DEVELOPMENT OF ELECTROPOLISHING TECHNOLOGY FOR SUPERCONDUCTING CAVITIES

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Abstract

In this paper, a brief review is given for electropolishing (EP) of niobium superconducting (sc) cavities. KEK original EP method is introduced. This method can produce high gradient of 40MV/m, which will be the fundamental limit of high pure niobium sc cavities. A required surface smoothness is estimated to be less than 2μm in order to prevent field enhancement problem in sc cavity.

ELECTROPOLISHING OF NIOBIUM CAVITIES

Surface preparation is one of major issues for superconducting (sc) RF cavities. Unloaded Q-value (Q_O) of sc cavities is in a range of 10^9 – 10^{11} and higher than 6 orders of magnitude than normal conducting cavities. Surface defects or surface contaminations make bad effect so sensitively on the RF sc performances: high Q and high gradient.

So far, chemical polishing (CP) or electropolishing (EP) has been used as the main preparation method for niobium cavities. As seen in Fig.1, EP produces a smoother surface than CP. Levelling mechanism in EP is illustrated in Fig.2. Electropolishing a metal as an anode, the electro-chemical reaction generates a liquid layer by the viscous complex salt near the surface. At peaks, anode current concentrates more than bottoms due to the smaller electric resistivity with the thin liquid layer and that results in levelling process. P.A.Jacquet [1] invented EP method in 1935. He found out that a plateau region appears in current density (see Fig.2 right) and plays an important role in EP process.

In the early feasibility study of sc cavities in 1960-1975th, people were of great interest in EP and many

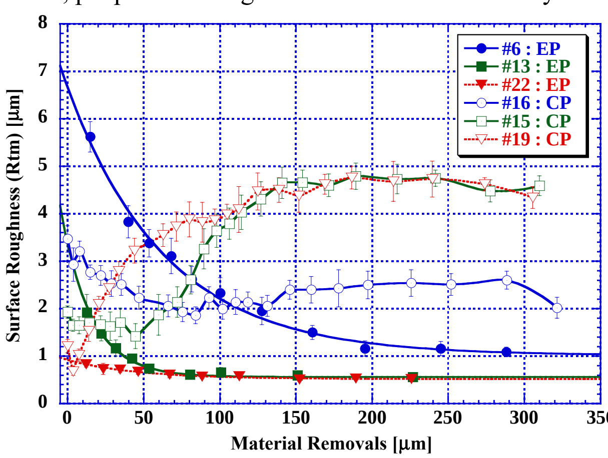

Figure 1: Surface roughness of niobium by EP or CP.

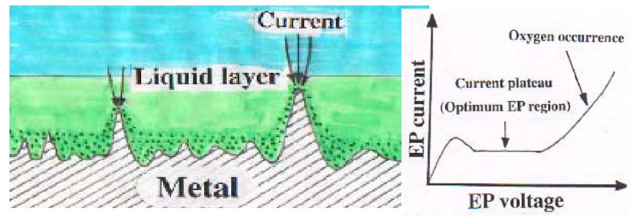

Figure 2: Principle of levelling process in electropolishing (left) and plateau in current density in electropolishing (right).

efforts took place. A most famous work was done by H.Diepers et al. in Siemens Company using the EP acid consisted of sulfuric acid and hydrofluoric acid : H_2SO_4 (>93%) : HF (40%) = 10 : 85 V/V in collaboration with KfK Karlsruhe in 1971 [2]. They developed that the optimum EP condition of niobium is not in the plateau current density but current oscillation as shown in Fig.3. The current oscillation reflects building up and partial decrement of oxide film on niobium surface. It decays in a few minutes after switching on voltage. In order to recover the oscillation, one has to agitated EP acid or to move cavity in switch off. Thus, their method results in intermittent EP. Combining this method with heat treatment and oxypolishing (OP), B.Hillenbrand et al. achieved 1490 Gauss in RF surface peak magnetic field (Hp) with an x-band TM_{010} cylindrical niobium cavity [3]. This number corresponds to the accelerating field gradient (Eacc) of 34MV/m. Its reproducibility was poor but it should be emphasized the high gradient performance by EP was already demonstrated in the pioneer studies.

