HELIUM MASS FLOW SYSTEM INTEGRATED INTO EPICS FOR ONLINE SRF CAVITY Q_0 MEASUREMENTS*

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Abstract

The SBIR funded Helium Mass Flow Monitor System, developed by Jefferson Lab and Hyperboloid LLC, is designed to measure the health of cavities in a Cryomodule in real-time. It addresses the problem of cavities with low Q0, which generate excess heat and evaporation from the 2 K super-fluid helium bath used to cool the cavities. The system utilizes a unique meter that is based on a superconducting component. This device enables high-resolution measurements of the power dissipated in the cryomodule while the accelerator is operating. It can also measure individual Cavity Q0s when the beam is turned off. The Linux-based control system is an integral part of this device, providing the necessary control and data processing capabilities. The initial implementation of the Helium Mass Flow Monitor System at Jefferson Lab was done using LabView, a couple of current sources & a nanovoltmeter. The device is a superconducting element tightly coupled to a heater installed in the helium return transfer line. The amount of power dissipated in the cryomodule is directly proportionate to the amount of heat required to quench the superconducting element. Once the device was proven to work at 2K the controls transitioned from LabView to a hand wired PCB & Raspberry Pi & finally to a PCB interface to a LabJack T7. This is interfaced to the open-source Experimental Physics and Industrial Control System (EPICS) control system. The EE support group preferred to support a LabJack T7 over the Raspberry Pi. 12 chassis were built and the system is being deployed as the cryogenic U-Tubes become available.

INTRODUCTION

The 2 K Refrigerator used to supply the cold helium to the CEBAF Superconducting Radio Frequency (SRF) Accelerator needs a STEADY Heat Load. Sudden variations "trip" the refrigerator causing hours long "Beam-off" times. The static heat load is the ~20-W heat leak into each of the 52 Cryomodules with 8 SRF Cavities each. More important is the 200 to 300-Watt dynamic heat load from each cryomodule at full gradient in the cavities. The sources of the variable heat are contamination on the inner surface of the cavities, field emission and others. They are lumped into the term Q0, which varies with the cavity's accelerating gradient. When changing the accelerating gradients or turning on or off RF in a Cryomodule, an automatic control system in EPICS changes power in resistive heaters built into all the cryomodules so the Cryogenic Load remains steady. But that automatic system needs accurate Q0s for each cavity at operating gradients to work well. Presently there is a ~500 W discrepancy when all the Cryomodules are turned off and the resistive heaters are set to the compensating values. This is near the difference that could cause a Central Helium Liquefier (CHL) Trip.

The Q0s in the automatic system's internal table are obtained by a combination of the original Q0s determined for each cavity in a new cryomodule by tedious Bomb Calorimetry methods or a less tedious "Heat Monster" method using the position settings of the not-well-calibrated Joule Thompson Valves that regulate the level of the 2 K helium bath in each cryomodule to determine heat dissipation. There was no good way to non-invasively determine the heat load of a CM. For over 30 years, Operators wanted an accurate gas flow meter placed in the helium return pipe of Cryomodules. The 2 to 3 K and 1/30 atm conditions for such a meter are an exceptional challenge. If successful, the flow signal could be calibrated as a Watt Meter signal. Thermodynamics reveals that one gram per second of helium evaporation from the 2 K bath of superfluid helium that cools the cavities is caused by 23 Watts of dissipation. Such a flow meter does not require accelerator access & can be used parasitically. Placed in the separable return pipe called a U-Tube, the meter could run while beam is on, showing total cryomodule dissipation – no tedious procedure. To assess individual cavity Q0s at various gradients, the beam has to be off and a simple closure and reopening of the JT valve would be required.

HISTORY

A hot wire meter was attempted at Jlab/SRF in 2004 [1] getting no good results. Several other failed attempts were made using commercial flow meters including hot wire and Coriolis designs. A paper by Japanese researchers [2] using a tin-plated quartz fiber and a superposed resistive heater coating of gold, utilizing the superconducting to non-superconducting transition to get a strong signal was successful in a laboratory setting.

