DESIGN OF A NEW ELECTROPOLISHING SYSTEM FOR SRF CAVITIES*

T. Tajima#, LANL, Los Alamos, NM 87545, USA, C. Boffo, FNAL, Batavia, IL 60510, USA,
M.P. Kelly, ANL, Argonne, IL 60439, USA, J. Mammosser, JLab, Newport News, VA23606, USA

Abstract

Electropolishing (EP) is considered the baseline surface treatment for Superconducting RF (SRF) cavities with the best hope of reliably achieving >35 MV/m accelerating gradient for the International Linear Collider (ILC). How to get reproducible results with electropolished ILC cavities has been discussed in a worldwide forum since late last 2005. This paper reviews some parameters discussed, show some new results and proposes a new design for the next EP facility.

INTRODUCTION

The SRF cavities that were electropolished have shown as high as 52 MV/m in accelerating gradient so far [1]. On the other hand, electropolished 9-cell TESLA type cavities have shown much wider spread in achieved gradients than chemically polished cavities [2]. This implies that the control of parameters necessary for successful EP is far more difficult for 9-cell cavities. There were two meetings, one at FNAL in October 2005 and one in Frascati in December 2005 to discuss the current situation, important issues and necessary future R&D [3, 4].

EP PARAMETERS

It has been agreed that most of the parameters that were determined by K. Saito et al. [5] and have been used for KEK and other cavities are mostly still valid, although some calibration is necessary under different configurations.

Current density, voltage and I-V curve

Both current density and voltage are very important parameters for EP. The current density is an important indicator of the reaction on the Nb surface. It starts oscillating when the EP starts as the anode voltage gets higher, and it goes up with higher removal rate. According to [5], 30-100 mA/cm^2 is the proper range. Most people tend to shoot for ~50 mA/cm^2 average current. Considering the fact that the irises are removed about twice as much as the equator with horizontal rotational EP [5], the current density at the irises must be higher than at the equators.

Regarding the voltage, the proper range was determined to be 8-16 V based on a sample test with the anode to cathode area ratio of 1:1, the distance 40 mm and the bath temperature of 23 °C [5]. However, DESY people have found that ~17 V is the optimum voltage for the TESLA 9-cell cavity configuration and they operate the EP at this voltage.

Figure 1 shows a typical I-V curve. It is well known that the plateau between V_b and V_c is an appropriate region for EP and it has been found that the closer to V_c, the smoother the resulting surface.

Since it is important to know where the operation point is in this I-V curve, the effect of other parameters on the I-V curve has been studied. The effect of solution agitation by cavity rotation and liquid flow was studied at JLab recently and the results will be shown in the later section.

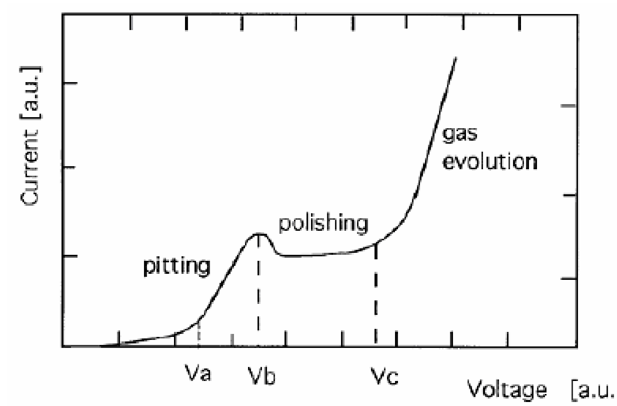

Figure 1: Schematic of the typical I-V curve [6].

Removal rate

Removal rate can be estimated from Faraday's law. Assuming that the dissolution product is Nb^{5+} and, if the current efficiency is 100 %, the removal rate *u* can be calculated as,

$$u = \frac{V_m i}{5F} \quad , \qquad (1)$$

where V_m is the molar volume of Nb, i is the current density, and F is Faraday's constant (96,487 coulombs per mole). Since the molar volume of Nb is 10.8 cm^3/mole, when the average current density is 50 mA/cm^2, the average removal rate is 0.67 μm/min. This is in good agreement with our observation. In the case of horizontal rotational EP, this corresponds to ~0.4 μm/min since the cavity is electropolished only when the surface is in contact with the EP solution (~60 % of the rotation time).

Increasing the removal rate, i.e., increasing the current density will lead to a faster polishing and shorter processing time, however it will generate more heat on the cavity surface, which could lead to non-uniform removal and consequently more work on the tuning of an unbalanced cavity. Therefore, keeping an average current density of ~50 mA/cm^2 is a reasonable choice.

