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Helium Flow Meter for Superconducting Radio Frequency (SRF) Cavity Power Dissipation Measurement

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Abstract. A SBIR sponsored helium gas flow meter, measures 3 K helium vapor evaporating from a superfluid, 2 K helium bath at 1/30 atm. The meter resolving helium evaporation to 0.05 g/s = 1 W. The Instrument Head is installed in the return U-Tube of Superconducting Radio Frequency (SRF) Cryomodules as a Power Meter. It measures power from 10 W to the 200 W range. The meter's sensitivity, in this unusual temperature and pressure range, is from the voltage signal change when the superconductor sensor (Tc=9.2 K) changes to normal conducing. Cooling from helium vapor is bucked against resistive heat from a resistive wire until the sensor's temperature is non-SC. The averaged heater current at the SC point is the stored signal. The Power generating a matched signal reading from the cryomodule's built-in resistive heaters is the sought-after Data. An Electronics Chassis using small power supplies and electronics, interfaced to an AtoD/DtoA LabJack T7 couples to Linux-based, EPICS providing control and data processing. The Flowmeter is successfully installed in 14 of 53 positions in CEBAF and 4 other applications. The Hyperboloid Flowmeter is now a commercial instrument, providing a rapid and reliable method for assessing cavity performance vs. accelerating gradient.

1. Introduction

This report is on the three-year development and implementation cycle of a helium gas flow meter, acting as a power meter (Watt Meter) that measures 3 to 7 K helium vapor evaporating from a superfluid, helium bath at 2 K, 1/30 atm. Superconducting Radio Frequency (SRF) Accelerators throughout the world will see this flowmeter as a necessary instrument to assess SRF Cavity health in-situ.

1.1 Central Helium Liquefier Limitations at JLab

The Continuous Electron Beam Acceleration Facility (CEBAF) at Thomas Jefferson National Accelerator Facility (JLab) uses a 2 K, Central Helium Liquefier (CHL) to supply the superfluid helium in which the SRF Cavities are immersed. The refrigerator requires a STEADY Heat Load because of limited dynamic range. Surges in the return helium flow due to drastic changes in the load tend to "trip" the refrigerator causing hours long "Beam-off" times. When this project started there was a ~500 W (near the CHL Trip value) discrepancy between cryomodule power into the

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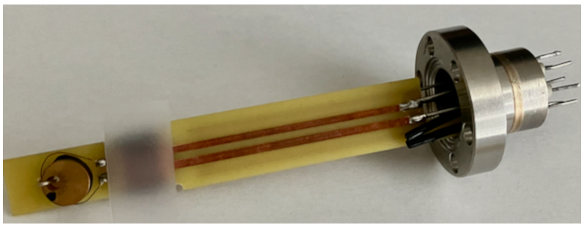

Figure 1. Instrument Head Assembly

Figure 2. Rack mountable Electronics Chassis

cryogenic system when Beam is on and the calculation of offsetting power from resistive heaters when cryomodules are turned off. The calculation uses tabulated Q0s, a lumped term for power dissipations which varies with the cavity's accelerating gradient. The Q0s are out of date.

1.2 Determining SRF Cavity Q0s

The Q0s were obtained from original Q0s determined for each cavity in a new cryomodule. For over 30 years, there was no good way to non-invasively determine the heat load of a cryomodule. Since 23 Watts of power evaporates one gram of helium per second from the 2 K helium bath, an accurate gas flow meter placed in the 2 to 3 K and 1/30 atm helium vapor return pipe of cryomodules, calibrated as a Watt Meter signal would work. The Hyperboloid Flowmeter described in this report fulfills this requirement, it resolves 1 to 2 Watts of cavity dissipation.

2. Development at JLab

A paper by Japanese researchers [1] indicated they successfully used a delicate, non-industrial, superconducting to non-superconducting transition to generate a strong signal and produce a flowmeter for these conditions.

