IMPROVEMENT OF CAVITY PERFORMANCE IN THE SACLAY/CORNELL/DESY'S SC CAVITIES

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Abstract

Development of 1.3 GHz Nb superconducting cavities for TESLA (TeV Energy Superconducting Linear Accelerator) has been carried out under an international collaboration. Three Saclay single-cell cavities, one Cornell two-cell cavity and one DESY nine-cell cavity were sent to KEK in order to compare the cavity performance. These cavities were tested at KEK after the following surface treatment: 1) high pressure rinsing, HPR, 2) chemical polishing and HPR, 3) electropolishing and HPR. Both the quench field and the cavity quality factor (Qo) at high fields were remarkably improved due to electropolishing in the single-cell cavities. No dependence of the quench field on the niobium RRR was observed in electropolished cavities.

1 INTRODUCTION

In superconducting cavities, the cavity performance strongly depends on surface preparation techniques. To obtain a smooth and clean surface, the cavity interior is finished by chemical polishing (CP) or electropolishing (EP). The high pressure rinsing (HPR) that follows has been proven effective to remove dust particles and chemical residues. A clean environment during assembly and careful handling are essential for suppression of field emission. By following these preparation steps, high accelerating gradients (Eacc) of 30~40 MV/m have been achieved without field emission in many cavities at KEK. In the latest investigation at KEK, it was noted that the cavities prepared by EP performed better than CP cavities [1]. To confirm this observation, extensive tests of both CP and EP cavities has been carried out at KEK in an international collaboration with CEA-Saclay (France), Cornell University (USA) and DESY (Germany). A steep drop of the cavity quality factor (Qo) at high fields has been frequently observed in CP cavities at these laboratories, even in the absence of field emission [2,3,4]. Baseline tests of the cavities sent to KEK were carried out at these laboratories, and the effect of surface treatment on cavity behavior was systematically studied at KEK.

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2 CAVITIES AND PREPARATIONS

2.1 1.3GHz Niobium Cavities

Five cavities chosen for this study are listed in Table 1. Three Saclay cavities, a Cornell cavity and a DESY cavity were manufactured at Cerca (France), Cornell University and Dornier (Germany), respectively. Heat treatment (HT) at high temperature was carried out on all cavities except S-3, in order to improve the thermal conductivity of niobium [5]. The residual resistivity ratio (RRR) of the cavity was measured by an inductive method with a pair of coils at Saclay [6] and DESY [7]. (On the Cornell cavity, the RRR was measured with the test sample.)

Table 1: Properties of the 1.3 GHz Nb cavities

Cavity			Heat Treatment	RRR
Saclay	1-cell	S-1	1300°C HT	320
		S-2	1000°C HT	200
		S-3	no HT	230
Cornell	2-cell		1300°C HT	(800)
DESY	9-cell		1400°C HT	600

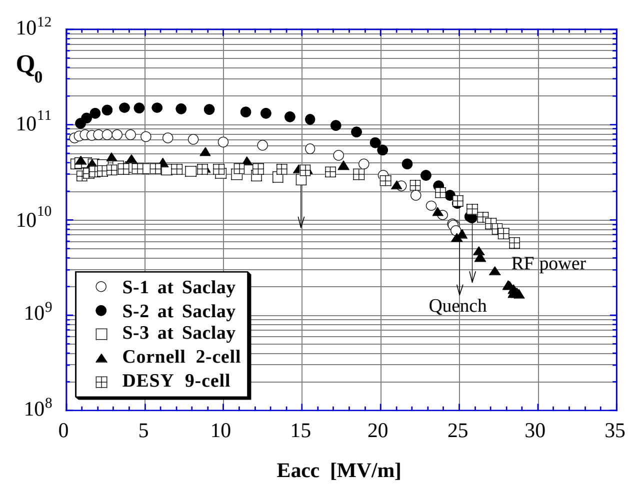

Figure 1: Test results at Saclay, Cornell and DESY

Test results at Saclay, Cornell and DESY are shown in Figure 1, and every cavity was finished by CP and HPR as described in the next section. The maximum accelerating gradient (Eacc,max) was limited by a quench in three Saclay cavities and by available rf power in the Cornell and DESY cavities. The quench field of 15 MV/m in S-3 (no HT) was relatively low in comparison with that in the other cavities after HT. A steep drop of the Qo was commonly observed above 18 MV/m in four cavities. In the Saclay cavities, neither x-rays nor field emission electron were observed at these higher fields. Similarly, thermometry measurement at 25 MV/m in S-2 could not detect any field-emission site. Each cavity was limited by a quench around the equator seam of electron beam welding (EBW).

