ON QUENCH PROPAGATION, QUENCH DETECTION AND SECOND SOUND IN SRF CAVITIES

R. Eichhorn# and S. Markham
Cornell Laboratory for Accelerator-Based Sciences and Education, Cornell University
Ithaca, NY 14853-5001, USA

Abstract

The detection of a second sound wave, excited by a quench, has become a valuable tool in diagnosing hot spots and performance limitations of superconducting cavities. Several years ago, Cornell developed an oscillating super-leak transducer (OST) for these waves that nowadays are used world-wide. In a usual set-up, several OSTs surround the cavity, and the quench location is determined by triangulation of the different OST signals. Convenient as the method is there is a small remaining mystery: taking the well-known velocity of the second sound wave, the quench seems to come from a place slightly above the cavity's outer surface. We will present a model based on numerical quench propagation simulations and analytic geometrical calculations that help explain the discrepancy.

INTRODUCTION

Superconducting Radio Frequency (SRF) cavities are fabricated carefully to make a smooth, uniform surface. This ensures that electric current flows uniformly on the surface of the cavity, so that minimal heating of the cavity surface occurs. Despite precautions taken, it is still common for cavities to bear small (sub-millimeter) surface defects that impede cavity performance. These defects cause localized excess heating. If severe enough, this can heat the surrounding superconducting material (in most cases niobium) to above its critical temperature. When this happens, the niobium becomes normal conducting and begins to heat even more rapidly. This causes a runaway effect wherein all the cavity's stored energy is quickly converted into heat, called a quench. Because defects cause quenching, which severely detriments a cavity's performance, it is important to be able to locate the defect so that it can be removed.

One method of locating a defect involves using oscillating superleak transducers (OSTs,[1]) to detect second sound waves emitted from the cavity. Second sound is a phenomenon observed in superfluid helium[2] wherein heat propagates as a wave with properties comparable to that of a classical sonic wave. The speed of the second sound depends somewhat on the parameters of the fluid, but is almost a constant of 20 m/s, within the temperature range of 1.6 to 2 K.

Once the second sound wave has been produced, the signal propagates through the helium until it reaches an OST. A typical arrangement is given in Fig. 1. By calculating the difference in time between when the quench occurred, which one can measure as the time at which the cavity begins to lose its stored energy, one can use trilateration to deduce the location of the defect [1]. Problematically, when this procedure is performed, there is a discrepancy between the predicted location of the defect and the defect's actual location. In fact, the defect is often detected to be off the surface of the cavity entirely. Also, others [3] have noted that the quench expands faster enough that it may not behave as a point-like emitter of a second sound wave.

Previously, we investigated the possibility of a delay between the loss of stored energy in the cavity and the triggering of a second sound wave [4]. As we did so we could explain a discrepancy in the order of 2-3 mm.

In this paper we will investigate how heat propagation in the niobium can contribute to the quench signal propagation and its effect on quench location.

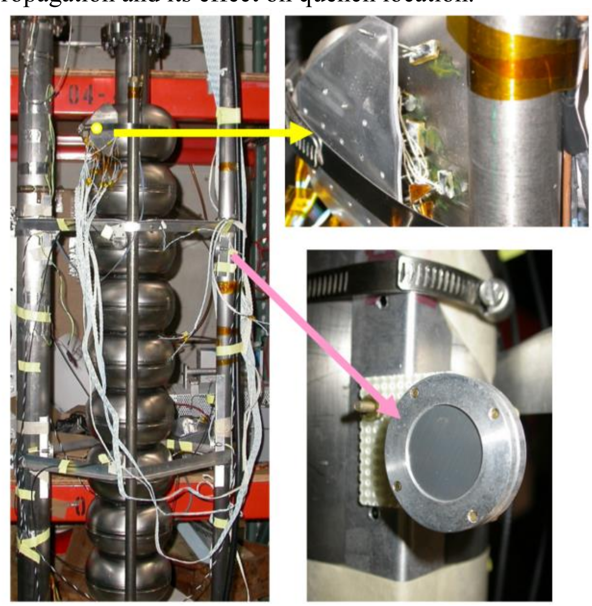

Figure 1: Basic layout of OST quench detection setup. OSTs are set up in an array around the exterior of the cavities, and submerged in He-II (Image from [1]).

GEOMETRICAL SETUP

Calculating Propagation Time

Figure 2 illustrates the basic geometry of the problem. For simplicity, the niobium is assumed to exist simply on a plane. The niobium is in thermal contact with a bath of helium-II. The OST is placed at a distance R from defect and an angle θ from the normal.

Naively, one would assume a signal propagates to the

#r.eichhorn@cornell.edu

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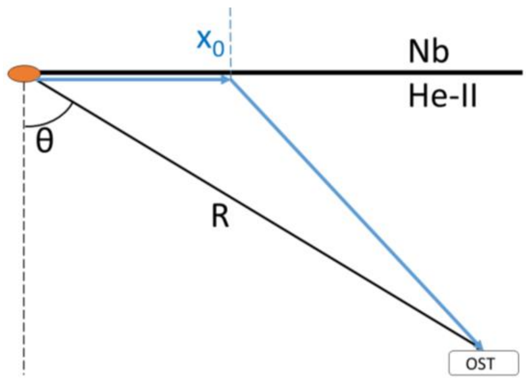

Figure 2: OST setup. In some cases a signal can arrive at the OST faster by travelling first along the surface of the niobium and then propagating through the helium.

