HIGH FLUX THREE DIMENSIONAL HEAT TRANSPORT IN SUPERFLUID HELIUM AND ITS APPLICATION TO A TRILATERATION ALGORITHM FOR QUENCH LOCALIZATION WITH OSTS

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Abstract

Oscillating superleak transducers of second sound can be used to localize quench spots on superconducting cavities by trilateration. However propagation speeds faster than the velocity of second sound are usually observed impeding the localization. Dedicated experiments show that the fast propagation cannot be correlated to the dependence of the velocity on the heat flux density, but rather to boiling effects in the vicinity of the hot spot. 17 OSTs were used to detect quenches on a 704 MHz one-cell elliptical cavity. Two different algorithms for quench localization have been tested and implemented in a computer program enabling direct cross-checks. The new algorithm gives more consistent results for different OST signals analyzed for the same quench spot.

INTRODUCTION

Small defects on the inner surface of superconducting cavities can result in a quench, the transition to the normal state. Heat fluxes in the kW/cm^2 range can occur at the cavity surface during a quench. For quality assurance and improvement of the production process defects have to be localized and investigated. So-called Oscillating Superleak Transducers (OST) have been used since 2008 for this localization [1]. Several OST sensors and the time of flight information make it possible to localize the defect by trilateration. In such tests however it is usually observed that the speed of heat propagation exceeds the speed of second sound literature values. There are several reasons for this effect. The second sound velocity depends on the heat flux density as will be discussed below. There could be a delay between the generation of second sound and the detection of dissipation by the RF signal [2]. In [3] we have shown that the heat transport in superconducting niobium can be significantly faster than the speed of second sound. Based on this result Eichhorn and Markhan have performed calculations taking into account the geometry between the OST detectors and the quench spot [4]. As a practical solution to cope with this effect at DESY an algorithm has been developed that uses a minimization method with the geometrical constraint that the quench spot needs to be on the cavity surface [5]. The algorithm will give accurate results if the quench spot is on or close to the equator. The applicability to different cavity geometries is not obvious. In order to develop a more suitable algorithm for non-elliptical cavities the physics of high flux heat transport in superfluid helium needs to be understood in detail. Here we present dedicated experiments with heaters as simulated quench hot spots. We have extended the Matlab code from [5] to allow to be used for arbitrary cavity shapes and added a new algorithm for quench localization. The two algorithms were finally tested for consitency with data obtained from a quench on a single-cell cavity equipped with 17 OSTs.

Dependence of the Second Sound Velocity on the Heat Flux Density in the Two-Dimensional Case

A possible explanation for propagation speeds exceeding literature values of the second sound velocity could be the dependence of the second sound speed on the heat flux density. Two publications from 1951 have addressed this theoretically in [6] and experimentally in [7]. In particular the measurements presented in [7] have qualitatively proven that the second sound velocity v_2 depends on the heat flux density q. This dependence of v_2 on q is based on two assumptions. First, the temperature of the second sound for greater heating pulses is significantly higher than the bath temperature due to localized heating, so that the propagation velocity is different. Second, the normal fluid component carries the entire entropy and a temperature rise means creation of more normal fluid component. In order to describe the change in velocity of the second sound Dessler and Fairbank introduced a correction factor Γ that reflects the sensitivity to heat flux density [8]. The measurable velocity of second sound v_2 is thus composed of the velocity for very small heating pulses $v_{2,0}$ and a term which is linearly dependent on the heat flux density q [8].

$$v_2 = v_{2,0} + \Gamma \cdot q \tag{1}$$

This relation was obtained in a two dimensional setup, from measurement in channels having constant cross section, so that the heating power density remains also constant. For a statement about the three-dimensional spread, the change of the heating power density must also be considered.

EXPERIMENTAL SETUP AND RESULTS

We have carried out experiments to determine the second sound velocity at different heat flux densities in three-

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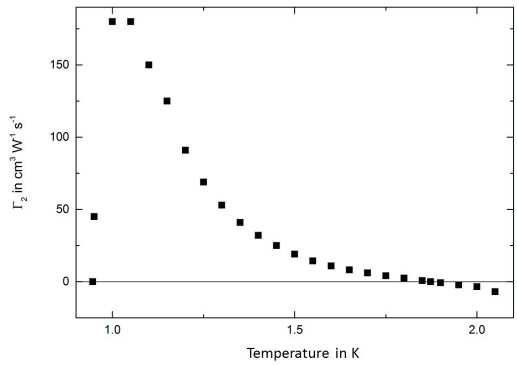

Figure 1: Plot of measurement data of the heat flux amplitude factor Γ by Dessler and Fairbank, re-plotted data from [8]. The important temperature for our investigation is the change in sign at T=1.873*pm*0.005 K. Replotted from [9].