For multi-cell structures, A.Reuth and O.Schmidt in Siemens Company invented a rather realistic EP system based on the current oscillation control in 1977 [4]. In their method, a cavity is set horizontally in an acid bath. EP acid is filled up to a half level of the cavity through a cathode tube set in it. Voltage is applied to the cavity for several minutes resting it until the current oscillation decreases. Then, switching off the voltage, EP acid in the cavity is agitated by pump acid circulation to remove the

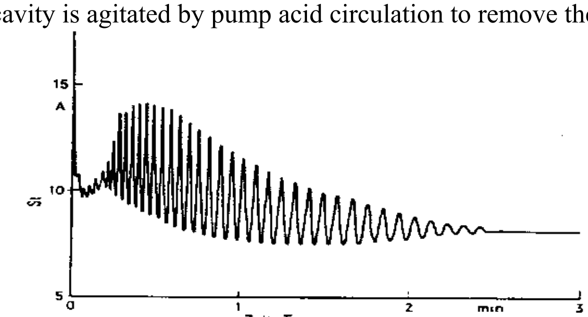

Figure 3: Current oscillation appeared in EP of niobium.

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oxide film on the surface. Thereafter, the cavity is rotated slightly and the voltage is applied again. Such a process is repeated up to the required material removal. In this method, hydrogen gas generated during EP escapes out easily through openings at the beam tube ends. However, this method was never used in their further R&D. EP was very complicate than CP. In those days, CP was getting enough high cavity performance and many laboratories had preferred CP to EP except for KEK.

Hydrogen increases seriously surface resistance of sc niobium cavities. S.Isagawa in KEK investigated this problem in 1979 [5]. He pointed out that hydrogen is picked up niobium material during chemical process like CP or EP and degrades the sc RF property. Hydrogen degassing is crucial to get excellent cavity performance.

Y.Kojima and T.Furuya et al. in KEK followed the current oscillation control at 500 MHz single-cell cavities with a belief in a benefit of the smoother surface by EP. They developed a cathode bag made of porous Teflon cloth to prevent hydrogen bubble attacking the cavity surface during EP. They reconfirmed that the process combined EP, OP and heat treatment produces a good sc cavity performance in 1982 [6]. However, using this KEK standard method for a multi-cell structure, it did not produce such an expected performance due to poor electropolishing around equator section of the cavity and by the imperfect hydrogen cure [7].

K.Saito et al. developed the horizontally rotating continuous electropolishing method (HRC-EP) for multi-cell cavity in 1986 as described in next section. He took Reuth's horizontal EP method but the EP condition was not in the current oscillation. HRC-EP produced high performance very reliably in TRISTAN 508 MHz 5-cell cavities. To date using this method with L-band (1300MHz) single-cell cavities, KEK has reached Eacc~40MV/m with a high probability. Now HRC-EP is regarded as the breakthrough technology for TESLA-800.

DEVELOPMENT OF HRC-EP

In 1985, KEK was preparing sc cavity production for TRISTAN energy upgrade program. They needed a new EP method to guarantee high cavity performance, in addition, to be suitable for the mass production. Siemens's method seemed to be inconvenient because the quantitative control of current oscillation was hard. The resultant intermitted EP procedure was too complicate. K.Saito searched other EP parameters easy in quantitative control and found out that EP condition of niobium is not always in current oscillation but current density of 30~100mA/cm^2 as shown in Fig. 4 , and at the acid temperature between 20^{O}C and 35^{O}C. In addition, he considered about continuous EP method against hydrogen problem. If niobium on anode is continuously applied a voltage, hydrogen ions (H^+) will not be picked up niobium by the potential barrier. The following chemical reaction occurs in EP :

$$2Nb + 10HF + 2H_2O \rightarrow 2H_2NbOF_5 + 5H_2 \uparrow \quad (1).$$

As mentioned in Fig. 2 , the liquid layer (niobium-fluorine complex) generated near the cavity surface governs the EP finishing. A balance between its generation and dissolving into the acid would determine the EP condition. Making a continuous mild agitation, the balance might keep a good EP condition. This agitation can be supplied by a slow continuous cavity rotation. He combined this idea to Reuth's horizontal EP method and innovated the HRC-EP. KEK and Nomura Plating developed the HRC-EP method in a close collaboration. The details are seen in the reference [8].

