it in the controlled environment of the ICU enclosure. A remote keypad assembly was added to allow control of the inverter from the ICU front panel.

Picture 22: Integration of the Inverter with Indoor Compressor Unit (ICU)

After the inverter, Sumitomo placed a load reactor assembly to filter the AC signal before it goes to the OCU and powers the Scroll capsule.

Picture 23: Load Reactor Filter

The charcoal trap, pressure gauge, and charging port generally found on the ICU were relocated inside a separate enclosure that could be mounted on the antenna outside the Outdoor Compressor Unit (OCU) enclosure. The supply line from the OCU enters the enclosure at the bottom and exits at the top; any oil residue will be captured and retained by the activated charcoal. To follow Sumitomo's recommended maintenance schedule, the charcoal trap must be replaced after 30.000 hours.



Picture 24: Auxiliary Enclosure for Charcoal Trap & Analog Pressure Gauge & Charging Point

The electrical wiring of the Sumitomo FA-70H compressor was modified to incorporate the inverter. The three-phase power that feeds the ICU goes directly to the inverter; the inverter output is filtered and sent to the OCU to power the Scroll capsule.

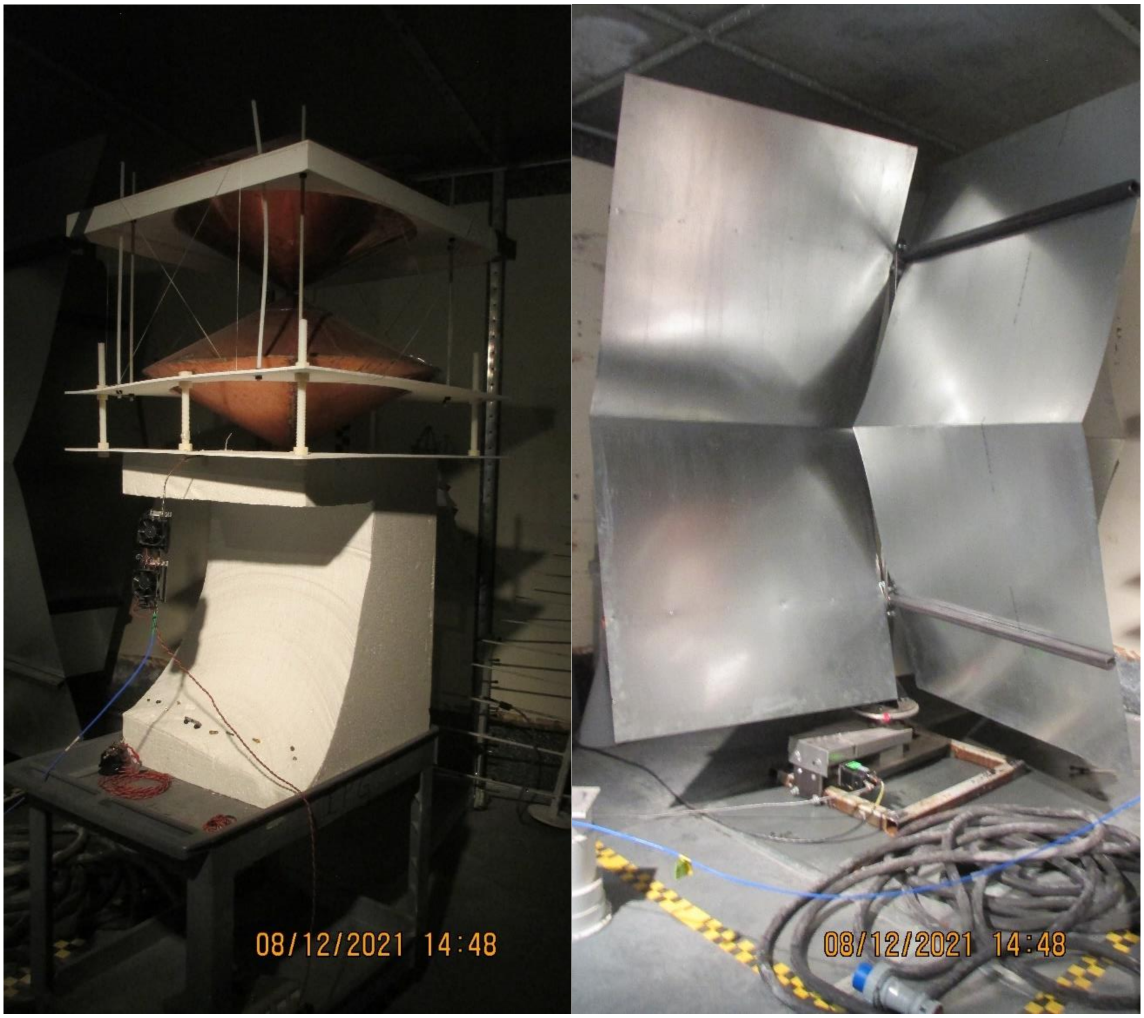
5.1.2 Firmware

The inverter introduces a delay in the compressor startup procedure, which will produce an error in the standard configuration and has to be addressed for the FA-70V. The compressor M&C electronics constantly check the return pressure. If the value exceeds 140 psi, the compressor shuts down, and the "MOTOR TEMP ERR" message is displayed on the small LCD screen of the ICU. Since the compressor takes longer to start, when the M&C electronics checks the return pressure for the first time, the capsule is not running yet, and the pressure is equal to the static pressure, which is higher than the 140psi limit. To solve the problem, the firmware introduces a delay to ensure the compressor runs before the return pressure is checked.

6 EMI/RFI Testing

Commercial inverters are susceptible to generating RFI due to their internal frequency and switching power electronics. The RFI emissions from the prototype compressor must be below the ALMA threshold level to be deployable in Chile. Dan Mertely measured the RFI emissions of the compressor over two frequency bands, 0-1 GHz and 0-3 GHz, for four operating frequencies and plotted the results with the limit set by the ALMA project. The RFI emissions are measured inside the VLA reverberation chamber. A broadband antenna and a wave steerer are needed for measurement. The antenna's output signal is amplified and fed to a spectrum analyzer. A custom piece of software plots the results and the threshold level on the same graph.

Picture 25: Compressor Inside VLA Reverberation Test Chamber



Picture 26: Reverberation Chamber Broadband Antenna & Wave Steerer

7 Results

7.1 *Compressor Frequency of 30 Hz*

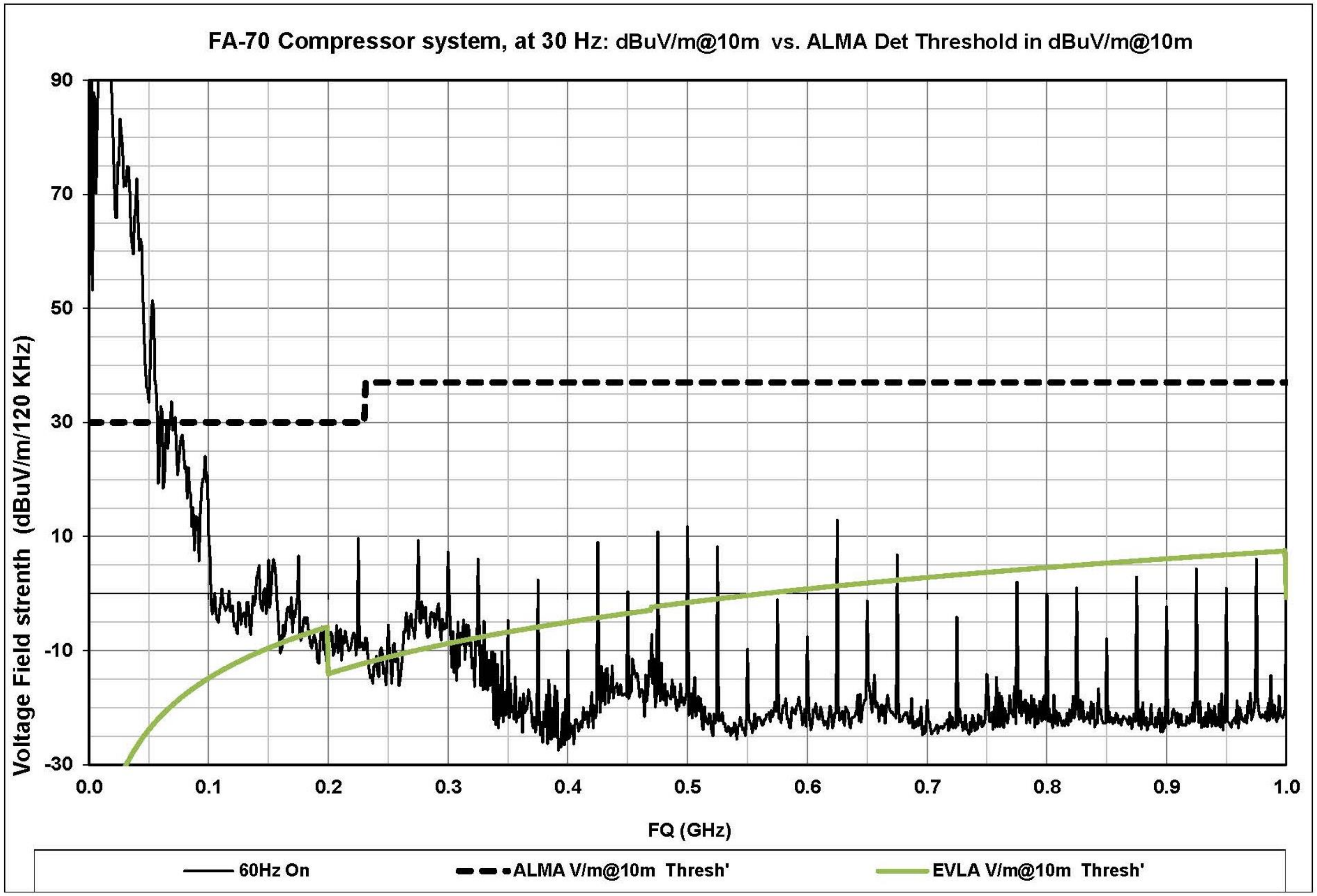


Figure 5: 0-1 GHz RFI Spectrum at 30Hz Compressor Frequency

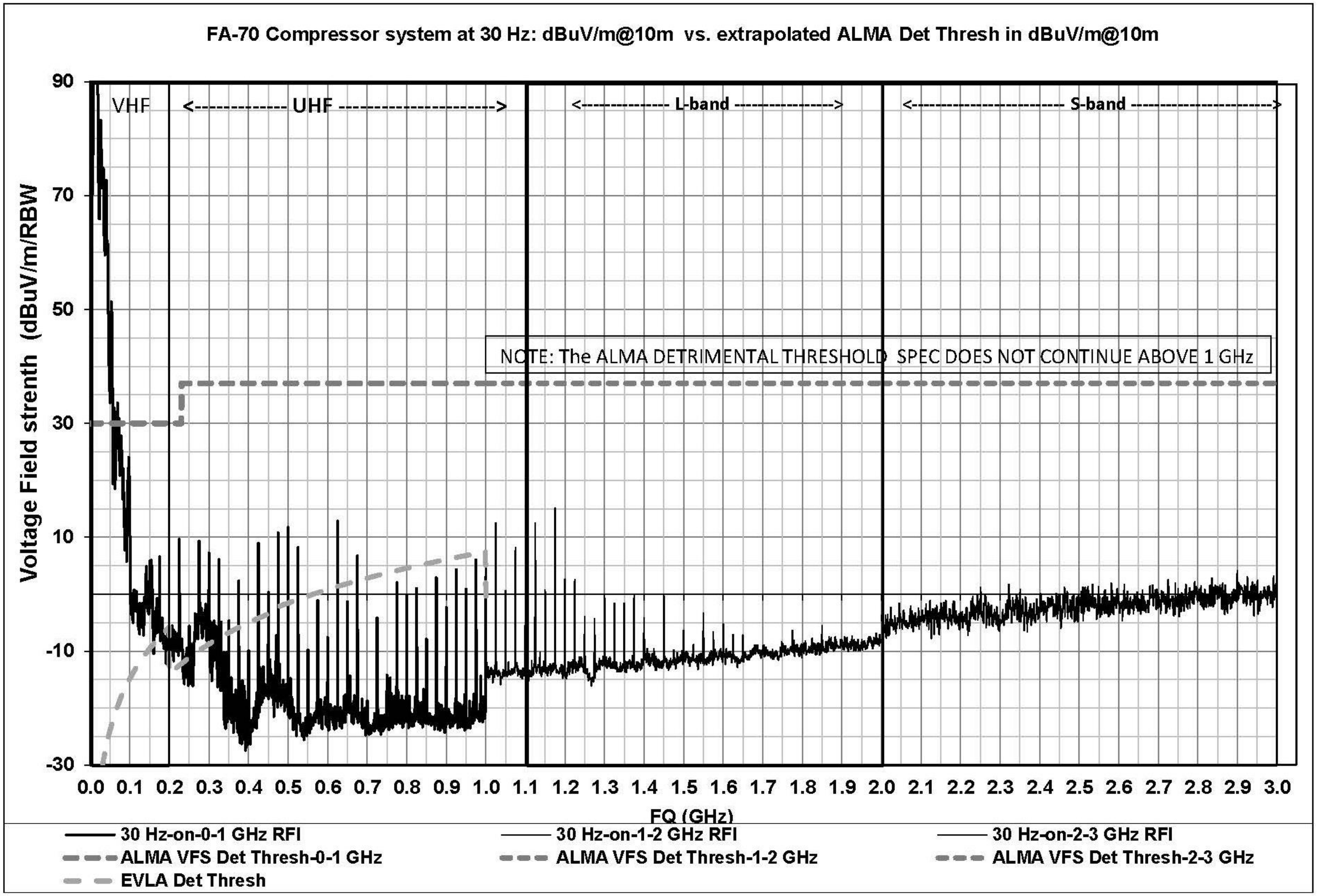


Figure 6: 0-3GHz RFI Spectrum at 30Hz Compression Frequency

7.1.1 Compressor Frequency of 40 Hz

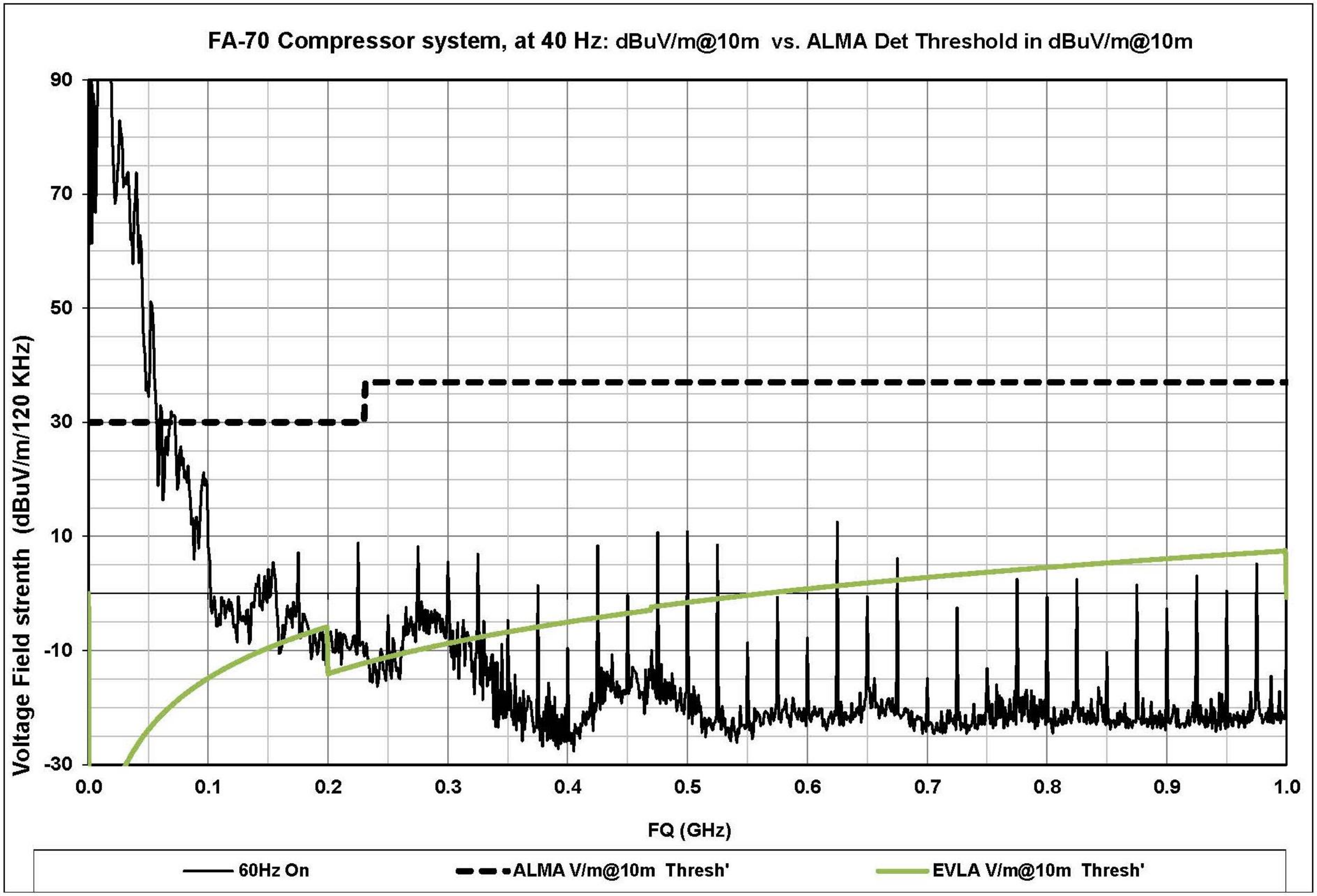


Figure 7: 0-1GHz FRI Spectrum at 40Hz Compressor Frequency

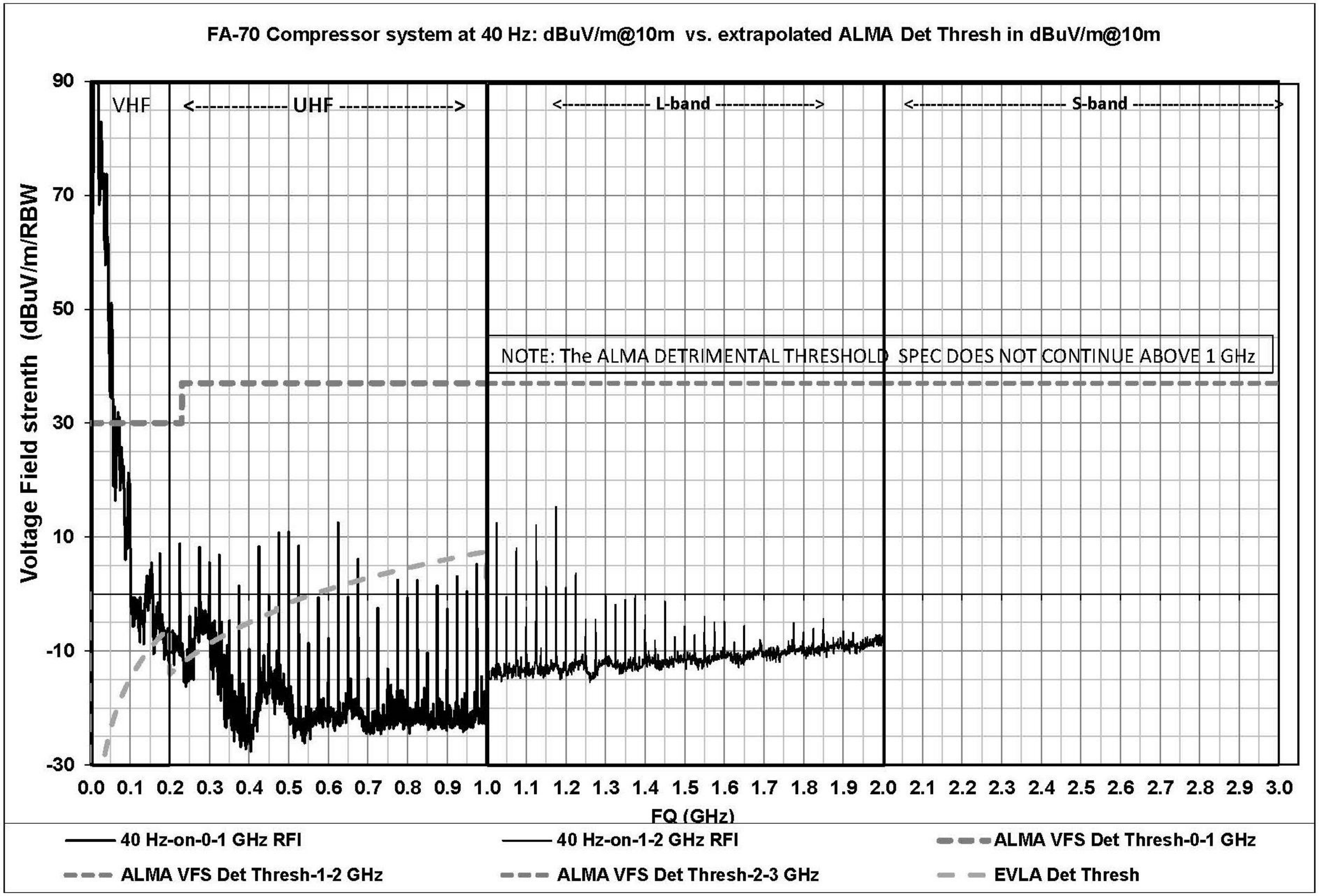


Figure 8: 0-3GHz RFI spectrum at 40Hz Compressor Frequency

7.1.2 Compressor Frequency of 50Hz

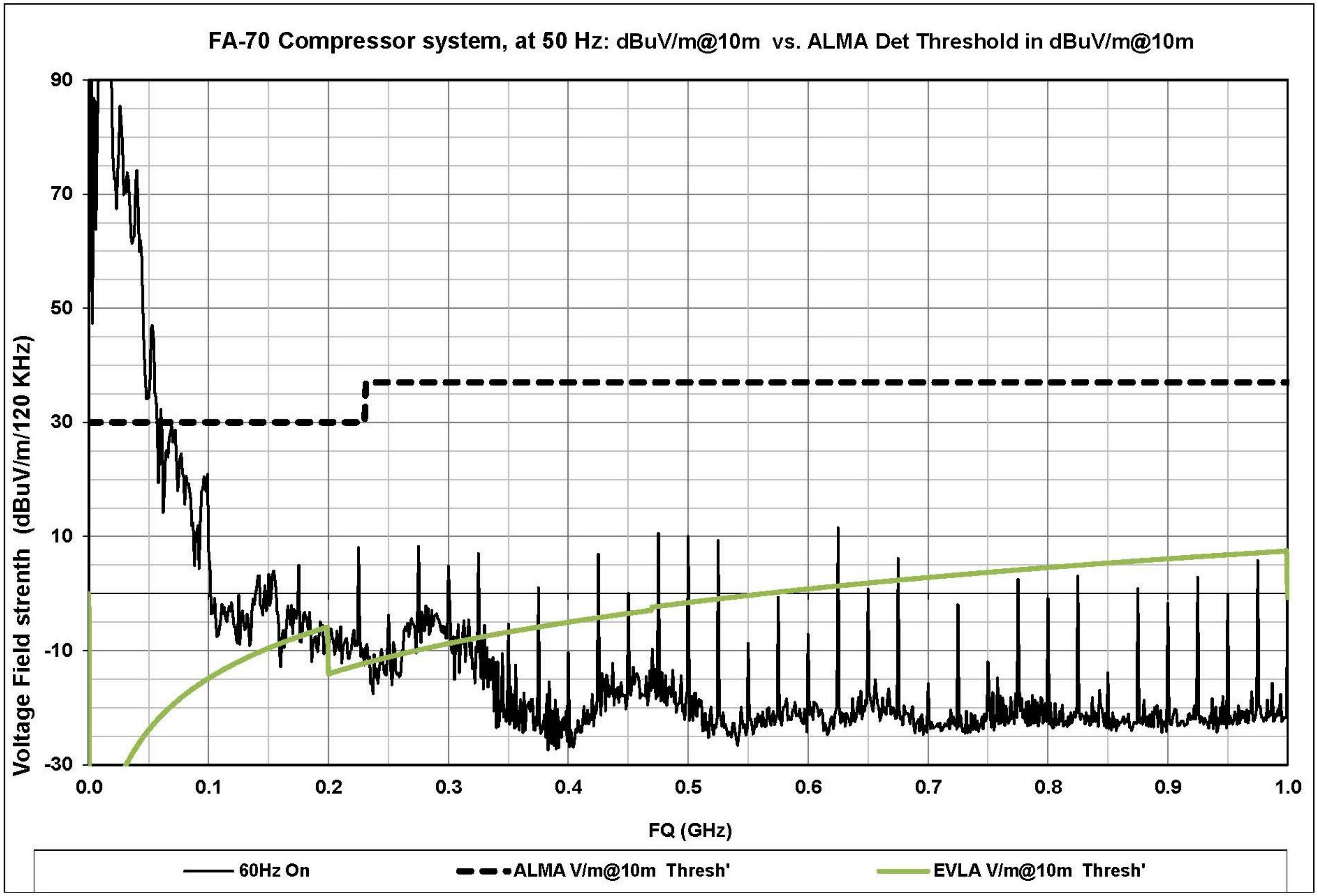


Figure 9: 0-1GHz RFI Spectrum at 50Hz Compressor Frequency

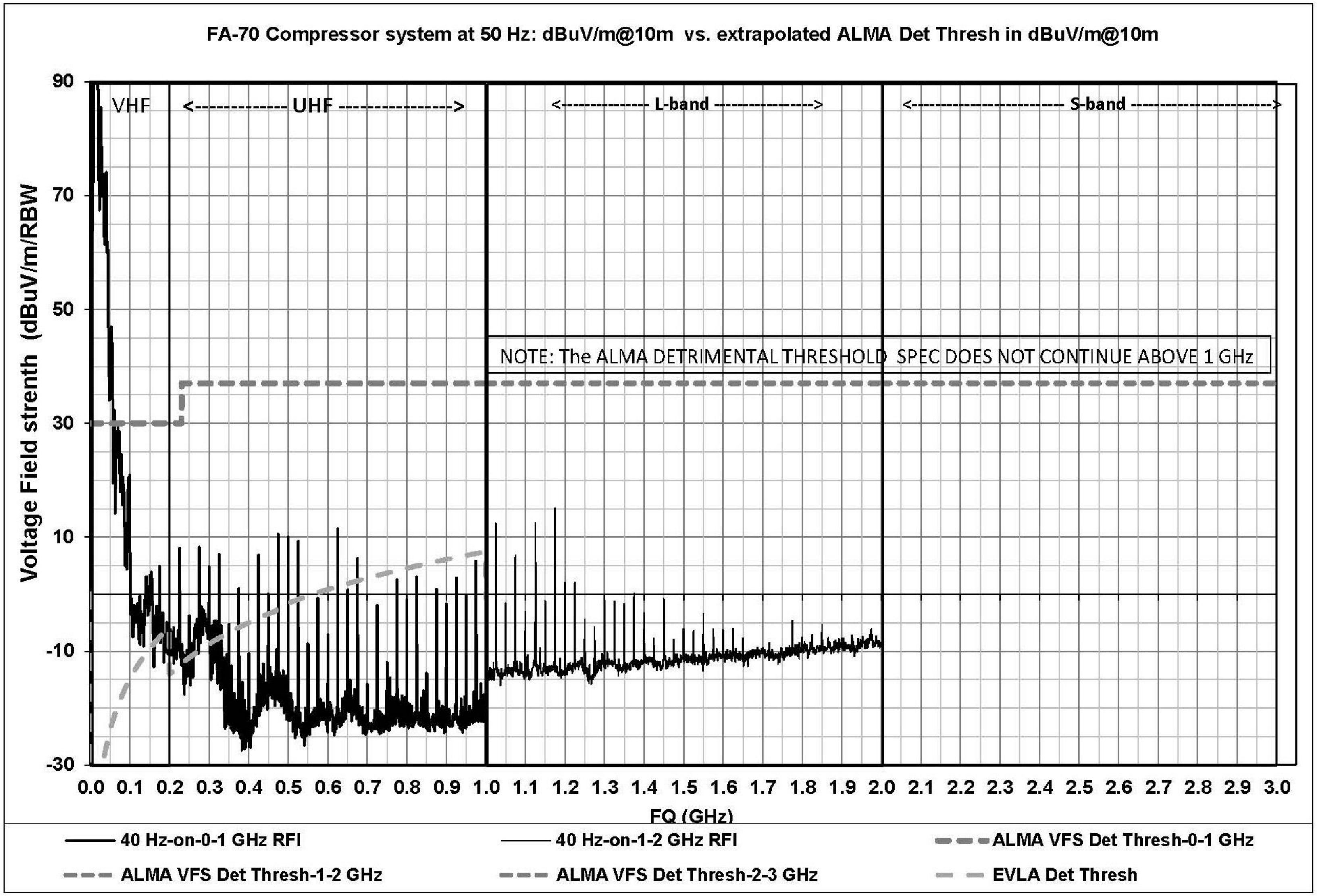


Figure 10: 0-3GHz RFI Spectrum at 50Hz Compressor Frequency

7.1.3 Compressor Frequency of 60Hz

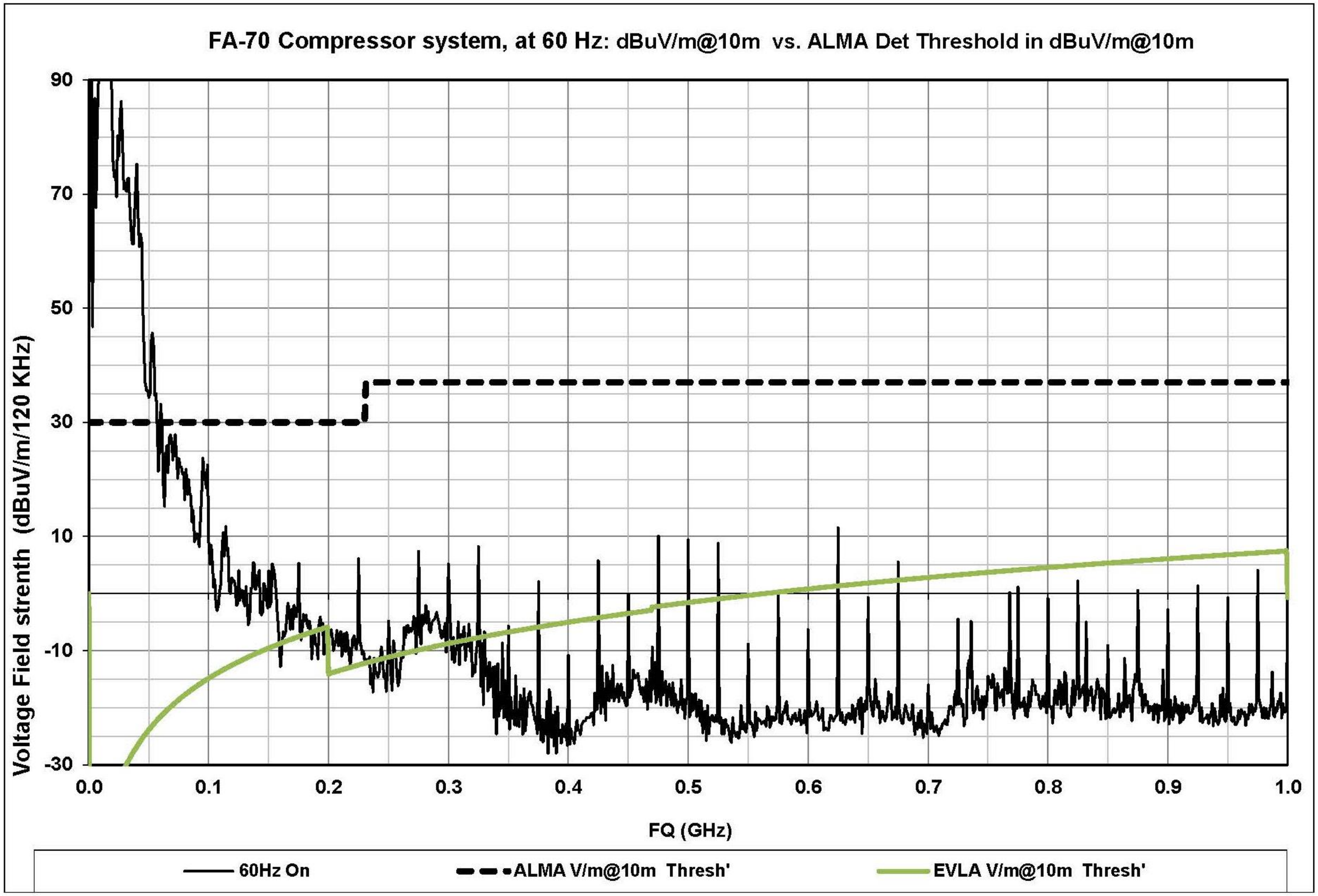


Figure 11: 0-1GHz RFI Spectrum at 60Hz Compressor Frequency

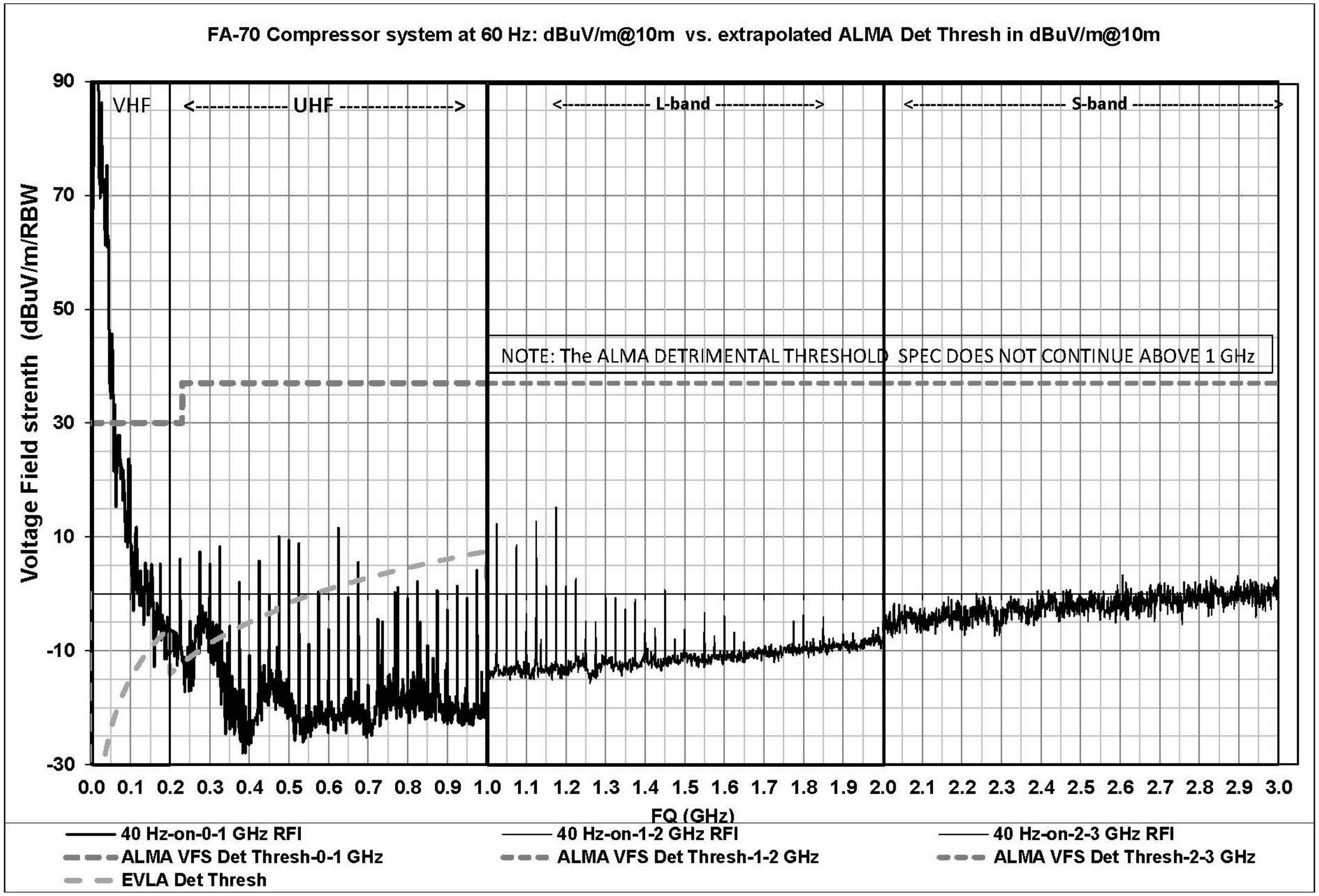


Figure 12: 0-3GHz RFI Spectrum at 60Hz Compressor Frequency

Below 100 MHz, the results are unreliable because the chamber would need to be larger to provide the recommended number of reflections. The emissions are at least 20dB below the threshold level, so powering the compressor at the ALMA site in Chile is safe.

