Designing a System to Locate a Defect in a Superconducting Accelerating Cavity

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Submillimeter-sized defects in a superconducting accelerating cavity can compromise the accelerating gradient of the cavity. Locating such defects and repairing them is one way to improve a cavity's gradient. Superconducting cavities require a bath of liquid Helium to keep them cold, and certain properties of liquid Helium can be used for locating cavity defects. Improving the accelerating gradient of superconducting cavities can help lower the costs of particle accelerator construction.

Introduction

Superconducting accelerating cavities are used to accelerate particles. The production process can leave defects on a cavity's interior surfaces, which must be very smooth. Smooth surfaces help to minimize the surface resistance in the cavities to maximize their acceleration gradient. Many procedures abate the development of defects, such as removing interstitial impurities, meticulous quality control, and cleaning procedures [1]. Nonetheless, the appearance of defects is still common.

Defects are submillimeter-sized regions that can enhance localized power losses in a cavity. As the temperature rises around a defect, the local superconductivity will return to a normal conducting state when a critical temperature is reached; this can induce what is called a "quench". This limits the accelerating gradient of the cavity, leading to a need for more individual cavities to reach the desired particle beam acceleration. Being able to locate and mitigate cavity defects is one way of improving the accelerating gradient. Cavities with higher accelerating gradients lead to the construction of shorter and cheaper particle accelerators.

I. Superfluid Helium

Helium has the lowest boiling point of any known substance, condensing to a liquid only upon reaching a temperature of 4.2 Kelvin. Liquid Helium can solidify at 1.5 Kelvin only under a pressure of almost 25 atm [2]. Upon condensation, the liquid is called Helium-I.

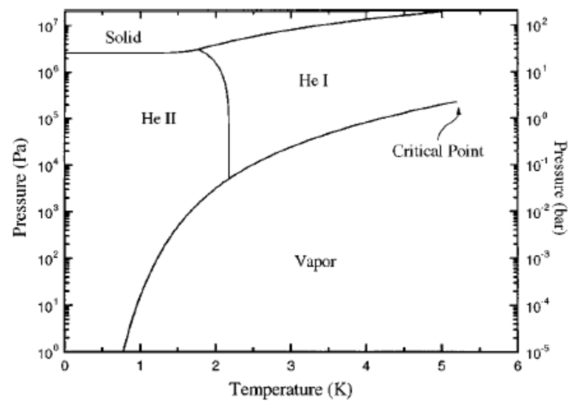

Figure 1: Phase diagram for Helium-4 [3]

Below a temperature threshold of 2.18 Kelvin, called the Lambda point (λ-point), liquid Helium-I undergoes a phase transition into Helium-II. The Lambda point is so-called due to the characteristic transition of specific heat of liquid Helium, above and below 2.18 K. Helium-II can be analyzed with a two-fluid model, which is a mixture of normal fluid and superfluid [4]. Helium-II has many interesting properties, such as the Fountain Effect, creeping up vertical walls, and evaporating without boiling. The superfluid component of Helium-II has no viscosity and can pass through holes or channels that are impermeable to other fluids, including Helium I. The superfluid also has no entropy; Helium molecules in the superfluid are in a single state, their ground state, whereas molecules in the normal fluid are in an excited state. This means that the normal fluid of two-fluid Helium carries all of the entropy. Superfluid Helium also has a million times the heat conductivity of Helium I, and several hundred times the heat conductivity of copper [5]. This is because heat travels as a wave in Helium-II, called second sound.

II. Second Sound

Heat propagates through Helium II as second sound. Second sound is a propagating wave of entropy due to fluctuations in temperature, a temperature-entropy wave. Second sound waves are analogous to the pressure-density waves we hear and feel and are all familiar with, known as first sound. In Helium II, at around 1.8 K, second sound travels at u_2=20 m/s. This is much faster than the rate of heat transfer through conduction in Helium-I, but slower than first sound (u_1=220 m/s). (For a more technical detail of second sound, consult Russell Donnelly's article, "The Two-Fluid Theory and Second Sound in Liquid Helium.")

