# DEFECT LOCATION IN SUPERCONDUCTING CAVITIES COOLED WITH HE-II USING OSCILLATING SUPERLEAK TRANSDUCERS*

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### *Abstract*

Superconducting RF cavity quench location is presently a cumbersome procedure requiring two or more expensive cold tests with large arrays of thermometers. One cold test identifies the cell-pair involved via quench field measurements. A second test follows with numerous fixed thermometers attached to the culprit cell-pair to identify the particular cell. A third measurement with many localized thermometers is necessary to zoom in on the quench spot. By operating superconducting RF cavities at temperatures below the lambda point the second sound wave emanating from the location where quench occurred can be utilized to triangulate on the quench-spot. Here a method which utilizes a few (e.g. 8) oscillating superleak transducers (OST) to detect the He-II second sound wave driven by the defect induced quench is discussed. Results characterizing defect location with He-II second sound wave OST detection, corroborating measurements with carbon thermometers, and second sound aided cavity repairs will be presented.


## INTRODUCTION

Due to major R&D efforts by many laboratories within the TESLA Technology Collaboration (TTC), DESY and JLAB have now successfully tested more than 20 cavities over 35 MV/m [1, 2]. Nevertheless the means for reliably producing cavities which achieve accelerating gradients >35 MV/m with a high yield remains to be demonstrated as one of the ILC highest priority R&D goals. Frequently, the cavity gradients are limited by defects on the RF surface which quench at field levels well below 35 MV/m. Such quench limited cavities may be repairable but the process of locating defects in 9-cell cavities remains a lengthy and cumbersome process.

Many laboratories are developing large scale thermometry systems to pin-point the quench locations. Here, we present a cost-effective and simple method to determine quench locations (defects). By testing a superconducting cavity in a superfluid helium bath it is possible to observe second-sound temperature waves driven by the conversion of stored RF energy to thermal energy at the defect [3, 4]. By measuring the time-of-arrival of the second sound wave at three or more detectors the defect location can be unambiguously determined in three dimensions. The work presented here builds upon and enhances the technique pioneered by Kenneth Shepard at Argonne National Laboratory more than thirty years ago [3]. By locating several germanium

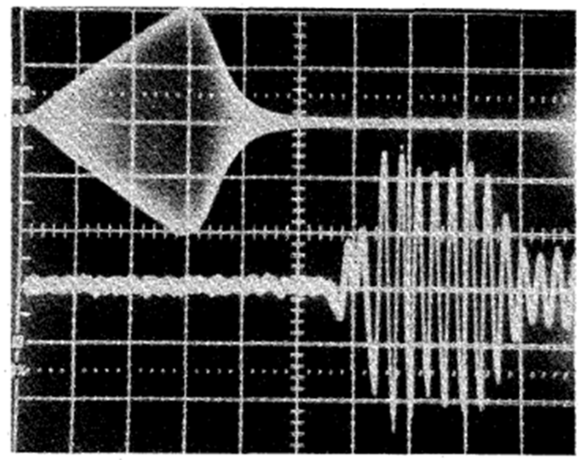

Figure 1: A quench event observed at ANL by Ken Shepard in the late 1970ies [3].

resistance thermometers inside the niobium tube of the split-ring resonators undergoing qualification tests cavity quench-spots were located. In this application, the second sound quench location technique was employed in a one-dimensional system. Figure 1 shows an oscilloscope photograph of the results [3]. The top trace is the RF field level in split-ring resonator, which was excited to $E_{acc}$ = 3.0 MV/m where the cavity quenched. The lower trace is proportional to the temperature of a thermometer located inside the split-ring resonator.

Here, we focus on pure three dimensional systems and on oscillating superleak transducers (OST). OSTs measure the fluctuating superfluid helium counterflow velocity to detect the time of arrival of second sound waves [5, 6, 7]. Resistive temperature transducers are still employed at Argonne and a detailed discussion of their development program can be found in reference [8].

This paper is split into four parts. First, we introduce the second sound detection system and present an example of the data used to locate defects. Second, we present results from direct thermometric measurements of the cavity outer surface which corroborate the second sound defect location. Third, we give two examples where second sound measurements initiated the successful repair of superconducting cavities and where multiple defects were located in a single cold test. Finally, we conclude with a brief summary of the impact of the work presented here and an overview of our future plans.

