Effort towards symmetric removal and surface smoothening of 1.3-GHz niobium single-cell cavity in vertical electropolishing using a unique cathode

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A detailed study on vertical electropolishing (VEP) of a 1.3-GHz single-cell niobium coupon cavity, which contains six coupons and four viewports at different positions, is reported. The cavity was vertically electropolished using a conventional rod and three types of unique cathodes named as Ninja cathodes, which were designed to have four retractable blades made of either an insulator or a metal or a combination of both. This study reveals the effect of the cathodes and their rotation speed on uniformity in removal thickness and surface morphology at different positions inside the cavity. Removal thickness was measured at several positions of the cavity using an ultrasonic thickness gauge and the surface features of the coupons were examined by an optical microscope and a surface profiler. The Ninja cathode with partial metallic blades was found to be effective not only in reducing asymmetric removal, which is one of the major problems in VEP and might be caused by the accumulation of hydrogen (H₂) gas bubbles on the top iris of the cavity, but also in yielding a smooth surface of the entire cavity. A higher rotation speed of the Ninja cathode prevents bubble accumulation on the upper iris, and might result in a viscous layer of similar thickness in the cavity cell. Moreover, a higher electric field at the equator owing to the proximity of partial metallic blades to the equator surface resulted in a smooth surface. The effects of H₂ gas bubbles and stirring were also observed in lab EP experiments.

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I. INTRODUCTION

A 1.3-GHz niobium (Nb) superconducting radio-frequency (SRF) cavity with a target field gradient of ~ 35 MV/m and a high Q_0 value of 10^{10} will be required for the future international linear collider (ILC) [1–3]. It is well known that the surface state of a cavity plays an important role in achieving the required performance. The rough surface and surface contaminants that remain after the surface treatment of a cavity degrade its performance because of magnetic field enhancement and field emission [4–6]. Electropolishing (EP), which is used to smoothen a surface by anodic dissolution in an electrolyte under mass transport control [7,8], was found to be a promising technique for the final surface treatment of Nb SRF cavities [9–11]. A Nb cavity, selected as an anode with aluminum (Al) as a counter electrode, is electropolished (EPed) in standard EP electrolyte (96 wt% H₂SO₄ and 48 wt% HF in a volumetric ratio of 9:1) [12]. In the EP process of Nb, the

EP rate is controlled by diffusion of F[−] ions, which is responsible for the dissolution of the so-called compact salt film Nb₂O₅, through a diffusion layer at the interface between the Nb surface and the electrolyte [13–15].

EP of the Nb cavities is presently carried out using the well-established horizontal EP (HEP) technique, in which a cavity filled up to 50%–60% with the electrolyte is set horizontally and rotated at 1 rpm during the EP process [16]. The HEP technique requires a complicated and expensive setup for the rotation of a cavity and for turning it vertically to drain out acid and water. A comparatively inexpensive system for the EP would be desirable taking into consideration that about 17000 cavities need to be mass produced for the ILC project. Vertical EP (VEP), in which the cavity is set in a fixed vertical posture, can be performed with a comparatively simple and inexpensive setup. The drainage of acid and rinsing of a cavity with water are easier because of the vertical posture of a cavity. Furthermore, as a cavity is filled with electrolyte only up to 60% in HEP, the EP rate remains lower in comparison to that in VEP, in which the cavity is fully filled. Research on VEP of the cavities is being carried out at different laboratories [17–22]. In contrast to the advantages, a VEP-treated cavity is usually found to be inhomogeneously polished along its length [23], where the upper half cell always shows the highest removal of Nb. It was reported that a higher flow rate of electrolyte on the upper half cell

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[18,23] or gravity [22] might result in a thin viscous layer, and hence higher removal at the upper half cell. The top iris surface usually suffers from bubble traces as well, since hydrogen (H_2) gas bubbles generating on an Al cathode reach the iris surface. After HEP, which usually results in less asymmetric removal [16], field flatness degradation was reported [24]. A higher shift in resonance frequency is usually observed for cavity cells with higher removal. Higher removal of upper cells of a nine-cell cavity in VEP, as reported in Ref. [25], might lead to a higher shift in resonance frequency in the upper cells and degrade field flatness. Field flatness tuning after a final surface treatment step, including light EP and high-pressure rinsing, might increase risk of contamination, which can affect cavity performance [20].