*Work supported by the US Department of Energy
#tajima@lanl.gov

Hydrogen gas generation

Since the gas molar volume is about 24.6 L at 1 atm and 300 K, assuming that $2H^+ + 2e^- \rightarrow H_2$ and that all the current is consumed for generating hydrogen gas, the gas generation rate H_{gen} is estimated as follows.

$$H_{gen}[\text{L/min}] = 24.6[\text{L/mole}] * \frac{\text{I}[\text{C/sec}]}{2 \cdot \text{F}[\text{C/mole}]} * 60 \quad , \qquad (2)$$

where I is the total current. When I=200 A for a 9-cell cavity, H_{gen}=1.53 L/min. Since the amount of generated hydrogen gas is about nine times as that for a single-cell cavity, this suggests the difficulty in removing the hydrogen gas effectively and it is understandable that there have been some 9-cell cavities that have suffered from Q disease. A better mechanism to effectively remove the hydrogen gas needs to be developed. Or, alternatively, methods to protect the cavity surface with a dense pentoxide layer formed by, e.g., adding small amount of HNO_3 in the EP mixture [7], need to be explored..

EP solution freshness

It has been agreed that the EP carried out using fresh acid mixture of 9:1 in volume of H_2SO_4 (96%) and HF (48%), respectively, in the right parameter range will be successful up to a point where the amount of dissolved Nb reaches some amount. Saito et al. have shown that the mixture containing up to 9 g/L of Nb is still usable if the solution is refreshed by adding fluorosulfuric acid (HSO_3F) based on the following chemical equilibrium in the EP solution [5].

$$H_2SO_4 + HF \Leftrightarrow HSO_3F + H_2O \qquad (3)$$

Recent studies at Saclay [8] have shown that:

- surface glossiness starts decreasing over 7 g/L, but
- with higher content of F^-, the glossiness remains up to larger amount of Nb, e.g., it remained the same up to 28 g/L with H_2SO_4(95.5%):HF(40.5%):H_2O=6.72:3:0.28 mixture. This suggests that controlling HF content in the mixture is very important for the success of EP.

HF content and its effect

The nominal HF content for the 9:1 mixture is ~100 cc/L. Saito et al. have shown that HF content of >60 cc/L shows the best surface roughness and brightness, but they have not tested the range over 100 cc/L [5]. HF is the most important ingredient of the mixture for EP and it can affect the polishing rate and solution aging so much that further studies to determine what is the more optimum content and how to detect and control the HF content to make the life of EP mixture longer are underway.

A practical method that has been used to detect the decrease of HF content is to monitor the voltage to keep the same current density since the necessary voltage gets higher with lower amount of HF, e.g., Saito et al. have found that the HF content needs to be increased if the necessary voltage reaches 14 V or higher for 50 mA/cm^2 average current density. Since this number changes with the cavity size and configuration, etc., this needs to be checked again, but once the correlation between the voltage and the HF content is taken for the cavity of interest and a criterion is established we can still use this method.

Agitation of solution

Whether it is horizontal or vertical EP, the EP solution needs to be agitated to keep the polishing going continuously. With the horizontal rotational EP, this is done by rotating the cavity about the beam axis in one direction and by circulating the solution.

Saito et al. have measured surface roughness versus moving speed of a Nb sample in both vertical and horizontal orientations [5]. The roughness did not change much up to ~ 60 mm/s and was 0.15-0.25 μm, but it increased to ~1.55 μm at 160 mm/s. Unfortunately, there is no data between 60 and 160 mm/s and it is not clear when it starts increasing significantly.

Recently, Mammosser et al. at JLab took I-V curves at different rotation speeds and flow rates [9]. Figure 2 shows the results. They have tried a combination of 0.2/0.9 rpm and 10/17 L/min. The rotation speed of 0.2 rpm corresponds to 2.2 mm/s (equator) and 0.73 mm/s (iris). The rotation speed of 0.9 rpm corresponds to 9.7 mm/s (equator) and 3.3 mm/s (iris).

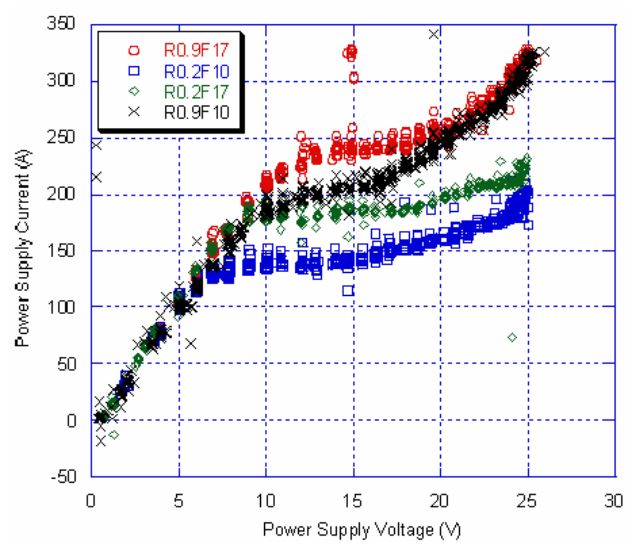

Figure 2: I-V curves for a 9-cell TESLA cavity at different rotation speeds and flow rates. "R0.9F17" denotes 0.9 rpm and 17 L/min.

