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Heat source localisation by trilateration of helium II second sound detected with transition edge sensors thermometry

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Abstract. The detection of second sound in He-II can be exploited during superconducting cavity testing to locate the germ of a quench. The sudden appearance of a hotspot generates this wave in the helium II bath, which is routinely detected by Oscillating Superleak Transducers (OST) reacting to the first arrived inter-component velocity front. Recently, we have developed Transition Edge Sensors (TES) that are able to detect second sound by measuring directly the temperature fluctuation of second sound (below milli-Kelvin, in sub-millisecond time scale) with a good native signal-to-noise ratio. We present the current state of development of second sound detectors based on TES, experiments aiming to characterize more thoroughly their behaviour as second sound detectors by thermometry, and the capabilities they provide in terms of localisation of the heat source in the case of direct sight.

1. Second sound detection with transition edge sensors

The localisation of quenching hotspots on superconducting radio frequency (SRF) cavities allows to identify defects on the cavity surface limiting their performance. A contactless method to achieve this during a cavity validation test is the detection of second sound in the surrounding helium II bath generated by the hotspot at the moment it appears. A network of detectors can be used as a GPS-like system to trace back the point in space at which the wave was produced, thus pinpointing the hotspot.

The most straightforward wave tracking method to localise emitters is trilateration. Three detectors placed around the emitter at known positions, not aligned, detect the wave's arrival at different instants of time. The moment at which the wave starts is known and taken as zero time. The length of the path from the emitter to each detector is calculated from the measured times of flight via the known wave velocity. Assuming direct line of sight between emitter and detectors, by simple geometrical analysis, the position of the emitter can be calculated: it is at the intersection of three spheres centred at each detector and with radii equal to the measured path length.

The established detectors for this purpose are the oscillating superleak transducers (OST) [1]. Recently, we have developed at CERN a second sound detection system based on transition edge sensors (TES) [2]. These are stripes of a bimetallic Au-Sn thin film on glass substrate, exhibiting superconducting transitions within He II temperature range. The presence of the two metals causes the transition to be smoother than for a pure material. This provides a range with a width of 100 mK to 200 mK in which the sensor has a linearly varying resistance and that can be shifted through the biasing current. Methods to fabricate such TES have been specified, tested and optimised at CERN. The main advantage of TES to OST is that they can be manufactured at very small sizes (present version is 1 mm while OST are above 1 cm), increasing spatial resolution.

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When testing a cavity that quenches and produces second sound, one does not know where the emitter is for sure. A validation of the method requires to compare the found trilateration solution to the known position of the source. Thus, the safe application of TES to cavity hotspot localisation requires an evaluation of the precision with which one can estimate the input distances for and results of the trilateration algorithm. For this purpose, an experiment was designed and run at lab scale with small second sound emitters (≈5 mm size) and TES, with completely specified geometry.

2. Description of the experiment

2.1. Setup

The setup for this experiment is shown in Fig. 1. 12 TES chips were positioned on a glass fiber epoxy plate with sub-mm precision. The TES were fabricated with different compositions, and some of them contain 20 nm of Au and 225 nm or 250 nm of Sn. Another plate containing 9 heaters in a row, spaced at regular pitch of 1 cm, was placed in front of the TES at a distance of 47 mm. The heaters were SMD of 3x6 mm^2 and 47 ohms resistance. The position of the heaters relative to the TES is known by design of the different elements (sensor plate, heater plate, supports and vertical spacers). The minimum distance between each sensor and each heater was calculated numerically from a 3D model of the setup.

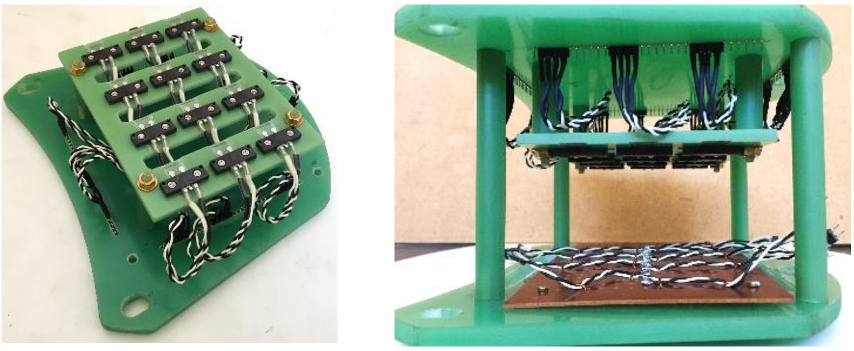

Figure 1. Experimental setup for TES second sound test.

