Initial Tests of L-band Niobium Superconducting Cavities for Linear Collider Application

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Abstract

Geometrical optimization of the cavity shape and improvements in surface preparation techniques are particularly important in future applications of superconducting cavities. A collaboration between CEBAF and KEK led to the fabrication of three 1.3 GHz single-cell niobium cavities with the optimized cell shape. These cavities were tested at low temperatures, and the maximum accelerating field of higher than 14.0 MV/m was achieved in the initial cold tests. The design considerations for single-cell and multi-cell cavities, the fabrication process, the surface treatments, and the first experiments with these cavities are described in this paper.

1. Introduction

Research and development of L-band superconducting cavities aiming at higher accelerating gradients and superior thermal stabilities started in 1989 following successful operation of the TRISTAN superconducting cavities at KEK. A frequency of 1.3 GHz [1,2] has been chosen for high gradient applications like TESLA (TeV Energy Superconducting Linear Accelerator). The main reasons for selecting this frequency are as follows. Firstly, lower frequency cavities can accelerate bunches of larger particle population, so the bunch size at the interaction point can be relaxed. Secondly, longer unit cavity length can reduce the total cost for cavities, couplers, tuners and control systems. On the other hand, the repetition frequency is limited to lower because of larger stored energy, then the length and so the cost for damping rings increase in a lower frequency system. Optimization has to be made strictly and occasionally, but we concluded to start with 1.3 GHz taking advantage of existing high power klystrons. Geometrical optimization for single-cell and multi-cell cavities was performed by using SUPERFISH and URMEL, and changes in the geometrical parameters depending on the cell shape were investigated. As for the multi-cell structure, the avoidance of harmful trapped modes which induce beam instabilities was considered. A collaboration between CEBAF and KEK has been established to develop improved superconducting cavities, and has led to the fabrication of single-cell cavities made from high purity niobium material. According to the surface preparation techniques based on experience obtained with the TRISTAN cavities, an electropolishing device and a vacuum furnace were developed. A cryostat, an RF measurement system and a pumping system for superfluid helium were prepared, and a whole system for the vertical cold test was completed in this year. The cold tests of the cavities have just begun, and improvements in cavity performances are expected in subsequent tests.

2. Design of single-cell cavity

Today, field emission and thermal quenching are the dominant obstacles which limit the maximum accelerating gradient (Eacc,max) of superconducting cavities. These phenomena are strongly related to the maximum surface electric field (Esp) and the maximum surface magnetic field (Hsp). Therefore, a cavity shape which has a reduced value of Esp/Eacc and Hsp/Eacc is favorable for obtaining higher Eacc. As for the values of R/Q depending dominantly on the beam tube radius, it is important to make the impedance of accelerating mode higher and those of higher order modes lower. First of all, it is necessary to understand the dependences of principal parameters for the accelerating mode on the cell shape. Typical geometries of a spherical shape are illustrated in Fig. 1. Among these variables, attention is paid particularly to the dependence of Esp/Eacc on the beam tube radius (Rb) as well as the taper of the cell (θ). The equator radius (Ra) is adjusted in order to match the resonant frequency of the cavity with the operating frequency. The change of the resonant frequency with Ra is 13 MHz per 1 mm. The flat section (d) at the equator is adopted for ease of welding. The cell length (L_1) is equal to a quarter wavelength. As the length of the beam tube (L_2) is arbitrary, it can be adequately lengthened so as to eliminate the influence of rf losses in the end plates. Figure 1-(a) and -(b) show R/Q, Esp/Eacc and Hsp/Eacc as a function of θ and Rb, respectively (calculated by SUPERFISH). Here, d=4.0 mm and L_1+L_2=140 mm are fixed, and other parameters are indicated in the figure. The values of R/Q decreases linearly with Rb. The cavity geometry with a high R/Q, a low Esp/Eacc ratio and a low Hsp/Eacc ratio is obtained in the small beam tube radii. On the other hand, a larger beam tube diameter is better for the relaxation of the wake fields. The ease of manufacturing and surface treatment is another consideration for the choice of the actual geometry. Taking these three viewpoints into account, we have chosen Rb to be 40 mm and θ to be 75 degrees. Our 1.3 GHz single-cell cavity is designed as shown in Fig.2, and a parameter of the accelerating mode is also listed.

