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HIGH-Q/HIGH-G R&D AT KEK USING 9-CELL TESLA-SHAPED NIOBIUM CAVITIES

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Abstract

Since April 2019, we have evaluated the performance of three TESLA-shaped niobium superconducting radio-frequency cavities at the vertical test facility of KEK-STF. These cavities were made of fine grain niobium materials with residual resistivity ratio > 300 and were annealed at 900 °C for 3 h. All cavities achieved a Q_0-value > 2 $\times 10^{10}$ and a maximum accelerated gradient of >35 MV/m when the standard process for International Linear Collider was applied. Then, additional surface treatments and experimental techniques for enhancing cavity performance were applied to the three cavities as follows: (i) 2-step baking at 70–75 °C for four hours followed by 120 °C for 48 h (ii) electropolishing process at a lower temperature than the standard condition (iii) cooling procedure to increase the cooling speed and the temperature gradient between cells before the vertical test. We herein report on these additional surface treatments and experimental techniques and the cavity performance after applying them.

HIGH-Q/HIGH-G R&D AT KEK

The International Linear Collider (ILC) project has been proposed as a next-generation collider experiment for elementary particle physics [1]. Therein, electron and positron beams are accelerated to a center of mass energy greater than 250 GeV in linac and head-on collisions. Several 1.3 GHz elliptical shaped 9-cell niobium SRF cavities are used for the main accelerator component. The ILC experiment has the capability to precisely verify the standard model in elementary particle physics and also search for various results indicating theoretical models beyond the standard model. In recent years, the consensus that cost reduction is essential for realizing an ILC project in the future has been formed. The major cost of an ILC is the preparation cost for about over 8000 SRF cavities. Improvements in maximum accelerating gradients decrease the number of cryomodules and shorten the length of the tunnels. Improvements in the RF surface resistance reduce the RF power and refrigerator power otherwise lost during operation. Thus, High-Q/High-G R&D of SRF niobium cavities is thought to be the most effective approach for cutting ILC costs. According to this consensus, KEK have proceeded with high-Q/high-G R&D for ILC-cost reduction, such as nitrogen infusion [2–4]. In this study, we tried to evaluate the effectiveness of methods regarded as promising in High-Q/High-G R&D by performing a vertical test at KEK STF.

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MOTIVATION FOR THIS STUDY

A summary of our study on improvements in the cavity performance of three TESLA-shaped niobium superconducting radio-frequency (SRF) 9-cell cavities performed at KEK-STF from the beginning of 2019 to date is presented in this paper. Theses cavities are 1.3 GHz elliptical shaped SRF cavities made of fine grain niobium material with residual resistivity ratio (RRR) > 300 and manufactured by Mitsubishi Heavy Industries Mechanical Systems Co. The cavities are referred as to MT-3, MT-5 and MT-6. The surface treatments applied to these cavities include electropolish (EP) and heat treatment at 900 °C for 3 h at KEK. As a result, we achieved Q_0-values greater than 2 $\times 10^{10}$ and the maximum accelerating gradient > 35 MV/m for the three SRF cavities using a standard surface treatment processes developed for ILC. In this study, we applied new surface treatments in order to enhance the cavity performance and compared the results with those of cavities to which ILC standard recipes had been applied; the following treatments were first examined at KEK: (i) EP method at a lower temperature than the KEK-standard condition (ii) two-step baking that has been reported to improve the Q_0-value by 15% and the achievable electric field by 20% [5]. In addition, we newly adopted an experimental technique for cooling the cavity faster than usual. This is the first case where a fast-cooling method was applied at KEK. We performed a vertical test measurement at KEK-STF to evaluate the efficacy. We report on the obtained results.