2.2. Instrumentation and signal acquisition

The experiments were conducted in a vertical cryostat of 200 mm inner diameter, operating in saturated superfluid regime. The bath pressure was controlled by an MKS regulation system within 3 Pa of precision. The temperature is obtained from the saturation P-T curve.

The TES were powered and read out in 4 wire configuration. The current was supplied by Keithley 2401 sources in the range of 0-5 mA with 0.5 µA precision. Two or three TES are connected in series to the same source, thus having two TES circuits. The voltage of each TES was read with NI9251analog input cDAQ modules with variable sampling rate up to 100 kS/s and a resolution of 0.4 µV. The heaters were powered through many 6V batteries in series and a NI9472 cDAQ digital output module acting as an electronic relay system. The current through the heater is measured for timing purposes by adding a 1 ohm auxiliary resistor in series and recording its voltage on the NI9251 modules. A LabVIEW interface allows to record data and trigger the heaters at user's order.

2.3. Protocol

In a first stage the electric behavior of the TES (V vs. I curves) was recorded at different temperatures, to assess their sensitivity to temperature variations (derivative of voltage with respect to temperature). This was done by stabilizing the pressure of the bath and then sweeping the current sufficiently slow (25 µA steps every 500 ms) and reading the voltage at low sampling rate (150 S/s). The measured values were averaged at each current step and later on the sensitivity was calculated by finite differentiation.

Later on, second sound detection experiments were conducted. The sensors were steadily biased at their optimal current. At each experiment, one heater at a time was pulsed through the user interface

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with up to 30 V and kept on for 35 ms. The voltages on TES and auxiliary resistor were recorded from 20 ms before to 30 ms after the heater is turned on. The sharp rise of the auxiliary resistor signal is taken as zero time. A few milliseconds later pulses are expected in the TES signals too, indicating the arrival of second sound. The experiment was repeated around 300 times, varying heater and voltage applied.

3. Results

3.1. Sensor characteristics
A typical set of transition curves measured with TES of 225 nm Sn thickness and their sensitivity functions are presented in Fig. 2. The V-I curves show that at low current the voltage is zero (superconducting regime), and from a given value of current it increases gradually, till the curve becomes a straight line that would pass through the origin if extrapolated (normal conducting regime). The sensitivity is found to be function of the current, at fixed bath temperature, showing a peak at some value, which is the optimal bias current.

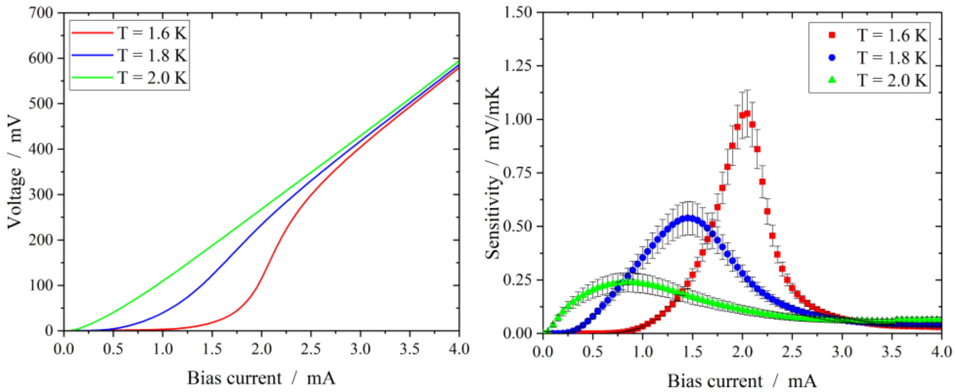

Figure 2. Characteristics of Au 20 nm / Sn 225 nm TES.

3.2. Second sound detection
The results presented in this section come from experiments done at 1.8 K, a usual temperature for cavity tests. Three TES with 225 nm of Sn were used, as they showed appropriate transitions to measure in this range. The sampling rate of the measurements was set to 20 kHz, in order to reproduce the capability of PXI DAQ systems commonly used in SRF testing environment.

The result of a second sound experiment is illustrated in Fig. 3. The plot shows the time evolution of the voltage drop on the auxiliary resistor in series with the heater and on the TES. The TES show a clear peak in the range of 2 ms to 5 ms after the start of the heating.

