VERTICAL ELECTROPOLISHING NIOBIUM CAVITIES*

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Abstract

Vertical electropolishing niobium cavities has been developed at Cornell University and applied successfully to a dozen half-cells and several single-cell 1.3-1.5 GHz niobium cavities. High gradients in excess of 35 MV/m were achieved.

INTRODUCTION

Electropolishing (EP) has been proven a necessary surface processing method for high-gradient superconducting niobium cavities [1]. Many labs now have acquired the capability of EP multi-cell cavities and of EP single-cell cavities [2]. Niobium cavities are electropolished in the horizontal position exclusively in these EP systems, following the original KEK/Nomura design [3].

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We have been developing EP capabilities for high-gradient research at Cornell University since 1999 [4]. In the course of half-cell EP studies, the continuous current oscillation EP [5] was discovered, extending the original intermittent current oscillation EP [6].

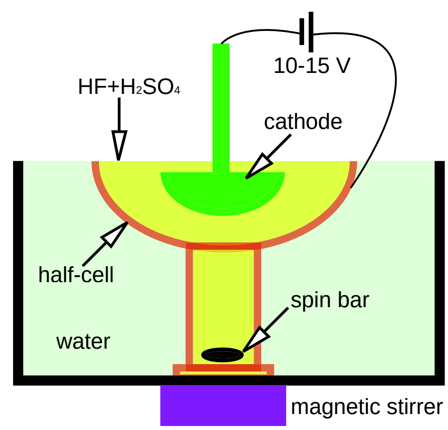
The half-cell EP method has the following characteristics: 1) Full acid coverage of the entire inner niobium surface of the half-cell; 2) Active and continuous acid agitation; 3) External cooling of the half-cell outer wall. Fig. 1 illustrate the original half-cell EP concept [5]. The half-cell is positioned vertically to facilitate full acid coverage. A Teflon-coated magnetic spin bar placed inside the half-cell cavity is driven by a remote magnetic stirrer and provides continuous acid agitation. The acid is contained inside the half-cell cavity by sealing its top equator surface and the bottom iris surface (or the bottom flange surface for beam-tube welded half-cells) with additional Teflon parts. The sealed half-cell assembly is immersed in bath water whose temperature is regulated.

At Cornell, more than 12 L-band cavity half-cells (some with a pre-welded beam tube) have been processed by the vertical half-cell EP method, totaling the EP time of more than 80 hours.

Fermilab has been developing EP capabilities for processing niobium cavities [7]. Vertical EP of half-cells has been successfully applied to 3.9 GHz cavities. A design is completed for vertical EP dumbbells. Vertical EP of 3.9 GHz dumbbells has been explored. Fig.2 shows the schematic layout of the polishing cell in the vertical dumbbell EP set-up.

Vertical EP single-cell niobium cavity has also been developed at Cornell University. It has been successfully used to process 6 L-band single-cell cavities, totaling EP time of more than 30 hours. The schematic layout is illustrated in Fig.3.

An important aspect of the vertical EP process is continuous acid agitation. Our initial half-cell EP was carried out in the intermittent current oscillation mode, following the original niobium cavity EP process of Diepers et al. [6]. The current begins to oscillate when the voltage is turned on. The current oscillation intially increases in amplitude and later decreases. The oscillation is active normally for 3-5 minutes and then disappears. At this point, the volt-



(a) Schematic layout

(b) Half-cell cavity assembly

(c) Beam-tube welded half-cell cavity assembly

Figure 1: Half-cell cavity vertical EP

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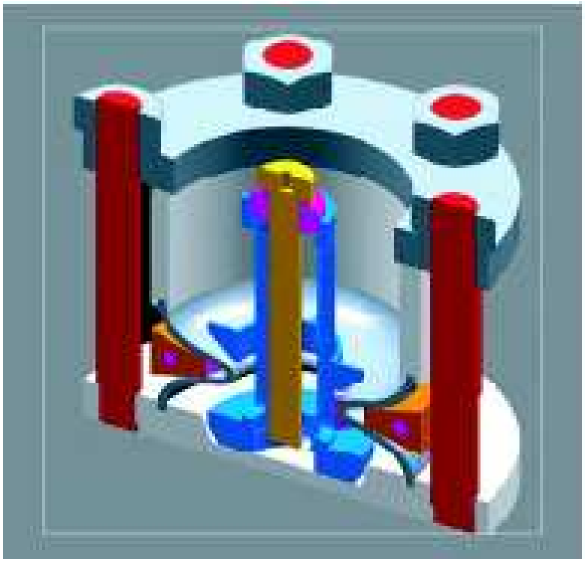

