High Field Q-slope and Superconducting Radio Frequency Cavity Testing

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High field Q-slope is a loss mechanism frequently encountered by superconducting radio frequency (SRF) cavities. The goal of this experiment was to identify correlations between cavity surface impurities, caused by either nitrogen gas or a thin layer of oxidized niobium, and high field Q-slope. Unfortunately, due to an unpredictable series of complications, cavity test results were not obtained in time to be included in this paper. Instead, this paper discusses many of the details and difficulties related to cavity testing that should be helpful to anyone who decides to pursue this project in the future.

I. INTRODUCTION

When a particle of charge becomes under the influence of an electric field, it experiences a force governed by Coulomb's Law. This is the principle behind the use of RF cavities in particle accelerators. RF cavities (example in Fig. 1) are essentially resonators that are designed to sustain oscillating electromagnetic fields. When an RF source is coupled to a cavity, electromagnetic fields are excited inside that resonantly build to high amplitudes. If a bunch of charged particles passes through the aperture of the cavity at the correct time, it will get pushed by the field inside, causing the bunch to be accelerated toward the opposite aperture. Thus, RF cavities are utilized by most modern accelerators as a means of providing particle beams with energy.

Electromagnetic fields that oscillate inside RF cavities cause electrons to move back and forth within the cavity wall. As these electrons experience resistive forces, they cause the cavity to heat up and lose energy. State of the art accelerators utilize superconducting RF cavities in order to minimize this type of energy loss. Cavity walls constructed from pure niobium have very low resistivity in an oscillating field when below niobium's critical temperature of 9.2K [1]. As a result, little energy is lost through the cavity wall, and more energy goes to accelerating the beam.

Even in superconducting cavities, however, many loss mechanisms exist, including field emission, multipacting, surface defects, hydrogen disease, etc.[1] Of these, one of the more ambiguous adversaries is high field Q-slope. Once the electromagnetic field inside an SRF cavity reaches a high enough amplitude, energy losses through the cavity walls begin to increase drastically as field amplitude increases. Research that has been conducted in the past suggests high field Q-slope can sometimes be cured by baking cavities at either 400°C or 110°C, but this result is not well understood [2]. The goal of this project is to continue exploring high field Q-slope and to try to pinpoint specific causes.

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[1] For a more detailed discussion of cavity loss mechanisms, see [2], 62-65

FIG. 1: Picture of a 1.5Ghz cavity mounted to a test stand

II. CAVITY FUNDAMENTALS AND TESTING

By far the most important figure of merit for describing RF cavities is the intrinsic quality factor, or Q_0. The quality of a cavity is roughly equal to 2π times the number of RF cycles it takes for the stored energy in the cavity to dissipate [3]. More precisely, it is defined by

$$Q_0 = \frac{\omega_0 U}{P_d} \tag{1}$$

where ω_0 is the eigenfrequency of the accelerating mode, U is the stored energy in the cavity, and P_d is the total power dissapated through the cavity walls [4]. We can also define $Q_0 = g/R_S$, where R_S is the surface resistance of the cavity, and g is a geometric factor, only dependent on the geometry of the cavity. This can be a useful way to define instrinsic quality, because it isolates the effects of a cavity's geometry and its the material properties. Cavities with high qualities are less susceptible to energy loss, and can more efficiently accelerate particles along a beam path.

Another important feature of cavities is the strength of the field that oscillates inside. The accelerating electric field, or E_{acc}, is defined to be the average electric field that an electron sees during its transit through a cavity. Naturally, in accelerators, higher accelerating field amplitudes are desirable. Generally, the magnetic field inside a cavity increases with E_{acc}. Hence, since superconductors have critical magnetic fields, there exists a maximum E_{acc}, above which an SRF cavity will quench, causing its quality to decrease by roughly a factor of 10^6.

Aside from this unfortunate phenomenon, there would ideally be no quailty dependence on the accelerating field; the quality would remain constant as the field increased. In reality, however, since loss mechanisms do exist, and are frequently dependent on E_{acc}, cavity quality will often change with respect to changes in the accelerating field. Thus, plots of Q_0 versus E_{acc} are good at depicting the performance of cavities.[2] Fig. 2 shows an example Q_0 versus E_{acc} plot showing the effects of high field Q-slope on quality.[3]

[2] For a more detailed discussion of Q_0 and E_{acc}, see [2], 46-49

[3] You may notice that high field Q-slope is appropriately named for its effect on a Q_0 versus E_{acc} plot.

