Cavity Performances in the 1.3 GHz Saclay/KEK Nb Cavities

E. Kako*, M. Bolore, Y. Boudigou, J.P. Charrier, B. Coadou,
E. Jacques, M. Juillard, J.P. Poupeau and H. Safa
CEA-Saclay, DSM/DAPNIA/SEA
91191 Gif-sur-Yvette, France

S. Noguchi, M. Ono, K. Saito and T. Shishido
KEK, High Energy Accelerator Research Organization
1-1, Oho, Tsukuba, Ibaraki, 305 Japan

Abstract

Three single-cell cavities, which had been tested at KEK, were sent to Saclay in order to compare the cavity performance. Two cavities made from Japanese niobium materials were fabricated and tested at Saclay. These cavities were prepared by the Saclay's standard surface treatment. Quench field, quench location and RRR in the cavity were measured in each cavity test. Their changes due to additional surface removal and heat treatment were investigated. Qo degradation without electrons at high fields was observed in every cavity test.

1. Introduction

In superconducting cavities, the cavity performance is governed by many factors like niobium material, forming method, electron beam welding, mechanical surface removal, surface treatment by chemical reaction, heat treatment, cleaning technique on cavity surface and so on. Therefore, a high quality control in each step is required in order to achieve a higher accelerating gradient with good reproducibility. After field emission has been suppressed by an improved clean environment, careful handling and a final cleaning by high pressure water rinsing, thermal quench is currently a dominant obstacle to limit the maximum accelerating gradient, Eacc,max. It is generally considered that thermal quench is caused by surface defects such as inclusions [1], scratches [2], welding imperfections [3], dust contamination and chemical residues produced during manufacture and surface preparation. However, the nature of surface defects is not still clear, especially in the cavities with a high quench field above 20 MV/m. As one clue to understand an essential factor causing thermal quench, exchange of the cavities and niobium materials was carried out between KEK and Saclay. Three KEK cavities and two Saclay/KEK collaboration cavities made from Japanese niobium materials were tested at Saclay.

*; visitor from KEK.

2. Preparation of the cavities and experimental procedure

A summary of the five cavities tested at Saclay is shown in Table I. The niobium sheet was supplied by Tokyo Denkai, except K1-03. The thickness is 2.5 mm, and the residual resistance ratio, RRR, is 200 in the specification. These cavities were fabricated at KEK, MHI (Kobe, Japan) and Cerca (Romans, France). Half-cells were formed by deep-drawing. Welding by electron beam was carried out from the different direction at iris and equator in each cavity, as listed in Table I.

The surface preparation of these cavities was carried out by the standard surface treatment at Saclay, and the procedure is summarized as follows;

a. Cleaning of all pieces and drying them in the clean room.
   Degreasing of the cavity in the ultra-sonic hot bath (50°C) for 15 min.
b. Chemical polishing with the mixed acid of HF : HNO_3 : H_3PO_4 = 1: 1: 2.
   Removal speed of about 1 μm/min. at 18°C.
c. Rinsing with ultra-pure water for 15 min.
d. High pressure water rinsing, HPR, in the clean room.
   Pressure of 85 bar, flow rate of 10 liter/min., 1 stroke for 35 min.
e. Drying under clean air flow in the clean room for about 3 hours.
f. Assembling, pumping and leak test in the clean room.

After this, the cavity is installed in the vertical test stand.

The cavity is equipped with two fixed rf antennas made of titanium. The coupling (Qin) of the input antenna is fixed to about $2.x10^{10}$, and the coupling (Qext) of the transmit antenna is $5.\text{-}10.x10^{11}$. The maximum available rf power supplied to the cavity is 150 W. The cavity is quickly cooled down within about 1 hour from 300 K to 4.2 K in order to avoid Qo-disease (100 K effect). The cavity test is usually carried out at around 1.6 K. In each cavity test, the quench location was determined by a temperature mapping system, which consists of nineteen carbon thermometers mounted on a movable arm. The cavity RRR mapping based on a magnetometric measurement was made with a rotating array of nine pairs of coils [4]. X-ray radiation and electron emission were always monitored during cavity test.

Table I. The cavities tested at Saclay.

cavity	niobium sheet	RRR (in spec.)	EB welding at	equator / iris
K1-01	Tokyo Denkai	200	KEK	inside / outside
K1-02	Tokyo Denkai	200	MHI	both-side / outside
K1-03	Heraeus	100	KEK	outside / outside
C1-13	Tokyo Denkai	200	Cerca	outside / inside
C1-14	Tokyo Denkai	200	Cerca	inside / inside

3. Cavity Test Results

3-a. The KEK cavities tested at Saclay

The surface preparations at KEK and Saclay are summarized in Table II. Three KEK cavities were prepared by the similar surface treatment at KEK. Mechanical polishing by tumbling in full-cell (K1-01 and K1-03) or by buffing in half-cell (K1-02) was carried out. The first polishing was done by electropolishing, EP. After heat treatment at 760-800°C for hydrogen degassing, the final polishing was carried out by chemical polishing, CP, with the mixed acid of 1:1:1 of the different ratio from the Saclay's acid. The cavity was baked out at 85°C for 1 night after assembling. The previous test results of these cavities are found in references [3,5].