Figure 2: Fermilab dumbbell vertical EP set-up.

age is turned off and acid agitation is started. Agitation is maintained for 3-5 minutes, during which period of time, a dark-colored layer on the niobium surface is disrupted and dissolved eventually. The voltage is then turned back on and the cycle repeats. The decrease in the current oscillation amplitude with time as the voltage is kept on without

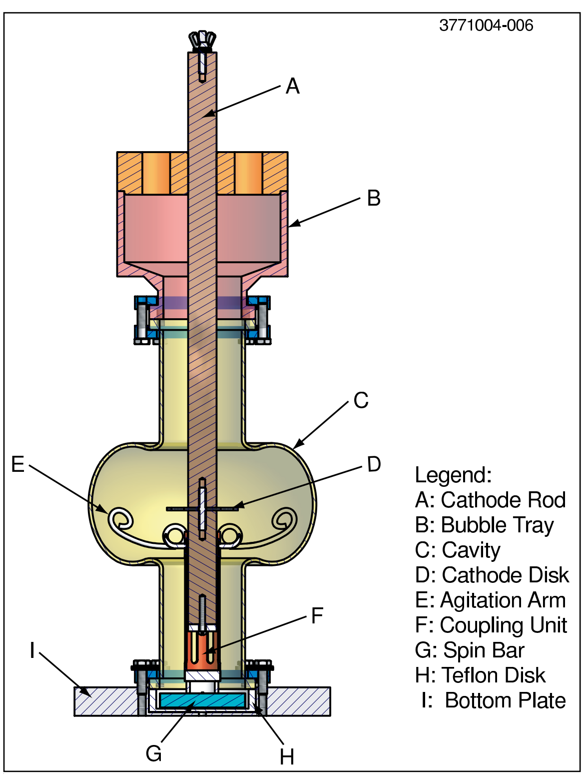

Figure 3: Cornell single-cell cavity vertical EP set-up.

active acid agitation suggests the growth of the thickness of the viscous layer at the acid-niobium interface. In the continuous current oscillation EP mode, an active acid agitation is supplied continuously. The hydraulic effect of the acid movement enhances diffusion of the viscous layer and reduces its thickness. The resulting continuous current oscillation is understood as the equilibrium between the growth force of the viscous layer due to anodization and the reduction force due to the enhanced diffusion.

The agitation mechanism is an important engineering component in a vertical EP system and must be carefully implemented. Design goal is to produce a laminar circulation of the acid at the acid-niobium interface. Factors dictating the acid hydraulics such as the acid volume, the cavity size and shape and the propeller size and geometry must be considered. Inadequate or excessive agitation causes surface passivation or pitting, leading to inferior cavity performance. For vertical EP of L-band half-cell cups, the magnetic spin bar (Fig.1) provides sufficient agitation and the material removal is fairly uniform. For vertical EP of L-band beam-tube welded half-cells, agitation at the interface between the acid and the cup inner surface is significantly damped. Similar situation occurs for vertical EP dumbbells. An improved agitation mechanism (Fig.2) has been devised for vertical dumbbell EP at Fermilab [7]. For vertical EP of L-band single-cell cavities, the agitation mechanism as shown in Fig.3 is found effective. Agitation at the interface of the acid and the cell inner surface is significantly enhanced due to the extension arms coupled to the magnetic spin bar. Tests have shown that there is literally no polishing when a spin bar alone is used for agitation. It should also be mentioned that the gravity seems to have an effect significant enough to perturbate the diffusion of the viscous layer. For this reason, the lower half-cell is normally less polished than the upper half-cell. Nevertheless, a symmetric polishing is easily obtained by flipping the cavity orientation.

PERFORMANCE OF VERTICAL ELECTROPOLISHED CAVITIES

Single-cell cavities fabricated with electropolished half-cells

Two 1.5 GHz single-cell cavities, LE1-35 and LE1-36, have been built with vertical electropolished half-cells.