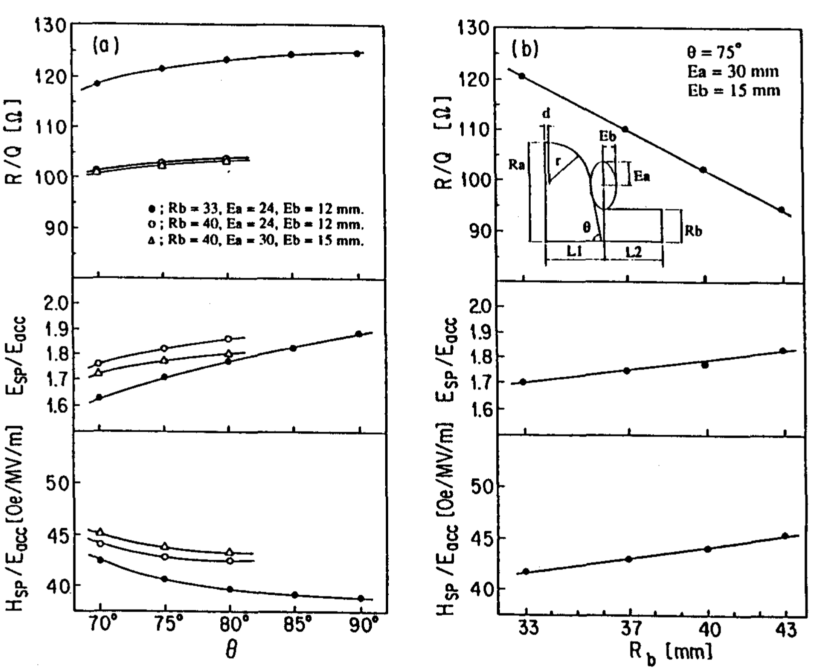
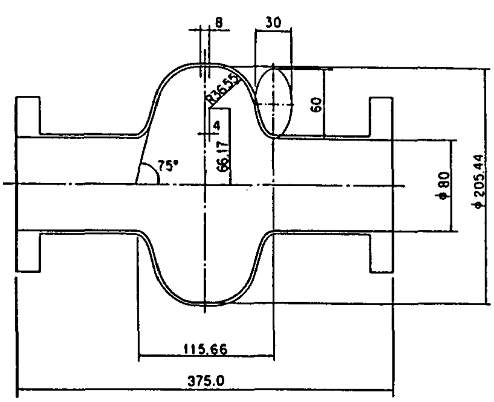


Fig. 1 The dependeces of principal parameters as a function of (a) θ and (b) Rb.



Frequency	1296 MHz
R/Q	102 Ω
Γ	274 Ω
Esp/Eacc	1.78
Hsp/Eacc	43.8 Oe/MV/m

Fig.2 An optimized 1.3 GHz, single-cell cavity.

3. Fabrication and surface treatment

The cavities are made from high purity niobium sheets (RRR=350) of 1/8 inch thick and the thermal conductivity is more than 60 W/mK at 4.2K. The half-cells were formed by deep drawing and were machined for electron beam welding. Figure 3 is a photograph of male and female dies made from aluminum alloy and a set of trimming jigs. The design of the dies was done at CEBAF, the fabrication was done at KEK and the deep drawing was carried out at CEBAF, (see Fig. 4). The half-cells, beam tubes and flanges were joined 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 [3]. An electropolishing device and a vacuum furnace were developed for the surface preparation. The surface treatments of the cavities were carried out by both electropolishing (E.P) and chemical polishing (C.P). The surface treatments were performed as follows.

