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HF FREE BIPOLAR ELECTRO-POLISHING STUDIES ON NIOBIUM SRF CAVITIES AT CORNELL WITH FARADAY TECHNOLOGY*

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Abstract

Cornell's SRF group and Faraday Technology have been collaborating on two phase-II SBIR projects. One of them is the development and commissioning of a 9-cell scale HF free Bipolar Electro-Polishing (BEP) system. Faraday Technology has upgraded their 1.3 GHz single-cell BEP system for hosting 9-cell cavities. Initial commissioning of the new system was done with a three single-cell cavity string, and a high gradient of 40 MV/m was demonstrated during the RF tests at Cornell. After this success with the test string, a 9-cell cavity was processed with the new system at Faraday and RF test was performed at Cornell. Here we report detailed results from these 9-cell scale HF free BEP studies.

INTRODUCTION

One of Cornell's activities during the last years has been the development of Vertical Electro-Polishing (VEP), which requires a much simpler and less expensive setup compared with the conventional Horizontal EP [1]. Cornell's VEP R&D focus has now shifted to more advanced topics. One topic is HF free VEP protocols in collaboration with Faraday Technology Inc. [2]. As the SRF projects become larger, the environmental impact of large usage of hazardous hydrofluoric (HF) based electrolyte in EP on niobium SRF cavities becomes not negligible. Therefore, R&D on a less hazardous or more eco-friendly niobium surface process has been performed and has made good progress [3, 4]. As part of recent progress on this eco-friendlier advanced EP work, Faraday Technology Inc. has established pulse forward/pulse reverse EP (Bipolar-EP) with an HF free electrolyte, and demonstrated high gradient performance with a single-cell cavity in collaboration with FNAL [5, 6]. As the further step of that success, Cornell's SRF group and Faraday Technology Inc. have started collaboration on Bipolar, HF free EP for multi-cell cavities. Faraday Technology has scaled up the Bipolar-EP system from single-cell scale to 9-cell cavity scale and commissioned the new 9-cell scale Bipolar-EP system with a three single-cell string provided by Cornell. The new 9-cell scale Bipolar-EP system was successfully used on a three single-cell string at Faraday Technology. High gradient RF performances of 40 MV/m were achieved with two of three single-cell cavities during the RF tests at Cornell [7]. Now a 9-cell cavity has been processed with that new Bipolar-EP system at Faraday Technology and has been tested at Cornell. This collaboration is supported by the Department of Energy's (DOE) phase-II Small Business Innovation Research (SBIR) program. The 9-cell cavity, MHI-02, processed and tested in this project has been loaned to Cornell from KEK as a part of the US-Japan collaboration program. In this paper, we report on the latest RF test results of the 9-cell cavity processed with HF free Bipolar-EP.

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BIPOLAR-EP ON A 9-CELL CAVITY AND RF TEST

Bipolar-EP

Figure 1 shows a general representation of the Bipolar EP anodic/cathodic pulse waveform. The waveform consists of 1) an anodic forward pulse to grow an oxide layer on the niobium surface, 2) voltage time off to dissipate the heat, remove reaction products, and replenishes reacting species, and 3) a cathodic pulse with reversed voltage to remove the oxide layer on the niobium surface, thus eliminating the need for HF. More detail descriptions of the bipolar EP techniques are published and can be found elsewhere [5, 8, 9].

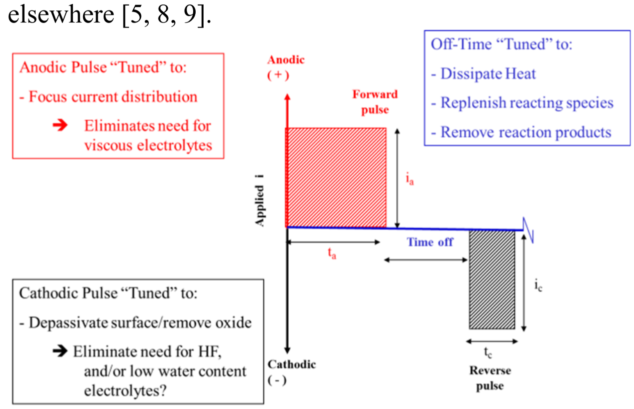

Figure 1: General bipolar EP process representation [6].

Bipolar-EP on a 9-cell Cavity

KEK's 9-cell cavity MHI-02 was processed in three successive treatments with different sulfuric acid concentrations as a synergistic activity (refer to Fig. 2 and Table 1).

1st Bipolar-EP Processing of the 9-cell Cavity

The 1st Bipolar EP on the 9-cell was performed using a HF free electrolyte of 4wt% H_2SO_4 followed by ultrasonic cleaning (USC). Applied pulse waveforms consist of an anodic pulse of 4V for 200 ms, off-time for 800 ms,

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and a cathodic pulse of 10V for 200ms. The total removal estimated from current integration was 63µm.

