ACHIEVEMENT OF 40 MV/m ACCELERATING FIELD IN L-BAND SCC AT KEK

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Abstract

Two superconducting cavities developed at KEK showed good cavity performances; E_{acc} = ~40 MV/m. The 1st cavity achieved 40 MV/m adopted 1400 °C heat treatment at half-cell and 120μ EP at single cell state. On the other hand, at the 2nd cavity no 1400 °C heat treatment was adopted and 30μm tumbling + 30μm EP were applied for surface polishing. In the rinsing procedures of both cavity, ultra-pure water was not used at all for initial 40 MV/m achievement of each cavities; only pure water was used. The niobium sheet of RRR = 200 were used for both cavities. Some degradation of Q_0 were observed in Q-E curve probably due to thermal heating. Peculiar temperature dependence (at 1.6 -1.8 K) of cavity performance was observed at 2nd cavity while not observed in the 1st cavity. An analysis of the cavity performances at maximum field may indicate the thermal quench but unusual one. To the 1st cavity, several attempts have been tried repeatedly for intending further improvement and for checking preparation systems.

1. Introduction

Several efforts have been continued to achieve a high accelerating gradient in the L-band superconducting cavity (1.3 GHz, TESLA type cavity) with reasonable cost and with good reliability. The R&D is still needed to resolve a lot of difficulties, however promising results were also obtained in several laboratories in the past couple of years. At KEK also, one niobium superconducting cavity (K-14) achieved quite good performances such as a maximum E_{acc} = 40 MV/m with $Q_0 = 8 \times 10^9$ at 1.8 K He-bath temperature. No severe Q_0 degradation due to the field emission were observed but some decreasing due to the thermal heating were observed. The maximum filed seems to be limited by the thermal quench, but it was not limited by the dissipation power(P_{CAV}). Even though the P_{CAV} were decreased by lowering the temperature, $E_{acc,\ max}$ were not changed. The thermal heating were partially caused by the light field emission as well as by the usual ohmic loss. After the first achievement of 40 MV/m accelerating field in K-14, recently another cavity (K-9) also showed good performances ($E_{acc,\ max}$ = 39 MV/m). It can be said that the corresponding maximum surface field (H_{sp}) of 1730 gauss might be very close to the practical limit that is expected from the H_c of dc-case; H_{sp} > 86% of H_c. These results show that the surface treatments developed at KEK have potential to prepare a quite good niobium surface for an accelerating cavity. The fabrication method and the surface treatments were not identical in each cavities. For example, the high temperature treatment (1400 °C) was applied for K-14 but not for K-9. On the other hand, the electropolishing (EP) and the high pressure rinsing (HPR) were commonly applied in both cavities, even though the conditions of these treatments were not same in detail. A superiority of EP compared to chemical polishing (CP) is showed in series tests at KEK as discussed in else where [1], especially at the field beyond E_{acc} = 30 MV/m. The results of these two cavities confirm this conclusion, at least for the treatments adopted at KEK. Since the first achievement of 40 MV/m, the K-14 cavity was repeatedly processed and measured for improving of its performance and for checking the newly developed HPR systems. Because this cavity had good surface condition at first treatment, it was thought that this cavity was quite suitable for optimization of HPR condition such as the pressure, rinsing time, quality of water etc., to improve performance further more. The details of surface preparations, experimental results and data analysis of each cavities, as well as the story of the repeated tests of K-14 are discussed in the following sections.

2. Cavity fabrication and Treatments

2-1. K-14 cavity

The noticeable surface preparations carried out for this cavity were summarized as follows: after forming the 2.5^t niobium sheets of RRR = 200 to half-cells by deep drawing, 1) 1400 °C annealing was adopted at half-cell state. Then the single-cell cavity with beam pipe was fabricated by EBW. The cavity shape is described in reference [2] (parameters of M-1, 2 of Table-1); R/Q = 110Ω, G = 266, E_{sp}/E_{acc} = 1.89 and H_{sp}/E_{acc} = 43.2 Oe/MV/m. The treatments of 2) tumbling (barrel polishing) (10μm), 3) EP (120μm) and 4) HPR (80 kgf/cm^2, with pure water) were carried out at single-cell state. The heat treatment was done as sandwiched configuration with titanium (Ti) sheets formed to the same half-cell shape, and all were installed in a cylindrical Ti box with supporting by tungsten-wires. In this configuration, both side surface of the Nb sheet faced to Ti surface with almost constant distance. The tumbling was finished relatively small removing compared to other cavities as shown in figure 1, even though the processing time was almost same as others (~10 days). This tumbling results of K-14 were possibly due to the Ti-layers formed during the high temperature heat treatment. The tumbling results of K-9 as shown in figure 1 is a typical result in KEK. Before EP, slight CP was applied to remove the polishing material of tumbling (fine ceramic molded by plastic) from surface to reduce a smearing of the chemical liquid used in the following EP. The standard EP at KEK [2] was applied and 120μm in average was removed. The 800 °C annealing for 5 hours was followed to degas hydrogen as a usual procedure. At the degassing the outer side of the cavity faced to Ti box and the beam pipes hall were covered by Nb-foils not so tightly. No slight EP nor CP was applied after the degassing even though it would be a chance that the inside of the cavity be smeared by the Ti-vapor. The HPR was applied just after the degassing with following conditions. A total amount of used water was 600-700 l for one hours rinsing, the water was passed through a 0.2μm filter installed before the nozzle and a water pressure measured at just after the filter was 80 kgf/cm^2 (pressure drop at the filter was ~10 kgf/cm^2). A final flow rinsing with 0.1μm filter was followed. Finally, the cavity was filled by a filtered nitrogen gas for transportation to KEK(~3 hours). At first treatment of this cavity, the pure water (not ultra-pure water) of 0.08 μS/cm conductivity was used in the HPR and in the final rinsing. Here after the cavity was never opened to atmosphere until a covering of the cavity by the coupler equipped flanges in the clean room (class 10 or better). During the HPR and the final rinsing the atmosphere environment was not so good; worse than class 1000.
The treatments applied for this cavity after the 4th measurements will be discussed later with the experimental results.

2-2. K-9 cavity

The Nb material and the fabrication method used for K-9 cavity were same of K-14; the 2.5^t niobium sheets of RRR = 200, the deep drawing and EBW were used. The cavity shape is same of C-1,2 of reference [2] except of Nb thickness; R/Q = 102Ω, G = 274, E_{sp}/E_{acc} = 1.78 and H_{sp}/E_{acc} = 43.8 Oe/MV/m. No high temperature heat treatment was adopted. The tumbling was applied for mechanical polishing and the result is shown in figure 1. In this case the removed thickness was about 40-50 μm at the equator and 20 μm at the beam pipe. The tumbling polished the cavity effectively almost as much as we expected. Then as a usual procedure, the slight CP(~7μm) was carried out. In EP, about 30 μm in average was removed. The degassing (800°C annealing) was applied under the almost same condition as discussed at K-14. At first and second processing, three rinsing such as a mega sonic rinsing (MSR), HPR and the final rinsing were sequentially applied. No slight EP nor CP was applied after the degassing at this cavity also. The obtained maximum E_{acc} were 25-28 MV/m. An additional EP of ~10μm and following rinsing of HPR and the final rinsing were applied in the third treatment, and another rinsing of HPR and the final rinsing lead to E_{acc} = 39 MV/m in the fourth measurement of this cavity.

