

# QUENCH STUDIES OF ILC CAVITIES \*

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## Abstract

Quench limits accelerating gradient in SRF cavities to a gradient lower than theoretically expected for superconducting niobium. Identification of the quenching site with thermometry and OST, optical inspection, and replica of the culprit is an ongoing effort at Jefferson Lab aimed at better understanding of this limiting phenomenon. In this contribution we summarize experiments that have been and are being developed at JLab for quench studies.

## INTRODUCTION

ILC project calls for construction of thousands of 9-cell SRF cavities. To make cost of the project financially sound, yield of high performance SRF cavities was set at 90 percent. One of the goals of cavity R&D part of ILC research program is to understand and to mitigate limitations in SRF cavities that inhibit reaching 90 percent yield. ILC R&D have shown that quench is one of the main limitations, and it is especially a typical problem in cavities made by new vendors. Such cavities are limited at 15-25 MV/m and additional chemical polishing has little or no effect. Understanding and mitigation of low field quench is an important part of proving ILC project feasibility.

A number of techniques and experiments have been and are being developed at Jefferson lab for localization, characterization, understanding, and mitigation of quench in ILC cavities. RF measurements along with thermometry, OSTs, optical inspection, high resolution thermometry, and replica profilometry provide non-destructive information about the quench region, whereas experiments such as dual mode excitation, artificial defect investigation, centrifugal barrel polishing, and electron beam re-melting are aimed at understanding and mitigation of the defect. Below we summarize ongoing quench studies at JLab.

## QUENCH LOCALIZATION

Quench field analysis of all TM<sub>010</sub> pass-band modes is a standard procedure at JLab to reduce ambiguity in  $\pi$ -mode quench location to two cells out of nine in a 9-cell ILC cavity. To find the responsible cell and location, two techniques are currently in use at JLab: 2-cell ILC thermometry and second sound detection with oscillating superleak

transducers (OSTs).

## Thermometry

After the ambiguity of quench location was reduced to two cells via pass-band measurements, JLab 2-cell ILC thermometry [1] is attached to these two cells. Each cell's thermometry has five G-10 boards with 32 Allen-Bradley 100 Ohm thermometers each that cover equator and regions around equator. Typically, during quench event, a heating spot of 4 - 8 thermometers diameter is seen on temperature maps. Analysis of temperature maps allows to identify the location of the quench-inducing defect. In case of type-II quench, we often find no dominating thermometer in the quench region below quench field. In case of type-I quench, a single thermometer in the quench region typically dominates the temperature map below quench field. In this case a clear preheating field dependence of the quench spot is recorded. Fig. 1 illustrates pre- and in-quench temperature maps.

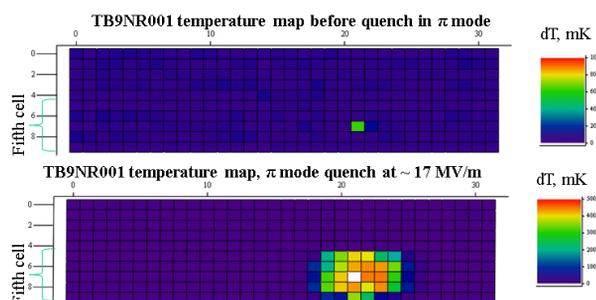


Figure 1: TB9NR001 was limited by a quench in the center cell at 17 MV/m in  $\pi$  mode. In the upper temperature map a single hot spot at the quench location dominates the temperature map below quench field. The lower temperature map was captured in repetitive quench at random quench development stage.

