STATUS AND CHALLENGES OF VERTICAL ELECTRO-POLISHING R&D AT CORNELL*

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Abstract

Advanced Vertical Electro-Polishing (VEP) R&D for SRF Niobium cavities continues at Cornell's SRF group. One focus of this work is new EP cathode development in collaboration with KEK and Marui Galvanizing Co. Ltd (Marui) in Japan, and another focus is on HF free or acid free VEP protocols in collaboration with Faraday Technology Inc. The outcomes of these activities could be a significant cost reduction and an environmentally-friendlier VEP, which would be a breakthrough for future large scale EP applications on SRF cavities. Here we give a status update and report latest results from these R&D activities.

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 ILC (>35MV/m with Q>$0.8x10^{10}$) [2] and High-Q cavities for LCLS-II (Q>$2.7x10^{10}$ at 16MV/m) [3], Cornell's VEP R&D focuses has shifted to more advanced topics. One focus is a new EP cathode development in collaboration with KEK and Marui. The EP process in vertical direction can be affected by gravity, resulting in a removal difference between the upper and lower half cells. To compensate for removal un-uniformity, a cavity typically needs to be flipped over after half of the target removal. Marui has been developing a new cathode named "i-cathode Ninja" to improve the removal uniformity during its VEP R&D with KEK [4, 5]. Marui's work coincides with Cornell's interest in removal R&D, and a collaboration between Cornell and KEK-Marui was started in 2014.

Another focus of our work is on 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&Ds on a less hazardous or more eco-friendly niobium surface process has been performed and has made good progress [6, 7]. 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 [8, 9]. Now Cornell's SRF group and Faraday Technology Inc. have started a 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 the progresses on these projects with detailed cavity test results.

NEW CATHODE R&D WITH KEK AND MARUI

The project goals were a demonstration of Ninja cathode VEP on a single cell cavity in Cornell VEP system and an RF test of that cavity.

Cornell's and Marui's VEP Cathode

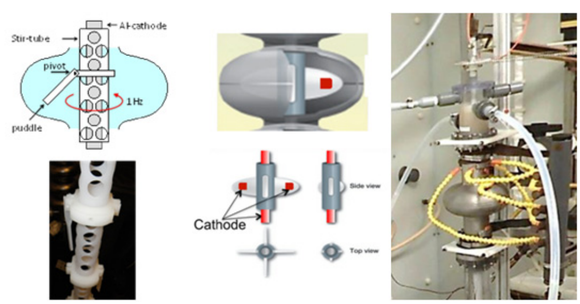

Figure 1: Images of Cornell VEP cathode (left); Marui's i-cathode Ninja type-I (middle), and single cell on the VEP stand at Cornell.

Cornell VEP cathode (Fig. 1, left) consists out of an aluminium rod and a stirring tube with paddles (one paddle per cell). Teflon mesh lapped around the stirring tube (not shown in the figure) guides the hydrogen bubbles produced on the cathode during the EP process to prevent them from attacking the niobium surface. Marui's Ninja cathode (Fig. 1, right) consists out of an aluminium cathode rod, polyvinyl chloride (PVC) tube, and retractable Teflon wings (four wings per cell). PVC is an acid resistance material, and inexpensive. It is therefore suitable for the early stage of the Ninja cathode development and for capital cost reduction of VEP. The retractable wings are kept inside the PVC tube during the installation, and are then opened when inside the cell. The gap between the wing edge and the cell surface is designed to be equal

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from iris to equator. Marui has developed several types of the Ninja cathode so far. The type-I and type-II Ninja cathodes were used for the first trial at Cornell [10]. The type-I is designed for having field uniformly from iris to equator by putting an Al coupon on top of each wing (Fig.1). The type-II has no Al coupon on the wings, but has more cathode surface inside the tube. The type-II is also designed to protect the Nb surface from hydrogen bubbles by covering the opening between the wings and the tube with Teflon mesh.