Trimmed half-cells of LE1-35 were initially electropolished for an inner surface removal of 160 μm. They are joined with beam tubes by electron beam welding. The two beam-tube-welded half-cells were post purified with titanium, improving RRR of the niobium to 500. Another 30 μm was removed by vertical EP and then half-cell equators were joined by electron beam welding. The completed cavity was etched for 5 μm with BCP1:1:2 removing the niobium vapor deposit from the inner surface. During the first cold test, the cavity had a rather low starting Q_0 of 5×10^9 at 1.5-1.6 K which also declined quickly as the

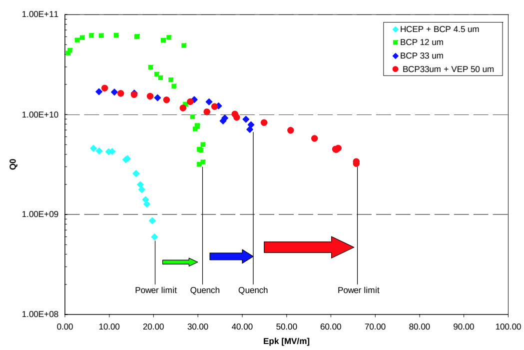

Figure 4: Results of the single-cell cavity LE1-35 fabricated with half-cells processed by vertical EP.

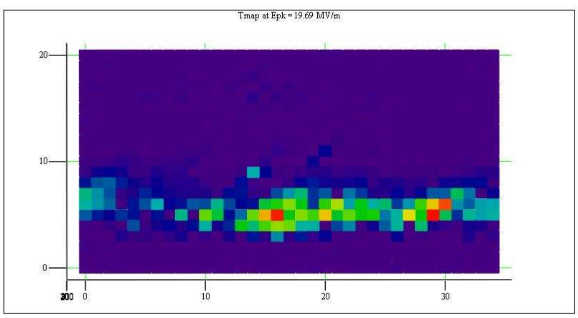

Figure 5: Hot zone in the lower half-cell of LE1-35.

field was raised (Fig.4). The temperature map showed a hot zone in the lower half-cell (Fig.5). Residual titanium on the inner surface was suspected to be responsible. The cavity was further etched for 12 μm with BCP1:1:2. This improved the cavity performance. However, the hot zone still emerged at higher gradients. At the highest gradient, the cavity was limited by quench at a point along the equator, suggesting a defect in the electron beam weld seam. An additional etch of 33 μm continued to push the gradient, limited again by quench at the equator. Finally, the cavity was processed by vertical EP, removing 50 μm. This significantly improved the cavity performance. The accelerating gradient reached 37 MV/m. Some field emission was present.

Half-cells of LE1-36 were initially post-purified. They were then processed by half-cell EP, removing about 90 μm. Due to the reduced strength of post-purified niobium, deformation occurred when post-purified half-cells were compressed by EP fixtures. Repair was done by re-stamping with a male die made of Teflon. Following electron beam welding at the irises and equator, the completed cavity was processed by vertical EP removing 30 μm. During the first cold test, Q_0 initially reached 1×10^{10} at 1.5-1.6 K then declined to 3×10^9 at an accelerating gradient of about 10 MV/m. Temperature map did not show preferential heating suggesting insufficient removal of the damaged layer might be responsible. The cavity is currently being processed with vertical EP for more material removal.

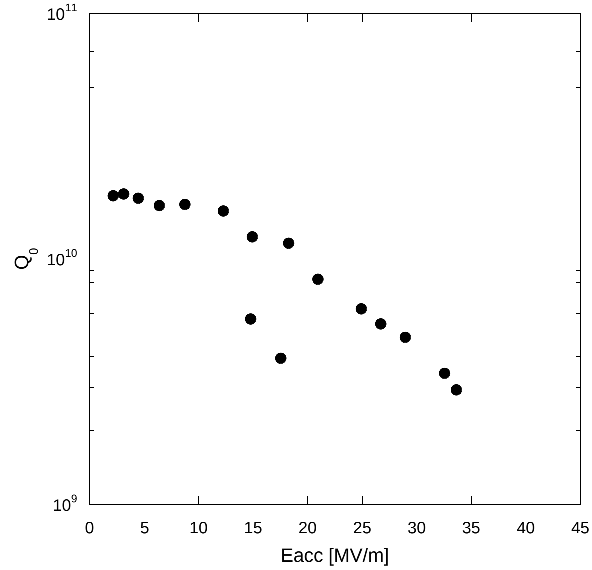

Figure 6: Result of LDP1-4 processed by vertical EP.