METHOD

We evaluated the cavity performance of three SRF cavities (MT-3, MT-5, and MT-6) to which cold EP, 2-step baking, and original cooling procedures (KEK-fast cooling and additional cooling methods) were applied. The conditions adopted in this study are summarized in Figure 1. 2-step baking is a surface treatment consisting of a pre-baking procedure for four hours at about 75 °C and thereafter, another baking procedure at 120 °C for 48 h, which has been the de-facto standard surface treatment to date. Literature [5] describes an example in which the maximum accelerating gradient and the Q_0-value of a 1.3 GHz TESLA-shaped niobium SRF cavity were increased by 20% and 15% by applying 2-step baking, respectively. In contrast, in this study EP was applied to cavities at a lower temperature condition than the KEK-standard. Usually, at KEK EP as KEK standard is performed at a temperature of 25–30 °C, whereas cold EP at KEK is performed at a temperature of 14-15 °C. Generally, cold EP has the effect of suppressing hydrogen

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absorption and sulfide precipitation on the niobium surface. In this study faster cool-down procedure, than ordinal one, was first applied to the cavity at KEK, during the cool-down process for the vertical test. The faster the cooling speed is, the lower and smaller the number and size of harmful niobium hydrides are. At other institutes, such as FNAL and JLab, fast cool-downs have been used for increasing the temperature gradient between the cells, resulting in a force that expels magnetic flux from the cavity walls and reduces the residual resistance. As a result, the Q_0 value is improved by a fast-cool down. However, unfortunately, the experimental facility at KEK STF is not directly connected to a refrigerator, and therefore, the cooling speed is not high enough. In other words, the SRF cavity has to be cooled by transferring liquid helium from a dewar at KEK STF. Hence, we developed an experimental technique for effectively increasing the cooling speed and the temperature gradient between the cells. Regarding the first, we transferred liquid helium as fast as possible by pumping a cryostat containing the cavity, so that the vacuum pressure was kept lower than the safety level. Regarding the latter, a 2-step cooling procedure consisting of pre-cooling and an additional cooling process were adopted.

	VT	EP	Bake	Cooling
MT3	VT4 (Baseline)	KEK-STD (20 um)	120 °C 48 h	KEK-STD
	VT5	KEK-cold (20 um)	75 °C 2h (cell1) / 75 °C 4 h (others) + 120 °C 48 h	KEK-STD
MT5	VT1 (Baseline)	KEK-STD (20 um)	120 °C 48 h	KEK-STD
	VT2	KEK-cold (20 um)	75 °C 4 h + 120 °C 48 h	KEK-STD
	VT5	KEK-cold (10 um)	75 °C 4 h + 120 °C 48 h	KEK-STD
	VT6	KEK-cold (20 um)	70 °C 4 h + 120 °C 48 h	KEK-STD w/ additional cooling
MT6	VT5 (Baseline)	KEK-STD (30 um)	120 °C 48 h	KEK-Fast w/ additional cooling
	VT6	KEK-cold (10 um)	70 °C 4 h + 120 °C 48 h	KEK-Fast w/ additional cooling

Figure 1: Surface treatment and cooling conditions used in this study

SURFACE AND HEAT TREATMENTS AND COOLING PROCEDURE USED IN THIS STUDY

Figure 2 shows an example of a time evolution plot of current density versus cavity temperature during electropolishing. The red line represents the current density, the blue line the cavity temperature, and the black line the polishing amount. It can be seen that the cavity temperature is nearly 25–30 °C for the standard condition, whereas it is <15 °C for the KEK cold EP. In cold EP, EP acid was cooled by controlling applied voltage to the cavity properly. It takes about 3.5 times longer for the cold EP to cool than for of KEK standard-EP.

Figure 3 shows an example of a time evolution plot of the cavity temperature and vacuum level during 2-step baking. The cavity temperature is measured by using the temperature sensors attached to the equator of the 1st, 3rd, 7th, and 9th cells, and the vacuum level is measured using the ion gauge installed at the end of the flexible tube connected to the vacuum port of the 1st-cell side. It has to be noted that there were problems in the two-step baking process applied before the MT-3 VT5, because the wire of the ribbon heater wrapped to 1-cell was broken at the start of baking. The issue was resolved very quickly, but the vacuum level deteriorated slightly from that of the ideal case, and the time cell 1 was kept at 75 °C was reduced to about 2 h.