2-3. Common features of treatments for K-14 and K-9 cavities

The same quality niobium sheet and the same fabrication method were used. The tumbling as mechanical polishing and EP(30- 120µm) for final polishing were carried out with total removed thickness of 100-150µm. Degassing (~800°C) after EP and the rinsing of HPR and final rinsing with pure water were applied. The sequence of the treatments described here (except the MSR and the additional slight EP for K-9, and 1400°C treatment for K-14) were applied also for several other cavities. Even though the quantities of removed thickness of EP or tumbling were scattered in some range, the good cavity performances such as E_{acc} of 25-30 MV/m were obtained with high probability. So K-9 and K-14 cavities confirmed again that the procedure described here [1] was quite reliable for achieving the high accelerating field without degrading the Q-value so much.

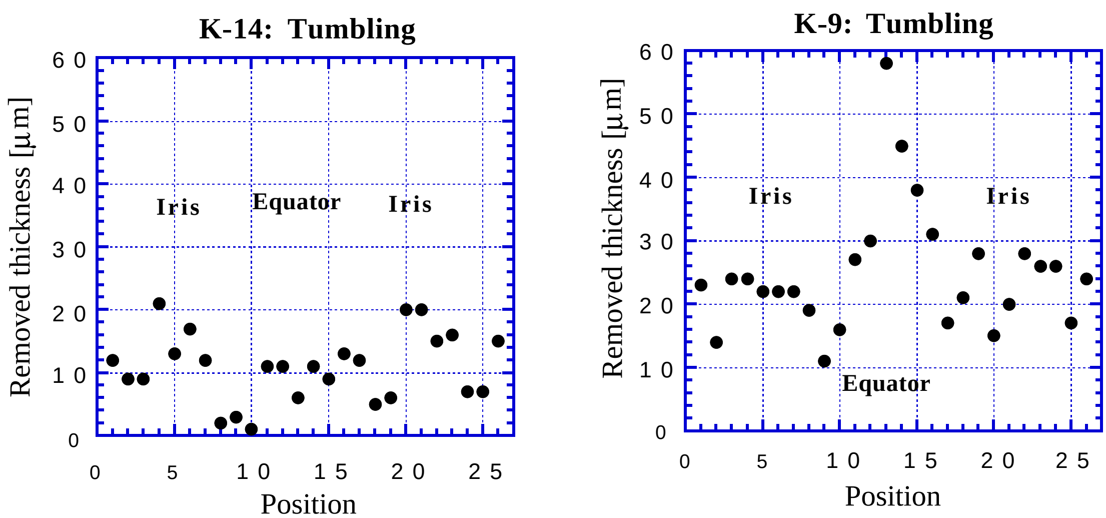


Figure 1. The polishing results by tumbling. Positions are aligned along the longitudinal line.

3. Experimental Results

3-1-1. First results of K-14: Run #1-#3

Figure 2 & 3 show the first results of K-14 cavity. No break down was observed until maximum E_{acc}. The decay time at quench was ~ 450µs (90-10% of transmit power). The localized hot spots were observed at the quench around the equator and the positions were changed depending on the He-temperature. Some Q-degradation was observed such as a decreasing from Q_0 = 4.7 x10^{10} at E_{acc} = 4 MV/m to Q_0 = 8.2 x 10^9 at E_{acc} = 40 MV/m in the He-temperature of 1.7-2.0 K. The residual surface resistance (R_{res}) measured at E_{acc} = 4.5 MV/m was ~4 nΩ. X-ray and electron yield measured by a GM counter at top of cryogenic and at a transmit coupler port, respectively indicated an enhancement factor of β~61 in Fowler-Nordheim plot. The experimental apparatus is described in reference [2]. From these observations, the field limitation might be thermal quench and the thermal heating might be mainly responsible for the Q-degradation. A terminology of "thermal heating" is using just for meaning a phenomenological term that show the heating no matter how the reason is, for the cases of not so much severe Q-degradation. Actually, the continuous X-ray or electron-yield may indicate that light field emission induced the heating, at least partially. On the other hand, the "field emission" was/will be used for explaining the steep Q-degradation. The quench at $E_{acc, max}$ will be discussed in 4-5. These results were obtained in three succession tests. Between the tests, the cavity was kept in vacuum but repeated the heat cycles; warm up to room temperature and cool down to 1.8 K. No degradation of cavity performances were observed except at the 3rd measurement where the temperature mapping was attached and some lowering of Q-values were observed (at > 30 MV/m) due to the degraded cooling power but the maximum E_{acc} was not changed. The mapping system applied here was not same to the described one in reference [2] (Fig. 3, 4, 5 of [2]) even though the elements of carbon resistor were same. Because that the data must be read simultaneously to detect the quench phenomena, whereas in the system of reference [2] the data were taken sequentially. Under the condition of limiting data points, only the equator region was covered. The reason why we choose the equator region and the results will be discussed later in 4-1 (the mapping data are shown in figure 9).

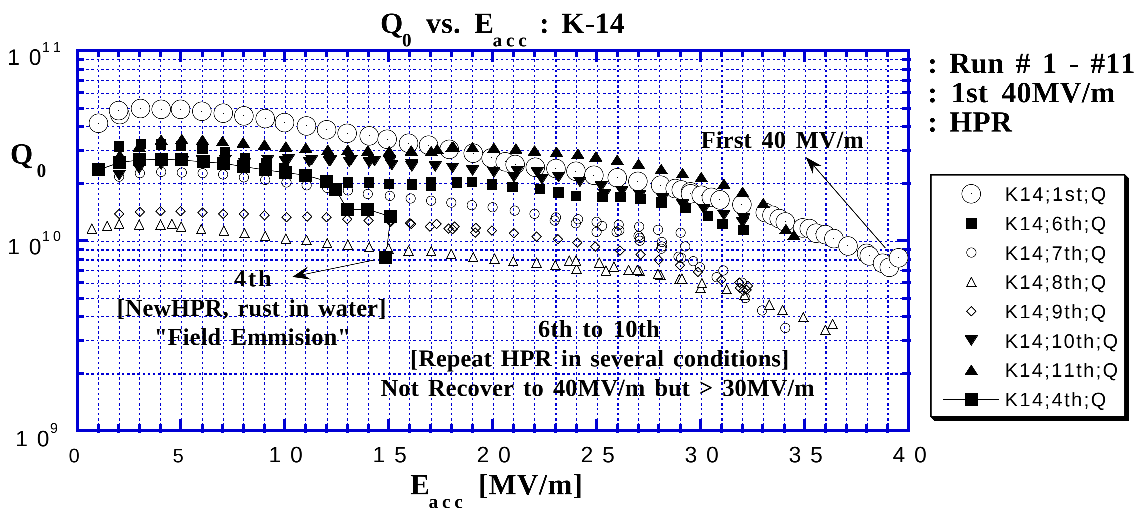
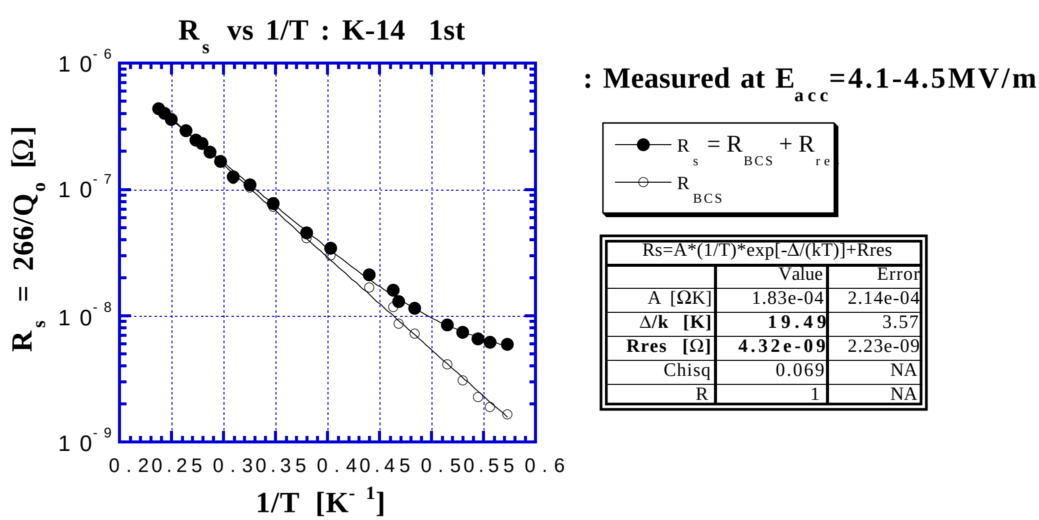