Electropolishing ; The E.P solution consisting of H_2SO_4 (95%) and HF (46%) was used, and initially, 120 μm were removed by the horizontal rotational electropolishing device [5] as shown in Fig.5. A heat treatment at 660°C for 24 hours with a titanium box was conducted in order to degas hydrogen dissolved into niobium during the electropolishing. On the samples, no deterioration of RRR due to the heat treatment was observed. Subsequently, the second electropolishing of 5 μm was performed followed by H_2O_2 rinsing. Finally, the cavity was carefully rinsed with demineralized (resistivity of 17 MΩcm), filtered (0.2 μm) and ultraviolet-sterilized pure water in conjunction with the ultrasonic agitation. This procedure is the same procedure that has been carried out for the TRISTAN superconducting cavities [5].

Chemical polishing ; The C.P solution is a mixture of HF (46%), HNO_3 (60%) and H_3PO_4 (85%) ; (1:1:1 in volume ratio). 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. (no annealing and H_2O_2 rinsing.)

The cavities are assembled in a clean room (class 100) and are equipped with an adjustable input and a fixed monitor coupler. After baking at 85°C for 12 hours, the vacuum pressure is improved generally to less than 2×10^{-9} Torr. Subsequently, the cavity is installed in the vertical cryostat and is cooled down to low temperature. The cryostat and the pumping system for lowering the helium temperature below the λ-point were prepared by modifying a part of the existing 508 MHz vertical test system.

Fig.3 Dies for deep drawing and a set of trimming jigs.

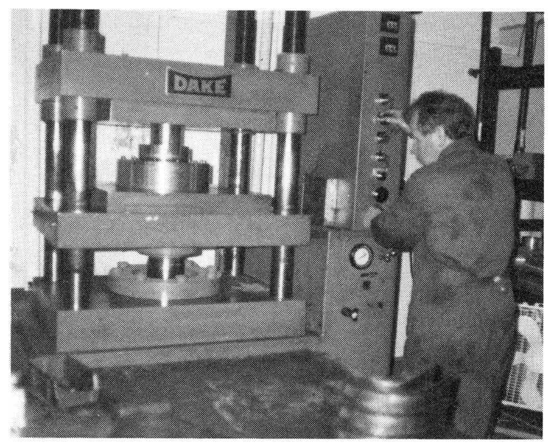


Fig.4 A performance of deep drawing at CEBAF.

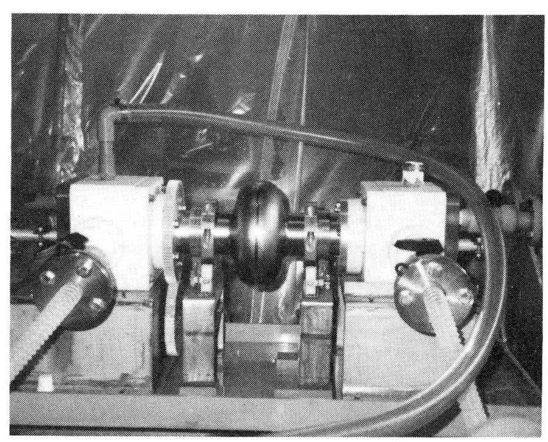


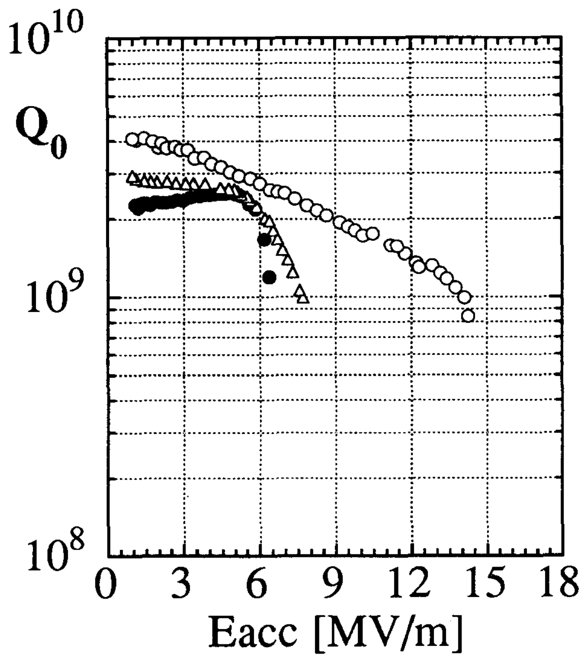
Fig. 5 A horizontal rotational electropolishing device (Nomura Plating Co., Ltd.).

