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RF PERFORMANCE OF MULTI-CELL SCALE NIOBIUM SRF CAVITIES PREPARED WITH HF FREE BIPOLAR ELECTRO-POLISHING AT FARADAY TECHNOLOGY*

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Abstract

Cornell's SRF group and Faraday Technology, Inc. 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 had completed the proof of principle of BEP on the single cell scale prior to the work reported here, and has now developed a new 9-cell scale BEP system. Cornell has fabricated three single cell cavities and has assembled them together as a 9-cell scale test string. The 9-cell scale test string has received BEP at Faraday Technology and RF testing has been performed on the three single cell cavities one-by-one at Cornell. Here we give a status update on the new 9-cell scale BEP system commissioning and on results from RF tests of the BEP cavities.

INTRODUCTION

Cornell's SRF group has led the development of Vertical Electro-Polishing (VEP), which requires a much simpler setup and is less expensive compared with the conventional Horizontal EP [1]. After the successes of the Cornell VEP on the high gradient cavities for the ILC (>35 MV/m with $Q>0.8\times10^{10}$) [2] and High-Q cavities for LCLS-II ($Q>2.7\times10^{10}$ at 16 MV/m) [3], 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. Currently hydrofluoric (HF) acid based electrolyte is used in EP. As the SRF projects become larger, the environmental impact of large usage of hazardous HF based acid on niobium 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 [4, 5]. 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 [6, 7]. Now Cornell's SRF group and Faraday Technology Inc. have started collaboration on Bipolar, HF free EP for multi-cell cavities. This collaboration is supported by the Department of Energy's (DOE) phase-II Small Business Innovation Research (SBIR) program. In this paper, we report on the progresses of this project with detailed cavity test results.

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NEW 9-CELL SCALE BIPOLAR-EP SYSTEM AT FARADAY TECHNOLOGY, INC.

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 [6, 8, 9].

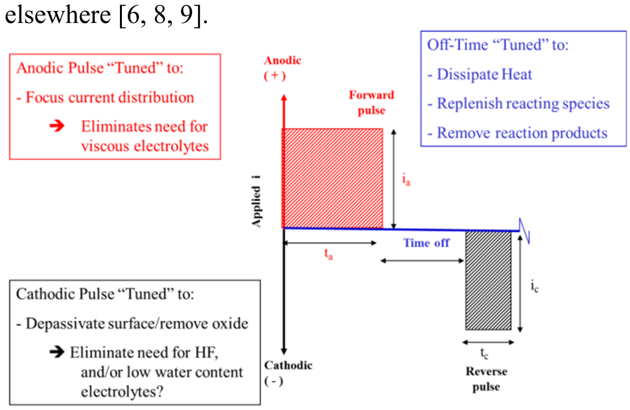

Figure 1: General bipolar EP process representation [6].

9-cell Scale Bipolar-EP

One of the project goals was scaling up the Bipolar-EP system from single cell scale to 9-cell cavity scale, and demonstration of the multi-cell scale Bipolar-EP process. While Faraday Technology Inc. upgraded the system to 9-cell scale, Cornell completed fabrication of three 1.3 GHz TESLA shape single cell cavities. Cavity IDs are LTE1-13, -14, and -15 (LTE: L-band TESLA shape Elliptical cavity). The three single cells were then connected via Teflon spacer rings and treated together as a 9-cell scale cavity equivalent string (TESLA 9-cell: 1250 mm; three 1-cell string: 1200 mm). Figure 2 shows the three single cell string (top; LTE1-14, middle; LTE1-15, bottom; LTE1-13) on the 9-cell scale Bipolar EP system at Faraday Technology Inc.

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Figure 2: The three 1-cell string on the 9-cell scale Bipolar-EP system at Faraday Tech.