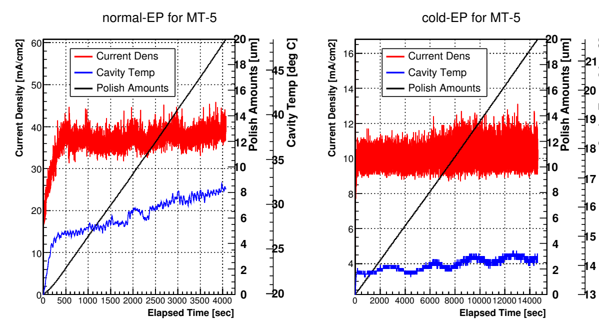

Figure 2: EP parameters applied before MT-5 VT1 (KEK-standard EP) and MT-5 VT2 (KEK-cold EP) as a function of elapsed time.

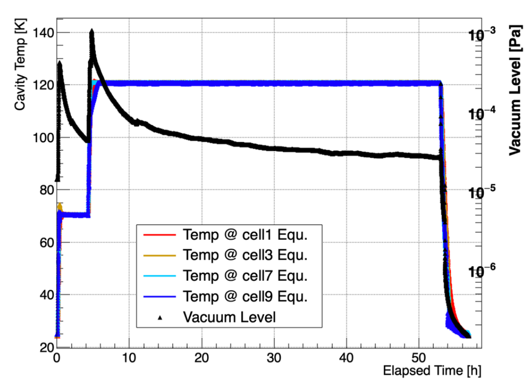

Figure 3: Temperature and vacuum level during 2-step baking as a function of elapsed time. This is the case for the bake applied before MT-5 VT6.

Figures 4 and 5 show examples of the temperature of each cell of a 9-cell SRF cavity during the cooling process at KEK. Figure 4 exhibits the cool-down data obtained during the KEK-standard cooling process, during which liquid helium was transferred from a dewar. In contrast, Figure

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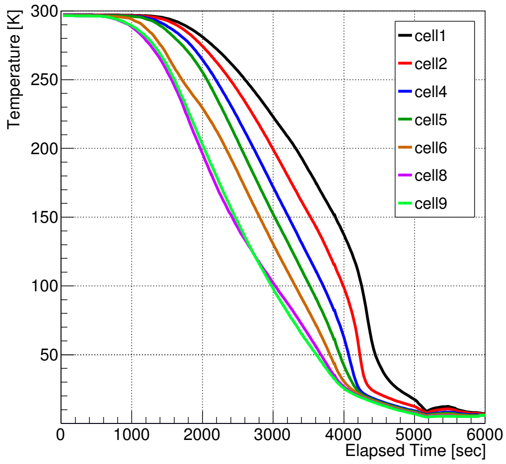

Figure 4: Temperature during KEK standard cooling process as a function of elapsed time

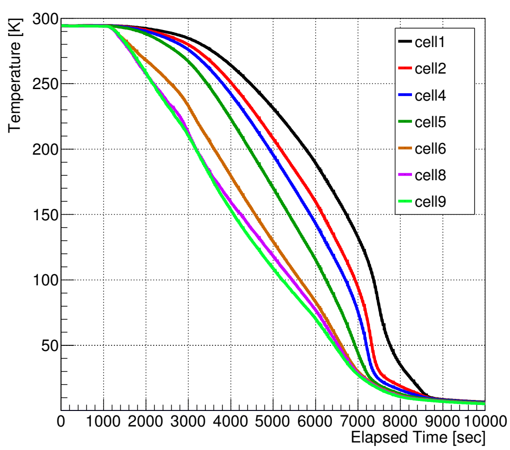

Figure 5: Temperature during KEK fast cooling process as a function of elapsed time

5 shows the result obtained during the KEK-fast cooling process, during which liquid helium was transferred as fast as possible while depressurizing the cryostat, so that the gas pressure did not exceed the allowed safety level. The KEK-fast cooling method increased the cooling speed by a factor of two compared with that of the KEK-standard. In addition, as mentioned above, we adopted a 2-step cooling method for increasing the temperature gradient between the cells of a 9-cell SRF cavity at the superconducting transition. Figures 6 and 7 show the time evolution of the magnetic field strength on the surface of the SRF cavity during helium transfer. Magnetic fields were evaluated by a flux gate sensor attached to the equator of each cell of the 9-cell SRF cavity. Figure 6 exhibits the obtained results of the pre-cooling process, and Figure 7 shows those of the additional cooling process. It was determined that the flux expulsion of all cells during the additional cooling process became larger than during the KEK-standard cooling process.

