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RECENT PROGRESS ON HF-FREE SURFACE TREATMENT BY BIPOLAR PULSED ELECTROPOLISHING FOR SRF Nb CAVITIES*

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Abstract

The bipolar pulsed electropolishing (BPEP) process, due to its HF-free nature, offers a safer, more environmentally friendly, and cost-effective alternative to conventional electropolishing, which uses concentrated HF and H_2SO_4 as the electrolyte. Jefferson Lab has developed a BPEP system that utilizes only diluted H_2SO_4 for the final surface processing of niobium superconducting radio frequency (SRF) cavities. This includes single cells, 7-cell CEBAF C100 cavities, and 9-cell TESLA-style cavities.

In this report, we present recent progress for BPEP-treated single-cell cavities at Jefferson Lab. Notably, one single-cell cavity, following a 120°C bake, achieved an accelerating gradient (E_{acc}) of 37 MV/m with a quality factor (Q_0) exceeding 1×10^{10} at 2 K. This result demonstrates the potential for the BPEP process.

INTRODUCTION

The bipolar pulsed electropolishing (BPEP) technique for niobium superconducting radio frequency (SRF) cavities was patented by Faraday Technology, Inc., through collaborative SBIR work with Jefferson Lab [1-3]. Previous studies by Cornell University, in collaboration with Faraday, reported that a 1.3 GHz TESLA-shaped 9-cell Nb SRF cavity treated with BPEP achieved an accelerating gradient of 35 MV/m [4]. Additionally, developments at Jefferson Lab have demonstrated the successful commissioning of its own BPEP setup for 1.3 GHz single-cell and multi-cell Nb cavities [3, 5].

BPEP uses an HF-free electrolyte and employs a novel approach to treat Nb SRF cavities. An anodic pulse anodizes the Nb surface to form Nb oxides, while intervening cathodic pulses mechanically erode the oxide layer through the action of hydrogen gas bubbles formed at the niobium surface via electrolysis.

Systematic studies on Nb samples have demonstrated that the removal rate and uniformity can be finely controlled using this method [3, 5]. The studies indicate that the removal rate of BPEP is proportional to the pulse repetition frequency (PRF). When the PRF is set at approximately 60 Hz, the BPEP removal rate is comparable to that of conventional EP, i.e., ~0.25 µm/min [5]. Conventional EP can lead to the formation of sulfur particles, in the form of sulfate and/or sulfite, on the niobium surface when using aged electrolyte with a 1:10 volume ratio of HF (49%) and H_2SO_4 (98%) [6]. These sulfur particles can act as field emitters, thereby limiting the RF performance of SRF cavities. In contrast, BPEP typically employs a lower concentration of H_2SO_4 (37% or less) and uses mixed metal oxides as the counter electrode, which exhibit a low overpotential for the hydrogen evolution reaction, approximately 20-50 mV at a current density of 10 mA/cm² in acidic media [7]. Consequently, BPEP significantly reduces the likelihood of sulfur particle formation on Nb surfaces [8]. Furthermore, the HF-free nature of BPEP offers substantial environmental benefits and is more cost-effective than other surface processing methods.

BPEP SYSTEM AT JLAB

A BPEP system has been implemented at Jefferson Lab and applied to various SRF cavities, including single-cell cavities, 1.5 GHz 7-cell CEBAF C100 cavities, and 1.3 GHz 9-cell TESLA-shaped cavities. This system utilizes a recently upgraded pulser system [9] that enables an adjustable PRF and operating voltage. It offers potential improvements in surface removal for different types of SRF cavities. Figure 1(a) illustrates the schematic diagram of the Jefferson Lab patented high power pulse generator and controller system [9]. The pulser depicted in the figure can generate the designed pulse structures, including anodic and cathodic pulse durations, off-time, and the potentials of both anodic and cathodic pulses. Diluted sulfuric acid is used as the electrolyte.

During the process, the oxide layer grows when the niobium cavity is at a positive potential, and the removal of niobium oxides occurs when the cavity alternates from a positive to a negative potential, thereby removing the niobium pentoxide formed. Figure 1(b) shows the setup for a 1.5 GHz 7-cell CEBAF C100 Nb SRF cavity inside a closed chemical cabinet, which is equipped with ultrasonic thickness gauges and thermocouples for in-situ monitoring of material removal and temperatures.

In order to evaluate the improved BPEP system, a series of comparative tests were performed between BPEP and conventional horizontal EP (HEP) using two 1.3 GHz TESLA-shaped single-cell Nb cavities, RDT-13 and RDT-5. Initially, both cavities underwent surface resetting through HEP, followed by further surface removal using BPEP. Vertical tests were subsequently carried out after each removal to assess RF performance. Comparable or superior RF performance achieved after BPEP, relative to HEP, would validate the successful development of the BPEP system at JLab. This study highlights BPEP's potential as a viable and effective surface processing technique for SRF cavities.

