

## GRADIENT IMPROVEMENT BY REMOVAL OF IDENTIFIED LOCAL DEFECTS\*

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### Abstract

Recent experience of ILC cavity processing and testing at Jefferson Lab has shown that some 9-cell cavities are quench limited at a gradient in the range of 15-25 MV/m. Further studies reveal that these quench limits are often correlated with sub-mm sized and highly localized geometrical defects at or near the equator weld. There is increasing evidence to show that these genetic defects have their origin in the material or in the electron beam welding process. A local defect removal method has been proposed at Jefferson Lab by locally re-melting the niobium material. Several 1-cell cavities with known local defects have been treated by using the JLab local electron-beam re-melting method, resulting in gradient and Q0 improvement. We also sent 9-cell cavities with known gradient limiting local defects to KEK for local grinding and to FNAL for global mechanical polishing. We report on the results of gradient improvements by removal of local defects in these cavities.

### INTRODUCTION

Recent effort in pushing gradient for reproducible realization of high gradient SRF cavities for ILC improved quench limit understanding [1][2][3][4]. A major conclusion is that the quench limit in real 9-cell cavities (with a surface area of about 1 m<sup>2</sup>) is caused by **highly localized defect**. Furthermore, the quench limitation can be roughly characterized by two types,

- Type-I: quench limit occurs at a gradient in the range of > 25 MV/m. There is normally no observable feature at the quench site through high-resolution optical inspection. Often times, a second EP effectively improves the quench limit to more than 30 MV/m.
- Type-II: quench limit occurs in a gradient range of 15-25 MV/m. It is often correlated with sub-mm sized geometrical defects (mostly pits but bumps are also observable) at or near the equator electron beam welding. Repeated EP has no or little effect in improving the quench limit, suggesting the permanent nature of these defects.

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More than 20% 9-cell cavities are limited by type-II quench. The failure rate tends to be higher for cavities built by new vendors. In order to achieve the ILC gradient yield goal of 90% at 35 MV/m, it is necessary to understand the origin of quench causing defects.

Guided repairing (grinding) has been used in labs for a long time as a means of recovering sub-standard cavities. More recently, improvement of the local grinding and development of new local repair methods have attracted a lot of attention. The value of these efforts is in two folds: (1) Help understand the origin of the quench causing defect, which in the long run will tell us how to improve the fabrication process for reliable mass-production, which is important for large-scale projects like ILC; (2) Provide useful means of recovering expensive cavities in a cost-effective manner. This may be very important for medium- or small-scale projects.

At Jefferson Lab, we have developed a local repair method by using electron-beam re-melting. Several 1-cell cavities with known local defects have been treated, resulting in gradient and Q0 improvement. We have been also collaborating with KEK and FNAL in development of 9-cell cavities repair method of local grinding (KEK) and global mechanical polishing (FNAL) techniques.

### LOCAL ELECTRON-BEAM RE-MELTING

#### *Development by Using Flat Niobium Samples*

We first developed the procedure and parameters of local electron-beam re-melting by using flat niobium samples with the same thickness as compare to that of a real niobium cavity. Fig. 1 shows a photo of such a sample with man-made pits (~200 μm in diameter) on its surface after local electron-beam re-melting. It is evident that these pits are completely eliminated.



Figure 1: Effect of local electron-beam re-melting. Man-made pits (~200 μm in diameter) are seeded in the central surface region of a niobium sample. Pits are visible in the left area (without re-melting) and are completely eliminated in the right area (with re-melting).

### 1-Cell Cavities and Results

Local repairing by electron-beam re-melting can be done either from the inside or from the outside of a cavity. Our present method was developed based on the existing JLab EBW machine and the re-melting is achieved through electron irradiation on the outer surface at the location of known defect. Fig. 2 shows the local re-melting process of a 1-cell cavity C1-1.

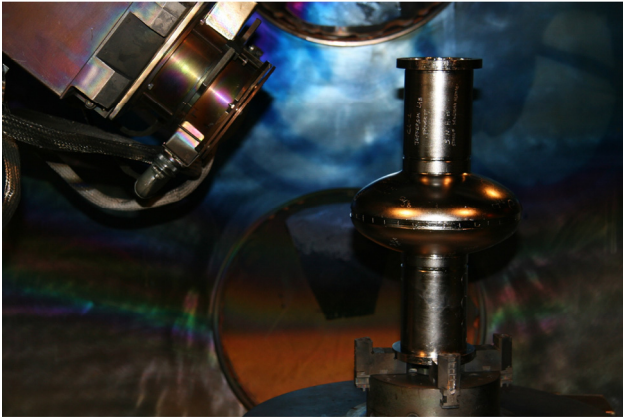


Figure 2: 1-cell niobium cavity C1-1 being treated at a known quench-causing defective area with local electron-beam re-melting by using JLab's in-house EBW machine.

