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Quench localisation in SRF cavity tests with transition edge sensors

H Furci, G Vandoni, A Macpherson, S Barriere, A Castilla, N Shipman, K Turaj, M Wartak, A Zwozniak

CERN, CH-1217 Meyrin, Switzerland
hernan.furci@cern.ch

Abstract. Transition edge sensors (TES) have recently been developed at CERN as second sound detectors for quench localisation on superconducting radio frequency (SRF) cavities. After validation of the concept of heat source localisation by TES in the laboratory, TES have been implemented as a diagnostic tool in SRF vertical testing cryostats at CERN SM18 facility. Two cavities were forced to quench by applying sufficiently high values of RF power. Simultaneously, RF and TES second sound signals were recorded. In this paper we present the particularities of each of the relevant tests, the nature of the read signals, as well as the analysis performed on them to locate the origin of the quenching spot.

1. Introduction

Diagnostics of superconducting radiofrequency (SRF) cavities prior to cryomodule assembly include determining the location of weak spots, giving rise to breakdown of the RF field - quenching [1]. A systematic and agile way to do this is *non-contact* thermal mapping. The sudden heating at the quenching spot creates a second sound wave in the He-II bath emitted by the external surface of the cavity. This wave travels at roughly 20 m/s [2], and can be tracked down to its origin, by detecting it at different times and positions around the cavity. A limited number of sensors, without contact with the surface of the cavity, suffices for a precise localization of the hot spot by trilateration [1]. Nowadays state-of-the-art non-contact thermal mapping tool is the Oscillating Superleak Transducer (OST) [4-6], a second sound "microphone" with a microporous moving membrane only letting through the superfluid component of He-II [3]. The inconvenience is its size, (typically above 1 cm in diameter) which limits space resolution [7] and the need of in-house developed electronics to obtain a voltage signal.

Transition Edge Sensors (TES) have recently been developed at CERN as an alternative second sound detector [8]. TES are extremely sensitive, fast and small thermometers based on the gradual transition of superconducting (SC) thin film alloy deposited on a glass substrate, from the SC to the normal-conducting state over a temperature range of 100 mK-200 mK. CERN's TES have a detection limit of roughly 0.1 mK fluctuations, a time constant estimated around 10 microseconds, and a total sensing area of 1 mm x 1 mm. Recent experiments have shown that second sound can be detected with these TES at bath temperature from 1.6 K to 2.1 K. Furthermore, the distance between the heat source and the TES can be determined within 1% precision based on literature value of second sound speed [2] and measured time lag between power step and TES signal. Several heat sources were located by simple trilateration with a precision better than 4 mm in more than 90% of the cases [9].

Here we apply the TES to the detection of second sound produced by a quenching cavity. TES were installed in a vertical SRF testing cryostat at the SM18 facility of CERN. Two cavities, with complex geometries, were successively tested and driven to quench while recording the bath temperature with a network of TES located in the superfluid bath. The signals were analyzed qualitatively and quantitatively. The analysis lead to locations that are suspected to be the origin of the RF field breakdown.

2. Cavity testing setup and protocol

All the cavities presented in this paper were tested in a 4 m deep, 1 m wide vertical cryostat in the SM18 CERN facility. The cavities went through surface preparation (chemistry, polishing, high pressure rinsing), clean room assembly of antennas and ports, mounting on the insert and pumpdown to UHV. The instrumentation of the cavity includes a few thermometers on its surface, magnetic field probes, RF antennas. In this paper we focus only on the results yielded by the TES.

The quench tests were conducted in saturated superfluid He regime. At stable temperature, the cavity was powered in steps through its fundamental power coupler (FPC) to a value of RF power high enough to generate quench. The transmitted power pick-up antenna signal was fed to a power meter (MODEL XXX), whose signal was recorded on the same DAQ device as the TES signals (NI9251 modules for analogue voltage input at 50 kHz sampling rate). The sudden drop in the transmitted power was used to trigger the DAQ recording and as zero-time reference.