Figure 2. First achievement of 40 MV/m by K-14
and the results obtained in the following HPR treatments.



Rs=A*(1/T)*exp[-Δ/(kT)]+Rres		
	Value	Error
A [ΩK]	1.83e-04	2.14e-04
Δ/k [K]	**19.49**	3.57
Rres [Ω]	**4.32e-09**	2.23e-09
Chisq	0.069	NA
R	1	NA

Figure 3. Surface resistance at low field: K-14.

3-1-2. Series tests of K-14: Run #4-#21

Intending to improvement, further HPR was tried but the result was quite degraded (run #4; $E_{acc,max}$ = 15 MV/m). The reason became apparent later such as the rust in water in the new HPR system. Occasionally, the development of the new system such as HPR was carried out simultaneously in the cavity test. Unfortunately, the rust was generated in the remained water after the initial test of the new HPR. Then the cavity was again rinsed at old HPR system and measured several times (run #6-#11). At the test of run #11, the heat treatment of 770°C was also tried with followed by the HPR before trying other treatments such as the EP, even though this heat treatment is usually adopted as the degassing. Figure 2 shows the results of these tests. The maximum fields reached to 32-36 MV/m but the Q-degradation like a field emission were observed. If we simply assume that the kink in the Q-E curve is starting point of the field emission, it seems that the data can be divided into two groups such that the 1st group (3 results) is stating at ~28 MV/m and 2nd group (3 results) is starting at ~32 MV/m or quench at this field. At this point the cavity could not reach 40 MV/m but still showed good performances (>30 MV/m), therefor this cavity was used to check another HPR system at JAERI (Japan Atomic Energy Research Institute; run #12-#14). The treatment with followed by the usual procedure (#12) showed the cavity performance of the 1st group; maximum E_{acc} = 36.5 MV/m but field emission started at 28 MV/m. However in the second and third treatments (#13, #14) at JAERI-HPR the results were not good; E_{acc} = 24 MV/m with field emission and E_{acc} =16.5 MV/m, respectively, as shown in the upper graph of figure 4. The reasons are that the cavity was dried in the JAERI clean room with open to atmosphere at second treatments, and that again the rust smeared the cavity in third treatment. This time the rust was generated at the nozzle after using a few weeks.

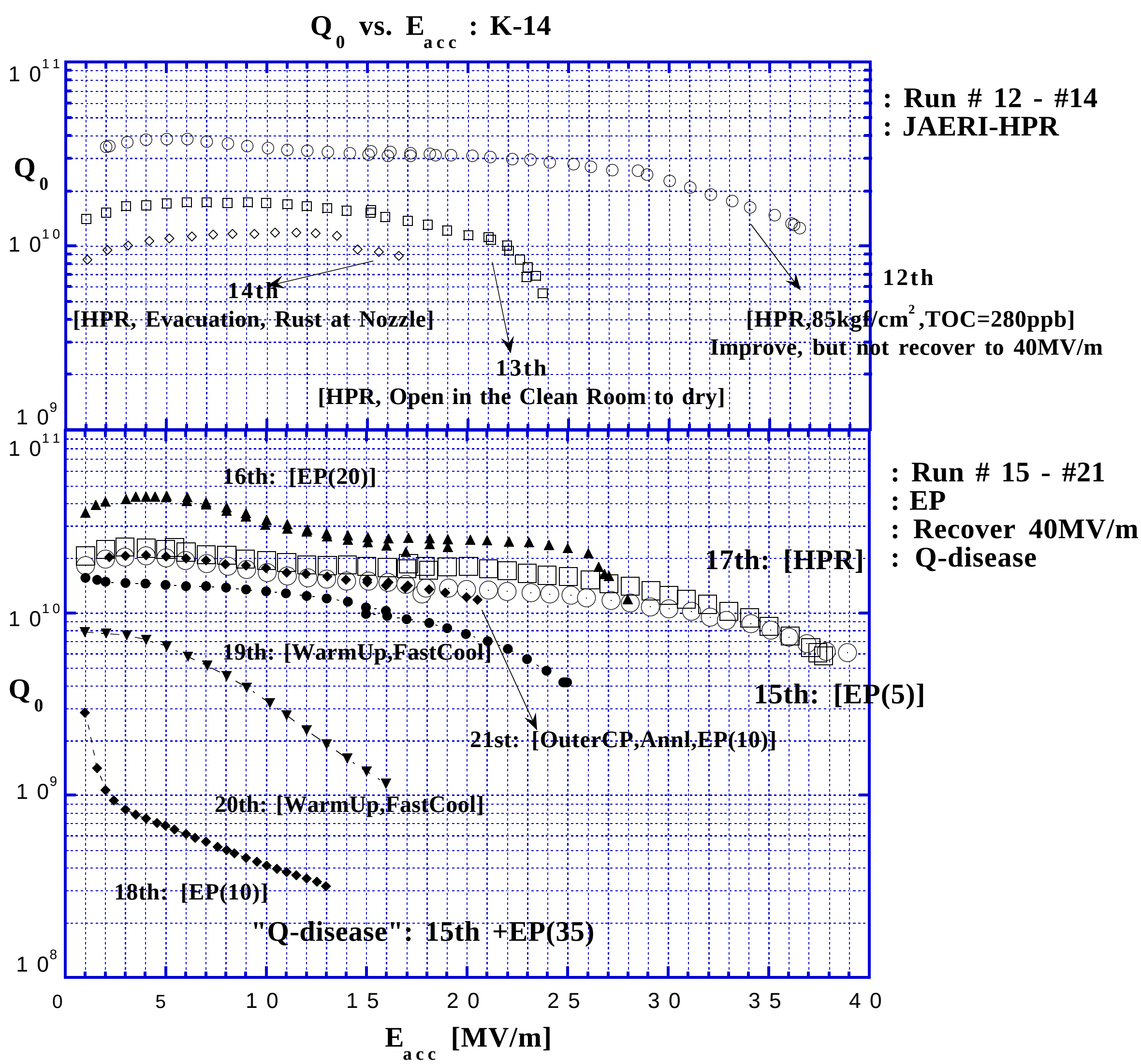


Figure 4. The performances of K-14 cavity in series tests; trying JAERI-HPR and EP.

