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GROOVED BEAM PIPE FOR DAMPING DIPOLE MODES IN RF CAVITIES

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Abstract

This paper concerns a computational study of an RF accelerating cavity equipped with grooved beam pipes. The method of grooved beam pipe proposed by the author is simple and effective in damping dipole modes in accelerating cavities. This method uses a grooved beam pipe as a waveguide through which dipole-mode RF power is extracted. A computational study has been carried out on a 500-MHz pillbox cavity loaded with two grooved beam pipes at both ends. Calculations have shown that the external Q value of the lowest dipole mode TM110 can be reduced to less than 20. As for the accelerating mode, the reduction in the shunt impedance due to the grooved beam pipes is negligibly small compared with when equipped with circular beam pipes. Following this idea, a grooved beam pipe is being developed at Cornell University for a super-conducting cavity for the CESR B-factory.

Introduction

Electron bunches circulating in a ring accelerator interact one another via long-range electromagnetic wakefields. This phenomenon causes the coupled-bunch instability, and leads to the emittance growth or loss of the beam. The components of long-range wakefields are higher-order modes (HOM's) excited by a bunch in the accelerating structure, which is usually a high-Q resonator. The range of interaction is related to the life of its carrier. Between circulating electron bunches, the range of wakefields is therefore determined by how long carrier HOM's oscillate after excited by a bunch passing through the accelerating structure. In other words, it depends on the (loaded) Q values of HOM's.

Future machines producing B mesons at luminosities of $10^{33\sim34}$ $cm^{-2}sec^{-1}$ or intense photon beams (synchrotron radiation) will need high-current and high-quality electron beams. Then, the key issue in the design of accelerating structures is how to suppress the coupled-bunch instability due to HOM's. A straightforward way to suppress the coupled-bunch instability is to make the wakefield range shorter than the bunch spacing by damping the carrier HOM's.

In order to damp HOM's by extracting the RF power out of the accelerating structure, several types of HOM couplers have been developed so far. Generally, HOM couplers can be divided into two types: coaxial couplers and waveguide ones. Comparing them, there is a significant difference that a coaxial line has no cutoff frequency while a waveguide coupler can be designed to set its cutoff frequency above the fundamental mode. Thus, coaxial couplers need some filter devices to confine the RF power of the fundamental mode inside the accelerating structure. Generally, waveguide couplers are simpler and useful in damping HOM's heavily.

Palmer has proposed an RF structure complex consisting of accelerating cells and waveguide couplers[1]. This structure is referred to as 'damped structure' and one of the accelerating tubes for linear colliders, which should be operated with high individual bunch loading and multiple bunches in order to attain high luminosities over 10^{34} $cm^{-2}sec^{-1}$. Following Palmer's structure, the KEK B-factory working group has been investigating a copper damped structure operated in the π mode at 500 MHz. At present, a two-cell prototype is under construction.

Weiland has proposed another damped structure referred to as 'single-mode cavity'[2], which is simple and axially symmetric. He has shown that a circular beam pipe itself with a large diameter works well as a waveguide for extracting HOM RF power out of a cavity. Monopole HOM's couple to the TM01 wave traveling in the beam pipe, and dipole HOM's to the TE11 wave. In order to guide out almost all the HOM's, it is necessary to lower the cutoff frequencies for both TM01 and TE11 waves by enlarging the beam pipe diameter. His calculations show that all the HOM's but the lowest TM110-like mode can be guided out, where the pipe diameter is almost half the cavity diameter. Enlarging the beam bore reduces the shunt impedance of the accelerating mode. So, a copper single-mode cavity would be inefficient. On the other hand, for a super-conducting cavity, a large beam bore does not become a problem concerned with the electric power efficiency.

The single-mode cavity still has a serious problem. That is the TM110-like mode trapped in the cavity. This mode is one of the most harmful HOM's causing the coupled-bunch instability. In order to guide out the TM110-like mode, a new method of grooved beam pipe has been proposed by the author[3]. This idea is based on the fact that the TE11 cutoff frequency of a circular beam pipe can be lowered by grooving its inner wall surface as shown in Fig. 1. We need not to enlarge the pipe diameter itself. This property of the TE11 wave can be explained, for example, by the fact that the TE10 cutoff frequency of a rectangular waveguide depends only on the width of the waveguide cross-section. We need four grooves to damp both horizontally and vertically polarized TM110-like modes. Two grooved beam pipes are attached to both ends of a cavity as shown in Fig. 2.

The next section concerns a computational study of a 500-MHz pillbox cavity equipped with grooved beam pipes. All the calculations have been carried out using the computer code MAFIA[4], which computes electromagnetic-field solutions for three dimensional structures.

