TECHNIQUES OF SC CAVITY PREPARATION FOR HIGH GRADIENT

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Abstract

High gradient of sc cavities was much improved in the past one decade. Today the accelerating field gradient >30 MV/m is produced routinely in single cell niobium cavities by electropolishing (EP). Recently, such a gradient has been achieved in TTF 9-cavities. In this paper, essential preparation techniques for the high gradient are introduced. Especially, EP is a breakthrough technique and its superiority will be resolved from recent new phenomena. In the last, recent results of multi-cell cavities with both β=1 and medium β are reviewed.

1 INTRODUCTION

Until now we have met several field limitations like surface defects, multipacting, and field emission and so on, however today these have been overcome by the techniques presented here. SC cavity fabrication technology has achieved the fundamental field limitation with niobium single cell cavities. From these experiences, a recipe for the high gradient >30 MV/m is: fabricate a cavity from niobium material with RRR~200, and before chemistries make mechanical grinding whole the cavity inner surface, in next remove the surface by 50~100 m with chemical polishing (CP) or electropolishing (EP), in addition take annealing for hydrogen degassing at 750~800OC, finally finish the surface with EP by at least 50 m and rinse with high pressure ultra-pure water rinsing (HPR), then assembly in a class 10 clean room. Here, techniques required in this recipe are introduced. Getting high gradient, new phenomena have appeared in field performance. Secondly I will present them and introduce their understandings. In addition, present achievement of the high gradient on single cell cavities is discussed on the fundamental field limitation: superheating. In the last, state of the art of high gradient in multi-cell cavities is reviewed.

2 ESSENTIAL FIVE THEQUNICS FOR THE HIGH GRADIENT > 30 MV/M

2.1 Centrifugal Barrel Polishing (CBP)

Superconducting RF cavity has a very high Q-value, therefore its performance is very sensitive to the surface imperfections: damaged layer, scratches, inclusions, electron beam welding defects, and contaminations. The role of preparation with sc cavity is to eliminate such problems. So far mechanical grinding has not been emphasized so much but it is more powerful and reliable than CP or EP to remove surface imperfections. In KEK, mechanical grinding for EBW seams, buffing for half-cells and barrel polishing (BP) for welded structures have been used successfully. Among theses methods, BP is

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simplest, where a cavity is rotated horizontally with small grinding stones (chips), water and soap, however, the material removal speed is very slow, for example two weeks for an average material removal of 40 μm. Recently, applying centrifugal barrel polishing (CBP), this problem was solved by KEK/Nomura Plating collaboration [1]. Fig. 1 shows the new CBP machine. This method gets a stronger friction between grinding stones and cavity inner surface by two opposite rotational motions. By this method, an average removal of 40μm was achieved in 8 hours with 1300MHz single-cell or 3-cell cavities. As mechanical grinding itself makes a damaged layer or contaminates surface with abrasives, thereafter the surface has to be refinished with stress- and contamination-free preparation techniques like CP or EP. During CBP or BP, hydrogen is picked up in niobium material, thus hydrogen outgas annealing is inevitable.

Figure 1: Centrifugal barrel polishing machine in KEK

2.2 Chemical Polishing (CP)

Chemical polishing is a very convenient surface preparation method. It has been used as a main preparation technique for sc niobium cavities in many laboratories except for KEK. This etches niobium surface chemically. This technique is needed for not cavity preparation but also cleaning of cavity parts like half cups or flanges before electron beam welding. Usually CP acid is consisted of nitric acid (61%), hydro-fluoric acid (46%) and phosphoric acid (85%) by volume ratio 1:1:1. The typical material removal speed is about 8 m/min at 300K Since discovered the hydrogen Q-disease in chemically polished cavities from high RRR niobium materials [2], one often uses the milder 1:1:2 mixture to prevent picking up hydrogen. Higher temperature is not preferable against the hydrogen Q-disease. When dumped the acid from the cavity, remained acid on the surface still continues reaction in undesirable condition (often called as runaway reaction), therefore the cavity has to be rinsed quickly with water. Fig.2 presents typical surface roughness by CP (1:1:1). It should be emphasized that in some cases CP rather makes rough the smooth surface. The surface finishing depends on the metallography of the niobium bulk. More information on CP is seen in the reference [3].
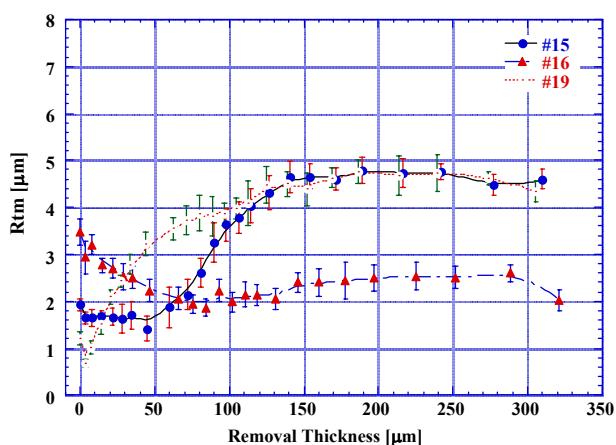
Figure 2: Typical surface finishing by CP(1:1:1).

