TESLA Activities at KEK

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Abstract

The status of R&D on L-band superconducting cavities for TESLA is described. KEK is focusing on high field issue. We have achieved 30 MV/m in a single-cell cavity by the combination of TRISTAN scc preparation method and 1400 °C heat treatment. The main object we are fighting is not a field emission loading but a fast breakdown. In addition, Qo-degradation after the breakdown is our another serious problem. Basic research programs have just started to understand its mechanism. We will report on cavity performance and the first output from these studies. We describe also some results from the study on clean work and niobium material.

I. INTRODUCTION

Since 1990, KEK has continued to develop L-band superconducting cavities for TESLA. At the initial stage, three 1.3 GHz single-cell niobium cavities were manufactured at CEBAF and tested at KEK [1]. In the beginning of 1993, we moved to a new experimental hall and started again cavity tests. Our TESLA activities have joined to the JLC program from this year. We have started to fabricate single-cell cavities in collaboration with companies and by ourselves also. Currently we are focusing on the high field issue using these single-cell cavities. We have achieved the high field gradient of 30 MV/m without field emission loading by the preparation technique developed for the TRISTAN sc cavity project and applying a 1400 °C high temperature heat treatment. Field emission is not a major issue for us at the moment, however, a fast breakdown and Qo-degradation after the breakdown are our present serious problems (Japanese Qo-disease ?). Also two nine-cell structures were fabricated as TESLA prototypes. One was made by CEBAF and another was made by MHI. Beside these studies using superconducting cavities, we have continued fundamental investigations on clean work, niobium material, the Japanese Qo-disease and so on. In this paper, we will report progresses in cavities and fundamental studies at KEK after the DESY workshop.

II. NEW EXPERIMENTAL HALL

Until the end of 1992, we had tested superconducting cavities in the TRISTAN assembly hall that was prepared for the TRISTAN project, however, we had to move to other place because KEK decided to construct an accelerator test facility (ATF) there for the JLC program. Instead of the assembly hall, we obtained a new experimental hall for our R&D on superconducting rf cavities. KEK TESLA group moved there on this February in 1993 and started further development on L-band cavities. Figure 1 shows an inside view of our new building. Currently we are constructing a new class 10 clean room in this hall for cavity assembly. We schedule to complete it by the end of the next January in 1994. A high temperature heat treatment system for L-band nine-cell cavities also will be built up there in near future.

III. SINGLE-CELL CAVITIES

The detailed information such as geometry of cavities, surface preparation, measurement and so on will be presented in other paper in this workshop [2]. Our progresses after the DESY workshop are summarized as follows.

1) A low Q problem at an early stage was solved.
2) An in-house cavity fabrication technique was established at KEK.
3) High temperature heat treatment at 1400 °C for single-cell cavities became available.
4) High pressure ultrapure water rinsing system was developed.
5) Two 9-cell structures as TESLA prototypes were fabricated.
6) Diagnostic systems were improved.

In these topics, 5) will be discussed later in detail. 6) is omitted here because it is minutely described in the reference [2]. By these efforts, we have achieved the accelerating field of Eacc = 20-30 MV/m in single-cell cavities without any field emission loading. Our present field limitation is the fast breakdown. This will be discussed later in this section.

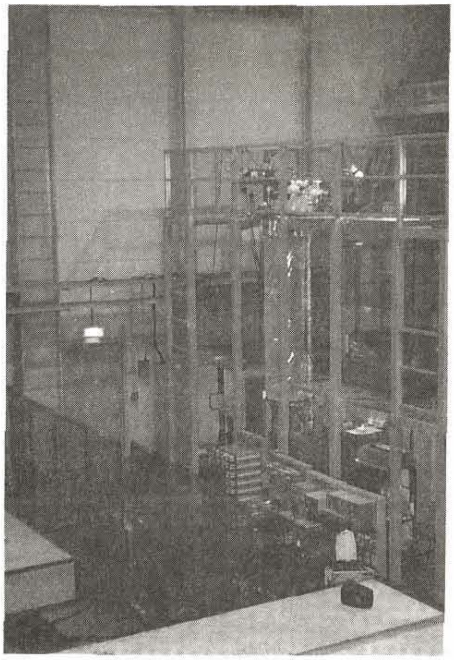

Fig. 1 An inside view of our new experimental hall.

Low Q problem in an early stage

We found this problem is due to the external magnetic field in the cryostat. By the measurement of the residual magnetic field strength, there was an external magnetic field of 150 mG in the cryostat [3]. We added another magnetic shield made of Permalloy in the helium vessel and reduced the residual magnetic field to less than 10 mG. Qo value of cavities was improved from 4×10^9 to $\approx 10^{10}$ by this cure.