2.2 *Surface Preparation Procedure*

Chemical polishing at Saclay was performed with a 20°C acid mixture of HF : HNO_3 : H_3PO_4 = 1:1:2 in volume, and a removal rate was about 1 µm per minute. After HPR at 90 bar for 40 minutes, the cavities were dried in a dust-free air flow for three hours. A similar surface treatment was carried out at Cornell and DESY, but the temperature of the same acid mixture was kept lower at less than 10°C in order to suppress hydrogen contamination.

For the initial test at KEK, only HPR at 85 bar for one hour was performed in the single-cell cavities, (for 1.5 hours in the two-cell cavity and for three hours in the nine-cell cavity). A second test was preceded by CP with a 25~30°C acid mixture of HF : HNO_3 : H_3PO_4 = 1:1:1, yielding a removal rate of 12 µm per minute (about ten times faster than that at Saclay). Finally, prior to the third test, EP was carried out with a horizontal, rotating electropolishing device [8]. An acid mixture of H_2SO_4 : HF = 10:1 was used, and the removal rate was 0.5 µm per minute at 30°C. In each case, HPR preceded the final cavity assembly. The wet cavity was pumped out and baked at 85°C for twenty hours. Then, the cavity was installed in the test stand, and no active pumping was performed during the cavity test.

Main difference in the surface preparation between KEK and the other laboratories is considered as follows: a ratio and temperature of an acid mixture for CP, drying method of a wet cavity, active pumping during a cold test.

3 EXPERIMENTAL RESULTS

3.1 *Three Saclay Single-cell Cavities*

Test results in the S-1, S-2 and S-3 cavities at KEK (1. HPR, 2. CP+HPR, 3. EP+HPR) are shown in Figures 2,