Since the surface area of a 9-cell cavity is 8010 cm^2 but the area in contact with EP solution is about 60 %, i.e., 4760 cm^2, a total current of 150 A, 200 A and 250 A corresponds to an average current density of 32 mA/cm^2, 42 mA/cm^2 and 53 mA/cm^2, respectively. The data shows that, with higher rotation speed and flow rate, the onset of the voltage for the plateau region gets higher and the voltage range for the plateau gets narrower. In addition, it looks that the onset voltage for the gas evolution regime gets lower with higher rotation speed. It should also be noted that these I-V curves are averages over the entire cavity surface. Local conditions may vary substantially.

Sulfur contamination

Studies have shown that the generation of sulfur is caused by the reduction of HF content [10]. Thus, controlling the HF content so that it can be kept in the proper range will reduce the amount of sulfur generation. Having a readily cleanable EP apparatus is probably key. Also, rinsing the cavity with either H_2O_2 or methanol can also remove sulfur. The best options for controlling sulfur contamination are still to be determined.

A NEW EP SYSTEM DESIGN

Horizontal EP

In parallel with the effort to understand the EP mechanism more scientifically and technologically, an effort to design and build a new EP R&D system in the US is about to begin. The main objective of this new system is to develop a simpler and more reliable EP system that will lead to an industry prototype.

Work on a new electropolishing apparatus at the joint ANL/FNAL superconducting cavity surface processing facility has begun. The initial specification is for a horizontal apparatus such as at DESY, KEK and JLab but with critical additions such as direct (water) cooling of the outside of the cavity to reduce temperature gradients and variations, readily cleanable acid storage vessels and plumbing to reduce sulfur buildup, an all aluminum heat exchanger for better heat exchange with the acid bath, and rapid acid fill, empty and rinse procedures.

Vertical EP

Due to some inherent advantages in vertical EP this technique deserves at least some further consideration. Figure 3 shows a conceptual drawing of a possible system. This system is a new version of a vertical EP. A vertical EP has the following advantages over horizontal EP.

- Less horizontal space is taken, which is more suitable for treating multiple cavities simultaneously.
- Simpler and probably less expensive
- Removing the generated hydrogen gas seems easier
- Theoretically, the Nb removal rate gets about 40% higher than the present horizontal system since all the surfaces are in contact with EP solution.
- Shortening the time between EP, acid draining and rinsing by eliminating the time of moving the cavity from horizontal to vertical position might be beneficial.
- It could be more reliable due to the elimination of sliding parts.

This system employs the solution agitation by bi-directional rotation like some of the washing machines and the flow of the solution. Whether this way of agitation will work or not has not been systematically studied yet, although ANL has some experience in agitating the cavity in this manner during their EP of 3-spoke cavity. Another issue would be how to maintain uniform removal from the top to the bottom cell.

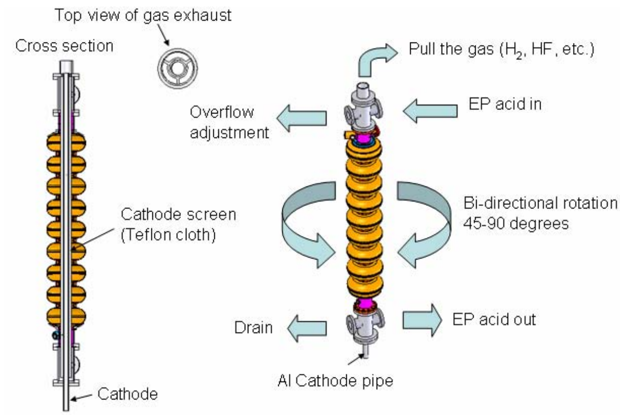

Figure 3: A conceptual drawing of a possible new EP system configuration. This is a new version of a vertical EP.

REFERENCES

[1] T. Saeki, SMTF meeting, FNAL, 5-7 October 2005.
[2] A. Matheisen, "Status of EP at DESY (update)," TTC meeting, Frascati, Italy, 5-7 December 2005.
[3] T. Tajima, "Nb Cavity EP summary as of December 2005," http://ilc-dms.fnal.gov/Members/tajima/EP_Summary_DEC2005.pdf.
[4] P. Kneisel et al., "Proposal for an R&D Plan towards better Understanding of the Electropolishing of Niobium Cavities," http://ilc-dms.fnal.gov/Members/tajima/Proposal17JAN2006.pdf.
[5] K. Saito et al., Proc. 4th SRF Workshop, KEK, Tsukuba, Ibaraki, Japan, 1989, p.635.
[6] P.A. Jacquet; Metal Finishing 47 (5) (1949) 48.
[7] T. Higuchi and K. Saito, "Development of Hydrogen-Free EP and Hydrogen Absorption Phenomena," Proc. SRF2003 Workshop, Travemunde, Germany.
[8] C. Antoine, EP tutorial http://ilc-dms.fnal.gov/Members/tajima/References/Antoine_EP_tutorial_01JUN2006.ppt.
[9] J. Mammosser, http://ilc-dms.fnal.gov/Workgroups/ElectroPolishing/existing/J-Lab/EP%20update60614.ppt.
[10] A. Aspart et al., "Aluminum and Sulfur Impurities in Electropolishing Baths," SRF2005 Workshop.