

## SURFACE SMOOTHNESS FOR HIGH GRADIENT NIOBIUM SC RF CAVITIES

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### Abstract

The author has analysed Q-slopes in Qo-Eacc excitation curves of superconducting RF niobium cavities using combined two models: global heating model and magnetic penetration model [1]. This analysis can derive the effective magnetic critical field of the niobium cavity surface. In chemically polished cavities, the resultant effective magnetic critical field looks to be smaller than the bulk niobium thermo-dynamical critical magnetic field due to the field enhancement effect. In this paper, advancing further this consideration, the relationship between the high gradient and the RF magnetic field enhancement factor will be deduced from the data analysis. Needed surface roughness will be less than  $2\mu\text{m}$  in Rz for the high gradient of  $> 30\text{ MV/m}$ .

### Q-SLOPE AT HIGH GRADIENT

We have currently three kinds of Q-slope with superconducting (sc) RF niobium cavities as seen in Fig.1, which have been not yet understood perfectly. Especially Q-slope III limits the achievable high gradient. By Saclay's or KEK's previous experiences, the Q-slope III in chemically polished cavities was hard to recover by baking. G.Ciovati et al. in JLAB have recently shown that the rather perfect recover of the Q-slope III is obtained with chemically polished cavities by the baking at  $120^\circ\text{C}$  or  $160^\circ\text{C}$  for 48 hours [2], however, the achievable gradient is not yet so much improved by the baking, for example 10% up. In KEK, 40MV/m has been obtained so often with electropolished cavities after  $120^\circ\text{C}$  baking for 48 hours. Electropolished cavity is

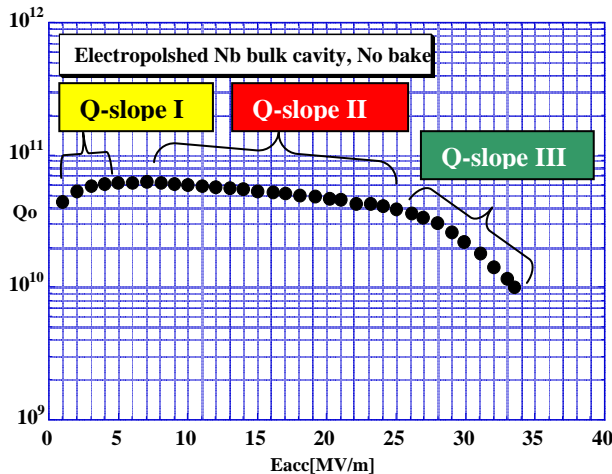


Figure 1: Q-slope observed in the chemically polished niobium cavities even after the baking in KEK.

recovered perfectly by the baking both Q dropping and the achievable high gradient. Now we have an agreement about the Q-slope III that the baking effect is due to the oxygen diffusing on the surface [3,4,5,6]. However, we have no agreement about the less baking effect on the high gradient with chemically polished cavities. The Q-slope III seems to be related to electron beam welding seam at equator section of the cavity, for example seamless niobium cavity seems to have no Q-slope III starting Eacc  $\sim 20\text{MV/m}$  with chemically polished cavities and is easy to achieve Eacc  $> 30\text{MV/m}$  [7]. J.Knobloch et al. have proposed the RF magnetic field enhancement model with the Q-slope III [8]. In their model, grain boundary steps at the EBW seam more likely enhance locally the RF magnetic field by a factor 2 and the local magnetic fields exceed the thermo-dynamical magnetic critical field ( $H_c$ ), then bring to the local heating due to breaking the superconducting state.

Chemical polishing (CP) has a rough surface compared with electropolishing (EP). Therefore, two mechanisms might be coupled in the Q-slope III of CP cavities: baking effect due to oxygen diffusing and RF magnetic field enhancement effect due to the rough surface. Baking recovers the Q-dropping but the high gradient might be still limited by the field enhancement effect due to the geometry of the CP rough surface. Of course, if the surface is smooth enough even in CP, the cavity will achieve  $40\text{MV/m}$  after the baking. Thus, the effective thermo-dynamical critical field  $H_c'$ , which is obtained by the parameter fitting of the Qo-Eacc excitation curve, will be given as:

$$H_c' = \frac{1}{\beta(R_z)} \cdot H_c(O) \quad (1)$$

Here,  $\beta$  is the magnetic field enhancement factor and depends on surface roughness:  $R_z$ .  $H_c$  is the real thermo-dynamical critical field of the surface and is influenced on the amount of oxygen contamination. As seen later, in case of EP we can easily compare  $\beta$  with the surface roughness because we can evaluate the finished surface roughness by an experimental formula. We will use Eq.(1) to deduce the relationship between the high gradient and the surface roughness for EP case.