A JLab attempt that improved the robustness of the instrument head was unsuccessful when placed in the return u-tube from a cryomodule because of signal did not rise above system noise. The sensor in Fig. 1 was installed in the LCLS-II test stand return transfer line. This superconductor was only a centimeter long and the heater was insufficiently coupled to the niobium wire. If it did quench there was insufficient voltage drop to measure.

The Solution

An SBIR topic to make "devices and methods for accurate in-situ measurement of SRF cavity Q0s" was suggested by JLab to DOE and posted. A grant was awarded by the Office of Nuclear Physics, DOE Office of Science, to Hyperboloid LLC in February of 2022. The robust superconducting design made by Hyperboloid was immediately successful in Vertical Dewar and then Cryomodule Test Facility Tests – resolving at the single digit Watt level using the Laboratory Grade Instruments. The readings appeared to be insensitive to the actual temperature of the gas as it flows through the instrument head to first order. A temperature diode is included in the instrument head to explore this variable in future tests.

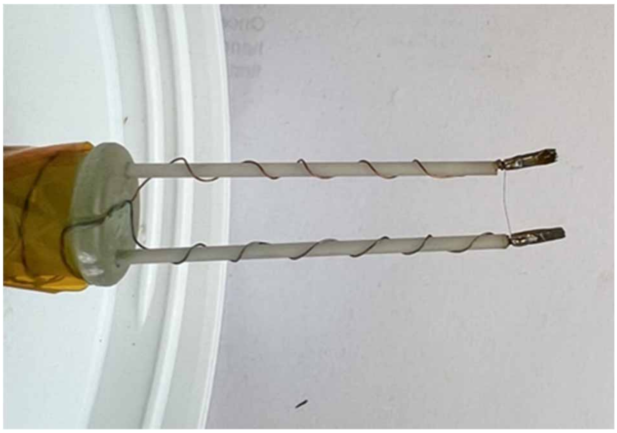

Figure 1: Hot Wire Anemometer attempt for testing of LCLS-II cavities – Too little signal!

How It Works

Cooling from helium flow is bucked against the heat from a rising sawtooth current in a heater. Sandwiched between them is a superconductor (SC) that yields a large resistance signal when heat raises its temperature high enough to go "normal" conducting (Tc ~ 9 K). The heater current value when the SC goes normal is calibrated directly in Watts using the resistance heaters in the cryomodules to create a calibration curve.

An expired patent US 5249866 A, using a similar superconducting technique envisions an analogue circuit keeping a heater current at the exact superconducting/ non-superconducting state. This method was initially rejected for this meter because of the method's inherent instabilities, but may once again be revisited. The digital environment allows storage of the signals and real time digital manipulation. We find the rolling average of the max heater current value over 5 saw-tooths for both calibration Curve generation and flow meter reading provides a consistent signal at the single digit Watt resolution. The hardware would remain a Laboratory curiosity without the subsequent developments in the electronics chassis designed by JLab and software integration into the EPICS control system by the accelerator software group. Chassis inexpensive current supplies, now available, provide the current for the Heater and the low current for the superconductor. (The appropriate choices of the resistive elements in the Instrument Head allow this simplicity.) High accuracy OP-Amps with exceptional common mode noise rejection detect the voltages of both the heater and the quench voltage of the superconductor as well as control the current to both.

HARDWARE

Initial Testing in the Vertical Test Area (VTA)

The VTA is a set of large vertical Dewars that are used primarily to qualify cavities before assembly into a cryomodule. The sensor was fitter to the bottom thermal shield on the Dewar insert of one of the smaller Dewars. The shield was fitted with a Kapton sealing ring (Fig. 2) to force the helium to flow past the installed sensor. This replicated the function of the return transfer line.

