AUTOMATING THE OPTICAL INSPECTION SYSTEM

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ABSTRACT

Superconducting radio frequency (SRF) technology is relatively new—its study began in the 20th century. Although great progress has been made, much is still unknown. Newman Laboratory, located at Cornell University, is dedicated to testing SRF cavities. Before a cavity is tested, it must be inspected for defects. A new optical inspection system will hopefully result in better cavity testing results at Cornell University's Newman Laboratory and be a part of future SRF technology.

INTORDUCTION

SRF Technology

SRF technology came about in the last century, giving scientists more tools with which to explore the world and try to explain observations. Particle accelerators, since their arrival, have given humans a glimpse into very distant past and a hope for the future. Most individuals know that everything is made of atoms, but now, thanks to particle accelerators, humans know that atoms are made of quarks, and quarks are made of other particles.

In order to further explore physics and other elements of science using particle accelerators, niobium cavities are needed. Cavities are devices that accelerate particles using electromagnetic forces. The unique donut-shape of cavities allows this to occur.

To take advantage of this technology, cavities with higher energy gradients are needed: The higher the energy gradient of a cavity, the shorter the particle accelerator. This is important because cavities cost hundreds of thousands of dollars. So, the shorter the accelerator, the smaller the amount of cavities needed.

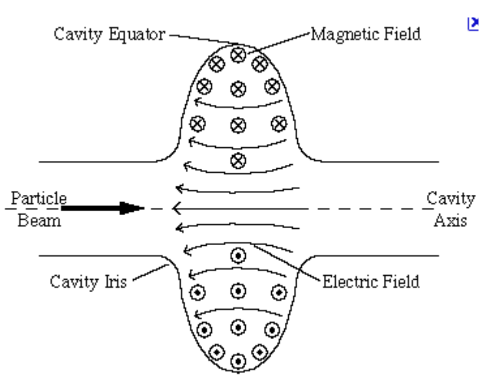


Figure 1: A diagram of a cavity that illustrates how magnetic and electric fields accelerate particles.

Cavity Fabrication

Cavities are made in several ways. They can be made by stamping niobium sheets into molds to create half-cells and then electron beam welding them together. They can also be made via spinning. Half-cells are made by spinning a niobium sheet and slowly pushing the metal into a half-donut shape. These half-cells are then electron-beam welded. This electron beam weld produces a bumpy line across the center of each cell in a cavity. This is known as the equator region and is crucial to cavity inspection.

Cavity Testing

Before placing a cavity into a particle accelerator, a cavity must be tested in order to determine its energy gradient. During a cavity test, a cavity is placed on a mount which is lowered into a deep pit in the ground. This pit is filled with liquid helium which cools the cavity down to a few degrees Kelvin. This is important because niobium cavities become superconducting at very low temperatures (approximately 9K). RF probes are placed into a cavity which excites resonant modes inside the cavity. When a cavity reaches its limit, it quenches—the Q drops dramatically, and that's how one determines the performance of the cavity.

Before a cavity is tested, it has to be inspected for defects. A defect could be a sharp feature or a pit. This usually occurs along the equator due to electron beam welding. Defects must be found and removed via mechanical polishing and/or chemical treatment because defects can cause cavities to quench prematurely. For optimal cavity performance, clean defect-free cavities are a must.

Current System at Cornell University

Components

The current optical inspection system at Cornell University consists of the following components: a light/mirror apparatus, cavity stand, and a camera with a long distance microscope, as well as other hardware.

The light/mirror apparatus consists of a stand (shown below), a hollow tube, a mirror and a light source. The stand—the height can be adjusted—acts as a support for the entire light/mirror apparatus. The hollow tube is mounted onto the stand and is long enough to accommodate any single- or multi-cell cavity. Inside the tube, a circular mirror is mounted at 45 degrees to allow the inner surface to be viewed. A light source made from LED lights encased in a gel is located directly above the mirror (shown below). Gel causes light to diffuse which is important when looking at a highly reflective surface.