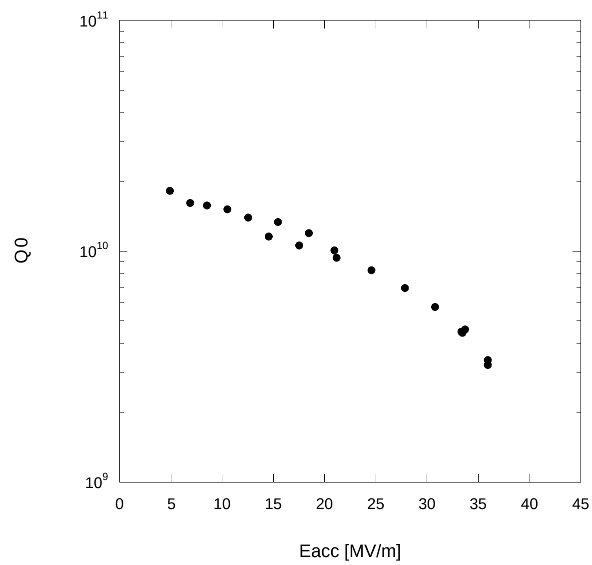

Figure 7: Result of LE1-35 processed by vertical EP.

Single-cell cavities processed by vertical EP

Among six single-cell L-band (1.3 GHz and 1.5 GHz) cavities processed by vertical EP, four reached an accelerating gradient of $\geq$35 MV/m.

Fig. 6 shows the 2 K result of LDP1-4, a 1.3 GHz TTF shape cavity. This is the first successful demonstration of vertical EP. Quench was the gradient limit. Fig. 7 shows the result of LE1-35, a 1.5 GHz CEBAF shape cavity. RF test was performed at 1.5 K. Some field emission was present

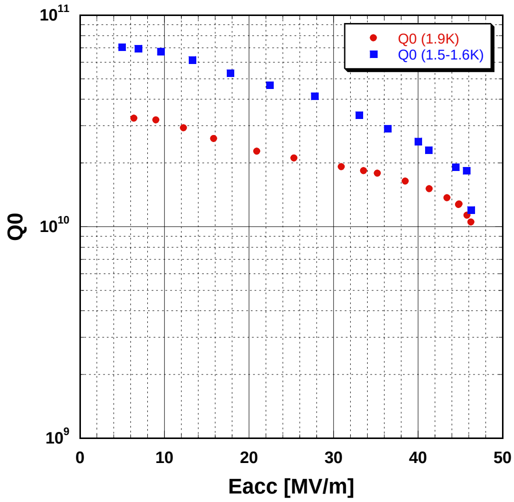

Figure 8: Result of LR1-2 processed by vertical EP.

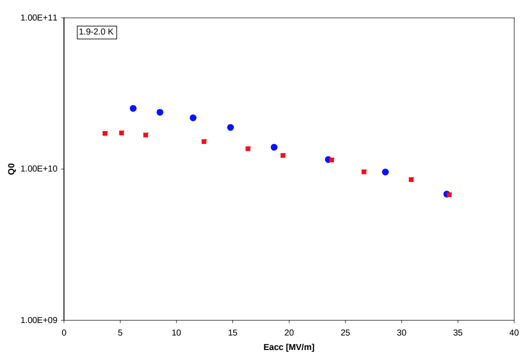

Figure 9: Result of LR1-4 processed by vertical EP.

at high gradients. Quench was the gradient limit.

Fig. 8 shows the result of LR1-2, a 1.3 GHz re-entrant shape cavity with a aperture diameter of 70 mm [8]. The highest gradient reached 46 MV/m in CW mode and 47 MV/m in long pulse mode. RF tests were performed at 1.5-1.9 K. There was little field emission present at high gradients. Quench was the gradient limit. Fig. 9 shows the 2K result of LR1-4, a 1.3 GHz re-entrant shape cavity with an aperture diameter of 60 mm. No field emission was present. Quench was the gradient limit. A defect at the overlap of the equator weld is likely to be the cause. This cavity is currently being processed by tumbling for defect removal. Further tests are forthcoming.