## SECOND SOUND DETECTION

The abrupt dissipation of the stored RF energy during quench can be a symptom of a surface defect. In each

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cavity cold test an array of OST are employed to locate the defect. A typical OST arrangement uses 8 transducers evenly distributed around the cavity. The OST employed here are parallel-plate capacitors with one rigid plate and one flexible-porous plate. The pore diameter is chosen to clamp the flow of the normal fluid while allowing the superfluid, with zero viscosity, to pass freely. The arrival of a second sound wave at the OST causes the flexible-porous-plate to move with the normal fluid as the second sound wave passes. The capacitance of the detector is continuously monitored to measure the arrival of the second sound wave.

Figure 2 shows the experimental data from an observed quench at 1.7 K. The top, step-like, trace shows the cavity field amplitude in a single-cell TESLA-style cavity, which was excited with an RF pulse to $E_{acc}$ = 28 MV/m. At this accelerating gradient the resonator quenched and the RF field decays. The lower three traces show the signals measured with three distinct OSTs immersed in the superfluid helium bath with the cavity. For clarity the other five transducer signals are not shown. In figure 1, the OSTs detect the arrival of the second sound wave 4.3 ms, 7.2 ms, and 7.9 ms after quench. This indicates that the defect in the cavity is 8.8 cm, 14.7 cm, and 16.1 cm from each OST respectively. Please note, this picture is representative of many quench events and the process is highly repeatable.

Using this method the defect location is determined to an area within a radius of 2-4 cm. Alternatively, using the second sound wave velocity as a free parameter and searching for the point where the signals converge improves the defect location estimate by a factor of ~3. Once the defect location is known the cavity interior is optically inspected and a course of repair can be determined.

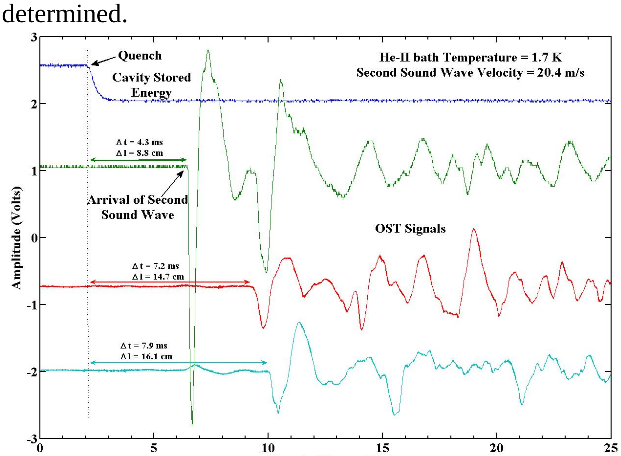


Figure 2: A typical quench event observed with three different transducers. The top trace is the amplitude of the cavity RF field. The lower three traces are the second sound signals measured with 3 distinct OST. The variation in the second sound wave time-of-arrival is well correlated with the variation in propagation distance to each transducer.

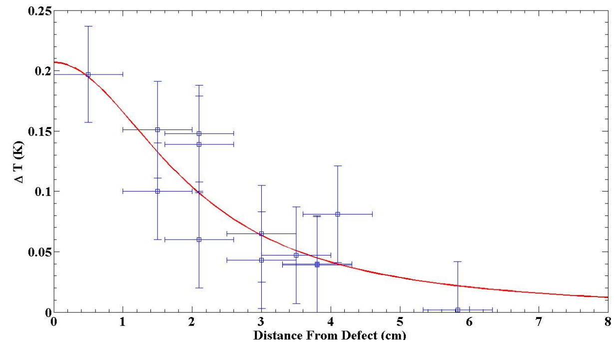


Figure 3: An example of the spatial distribution of cavity heating due to a defect.

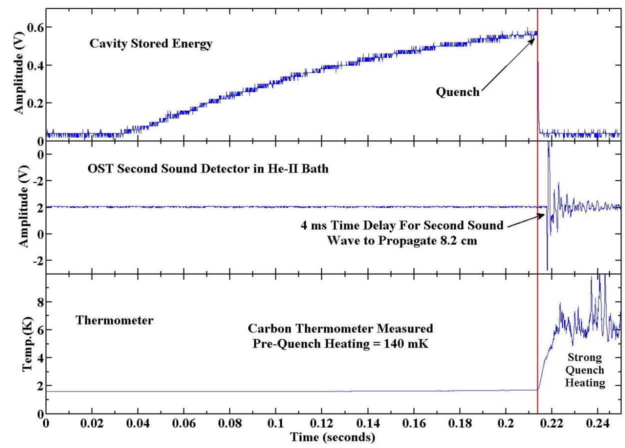


Figure 4: A single quench event measured with an OST in the He-II bath 8.2 cm away from the cavity defect and with a carbon thermometer attached to the cavity surface 2 cm away from the cavity defect.