8 Test Results at the Sumitomo Factory

Only the compressor could be evaluated at the factory because the 3-stage cryocooler and test cryostat were unavailable.

8.1 *Helium Flow Maps*

A flow map graphically displays the compressor helium flow versus its power draw for different differential pressures (difference between the supply and return pressures) and a set of return pressures (suction pressure). A cryo-test-cart similar to ours was used at the Sumitomo factory in Allentown to create the flow maps. The compressor runs at a fixed frequency and flows through the needle valve, which is adjusted to change the pressure values. In combination with the needle valve adjustment, helium is added or withdrawn from the circuit to obtain the required differential and return pressure values.

8.1.1 30Hz

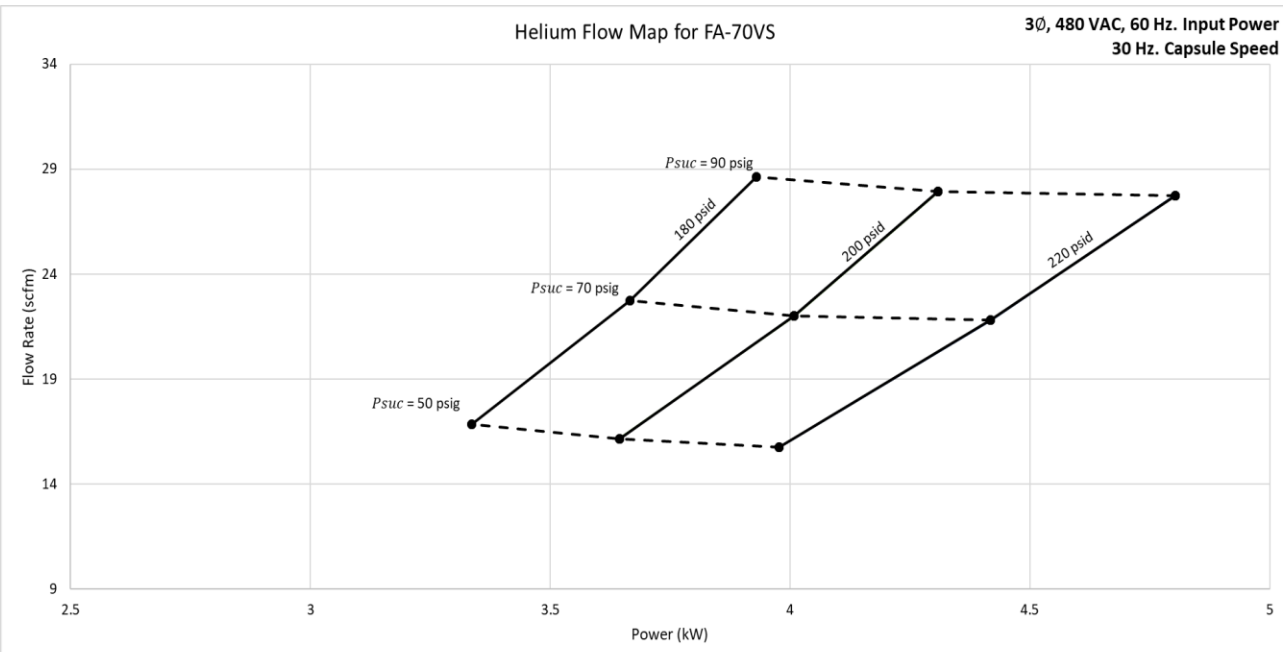


Figure 13: Compressor Helium Flow Versus Power @ 30Hz

The higher differential pressure values require adding helium to the circuit, forcing the compressor to work harder, which increases power consumption. To increase the suction pressure, the needle valve has to open more, raising the flow and forcing the compressor to work harder.

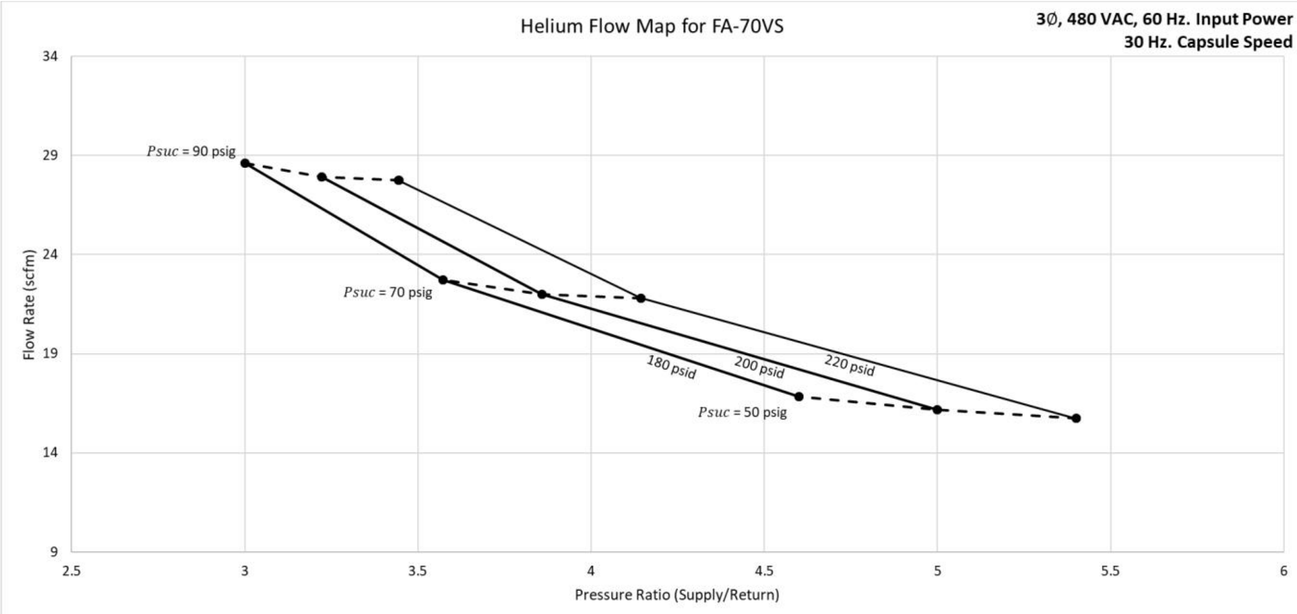


Figure 14: Compressor Helium Flow Versus Differential Pressure @ 30Hz

What is interesting about this representation is that the flow varies strongly with the return pressure but is almost independent of the supply pressure.

8.1.2 35Hz

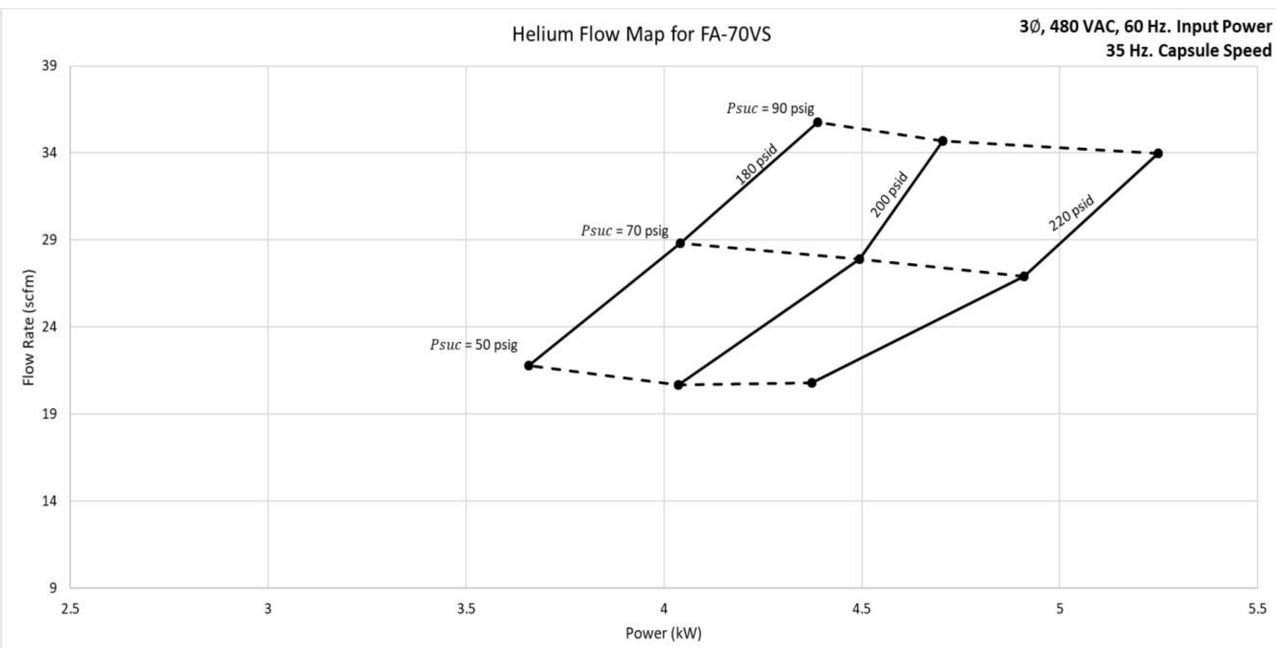


Figure 15: Compressor Helium Flow Versus Power @ 35Hz

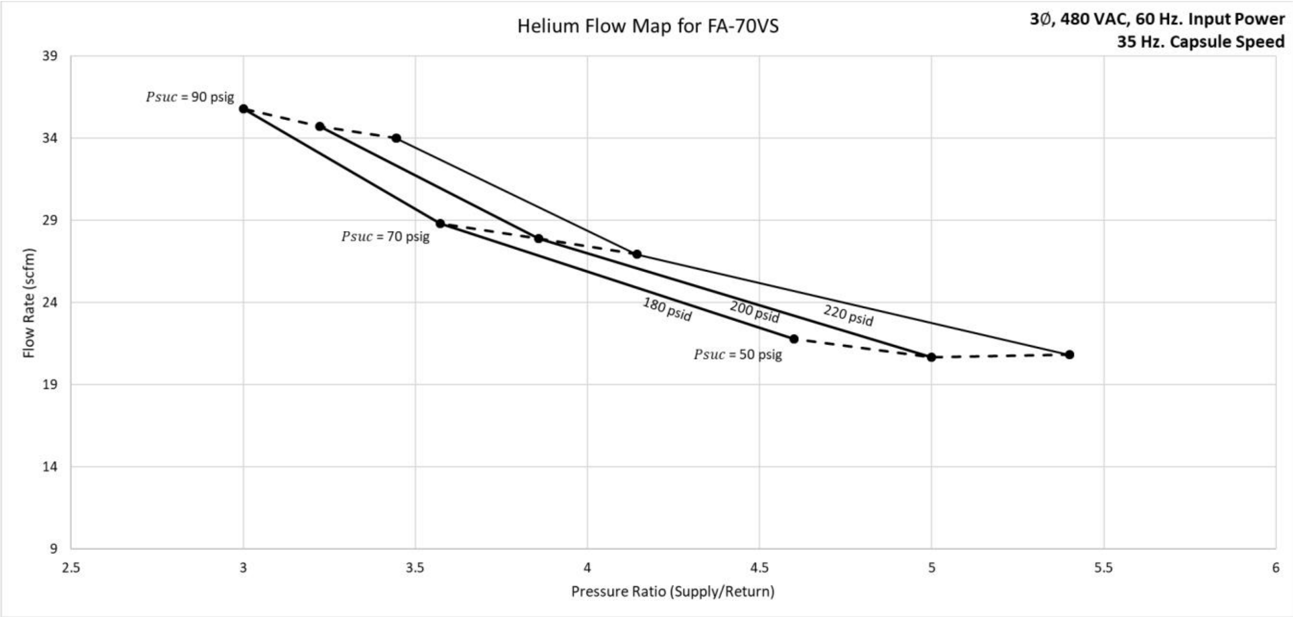


Figure 16: Compressor Helium Flow Versus Differential Pressure @ 35Hz

8.1.3 40Hz

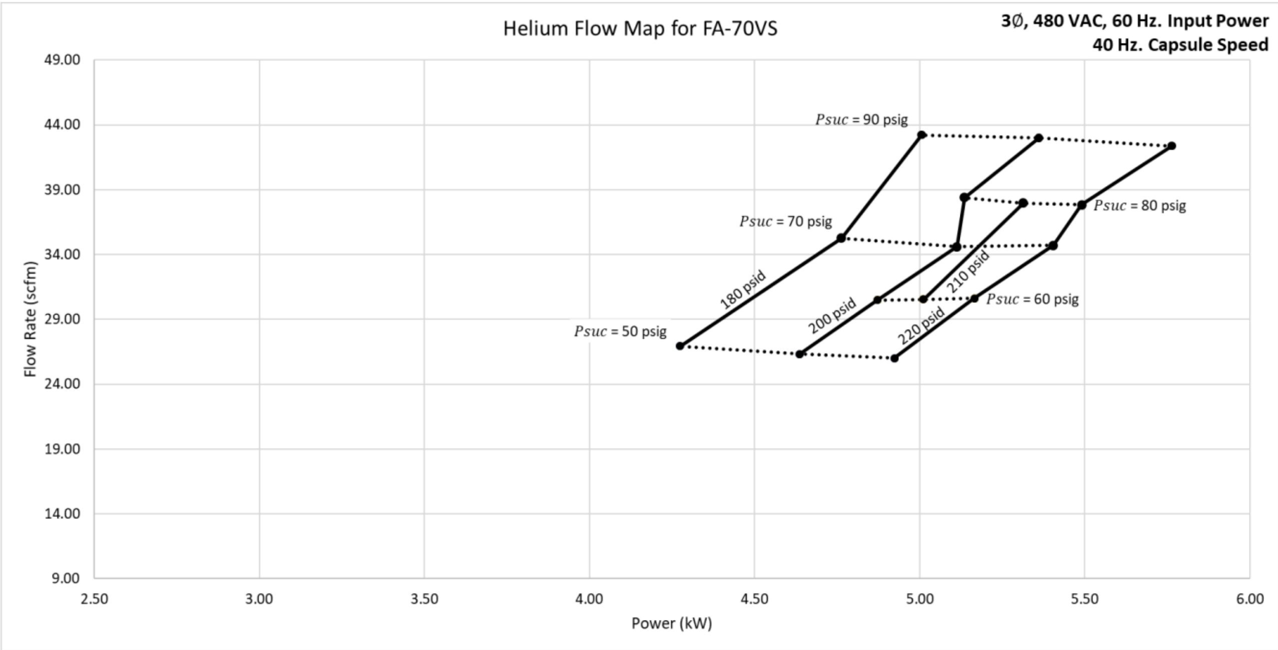


Figure 17: Compressor Helium Flow Versus Power @ 40Hz

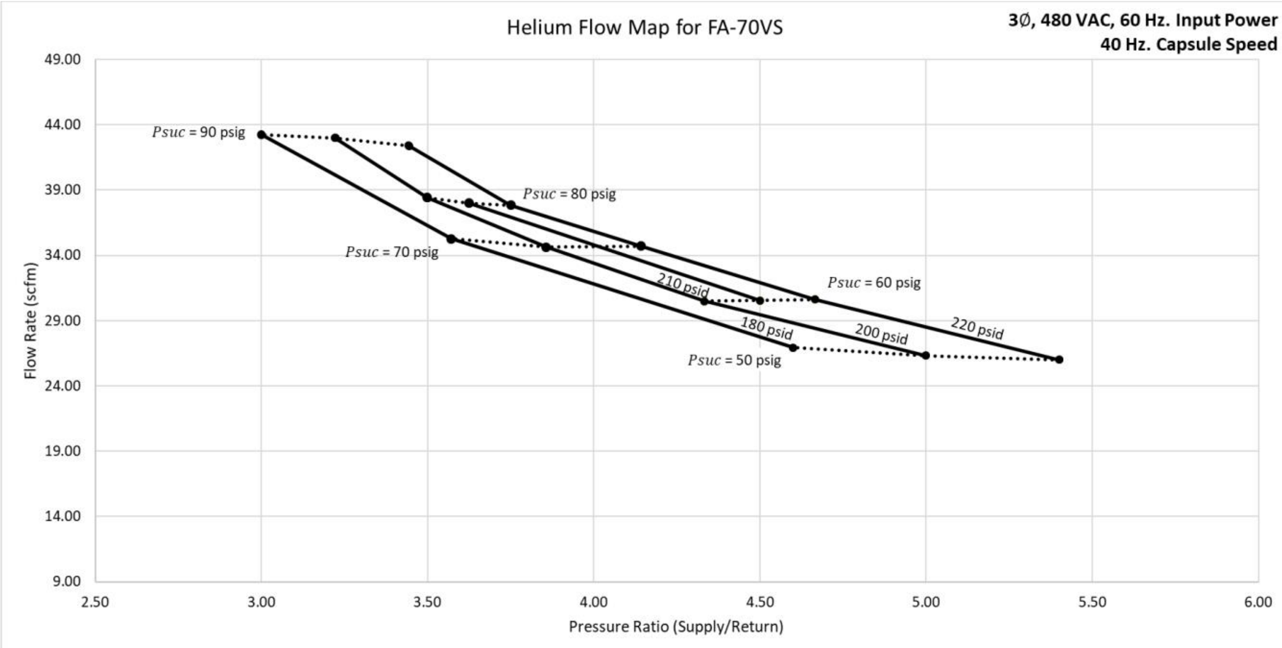


Figure 18: Compressor Helium Flow Versus Differential Pressure @ 40Hz

8.1.4 45Hz

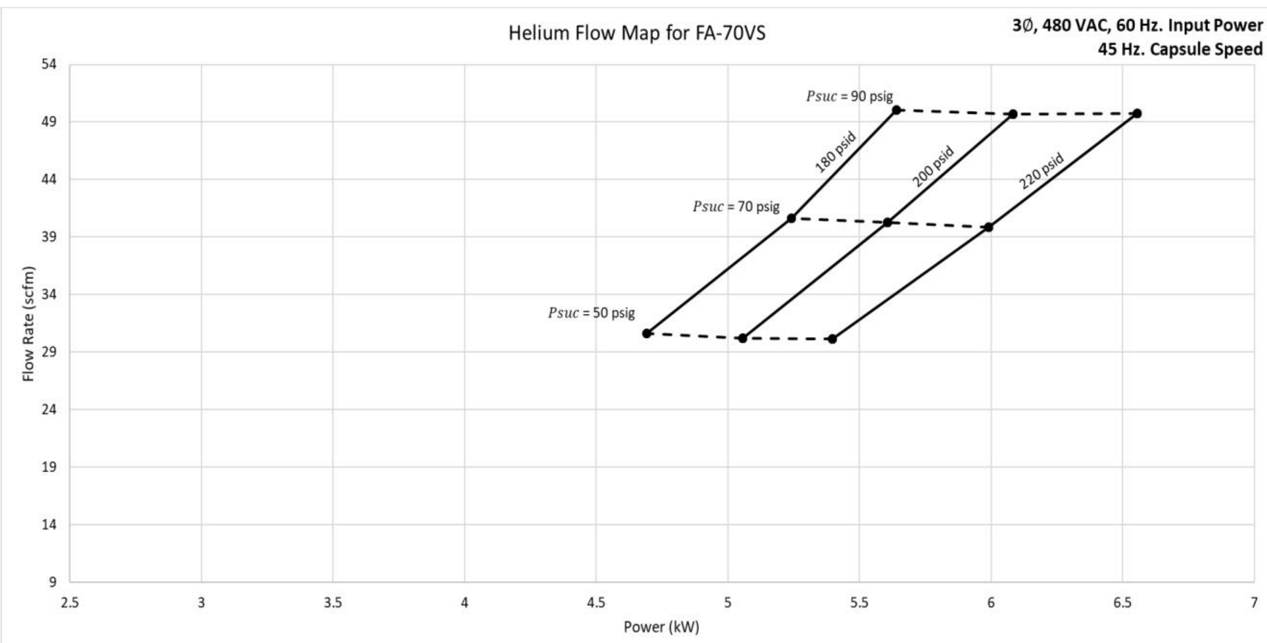


Figure 19: Compressor Helium Flow Versus Power @ 45Hz

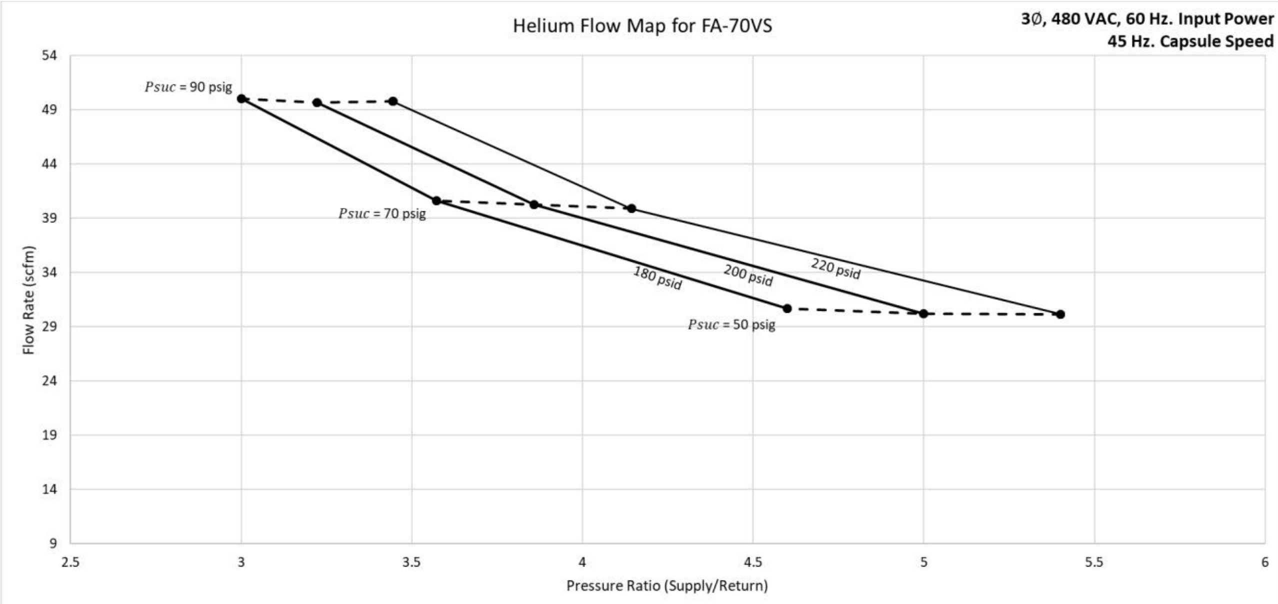


Figure 20: Compressor Helium Flow Versus Differential Pressure @ 45Hz

8.1.5 50Hz

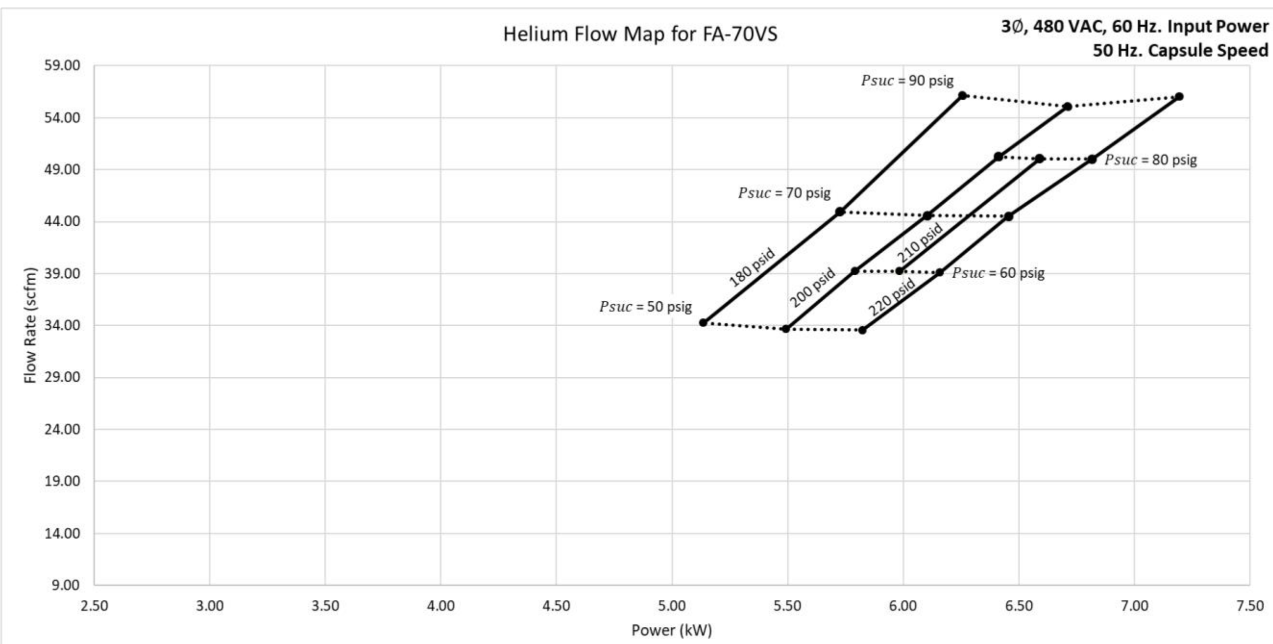


Figure 21: Compressor Helium Flow Versus Power @ 50Hz

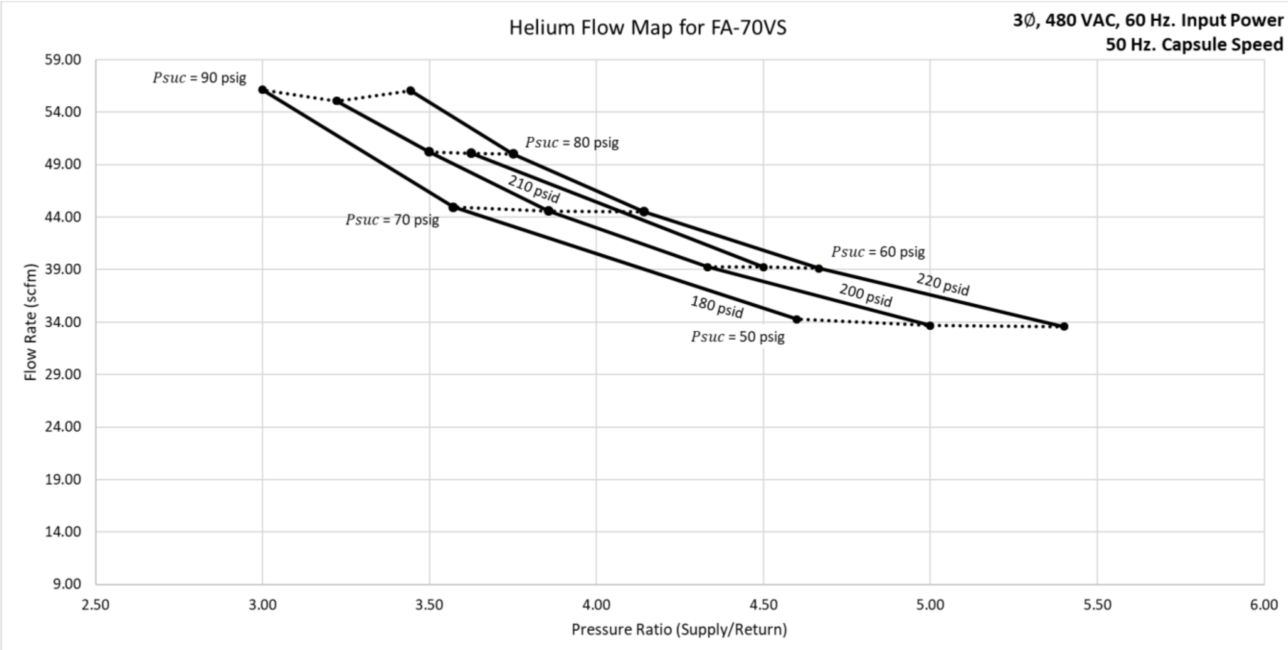


Figure 22: Compressor Helium Flow Versus Differential Pressure @ 50Hz

8.1.6 55Hz

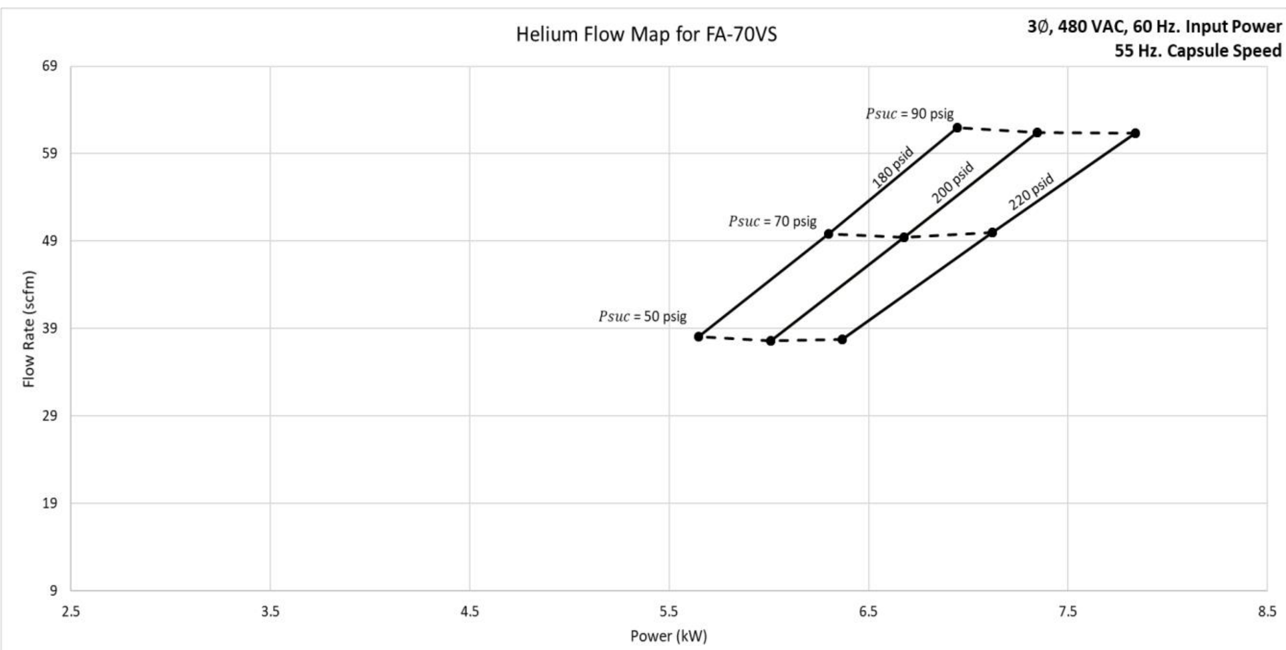


Figure 23: Compressor Helium Flow Versus Power @ 55Hz

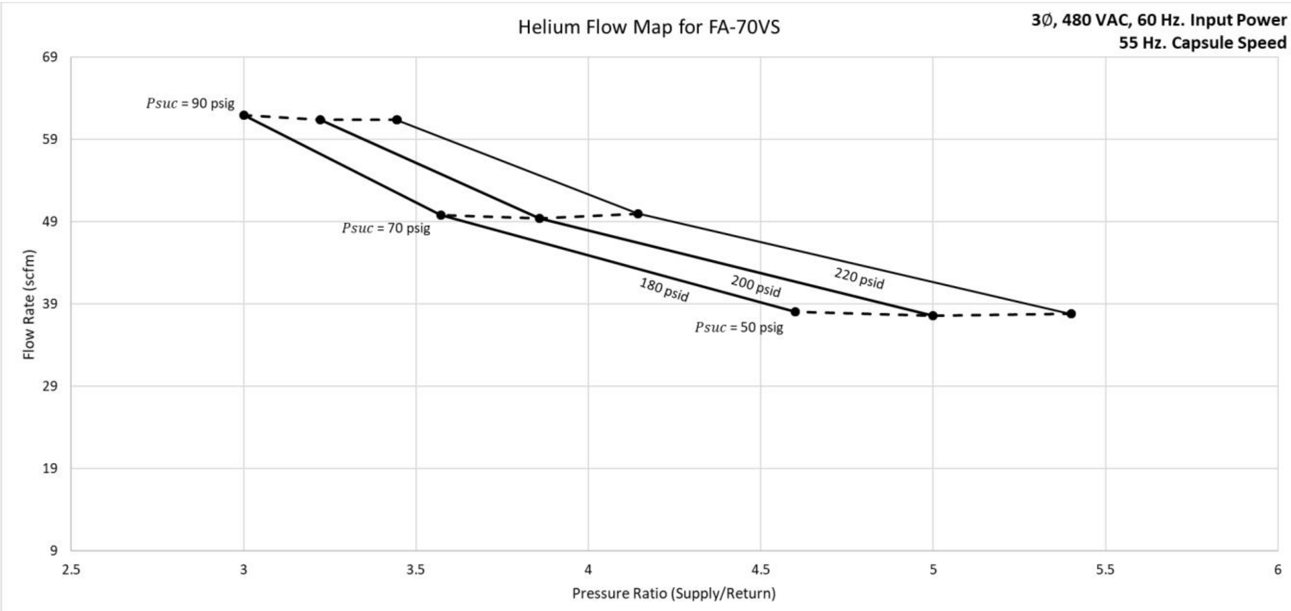


Figure 24: Compressor Helium Flow Versus Differential Pressure @ 55Hz

8.1.7 60 Hz

Comp. Speed [Hz.]	Flow Cart Supply [psig]	Flow Cart Return [psig]	Flow Rate [scfm]	Power [kW]	Notes	Pressure Ratio
60	230	90	66.93	6.64	0	2.56
60	250	90	66.60	7.04	0	2.78
60	270	90	66.46	7.49	0	3.00
60	290	90	66.05	7.81	0	3.22
60	310	90	65.70	8.28	0	3.44
60	330	90	65.20	8.70	0	3.67
60	330	70	52.92	8.37	0	4.71
60	310	70	52.99	8.06	0	4.43
60	290	70	53.28	7.61	0	4.14
60	270	70	53.58	7.22	0	3.86
60	250	70	54.01	6.80	0	3.57
60	230	70	54.29	6.46	0	3.29
60	230	50	41.52	6.14	0	4.60
60	250	50	41.36	6.48	0	5.00
60	270	50	41.05	6.80	0	5.40
60	290	50	40.83	7.41	0	5.80
60	310	50	40.40	7.67	0	6.20
60	330	50	40.11	7.94	0	6.60
60	330	30	24.22	7.00	* Capsule Chatter	11.00
60	310	30	25.64	6.72	* Capsule Chatter	10.33

60	290	30	27.29	6.68	0	9.67
60	270	30	27.82	6.39	0	9.00
60	250	30	27.90	5.99	0	8.33
60	230	30	27.98	5.66	0	7.67

Table 7: Factory Data @ 60Hz

The data in Table 7 shows again that the flow is set by the return pressure, not the supply pressure. A supply pressure increase of 100psi for a fixed return pressure changes the flow by less than 2scfm. However, the power consumption increases by 1.7 to 1.9kW.