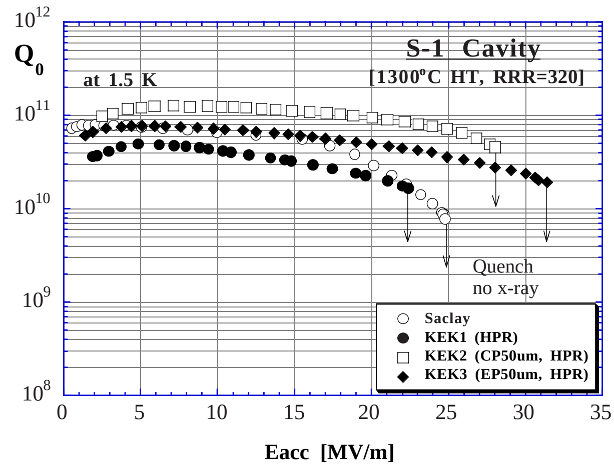

Figure 2: Test results in the S-1 cavity

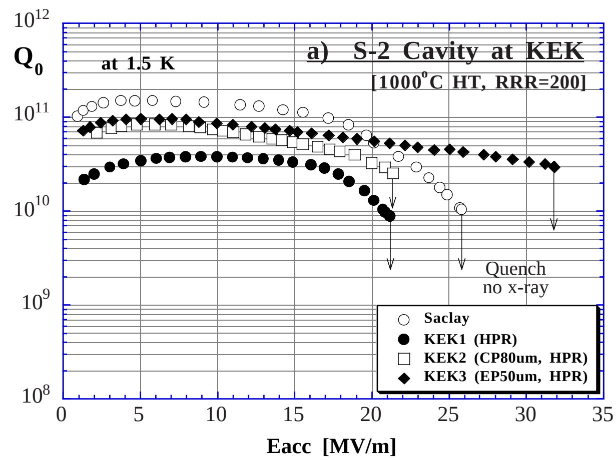

Figure 3-a): The S-2 cavity tested at KEK

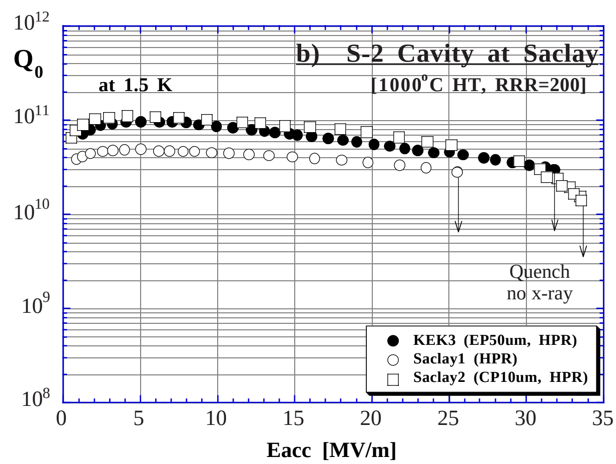

Figure 3-b): The S-2 cavity tested at Saclay

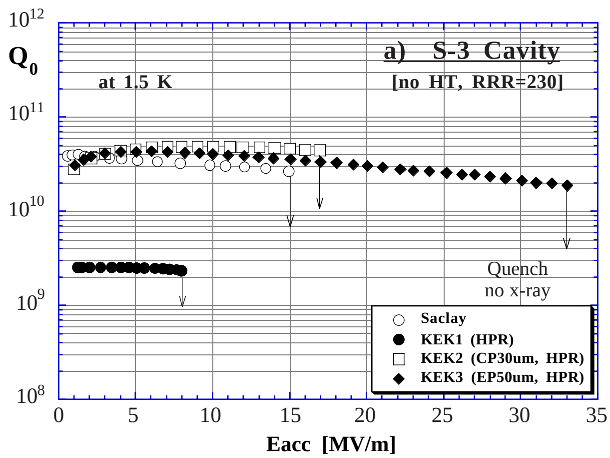

Figure 4-a): Test results in the S-3 cavity

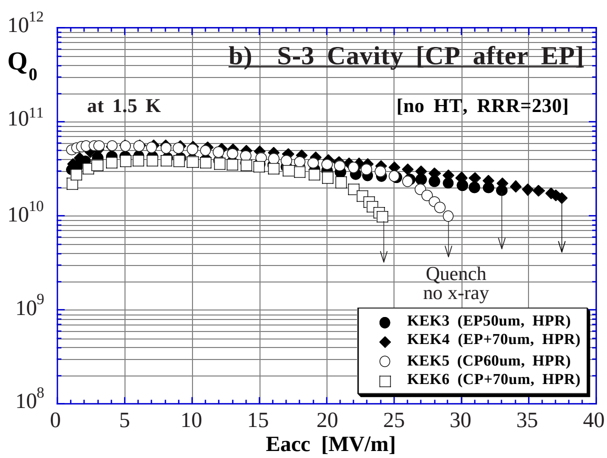

Figure 4-b): Cavity degradation due to CP after EP

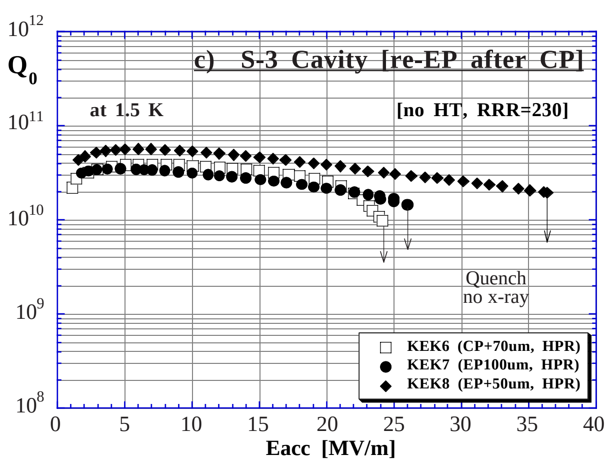

Figure 4-c): Performance recover due to re-EP

3-a) and 4-a), respectively. In all cases of three cavities, a quench (without field emission) was the ultimate field limitation, similar to the Saclay results. Both the quench field and the Qo had deteriorated in the first test at KEK (after HPR), presumably due to surface contamination during transport (*e.g.*, exposure to the air). However, the cavity performance was recovered by CP. Then, EP augmented the quench field to above 30 MV/m. The effect of 50µm EP with cavity S-3 (no HT) was especially pronounced, pushing the quench field up from 17 MV/m to 33 MV/m. Moreover, in each test after EP, a steep Qo drop at high field was not observed, and changed to a standard slope. The cavity performance in each cavity has clearly improved due to EP, and the test results after EP of 50µm in three cavities are summarized in Figure 5.

As shown in Figure 4-b), additional EP of 70 µm was performed on cavity S-3, improving the quench field to 37 MV/m. A subsequent surface removal by CP of 60µm clearly degraded the cavity performance. (A similar effect was found in reference [9]). Additional CP lowered the quench field even more and the steep decline of the Qo at high fields appeared again. Finally, CP of total 130µm reduced the quench field from 37 MV/m to 24 MV/m. Successive tests were carried out to verify the performance recover due to EP, as seen in Figure 4-c). The steep Qo drop above 20 MV/m was eliminated by 100µm EP, but an increase of the quench field was not enough. Consequently, additional EP of 50 µm made the cavity performance recover perfectly.

