REPAIR SRF CAVITIES BY RE-MELTING SURFACE DEFECTS VIA HIGH POWER LASER TECHNIQUE

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Abstract

As field emission is gradually under control in recent SRF activities, cavity performance is limited by hard quench in most cases. Surface defect has been identified as one of main sources caused cavity quench, scattering cavity accelerating gradient from 12MV/m to 40MV/m. Laser re-melting technique is able to re-shape sharp pit rim to be a flat and smooth surface. In Fermilab, a sophisticated laser repair system has been developed for 1.3GHz quench-limited cavities. A pit in a 1.3GHz single-cell cavity was re-melted by high power laser pulse, after the laser processing the cavity took 30μm light Electropolishing. The cavity gradient achieved 39MV/m in initial run; after another 30μm Electropolishing, it reached 40MV/m. An improved laser repair system, which is able to re-melt surface defects in one meter-long 9-cell SRF cavity, has been developed at Fermilab after the success on single-cell cavity. It successfully re-melted a pit in 9-cell SRF cavity TB9ACC017.

INTRODUCTION

Superconducting Radio Frequency (SRF) cavity is a key component in state-of-the-art accelerators. It has many orders of magnitude higher intrinsic quality factor (Q0) than copper cavity due to extremely low RF loss on cavity wall, thus save cost for RF power in accelerator operation. It reduces total cost of accelerator even accounting refrigerator power which is for liquid helium production. Moreover, the SRF cavity has large beam aperture. It imposes less beam disruption such as energy spread, beam halo, etc; and provides high quality beams for physics research. Therefore SRF technology has been widely used in large accelerator projects and huge amount of high performance SRF cavities are demanded.

Recent SRF cavity performance reports [1, 2] indicate that field emission is gradually under control; and many SRF cavities limited by hard quench. Surface defects e.g. pits, bumps, cracks, scratches, etc., have been identified as a main source quenched cavities at a board spread of accelerating gradient, which is from 12MV/m to 40MV/m. It dramatically decreases reproducibility of cavity RF performance [3], and thus increases the whole accelerator costs.

Computer simulation indicates that magnetic field is enhanced at edge of a defect, which leads to localized heating when the cavity is at high fields. The enhancement factor correlates to sharpness of the defect edge [4, 5]. When the enhanced magnetic field at the defect edge exceeds local critical magnetic field, the edge would transit from superconducting to normal conducting

state. This leads to a sudden increase in surface impedance. If the increasing in surface impedance causes the cavity wall temperature to locally exceed the critical temperature, the entire cavity will quench [6, 7]. This conclusion has been experimentally confirmed by using optical inspection techniques [8, 9], replica techniques [10, 11], full t-mapping system [12, 13], and Oscillating Superleak Transducers technique [14].

Therefore, to smooth the sharp defect rim is able to effectively reduce the field enhancement fact. It would improve cavity RF performance as well as reproducibility. Based on this purpose, several cavity repair techniques have been developed by KEK, Cornell University and Thomas Jefferson Lab [15, 16, 17]. These techniques include locally mechanical grinding the defects, tumbling the cavity, re-melting the defect by electron beam.

In this work, we propose to use high power laser pulse to re-melt pits which have shape rim to flat surface. Compared to mechanical grinding and EB re-melting technique, laser technique is able to re-melt flaws within a second in the air. Hence it doesn't need a serial of mechanical heads from the coarsest to finest to grind the flaw step by step, nor is a vacuum system necessary for electron beam. Here we show after re-melting a pit by laser pulse, the cavity accelerating gradient was improved to 40MV/m which is very close to the theoretical limitation of TESLA shape cavity [18].

LASER RE-MELTING SYSTEM

The laser re-melting system developed at Fermilab is aimed to remove flaws which limit cavity below 20MV/m. The accelerating gradient would be restored upon 35MV/m, which is ILC goals representing the highest level in SRF field.

Concerns of system design are how to delivery high power laser beam to pit location through one meter-long and dark cavity. The pit dimension is typically 100-400 μm in diameter and 10-150 μm deep. Therefore a high-resolution CCD camera and a diffusing light are required for tracking pits. A huge amount of oxygen would dissolve in Nb surface if laser processing were implemented in the air without any protection. The thick oxygen layer, causing extra RF surface loss, leads cavity quench at the re-melting spot as well. Thus the molten region needs to be protected by inert gas; here we use high pure Argon gas.