Some interesting features are appeared from these experiences. The cavity suffered by the rust in the HPR showed maximum E_{acc} = 15-16 MV/m in both rust troubles. The cavity left open in the clean room can reach E_{acc} > 20 MV/m; maximum = 24 MV/m but field emission started at 22 MV/m. If cavity is treated properly, the present HPR can recover the performances up to 28 MV/m or 32 MV/m without field-emission-like Q-degradation for the cavity suffered by the rust. The reason why the results of HPR were divided into two group are not clear, even though the suspicious are the changing of unknown factor of water, the dust introduced by the tool used at final rinsing, etc. So far HPR and the final rinsing had tried several times but these never recover the 40 MV/m, therefor series tests including slight EP were carried out (run #15-#21), as shown in lower graph of figure 4. The first slight EP of 5µm with followed by HPR and final rinsing achieved the result (run #15) that the cavity almost recovered its initial field gradient but still Q_0 were factor of 1.5-2.5 smaller than the initial values; $Q_0 = 6.1\ x10^9$ at $E_{acc,\ max} = 39$ MV/m without field-emission-like Q-degradation. The second EP of 20µm and the usual rinsing achieved only $E_{acc} = 28$ MV/m (run #16) but further rinsing of HPR and final rinsing (run #17) achieved almost same but a little degraded results of run #15; $E_{acc,\ max} = 38$ MV/m. Unexpectedly the third EP of 10µm caused the so called Q-disease (run #18). The fast cool down were tried in the following two tests but these procedures could not help so much for this cavity (run #19-#20). The degassing (720°C, 5 hours annealing) to cure the Q-disease and 10µm EP to assure Ti removing, and also out side CP for assurance of good heat contact in He-bath, were tried in the following test. The results (run #21) were still not good such as $E_{acc,\ max} = 20.5$ MV/m but the Q-disease was cured and Q_0 were almost identical with the recovered Q_0 obtained in run #15 up to $E_{acc,\ max} = 20.5$ MV/m.

K-14						
	Parameters	*R/Q = 110Ω, G = 266, E_{sp}/E_{acc} = 1.89 and H_{sp}/E_{acc} = 43.2 Oe/MV/m.*				
Run #	Treatments	$E_{acc,max}$ [MV/m]	Q_0 at $E_{acc,max}$	$Q_{0,max}$	Field Emiss.	Comments
1	HT-1400, EP, Anl, HPR ,..	**39.5**	$8.2\ x10^9$	$5.0\ x10^{10}$	No	**1st 40MV/m**
2	*Warm Up, keep Vac.*	**40.1**	$7.6\ x10^9$	$4.7\ x10^{10}$	No	Temp. dep. of E_{acc}...
3	*Warm Up, keep Vac.*	**39.7**	$6.4x10^9$	$4.6\ x10^{10}$	No	Temp. mapping.
4	New HPR	*15.1*	$1.3\ x10^{10}$	$2.7\ x10^{10}$	Yes	**Rust** trouble of New HPR
5	HPR					Cool down but not complete test
6	*Warm Up*	32.0	$1.1\ x10^{10}$	$3.2\ x10^{10}$	No	Resume #5 test. Q-deg. start at~28MV/m
7	HPR	34.0	$3.5\ x10^9$	$2.3\ x10^{10}$	Yes	F.E. start at ~28MV/m
8	NewHPR	36.3	$3.7\ x10^9$	$1.2\ x10^{10}$	(No)	Fix NewHPR. Q-deg. start at ~32MV/m
9	NewHPR	32.3	$5.8\ x10^9$	$1.4\ x10^{10}$	(No)	**P=105kgf/cm^2**. Quench at 32MV/m
10	HPR	32.1	$1.3\ x10^{10}$	$2.7\ x10^{10}$	No	Quench at 32MV/m
11	HPR	34.5	$1.1\ x10^{10}$	$3.5\ x10^{10}$	Yes	F.E. start at ~28MV/m
12	JAERI-HPR	36.5	$1.3\ x10^{10}$	$3.8\ x10^{10}$	Yes	F.E. start at ~28MV/m
13	JAERI-HPR	*23.4*	$6.9\ x10^9$	$1.7\ x10^{10}$	Yes	Dry in CleanRoom. F.E. start at 22MV/m
14	JAERI-HPR	*16.5*	$8.9\ x10^9$	$1.2\ x10^{10}$	(Yes)	**Rust** at nozzle.
15	**EP(5µ)**, HPR	**38.9**	$6.1\ x10^9$	$2.1\ x10^{10}$	No	Almost **Recover.**
16	EP(20µ), HPR	28.0	$1.2\ x10^{10}$	$4.4\ x10^{10}$	Yes	F.E. start at ~26MV/m
17	HPR	**37.7**	$5.9\ x10^9$	$2.3\ x10^{10}$	(No)	Almost Recover.
18	**EP(10µ)**, HPR	*13.0*	$3.2\ x10^8$	$2.8\ x10^9$		**Q-disease.**
19	*Warm Up*	*25.0*	$4.2\ x10^9$	$1.6\ x10^{10}$	(No)	Fast Cool Down.
20	*Warm Up*	*16.0*	$1.2\ x10^9$	$7.9\ x10^9$	(No)	Fast Cool Down.
21	OutCP, Anl, EP	*20.5*	$1.2\ x10^{10}$	$2.1\ x10^{10}$	No	Cure Q-dis. But not recover.

Table 1. Summary of K-14 measurements.

The efforts to recover the good performances are still continued, especially the Q-disease observed after the small quantities of EP (35 μm after run #15) is interesting in conjunction with the 1400°C heat treatment. The repeated measurements of K-14 are tabulated in Table 1.

3-2. Results of K-9

The high gradient of 39 MV/m was obtained at the fourth measurement of this cavity, as shown in figure 5. Unfortunately for this cavity, the HPR just after the degassing was carried out with using the new HPR that would be possessed of the rust trouble at discussed in K-14 cavity. This was a first trial of the new HPR and the rust trouble became apparent later in run #4 of K-14 as discussed before. The results of 1st test were such that $E_{acc,\ max}$ = 25 MV/m and relatively steep Q-degradation was observed but not so much as the field-emission-like; Q_0 = 1.9 x10^{10} at E_{acc} = 5 MV/m decreasing to Q_0 = 8.6 x10^9 at E_{acc} = 24.9 MV/m. In the second treatment, MSR as well as HPR were tried and the obtained results were such that $E_{acc,\ max}$ = 28.2 MV/m with almost flat Q-value of 2 x10^{10} up to 22 MV/m but at this point the steep Q-degradation was started and degraded to 6 x10^9 at $E_{acc,\ max}$. Slight EP of 10μm with followed by the usual rinsing including of HPR were applied and the results were $E_{acc,\ max}$ = 33.4 MV/m without the field-emission-like Q-degradation at He-temperature of 1.75 K. The surface resistance at low field is shown in figure 6.