THE FIRST RESULTS OF NEW 9-CELL SCALE BIPOALR-EP SYSTEM

Baseline RF Test Preparations

The 1st RF test run Cornell performed on the three single cell cavities one-by-one was a baseline RF test after the Cornell VEP protocol. For the baseline test, the cavities were prepared with bulk VEP (120 µm), furnace degassing (800degC, 2hrs in vacuum), light VEP (10µm), and standard low temperature baking (120degC for 48hrs in vacuum). VEP was done one-by-one, not as the string. A standard HF based electrolyte was used, and all VEPs were followed by ultra-sonic cleaning (USC) and high pressure DI water rinsing (HPR), which was also a standard rinsing protocol post VEP at Cornell.

Baseline RF Test Results

Figure 3 shows the RF test results of the three single cells as Q_0 vs. E_{acc} at 2 K. The symbols without colour fill represent the baseline results (VT1). During the 1st run, all cavities were limited by quench around 20-22 MV/m with the same 2 K Q_0 of 1.4×10^{10} without detectable field emission. The achieved fields were lower than that of a typical Cornell VEP result (quench >30 MV/m), but acceptable as a baseline performance to proceed. Optical inspection post 1st run showed no specific features or defects on the RF surfaces.

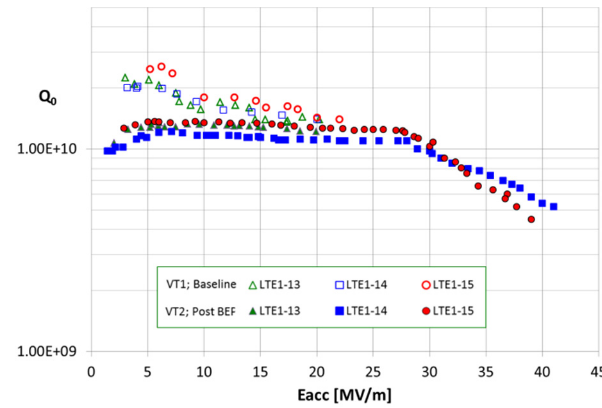

Figure 3: RF test results from the 1st and 2nd RF test runs at 2K.

9-cell Scale Bipolar-EP on the Cavity String

The 2nd RF test run was performed post 9-cell scale Bipolar-EP. After the baseline test, cavities were shipped to Faraday Technology Inc., assembled as the string, and processed with Bipolar EP on the new 9-cell scale system using HF free electrolyte of 10wt% H_2SO_4 followed by USC. Applied pulse waveforms consist of anodic pulse of 4V for 100ms, off-time for 400ms, and cathodic pulse of 10V for 100ms. The total removal estimated from current integration was 64µm and total duration time was 120hrs. Operating temperature was kept below 26degC. Figure 4 shows optical inspection images of the equator welding seam on the RF surface post VEP and post Bipolar-EP. Similar surface finish to the Cornell VEP was seen on the surface post Bipolar-EP. Cavities were shipped back to Cornell, rinsed again with USC and HPR, and then tested. We emphasize that cavities had no standard 120 °C bake prior to the 2nd run on purpose to confirm the benefit of the low temperature bake by testing cavities again after 120 °C bake.

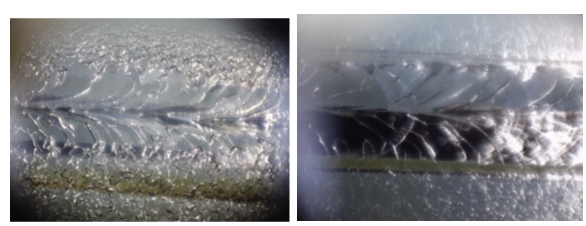

Figure 4: Optical inspection images of the equator weld seam; Cornell VEP (left), Bipolar EP (right).