4. Results of initial cold tests

The vertical cold tests of the cavities have just begun and have been performed only three times up to present. The three tested cavities are characterized as follows:

1. a chemical polished CEBAF/KEK cavity, RRR=350, no annealing.
2. an electropolished CEBAF/KEK cavity, RRR=350, annealing at 660°C for 24 hours.
3. an electropolished IHM/KEK cavity, RRR=100, annealing at 750°C for 10 hours.

The IHM/KEK (IHM: in-house made) cavity is the first cavity which was fabricated at KEK using the same method that was used for the CEBAF/KEK cavity. This cavity was made from low RRR niobium material. The surface preparation of the cavity is the same as that mentioned above.



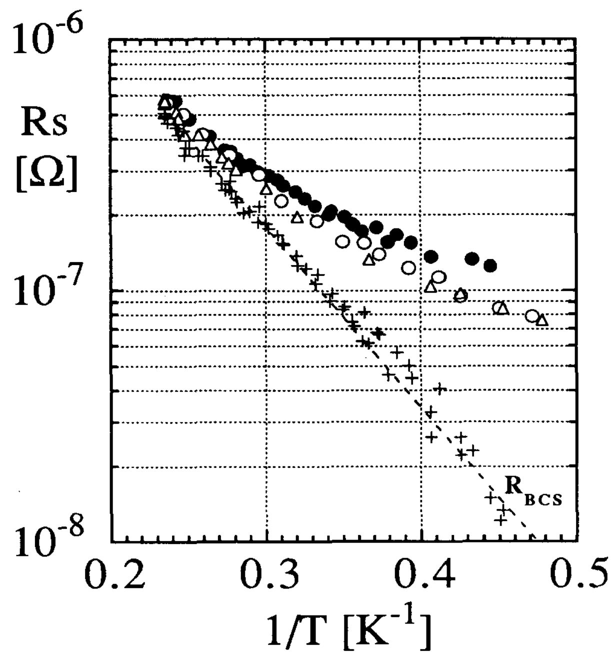


Fig. 6 Q_0 - Eacc plots for three niobium cavities measured at 2.1K.

Fig. 7 Temperature dependence of the rf surface resistance (Rs).

[o ; C.P- CEBAF/KEK, ● ; E.P- CEBAF/KEK, Δ ; E.P- IHM/KEK]

Table I. Summary of the vertical cold test for the three cavities.

cavity	Eacc,max	limitation	field emission	Q_0-degradation
C.P- CEBAF/KEK	14.3 MV/m	Quench	No	Yes
E.P- CEBAF/KEK	(6.4)	(field emission)	Yes	No
E.P- IHM/KEK	7.7	Quench	Yes	No

cavity	Rres [nΩ]	Δ/k [K]	β (Δ1/Q_0)	α [x10^{-12} $(m/MV)^2$]	γ
C.P- CEBAF/KEK	72.3	18.51	-----	1.02	27.4
E.P- CEBAF/KEK	108.9	18.55	256	------	------
E.P- IHM/KEK	71.4	18.87	527	0.36	7.75

[β ; field enhancement factor, α ; $\Delta(1/Q_0) = \alpha E_{sp}^2$, γ ; $Q_0 \Delta(1/Q_0) = \gamma (H/H_c)^2$]

Figure 6 shows the Q_0 value vs. the accelerating gradient (Eacc) measured at 2.1K for the three 1.3 GHz single-cell cavities. The temperature dependences from 4.2K to 2.1K of the rf surface resistance (R_s) for these cavities are shown in Fig. 7. The residual surface resistances (R_{res}) calculated from fitting the $R_s(T)$ data to the BCS formula were 72 nΩ, 109 nΩ and 71 nΩ, in the C.P- CEBAF/KEK, the E.P- CEBAF/KEK and the E.P- IHM/KEK cavities, respectively. R_{BCS}, "+" in Fig.7, represents the BCS surface resistance calculated by [$R_s(T)$ - R_{res}]. The energy gap parameter, Δ/k, obtained from the R_{BCS} was a similar value for each cavity. The results of the vertical cold test are summarized in Table I. A preliminary summary of the test results for these cavities is as follows.