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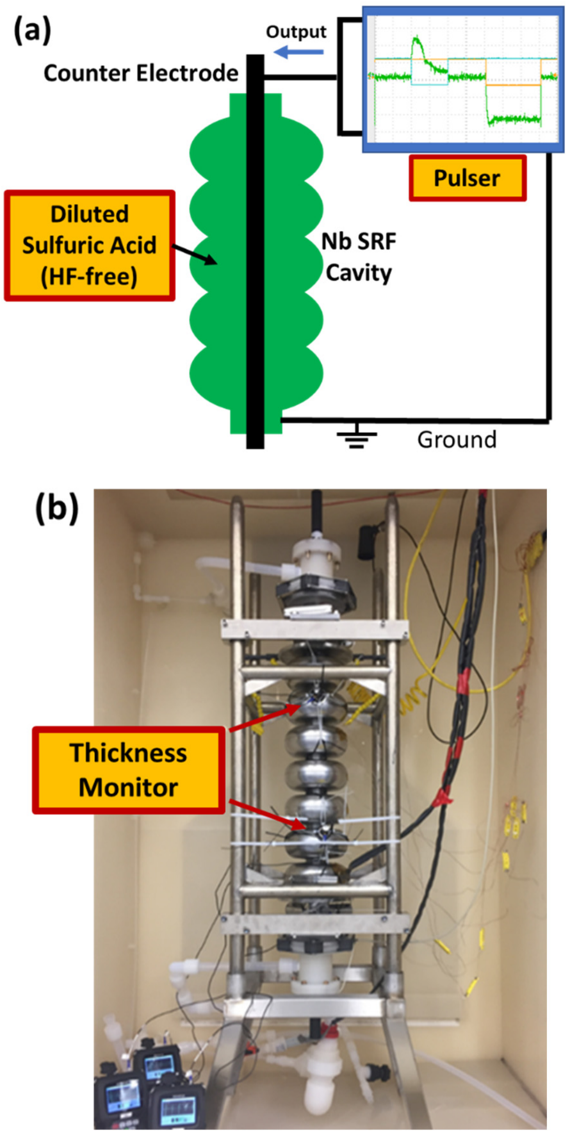

Figure 1: (a) Schematic diagram of the Jefferson Lab system; (b) BPEP Setup for a 1.5 GHz 7-cell CEBAF C100 Nb SRF cavity inside a closed chemical cabinet at JLab.

BPEP PROCESSING FOR 1.3GHZ SINGLE CELL SRF CAVITIES

The BPEP parameters, such as pulse repetition frequency and the structures of anodic and cathodic pulses, play a crucial role in influencing surface removal and levelling during processing [3, 5]. For the BPEP treatment of these two single-cell cavities, we employed a waveform consisting of a 30 ms cathodic pulse, followed by a 20 ms off time, a 20 ms anodic pulse, and another 20 ms off time, resulting in a repetition frequency of 11 Hz. The measured current pulses for the two cavities were found to be highly consistent. Figure 2 illustrates the current pulse of the single-cell cavity RDT-13 from the start of BPEP processing to 5 hours, with measurements taken at one-hour intervals, demonstrating that the process remained stable throughout. During the BPEP process, no cooling water was sprayed to the exterior of the cavity, and the cavity temperature was slightly increased of approximately 1-2 degrees. This minor temperature rise did not impact the processing. The material removal rate was approximately 0.05 µm/min.

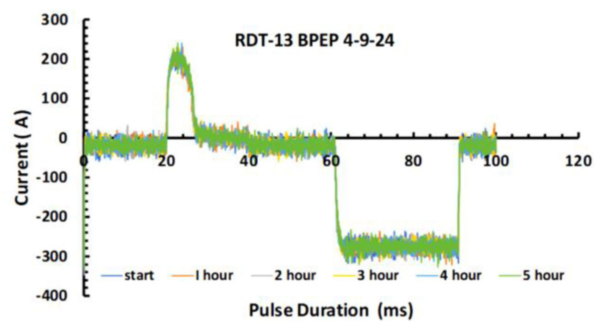

Figure 2: Measured current pulse during BPEP processing over time for the 1.3 GHz TESLA-shaped single-cell cavity RDT-13.

CAVITY TEST RESULTS AND ANALYSIS

Vertical Test Results

After a 40 µm HEP surface reset, the single-cell cavity RDT-13 underwent a total of 18 µm of material removal through BPEP. A comparison of the vertical test results at 2K before and after BPEP shows that the RF performance remained nearly the same, both in terms of quench field (E_{acc} ~22 MV/m) and Q_0 ($>1\times10^{10}$ at 2K) without field emission, as illustrated in Fig. 3.