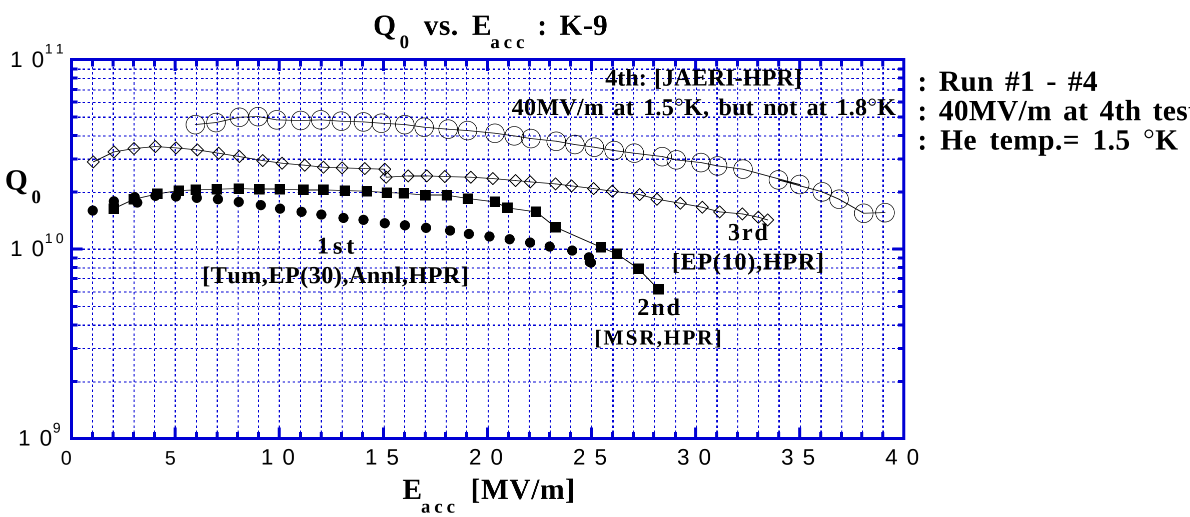
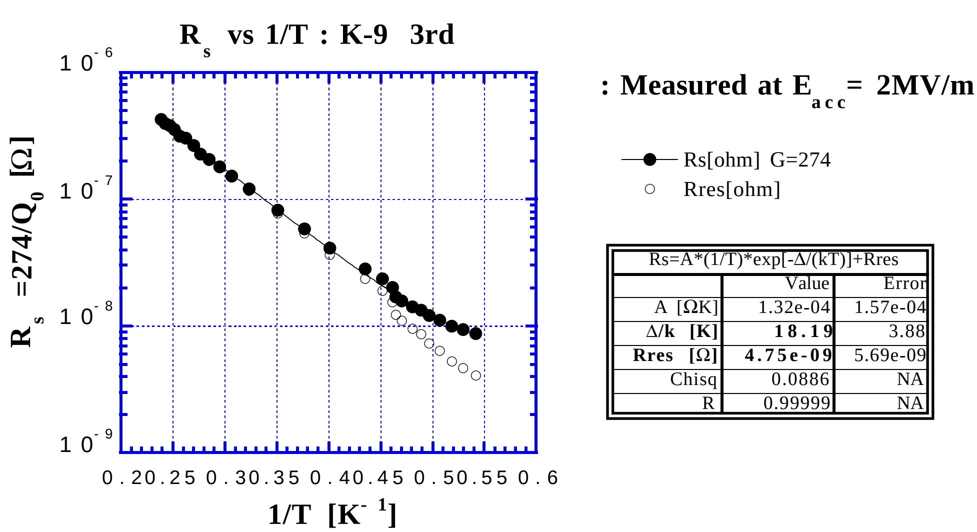


Figure 5. Cavity performances of K-9.



Rs=A*(1/T)*exp[-Δ/(kT)]+Rres		
	Value	Error
A [ΩK]	1.32e-04	1.57e-04
Δ/k [K]	**18.19**	3.88
Rres [Ω]	**4.75e-09**	5.69e-09
Chisq	0.0886	NA
R	0.99999	NA

Figure 6. Surface resistance at low field: K-9.

Additional rinsing was applied by JAERI HPR (the rust trouble was already fixed) and the results were such that $E_{acc,\ max}$ = 31.5 MV/m with Q_0 =2.2 x10^{10} at 1.79 K and $E_{acc,\ max}$ = 39 MV/m with Q_0 =1.6 x10^{10} at 1.55 K He-temperature. The Q-degradation like a field emission were not observed in both temperature at 4th and in the data of 3rd test but the similar Q-degradation of K-14 were observed. The temperature dependence of $E_{acc,\ max}$ of K-9 were observed unexpectedly as shown in figure 7, where the data of 3rd and 4th are combined, and the case of K-14 and the datum of CEBAF are also shown for convenience; the data of K-14 will be discussed in 4-5. The very steep dependence on He-temperature was shown for K-9 but not for K-14 at below the λ-point. Summary of K-9 are tabulated in Table 2.

K-9						
Parameters	*R/Q = 102Ω, G = 274, E_{sp}/E_{acc} = 1.78 and H_{sp}/E_{acc} = 43.8 Oe/MV/m.*					
Run #	Treatments	$E_{acc,max}$ [MV/m]	Q_0 at $E_{acc,max}$	$Q_{0,max}$	Field Emiss.	Comments
1	EP(30μ),HPR	24.9	8.6 x10^9	1.9 x10^{10}	(No)	steep Q-deg.
2	MSR, HPR	28.2	6.2 x10^9	2.1 x10^{10}	Yes	F.E. start at ~22MV/m
3	EP(10μ),HPR	33.4	1.4 x10^{10}	3.5 x10^{10}	No	He-temp ~ 1.75 K
4	JAERI-HPR	**39.1** 31.5	1.6 x10^{10} 2.2 x10^{10}	5.0 x10^{10}	No	He-temp ~ **1.55** **K** He-temp ~ 1.79 **K**

Table 2. Summary of K-9 measurements.

4. Discussion and conclusion

4-1. Q degradation

The results of Q-E curve of K-14 and K-9 are very promising results that the treatments discussed above have potentials to reach the almost practically expected limit of surface field strength. However, if we compare our results with the data of CEBAF [3] some degree of Q-degradation are apparent and the some heating mechanism must be taking place at the surface. Qualitatively almost same Q-degradation are observed in all the good cavity performances including the recovered results of K-14 and K-9 as shown in figure 8 (the extraction of Q_0 at T= 0 K as explained in figure 8, may be justified by the discussion at 4-5). It seems that two kind of slopes in Q-degradation are observed; less steep slope for K-14, 15th and K-9, 4th. The naive speculations are such that the heating sources are scattered over the surface and the sources of near the equator are responsible for ohmic loss (R x i^2), whereas the sources of near the iris are responsible for <u>light</u> field emission (see 3-1-1 about the "thermal heating"). For more steep slopes (K-14, 1st & K-9, 3rd) the later sources at iris may also contribute to Q-degradation in addition to the former sources near the equator. The probability of the existence of the former sources are much large due to the field distribution inside the cavity (shown in figure 3 of reference [2]); flat H-field extend up to ±4cm from the center in the beam axis, on the other hand E-field is concentrated at the iris. Therefore, the heating around the equator is always expected. On the other hand, the probability of the later case is small, but their larger effects on Q-degradation can be expected because of the exponential dependence on E_{sp}. Whereas the ohmic loss can be expected as increasing with fourth power of field at most if we use the results at 4-5; R_{res} show the quadratic dependence on E_{acc} (see figure 11). The naive speculation can be summarized as follows. The relatively large number of heating sources exist around the equator but each source has week heating power. On the other hand, small number sources are near the iris with stronger field dependent heating power with the assumption of the <u>light</u> field emission and occasionally sources exist scarcely at larger E-field. Actually as described in 3-1-1, the X-ray & electron yield of β ~ 60 were observed and the heating at near the equator can be expected from the temperature mapping data at quench. The data of mapping were taken in 3rd measurement of K-14 (almost same performance of 1st, except small Q-deg. due to the mapping; see 3-1-1) with covered only equator region because of the assumption that the field emission were not so much responsible for Q-degradation. The assumption is consistent with the data that the local heating were observed in the equator region at the quench as shown in figure 9. Figure 9 shows not only the localized heating position but also the changing of the position depending on the He-temperatures. The temperature dependence of the achievable field strength were also obtained (at 2nd test as shown in figure 7) in the temperature range between 1.8-4.2 K. The interesting results were such that the achievable field were almost constant (E_{acc} = 40 MV/m) up to the λ-point. However above the λ-point the achievable field were jumped to decreased value of 28 MV/m at the λ-point and monotonously decreasing to 18 MV/m at 4.2 K, and the heating position were shifted to another place (almost 90° apart in azimuth angle) from the position at below the λ-point. The possible explanations can be attributed to the above speculation of scattered heating sources, and the changing of the cooling power especially at the λ-point; the cooling by He-I and He-II. Suppose the scattered source(s) be heating with a little difference of magnitude, then the changing of the cooling conditions may choose one of them as the heating position that would be responsible for quench. If we adopted this picture, the next question was that the heating sources were defects or contamination, and if the contamination were responsible for the quench whether the HPR could remove these or not. This was main reason to try further HPR, especially more powerful HPR such as a higher pressure obtainable at new HPR. The answer for these are not yet clear partially because of the troubles of the rust as described in 3-1-2. And because of the lack of good rinsing system that would be qualitatively exceeding the present one.