Figure 3: Typical surface finishing by EP

2.3 Electropolishing

Electropolishing is more complicated compared with CP. It removes niobium metal surface by electro-chemical reaction. Electric voltage around 25 V is applied between niobium (anode) and pure aluminum (cathode) in the mixture consisted of sulfuric acid (>93%) and hydro-fluoric acid (46%) by volume ratio 10:1. The runaway reaction does not occur because the reaction stops by switching off voltage. As seen in Fig.3, the finished roughness is smoother than CP but depends on the initial roughness or the amount of material removal.

A suitable EP system for niobium multi-cell cavities: horizontal continuous EP (HCEP) was developed in KEK for the TRISTAN sc cavities [4]. Fig.4 illustrates the system. In this method, a cavity is set horizontally. EP acid is put up to the half level of the cavity through a cathode tube setting slightly below the centre of beam axis. Overflowed acid from holes in both sides is back to a reservoir tank with a heat exchanger, and cooled, then pumped up again to the cavity. The hazardous acid is thus closed in the system. The cavity is slowly and continuously rotated during EP. EP voltage is applied continuously. Removal speed by HCEP is about 0.4μm/min at 300K. Two points are very curtail with EP of cavities: 1) to get a high enough current density > 30 mA/cm^2 in order to make smoother surface and 2) to have an enough exhaustion space for hydrogen gas against hydrogen Q-disease. In addition, recently we have developed that the continuous EP has an important role against the hydrogen Q-disease [5]. HCEP have an enough cathode surface, thus high current density is easily obtained. In addition, hydrogen can escape easily from the holes on the both rotary sleeves. Each cell is equally polished in case of multi-cell cavity. As shown in later, now HCEP is a key technology for high gradient. More information is seen the reference [4].

2.4 High Pressure Water Rinsing (HPR)

After CP or EP, the cavity inner surface has to be water rinsed carefully to remove chemical residues or particles against field emission problem. Use of ultra-pure water is essential, but only that is not enough to eliminate field
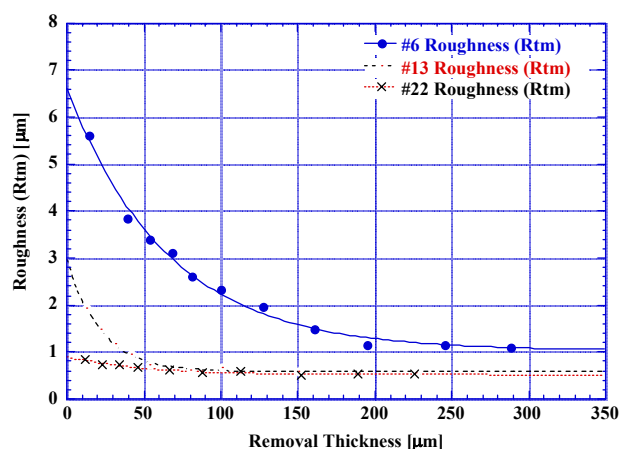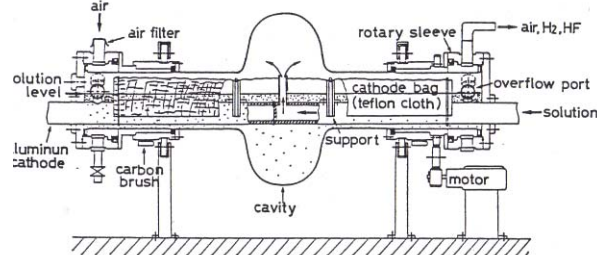

Figure 4: Horizontal continuous electropolshing (KEK)

emission. High pressure rinsing with ultra-pure water (HPR) at around 90kg/cm^2 is very powerful to remove particles on the surface. In 1991,D.Bloess developed it in CERN [6]. After that it has been used routinely in many laboratories [7,8], then field emission problem has been solved. HPR is another key technique for high gradient.