Different shapes of cathodes have been used on a demountable cavity to demonstrate their effect on removal uniformity in buffered EP [20]. However, the cathode with the optimized shape can neither be applied to a real cavity, which cannot be demounted to insert such cathodes, nor can reduce longitudinal asymmetry in Nb removal. The issues in VEP are yet to be resolved. In this article, we report a systematic study on VEP technique to understand actual causes of the problems in VEP, effects of different designs of our special cathodes named as Ninja cathodes on removal and surface roughness, and optimization of VEP conditions. Moreover, lab EP experiments performed to support the results of VEP experiments are also reported.

II. EXPERIMENTS

A. VEP experiment

1. Coupon cavity

In order to optimize VEP parameters, a Nb single-cell ILC/TESLA-type coupon cavity, which was designed to have six disk-type Nb coupons in a diameter of 8 mm, was used for VEP experiments. The cavity design, except the coupon positions, is similar to a coupon cavity used in the HEP process [26]. The coupons are set at the top and bottom beam pipe, the top and bottom iris, and equator positions of the cavity, as shown in the photograph of the cavity in Fig. 1. The coupons were set to the cavity with electrical isolation allowing EP current measurement for individual coupons. The measured coupon currents provide important information to understand the EP phenomenon at different locations of the cavity. The cavity also contains viewports at the iris and equator positions. These viewports are useful for *in situ* observation of the interior of the cavity. The coupons were detached from the cavity for surface studies to realize the surface state at the corresponding positions of the cavity. The special features of the coupon cavity could save time and cost for investigation of VEP parameters for 1.3-GHz Nb ILC/TESLA-type cavities.

FIG. 1. 1.3-GHz Nb coupon cavity with six disk-type Nb coupons at beam pipe, iris, and equator positions shown by red arrows. Inset: Photograph of a coupon.

2. Ninja cathodes

Three different types of Ninja cathodes (NC), named as NC-1, NC-2, and NC-3, were developed for VEP of 1.3-GHz Nb single cell ILC/TESLA-type elliptical cavities. The cathodes consist of four retractable blades, which can be expanded after easy insertion of the cathode into the cavity cell. The Ninja cathodes can be rotated at different speeds inside the cavity during VEP. The NC-1 was prepared with four Al blades and a centered Al rod, which were used as a cathode. In NC-2, the Al blades were replaced with insulating blades. The NC-3 was prepared with partial metallic blades, in which the metallic Al cathode parts on the insulating blades existed near the equator. The blades were found effective in agitation of electrolyte as confirmed with a transparent mock-up cavity [27]. In all three Ninja cathodes, the center rod was surrounded by an insulating housing having slits to pass charge carriers. Schematics in Fig. 2 show the three types of Ninja cathodes.

3. VEP setup and conditions

A VEP setup was developed to process surface treatment of single-cell cavities as shown by a schematic in Fig. 3. The system is equipped with water and acid pipelines, separate pumps for acid and water, and was designed to select upward and downward flow directions for acid and water. The Ninja cathodes can be rotated using an ac motor of variable rotation speed. The system is also equipped with air coolers used to blow cool air uniformly at the cavity surface during VEP and with a water chiller used for cooling of electrolyte in an acid reservoir. A power supply with a power capacity of 6 kW (20 V, 300 A) was used for VEP. Thermocouples were set in the acid reservoir and at the outer surface of beam pipe, iris, and equator positions to measure temperatures. Temperatures, applied voltage, and EP currents for the cavity and coupons were recorded using a data logger.

FIG. 2. Schematics of (a) NC-1 with Al blades, (b) NC-2 with insulating blades, and (c) NC-3 with partial metallic blades. (d) Ninja cathode inside a cavity cell. Red color in the figures represents Al cathode whereas white and grey colors indicate the insulating parts.

FIG. 3. Schematic of VEP setup for a one-cell cavity.