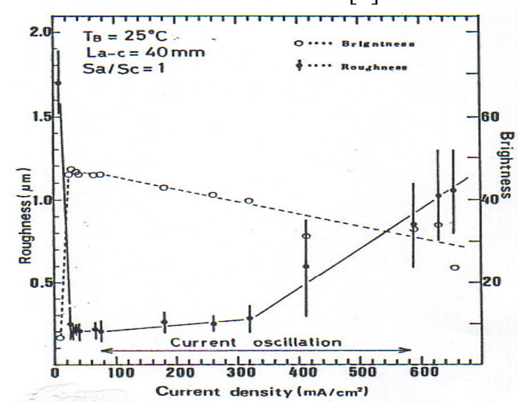

Figure 4: Optimum current density of niobium EP.

HRC-EP is presented in Fig.5. EP acid overflows from open mouths on the rotary sleeves, and retunes by gravity in a reservoir tank with a heat exchanger cooling the solution. Acid pumping speed into cavity depends on the cavity surface areas and is 60 l/min. for the TRISTAN 508 MHz 5-cell cavities. A porous Teflon bag cut open at the bottom side covers the cathode made of pure aluminium tube. This system has many advantages than Reuth's method. 1) EP acid is closed in the system, thus the system becomes very safe against the hazardous EP solution. 2) Only the inside surface is polished. It prolongs the life of EP solution. 3) Even the simple straight cathode structure can get enough current density because that only half of the cell surface immerses in EP solution increases the anode effective surface. Thus one can obtain a good polishing in all inner surfaces. 4) The control is much easy due to the continuous EP. 5) OP is no needed. That made the preparation very simple. Prevention of hydrogen problem by continuous potential control was just recently confirmed [9]. When niobium surface has a damage layer like by mechanical grinding, the potential control has no help against hydrogen [10]. In TRISTAN sc cavity production, we made buffing all half-cells and the potential control did not work. Therefore the

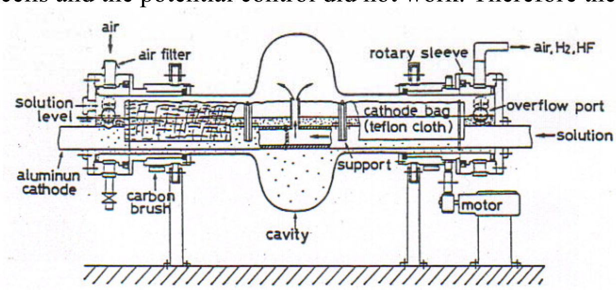

Figure 5: Horizontal rotated continuous electro-polishing.

all TRISTAN sc cavities (32 cavities) were heat treated to degas hydrogen. The average field gradient of 9.6±1.4 MV/m and Q_O=2.8±0.2 at 5 MV/m @4.25 K were obtained in the vertical test. In that time, this performance was high comparing with other laboratory, for instance DESY-HERA.

SUPERIORITY OF EP WITH HIGH GRADIENT

After the TRISTAN, KEK L-band group started TESLA activity since 1990. One issue of this activity was to establish high gradient technology over 30MV/m based on TRISTAN sc cavity technique. Let's see the past 10 years history in Fig.6. This graph shows the achieved highest gradient in each year with L-band single-cell niobium cavities. Until 1994 a steady improvement is seen by several developments: high purity niobium material, 1400^{O}C high temperature annealing (HT), high peak power processing (HPP). In 1995, high-pressure water-rinsing method (HPR) innovated by D.Bloess in CERN [11] was routinely used for L-band cavities by K.Saito [12] and P.Kniesel [13]. HPR can remove particle contamination on cavity surface very efficiently and results in elimination of field emission problem. Thus, HPR brought the jump in 1995. Since then gradient looks to be saturated around 40MV/m. Here it should be emphasized that 40 MV/m was achieved almost by EP except for two results by P.Kneisel in Fig. 6 (■ Nb bulk cavity, ■Nb/Cu clad cavity), which were obtained by CP. Today, we have 3 results with 40MV/m by CP including more recent result in Saclay [14]. CP can achieve 40MV/m but the probability is very low.