2.1. UK4Rod cavity

The UK4Rod cavity was built within the crab-cavity development for the High Luminosity (HiLumi) LHC project [10,11]. It takes its name from 4 deep concave elements, called ‘rods’. The cavity was tested with vertical beam axis. A single wafer with 6 TES (see Fig. 1) was mounted parallel to the cavity beam axis on one side of it, close to the top of two rods. The measurements were performed between 2.05 and 2.10 K. As a drawback of this temperature range, second sound speed is not constant as it would be at lower temperature but fluctuates by 5% to 10% within the ~ 50mK bath temperature fluctuations

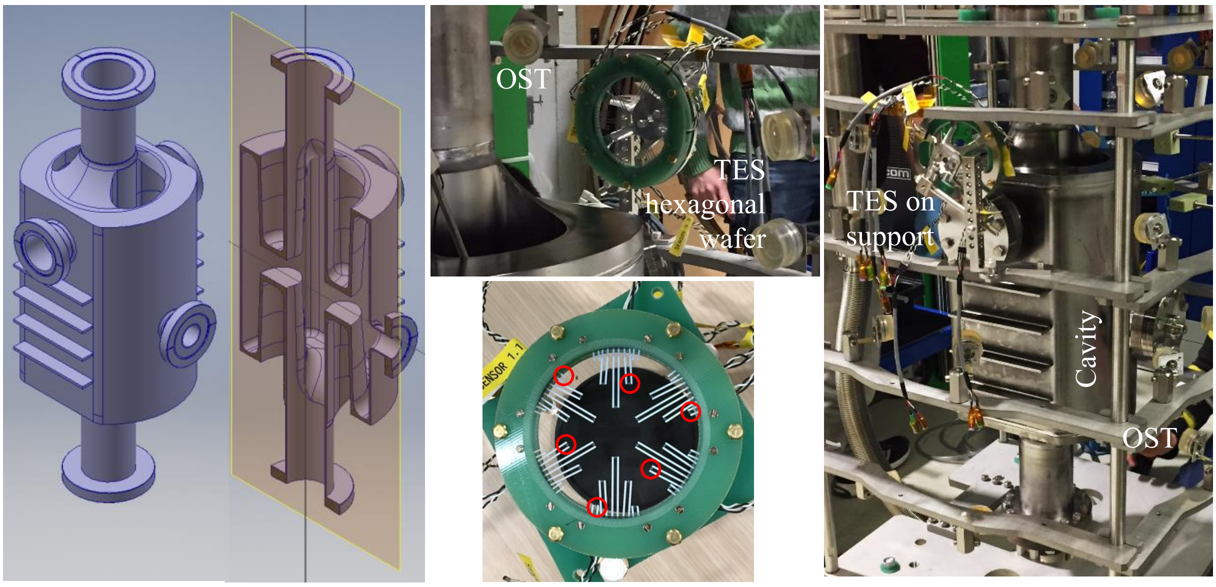

Figure 1. UK4Rod cavity, TES Hexagonal wafer and full setup with TES.

2.2. Double quarter wave, proof of principle, crab cavity

The double quarter wave, proof of principle, crab cavity is also part of the HiLumi project [10, 12]. The DQW design was recently chosen as one of the two ‘beam crabbing’ devices for LHC and is currently tested in a cryomodule installed in the CERN SPS [13,14]. The complex geometry of this cavity presents no revolution symmetry and has concave zones at the top and bottom (‘capacitive plates’), hence some points may be not visible at certain angles from outside the cavity (see Fig. 2). Also, the stiffening frame around the cavity may impede the direct sight of certain zones, deflecting second sound from these areas and thus increasing distances to the sensors. The cavity was tested with horizontal beam axis. Two TES wafers, with 4 sensors each*,* were placed above and below the cavity, with horizontal wafer planes. The quench measurements were taken at 1.75 K and 1.8 K, where second sound speed is quite constant at 20.0 ± 0.1 m/s.