The S-2 cavity, which had been tested at KEK, was sent back to Saclay again, and the test results at Saclay are shown in Figure 3-b). Both the quench field and the Qo had degraded in the first test at Saclay (after HPR), as similar to the case at KEK. Exposure to the air during transport seems to have certainly an undesirable effect upon the surface condition of a cavity [10]. However, one may notice that a decline of the Qo at high fields is remaining very weak. A similar cavity performance to the

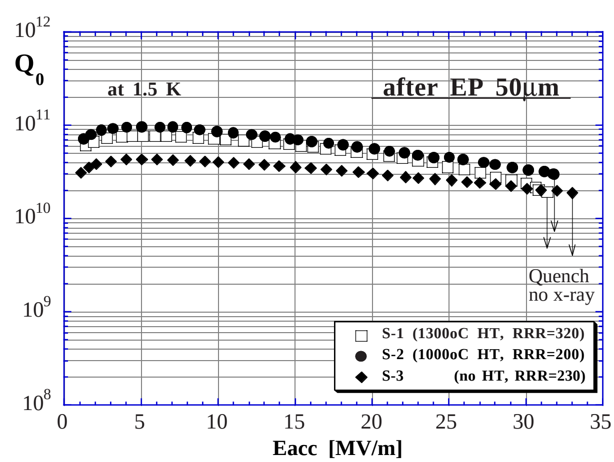

Figure 5: Three cavities after EP of 50µm

result by EP at KEK was obtained after a surface removal of only 10µm by CP. Although the steep Qo drop was observed above 30 MV/m again, the high quench field of 34 MV/m have been still maintained even after CP. (This cavity test was performed after baking at 100°C [11].)

3.2 Cornell two-cell Cavity

A very high RRR of 800 was obtained by heat treatment at 1300°C. At Cornell, the Eacc,max of 28 MV/m had been achieved after high peak-power processing (HPP) [12]. This cavity consists of two cells with a polarized cell-shape and two extremely short cut-off tubes. In the first test at KEK (HPR) as shown in Figure 6, both the quench field and the Qo were drastically degraded. The residual surface resistance (Rres) of 80 nΩ resulted from large rf losses on end-plates made of stainless steel, because of a short length of the cut-off tubes. The large Rres was reduced to 40 nΩ due to a change of the top end-plate to niobium one in the second test by CP, and the

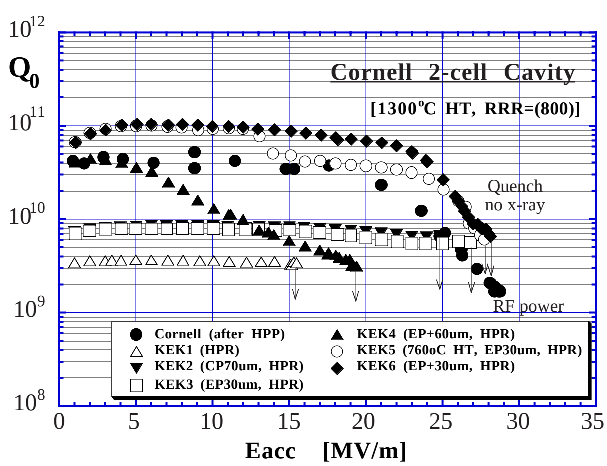

Figure 6: Test results in the Cornell two-cell cavity

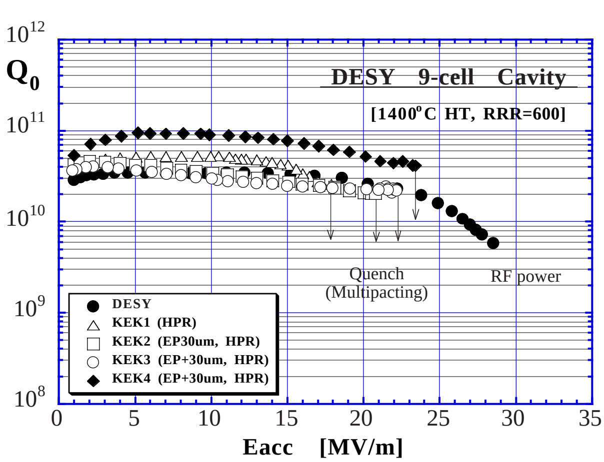

Figure 7: Test results in the DESY nine-cell cavity

quench field was improved to 25 MV/m. In the fourth test, a normal Rres of 7 nΩ was obtained by inserting a niobium tube in the bottom side. However, hydrogen Qo-disease [13] (as discussed in the later section) was observed in this test after EP of total 90µm. Therefore, heat treatment at 760°C for five hours carried out for hydrogen degassing, prior to the fifth test. Consequently, a high Qo of 1×10^{11} was obtained, but several quench events around 15 MV/m led a sudden drop of the Qo to 5×10^{10}. (A similar behavior was sometimes observed in other cavities: see, Figure 10-a). Here, the degraded Qo was recovered after warming the cavity up to 100K and re-cooling down.) The cause of the quench is considered to be excessive heating by impact electrons due to multipacting at equator, and the resultant Qo degradation is due to flux trapping induced by a thermal current under normal conducting state during quench [14]. Finally, the Eacc,max of 28MV/m was achieved, but a steep Qo drop above 23 MV/m was observed, similar to the result by CP at Cornell. The steep Qo drop without x-rays did not change by additional EP of 30µm (KEK6). This observation after EP of total 150µm is in contrast to the results in the Saclay cavities. The high RRR after HT might influence the cavity performance.