2.5 800°C Vacuum Furnace

Today it is well known that niobium cavities made from high pure material pick up hydrogen during BP, CP or EP and result in the hydrogen Q-disease. The hydrogen precipitates to niobium hydro-ride during slow cooling down between 150 and 90K [2] in cold test. It is a weak superconductor and increases surface residual resistance of niobium cavities remarkably. Since fast cool-down would be difficult in accelerator complex, one has to eliminate the problem before the final cavity assembly. Hydrogen in niobium bulk is easily degassed at a temperature above 600°C. Usually we heat cavities at around 800°C in a vacuum furnace. A vacuum furnace at least 750°C should be prepared for scrf cavity R&D. 750-800°C is too low to have titanium solid getter [9] but it would be safer to use titanium box with niobium cavities in order to prevent material degradation from residual gas in the furnace.

1400°C high temperature annealing in DESY is not always needed as long as one uses EP. The niobium material with RRR~200 seems to be good enough in EP case. It should be stressed that in some cavities with even RRR~200 we have no hydrogen Q-disease without any heat treatment. Therefore, present understanding about the hydrogen Q-disease is limited. There might be a method except for annealing to eliminate it.

3 NEW PHENOMENA

Field emission has gone by HPR. In addition, by improvements in quality of niobium material and electron beam welding, thermal instability caused by surface imperfections has been improved so much. Then, new phenomena related to the fundamental field limitation have appeared.

3.1 Superiority of EP with High Gradient

One is the superiority of EP over CP. It was reported in 1997 from KEK [10]. Fig.5 shows a recent more clear result in KEK [11]. It was tested using a cavity from Saclay (S-3) with RRR=230 and no annealing. The gradient upgraded to 38 MV/m by the second EP (totally 120μm removed by EP). Then switched to CP, field emission like Q-degradation (called Q-slope) appeared and the gradient degraded to 29 MV/m by the first CP (70μm) and 24 MV/m by the second CP (totally 130μm by CP). Taking EP again, the Q-slope has gone and the gradient improved to 40 MV/m by the successive EP (totally 150μm after CP). This fact shows the clear superiority of EP over CP with the high gradient. Similar results were reported from Jlab/KEK [12] or DESY/CERN/Saclay collaboration [13].
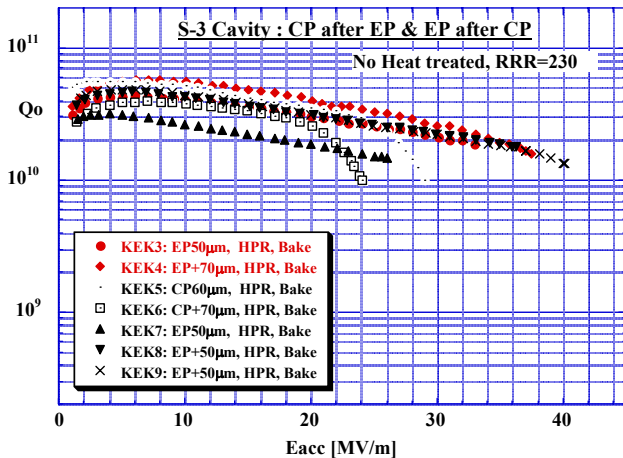

Figure 5: Superiority of EP over CP with high gradient

3.2 Baking Effect

The first report of baking effect was on niobium coated film cavities by P.Bosland in Saclay [14]. In 1999, P.Kneisel in Jlab made more systematic studies on this effect with niobium bulk cavities and found two effects: 1) BCS surface resistance is reduced by a factor 2 after baking, 2) Q-slope with electropolished cavity is improved by baking, resulting in high gradient [15]. Similar results were also reported from DESY[13] and Saclay [16]. Fig.6 shows the recent result in KEK. One cavity was electropolished and cold tested without baking(●). Clear Q-slope appeared and the gradient was limited to 32 MV/m due to heating. After the cold test, the cavity was just baked at 120OC for 2 days and re-tested(▲). The Q-slope disappeared and the gradient improved to 40 MV/m. On the other hand, the similar experiments were done with chemically polished cavities in Saclay [16,17], however,

