Design of a Prototype of RF Cavity for the KEK *B*-Factory (KEKB)

Tatsuya KAGEYAMA, Nobumasa AKASAKA, Yasunao TAKEUCHI,
and Yoshishige YAMAZAKI
KEK, National Laboratory for High Energy Physics
Oho 1-1, Tsukuba, Ibaraki, 305 JAPAN

Abstract

A prototype of normal conducting RF cavity for the KEK *B*-factory (KEKB) has been designed on the basis of choke mode cavity originally proposed as a damped structure for linear colliders. The KEKB prototype cavity is loaded with a coaxial waveguide for damping higher order modes (HOM's). The waveguide is equipped with a notch filter to block the *TEM* wave coupled with the accelerating mode. Other HOM waves passing through the filter are absorbed by bullet-shape sintered SiC ceramics. Research and development work is underway to verify the cavity performance in high power operation, and in high-current beam handling.

1. INTRODUCTION

The KEK *B*-Factory (KEKB) is a two-ring asymmetric e^+e^- collider, which will be capable of producing *B* meson pairs at a luminosity of $10^{33\text{-}34}$ cm^{-2}sec^{-1}. The collider consists of a 3.5-GeV positron ring and an 8-GeV electron ring. Both rings are required to store high-current beams with low emittances to achieve the high luminosity.

The key issue in cavity design for high-current and low-emittance beam machines is to suppress the excitation of HOM fields by bunches passing through the cavity. HOM fields in high-*Q* RF structures are harmful, because they cause coupled-bunch beam instabilities, which lead to emittance growth, or beam loss. A straightforward way to suppress the coupled-bunch instabilities is to damp HOM's by effectively extracting the field energy out of the cavity. A number of HOM-damped cavity structures have been proposed and studied at accelerator laboratories around the world.

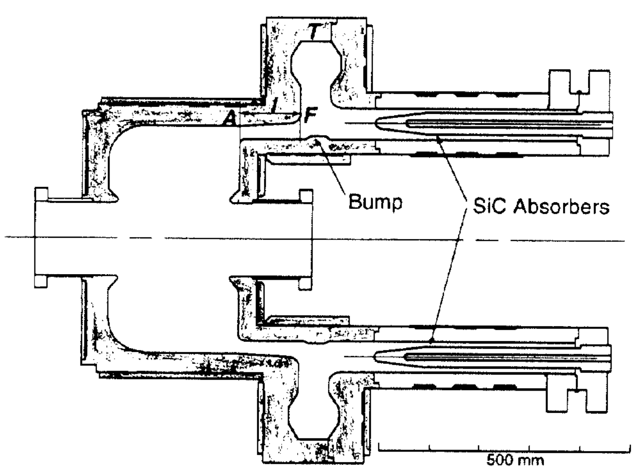

Figure 1. A schematic drawing of the prototype of the HOM-damped cavity for KEKB.

A prototype of normal conducting cavity for KEKB has been designed on the basis of choke mode cavity [1]. The axial symmetry of choke mode cavity makes all simple. For example: 1) No concentration of wall currents of the accelerating mode assures good performance in high power operation. 2) The main cavity parts can be precisely machined by turning lathe. 3) Precise electromagnetic and thermal-structural analyses are possible by two-dimensional codes only.

The first prototype to verify the performance in high power operation is under construction. In 1996, the verification for high-current beam handling is also scheduled at the TRISTAN accumulation ring.

2. PROTOTYPE CAVITY

2.1. *General Design*

The original choke mode cavity [1] is a pillbox cavity loaded with a parallel plate radial waveguide equipped with a notch filter of a coaxial-waveguide type. The notch filter blocks the radial wave coupled with the accelerating mode. Other radial waves coupled with HOM's pass through the filter and travel outward.

We have chosen another scheme of choke mode cavity for KEKB as shown in Fig. 1, where the accelerating cavity is loaded with a coaxial waveguide equipped with a notch filter of a radial-waveguide type. This scheme is to reduce the radial size of the cavity structure and the total volume of microwave absorbers.