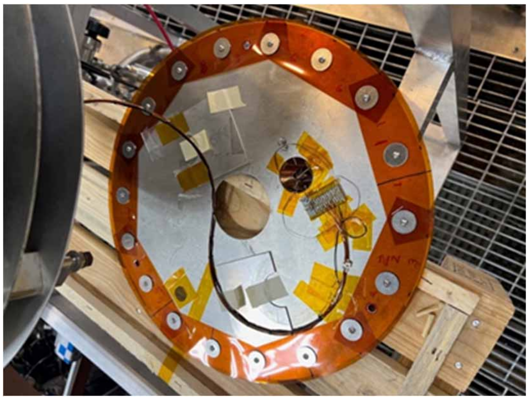

Figure 2: Kapton sealing ring forced boil-off helium to pass through the sensor head.

Figure 3: Dewar insert with helium sensor.

The vertical Dewar operation was ideally suited to the sensor development. In the morning the Dewar was filled (4.2K helium) and pumped down to 2K. In each Dewar there is a resistive heater, so careful measurements could be made over hours before the helium had all evaporated back into the closed loop system. We were using one of the two small Dewars so as we did not impact the cavity production. Figure 3 shows the first helium flow meter sensor fitted to the Dewar insert.

Figure 4: Final sensor configuration mounted on blade for installation into the return U-Tube.

Sensor Description & Installation

Each of 53 cryomodules in the CEBAF machine is connected to the CHL with four U-Tubes. These are vacuum insulated stainless steel pipes that supply 2 K & 40 K to each cryomodule. The sensor is installed in the 2K return U-Tube (Fig. 4). The modification required cutting holes in the stainless steel vacuum shell as well as the inner helium pipe. The sensor blade is attached to a 10-pin cryogenic rated vacuum feedthrough connector.

There are several steps required for such a modification. Once the drawings are complete, signed off, and all Operational Safety Procedures (OSPs) are in place the work can begin. Another complicating issue is that many of the U-Tube have become activated from the high radiation areas where they are used. The Radiation Safety group sets up a perimeter with yellow plastic tarps to catch the dust and metal fragments that are generated from the drilling and grinding. There are ~40 layers of super-insulation (silvered mylar) that must be carefully cut away from the vacuum shell to the 2˚K inner transfer line. (Fig. 5) When the spool piece nipple is welded to the 2˚K piping it is then cold shocked multiple times with liquid nitrogen then leak checked to confirm weld integrity. Once the final weld is made and leak checked the sensor assembly is installed and leak checked again. After all of this and documented inspections there is a final pressure test.

Figure 5: Sensor installed in the return U-Tube.

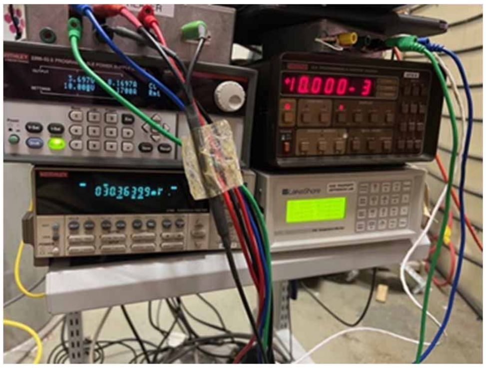

Figure 6: Instruments in VTA that were used for measuring RRR of niobium, controlled in LabView.

Initial Configuration

When the SBIR phase 1 was funded, we looked at options for build, buy, or steal. The experiment needed a sensitive voltmeter, a DC excitation source, and a heater power supply. Additionally, we needed to monitor the helium flow temperature passing the detector. In the Vertical Test Area (VTA) (Fig. 6) there was a set of hardware and software that was ideally suited for or helium power meter needs!

We used the Keithley model 224 Programmable Current Source as the superconductor excitation. It was found that 10 mA was sufficient excitation current to generate a clean voltage signal when the superconducting element quenched. The Keithley model 2182 Nanovolt Meter was used to monitor the superconductor quench voltage, and the Keithley model 2200-32-3 Programable Power Supply was used to supply the heater current to generate the quench. A Lake Shore model 218 Temperature Monitor tracked the sensor temperature to make it clear when the sensor should be superconducting.