Four VEP experiments named as VEP-1 to VEP-4 were carried out with a conventional rod cathode and NC-1 to NC-3, respectively. An acid electrolyte, which was a mixture of H_2SO_4 (98 wt%) and HF (55 wt%) in a volumetric ratio of 9:1, was used for VEP. The electrolyte was circulated in the cavity during VEP in the bottom to top direction at a flow rate of ~ 51 l/min. Electrolyte and cavity temperatures in the VEP experiments were maintained below 30°C . In the post-VEP process, the cavity was rinsed with ultrapure water at the VEP system followed by the disassembling of the cavity from the system and water rinsing in an ultrasonic bath.

B. Lab EP experiments

Two lab EP experiments, namely lab EP-1 and EP-2, were carried out without and with agitation of the EP acid, respectively, to understand the effects of a cathode position and agitation on an Nb surface. In both experiments, four Nb square samples of size $20 \times 14 \text{ mm}^2$ were prepared for being EPed. The positions of the samples with respect to a cathode were set in such a way that they simulated the top and bottom iris positions of the cavity in VEP-1 and VEP-2. The samples were set horizontally at different positions near a horizontally set Al cathode plate in a size of $\sim 30 \times 25 \text{ mm}^2$. All of the samples kept the same distance from the cathode. Two of the samples were set just above and below the cathode while both samples were facing the cathode. Other two samples were set aside to the cathode while both were facing downwards. A schematic in Fig. 4(a) shows the positions of the samples and Al cathode and electrical connections for EP. The top and side top sample surfaces should exhibit a similar phenomenon as experienced by the top iris surface with NC-1 and the rod cathode, respectively. The position of the bottom sample simulated the bottom iris coupon, whereas the side bottom sample facing down was used to observe an effect of gravity. An assembly of the samples and cathode was set in an EP bath maintained at 19°C – 22°C . The EP bath and stirrer used for the acid agitation are shown in Fig. 4.

C. Removal thickness and surface study

Cavity wall thicknesses at its different positions were measured before and after a VEP experiment using an ultrasonic thickness gauge to obtain removal thicknesses. An averaged removal thickness of the cavity was calculated from the current integration. The removal thicknesses of the Nb square samples were calculated from their weight loss measured with a precision of 0.1 mg. Surfaces of the Nb disk coupons and square samples were investigated with a surface profiler and a polarized light microscope, which

FIG. 4. (a) Schematic showing the arrangement of Nb samples near the Al cathode and electrical connections to measure EP currents from individual samples, (b) EP bath, and (c) stirrer for the acid agitation.

was effective to get a clear morphology of a smooth surface. The profiler makes a line scan to provide a surface profile of the arithmetic roughness R_a and R_z , which is an average of the differences between the five highest peaks and five deepest valleys. Scanning lengths for the Nb disk coupons and square samples were chosen to be 2.4 and 4 mm, respectively. The coupons and square samples used in this study were prepared from the same sheet of Nb provided by Tokyo Denka Co., Ltd. and had a similar rolling surface with an average roughness R_a of 0.6 and R_z of 4.5 μm .

III. RESULTS AND DISCUSSION

A. VEP with rod cathode and NC-1

The VEP experiments, named as VEP-1 and VEP-2, were carried out with a conventional rod cathode and the NC-1, respectively, for ~ 2.5 h. The Ninja cathode was rotated at ~ 1 rpm during VEP. A voltage of ~ 9 V was applied to the cavity and coupons in both the VEP experiments. EP current densities for the cavity and coupons in the cell against the elapsed time are shown in Fig. 5. An average cavity current density of 25–30 mA/cm^2 was recorded in VEP-1 and VEP-2. In both VEP experiments, the highest and the lowest EP current densities were recorded for the top and bottom iris coupons, respectively. In the case of the rod cathode, nonperiodic high current spikes were seen in the current

density profiles of the iris coupons. In the case of NC-1, the periodic peaks seen in the current density profile of the top iris coupon were in synchronization with the instance when the Al blades were facing the coupon. At a rotation speed of 1 rpm, four Al blades crossed the coupon and resulted in four periodic current peaks in one minute of time span. However, no such peaks appeared in the current density profiles for the equator and bottom iris coupons.