The KEK cavities were sent to Saclay and were tested after surface removal of 10-75μm by CP as mentioned in the previous section. The comparison of the test results between KEK and Saclay is shown in Figure 1.

K1-03 :

This cavity was tested four times at KEK, and total surface removal is about 360μm. The improvement of the quench field by the successive surface removal by CP was not seen, and the quench field in four tests was 19.5, 18.6, 17.5 and 18.6 MV/m. The quench location was observed on the EBW seam at the equator, but any visible defect was not identified around the quench location by the inspection with the small CCD camera. This cavity was tested at Saclay after CP 30μm. Thermal quench was observed at 18.5 MV/m at the same location. Therefore, the absolute value of the field gradient is in good agreement between KEK and Saclay. The difference in the Qo values is explained by the residual magnetic field in the cryostat and the helium bath temperature; 15 mG and 1.8 K at KEK, 5 mG and 1.6 K at Saclay.

Table II. The surface preparations at KEK / Saclay.

cavity	at KEK	at Saclay
K1-01	Tum., EP-10μm, 800°C 5H,	CP-75μm, HPR-95bar
(K-4)	CP-20μm, HPR-85bar	
K1-02	EP-170μm, 760°C 5H,	CP-10μm, HPR-85bar
(M-4)	CP-80μm, HPR-85bar	
K1-03	Tum., EP-240μm, 760°C 5H,	1. CP-30μm, HPR-80bar
(MK-0)	CP-115μm, HPR-85bar	2. 1300°C HT,
(at KEK)		CP-160μm, HPR-85bar
C1-13	----	(no HT), CP-100μm/150μm/250μm, HPR-85bar
	800°C 2H,	CP-15μm/65μm, HPR-85bar
C1-14	----	(no HT), CP-100μm/150μm/250μm, HPR-85bar
	800°C 2H,	CP-15μm/115μm, HPR-85bar

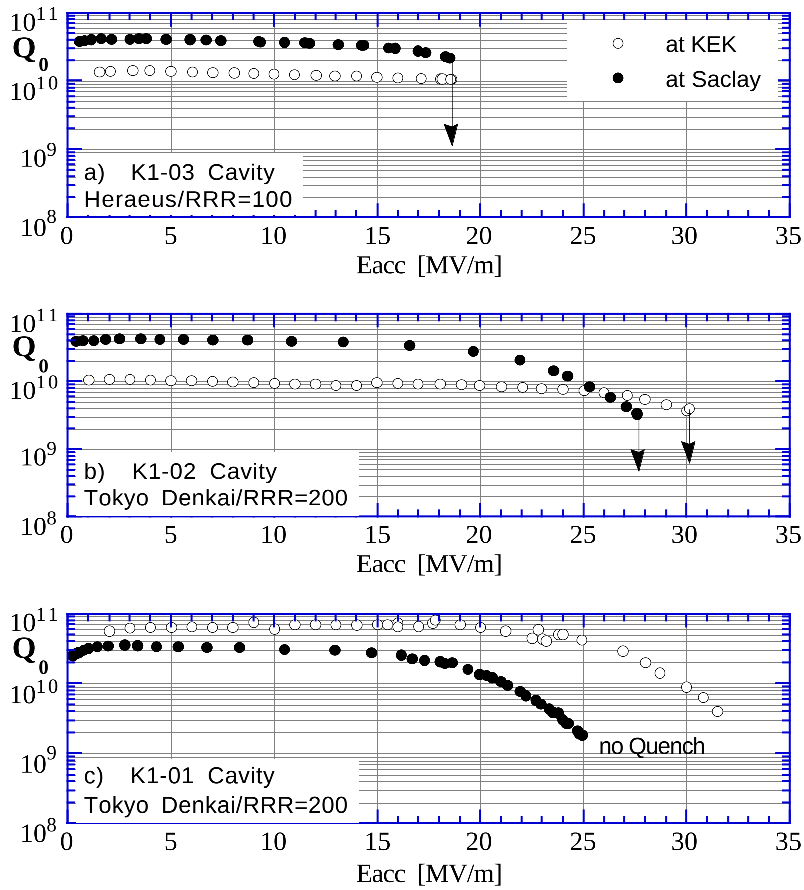


Figure 1. The Qo-Eacc curves in the KEK cavities tested at KEK and Saclay; a) K1-03 cavity, b) K1-02 cavity, c) K1-01 cavity.