Figure 1 shows the sketch of laser re-melting system. The high power collimated laser beam comes horizontally

through one side of cavity; the beam direction is changed to vertical by a 45º tilted mirror holding in laser head; the laser beam is finally focused on cavity wall by several optical lenses. A LED light panel is attached beneath the laser head.
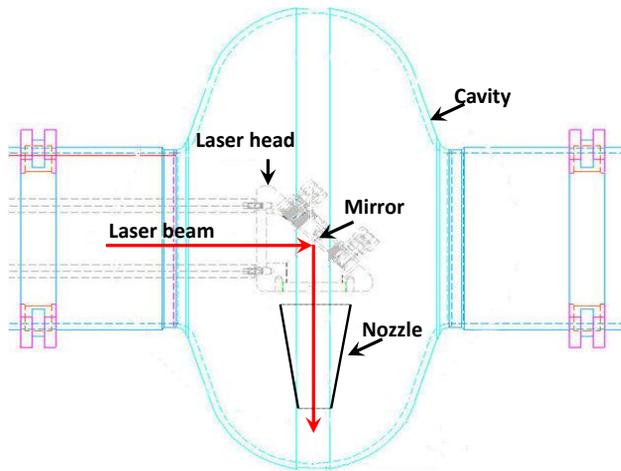
Figure 1. The Sketch of Laser Re-melting System.

Figure 2 is an image of the prototype laser re-melting system built in Fermilab for single-cell cavity. Here we use SLS 200 pulsed YAG laser source (LASAG, inc.), which is able to generate maximum 5 kW peak power within 10 ms duration. In the system, a CCD camera, which shares the same optical structure with laser beam, is installed at the end of laser beam deliver line. Clear surface image illuminated by a LED light source is shown on the monitor. The relative position of cavity and laser beam is able to be finely adjusted by high performance stages and lab jacks. Gas nozzle hold by rods comes through the other side of cavity.
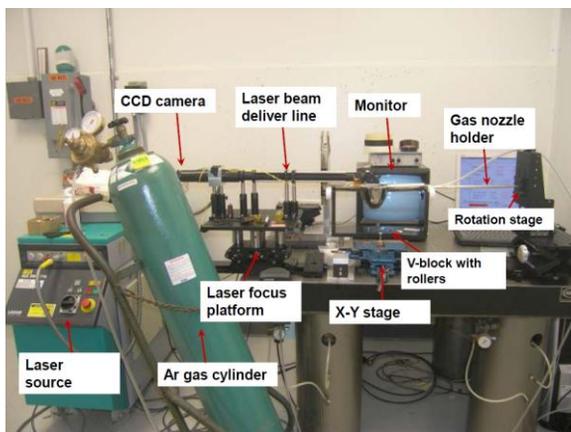
Figure 2: The prototype laser re-melting system in Fermilab.

After commissioning of the prototype of laser re-melting system, Fermilab designed and built a re-melting system (illustrated in Figure 3) for 9-cell SRF cavities. The new system optimizes the mechanical structure of nozzle. The gas tube as well as the laser beam line is able

to slide into cavity from one side. The improved design simplifies the operating procedures, saves space for the whole machine, and thereby improves the system reliability.
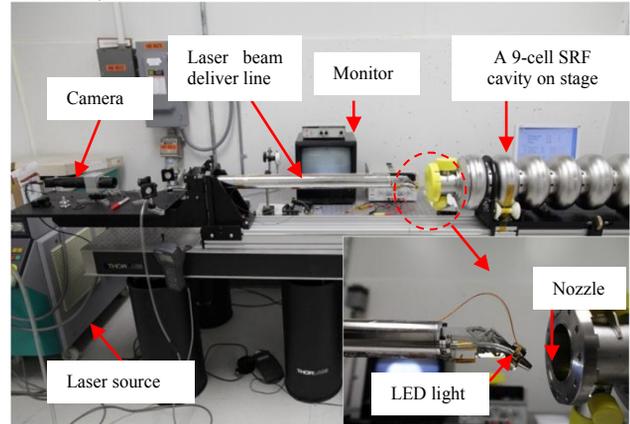
Figure 3: The laser re-melting system for 9-cell SRF cavity in Fermilab.