The cavity viewports near the top and bottom irises were observed carefully to see the phenomenon occurring during VEP. In both VEP experiments, the top viewport surface always remained covered with H_2 bubbles generated at the cathodes. Photographs of the viewports in Figs. 6(a) and 6(b) clearly show the accumulation of bubbles in the case of the rod cathode and NC-1, respectively. When the blades faced the top viewport, a huge amount of bubbles, like a fume, struck and covered the viewport surface while the existing tiny bubbles on the viewport were displaced by the huge amount of bubbles [see Fig. 6(c)]. With the rod cathode, the bubbles stayed on the viewport surface for a longer time and moved upward very slowly with the acid flow.

Average removal thicknesses of the cavity calculated from the current integration were 58 and 56 μm in VEP-1 and VEP-2, respectively. Removal thicknesses measured at different positions of the cavity with the ultrasonic thickness gauge are as shown along the cavity length in Fig. 7. The removal thickness trends clearly show that Nb removal was the highest at the top iris and the lowest at the bottom iris, as was also reported in Refs. [22,23].

A typical microscope image of a coupon surface before EP and microscope images of the coupons after VEP are shown in Figs. 8 and 9, respectively. Surface roughness R_a and R_z of the coupons measured after both the VEP experiments are summarized in Table I and compared in Fig. 10. The roughness R_a and R_z included microroughness as well as a macroscopic surface profile in the scanning range. In the case of the rod cathode, the top iris surface was found macroscopically rough, whereas the equator surface was microscopically rough owing to selective etching of grains. The cathode blades were found effective in smoothening the surfaces of all the coupons. The original rolling marks on the coupon surfaces still

FIG. 5. Coupon and cavity current densities obtained with (a) rod cathode and (b) NC-1. The red dotted vertical lines in (b) show the times when the blades faced the top iris coupon. The grey solid vertical lines in (b) represent the logged signal of cathode rotation.

FIG. 6. Top iris viewport during VEP. (a) Bubbles in the case of the rod cathode, (b) bubbles before passing a blade of NC-1, and (c) a huge amount of bubbles, which removed sticking bubbles, while passing a blade of NC-1.

FIG. 7. (a) Black dots show positions of thickness measurements. Trends of the removal thicknesses in VEP performed with (b) rod cathode and (c) NC-1.

FIG. 8. Optical microscope image of a typical non-EPed coupon surface. Inset: Zoomed-out image of the surface.

TABLE I. Surface roughness of the coupons after VEP with the rod cathode and NC-1.

Coupon position	Roughness Ra/Rz (μm)	
	Rod cathode	NC-1
Top beam pipe	0.31/1.8	0.28/1.8
Top iris	2.98/13	0.50/2.3
Equator	0.94/5.3	0.22/1.3
Bottom iris	0.26/1.8	0.28/2.2
Bottom beam pipe	0.24/1.6	0.27/1.6

remained after VEP since a removal thickness at all the positions except the top iris was $\sim 50 \mu\text{m}$ or less. However, the level of removal was enough to understand the effect of VEP on the coupons.

Although a higher flow of the electrolyte on an Nb surface enhances the EP rate, we believe that a higher electrolyte flow on the top iris owing to electrolyte circulation [18,23] and gravity as stated in Ref. [22] might not be the main reasons for the higher removal at the top iris. Furthermore, by reducing the temperature intentionally at the top iris, it was observed that the higher removal was not because of a temperature difference at the top and bottom irises. We attributed the higher removal at the top iris to the accumulation of H_2 bubbles, which might reduce a viscous layer thickness in the diffusion regime. A higher number of F^- ions and its species might diffuse through a thin diffusion layer to enhance the EP rate since the concentration gradient of F^- ions in the thin diffusion layer could be higher [14,18]. The huge amount of bubbles generated from Al blades seems to be the cause of the periodic peaks which appeared in the current density profile of the top iris coupon. The lower removal at the bottom iris

FIG. 9. Optical microscope images of the coupons after VEP with the rod cathode (left) and NC-1 (right). Coupons located at (a) top beam pipe, (b) bottom beam pipe, (c) top iris, (d) bottom iris, (e) and (f) equator. Insets show zoomed-out images of the surfaces.