baking effect is less compared with electropolished cavities. The result is also observed in Fig. 5 too. In theses tests, baking was carried out for both EP and CP: Q-slope is dominant with CP even taking bake.
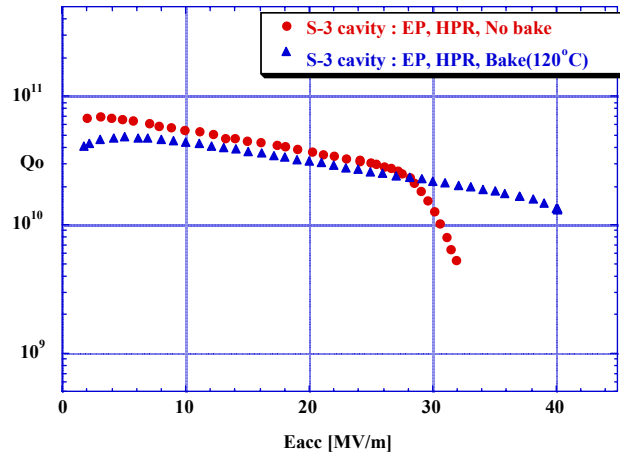

Figure 6: Baking effect on electropolished niobium cavity (1300 MHz, single cell cavity)

3.3 Understanding of Baking Effect and the Superiority of EP

Mechanism of the baking effect is explained as followings [18]: electropolished or chemically polished niobium surface is coated lightly by NbO_X (x<1) and Nb_2O_{5-y} covered with hydrogen bonded H_2O/C_xH_y (OH) $_z$. Such a surface deteriorates surface resistance of the cavity at high fields by interface tunnel exchange (ITE) of conduction electrons in metallic NbO_x between localized states of Nb_2O_{5-y} and states of niobium, resulting in Q-slop. In 120^OC baking for 2 days, oxygen diffuses over the London penetration depth λ_L(50~100nm), then Nb_2O_{5-y} becomes thinner and NbO_x precipitation into niobium [12,17,18,19]. Thus, the Q-slope disappears after baking with electropolished cavities.

On the other hand with CP, surface is rougher than EP case. It brings a local field enhancement and results in Q slope not improved by baking. J.Knobloch in Cornell University made a simulation [20]. In equator section with high surface RF current, rather sharp steps are there between large gain boundaries by electron beam welding. Assuming 10μm step, magnetic field enhancement factor was calculated parameterizing slope angle. His typical result is shown in Fig.7. A field enhancement of factor 2 is more likely to happen. As discuss later the fundamental field limitation is 40 MV/m with niobium, if the enchantment factor is 2, niobium becomes normal conducting at 20MV/m and starts to heat remarkably. As seen in Fig 2, CP could make sharp the electropolished surface easily, then results in Q-slope. On the other hand, electropolishing the CP surface, steps become smooth and results in disappearing of the Q-slope. However, so far three exceptions are there on the Q-slope by CP. One is in Jlab [21] and the other is more recently in Saclay [22]. Both welded niobium cavities achieved 40 MV/m by CP without Q-slope. Considering about seamless cavity,

which has no electron beam welding [23,24], Q-slope would not appear even with CP. The trend is seen hydro-formed DESY cavities but still the gradients were limited around 30 MV/m and were upgraded to 40 MV/m by electropolshing [24]. The third exception is in Nb/Cu clad seamless cavity, which achieved 43 MV/m by CP after 800$^{\mathrm{o}}$C annealing [24]. The Q-slope is not explained by only the surface roughness. Still something is being missed for its perfect understanding.
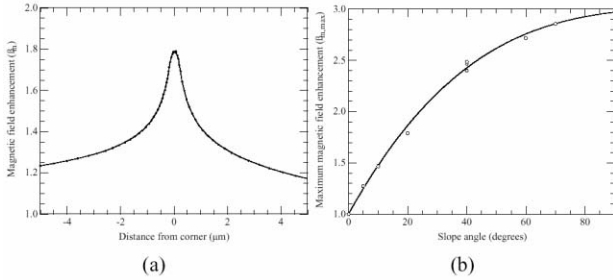

Figure 7: Magnetic field enhancement.
(a) Field enhancement along the rf surface near the corner (slope angle = 20$^{\mathrm{O}}$). (b) Maximum enhancement versus slope angle (copied from the ref. [20])