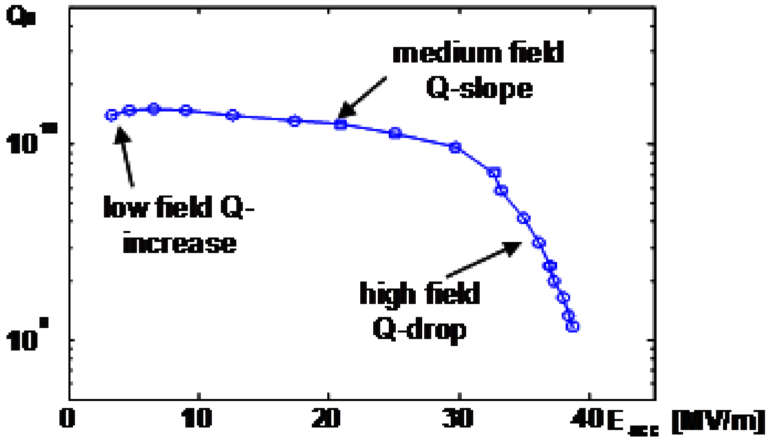

FIG. 2: Example Q_0 versus E_{acc} plot depicting high field Q-slope

Due to their practicality, cavities are often tested for their Q_0 versus E_{acc} plots. In general, a test is conducted by cooling a cavity below its critical temperature, and coupling it to an RF source. The quality of the cavity is calculated using what can be determined about the RF power supplied, the power reflected, and transmitted field probe signal. Due to radiation hazards, the SRF group at Cornell University only tests cavities when they are placed in a covered pit.

The general testing procedure followed at Cornell University is as follows. The cavity to be tested is initially mounted into a test stand (shown in Fig. 3). The tester then carries out a leak check of the vacuum system. To do this, a Residual Gas Analyzer (RGA) is attached to the vacuum pump that can detect traces of helium as they are pumped away. Small amounts of helium gas are sprayed around each of the seals in the vacuum system. If a seal is weak and helium is able to enter the vacuum, then the RGA readout shows an increase in helium in the system, and therefore, the leak is detected. Once the system is leak free, the test stand is lowered into a testing pit, and the pit is cooled down, primarily by liquid helium. The top part of the test stand, known as the top plate (Fig. 3) temporarily remains exposed to the testers. All wires and vacuum pipes that need to be inside the pit during the test are fed through the top plate. Once the necessary connections have been made, the top plate is covered to prevent the tester from suffering radiation exposure, and once the plate is covered, RF power can be supplied to the cavity.[4]

As a cavity loses RF power through its walls, it heats up. A thermometry system can be used during a test to map out the temperature of the outer surface of a cavity. Since different loss mechanisms cause the cavity surface to heat up in unique ways, thermometry allows a tester to identify which loss mechanisms are prevalent.

The thermometry system utilizes Allen Bradley resisters to measure the temperature of the outer surface of a cavity at 756 different locations (each resister covers approximately one square centimeter of cavity surface area) [4]. The resisters are sanded down on one side so that their copper cores are exposed, and then covered with a thin layer of GE varnish to prevent electrical conductivity to the cavity surface. 36 circuit boards are assembled with

[4] This is a very brief summary of the actual testing procedure used by the SRF group at Cornell University. For a more detailed procedure, see [4], 49-84, or [1], 145-169