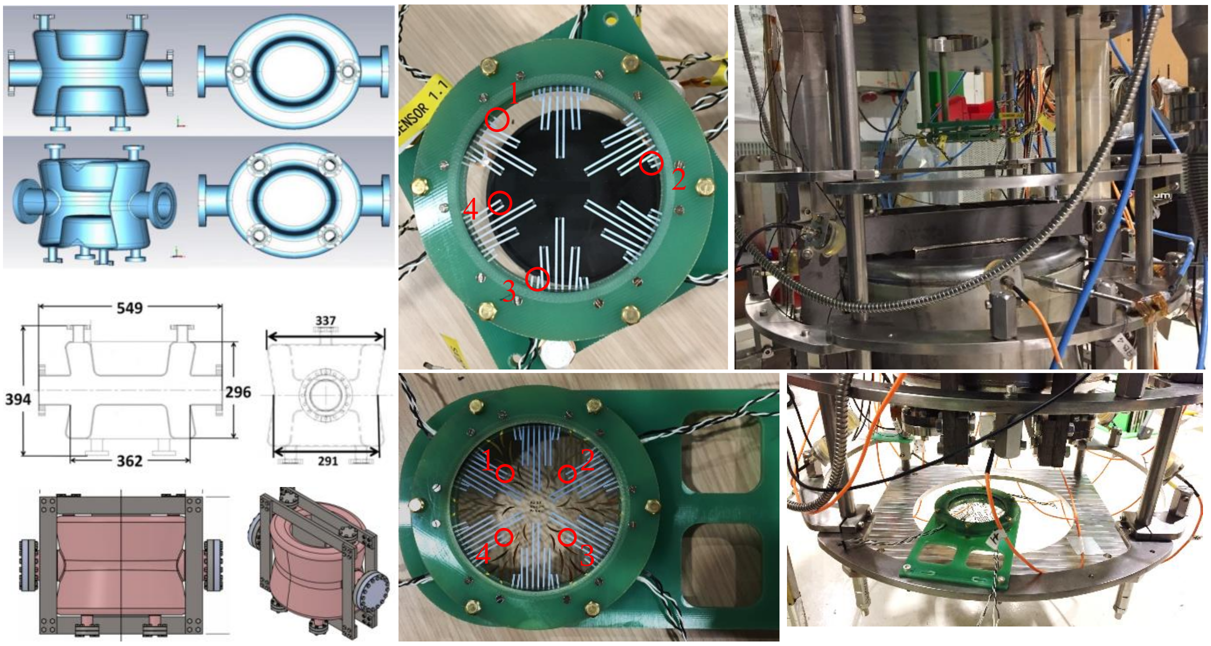

Figure 2. DQW PoP CRAB cavity, and full setup with TES.

3. Results from the UK4Rod test

The quenches of the UK4Rod cavity produced a virtually instantaneous drop of the RF transmitted power signal, set as t=0. The time of flight (TOF) of second sound was defined as the time at which the signal rises above its average noise level by 100 %. In many cases, a very sharp peak was observed on the TES signal at around t=10 ms. In others, a rather slow excursion was seen at times between 15 and 22 ms. Sometimes both types of signal are observed in the same quench event. Figure 3 shows examples of TES and RF signals.

The trilateration algorithm was applied taking the 6 TES in groups of 3 (20 combinations) to obtain the origin points depicted in Fig. 3 (bottom left). The packed cloud of points on the cavity edge closer to the wafer corresponds to the acute peaks, while the disperse cloud comes from the slow excursions data. This seems to indicate two different quenching or second sound production mechanisms.

Only the first type could be precisely located on the surface of the cavity. However, the fact that the signal comes from locations closest to the sensors seems to indicate that the cavity could be heating simultaneously all over the surface, or that the quench is propagating very fast.

The second type has however some structure (Fig. 3 right center), showing three peaks in the histogram (bottom right) of estimated distance from the trilateration point to the center of the wafer. Our hypothesis is that the second sound comes from a non-direct sight spot, presumably the high E-field zone on the rods. More sophisticated wave tracking methods are required to evaluate deflected second sound paths.