Ninja Cathode VEP at Cornell

Figure 1 (right) shows a 1.3GHz TESLA shape single cell cavity (NR1-2) with Ninja cathode in the Cornell VEP system. NR1-2 had been processed by VEP using the Cornell cathode and tested already. To reset the RF surface prior to the Ninja cathode VEP, NR1-2 had mechanical polishing (30µm), Buffered Chemical Polishing (BCP, 60µm), and furnace degassing (800degC, 2hrs). Cornell then performed two VEPs (20µm each) using the Ninja cathodes of type-I and type-II, followed by low-temperature baking (120degC for 48hrs) and RF test. A HF based EP electrolyte was used for all VEPs on NR1-2, which is an acid mixture of sulphuric acid and hydrofluoric acid in 9~10:1 ratio in volume. Detail parameters of these VEPs can be found on Ref. [11]. Optical inspections were done after each VEP process on NR1-2 (Fig. 2). Similar defects or features were seen on both surfaces after Cornell and Ninja VEP.

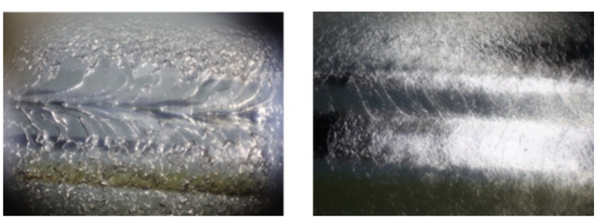

Figure 2: Optical inspection images of the equator weld seam on the RF surface; Cornell VEP (left), Ninja cathode type-I (right).

Cavity RF Test

Figure 3 shows the RF test results of NR1-2 as the quality factor of Q_0 versus the accelerator field gradient E_{acc} at 2K. The blue circles show the test result after the Cornell cathode VEP. The cavity quenched at 33MV/m with Q_0 of $1.2x10^{10}$ without field emission. The red triangles show the result after the Ninja cathode VEP. The quench field was 35MV/m with Q_0 of $0.9x10^{10}$ without field emission. Thus, the Ninja cathode provided a cavity RF performance comparable with the Cornell cathode.

HF FREE BIPOLAR-EP R&D WITH FARADAY TECHNOLOGY, INC.

After the initial success of Bipolar-EP R&D on single cell cavities, Faraday Technology Inc. and Cornell have been collaborating on the projects based on Bipolar EP techniques, which are supported by DOE's phase-II SBIR program.

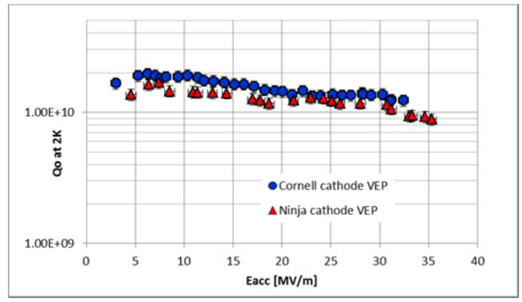

Figure 3: RF test results of NR1-2 at 2K.

Bipolar-EP

Figure 4 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 [8, 12, 13].

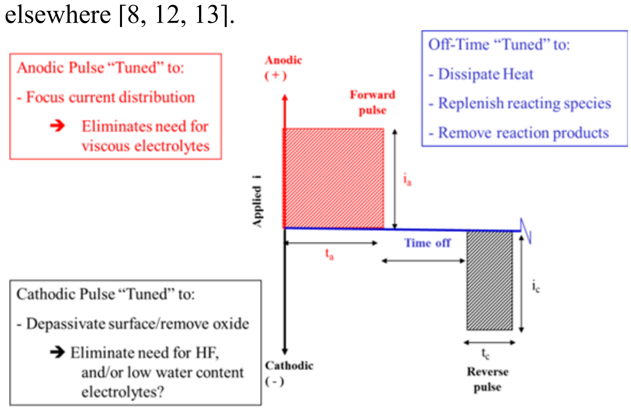

Figure 4: General bipolar EP process representation [8].

Figure 5: The three 1-cell string.

