ILC TESTING PROGRAM AT CORNELL UNIVERSITY*

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Abstract

Cornell University's superconducting cavity development program is one contributor to the global collaborative effort on critical SRF R&D for the ILC. We conduct R&D in support of the baseline cavity development as well as several alternate cavity development paths. For the baseline program we are preparing and testing ILC cavities. We have developed a new quench detection system and successfully applied it to ILC 9-cell and 1-cell cavities to find quench producing defects, which were characterized with subsequent optical examination. We have successfully repaired a 9-cell cavity using tumbling to raise the accelerating gradient from 15 to above 30 MV/m. We have identified quench producing defects in single-cell cavities using our large-scale thermometry system and subsequently extracted and inspected the defect region with an SEM. For the alternate R&D, we are developing reentrant cavity shapes with 70 mm and 60 mm apertures, and a simpler, potentially faster and less expensive electropolishing method called vertical electropolishing. We are also assisting in developing new cavity vendors by rapidly testing single-cell cavities they produced to qualify their fabrication methods.

INTRODUCTION

In the early-1990's the Cornell SRF group helped initiate the development of $\beta = 1$ cavities for TESLA. This work continues today supporting the ILC S0 goal of reproducibly producing high-Q $E_{acc} > 35$ MV/m superconducting niobium cavities set forth by the ILC-GDE [1]. The critical S0 high-gradient project is addressing and advancing the major technical issues limiting the technology, including niobium cavity material, design, fabrication, processing, handling, and testing.

Cornell has many unique facilities in support of the collaboration activities. This paper will review the Cornell programs/facilities and give examples of their recent employment in support of the ILC high-gradient goals.

First, we review a new method developed for quench detection in 9-cell and 1-cell cavities, followed by optical inspection [2]. We compare the defect imaging capability with more detailed imaging by SEM after extraction of a defect from a single cell cavity. We discuss the repair of one 9-cell cavity by tumbling [3]. We discuss the tests performed at Cornell on multi-cell reentrant cavities and review the unique Cornell cavity processing features, a vertical electropolish (VEP) apparatus [4]. We have shown that individual cells of a 9-cell have surpassed 35 MV/m after the VEP treatment. Finally, we review our recent work pre-qualifying a new Americas region cavity vendor, a collaboration between Niowave, Inc. and C.F. Roark Welding and Engineering Co., Inc.

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A NEW METHOD FOR DEFECT LOCATION

We are following the general ILC R&D strategy for raising the high-gradient cavity yield by locating the quench producing defects in low-performing cavities, followed by optical inspection and repair. In the past year we have assembled and demonstrated a new and efficient quench-spot location system using 2nd sound in superfluid helium. This system employs an array of oscillating superleak transducers (OSTs) to detect the second sound waves generated during quench, figure 1. The distance between three or more transducers and the quench-spot is determined by measuring the time-of-flight between the arrival of the second sound wave at each transducer and the cavity quench location. With this information the quench location can be unambiguously determined in three dimensions.

The unique 2nd sound defect location system was employed on 37 cold tests in the past 18 months. Subsequent optical inspections of the second sound located quench-spots have found pits, bumps, and areas with no optically visible defects at all. This work is reviewed in detail in reference [2]. Figure 2 shows one of the pits observed with the optical Questar based system.

DEFECT EXTRACTION FROM A SINGLE-CELL AND SEM INSPECTION

After preparing a single-cell 1.5 GHz cavity with VEP and testing with our standard thermometry system with 760 fixed thermometers [5] we identified a quench spot and the pre-heating at this quench spot from temperature maps taken out to $E_{acc} = 29$ MV/m. After extracting from the cavity a 1 cm^2 sample centered on the quench region we examined the sample in the SEM and found a large pit near the equator weld, as shown in Figure 3. We can see many interesting details of the pit with the SEM. Such features do not show up with optical remote distance detection; see Figure 4 for an example. Hence the optical system can only serve a rough but useful guide to the detailed nature of defects.

