High Field Studies on L-band Superconducting Cavities at KEK

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Abstract

Several 1.3 GHz single-cell and nine-cell niobium cavities were fabricated to attain a higher maximum accelerating gradient and to understand the phenomena limiting it. Vertical cold tests at ~1.8 K for the 4 single-cell cavities prepared by various surface treatments have been conducted 15 times. In eight of the tests, maximum accelerating gradients (Eacc,max) of more than 14 MV/m were obtained with no field emission. Furthermore, Eacc,max values of higher than 20 MV/m with a high Q_0 value of $\sim 10^{10}$ were achieved repeatedly after heat treatment at 1400°C. Once quenching was observed at Eacc,max (14~20 MV/m), however, a common phenomenon resulting in Q_0-deterioration occurred in every test. The cavity performances and the phenomenon at high fields are reported in this paper.

I. INTRODUCTION

The development of high gradient superconducting cavities is an essential factor for their application in future accelerators, such as B-Factory and TESLA (TeV Energy Superconducting Linear Accelerator). The understanding of the current limitations of cavity performances is crucial for attaining a higher accelerating gradient. In the case of the TESLA application, an accelerating gradient of higher than 25 MV/m with a Q_0 value of $>5\times10^9$ and a cost reduction to less than 20 k$/m are required. Our activity has been devoted to realizing these two objectives, and a series of the cavity tests have been continued at KEK since 1990 [1, 2]. Accelerating gradients of higher than 20 MV/m were successfully achieved by the technologies developed at KEK and CEBAF, and understanding of the Q_0-deterioration which begins just after quenching at Eacc,max is an urgent problem at present.

In superconducting cavities, the high field phenomena which limit the maximum accelerating gradient (Eacc,max) are principally multipacting, thermal break-down, field emission and Q_0-disease. Among them, field emission is currently the most difficult problem to suppress. The field emission phenomenon is explicated by the quantum mechanical tunneling of electrons through the modified potential barrier at the surface of a metal in a high external electric field. Dust and foreign material on the surface, chemical residue from surface treatment and surface irregularities such as projections, scratches or weld imperfections are considered to be potential sources of emitted electrons. The emitted electrons are accelerated and impact elsewhere on the cavity surface. Consequently, the steep decrease in the value of Q_0 is observed.

We developed a temperature mapping system with a high thermal sensitivity under superfluid helium. The temperature rise due to the power deposition from electron impact can be detected by carbon thermometers attached at the outer surface of the cavity. Temperature mapping of the cavity surface is important in order to understand the phenomena limiting Eacc,max. In each cavity test, the appearance of the heating sites was clearly observed after quenching at the Eacc,max, in spite of their absence before quenching. This phenomenon is discussed in the later section.

II. EXPERIMENTAL RESULTS

Four single-cell cavities and two nine-cell cavities have been tested repeatedly for various surface preparation. Initial RRR values of these cavities are as follows; 350 (C1 and C2), 250 (9C), 200 (M2 and 9M), 100 (M1). Here, the 9C and 9M represent nine-cell cavities fabricated at CEBAF and MHI, respectively, and the others are single-cell cavities in the same notation. Figure 1 shows the single- and the nine-cell cavities waiting for the installation in the vertical cryostat for the cold test. The inner surface of the cavity was treated by electro-polishing (EP) or chemical polishing (CP). Heat treatment at 760°C for hydrogen degassing was pursued. In some cases, 1400°C heat treatment with titanium-gettering was applied for purification. A high pressure water rinsing (HPR) system with 80 kg/cm^2 ultra-pure water was developed

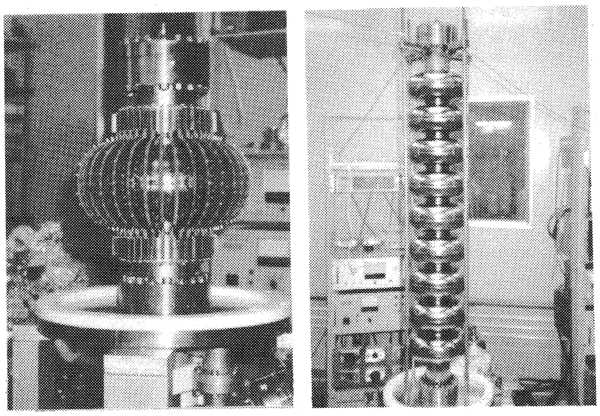

Fig. 1 A single-cell cavity with attached carbon thermometers (left) and a 9-cell cavity (right) installed in the vacuum stand.

for the active removal of dust or debris on the cavity surface. Careful ultra-pure water rinsing combined with ultrasonic agitation, and assembly in a clean environment were always executed. Prior to the test, pre-cooling with liquid nitrogen was carried out for one night in order to reduce consumption of liquid helium. The helium bath temperature was reduced to around 1.8 K by three rotary pumps (total 260 l/s).