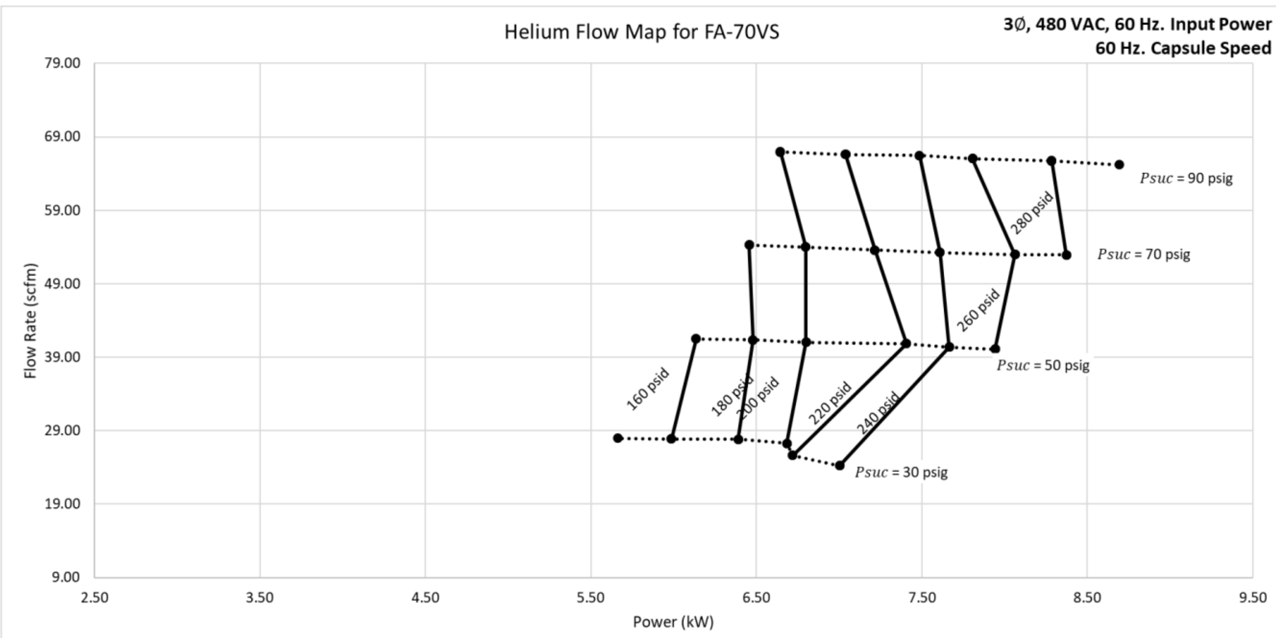


Figure 25: Compressor Helium Flow Versus Power @ 60Hz

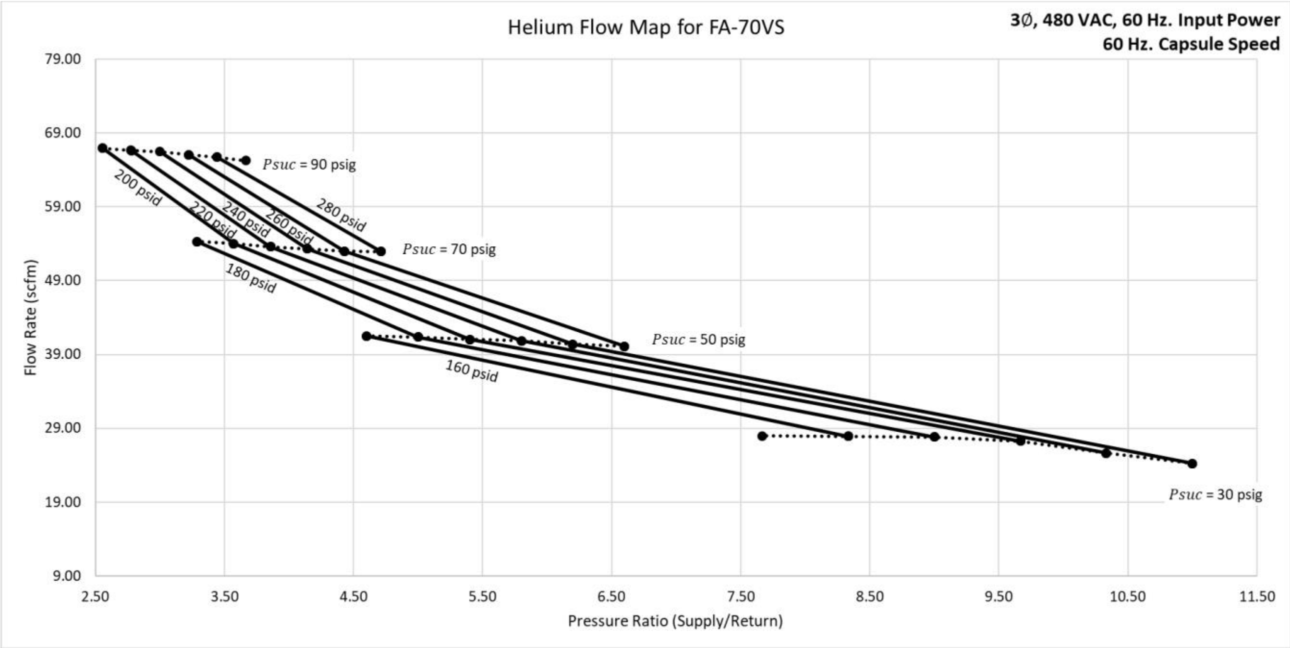


Figure 26: Compressor Helium Flow Versus Differential Pressure @ 60Hz

8.1.8 70Hz

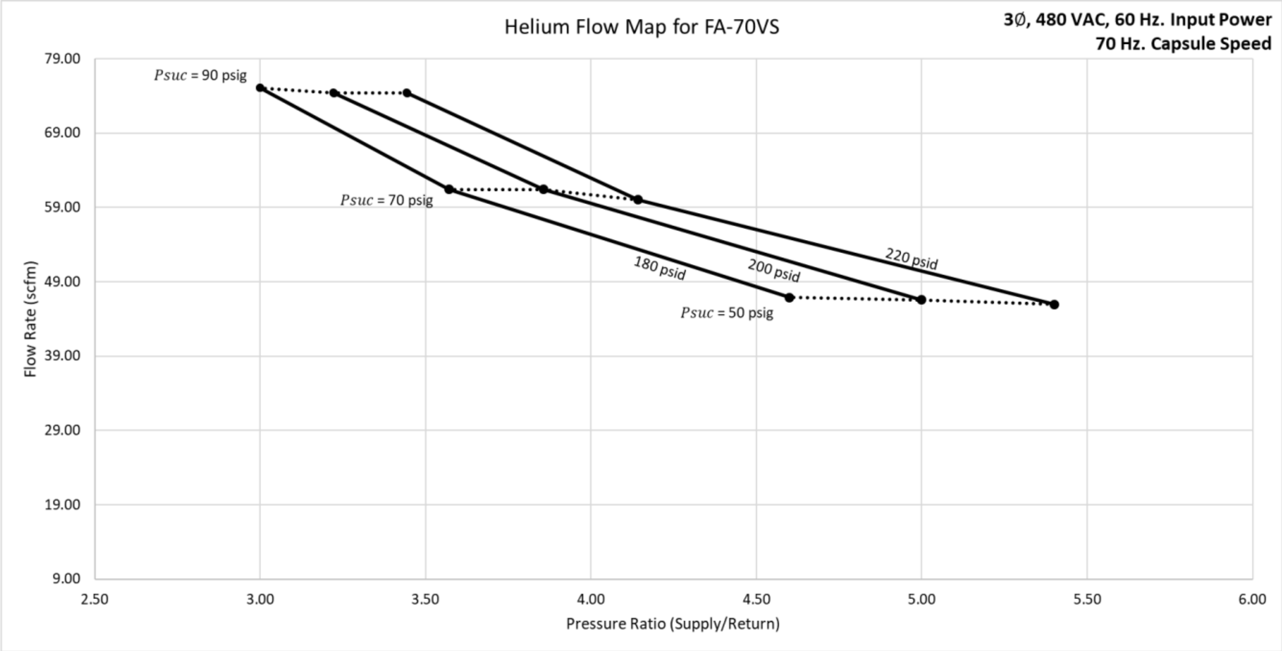


Figure 27: Compressor Helium Flow Versus Differential Pressure @ 70Hz

8.1.9 75Hz

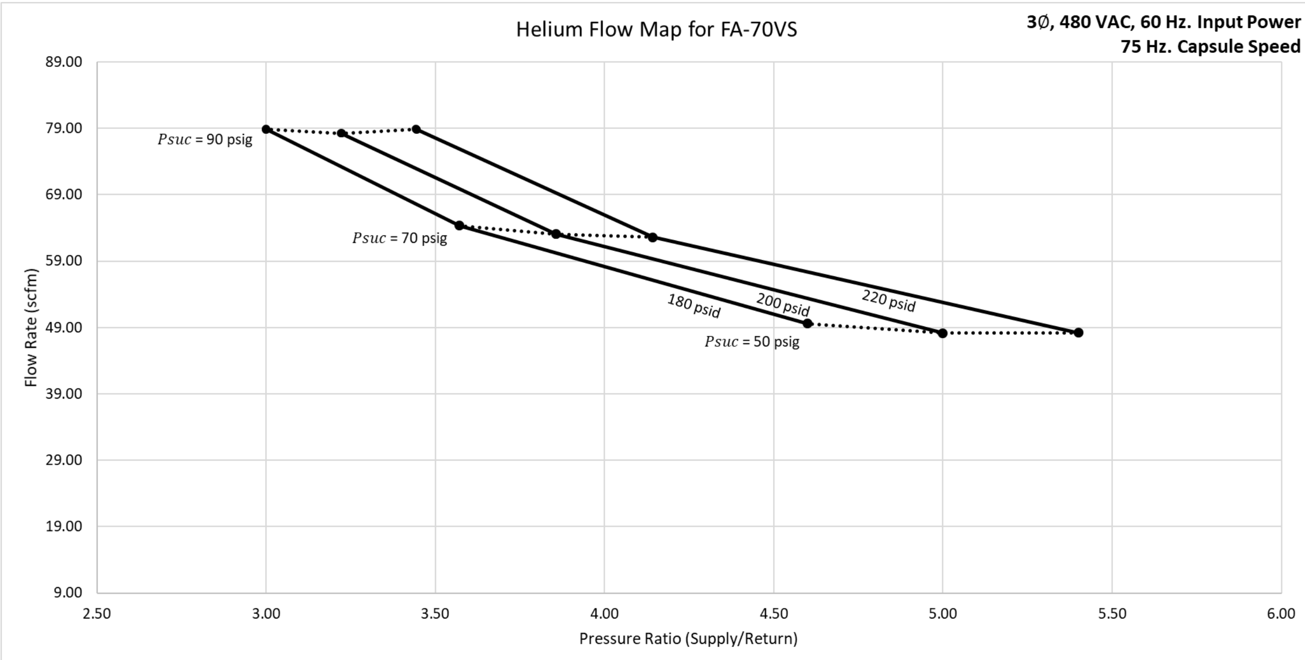


Figure 28: Compressor Helium Flow Versus Differential Pressure @ 75Hz

8.2 *Power vs. Frequency*

This power measurement was obtained with an AEMC PEL-105 Power/Energy data logger while the compressor ran in bypass mode. In bypass mode, the helium is recirculated internally through the IRV valve. The IRV opens when the differential pressure exceeds 220psi, so the motor must work harder than when a cold head is connected. The power measured in bypass mode represents the maximum value at a specific static pressure.

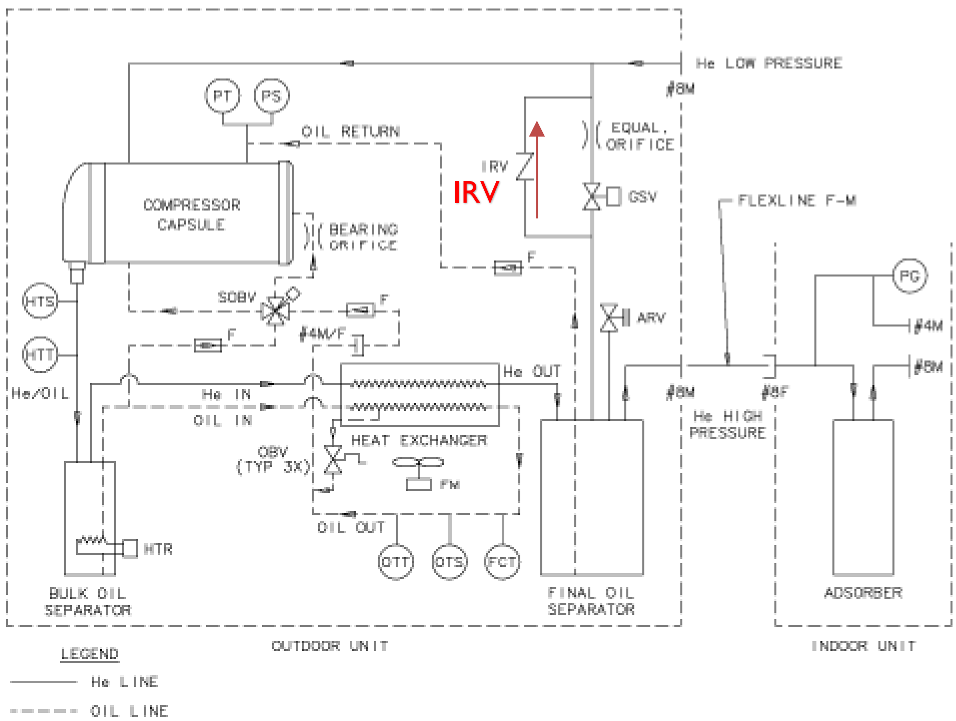


Figure 29: Compressor Flow Diagram (FA-70H Helium Compressor Operating Manual)

Frequency	Power kW	Power kVA	Power Factor	TAN	L1 current A	L2 Current A	L3 Current A
30	4.49	6.17	0.72	0.23	6.2	8.01	8.32
35	5.25	7.11	0.73	0.23	7.31	9.15	9.48
40	5.96	7.94	0.74	0.23	8.41	10.1	10.59
45	6.7	8.84	0.75	0.23	9.48	11.18	11.6
50	7.29	9.54	0.76	0.23	10.38	11.92	12.5
55	7.93	10.28	0.77	0.23	11.33	12.82	13.43
60	8.67	11.1	0.78	0.22	12.56	13.72	14.29
65	9.56	11.98	0.79	0.21	13.66	14.68	15.46
70	10.5	12.89	0.81	0.2	14.73	15.83	16.61

Table 8: Compressor FA-70VS Power vs. Frequency

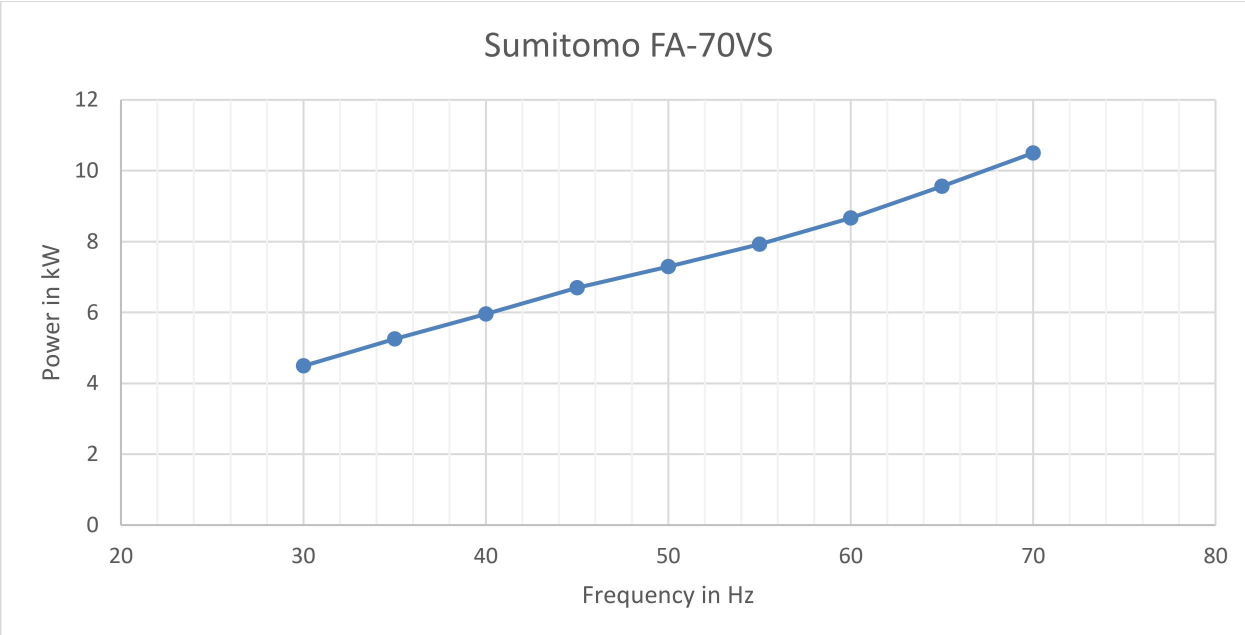


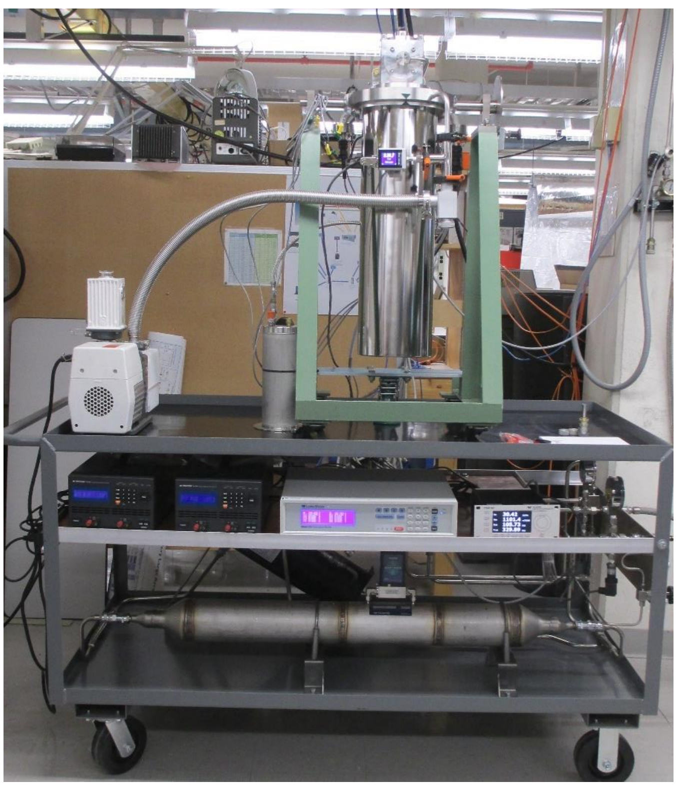
Figure 30: Compressor FA-70VS Power vs. Frequency Graph

The results show a linear dependency between the compressor power consumption and its operating frequency.

9 Test Results – NRAO Socorro Facility

9.1 *Laboratory Setup*

Picture 27: Sumitomo FA-70V Compressor Installed in DSOC Mechanical Room



Picture 28: Cryo-Test-Cart Taking Data

9.2 *Flow Measurement*

This measurement uses the adjustable needle valve on the cryo-test cart. To start the measurement, the valve is closed, and the compressor runs on full bypass mode. Then, the valve is opened slowly until the return pressure comes close to 140psi (the Limit set by the Sumitomo safety interlock).

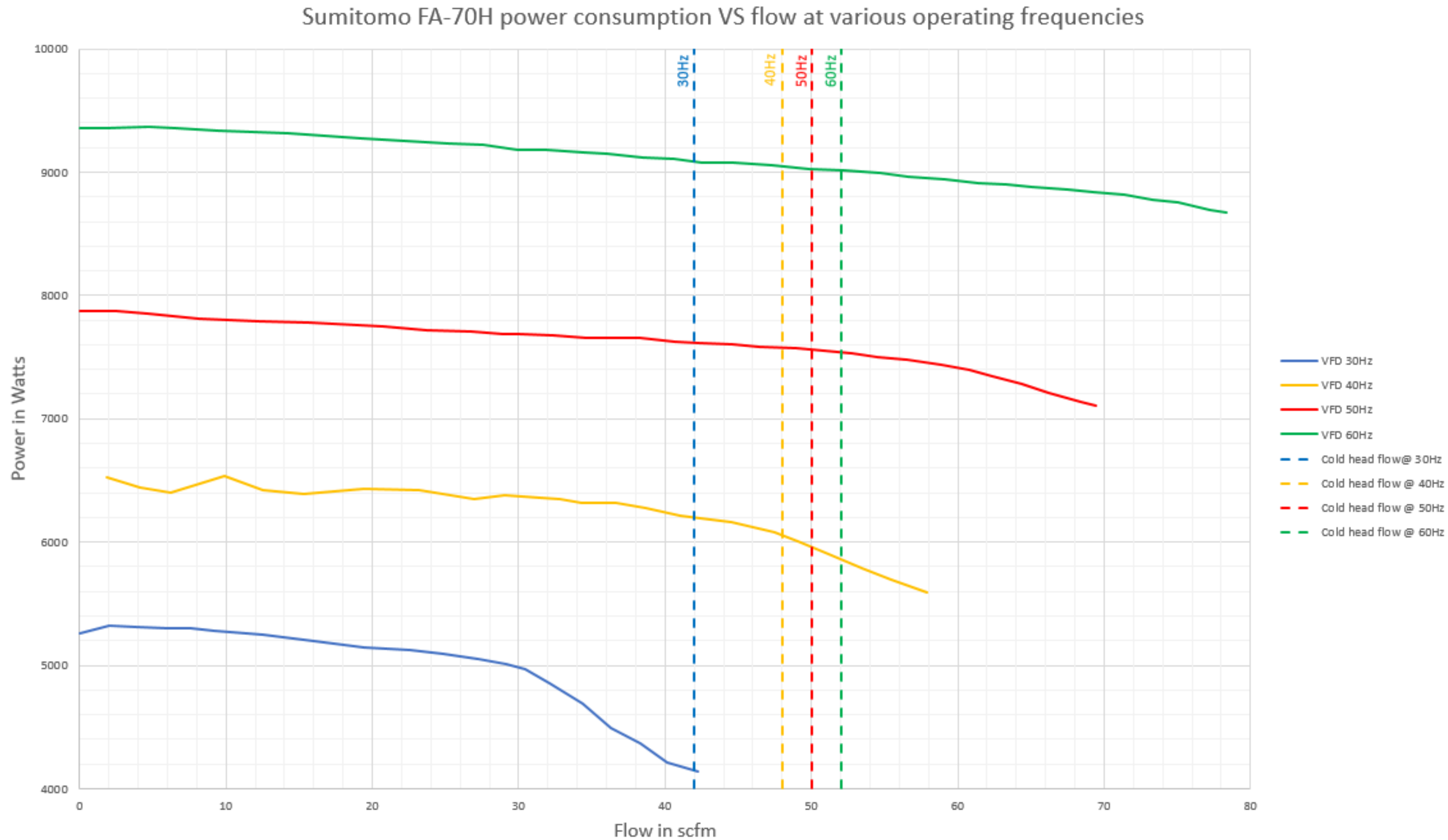


Figure 31: Flow Measured with the Adjustable Needle Valve vs. Frequency

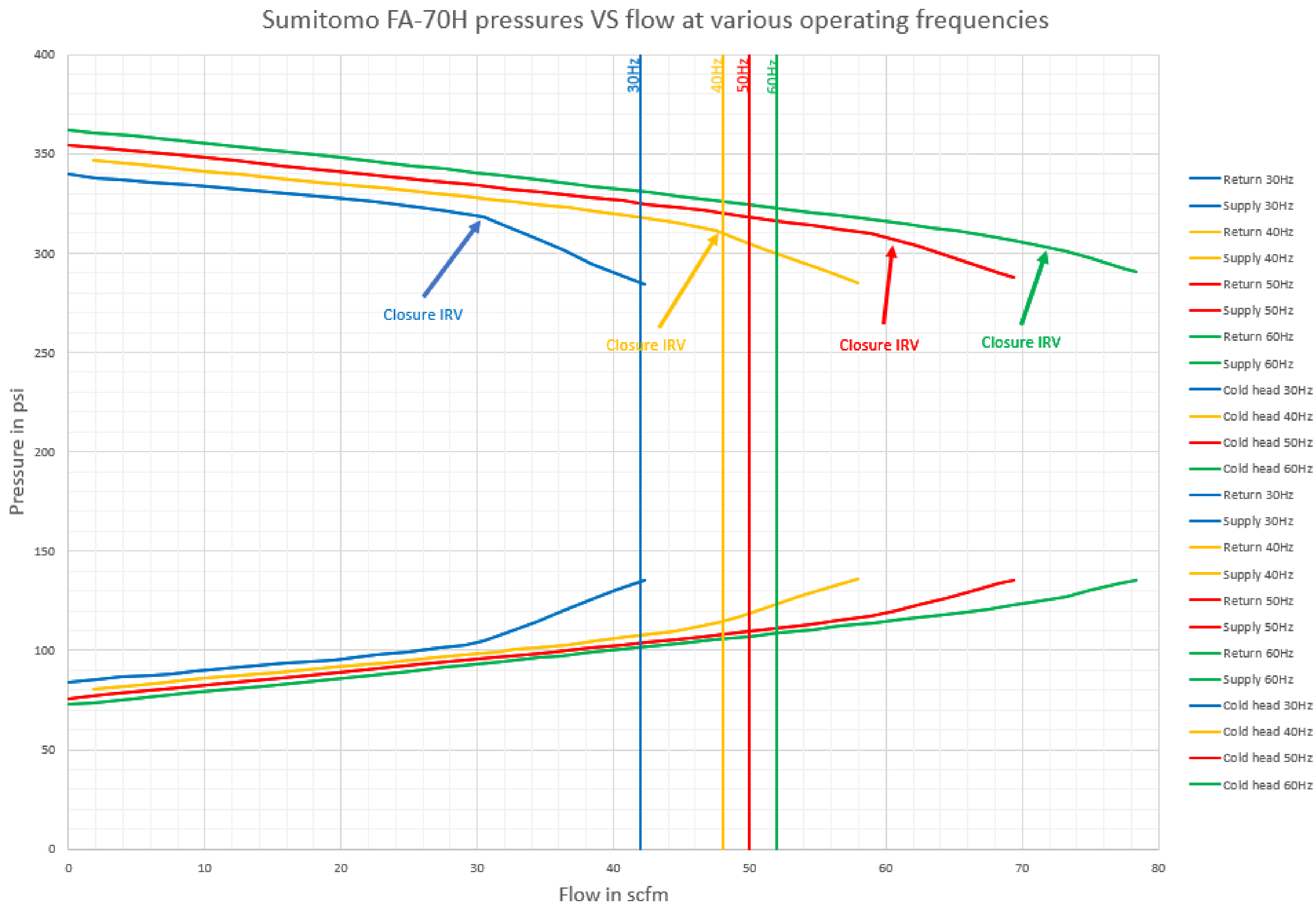


Figure 32: Differential pressure measured with Adjustable Needle Valve vs. Frequency

The supply and return pressure curve inflection happens when the Internal Relief Valve (IRV) closes, and all the high-pressure helium the compressor produces flows through the needle valve and the flow meter. When the IRV is opened and part of the helium is bypassed internally, that portion of the high-pressure helium does not contribute to the cooling and is considered waste. The inflection point's position varies with frequencies; the optimum position is when the required cold head flow intercepts that point. According to the data at 40Hz, the compressor flow through the 3-stage cold head is about 48scfm and intercepts the pressure curves at their inflection point. **This indicates 40Hz as the optimum operating frequency for the compressor.**

9.3 *Temperature Variations with Compressor Frequencies*

A series of 27-point load maps was done to characterize the impact of the compressor operating frequency on the cryocooler performance and power consumption. **The compressor had a constant 230psi static pressure throughout the test**. The load map was run for four operating frequencies, 30Hz, 40Hz, 50Hz, and 60Hz.

A 27-point file was used to test the performance of the cryocooler over a broad range of thermal loads.

Point number	3rd stage load in Watts	2nd stage load in Watts	1st stage load in Watts
1	0.4	4	10
2	0.4	4	20
3	0.4	4	30
4	0.4	8	30
5	0.4	8	20
6	0.4	8	10
7	0.4	12	10
8	0.4	12	20
9	0.4	12	30
10	0.8	12	30
11	0.8	12	20
12	0.8	12	10
13	0.8	8	10
14	0.8	8	20
15	0.8	8	30
16	0.8	4	30
17	0.8	4	20
18	0.8	4	10
19	1.2	4	10
20	1.2	4	20
21	1.2	4	30
22	1.2	8	30
23	1.2	8	20
24	1.2	8	10
25	1.2	12	10
26	1.2	12	20
27	1.2	12	30

Table 9: Points Used to Create Load Map for the 3-Stage Sumitomo RDK-3ST-R3 Cold Head

9.3.1 First Stage

The 30 Hz trace is yellow, the 40 Hz trace is white, the 50 Hz trace is green, and the 60 Hz trace is blue. The temperature scale on the left is displayed in degrees Kelvin. The horizontal axis follows the 27-point file in Table 9: Points Used to Create Load Map for the 3-Stage Sumitomo RDK-3ST-R3 Cold Head.

