Study of Temperature Wave Propagation in Superfluid Helium Focusing on Radio-Frequency Cavity Cooling

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Abstract. Oscillating Superleak Transducers (OSTs) can be used to localize quenches of superconducting radio-frequency cavities. Local hot spots at the cavity surface initiate temperature waves in the surrounding superfluid helium that acts as cooling fluid at typical temperatures in the range of 1.6 K to 2 K. The temperature wave is characterised by the properties of superfluid helium such as the second sound velocity. For high heat load densities second sound velocities greater than the standard literature values are observed. This fast propagation has been verified in dedicated small scale experiments. Resistors were used to simulate the quench spots under controlled conditions. The three dimensional propagation of second sound is linked to OST signals. The aim of this study is to improve the understanding of the OST signal especially the incident angle dependency. The characterised OSTs are used as a tool for quench localisation on a real size cavity. Their sensitivity as well as the time resolution was proven to be superior to temperature sensors glued to the surface of the cavity.

1. Introduction

In accelerators like the Large Hadron Collider (LHC) at CERN superconducting cavities are used to accelerate charged particles by means of an alternating electromagnetic field. The resonant frequency, the maximum acceleration gradient and the quality factor of the cavity are the main features of such a resonator. The use of superconducting materials for the cavities can improve the quality factor by several orders of magnitude. The quality factor provides information on the dissipated power that is then converted into heat, which the cooling system needs to extract. According to today's state of the art superconducting cavity technology such resonators are made of a sputtered niobium layer on a copper substrate or out of bulk niobium. The quality of the inner surface is very important for these resonators because even small defects on the surface result in the dissipation of energy. This energy can cause a quench, the transition to the normal state. Heat fluxes in the kW/cm² 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 [1] for this localization. OSTs make use of the unique properties of He II to detect the failures by the propagating temperature wave originated in the local hot spot at the cavity surface. Using several OST sensors and the time of flight information to each sensor makes it possible to localize the defect by trilateration.
2. Second sound propagation in He II

Under its own vapor pressure helium fundamentally changes its properties when cooled below 2.1786 K [2]. This superfluid phase called He II has better thermal conductivity by about seven orders of magnitude than the He I called phase above this temperature [3]. Superfluid helium exhibits a unique heat transfer process. Temperature waves propagating in He II are called second sound. For small heating pulses, means small temperature differences, the speed of propagation of the second sound is only dependent on the absolute temperature of the helium bath. Figure 1 shows literature values of this dependence.

![Figure 1](image)

**Figure 1.** Measured data of second sound velocity $v_{2,0}$ as a reference velocity. Measurement data are taken as recommended data from [2]. This collection of second sound data by Donnelly and Barenghi states that the resonant method has been used in all referenced measurements.

2.1. The two-fluid model description

Most of the observed properties of He II can be described by the so-called "two-fluid model"[4]. It assumes that He II consists of two different components. These components are described as the "super fluid" and "normal fluid" component. The theory attributes the viscosity and entropy of helium completely to the normal fluid component; their values for the superfluid component are zero. The ratio of the two components is determined in the "two-fluid model" only by the temperature of the helium.

2.2. Dependence of the second sound velocity on the heat flux

Two publications in the Proceedings of the Physical Society London from 1951 have shown the change in velocity of the second sound with the amplitude of a heat pulse, theoretically in [5] and experimentally in [6]. The measurements carried out by Osborne have qualitatively proven the influence of heat flux density on second sound velocity. It was quantitatively verified in 1956 by Dessler and Fairbank [7]. The theory of Temperley was improved a few years later by Khalatnikov [8] for lower temperatures. This dependence of the second sound velocity on the heat flux is based on two assumptions. First, the temperature amplitude of the second sound is significantly higher than the bath temperature, due to
localised 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 $\Gamma_2$-factor that reflects the sensitivity to heat flux. 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 $\dot{q}$ in W/cm$^2$, from [7]:

$$v_2 = v_{2,0} + \Gamma_2 \cdot \dot{q}$$  \hspace{1cm} (1)

![Figure 2. Plot of measurement data of the heat flux amplitude factor $\Gamma_2$ by Dessler and Fairbank, replotted data from [7]. The important temperature for our investigation is the change in sign at $T\sim1.86$ K.]