2.1 The Hyperboloid LLC – JLab Solution

This report describes a robust flowmeter that is successful as the sought-after Watt Meter after development and implementation at JLab and elsewhere. The work is an outgrowth of a 2021 DOE SBIR topic to make "devices and methods for accurate in-situ measurement of SRF cavity Q0s". A Phase I grant was awarded to Hyperboloid LLC in February of 2022 and the Grant advanced to Phase II in April of 2023. The Grants utilized a Cooperative Research and Development Agreement (CRADA) with Jefferson Science Associates (JSA), the operating contractor for JLab.

2.2 How It Works

The Instrument Head Assembly (See Figure 1) consists of a Lake Shore, DT-670A1-CU Silicone Diode (temperature diode) and the Instrument Head Bobbin (IHB) whose signals convey along the traces on a Printed Circuit Board (PCB) to an 8-pin, cryogenic rated, CF flange based, helium-to-vacuum feedthrough. Cooling from helium vapor flow from the cryomodule is bucked against the heat from a current in a resistive heater wire in the IHB. Sandwiched between it is a superconductor (SC) that yields a large voltage signal when the heating raises its temperature high enough to go "normal" conducting (Tc ~ 9 K), called a "Quench". Increasing flow directly corresponds with increasing Heater Wire Current. This Current is the flowmeter's "Signal". The wired-in digital environment in the Experimental Physics and Industrial Control System (EPICS),

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allows storage of the signals and real time digital manipulation to resolve power dissipations to within 1 to 2 Watts.

2.3. JLab Designed Electronic Chassis

The Instrument Head would remain a Laboratory curiosity without the subsequent developments in the Electronics Chassis (Figure 2) designed by JLab and software integration into the EPICS control system by the accelerator software group detailed in an earlier report [2].

3. Hardware and Control

3.1 Initial Successes

The first flowmeter IHB made was installed in the JLab Vertical Test Area (VTA) Dewar, where it showed that the concept worked over a large range of 10 to 180+ W. It can measure individual cavity dissipation as well as total CEBAF cryomodule power dissipation when all cavities are at operating gradient. Further tests were successful when the flowmeter was placed in the return vapor U-Tubes in JLab Cryomodule Test Facility (CMTF).

3.2 U-Tubes

Each of 53 cryomodules in the CEBAF accelerator is connected to the CHL with four U-Tubes. These are vacuum insulated stainless-steel pipes that supply and return helium to the 2 K & 40 K circuits in each cryomodule. They are a way for cryomodules to be connected/ disconnected from the cryogenic piping without disturbing the system. When the U-Tubes are "pulled" for a disconnection, the sub-atmosphere, Return Vapor U-Tube is available for opportunistic modification and installation (Figure 3) of the easy-to-access flowmeter.

3.3 Exceeding the SBIR Phase 1 Plan

A flowmeter was installed in CEBAF itself at Linac Zone 1L12 during a warm-up, cool-down cycle and was immediately successful. This installation exceeded the SBIR Phase 1 plan. We modified the "pulled" U-Tube rather than make a new U-tube. Modification of U-Tubes saved ~$16,000 each over Phase II and allowed more flowmeters to be installed.

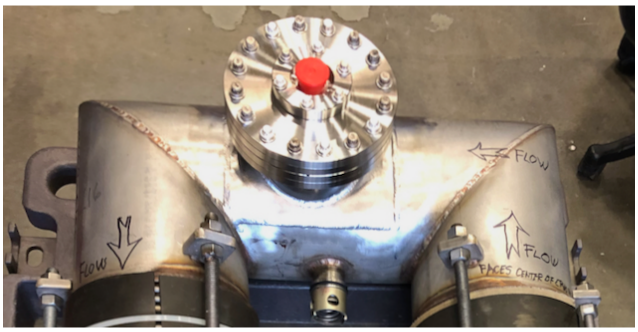

Figure 3. Modified U-Tube

3.4 The U-Tube Modification

The one-week modification cycle installs branch tubes with CF Flanges mated to electrical feedthrough caping flanges. A 30-inch long, 26-gauge manganin lead cable is soldered to the 8-pin feedthrough at the helium pipe branch and snakes through a super-insulation cap to a Burndy style, 19-pin plug, plugging in the inside of the vacuum to air feedthrough.