KEK in-house fabrication

For the future mass production, it is very helpful to have a detailed knowledge about manufacturing technique, man-power and so on. Several single-cell cavities have been already fabricated at KEK [4]. We manufactured elliptical shaped cavities which were scaled up from the Cornell/CEBAF 1.5 GHz cavity. Half cells are formed by deep drawing from 280ϕ-2.5 mm thick niobium sheets with RRR=200, then machined using a set of trimming jig. We measured the cell shape with a three-dimensional measuring equipment. Figure 2 shows a measurement scene at KEK. Measured deformation from a circle at the equator is less than 100 µm. Shrinking due to electron beam welding (EBW; 115 kV, 28 mA, 2.5 mm niobium thickness) is 0.6 ± 0.1 mm at the equator. We made beam tubes from the rolled and electron beam welded 2.5 mm thick niobium pipes. The total man-power-hour is about 15 hours to complete a single-cell cavity,

Fig. 2 Three-dimensional shape measurement at KEK.

which includes forming of half cells, trimming, rolling of beam tubes, machining of beam tube flanges and the all electron beam welding.

High temperature heat treatment

High temperature heat treatment (HT) was proved to be very effective to push up an onset field of field emission loading [5, 6]. Although the field emission is not a serious problem with the KEK's standard surface preparation procedure at the moment, we applied HT in expectation of purification, better outgassing, homogenization and their good effects on cavity performance. We examined the HT condition by measuring RRR value of niobium samples. Figure 3 shows a configuration of a single sided titanium (Ti) treatment (SST). In a case of a double sided Ti treatment (DST), another Ti pipe is added in the cavity. Results of RRR measurement are summarized in Table 1. These measurements indicate that RRR of outside cavity wall is improved to 300-350 in both cases, and to 300 that of inside cavity wall in DST. Any definite improvement of RRR value can not be seen in inside cavity wall in SST.

Table 1 Change in RRR value by 1400 °C heat treatment.

	Double sided Ti		Single sided Ti	
	before	after	before	after
Outside of Nb box	201	59	178 198	62 64
Inside of cavity	192 189	278 313	181 183	213 209
Inside of Ti box	213 197 98 139 162 179	364 370 347 326 352 374	190 185 193 177 199 202 193 194	342 325 346 312 297 271 323 333

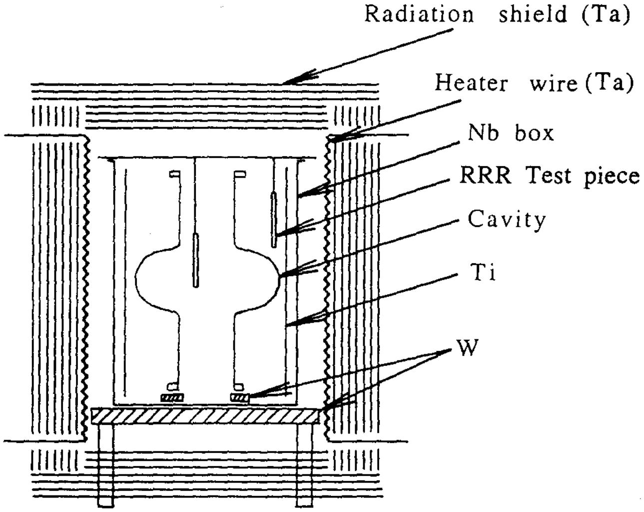

Fig. 3 Configuration of our high temperature heat testament with a singe sided titanium treatment.

So far we have treated five single-cell cavities with HT and an increase of the maximum accelerating field gradient is observed in four cavities. In three cavities, the field gradient was fairly improved, from 14-17 MV/m to 20-30 MV/m without field emission loading. Figure 4 shows a Qo versus Eacc curve of the best test. A tendency of the memory effect of HT is seen in two cavities (see Table 2). As is worried the titanium contamination during the heat treatment, we always took a final polishing by 20-60 μm to cavities.

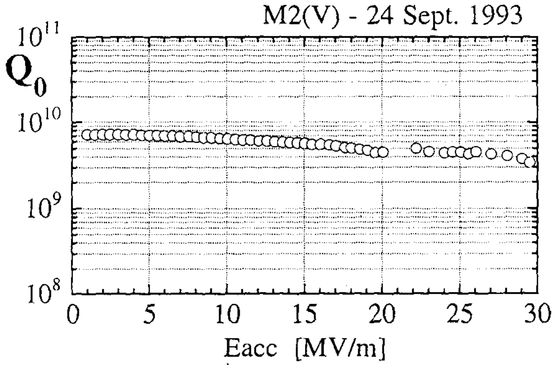

Fig. 4 Qo versurs Eacc curve in our record with achieved field gradients.