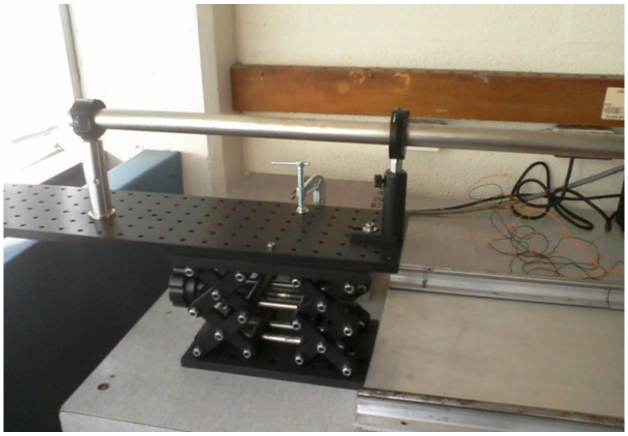


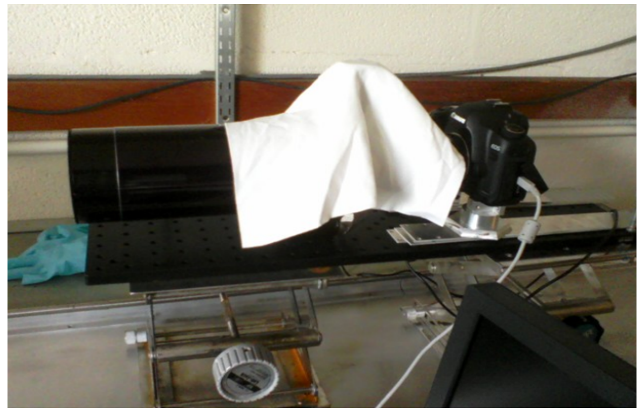
Figure 2: The light mirror/apparatus is mounted onto this adjustable stand. Rails used to move the cavity stand along the beam symmetry axis are visible in the right side of this image.

The cavity stand is an aluminum fixture that supports the cavity. Specifically, it supports a cavity's beam tubes, allowing for an individual to rotate the cavity during inspection. This stand moves in the z-direction— it runs parallel to the beam tubes of the cavity— with the help of rails.

Figure 3: The actual light/mirror portion of the light/mirror apparatus. The mirror is located beneath a slit in the gel substance. This substance spreads out the light from the LEDs reducing glare on the cavity surface.

A digital camera is connected to a QUESTAR long distance microscope, and this entire set-up is set on top of a stand similar to the one on which the light/mirror apparatus is mounted (shown below). This device is connected via USB cable to a computer. Using a program, a person inspecting a cavity will be able to view the surface of that cavity on the PC.

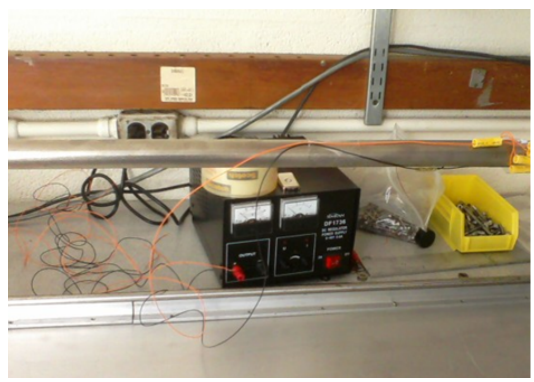
Figure 4: The QUESTAR long distance microscope is the long black cylinder in the left side of this picture. It is attached to a digital camera which is hooked up to a computer using a USB cable.



How a Cavity is Inspected

Using the components described above, a cavity can be inspected for any imperfections. Clean, defect-free cavities are extremely important for desirable results during cavity testing, so cavity inspection is crucial.

Figure 5: The power supply provides electricity to



power the LED lights. Adding too much power could cause the lights to blow out, so great care is taken.

First, a cavity is placed on the cavity stand. Then, the power supply (pictured above) is turned on and adjusted until the LED lights are bright. The stand supporting the light/mirror apparatus is adjusted to fit inside the cavity without scraping the interior of the cavity, and the cavity stand is moved along the rails until the light/mirror apparatus is close to the equator region of the cavity. The camera is turned on, and its stand is also adjusted. After focusing, one should be able to see the inside of a cavity (see image below).

Figure 6: The inside of LR1-3. A cavity is named according to the company that made it and the series number. Since several are made in a series, an additional number indicates when it was made. This cavity was made by LR, 1st series, 3rd cavity in that series.

Pictures are taken and saved for several reasons; however, cavities go through processing such as mechanical polishing in order to remove dust and foreign particles. By taking images of the cavity surface and saving them, tracking changes in the cavity surface becomes possible. This is important because the individuals that perform cavity tests need to see how a certain process changes the surface in order to create consistent cavity test results.

Any images that show a possible defect are recorded, and the location of the possible defect on the cavity is taken note of as well. The location is determined using a coordinate system which will be explained later on in the paper.