RE-MELTING A PIT IN SRF CAVITY

The system is able to generate laser spot from 500µm to 1000µm in diameter; the depth of the dome shape molten volume varies from 250µm to 500µm at different laser power level, which is appropriate to cover the pits size as described above.

The laser parameters optimization has been carried out via Nb coupon. We tested all types of laser pulse forms at different power levels. As the consequence, we found trapezoid shape is the most appropriate shape to generate an extremely flat and shinning surface. The peak laser power is 4kW; the total pulse duration is 10ms, the ramp-up time is 50% of the total duration, and the ramp-down is 10%. The laser spot size is 700µm in diameter and depth of molten volume is about 300µm. Figure 4 shows a man-made pit on Nb coupon was re-melted by laser pulse. The pit depth was reduced from 120µm to 30µm, and the pit rim is much smoother than before.
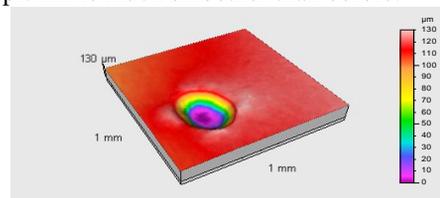
A. Man-made Pit Profile on Nb Coupon
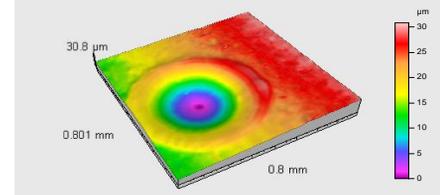
B. The pit profile after laser re-melting.

Figure 4: Profile comparison before and after re-melting a pit on Nb coupon.

Even with pure Argon purging during niobium laser melting, it is assumed the purity grade does not fully

eliminate the partial oxygen content near the laser melting spot. A laser pulse of 10ms melts local niobium where temperature decreases exponentially within a second with continued Argon gas purging after the laser pulse disappears. Once the niobium temperature drops below ½ of its melting temperature, the oxygen diffusion slows down significantly to below $1 \times 10^{10} \text{m}^2/\text{s}$ [19]. From the same reference, one can construct an integration based on diffusion constant dropping over the time. Such diffusion length of oxygen in niobium was determined to be 7µm for 10ms laser irradiation. The overall calculated oxygen polluted layer shall be less than 10µm. If the oxygen partial pressure is low, this polluted layer may not cause RF heating. We decided a greater than 10µm material removal is necessary due to less ideal Argon purity.

After coupon study, we re-melted a pit in 1.3GHz single-cell cavity TE1ACC003, which had a pit in equator region, caused the cavity quench at 36MV/m.
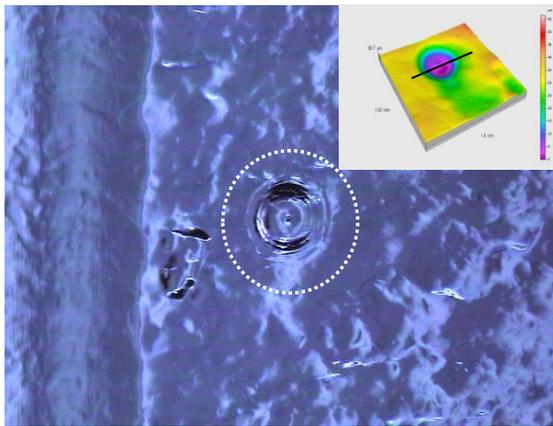
A. Inspection image of laser spot after re-melting the pit and light electropolishing.
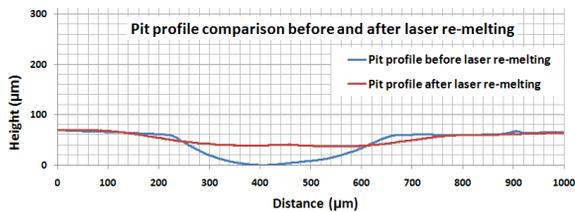
B. Profile comparison before and after laser re-melting the pit.

Figure 5: Profile comparisons before and after laser re-melting the pit in 1.3GHz single-cell cavity TE1ACC003 obtained using a stylus profilometer scanning on surface replica. At top (A) is the inspection image after re-melting the pit and light electropolishing, in the middle (B) is the profile comparison before and after laser re-melting. The black lines across the photographs indicate the path of the stylus.