9-CELL DEFECT REPAIR BY TUMBLING

Cornell's work with single cell cavities [2] discussed later demonstrated that "bump-like" defects can be fixed with additional etching, e.g. BCP. However, there is mounting evidence that there are pit-like defects which cannot be fixed with heavy EP. Several ideas are

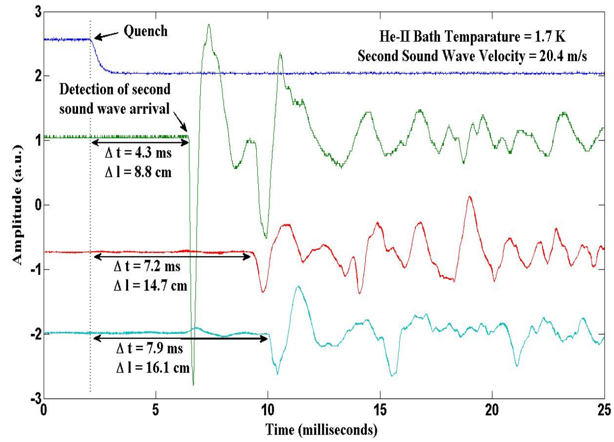

Figure 1: A quench event. Four traces are shown: 1) the upper trace is the quenching-cavity transmitted power, 2-4) the lower traces are transducer second sound signals.

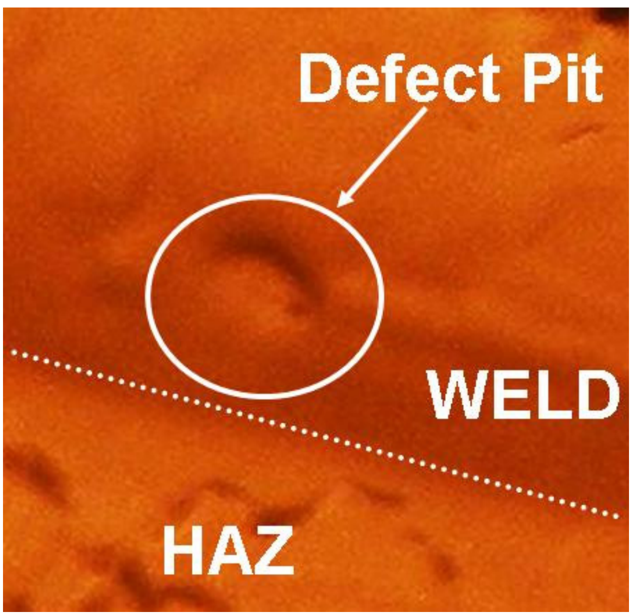

Figure 2: The 9-cell reentrant cavity pit defect.

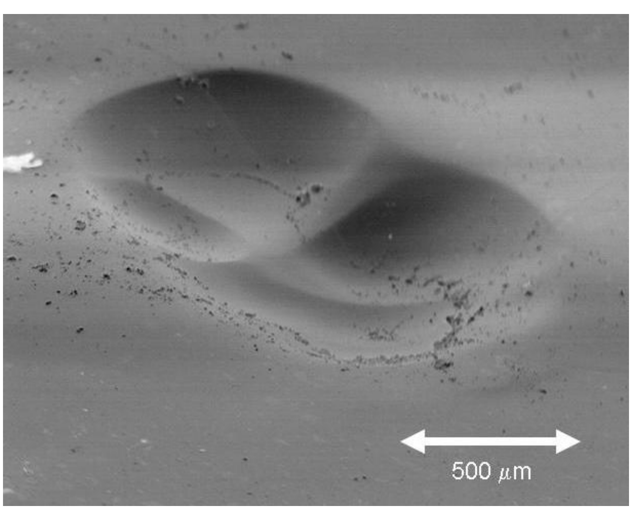

Figure 3: Pit defect found at quench location in a single cell cavity. The bar is 500 microns.

currently under investigation to fix such defects: centrifugal barrel polishing, local grinding/polishing, electron-beam melting, laser melting, tumbling, etc. We employed a simple cavity tumbling apparatus which is cheap and simple to operate. The apparatus was initially developed to tumble two-cell cavities for the ERL Injector cryomodule [6]. It was modified to tumble cavities with one to nine cells. In this configuration the Cornell tumbling apparatus removes ~10 µm of surface material per day at the equator weld. This removal rate is significantly less than centrifugal barrel polishing but the system is lower in cost and easier to implement.