### SURFACE ROUGHNESS AND GRADIENT

Fig.2 shows the variation of the niobium surface roughness with increased material removals for both EP and CP. In case of EP, it depends on the initial surface roughness and exponentially reduces with increased amounts of EP. The data fitting by Eq.(2) :

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$$R_Z[\mu m] = R_o \cdot \exp\left(-\frac{d}{d_o}\right) + R_{Zres} \quad (2).$$

gives the parameters:  $R_o$ ,  $d_o$  and  $R_{Zres}$  in Table 1 for the three different initial surface roughness.

In the case of CP, it does not monotonously decrease with increased amounts of CP. At the first several  $10\mu m$  removal, it becomes smooth but the further removals bring a rougher surface, of which roughness depends on the grain size of the niobium material. Generally saying the finished roughness by CP will be in between 2 and  $5\mu m$  in Rz after the material removals of  $> 100\mu m$ .

Fig. 3 shows the correlation between the achievable gradient and the amounts of material removal of niobium cavities. These results will include several effects: removal of the surface damage layer, the finishing surface roughness and accidental surface defects, and so on. However, systematic trends can be seen in the graph depending on the preparation method. The black circles are for the chemically polished cavities. The empty circles are for electropolished cavities. The empty triangles are for the cavities initially removed by barrel polishing then electropolished. In every case, the cavity was baked. In the EP case, the achievable gradient increases monotonously with increased material removals. In the case of EP after barrel polishing also, it quickly improves by the additional EP. In the CP case, it saturates between 20 and 27 MV/m but the additional EP improves the gradient quickly with increased material removals. One reasonable interpretation for such improvements is the effect of finished surface roughness. At the small material removals less than  $50\mu m$ , such an improving feature might relate to the elimination of surface damage layers

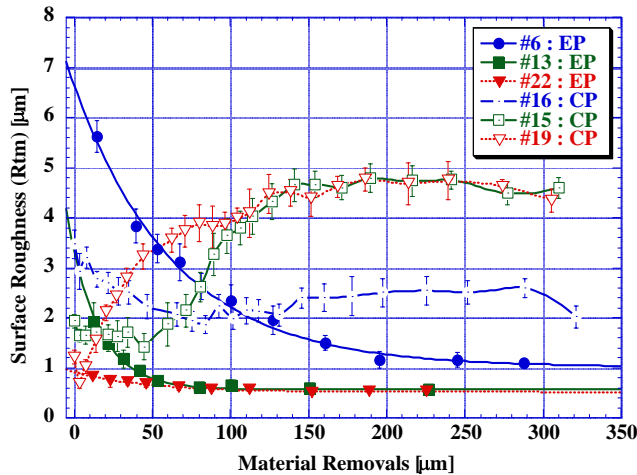


Figure 2: Variation of the surface roughness by EP or CP.

Table 1: Removal characteristics of electropolishing

Initial surface roughness [ $\mu m$ ]	$R_o$ [ $\mu m$ ]	$d_o$ [ $\mu m$ ]	$R_{Zres}$ [ $\mu m$ ]
7	5.65	64.4	1.01
3.5	2.80	19.9	0.56
1	0.40	46.7	0.52

but it will reflect the effect of the surface roughness at the further removals  $> 50\mu m$ . Fig. 2 well explains the results of Fig. 3. The rough surface might enhance the magnetic field locally, which brings to the quench.

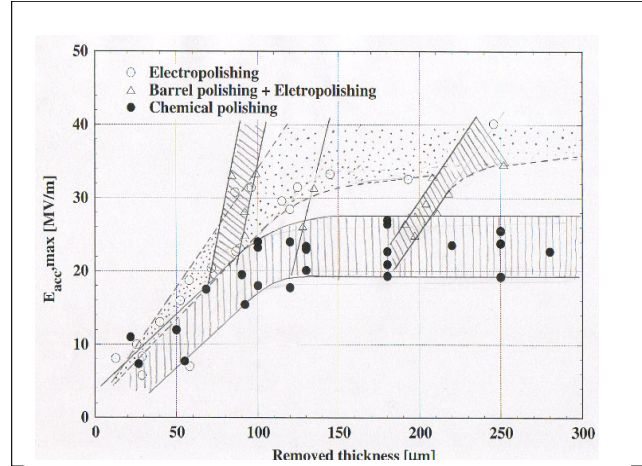


Figure 3: A relationship between the amount of material removal and the achievable gradients.