## Second Sound Detection

Second sound detection with oscillation superleak transducers is another method put forward recently at Cornell University for quench localization in 9-cell ILC cavities [2]. Second sound detection offers unique advantage over thermometry for quench localization by being shape-independent. Since the technique is not limited by the cavity shape, it can be applied not only to

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the baseline ILC shape, but also to alternative cavity design shapes. OSTs were used at JLab to locate quenches in TB9RI019, TB9RI027, TB9NR001, Jlab LG-1, PKU2, Seamless DESY 9-cell as well as in ICHIRO-07 and MHI-08 where our 2-cell thermometry cannot be attached [3]. We also used OSTs during 3.5 cell cavity and crab cavity testing. In Fig. 2 second sound detection data for  $3\pi/9$ -mode quench in JLab LG-1 is plotted for some of the OSTs. From the data we determine second sound time-of-travel from quench location to each OSTs, and, after the cavity is removed from the dewar, triangulation from OSTs to quench location is done. It is interesting to note that in this case, Fig. 2, as well as in some other measurements, we observed first sound wave arrival with Cornell oscillating superleak transducers.

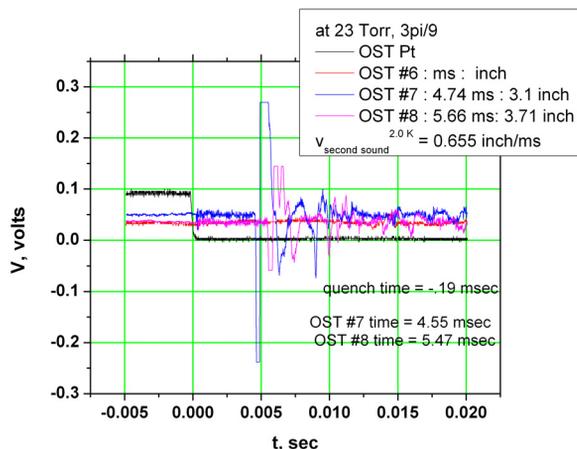


Figure 2: OST data captured during JLab LG-1  $3\pi/9$ -mode quench. Black line is transmitted power trace on the oscilloscope. Red, blue, and magenta lines are responses from different OSTs around the cavity.

## QUENCH CHARACTERIZATION

After the quench location has been found by thermometry and second sound detection, thermometry provides information on the preheating field dependence in the quench region below quench. Besides 2-cell ILC thermometry, which has about 1 cm spacing between different thermometers, a high resolution thermometry with spacing of 1.2 mm have been recently developed for quench-related studies. The new system allows quench localization with 1 mm precision, preheating distribution around quench location, and hot spot evolution with field. Finally, optical inspection and replica techniques are used to characterize topography of the quench region.

### Optical Inspection

Three types of optical inspection systems are in use today around the world for inside surface inspection of SRF cavities. The first type uses a videoscope guided inside the cavity with a rigid tube [4], [5]. Typical resolution of

these systems is estimated to be a few tens  $\mu\text{m}$ . The second type has a CCD/CMOS-camera carrying tube that is inserted horizontally inside the cavity [6]. The camera captures image of the surface reflected from the 45 degree mirror located next to the camera. This camera is estimated to have resolution of 6  $\mu\text{m}$ , and equipped with special lighting developed at KEK, which is capable of line depth profile of a feature. Finally, the third type uses a horizontally inserted tube that carries only mirror, the image is captured by a long distance microscope placed outside the cavity [7]. This system is estimated to have 3-4  $\mu\text{m}$  resolution. At JLab we have worked with all three types of these inspection systems. Most often for 9-cell ILC cavity inspection we use the second type borrowed from KEK, while simultaneously working on development and improvement of our third type inspection system. In Fig. 3 a  $\pi$ -mode limiting defect in TB9NR001 is shown captured with KEK system.