<u>K1-02 :</u>

At KEK, the quench field was 30.1 MV/m with field emission, and the quench location was not on the EBW seam but between equator and iris, where the surface magnetic field is still maximum. After CP 10µm at Saclay, thermal quench was observed at 27.6 MV/m, which is a little lower field than that at KEK. The quench location did not change, (see Figure 10. a). The Qo value at more than 20 MV/m strongly deteriorated without electrons. But, very weak x-rays were detected above 26 MV/m.

<u>K1-01 :</u>

Thermal quench due to surface defects is usually not accompanied with x-ray radiation and electron emission. However, a quench phenomenon together with x-ray and electron has been frequently observed in the wide field range of 15-25 MV/m [6]. The cavity field level is very unstable at these fields due to electron activity. This phenomenon is usually processed out after many (or several) quench events. The observation by thermometry showed that the quench occurred at the equator region and the quench location shifted with the increase of the quench field. This phenomenon is considered to be caused by multipacting around equator. At KEK, the heavy processing level was observed at 18-23 MV/m in this cavity. The sources of field emission were produced during processing. Consequently, the Eacc,max was limited by hard x-ray due to strong field emission at 31.8 MV/m. This processing level was also observed at 18-23 MV/m at Saclay. No electrons and x-rays were detected after processed out. However, the steep drop of the Qo value with no field emission was observed at more than 20 MV/m, similar to the K1-02 cavity. The Eacc,max was limited by available rf power at 25.0 MV/m. This Qo degradation is discussed in the later section.

1300°C HT :

In the K1-03 cavity, 1300°C HT with titanium was carried out by the optimized heat treatment temperature cycle [7] in the Saclay's furnace. After heating at 1300°C for 4 hour, the temperature was slowly lowered to 900°C for about 40 hours. The vacuum pressure was $1.5\text{-}0.5\times10^{-5}$ mbar at 1300°C and $5.\times10^{-7}$ mbar at 900°C. After the heat treatment, the average RRR of the cavity was improved from 100 to 320, and the quench field was increased from 18.5 MV/m to 26.2 MV/m, as shown in Figure 2. The quench location moved to the other equator region. Electrons and x-rays were observed at more than 21 MV/m, and the detected electron current was 0.2 nA at 26.2 MV/m, (see Figure 10. b).

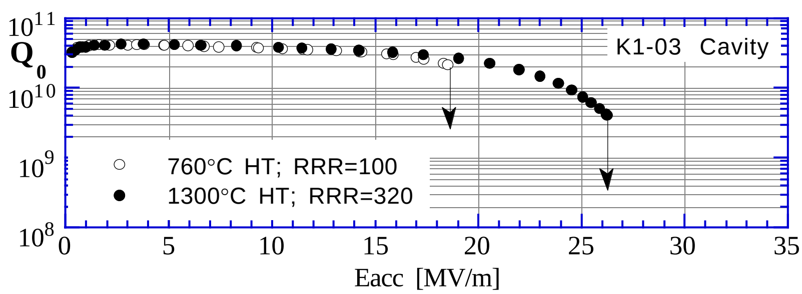


Figure 2. The effect of 1300°C HT at Saclay in the K1-03 cavity.

3-b. The Saclay/KEK collaboration cavities

There are two differences in the C1-13 and C1-14 cavities. Two pairs of niobium sheets were made from the different ingot. The RRR of the Nb samples was measured by the conventional method at Saclay, and they were 150 and 200. Welding by electron beam at equator was carried out from exterior in C1-13 and from interior in C1-14 in order to compare its effect. Figure 3 and 4 show the test results in no HT and after 800°C HT.

Cavities before HT :

The RRR mappings measured by the magnetic probes are shown in Figure 5. The average RRR is 140 in C1-13 and 190 in C1-14. These values are a little lower than that of the samples. In the first measurement after CP 100µm, strong field emission occurred at about 5 MV/m in both cavities. This cause is presumed to be due to insufficient surface removal at iris. After additional CP 50µm, field emission was eliminated, and the Eacc,max was limited by thermal quench at 19.6MV/m in C1-13 and at 20.9MV/m in C1-14.