Monopole and dipole HOM's excited in the cavity are coupled with *TEM* and TE_{11} waves of the coaxial waveguide, respectively. On the other hand, the notch filter blocks the *TEM* wave coupled with the accelerating mode. RF waves passing through the filter are absorbed by sixteen bullet-shape sintered SiC absorbers inserted from the waveguide end.

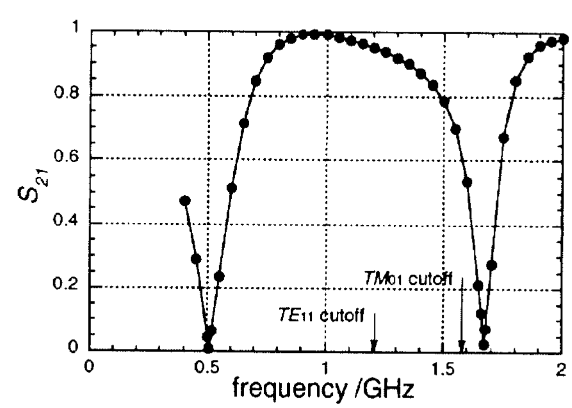

Figure 2. The frequency response of S_{21} of the notch filter.

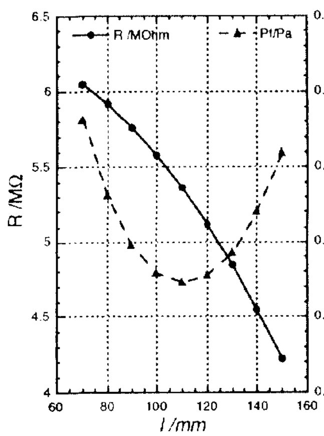

Figure 3. The ratio P_f/P_a and the shunt impedance are plotted as a funciton of l.

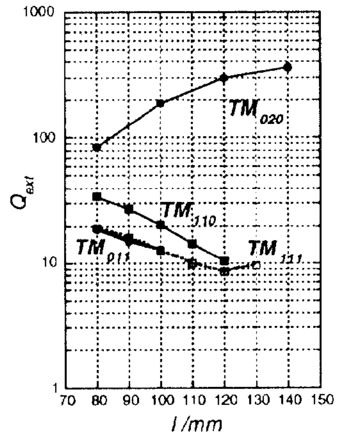

Figure 4. The Q_{ext} values of some harmful HOM's are plotted as a function of l.

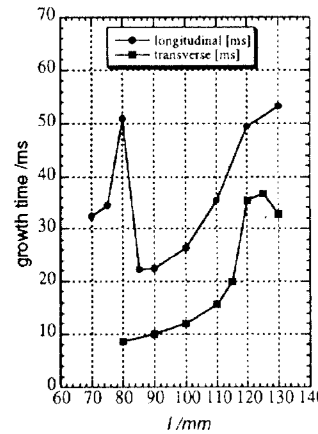

Figure 5.. Each growth time response to l for the longitudinal and transverse coupled-bunch instabilities.

2.2. *RF Properties*

The gap dimensions of the notch filter and the coaxial waveguide were carefully determined so as to avoid multipactoring discharges at the accelerating frequency.

The S parameters of the notch filter were calculated using the program HFSS (High Frequency Structure Simulator). Figure 2 shows the frequency responses of S_{21} (transmission) for *TEM* waves. The first stop frequency for *TEM* waves can be precisely tuned to the accelerating frequency 0.509 GHz by lathe-machining of the bump at the bottom of the filter structure. The *TEM* second stop frequency is raised to 1.67 GHz from 1.39 GHz by deforming the outer volume of the filter. The first and second stop frequencies for TE_{11} waves are 0.53 GHz and 1.68 GHz, respectively.

Near the *TEM* and TE_{11} second stop frequencies, some HOM's may be trapped within the cavity. To avoid this problem, the beam bore diameter was enlarged to 145 mm. The cutoff frequencies of the bore for TM_{01} and TE_{11} waves are indicated by arrows in Fig. 2.

The filter position along the waveguide is arbitrary to some extent, but affects the accelerating efficiency and the HOM-damping. Unfortunately, we cannot usually get the best performances for both at the same time.