FIG. 10. Roughness Ra (up) and Rz (down) of coupons after VEP was performed with the rod cathode and NC-1.

compared to the equator and beam pipes might be because of a stagnant acid flow at its surface.

Surface roughness was supposed to be influenced by residence time of bubbles on the surface. In the case of the rod cathode, since bubbles were staying on the top iris surface for a longer time, the EP rate might increase locally at the bubble positions to make the surface rougher. The reason of the rough equator surface is discussed in Sec. III E below.

B. Lab EP without stirring

In order to examine the effect of H_2 bubbles on Nb removal and surface roughness, the lab EP-1 experiment was carried out with four Nb samples using the setup shown in Fig. 4 at an applied voltage of 12–14 V for 2 h. Although the voltage and temperature were slightly different from those in the VEP experiments, the different parameters were still in the range of usual EP parameters for Nb [28], and should not alter comparative results of the bubble effect on the four Nb samples. EP current densities for these samples are shown as a function of the elapsed time in Fig. 11. An EP current density was found to be the highest for the top, the second highest for the side top, and the lowest for both of the bottom samples. Removal thicknesses calculated from weight loss of the samples are shown in Table II. Removal dependence on the sample and cathode positions was found to be similar to the one in VEP-1 and VEP-2. The highest current for the top sample was supposed to be a result of an accumulation of H_2 bubbles because the sample surface was directly affected by bubbles. Some bubbles obviously moved to accumulate on the side top sample also and might result in the second highest EP current. The two bottom samples, where H_2 bubbles could not accumulate, showed the lowest and similar current densities. The similar current densities for

FIG. 11. Current density profiles for the Nb samples located at different positions relative to the cathode.

both bottom samples facing upward and downward revealed that the gravity might not enhance the EP rate significantly. In another experiment, we have introduced air bubbles beneath an Nb sample and observed that air bubbles also enhance the EP rate. This test indicated that H_2 gas might not trigger any chemical reaction to enhance the EP rate, while the higher EP rate might be merely a result of the physical impact of H_2 gas bubbles that impaired a viscous layer.

Figure 12 represents optical microscope images of the sample surfaces. Surface roughness of the samples is given in Table II. The surface morphologies of the top and side top samples were found to be similar to that of the top iris surface after VEP with NC-1 and rod cathode, respectively. Similar to the top iris surface found with the rod cathode, the side top sample surface was macroscopically rough with bubble footprints since bubbles stayed on the surface for a longer time.

C. Effect of stirring in lab EP and VEP

In the lab EP-2 experiment carried out with the stirrer and the same setup with four new samples, sample currents were recorded at different rotational speeds of 0, 70, 140, and 210 rpm. It was found that the samples showed similar EP current densities at 210 rpm. The samples were therefore EPed at 210 rpm and ~ 14 V for around 2 h. The current density profiles for these samples are shown in Fig. 13. The slightly higher current density for the side bottom sample was because of the EP of the exposed surface of an Nb connector used to make electrical contact

TABLE II. Removal thicknesses and surface roughness of the samples after lab EP-1.

Sample position	Removal thickness (μm)	Ra/Rz (μm)
Top	77.8	0.25/1.3
Side top	47.5	0.8/4.6
Bottom	40.7	0.36/2.5
Side bottom	39.0	0.29/2.2

FIG. 12. Optical microscope images of the Nb samples after lab EP-1. Insets show zoomed-out images.

FIG. 13. Current densities for the Nb samples at a stirring speed of 210 rpm.

with the sample. Optical microscope images of the sample surfaces are shown in Fig. 14. Surface roughness and removal thicknesses calculated from their weight loss are mentioned in Table III. The surface images and the results in Table III revealed that the EPed surfaces and removal thicknesses were similar regardless of their positions.