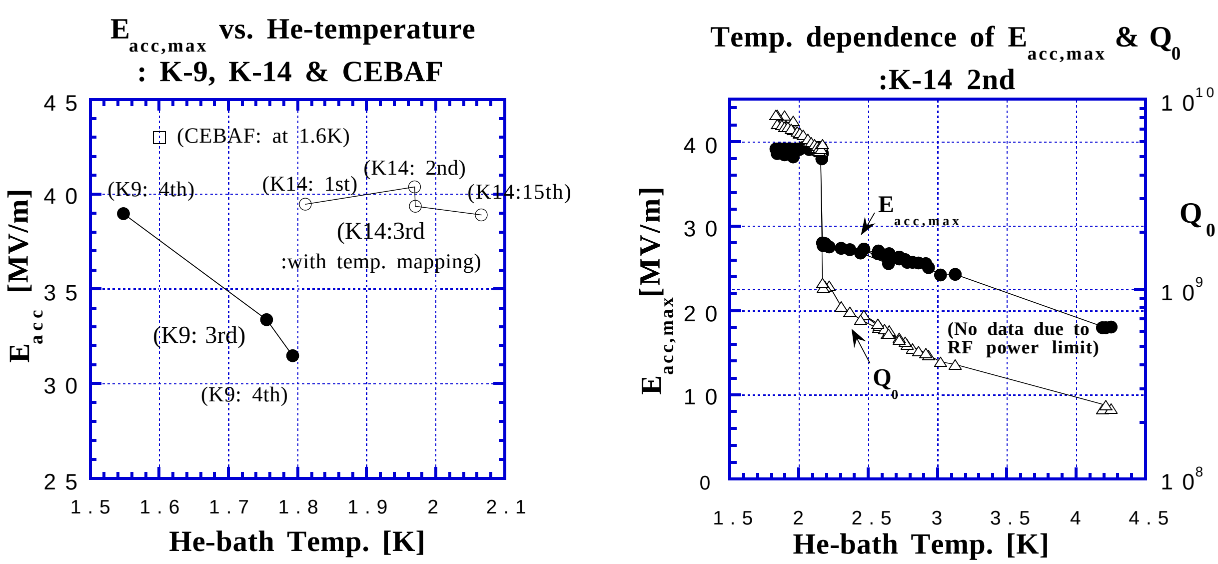


Figure 7. He-bath temperature dependence. The left graph shows peculiar temp. dependence of $E_{acc,\ max}$ for K-9. The right graph shows temp. dependence of $E_{acc.\ max}$ and Q_0 observed in K-14.

4-2. Rinsing

Two possible damage by the rust water in K-14 can be considered as follow: the surface was only smeared, or not only smeared but also scratched by the rust water. The experimental results that the rinsing only never recovered the 40 MV/m, indicate that the present HPR has not ability to clean completely the smeared surface if the surface was only smeared as the former possibility. If the damage is the later case and if the HPR clean the surface sufficiently, the defects generated by the rust degraded the performance above 32 MV/m (if we take the starting E_{acc} of the field-emission of group-2. See the discussions in 3-1-2) and the size of defects might be smaller than 5µm because that the 5µm EP could almost recover the original performance. The discussions described here are two extreme cases, so the real situation may be between them. Similar discussion can also be applied for the Q-degradation described in 4-1. If the HPR can clean the surface sufficiently, the surface quality polished by the EP determine the present Q-degradation, or the insufficient HPR is responsible for the Q-degradation at least in the region of E_{acc} above 30 MV/m. Further discussion about the possibilities of the Q-degradation caused by the present rinsing will be explained in 4-4, that emerged from the rinsing at 4th test of K-9 cavity. Any way, the rinsing system of more powerful one can resolve these uncertainties. The R&D of other method such as the hot water rinsing, MSR, etc., as well as the optimization of the condition of the present HPR are all required to realize the qualitatively superior rinsing method.

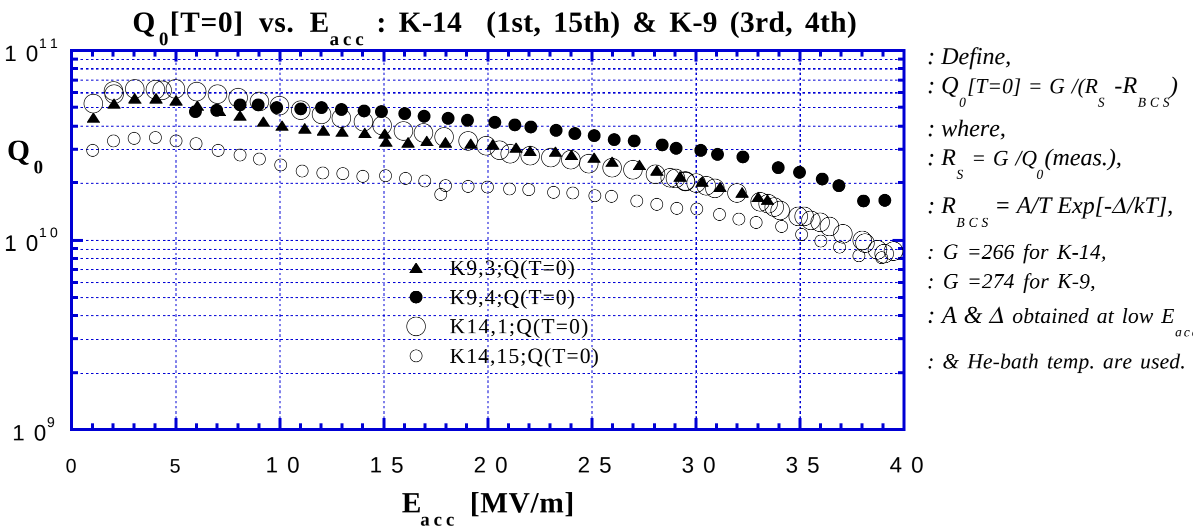


Figure 8. The extracted Q_0 at T= 0 K from good cavity performances.