These results open several questions: 1) has EP superiority with high gradient, 2) why 40MV/m, and 3) is the saturation in high gradient by technology reason or fundamental field limitation, so on. The first question was answered by a hard work in KEK L-band group in 1997 [15]. The other questions will be answered later in this paper. Fig.7 shows a more recent clear result on the superiority of EP by E.Kako in KEK [16]. It was done using a cavity (S-3) from Saclay with RRR=230 and none annealing. The gradient upgraded to 38 MV/m by the second EP. Then switching to CP, field emission like

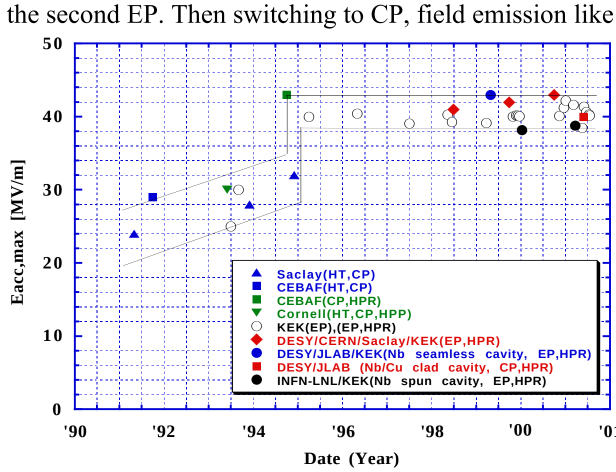

Figure 6: Review of the high gradient in last 10 years.

Q-degradation (called as Q-slope) appeared and the gradient degraded to 24 MV/m by the second CP. Taking successive EPs, the Q-slope has disappeared and the gradient improved to 40 MV/m. This fact shows a clear superiority of EP over CP with high gradient. Similar results were reported from Jlab/KEK [17] and DESY/CERN/Saclay collaboration [18]. Q-slope really appears in electropolished cavities too. It disappears by 120^{O}C baking during vacuum evacuation [19] but in case of CP it still stays even taking bake.

J.Knobloch calculated the field enhancement at grain boundary step (~10 μm) on electron beam welded seam on cavity equator section in order to explain the Q-slope in chemically polished cavities [20]. His conclusion is that a field enhancement factor about 2 can easily happen on such a grain step, and the critical field reduces to the half of the smooth surface. The critical field with niobium sc cavity is 40MV/m as discussed later, therefore in chemical polished cavity, the superconductivity is locally broken around Eacc=20MV/m and resulting in Q-slope.

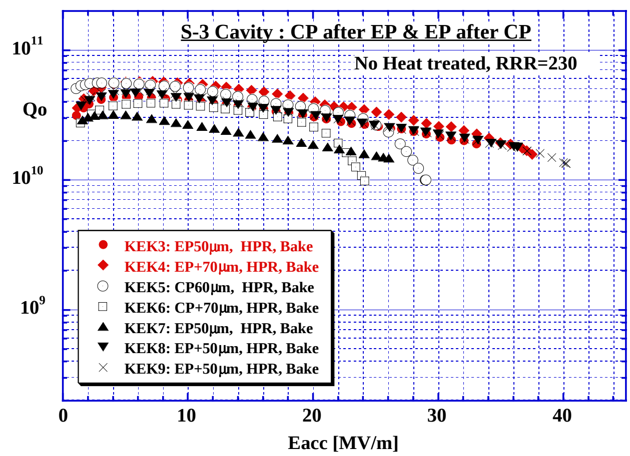

Figure 7: Evidence of the superiority of EP over CP with high gradient performance.