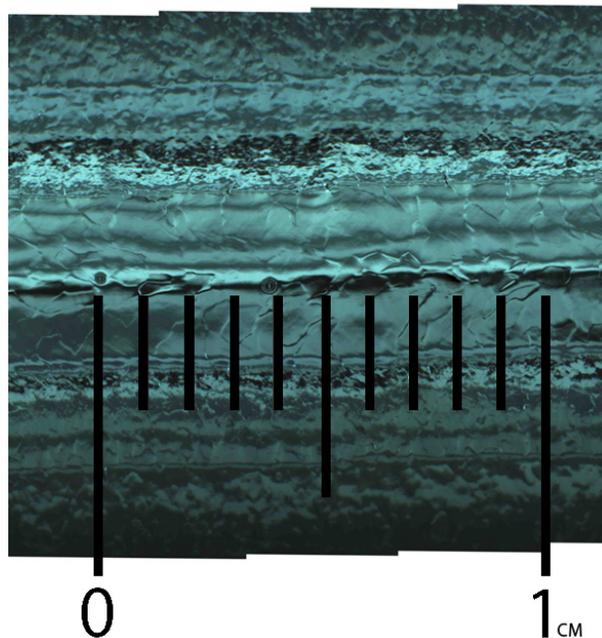


Figure 3: Inside surface of the TB9NR001 fifth cell equator region at 334 degrees, where the  $\pi$ -mode quench was localized with the thermometry and OSTs.

### High Resolution Thermometry

2-cell ILC thermometry system that we use for quench localization at JLab, also captures preheating field dependence in the quench region below quench. Several different preheating field dependence have been reported at the preheating quench locations, indicating different physical mechanisms [8]. However, because whole surface 2-cell ILC thermometry system has spacing of about 1 cm between thermometers, it does not provide spatial resolution and hot spot spatial evolution with field in the quench region. To obtain this information a high resolution ther-

metry has been recently built at Jefferson Lab [9]. With this system we were able to identify the pit responsible for  $\pi$ -mode quench in TB9NR001 at the twin cat-eye feature region, and to measure heating evolution around the feature. This is *not* possible with conventional-size thermometer. In Fig. 4 we show a defect captured by the optical inspection system, the temperature distribution registered by the high resolution thermometry at the defect before the quench, and the photo of the high resolution thermometry sensor.

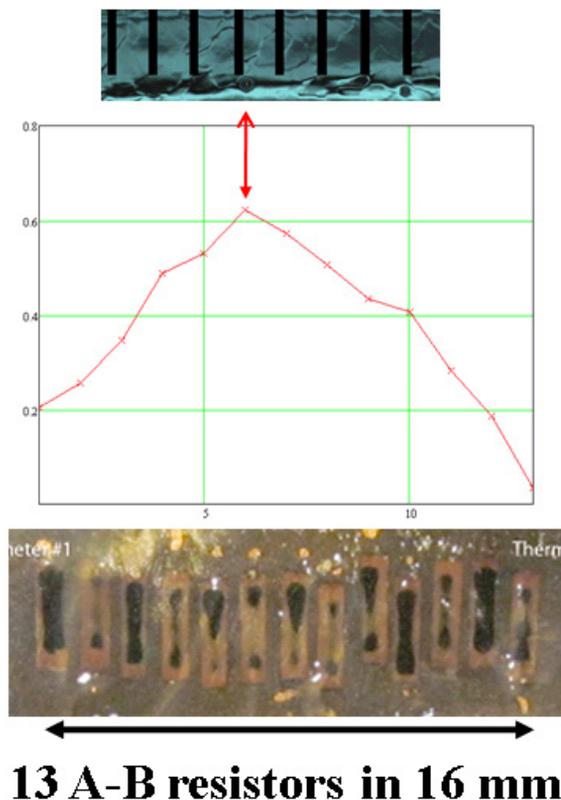


Figure 4: Using the new high resolution thermometry, we were able to distinguish preheating from two pits in twin cat-eye feature and identify the pit responsible for  $\pi$ -mode quench in TB9NR001. The upper picture shows twin cat-eye feature found with the optical inspection in TB9NR001 at the predicted  $\pi$ -mode quench location (spacing between black lines on the picture is about 1 mm). The center picture shows heating distribution in the quench region. The lower picture presents a photo of high resolution thermometry sensor.

### Replica Measurements

Replica is a non-destructive technique to characterize topography of the inner surface near equator of the cavity. In our experiments we used two-compound replica material kindly provided to us by Dr. F. Furuta<sup>1</sup> of KEK. After components are mixed in the ratio 1:1 by weight, the mixture

<sup>1</sup>Dr. F. Furuta is now at Cornell University

is poured inside the cell of interest and let to be cured for about 1 hour. After one hour replica can be extracted from the inside of the cell and analyzed in microscope. It is important to remember that replica represents a negative image of the surface, unless replica of the replica was made. Features in PKU2 and TB9NR001 as well as in a few single cells were characterized with this technique [10].