IMPORTANCE OF AUTOMATION

Due to several issues with the current optical inspection system, an automated system is in the best interest of Newman Laboratory. Several other well-known SRF labs have automated systems for cavity testing. One of these labs is Fermilab, located in Batavia, Illinois, USA. The plan that will be described in later sections was inspired by their system.

Issues with Current System

The current optical inspection system has several issues that will hopefully be corrected with the automated system. They are:

- Vibration—caused by movement of cavity, air conditioning, etc.
- Time—moving the cavity and rotating it, and taking pictures of the entire cavity takes time.
- Human error—since the current system is controlled by people, error is bound to happen.

Vibrations will occur no matter what, but the current equipment used to for optical inspection is not made to dampen vibrations. So, every time the cavity is moved or rotated, a stand is adjusted, or someone accidently bumps into the table, vibrations occur. This is a problem because most of the light/mirror apparatus is suspended in the air, and vibrations cause it to oscillate. All of this contributes to blurry images which results in a poor inspection. Defects can be missed, and defects could possibly cause field emissions during cavity testing. Surfaces that are able to damp vibrations are important to a successful cavity inspection.

There is an old saying that "Time is of the essence." This statement is definitely true for niobium cavities. As mentioned previously, before they can be tested, cavities have to be clean and defect-free. This can result in more than one session of mechanical polishing or chemical treatment, etc. Each time a cavity is processed, it must be inspected; so, if a cavity has to go through a procedure more than once, it would have to be inspected more than once. Cavity inspection can take hours; therefore, automation is important to reduce time consumption.

Whenever people are involved, there is always human error present. This is especially true for the process of cavity inspection. An individual moves the cavity along the z-direction and rotates it. It is very easy to move too far from the area of interest, or miss a section when rotating. It is also easy to take pictures that overlap. By automating the system, motors will move the cavity and rotate it with precision which will reduce human error.

How the New System Will Eliminate/Reduce Issues

The new system is designed to reduce the three major issues with the old system. Parts were chosen that produce few vibrations—some even dampen vibrations. Computer-controlled motors reduce time as well as eliminating human error. Together, all these will result in better and faster optical inspections.

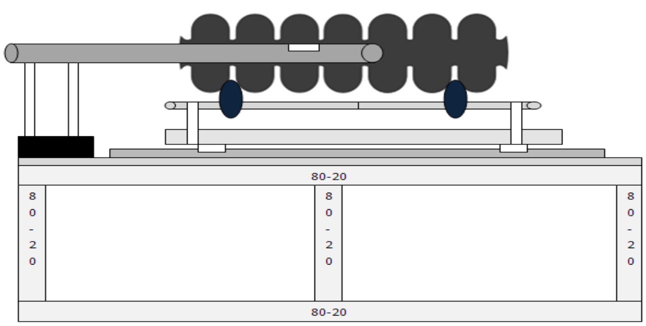
The vibration problem will be minimized by the method of reduction. Great care was taken to select parts for the new optical inspection system that will reduce vibrations. For instance, a new set of rail guides that have a unique shape will allow for smoother movement of the cavity. Smooth movement means that fewer vibrations will occur. In addition to new rails, the entire optical inspection system will be mounted onto a frame of 80-20. 80-20 is a system of building materials that have a specific shape made from an aluminum alloy. The shape and aluminum alloy result in materials that aren't heavy yet provide strength. In addition, the 80-20 shape that was chosen is supposed to reduce vibrations (see image below).

Figure 7: 3030 T-Slotted Profile 15 Series 80-20 that was chosen for the new optical inspection system. It should dampen vibrations.

Not only will the new optical inspection system reduce vibrations; it will also save time. Motors will be doing most of the work, resulting in shorter cavity inspections. The pictures will be stored on a computer, and if someone wants to view them later, the images can be called up using a MATlab program which will be described further on in this paper.

The final issue that the new optical inspection system will fix is human error. Human error in a cavity inspection can result in a missed defect which can give poor results during cavity testing. By using computer-controlled motors, human error is eliminated.

Figure 8: A computer sketch of the new optical inspection system. An 80-20 frame and aluminum plate will serve as a table for the entire system.



THE NEW SYSTEM

Components

The new optical inspection system at Cornell University will consist of many different parts—some from the current system, some that are new. All of these parts should work together to create a more efficient way to inspect cavities. (A sketch of the new system is shown above).

