QUENCH DYNAMICS IN SRF CAVITIES: CAN WE LOCATE THE QUENCH ORIGIN WITH 2ND SOUND?[*]

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Abstract

A newly developed method of locating quenches in SRF cavities by detecting second-sound waves has been gaining popularity in SRF laboratories. The technique is based on measurements of time delays between the quench as determined by the RF system and arrival of the second-sound wave to the multiple detectors placed around the cavity in superfluid helium. Unlike multi-channel temperature mapping, this approach requires only a few sensors and simple readout electronics; it can be used with SRF cavities of almost arbitrary shape. One of its drawbacks is that being an indirect method it requires one to solve an inverse problem to find the location of a quench. We tried to solve this inverse problem by using a parametric forward model. By analyzing the data we found that the approximation where the second-sound emitter is a near-singular source does not describe the physical system well enough. A time-dependent analysis of the quench process can help us to put forward a more adequate model. We present here our current algorithm to solve the inverse problem and discuss the experimental results.

INTRODUCTION

Superconducting radio-frequency (SRF) cavities is the leading technology for future linear accelerators. A quench often is the limiting factor of a cavity performance. It is widely assumed that quench is caused by some abnormality: either a surface defect or a localized material contamination near RF surface of the cavity. To study the nature of this defect it is necessary to locate a quench origin on the cavity surface. It has been also demonstrated that by removing some amount of material (by either mechanical grinding or chemical etching) from the quench origin one can increase the maximum accelerating gradient of the cavity.

A traditional approach for locating a quench origin is to use a multichannel temperature mapping of the cavity surface. To achieve a sub-centimeter accuracy one needs to develop either a system with many thousand thermometers, which is expensive and cumbersome to operate, or a system with a fewer channels but also with a limited coverage, which would require a multiple cooldowns with different thermometer configurations to “zoom-in” on suspected region.

The SRF group at Cornell University used Oscillating Superleak second-sound Transducers (OST)[1] to detect second-sound emitted by a quench[2]. Time delay between the onset of a quench (as indicated by RF electronics) and arrival of second-sound to an OST defines the distance between the OST and the second-sound emitter. With a few OSTs (usually eight) placed strategically around the cavity, one can hope to deduce the location of the emitter by solving the inverse problem.

This technique was later adapted by other SRF labs. This paper discusses the experience with one such a system at Fermilab.

THE INVERSE PROBLEM

Unlike the thermometry mapping that detects the quench location directly, the second-sound detection technique is an indirect method that trades off the hardware complexity for the problems with data analysis. So it is of prime importance to have a reliable solution to the inverse problem. It is impossible to solve this problem in general terms, so a common approach if we make some assumption on the heat source parameters and try to solve the problem withing this model framework. The simplest and the most common assumption is that the heat source is a singular point between the detectors with unknown coordinates. Also, the duration of the quench is assumed to be much shorter than the second-sound travel time to the nearest sensor. (Experimentally we observe that during the quench the stored energy in the cavity decays within about 0.5 msec.) Within this framework there are essentially two approaches to the solution. We can choose three sensors and solve trilateration problem directly, essentially by finding the intersection point of three spheres with centers at the selected sensors and the radiuses equal to the corresponding distances (as determined by second-sound arrival time) to the source. Alternatively we can use all available data and find a minimum norm solution to an overdetermined system of nonlinear equations:

$$(x_0 - x_i)^2 + (y_0 - y_i)^2 + (z_0 - z_i)^2 = C^2 \cdot t_i^2, \qquad (1)$$

where (x_0, y_0, z_0) are the coordinates of the quench origin, (x_i, y_i, z_i) and t_i are respectively coordinates and measured time delay of the transducer number *i*, *C* is the second-sound velocity, and *n* is the number of transducers.

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The solution would minimize the following error function $f(x_0, y_0, z_0)$:

$$\sum_{i=1}^{n} \left[(x_0 - x_i)^2 + (y_0 - y_i)^2 + (z_0 - z_i)^2 - C^2 \cdot t_i^2\right]^2 \tag{2}$$

For minimization we used Nelder-Mead algorithm in GNU Octave implementation (downhill simplex method).

The second method can be easily modified to incorporate additional restriction on the possible solution. E.g. we can force the source to be on the cavity surface. We can also make the model more sophisticated by adding additional parameters describing the heat source, e.g. by describing it as a sphere of a finite radius.

We did an extensive Monte-Carlo analysis of the minimization method with simulated data. We assumed that the major source of error is an uncertainty in OST locations. We found that the output error (the RMS of the source position) is always smaller than the input error (the RMS of the OST positions) and that the problem is stable even for large input errors. For detailed analysis please refer to the [3].

EXPERIMENTAL SETUP

All of the experimental result described in this paper were performed on the Vertical Test System (VTS) at Fermilab[4]. Both nine and single-cell "TESLA"-shape cavities were used[5].

The OSTs are of original Cornell's design. We use a DC-bias scheme to read them out. The preamp is located on the top of the cryostat in an attempt to reduce the length of the parasitic capacitance of the cable to the OST. The amplified signal is routed to the instrumentation rack where it is read by simultaneously-sampling 24-bit data-acquisition (DAQ) board[6]. The same DAQ reads all eight OST channels as well as the amplitude of the transmitted RF-power and vapor pressure in the helium bath.

For tests with a 9-cell cavity we usually place OSTs in pairs in diametrically opposite locations in the plane of the equatorial weld of cells 2, 4, 6, and 8. Each pair was rotated relative to the next one by 90 degrees.

For single-cell cavity tests we usually installed OSTs in two planes just above and below the plane of the equatorial weld (see Figure 1).