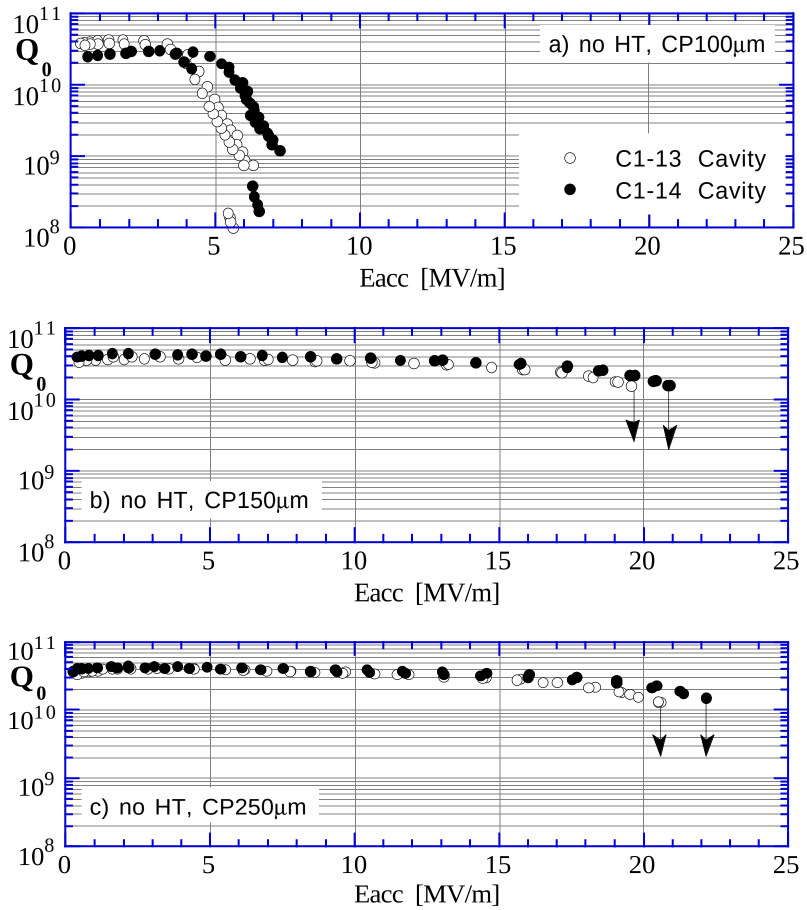


Figure 3. The Qo-Eacc curves in the Saclay/KEK collaboration cavities;
a) no HT, CP100µm, b) no HT, CP150µm, c) no HT, CP250µm.

The temperature mappings were measured during quick repetition of thermal quench. The normal conducting area due to thermal quench was observed around equator region as shown in Figure 6. Its center is very close to the EBW seam. The quench location was moved by further CP 100µm, but the quench fields were not improved so much. In conclusion, the obtained cavity performances were very similar in both cavities. The Eacc,max were limited by thermal quench at 20-22 MV/m, and the quench location changed in each test after CP. The quench fields in these cavities are a little better in comparison with the quench field (17.5 MV/m in average, [8]) in the other no-HT Saclay's cavities, which were made from Heraeus niobium (RRR=280) and were fabricated by Cerca.

Cavities after 800°C HT :

Heat treatment at 800°C is effective not only for hydrogen degassing but also for relieving stress in the forming process and homogenizing the niobium material. Two cavities were heat-treated at 800°C for 2 hours without titanium in the DESY's furnace. The vacuum pressure was 4.-2.x10^{-6} mbar at 800°C. After 800°C HT and CP 15µm, the RRR in both cavities have deteriorated (Figure 5), and their quench fields have also decreased. The

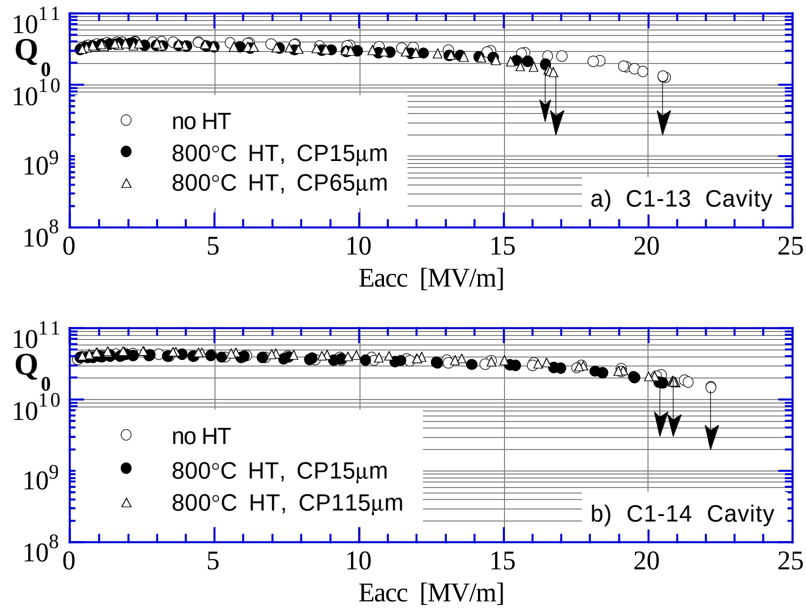
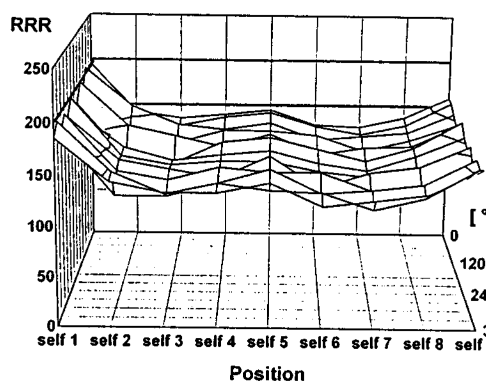
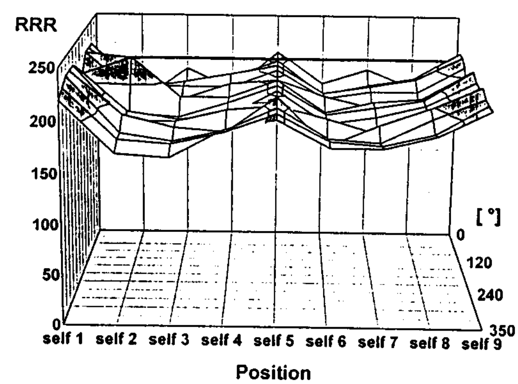