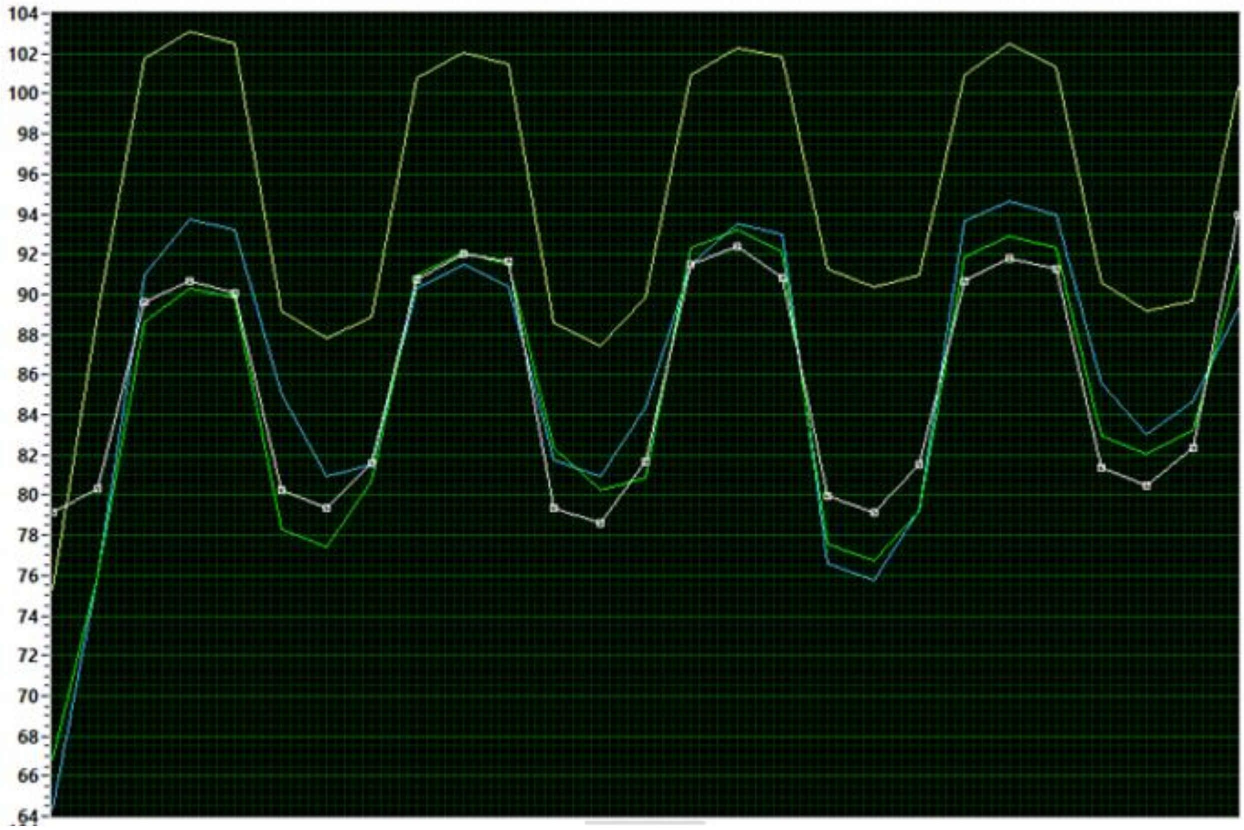


Figure 33: First Stage Temperature for Compressor Frequencies of 30Hz up to 60Hz in 10Hz Steps

The first stage temperature increased by 8-10 degrees when the frequency is lowered to 30Hz. This is a big step considering that between 50Hz and 40Hz, the difference stays within one degree.

The 35Hz trace is in White, 40Hz in Red, 45Hz in Green, 50Hz in Blue, 55Hz in Yellow, and 60Hz in Purple. The temperature scale on the left is given in degrees Kelvin.

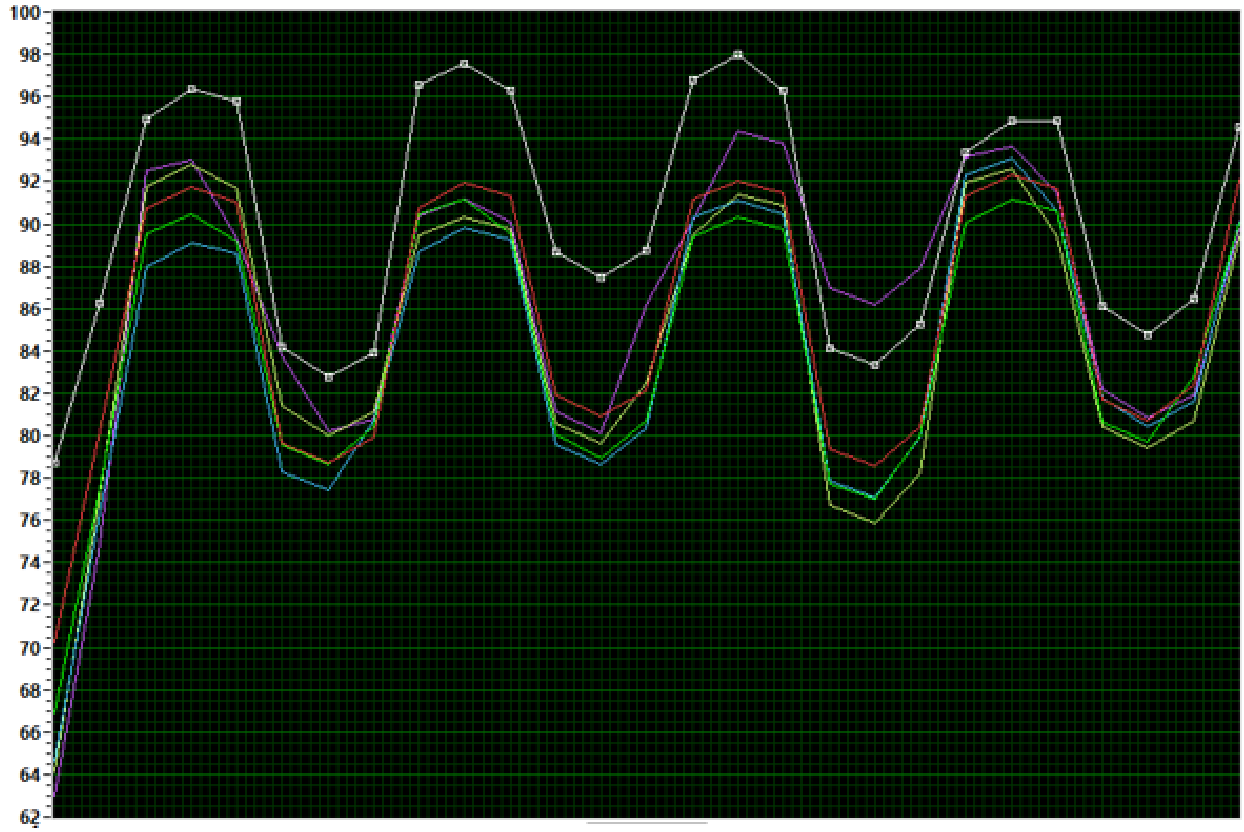


Figure 34: First Stage Temperature for Compressor Frequencies of 35Hz up to 60Hz in 5Hz Steps

At 35Hz, the first stage is between 4-6K warmer than at 40Hz and above. The response at 60Hz is peculiar and doesn't match the previous measurement; it should have been repeated.

9.3.2 Second Stage

The temperature scale on the left is given in degrees Kelvin. The trace colors are the same as for the first stage.

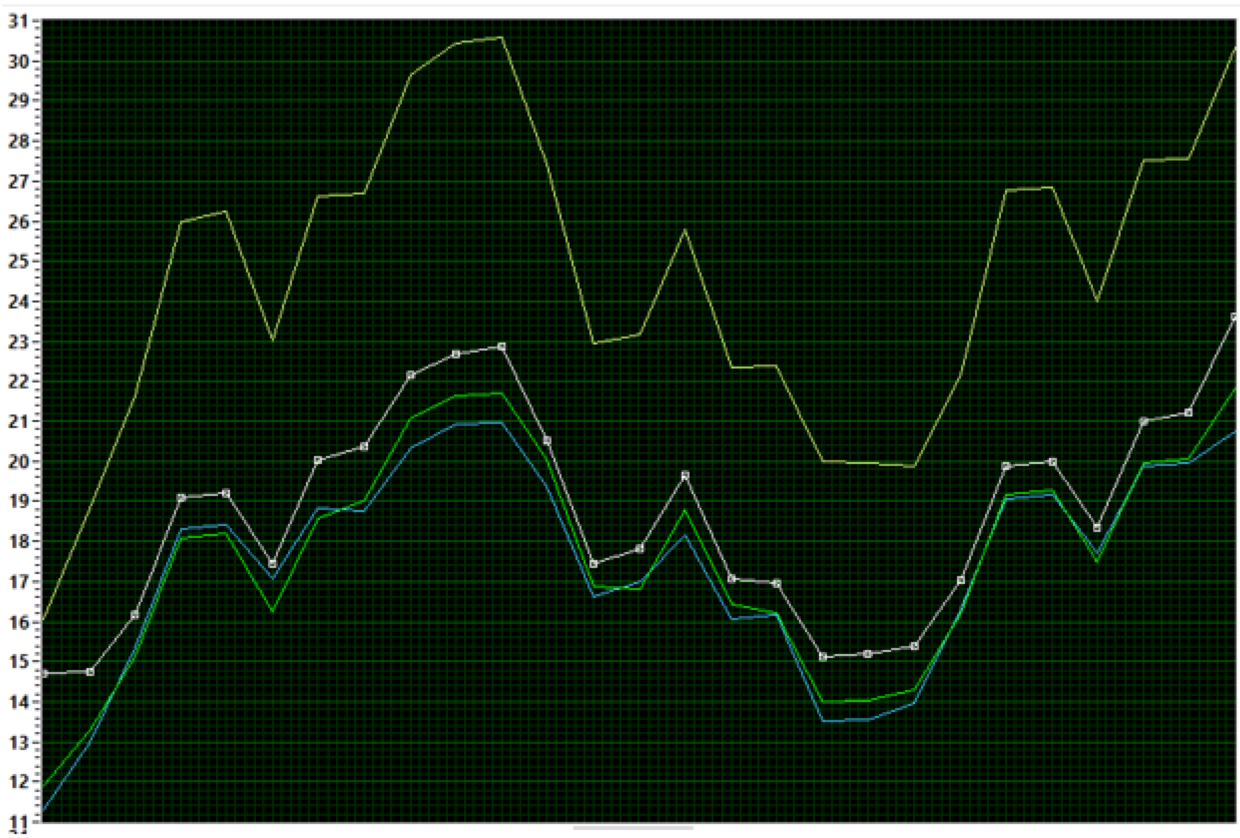


Figure 35: Second Stage Temperature for Compressor Frequencies of 30Hz up to 60Hz in 10Hz Steps

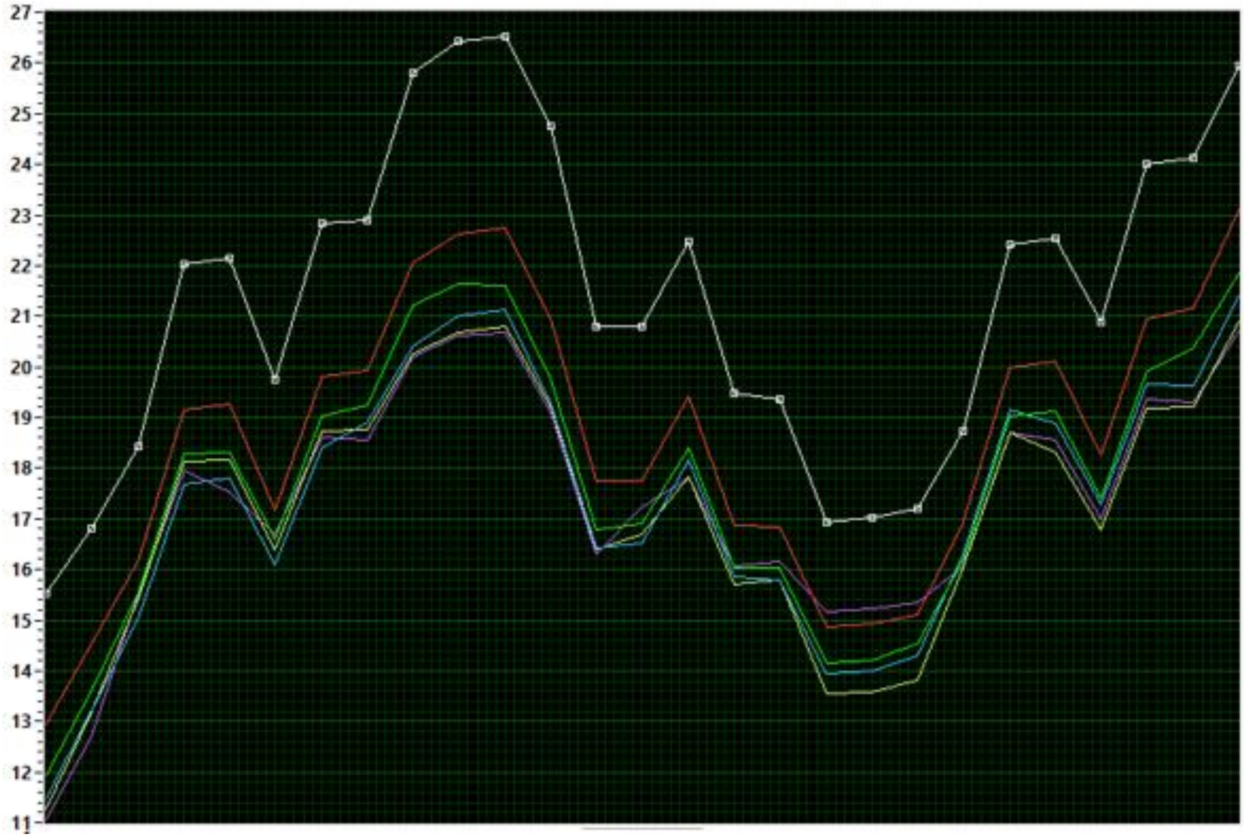


Figure 36: Second Stage Temperature for Compressor Frequencies of 35Hz up to 60Hz in 5Hz Steps

The second stage temperatures are within 2K for all compressor frequencies above 40Hz. The larger temperature gap seen at 30Hz and 35Hz indicates that the cryocooler's performance is degraded. This loss in cooling power is a combination of flow reduction and lower differential pressure.

9.3.3 Third Stage

The temperature scale on the left is given in degrees Kelvin, and the color assignment is the same as the first and second stage plots The small reservoir of liquid Helium helps maintain the third stage's temperature stability. The influence of the first and second stage temperatures is negligible for a fixed third stage heat load.

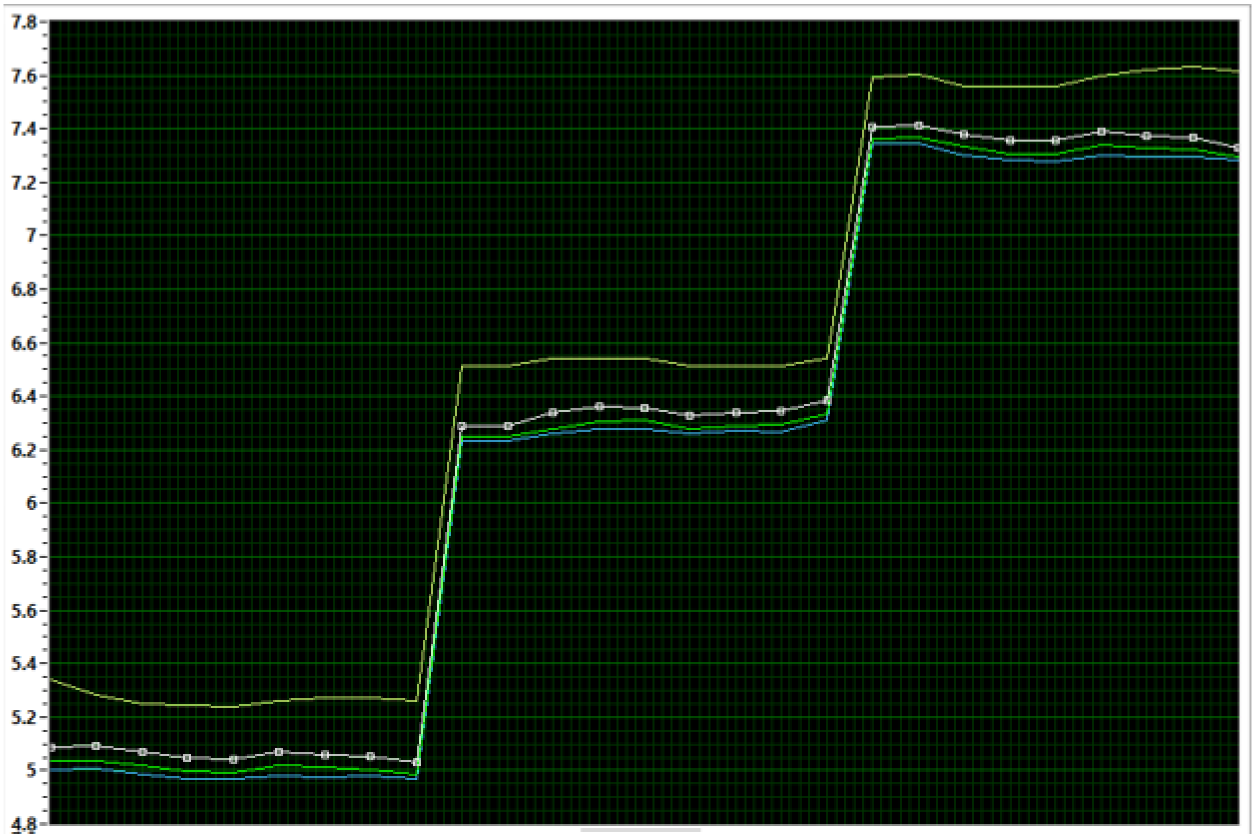


Figure 37: Third stage Temperature for Compressor Frequencies of 30Hz up to 60Hz in 10Hz steps

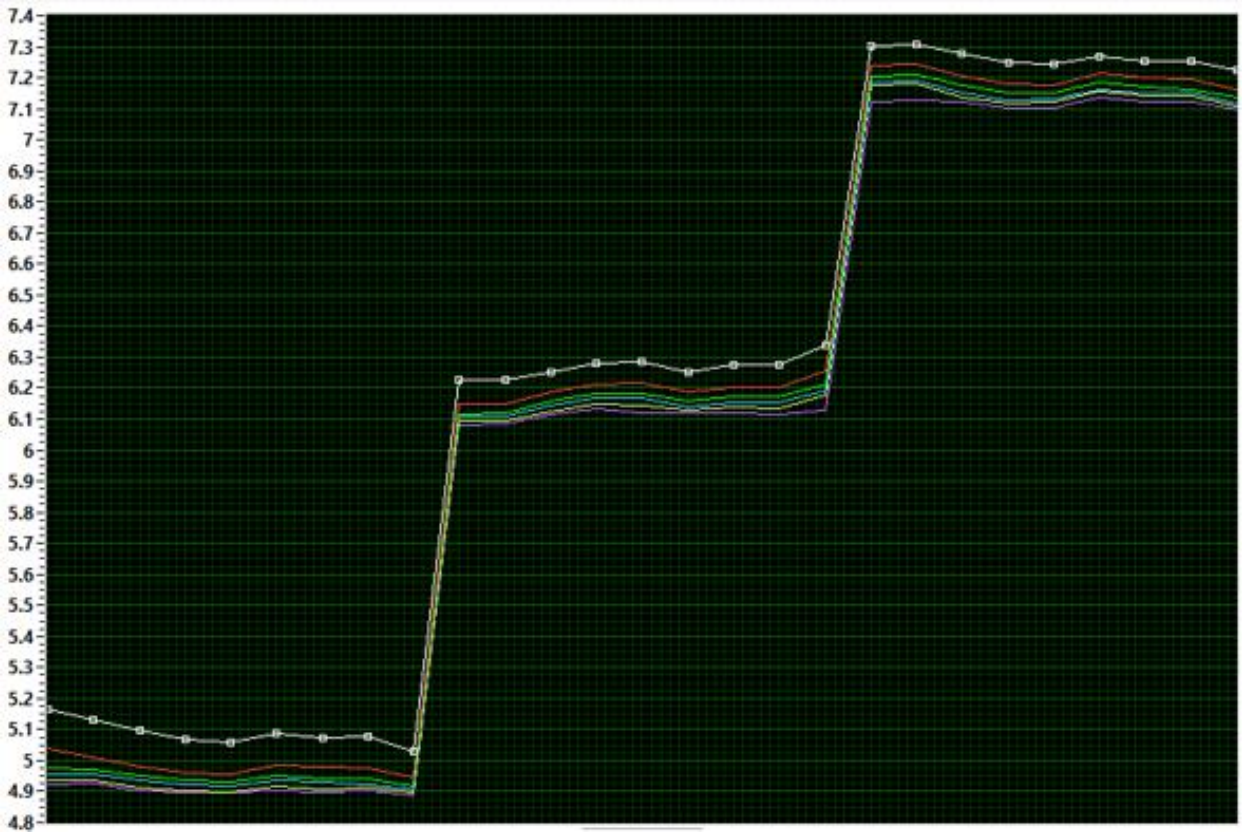


Figure 38: Third stage Temperature for Compressor Frequencies of 35Hz up to 60Hz in 5Hz steps

On the third stage, while the temperature increase at 35 Hz is relatively small, the gap with 40 Hz is more noticeable than it is between the other frequency steps. The third stage temperature is the most critical for ALMA since the SIS mixer's conversion gain degrades rapidly when its temperature exceeds 5.5 K.

3rd stage heat load	3rd stage temperature
0.4 Watts	4.9 to 5.1 K
0.8 Watts	6.1 to 6.3 K
1.2 Watts	7.1 to 7.3 K

Table 10: Test Cryostat 3rd Stage Temperature for Various Heat Loads

The three heat load values applied to the third stage indicate that above 500mW, the stage temperature is too high for the SIS mixers. This highlights the fact that the 3-stage cold head requires the compressor to run at a higher frequency for optimal performance.

9.3.4 Helium Flow

The 30 Hz trace is yellow, the 40 Hz trace is white, the 50 Hz trace is green, and the 60 Hz trace is blue. The helium flow scale on the left is given in scfm.

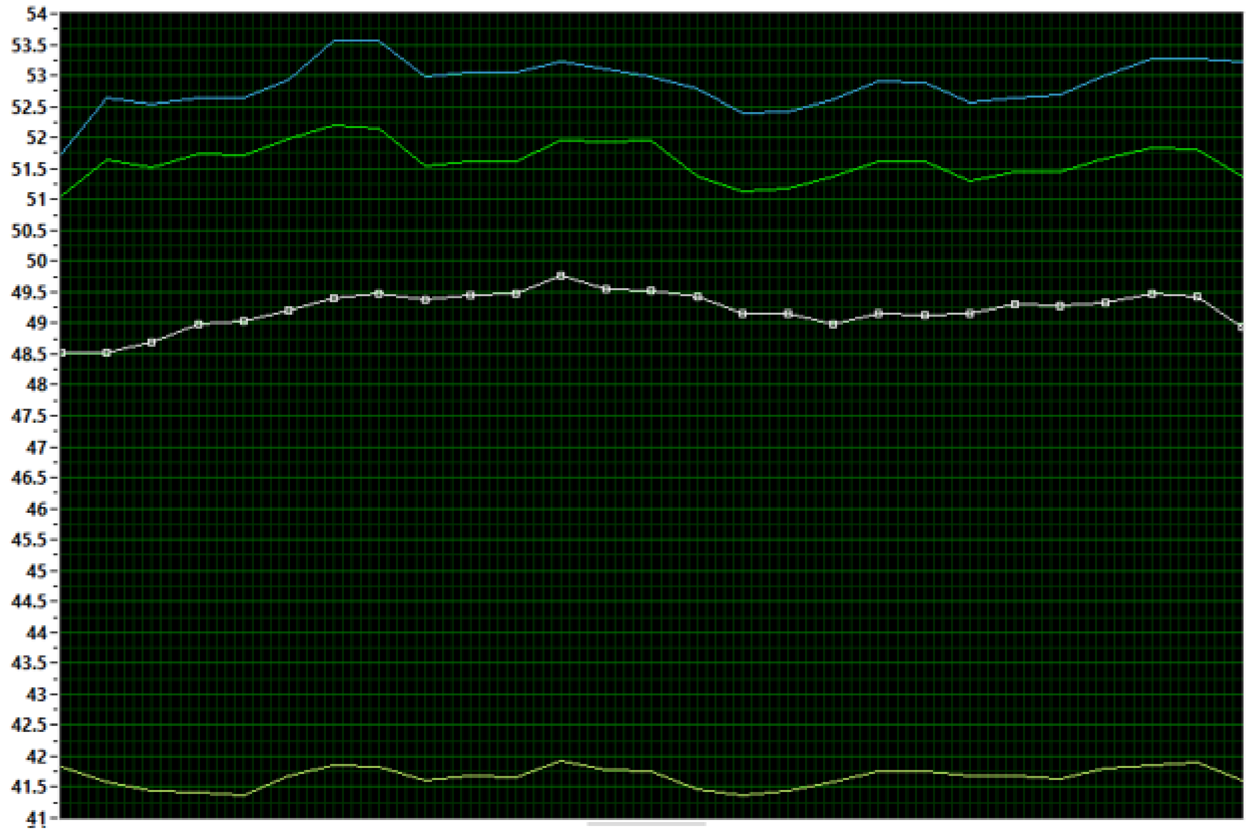


Figure 39: Helium Flow Temperature for Compressor Frequencies of 30Hz up to 60Hz in 10Hz Steps

The Helium flow varies with the compressor frequency, but the variation is not linear because of the IRV. Above 40Hz, part of the flow circulates through the IRV and is not registered by the flow meter. The flow variations due to the stage's temperature are minor.

The 35Hz trace is in White, 40Hz in Red, 45Hz in Green, 50Hz in Blue, 55Hz in Yellow, and 60Hz in Purple.

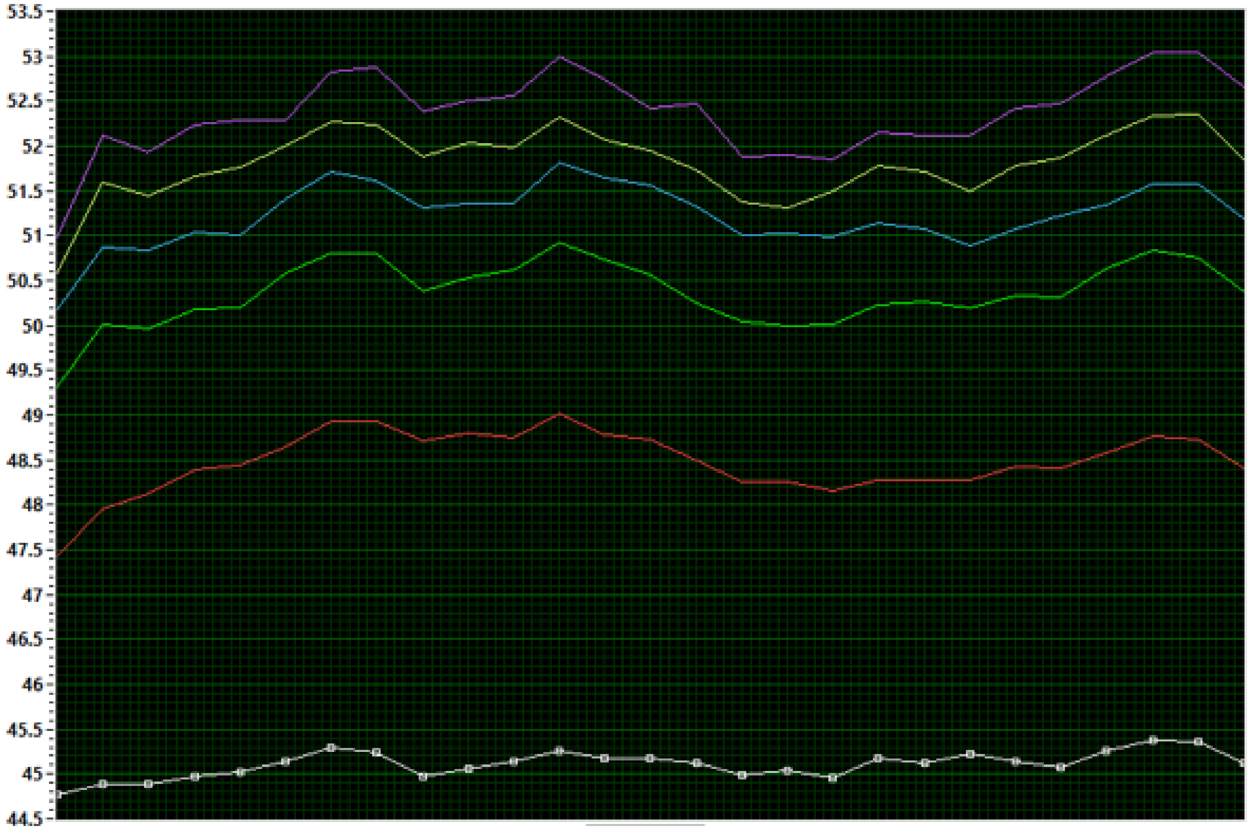


Figure 40: Helium Flow Temperature for Compressor Frequencies of 35Hz up to 60Hz in 5Hz Steps

9.3.5 Supply Pressure

The color assignment is the same as the previous plots. The pressure scale on the left is given in psi.

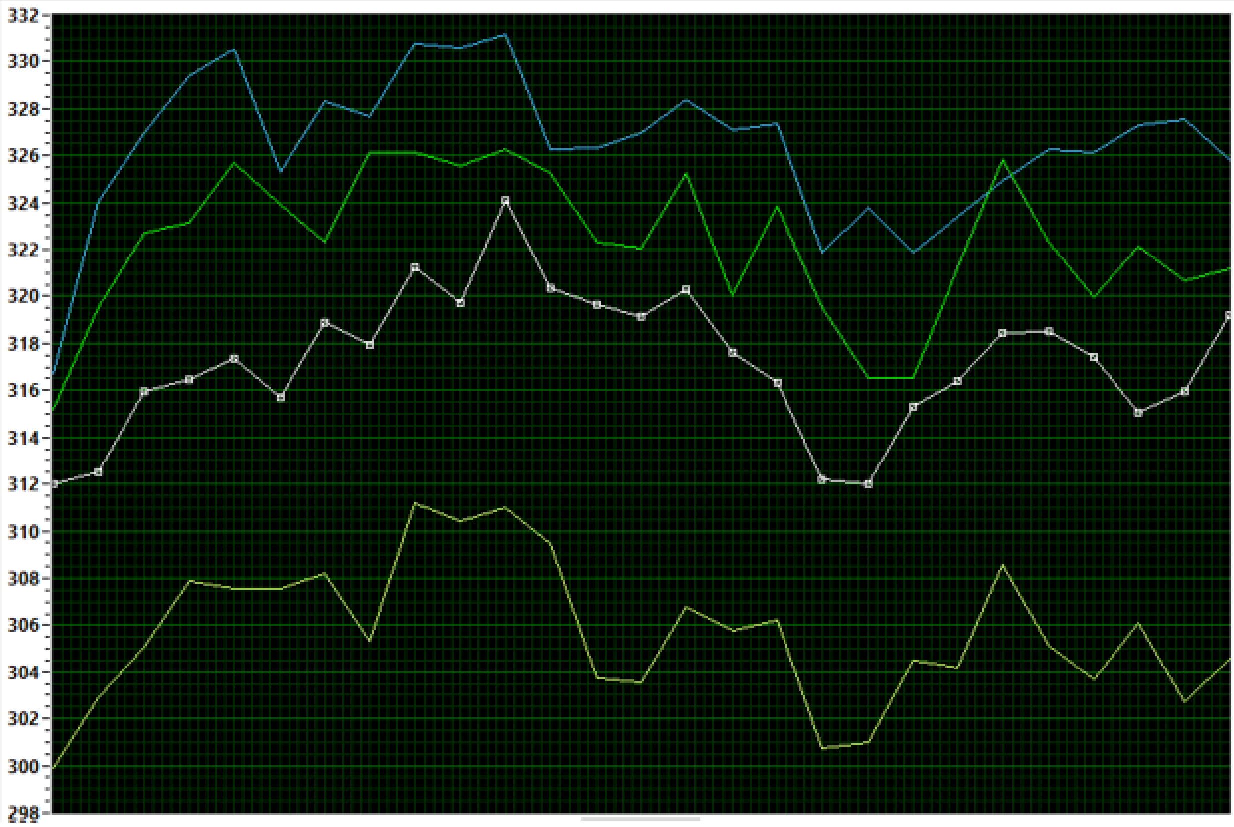


Figure 41: Supply Pressure Temperature for Compressor Frequencies of 30Hz up to 60Hz in 10Hz Steps

The supply pressure variation exceeds 10psi, regardless of the compressor frequency.

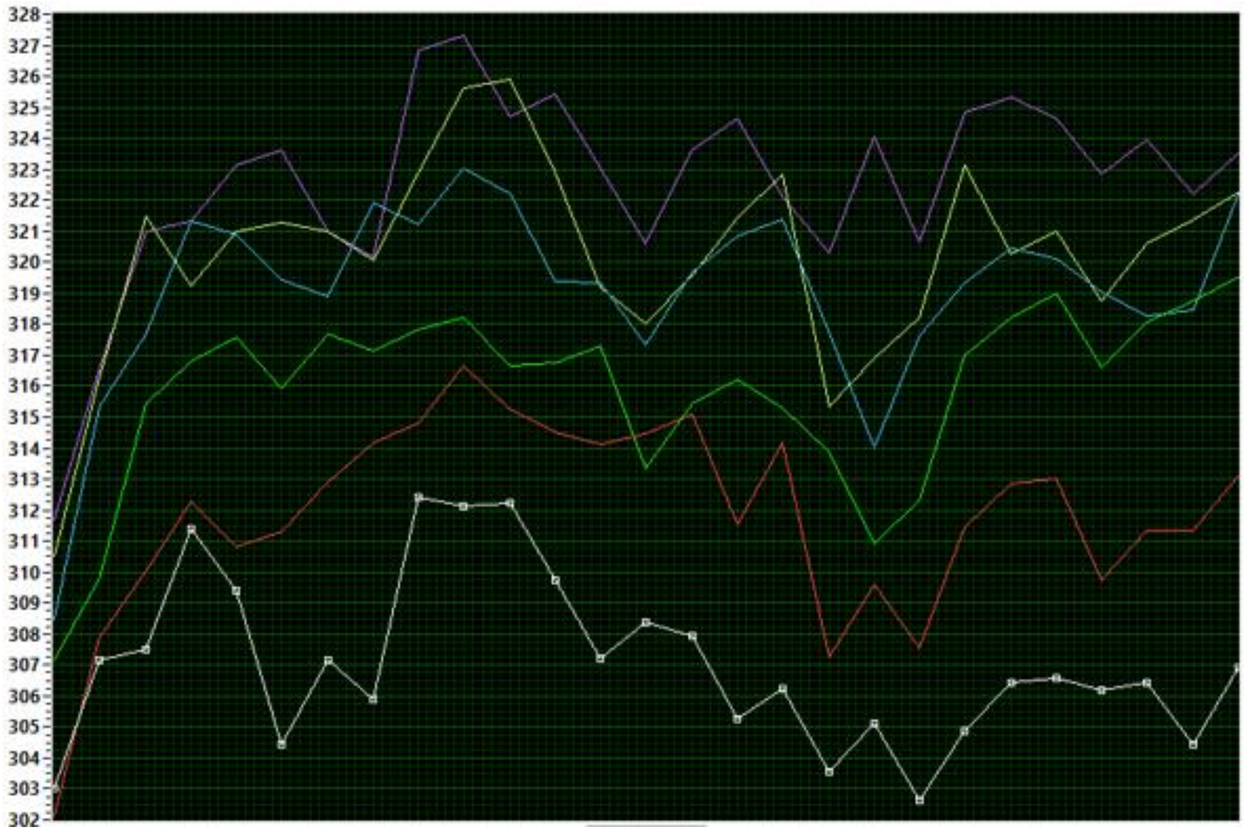


Figure 42: Supply Pressure Temperature for Compressor Frequencies of 35Hz up to 60Hz in 5Hz Steps

9.3.6 Return Pressure

The color assignment is the same as the previous plots. The pressure scale on the left is in psi.