3.3 DESY nine-cell Cavity

The DESY cavity is one of the prototype nine-cell cavities with no port for couplers. This cavity was tested many times at DESY [4], and the best result after heat treatment at 1400°C for 6 hours is shown in Figure 7. The field flatness of the accelerating mode was 96% at DESY, but this value reduced to 80% at KEK due to deformation (like banana-shape) during transport. In the first test at KEK (HPR), the Eacc,max was limited by quench at 18 MV/m. The attained Eacc,max was gradually improved by successive EP of every 30µm, but it was still limited at 23 MV/m even after EP of total 90µm. The cause of this limitation was due to multipacting at equator. This phenomenon together with electron emission and x-ray radiation has been frequently observed at the field range between 15 MV/m and 24 MV/m in single-cell cavities. After rf processing with repeated quenches, the final achievable accelerating gradient is increased while the multipacting barrier is usually processed out. The time passing through this field range is normally within five to thirty minutes in single-cell cavities. It is considered that the processing time depends on the number of cells in the cavity. Although rf processing to overcome the multipacting barrier had been continued for more than six hours, it was difficult to process out in this case. Therefore, cure and understanding of multipacting limiting the attainable Eacc,max are needed in order to achieve higher fields in electropolished nine-cell cavities.

4 DISCUSSIONS

4.1 Effect of Electropolishing

The quench field and the residual surface resistance (Rres) after each treatment in three Saclay cavities are summarized in Figures 8-a) and b). There was no difference in the results by CP between at Saclay and at KEK. Not only improvement of the quench field but also elimination of the steep Qo drop at high fields were clearly observed after EP. On the other hand, the Rres remained unchanged by EP. The relatively high surface resistance of the S-3 cavity may be due to the small grain size (this cavity was never heat-treated).

A quench and a Qo drop are obviously an independent phenomenon in a cavity, since a quench occurs in only one local spot and a Qo drop is due to enhanced surface losses in a whole cavity. The location occurring quench was identified by several tens of fixed thermometers at KEK and by a rotating thermometry system at Saclay [6]. At KEK, quenches in EP cavities were usually observed at area with a high surface current (not just along equator), if there was no visible welding imperfection [15]. On the other hand, in CP cavities tested at Saclay, quenches almost always occurred at an equator EBW seam or around the vicinity. Moreover, the quench location moved to the other equator region in each test after additional CP, but the quench field did not improve so much [3]. This observation shows that surface defects causing quenches are localized only around the equator region, and their size and resistivity are very similar. It is supposed that such kind of surface defects are not welding imperfections but arises by a chemical reaction during CP. A grain size neighbor the EBW seam has grown larger by recrystalization due to heat flux from an electron beam. Surface irregularity at this region is assumed to be much enhanced than that at the other normal area. Niobium samples with a EBW seam was removed by CP and EP, and measurement of a surface roughness and surface inspection with an optical microscope were carried out. The surface roughness at the thermally influenced region is shown in Figure 9. The grain boundaries were severely etched by CP of 200µm, and the deep gap and the sharp edge were observed in a). On the contrary, EP of 50µm is very effective to make the grain boundaries smooth, as seen in b). This effect may contribute to the difference in the quench location and the quench field between CP and EP cavities.