RF Test Results Post 9-cell Scale Bipolar-EP

The solid symbols (colour filled) in Fig. 3 represent RF test results post 9-cell scale Bipolar-EP (VT2). Table 1 summaries the 1st and 2nd run, shows the achieved field gradient ($E_{acc,\,max}$) and Q_0 at $E_{acc,\,max}$ at 2K. During the 2nd run, LTE1-13 quenched at the same field, but the other two cavities achieved significant high gradients around 40MV/m. All cavities were field emission free. From the Q_0 point of view, the 2nd run results show very flat Q_0 curves at low to medium fields, but somewhat lower Q_0 overall than during the 1st run. Both of the high gradient

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cavities show Q-slope starting from ~27 MV/m. This could be a typical behaviour of a cavity which had no 120 ºC bake post EP.

Table 1: Summary of The $E_{acc,\,max}$ and Q_0 at 2 K

	VT1; Baseline RF test		VT2; RF test post BEP	
	Eacc max, Qo at 2K		Eacc max, Qo at 2K	
LTE1-13	20MV/m	1.4E+10	20MV/m	1.22E+10
LTE1-14	20MV/m	1.4E+10	41MV/m	5.2E+09
LTE1-15	22MV/m	1.4E+10	39MV/m	4.5E+09

SERIES RF TESTS FOR Q_0 IMPROVEMENT

The reason of the lower Q_0 after the 9-cell scale Bipolar-EP could be that the current parameters of the pulse wave forms were not yet optimized for the new 9-cell scale system, or simply due to omitting the 120 ºC bake. To investigate this further, additional surface treatments on the single cell cavities and a series of RF tests were performed at Cornell. Two surface treatments were selected to be applied; one is a standard low temperature baking (120degC for 48hrs in vacuum) to remove high field Q-slope, and the other one is HF rinse (filled cavity with HF acid for 10~30 min. at room temperature) which removes the surface oxide layer on the nm-scale, and potentially could increase all Q_0 values, but not remove the high field Q-slope. RF tests were performed after each process step. Work on LTE1-13, which quenched at a low field, was held, waiting for test results from the other two cavities.

LTE1-14

LTE1-14 had the 120 ºC bake first. Figure 5 compares the Q_0 of post Bipolar-EP (VT2) and post 120 ºC (VT3) bake at 2 K. High field Q-slope above 28MV/m was removed by the 120 ºC bake, but overall Q_0 values were degraded. No degradation was seen on the quench field; it was almost unchanged (~40 MV/m). There was no detectable field emission during the test. Following this test, LTE1-14 had a HF rinse and is ready for the next RF test.

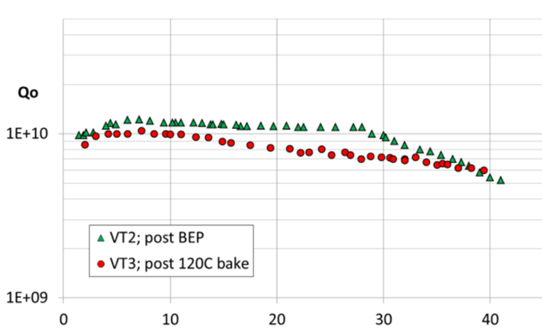

Figure 5: The results of LTE1-14, comparing Q_0 post Bipolar-EP and post 120 ºC bake at 2K.

LTE1-15

LTE1-15 received the HF rinse first, and then had the 120 ºC bake. The RF test results are summarized in Fig. 6. As we expected, HF rinse pushed the Q_0 values up. The cavity quenched at same field of ~40 MV/m, but a high field Q-slope remained. The 120 ºC bake post HF rinse on LTE1-15 removed the high field Q-slope, and made the Q_0 profile comparable with that of Cornell VEP. The quench field was slightly degraded to 36 MV/m.