(a). The C.P- CEBAF/KEK cavity achieved the maximun accelerating gradient of 14.3 MV/m with no field emission, and its limitation was the quenching.

(b). Both of the electropolished cavities suffered from the strong field emission loading at field level higher 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 assembling.

(c). Assuming that the R_{BCS} for the 1.3 GHz cavities at 2.1 K is 10 nΩ and that the R_{res} could be lowered to 6 nΩ like the TRISTAN superconducting cavities [5], a Q_0 value of more than 1.0×10^{10} is expected. However, the Q_0 values were much lower due to the large R_{res}. The R_{res} are roughly one order higher than the R_{BCS} at 2.1K. We think that the most probable 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 in the direction perpendicular to the beam axis. An improved magnetic shield is under preparation.

(d). The Q_0 values decrease gradually due to heating of the cavity wall with the increment of Eacc. The rate α and γ (see the bottom of Table I) [6] seem to be larger in the chemical polished cavity than that in the electropolished cavity.

Q_0 - degradation

A phenomenon in which the Q_0 values fall significantly under certain cooling conditions has been reported by several laboratories [7-9]. This phenomenon has been recognized especially in the niobium cavity made from high purity niobium material like the CEBAF/KEK cavities. In our experiments, this Q_0 degradation was observed only for the chemical polished cavity after keeping at 90~105K for 15 hours. The R_s at 4.2 K and low fields increased from 530 nΩ to 1400 nΩ. The Q_0 values were recovered to the suitable 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. For the electropolished cavity, the result is consistent with the report that the Q_0 degradation was not observed because of the hydrogen degassing by the heat treatment [4].

5. Multi-cell structure

An initially designed cell shape [1] for 1.3 GHz 9-cell structure is illustrated in Fig. 8(a). In this design, a flat section (2.5 mm) for welding at the iris was adopted on the basis of the single-cell structure as shown in Fig.2. However, the consideration for higher order modes (HOM) was insufficient, and the so-called trapped modes [10, 11] in the TM_{110}-passband as shown in Fig. 9(a) exist. Since the electromagnetic field in the end-cell is extremely weak in the trapped modes, it is very difficult to damp HOM by HOM couplers located at the beam tube. The results calculated for various geometries to eliminate the trapped modes suggested that the formation of the trapped modes was sensitive to the iris geometry. This implies that a stronger coupling between adjacent cells is more effective to eliminate the trapped mode. Therefore, some modifications in the iris were performed for an ellipse, a flat section, and a radius. The finally obtained cell shape as shown

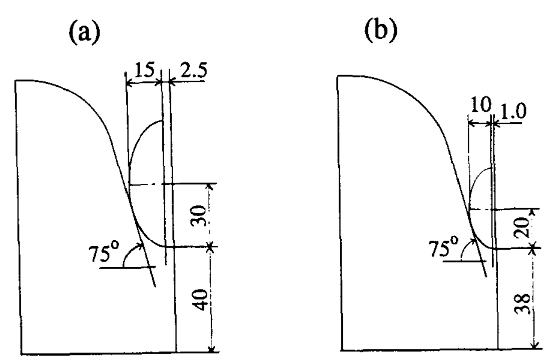


Fig. 8 (a) an initial cell shape, (b) an improved cell shape.

in Fig. 8(b) comfirms the elimination of the trapped modes problem ; strong enough coupling to the HOM couplers at the beam tube can be expected as shown in Fig. 9(b).

Geometrical parameters of the 1.3 GHz 9-cell structure with the improved cell shape are summarized in Table II, (calculated by URMEL). In this design the frequency of the end-cell is adjusted by a variation in the cell length rather than in the cell diameter (which is the usual case). Figure 10 shows the pass-band of the longitudinal and transverse HOMs. The dominant HOMs are listed in Table III, and their impedances are also provided. A 1.3 GHz 5-cell copper model cavity with demountable beam tubes has been prepared already. Tuning of the accelerating mode has been done and measurements of external Q values of the HOMs are carried out. For the next step, these results will be incorporated in the construction of a prototype niobium multi-cell structure. Hereafter, design of high power input couplers and HOM couplers will be initiated.