High pressure ultrapure water rinsing system

High pressure ultrapure water rinsing (HPR) is also expected to improve an onset field of field emission [7], and becoming popular [8]. We have also developed a high pressure ultrapure water rinsing system with a maximum pressure of 85 kg/cm^2, and applied it to single-cell and 9-cell cavities. At the beginning, a nozzle made of tungsten carbide was used. But during the third operation for cavity rinsing, we saw the pressure drop and found that the nozzle was scraped. We suspect that the contamination from the nozzle is one of the causes for field emission loading in some measurements. After changing the nozzle material to stainless steel, we applied HPR to a single-cell cavity. Eacc of 24 MV/m was achieved without field emission loading, but this does not mean the effectiveness of HPR since we can achieve 25-30 MV/m without field emission with the standard surface treatment. The details will be described in the reference [9].

Japanese Qo-disease

The cold test results are summarized in Table 2. Our current field limitation is the fast breakdown. This breakdown suddenly happens without any precursors. Field emission loading has been never seen in Qo versus Eacc curves in our recent eight tests. Our another problem is a Qo-degradation which happens as a result of the fast breakdown. It should be emphasized that it is observed in our every cavity. Figure 5 shows the phenomenon in the Qo versus Eacc curve, and Figure 6 shows it in temperature maps. Just below the breakdown field level, any heating site is not observed (A). After the breakdown, Qo values began to degrade at low field. RF processing can not improve Qo values, even makes them worse. With increasing RF power, a local heating appears at an iris (B), and finally the trajectory of field emitted electrons becomes clear (D). We have following views about the fast breakdown and the Qo-degradation.

Table 2 Summary of tests for KEK L-band single-cell cavities.

Cavity	Test	RRR	Surface Treatment	Annealing	Eacc,max
C-1	I	350	C.P (70μm)	no	14.3 MV/m
	II		C.P (10μm+5μm)	760°C, 5 hours	15.5 MV/m
	III		HNO_3, C.P (5μm)	no	field emission
	IV		C.P (25μm)	no	13.6 MV/m
	V		C.P (35μm+50μm)	1400°C, 6 hours	25.1 MV/m
C-2	I	350	E.P (120μm+5μm)	660°C, 24 hours	field emission
	II		C.P (30μm+5μm)	760°C, 5 hours	15.6 MV/m
	III		no additional treatment.		field emission
	IV		E.P (100μm+20μm)	1400°C, 4 hours	20.5 MV/m
	V		E.P (30μm), HPR	no	20.4 MV/m
	VI		C.P (35μm)	no	20.2 MV/m
	VII		C.P (30μm), anodize	no	17.5 MV/m
M-1	I	100	E.P (110μm+5μm)	750°C, 10 hours	field emission
	II		E.P (80μm), HPR	1400°C, 4 hours	field emission
M-2	I	200	C.P (100μm+5μm)	760°C, 5 hours	17.3 MV/m
	II		E.P (100μm+30μm) Tumbling, HPR	765°C, 7hours	field emission
	III		C.P (100μm+5μm)	760°C, 6hours	field emission
	IV		E.P (100μm)+C.P (60μm)	1400°C, 6 hours	field emission
	V		E.P (115μm)+C.P (20μm)	710°C, 8 hours	29.5 MV/m
K-1	I	200	E.P (110μm)+C.P(15μm)	710°C, 10 hours	14.0 MV/m
	II		C.P (35μm)+C.P (40μm)	1400°C, 6 hours	17.1 MV/m

1) This fast breakdown accompanies the vacuum bursts and x-rays bursts.
2) This occurs over the wide field gradient range; Eacc =11.5 - 30 MV/m.
3) This happens for any preparation such as CP, EP, anodizing and annealing (760, 1400 °C).
4) This dose not concern to cavity materials; Fansteel material or Tokyo Denkai material.
5) This appears in different shaped cavities; spherical (KEK) or fully elliptical shaped cavities (Cornell/CEBAF type).
6) This does not related to the material of antenna (copper/niobium) of the input coupler.
7) The edge roundness of pickup port does not concern to this phenomenon; sharp or round edge.
8) CP or EP over 15 μm is needed to recover the performance.
9) Any other laboratories have never reported such the Qo-degradation. Is it the Japanese

Qo-disease ?

Once two points multipacting at the equator [10] was suspected as a cause of the breakdown. This mechanism is expected to have the field level of the first order around 17 MV/m for 1.3 GHz cavities. However, the fast breakdown level of cavities heat treated at 1400 °C is 20-30 MV/m and it seems too high. Now we think the most of the fast breakdowns are vacuum discharge at the location of low voltage capability in high surface electric field region. Our recent investigation on vacuum discharge with niobium samples reveals that once the vacuum discharge happens, the breakdown field degrades much and the successive processing can not improve the field any more (see Fig.15). This is very similar to the Japanese Qo-disease.