The results of Eacc,max obtained for 15 tests on 4 single-cell cavities are summarized in Fig. 2, in which Roman numerals inside the parentheses indicate the n'th test of the cavity after retreatment. The limitation of Eacc,max illustrated by quench and field emission are clearly separated at 13 MV/m as shown in the figure. Here, we define the quench as the instantaneous disappearance of the cavity field due to abnormal heating or discharge somewhere inside the cavity. In eight of the tests, Eacc,max of higher than 14 MV/m was achieved with no field emission and high Q_0 values. In three tests (IV,V,VI) of the C2 cavity after heat treatment at 1400°C, the Eacc,max values were remarkably improved from 15.5 MV/m to 20.5 MV/m, but in each test the Eacc,max was limited by the similar phenomenon at the same gradient independent of the type of surface treatment (EP or CP). The deterioration of Q_0 values occurring after quenching at the Eacc,max is a common phenomenon observed in all our tests [1], and this is discussed in the next section. On the other hand, the cavities suffering from field emission have Eacc,max values of less than 12 MV/m, and the Q_0 values at Eacc,max degrade to less than 10^9 due to strong electron loading. The field enhancement factor (β) obtained by F-N plots of $\Delta(1/Q_0)$ is usually between 200 and 400. The causes of the field emission in our tests seem to lie in the surface preparation of the cavities. The cause of field emission in the case of C1(III) and C2(III) is poor polishing. After Q_0-deterioration in a previous test, the removal of 5 μm in C1(III) and only warm-up in C2(III) could not recover the cavity performance. Consequently, removal of more than 15 μm is necessary to take away the emitter sources after Q_0-deterioration. In the M1 cavity, a number of pits existed at the equator and iris because of weld imperfections. We suspect that the effect of tumbling, which was performed for the M2 cavity just after the successful result of M2(I), was responsible for the poorer results in the cases of M2(II) and (III). However, we could not identify the real emission site of electrons by eye after each test.

Residual surface resistances (Rres) in a series of cavity tests are indicated in Fig. 3, labeled with CP and EP. The Q_0-disease due to hydrogen precipitation was observed in C1(I) [CP 70μm-7min., no heat treatment] after pre-cooling. After warming up to room temperature and fast cooldown to helium temperature within 1 hour, the Rres was considerably reduced from 900 nΩ to 72 nΩ. Relatively large Rres in the initial 4 tests were caused by a residual magnetic field (~150 mG). An improved magnetic shield reduced the residual field to less than 10 mG, and the Rres were reduced to 10~30 nΩ regardless of the surface treatment (EP or CP). In two tests, however, the values of Rres were still large. In M1(II) [EP 80μm-2.5 hr. after 1400°C] and M2(III) [abnormal CP 100μm-"40min." before 760°C], weak Q_0-disease may arise from relatively long term chemical exposure.

Figure 4 shows Q_0-Eacc plots for the 8 cavity tests

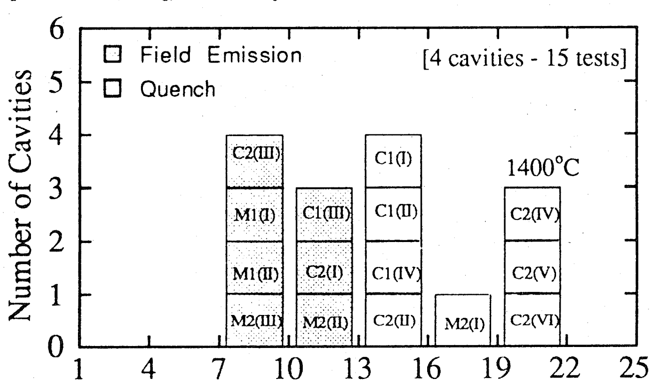

Fig. 2 Distribution of the Eacc,max for 15 tests on 4 single-cell cavities.