First, we examine some RF properties of the accelerating mode, for example, the shunt impedance and the field energy distribution in the cavity with the notch filter. Let us define the filter position along the waveguide by l, which is the distance between surfaces A and F shown in Fig. 1. Let us also represent the stored energy and power dissipation in the cavity (the left side of surface A) by U_a and P_a, and those in the notch filter by U_f and P_f. Figure 3 shows the ratio of P_f/P_a as a function of l, together with the response of the shunt impedance. They were calculated using the program SUPERFISH. The notch filter functions as a quarter wavelength ($\lambda_{TM010}/4$) resonator at the accelerating frequency. When the total electrical length from the waveguide aperture (surface A) to the top end of the filter (surface T) is close to a half wavelength $\lambda_{TM010}/2$ (l=110mm in Fig. 3), the electrically-short boundary at surface T is mapped onto surface A, and the ratio of U_f/U_a (P_f/P_a) becomes minimum. But this is not a necessary condition in design of choke mode cavity. For optimizing the efficiency of beam acceleration, a shorter coaxial waveguide between A and F is desirable. In Fig. 3, the shunt impedance increases as l becomes smaller.

Next, we examine the relation between the performance in HOM damping and the filter position. *TEM* and TE_{11} waves coupled with HOM's are partially reflected at the gap transition (surface F). Therefore, the distance l is expected to play an important role to determine the HOM-damping performance. In Fig. 4, the external Q values (Q_{ext}'s) of some harmful HOM's are plotted as a function of l. In this graph, Q_{ext} is defined as the coupling to the coaxial waveguide beyond the notch filter. The calculation technique for HOM Q_{ext}'s of the KEKB cavity is also reported in this conference [2]. In Fig. 4, each Q_{ext} response shows a clear dependence on l. For example, the Q_{ext} values of the TM_{020} mode increases as l becomes large, while other HOM Q_{ext}'s decrease. We have also calculated the growth rates of the longitudinal and transverse coupled-bunch beam instabilities due to eight cavities of this type for the KEKB 3.5-GeV e^+ ring [2]. Figure 5 shows the response of each growth time to l. It should be noted that the contribution from the TM_{020} mode to the longitudinal instability is very small because of its small transit time factor. A waveguide length of l = 120~130 mm is desirable to suppress both instabilities.

The waveguide length l was determined to be 120 mm by taking into account both RF performances stated above. We have chosen better HOM damping at a little sacrifice of the efficiency in beam acceleration. Some RF parameters are listed below for the accelerating mode when l = 120 mm.

Table 1
RF parameters of the accelerating mode

f = 0.5086 GHz	Vc = 0.6 MV	Pc=70 kW (*)
R/Q = 150 Ω	Q = 3.3x10^4 (*)	R = 5.0 MΩ (*)

(*) A degradation of ~5% due to copper surface imperfections is taken into account.

2.3. *Thermal Structural Analysis*

The cavity parts shaded in Fig. 1, whose inner surfaces with heat generation due to the wall currents of the accelerating mode, are made of oxygen-free copper (OFC). The coaxial waveguide parts beyond the filter are made of stainless steel to reinforce the

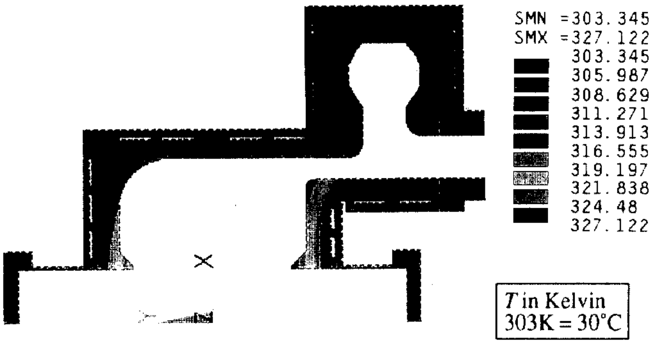

Figure 6. The temperature contour over the model resulting from the thermal analysis.