Since H_2 bubbles might be responsible for asymmetric removal of Nb, the Al blades were replaced with insulating blades in NC-2 to avoid a direct impact of H_2 bubbles and with partial metallic blades in NC-3 to maintain proximity of cathode to the equator with a reduced impact of H_2 bubbles on the top iris surface. In order to know the effect of stirring in VEP, NC-2 was used with different rotation speeds during VEP. Coupon currents were recorded at several rotation speeds from 1 to 50 rpm. The coupon current densities at 1 and 50 rpm are shown in Fig. 15. The current densities for the bottom iris and equator coupons increased with an increase in the rotation speed and became similar to the top iris coupon current density at 50 rpm. This

FIG. 14. Optical microscope images of the Nb samples EPed at a stirring speed of 210 rpm. Insets show zoomed-out views of the surfaces.

speed was considered as an appropriate speed and was therefore used in further study of VEP.

The stirrer and NC-2 at the high rotation speeds displaced H_2 bubbles away from the Nb sample surfaces in lab EP and the top iris surface in VEP. The bubble accumulation on the surfaces stopped because of the rapid displacement of bubbles as observed through the top iris viewport. Furthermore, an adequate high rotation speed might improve the uniformity of electrolyte flow to form a viscous layer of a similar thickness on the Nb surface regardless of the positions. These might be the probable reasons of the uniform Nb removal in the lab EP and similar coupon currents in the cavity cell.

D. Polarization curves with NC-2 and NC-3

A polarization curve, which is a curve of EP current against applied voltage, provides information of the phenomenon occurring at the EP surface as the voltage increases. A polarization curve contains four regions, namely etching, oscillation, polishing, and gas evolution, in different voltage ranges. In a lower voltage range, the current follows Ohmic behavior and this region is called the etching region, in which removal occurs by preferential etching of grains. In the oscillation region at a higher

TABLE III. Removal thicknesses and surface roughness of the Nb samples EPed at 210 rpm.

Sample position	Removal thickness (μm)	Ra/Rz (μm)
Top	47.6	0.44/2.2
Side top	44.3	0.39/2.4
Bottom	45.0	0.32/2.0
Side bottom	46.7	0.31/1.8

FIG. 15. Coupon current densities with NC-2 at rotation speeds of 1 and 50 rpm.

voltage, a salt film of Nb_2O_5 starts to be formed on the Nb surface and the current oscillates in this region as a result of formation and removal of the film. In the polishing region, a plateau appears in a wide range of applied voltages and Nb dissolves under the current limiting condition. The current density in this region depends on the diffusion of F^- ions, while it remains independent of an applied voltage. At further higher voltages oxygen starts to evolve from the Nb surface, resulting in the current enhancement. EP is usually performed in the polishing region to get a smooth surface.

To understand the effect of NC-2 and NC-3 at different positions of the cavity, polarization curves were obtained for individual coupons and the cavity with both cathodes at 0 and 50 rpm. The polarization curves obtained with NC-2 at 0 and 50 rpm are shown in Figs. 16(a)–16(h). The polishing regions for the top and bottom beam pipe coupons at 0 rpm appeared from ~ 6 V [see Fig. 16(a)]. The polishing regions for the iris and equator coupons started at higher voltages where the highest voltage was required for the equator coupons. Further higher voltages were required to get polishing regions for the iris and equator coupons when NC-2 was rotated at 50 rpm [see Fig. 16(e)–16(h)]. The polishing regions for the equator

coupons appear unclear even at the maximum applied voltage of 20 V [see Fig. 16(g)].

The polarization curves obtained with NC-3 at rotational speeds of 0 and 50 rpm are shown in Figs. 17(a)–17(d) and in Figs. 17(e)–17(h), respectively. Similar to NC-2, the polishing regions for the iris and equator coupons appeared at higher voltages compared to that for the beam pipe coupons. At 50 rpm, the polishing regions were seen at further higher voltages. However, the required voltages were significantly lower than that in the case of NC-2. The polishing regions for the equator coupons appeared clearly from ~ 11 V with NC-3 even though the rotation speed was 50 rpm. The results revealed that the partial metallic blades and the high rotational speed were effective in providing polishing regions at a comparatively lower voltage and similar EP currents for the coupons in the cavity cell.

In the case of NC-2, an electric field experienced by the equator surface was obviously lower than that on the beam pipe and iris positions owing to the larger distance from the cathode. In addition, screening of the cathode by H_2 bubbles might reduce the electric field at the Nb surface and the ion migration to the cathode [20]. The low electric field was possibly the reason for the requirement of the highest voltage to find the polishing region for the equator position.