3.5 Mounting Orientation and Position in the Pipe

The choice of the mounting the flowmeter IHB perpendicular to the flow direction in the pipe was made to simplify the assembly. We validated that the flowmeter IHB gave the same reading in both orientations in a simultaneous test in the VTA where the IHB were next to each other.

The flowmeter's IHB is mounted in the center of the 2 ips (inch pipe size) pipe in the CEBAF U-Tubes and the center of the 3 ips pipe of the return transfer line from the LCLS-II-HE cryomodule.

3.6 Electronics Chassis

The matured version of the Electronics Chassis uses a LabJack T7 (labjack.com) as the AtoD/DtoA. The system is installed with the ethernet interface but de-bugged on the bench with a laptop & USB connection. A custom printed circuit board mounts the other electronic components. Each chassis supports two flowmeters. Chassis are installed in racks of the accelerator service buildings. We use a BELDEN 6546PA 0081000 Multipair Cable, Security Shielded, 8 Pair, 22 AWG cable between U-Tube and Electronics Chassis, a major factor in maintaining low noise readout. The chassis are connected to the EPICS control system via Ethernet. [2] The controlling software runs on a soft IOC hosted on accelerator operations networks.

4. Operation

4.1 Saw Tooth Mode Operation

Dissipation power readings for a cavity at a gradient are found by the following procedure. The GUI control screen for an individual flow meter using Saw Tooth Mode is shown in Figure 4. Using this mode, Heater Current Value (central trace) is ramped at a programable rate until a programable percentage (value on the left of the GUI) of the SC starts to go normal (quench) as seen in the top trace by an increase in voltage from a base of ~0.020 V. The maximum current values are recorded and displayed on the left. A 'restart' resetting of the heater current at a settable small (~10%) drop, allows the SC to switch to superconducting again, and the saw tooth current cycle is repeated. The control system calculates a Rolling Average of the latest maximum heater current values. The number of values in the average is usually set between 5 to 100 cycles. EPICS calculates a "Mean Quench Delta" of the averaged current values. A "reading" for the cavity at its gradient is "taken" when this Delta reaches a low value, typically ±0.001. The Rolling Averaged Heater Current (RAHC) is placed in the "Target Reading" register.

To avoid any changes in response due to temperature, the procedure then contemporaneously calibrates the RAHC "Target Reading" to a dissipation Power Data Point in Watts. This is the Data sought after. The calibration is obtained by turning off the cavity and "hunting" for a power value from the built-in resistive heaters in the cryomodule that generates that same RAHC "Target Reading". Q0s are calculated using these power data points.

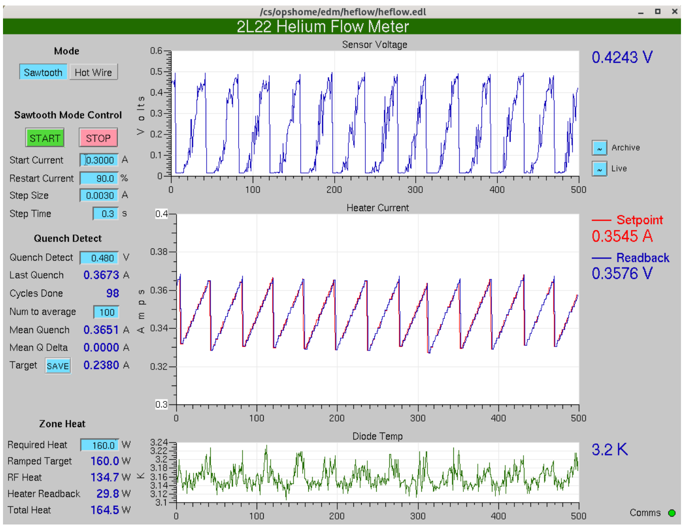

Figure 4. The Saw Tooth Control Screen showing cyclic rise in SC voltage, heater wire current and temperature diode temperature with control parameters on the left.

