TEST RESULTS ON L-BAND Nb AND Nb/Cu SUPERCONDUCTING CAVITIES

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Abstract

Single-cell 1.3 GHz niobium (Nb) and niobium-coated copper (Nb/Cu) cavities were fabricated and tested at low temperatures. The niobium cavities were made from high purity material to obtain a superior thermal stability. The copper cavities were formed by electroforming to acquire a high thermal conductivity, and their inner surfaces were coated with a niobium thin film. In the initial cold tests, maximum accelerating fields of higher than 10 MV/m were achieved in both cavities. Q_0 values at 10 MV/m (T=2.1K) were 1.8×10^9 in the Nb cavity and 2.0×10^8 in the Nb/Cu cavity.

Introduction

Research and development of L-band superconducting cavites with higher accelerating gradients and superior thermal stabilities started in 1989 following successful operation of the TRISTAN superconducting cavities at KEK. The L-band superconducting cavities have extensive applications for linear accelerators, recyclotrons, FEL drivers and other devices. Our most interesting application of L-band superconducting cavities is the future TeV electron-positron linear collider. This collider is named TESLA (TeV Energy Superconducting Linear Accelerator)[1]. Toward the future application of L-band superconducting cavities in TESLA, quality factor (Q_0) and accelerating gradient (Eacc) in excess of the presently achieved values are required. These goals, defined by the TESLA parameters proposed in reference [2], are $Q_0 = 8 \times 10^9$ and Eacc = 30 MV/m for the 1.3 GHz 9-cell superconducting cavities.

In superconducting cavities, the thermal quenching caused by local defects and field-emitted electrons are the dominant obstacles which limit the maximum accelerating gradient. One of the solutions for these problems is the improvement of thermal stabilization by increasing the thermal conductivity of the cavity walls [3]. In a bulk niobium cavity, the use of high purity niobium material leads to the enhancement of its thermal conductivity. A collaboration between CEBAF and KEK led to the fabrication of three 1.3 GHz niobium cavities made from high purity niobium material (RRR=350). On the other hand, replacing niobium with a higher thermal conducting material like high purity copper is another possible solution. The copper cavities made by electroforming[4] possess many advantages like a high thermal conductivity, omission of electron beam welding, and smooth inner surfaces. The sputter coating technique of niobium thin film onto the inner surfaces of the copper cavities has been investigated vigorously at Kobe Steel, Ltd [5]. Two kinds of the L-band superconducting cavities with a high thermal conductivity have been tested at low temperatures, and improvements in their performances have continued.

Fabrication and surface processing

Single-cell 1.3 GHz niobium and niobium-coated copper cavities were fabricated with the same cell geometry. The optimization of the cell shape was perfomed by using SUPERFISH and URMEL, and their geometrical parameters are shown in Table I. The detailed dimensions of the cavity can be seen in reference [7]. Figure 1 is a photograph of a niobium cavity and a niobium-coated copper cavity, each of which is mounted on a bottom plate of the helium vessel for cold tests. So far, four cavities were tested, and the preparation of these cavities is as follows.

Niobium cavity

The niobium cavities were made from high purity niobium sheets (RRR=350) with 1/8 inch thickness and a thermal conductivity of more than 60 W/mK at 4.2K. The half-cells were formed by deep drawing and were trimmed. The half-cells, beam tubes and flanges were welded by electron beam welding from the outside. This cavity fabrication process is the same process that was used for the 1.5 GHz 5-cell CEBAF cavities [8]. An electropolishing device and a vacuum furnace were developed for the surface preparation of the L-band cavities. The surface treatments of the cavities were carried out by both electropolishing (E.P) and chemical polishing (C.P), and their performances were compared.

Electropolishing (E.P-Nb cavity) ; The E.P solution consisting of H_2SO_4 and HF was used, and initially, 120 μm were removed by the horizontal rotational electropolishing device [9]. A heat treatment of 660°C for 24 hours with a titanium box was conducted in order to degas hydrogen absorbed into niobium during the electropolishing. No deterioration of RRR occured during annealing. Subsequently, the second electropolishing of 5 μm was performed followed by H_2O_2 rinsing. Finally, the cavity was carefully rinsed with the demineralized (resistivity 17 MΩcm), filtered (0.2 μm) and ultraviolet sterilized pure water, and the ultrasonic agitation.

Table I.
Geometrical parameters of the L-band single cell cavities.