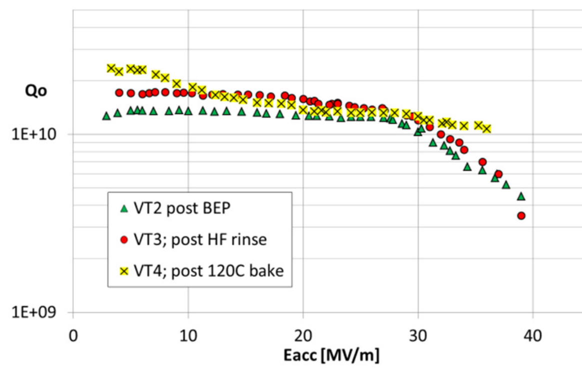

Figure 6: The results of LTE1-15, comparing Q_0 post Bipolar-EP (VT2), post HF rinse (VT3), and post the 120ºC bake (VT4) at 2 K.

Analysis of R_{BCS} and R_0

The residual resistance R_0 and the BCS resistance R_{BCS} were estimated from the temperature dependence of Q_0 on each RF test as is summarized in Fig. 7.

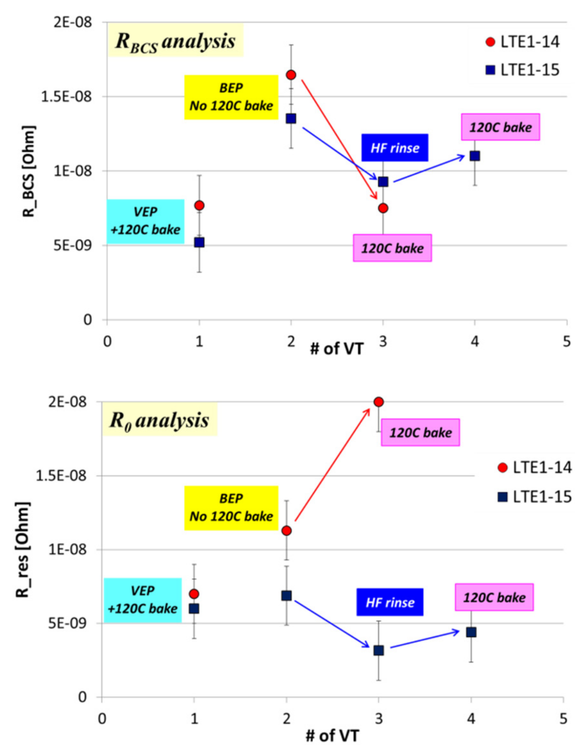

Figure 7: The analysis of R_{BCS} (Top) and R_0 (bottom) at 5MV/m.

The behaviours of R_{BCS} indicate that the standard 120 ºC bake is needed to remove high field Q-slope post Bipolar EP. On the other hand, the behaviours of R_0 suggest that RF surface post 9-cell scale Bipolar-EP had some contaminated layer (e.g. lossy oxide or oxygen rich

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niobium), which increased R_0, thereby lowering Q_0, when the 120 ºC bake was applied right after the 9-cell scale Bipolar-EP. But it is also suggested that a contaminated layer can be removed by applying HF rinse prior to the 120 ºC bake. During the early work on Bipolar-EP by FNAL and Faraday tech, no HF process was needed post single cell scale Bipolar-EP to achieve comparable high field and high-Q with standard Horizontal-EP. This is the first trial of the new 9-cell scale Bipolar-EP system with the single cell string, and further system commissioning or a parametric study on pulse waveforms are likely needed to optimize the process parameters so that no HF rinsing will be needed post the 9-cell scale Bipolar-EP.

SUMMARY

A new 9-cell scale Bipolar-EP system was completed and successfully used on a three single-cell string at Faraday Technology. High gradient RF performances were achieved with two of three single cell cavities during the RF tests at Cornell. Currently, the RF surface post 9-cell scale Bipolar-EP seems to have some contaminated layer and needs to be treated with a HF rinse and 120 ºC bake in a proper order to achieve high Q and high field. A more systematic study to optimize pulse waveform parameters for the 9-cell scale Bipolar-EP and to determine the resulting properties of the RF surface of multi-cell cavities will be necessary to arrive at a fully HF free 9-cell scale Bipolar-EP process.

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