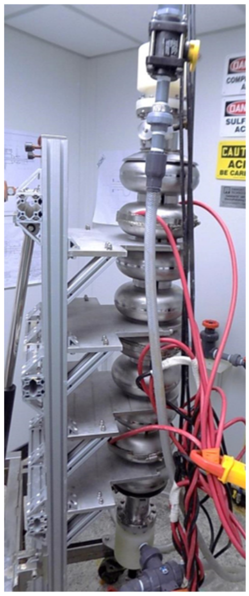

Figure 2: The 9-cell cavity on the 9-cell scale Bipolar-EP system at Faraday Technology.

Figure 3 shows optical inspection images of the equator-welding seam on the 9-cell cavity's RF surface post Bipolar-EP. No specific features or defects were found, but the entire cavity's inner surface had a golden-brown finish surface (Fig. 3, left). A blue spot was also seen on the equator. The images suggest that the RF surface has a thicker oxide or oxide rich niobium layer on it compared with the surface after Bipolar-EP under more optimal conditions. The 9-cell was then rinsed again with USC and high-pressure DI water (HPR) and tested. The 9-cell cavity had no standard 120°C bake prior to the RF test, since one of the RF test results of a cavity from the three single-cell string had shown Q degradation due to a 120°C bake right after Bipolar-EP.

Figure 3: Optical inspection images of the equator weld seam post Bipolar EP with 4% (left), 9% (middle), and 11% (right) of H_2SO_4.

RF Test Results after the 1st Bipolar-EP

The data set of green triangles in Fig. 4 represents RF test results post the 1st Bipolar-EP on the 9-cell cavity at 2K. The Q_0 at low field is about 9.3×10^9; the 9-cell shows significant Q-slope above 10MV/m, limited by quench at 19 MV/m. The cavity was field emission free. The analysis of all Q_0 vs. E results is summarized in the next section.

2nd Bipolar-EP Processing of the 9-cell Cavity

The 2nd Bipolar EP on the 9-cell cavity was performed using a HF free electrolyte of 9wt% H_2SO_4 followed by USC. Applied pulse waveforms consist of an anodic pulse of 4V for 100 ms, off-time for 600 ms, and a cathodic pulse of 10V for 100 ms. The total removal estimated from current integration was 8.5µm. Optical inspection was performed and the surface finish was similar to that after a Cornell VEP (Fig. 3, middle). The 9-cell cavity was then rinsed again with USC and HPR, and tested. The 9-cell had no standard 120°C bake prior to RF test this time also.

RF Test Results after the 2nd Bipolar-EP

The data set of red circles in Fig. 4 represents RF test results post the 2nd Bipolar-EP on the 9-cell cavity at 2K. The Q_0 at low field is about 1.3×10^{10}, but shows Q-slope above 12 MV/m, and is limited by quench at 19 MV/m, which is almost same maximum field as during the 1st run. The cavity was field emission free.

3rd Bipolar-EP Processing of the 9-cell Cavity

The VT results after the previous two BEP processes indicate that higher acid concentration may produce higher Q. Following this idea, the 3rd Bipolar EP on the 9-cell cavity was performed using a HF free electrolyte of 11wt% H_2SO_4 followed by USC. Applied pulse waveforms consist of an anodic pulse of 4V for 100 ms, off-time for 600 ms, and a cathodic pulse of 10V for 100 ms. The total removal estimated from current integration was 7 µm. Optical inspection was performed and a light-yellow surface finish was seen over the cavity inner surface (Fig. 3, right), but no defect or specific features were seen. A light-yellow finish surface on the end groups was visible to the naked eye, too. These light-yellow surface finish suggests that there is thicker, and potentially lossy oxide or oxygen rich niobium layer on the RF surface. The 9-cell cavity was then rinsed with USC and HPR and tested. As before, the 9-cell cavity had no standard 120°C bake prior to the RF test.

RF Test Results after the 3rd Bipolar-EP

The data set of blue squares in Fig. 4 represents the RF test results of the 3rd run at 2K. The Q_0 at low field started with 2×10^9, but was improved up to 5×10^9 during RF processing. The field gradient was limited around 12 MV/m due to the severe field emission, but the cavity showed no quench limit.

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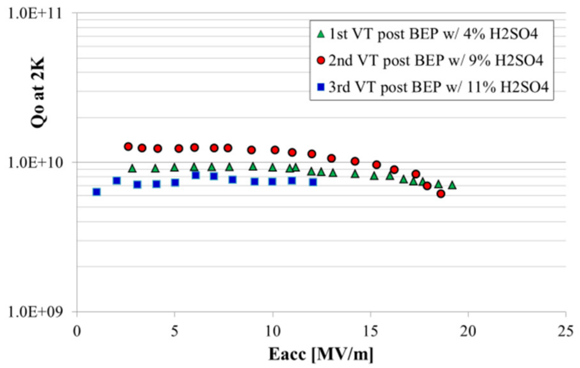

Figure 4: RF test results of the 9-cell cavity post Bipolar-EP with different conditions.