HIGH GRADIENT WITH MULTI-CELL CAVITIES

Next question is whether the superiority of EP can realize in multi-cell cavity. We have confirmed it by collaborations with Jlab and DESY. Fig.8 shows the recent result in DESY collaboration. High gradient performance is required for TESLA application. DESY current preparation is a combination of 1400^{O}C hot annealing to purify niobium material by titanium getter, CP, and HPR. Their results by this process are shown in Fig.8 by hatched area [21]. The specification of TESLA-500: Eacc=23.5 MV/m @ Q_O=1x10^{10} is well satisfied. However, the TESLA-800 specification: Eacc=35 MV/m @ Q_O=5 x 10^9 is in a far way.

New TTF 9-cell cavities were electropolished in KEK (Nomura Plating) and tested in DESY. First results are presented in Fig.8 (▲,●,■). 35MV/m was achieved in four cavities (one result is not presented in Fig.8) and the superiority of EP is clearly reconfirmed with TTF 9-cell cavities. Now, HRC-EP is the breakthrough technology for TESLA-800. The technology transfer is under way from KEK to DESY or Jlab.

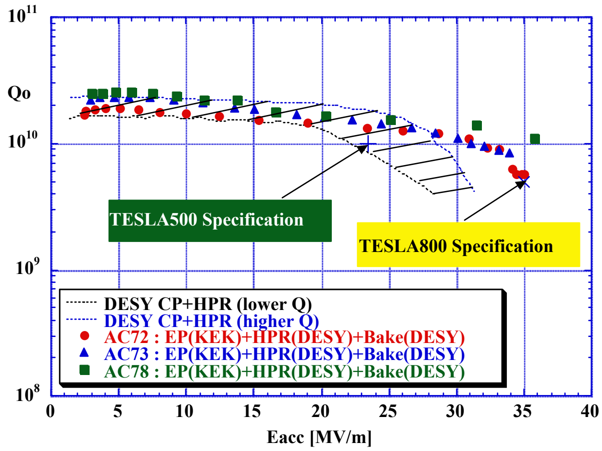

Figure 8: Results of electropolished TTF cavities.

CRITICAL FIELD OF NIOBIUM CAVITY

Here, let's discuss why the gradient is limited around 40MV/m with high pure niobium sc cavities. One candidate of the fundamental field limitation in sc RF application is superheating [22]. By this hypothesis critical field (Hsh) at a temperature T is given from an energy valance in a metastable state between a flux nucleation and sc condensation:

$$\frac{1}{2}\lambda_L(T)H_{sh}^2(T)=\xi(T)H_C^2(T) \qquad (2).$$

Here, λ_L is London penetration depth, ξ coherent length and H_C thermo-dynamical critical field. The factor 1/2 of the left hand in eq.(2) comes from the effective AC field (Hsh/$\sqrt{2}$). Superheating is based on G-L theory, which is available to the band-gap energy close to zero. Here, this condition will be satisfied because the considered magnetic field is close to H_C. Temperature dependences of λ_L, ξ were calculated from H_{C2}(T) and H_C(T) measurement results with Tokyo Denkai niobium material (RRR=400) using the relationships by G-L theory [23] :

$$H_{c2}=\frac{\phi_o}{4\pi\cdot\xi^2}\ ,\quad H_c=\frac{\phi_o}{4\pi\cdot\xi\cdot\lambda_L}\ ,\quad \phi_o=2.07\cdot10^{-7}\ Gauss\ cm^2 \qquad (3).$$

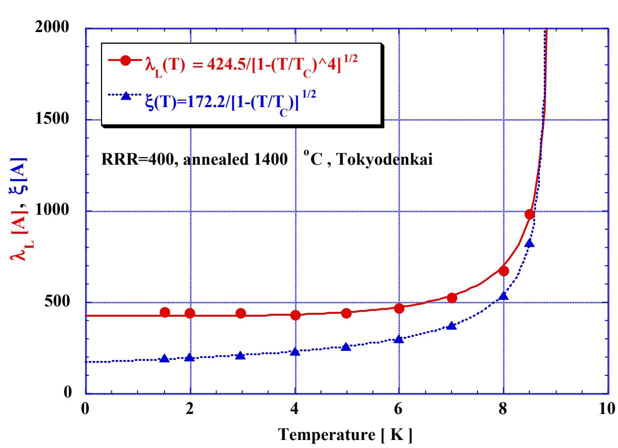

Figure 9: Temperature dependence of λ_L and ξ .