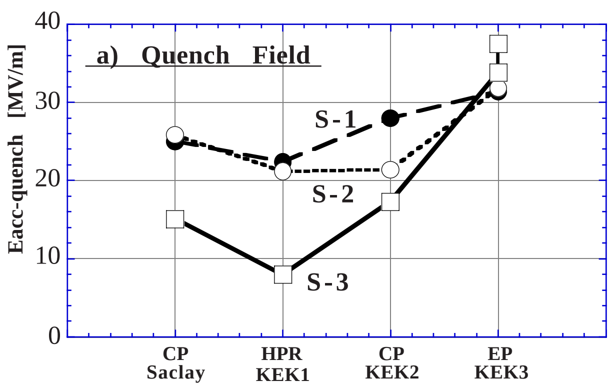

Figure 8-a): Summary of the quench field

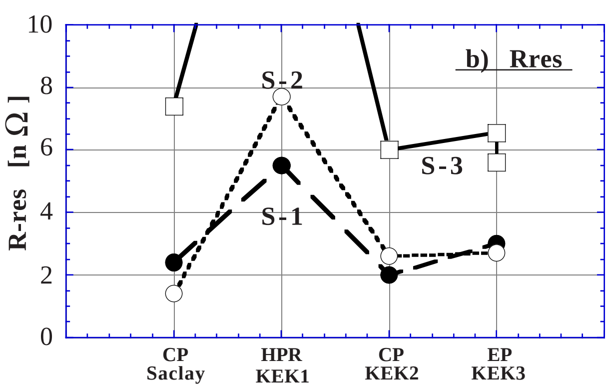

Figure 8-b): Summary of the Rres

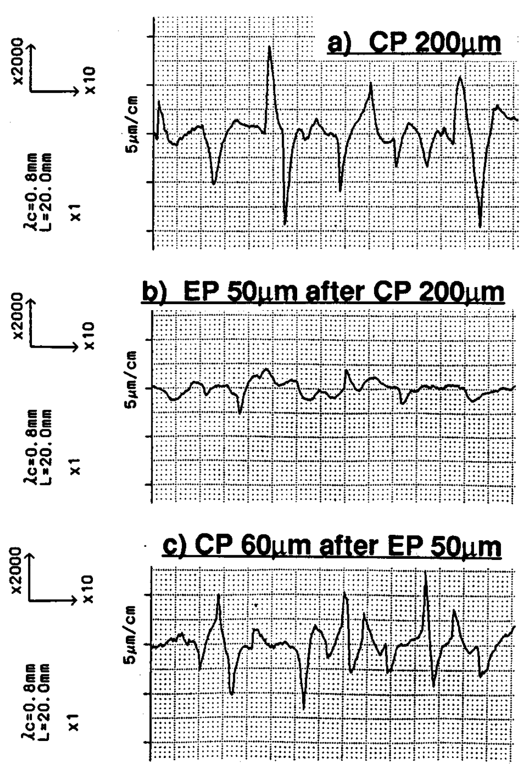

Figure 9: Surface roughness at the region thermally influenced by an electron beam in niobium samples.

4.2 Hydrogen Qo-disease

The cavities were parked at 100K for two hours to investigate possible hydrogen problem of the niobium (Qo-disease, [13]). It is well-known that heat treatment above 700°C for hydrogen degassing is effective to avoid the Qo-disease. Fast cool-down passing through quickly the dangerous temperature region around 100K is another solution. However, the fast cooling is not always a possible cure for cavities installed in horizontal cryostats with a large thermal capacity. The parking time for two hours was determined by an estimation from cooling speed in an actual horizontal cryostat. The obtained Rres results in five cavities are listed in Table 2. The effect of parking at 100K in the Saclay, Cornell and DESY cavities is shown in Figures 10-a), b) and c), respectively. No Qo-disease was observed in three Saclay cavities with the RRR of 320, 200 and 230. On the other hand, heavy Qo-disease had occurred in the Cornell cavity with the high RRR of 800. Even fast cooling could not avoid Qo-disease (KEK3). Moreover, EP of only 60µm after hydrogen degassing at 760°C led Qo-disease, again (KEK5). A similar effect was observed also in the DESY cavity with the high RRR of 600. Therefore, high temperature HT for improving the thermal conductivity of niobium is more dangerous in electropolished cavities. Here, it is noteworthy that no Qo-disease was observed in the S-3 cavity without any HT (See, Figure 10-a).), even after large amount of chemistry by totally CP of 330µm and EP of 270µm. These results show an omission of 760°C HT after EP [16]. In electropolished cavities with an intermediate RRR around 200, neither hydrogen degassing nor purification of niobium seems to be indispensable for achieving a high Eacc,max above 30 MV/m.

Table 2: The Rres following a 100K park for two hours

Cavity	Surface Treatment	Initial*	100K,2h	ΔRres
S-1	1300°CHT,CP140µm	5.5	10.5	+5.0 nΩ
S-2	1000°CHT,CP130µm	7.7	8.0	+0.3 nΩ
S-3	no HT,CP200µm	6.1	5.9	- 0.2 nΩ
	+EP120µm	5.6	5.3	- 0.3 nΩ
	+CP130µm/EP150µm	4.9	5.0	+0.1 nΩ
Cornell	1300°CHT,CP270µm			
	+EP90µm	7.4	2260.	+2250 nΩ
	760°CHT,+EP60µm	3.6	162.	+158 nΩ
DESY	1400°CHT,CP170µm			
	+EP90µm	5.5	94.	+88 nΩ