## ROUGHNESS ESTIMATION OF CAVITY INNER SURFACE

For the initial roughness of  $6\mu m$ , which is a typical value at the equator section of half-cells, the surface roughness with a material removal:  $d$  by EP is given as the following formula:

$$R_Z[\mu m] = 4.92 \cdot \exp\left(-\frac{d}{41.7}\right) + 0.82 \quad (3).$$

This formula is a result from data fitting of the parameters in Table 1 as seen in Fig.4. We remark the equator area of the cavity, where the RF surface magnetic field is high. We can calculate the averaged material removal of whole the inner surface from the total charge by EP or the weight difference of the cavity before and after EP. The material removal is not uniform in our EP but the distribution can be measured. We know the removal ratio at the equator section on the averaged removal is 0.6 [9]. Thus, the material removal at equator section can be calculated from the averaged removal:

$$d_{equator} = 0.60 \cdot d_{averag} \quad (4).$$

The surface roughness at equator area is estimated inputting  $d_{equator}$  into Eq.(3).

On the other hand, the RF magnetic surface field enhancement is estimated by the following procedure. The author proposed the  $Q_0$  ( $E_{acc}$ )-function from the  $Q$ -slope analysis as following [1]:

$$Q_0(E_{acc}) = \frac{\Gamma}{R_S} = \frac{\Gamma}{R_{BCS} + R_{res}} \quad (5),$$

here  $R_{BCS}$  depends on the  $E_{acc}$  as following:

$$R_{BCS}(E_{acc}) = \frac{A}{T_B + C \cdot E_{acc}} \cdot \exp\left[-\frac{B \sqrt{1 - \left(\frac{H_p}{\sqrt{2} \cdot H_c}\right)^2}}{T_B + C \cdot E_{acc}}\right] \quad (6),$$

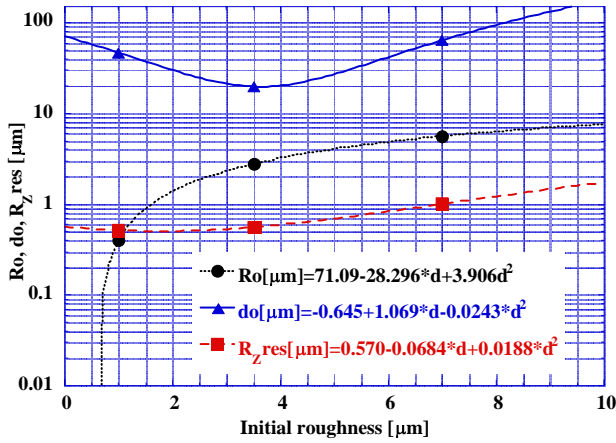


Figure 4: Characteristic parameters in EP and the fitting by the formula (1).

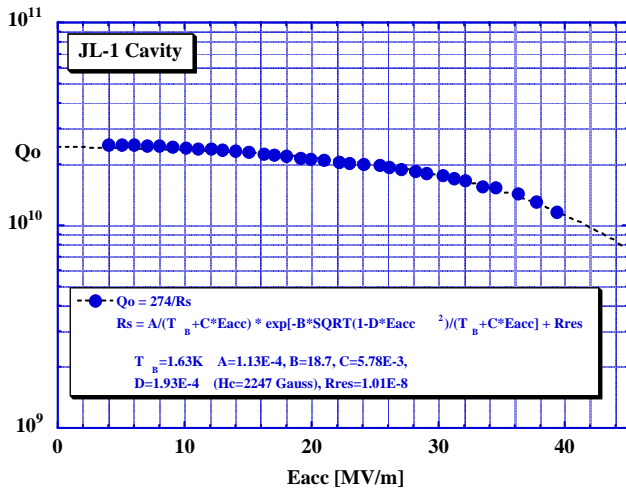


Figure 5: An example of the parameter fitting by the proposed formula.

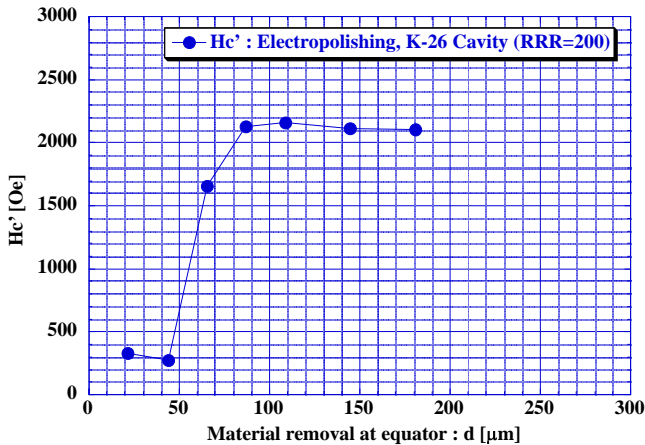


Figure 6: The obtained thermo-dynamical magnetic critical field by the parameter fitting by the proposed formula for an electropolished cavity with increased material removals.