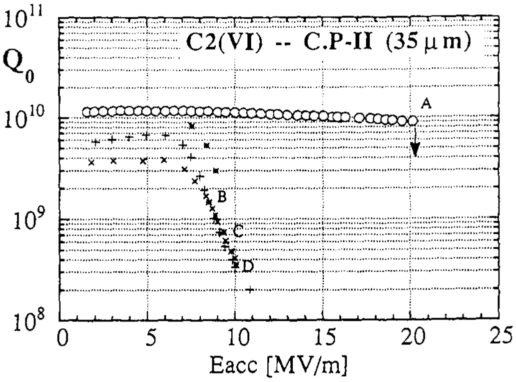

Fig. 5 Qo-degradation after the fast breakdown.

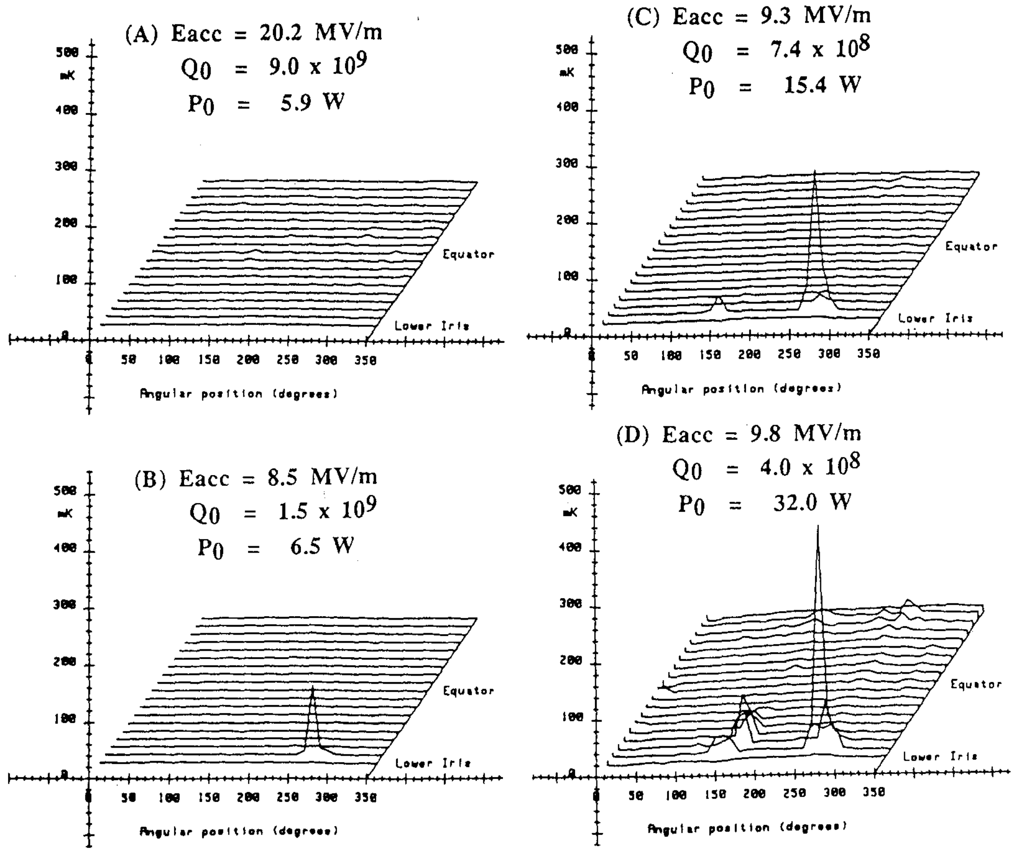

Fig. 6 Heating sites in the Qo-degradation after the fast breakdown.

IV. NINE-CELL STRUCTURES

We have fabricated two 9-cell structures as TESLA prototypes. One (9-C) was made at CEBAF [11]. Another (9-M) was manufactured in collaboration with MHI [12]. These have different shapes each other. The 9-M cavity has an improved shape against trapped mode. Fabrication method is the same as single-cell cavities. A horizontal rotating electropolishing system [13] was newly built up for these structures (see Fig.7). After the 80 μm electropolishing, we annealed them for five hours with Ti, at the vacuum pressure of 4×10^{-4} torr at 760 °C, in an industrial vacuum furnace that had been used to the TRISTAN sc cavities. These cavities are finally electropolished by 10 μm and rinsed with the high pressure ultrapure water.