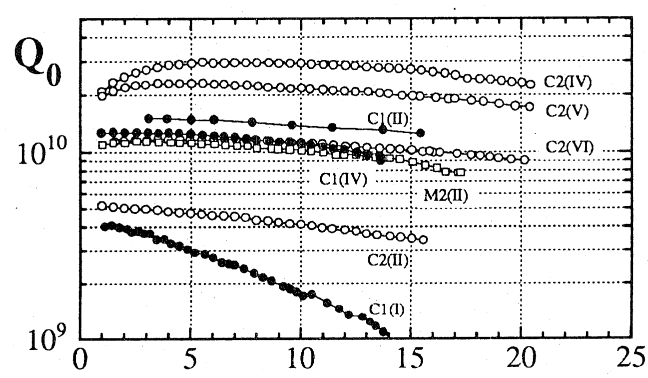

Fig. 4 Q_0 - Eacc plots in the case of no Q_0-drop by field emission for the single-cell cavities.

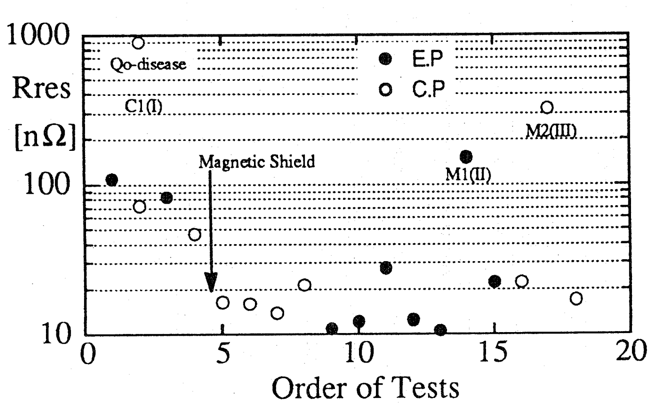

Fig. 3 Residual surface resistances for each test.

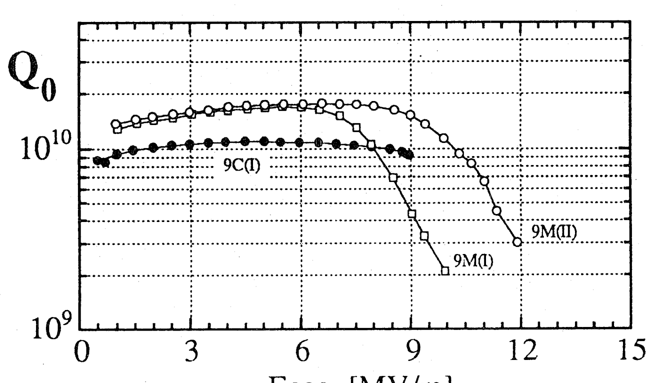

Fig. 5 Q_0 - Eacc plots for the 9-cell cavities.

limited by quench. C1(I) and C2(II) are the results before the installation of the improved magnetic shield, and the others are after it. As a result of the improved magnetic shield and heat treatment at 760°C or 1400°C, the Q_0 values of above 10^{10} at low field were obtained. The difference between C1(I) [CP, no heat treatment and fast cool-down] and C2(II) [CP, 760°C] indicates the effect of the heat treatment. The decrease of the Q_0 value with the increment of Eacc is considerably large with no heat treatment due to the influence of hydrogen. The highest Q_0 value was attained in C2(IV) [EP 20μm] after heat treatment at 1400°C. The Q_0 value gradually decreased with the successive surface treatment in C2(V) [EP 30μm] and C2(VI) [CP 35μm] probably due to the influence of hydrogen. The Q_0 value of 9×10^9 at 20 MV/m was still maintained in C2(VI), in spite of the total removal of 85μm after heat treatment at 1400°C. The Eacc,max values in these three tests were limited at the same field of 20.5 MV/m.

The test results of the 9-cell cavities are shown in Fig.5. Both 9C and 9M were treated by an initial EP of 80μm, heat treatment at 760°C for 5 hours and a final EP of 10μm. The 9C cavity was limited at 9.0 MV/m due to a self-pulsing phenomenon of the repetition between heating and cooling at the defects. In 9M(I) and 9M(II) [additional EP 20μm], the Eacc,max were limited at 10-12 MV/m by strong x-ray radiation, and the reason for the field emission lies in the surface contamination during HPR [2].