FIG. 16. Polarization curves obtained for the beam pipe, iris, and equator coupons, and cavity with NC-2 at 0 rpm (a)–(d) and 50 rpm (e)–(h). Solid vertical lines represent a transition from the etching region to the oscillation region followed by the polishing region.

Other than this, a higher acid flow rate on the Nb surface at the higher rotation might impair the salt film. To form an intact salt film in the presence of the cathode screening, a higher voltage was required.

The partial metallic blades obviously enhanced an electric field on the equator because of their proximity to the equator. Moreover, during the cathode rotation H₂ bubbles scattered from the cathode blades to reduce the screening effect. As a result of these phenomena, the polishing regions appeared at comparatively lower voltages. We believe that an anode–cathode distance becomes important especially when the cathode to anode surface area ratio is lower. We will report the effect of a cathode area and an anode–cathode distance in the next paper.

E. VEP with NC-2 and NC-3

VEP-3 was carried out with NC-2 at an applied voltage of 14–16 V. VEP-4 was carried out with NC-3 at a comparatively lower voltage of ~13 V, which was found to be adequate to perform EP in the polishing region. The VEP experiments were performed with cathode rotation at 50 rpm for more than 2 h. The average removal thicknesses were calculated from the current integration to be 54 and 47 μm in VEP-3 and VEP-4, respectively.

Removal thicknesses at different positions of the cavity in VEP-3 and VEP-4 are shown in Fig. 18. In both VEP experiments, the removal thickness at the top iris was measured to be ~1.5 times larger than that at the bottom iris. The trends of removal thicknesses clearly revealed that the longitudinal asymmetry in removal as found with the

FIG. 17. Polarization curves obtained for the beam pipe, iris, and equator coupons, and cavity with NC-3 at 0 rpm (a)–(d) and 50 rpm (e)–(h). The solid vertical lines represent a transition from the etching region to the oscillation region followed by the polishing region.

rod cathode and NC-1 was significantly reduced with NC-2 and NC-3.

Figure 19 shows optical microscope images of the coupon surfaces after the VEP experiments. Average roughness values of R_a and R_z obtained after several cycles of scanning the coupon surfaces are given in Table IV and are compared in Fig. 20. Maximum deviations in R_z from the average values were found to be between ± 0.05 to $\pm 0.3 \mu\text{m}$ for the coupons except the equator coupons in VEP-3. A maximum deviation in R_z for the equator coupon after VEP-3 was around $\pm 0.5 \mu\text{m}$. From the images and roughness results, it was evident that NC-2 provided a rough equator surface, while the beam pipe and iris surfaces were found to be smooth and bright. In contrast

to the NC-2, with the NC-3, the entire surface of the cavity including the equator was found to be smooth and bright with a maximum R_z of $2 \mu\text{m}$ at the top iris. The top iris coupon surface seemed to be slightly affected by H_2 bubbles generated on the partial metal blades. However, it was much smoother than that found with NC-1 and the rod cathode. Furthermore, step heights between the grains appeared to be lower with NC-3.

Although a high rotation of NC-2 and NC-3 reduced the bubble accumulation and asymmetry, it might create a higher turbulent flow of the acid on the top iris surface. The impact of the reduced quantity of H_2 bubbles and the higher flow at the top iris might enhance the EP rate locally to induce a removal asymmetry ratio of ~ 1.5 as obtained at

FIG. 18. (a) Black dots show positions of thickness measurements. Comparison of removal thicknesses along the cavity length for the VEP experiments performed with (b) NC-2 and (c) NC-3.

50 rpm. The removal asymmetry for a nine-cell cavity might be different from that obtained in the one-cell cavity and its effect on field flatness, especially after final light VEP, needs to be examined. A Ninja cathode needs to be modified by covering the cathode housing with a meshed sheet, as in Ref. [25], to guide bubbles along the cathode so as to further reduce the removal asymmetry and by enhancing a cathode surface area to reduce the screening effect. However, there might be a possibility that H_2 gas can leak out from a meshed sheet [16] especially in the absence of acid circulation in a cavity during VEP. Asymmetry was reported even when a cathode meshed bag was used while

TABLE IV. Average roughness of the coupons before and after VEP with NC-2 and NC-3.