4.2 Hot Wire Mode

An expired patent US 5249866 A, using a similar superconducting technique envisions an analogue circuit keeping a constant heater current at a constant percentage of

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superconducting to non-superconducting state. This "Hot Wire Anemometer" mode is made available in a separate EPICS GUI screen. The percentage normal signal is very sensitive and hence noisy and varies cyclically with minutes periodicity we presume are wave-like pressure variations in the piping of the large CEBAF Cryogenic System. The Hot Wire Mode is cumbersome to implement, requiring a nonstandard, high time resolution strip tool to calibrate against cavity-off, cryomodule heater generated stepped portions of the graph.

Hot Wire Mode was also initially rejected for this meter because of the method's inherent instabilities. However, an innovation in the Electronics Chassis circuitry is planned for implementation and trial soon where the heater current will automatically be changed to keep the percentage of the normal state of the SC at a set value. The resulting stability of the reading may make the Hot Wire Mode, with its greater sensitivity, the preferred operational mode.

4.3 Influence of the JT Valve

Initial flowmeter readings were done with the JT valve closed to avoid the added flashed helium vapor superposing on and diluting the cavity dissipation flow signal and reducing the resolution. This closing forced added, awkward helium fill cycles with stabilization delays, adding to the measurement time. As we gained operational experience, we found that "freezing" the JT Valve at a setting that maintained the helium liquid level within normal range throughout the readings didn't reduce the resolution appreciably and significantly sped up measurement time. This technique will also be applied to measuring whole cryomodule dissipation power while beam is on. Operators found that freezing the JT Valve with all cavities on for the short time necessary for a single full cryomodule reading didn't interfere with beam operations.

4.4 Operator Implementation

Strategical methods and practices keep flow meter measurements smooth and apart from causing any damage to other accelerator systems. An automatic accelerator damage-control feature that turns off RF power to the cavities when manipulating the cryomodule heaters must be masked at the start of individual cavity measurements and, more importantly, un-masked after measurements are complete. Plots of vital accelerator and cryogenic variables must also be watched during measurements. For the Sawtooth Mode, the CEBAF operators developed a Python Script to automatically perform this masking and un-masking, start the strip tooling and other vital functions. A second Python Script performs the "hunting" for the

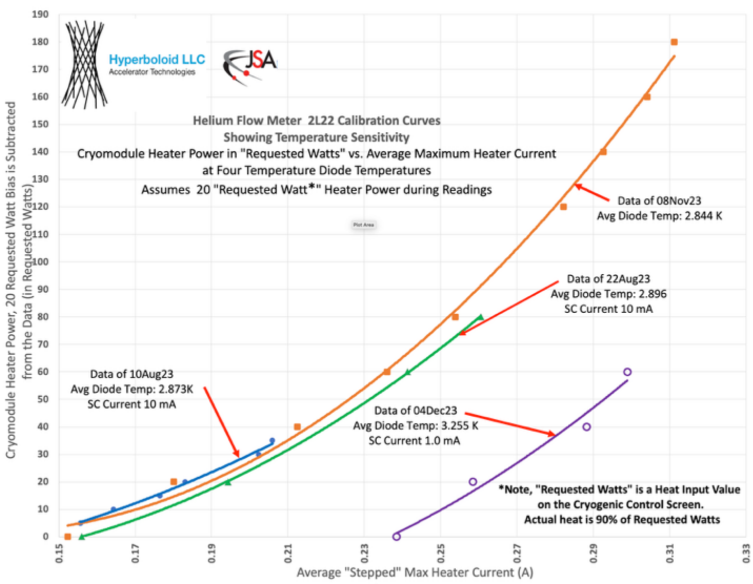

Figure 5. Calibration Curves of the Flowmeter at 2L22, showing Temperature Dependency

Power Data Point, using the built-in cryomodule heaters, that matches the RAHC.

4.5 Temperature Sensitivity and Whole Cryomodule Readings

All developmental readings of the flowmeter are opportunistic due to beam operations or other tests having higher priority. But, using the 2L22 cryomodules resistive heaters, we generated 4 Calibration Curves of RAHC when bath temperatures were different shown in Figure 5, indicating a temperature sensitivity of about 180 W/K.