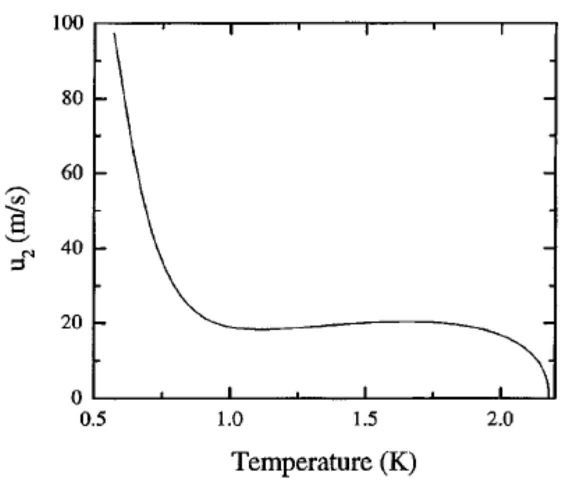

Figure 2: Velocity of 2nd sound changing with temperature [3]

III. Oscillating Superleak Transducers (OSTs)

Second sound can be produced or measured with special transducers that can act as either a microphone or a speaker. These transducers can convert second sound oscillations into electrical signals, and vice versa. A brass disk forms one side of a cylindrical parallel-plate capacitor, an Aluminum thin film forms the other. The Aluminum coats a micro-porous polycarbonate diaphragm that is impermeable to normal liquid Helium, but allows superfluid Helium to flow through freely due to its zero viscosity [6]. The diaphragm also remains flexible when submersed in liquid Helium. When second sound oscillations reach the transducer, the flexible diaphragm swells and contracts. Because of the metal coating on the diaphragm, these oscillations translate into an oscillating plate on the cylindrical capacitor, leading to fluctuations in capacitance. The changes in capacitance can be measured and recorded on an oscilloscope.

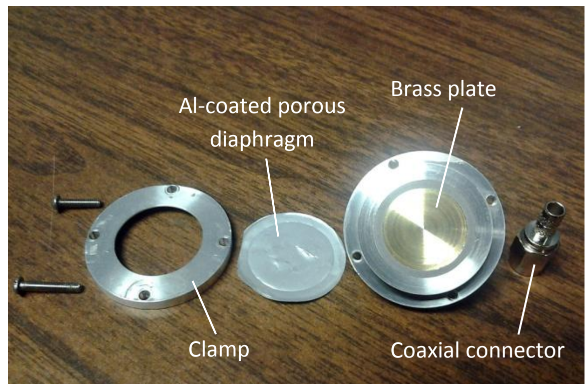

Figure 3: Dismantled OST microphone, in order of assembly

IV. Trilateration

Trilateration uses geometry to locate a point, P, from 3 known locations, A, B, and C. This is done with the known distances between point P and each stationary location A, B, and C. The distances AP, BP, and CP represent the radii of spherical surfaces centered at A, B, and C respectively. The intersection of any 2 of these 3 spheres will form a circle; the intersection of all 3 spheres consists of 2 points. This system, 3D trilateration, is used by a smartphone when it reports the user's location using 3 or more GPS satellites of known location.

In application, point P is the source of a signal of known or measurable speed. After propagating from the source, this signal is recorded upon arrival at locations A, B, and C. The elapsed times (t_{NP}, where N=A,B,C) are measured between the signal's emission at P and the signal's arrival at each location A, B, and C. From the signal's speed and the travel time to each known location, the distances AP, BP, and CP can be calculated, shown below, and used for trilateration. More than 3 known locations can be used to increase the accuracy of locating point P.

$$2^{nd}\ sound\ velocity \equiv u_2 = \frac{\Delta x}{\Delta t}$$
$$AP = u_2 \Delta t_{AP}, BP = u_2 \Delta t_{BP}, CP = u_2 \Delta t_{CP}$$
$$R_{AP} = AP, R_{BP} = BP, R_{CP} = CP \qquad (1)$$

The R_{AP}, R_{BP}, and R_{CP} values represent the radii of the spheres that intersect at the location of the signal's source.