Test results

The test results of these 9-cell cavities are shown in Fig.8. The 9-C cavity was limited to 9 MV/m in the accelerating field gradient by breakdown with a self pulsing of a repetition time about 1.5 seconds. Since we have no diagnostic system for 9-cell cavities, we do not know the heating location. However, from measurements of maximum stored energy on nine pass band modes, we suspect that both or one of the second cells from the beam tubes has bad spots. We are making an inspection system of cavity inner surfaces and a mechanical grinding system. We will inspect inside this cavity, and then mechanically grind off when candidates of bad spots are found.

We measured twice the 9-M cavity. The maximum fields were limited to 10 and 12 MV/m by field emission loading. As is mentioned before, we suspect that the contamination from the nozzle of our HPR system is an origin of field emission loading in these two tests.

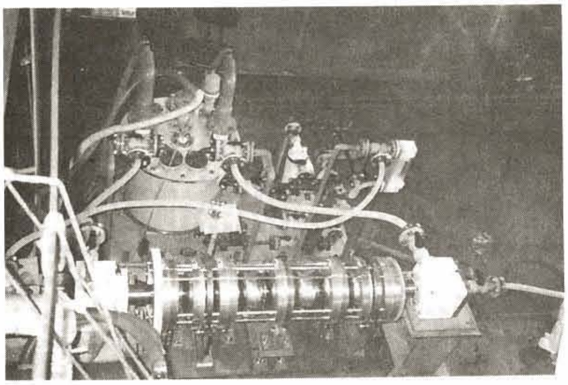

Fig. 7 Electropolishing system of L-band 9-cell cavities.

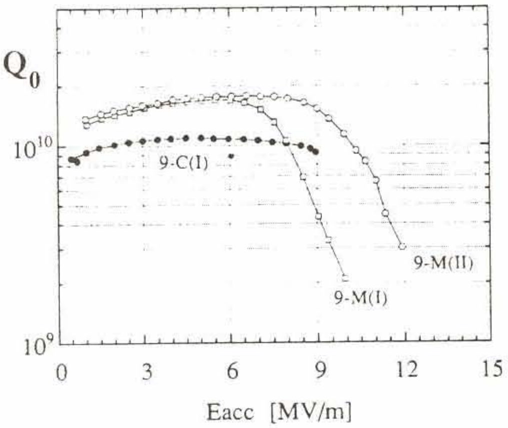

Fig. 8 Cold test results on 9-cell L-band cavities at KEK.

V. OTHER ACTIVITIES

Beside studies using cavities, we have continued fundamental investigations on clean work, niobium material and the Japanese Qo-disease. Here we briefly describe some recent results from these studies.

Clean work

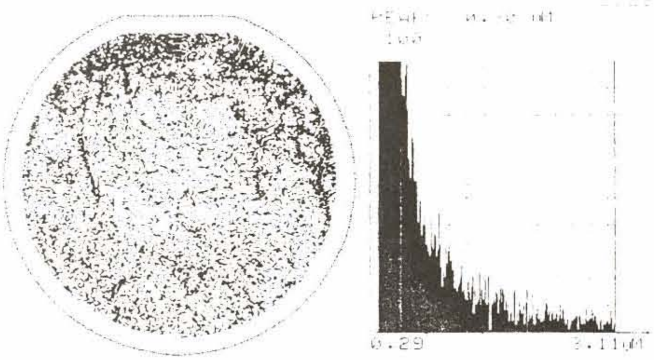

Fig. 9 Residual particle distribution on a silicon wafer rinsed with the TRISTAN rinsing procedure.

As already mentioned, field emission loading is not a problem on our single-cell cavities at least up to Eacc = 30 MV/m with our standard treatment. However, there are two reasons to do clean work studies. One is to improve the reliability on the surface treatment. The second is to establish a speedy and effective rinsing method, which leads to a cost down of surface treatment.

We evaluated environment, chemicals, rinsing processes such as HPR and megasonic agitation using silicon wafers. The number of particles left on surface was counted by a scanning laser particle counter [14]. Figure 9 shows the distribution of the residual particles on a wafer rinsed with the TRISTAN standard method, and Figure 10 shows that with HPR. Comparing these results, one can see that HPR enables to reduce the number of particles to one tenth from the TRISTAN's. The details of experiments and results are described in the reference [9]. Here we summarize the results as follows; 1) Megasonic rinsing is much effective than HPR to reduce particulate matters, 2) Use of clean chemicals such as electric grade for semiconductor technology looks more effective to reduce particles, 3) Surface treatment in a clean room is important to eliminate micro particles.