Table 1: Bipolar-EP Parameters used on the 9-cell Cavity

	wt% H_2SO_4	Anodic pulse	Time off	Cathodic pulse	Remov-al
1st run	4%	4V, 200ms	800ms	10V, 200ms	63μm
2nd run	9%	4V, 100ms	600ms	10V, 200ms	8.5μm
3rd run	11%	4V, 100ms	600ms	10V, 200ms	6.9μm

DISCUSSION

Analysis of R_{BCS} and R_{res}

The cavity quality factor Q_0 is converted into the surface resistance R_s by the following equation.

$$R_S = \Gamma / Q_0$$

Γ is the geometry factor which solely depends on the cavity geometry. For a more detailed understanding, R_s is usually divided into the BCS resistance (R_{BCS}) part and the temperature independent residual resistance (R_{res}) part. Minimizing both R_{BCS} and R_{res} are important to achieve the highest Q_0.

$$R_S = R_{BCS} + R_{res}$$

The residual resistance R_{res} and the BCS resistance R_{BCS} were estimated from the temperature dependence of Q_0 measured during each of the three RF tests (Fig. 5) as is summarized in Fig. 6.

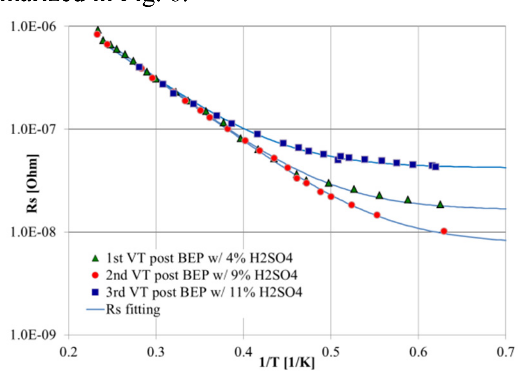

Figure 5: Temperature dependence of Q_0 plotted as R_s vs. 1/T.

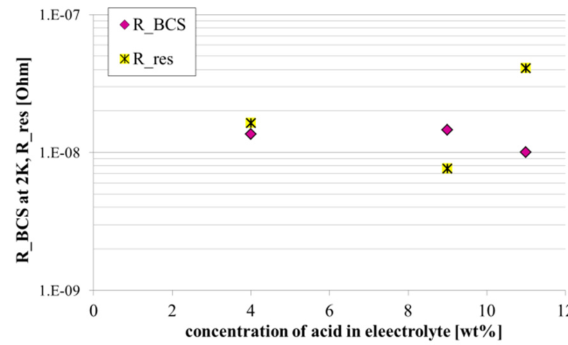

Figure 6: The estimated R_{BCS}(2K) and R_{res} at 5MV/m for each RF test result.

The 3rd run with the higher concentration acid of 11% H_2SO_4 succeeded to reduce R_{BCS} to 10nΩ, but the R_{res} was significantly increased to 41nΩ which overall resulted in lower Q_0 of the 9-cell cavity. If the residual resistance can be reduced to 5 nΩ, the Q_0 would be improved to $2x10^{10}$ which would be close to the performance after conventional EP. Based on the results of the 1st run and 3rd run, low or high acid concentration can generate a thick and potentially lossy oxide or oxygen rich niobium layer, which was visible during optical inspection. The Bipolar-EP conditions with 9% H_2SO_4 might be closest to the optimal conditions for achieving high Q_0. Further parametric studies on the impact of the acid concentration, more statistics for the Bipolar-EP process followed by RF test on the 9-cell cavity, and investigation of the 120°C bake effect on the 9-cell scale Bipolar-EP will be needed in the future. Some system upgrade, e.g. make the current supply source larger, to investigate higher acid concentrations with a 9-cell cavity might also be needed.

SUMMARY

A new 9-cell scale Bipolar-EP was successfully demonstrated on a 9-cell cavity at prepared by Faraday Tech. The RF tests post three different Bipolar-EP conditions were performed at Cornell. Field gradients of 20 MV/m with low-field cavity quality factors Q_0 of $1.3x10^{10}$ were achieved at 2K without std. 120°C bake so far. Analysis of the temperature dependence of Q_0 suggests that an acid concentration of H_2SO_4 between 9~10wt% is optimal to minimize total surface resistance R_s. Further parametric studies on acid concentration, more statistics for the Bipolar-EP process on a 9-cell cavity, and investigation of a 120°C bake effect on a 9-cell scale Bipolar-EP cavity will be needed in the future to further improve this promising alternative cavity etching process.

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