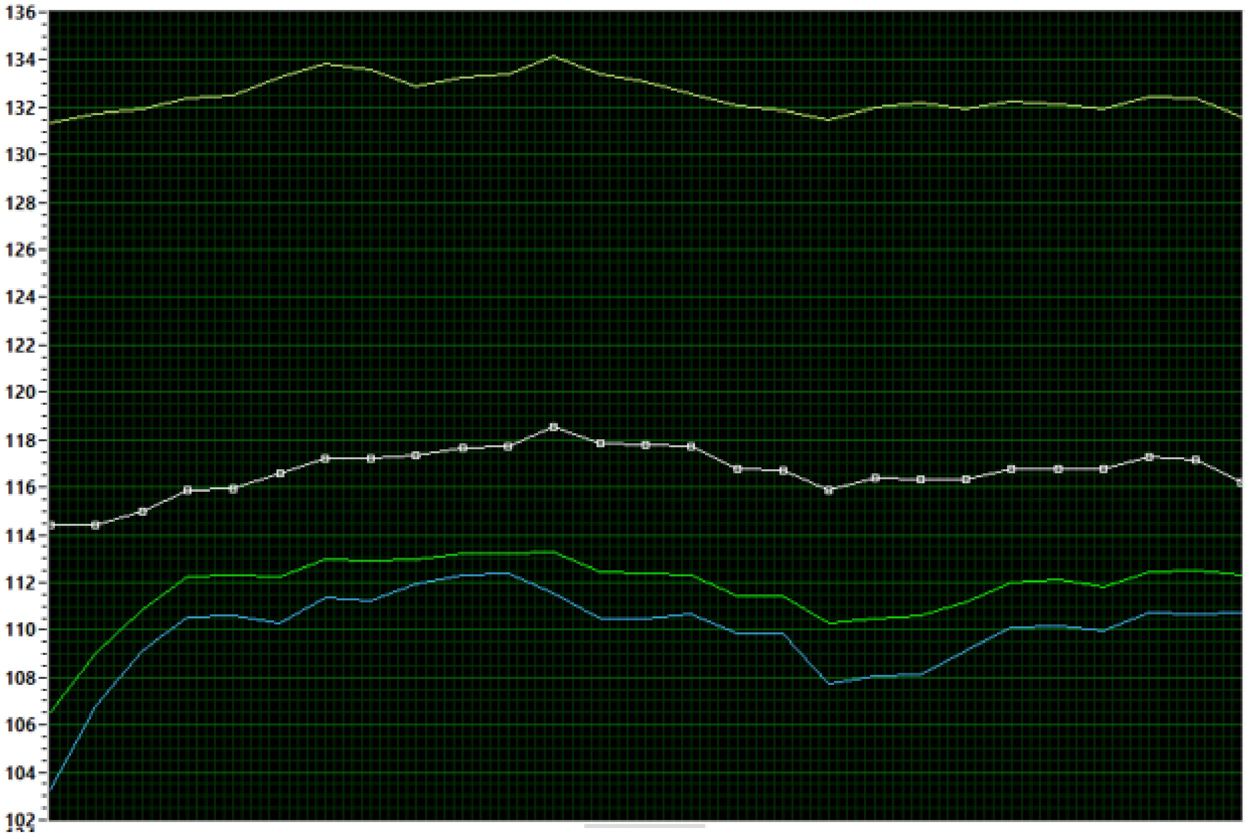


Figure 43: Return Pressure Temperature for Compressor Frequencies of 30Hz up to 60Hz in 10Hz Steps

The return pressure or suction pressure decreases with the compressor frequency. Its variations with stage temperatures are reduced, and the behavior is more aligned with the flow.

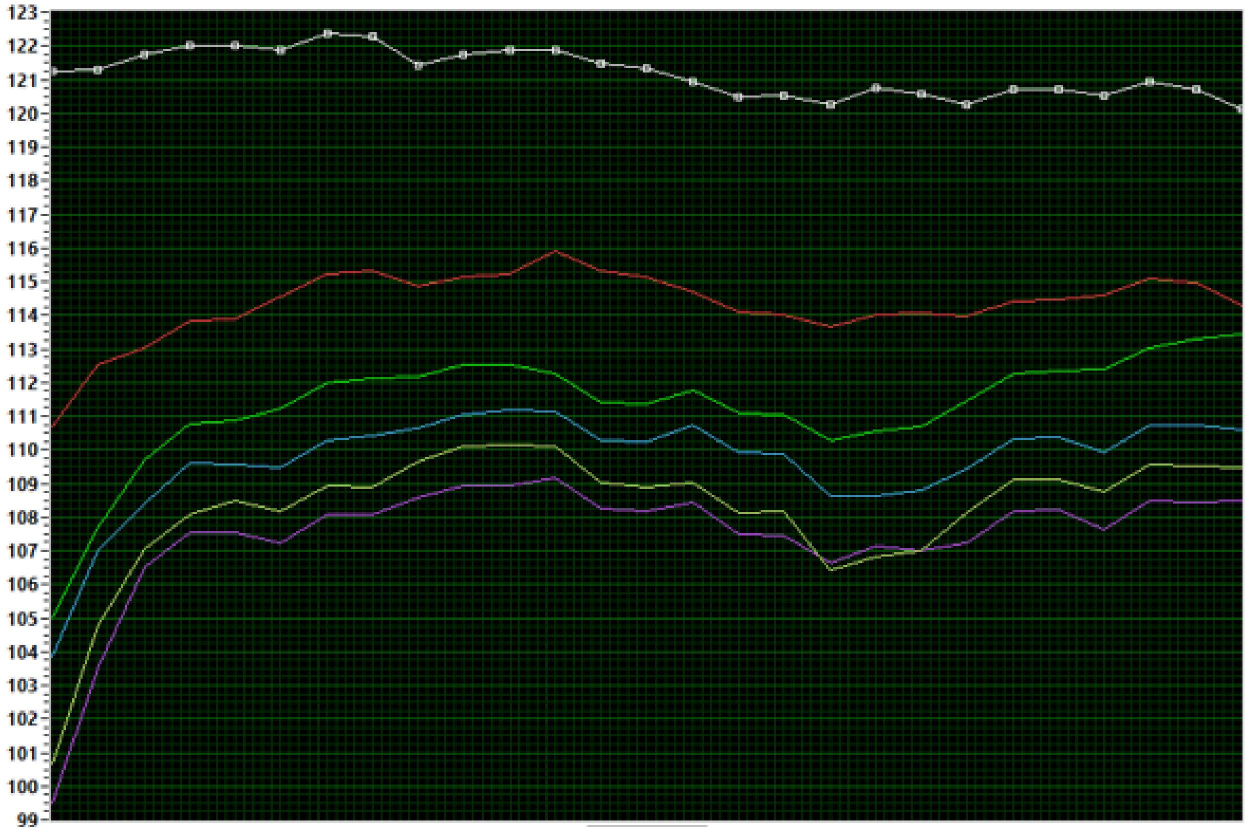


Figure 44: Return Pressure Temperature for Compressor Frequencies of 35Hz up to 60Hz in 5Hz Steps

It is intriguing to observe how the supply pressure behaves differently from the return pressure. While the return pressure variation is predictable and proportional to compressor frequency, the supply pressure is considerably more erratic. This again indicates that controlling the return pressure using the compressor frequency should be more effective with less influence from the stage temperatures.

9.3.7 Power Consumption

The 30 Hz trace is yellow, the 40 Hz trace is white, the 50 Hz trace is green, and the 60 Hz trace is blue. The power scale on the left is in Watts.

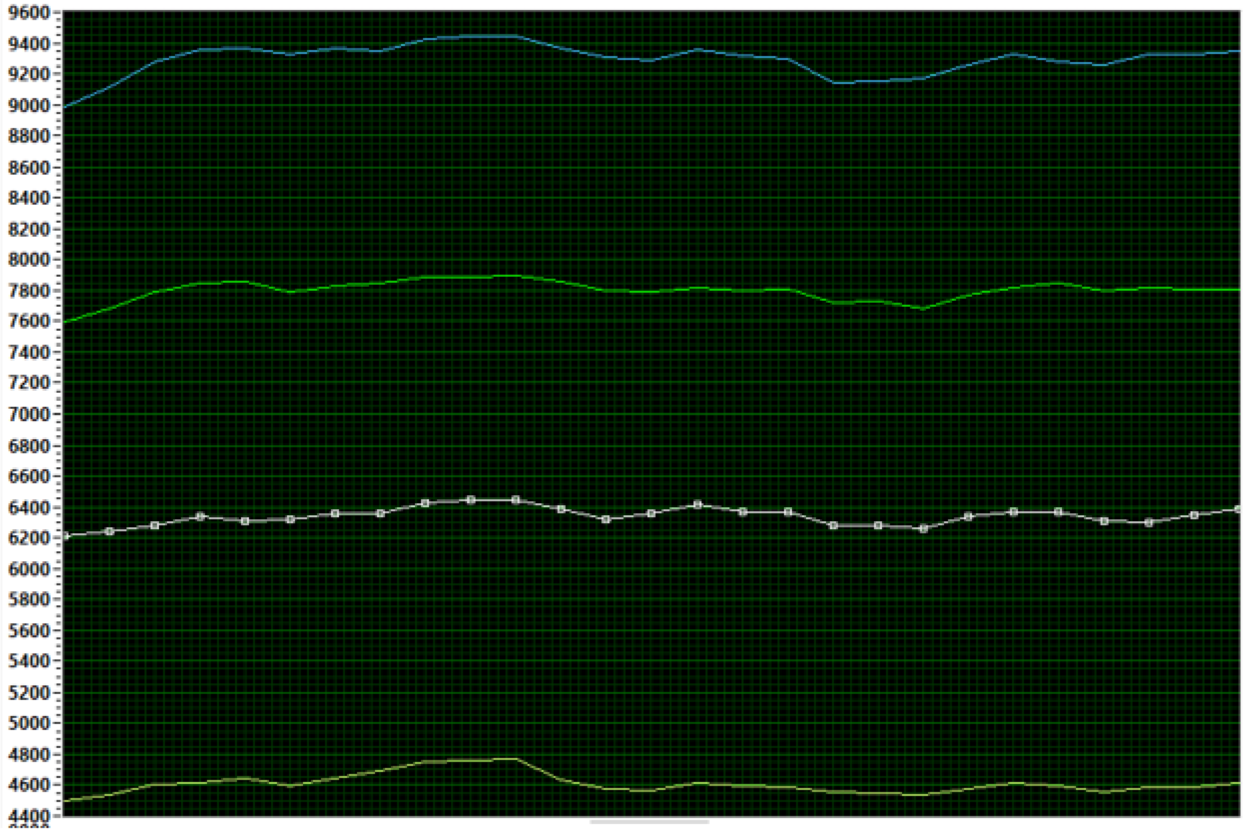


Figure 45: Power Consumption Temperature for Compressor Frequencies of 30Hz up to 60Hz in 10Hz Steps

The 35Hz trace is in White, 40Hz in Red, 45Hz in Green, 50Hz in Blue, 55Hz in Yellow, and 60Hz in Purple.

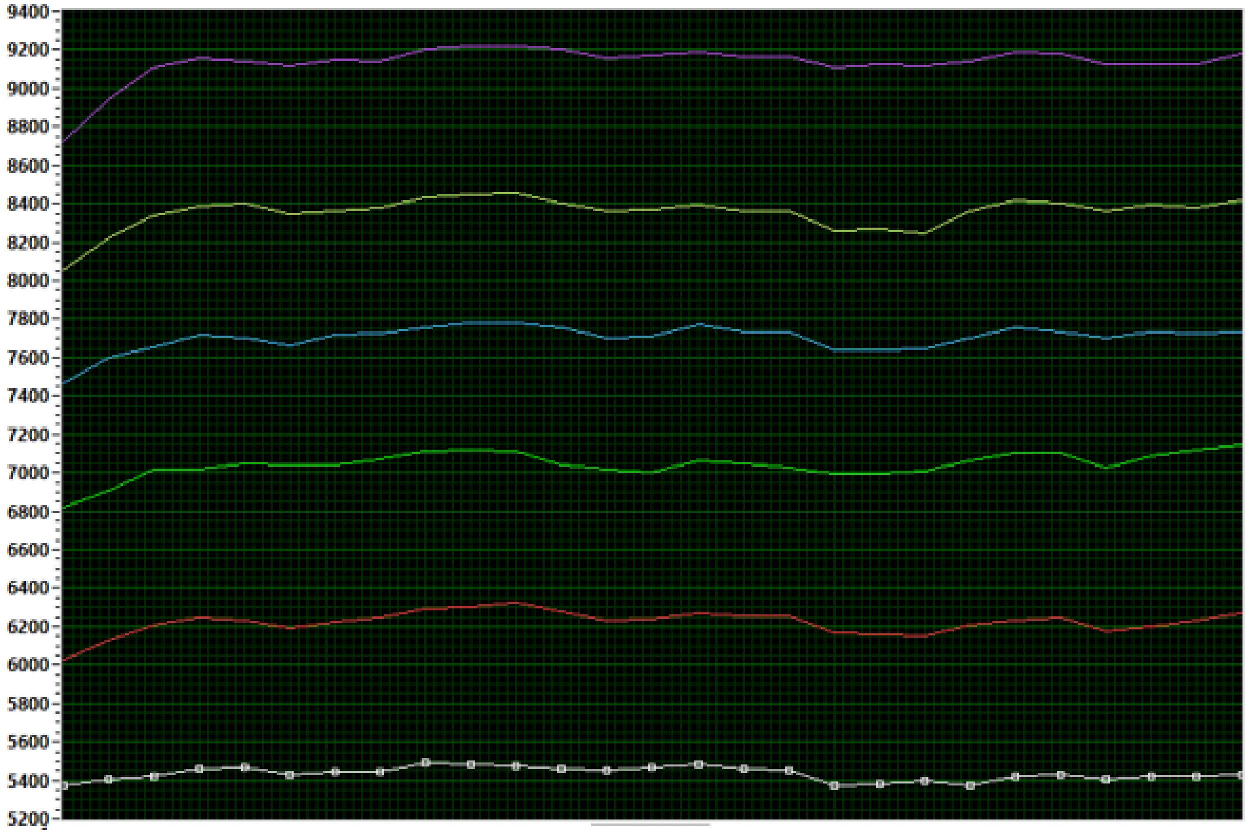


Figure 46: Power Consumption Temperature for Compressor Frequencies of 35Hz up to 60Hz in 5Hz Steps

As expected, the compressor power consumption is proportional its operating frequency.

9.4 *Temperature Variations with Static/Charging Pressure*

To characterize the influence of charging pressure on cryocooler performance and compressor power consumption, the 27-point load map was run for four charging pressure values: 203psi (White trace), 213psi (Red trace), 223psi (Green trace), and 233psi (Blue trace). The compressor frequency was set to 40Hz.

9.4.1 First Stage

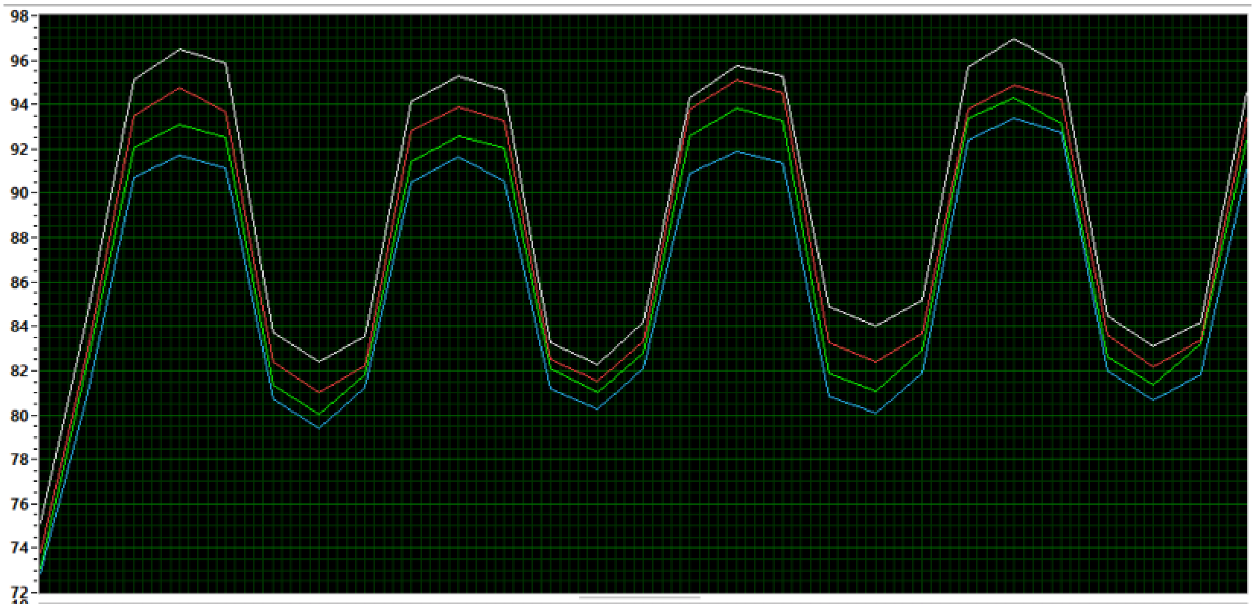


Figure 47: First Stage Temperature for Four Different Charging Pressures 203psi, 213psi, 223psi, and 233psi

9.4.2 Second Stage

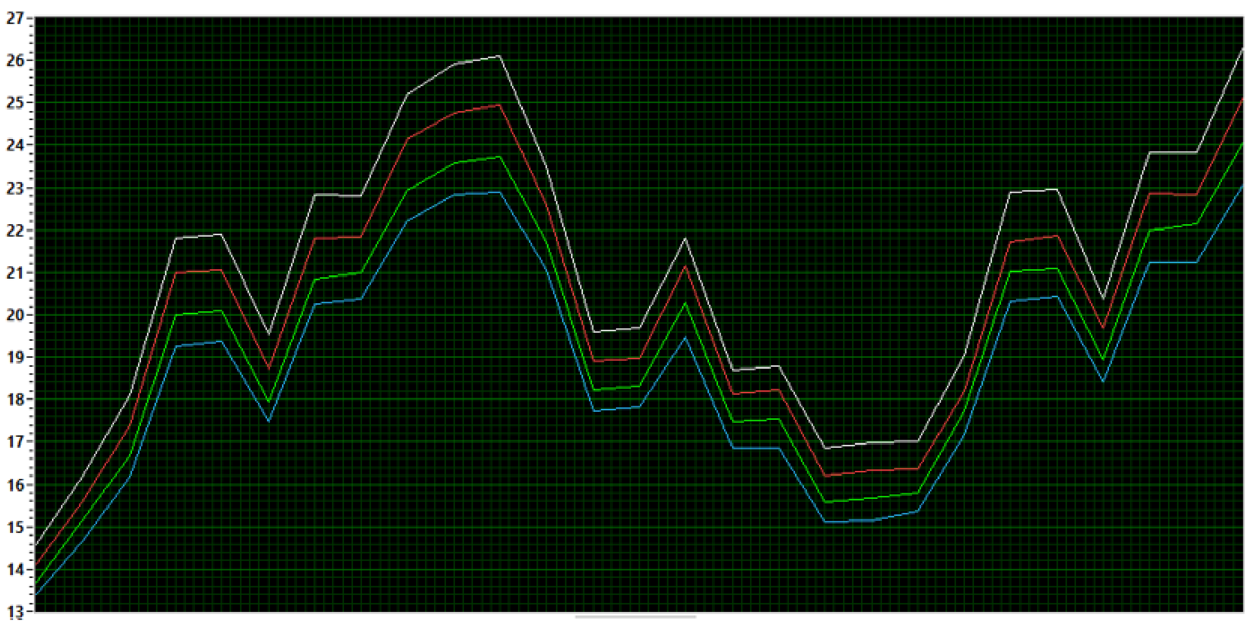


Figure 48: Second Stage Temperature for Four Different Charging Pressures 203psi, 213psi, 223psi, and 233psi

9.4.3 Third Stage

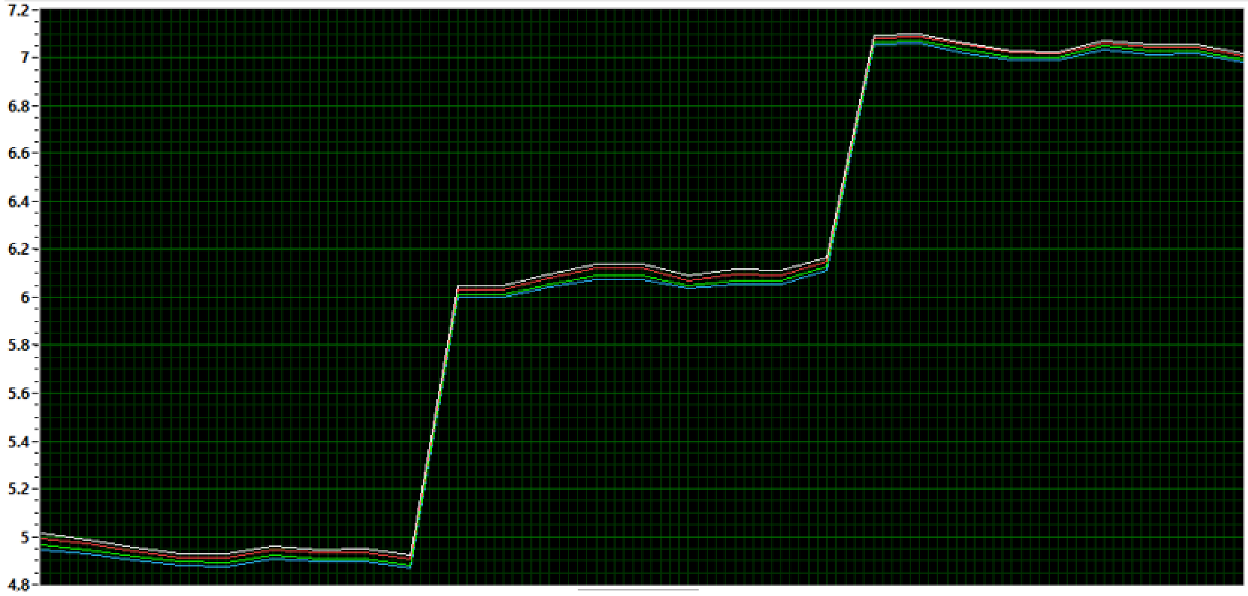


Figure 49: Third Stage Temperature for Four Different Charging Pressures 203psi, 213psi, 223psi, and 233psi

The influence of the static pressure on the stage temperature is small. A 10psi increase in static pressure only translates to a 1K drop on the first and second stage and 0.05K on the third stage.

9.4.4 Flow

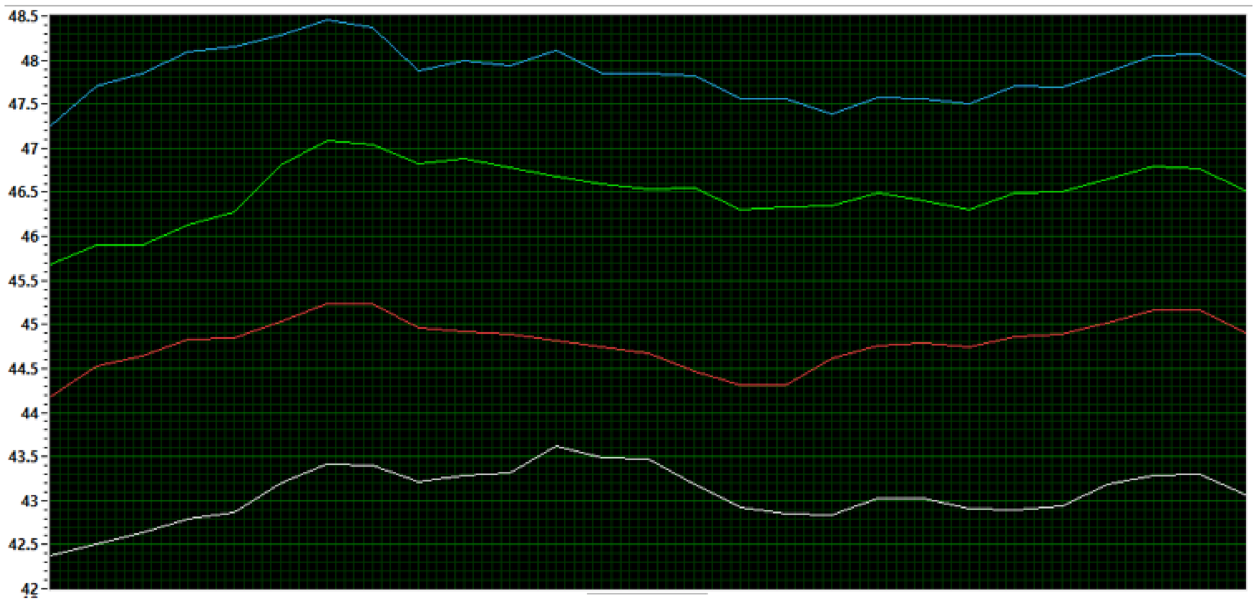


Figure 50: Helium Flow for Four Different Charging Pressures 203psi, 213psi, 223psi, and 233psi

The flow variation with the static pressure is less than 2scfm per 10psi.

9.4.5 Supply Pressure

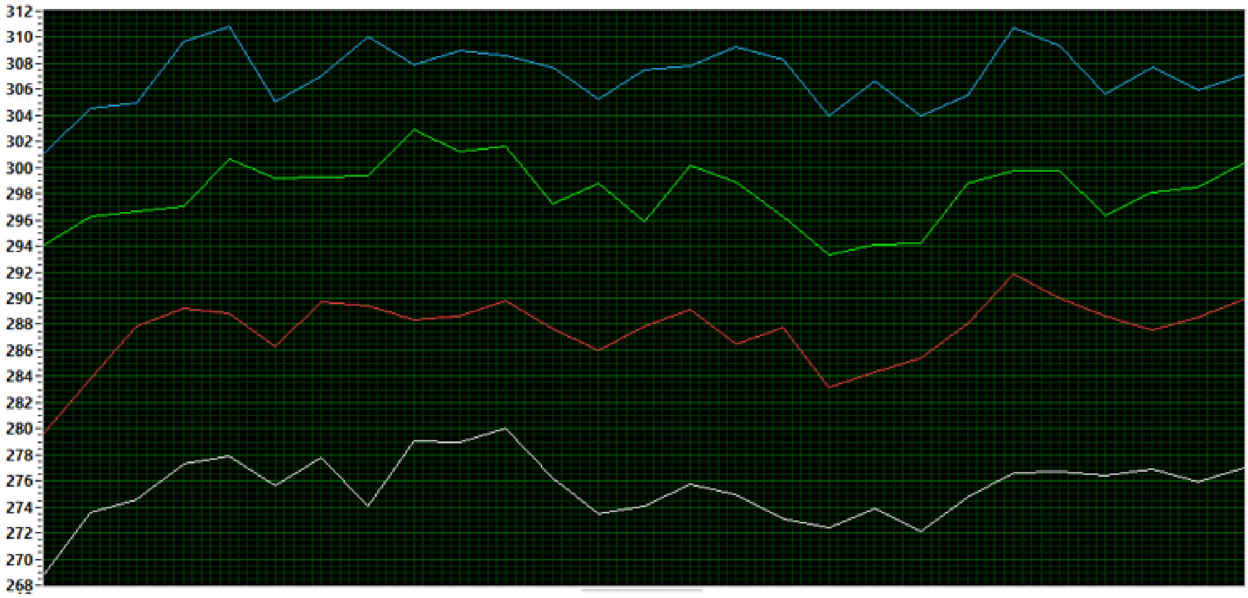


Figure 51: Supply Pressure for Four Different Charging Pressures 203psi, 213psi, 223psi, and 233psi

9.4.6 Return Pressure

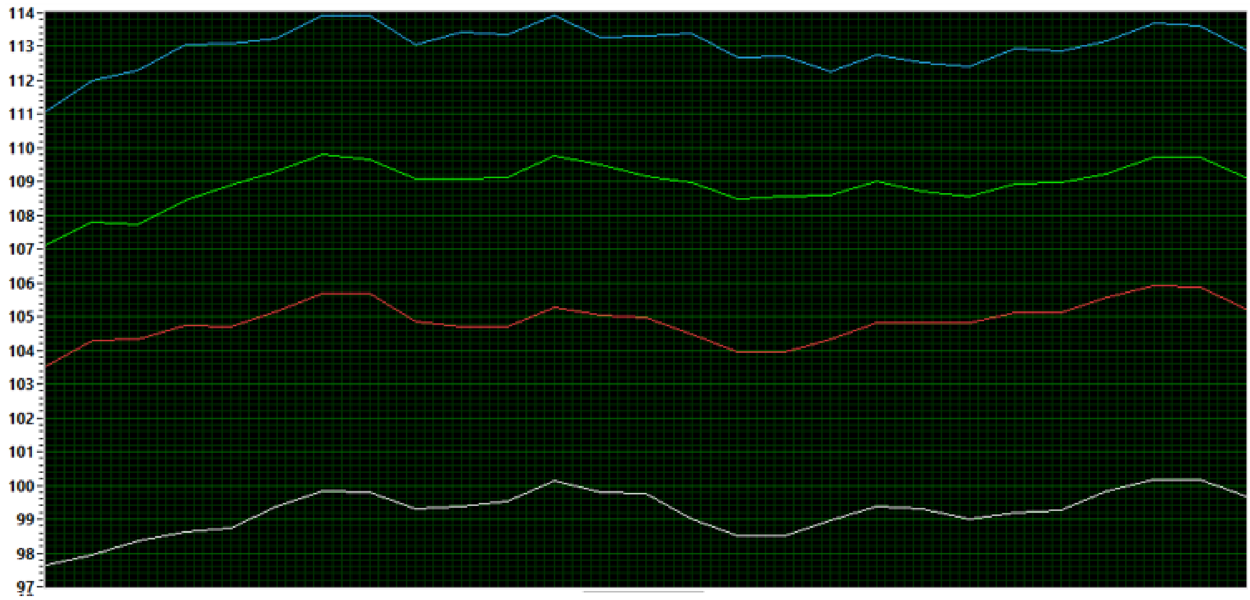


Figure 52: Return Pressure for Four Different Charging Pressures 203psi, 213psi, 223psi, and 233psi

9.4.7 Power Consumption

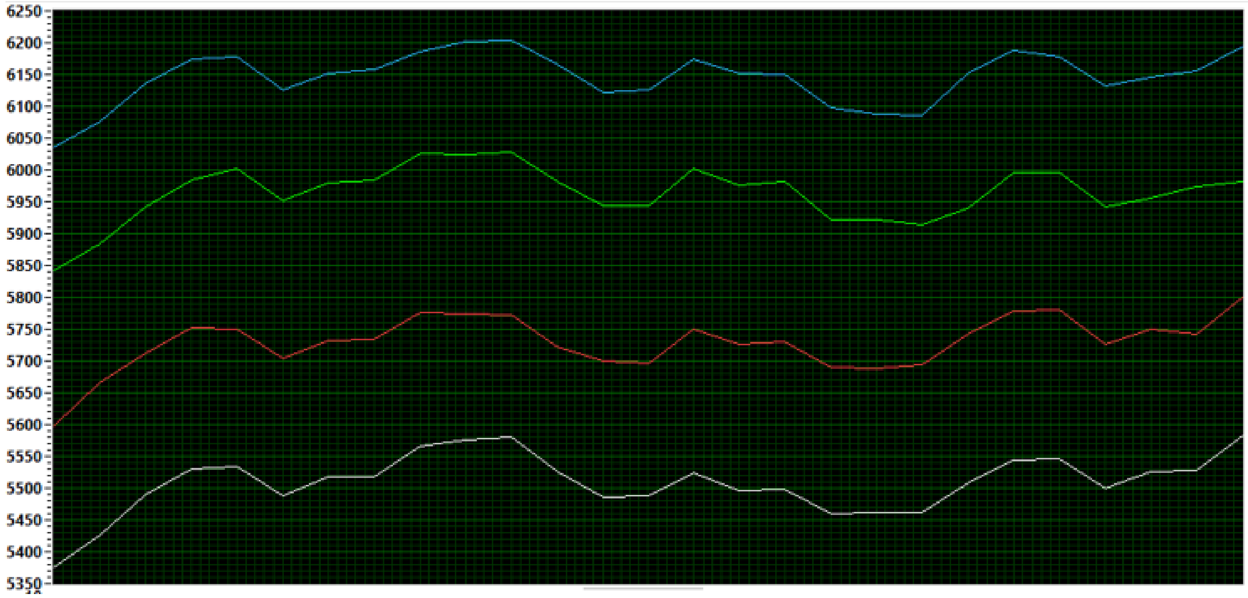


Figure 53: Power Consumption for Four Different Charging Pressures 203psi, 213psi, 223psi, and 233psi

A 10 psi pressure increment translates into an additional 200 W power draw. The recommended charge pressure for the 3-stage cold head is 230 psi, but it is interesting to note how dropping the pressure by 30 psi increases the third stage temperature by less than 0.1K while reducing the power consumption by 600W.

10 Test Results at ALMA OSF site

10.1 *Container Installation*

The compressor Indoor Control Unit (ICU) and Outdoor Control Unit (OCU) are placed inside duplicates of the ALMA antenna enclosure to protect them from the environment. The temperature of the ICU enclosure is controlled to meet the manufacturer's requirements. Since the Sumitomo FA-70 outdoor enclosure is larger than the previous model, the CNA-61D, its protective enclosure had to be modified.

Dimensions	CNA-61D	FA-70H
Height	948.2 mm	1028 mm
depth	901 mm	927.53 mm
Width	321 mm	337.33 mm

Table 11: Dimensions of the Sumitomo CNA-61D and FA-70 Outdoor Compressor Units

Picture 29: Enclosure for the ICU on the Left and OCU Enclosure on the Right

The enclosures are bolted to rails to minimize the number of penetrations on the container's roof that could be the source of leaks.