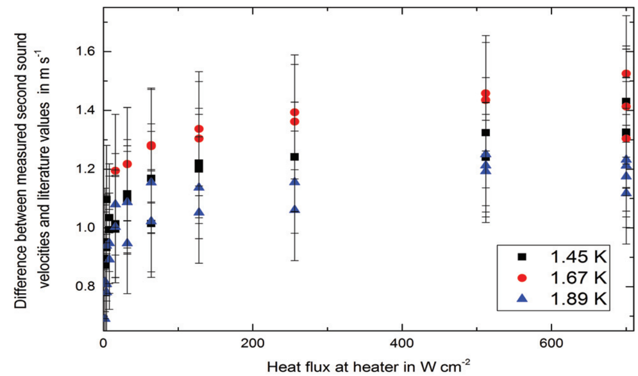

Figure 2: Difference between the measured second sound velocity and the literature data versus applied heating flux densities. Data are shown for one OST at 5 cm distance directly facing the heat source. Replotted from [9].

dimensional geometry. In a second setup we have tested the angular dependence of the signal rise-time. A more detailed description can be found in [9]. In this paper a brief summary of two experimental results of particular interest for the application to superconducting cavities is given.

Dependence of the Second Sound Velocity on the Heat Flux Density in the Three-Dimensional Case

Figure 2 shows 45 measurements of signal speeds for heat flux densities between 1 and 350 W/cm^2, at three different temperatures. In this setup an RF heater was used to simulate the quench spot. This made exact localization and measurement of the heat flux possible. To emphasize these deviations, only the difference between the measured and the literature values of $v_{2,0}$ are plotted. For all three temperatures, the dependence of the change in the velocity of the second sound with the heat flux shows approximately the same trend. After an initial steep rise, the curve flattens gradually. The measured velocity differences are significantly higher than the standard deviation. The measurement at 1.65 K shows the greatest deviation from the literature value, at a temperature of 1.89 K, the smallest deviations. At 1.45 K deviation values are determined in between the values at the other tested temperatures. The introduced dependency of the second sound velocity from the heat flux amplitude by Dessler and Fairbank, see section 2.2, predicts no change in velocity for a bath temperature of 1.88 K. At 1.89 K the same trend as in the measurements at 1.45 K and 1.67 K was found, thus the described effect cannot be the main influence on the presented results and other effects have to be considered. Likewise, this theory would predict the maximum deviation of our measurements at 1.45 K. One possible explanation for these results could be due to boiling processes. Gas bubbles have been visually observed in our glass cryostat at high heat fluxes. These bubbles will create a first sound phenomena, so a density wave propagates as well towards the OST. Williams et al. have however estimated that the sensitivity of OSTs on first sound is negligible small, at least for temperatures above 1.5 K [10]. The first sound propagation velocity in He II is roughly ten times faster than second sound [11]. One theory of Dessler [12] predicts an interaction of the first and second sound and could explain propagation velocities between the first and second sound. Improvements of the electrical insulation of the high power RF heaters are planned to enable further increase of heat fluxes in our set-up without electrical breakdowns at the heater.

Angular Dependence of the Second Sound Signal

In cavity tests it is observed that signals from different OSTs show significantly different slopes dV/dt. To test whether this can be related to the incident angle between the heat source and the OST a dedicated experiment has been set up. Eleven resistors have been placed opposite to an OST, see Fig. 3 inset. The results show a clear correlation between incident angle and slope, see Fig. 3. This can be used as a valuable crosscheck for analyzing data from cavity quenches.