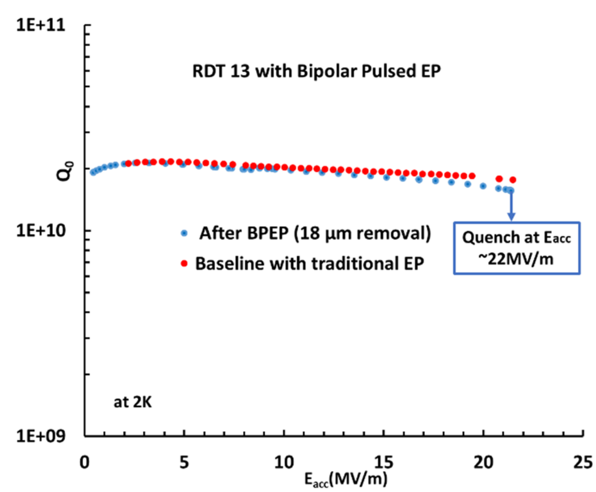

Figure 3: RDT-13 vertical test results comparison before and after the BPEP processing.

After the 40 µm HEP surface reset, the single-cell cavity RDT-5, was high-pressure water rinsed (HPR) and cleanly assembled in a Class 100 cleanroom. The vertical test results show that the cavity gradient was limited by field emission (FE) induced quench at E_{acc} ~23 MV/m, with the first quench occurring around 14 MV/m, accompanied by heavy radiation, as shown in Fig. 4 (green square hollow marker). The field emission limitation may be due to sulfur contamination during the HEP processing. Subsequent re-HPR could not completely remove this contamination. The

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vertical test results (brown triangle marker in Fig. 4) indicate that the cavity remained limited by strong FE, though the gradient improved to ~31 MV/m after long-time RF processing.

After this, a 20 µm BPEP treatment and HPR were performed on RDT-5. The subsequent vertical test shows that the FE was completely removed, but the cavity was limited by high-field Q-slope (HFQS). The cavity gradient reached ~28 MV/m, limited by RF power rather than quench, as indicated by the blue diamond marker in Fig. 4. To overcome the HFQS limitation, we applied the standard low-temperature baking procedure: in-situ baking at 120 °C for 24 hours.

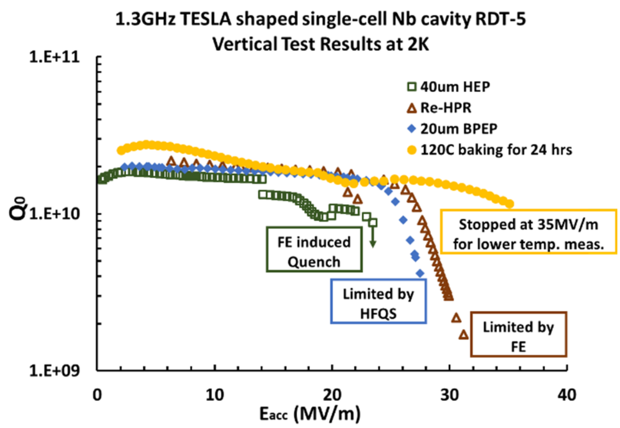

Figure 4: Vertical test results of RDT-5 at 2K after each surface treatment step, comparing BPEP and HEP. The results indicate that BPEP can produce surfaces of comparable quality to those achieved with HEP.

The vertical test results after the low-temperature baking indicate that the HFQS was eliminated, with a maximum gradient of 35-37 MV/m, as illustrated by the yellow circle marker in Fig. 4. The cavity was not quenched at 2 K to avoid reducing Q_0 due to flux trapping. Multi-temperature Q_0 vs. E_{acc} curves were carefully measured from 1.6 to 2 K, revealing that the quench field of the cavity was around 37 MV/m with an excellent Q_0 exceeding 1×10^{10} at 2 K, as shown in Fig. 5.

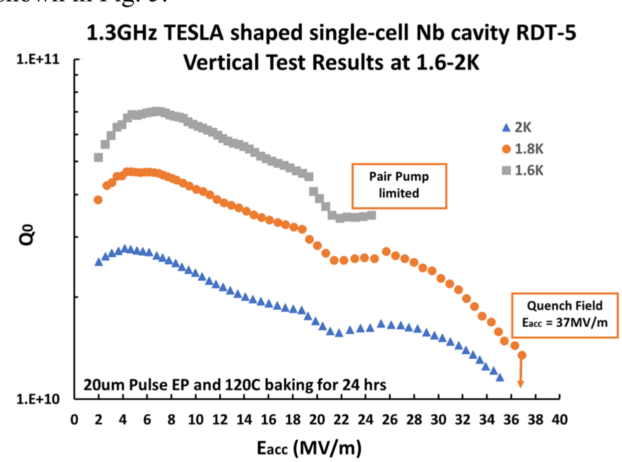

Figure 5: Multi-temperature Q_0 vs. E_{acc} curves for RDT-5, measured across a temperature range of 1.6 to 2 K.

CONCLUSION

The BPEP technique has been successfully implemented at Jefferson Lab with a customized setup, demonstrating its capability to produce Nb surface quality comparable to conventional EP. The vertical test results from single-cell cavities treated with BPEP, including after low-temperature baking, show that BPEP can achieve high accelerating gradients (up to 37 MV/m) with excellent quality factors ($Q_0 > 1\times10^{10}$ at 2 K), while also offering significant environmental and cost advantages due to its HF-free nature. These findings affirm BPEP as a viable and effective surface processing technique for SRF cavities, with potential for broader applications.

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