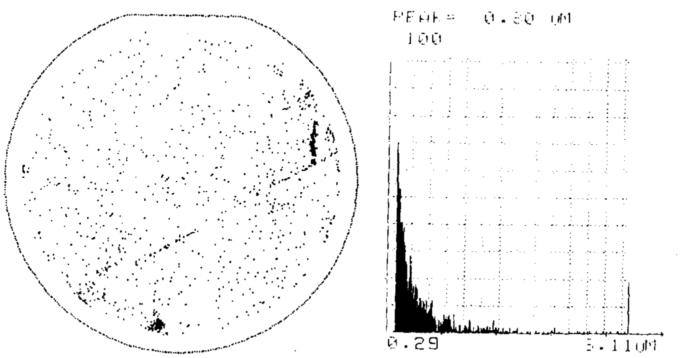

Fig. 10 Residual particle distribution on a silicon wafer rinsed with HPR.

Thermal conductivity measurements

So far we have used RRR values to estimate thermal conductivity of niobium material. This is enough for the liquid helium temperature because there is a well known relationship between a RRR value and a thermal conductivity in the superconducting state (λs) at 4.2 K as following[15];

$$RRR(4.2K)= 4{\cdot}\lambda s \ (W/mK).$$

However, we have no formula to estimate it at superfluid temperatures. It so depends on crystallization of material bellow 3 K (see Fig.11). We have started to measure the thermal conductivity of niobium material [16]. Figure 11 shows a comparison of those in the normal conducting state and the superconducting state. The normal conducting state is driven by applying the magnetic field of 1 Tesla parallel to the sample. Between 9 and 3 K, one can see clearly the condensation effect of cooper pairs in the superconducting state, which do not contribute to heat transfer. Figure 12 is our preliminary result for Tokyo Denkai's niobium materials with RRR = 50 - 400.

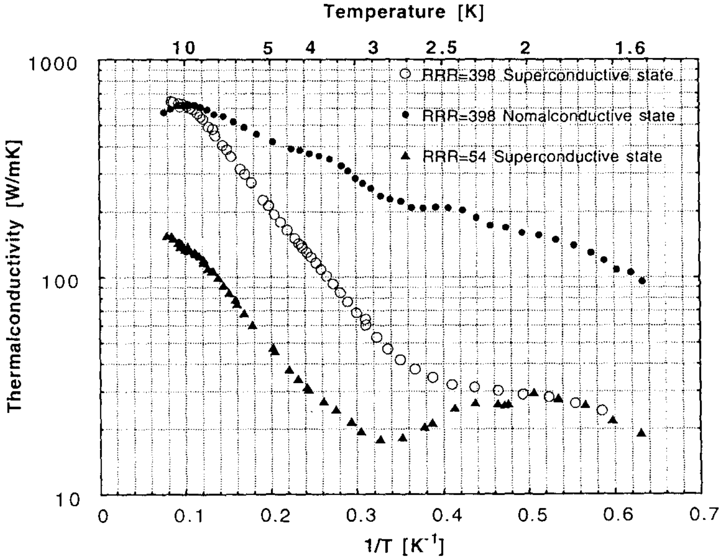

Fig. 11 Comparison of thermal conductivity between normal conducting state and superconducting state in niobium materials with RRR = 400.

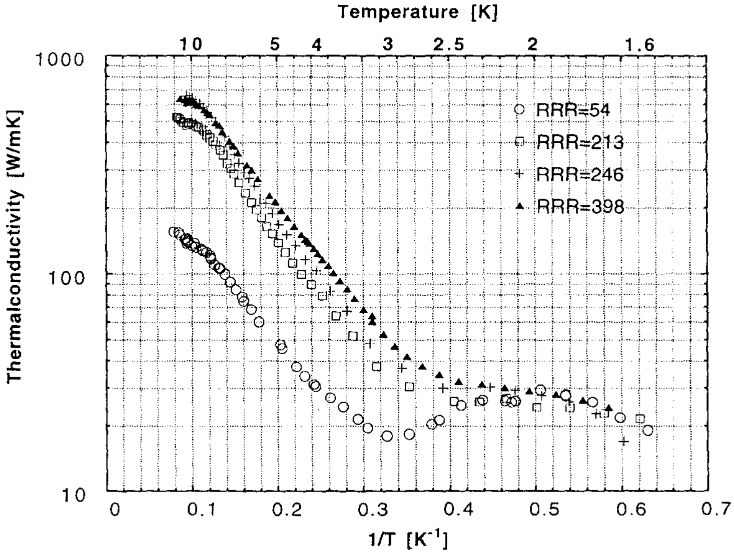

Fig. 12 Thermal conductivity of niobium materials with RRR= 50 - 400.