Table II. Parameter list of the 1.3 GHz, 9-cell KEK-TESLA cavity

Frequency	1296	MHz
Effective length	104.094	cm
R/Q	964.0	Ω
r	255.4	Ω
Esp/Eacc	2.05	
Hsp/Eacc	45.2	Oe/MV/m
Cell to cell coupling coefficient	2.61	%
Radius of beam tube	38	mm

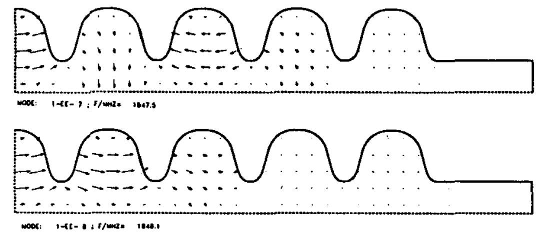


Fig. 9 (a) Traped modes existing in the initial cell shape; E-fields of TM_{110}-5π/9 mode (top) and TM_{110}-3π/9 mode (bottom).

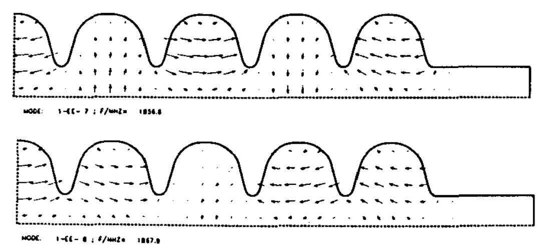


Fig. 9 (b) The same modes as above in the improved cell shape.

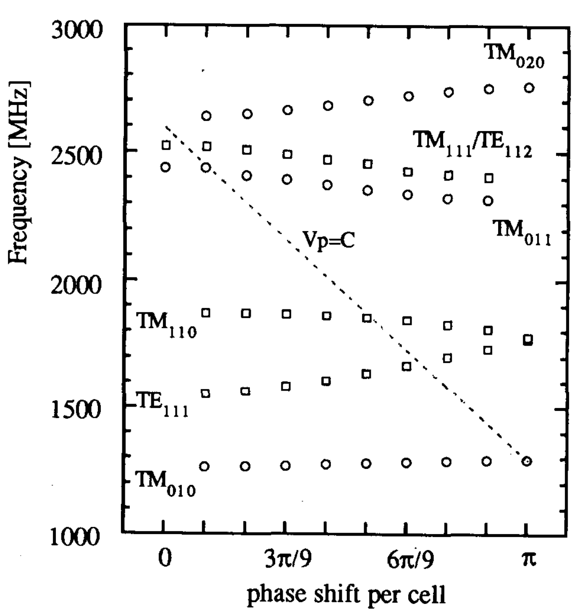


Fig. 10 Higher order modes of the 1.3 GHz, 9-cell KEK-TESLA cavity.

Table III. Higher order modes of the 1.3 GHz, 9-cell KEK-TESLA cavity.

mode	frequency [MHz]	R/Q [Ω]	(R/Q)t [Ω/m]	k [V/pC]
TM_{011}-3π/9	2392	52.1		0.195
2π/9	2408	123.0		0.465
π/9	2436	124.5		0.476
0	2437	12.9		0.049
TM_{020}	2640~2760			
TM_{021}	3300~3620	< 100.		< 0.550
TM_{030}	3650~3790			
TE_{111}-6π/9	1668		1789.	
7π/9	1700		1640.	
8π/9	1731		13.	
π	1771		246.	
TM_{110}-6π/9	1844		1061.	
5π/9	1856		901.	
TM_{111} π/9	2520		242.	
/TE_{112} 0	2523		1502.	

[2.0 cm off axis]

6. Summary

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 for three niobium cavities were performed. 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 these goals.

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