2.3. Three-dimensional propagation of second sound

The described dependence of the second sound velocity was measured 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. As early as 1967 Guernsey et al. [9] have observed that in three-dimensional propagation of second sound not only a wave with elevated temperature may occur in relation to the helium bath, but also a temperature wave with a lower temperature. It was mathematically described by Atkin and Fox [10] for the case of a spherical wave for a point-like heat source. They note that the deviation of the temperature of the second sound from the helium bath is independent of the heating power, but depending on the change of the heating power in time. When a heater is switched on, a second sound wave with an elevated temperature is generated. In contrary if the heater is switched off again, the temperature wave propagates with a value smaller than the temperature of the helium bath. In [11] Zhang and Murakami show this effect experimentally and underpin this with simulations.
2.4. Oscillating Superleak Transducers
Oscillating Superleak Transducers (OSTs) are sensors that have been developed in 1968 by Edwards and Rudnick [12] to detect second sound in He II. They are based on a membrane whose small pores practically enable only the superfluid component to pass. A scanning electron microscope (SEM) image of such a membrane is shown in Figure 3. On one side of the membrane a certain volume of helium is enclosed in the OST. A change in the ratio of the two components in He II, which is the same as a changed temperature on one side of the membrane, lead to a flow of the superfluid component through the micro porous structure of the membrane. The resulting change in volume displaces the membrane. The deflection of the diaphragm is detected in a capacitive way. For this, the membrane on the outside of the OST is gold coated and on the inside there is a non-deformable counter electrode. A voltage applied between the diaphragm and the counter electrode thus varies with a deformation of the membrane. An OST reacts with a decaying oscillating voltage change on the arrival of a second sound wave created by a small positive $\Delta T$.

![Figure 3. SEM picture of the gold coated, micro-porous membrane used for the OST.](image)

Due to the high sensitivity of OSTs small and very short temperature changes can be reliably detected. Thus, this sensor is very well suited to sudden heat inputs in superfluid helium. That is the case during a quench of a superconducting cavity. For known positions of at least three OST signals the quench hot spot on a superconducting RF resonator can be localized.

2.5. Quench localization
The stored energy in a cavity resonator is proportional to the measured transmitted power to a weakly coupled pick-up antenna. In a quench this power suddenly drops, which allows a precise determination of the start of the quench. The voltage drop on a charged OST indicates the moment at which the second sound arrives at the OST location with an elevated temperature. Theoretically, the quench spot can be accurately determined from the time of flight, the known second sound velocity and the positions of three OSTs. In practice, this is often not possible because the calculated quench spot is not on or near the surface of the cavity. Since the heat source must be on the surface of the cavity, the signal has reached the OSTs sooner than expected. This increased signal propagation velocity has been widely observed [13], however, could be quantified only very imprecisely because of the unknown position of the quench spot. For an approximate determination of the quench spot, the speed was used as fit parameter and the surface of the cavity was added as further constraint for the calculation.
3. OST measurement set-up and results
A series of experiments was carried out to determine the second sound velocity at different heat flux densities at the heater spot in three-dimensional geometry. Emphasis was put on the shape of the detector signal related to the membrane reaction and the discrimination between first and second sound signal detection with OSTs.

3.1. Experiential set-up
The set-up is immersed in a helium bath cryostat whose temperature can be controlled by means of a capacitive pressure sensor (10^{-2} to 100 mbar abs.) and a butterfly valve between about 1.4 K and 2.5 K. For the experiments, the quenching of a cavity was simulated by heat pulses with an electrical resistance. Either 68 \, \Omega SMD resistors with a heating surface of 0.15 cm^2 or a 50 \, \Omega RF resistance with a surface area of 0.5 cm^2 was used. The DC resistor can be powered up to 50 W, the RF resistance up to 350 W. In the current set-up each case is limited by the available amplifiers and for the current RF resistance set-up as well by the electrical breakdown resistance of He II. The second sound was detected by OSTs that were produced according to the design of the Cornell University [1] at CERN. The OST was thereby charged via a high resistance to 120 V. Voltage changes caused by the second sound are capacitive coupled out and read by an oscilloscope. The distance between the OST and the heater was 5 cm in all experiments focused on heat flux and temperature dependency. The distance between the heater and the OST was measured prior to cooling of the experiment. During the experiment, both the heating pulse and the OST-signals are recorded with an oscilloscope. The heating pulses had durations of 0.5 ms to 10 ms. The propagation velocity of the second sound signal is calculated by the previously measured distance divided by the time between the start of the heating pulse and the moment of dropping voltage on the OST channel.

3.2. Verification of the experiential set-up for small heat pulses

![Figure 4](image)

*Figure 4.* Measured second sound velocity by pulse method compared with reference data [2]. The error bars for the velocities are plotted in the graph; they are partly smaller than the markers.

For low heating powers the experimental set-up has been successfully verified compared to the literature values of the second sound. In this low heating power case the 68 \, \Omega resistor is used and the heating
power is 0.24 W for duration of 0.5 ms. Figure 4 shows the measured velocities of the second sound including the estimated errors for the measured second sound velocity influenced by the uncertainty of the distance determination and the time difference detection. This measurement confirms the functionality of the chosen set-up and the good reproducibility of the literature values in spite of the less precise measurement of the time of flight method.