V. Design

A system was developed for locating a defect inside a fully assembled pure Niobium quarter-wave resonator (QWR), a type of superconducting radio-frequency (SRF) cavity.

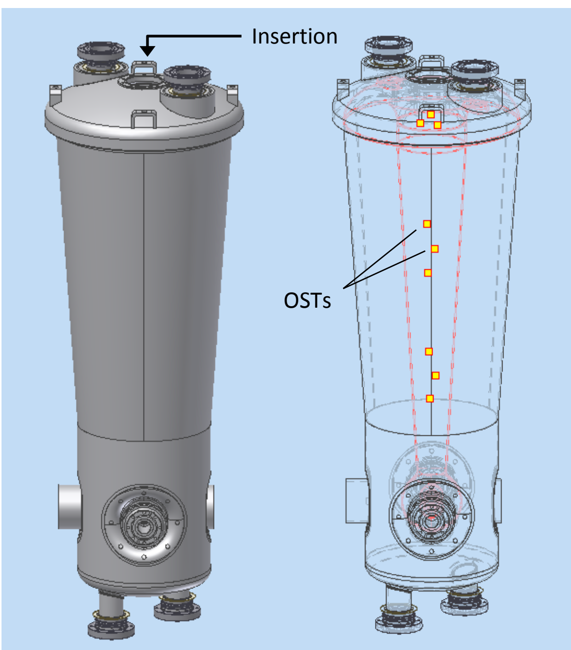

Figure 4: QWR diagram showing position of OSTs (yellow squares) and entrance where the system is inserted

The system consists of a support structure positioning 9 second sound microphones (OSTs) throughout the inside of the cavity's center conductor. The center conductor is outlined in dotted-red in figure 4.

Using second sound for locating a defect is preferable over using first sound because the velocity of second sound is less than a tenth the velocity of first sound. This matters because the measurement electronics have a time-measurement error of ±0.1ms. This translates into an error in position measurement, shown below.

$$1^{st}\ sound\ velocity \equiv u_1 \approx 220\frac{m}{s}$$
$$2^{nd}\ sound\ velocity \equiv u_2 \approx 20\frac{m}{s}$$
$$t \equiv time\ elapsed\ from\ quench\ to\ detection$$
$$\Delta x_n \equiv distance\ traveled\ by\ n^{th}\ sound\ wave$$
$$t = t_\alpha \pm 0.1ms$$
$$\Delta x_1 = u_1 t_\alpha \pm 0.1ms\ u_1 = u_1 t_\alpha \pm 22mm \qquad (2)$$
$$\Delta x_2 = u_2 t_\alpha \pm 0.1ms\ u_2 = u_2 t_\alpha \pm 2mm \qquad (3)$$

Equations (2) and (3) show the difference of an order of magnitude in accuracy between using first sound versus using second sound for detection.

On the support structure, 9 microphones are organized in a manner that allows for measurement in 3 dimensions, by having 3 degrees of freedom – radial (r), azimuthal (ϕ), and vertical (z). The organization also allows the system to be quickly installed and removed from an assembled quarter-wave cavity. This is partly due to the slim structure being able to fit through 3 inch and 2¼ inch entry holes at the top of the cavity (figure 4). Near the top of the cavity, 3 microphones sit in a plane perpendicular to the cavity's axis. These microphones can measure the location of a second sound source in the azimuthal and radial directions, but cannot determine whether a source is above or below them. Below this array, 2 sets of 3 microphones are organized in a helix; they can locate a second sound source in the vertical direction, as well as enhance accuracy in the azimuthal and radial directions.

Sitting in the center conductor, the structure is immersed in the same liquid Helium bath that keeps the accelerating cavity cold and superconducting. Using the velocity of second sound, and the time elapsed between a cavity quench and the detection of second sound by each microphone, distances can be calculated between the defect location and each microphone. This is done using 3D trilateration with 9 spheres. For visualization, 2D trilateration is illustrated below with 3 OSTs pinpointing a defect.