OST in $\Delta t = R/v_{SS}$, where v_{SS} is the velocity of second sound in helium-II, in our case held fixed at 20 m/s. However, if the signal also propagates across the niobium, following the path shown in Fig. 2, it will arrive at the OST in

$$\Delta t = \frac{x_0}{v_{Nb}} + \frac{\sqrt{(R\sin\theta - x_0)^2 + (R\cos\theta)^{\,2}}}{v_{SS}} \quad (1)$$

For large angles θ, this can be faster than the direct signal propagation it the propagation in niobium is faster than in Helium ($v_{Nb} > v_{SS}$). Minimizing this equation with the constraints $0 < x_0 < R\sin\theta$, we can find the value of x_0 that minimizes Δt, from which we can infer the time it takes for the fastest signal to reach the OST. The fastest propagation signal is simply $\Delta t = R/v_{SS}$ unless the angle reaches the threshold:

$$\theta_{thresh} = \arctan(\frac{v_{SS}}{\sqrt{{v_{Nb}}^2 - {v_{SS}}^2}}) \quad (2)$$

The full solution to the propagation problem, then, is:

$$\Delta t(\theta \leq \theta_{thresh}) = \frac{R}{v_{SS}} \quad (3)$$

$$\Delta t(\theta > \theta_{thresh}) = \frac{R\sin\theta}{v_{Nb}} + R\cos\theta\sqrt{\frac{1}{{v_{SS}}^2} - \frac{1}{{v_{Nb}}^2}} \quad (4)$$

If one takes $v_{Nb} = 69$ m/s, a value known as the thermal signal propagation derived from the diffusivity calculation[5], based on normal conducting niobium's thermal properties, we can plot $\Delta t(\theta)$ as shown in Fig. 3.

Depending under which angle the OSTs are in relation to the initial quench location, a significant propagation time disparity can exist. The situation gets more serious, if one assumes the thermal diffusion velocity of super-

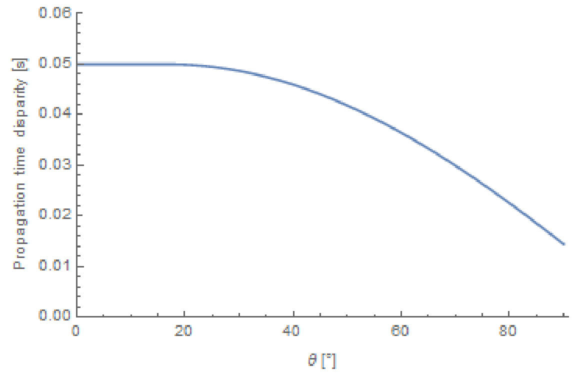

Figure 3: Propagation time (s) as a function of θ (R = 1m, $v_{SS} = 20$m/s, $v_{Nb} = 69$m/s).

conducting niobium, being 800 m/s. As a result, the onset angle according to (2) gets smaller and the disparity increases.

To test under which speed the heat propagates inside the niobium, and whether it is the diffusivity speed of normal or of superconducting niobium, we conducted a numerical simulation, described below.

NUMERICAL SIMULATION

Computational Setup

In order to numerically simulate time dependent quench dynamics, we use our Matlab program Sherry. Details of the setup and input parameters for this simulation have been published before[4]. Our model considers a niobium cavity with a surface defect characterized by normal conducting resistivity. The remainder of the cavity is initially in the superconducting state, and undergoes thermal breakdown. The simulation assumes a cylindrically symmetrical geometry, centered on the defect. This reduces the model cavity to a quasi-two-dimensional problem. The specifics of our setup are based on canonical computational methods for heat conduction.

Relevant Output

For each time step, Sherry calculates the heating on the RF surface of the cavity, the thermal diffusion through the niobium based on the heat capacity and the thermal conductivity, as well as the heat flux between the niobium and helium-II. Figure 4 shows the radius of normal conducting niobium on the RF side of the niobium as a function of time. The second curve in Fig. 4, starting at t = 80 μs show the radius of the outer surface of the niobium, having a heat flux above 1.5 W/cm^2. We assumed this value to be the triggering threshold for a detectable second sound wave- however, our arguing does not depend on that value, specifically.