On the other hand, by the theory (high purity limit with ξ) temperature dependences of λ_L and ξ are expected as following:

$$\lambda_L(t)=\frac{\lambda_L(0)}{\sqrt{1-t^4}}\ ,\quad \xi(t)=\frac{\xi(0)}{\sqrt{1-t}}\ ,\quad t=\frac{T}{T_c} \qquad (4).$$

As seen in Fig.9, the calculated λ_L and ξ from experiment results are nicely fitted by eq.(4). As the theoretical temperature dependence of Hc is:

$$H_c(t)=H_c(0)\cdot(1-t^2) \qquad (5),$$

so the theoretical temperature dependence of H_{sh} is :

$$H_{sh}(t)=H_c(0)\cdot\sqrt{\frac{2\cdot\xi(0)}{\lambda_L(0)}}\cdot\sqrt{\frac{1-t^4}{1-t}}\cdot(1-t^2) \qquad (6).$$

On the other hand, for niobium sc cavities, Hsh(T) was directly calculated from the data in Fig.9 [24] and presented in Fig.10 by solid line. Critical fields (Hcf) at various temperatures of niobium sc cavity were nicely measured at Cornell University by short pulse measurement method (■) [25]. These data are presented in Fig.10 with KEK CW measurement results (○). Hsh(T) fits well all the date over the temperature range between 1.5K and 8.5K. It should be emphasized that only H_C(T) or H_{C1}(T) can not fit all the data satisfactorily [25]. Hsh is asymptotic to 1800 Gauss below 3K (t=0.32), which corresponds to Eacc = 41 MV/m. This value explains the saturation of the gradient around 40MV/m in high purity niobium sc cavities.

In order to reconfirm this analysis, Hcf(T) on Nb_3Sn (▲) or Pb (●) cavity [25] was parameter fitted by eq.(6) (dotted lines) in Fig.10. Good fittings were obtained. From this analysis, one will realize that high gradient of sc cavities has come to the fundamental limitation by superheating. As seen in eq.(6), Hsh depends on κ_{GL}($\equiv 1/\sqrt{2}\cdot\lambda_L/\xi$). For niobium cavity, beyond 40MV/m might be possible by κ_{GL} moderation [26] or new cavity design reduced Hp/Eacc ratio. If Hp/Eacc=40 Gauss/(MV/m), 45MV/m is possible.

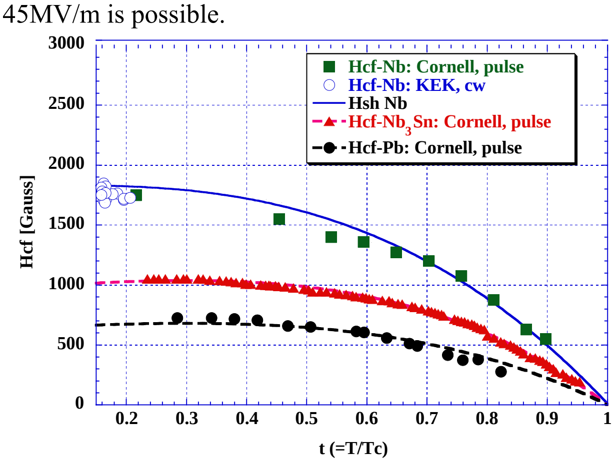

Figure 10: Critical RF fields (Hcf) of sc cavities and Hsh.