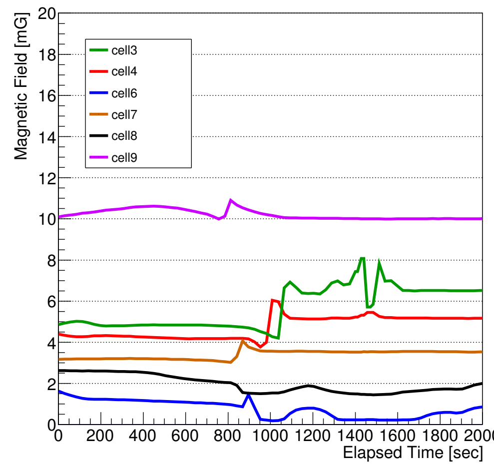

Figure 6: Flux expulsion during pre-cooling procedure as a function of elapsed time

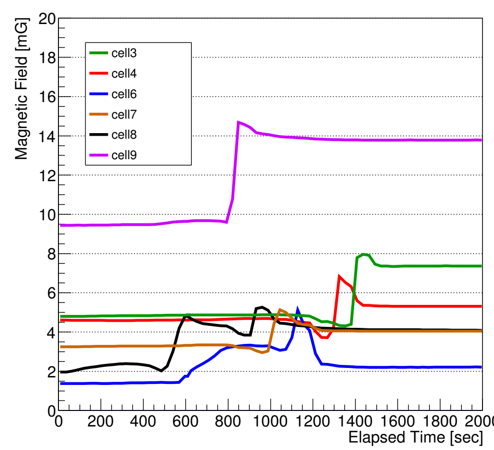

Figure 7: Flux expulsion during additional cooling procedure as a function of elapsed time

EVALUATION OF THE CAVITY PERFORMANCE

The Q-E curves of the MT-3, MT-5, and MT-6 cavities are shown in Figures 8, 9, and 10. The horizontal axis represents the accelerating gradient, the left and right vertical axes represent the Q_0 value and the radiation level detected during the measurement, respectively. The data points on the Q-E curve and the radiation level are represented by circled points and cross points, respectively. For simplicity, only the data for the π mode measurement are plotted here. The Q_0-value has a 10% error; hence, no improvements were observed for when the KEK-standard cooling procedure was adopted, as shown in Figures 8 and 9. In contrast,

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Table 1: Summary of Obtained Results from Passband Mode Analyses (Unit is MV/m)

Cell	MT3 VT4	MT3 VT5	MT5 VT1	MT5 VT2	MT5 VT5	MT5 VT6	MT6 VT5	MT6 VT6
1 & 9	36.9	36.6	36.3	36.3	35.7	40.7	>42.8	39.5
2 & 8	42.0	36.6 (F.E.)	>40.4	40.2	40.2	>40.7	>42.8	>43.6
3 & 7	43.8	>38.9	41.0	>39.6	>34.7	>40.7	>42.8	43.5
4 & 6	45.1	>40.5	39.0	40.0	31.1 (F.E.)	>40.7	>42.8	41.2
5	43.0	>41.9	40.4	40.6	>40.2	>40.7	>42.8	43.6
EP	STD	Cold	STD	Cold	Cold	Cold	STD	Cold
bake	STD	2-step	STD	2-step	2-step	2-step	STD	2-step
Cooling	STD	STD	STD	STD	STD	2-step	Fast + 2-step	Fast + 2-step