The baseline vacuum in the EBW machine chamber is  $8E-7$  Torr. At each dose of electron irradiation, some gas species (mainly  $H_2$  and  $CO_2$ ) are release for a short duration. This is shown in Fig. 3, in which case, three  $H_2$  and  $CO_2$  spikes are recorded, corresponding to three bursts of electrons at two treated areas. During the process of treatment of multiple areas, the EBW machine gun head needs to move and sometimes a small air leak is observed. In this case, we allow enough time for the system to recover to the baseline vacuum level.

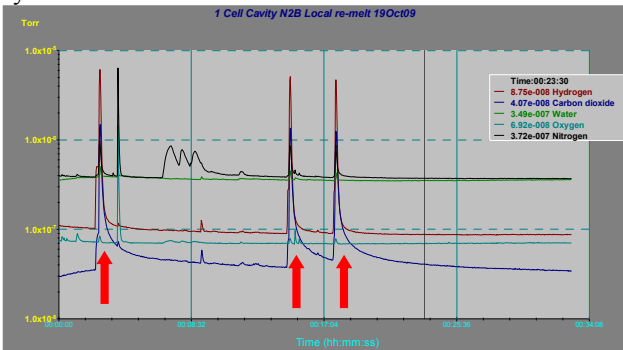


Figure 3:  $H_2$  &  $CO_2$  spikes recorded during the local electron-beam re-melting treatment cavity N2B. Each spike corresponds to one dose of electron irradiation.

Following the local electron-beam re-melting treatment, the cavity C1-1 was BCP etched for  $5 \mu m$  removal from the inner surface and HPR rinsed and RF tested at 2 K. Fig. 4 gives the test result before and after the treatment. The quench limit is improved to 27 MV/m from 19 MV/m and the quench location is unrelated to the previous one before the local electron-beam re-melting treatment.

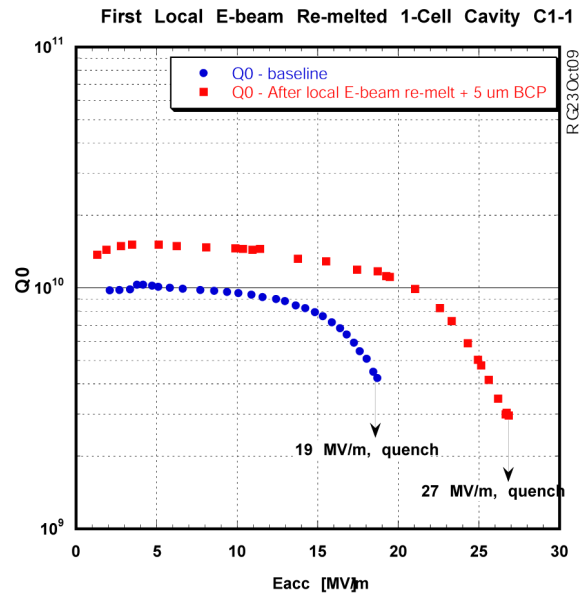


Figure 4:  $Q(E_{acc})$  curves of 1-cell niobium cavity C1-1 before and after an electron-beam re-melting treatment at the quench location determined during the baseline test.

### LOCAL MECHANICAL GRINDING

As reported earlier, a JLab in-house built large-grain 9-cell cavity JLAB LG#1 reached a quench limited at a weld repair of the center cell equator EBW joint [5]. The cavity was later on sent to KEK for defect removal by local grinding [6]. Several EP processing were also done at KEK with an accumulated removal of  $85 \mu m$ .

After the cavity was returned to JLab, it was RF test at 2 K following field flatness tuning, HPR, and 48 hour bake at  $120^\circ C$ . From the pass-band measurements, the center cell (cell #5) reached a surface field corresponding to a  $\pi$ -mode equivalent gradient of 43 MV/m (see Fig. 5), confirming the successful removal of the known defect in the center cell by the KEK local grinding treatment.

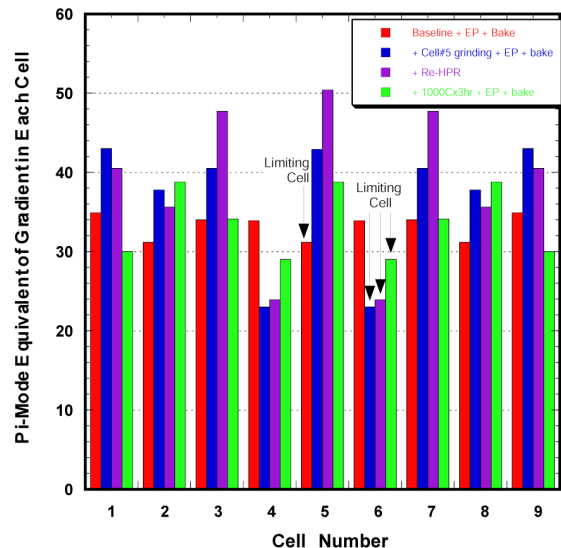


Figure 5: Gradient performance of each cell of JLAB LG#1 following various treatments including local grinding at KEK.