This sensitivity will be important when assessing whole cryomodule dissipation when beam is on, when we can't turn cavities off. Instead of the contemporaneous "hunt" for a Power Data Point, we will probably have to expand a calibration curve of Power vs. RMHC as in Figure 5 into a Calibration "Surface", adding Temperature Diode Temperature on a third axis and obtain the power dissipation reading using software to interpolate a power value from the surface.

4.6 Higher Helium Pressure

Some readings around 1 atm and 4 K were taken. They were exploratory and are not worth elaboration other than indicating the flowmeter may be usable at these denser helium vapor realms. A serious characterization will be attempted soon using the 2-cavity cryomodule in the UITF at JLab where the Nb3Sn Cavities are run at 4.5 K.

5. Results

The typical calibration curves resulting from the use of the built-in heaters for one cryomodule were already shown in Figure 5, showing a range for the flowmeter that extends from several Watts to beyond 180 W. To date, individual cavity power dissipations at various gradients were characterized for 4 CEBAF cryomodules and 6 LCLS-II-HE cryomodules. Figure 6 shows a typical CEBAF result, and Figure 7 shows a typical LCLS-II-HE result. As of this date, we have not been given enough CEBAF beam-off Study Time to use all the 14 installed flowmeters or to develop the total cryomodule measurement protocol.

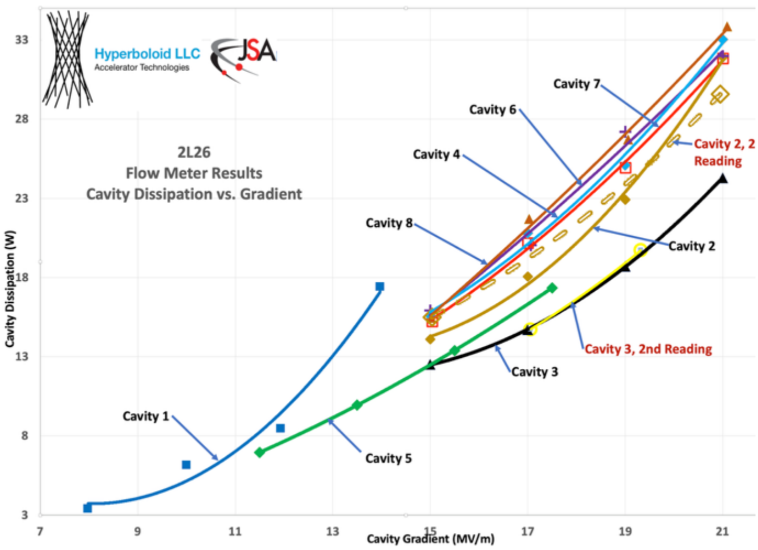

Figure 6. 2L26 Dissipation vs. Gradient with Trendlines including two repeat measurements

5.1 Repeatability

And added result is seen in Figure 6, It shows additional data from a repeat of data taking for two cavities shown by red callouts. Cavity 2's readings superpose on the original data and Cavity 3's readings are within 2 W.

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5.2 LCLS-II-HE Cryomodule Testing at JLab

The LCLS-II-HE cryomodule tests use *only* the flowmeter to measure the cavity dissipations to obtain Q0s, taking far fewer shifts than the original method.