As can be seen, the propagation speed of the heat on the inner surface and the expansion of the outer heat zone are constant and identical. The calculated value from the simulation was 67 m/s, which agrees quite closely the previously cited value of 69 m/s. This gave us sufficient motivation to use the thermal diffusivity value for normal

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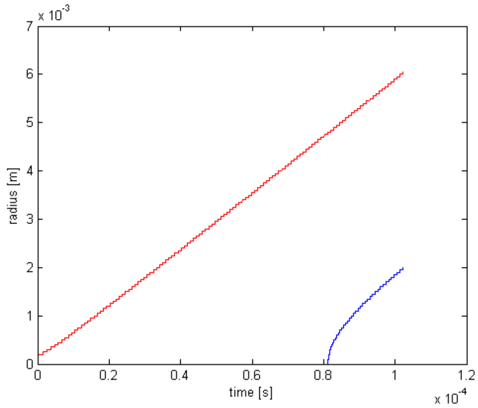

Figure 4: Radius of the normal conducting region on the RF side of the cavity (red curve) and radius of heated zone after the heat propagated through the niobium.

conducting niobium for our model, rather than the value of 800 m/s for superconducting niobium.

EXAMPLE SETUP

Using the difference between the naïve assumption of propagation time, $\Delta t = R/v_{SS}$, and our full solution in (3) and (4), we can predict the disparity between the real defect location and the computed defect location using the OST quench detection method.

As an example, one can take a simple geometry with three OSTs set up in an equilateral triangle centered on the defect. Each OST is at R = 0.5 m and an angle θ from the defect. Using canonical trilateration methods with a sphere radius of $v_{SS}\Delta t(\theta)$, one can calculate the expected location of the defect that triggered the quench. A two dimensional analogue of this setup is depicted in Fig. 5.

The black circles represent the true distance from the OSTs to the defect. Their intersection is the true location of the defect. The blue circles represent the predicted location of the defect using pure second sound propagation, only. Their intersection is marked by the green circle, which represents the predicted location of the defect. Figure 6 calculates the error in position resulting from neglecting heat propagation through the

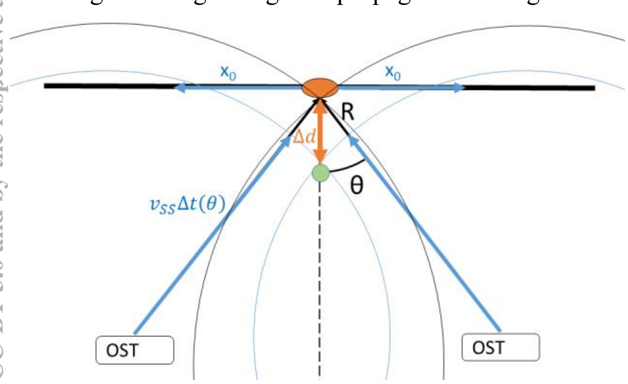

Figure 5: Two dimensional analogue example setup. The distance between the red and green intersection points is Δd, the error in reconstructing the quench location when only considering second sound.

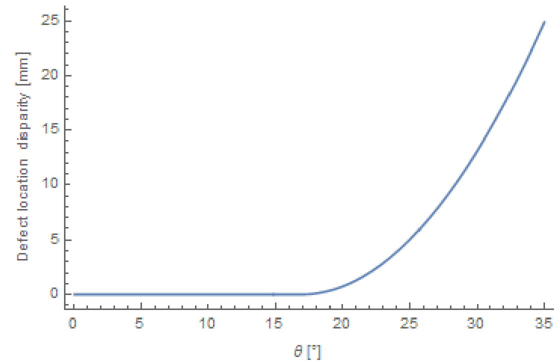

Figure 6: Defect location disparity as a function of θ, based on our specified setup.

niobium $\Delta d(\theta)$ as a function of the angle. As can be seen, at angles greater than 20° the dislocation can be several millimetres- which is what experimenters observed.

CONCLUSION

Using purely geometrical arguments, we found an explanation for the disparity between defect location and OST quench detection predictions, if the heat propagates through the niobium faster than it propagates through the helium. We conducted numerical quench propagation calculations that found the signal velocity through niobium to be close to the theoretical thermal diffusivity value in normal conducting niobium, 69 m/s. In [4], we showed that a faster than expected second sound signal of one OST can be explained by the different time constants involved in triggering the second sound wave and in detecting the energy loss due to the quench. This paper adds insight to phenomenon of signal propagation through niobium, and shows how not accounting for this effect can lead to disparities between the detected and actual location of a defect. Besides some small remaining questions, the main contributors to this disparity in second sound quench detection have now been identified.

REFERENCES

[1] Z. A. Conway, D. L. Hartill, H. S. Padamsee, and E. N. Smith. “Oscillating Superleak Transducers for Quench Detection in Superconducting ILC Cavities Cooled with He-II” Proc. of the LINAC08 Conf., Victoria, BC, Canada (2008)

[2] C. C. Ackerman, B. Bertman, H. A. Fairbank, and R. A. Guyer, Phys. Rev. Lett. 16, (1996) 789.

[3] Y. Maximenko et al, “Quench Dynamics is SRF Cavities: Can We Locate the Quench Origin with Second Sound?”, Fermilab Internal Report 1152-TD.

[4] R. Eichhorn, S. Markham, “On the Mystery of using Helium’s Second Sound for Quench Detection of a Superconducting Cavity” Physica Precedia, (2014) in press.

[5] B. J. Peters, “Advanced Heat Transfer Studies in Superfluid Helium for Large-scale High-yield Production of Superconducting Radio Frequency Cavities” Diploma Thesis, KIT Karlsruhe (2014).