## QUENCH UNDERSTANDING

Two experiments have been designed at Jefferson Lab towards better understanding of quench nature. One experiment exploits pass-bands of  $TM_{010}$  mode in 9-cell ILC cavity. The other experiment probes the contribution of a geometrical feature to heating and quench by creating a simple pit with known geometry on the RF surface. Thermometry then can provide information on heating as function of field at the pit location.

### Dual Mode Excitation

Dual mode excitation was used in earlier days of RF superconductivity to demonstrate thermal nature of quenches at that time [11]. We decided to use technique today on 9-cell cavities to get better understanding on the nature of quenches limiting SRF cavities today. We have measured seven quenches with this technique in three different cavities. The data for all defects can be fit by a simple formula,  $H_1^\alpha + H_2^\alpha = \text{const}$ , with one fitting parameter  $\alpha$ , where  $H_1$  and  $H_2$  are respective fields in each mode,  $\alpha$  is the exponent expected to be  $1 < \alpha < 2$ , with  $\alpha = 2$  corresponding to a pure thermal quench,  $\alpha = 1$  corresponding to a pure magnetic quench. For the quenches we measured, the exponents lie between 1.4 and 1.9 [12]. In JLab LG-1 one of the defects was limiting the achievable gradient to  $E_{acc} = 40.5$  MV/m in  $8\pi/9$  mode corresponding to  $B_{peak} = 173$  mT in the end cells. Surprisingly, the exponent for this quench was 1.5, and so the quench was not pure magnetic. The closest to pure thermal quench was measured in TB9NR001 with exponent being about 1.9. In Fig. 5 we plot dual mode excitation measurement in TB9NR001 for this defect. The best fit to the data gives exponent of about 1.9, closest to pure thermal quench we have measured so far. This data led us to speculate that foreign contamination may be the source of the twin cat-eye feature at the  $\pi$ -mode quench location.

### Artificial Geometrical Defect

A topographical feature is usually found in the type-I quench region. The feature often has a complicated geometry, which makes it hard to understand analytically how geometry contributes to the breakdown. In order to elucidate this question, we decided to create artificial pits on the inside surface of RF cavity in the high magnetic field region near equator [13]. Four pits were created 90 degrees apart in the high magnetic field region, but outside heat affected zone. The resulting cavity was limited at 13 MV/m

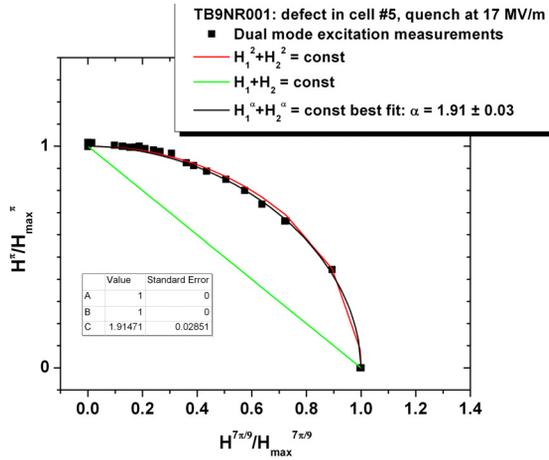


Figure 5: Dual mode excitation of  $\pi$ -mode quench in TB9NR001. Black squares are the data, the black line is the best fit. The red line is theoretical estimate for a pure thermal quench. The green line is the theoretical estimate for a pure magnetic quench.

by quench at one of the defects. Preheating data recorded with the thermometry shows field dependent behavior with several slope transitions. It is being analyzed and compared with numerical simulations. High resolution thermometry studies on dominating defect are underway. In Fig. 6 we plotted temperature versus field for all four defects as well as the thermometry data from TB9NR001  $\pi$ -mode quench region for comparison.