4. Results from the DQW PoP crab test

The quench behaviour of the DQW cavity was quite different from the one of the UK4Rod. A self-pulsating quench spot can be deduced from the oscillating RF power signals: a hot spot becomes

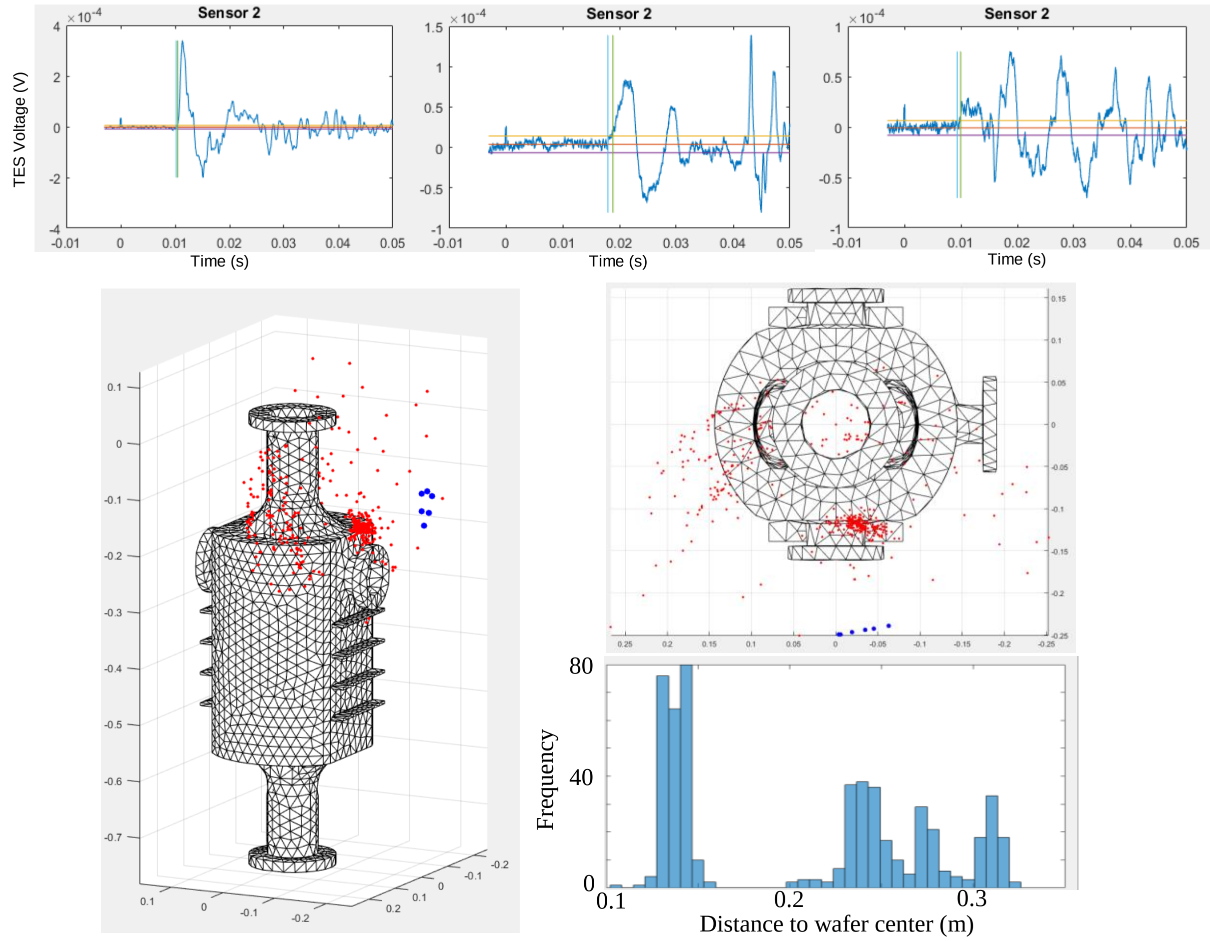

Figure 3. Results from the UK4Rod test. Top: examples of TES signals, sharp, slow and mixed types. Left bottom and right center: trilateration algorithm results applied to all the data. Bottom right: distribution of distance to the center of the wafer of these events.