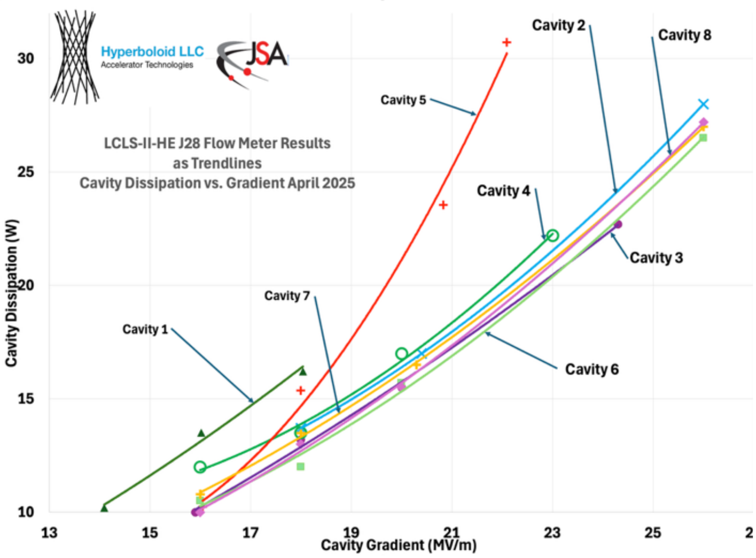

Figure 7. LCLS-II-HE Dissipation vs. Gradient with Trendlines

5.3 Other SRF Laboratory Experience

A single flowmeter was installed in the cryomodule Test Stand at the SNS at ORNL. To date, the EPICS Software is not installed. Nevertheless, recent tests of that flowmeter at 4 K and 2 K showed that flowmeter is working. “Manual” readings that verified operation were accomplished using The LabJack’s Kipling software on a laptop computer directly connected to the LabJack unit in the Electronics Chassis via a USB cable.

6. A Disturbing Problem

After the CEBAF first down period in 2023, when eleven flowmeters were installed, there was only study time to minimally characterize the five associated with C-100 cryomodules. One of these flowmeters, at Linac Position 2L24 yielded readings we didn’t understand. During the down period of 2024, six more flowmeters were installed and the IH at 2L24 was replaced. We found that 5 flowmeters had similarly errant readings while the substituted IH at 2L24, now, responded correctly. With further investigation, and to our amazement, we found that the purportedly superconducting wire imbedded in the non-responsive IHBs is not superconducting!

6.1 Manufacturer Contact

Contacts with the wire manufacturer revealed that the two very small reels of wire purchased by Hyperboloid came from a very large batch with no failures reported. We tested the original 2L24 IHB Assembly and its unwound wire for superconductivity in two tests in the VTA Dewar at 4.2 K along with the entire remaining reel of wire and along with sample lengths saved from early manufacturing. Only the 2L24’s wire was not superconducting. We sent it to the manufacturer for analysis. Our only explanation is that a small length of non-SC wire in the reels purchased by Hyperboloid LLC was incorporated in the 6 IHB. Certainly, the wire in the first portion of the 1st reel was superconducting because of the success of the initial trials of the flow meter. The manufacturer has not communicated the results of their analysis.

6.2 Non superconducting IHB yielded less resolved data

All flow sensitivity was not lost from the IH with the non-superconducting wire. The non-SC wire did have a resistive range over the temperatures produced by the heater wire. The Software and

Electronics Chassis could resolve within this range. The operators characterized cavity heat dissipation in individual cavities of Linac Position 2L25 using Hot Wire Mode with less resolution.

7. Installation Status

- Fourteen successful superconducting flowmeters are installed in CEBAF.
- One CEBAF flowmeter, at 2L25, with non-superconducting wire, was able to characterize cavity dissipation power at reduced resolution.
- Two flowmeters are installed in the Transfer Line for the LCLS-II-HE cryomodule Qualification Tests in the Low Energy Research Facility (LERF) at JLab.
- Two flowmeters are installed in separate U-Tubes at the cryomodule Test Facility (CMTF) in the JLab Test Lab. One in the U-Tube for JLab cryomodules, and one in the U-Tube for PPU (SNS) cryomodules.
- One flowmeter is installed in the transfer line in the UITF in the JLab Test Lab.
- One Flowmeter is installed in the ONRL SNS cryomodule Test Facility.

8. Conclusions

At the end of a 3-year development period, the Hyperboloid Helium Flowmeter is a proven instrument to measure individual SRF Cavity dissipations in-situ at various gradients with high accuracy. With the expected further development of procedures, the flowmeter has the range to periodically measure total cryomodule dissipation during beam operations. These capabilities will allow CEBAF to extend the correction of its database of Q0 and decrease the number of sudden variations in the cryogenic load that potentially "trip" or over-burden the CHL. This will avoid, non-productive, hours long "Beam-off" times, a very valuable resource. The flowmeter is now in a state of development that the world-wide SRF community can similarly benefit from installation of the flowmeter and integration into their operations.

9. Acknowledgments

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References

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