After re-melting the pit, the cavity was lightly electropolished 30µm followed by high pressure water rinsing, then it was assembled in class-10 clean room, and 120°C baked. After vertical test the laser spot was inspected by Kyoto system, the image is shown in Figure 5. The surface profile was extracted by replica technique. The figure 5 also depicts profile comparison before and after laser re-melting. The pit profile was re-shaped, depth was reduced from 60µm to less than 20µm; the rim of pit was much smoother than before.

CAVITY TESTING RESULT

The vertical test result is shown in Figure 6, the plot (A) is a comparison curve of Q_0 vs. E_{acc} before and after re-melting the pit. The cavity achieved 39MV/m at temperature 2K, no filed emission happened. The gradient was improved 3 MV/m. But after first quench, the cavity maxium gradient dropped to 33MV/m. Heating was obtained by a 16-thermometers band which indicated quench location was at laser spot both at 39MV/m and 33MV/m. This phenomenon (quench caused gradient dropping) was firstly observed and discribed in reference [18]. According to the reference, the external magnetic flux traps through the impurities on cavity surface during the first quench; the flux produces normal conducting cores, which quenched the cavity at lower gradient. The flux trapping phenomenon can be recovered after warming cavity up to room temperature and then cooling it down back to 2K. We followed this procedure and restored the cavity gradient back to 39MV/m. This phenomenon indicates that the oxygen layer on laser spot introduced impurities and the thickness was more than 30µm. The cavity, thus, took another 30µm light electropolishing (totally 60µm EP after laser re-melting), then followed the same procedure described above. This time the gradient reached 40.3MV/m, and dropped to 38MV/m after first quench (Figure 6 (B)), the gradient degeneration caused by flux trapping was improved.
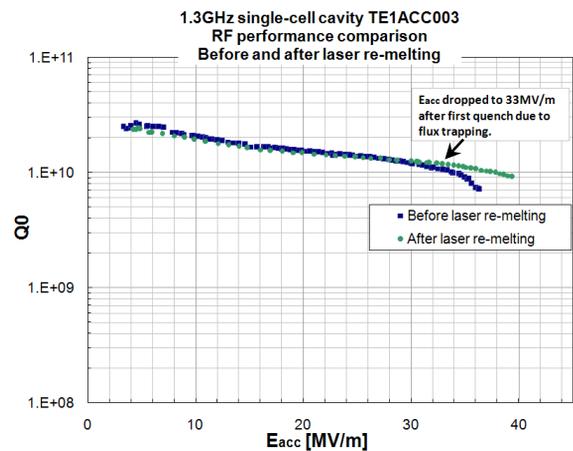
A. 1st vertical test result after laser re-melting pit and plus 30µm electropolishing.

1.3GHz single-cell cavity TE1ACC003
RF performance after laser re-melting plus totally 60μm EP
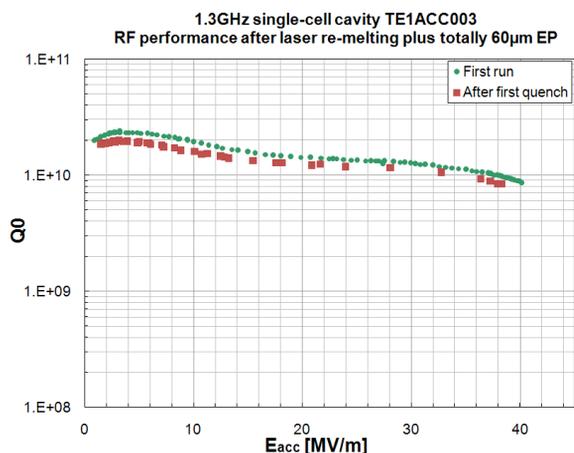
B. 2nd vertical test after taken another 30μm electropolishing (totally 60μm).

Figure 6: Cavity vertical test result after laser re-melting the pit.

CONCLUSION

A sophisticated laser re-melting system has been developed in Fermilab for 1.3GHz SRF cavity. Laser parameters was carefully studied and optimized via niobium coupon. The pit in 1.3GHz single-cell cavity was successfully re-melted by high power laser pulse, cavity took 30μm light EP, the gradient achieved 39MV/m in initial run, the flux trapped into cavity after first quench and caused the gradient degeneration, but this degeneration was improved by another 30μm light EP. The test result suggests laser re-melting technique is very promising to increase cavity performance reproductively. The technique itself is simple and easy for implement.

ACKNOWLEDGMENT

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