Initial*; fast cool-down within 1 hour from 300K to 4.2K

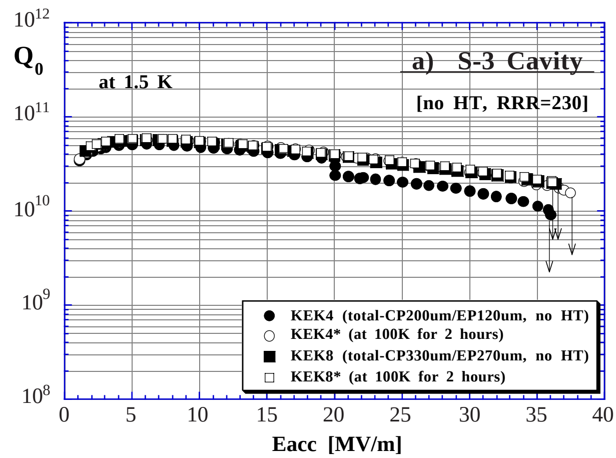

Figure 10-a): Effect of a 100K park in the S-3 cavity

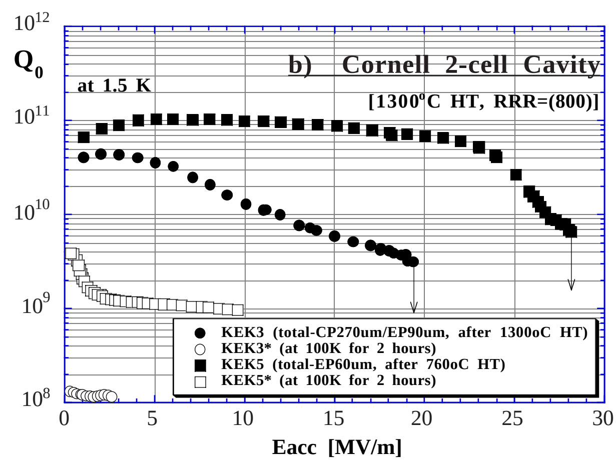

Figure 10-b): Effect of a 100K park in the Cornell cavity

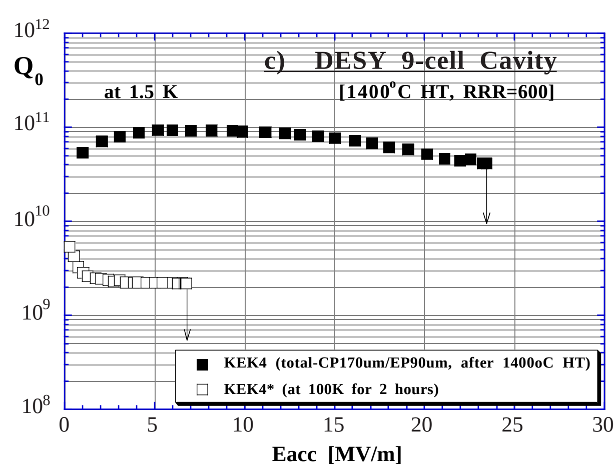

Figure 10-c): Effect of a 100K park in the DESY cavity

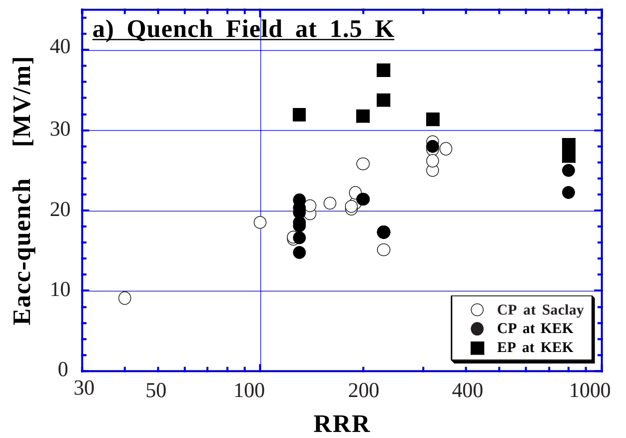

Figure 11-a): RRR dependence of the quench field
(Six cavities tested at Saclay [3,17] are added in the data of CP at Saclay. A Saclay cavity with RRR=40 was made from reactor grade niobium. Test results on a KEK cavity with RRR=130 are shown in detail in reference [18].)