Two other vertical EP processed cavities include LE1-36 and LE1-37, both of the CEBAF shape. The result of LE1-36 is already mentioned in previous section. LE1-37 was fabricated with large grain niobium produced by OTIC, a niobium producer in China. It reached 22 MV/m. The gradient limit was quench, originated from a defect near the equator as revealed by the temperature map. The defect was later identified being a pit. It is currently being processed by BCP1:1:2 etching in order to remove the pit.

DISCUSSIONS

Investigations on Q-disease

Studies are underway to investigate whether or not vertically electropolished cavities have Q-disease caused by hydrogen. Two cavities haven been tested. One does not show Q-disease and the other does. The EP process for the cavity that showed Q-disease suffered losing the temperature control for extended period of time. The highest acid temperature reached 50 °C. It is suspected that the cavity picked up an excessive amount of hydrogen during this temperature runaway. Further studies on Q-disease are needed.

Advantages of vertical EP

The vertical EP method has several advantages that are worth mentioning.

- The cavity and cathode are both fixed in position, allowing fixed electrical connections with power supply terminals. This reduces the complexity of the system and makes it readily scalable.
- The acid mixture is contained in the cavity itself, eliminating external pluming and pumps which are necessary in a horizontal EP system for acid circulation. This reduces the system complexity, acid inventory and the risk of introducing contaminants.
- The cavity inner surface is completely covered by the acid, this increases the efficiency of the process and reduces the risk of hydrogen pick-up by the cavity.
- The cavity is directly cooled by water (bath or shower), eliminating the heat exchanger. This again reduces the system complexity and increases the system MTBF.
- The process operates at a fixed voltage. The acid agitation speed is nominally fixed also. The only parameter requiring active control is the temperature. This simplifies the operation of the process.
- The process operates in the continuous current oscillation mode. Deviation from nominal current oscillation reflects the ill balance between the two competing processes governing the viscous layer at the acid/niobium interface. The disappearance of current oscillation provides a prompt warning signal in case of process malfunctioning.
- The polishing cell is an open system. This reduces the possibility of elevated hydrogen gas pressure and increases the safety of the process.

Multi-cell vertical EP

Multi-cell vertical EP is being developed at Cornell. First trial has been completed with a 5-cell TTF cavity. The cavity inner surface was removed uniformly at a rate consistent with that of the single-cell vertical EP. Further developments are needed. It is planned to vertical EP the first 1.3 GHz 9-cell re-entrant cavity, which is currently under fabrication.

CONCLUSIONS

Vertical EP of half-cells and single-cell cavities has been successfully developed. Several singe-cell cavities processed by vertical EP achieved an accelerating gradient in excess of 35 MV/m. Multi-cell vertical EP is under development. Initial trail showed promising results. The vertical EP method has several advantages that make it suitable for processing niobium cavities at the industry scale.

REFERENCES

[1] K. Saito, in: Proceedings of the 2003 Particle Accelerator Conference, Portland, OR, USA, 2003, p.462.

[2] T. Tajima, Nb cavity EP summary as of December 2005, Technical report LA-UR-06-1147, Los Alamos National Laboratory; Also available in electronic format at the Web ($http://ilc-dms.fnal.gov/Members/tajima$ $/EP\_Summary\_DEC2005.pdf$).

[3] K. Saito et al., in: Proceedings of the 4th Workshop on RF Superconductivity, KEK, Tsukuba, Japan, August 14-18, 1989, p.635.

[4] R.L. Geng et al., in: Proceedings of the 9th Workshop on RF Superconductivity, Santa Fe, NM, USA, November 1-5, 1999, p. 238.

[5] R.L. Geng et al., in: Proceedings of the 11th Workshop on RF Superconductivity, (http://srf2003.desy.de/), Lübeck-Tra vemünde, Germany, 2003.

[6] H. Diepers et al., Physics Letters, 37A (1971) 139.

[7] C. Boffo et al., these proceedings.

[8] R.L. Geng et al., in: Proceedings of the 2005 Particle Accelerator Conference, Knoxville, TN, USA, 2005, p.653.