3.4 Present Achievements and Critical Field of Niobium Cavities

High gradient of 40 MV/m was repeatedly achieved in many 1300 MHz single cell niobium cavities by EP based preparation. Achieved rf magnetic fields in KEK: surface peak magnetic fields Hp were calculated from the gradients : Hp(Gauss) = 43.8$_{\Gamma}$Eacc (MV/m) and plotted (X) in Fig.9 with Cornell data(■) [25] at higher temperatures than 4K and 2K. Cornell data are by pulse measurement and KEK data by cw measurement. One hypothesis of the fundamental field limitation of scrf application is superheating model [26]. In this theory, the maximum field (Hsh) at a temperature T is decided by an energy valance between a flux nucleation and sc condensation:

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

Temperature dependence of superheating field (Hsh) was calculated for RRR=400 Tokyo Denkai niobium material using the measurement results: London penetration depth $\lambda_L(T)$, coherent length $\xi(T)$ and sc lower critical field $H_C(T)$ [27].

$$H_{sh}(T) = \sqrt{\frac{2}{(\lambda_L(T)/\xi(T))}} \cdot H_C(T) = \sqrt{\frac{2}{\kappa(T)}} \cdot H_C(T) \qquad (2).$$

H$_{sh}$ is presented by solid line with other H$_C$ and H$_{C1}$ in Fig.9. Only H$_{sh}$ fits all the date over the temperature range between 1.5 K and 8.5K. H$_{sh}$ is asymptotic to 1800 Gauss below 3K. This niobium material has a little bit low T$_C$: 8.7K. Other calculation (···) was done for higher RRR(>2000) material from French's data [28] but the result has only a small difference from the RRR=400 case. This fact shows sc cavity fabrication technology has come to the fundamental limitation with niobium.
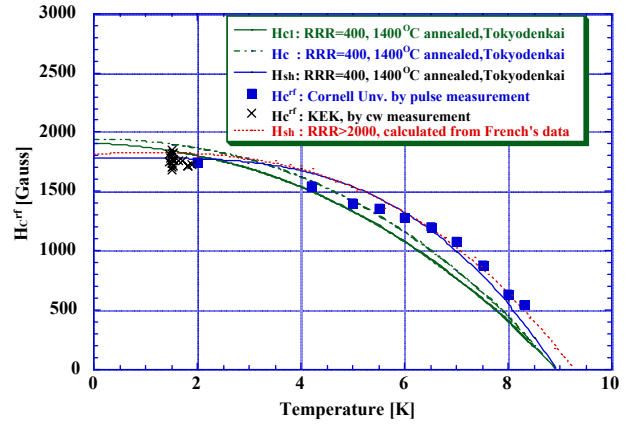

Figure 8 : Critical rf fields of niobium cavities

4 HIGH GRADIENT WITH MULTI-CELL CAVITIES

High gradient performance is required in the next generation scrf application. TESLA for e-/e+ linier collider, proton sc LINAC or CEBAF upgrade are its examples. Here, present status of the high gradient with multi-cell cavities is briefly reviewed

4.1 DESY TTF 1300MHz 9-Cell Cavities

In DESY present preparation is done by CP and HPR. They take two annealings at different temperatures: 800$^{\mathrm{o}}$C for out-gassing hydrogen, and 1400$^{\mathrm{o}}$C annealing with titanium getter for material improvement. The latest results are shown in Fig. 9 by hatched area [29]. The specification of TESLA-500: 23.5 MV/m @ Q$_0$=1x10^{10} is satisfied but Q-slope is a problem for TESLA-800 specification: 35 MV/m @ Q$_0$=5 x 10^9. Recently DESY/KEK collaboration is under going. New TTF 9-cell cavities were electropolished in KEK (Nomura Plating) and tested them in DESY. First results are presented in Fig.10 (▲ , ●). Although Q-slope was still seen over 30MV/m but the superiority of EP is clear. EP is expected to be a breakthrough for TESLA-800. Now EP system is under constructing in DESY.
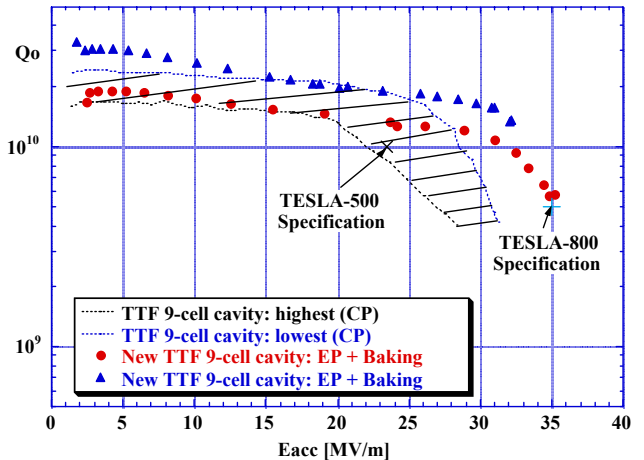

Figure 9: The latest results of DESY TTF 9-cell cavities and electropolished cavity performance.