## THERMOMETRIC DEFECT LOCATION

The comparison of second sound and steady state thermometric measurements for a defect located on a 9-cell reentrant cavity were reported on in [4]. This result demonstrated the correlation between second sound and fixed thermometer array defect location. However, due to a failure of the input coupler feedthrough from very high power application during testing we were only able to weakly couple to the cavity. The maximum achievable accelerating gradient was limited to 8 MV/m in the cell with the defect.

Here we compare the results of second sound and thermometric measurements performed at field amplitudes around the quench field. Both, steady state and static measurements are presented.

Figure 3 compares the second sound defect location to the actual defect's temperature distribution for a cavity excited to a field amplitude of $E_{acc}$ = 23 MV/m just below the quench field of 24 MV/m. There are two sets of data shown here:

- The temperature rise of the cavity outer surface measured with a thermometer array centered on the second sound determined defect-location, the solid points with error bars.

- The estimated heating due to a simulated defect from thermal model codes [9], the continuous line.

The horizontal axis is the radial distance away from the defect location determined by second sound. The vertical axis is the temperature rise due to heating, the difference between the measured temperature at $E_{acc}$ = 23 MV/m and the measured temperature when the cavity is not excited. Notice, the defect location determined by thermometric measurements agrees with the second sound measurements to ~5 mm.

Figure 4 compares the dynamic heating of the cavity to the detection of second sound waves. There are three sets of data shown. The top trace is the amplitude of the cavity RF field. The middle trace is the signal from an OST located 8.2 cm away from the defect in the helium bath. The lower trace is the cavity surface heating measured with a carbon thermometer in contact with the cavity outer surface and 2 cm away from the defect. During quench the cavity heats to >9 K, the critical temperature of niobium. The second sound detector does not measure the arrival of the second sound wave (heat) until after it propagates to the OST. Notice the change in temperature scale between figures 3 and 4. The thermometer in figure 4 heats 140 mK just before quench, an amount only barely visible on this scale. After quench it warms up, note that 6K is the upper temperature limit of the electronics used for this measurement.

## SECOND SOUND APPLICATION EXAMPLES

In the past year the second sound defect location system led to the location and characterization of many defect limited cavities and three of these cavities were repaired at Cornell. We will briefly review these results in this section and comment on the status of another cavity awaiting repair.

First, two single-cell cavities were defect limited due to a flaw in the die used to form the cavities. The initial cold tests found these cavities defect limited and second sound measurements located the defects to the same spot on the cavity surfaces. Subsequent optical inspection found a strange bump which was quickly determined to be due to a flaw in the die used to form the cavities. Removing the bumps with BCP etching removed the defects and increased the cavity quench fields. Figure 5 shows the cavity defect. This defect was located with second sound measurements with a single cold test. For both cavities, fixing the defect increased the cavity accelerating gradient from ~20 MV/m to ~30 MV/m.

In another example, second sound measurements located a pit-defect on the equator weld of a reentrant 9-cell cavity, reported on in [10]. Note that this pit is on the weld and not in the heat affected zone. This cavity was tumbled, removing just enough material to eliminate the weld pit. After reprocessing the cavity accelerating gradient exceeded 30 MV/m; previously the defect-limited cavity quenched at 15 MV/m [10].

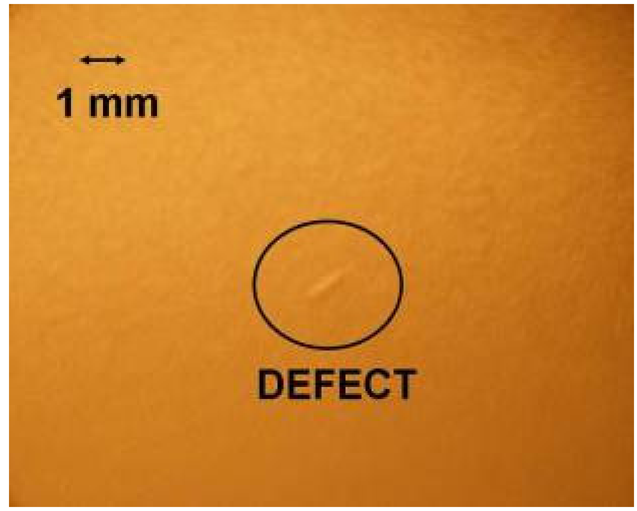


Figure 5: Defect located with second sound.