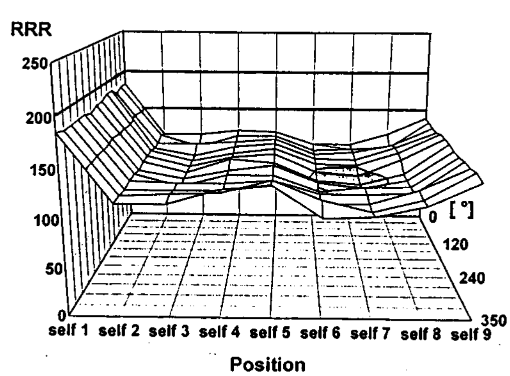
Figure 4. The Qo-Eacc curves before/after 800°C HT;
a) C1-13 cavity and b) C1-14 cavity.



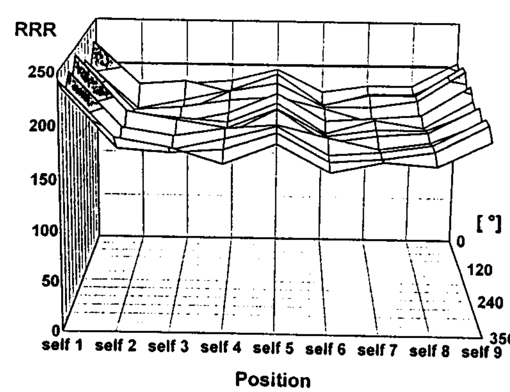
a) C1-13 cavity ; no HT.



b) C1-14 cavity ; no HT.



c) C1-13 cavity ; 800°C HT.



d) C1-14 cavity ; 800°C HT.

Figure 5. The RRR mapping before/after 800°C HT in the C1-13 and C1-14 cavities ; self1/upper-iris, self5/equator and self9/lower-iris.