Picture 30: Container with Compressor Enclosures Mounted on the Roof at the OSF

Picture 31: Cryo-Test Cart and Sumitomo Test Cryostat Installation Inside the Container

The cryo-test cart was secured to the container's wall with brackets to prevent movement during the transfer from the OSF to the AOS.

Picture 32: Charcoal Trap Enclosure Mounted on the Container Wall, the Helium Lines Come from the Compressors on the Roof

A couple of heat pumps were mounted on the side of the container to control the temperature inside for the test instrumentation.

Picture 33: Two Heat Pumps Mounted on the Side of the Container to Control the Inside Temperature

10.2 *Test Results*

The inverter was delivered with the M-connect software to set up and monitor parameters. An SI Ethernet module had to be installed on the inverter to establish an Ethernet connection with the ALPACA laptop. The Block Diagram menu 05: Motor Control displays the inverter's voltage, current, and power values. The small offset (~1.3Hz) in the frequency readback is due to my oversight in updating parameter 05.006, Motor Rated Frequency, to 50Hz to match the Chilean power frequency.

10.2.1 Power

Frequency	Output Voltage	Output Current	Torque Current	Power
05.001	05.002	04.002	04.003	05.003
Hz	Volt	Amp	Amp	kW
31	216	11.74	10.63	3.92
36	250	12.15	11.05	4.69
41	284	12.36	11.11	5.44
46	320	12.58	11.2	6.2
51	354	12.39	10.91	6.69
53	368	12.23	10.78	6.81
55	378	12.21	10.67	7.01
57	378	12.57	11.05	7.27
59	380	13.16	11.61	7.56
61	378	13.89	12.2	7.92
63	376	14.63	12.77	8.33

Table 12: Power Data with Outdoor Enclosure in Position

Picture 34: Enclosure with louver removed showing the compressor fan.

Picture 35: Sides of the Outdoor Enclosure Removed to Test Impact on the Power Consumption

Frequency	Voltage L1,L2,L3	Output Current	Torque Current	Power
01.002	05.006	04.002	04.003	05.004
Hz	Volt	Amp	Amp	kW
31	214	11.03	10.16	3.76
36	250	11.46	10.54	4.48
41	284	11.76	10.5	5.13
46	318	11.82	10.53	5.84
51	354	11.68	10.26	6.27
53	368	11.56	10.2	6.5
55	378	11.69	10.29	6.71
57	378	12.17	10.75	6.95
59	378	12.67	11.13	7.28
61	378	13.22	11.64	7.63

Table 13: Power Data with the Outdoor Enclosure Removed

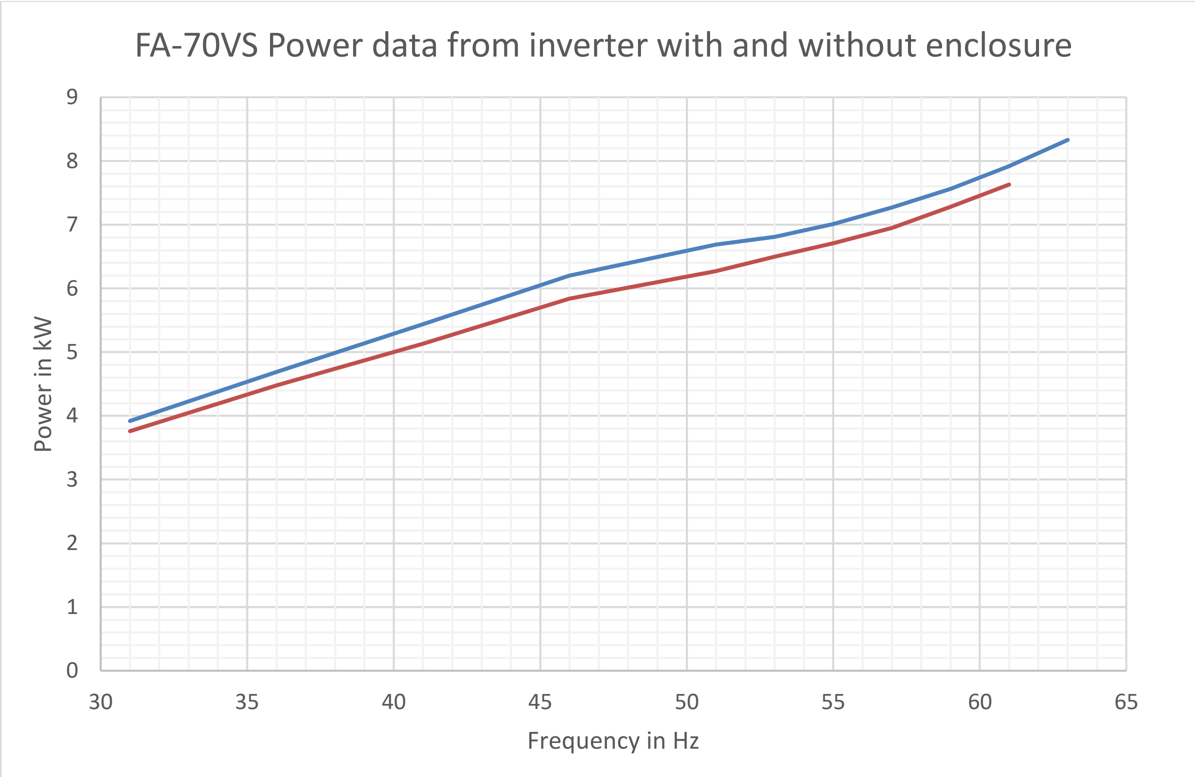


Figure 54: Compressor FA-70VS Power Consumption with Outdoor Enclosure in Position and Without It

The enclosure restricts airflow to the compressor, causing the cooling fan and the compressor to work harder; on average, an additional 200W is consumed. The Sumitomo FA-70H compressor operating manual specifies a load current of 13 amperes. As we increase the frequency beyond the nominal 50Hz, the inverter output current rises rapidly, and the capsule's temperature follows. During the test at the OSF, the compressor exceeded the capsule's temperature limit and shut down. Although I was not monitoring the compressor temperature then, the fact that I could not restart it immediately and had to wait nearly an hour for the capsule temperature to drop below 61°C to reset the switch confirmed the high compressor winding temperature.

The primary reason is that testing in Socorro was conducted with a 60Hz input frequency, whereas in Chile, it operates at 50Hz. I could run the compressor at 70Hz when the input frequency was 60Hz, but that is impossible at 50Hz. When the output voltages plateau at 55Hz, the current increases rapidly and exceeds 13 amperes at approximately 60Hz.

10.3 *Spare ALMA Front End Cryostat*

Day	Time	Compressor	Frequency in Hz	4K stage in K	15K stage in K	110K stage in K	Flow in scfm	P supply in psig	P return in psig
6/11/2022	**8:21 AM**	**FA-70H**	**50**	**3.03**	**20.98**	**94.76**	**50.7**	**307.2**	**79.6**
6/11/2022	11:30 AM	FA-70V	50	3.12	21.59	94.56	52.3	326.4	92.7
6/11/2022	2:14 PM	FA-70V	45	3.18	22.3	95.39	51.1	321.2	94.8
6/11/2022	3:00 PM	FA-70V	45	3.38	22.47	95.51	50.2	328.2	101.8
6/11/2022	5:00 PM	FA-70V	40	3.48	24.1	97.79	47.2	314.5	107.3
6/11/2022	7:00 PM	FA-70V	35	3.71	27	100.62	43.9	296.3	110.1
6/11/2022	8:30 PM	FA-70V	30	3.94*	28.65*	102.06*	39.7	295.7	118.1
6/12/2022	2:38 PM	FA-70V	50	3.34	24.64	101.86	51.9	329.6	93.3
6/12/2022	4:17 PM	FA-70V	40	3.54	26.46	102.69	46.7	318.2	104.4
6/12/2022	6:08 PM	FA-70V	35	3.69	29.15	104.42	43.8	303.8	107.4

Table 14: Temperature of the Spare ALMA Front End #05 with the FA-70H Compressor and the Prototype Variable Speed FA-70V

The temperature data taken with the FA-70H compressor as a reference did not include the thermal load from Bands 3, 6, and 7 because they were not powered while they were ON with the FA-70V.

			Band 3			Band 6			Band 7		
Day	Time	Compressor	4K	4K mixer0	4K mixer1	4K	4K mixer0	4K mixer1	4K	4K mixer0	4K mixer1
6/11/2022	**8:21 AM**	**FA-70H**									
6/11/2022	11:30 AM	FA-70V									
6/11/2022	2:14 PM	FA-70V									
6/11/2022	3:00 PM	FA-70V	5.16	5.17	5.01	4.14	4.42	5.03	4.28	4.46	4.49
6/11/2022	5:00 PM	FA-70V	5.25	5.28	5.12	4.3	4.56	5.15	4.4	4.59	4.6
6/11/2022	7:00 PM	FA-70V	5.42	5.43	5.26	4.49	4.75	5.32	4.57	4.78	4.8
6/11/2022	8:30 PM	FA-70V									
6/12/2022	2:38 PM	FA-70V	5.23	5.24	5.06	4.22	4.51	5.1	4.35	4.55	4.58
6/12/2022	4:17 PM	FA-70V	5.36	5.36	5.2	4.41	4.67	5.26	4.5	4.72	4.74
6/12/2022	6:08 PM	FA-70V	5.49	5.49	5.34	4.56	4.82	5.4	4.65	4.88	4.89

Table 15: Band 3, 6, and 7 Third Stage and Mixers Temperatures

This is only a relative measurement of the cartridge temperatures for different compressor speeds. Still, the information is relevant since both compressors should perform equally when the inverter frequency is set to 50Hz, and their charge pressures are the same.

	Cold head			Band 3			Band 6			Band 7	
	4K stage	15K stage	110K stage	4K	4K mixer0	4K mixer1	4K	4K mixer0	4K mixer1	4K	4K mixer0
Delta T 50Hz/40Hz in K	-0.36	-2.51	-3.23								
Delta T 50Hz/40Hz in K	-0.2	-1.82	-0.83	-0.13	-0.12	-0.14	-0.19	-0.16	-0.16	-0.15	-0.17

Table 16: Temperature Variation Between 50Hz and 40Hz Compressor Operating Frequency

The temperature variations seen on the 4K stage when the frequency is reduced to 40Hz do not exceed 0.2K This seems to be a small penalty, but it will have to be confirmed with a fully populated (10 cartridges) ALMA Front End.

11 Test Results at ALMA AOS Site

The container was moved to the AOS on June 17th, 2022, and set down close to the building entrance to establish power and network connections. The move went well, but we encountered a few problems with the equipment; the lakeshore temperature controller failed when powered up, and network communication with the compressor could not be established. It took several weeks to resolve the Ethernet communication problem and repair the temperature monitor. The compressor was running during that time, but no data could be collected. The main purpose of the AOS testing was to establish the reliability of the FA-70V compressor at the high site.

Picture 36: Container Arriving at the AOS

Picture 37: Container Set Down Close to the AOS Entrance

Mike had to develop new test software because the measurements were now focused on reliability rather than performance demonstration. Heat loads were applied to the test cryostat, and the information collected was averaged and recorded until we decided to stop or an event triggered the safety interlock.

11.1 *Inverter voltage and current variation with frequency*

This test was performed at the AOS but not at the OSF. To determine which frequency range was available, I had the compressor drive the coldhead on the test cryostat while I swept the frequency from 35 Hz to its upper limit (TBD). The test was interrupted at 58 Hz when the compressor shut down. Although the error message indicates "Motor Temp ERR, " the compressor stopped, most likely because the current exceeded the 16A limit. I could restart the compressor immediately and did not have to wait for the scroll temperature to drop as I had to previously.

Commanded Frequency in Hz	Output Frequency in Hz	Motor Speed in rpm	Output voltage in Volts	Output Current in Amps	DC bus Voltage In Volts
35	36.4	2100	280	11.22	521
40	41.45	2400	318	11.63	518
45	46.44	2700	356	11.72	517
50	51.54	3000	366	12.38	512
55	56.71	3300	364	13.66	512
58	59.91	3480	364	15.41	513

Table 17: Inverter Voltage and Current Variation with Frequency

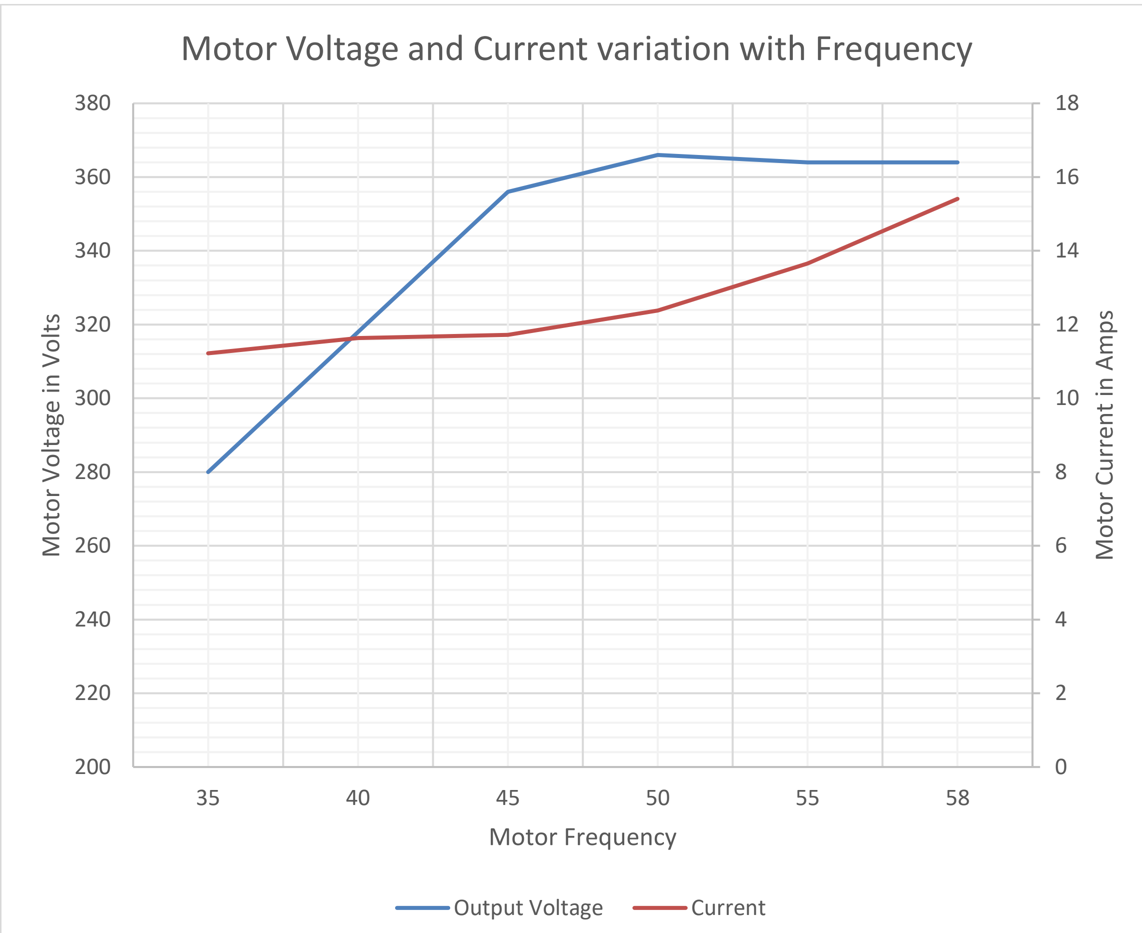


Figure 55. Variation of the Compressor Motor Voltage and Current with Frequency

The motor voltage increases linearly up to 45 Hz before leveling off. The maximum value of 366V is achieved at 50Hz and remains constant at 364V thereafter. The current experiences an increase of less than 1A until 50Hz; beyond that frequency, it begins to rise rapidly. The compressor trips at a maximum current draw of 16 amperes. This indicates that the maximum operating frequency at the AOS is 55Hz, just five Hertz above the line frequency.

12 ALMA Frontend #5 Operation with FA-70V Compressor

12.1 *Cooldown*

The ALMA frontend #5 was cooled using the variable-frequency compressor. Initially, the active control of the differential pressure was activated (see section 13). The software adjusted the compressor frequency to keep the differential pressure to a preset value. As the Frontend cools, the flow increases, and the differential pressure drops. The frequency is increased to raise the differential pressure. The cooldown was interrupted by a compressor shutdown. What caused the shutdown was initially unclear, but the error message "Motor Temp ERR" appeared.

Picture 38: Motor Temp Err is displayed after the compressor's shutdown

This suggests a high compressor winding temperature. According to the Sumitomo user manual, this can occur when the return pressure exceeds 140 psi, but the last recorded return pressure was 134.3512 psi. A static pressure above 255 psi could also trigger the error, but the static pressure was set to 1.65 MPa (240 psi), and the compressor would have stopped soon after startup. The only explanation might be the high motor current due to increased frequency; however, the last recorded frequency was 49.73 Hz, a value not even close to the 55Hz previously established operating limit.

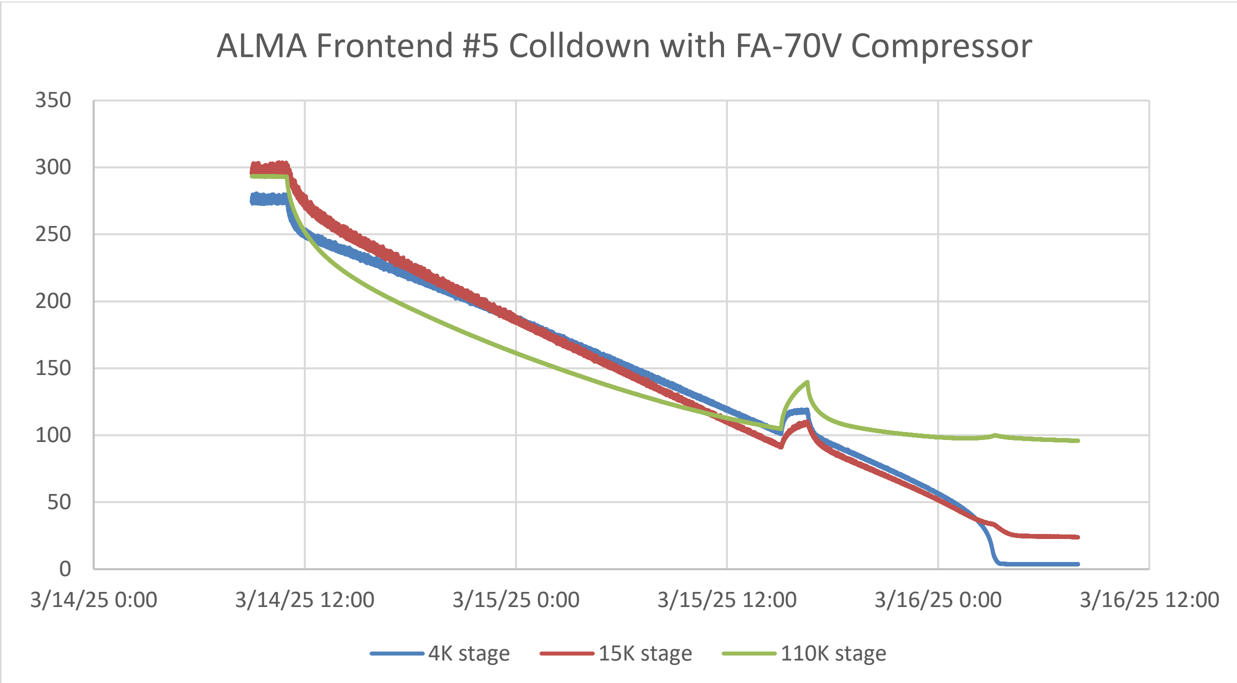


Figure 56: ALMA Frontend #5 Cooldown at AOS with FA-70V Compressor

To finish the cooldown, the active control of the differential pressure was suspended, and the frequency was set to 40 Hz.

12.2 *Power Measurements*

Previously, a sudden shutdown of the compressor was always caused by a high current when commanded to a high frequency. To determine if this was the case, the inverter motor control parameters (M-connect, Block Diagrams, Menu 05) were recorded over a complete frequency sweep. The new values were also compared to the last measurement taken at the OSF before transporting the container to the AOS.

The AOS data are in red in the comparison table.

Frequency	Voltage L1,L2,L3	Current Magnitude	Current Torque	Power
05.001	05.002	04.002	04.003	05.003
Hz	Volt	Amp	Amp	kW
36	250	12.15	11.05	4.69
36	280	12.5	11.35	5.48
41	284	12.36	11.11	5.44
41	320	12.83	11.54	6.2
46	320	12.58	11.2	6.2

46	358	12.73	11.11	6.82
51	354	12.39	10.91	6.69
51	364	13.97	12.47	7.76
53	368	12.23	10.78	6.81
53	364	14.59	12.97	8.15
55	378	12.21	10.67	7.01
57	378	12.57	11.05	7.27
59	380	13.16	11.61	7.56
61	378	13.89	12.2	7.92
63	376	14.63	12.77	8.33

Table 18: Comparison of Inverter Motor Parameters at the OSF in 2022 and at the AOS in 2025

The results indicate an increase in output voltage and a lower maximum value. The maximum value decreased from 380VAC to 364VAC and was reached earlier, at 51 Hz compared to 55 Hz. Additionally, the current and output power were also higher. The compressor stopped twice at 52 Hz and 53 Hz during the test. It took several minutes at 52 Hz and a short time at 53 Hz for the compressor to stop.
Based on the new data, the compressor shutdown during cooldown was most likely due to high current.

12.3 *Inverter Change in Performance*

I met with the Sumitomo engineering team on Zoom to discuss the latest power measurements and identify possible reasons. We identified three areas to investigate.

- Measure the three-phase AC input voltage to the container
- Reduce the static pressure to 1.6 MPa (230 psi)
- Review and change some of the inverter settings

12.3.1 Three-phase power to the container.

The AC voltage at the input electrical panel was measured; the three phases were well-balanced, and the voltage was 386 VAC. This indicates a 16 VAC drop compared to the voltage at the OSF. The electrician measured the voltage at the transformer, which was also 386VAC, indicating that the cabling was fine. Raising the voltage was not possible without replacing or tuning the transformer.

12.3.2 Adjusting the static pressure

A higher static pressure will cause the compressor to work harder and increase power consumption (see section 9.4). The pressure was set to 1.6 MPa at the OSF and 1.65 MPa when we connected the FA-70V to the ALMA FE #5. I reduced the pressure and repeated the power measurement.

Helium Circuit Static Frequency 1.65 MPa (240 psi)						
Set Freq Hz	Motor Speed rpm	Output Voltage VAC	DC Bus Voltage VDC	Output Power kVA	Torque Current A	Output Current A
35	2100	280	517	5.22	10.88	12.16
40	2400	320	515	6.17	11.22	12.6
45	2700	358	513	6.69	10.89	12.35
50	3000	365	512	7.805	12.415	13.985
51	3060	364	513	7.94	12.64	14.22
52	3120	364	512.5	8.14	12.96	14.575
53	3180	364	513	8.32	13.25	14.93

Table 19: Power VS Frequency with 1.65 MPa Static Pressure

Helium Circuit Static Frequency 1.60 MPa (230 psi)						
Set Freq Hz	Motor Speed rpm	Output Voltage VAC	DC Bus Voltage VDC	Output Power kVA	Torque Current A	Output Current A
35	2100	280	515	4.86	10.07	11.31
40	2400	318	517	5.69	10.32	11.68
45	2700	356	512	6.32	10.28	11.77
50	3000	364	513	6.96	11.07	12.51
52	3120	364	513	7.39	11.77	13.29
54	3240	364	514	7.79	12.38	13.96

Table 20: Power VS Frequency with 1.60 MPa Static Pressure

	Output Power kVA	Output Current A
Delta 240/230 @ 35 Hz	0.36	0.85
Delta 240/230 @ 40 Hz	0.48	0.92
Delta 240/230 @ 45 Hz	0.37	0.58
Delta 240/230 @ 50 Hz	0.85	1.48
Delta 240/230 @ 52 Hz	0.75	1.29

Table 21: Impact of the Static Pressure on the Compressor Power

Although a 0.5 MPa static pressure difference may appear minor, it affects the compressor's power consumption and limits the inverter's frequency range.

12.3.3 Adjustment of the inverter settings

Sumitomo's engineer proposed changing the setting inside the Parameter Menu 05, Motor Control.

Parameter 05.006 Motor Rated Frequency 50.00 Hz
Parameter 05.009 Motor Rated Voltage 400 V

Parameter 05.010 Motor Rated Power Factor 0.95

New inverter settings						
Set Freq Hz	Motor Speed rpm	Output Voltage VAC	DC Bus Voltage VDC	Output Power kVA	Torque Current A	Output Current A
35	2100	280	516	4.83	10.11	11.41
40	2400	320	516	5.82	10.77	11.96
45	2700	360	513	6.34	10.32	11.92
50	3000	364	512	7.02	11.17	12.67
52	3120	364	512	7.55	11.99	13.51
54	3240	364	512	7.57	11.97	13.51
55	3300	364	514	7.68	12.33	13.91
57	3420	364	513	8.00	12.74	14.37

Table 22: Power VS Frequency with new settings

	Output Power kVA	Output Current A
Delta @ 35 Hz	-0.02	0.10
Delta @ 40 Hz	0.13	0.28
Delta @ 45 Hz	0.01	0.15
Delta @ 50 Hz	0.06	0.15
Delta @ 52 Hz	0.16	0.23
Delta @ 54 Hz	0.18	0.22

Table 23: Impact of the New Inverter Settings on the Compressor Power

The new settings had a minor effect on power consumption and output current, registering a power reduction of less than 200 W at 54 Hz. This falls within the observed measurement variation and is therefore not considered critical. This research demonstrated the impact of charge pressure and input voltage on the inverter's performance. For optimal performance of the cryocooler and inverter, it is recommended to adhere to the manufacturer's guidelines and maintain the static pressure at 1.6 MPa. While it would have been preferable to have the 400VAC nominal voltage delivered to the container, this parameter is beyond our control and does not interfere with the measurements below 50Hz.

12.4 *Influence of the Compressor Frequency on the Frontend Temperatures*

The study's primary goal was to determine whether the compressor could operate at a lower frequency to minimize power consumption while maintaining the required stage temperatures. The third stage is critical to guaranteeing the SIS mixer's operation.

Three sets of measurements were conducted:

- Frontend #5 with three bands active, Band-3, Band-4 and band-6. Compressor static pressure set to1.65MPa
- Frontend #5 no band active, compressor static pressure 1.6MPa

- Frontend #5 with three bands active, Band-3, Band-4 and Band-6. Compressor static pressure set to 1.6 MPa

A minimum of one hour of waiting time was respected between frequency changes for temperature stabilization.

12.4.1 Frontend #5, Three Active Bands and Static Pressure of 1.65MPa

Three Frequency Bands active, Band-3, Band-4 and Band-6. Static pressure set to 1.65MPa (240 psi)													
Compressor Frequency	4K stage	4K link 1	4K link 2	4K far side 1	4K far side 2	15K stage	15K link	15K far side	15K shield	110K stage	110K link	110K far side	110K shield
35 Hz	4.15	4.51	4.55	4.26	5.01	25.13	23.61	23.94	24.26	93.83	106.14	117.87	119.84
40 Hz	3.92	4.29	4.33	4.06	4.76	23.09	21.80	22.11	22.42	93.05	106.10	118.44	120.42
45 Hz	3.87	4.24	4.28	4.02	4.71	22.50	21.28	21.58	21.90	92.68	106.00	118.57	120.57
50 Hz	3.86	4.23	4.27	4.00	4.69	22.19	21.00	21.30	21.62	92.47	105.89	118.62	120.64
Δ 35/50 Hz	0.29	0.28	0.28	0.26	0.31	2.93	2.61	2.63	2.65	1.36	0.24	-0.75	-0.80
Δ 40/50 Hz	0.06	0.06	0.06	0.06	0.07	0.90	0.80	0.81	0.81	0.58	0.21	-0.18	-0.22
Δ 45/50 Hz	0.01	0.02	0.01	0.02	0.02	0.30	0.28	0.28	0.29	0.20	0.11	-0.06	-0.07

Table 24: Temperatures of Frontend #05 featuring three active bands and a static pressure of 1.65 MPa across various frequencies

12.4.2 Frontend #5, no Active Band and Static Pressure of 1.6 MPa

No Active Band. Static Pressure set to 1.6 Mpa (230 psi)													
Compressor Frequency	4K stage	4K link 1	4K link 2	4K far side 1	4K far side 2	15K stage	15K link	15K far side	15K shield	110K stage	110K link	110K far side	110K shield
35 Hz	4.20	4.52	4.57	4.28	5.02	28.40	26.63	27.06	27.39	103.42	117.82	131.13	133.27
40 Hz	3.82	4.16	4.20	3.94	4.61	25.17	23.75	24.15	24.45	100.96	116.08	129.89	132.08
45 Hz	3.69	4.03	4.07	3.83	4.47	23.45	22.18	22.53	22.86	98.85	113.87	127.89	130.13
50 Hz	3.66	4.00	4.04	3.79	4.42	22.87	21.64	21.98	22.30	97.67	112.48	126.34	128.59
52 Hz	3.61	3.95	3.99	3.75	4.37	22.34	21.16	21.49	21.80	96.59	111.19	124.90	127.14
50 Hz	3.62	3.96	3.99	3.75	4.37	22.20	21.02	21.34	21.65	95.81	109.95	123.32	125.58
45 Hz	3.60	3.94	3.98	3.73	4.35	22.07	20.90	21.21	21.51	94.67	108.15	120.90	123.19
40 Hz	3.66	3.98	4.02	3.77	4.40	22.60	21.37	21.67	21.98	94.97	107.84	120.03	122.26
35 Hz	4.01	4.32	4.36	4.08	4.78	25.52	23.94	24.28	24.57	96.46	108.62	120.15	122.27
Δ 35/50 Hz	0.54	0.52	0.53	0.48	0.60	5.53	4.99	5.08	5.08	5.75	5.34	4.79	4.68
Δ 40/50 Hz	0.16	0.16	0.16	0.15	0.19	2.31	2.10	2.17	2.15	3.29	3.59	3.54	3.49
Δ 45/50 Hz	0.03	0.04	0.04	0.04	0.04	0.58	0.54	0.55	0.56	1.18	1.39	1.55	1.53
Δ 52/50 Hz	-0.05	-0.05	-0.05	-0.04	-0.05	-0.53	-0.48	-0.49	-0.50	-1.08	-1.29	-1.45	-1.46
Δ 52/50 Hz	-0.01	-0.01	0.00	0.00	0.00	0.14	0.14	0.15	0.15	0.78	1.24	1.58	1.56
Δ 45/50 Hz	-0.02	-0.02	-0.02	-0.02	-0.02	-0.13	-0.13	-0.14	-0.14	-1.14	-1.80	-2.42	-2.39
Δ 40/50 Hz	0.04	0.03	0.03	0.02	0.03	0.40	0.34	0.32	0.33	-0.85	-2.11	-3.29	-3.32
Δ 35/50 Hz	0.39	0.36	0.36	0.33	0.41	3.32	2.92	2.94	2.92	0.65	-1.33	-3.17	-3.31

Table 25: Temperatures of Frontend #05 featuring no active bands and a static pressure of 1.60 MPa across various frequencies

12.4.3 Frontend #5, Three Active Bands and Static Pressure of 1.6 MPa

This is the most significant test because it features three active bands representing the maximum load during normal operation, with the static pressure adjusted to the recommended value.