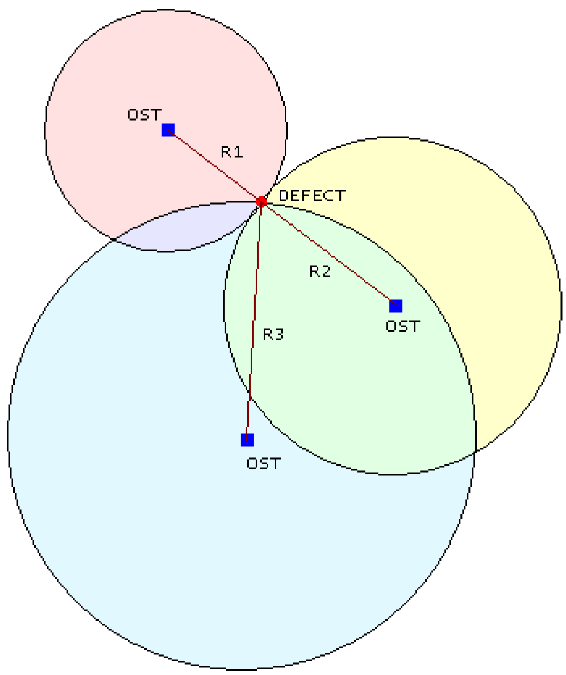

Figure 5: 2D simplification of 3D trilateration for locating a defect, using circles rather than spheres

The final design for the support structure consists of a threaded rod, which serves as a central axis, and support frames for fixing the microphones around the rod. The top array of microphones is held in place with an equilateral triangle made of sheet metal, and bent at the corners. The microphones are held in place with screws. The 2 helix sets each consist of 6 sheet metal rectangles, each bent 90° and 1 inch from one end. The 6 bent metal strips hold 3 microphones in an equilateral triangular shape, and separate the microphones by an equal distance apart in the vertical direction. This creates the helical shape. The top array of OSTs can fit through a 3 inch diameter clearance hole in the Helium jacket at the top of the cavity; this jacket is what encases the liquid Helium bath around the cavity. The top set of OSTs is positioned in the spacing between the Helium jacket and the entrance to the center conductor. The 2 lower sets of microphones can fit through a 2¼ inch clearance hole at the top of the center conductor, allowing them to be fixed within the center conductor. The entire structure is fixed in place at one end, with an attachment at the top. This attachment is held to the top of the cavity with screws.

Several designs were investigated before reaching the final design for the system. Designs, drafted mostly on Autodesk Inventor, were tested using cardboard scraps. The cardboard simulated the sheet metal and allowed for quick testing at no extra costs.