4.2 SNS 805MHz 6-Cell Cavities

SNS project [30], which is aiming neutron material science, is under constructing in USA by 6 laboratory collaborations. This is a new scrf application: proton LINAC. Jlab has the responsibility for scrf modules. The base techniques of preparation are CP and 800°C annealing and HPR. They have upgraded CP system in the CEBAF class 100 clean room. New 800°C furnace was also installed in Jlab. Fig. 10 shows the results of prototyping with 805 MHz β= 0.61 and 0.81 6-cell cavities [31]. The Q-slope proper in CP is observed but the specification is over in every cavity. Proton sc cavities is not so easy due to the squashed shape but the results show a very good starting for SNS project.
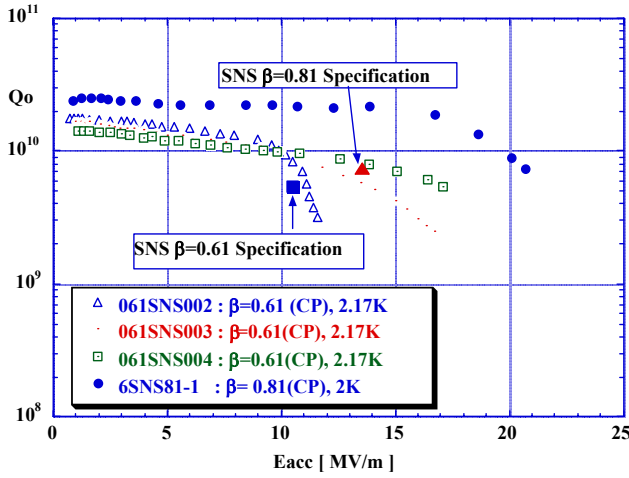

Figure 10: Cavity performance with SNS 805 MHz β=0.61 and 0.81 6-cell cavities

4.3 CEBAF Upgrade 1.5GHz 7-Cell Cavities

The other project in Jlab is to upgrade the CEBAF energy from 6 GeV over than 12 GeV [32]. They are designing new cavities with 1.5 GHz 7-cell structures. The first two cavities were tested. The results are presented in Fig.11. After the baseline tests by CP, they were electropolished in KEK. The specification in the CEBAF upgrade is Eacc=12MV/m and Qo=6.5x10^9 at 17.5W dynamic heat losses. The electropolshing result encourages for them to push up the gradient up to Eacc > 18 MV/m (limited RF power) at the same dynamic heat loss. That will increase the energy to 16 GeV. EP system is under construction in Jlab.

5 CONCLUSIONS

One conclusion to be emphasized is that by present preparation techniques the fundamental field limitation has been developed to be around 40 MV/m (1800 Gauss) with niobium sc cavities. The other conclusion is about the better understanding of the importance of smooth surface related to both field enhancement effect and the fundamental limitation. Standing on this understanding, mechanical grading before chemistries is very important in not reliably grinding off surface imperfections but also arranging properly the surface roughness. The combination of EP and CBP could be a most reliable preparation method in a large scale cavity production.
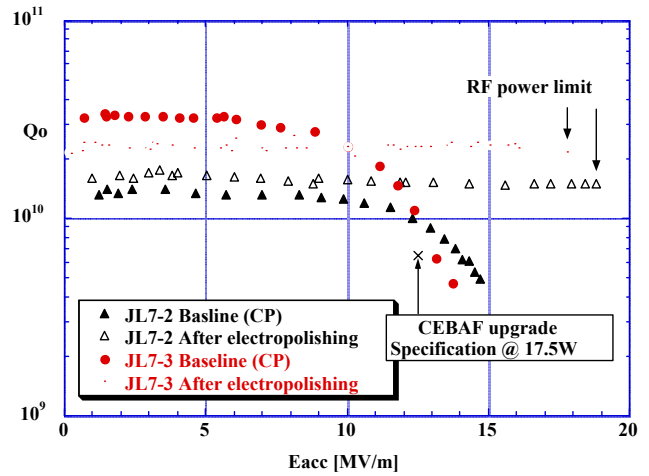

Figure 11: Performance of CEBAF upgraded cavities

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