III. Q_0 - DETERIORATION AFTER QUENCH

A temperature mapping system consisting of 684 carbon resistors as shown in Fig. 1 was developed to investigate in more detail the mechanism of Q_0-deterioration after quenching at Eacc,max. The data acquisition system is almost the same as that in ref. [3]. To increase the thermal sensitivity under superfluid helium, it is essential that the sensors of the thermometers possess good thermal contact to the niobium surface and efficient thermal insulation against the surrounding helium. A carbon resistor (51Ω, Allen-Bradley) was embedded in a housing made from STYCAST for thermal insulation. The carbon of the resistor was exposed only at the contact surface with the niobium, and was coated with electrically insulated thin layer. The sensor was bonded to the niobium surface using varnish with good thermal conductivity at low temperature, and was fixed firmly by spring action from the support board. 19 sensors spaced about 10mm apart in one meridian were attached every 10 degrees in the azimuthal direction. In this temperature mapping system, the thermal sensitivity of temperature rise is 5 mK and the scanning time of a whole cavity is 20 seconds.

Quenching at Eacc,max and Q_0-deterioration thereafter are a common phenomenon existing in all our tests which achieved 14~20 MV/m with no field emission. At the moment of quench, the cavity tuning loop becomes unlocked and the vacuum pressure decreases for an instant. After this, a Q_0 value at high field begins to deteriorate gradually, and rf processing causes a further Q_0-deterioration. Consequently, a final Q_0 value of less than 10^9 at 8~10 MV/m is usually observed. To detect the phenomenon at the moment of quench is quite difficult because the phenomenon is considerably faster than the scanning time of the system. Moreover, it happens infrequently, only a few times per cavity test. Therefore, the temperature rises reflects the stationary phenomena resulting in Q_0-deterioration after the quench.

Temperature mapping before and after Q_0-deterioration is indicated in Fig. 6 and Fig.7. As seen in these figures, any obvious heating sites above the sensitivity do not exist before quenching at Eacc,max, but after the Q_0-deterioration some remarkable temperature rises in the vicinity of the iris are observed. The temperature rise, ΔT, at the lower iris in Fig. 6 (b) increases sharply with Eacc. The β value obtained by F-N plots of ΔT is 333, and it is consistent with that of $1/\Delta Q_0$, (357). Small temperature rises are also seen at the upper iris on the same meridian. In Fig. 7(b), two heating sites at the iris appeared initially, and then increased to four during rf processing. Finally, these heating sites changed to four ridge lines with increasing input rf power. The temperature rises in these figures are explicitly caused by energy deposition of the impact electrons. The Q_0-deterioration after the quench is due to field emitted electrons from the sources generated by the phenomenon at quench and the subsequent rf processing. Rf processing has not been effective in all our tests. Rf processing in the strong field emission region increases the number of the heating sites and causes the Q_0 value at the low field to degrade gradually. This means that the defects produced by electron bombardment grow increasingly in both number and size. Additional R_{res} caused by this phenomenon, ΔR_{res}, are usually 15~40 nΩ.

The temperature rise by field emission after quench was clearly observed. However, the identification of the trigger of this phenomenon is our urgent objective.

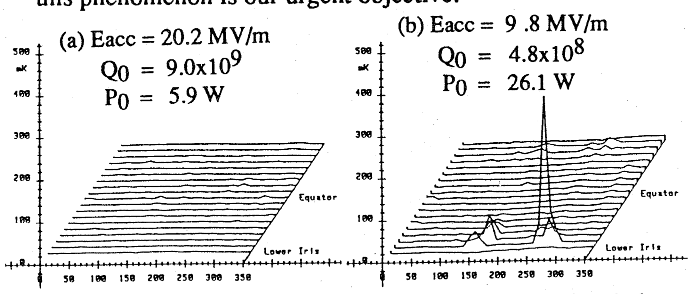

Fig. 6 Temperature mapping [Test: C2(VI)] ; (a) at just below Eacc,max before quenching, and (b) in the strong electron loading region after quenching at Eacc,max.

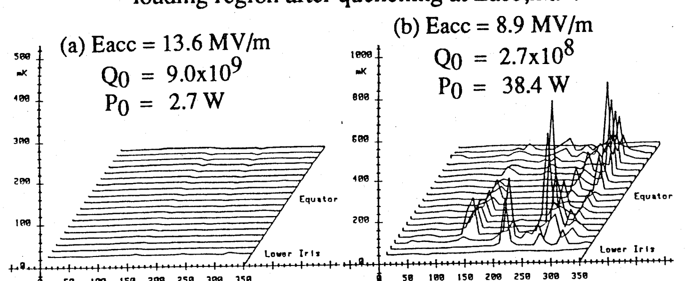

Fig. 7 Temperature mapping [Test: C1(IV)].

IV. REFERENCES

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