Frequency	1296	MHz
R/Q	102	Ω
Γ	274	Ω
Esp/Eacc	1.78	
Hsp/Eacc	43.8	Oe/MV/m
Radius of beam tube	40	mm

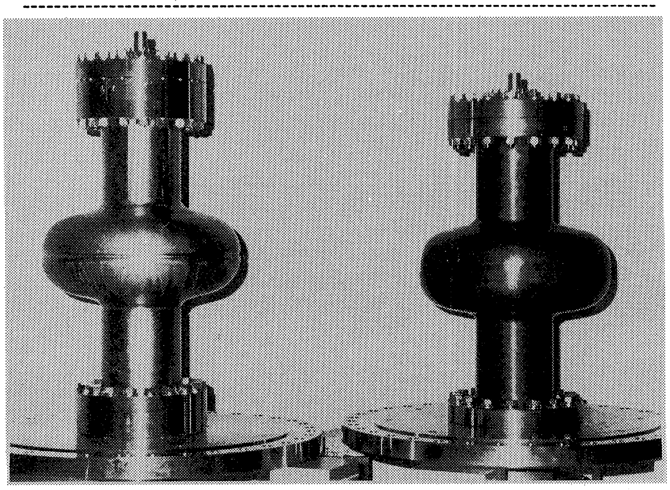

Fig. 1 A niobium cavity [left] and a niobium-coated copper cavity [right].

Chemical polishing (C.P-Nb cavity) ; The C.P solution is a mixture of HF, HNO_3 and H_3PO_4 ; (1:1:1). The acid was poured into the cavity, and 70 μm were removed only inside the cavity. Then, the rinsing with the ultra-pure water mentioned above was carried out with great care for 120 minutes.

Niobium -coated copper cavity

The electroformed copper cavities were fabricated using the following process; 1. the manufacturing of the aluminum core and the mechanical polishing on the outer surface, 2. the electroforming (2~3mm in thickness) of copper onto the aluminum core, 3. the resolution of the aluminum core in a chemical bath (an aqueous solution of NaOH). The ICF stainless steel flanges were welded by electron beam welding. Prior to niobium coating, the inner surfaces of the copper cavities were electropolished by using the E.P solution consisting of CrO_3, H_3PO_4 and H_2O. After electropolishing of 30 μm and rinsing with the ultra-pure water, annealing of the copper cavity at 600°C for 6 hours was performed for degasing of hydrogen and recrystallization of copper to obtain higher thermal conductivity. The coating of the niobium thin film was carried out by means of an rf magnetron sputtering. The niobium thin film of 2~3 μm in thickness was deposited onto the inner sueface of the copper cavitiy at the deposition rate of 2 Å/sec. Typical sputtering conditions [10] are Ar pressure of 3 mTorr, cavity temperature of 350°C, and rf power of 1500 W.

The first tested cavity (Nb/Cu-[I]) was prepared with the above procedure. In the second test (Nb/Cu-[II]), the additional coating of 3 μm onto the first tested cavity was performed.

The cavities are assembled in a clean room (class 100) and are equipped with adjustable input and fixed monitor couplers (see Fig.1). After baking at 85°C for 12 hours, the vacuum pressure is improved generally to less than $2x10^{-9}$ Torr. Then, the cavity is installed in the vertical cryostat and is cooled down to low temperature. The pumping system of superfluid helium and the cryostat were prepared by modifying a part of the existing 508 MHz vertical test system.

Test results and discussion

One of the benefical features of a superconducting cavity is a low rf loss resulting from a small rf surface resistance. The rf surface resistance (R_s) of the superconducting cavity is expressed by the addition of a temperature independent term (R_{res}) and a temperature dependent term (R_{BCS}) ; $R_s = R_{BCS}(T)+R_{res}$. R_{res} is the residual surface resistance and depends strongly on surface irregularities, surface contaminants such as chemical residues and dust, trapped magnetic flux, etc.. R_{BCS} is the BCS surface resistance derived from the BCS theory and is expressed by the following equation; $R_{BCS}(T) = A\omega^2/T \exp(-\Delta/kT)$, at $T<Tc/2$ and $hf<<\Delta$. Here, A is the material constant, 2Δ is the energy gap and k is the Boltzman constant. Therefore, reducing the operating temperature and minimizing the R_{res} by advanced surface treatment are particularly important in order to obtain higher Q_0 values. For instance, in the 508 MHz 5-cell superconducting cavities for TRISTAN, the average Q_0 value at 4.2K and low fields is $3.4x10^9$. The estimated $R_{BCS}(4.2K)$ is 74nΩ, and the R_{res} is 6 nΩ because of the improvements in the surface preparation techniques [6]. As for the L-band superconducting cavities, the R_{BCS} at 4.2K becomes a large value because of a square dependence on the frequency, so that the operating temperature has to be reduced to around 2.0K. Assuming that the R_{BCS} for 1.3 GHz at 2.0K is 10 nΩ and that the R_{res} could be lowered to 6 nΩ like the TRISTAN superconducting cavities, the attainment of a Q_0 value of more than $1.0x10^{10}$ is expected.