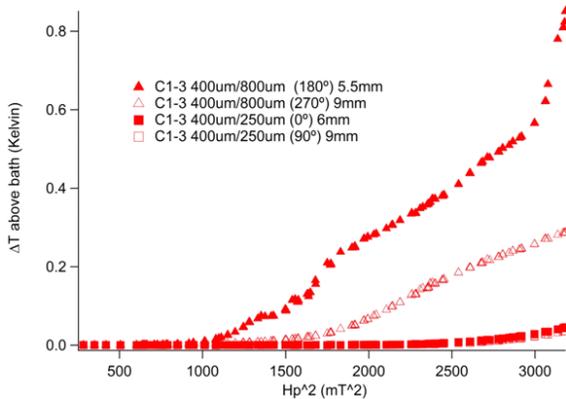


Figure 6: Thermometry data for artificially created pits in C1-3 cavity. Red solid triangles are the preheating data for the dominating defect that caused quench at the highest field. Red solid squares, red empty triangles, and red empty squares are the preheating data for the other three defects.

### QUENCH MITIGATION

Once the quench is localized, it is often found that type-I quench location coincides with a single topographical feature on the inside surface of 9-cell ILC cavities. Removal of such feature has been demonstrated to improve maximum gradient. However, it also has been shown that this

feature cannot be removed by additional chemical polishing, other methods have to be employed. At Jefferson Lab electron beam re-melting is under development as a local defect removal technique. We also, following Fermi Lab, pursue understanding and optimizing of centrifugal barrel polishing.

### Electron Beam Melting

Electron beam re-melting is a local defect repair technique under study at Jefferson Lab [14]. After preliminary encouraging results with single cell cavities, Fig. 7, modeling and engineering is ongoing to integrate a 9-cell cavity repair fixtures into the existing electron beam welding machine.

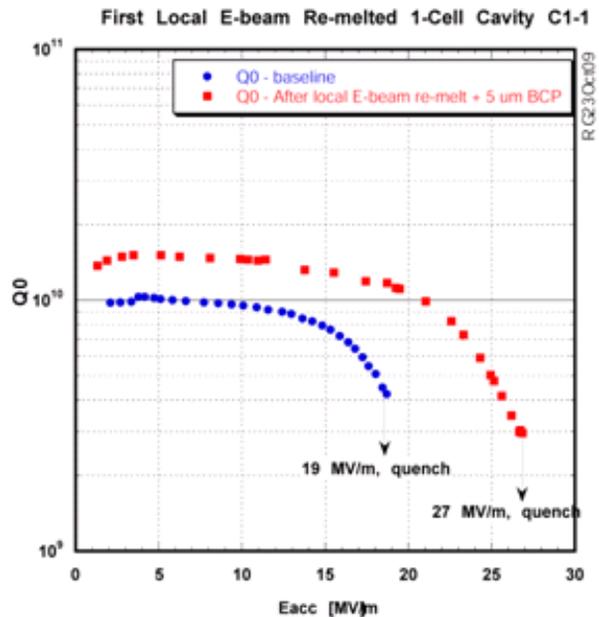


Figure 7:  $Q_0$  vs  $E_{acc}$  for a single cell cavity before and after EB re-melting. After EB re-melting the quench field improved from 19 MV/m to 27 MV/m.

### Mechanical Polishing

As a part of integrated cavity processing development we study centrifugal barrel polishing for best surface preparation [15]. As the first step, we reproduce CBP recipe developed at Fermi lab and analyzed samples prepared with this recipe for contamination and roughness. The data shows the evolution of surface roughness as a function of preparation step as well as effectiveness of post-CBP cleaning techniques.

### CONCLUSION

In this contribution we summarized experiments that have been and are being developed at JLab for quench studies. Quench identification with thermometry and second

sound, its characterization with optical inspection, thermometry, and replica are standard processes at JLab aimed at understanding quench origin. Recently developed high resolution thermometry was specifically created for quench region heat evolution and high resolution quench spot characterization. Dual mode excitation and artificial pits measurements were designed to probe the nature of quench and experimentally evaluate topography contribution to quench. Studies under way at JLab to develop quench mitigation techniques, such as electron beam remelting and centrifugal barrel polishing.

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