Development of Superconducting Cavities for High Gradient Applications

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Abstract

The 1.3 GHz single-cell niobium cavities have been tested for various surface treatment methods. In the best cavity, the maximum accelerating gradient of 15.5 MV/m and the Q_0 value of 1.3×10^{10} at that gradient were achieved at a temperature of 2.1K. Improvement of the residual magnetic field inside the cryostat reduced drastically the residual surface resistance to around 10 nΩ.

1. INTRODUCTION

Superconducting rf cavities are becoming conventional tools in particle accelerators, and efforts aimed at higher gradient applications like FEL drivers, proton LINACs and electron-positron linear colliders are being continued in several laboratories around the world. In KEK, development of the 1.3 GHz niobium cavities for high gradient applications was started in 1990. An RF measurement system at low temperature was completed in 1991, and vertical cold tests for these cavities have been continued in order to attain a higher maximum accelerating gradient and to understand phenomena limiting it. Reports of initial cold test results have already described in references [1,2]. In this paper, progress and improvements in cavity performances in subsequent tests are reported.

2. FABRICATION AND SURFACE PROCESSING

Up to the present, we have made 4 single-cell cavities. One was made at MHI, and the others were made from high purity niobium materials (RRR=350) under a collaboration with CEBAF [1] ; deep drawing and electron beam welding were carried out at CEBAF. The surface preparation techniques based on experience obtained with the TRISTAN superconducting cavities [3] have been employed in polishing, annealing and rinsing. Both electropolishing (E.P) and chemical polishing (C.P) have been employed in the search for the most effective surface preparation method of the cavities. Annealing for the hydrogen degassing is absolutely essential in the avoidance of the hydrogen precipitation progressing during pre-cooling using liquid nitrogen. Annealing has been performed at a temperature of 760°C and

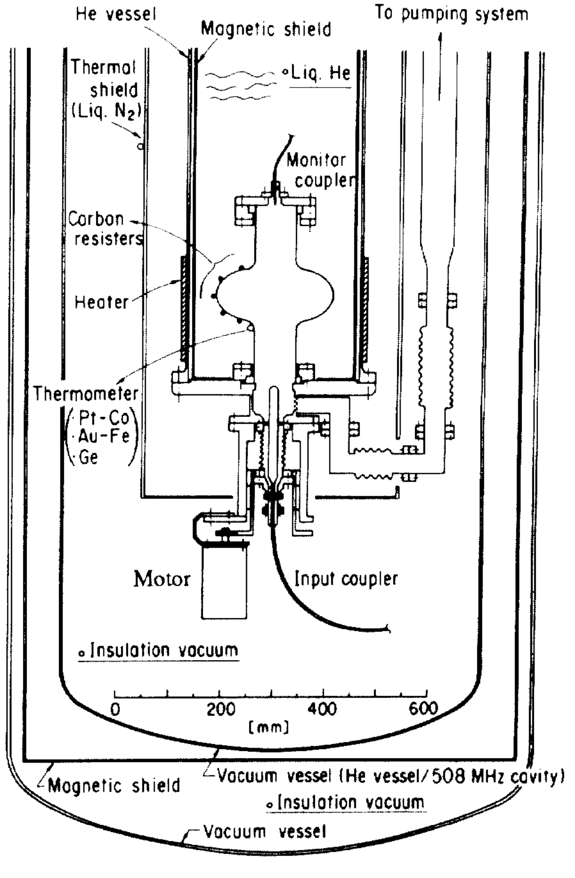

Figure 1. Schematic drawing of the L-band vertical test stand.

a vacuum pressure of less than 1x10^{-5} Torr with a titanium box. Subsequently, the final polishing of 5 μm was carried out followed by careful rinsing with ultra-pure water. After being equipped with an adjustable input and a fixed monitor coupler, the cavity is baked at 85°C for 15 hours. The cavity is installed in the vertical cryostat as shown in Figure 1. The vacuum pressure generally comes to less than 3x10^{-9} Torr at room temperature.

3. TEST RESULTS AND DISCUSSION

The vertical cold tests for three niobium cavities have been performed six times (A~F in Table 1). A summary of their surface treatments and test results measured at 2.1 K is listed in Table 1, and the performance characteristics of these cavities are shown in Figure 2 where the Q_0 value is plotted as a function of the accelerating gradient. The temperature dependences from 4.2 K to 2.1 K of the rf surface resistances (Rs) for the typical three tests are shown in Figure 3. The residual surface resistance (R_{res}) and the parameters of the BCS surface resistance (R_{BCS}) obtained from fitting the Rs(T) data to the BCS formula are summarized in Table 2 together with the field enhancement factor (β) obtained by F-N plots of $\Delta(1/Q_0)$.