Coupon position	Roughness Ra/Rz (μm)	
	NC-2	NC-3
Top beam pipe	0.35/2.1	0.24/1.3
Top iris	0.20/1.1	0.32/1.7
Equator	1.17/6.3	0.24/1.3
Bottom iris	0.20/1.1	0.23/1.1
Bottom beam pipe	0.22/1.3	0.30/1.6

the acid was not circulated [25]. We believe that a cathode rotation speed can be minimized to stop bubble accumulation and reduce turbulence at the upper iris when a Ninja cathode covered by a meshed Teflon sheet, which can at least reduce the number density of H_2 bubbles, and an adequate flow rate of acid circulation are used.

The rough equator surface in the case of NC-2 was similar as found with the rod cathode and was attributed to insufficient voltage for carrying out EP in the polishing region. It can be clearly seen in the polarization curves in Fig. 16(g) that the applied voltage of 14–16 V in VEP-3 was less than a voltage required for EP of the equator surface in the polishing region. Applying a voltage of ~ 20 V or higher to find the polishing region for the equator might result in Nb removal at the irises and beam pipes in the gas evolution region. Moreover, a higher electrical power enhances cavity surface and electrolyte temperatures, which might generate an excess amount of sulfur on the Nb surface as expressed by Eozenou *et al.* [13].

FIG. 19. Optical microscope images of the coupon surfaces after VEP with NC-2 (left) and NC-3 (right). Coupons located at (a) top beam pipe, (b) bottom beam pipe, (c) top iris, (d) bottom iris, (e) and (f) equator. Insets show zoomed-out images of the surfaces.

FIG. 20. Comparison of average roughness Ra (up) and Rz (down) of the coupons VEPed with NC-2 and NC-3.

IV. CONCLUSION

The VEP experiments for an Nb coupon cavity having six Nb coupons were carried out with the conventional rod and three types of Ninja cathodes (NC-1, NC-2, and NC-3) designed to have four retractable blades. The NC-1, NC-2, and NC-3 contained different types of blades, which were metallic, insulating, and partially metallic, respectively. The rod cathode and NC-1 resulted in the asymmetric removal of Nb along the cavity length where the removal at the top iris was measured to be approximately 3 times higher than that at the bottom iris. The longitudinal asymmetric removal might be a result of the accumulation of H_2 gas bubbles on the top iris surface since the bubble accumulation might reduce a viscous layer thickness to enhance the EP rate. A longer residence time caused the bubbles on the surface to leave their footprints on the surface and enhance roughness as found on the top iris surface with the rod cathode. The effect of bubbles on Nb removal and surface roughness was observed in lab EP experiments as well. NC-2 with insulating blades was designed to avoid direct impact of H_2 bubbles on the upper iris as found with the Al blades. This cathode at the rotation of 50 rpm significantly reduced the asymmetry in Nb removal with a removal thickness at the top iris that is ~ 1.5 times higher than that at the bottom iris. However, this cathode, similar to the rod cathode, resulted in the rough equator surface because of preferential etching of the grains. The rough equator surface was attributed to the screening of the cathode by H_2 gas bubbles and a larger anode-cathode distance, which reduced electric charge migration to the cathode and electric field at the equator. NC-3 with the partial metallic blades was designed to keep a cathode close to the equator and reduce the impact of bubbles on the top iris surface. The proximity of the partial metallic blades to the equator enhanced an electric field on the equator surface, whereas the screening of the cathode blades might be lower due to the scattering of the bubbles during the rotation of the

cathode. The polarization curves, which showed an apparent EP plateau for the equator as well, reflected the effect of the cathode blades of NC-3. NC-3 applied with 50 rpm reduced the asymmetric removal of Nb as similar as found with NC-2 and resulted in a smooth surface of the entire cavity including the equator position.

A modified cathode having a larger surface area and covered with a meshed sheet is now under testing for VEP of single-cell Nb SRF cavities to find its effect on the removal and performance of the cavities in vertical tests. A successful cathode will be applied to a nine-cell cavity to study its effect on removal, field flatness, and rf performance.

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