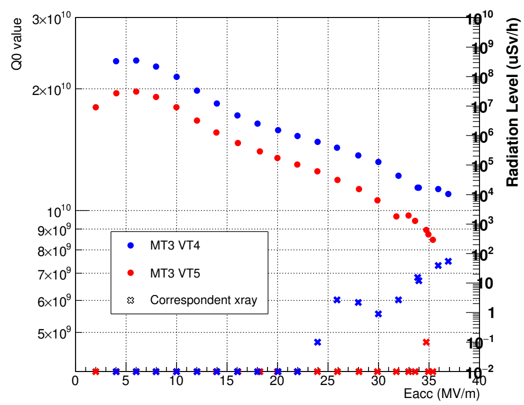

Figure 8: Vertical test results for MT-3 for π mode measurement

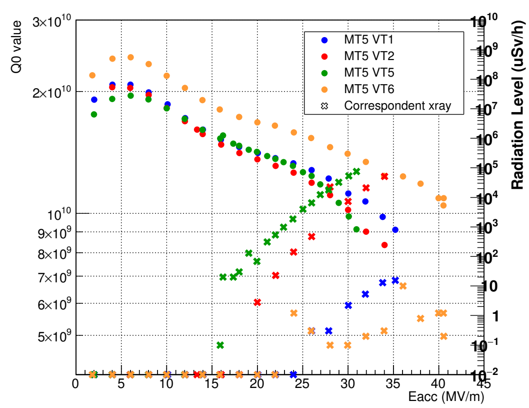

Figure 9: Vertical test results for MT-5 for π mode measurement

the Q_0-value was improved significantly, especially for low E-fields after fast cooling and/or the 2-step baking method. The analysis results from all pass-band mode measurements are shown in Table 1, wherein the maximum accelerating gradient for each cell is summarized. In this study, an improvement of the acceleration gradient was observed only for the 2-step cooling process. No significant improvement was observed for the KEK-standard cooling procedure. The yield rate for the improvement in the quench field was 50% when combining 2-step baking with the other cooling procedure. We would like to collect more statistics in future research projects to confirm this trend.

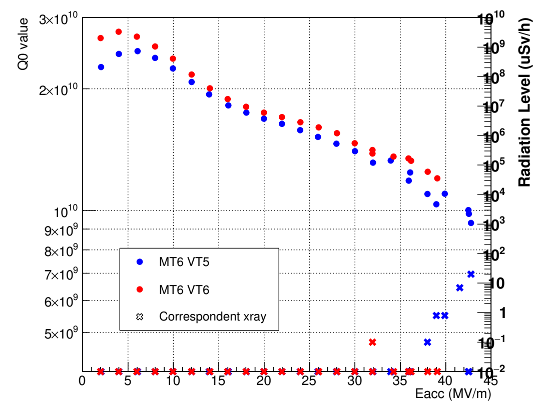

Figure 10: Vertical test results for MT-6 for π mode measurement

SUMMARY

We investigated the effectiveness of cold EP, 2-step baking, and the standard cooling procedure, with the aim of achieving a high cooling speed (KEK-fast cooling) and a high temperature gradient between the cells (2-step or additional cooling), for High-Q/High-G R&D at KEK. This is the first study in which these treatments and cooling conditions were tested at KEK. We used three 1.3 GHz TESLA shaped niobium SRF 9-cell cavities made of fine grain niobium materials with RRR > 300 which had been annealed at 900 °C for 3 h. We evaluated the cavity performance by a vertical test at KEK-STF. All cavities achieved a Q_0-value of > 2 $\times 10^{10}$ and a maximum accelerated gradient of >35 MV/m for the standard surface treatments for ILC. We compared the maximum accelerating gradients and the Q_0 values, corresponding to the conditions summarized in Figure 1. As a result, no improvement could be observed when only 2-step baking was applied, whereas significant improvement in the Q_0-value could be observed for the combination of 2-step baking with the other cooling procedure. The yield rate for improvements in the maximum accelerated gradient was 50% even when combining 2-step baking with the other cooling procedure.

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