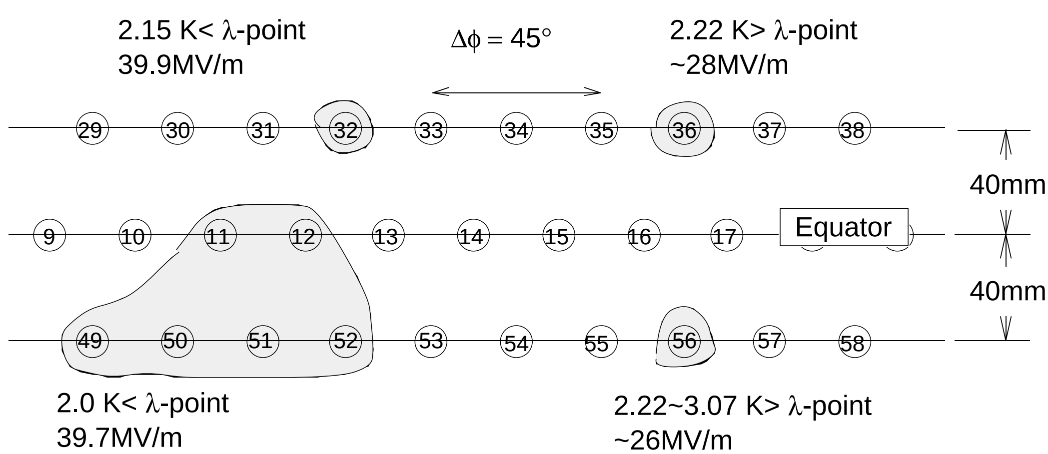
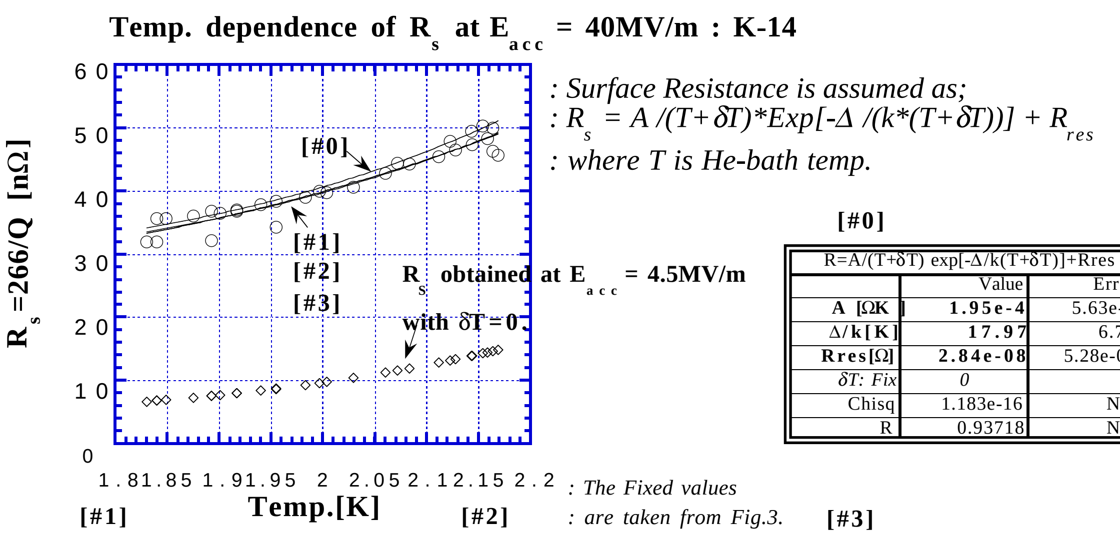


Figure 9. The heating positions at quench for different He-temperatures. The number indicate the positions of carbon resistors. The data of all equator and upper & lower-halves were taken simultaneously at quench.

4-3 Heat Treatment at 1400 °C

Generally, by the high temperature treatment (HT) of niobium bulk, re-crystallization, relaxation of the stress, degassing, curing the Q-disease, improving RRR, etc., are expected. But it is not clear that what effects are really important things for achieving the high gradient. Actually this treatment is not necessarily condition for E_{acc} = 40 MV/m as indicated by the CEBAF data or K-9, and also no superiority of the HT of 1300-1400 °C was shown in the range of E_{acc} <30 MV/m (for not so much Q-degradation cavities) [2, 4] until the good performances exhibited in K-14. If the HT of

1400°C contribute to the good performance of K-14, it may be caused by the condition of HT as described in 2-1; both side annealing at half cell. At this moment we can't say any definite conclusion about the effects of HT-1400°C, but the good results itself and small removing at the tumbling and also Q-disease after only 35µm EP may suggest that the niobium condition of K-14 is different from the non HT-1400°C cavities. Repeating the same treatments of K-14 on several new cavities are planed to confirm the effects of HT-1400°C, at least statistically.



[#0]

R=A/(T+δT) exp[-Δ/k(T+δT)]+Rres		
	Value	Error
A [ΩK]	**1.95e-4**	5.63e-4
Δ/k[K]	**17.97**	6.72
Rres[Ω]	**2.84e-08**	5.28e-09
δT: Fix	*0*	
Chisq	1.183e-16	NA
R	0.93718	NA

[#1]

R=A/(T+δT) exp[-Δ/k(T+δT)]+Rres		
	Value	Error
A[ΩK]: Fix	*1.83e-4*	
Δ/k[K]: Fix	*19.49*	
Rres[Ω]	**2.66e-08**	1.09e-09
δT	**0.23**	0.022
Chisq	7.32e-17	NA
R	0.96161	NA

[#2]

R=A/(T+δT) exp[-Δ/k(T+δT)]+Rres		
	Value	Error
A[ΩK]: Fix	*1.83e-4*	
Δ/k[K]	**22.41**	7.908
Rres[Ω]	**2.28e-08**	1.13e-08
δT	**0.707**	1.3366
Chisq	7.27e-17	NA
R	0.9619	NA

[#3]

R=A/(T+δT) exp[-Δ/k(T+δT)]+Rres		
	Value	Error
A [ΩK]	**8.98e-05**	0.0090
Δ/k[K]	**18.63**	508.42
Rres[Ω]	**2.33e-08**	9.49e-08
δT	**0.415**	41.66
Chisq	7.26e-17	NA
R	0.96192	NA

Figure 10. The surface resistance at E_{acc} = 40 MV/m.
The data are fitted to BCS term + residual term
as a function of He-bath temperature.