Figure 2 shows the Q_0 value vs. the accelerating gradient (Eacc) measured at 2.1K for the four 1.3 GHz single-cell cavities explained above; *i.e.*, the electropolished Nb cavity, the chemical polished Nb cavity, the initial Nb/Cu cavity and the second coated Nb/Cu cavity. The temperature dependences from 4.2K to 2.1K of the R_s for these cavities are shown in Fig. 3. The R_{res} and the parameters (A and

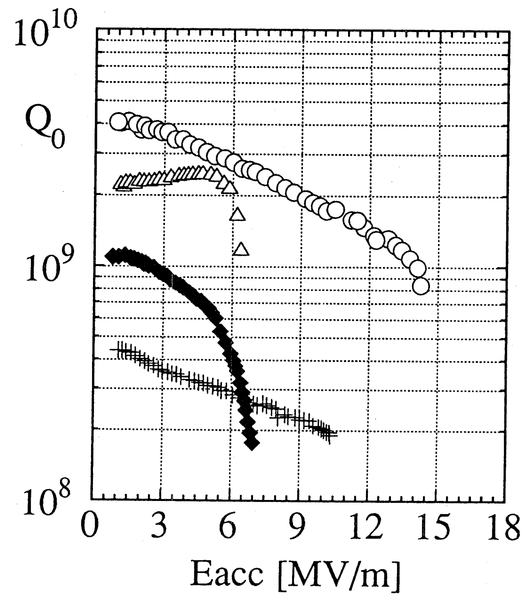

Fig. 2 Qo - Eacc plots for the 1.3 GHz single cell Nb and Nb/Cu cavites measured at 2.1K.
(Δ ; E.P-Nb cavity, o ; C.P-Nb cavity)
(+ ; Nb/Cu - [I] , ◆ ; Nb/Cu - [II])

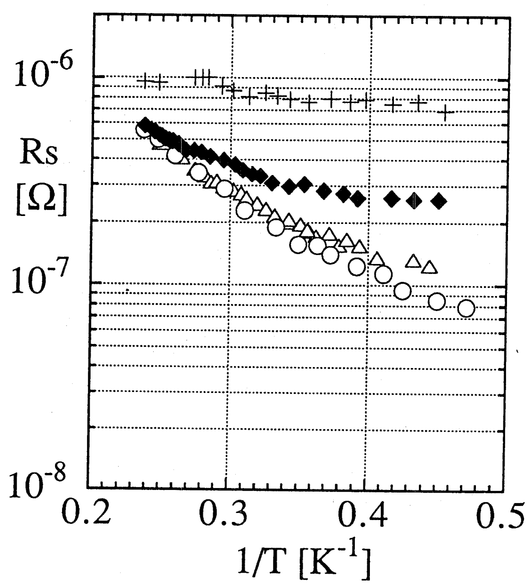

Fig. 3 Temperature dependence of the rf surface resistance (Rs) for the Nb and Nb/Cu cavities.
(Δ ; E.P-Nb cavity, o ; C.P-Nb cavity)
(+ ; Nb/Cu - [I] , ◆ ; Nb/Cu - [II])

Table II.
Summary of the rf surface resistances.

cavity /	Rres [nΩ] ;	A [ΩK] ;	Δ/k [K]
E.P-Nb /	109,	1.55×10^{-4},	18.55
C.P-Nb /	72,	1.66×10^{-4},	18.51
Nb/Cu-[I] /	742,	---- ,	----
Nb/Cu-[II] /	237,	1.16×10^{-4},	18.50

[$R_{BCS} = A/T \exp(-\Delta/kT)$]

Δ/k) of the R_{BCS} from fitting the $R_s(T)$ data to the BCS formula are provided in Table II. Although the cold tests have just begun and were performed only four times, the test results for these cavities can be summarized as follows.

(a). The chemical polished Nb cavity achieved the maximun accelerating gradient of 14.3 MV/m with no field emission, and its limitation was the quenching. The electropolished Nb cavity, however, suffered from the strong field emission loading at more than 5.8 MV/m, and a steep drop of the Q_0 value was induced. The reason for this may lie in surface contamination during treatments or assemblage.