The heater current ramp rate and sensor quench detection threshold are all programable. The initial procedure was to ramp up the heater current at 1milliamp/second until the sensor quenched, then the heater current was shut off. The quench detection voltage can be set from 10’s of millivolts to over 1 volt. It is interesting that the way the superconducting element and heater element are coupled together one can see the beginning of a quench all the way to a hard quench (Fig. 7). As we understood how the system performed, we instituted a ‘restart’ setting that enabled the

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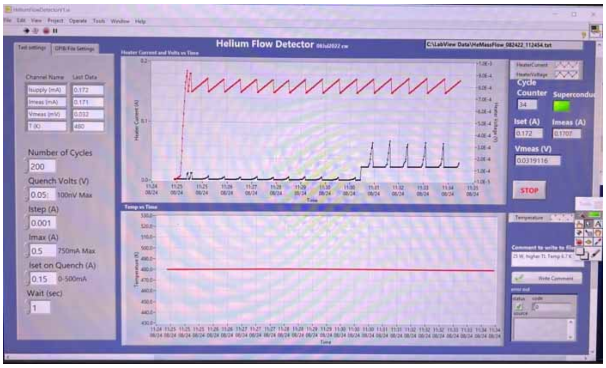
heater to dwell around the quench threshold & speed up the data taking.



C:\LabView Data\HeMassFlow_082422_112454.txt

Channel Name	Last Data
Isupply (mA)	0.172
Imeas (mA)	0.171
Vmeas (mV)	0.032
T (K)	480

Number of Cycles 200

Quench Volts (V) 0.05 100nV Max

Istep (A) 0.001

Imax (A) 0.5 750mA Max

Iset on Quench (A) 0.15 0-500mA

Wait (sec) 1

Cycle Counter 34

Iset (A) 0.172

Imeas (A) 0.1707

Vmeas (V) 0.0319116

Comment to write to file: 25 W, higher Tl, Temp 6.7 K

Figure 7: The black trace is the quench voltage showing start of quench threshold on the left and hard quench threshold on the right

Calibration

A CEBAF cryomodule has 8 sets of cavities, there are a variety of configurations over the years. The initial design was based on four cavity pairs installed in a cryomodule: two 5 cell cavities in a common helium vessel for an energy gain of 20 MV (C20) over the ~10-meter insertion length. The latest configuration is 8 – 7 cell cavities, each in their own helium vessel for an energy gain of 100 MV (C100)! Each cavity has an electric heater coupled to the helium bath; in the case of the C20s the heaters are in the helium bath, the C100s have the heater bolted to the outside of the stainless steel helium vessel, resulting in a slower time response.

The cryomodule heaters are critical to safe & reliable operation of the CHL. The 2K helium refrigerator has a limited dynamic range and cannot maintain sub-atmospheric operation with surges in the return helium flow due to drastic changes in the load. Hence when the RF is shut off in a cryomodule the heaters are turned on to keep the cryogenic load constant. These heaters are used to generate calibration curves of the helium flow sensors. Figure 8 shows a typical calibration curve for Low Power (Individual Cavity Q0 measurement) Mode.

Orphan Systems

The cryomodule heaters are an example of a system that crosses a few group boundaries; The heaters are installed in the cryomodules by the SRF group, the power supply that generates the heat is supplied by the RF/LLRF group and CHL/operations depend on the correct calibration of the static to dynamic heater setting. As a part of this exercise a four-wire measurement was made on all of the heaters to confirm the actual power being delivered to the respective helium bath. This is based on the Q0 of the individual cavities and the accelerating gradient that they operate at. The Flow Meter, operating as a Watt Meter ties these systems together.