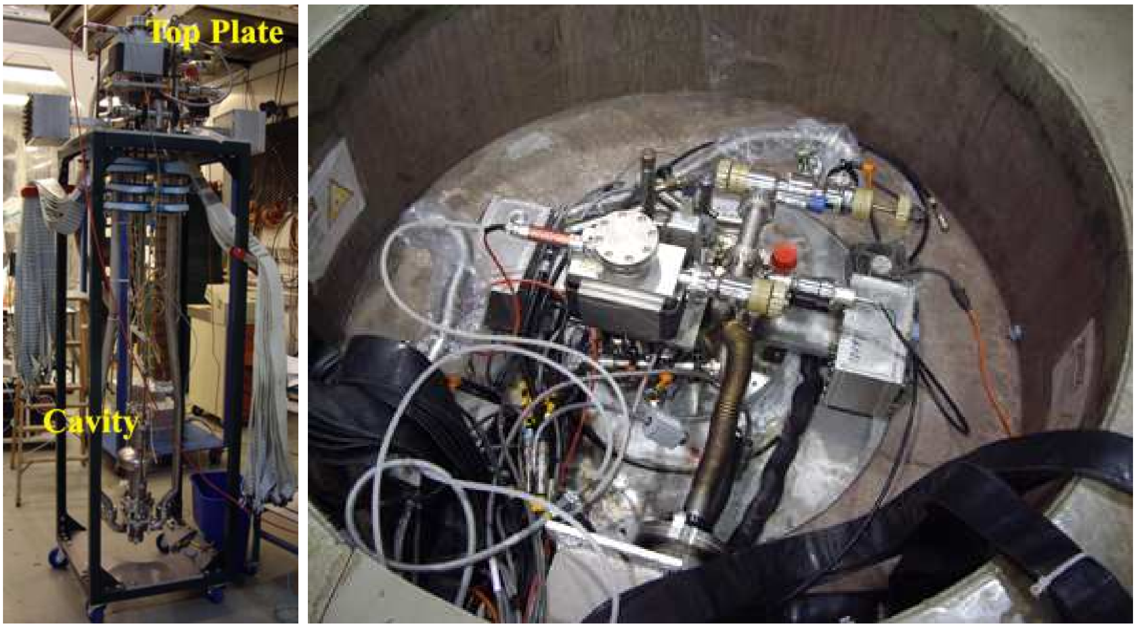

FIG. 3: Left to right: test stand housing the 1.5Ghz cavity; top plate of the test stand inserted into testing pit

21 thermometers on each, and these boards are placed in a housing system that allows each resister to be pressed firmly against the outer surface of the cavity. Fig. 4 shows an example thermometer board, and a picture of thermometer boards secured around the outside of a cavity. A thick layer of Apeazon N-grease is applied to each thermometer to ensure good thermal contact with the cavity, and to prevent liquid helium from getting in the space between a thermometer and the cavity. Each thermometer board is wired through the top plate of the test stand, to a SCXI system that can be controlled by a computer.

The resistance of each Allen Bradley resister changes significantly with small changes in temperature. By applying current, the resistance of each resistor can be calculated, and the temperature of the outside of the cavity can be mapped out.

III. PROCEDURE AND OBSTACLES

The following section outlines the progress that has been made, and the obstacles that should be avoided in the future.

A standard "tesla shaped" 1.5Ghz cavity was used for this experiment. Prior to the beginning of summer, the cavity had been etched by a buffered chemical polish (BCP), and placed in a class 10 clean room. From here, the cavity was given a high pressure rinse (HPR) intended to knock off any residual dust particles on the inside surface.[5] After having at least 24 hours to dry, indium seals were used to mount the cavity to a test stand. A vacuum pump was attached to the test stand, and left to pump on the cavity for roughly 24 hours until the pressure inside reached as low as 10^{-7}torr. A leak check was then performed on the vacuum system. Only one leak was found, on the lower flange of the cavity, and it was fixed

[5] For details on BCP, HPR, and other cavity preparation techniques, see [2], 26-40

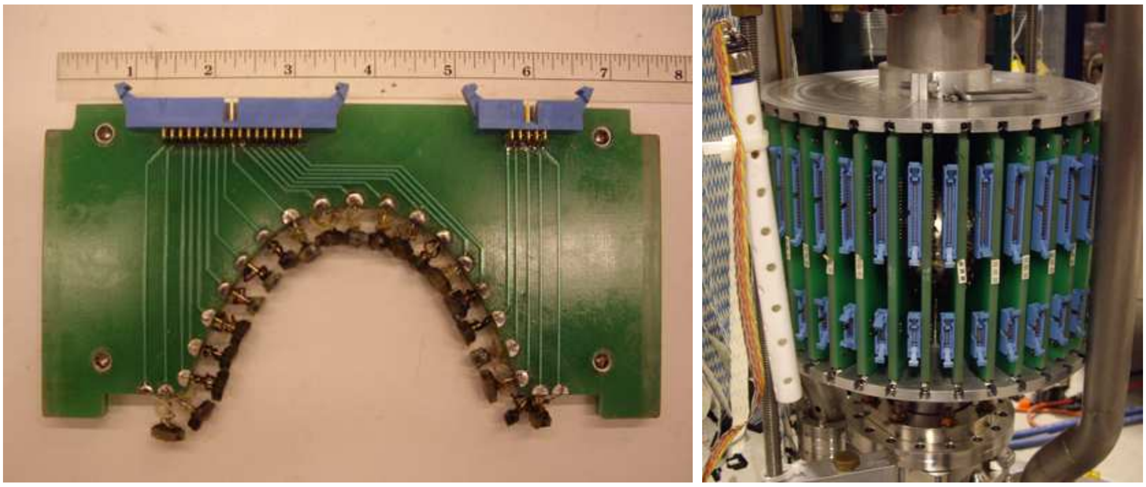

FIG. 4: Left to right: thermometer board with 21 Allen Bradley resistors; cavity with boards mounted to cavity wall in preparation for temperature mapping