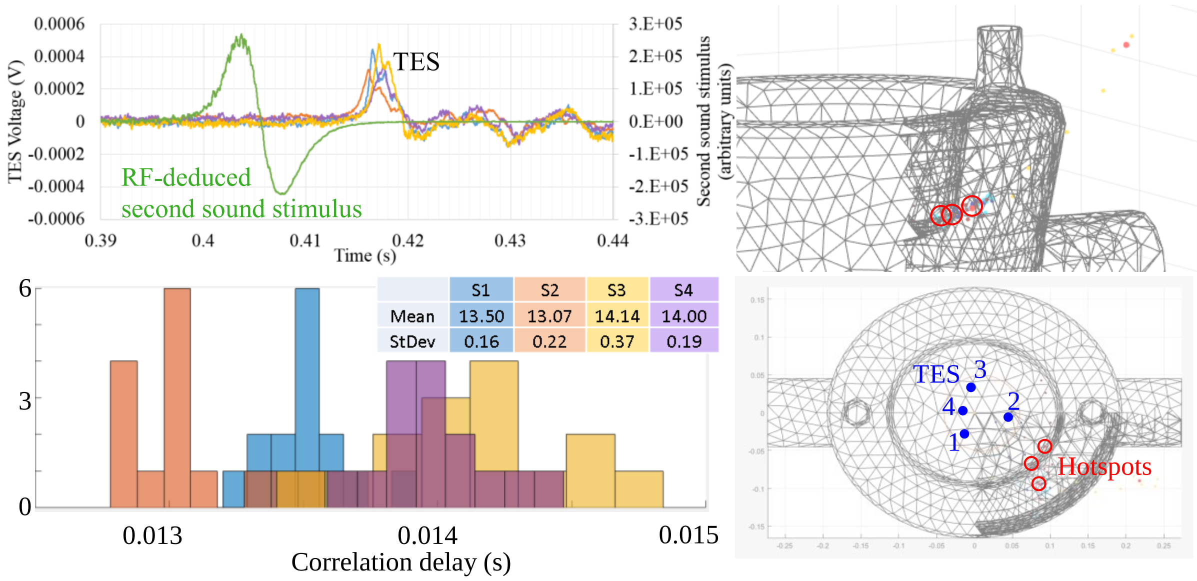

Figure 4. Results from the DQW PoP crab test. Left top: examples of TES and RF signals. Left bottom: histogram of TOF for each sensor. Right: trilateration points next to cavity geometry.

unstable, quenches the cavity thus reducing the power, the cavity is then cooled down and ready to accept power again and the process repeats. Upon a quench, the RF transmitted power does not drop instantaneously, but within a time frame of 10 ms. This required that the TOF be determined by time correlation of the TES signal with the estimated second sound stimulus (SSS) profile deduced from the time evolution of the dissipated RF power. The SSS is proportional to the time derivative of RF dissipated power on the cavity wall, which was deduced from the cavity power balance. Only the TES above the cavity detected strong enough events. These 4 sensors produce 4 combinations of 3 to apply trilateration. The combination of TES 1-3-4 is not taken into account because the TES are almost aligned, which results detrimental for the algorithm precision. The TOF was determined by statistical analysis for each sensor individually (see histograms in Fig. 4) and the three considered combinations gave the results indicated with red circles in Fig. 4. The quench origins lay only 2 cm away from each other, close to the surface of the cavity, slightly inside the concave zone. This is a high E-field zone, suggesting that the quench is initiated at a field emission attracting center.

5. Conclusions

Tests performed with superconducting radio frequency cavities have confirmed that Transition Edge Sensors can be used as second sound detectors with the aim of precisely localising quenches. Clear second sound signals were registered with TES during two SRF cavity tests. Diverse time shapes of the TES signals were observed, which could point to different mechanisms of quench initiation or heat transfer. The evaluation of results with direct sight trilateration algorithm has given, for some events (supposedly in which the sensors have direct view of the hotspot) very clear indication of a hotspot location with 2 cm precision. The application of more complex algorithms with geodesic calculation of second sound path and elaboration of quench maps could help to get a better insight in those cases where former algorithm fails. Future tests are planned installing sensors such as to cover a wider surface around the cavity and ensuring direct view of all cavity surface portions by at least a few of them.

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