(b). As mentioned above, it is possible to achieve the Q_0 values of more than 1.0×10^{10} in the L-band cavities. However, the Q_0 values were much lower due to the large R_{res}. The R_{res} of the electropolished and the chemical polished Nb cavities are 109 nΩ and 72 nΩ, respectively, and they are roughly one order higher than the R_{BCS} at 2.1K. We think that the most possible origin of the large R_{res} is the trapped magnetic flux. The measured residual magnetic field inside the L-band cryostat amounted to 160 mGauss at its maximum to the perpendicular direction against the accelerating field. A magnetic shield made of Permalloy is under preparation.

(c). The Q_0 values decrease gradually due to heating of the cavity wall with the increment of Eacc. The rate defined by α ($\Delta(1/Q_0) = \alpha E_{sp}^2$) was considerably larger in the chemical polished cavity than that in the electropolished cavity.

(d). The initial Nb/Cu cavity attained the maximum accelerating gradient of 10.4 MV/m in spite of the low Q_0 value due to the R_{res} of 742 nΩ. It was not limited by the field-emitted electrons, but rather by available rf power. In the second coated Nb/Cu cavity, the R_{res} decreased to 237 nΩ, and the Q_0 value at the low field was improved to 1.0×10^9. The field emission, however, occured from 5.5 MV/m, and the Q_0 values finally degraded to less than that of the initial cavity. The improvement in the residual surface resistance might indicate that the extremely thin layer of the niobium film existed locally in the cavity surface.

(e). It can be considered that the cause of the large R_{res} in the Nb/Cu cavity lies in the inherent properties of the niobium thin film, for instance, granular structure, porosity, and the presence of impurities.

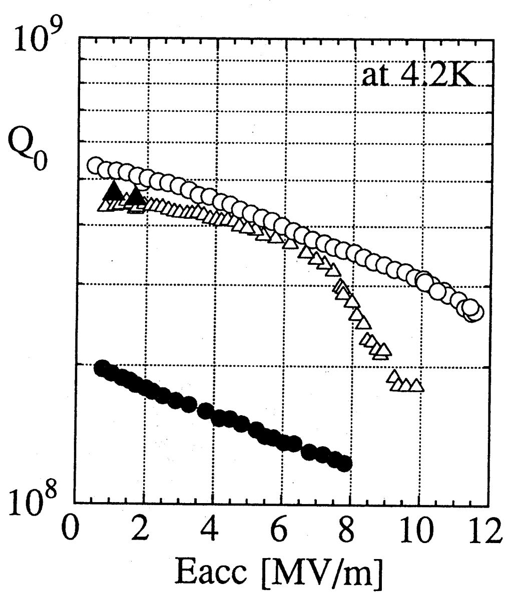

Fig. 4 Q_0-Eacc plots for the niobium cavities (E.P and C.P) measured at 4.2K under different cooling down conditions.
(o ; C.P - fast cooling down)
(● ; C.P - after 15 hours at 90~105 K)
(Δ ; E.P - fast cooling down)
(▲ ; E.P - after 11 hours at 70~130 K, only low field)

A phenomenon in which the Q_0 values fall significantly under certain cooling conditions has been reported by several laboratories [11-13]. This phenomenon has been observed especially in the niobium cavity made from high purity niobium material as well as our niobium cavities. Figure 4 shows the test results obtained under different cooling down conditions for the electropolished and the chemical polished niobium cavities. The fast cooling down from room temperature to helium temperature was carried out within 1 hour. The Q_0 degradation was observed only for the chemical polished cavity after keeping at 90~105K for 15 hours. The R_s at the low field increased from 530 nΩ to 1400 nΩ. The Q_0 values were improved to the consistent values after warming up to room temperature and fast cooling down to helium temperature. This phenomenon in the chemical polished cavity is similar to that observed at other laboratories. As for the electropolished cavity, this result is consistent with the report that the Q_0 degradation was not observed because of the heat treatment to degas hydrogen [9].

Conclusion

Steady progress has been made in developing the L-band superconducting cavities for high gradient applications. The vertical test system was completed, and the initial test results for the niobium and the niobium-coated copper cavities were obtained. Although the achieved accelerating gradients and quality factors encouraged us, eliminating the field-emitted electrons is the most important problem. Some improvements in surface treatments and handling techniques are still required in order to achieve the desired values.

Acknowledgements

The authors are much indebted to Dr. R. Sundelin and Dr. P. Kneisel for their cooperation in this collaborative program between CEBAF and KEK. They are grateful to Prof. Y. Kimura and Prof. S. Kurokawa for their continuous support and encouragement. They also would like to thank Dr. K. Hosoyama and Mr. Y. Kojima for the operation of the helium refrigerator system. Acknowledgement also is due to Mr. K. Miyamoto for his kindness in helping with the importation and transportation of the niobium cavities.

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