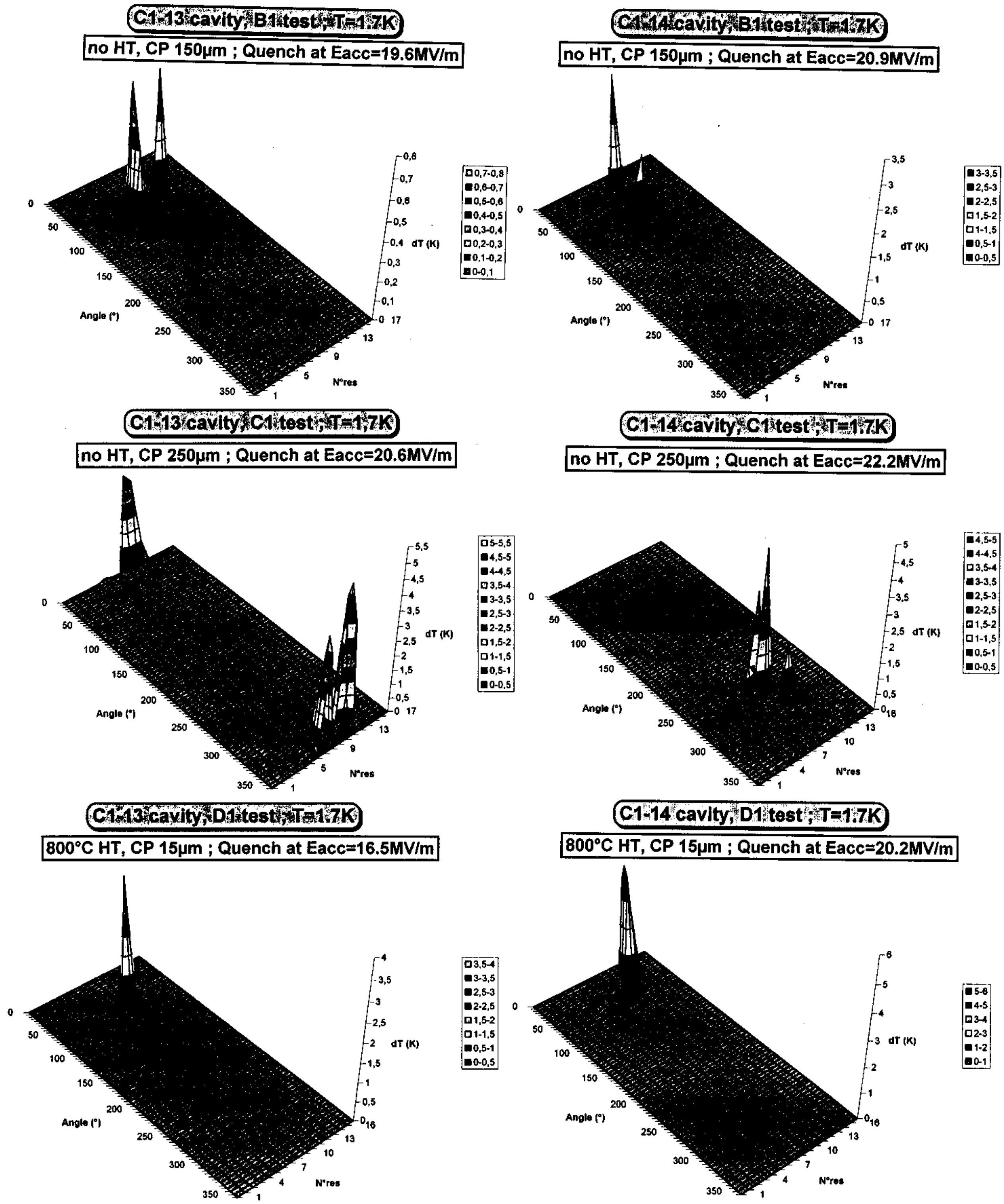


Figure 6. The quench location in a series of the cavity tests in the C1-13 and C1-14 cavities.

quench location was not at the same position before and after 800°C HT. Moreover, the quench fields did not change even by further CP 50-100μm. The conclusion is there was no benefit after 800°C HT both in the Qo value and in the quench field. However, the result might be dependent on the quality of the vacuum furnace.

4. Discussion

4-a. Summary of the test results

The test results for the five cavities are summarized in Figure 7 and Table III. The obtained Qo values at low fields are reproducibly 3.-5.x10^{10} in every test. The residual surface resistance, Rres, is 5.6-8.7 nΩ with no clear difference due to heat treatment. However, the Qo values at high fields are unusually deteriorated with the increase of the field, as similar to the other Saclay's cavities [8]. The drop of the Qo value starts at 15-20 MV/m. There is no difference due to heat treatment as seen in Figure 7.

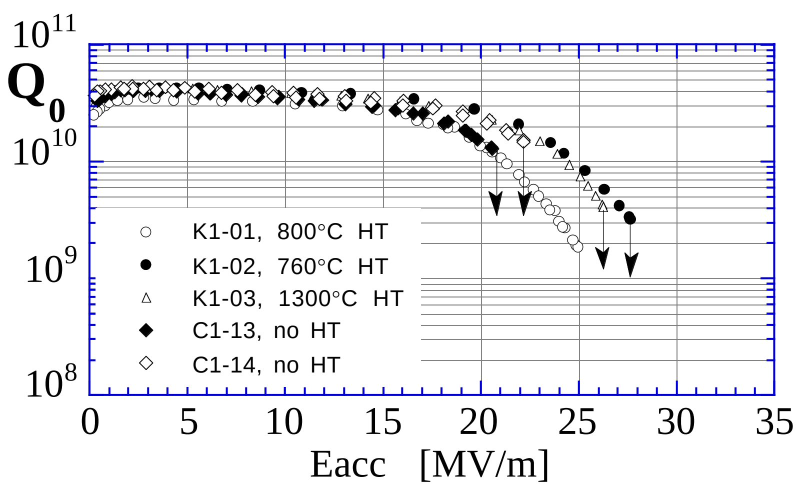


Figure 7. The Qo-Eacc curves in the five cavities tested at Saclay.