Hc1 and Hc2 measurements

The lower critical magnetic field (Hc1) will become much important when we solve the problem of the fast breakdown. The magnetic characteristics of type II superconductors strongly depend on vortex effect, which is dominated by crystallization, impurities, defects and residual stress in material. So, it will give us an information about inhomogeneity of materials. We have started measurement of Hc1 and Hc2 of niobium with a simple inductive method. Figure 13 is typical output from a pick up coil, for niobium samples as received, 1400 °C heated and chemically polished by 100 μm. The temperature dependencies of Hc1 for those samples are shown in Fig.14. As is seen in Fig.13, the as received sample shows a strange behavior, which probably comes from surface imperfection. The detailed study is still continued.

Surface analysis

Two single-cell cavities (C-2 and M-2) were cut and opened to investigate the inside surface with microscope and SEM to get a hint of the fast breakdown and the Japanese Qo-disease. Several voids were observed on niobium surfaces by a preliminary study. Now surface studies are intensively under way.

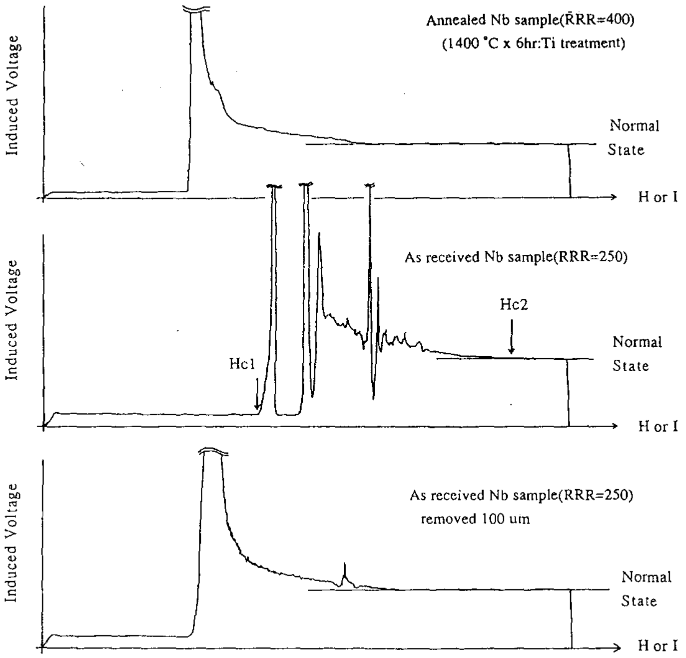

Fig. 13 Induced voltage signal from a pick up coil on niobium samples.

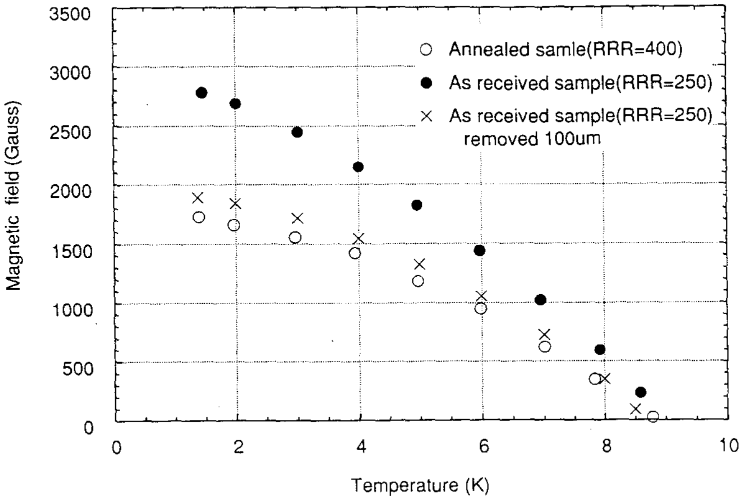

Fig. 14 Temperature dependence of Hc1.

Breakdown field measurement

Many observations suggest that the fast breakdown is a vacuum discharge in the cavity. We have started to investigate breakdown fields under the collaboration with the Saitama University. This experimental method is that one applies DC pulsed high voltages between the electrodes, at room temperature in the vacuum pressure of 1 x 10^{-10} torr [17]. The anode-cathode distance is changeable 10 to 0.3 mm. Figure 15 is outputs in our first experiment. Two kinds of niobium samples were tested in this experiment. One is a set of electrodes machined from the forged niobium material, then degreased and rinsed with ultrapure water. Another set is chemically polished by

100 µm after the machining, then rinsed with ultra pure water. The first breakdown field is very different in each other. The breakdown field decreases much in the second breakdown in both cases and conditioning effect is very week. We have a plane to make systematic experiments on niobium samples treated with various methods.