Recently, a 9-cell reentrant cavity was tumbled to fix equator weld defects [3]. Tumbling successfully repaired this cavity, which originally quenched at an accelerating gradient of 15 MV/m. The cavity now reaches an accelerating gradient exceeding 30 MV/m, figure 4. This shows that tumbling is a good way to repair defects, like pits.

After tumbling, processing with VEP (removed ~180 µm), 600^0C baking for 10 hours, and micro-VEP (removed ~25 µm) the 9-cell reentrant cavity had a lower quality factor than expected. Most likely this is due to insufficient hydrogen-degassing of the larger quantity of hydrogen absorbed during tumbling and subsequent vertical EP. More work is planned to complete the development of the tumbling/degassing techniques for the production of high-Q and high-gradient cavities.

ALTERNATE CAVITY DESIGNS

Cornell is pursuing alternate cavity shapes which are designed to minimize the ratio of surface magnetic field to accelerating gradient in order to increase the maximum accelerating gradient limited by the RF critical field of niobium. One proposed shape, the Cornell reentrant design [7] achieved accelerating gradients exceeding 50 MV/m in single cell tests at Cornell [8] after post-purification (at Cornell), tumbling (at KEK) and EP (at KEK). Implementing this achievement in 9-cell cavities is the area of active work.

A joint venture between Advanced Energy Systems, Inc., and Cornell has fabricated two multi-cell reentrant cavities: a 9-cell and a 3-cell [3]. The 9-cell reentrant cavity's accelerating gradient increased dramatically after we employed second sound detectors to locate the gradient limiting pit-defect (figure 2), tumbling to repair the defect, and vertical electropolishing. The lower Q is most likely due to excess hydrogen contamination accumulated during tumbling. We found similar low-Q behavior with the 3-cell reentrant cavity which was also tumbled to smooth out the equator weld region and hydrogen-degassed with the standard temperature and time. The Q-disease showed up in the 3-cell after parking the cavity in the dangerous temperature zone (100 – 150 K) for 30 hours. Tests results for both cavities are shown in figure 4.

The finding of Q-disease in the two multi-cell reentrant cavities necessitates further processing to remove the hydrogen from the bulk niobium. JLAB has recently baked the reentrant 9-cell cavity at 600^0C for 10 hours. A cold test is planned for the 9-cell reentrant cavity in the next 2-3 months. Future 1350^0C post-purification steps are planned for the reentrant 3-cell cavity. If this is successful it will also be applied to the reentrant 9-cell cavity.