EXPERIMENTAL DATA

Once we started analyzing the real data, the first problem that becomes apparent was that the error (Eq. 2) was much greater then what we would expect. The problem becomes even more obvious if we would try to reconstruct the second-sound emitter location by using triangulation. In that case the answer would strongly depend on which OSTs we have chosen for analysis. As one can see from Figure 2 if we use a pair of OST on the left side the solution would lay few centimeters on the left side from the (known) quench origin, the pair on the right would give solution few centimeters on the right side, and using one OST from the left side and one from the right would have no solution at all (the corresponding circles do not intersect).

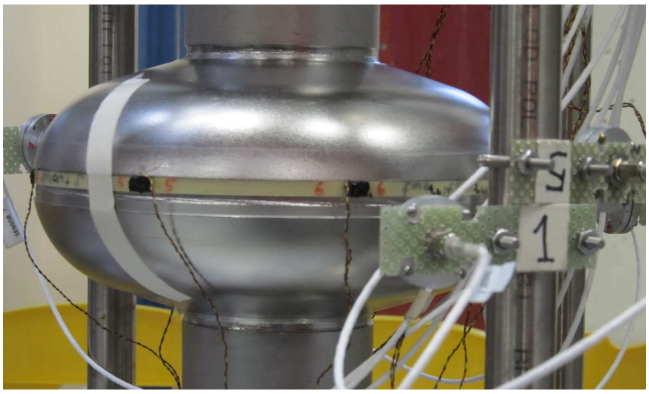

Figure 1: OSTs installed on 1-cell cavity.

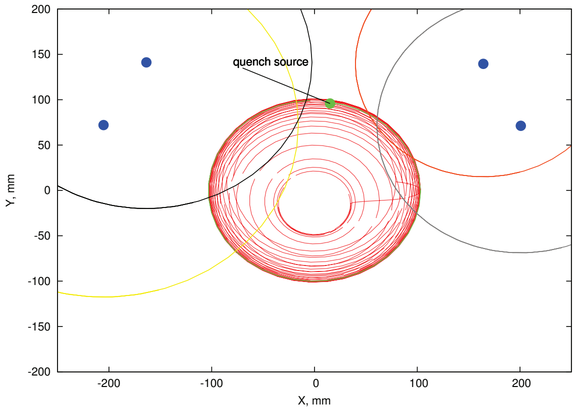

Figure 2: Discrepancy in quench location.

In another test we had a quench located almost directly underneath an OST. The measurements revealed that the second sound traveled less than the distance to the cavity surface (see Figure 3).

That problem was also observed by Cornell group and their solution for improving the convergence was to use second-sound velocity as a fitting parameter [2]. This approach has no physical meaning and the problem demands more analysis to fully understand the underlying processes.

SECOND-SOUND EMITTER

As we mentioned in the beginning, in a popular model of a quench event in an SRF cavity, the RF energy dissipates almost instantaneous in a very small region on the cavity surface. That point-like object emits second-sound waves. In our opinion the existing data strongly indicate that this model is too crude and may result in substantial systematic

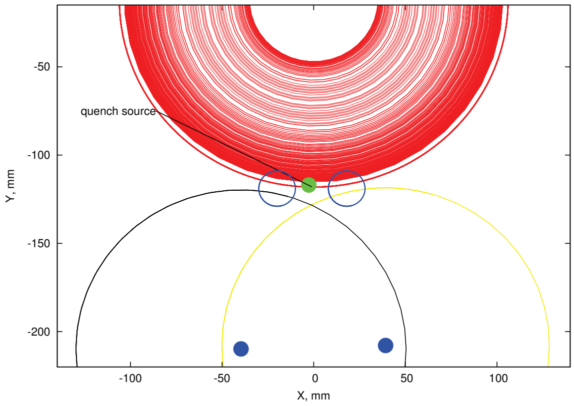

Figure 3: Discrepancy in quench location.

error in locating the quench origin.

We have started developing a comprehensive numerical model that describes quench dynamics. The first results show that during the quench, the hot spot on the cavity surface grows to a size of a few centimeters in a fraction of millisecond time. That means that the corresponding He-I/He-II interface will be moving with velocity exceeding the second-sound velocity (about 20 m/sec). This interface cannot emit second-sound until its velocity becomes equal (or less) to the velocity of second-sound. That happens by the time when most of the stored RF energy has dissipated (in about 0.3 to 0.5 msec).

Besides propagating along the cavity wall, the heat from the quench also flows into helium. This is more complicated process since it involves multiple processes: thermal conductivity in liquid helium, convective heat transfer, two-phase heat transfer (since the temperature of the cavity surface can reach almost 100K we know that helium vapor must be present), etc. But we also know that heat transfer in normal helium is less efficient than thermal conductivity of Nb with RRR = 300. So it appears safe to assume that the He-I/He-II interface propagates about a centimeter (or somewhat less) in the direction normal to the cavity surface.

CONCLUSION

Locating quench origin in SRF cavities by means of detecting the emitted second-sound has already been proven to be a useful tool. But we believe that inverse problem arising in related data analysis remains a challenge. The model currently employed for its solution is too crude and can lead to substantial systematic errors which, in turn, cast some doubts on reliability of the entire method.

To develop more adequate model we need to understand better the dynamics of the quench on a sub-millisecond time-scale. The existing experimental data and numerical simulations that just have been started suggest few important corrections to the model. The second-sound is emitted with some time delay (of a fraction of millisecond) after the onset of the quench. The emitter itself is not a point-like object, but an a 3d object with characteristic dimensions comparable to the distance to second-sound detectors. We hope that further research will yield information about this object suitable for incorporating into a parametric model.

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