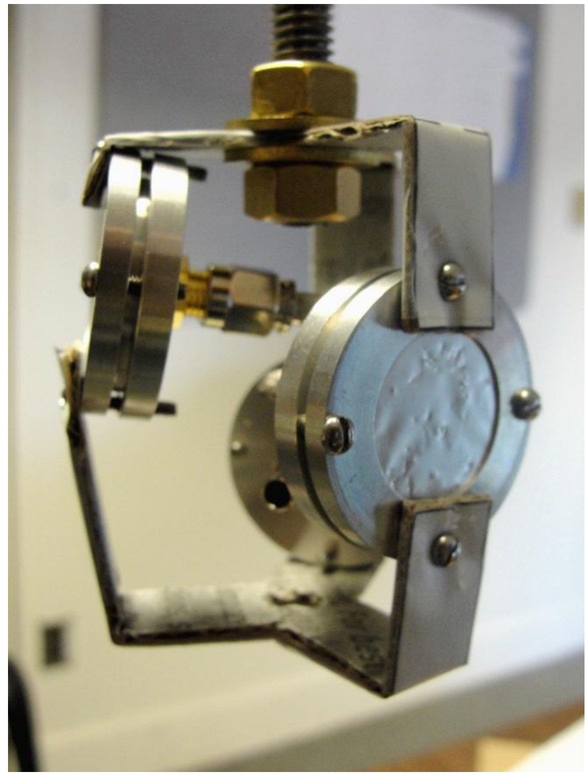

Figure 6: Early design for helical support structure being tested with cardboard

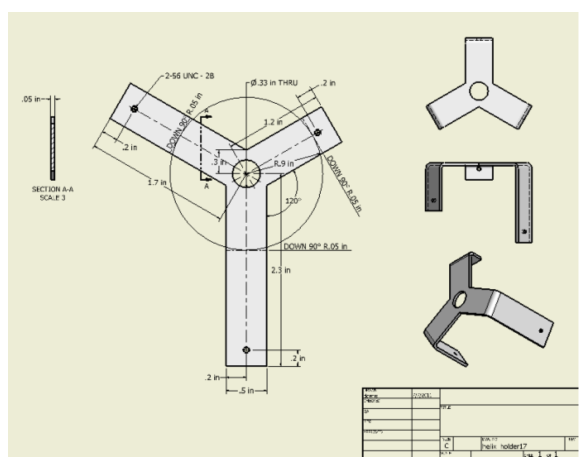

Figure 7: Corresponding Autodesk Inventor draft for cardboard model in figure 6

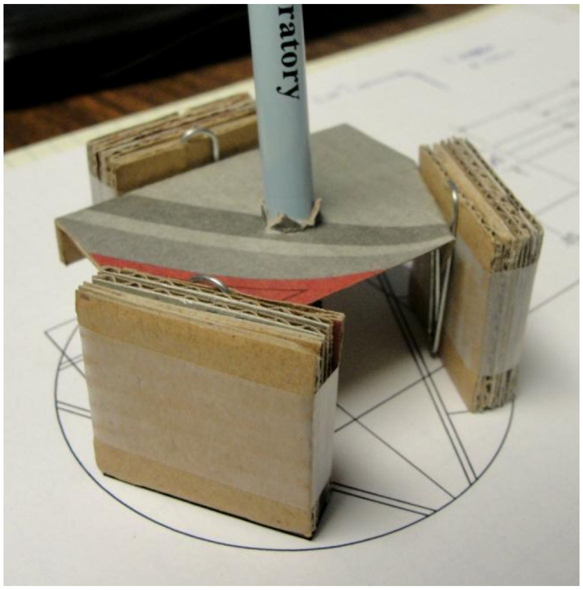

Figure 8: Early cardboard model positioned over its corresponding draft, contained within a 3 inch circle

VI. Conclusion

Unfortunately a field-test was not possible due to complications in the anticipated quarter-wave resonator testing schedule, and unavailability of other quarter-wave cavities to test. Hypothetically, testing the detection system would involve assembling and wiring-up the entire microphone support structure. The structure would be lowered into a quarter-wave cavity and bolted at the top. The first test would be making sure the system fits securely into the cavity.

The cavity's Helium jacket would be filled with liquid Helium, immersing the microphone system. The accelerating fields would be powered up until a defect within the cavity produces a quench, which can be measured on an oscilloscope. The quench, producing large amplitude second sound waves, should be followed closely by responses from the microphones, also measurable on the oscilloscope. By measuring the time delays between the event of a quench and the response from each microphone, distances can be calculated between the second sound source and each microphone using the velocity of second sound and the known locations of each microphone in the cavity.

Using trilateration, the intersection of the spheres with radii corresponding to each distance could be calculated mathematically, providing a 3-dimensional coordinate for the defect somewhere in the cavity. The location would be inspected by microscope for the suspected defect.

With permitted time, testing of this system is possible.