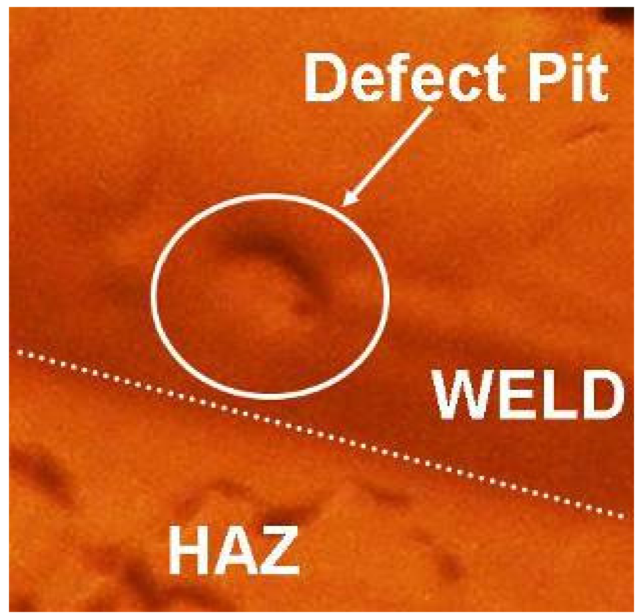


Figure 6: Defect located with second sound on a cavity equator weld. The defect is circles and the weld and heat affected zone (HAZ) are labeled [9].

It is interesting to note that exciting different eigenmodes of multi-cell cavities has been used to locate multiple defects in a single cold test. During a test of an ILC 9-cell cavity, defects were found in three different cells. This was done by powering different modes of the $TM_{010}$ passband during a single cold test [11]. This technique is not regularly employed at Cornell during multicell cavity testing.

## SUMMARY

Locating cavity defects, which cause quench, with second sound measurements is a simple and powerful technique. In one cold test cavity defects are located with a small amount of hardware which is easy to integrate into a vertical test. It is shown that second sound telemetry is well correlated with direct thermometric mapping of the cavity outer surface. This eliminates the need for repeated testing, accommodating thermometric measurements to localize the defect location.

Cornell has successfully used this technique over 30 times in the past year and successfully repaired three cavities, with more second sound guided cavity repairs forthcoming.

## FUTURE PLANS

The current OST design yields transducers with a diameter of ~1.25", and are cumbersome while trying to fit them into all of the areas we would like to put them, e.g. inside cavity helium vessels. We have developed a design which would shrink the OST diameter to ~1/2". The redesigned transducers will undergo the first round of cold tests in the next two months. Locating OST transducers inside the helium jacket of completed cavities is of interest to us for use in quench detection and quench location systems. We have observed pre-quench defect heating in pulsed cavity test but more work is needed before the validity of this technique can be demonstrated for cw systems.

Finally, we are developing a software based data acquisition and analysis system to simplify the process of quench detection and location further. Figure 7 gives an example screen shot of the system under development.

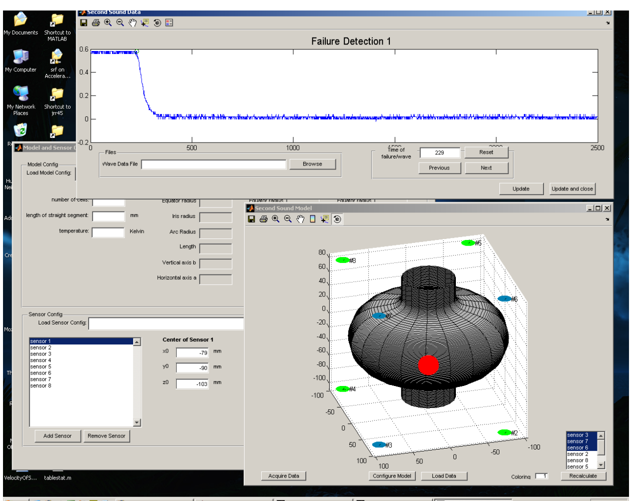


Figure 7: An automated second sound data acquisition and analysis software package is being developed for even easier quench-spot location.

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