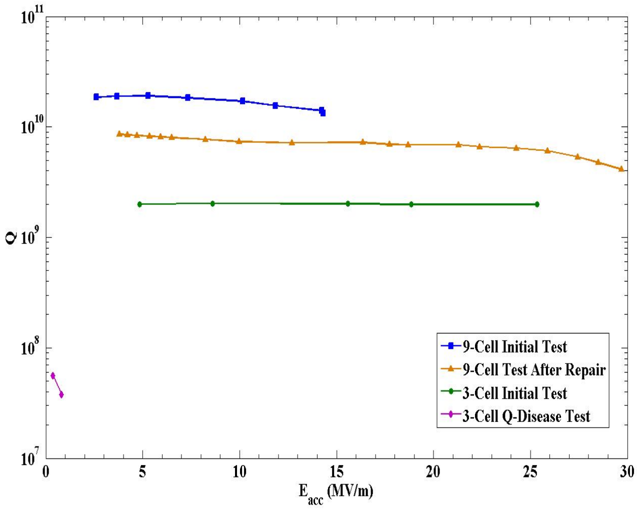

Figure 4: RF performance of the two multi-cell reentrant cavities fabricated in a joint effort between AES and Cornell University. Four RF performance curves are shown: 1) the 9-cell cavity at 2.0 K limited by a pit-defect, 2) the 9-cell cavity at 1.7 K after tumbling-repair of pit-defect, 3) the 3-cell cavity after its first cooldown at 1.6 K, and 4) the 3-cell cavity after a warm-up to 100^0C-135^0C for 30 hours and a rapid cool to 1.6 K.

ALTERNATE PROCESSING

Electropolishing (EP) is a critical treatment step for the production of niobium cavities with accelerating gradients > 35 MV/m [9]. The majority of EP facilities are using the continuous EP method developed at KEK [10] with the cavity held in the horizontal orientation. We have developed an alternative method, vertical electropolish, which was designed to be less expensive and easy to install to support the mass-processing of cavities during ILC construction, refer to [4, 11]. The continuous VEP procedure:

- Eliminates rotary acid seals
- Eliminates sliding electrical contacts
- Eliminates the cavity vertical/horizontal position control fixturing
- Simplifies the acid pluming/containment

We have employed the VEP procedure in the past year during the processing of two 9-cell cavities and numerous 5-cell, 3-cell, and single cell cavities. The aim of this work is to successfully process and test 9-cell ILC cavities with accelerating gradients > 35 MV/m. Defects have prevented the 9-cell ILC cavities processed with VEP from reaching the gradient goal in the π-mode. However, we have demonstrated, in individual cells, accelerating gradients which exceed 35 MV/m in two different 9-cell cavities processed with VEP: a reentrant 9-cell cavity fabricated by AES/Cornell and the TESLA-style 9-cell cavity ACCEL-9. Refer to table 1 for the mode measurement table for one of the ACCEL-9 cold tests and to reference [3] for details of the reentrant 9-cell cavity tests.

Table 1: Mode Measurement Table ACCEL-9

Mode	E_{pk}(MV/m)	Quench Location
π	51.4	Cell 1
$8\pi/9$	45.9	Cell 1
$7\pi/9$	Under Analysis	Cell 5, under analysis.
$6\pi/9$	48.8	Cell 1
$5\pi/9$	76.5	Cell 5
$4\pi/9$	60.6	Cell 4
$3\pi/9$	77.0	Cell 5
$2\pi/9$	29.8	No Quench
$\pi/9$	Not Tested	Not Tested

NEW VENDOR CAVITY EVALUATION

To build the ~14,000 cavities required for the ILC each of the three world regions must have a sizable industrial base of qualified companies to draw cavities from [1]. We have recently prequalified two new cavity vendors: Niowave/Roark [12] and AES, Inc.

The pre-qualification goal of the cold tests performed here was to determine if the cavities were limited by defects to accelerating gradients less than 25 MV/m, not to initially push the cavities to the highest possible quality factors and accelerating gradients. In support of this, the cavities were chemically polished with a 1:1:2 buffered chemical polish (BCP) at T<17^0C with the following procedure:

1) Cavity is packed in ice.
2) Chilled (8^0C) 1:1:2 BCP is transferred to the cavity.
3) The BCP solution etches the cavity until the temperature rises to 15-16^0C.
4) The cavity is drained, rinsed with DI H_2O, and rotated 180^0
5) Steps 1-4 are repeated until the desired amount of material is removed.

After chemical polishing the cavities were prepared by:

1) Ultrasonically degreased in a 1% Alconox and 99% DI H_2O solution for 30 minutes.
2) Rinsed with DI H_2O
3) Ultrasonically cleaned in a DI H_2O bath for 30 minutes.
4) 2 hour high-pressure rinse in a class 10 cleanroom.
5) After drying for 24 hours the fundamental power coupler and the transmitted power coupler were installed in the same class 10 cleanroom.