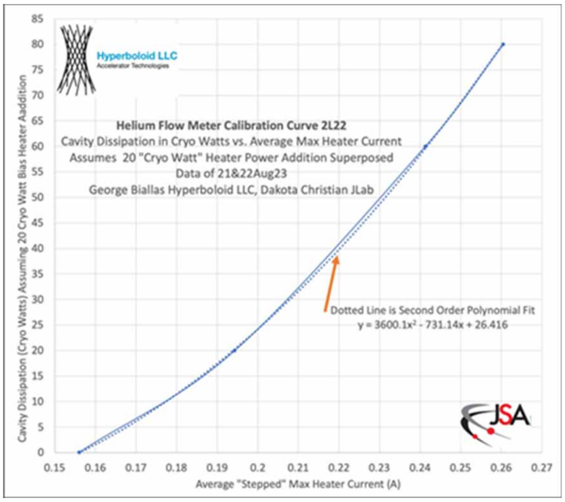


Figure 8: Helium flow meter calibration for cryomodule 2L22.

Migration from LabView to EPICS

As the project matured, a hand wired board was built to perform these basic functions; 1. A fixed 10mAmp excitation for the superconducting element, 2. Instrumentation amplifier with excellent common mode rejection ratio (90dB), 3. Programmable current source for the heater, & 4. Voltage monitor and 10 µAmp excitation for the temperature sensor. This was interfaced to a Raspberry Pi (rPi) Version 4B fitted with a Waveshare high precision AD/DA board.

- Standard Raspberry Pi 40PIN GPIO extension header, supports Raspberry Pi series boards, Jetson Nano
- Onboard ADS1256, 8ch 24bit high-precision ADC (4ch differential input), 30ksps sampling rate
- Onboard DAC8552, 2ch 16bit high-precision DAC
- Onboard input interface via pinheaders, for connecting analog signal
- The pinout is compatible with Waveshare sensor interface standard, easy to connect various analog sensor modules
- Onboard input/output interface via screw terminals, for connecting analog/digital signal
- Features AD/DA detect circuit, easy for signal demonstration

This configuration worked well but there was resistance from the controls group, networking/security folks and the EE support group that would have to maintain the final implementation. The decision was made to replace the rPi with a LabJack T7(labjack.com). The T7 has 14 instrumentation amplified 16-bit analogue inputs, 2 analogue outputs (12-bit), 23 digital I/O, and up to 10 digital counters/timers. The T7 can use USB or Ethernet, and numerous built-in firmware features. Additionally, T7 devices are capable of stand-alone operation by running Lua Scripts. The system is installed with the ethernet interface but de-bugged on the bench with a laptop & USB connection. Figure 9 shows three of the completed chassis ready for installation.

Figure 9: Commercially completed two channel helium flow meter chassis, 12 were fabricated

SOFTWARE

Initially LabView was used since the RRR measurement apparatus was 90% of what was required for the helium power meter application. This migrated to a rPi interface then settled on LabJack.

Operational Deployment

Each flow meter requires one analogue output (heater current) and three analogue inputs (sensor voltage, heater current readback, and diode temperature). Each chassis with integrated LabJack supports two flow meters. Chassis are installed in accelerator service buildings, and are connected via Ethernet. The controlling software runs on a soft Ioc hosted on accelerator operations networks. Communication between the soft IOC and LabJack devices is via Modbus TCP.

Application

The controlling software is a standard EPICS application, consisting of an EPICS database, SNL sequencer, and configuration/startup scripts. The application itself is simple, comprising only ~100 lines of code, excluding EPICS databases and scripts. When initiated, heater current is slowly ramped until a quench is detected. The current at quench is saved, the heater current reduced and then ramped again until a subsequent quench is detected. The previous n quench currents are averaged, and this mean used to calculate the dissipated power from the calibration curve.