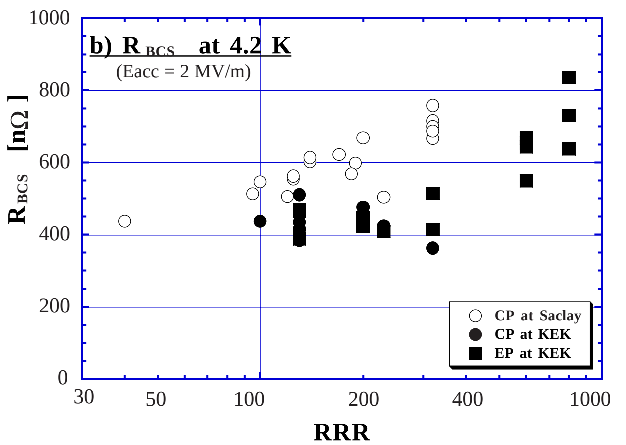

Figure 11-b): RRR dependence of the BCS resistance

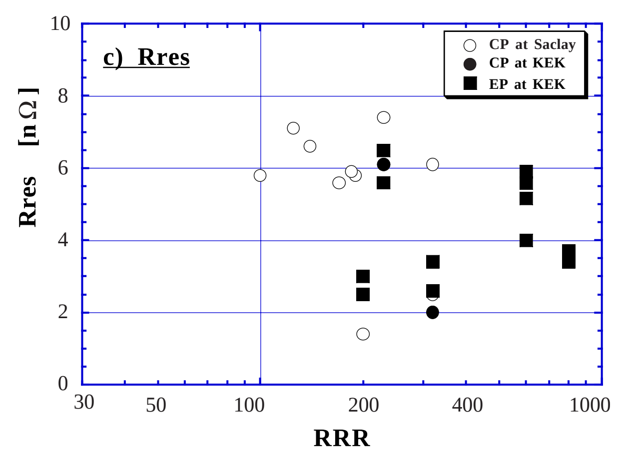

Figure 11-c): RRR dependence of the residual resistance

4.3 RRR Dependence

High RRR niobium with its large thermal conductivity is needed to thermally stabilize surface defects that might otherwise cause a quench at a high gradient. A theoretical prediction of a quench field in a small defect (radius, r, and resistance, R) gives a following equation: Eacc,quench = Const · [RRR / r·R]$^{1/2}$, [19]. The experimental correlation between a quench field and an average RRR of a cavity is plotted in Figure 11-a). The results with the CP cavities at both Saclay and KEK are consistent with above mention, where the quench field proportionally increases with the RRR. After EP, however, no dependence of quench field on RRR between 130 and 800 was observed. In electropolished cavities, there seems to be no advantage with a higher RRR from a point of view in achieving a high gradient and avoiding Qo-disease (as described in the previous section). This result demonstrates that the origin of quench may differ in CP and EP cavities.

The observed surface resistance (Rs) is expressed by the sum of a temperature dependent term (R_{BCS}) and a temperature independent term (Rres): Rs(T) = R_{BCS}(T) + Rres. The R_{BCS} is derived from the BCS theory, which is roughly proportional to $(\omega^2 /T) \cdot \exp [- \Delta/T]$. The Rres depends on surface contaminants such as chemical residues and dust, damage from machining or welding, and trapped magnetic flux. The R_{BCS} at 4.2K and Rres as a function of RRR is shown in Figure 11-b) and c). For clean superconductors with a large electron mean free path (l), a following relation is given: $R_{BCS} \propto l$, [20]. Therefore, it is expected that R_{BCS} increases with RRR by a relationship of RRR $\propto \sigma_n \propto l$, (σ_n is a normal state conductivity). This tendency is seen in Figure 11-b), although there is some scatter in the data. The R_{BCS} at KEK are relatively lower in comparison with the R_{BCS} at Saclay. The reason for this difference is not clear, but the different procedures in surface preparation or test system between both laboratories might be considered. As for Rres, it was shown in the past experiments that a residual magnetic field (Bres) inside a cryostat [9] or direct generation of phonon by rf electric field [21] had given a dependence of Rres on RRR. In many experimental facts, high temperature HT has shown an effect to reduce Rres. A calculation of Rres for a given RRR deduced a relationship of Rres $\propto$ 1/RRR, [22]. This tendency is roughly observed in Figure 11-c). There is no difference in the Rres between CP and EP cavities. Here, influence of the Bres to the Rres is estimated to be less than 2 nΩ with the Bres of about 5 mGauss in both laboratories. The remaining part is assumed to be dependent on an inherent surface nature in each cavity.

5 SUMMARY

a. In three Saclay cavities, EP of 50 μm eliminated the steep Qo drop at high fields in CP cavities and pushed up the quench field to more than 30 MV/m.
b. Chemical polishing after EP gradually reduced the quench field and caused the Qo drop at high fields to appear again. After this, the cavity performance has recovered perfectly by additional EP.
c. One cavity, which had been sent back to Saclay, reproduced the cavity performance with EP at KEK.
d. A steep Qo drop at high fields was still observed after EP in the Cornell cavity. The limitation in the DESY cavity was due to multipacting barrier around 20 MV/m.
e. No Qo-disease was observed after parking the Saclay cavity at 100K for two hours, especially, even in the no HT cavity after EP. On the other hand, heavy Qo-disease was observed in the Cornell and DESY cavities with a high RRR by HT.
f. No dependence of the quench field on RRR was seen between RRR = 130 and 800 in EP cavities.
g. The R_{BCS} at 4.2K was proportional to RRR with some scatter, and the Rres was roughly proportional to 1/RRR. There was no difference in the Rres between CP and EP cavities.

6 ACKNOWLEGEMENT

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