the term  $C \cdot E_{acc}$  in the denominator of Eq.(6) comes from the global heating effect. Here A, B and  $R_{res}$  can be obtained by the measurement of the temperature dependence of surface resistance at low fields. The other parameters in Eq.(6) are obtained by the parameter fitting of Qo-Eacc excitation curve as Fig. 5.  $H_c'$  couples to  $H_c$  by Eq.(1) if there is a field enhancement  $T_b$  is the bath temperature.  $H_p$  is the surface RF magnetic field on the cavity surface, which is given as:

$$H_p[\text{Oe}] = \alpha \cdot E_{acc}[\text{MV/m}] \quad (7)$$

In our cavity  $\alpha$  is 43.8 Oe/[MV/m].  $H_c'$  should be close to  $H_c$  for a heavily electropolished and baked cavity. Fig.6 shows  $H_c'$  by the parameter fittings for an electropolished and baked cavity (K-26) with increased material removals by EP.  $H_c'$  converges around 2150 Oe after removing more than 85  $\mu\text{m}$ . This number is bigger by 7.5% than that of bulk niobium measurements (2000 Oe [10]) but is within the experiment errors. For other analysis, we take this number: 2150 Oe as the true thermo-dynamical critical magnetic field with the smooth surfaces (no field enhancement). Thus field enhancement factor  $\beta$  is calculated as:

$$\beta(R_z) = \frac{H'_c}{2150} \quad (8)$$

from the fitted number of  $H_c'$ . Fig.7 thus shows the calculated magnetic field enhancement factors by this method for K-26 cavity.

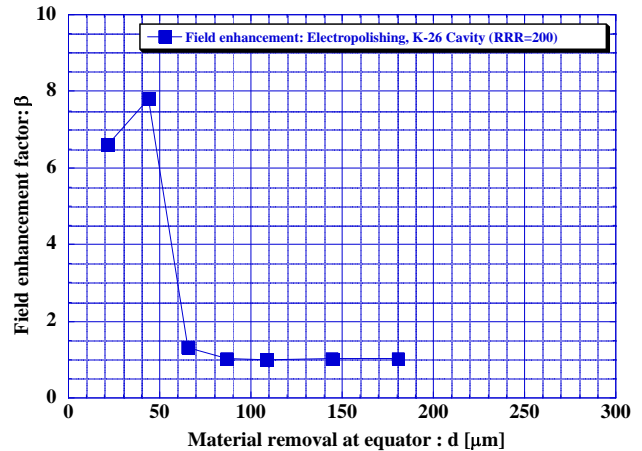


Figure 7: Field enhancement factor with the increased material removal by EP.

### RELATIONSHIP BETWEEN SURFACE ROUGHNESS AND THE FIELD ENHANCEMENT

We have other cavity results, which above analysis is available. Fig.8 includes such results. It shows the relationship with the surface roughness and the field enhancement. The remarkable field enhancement occurs from the surface roughness around  $R_z = 2 \mu\text{m}$ . Reminding of Fig.2, the smoother surface less than 2  $\mu\text{m}$  is hardly expected in the chemical polished cavities. This result

well explains why the CP cavity is hard to get the higher gradient than 30 MV/m. Thus, one can understand the surface smoothness must be better than 2  $\mu\text{m}$  for high gradient.

### CONCLUSION

We have analyzed the Qo-Eacc excitation curves of electropolished niobium cavities based on the global heating and RF magnetic field penetration models, in addition RF magnetic field enhancement model. The relationship between the surface roughness and the field enhancement was deduced. The remarkable field enhancement starts from about 2  $\mu\text{m}$  of the surface roughness in Rz. To get the high gradient Eacc > 30 MV/m, the surface roughness should be smoother than 2  $\mu\text{m}$ .

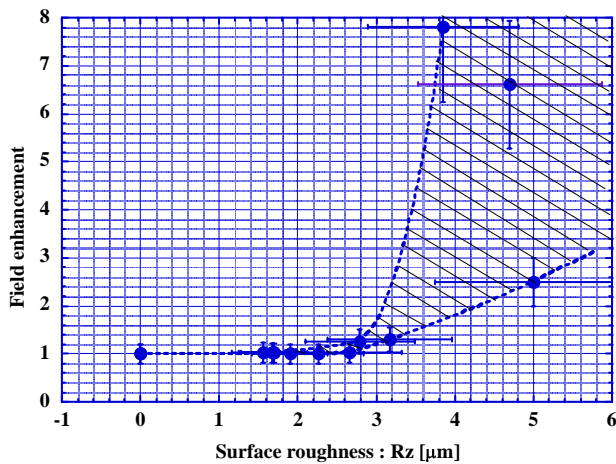


Figure 8: Relationship between the surface roughness and the field enhancement.

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