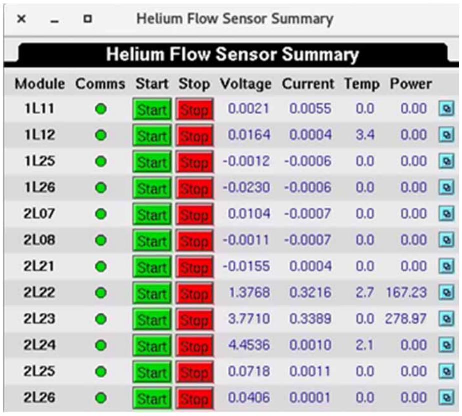
User-selectable parameters include start and restart current, current step, step (ramp) time, quench detect voltage, and quenches to average for power calculation. The current – power translation curve is implemented as a quadratic.

Configuration Management

The catalog of helium mass flow sensors and supporting LabJack modules is stored in the CEBAF Element Database (CED). Following a model used for many other accelerator systems at Jefferson Lab, this allows for scalable and convenient deployment of controls, screens & boot scripts, and automatic archiving of PVs. The present inventory is shown below in CED's web interface.

User Interface

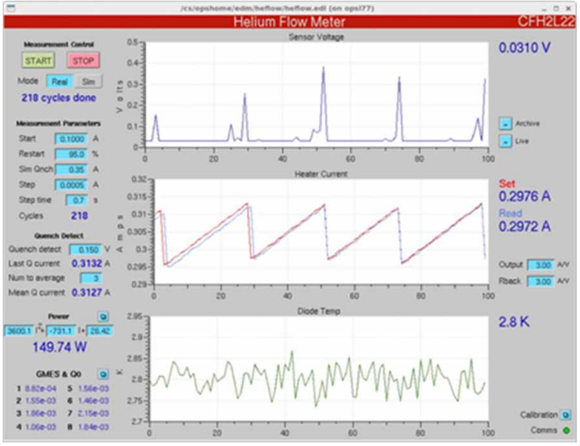
The GUI employed is the EDM display manager. A screen generator (OTF – On The Fly in Jlab parlance) program produces a summary screen from CED data on demand. This provides a quick-view summary of all flow meters, start/stop controls for each, and links to the primary control screens. (Fig. 10). The main control screen for an individual flow meter is shown in Fig. 11.



Helium Flow Sensor Summary

Module	Comms	Start	Stop	Voltage	Current	Temp	Power	
1L11	●	Start	Stop	0.0021	0.0055	0.0	0.00	◙
1L12	●	Start	Stop	0.0164	0.0004	3.4	0.00	◙
1L25	●	Start	Stop	-0.0012	-0.0006	0.0	0.00	◙
1L26	●	Start	Stop	-0.0230	-0.0006	0.0	0.00	◙
2L07	●	Start	Stop	0.0104	-0.0007	0.0	0.00	◙
2L08	●	Start	Stop	-0.0011	-0.0007	0.0	0.00	◙
2L21	●	Start	Stop	-0.0155	0.0004	0.0	0.00	◙
2L22	●	Start	Stop	1.3768	0.3216	2.7	167.23	◙
2L23	●	Start	Stop	3.7710	0.3389	0.0	278.97	◙
2L24	●	Start	Stop	4.4536	0.0010	2.1	0.00	◙
2L25	●	Start	Stop	0.0718	0.0011	0.0	0.00	◙
2L26	●	Start	Stop	0.0406	0.0001	0.0	0.00	◙

Figure 10: Quick view summary.



Mode: Real
218 cycles done

Measurement Parameters
Start 0.1000 A
Restart 95.0 %
Sim Qnch 0.35 A
Step 0.0005 A
Step time 0.7 s
Cycles 218

Quench Detect
Quench detect 0.150 V
Last Q current 0.3132 A
Num to average 3
Mean Q current 0.3127 A

Power
3600.1 I² -731.1 I+ 26.42
149.74 W

GMES & Q0
1 8.82e-04 5 1.56e-03
2 1.55e-03 6 1.46e-03
3 1.86e-03 7 2.15e-03
4 1.06e-03 8 1.84e-03

0.0310 V
Set 0.2976 A
Read 0.2972 A
Output 3.00 A/V
Rback 3.00 A/V
2.8 K

Figure 11: The top trace is the quench voltage showing start of quench threshold.