The components that will remain from the current system are the following: the light/mirror apparatus and the camera/long distance microscope. The light/mirror apparatus was recently improved, and it works well. It provides light that is gentle enough not to produce a glare, but strong enough to view defects. The adjustable stand and the length of the apparatus accommodate different types of cavities which is important for future cavity inspections at Newman Lab. The camera and long distance microscope also work well. The result is good, high resolution images which help individuals detect defects.

In addition to the parts from the current system, the new system will feature many new parts such as an 80-20 frame, a SKF LLT Profile Rail Guide system, a new set-up to support a cavity, and motors. As described previously, the 80-20 frame will dampen vibrations, and it will provide a solid base for the entire system. A one-inch thick aluminum plate will be used as a surface on which the system will be mounted. The profile rail guide system will be mounted on top of the aluminum. Consisting of a set of rails parallel to each other with two flanged carriages on each rail, this set-up will be controlled by a stepper motor. It will move the cavity along the z-direction. The carriages will hold a piece of aluminum, or some other kind of metal, on which two shafts will be mounted. Each of these shafts will have two rubber wheels on them. These wheels will support the cavity and rotate it with the help of another stepper motor.

How the New System Will Work

The new system will be used in a manner similar to that of the current system. An individual will place a cavity on the new stand, making sure the rubber wheels are adequately supporting the cavity. The power supply will then be turned on and adjusted until the light is well-lit. Then, a computer will be turned on, and a program will run the motors: One will move the cavity along the z-direction until the light is at a desired location (usually the equator), and the other motor will rotate the cavity. The computer will keep track of how much the motors moved. This will allow for the individual inspecting the cavity to know which images correspond to a certain area of the cavity surface. Once the motors move the cavity, one should be able to see an image on the computer after focusing the camera.

CONCLUSION

Steps Taken to Produce a Plan

In order to produce a plan for a new optical inspection system, several steps were taken. The first step was using the current system. To see what needed improvement, the current system was used to inspect four cavities. This showed the issues of vibration, time and human error. The next few steps were intertwined. One of these steps was to come up with a plan using stepper motors. Several were made and modified until one plan was chosen. Another of these steps was to look for parts online and in catalogues. After consulting with many individuals, a list of products needed for the new system was compiled, and a rough sketch was made on the computer.

Products Needed for Optical Inspection System:

Type	*Specifics*	*Price*	*Quantity*	*Total Price*
Stepper Motor: MDrive Hybrid 23 Double Stack Length with Quick Start Kit	QuickStart Kit-MAI3CRL23B6-EJM	$825.03	2	$1650.06
Linear Guide Rail: SKF LLT Profile Rail Guide System with flanged extended length carriages (LA)	LLTHS30LA2T12700P3E0MS3 -system -carriage size 30 -two carriages per rail -2700mm length rails	About $1000	2	About $2000
Gear Reducer: Thomson Micron with Redimount Kit	XT060-005-RM060-1	$374.74	2	$749.48
Aluminum Plate for the top of the frame	6061 Aluminum Plate -24" wide -120" long -1" thick	$1167.99	1	$1167.99
Rubber Wheels	5.00008.835EN Endura Solid Elastomer (4-6 Series Models) -8" diameter -1/2" precision sealed ball bearing	$40.11 + freight	4	$160.44
Stainless Steel Shaft: D-Shaft McMaster	8632T11 Steel -1/2" diameter -48" long	$27.83	4	$111.32
80-20, brackets and fasteners	3030 T-Slotted Profile 15 Series with 7030 (cut to length) -Four 120" long -Four 24" long -Four 36" long	$144/ea 120" long + $28.80/ea 24" long + About $30/ea 36" long + $2.08/ea for cutting	12 total + fasteners and brackets	Around $1000.00

Figure 9: A screen shot of the list of products for the new system.

Inspecting Cavities

As mentioned previously, four cavities were inspected to find issues with the current system. In addition, they were inspected in order to create a program using MATlab that will allow an individual to call up an image of a specific location on a cavity surface. A program was written using a set of coordinates: the first is a number that corresponds to an angle from a reference point on the cavity equator. The second coordinate is a number that corresponds to distance away from the equator. To the right of the equator is positive, to the left—negative. Unfortunately, the program needs some tweaking, but after it is fixed, it will help with cavity inspections.

Hopes for the New System

The new system was designed with a lot in mind. Issues of vibration, time and human error will hopefully be reduced with new products and motors. Individuals who will use the new system should have more successful cavity inspections which will hopefully lead to more successful cavity tests. The future of SRF technology is changing, and the new optical cavity inspection system at Cornell University will hopefully be a part of it.