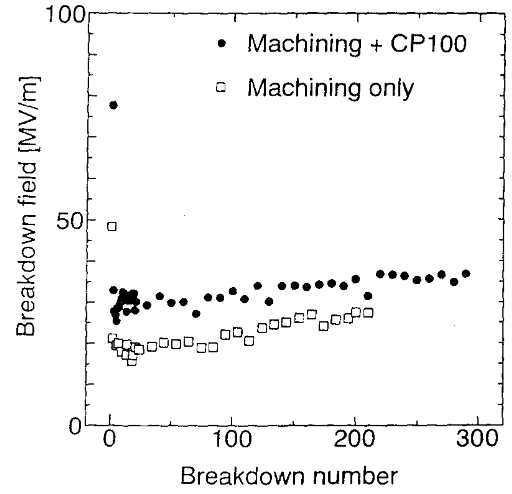

Fig. 15 Breakdown field on niobium by DC pulsed discharge.

VI. SUMMARIES

R&D of high gradient superconducting cavities for TESLA is being continued in the new experimental hall. By the combination of the high temperature annealing at 1400 °C and the TRISTAN standard surface treatment, we have achieved accelerating gradients of 20-30 MV/m reproducibly without field emission loading in single-cell cavities. Effect of 1400 °C or HPR on the suppression of field emission is not seen, so we conclude that both are not indispensable for single-cell cavities at these field gradients.

The fast breakdown and the resultant Qo-degradation are very serious problems for us, which happen in all single-cell cavities. The 1400 °C HT looks effective to push up the breakdown field and the attainable field gradient. We suspect that the fast breakdown is a vacuum discharge, and have started studies on DC vacuum discharge using niobium samples treated with various methods.

We have great concern for a development of a simple and effective rinsing procedure. The study using silicon wafers has shown that megasonic rinsing is very promising.

The material property of niobium is another concern of us, and may become much important subject at higher field. We will spare our effort also on this subject.

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REFERENCES

[1] E.Kako et al., "Initial Test of L-band Niobium Superconducting Cavities for Linear Collider Application", Proc. of the 5th Workshop on RF Superconductivity, DESY, Hamburg, Germany, August 19-23, 1991, P.751.

[2] E.Kako et al., "Test Results on High Gradient L-band Superconducting Cavities", in this workshop.

[3] E.Kako et al., "Development of Superconducting Cavities for High Gradient Applications", Proc. of the 3rd European Particle Accelerator Conference(EPAC), Berlin, Germany, 1992, P.1272.

[4] H.Inoue et al., "In-House L-band Niobium Single Cell Cavities at KEK", Proc. of the 18th Liner Accelerator Meeting in Japan, KEK, Tsukuba, Japan, July 21-23, 1993, P.323, in Japanese.

[5] H.Padamsee et al.,"New Results on RF and DC Field Emission", Proc. of the 4th Workshop on RF Superconductivity, KEK, Tsukuba, Japan, August 14-18, 1989, P.207.
[6] R.Röth et al., "Suppression of Field Emission in Superconducting S-band Accelerating Structures", Proc. of the 2nd European Particle Accelerator Conference (EPAC), Niece, France, 1990, Vol. 2, P.1097.
[7] Ph. Bernard et al., "Superconducting Niobium Sputter-Coated Copper Cavities at 1500 MHz", ibid. ref. [1], P.487.
[8] P.Kneisel et al.,"Experience with High Pressure Ultrapure Water Rinsing of Niobium Cavities", in this workshop.
[9] K.Saito et al., " Study of Ultra-clean Surface for Superconducting Cavities", in this workshop.
[10] W.Weingarten, "Electron Loading", Proc. of the 2nd Workshop on RF Superconductivity, CERN, Geneva, Switzerland, July 23-27 1984, P.551.
[11] K.Saito et al., "Development of a Superconducting Cavity for High Gradient Accelerators", Proc. of the XVth International Conference on High Energy Accelerators(HEAC),Hamburg, Germany, July 2-24 1992, P.969.
[12] M.Matsuoka et al., "Manufacturing of the L-band 9-Cell Niobium Cavity", Proc. of the 18th Linear Accelerator Meeting in Japan, KEK, Tsukuba, Japan, July 21-23 1993, P.304, in Japanese.
[13] K.Saito et al.,"R&D of Superconducting Cavities at KEK", ibid., ref.[5], P.635.
[14] C.Z.Antoine et al.,"Dust Contamination During Chemical Treatment of RF Cavities", ibid. ref. [1], P.456.
[15] H.Padamsee, "The Technology of Nb Production and Purification", ibid. ref.[9], P.339.
[16] H.Umezawa et al., "Development of High Purity Niobium Material for Superconducting Cavities", ibid. ref.[4], P.318, in Japanese.
[17] S.Kobayashi et al., "Vacuum Breakdown Strength of Vacuum-degassed Oxygen-free Copper Electrodes", IEEE Transactions on Electrical Insulation, Vol. 28 No. 4, August 1993, P.500.