To confirm that we are actually measuring second sound, a systematic determination of the TES peak start time was done. This time of flight (TOF) was determined as the first sample for which the voltage exceeds the average DC biasing voltage plus a noise index, right before the highly exceeding peak (see Fig. 3). The correlation between the TOF and the known distance between different heater-sensor pairs was used to measure the velocity of the detected wave. This velocity is found to be equal to literature values of second sound speed [3] within 2% precision. Inversely, if we simply correlated the product of the measured TOF by second sound speed values in the literature with the actual emitter-detector distance in the setup, we find that the agreement is good within 2% too. This tells us that an uncertainty below 2% is expected in the determination of source-detector distance in a real scale cavity test.

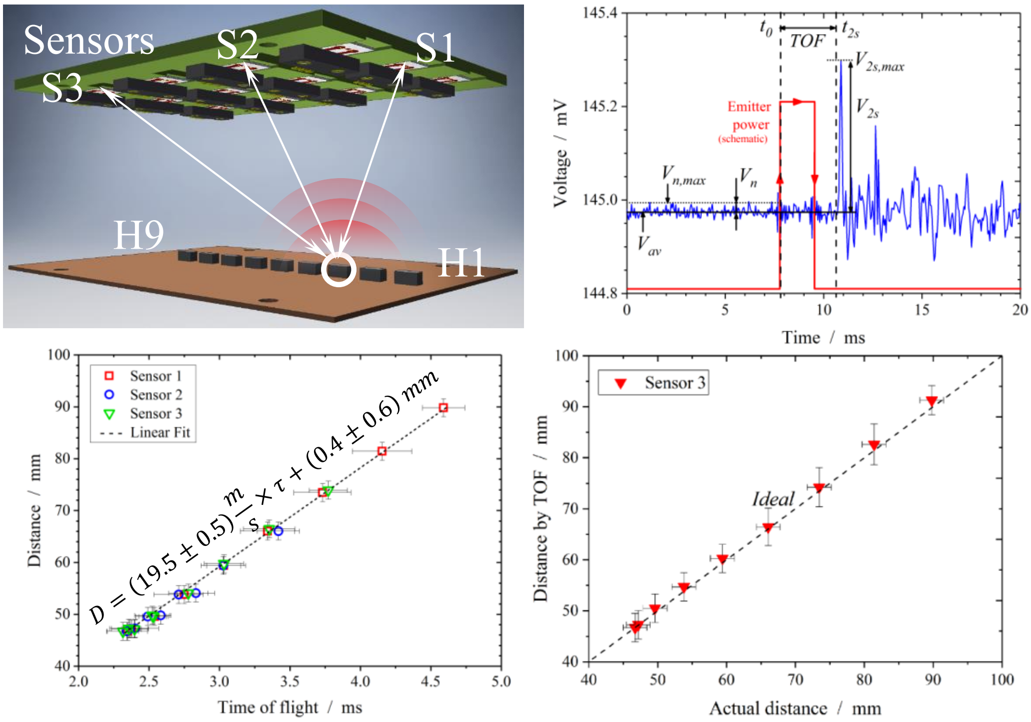

Figure 3. Second sound detection. Left: raw signal. Centre: Second sound speed determination. Right: evaluation precision of distance determination by TOF.

3.3. Trilateration

In order to have more sensors in a good sensitivity range and thus produce more useful data, the tests that we present in this section were performed at 2.0 K, which is a representative temperature of SRF cavity tests too. The aggregate of all the experiments was organised into a big database containing per element one single experiment, specified by heater pulsed, and one TOF per TES. We pretend from this point on that we ignore where the heater was; we assume that we only know the coordinates of the position of the TES. With a set of 5 TES, we can form 10 different subsets of 3 sensors each, with which to apply the trilateration algorithm. However, in each experiment, only the sensors that detected second sound with a signal-to-noise ratio (SNR) greater than 10 were considered. SNR was calculated as the peak maximum amplitude divided the noise index. This reduced the number of valid TES triads in each experiment, for which the trilateration point was calculated.

A summary of the trilateration results thus obtained in presented in Fig. 4. Each dot represents the result of a triad in some experiment, which means that there can be many dots per experiment. The dots in the same colour come from experiments in which the pulsed heater was the same. The blue full dots show the position of the TES. To evaluate the quality of the trilateration predictions, the rectangles in the lower plane, which represent the actual edges of the heaters in the setup, were added. It becomes quite clear that the prediction through trilateration is only a few millimetres away from the actual position of the heaters.