12.4.3.1 Plots

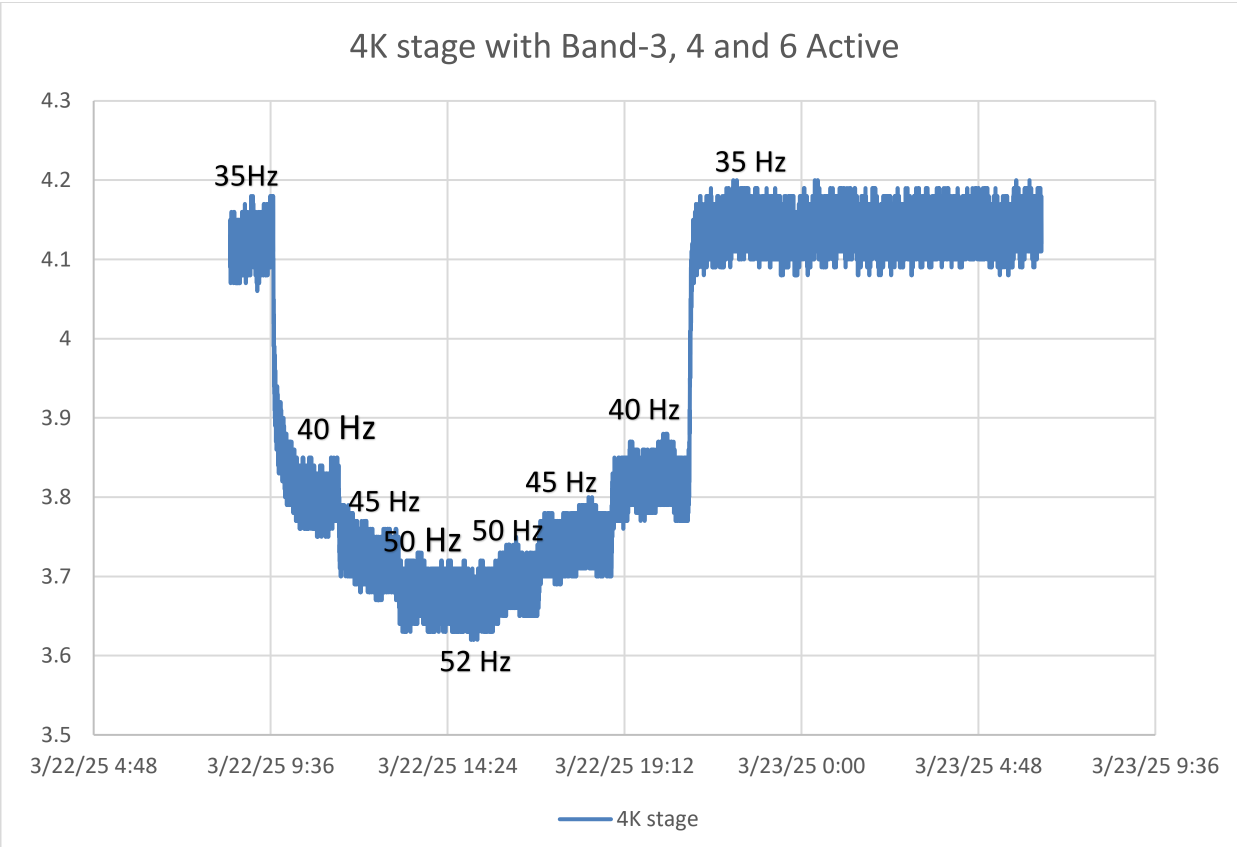


Figure 57: Temperature of 4K Stage VS Frequency

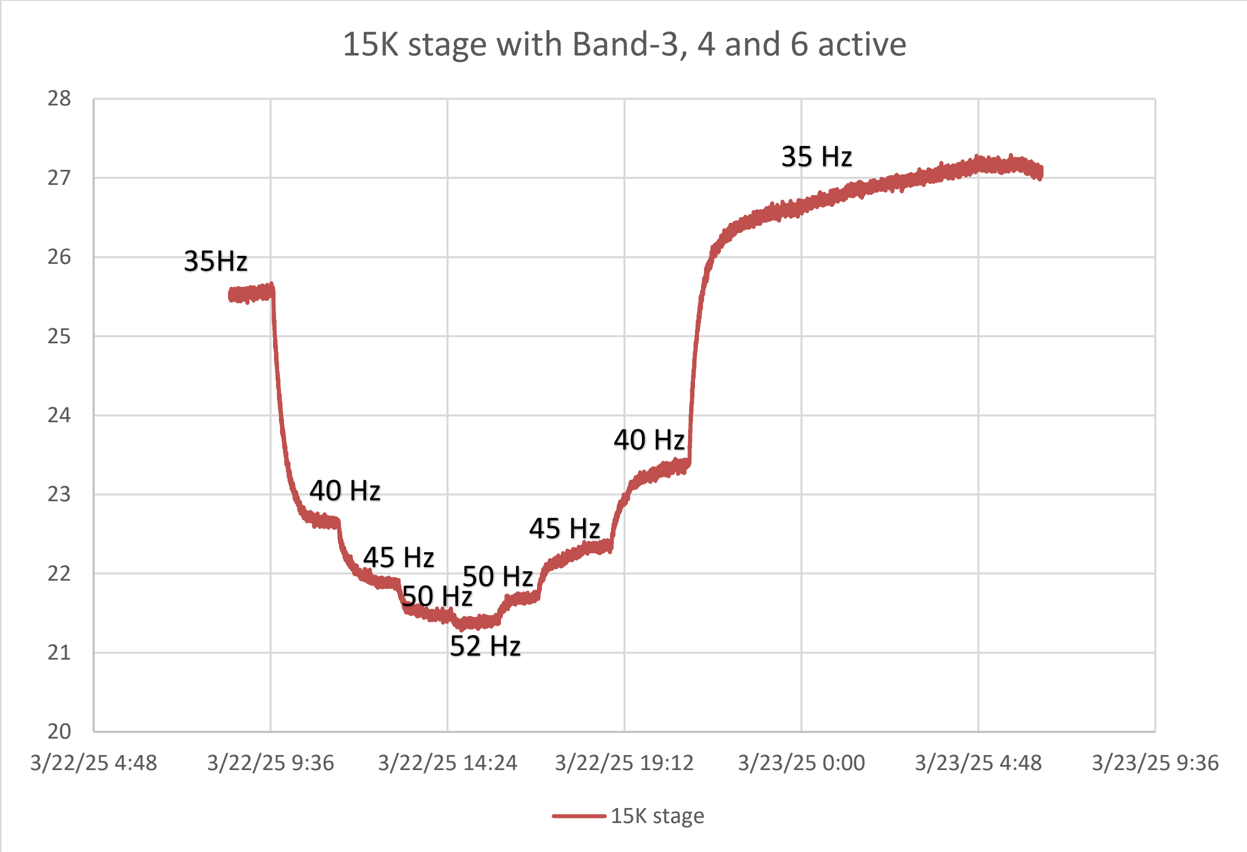


Figure 58: Temperature of 15K Stage VS Frequency

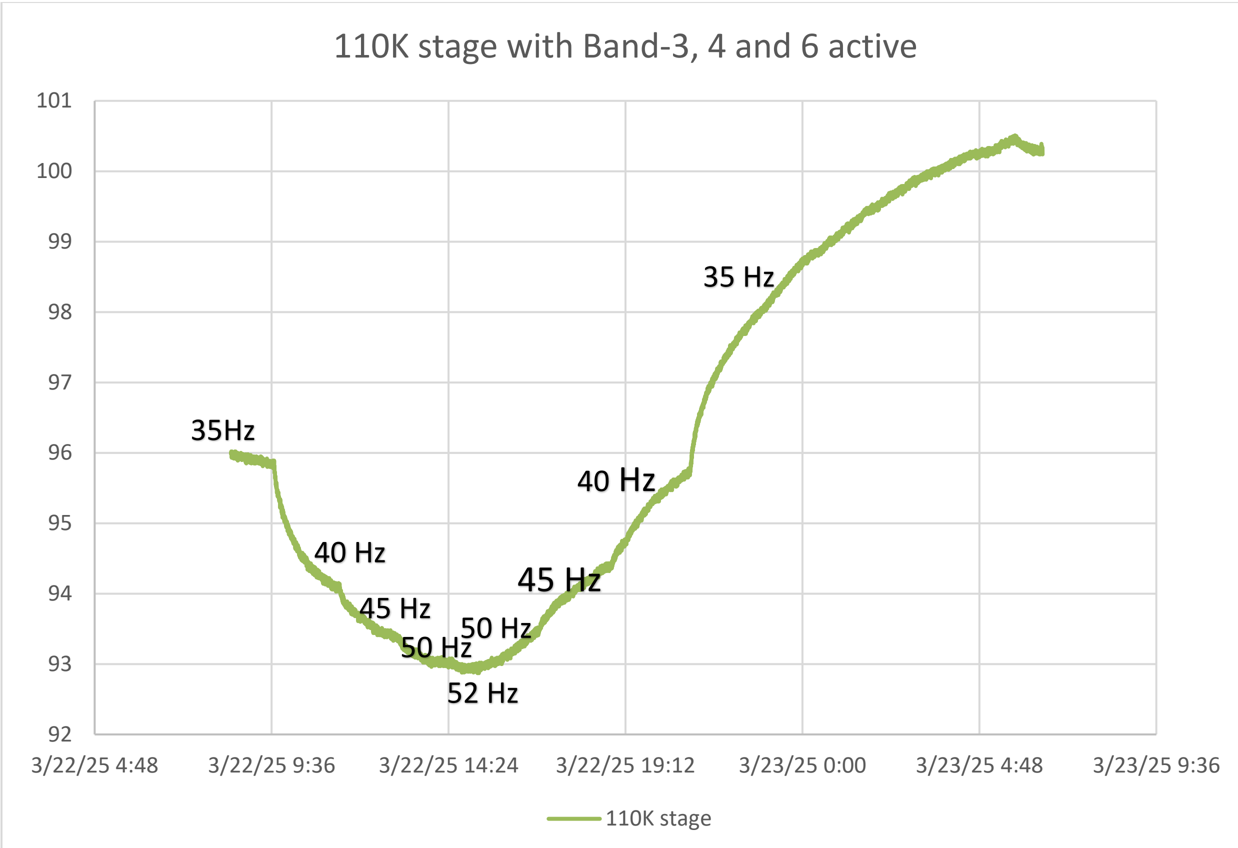


Figure 59: Temperature of 110K Stage VS Frequency

12.4.3.2 Table

Three Frequency Bands active, Band-3, Band-4 and Band-6. Static pressure set to 1.6MPa (230 psi)													
Compressor Frequency	4K stage	4K link 1	4K link 2	4K far side 1	4K far side 2	15K stage	15K link	15K far side	15K shield	110K stage	110K link	110K far side	110K shield
35 Hz	4.13	4.49	4.54	4.25	4.99	25.55	23.98	24.32	24.60	95.83	108.05	119.55	121.53
40 Hz	3.80	4.19	4.23	3.97	4.65	22.65	21.40	21.70	21.99	94.09	107.11	119.30	121.25
45 Hz	3.70	4.10	4.15	3.89	4.55	21.88	20.72	21.02	21.30	93.38	106.59	119.00	120.98
50 Hz	3.68	4.07	4.12	3.87	4.52	21.48	20.36	20.65	20.95	93.01	106.34	118.89	120.90
52 Hz	3.67	4.07	4.12	3.87	4.52	21.42	20.32	20.60	20.90	93.04	106.37	118.94	120.99
50 Hz	3.69	4.09	4.13	3.88	4.54	21.71	20.57	20.85	21.16	93.45	106.65	119.15	121.22
45 Hz	3.74	4.14	4.18	3.93	4.60	22.36	21.14	21.45	21.75	94.40	107.64	120.05	122.13
40 Hz	3.80	4.21	4.25	3.99	4.68	23.38	22.06	22.38	22.68	95.69	108.94	121.36	123.42
35 Hz	4.13	4.52	4.57	4.28	5.03	26.77	25.09	25.45	25.75	99.06	112.25	124.56	126.51
Δ 35/50 Hz	0.45	0.42	0.42	0.39	0.47	4.08	3.62	3.67	3.65	2.82	1.72	0.66	0.64
Δ 40/50 Hz	0.13	0.12	0.12	0.10	0.13	1.17	1.04	1.06	1.05	1.08	0.78	0.41	0.35
Δ 45/50 Hz	0.03	0.03	0.03	0.03	0.03	0.40	0.36	0.37	0.35	0.37	0.25	0.11	0.08
Δ 52/50 Hz	0.00	0.00	0.00	0.00	0.00	-0.05	-0.04	-0.05	-0.04	0.03	0.04	0.05	0.09
Δ 52/50 Hz	-0.02	-0.02	-0.02	-0.01	-0.02	-0.29	-0.25	-0.25	-0.25	-0.41	-0.28	-0.21	-0.23
Δ 45/50 Hz	0.05	0.05	0.05	0.05	0.06	0.65	0.57	0.60	0.59	0.95	0.98	0.90	0.91
Δ 40/50 Hz	0.12	0.12	0.12	0.11	0.14	1.66	1.50	1.53	1.52	2.24	2.28	2.21	2.20
Δ 35/50 Hz	0.44	0.43	0.44	0.40	0.49	5.05	4.52	4.60	4.59	5.61	5.60	5.41	5.29

Table 26: Temperatures of Frontend #05 featuring three active bands and a static pressure of 1.60 MPa across various frequencies

The results indicate a consistent temperature change with frequency across different locations on each stage. This suggests that recording the variation in stage temperature sensors is sufficient to estimate the temperature change in other locations. The 4K stage temperature increase from 50 Hz down to 40 Hz is less than 0.15 K. Lowering the compressor frequency to 35 Hz triggered a change greater than 0.4K. This confirms the measurement done in the laboratory with the test cryostat (see section 9.3). Therefore, operating the compressor below 40Hz is not recommended.

13 Active Frequency Control

While the main goal of the variable frequency was to lower the compressor power consumption, other applications were also explored.

13.1 *Active control of the differential pressure*

The compressor's operating frequency can control the supply and return pressures within a limited range. The faster the compressor operates, the higher the supply pressure. The aim was to use the compressor frequency to maintain the differential pressure and observe whether it would help reduce the temperature variations caused by the diurnal changes in ambient temperature. The same algorithm can be used to control the Supply or Return pressure.

13.1.1 Control algorithm

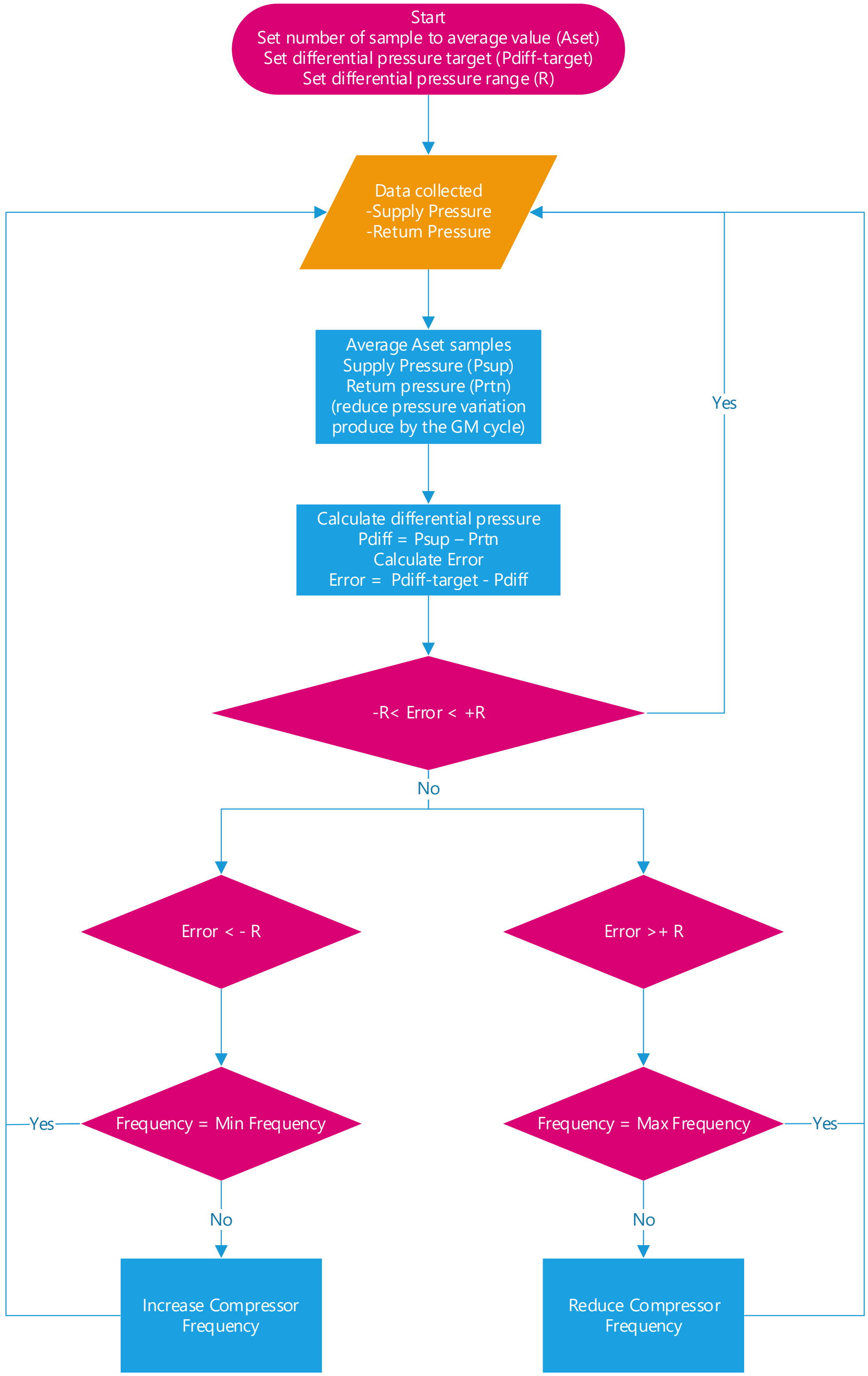


Figure 60: Algorithm to control the differential pressure

The supply and return pressure pulse at the coldhead frequency requires averaging multiple samples to obtain a representative value. The average number of samples acts as an input parameter for the control loop, with 20 set as the default value. The longer the averaging time, the longer it takes for the control loop to respond to a change. After both pressures have been averaged, the average differential pressure is computed and compared to the target value, which also serves as an input for the control loop. If the differential pressure is within range, the compressor frequency remains constant while the program collects additional samples. The compressor frequency is adjusted according to the table below if the differential pressure falls outside the range. Once the frequency reaches the minimum or maximum value, it remains there until directed to change by a modification in the Error sign.

-(R + 2) < Error < -(R + 1)	R+1 < Error < R+2
Compressor Frequency – 0.1Hz	Compressor Frequency + 0.1 Hz
-(R + 3) < Error < -(R + 2)	R+2 < Error < R+3
Compressor Frequency – 0.2Hz	Compressor Frequency + 0.2 Hz
Error < -(R + 3)	R + 3 < Error
Compressor Frequency – 0.3Hz	Compressor Frequency + 0.3Hz

Table 27: Frequency response based on the differential pressure error

Maintaining a constant differential pressure during the cooldown should be achievable. With a static pressure set at 1.65 MPa (240 psi), the differential pressure at the start of the cooldown was approximately 1.72 MPa (250 psi), but when the receiver cooled down, it dropped to 1.52 MPa (220 psi). Section 8.3 indicates that increasing the frequency from 35 Hz to 55 Hz changed the differential pressure by more than 0.2 MPa (30-35 psi).

13.2 *Compressor instability*

13.2.1 Discovery of a Periodic Pressure Instability (PPI)

While developing the differential pressure control software, a periodic instability was discovered. The error, which corresponds to the difference between the average differential pressure and the target value, was recorded while the control loop was active. The plot indicates a periodic increase in amplitude, suggesting that some element in the system disturbed its stability.

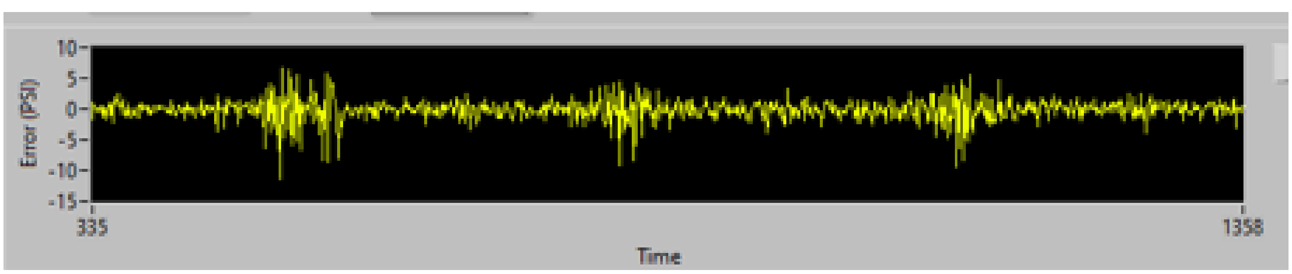


Figure 61: Periodic increase in the error signal

The control software depends on the error to calculate the new frequency, aiming to keep the differential pressure as stable as possible. Therefore, sudden changes in the error lead to rapid frequency adjustments with increased amplitude. The periodicity of this instability suggests that it is not random but systematic, warranting further investigation.

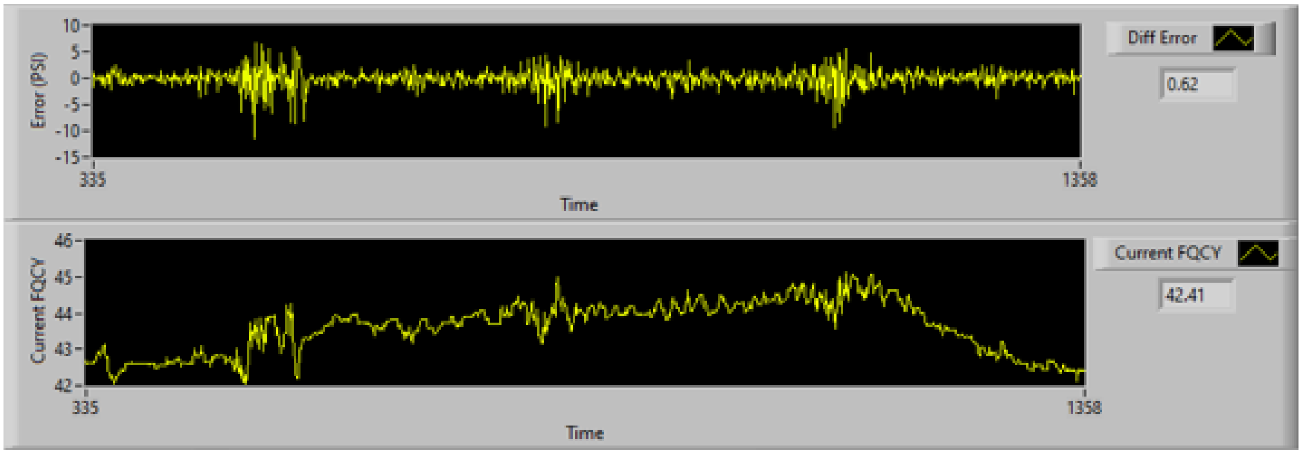


Figure 62: Frequency response to the error signal

The frequency response shows the same periodic instability. The larger frequency jumps suggest that the system is attempting to compensate.

13.2.2 Instability while controlling the supply pressure.

The PPI was discovered during the development of the differential pressure control software. To investigate the source of the PPI, we adjusted the software to regulate the supply pressure. The principle of operation remains the same: the supply pressure is averaged and compared to a target value, and the error signal drives the proportional frequency response.

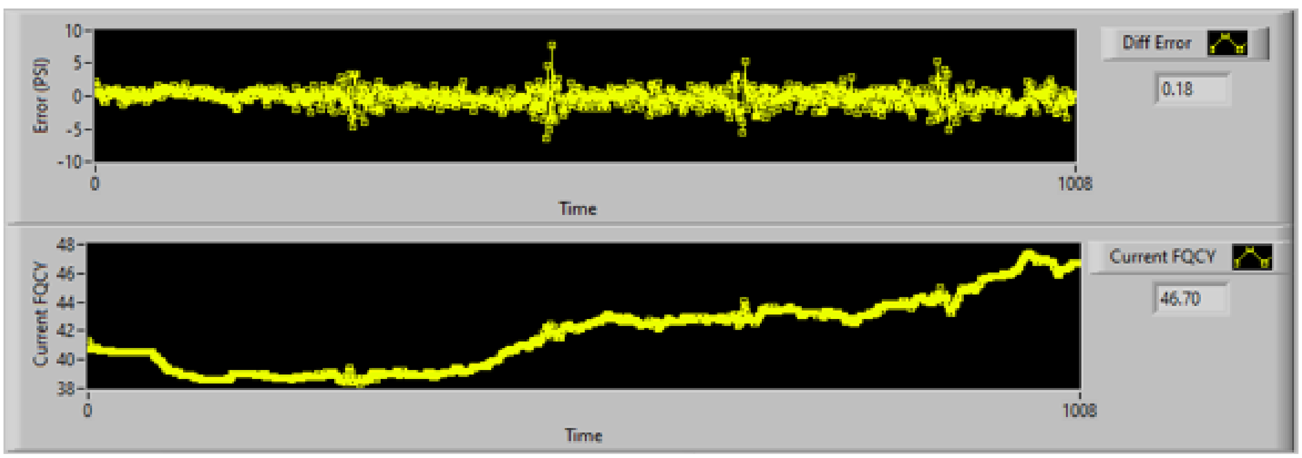


Figure 63: PPI present while controlling the supply pressure

The same PPI was recorded while controlling the supply pressure.

13.2.3 Instability while replacing the coldhead with an adjustable orifice

To determine whether the compressor or the coldhead produces the PPI, the helium flow was redirected through the needle valve on the cryo test cart. The valve was adjusted to achieve a flow comparable to the coldhead's.

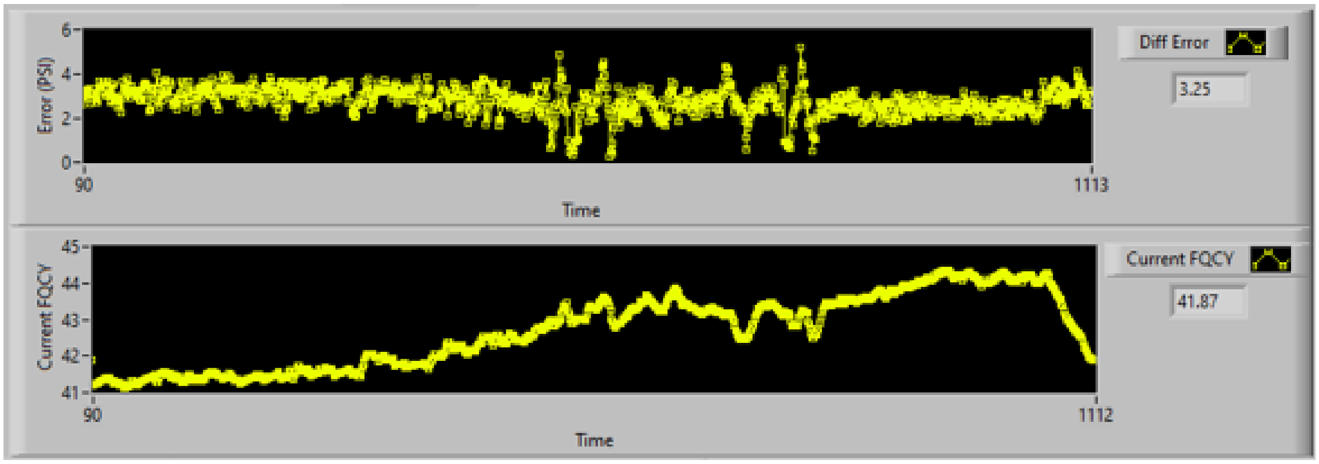


Figure 64: Instability generated by the compressor

While the test did not run long enough to see the periodicity, the measurement showed the instability, indicating that the compressor is the source.

13.2.4 Microphone experiment

A microphone was installed inside the outdoor compressor unit to measure the noise level and identify the source of the PPI. The idea was that rapid changes in pressure might correspond to sudden shifts in compressor behavior that variations in noise levels could detect.

13.2.4.1 Test equipment

The test equipment was comprised of:

Picture 39: Audix TM1 Omnidirectional Condenser Measurement Microphone

Picture 40: Focusrite Scarlett Solo 4th Gen USB Audio Interface

13.2.4.2 Installation

The microphone was placed on the bulk oil separator inside the outdoor compressor enclosure. The cable was routed inside the container and connected to the Focusrite audio interface. The output of the audio interface was plugged into the laptop using a USB cable. The noise levels were monitored and recorded using the Smaart SPL software package.

Picture 41: Installation of the condenser Microphone Inside the Sumitomo Outdoor Enclosure

13.2.4.3 Results of the Audio Monitoring

The Smaart SPL software was used to record various acoustic parameters. Sound Pressure Level (SPL) measures the intensity of air pressure variations caused by a sound wave. As sound waves travel, they push air into rapidly shifting states of high and low pressure (compression and rarefaction), and SPL assesses the strength of those changes. SPL measures pressure deviations, not ambient air pressure itself.

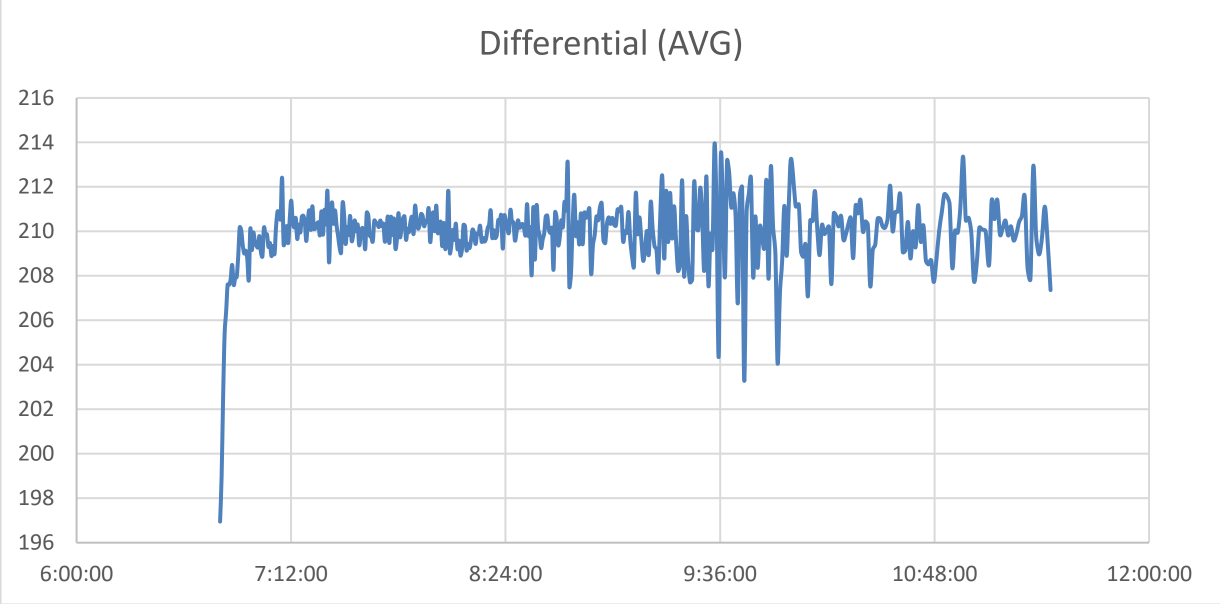


Figure 65: Compressor Differential Pressure

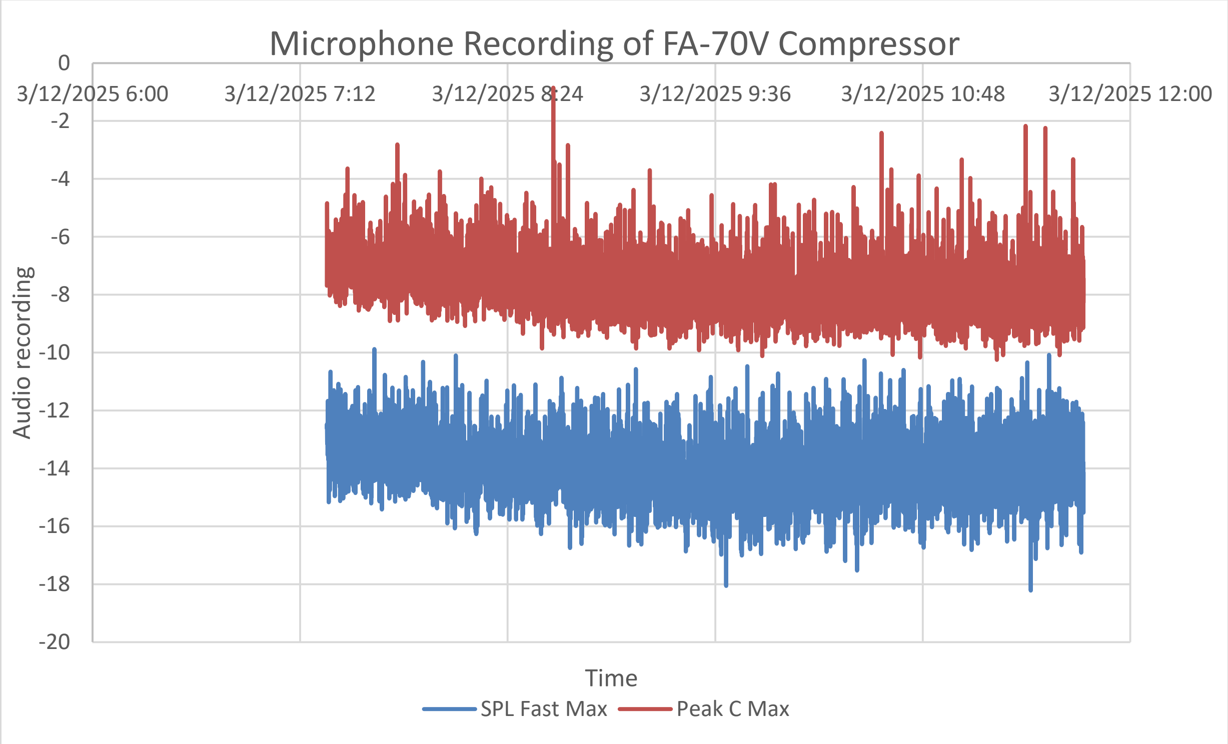


Figure 66: Audio Recording of the Compressor

The differential pressure recording indicated increased instability around 9:36 am, whereas the audio recording did not reflect this change. The audio test did not reveal the expected noise increase. The positioning of the microphone might not have been optimal, but it was the best-effort solution due to time constraints. Further testing will be done in Socorro with the FA-40 compressor.

14 Resume

The scope of this ALMA study included:

1. To design and build a prototype Sumitomo FA-70H compressor capable of operating at variable frequencies.
2. To assemble a complete set of test instrumentation to measure the performance of this new compressor.
3. To develop the software to control the test equipment and monitor the system key parameters.
4. To measure the performance of the new compressor in the laboratory environment.
5. To ship everything to Chile.
6. To install the compressor and test equipment inside the ESO container.
7. To repeat the laboratory tests at the OSF and cool a spare ALMA frontend.
8. To transport the container to the AOS
9. To run a long-term evaluation to test the reliability of the system in environmental conditions comparable to an ALMA antenna
10. To write a final report

What has been achieved:

1. In collaboration with Sumitomo Allentown, an FA-70H compressor was modified to accommodate a Nidec inverter. The inverter replaced the adsorber within the indoor compressor unit, and a new enclosure was built to house it.
2. A new cryo-test-cart was built to measure 3-stage coldhead temperatures, compressor pressures, and flow. A Sumitomo test cryostat and a 3-stage coldhead were purchased to complete the test instrumentation.
3. LabVIEW software was developed to operate the cryo-test cart and run different tests, including cooldown and load map.
4. The compressor was extensively tested in the laboratory to develop the software and measure key performance.
5. The equipment was boxed, and crated, and shipped to Chile.
6. The compressor was installed on the roof of the ESO container and protected by ALMA enclosures (separate enclosures for the indoor and outdoor units). The test instrumentation, including the cryo-test cart and the Sumitomo test cryostat, was placed inside the container.
7. After the container installation was completed, the equipment was tested at the OSF to confirm that no damage occurred during shipping. The spare ALMA frontend #05 was also installed inside the container. This receiver was cooled at various compressor frequencies to evaluate the impact on the stage temperatures.
8. The container was loaded on a flat-bed truck and transported to the AOS. It was set close to the AOS building to facilitate power and network connections.

9. Over the study's duration, the system accumulated more than 16000 hours of operation, most of them at the AOS. The only problem encountered on the compressor side was the failure of the SI Ethernet module of the NIDEC inverter.