QUENCH LOCALIZATION

A Software for Quench Localization for Arbitrary Cavity Shapes

For the reconstruction of the quench spot from OST data by trilateration a MATLAB code has been developed at DESY [5]. It uses a line-of-sight calculation, suitable for elliptical cavities where most of the quenches occur at or near the equator [5]. It is based on a minimization with the geometrical constraint that the quench spot needs to be on the cavity surface [5]. For every surface point on the cavity the algorithm calculates the geometrical distance to each detector, indicated by the brown lines in Fig. 4 (left). For each detector the distance as expected from a predefined second sound velocity is calculated, indicated by the blue lines in Fig. 4 (left). For each detector and surface point the difference between geometrical and expected distance is

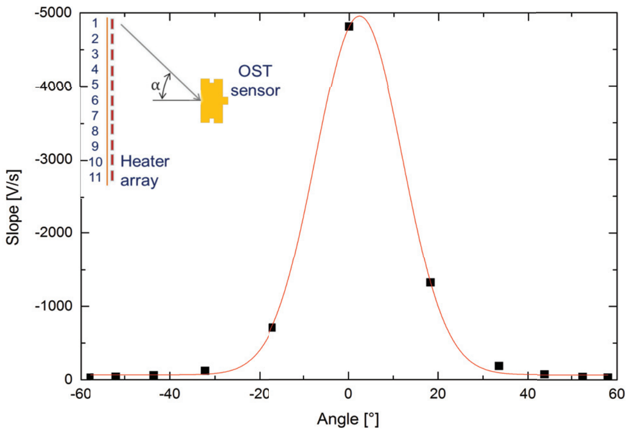

Figure 3: Measured slope of the OST signal dependent on the incident angle to the membrane of the OST. The LHe temperature is 1.77 K. The heater heat flux is 13.6 W/cm^2. Inset: Schematic of the experimental set-up to test the influence of the inclination angle of the second sound wave on the OST membrane. The angle is determined between the heater (3x6 mm^2) and the geometrical center of the membrane with a diameter of 19 mm. Replotted from [9].

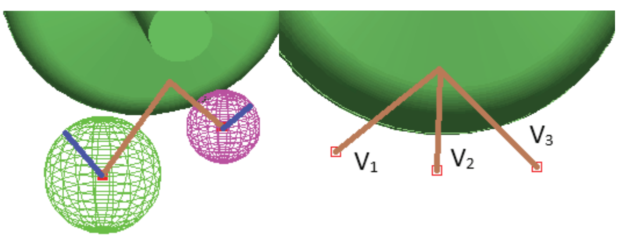

Figure 4: Left: Algorithm I obtaines the quench spot by a constraint fit using a fixed propagation speed. Right: Algorithm II uses the propagation speed as a fit parameter and minimizes the differences in speed to obtain the quench spot.

calculated. The surface point that minimizes the sum over all detectors used is taken as the quench spot.

We have included two new features in this program. In the version from DESY the cavity shape is represented by an analytical formula, while our program allows to import CAD files. This is relevant for non-elliptical cavities as the LHC crab cavity prototypes tested at CERN [13]. Additionally a new algorithm has been implemented. For every detector it calculates the distance to each surface point and the velocity from the running time. Then the standard deviation (SD) of the velocities for all detectors are calculated for every point. The vertex with the smallest SD is the quench spot, see Fig 4 (right). A constraint can be set that the propagation speed needs to exceed a threshold.

Comparision of Algorithms

An elliptical single-cell β=0.65 cavity has been tested with 17 OSTs in a vertical bath cryostat at, see Fig. 5. A quench was detected by 8 OSTs. In order to test the two algorithms for consistency and robustness the quench spot was calculated for several combinations of detectors, see

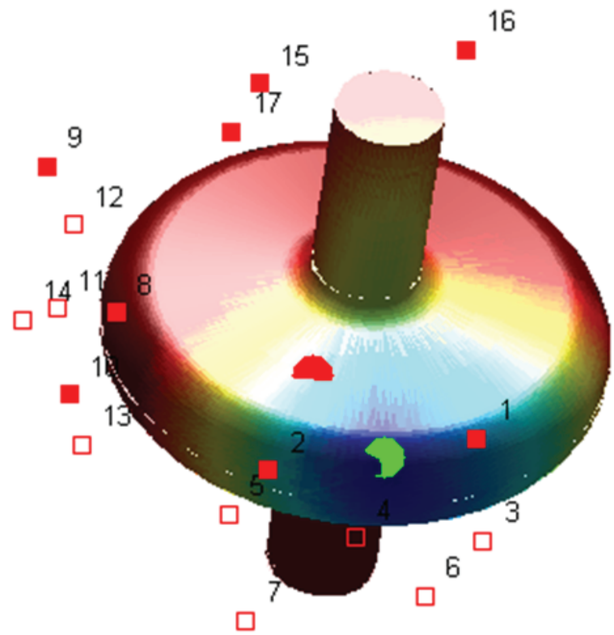

Figure 5: Position of OSTs around an elliptical single-cell β=0.65 cavity. The red/green spot indicates the quench spot as predicted by Algorithm I/II. To determine these spots the time of flight information of the detectors indicated by the closed symbols were used. Contour plot colors indicate the standard deviation of the propagation speed. Blue/red color indicates lowest/highest values.