Only in the case of B with no annealing, Q_0-degradation occured after keeping at 90~105K for 15 hours (pre-cooling). So, the test was carried out after warming up to room temperature and fast cooling down to helium temperature within 1 hour. Although the pre-cooling was performed in the other cases, the Q_0-degradation did not arise.

The maximum accelerating gradients of more than 14 MV/m were achieved for the chemically polished cavities (B, D and F). However, after quenching once at around the maximum accelerating gradient, sources of field-emitted electrons were generated in the surface of these cavities. The cavity performances were not recovered after then due to the field emmision accompanied with deterioration of a vacuum pressure and strong x-rays. The cause of this is not clear, but

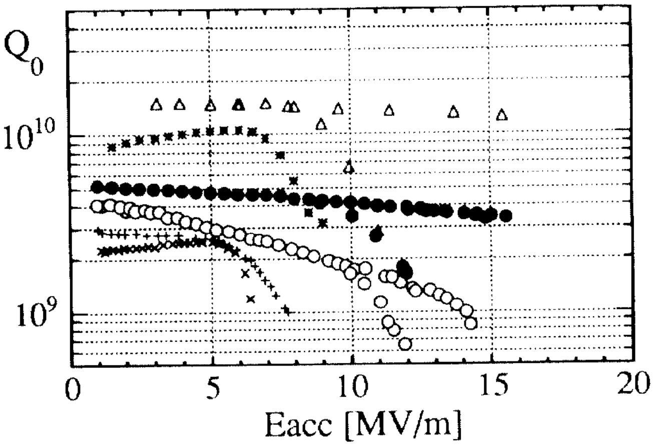

Figure 2. Q_0 value vs. accelerating gradient (Eacc) measured at 2.1K. (A- [x], B- [o], C- [+], D- [●], E- [*], F- [Δ]).

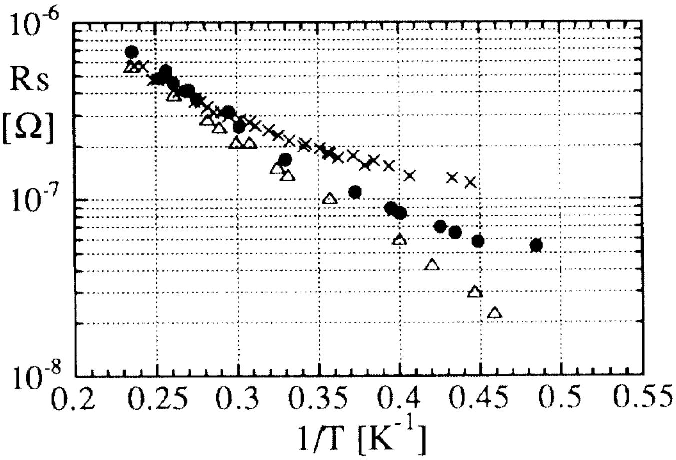

Figure 3. Temperature dependence of the rf surface resistance. (A- [x], D- [●], F- [Δ]).

Table 1.
Summary of cavity treatments and vertical test results measured at 2.1K on the 1.3 GHz single-cell niobium cavities.

No;	Cavity	RRR	Surface Treatment	Annealing	Q_0 (low field)	Eacc,max [MV/m]	Q_0 (Eacc,max)	Limitation
A;	K-2	350	E.P (120μm+5μm)	660°C, 24hours	$2.3\text{x}10^9$	6.4	$1.2\text{x}10^9$	Field Emission
B;	K-1	350	C.P (70μm)	no	$3.9\text{x}10^9$	14.3	$8.4\text{x}10^8$	Quench / (F.E)
C;	M-1	100	E.P (110μm+5μm)	750°C, 10hours	$2.9\text{x}10^9$	7.7	$1.0\text{x}10^9$	Field Emission
D;	K-2	350	C.P (30μm+5μm)	760°C, 5hours	$5.0\text{x}10^9$	15.6	$3.4\text{x}10^9$	Quench / (F.E)
>>>> The magnetic shield was improved. <<<<								
E;	K-2	350	no additional treatment.		$1.1\text{x}10^{10}$	9.0	$3.2\text{x}10^9$	Field Emission
F;	K-1	350	C.P (10μm+5μm)	760°C, 5hours	$1.5\text{x}10^{10}$	15.5	$1.3\text{x}10^{10}$	Quench / (F.E)

Table 2.
Summary of surface resistances and field enhancement factors.