15 Conclusion

The ALMA cryogenic subsystem operates continuously, consuming an average of 7 kW of power and requiring costly coldhead periodic maintenance. Any possibility of offsetting maintenance costs with a reduction in energy consumption is interesting to understand and should be pursued.
With that objective in mind, a novel Sumitomo compressor was developed and built to operate at variable frequency, following the principle that the lower the frequency, the lower the power consumption.
Operation in Chile already benefits from the reduced line frequency of 50 Hz. While this positively impacts the compressor's power consumption, it is less beneficial for the cooling power due to the reduction of the coldhead's cooling cycle from 72rpm to 60rpm. The AC voltage amplitude also influences the compressor's operating frequency range. At the AOS, the combination of both limited its maximum running frequency to 52 Hz, which was a disappointing result. However, the goal was to reduce the frequency, not to increase it.
The lab tests in Socorro and several ALMA FE #05 cooldowns indicated that the compressor could be operated at a reduced frequency of 40Hz with negligible impact on the coldhead stage temperatures. Reducing the compressor frequency to 40Hz will save 1200W, and extend the interval between adsorber maintenance by 6000 hours (8 months).
The standard FA-70H compressor costs $19,470, while the variable speed version, FA-70V, is estimated to cost $25,000. The cost difference is $5,530, but the FA-70V compressor consumes 1,200W less. Assuming 8,500 hours of operation per year at an energy cost of $0.135 per kWh, this compressor will save $1,377 per year in electricity, allowing it to recover the initial cost difference in just over four years.

The test instrumentation built to evaluate the prototype provides helium flow in addition to the cold head stage temperatures and compressor pressures, a key parameter not yet available to the ALMA cryogenic team. Now that the compressor study is ending, this equipment will stay in Chile to help the ALMA's cryogenic team test new compressors and troubleshoot existing ones. The test cryostat and the load map software will allow testing a coldhead before and after repair.
The use of compressor frequency to regulate pressure variations caused by daily temperature changes is being investigated for ngVLA. The effort to control the differential pressure has had limited success; our next test will focus on the return pressure, which seems to control the flow.

16 Appendix

16.1 *Temperature Sensor Calibration Files for LakeShore 224 Temperature Monitor*

16.1.1 R800 Platinum/Cobalt resistance thermometer

File format to program the LakeShore 224 temperature monitor with the curve handler software.

```
Sensor Model:
R800
Serial Number:  Standard
```

Data Format: 3 (Ohms vs. Kelvin)
SetPoint Limit: 340.0 (Kelvin)
Temperature coefficient: 2 (Positive)
Number of Breakpoints: 197

No.	Units	Temperature (K)	No.	Units	Temperature (K)	No.	Units	Temperature (K)	No.	Units	Temperature (K)
1	7.79200	4.000	31	12.1920	34.000	61	23.8310	68.000	91	47.1910	128.000
2	7.93700	5.000	32	12.4500	35.000	62	24.6110	70.000	92	47.9510	130.000
3	8.06600	6.000	33	12.7160	36.000	63	25.3930	72.000	93	48.7110	132.000
4	8.18200	7.000	34	12.9890	37.000	64	26.1770	74.000	94	49.4690	134.000
5	8.28900	8.000	35	13.2700	38.000	65	26.9620	76.000	95	50.2250	136.000
6	8.38800	9.000	36	13.5580	39.000	66	27.7480	78.000	96	50.9800	138.000
7	8.48300	10.000	37	13.8530	40.000	67	28.5340	80.000	97	51.7340	140.000
8	8.57400	11.000	38	14.1540	41.000	68	29.3240	82.000	98	52.4860	142.000
9	8.66400	12.000	39	14.4610	42.000	69	30.1140	84.000	99	53.2370	144.000
10	8.75500	13.000	40	14.7740	43.000	70	30.9020	86.000	100	53.9870	146.000
11	8.84800	14.000	41	15.0930	44.000	71	31.6900	88.000	101	54.7350	148.000
12	8.94500	15.000	42	15.4170	45.000	72	32.4770	90.000	102	55.4820	150.000
13	9.04600	16.000	43	15.7460	46.000	73	33.2620	92.000	103	56.2290	152.000
14	9.15000	17.000	44	16.0800	47.000	74	34.0470	94.000	104	56.9750	154.000
15	9.26200	18.000	45	16.4190	48.000	75	34.8300	96.000	105	57.7200	156.000
16	9.38000	19.000	46	16.7620	49.000	76	35.6130	98.000	106	58.4640	158.000
17	9.50600	20.000	47	17.1090	50.000	77	36.3940	100.000	107	59.2070	160.000
18	9.64000	21.000	48	17.4600	51.000	78	37.1740	102.000	108	59.9490	162.000
19	9.78300	22.000	49	17.8140	52.000	79	37.9520	104.000	109	60.6900	164.000
20	9.93400	23.000	50	18.1720	53.000	80	38.7300	106.000	110	61.4290	166.000
21	10.0940	24.000	51	18.5340	54.000	81	39.5060	108.000	111	62.1680	168.000
22	10.2630	25.000	52	18.8980	55.000	82	40.2800	110.000	112	62.9060	170.000
23	10.4420	26.000	53	19.2650	56.000	83	41.0540	112.000	113	63.6440	172.000
24	10.6290	27.000	54	19.6350	57.000	84	41.8260	114.000	114	64.3800	174.000
25	10.8260	28.000	55	20.0070	58.000	85	42.5970	116.000	115	65.1150	176.000
26	11.0310	29.000	56	20.3820	59.000	86	43.3660	118.000	116	65.8500	178.000
27	11.2460	30.000	57	20.7590	60.000	87	44.1340	120.000	117	66.5830	180.000
28	11.4690	31.000	58	21.5180	62.000	88	44.9000	122.000	118	67.3160	182.000
29	11.7010	32.000	59	22.2840	64.000	89	45.6650	124.000	119	68.0480	184.000
30	11.9420	33.000	60	23.0550	66.000	90	46.4290	126.000	120	68.7790	186.000

No.	Units	Temperature (K)	No.	Units	Temperature (K)	No.	Units	Temperature (K)
121	69.5090	188.000	151	91.1000	248.000	181	112.209	308.000
122	70.2390	190.000	152	91.8110	250.000	182	112.905	310.000
123	70.9670	192.000	153	92.5210	252.000	183	113.601	312.000

124	71.6950	194.000	154	93.2300	254.000	184	114.296	314.000
125	72.4220	196.000	155	93.9390	256.000	185	114.991	316.000
126	73.1490	198.000	156	94.6480	258.000	186	115.685	318.000
127	73.8750	200.000	157	95.3560	260.000	187	116.379	320.000
128	74.6000	202.000	158	96.0640	262.000	188	117.073	322.000
129	75.3240	204.000	159	96.7710	264.000	189	117.766	324.000
130	76.0480	206.000	160	97.4780	266.000	190	118.458	326.000
131	76.7700	208.000	161	98.1840	268.000	191	119.150	328.000
132	77.4930	210.000	162	98.8890	270.000	192	119.841	330.000
133	78.2140	212.000	163	99.5950	272.000	193	120.532	332.000
134	78.9350	214.000	164	100.299	274.000	194	121.222	334.000
135	79.6560	216.000	165	101.004	276.000	195	121.912	336.000
136	80.3750	218.000	166	101.708	278.000	196	122.601	338.000
137	81.0940	220.000	167	102.411	280.000	197	123.289	340.000
138	81.8130	222.000	168	103.114	282.000			
139	82.5300	224.000	169	103.816	284.000			
140	83.2480	226.000	170	104.518	286.000			
141	83.9640	228.000	171	105.220	288.000			
142	84.6800	230.000	172	105.921	290.000			
143	85.3960	232.000	173	106.621	292.000			
144	86.1110	234.000	174	107.321	294.000			
145	86.8250	236.000	175	108.021	296.000			
146	87.5390	238.000	176	108.720	298.000			
147	88.2520	240.000	177	109.419	300.000			
148	88.9650	242.000	178	110.117	302.000			
149	89.6770	244.000	179	110.815	304.000			
150	90.3890	246.000	180	111.512	306.000			

16.1.2 RuO-R0705

Sensor Model: RuO RO705
Serial Number: RuO RO705
Data Format: 4 (Log Ohms vs. Kelvin)
SetPoint Limit: 350.0 (Kelvin)
Temperature coefficient: 1 (Negative)
Number of Breakpoints: 200

No.	Units	Temperature (K)	No.	Units	Temperature (K)	No.	Units	Temperature (K)	No.	Units	Temperature (K)
1	3.00260	350.000	31	3.05077	16.500	61	3.14510	4.210	91	3.15299	3.910
2	3.00270	300.000	32	3.05200	16.000	62	3.14535	4.200	92	3.15327	3.900
3	3.00325	273.000	33	3.05327	15.500	63	3.14560	4.190	93	3.15354	3.890
4	3.00371	250.000	34	3.05465	15.000	64	3.14585	4.180	94	3.15381	3.880
5	3.00452	225.000	35	3.05610	14.500	65	3.14613	4.170	95	3.15409	3.870
6	3.00571	200.000	36	3.05767	14.000	66	3.14638	4.160	96	3.15439	3.860
7	3.00721	175.000	37	3.05934	13.500	67	3.14662	4.150	97	3.15467	3.850
8	3.00912	150.000	38	3.06111	13.000	68	3.14687	4.140	98	3.15494	3.840
9	3.01139	125.000	39	3.06300	12.500	69	3.14712	4.130	99	3.15524	3.830
10	3.01406	100.000	40	3.06506	12.000	70	3.14740	4.120	100	3.15552	3.820
11	3.01700	77.000	41	3.06726	11.500	71	3.14765	4.110	101	3.15579	3.810
12	3.01815	70.000	42	3.06967	11.000	72	3.14789	4.100	102	3.15609	3.800
13	3.02014	60.000	43	3.07225	10.500	73	3.14817	4.090	103	3.15637	3.790
14	3.02277	50.000	44	3.07507	10.000	74	3.14842	4.080	104	3.15667	3.780
15	3.02453	45.000	45	3.07809	9.500	75	3.14866	4.070	105	3.15697	3.770
16	3.02657	40.000	46	3.08146	9.000	76	3.14894	4.060	106	3.15725	3.760
17	3.02755	38.000	47	3.08515	8.500	77	3.14919	4.050	107	3.15755	3.750
18	3.02861	36.000	48	3.08923	8.000	78	3.14947	4.040	108	3.15785	3.740
19	3.02980	34.000	49	3.09892	7.000	79	3.14974	4.030	109	3.15815	3.730
20	3.03109	32.000	50	3.11123	6.000	80	3.14999	4.020	110	3.15845	3.720
21	3.03255	30.000	51	3.12788	5.000	81	3.15027	4.010	111	3.15872	3.710
22	3.03423	28.000	52	3.14292	4.300	82	3.15054	4.000	112	3.15903	3.700
23	3.03615	26.000	53	3.14314	4.290	83	3.15079	3.990	113	3.15933	3.690
24	3.03831	24.000	54	3.14339	4.280	84	3.15106	3.980	114	3.15963	3.680
25	3.04087	22.000	55	3.14364	4.270	85	3.15134	3.970	115	3.15993	3.670
26	3.04387	20.000	56	3.14364	4.260	86	3.15162	3.960	116	3.16026	3.660
27	3.04560	19.000	57	3.14414	4.250	87	3.15189	3.950	117	3.16056	3.650
28	3.04751	18.000	58	3.14439	4.240	88	3.15217	3.940	118	3.16086	3.640
29	3.04852	17.500	59	3.14461	4.230	89	3.15244	3.930	119	3.16116	3.630
30	3.04961	17.000	60	3.14485	4.220	90	3.15272	3.920	120	3.16149	3.620

No.	Units	Temperature (K)	No.	Units	Temperature (K)	No.	Units	Temperature (K)
121	3.16179	3.610	151	3.17173	3.310	181	3.19940	2.640
122	3.16209	3.600	152	3.17208	3.300	182	3.20036	2.620
123	3.16242	3.590	153	3.17243	3.290	183	3.20134	2.600
124	3.16271	3.580	154	3.17278	3.280	184	3.20235	2.580
125	3.16304	3.570	155	3.17313	3.270	185	3.20336	2.580
126	3.16337	3.560	156	3.17351	3.260	186	3.20436	2.540
127	3.16367	3.550	157	3.17386	3.250	187	3.20539	2.520
128	3.16400	3.540	158	3.17423	3.240	188	3.20645	2.500
129	3.16432	3.530	159	3.17458	3.230	189	3.20801	2.480
130	3.16465	3.520	160	3.17496	3.220	190	3.20962	2.440
131	3.16495	3.510	161	3.17531	3.210	191	3.21125	2.420
132	3.16527	3.500	162	3.17569	3.200	192	3.21293	2.380
133	3.16560	3.490	163	3.18344	3.000	193	3.21463	2.350
134	3.16593	3.480	164	3.18424	2.980	194	3.21635	2.320
135	3.16628	3.470	165	3.18506	2.960	195	3.21809	2.320
136	3.16661	3.460	166	3.18591	2.940	196	3.21990	2.260
137	3.16693	3.450	167	3.18673	2.920	197	3.22170	2.230
138	3.16726	3.440	168	3.18758	2.900	198	3.22355	2.200
139	3.16758	3.430	169	3.18845	2.880	199	3.23686	2.000
140	3.16794	3.420	170	3.18929	2.860	200	3.25898	1.500
141	3.16826	3.410	171	3.19016	2.840			
142	3.16862	3.400	172	3.19106	2.820			
143	3.16894	3.390	173	3.19195	2.800			
144	3.16929	3.380	174	3.19285	2.780			
145	3.16965	3.370	175	3.19374	2.760			
146	3.16997	3.360	176	3.19465	2.740			
147	3.17032	3.350	177	3.19560	2.720			
148	3.17067	3.340	178	3.19654	2.700			
149	3.17102	3.330	179	3.19747	2.680			
150	3.17138	3.320	180	3.19844	2.660			

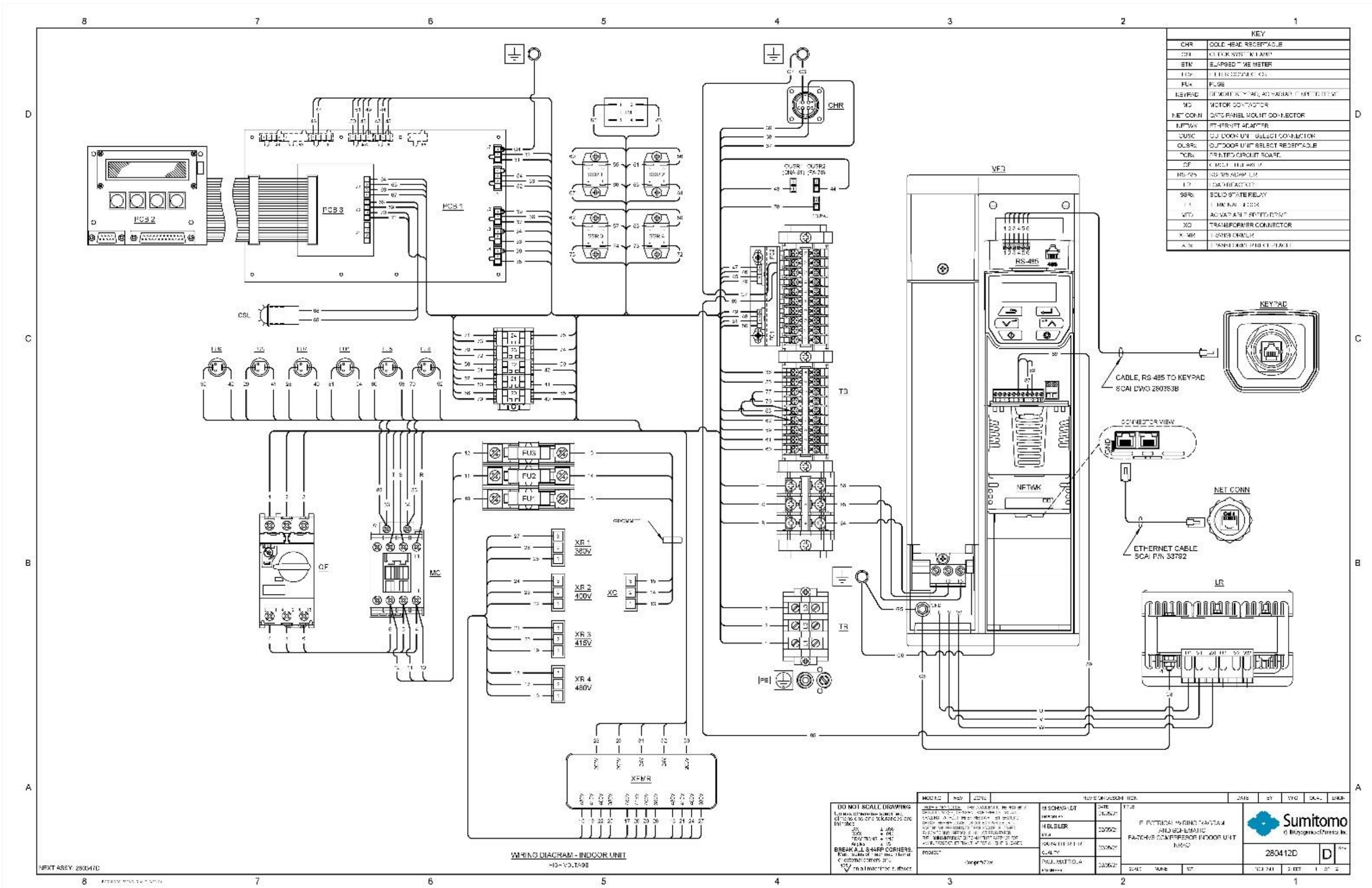
16.1.3 DT-500

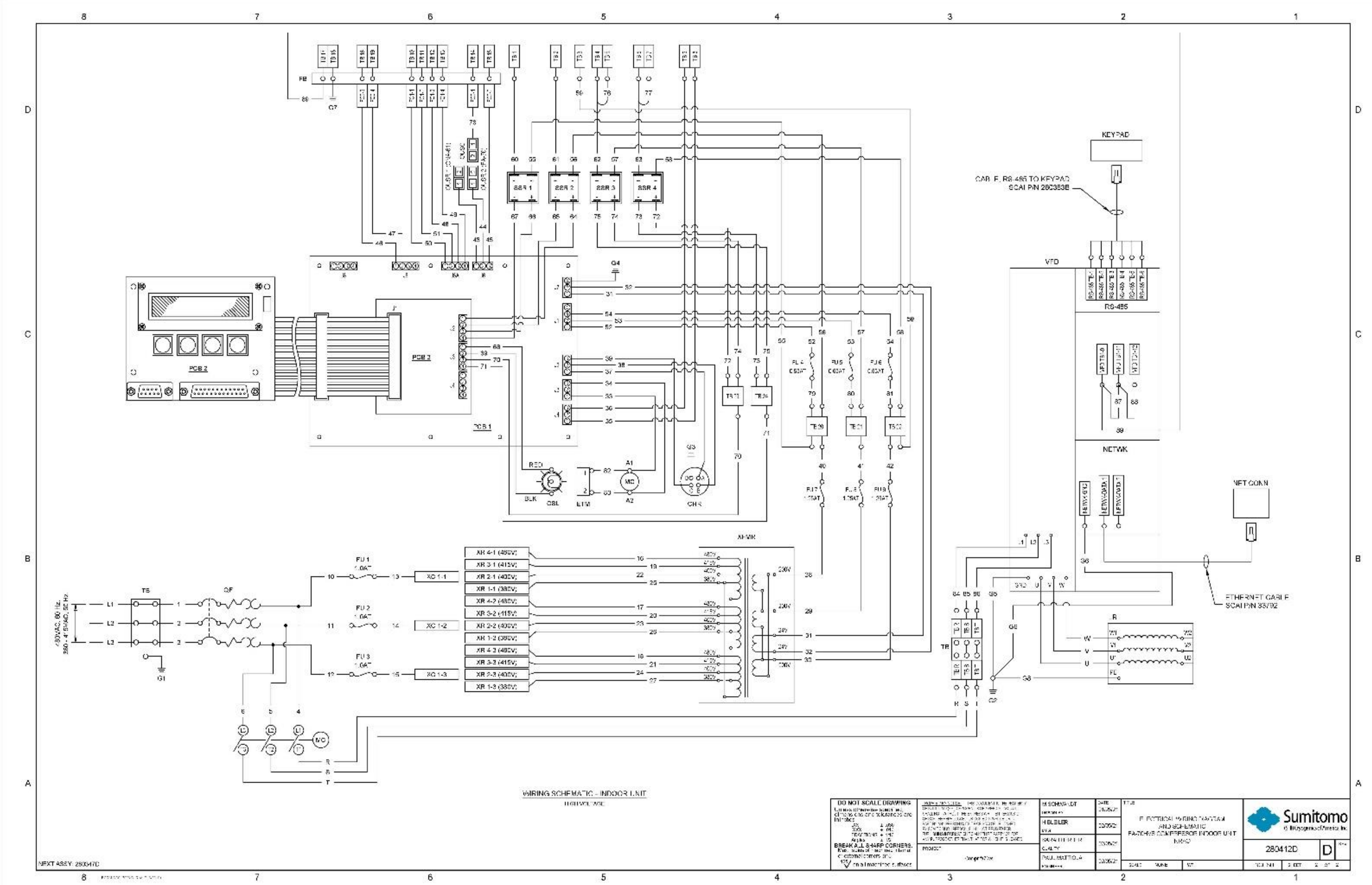
Sensor Model: DT-500-DRC
Serial Number: DT-500-DRC
Data Format: 2 (Volts vs. Kelvin)
SetPoint Limit: 380.0 (Kelvin)
Temperature coefficient: 1 (Negative)
Number of Breakpoints:
124

No.	Units	Temperature (K)	No.	Units	Temperature (K)	No.	Units	Temperature (K)	No.	Units	Temperature (K)
1	1.35970E-01	380.000	32	5.72680E-01	225.000	63	1.00240	70.000	94	2.12460	10.000
2	1.48460E-01	375.000	33	5.86720E-01	220.000	64	1.01510	65.000	95	2.15240	9.500
3	1.61920E-01	370.000	34	6.00840E-01	215.000	65	1.02760	60.000	96	2.18180	9.000
4	1.75960E-01	365.000	35	6.15040E-01	210.000	66	1.03970	55.000	97	2.21270	8.500
5	1.90370E-01	360.000	36	6.29280E-01	205.000	67	1.05150	50.000	98	2.24520	8.000
6	2.05000E-01	355.000	37	6.43530E-01	200.000	68	1.06320	45.000	99	2.27900	7.500
7	2.19740E-01	350.000	38	6.57770E-01	195.000	69	1.07520	40.000	100	2.31420	7.000
8	2.34580E-01	345.000	39	6.72010E-01	190.000	70	1.08040	38.000	101	2.35050	6.500
9	2.49430E-01	340.000	40	6.86220E-01	185.000	71	1.08590	36.000	102	2.38770	6.000
10	2.64320E-01	335.000	41	7.00410E-01	180.000	72	1.09230	34.000	103	2.42540	5.500
11	2.79190E-01	330.000	42	7.14570E-01	175.000	73	1.10030	32.000	104	2.46310	5.000
12	2.94070E-01	325.000	43	7.28680E-01	170.000	74	1.11150	30.000	105	2.47800	4.800
13	3.08930E-01	320.000	44	7.42760E-01	165.000	75	1.11920	29.000	106	2.49280	4.600
14	3.23750E-01	315.000	45	7.56800E-01	160.000	76	1.12930	28.000	107	2.50750	4.400
15	3.38430E-01	310.000	46	7.70810E-01	155.000	77	1.14340	27.000	108	2.52200	4.200
16	3.52940E-01	305.000	47	7.84780E-01	150.000	78	1.16450	26.000	109	2.53610	4.000
17	3.67290E-01	300.000	48	7.98730E-01	145.000	79	1.19550	25.000	110	2.54990	3.800
18	3.81550E-01	295.000	49	8.12650E-01	140.000	80	1.23780	24.000	111	2.56330	3.600
19	3.95740E-01	290.000	50	8.26520E-01	135.000	81	1.28950	23.000	112	2.57620	3.400
20	4.09880E-01	285.000	51	8.40350E-01	130.000	82	1.35750	22.000	113	2.58860	3.200
21	4.23880E-01	280.000	52	8.54120E-01	125.000	83	1.43890	21.000	114	2.60050	3.000
22	4.37730E-01	275.000	53	8.67880E-01	120.000	84	1.51590	20.000	115	2.61170	2.800
23	4.51370E-01	270.000	54	8.81560E-01	115.000	85	1.59440	19.000	116	2.62230	2.600
24	4.64830E-01	265.000	55	8.95200E-01	110.000	86	1.66510	18.000	117	2.63210	2.400
25	4.78180E-01	260.000	56	9.08810E-01	105.000	87	1.73250	17.000	118	2.64100	2.200
26	4.91510E-01	255.000	57	9.22380E-01	100.000	88	1.79420	16.000	119	2.64910	2.000
27	5.04790E-01	250.000	58	9.35910E-01	95.000	89	1.85610	15.000	120	2.65280	1.900
28	5.18100E-01	245.000	59	9.49390E-01	90.000	90	1.91860	14.000	121	2.65620	1.800
29	5.31520E-01	240.000	60	9.62770E-01	85.000	91	1.97300	13.000	122	2.65930	1.700
30	5.45080E-01	235.000	61	9.76100E-01	80.000	92	2.02360	12.000	123	2.66220	1.600
31	5.58800E-01	230.000	62	9.89330E-01	75.000	93	2.07310	11.000	124	2.55470	1.500

16.2 *Sumitomo Variable Speed FA-70 Compressor Wiring Diagrams*

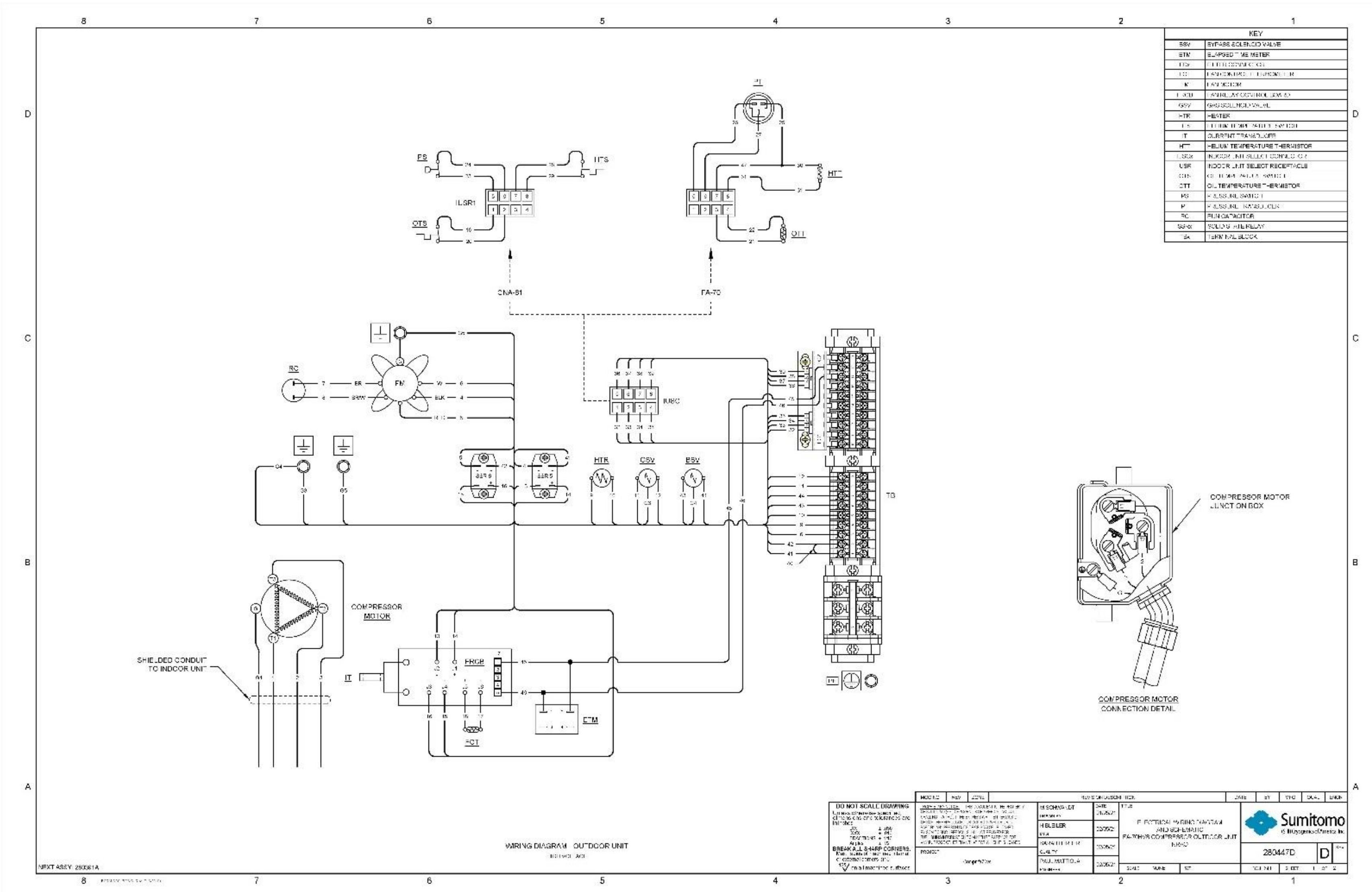
16.2.1 Indoor Compressor Unit (ICU)

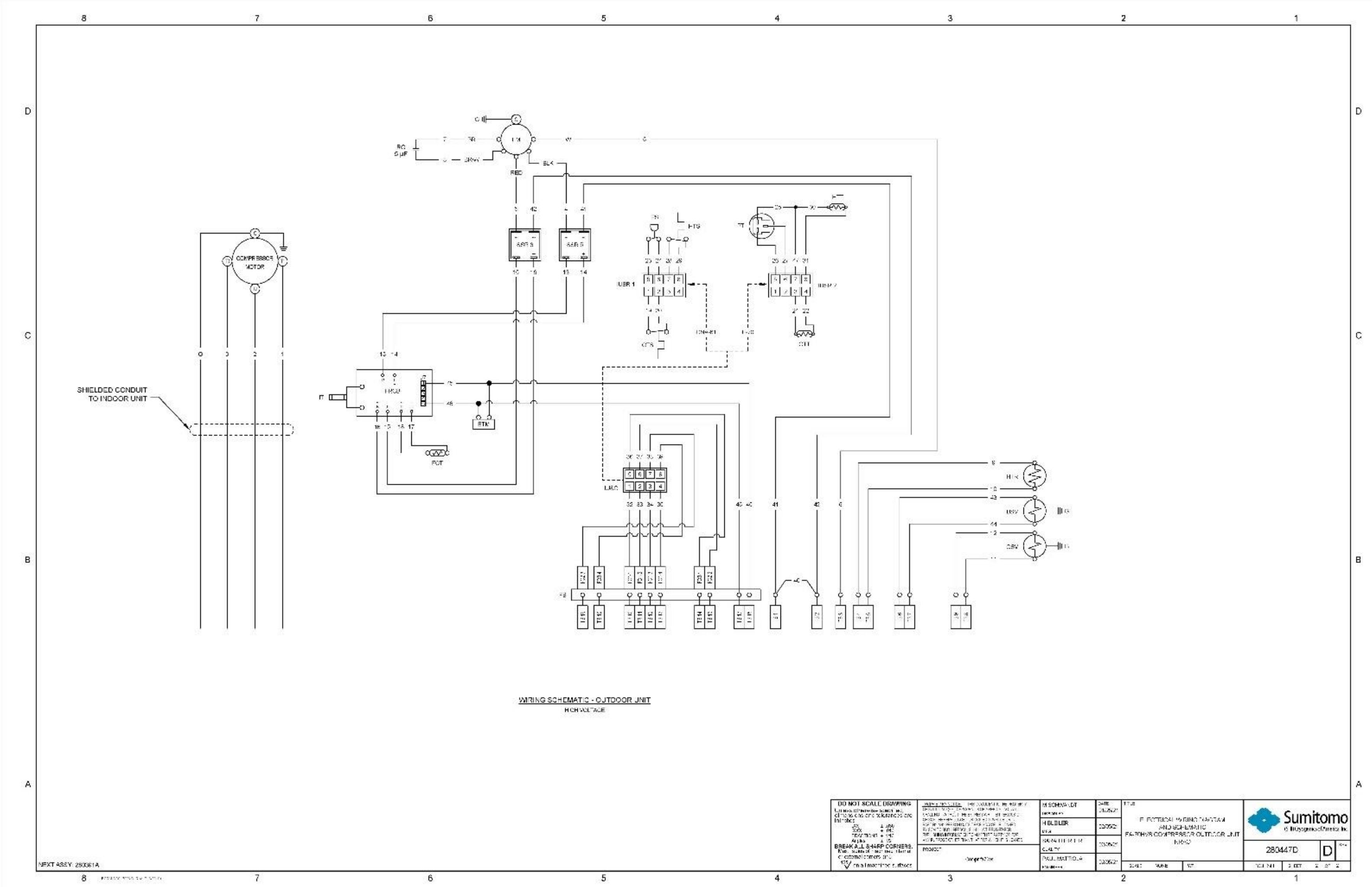




WIRING SCHEMATIC - INDOOR UNIT
KEYPAD
CABLE, RS 485 TO KEYPAD SCAI P/N 280353B
VFD
RS-485
NETWK
NET CONN
ETHERNET CABLE SCAI P/N 33702
PCB 2
PCB 1
SSR 1
SSR 2
SSR 3
SSR 4
XFMR
DO NOT SCALE DRAWING
BREAK ALL SHARP CORNERS.
M SCHWANDT
H BUBLER
PAUL MATTIOLA
ELECTRICAL WIRING DIAGRAM AND SCHEMATIC
FA-70HVS COMPRESSOR INDOOR UNIT
NRAO
Sumitomo
280412D
D
NEXT ASSY: 280347C

16.2.2 Outdoor Compressor Unit (OCU)





COMPRESSOR MOTOR
SHIELDED CONDUIT TO INDOOR UNIT
WIRING SCHEMATIC - OUTDOOR UNIT
HIGH VOLTAGE
DO NOT SCALE DRAWING
BREAK ALL SHARP CORNERS.
Sumitomo
280447D
D
NEXT ASSY: 280061A