by adjusting the tightness of several bolts around the flange. All of the above steps took place inside a class 10 clean room. Once the vacuum system was leak free, the test stand was moved outside of the clean room in preparation for setting up the thermometry system.

Two metal washer shaped disks with grooves in them are used to make a housing system for securing thermometer boards to the outside of the cavity. Each disk is attached around the beam pipe section of the cavity on either side. The grooves in the disks allow thermometer boards to be slid towards the cavity and screwed into place. After the disks were attached to the beam pipe and the boards were slid into place, they were each wired to the top plate. Two ribbon cables, one with 32 pins and the other with 10 pins, attach to each thermometer board. During a test, the cavity is moved up and down as much as 4 inches. Care was taken in leaving enough slack in each ribbon cable to prevent cables from coming undone due to this motion.

After the thermometry system was mounted to the cavity, several minor adjustments were made to the top plate of the test stand, and a crane was used to lift the stand, and lower it into the testing pit. With the pit uncovered, cables were attached to the test stand through the top plate. Before any testing of the cavity began, the status of the thermometry system was checked, and found to be too poor to continue. At room temperature, each thermometer, if working properly, should read a resistance of around 120 ohms. Of the 756 thermometers, approximately 350 gave faulty readings, having either extremely low (close to zero ohms) or extremely high (several kilo-ohms) resistances.

This problem was tackled for several weeks, and turned out to be caused by a myriad of factors. 24 ribbon cables are used to hook up all 756 resistors from the top plate of the test stand, to a computer controlled SCXI system. Each of the 24 cables is responsible for either 30 or 32 thermometers. On one end, the cables attach to the top plate via a standard pin connector. On the opposite end, each cable runs into a terminal box, which is plugged into a module that is part of the SCXI system (shown in Fig. 5). Each terminal box can be opened, and thermometers can be individually shorted out of the system using small pieces of wire.

The first, most obvious problem that was found with the thermometry system was that the terminal connectors were not fastened tightly enough into their corresponding modules.

After securing these connections, the number of faulty thermometers dropped by about 100, from 350 to 250.

Due to architecture of the thermometry system, thermometers are not entirely immune to cross-talk. If a broken thermometer with an extremely high resistance (several kilo-ohms) exists, it can alter the resistance readings of other thermometers. To correct this problem, thermometers with faulty high resistances were manually shorted out of the system through the terminal boxes. While this correction helped to increase the stability of resistance readings in general, it did not significantly reduce the number of faulty thermometers.

After extensive analysis, it was found that many of the thermometers lacked a thin layer of GE varnish that electrically insulates them, and prevents them from shorting to the cavity surface. Most likely, bits of varnish had been scraped off over time by a screwdriver, which is traditionally the tool of choice for applying grease to thermometers. In the future, a softer applicator should be used, such as a Q-tip with one end cut off. All 756 thermometers received a fresh layer of GE varnish, and in process, nearly 200 broken resistors were replaced. As a result, the total number of faulty thermometers, as seen by the computer, dropped to roughly 90. With less then 100 bad thermometers, the thermometry system was ready for cavity testing.

FIG. 5: Left to right: terminals connected to modules, with one disconnected; terminal box with lid removed

Unfortunately, before a test could be completed, several leaks opened up in the vacuum system. The remainder of my time at Cornell was essentially spent searching for vacuum leaks. There are a couple leak checking techniques discussed below that could prove to be useful to someone who picks up this project in the future.

An in-pit leak check is a good technique that can be used to easily see if a vacuum leak exists below the top plate of the test stand. When the cavity is placed in the pit, its pressure is pumped down and monitored using an ion pump. The ion pump works basically by ionizing particulates and using an electric field to pull them out of a low pressure region in the form of a current. Hence, if the pressure increases, and more particulates exist, the current reading on the ion pump will increase, and vise versa. When the test stand is placed in the pit, the pressure in the pit outside of the vacuum system can be pumped down while the current on the ion pump is monitored. Any significant change in the current reading on the ion pump is evidence that some leak exists in the system below the top plate.