To rigorously demonstrate this we calculated the rate of success of the method with the following criterion. We defined a tolerance parameter as the maximum admissible distance from the trilateration point to the closest point on the heater that produced it, to define a case as successful. We plotted for each heater the percentage of the points found within a given value of tolerance around that heater. We also plotted the aggregate percentage of successful cases around any heater for a given tolerance. This is shown in Fig. 5. From this analysis, although for some heaters the success was higher than for others, overall, the trilateration results reach a reliability close to 90% with a tolerance as low as 2 mm.

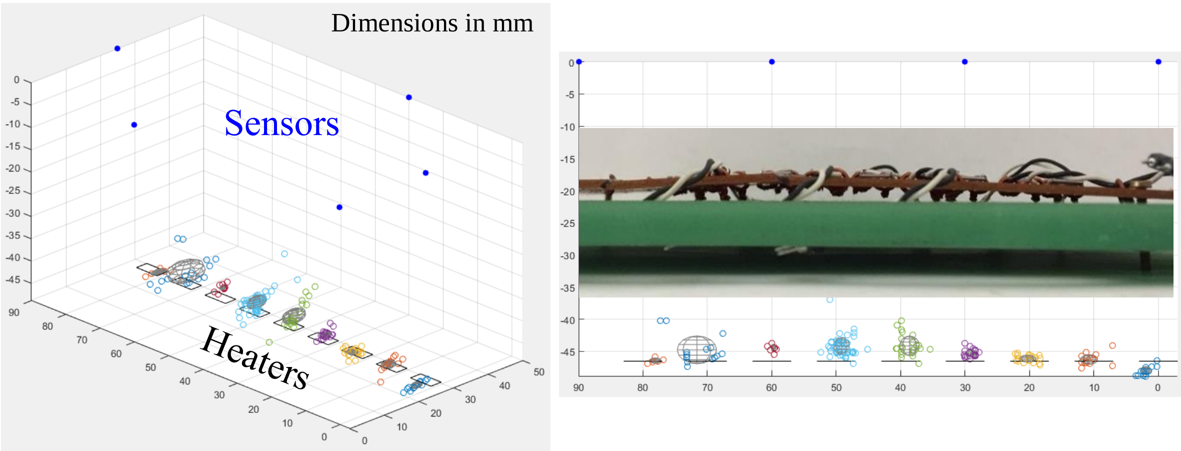

Figure 4. Results of second sound trilateration localisation of 9 heat sources with 5 TES at 2 K.

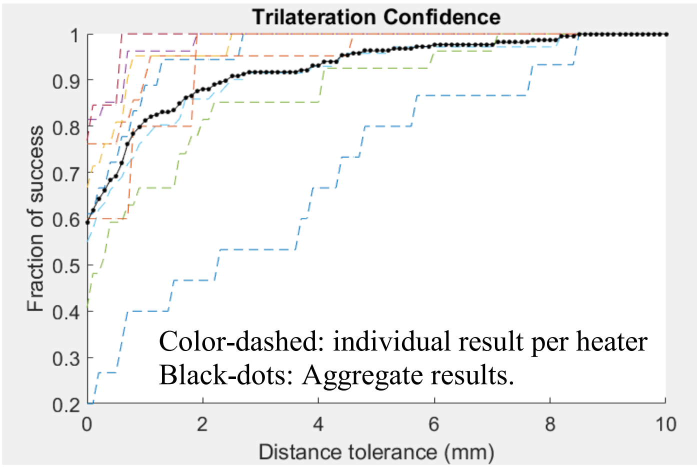

Figure 5. Evaluation of the rate of success of the trilateration method.

4. Conclusions and outlook

Transition edge sensors were developed at CERN through different microfabrication methods, with the purpose of using them in SRF cavity quench diagnostics. The sensors were tested in the lab at equivalent cavity testing conditions, to validate them as a tool for the localisation of second sound emitters through the trilateration algorithm. In an experiment with 5 sensors and 9 heaters, a rate of success of 90% of the heater surface localisation was achieved within a tolerance of 2 mm. This validates the TES as a heat source localisation mechanism through second sound detection.

The next step was the implementation of TES in large SRF testing facilities at CERN, in order to inspect the capabilities of TES, not only to detect the second sound produced by real quenching cavities, but also to localise with a given spatial resolution the point on the cavity surface where second sound is originated [4]. Additionally, intensive studies on second sound propagation, intensity and pulse shape are envisaged, to be able to extract more information from the cavity tests than just the time of flight.

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