4-4. Peculiar Temperature dependence of K-9

The temperature dependence of $E_{acc,\ max}$ as given in figure 7 is possibly explained by the cooling power at the inside surface of the cavity. It seems that the thermal heating is mainly responsible for the Q-degradation of K-9 and the field emission does not contribute so much to it, because of the qualitatively similar shape of Q-E curve as discussed in 4-1 and shown in figure 8. Also the good performances of $E_{acc,\ max}$ = 33.5 MV/m as well as the small residual resistance of ~4 nΩ at 3rd measurement, may indicate that K-9 cavity had already almost same quality of surface of K-14, even though the field of $E_{acc,\ max}$ = 40 MV/m was not achieved at 1.76 K He-temperature. If the heat conductance of K-9 is worse than the K-14 case, the attainable field may be reduced. In other word, if the deposit power can be reduced by reducing the surface resistance (by lowering the temperature) then the attainable field should be increased up to the field corresponding to the quench power dissipation, or up to the allowed maximum field (H_{sp} = $H_{critical}$ for rf-field), if we are lucky. At the 4th measurement, the cavity was measured at two He-temperatures and at the temperature of 1.55 K the field of $E_{acc,\ max}$ = 39 MV/m was attained, whereas $E_{acc,\ max}$ = 31.5 MV/m at 1.79 K. It also seems that the well correlation of $E_{acc,\ max}$ data of 3rd and 4th as a function of temperature may indicate that the additional HPR (at 4th) does not help so much once the good surface was obtained (at 3rd) for improving the attainable field. However the trend of Q-degradation seems to be changed as shown in figure 8, especially at higher field; less steep at 4th. If it is true, the configuration of heating position(s) be changed by the rinsing (HPR or final rinsing) if we adopted the naive speculation discussed in 4-1. The less steep slope of Q-degradation at 4th test means the clean up the heating sources at the iris, and this removing can also contribute to reducing the dissipation power at same E_{acc}. The discussion described here may indicate that the present rinsing is responsible for Q-degradation at least partially. The almost saturation effect of HPR for good performance cavity was already discussed in conjunction with the series test of K-14 (3-1-2), and there already some variety of Q-degradation were discussed even though the temperature effect are not removed. More or less the Q-degradation is affected by the rinsing. The worse cooling assumed for K-9 cavity is another subject to investigate. The thermal conductance of niobium and the Kapitza resistance may be responsible for the cooling power. Does the heat treatment of 1400°C applied for K-14 improve the cooling power ? The slight outer CP and HT of 1400°C for K-9 cavity are planed for obtaining better thermal conductance.

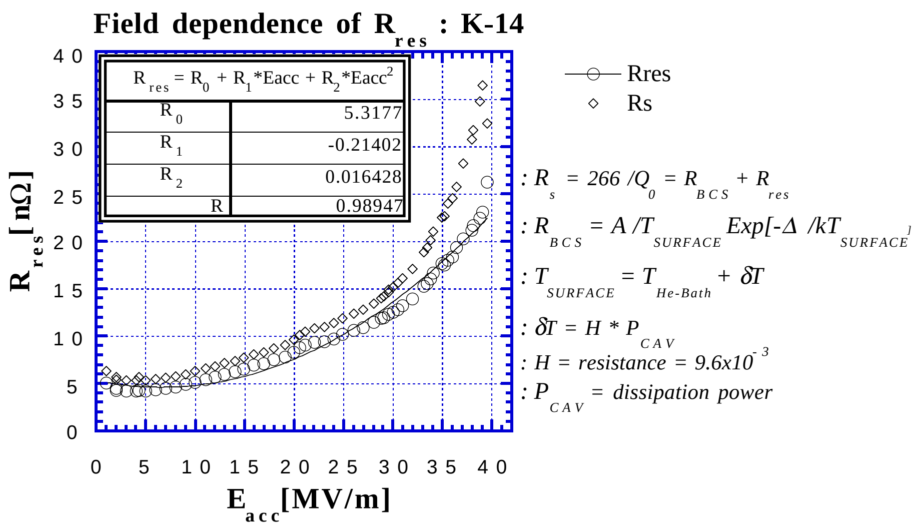


Figure 11. The field dependence of R_{res}. $R_s = 266 /Q_0$ are also shown for comparison.

4-5. Field limitation of K-14

The temperature dependence of attainable E_{acc} and Q_0 may indicate some information about the quench mechanism at quite high field such as the case of E_{acc} = 40 MV/m (E_{sp} = 75.6 MV/m, H_{sp} = 1730 gauss) of K-14. As shown in figure 7, $E_{acc, max}$ is almost constant of 40 MV/m at below the λ-point whereas the Q_0 are still increasing with decreasing the temperature. This indicate that the dissipation power did not limit the maximum field. The same data are re-plotted in terms of R_s and fitted to temperature dependent term and independent term; $R_s = R_{BCS} + R_{res}$, as shown in figure 10. The fittings are carried out with or without some fixed parameters that are obtained at the low field (the values of figure 3). All fits give qualitatively same results; R_{res} = 23-28 nΩ, Δ/k = 18-22 K and δT ~ 0.4 K if temperature difference between the inner surface and He-bath (δT) is included. So the data at 40 MV/m consist with the picture that R_{BCS} is same as obtained at low field, R_{res} is ~27nΩ and δT is ~0.23 K if we adopted the case #1 in figure 10. Then the effective heat resistance (H) of whole cavity is calculated as $H = \delta T/P_{CAV} = 9.6 \times 10^{-3}$ where the cavity dissipation power (P_{CAV}) of 24W at E_{acc} = 40 MV/m is used. Using the BCS parameters (A & Δ) and the H, the temperature independent part of the surface resistance (R_{res}) can be deduced as shown and explained in figure 11. The analysis applied at figure 8 (deduction of Q_0[T=0]) is corresponding to δT=0 because of lack of information except K-14, 1st and because that small δT and then small contribution to R_s compared to R_{res} at lower E_{acc} (<30 MV/m) are expected. The R_s calculated from the Q_0 of 1st test, included the effects of the temperature fluctuation especially at higher fields; not only the fluctuation of He-bath temperature but also the difference between the inner surface and He-bath. The obtained R_{res} show quadratic dependence on E_{acc} except the data at maximum field.

This discrepancy is not conclusive because of measurements error ($\Delta E \sim \pm 5\%$; mainly came from power measurements) and of the parameter's error deduced in this section (due to narrow temperature range used at 40 MV/m; 1.82-2.17 K). Here please remind the facts that the surface resistance represents the quantity averaged over the surface, on the other hand the phenomena caused by the defects or contamination might be very localized. So R_{res} deduced above are not directly indicating the natures of the defects or contamination. However, it may be possible that this small discrepancy indicate the signal of something new at just before quench. More directly, the fact that $E_{acc,\ max}$ is limited by the surface field (E_{sp} or H_{sp}) and not limited by the dissipation power, indicate that the quench at maximum field is not caused by the simple thermal quench. Does the H_{sp} already reach the maximum limit to destroy the superconductivity, or more simply, the maximum E_{sp} ignite the sparking to initiate the quench, but with relatively long decay time of 450μs? Also the observation of the localized heating at the quench may not consistent with the later case of the sparking unless both of the localized heating at the equator and of the sparking at the iris were happened simultaneously. The answer is not available now, but the reducing R_{res} at higher field (corresponding to less Q-degradation) is more urgent problem to answer. Because of the much less Q-degradation of CEBAF cavity , even though the same quality of Nb sheet (RRR = 200, supplied by Tokyo-Denkai) were used. Whatever the quench mechanism is, the source initiating the quench seems not to be fixed to one position, so several (or many?) such sources are at surface. Do they also responsible for the Q-degradation? At the analysis of Q-degradation (4-1), we implicitly assumed that both sources are same; heating around the equator are assumed from the localized heating measured at the quench. Is this assumption consistent with the quench phenomena described above ($E_{acc,\ max}$ is not limited by the dissipation power)? It might be true that the present surface treatments are responsible for the relatively large R_{res} at higher accelerating field. To realize the smaller R_{res} is very important not only for answer the above questions but also for establishing the more reliable construction method of superconducting cavity. The feasibility of small R_{res} is already shown by CEBAF cavity.

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