3.3. Second sound velocity for high heat flux densities

For measurements with the radio-frequency resistance at high heat fluxes a faster signal propagation could be determined that was well below the stated results of up to 50 % faster signal propagation [16]. Figure 5 shows 45 measurements of signal speeds for heating flux of 1 W/cm² - 350 W/cm², at three different temperatures. To emphasize the deviations, only the difference between the measured and literature values is plotted versus the applied specific heat flux on the heater surface.

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.

Figure 5. Difference between the measured second sound velocity and the literature data versus applied heating flux densities. Only the maximum observed deviation from three different OSTs is shown vs. the heat flux. The closest sensor located at 5 cm distance detects the second sound signal with Δv₂=+1.2 m/s. Sensor two and three at 10 cm and 15 cm respectively show no significantly higher than literature values for all heat fluxes.

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 estimated that the sensitivity of OSTs on first sound is negligible small, at least for temperatures above 1.5 K [12]. First sound propagation velocity in He II is roughly ten times faster than second sound [2]. One theory of Dessler [15] 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.

3.4. Influence of the inclination angle between OST membrane and second sound impinge

The reaction of the OST membrane to an incident second sound wave has been additionally studied in the experimental set-up. Eleven resistor type heaters were placed at a support plate parallel to the OST membrane. Figure 6 demonstrates the heater and OST arrangement, which allows angles of incident up to $\alpha = \pm 60^\circ$ with a direct distance of heater number 6 of 31.75 mm. The membrane of the OST has an active diameter of 19 mm defined by the front cover of the OST.

![Figure 6. 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 $\alpha$ is determined between the heater (3x6 mm$^2$) and the geometrical center of the membrane with a diameter of 19 mm.](image)

The distribution function of the signal slope measured with the OST is shown in Figure 7. The graph shows the measured data points plus a fit with a Gaussian distribution for indication.

![Figure 7. Measured slope of the OST signal dependent on the incident angle to the membrane of the OST at 1.50 K LHe temperature. The heat flux on the heater surface is 13.6 W/cm$^2$.](image)
One can see that there is a small shift in the orientation angle of the OST membrane to the heater array in the range of 3° to 4° after cooldown. This shift is also visible in Figure 8 and Figure 9 for higher saturation temperature of 1.77 K and 2.1 K, respectively. The recorded peak value of the signal slope reduces from 12000 V/s at 1.5 K to -5000 V/s at 1.77 K down to -2000 V/s at 2.1 K. Since the heater array is located on a flat plane the distance as well as the propagation time for the second sound is varying for different heaters. Figure 10 shows the measured data well representing the additional distance to the OST location between heater 6 (minimum distance) to heater 1 or 11. One can observe a flattening of the dependency for heaters 5 to 7. For these heaters a part of the OST membrane is still facing the heater in a direct way, see Figure 6. To separate the two influences a compensation for the changing distance for different heaters will be implemented by curving the heater array following the shape shown in Figure 10 in the next measurement run.

Analyzing the effect of the heater distance compared to the time delay of the recorded OST signal gives an indication of the membrane interaction with the incident of the second sound wave, see Figure 10. The delay of recorded OST signal is flattened in the range of ±20° which corresponds to the OST...
membrane size of 19 mm. Figure 10 shows additionally that the signal delay is smaller than expected for incident angles greater than ±20° due to the geometric effect. The scaling factor bases on the distance to the center of the OST membrane while the impingement of the second sound wave interacts already earlier with the parts of the OST membrane generating membrane reaction and a signal. Further analysis of the influence of the distance between the OST and the heater on the slope of the signal showed only minor influence of 60 V/s, 58 V/s to 38 V/s slope at 2.15 K for three OSTs in straight configuration at 50 mm, 100 mm and 150 mm distance, respectively.

Figure 10. Measured propagation time from begin of the heating pulse to the start of the detection at the OST. The applied heat flux is 8.6 W/cm², data are corresponding the value of Figure 7. The two axis are scaled in a way that the measured delay corresponds to the distance of the heater spot to the centre of the OST membrane, using a second sound velocity of 20 m/s at 1.50 K.

Figure 11. Maximum value of the measured OST signal slopes for heater position #6 (compare Figure 6) facing directly the centre of the OST membrane versus applied heat flux at the heater surface.
The analysis of the measured signal slopes at different temperatures and heat fluxes of the pulsed heater show a strong temperature influence, see Figure 11. For low temperatures T=1.50 K the maximum slope of the OST recorded signal increases with heat flux. This effect diminishes for higher temperatures and at T=2.10 K there is almost no influence of heat flux visible.

4. Conclusions
High density, three dimensional heat flux in superfluid helium has been investigated using OSTs. It has been shown that the non-linear relation between heat flux and change of second sound velocity is not the main reason for the widely observed faster than second sound propagation during cavity quenching. Localized boiling effects in the vicinity of the heat spots could be an explanation. The slope of the measured OST signals (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. Careful data analysis is however advised, because the slope also strongly depends on temperature and heat flux.

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