Table III. The summary of the test results at Saclay.

cavity	HT	Rres (nΩ)	A ($\times10^{-4}$)	Δ/k (K)	Eacc,max (MV/m)	limitation	ave. RRR (in cavity)
K1-01	800°C	8.7	1.90	18.4	25.0	rf power	- - -
K1-02	760°C	5.6	1.90	18.3	27.6	Quench	170
K1-03	760°C	5.8	1.67	18.3	18.5	Quench	100
	1300°C	6.1	2.03	18.1	26.2	Quench	320
C1-13	no	6.6	1.73	17.9	20.6	Quench	140
	800°C	7.1	1.95	18.7	16.5	Quench	125
C1-14	no	5.8	1.72	18.0	22.2	Quench	190
	800°C	5.9	1.75	18.3	20.2	Quench	185

(Here, Rs = (A/T) exp [-Δ/kT] + Rres.)

4-b. Qo degradation at high fields

There is a similar observation at the other laboratories [9,10], but only in a few cavity tests. On the other hand, the Qo degradation at high fields are systematically observed in all cavities tested at Saclay without exception. Firstly, the rf measurement system was strictly examined in order to identify where the extra rf power had been dissipated. Consequently, there was no doubt that enhancement of the rf losses on the cavity surface had caused the Qo degradation. As shown in Figure 8, the increase of the surface resistance, ΔRs, with $Eacc^2$ seems to be an exponential function like field emission loading. The electron current, Ie [nA], was detected only in K1-03. The field enhancement factor, β_e, of 186 is calculated from the F-N plots as shown in Figure 9. In the similar calculation with Δ(1/Qo), the β_Q of about 100 is obtained with no relation to the presence of electrons. This means that field emission loading in K1-03 is not a main part among the whole rf losses in the cavity. The temperature mappings just before thermal quench are shown in Figure 10. Hot spots at the quench location in K1-02 and temperature rises due to impact electrons

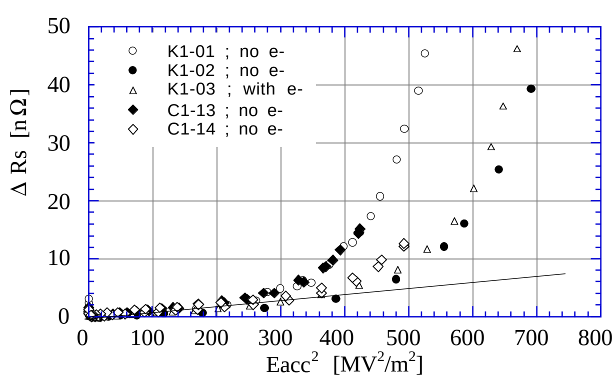


Figure 8. The increase of Rs with $Eacc^2$.

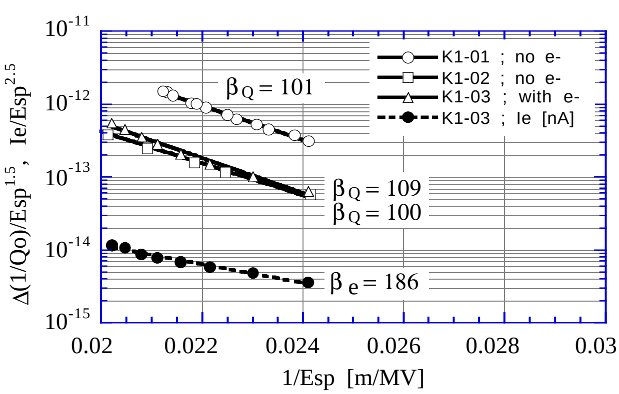


Figure 9. The F-N plots of Qo and Ie.

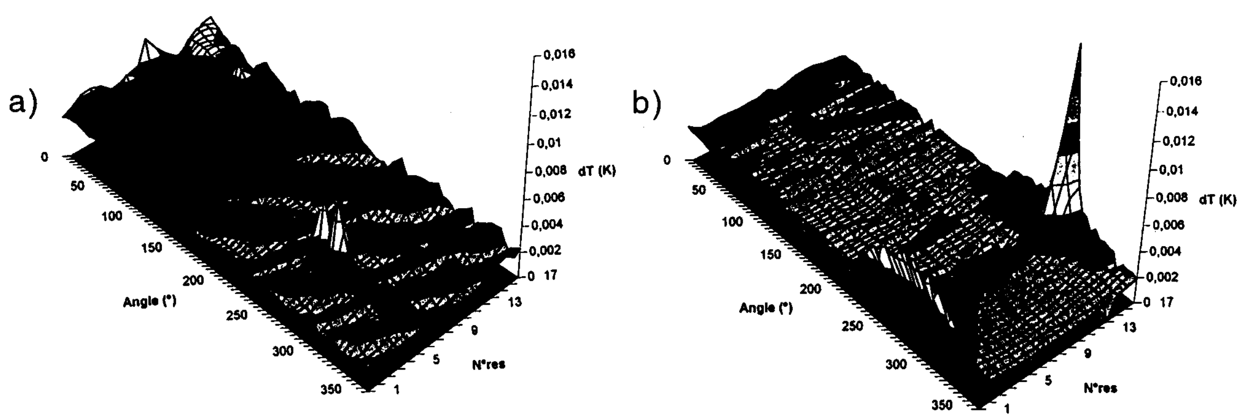


Figure 10. The comparison of the temperature mapping.
a) K1-02 /without electron; at Eacc=27.5MV/m, Qo=3.2x10^9, Po=27W.
b) K1-03 /with x-ray and electron; at Eacc=26.3MV/m, Qo=4.1x10^9, Po=19W.