OPERATION

To obtain Low Power Mode measurements we first setup and execute the calibration process and make a calibration curve. The calibration process begins with all cryomodule cavities turned off. We then ramp down the electric heaters to 20W (Bias). In anticipation of closing the JT valve and boiling off a considerable amount of helium we make sure to slightly overfill the cryomodule helium bath. Once the bath is filled, we close the JT valve. More so, we set the closing position to be slightly beyond the valves actual closing point. This is to ensure that constant pressure is being placed on the valve and thus creates a tighter seal around it. From here, there is just enough helium boil off running through the U-Tube for the meter to see. One this activity is detected we wait for the flow of evaporated helium to stabilize. After stability, we wait for the superconducting material to quench. After the quench, the heating element's current is reduced to 70% of where it was during the time of quench. A saw-tooth pattern of the heating element's current read back initiates. For calibrating and measuring we take at least 5 readings of the current (Amps) at which the heating element had to rise to, in order to cause the superconducting material to quench. After the initial reading from our 20-watt bias, we increase the electric heaters by ~10 W or more. As long as all affected systems and levels are nominal, we repeat these steps up to ~60-W. For each electric heater setpoint (i.e. 10 W, 20 W, 30 W…), average the 5 heating elements quench currents, and create a plot of heater setpoint vs heater current. From this process we eventually obtain a calibration curve specific to the cryomodule it was measured from.

In a similar fashion, cavity performance and power dissipation from individual cavities are measured. The process begins the same way as with calibration. After the JT valve is initially closed and there is flow stability across the meter, we keep the electric heaters set to their 20 W bias and prepare to turn on the SRF cavities one by one. We turn the chosen cavity on at its typical running gradient (MV/m) and obtain 5 quenches. As long as all affected systems and levels are nominal, we repeat these steps for each cavity in interest.

Strategical methods and practices will keep flow meter measurements smooth and apart from causing any damage to other systems. When initially closing the JT valve it is fine to do it in a rather abrupt way. However, when opening the valve, it is important to use cation. Behind the valve, on the helium supply side, the inlet pipe has little to no flow. Stagnate cold helium begins to warm up and causes an increase in pressure within the line. If pressure builds up too high on the supply side, then, when the JT valve is opened, a large pressure oscillation may occur which will likely trip the cryogenic plant (CHL). Another difficulty which arises from closing the JT valve comes from the helium boil off. The cryomodules are intentionally kept submerged in liquid helium for many reasons. When taking measurements, it is critical to not allow helium boil off to exceed a submersion of the cryomodule.

As of this date, we have not been given enough CEBAF – off Study Time to optimize the parameters for obtaining the best Low Power Mode resolution. No time has been devoted to developing the parameters for High Power Mode operation to obtain high-resolution measurements of the power dissipated in the entire cryomodule while the accelerator is operating. One critical issue for the latter mode is how the Joule-Thompson (J-T Valve) helium supply valve is incorporated into the procedure.

CONCLUSIONS

The initial sensor design worked very well the first time we tried it in the VTA. Minor modifications were done to improve it's performance – actually the signal levels were so large that we were able to reduce the size of the sensor. We feel confident that after the studies of both Low Power Mode and High Power Mode are completed, the CEBAF operators will have Watt Meters available at the 12 installed positions that are able to resolve better than single digit power dissipation. The remainder of the Phase II SBIR Grant to Hyperboloid will be able to populate more of the 53 Cryomodule positions in CEBAF during future down periods.

ACKNOWLEDGEMENTS

I would like to recognize and thank the DOE SBIR Grant #DE-SC0022380 for funding this project along with John Fischer & Arron Auston for undertaking the hard work of the U-Tube modification. Scott Thompson & Casey Heck along with John & Aaron saw that everything was in compliance with all safety inspections and pressure vessel compliance.

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