Table 1. The coordinates are defined in that way: The x-axis is along the beam tube and the center of the coordinate system is on the beam-axis at the lower iris. Both algorithms predict the quench spot to be close to the equator (x=138 mm would be directly at the equator). The position as found by the two algorithms is only consistent within a few cm. Algorithm II gives more consistent results for the different detector combinations, see the lower standard deviations in Tab. 1. The y-postion is inconsistent for the two algorithms. A possible explanation is that Algorithm I rather finds a solution closer to the detectors than the actual quench spot, because the actual propagation speed is higher than $v_{2,0}$. On the other hand Algorithm II assumes that the propagation speed is constant. This assumption is invalid if there is an area of faster heat transport or a delay between the emission of second sound and the detection of the the quench from the RF signal. To develop a more efficient algorithm the physics of three dimensional high flux heat transport in superfluid helium and the cavity material has to be investigated in more detail. Emphasis should be given to find out whether the propagation speed can be assumed as constant. For this the interaction between first and second sound should be studied and dedicated experiments with high high heat flux should be performed.

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Table 1: Predicted Quench Spot Location as Determined by Two Algorithms for Different Detector Combinations Used

	Algorithm 1			Algorithm 2				
Detectors	x [mm]	y [mm]	z [mm]	x[mm]	y [mm]	z [mm]	velocity [m/s]	SD [m/s]
1,2	101.8	9.8	-170.9	85.8	25.4	-179.6	29.1	0.0
1,2,8	110.2	-23	-155.3	112.4	14.4	-146.5	29.6	0.1
1,2,8,9	112.4	-39.3	-141.8	108	15.9	-161.3	27.63	2.7
1,2,8,9,10	112.4	-45	-140.1	108	15.9	-161.3	27.2	2.5
1,2,8,9,10,15	115.5	-44.1	-120.2	105.2	16.4	-166.1	26.8	2.5
1,2,8,9,10,15,16	118.6	-37.6	-102.3	103.6	16.6	-168.3	26.3	2.8
1,2,8,9,10,15,16,17	118.6	-37.6	-102.3	103.6	16.6	-168.3	25.85	2.9
Median	112.4	-37.6	-140.1	105.2	16.4	-166.1		
SD	5.8	19.4	26.2	8.5	3.6	10.0		

CONCLUSIONS AND OUTLOOK

High flux three dimensional heat transport in superfluid helium has been investigated using OSTs. It has been shown that the relation between heat flux density and second sound velocity is not the main reason for the widely observed faster than second sound heat propagation after a cavity quench, but rather localized boiling effects in the vicinity of the heat spots. The delay between the generation of the second sound and its detection by the RF trigger signal in combination with a faster heat transport in the niobium cannot completely explain the fast heat transport. Our experiments with RF heaters show that a faster than second sound heat transport is possible in the absence of these two effects for high heat flux densities. The slope of the measured OST signal (voltage vs time) is directly related to the angle between heat source and OST. This can serve as a valuable cross check for quench positions obtained by trilateration.

17 OSTs were used to detect quenches on a 704 MHz single-cell elliptical cavity. OST signals from 8 sensors were used for data analysis. An algorithm that uses the speed of second sound as a fit parameter has been implemented in a computer program in addition to a code developed at DESY. The computer program gives the user a direct visualization of the quench hot spot as predicted by the two algorithms, allowing for direct crosschecks. In the future we plan to implement several new features to the program. In Algorithm II lines going through the cavity will be avoided and the speed in the niobium will be set by the user. The algorithm then minimizes the way in the niobium. To both algorithms we will add an option to include a delay time, taking into account that second sound might be generated before being detected by the RF signal. The program will display the rise time and the angle between each detector and quench spot. The user can use this information as a crosscheck. For example a fast rise time and a wide angle are inconsistent as we have shown above.

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