Despite the successful removal of defect in the center cell, the  $\pi$ -mode gradient was limited at 21 MV/m, a degradation as compared to the gradient limit reach in the previous test (30 MV/m). Further studies with second sound sensors revealed the quench location to be a weld irregularity in the cell #6 equator EBW joint.

The cavity was later on additionally high pressure water rinsed for advanced quench studies [7]. Cell #5  $\pi$ -mode equivalent gradient reached 50 MV/m. However, cell #6 remained limited by the same defect at the same gradient level. Finally, the cavity was vacuum furnace heat treated, electropolished for 30  $\mu\text{m}$ , and baked at 120 °C for 48 hours. A fairly high  $Q_0$  was measured [8]. The performance of cell #6 was slightly improved, but quench-limited by the same defect.

## GLOBAL MECHANICAL POLISHING

Mechanical polishing is a well known method for resetting the RF surface of a niobium cavity. This method was recently further optimized at FNAL with a “mirror finish” achieved [9] through a centrifugal barrel polishing (CBP) method. A 9-cell cavity AES6 was initially quench-limited at 14 MV/m due to a defect near the equator weld of center cell (Fig. 6a). After additional treatment (annealing at 800 °C for 2 hour, light EP 25  $\mu\text{m}$ , in-situ baking at 120 °C for 48 hours), the quench limit was improved to ~ 20 MV/m. This time the quench source was again in the center cell equator weld region (close to the original defect).

Ultimately, the cavity was sent to FNAL for resetting the whole inner surface with CBP method. Approximately 100  $\mu\text{m}$  was removed based on the ultrasonic thickness measurement. A mirror finish was created due to the FNAL CBP treatment. Fig. 6b shows the inner surface of the cavity at the location of the previously identified defect location (Fig. 6a). After the cavity was returned to JLab, it was vacuum furnace heat treated at 540 °C for 13 hours. Due to a facility malfunctioning, the required cycle of 800 °C X 2hour was not achieved. Based on the integrated outgassed hydrogen species, we decided to proceed for a light EP of 35  $\mu\text{m}$  removal. The cavity was tested at 2 K after the standard in-situ bake at 120 °C for 48 hours. The cavity reached a gradient of 36 MV/m at  $Q_0 > 1E10$ , limited by quench. After a 12 hour soaking at 100 K, the cavity was re-tested, showing only a 9% Q loss. Fig. 7 gives a summary of all the RF tests of AES6.

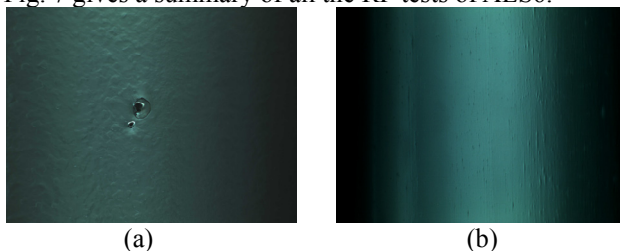


Figure 6: Image of the inner surface of center cell of cavity AES6 in the known quench-causing defect area before (a) and after (b) the FNAL CBP treatment.

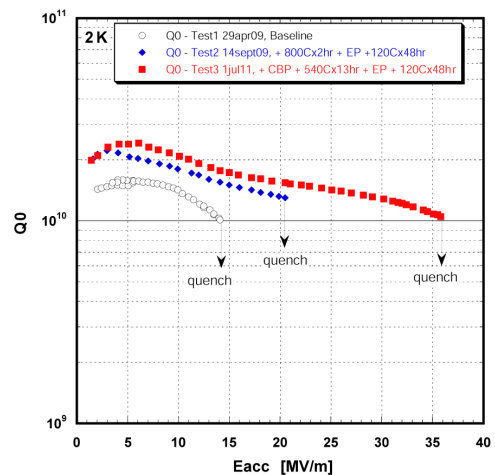


Figure 7: Summary of AES6 RF test results at 2K.

## CONCLUSION

A local repair method using electron-beam re-melting was developed at JLab and was successfully demonstrated in 1-cell niobium cavities. Extension of this method to a 9-cell cavity is the next step. In collaboration with KEK, a 9-cell large-grain niobium cavity was successfully repaired at the known quench location, further validating the KEK local repair method. In collaboration with FNAL, a 9-cell fine-grain niobium cavity was successfully recovered to meet the ILC vertical test acceptance. A surprising discovery is that heat treatment at 540 °C for 13 hours is still acceptable for outgassing heavy-hydrogen-loaded CBP cavities without causing severe Q-disease.

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