Once a leak is found using the in-pit leak check technique, the location of the leak must be pinpointed. Most leaks can be identified via a simple leak check, where small amounts of helium gas are sprayed around seals in the vacuum system while the RGA helium level readout is monitored. Some small leaks, however, can be hard to identify using this method. To conduct a more rigorous check, each seal can be wrapped in plastic wrap, essentially creating an airtight bag surrounding it. Helium can then be sprayed directly into the bag until it is inflated. Any increase in the output of the RGA would indicate a leak in that seal. This is simply a more precise leak checking technique, since it isolates regions of the vacuum system.

If a leak is found in a seal, it is important to either fix the leak, or purge the seal with nitrogen gas before leak checking continues. Nitrogen purging can be done by wrapping a leak in airtight plastic wrap and supplying the bag with a continuous flow of nitrogen gas. This prevents residual helium in the air from entering the vacuum system through the leak, thereby throwing off the RGA output.

During a leak check, unpredictable RGA output could indicate that there exists a large leak in some area that has not yet been checked. As a leak check progresses, residual helium escapes into the air and gets pushed around by air currents in the workspace. This residual helium can eventually find its way to a large unchecked leak in the vacuum, causing either a slow rise or a large spike in the helium level read by the RGA. For instance, while leak checking the 1.5Ghz cavity, a large leak was found in the base of the vacuum pump that had an unpredictable effect on the RGA leak checking system.

After a thorough leak check, it was decided that the cavity was to be removed from the test stand, given a HPR, and resealed to the test stand with indium wire seals. This represents the current state of the experiment.

IV. CONCLUSIONS

Clearly, there is much experimental work that needs to take place before any conclusive results can be presented. This conclusion is designed to outline the future of this project, rather then to present the results. The remaining work that should carried out is described below.

First and foremost, the cavity should be tested for its quality factor ($Q(E)$), and its surface temperature distribution. Ideally, its Q_0 versus E_{acc} curve will look normal, and the high field Q-slope will be evident. The tester should take note of any hot spots on outer surface of the cavity.

The cavity should then be removed from the testing stand and dipped into hydrofluoric acid. This will remove the oxide layer that grows on the inside surface of the niobium cavity. After the acid wash, it should be given a HPR, reattached to the test stand, pumped down to low pressure, and then tested again. Most likely, the Q_0 versus E_{acc} will not have changed significantly. The real purpose of this part of the experiment is to see if the hot spots on the outer surface of the cavity move around due to the removal of the oxide layer. Moving hot spots indicate that oxide growing inside a cavity can introduce losses to the system.

After the second test is complete, the cavity should again be removed, and then baked and vented with nitrogen gas. This will cause nitrogen to contaminate the inner niobium surface. The cavity should be given a third test, and any changes in the $Q(E)$ curve should be noted. If nothing changes, this is a good indication that nitrogen has no effect on loss mechanisms, or high field Q-slope.

From here, the direction of the experiment should depend on the success or failure of previous tests. While experimenting, it is a good idea to keep in mind the various techniques and fixes related to thermometry and leak checking that came out of the work conducted this summer. These techniques are summarized in the list below.

- Apply Apeazon N-grease to thermometers using a soft applicator, like a Q-tip with one end cut off, in order to avoid scraping GE varnish off of the surfaces of the thermometers.
- Thermometers that do not have a layer of GE varnish applied should not be used in the thermometry system, because they can short to the cavity surface.
- Be sure that all terminals are tightly secured into their corresponding modules. A good way to be sure of this is to firmly press on each of the terminals while constantly monitoring the total number of faulty thermometers.
- Any thermometers that read extremely high resistances (several kilo-ohms or more) at room temperature should be shorted out of the system inside the terminal boxes. This improves the stability of working thermometers.
- An in-pit leak check can be performed to check if any leaks exist below the top plate. This is done by securing the test stand in the testing pit, and pumping down the pressure in the pit while monitoring the current reading on the ion pump.
- Be sure to check the vacuum pump for leaks before searching for leaks on the test stand.
- When leaks are found, they should either be fixed, or purged with nitrogen gas before leak checking continues.
- A good way to isolate a specific seal and check it for leaks, is to wrap it in airtight plastic, and purge the plastic with helium gas while monitoring the RGA output.

V. ACKNOWLEDGMENTS

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