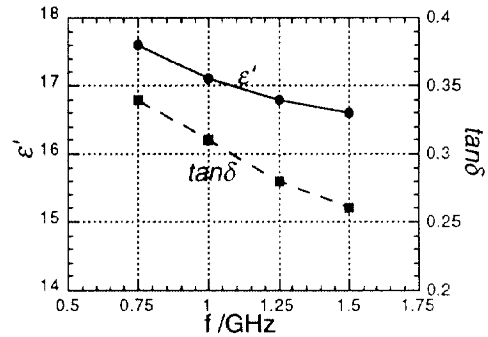

Figure 7. The dielectric constant and loss tangent of the SiC ceramics are plotted as a function of frequency.

whole cavity structure. Vacuum furnace brazing and electron-beam welding techniques are employed to assemble the parts.

For the cavity loaded with the rated input power in Table 1, thermal and thermal-stress analyses were carried out using the finite element analysis program ANSYS. Figure 6 shows the temperature contour over the model resulting from the thermal analysis. The boundary conditions are as follows: On the surfaces of the cooling-water channels, the temperature is fixed at 30°C. The outside surfaces of the cavity are thermally insulated to the air. In Fig. 6, there are two points with the maximum temperature rise, one is at the tip of the right nosecone and the other around the corner of the waveguide aperture. The maximum temperature rise less than 30°C is acceptable. Therefore, the prototype cavity will be capable of stable continuous operation at the rated input.

2.4. *HOM Absorber*

For HOM absorption, sixteen bullet-shape sintered SiC (silicon carbide) ceramics are inserted from the end of the coaxial waveguide as shown in Fig. 1. The dimensions are 40 mm in diameter, and 400 mm in total effective length including a 100-mm nosecone section. Each SiC absorber has a cooling water channel bored inside and is directly cooled. The HOM power to be handled will be on the order of ~10 kW per cavity, corresponding to ~1 kW per absorber. Figure 7 shows the frequency responses of the dielectric constant ε' and the loss tangent $\tan\delta$, measured using a dielectric probe kit (HP85070A).

Some reasons why we have chosen SiC ceramics are as follows: 1) SiC is a fine and dense ceramics which has a high mechanical strength and a low outgassing rate, and is chemically inert. 2) SiC has a relatively high thermal conductivity of ~120 W/mK at room temperature, which is about one half of that of Aluminum (230 W/mK). 3) At the 2.5-GeV electron linac in KEK, nearly two hundred SiC absorbers (diameter = 24 mm, length = 300 mm) have been used for the S-band waveguide loads without any troubles for about ten years. A prototype of S-band SiC absorber was tested up to a peak power of 10 MW with a pulse width of 3.5 μs at 50Hz, corresponding to a average power of 1.75 kW [3]. Among these reasons, the third one most encouraged us to use SiC ceramics.

A prototype of SiC absorber for the KEKB cavity was made to verify the performance as HOM absorber in vacuum. The prototype absorber was inserted from the end of a L-band rectangular waveguide (WR650), where the standing-wave ratio VSWR was measured ~1.1. The high power test was carried out using a pulsed klystron (f = 1296 MHz) up to a peak power of 80 kW with a pulse width 520 μs at 50 Hz, corresponding to a average power of ~2 kW. The prototype SiC absorber functioned normally without any vacuum, thermal, or discharge trouble.

The outgassing rate of the SiC ceramics was also measured using a cylindrical sample (diameter = 50 mm, height = 50 mm). After 24-hour baking at 150°C, the outgassing rate at room temperature was 3×10^{-12} Torr·l/s·cm^2.

3. SUMMARY

Extensive R/D work on the first prototype of the HOM-damped cavity for KEKB is underway to verify the performance in high power operation. In 1996, the verification for high-current beam handling is also scheduled at the TRISTAN accumulation ring.

In parallel with the development of the HOM-damped cavity, R/D work on a new structure named ARES [4], [5] (Accelerator Resonantly coupled with Energy Storage) is in progress. ARES is a coupled-cavity structure, where an accelerating cavity is coupled with an low-loss energy storage cavity by a resonant coupler (coupling cavity). The storage cavity is operated in the TE_{015} mode with a high Q value. ARES will be capable of heavy beam loading by suppressing the coupled-bunch beam instability due to the accelerating mode itself.

4. ACKNOWLEDGMENTS

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5. REFERENCES

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