Cavity ;	A	B	C	D	E	F
R_{res} [nΩ]	109.	70.	71.	44.	14.	8.
A [$\times 10^{-4}$ΩK]	1.55	2.72	1.77	3.09	2.60	2.00
Δ/k [K]	18.6	20.5	18.9	20.1	19.6	18.8
β	256	147	527	184	275	169

[Here, $R_s = R_{BCS} + R_{res}$, $R_{BCS} = A/T \exp(-\Delta/kT)$.]

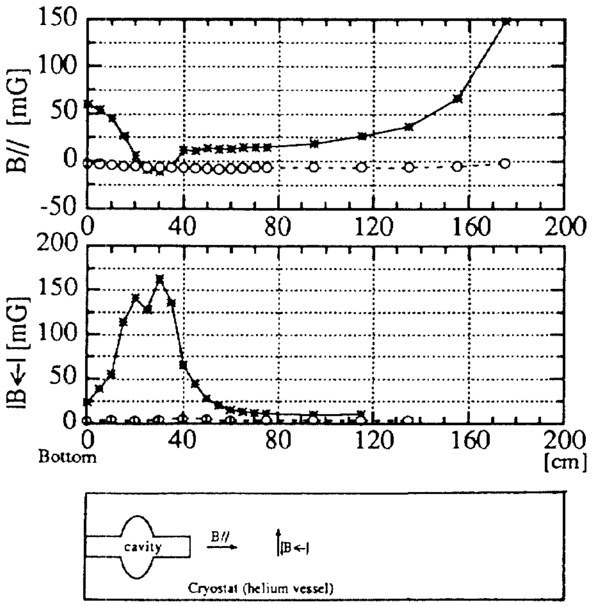

Figure 4. Distribution of the residual magnetic fields inside the helium vessel of the cryostat. B// and IB<-I are the magnetic fields in the direction parallel and perpendicular to the beam axis, respectively. (Initial- [*] ; Improved magnetic shield- [o]).

these cavities have very similar behavior as for the first quenching field level, the occurrence of the field emission and its field level. In the case of E with no additional surfase treatment after D, the maximum accelerating gradient was deteriorated further compared with D due to the field emission. Temperature rise at the iris was detected by carbon resisters in the cases of E and F.

The electropolished cavities (A and C) exhibited strong field emission loading at around 6 MV/m and a steep drop in the Q_0 value. Since surface contamination during electropolishing can be considered as one of the probable origins of this, the cathode made from niobium instead of the present aluminum one will be used in the next treatment. Moreover, a high-pressure water rinsing system using 80 bar ultra-pure water is being prepared to eliminate sources of field emitted electrons and to attain a much higher accelerating gradient (the aimed goal is 30 MV/m).

The Q_0 values at the low field in the initial tests were much lower than the expected value predicted by R_{BCS} at 2.1K. One cause of this large R_{res} lay in the residual magnetic field inside the helium vessel of the cryostat. The measured distribution of the magnetic field is shown in Figure 4. The magnetic field of 150 mGauss existed at the equator perpendicular to the surface. The reason for this seems to be due to magnetization of the helium vessel, made from SUS-316L, induced by the current of the heater attached outside it (see Figure 1). An improved magnetic shield was installed in the liquid helium bath as shown in Figure 1. The magnetic shield was made from a material maintaining a high relative magnetic permeability ($\mu_i \sim 70000$) even at low temperature; (Permalloy TMC-R manufactured by TOKIN Co., Ltd.). The residual magnetic field was reduced drastically to less than 10 mGauss as shown in Figure 4.

The Q_0 values were remarkably improved to more than 10^{10} by the elimination of the residual magnetic field, and the R_{res} became nearly equivalent to the R_{BCS} at 2.1 K. A comparison between the results of D and E in Table 2 suggest a reduction of the R_{res} of about 30 nΩ caused by the reduced residual magnetic field. An additional surface resistance (R_{add}) due to a static magnetic field (B_{st}) in the direction perpendicular to the beam axis is given experimentally by the relation of R_{add} [nΩ] = 0.15 B_{st} [mG] at 500 MHz in reference [4]. In our case, the estimation for this is 36 nΩ, taking the frequency dependence of $f^{1/2}$ into account. This value is consistent with our result.

For the next step, fabrication of the 1.3 GHz 9-cell niobium cavity with optimized cell shape [1] has been initiated at both MHI and CEBAF. Upgrading the ability of the helium pumping system for lowering the helium temperature below 2 K is also scheduled.

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5. REFERENCES

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