SURFACE ROUGHNESS

In the section 3 one would understand the importance of the cavity surface smoothness for high gradient performance. Here let's evaluate quantitatively the required surface smoothness analyzing Q-slope. In the presence of RF field, surface resistance (Rs) of our niobium cavities with Hp/Eacc=43.8 Gauss/(MV/m) will be written as following [27]:

$$R_S(Eacc) = R_{BCS}(Eacc) + R_{res}$$

$$= \frac{A}{T + C\cdot Eacc}\cdot \exp[\ -\frac{B}{T + C\cdot Eacc}\cdot \sqrt{1-\left(\frac{43.8Eacc}{\sqrt{2}\cdot H_c}\right)^2}\ ] + R_{res} \quad (7).$$

A factor $1/\sqrt{2}$ front of H_C in eq. (7) comes from the AC effective field. A, B and Rres are obtained by the temperature dependence measurement of Rs at low field. C・Eacc term in eq.(7) appears by heat stay effect on the RF surface due to the poor thermal conductivity in sc state. In our case these values are A=1.45E-4, B=18.6. Rres =2~10nΩ, and C = (3~5)E-3. When fixed A, B and Rs to the experimental values, eq.(7) includes two free parameters : C and Hc. Fig.11 shows the fitting results with a cavity performance by EP or CP. Eq.(7) nicely fits both results with reasonable H_C value: Hc=2230 Gauss for EP smooth surface. For the enough electropolished surface, the resultant Hc is the real thermo-dynamic critical magnetic field because no field enhancement happens. Remembering Knobloch's simulation, the resultant H_C value (954 Gauss) in CP will include a field enhancement effect. The ratio of 2230/954=2.34 is considered as a field enhancement factor due to the rough surface by CP finishing.

If one approves this analysis, one can obtain a relationship between surface roughness and the field enhancement factor. We have data with successive

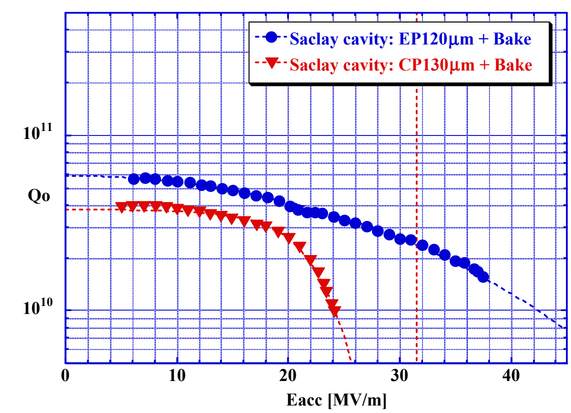

Figure 11: New Q-slope analysis.

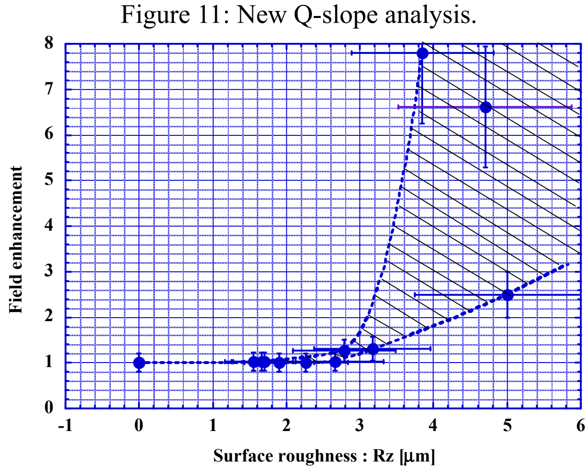

Figure12: Estimated surface roughness versus the field

material removals and the Qo-Eacc excitation curves, for instance Fig.7. We can deduce the field enhancement fitting each Qo-Eacc excitation curve by eq.(7). In addition, we know the surface roughness from the relationship between the material removal and the surface roughness in Fig1. Thus, we obtained Fig.12. The detail will be presented somewhere else. This result is a preliminary one but suggests the surface roughness should be less than 2µm (Rz) to prevent RF field enhancement in sc cavities. The roughness of coarse will depend on the RF frequency.

SUMMARY

We have identified EP is an excellent technology for high gradient sc cavities by the smooth surface finishing. TESLA-800 is ready if one applies EP. High gradient of sc high purity niobium cavities is limited 40MV/m by fundamental limitation: superheating field. Still beyond 40 MV/m might be possible choosing new cavity shape or by the moderation of κ_{GL} of niobium material. The required surface smoothness will be less than 2µm in R_Z to prevent field enhancement with 1300MHz sc cavities.

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