in K1-03 are observed. In both cases, however, it might be impossible to explain this additional rf losses of 15-20 W by heat-up at a small localized area. Considering a homogeneous heating in the whole rf surface is rather reasonable. The reason for this abnormal rf losses is not understood at present, but it is thought that a nature of rf surface characterized by the Saclay's surface preparation could contribute to this Qo degradation at high fields.

4-c. RRR and quench fields

The quench fields obtained in these tests and the RRR measured in the cavity are plotted in Figure 11. There is a well-known relation between RRR and quench field, Eq, as given by Eq $\alpha \sqrt{RRR}$ in reference [11]. This tendency is also seen in Figure 11, except for two KEK cavities. The improvement of the RRR made the quench field higher (1300°C HT), and the deterioration of the RRR made the quench field lower (800°C HT). However, there is a clear difference in the quench field between K1-01/K1-02 and C1-13/C1-14. Here, the similar niobium material from Tokyo Denkai was used, and the same final surface preparation was carried out at Saclay. The high quench fields in the KEK cavities have been still kept after the surface preparation at Saclay. Therefore, this might be dependent on the surface preparation at KEK [10]. On the other hand, in the Saclay/KEK collaboration cavities, the quench location moved to the other equator region in each test after additional CP, but the quench field did not improved so much. This result shows that the surface defects are localized only around the equator region, and their size and resistivity are very similar. It is difficult to explain this by inclusions in niobium or welding imperfections, because the quench field caused by such kind of surface defects might be independent on the method of surface preparations. One speculation is that a chemical reaction between niobium and acid during CP produces a resistive alloy or a chemical compound of impurities, especially at grain boundaries, where many impurities might concentrate due to recrystallization by electron beam.

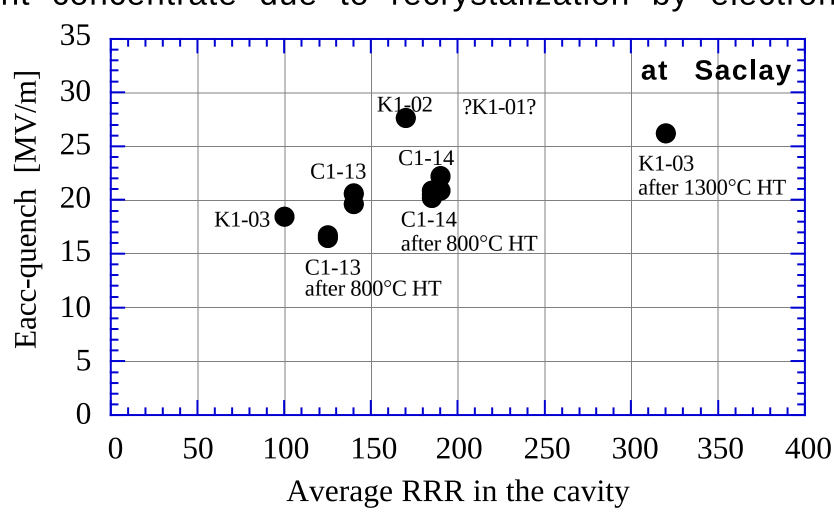


Figure 11. The quench fields vs. the average RRR in the cavity.

5. Conclusions

The relative accuracy of the field gradient was in good agreement between Saclay and KEK. The quench field of 20-22 MV/m in the no-HT Saclay/KEK collaboration cavities was higher than that in the Saclay's cavities and lower than that in the KEK cavities. Heat treatment at 1300°C improved the RRR and pushed up the quench field, but there was no benefit after 800°C HT. Thermal quench was always observed at an equator region, except for one test. The quench location moved to the other equator region by CP or HT. Every cavity tested at Saclay showed the Qo degradation at high fields. It needs further works to understand this phenomenon.

Acknowledgments

The authors would like to thank the members of DAPNIA/SEA for their cooperation in pursuing this study. Our thanks also go to A. Matheisen and D. Proch for heat treatment at DESY. One of us, E. Kako, would particularly like to thank J. Gastebois and B. Aune for making the arrangements of his stay at CEA-Saclay. Special thanks are given to P. Bosland and H. Safa for their exceptional hospitality during his stay in France.

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