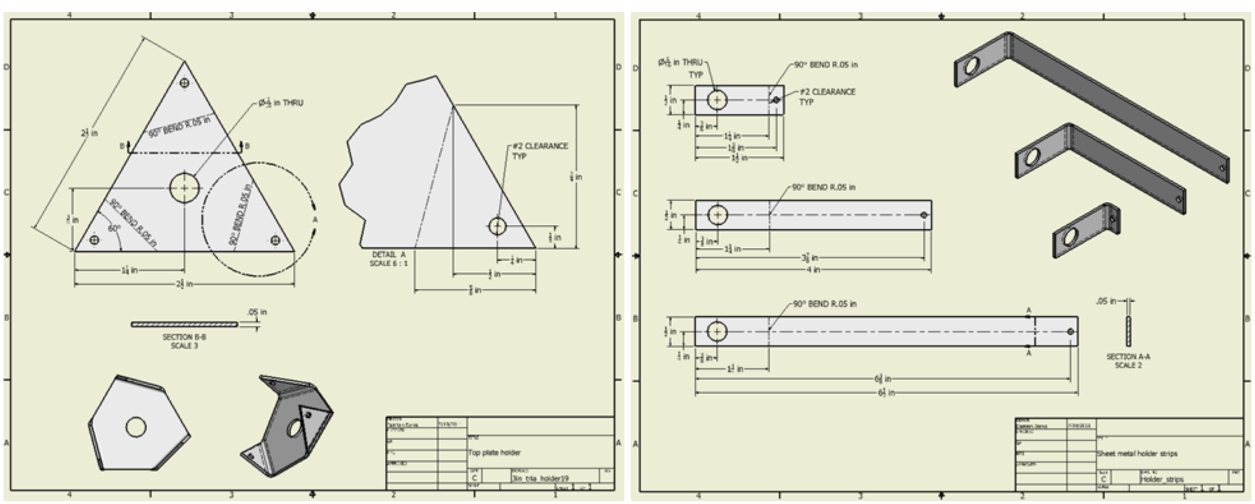

Figure 9: Final drafts for microphones supports. Left: Support piece for top set of microphones (Expand: http://postimage.org/image/vqhvek5g/). Right: Support pieces for helical set of microphones (Expand: http://postimage.org/image/vqjixwn8/)

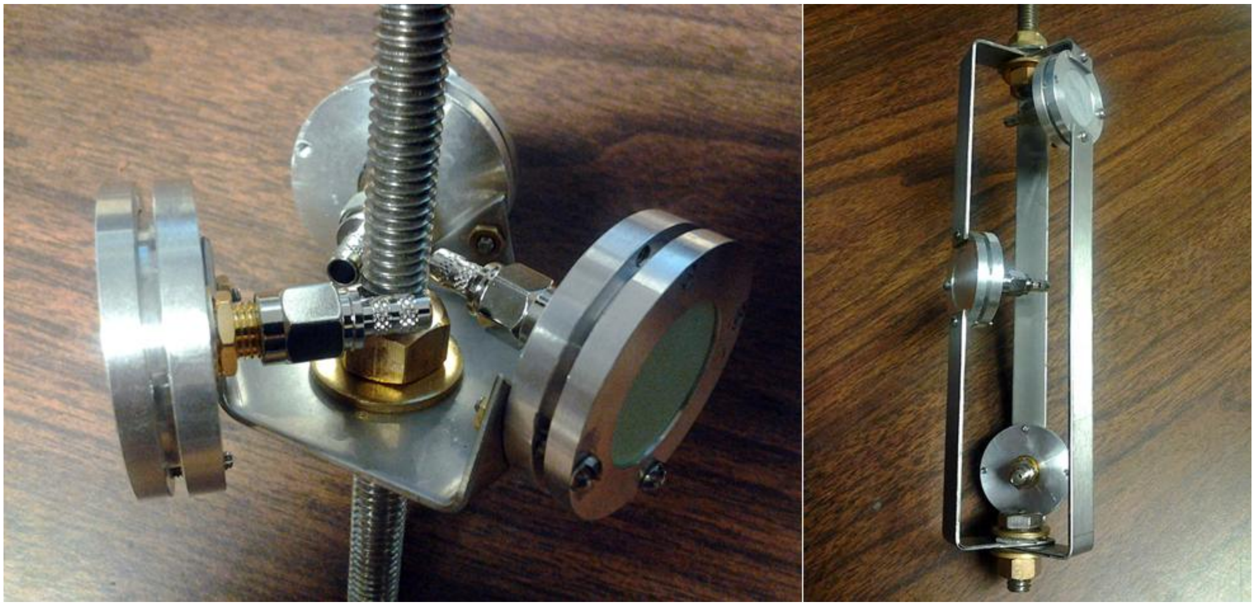

Figure 10: Final assembled models for the microphone supports. Left: Top microphone array (Expand: http://postimage.org/image/zui6wj50/). Right: Helical microphone array (Expand: http://postimage.org/image/vqcwsio4/

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