After the processing steps described above, the cavities were tested at 2.0 K in a vertical dewar. Each vertical test was equipped with two calibrated ruthenium oxide resistors for bath temperature monitoring and an array of 8 OSTs for quench-spot location, if necessary.

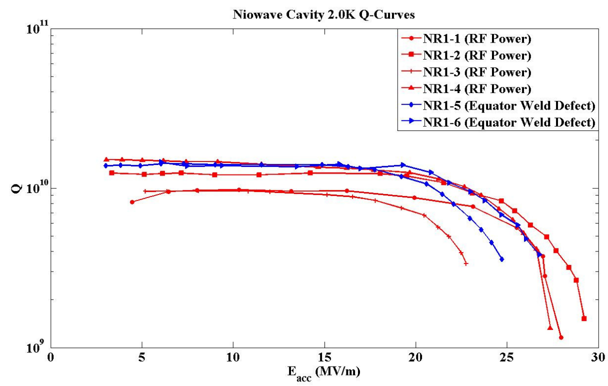

Figure 5: Q-curves for the six Niowave Inc. single-cell cavities tested at Cornell. All cavities exhibited the high-field Q-slope common to BCP cavities and two cavities quenched at equator weld defects.

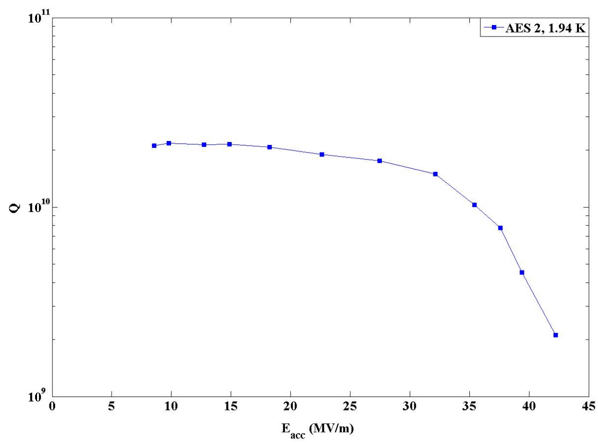

Figure 6: AES cavity 1.94 K performance after vertical electropolishing and hydrogen degassing. The cavity started field emitting at 22 MV/m and never quenched.

The RF performance for the BCP treated Niowave/Roark cavities is shown in figure 2. All of the cavities exhibited high-field Q-slope due to the heavy BCP treatments they received. Five of the cavities achieved continuous wave accelerating gradients greater than 25 MV/m. Of these five cavities only two were limited by defects, these defects are discussed in reference [12]. The sixth cavity's (NR1-3, figure 5) maximum achievable continuous wave accelerating gradient was limited to 23 MV/m by Q-slope, but it did not quench. During pulsed operation this cavity attained accelerating gradients of 25 MV/m without quench.

In addition to the pre-qualification tests of the Niowave/Roark cavities Genfa Wu (FNAL) performed identical tests on Advanced Energy Systems (AES), Inc., cavities at Cornell. One of these AES cavities was recently processed with vertical electropolishing and tested. The cavity received a heavy 200 μm vertical electropolish, a 48 hour 800^0C bake to degas the hydrogen from the niobium, a 25 μm micro-vertical electropolish, ultrasonic cleaning, HPR, clean assembly, and a 48 hour 120^0C bake prior to testing at 2K. The measured performance of this cavity is shown in figure 6. Notice the large high-field Q-slope. 4 hours before the cold test the vacuum system connected to the cavity was violated resulting in a jump in the cavity vacuum from 5e-8 torr to 2 torr, resulting in field emission during the test. Further testing after additional HPR is planned.

SUMMARY

The Cornell SRF program is assisting in all areas of ILC cavity prototyping, testing, repair, and the associated basic R&D to improve processes. We have many one-of-a-kind facilities which complement existing and developing programs. We will continue to develop new techniques for the production of high-gradient cavities.

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