9-cell Scale Bipolar-EP

One of the project goals were scaling up of 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 1.3GHz TESLA shape single cell cavityies. Cavity Ids are LTE1-13, -14, and -15. 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: 1250mm; three 1-cell string: 1200mm). Figure 5 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.

Baseline RF Test Preparations

Cornell performed two RF test runs on the three single cell cavities one-by-one. The 1st run was a baseline RF test after the Cornell VEP protocol, and the 2nd run was post Bipolar-EP. For the baseline test, the cavities were prepared with bulk VEP (120µm), furnace degassing (800degC, 2hrs), light VEP (10µm), and low temperature baking (120degC for 48hrs). 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 6 shows the RF test results of the three single cells as Q_0 vs. E_{acc} at 2K. The symbols without colour fill represent the baseline results. During the 1st run, all cavities were limited by quench around 20-22MV/m with the same 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 >30MV/m), but acceptable as a baseline performance to proceed. Optical inspection post 1st run showed no specific features or defects on the RF surfaces.

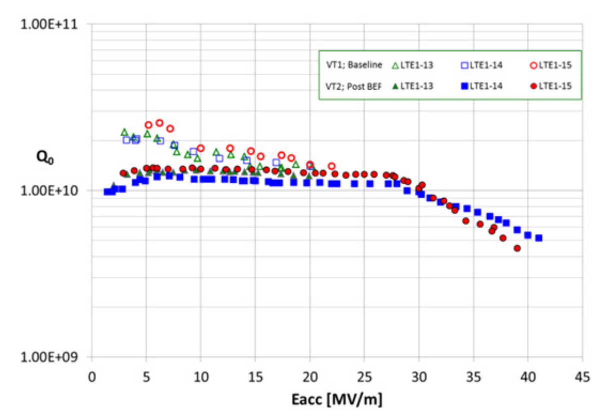

Figure 6: RF test results from the 1st and 2nd RF test runs at 2K.

Bipolar-EP on the Cavity String

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 7 shows an optical inspection image of the equator welding seam on the RF surface post Bipolar-EP. Similar surface finish to the Cornell VEP was seen. Cavities were shipped back to Cornell, rinsed again with USC and HPR, and then tested. We emphasize that cavities had no standard 120C bake prior to the 2nd run on purpose to confirm the benefit of the low temperature bake by testing cavities again after 120C bake in the future.

Figure 7: Optical inspection image post Bipolar-EP.

RF Test Results post 9-cell Scale Bipolar-EP

The solid symbols (colour filled) in Fig. 6 represent RF test results post Bipolar-EP. Table 1 summaries the achieved field gradient ($E_{acc,\ max}$) and Q_0 at $E_{acc,\ max}$, 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 shows very flat Q_0 curves at the low to medium field, but somewhat lower Q_0 than during the 1st run. This was the first trial of 9-cell scale bipolar-EP, so it is too early to say if this is a specific feature of the new system, or simply due to omitting the 120C bake. Further R&D will address the source of the lower Q_0. Both of the high gradient cavities show Q-slope starting from ~27MV/m. This could be a typical behaviour of cavity which had no 120C bake post EP. Further RF testing post additional 120C bake is planned and will give additional insight. Other surface treatments (e.g. HF rinsing) will also be applied on the cavities to investigate and potentially cure the lower Q_0.

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

	1st run; Baseline RF test		2nd run; RF test post BEP	
	E_{acc} max,	Q_0 at 2K	E_{acc} max,	Q_0 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

SUMMARY

Vertical EP with the new Ninja cathode was demonstrated on a single-cell cavity at Cornell. RF performance was good and comparable with that using the Cornell cathode. A parametric study will be necessary to optimize removal uniformity. The development of a 9-cell scale Ninja cathode is in progress at Marui.

A new 9-cell scale Bipolar-EP system was completed and successfully demonstrated on a three single-cell string at Faraday Technology. High gradient RF performances were achieved with two of three single cell cavities during RF test at Cornell. Further RF testing post additional 120C bake and surface treatments of the single cell cavities are in progress at Cornell to explore ways towards higher Q_0 and higher yield.

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