Pillbox Cavity loaded with Grooved Beam Pipes

Grooved Beam Pipe

Let us start with a circular beam pipe with the inner diameter = 10 cm, whose wall surface is to be grooved as shown in Fig. 1. Every groove has the same width and depth. The cutoff frequency of the TE11 wave was calculated with MAFIA changing the groove depth

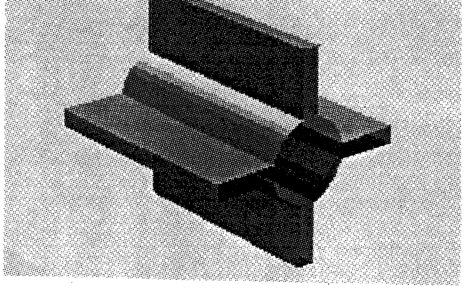

Fig. 1 A three dimensional view of a grooved beam pipe.

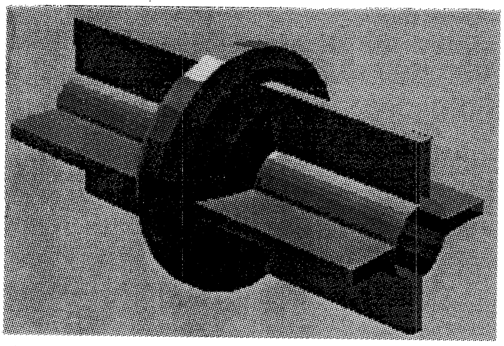

Fig. 2 A three dimensional view of an RF cavity loaded with grooved beam pipes at both ends.

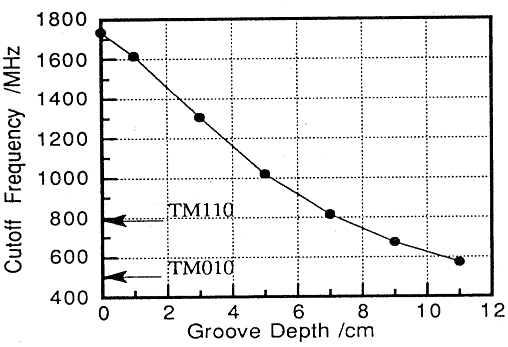

Fig. 3 The cutoff frequency of the TE11 wave in a grooved beam pipe versus the groove depth.

from 0 cm to 11 cm, while the groove width fixed at 2 cm. Figure 3 shows the calculated cutoff frequencies plotted as a function of the groove depth. As the groove becomes deeper, the cutoff frequency becomes lower. Since the 500-MHz pillbox cavity has the TM110 mode at 790 MHz, the groove should be deeper than about 7 cm to guide it out. With deeper grooves, the TM110 mode could be more heavily damped.

In this paper, we will confine ourselves to how to guide out the lowest dipole HOM TM110. If you also want to guide out monopole HOM's, the pipe diameter itself should be made large enough so that the TM01 cutoff frequency can be set below the lowest monopole HOM frequency. That is because the effect of longitudinal grooves on the TM01 cutoff frequency is small.

The External Q Value of the TM110 Mode

Here, for the grooved beam pipes to be attached to the 500-MHz pillbox cavity, we will temporarily set the groove depth at 11 cm and the groove width at 2 cm. From Fig. 3, the TE11 cutoff frequency of the beam pipe becomes about 570 MHz. This frequency is low enough compared with that of the TM110 mode and higher than that of the accelerating mode.

The next task is to calculate the external Q value of the TM110 mode in the cavity coupled to the grooved beam pipe. Let us start with a theoretical work by Slater[5]. That concerns the tuning curve behavior for a resonant cavity coupled to a waveguide duct terminated with a movable short-circuiting plunger. The terminated waveguide works as a tunable resonator coupled with the cavity. Here, we assume that the cavity has a resonance at f_a in the frequency range of our concern. The frequency of the coupled-resonator system f is determined from the plunger position d by the following equation:

$$d = \frac{\lambda_g}{2\pi}\tan^{-1}\frac{1/Q_{ext}}{f/f_a - f_a/f} + \frac{1}{2}n\lambda_g, \quad n = \text{integer}, \qquad (1)$$

where Q_{ext} is the external Q value of the cavity resonance; λ_g is the guide wavelength corresponding to the frequency f. The plunger position d is the distance measured from a certain reference surface. This surface is referred to as 'detuned short surface'. When we transmit an RF wave to a cavity through a waveguide and its frequency is detuned from the cavity resonance, we observe that the transmitted RF wave is reflected at the detuned short surface. The method of tuning curve is useful in designing waveguide-loaded cavity structures. Examples are found in Refs. 6-7.

Figure 4 shows a schematic drawing of the coupling aperture of the pillbox cavity to the grooved beam pipe. At the end wall of the pillbox cavity, there are four radial slits around the beam bore in order to adjust the coupling between the cavity and beam pipe. The slit width is equal to the groove width. The slit length represented by SL in Fig. 4 can be changed from 0 to 11 cm. When SL = 0 cm, the coupling aperture is the beam bore itself. When SL = 11 cm, the aperture shape is the same as the beam pipe cross-section.

The tuning curve was calculated for SL = 0, 3, 5, 7, 9 and 11 cm. Figure 5 shows a three dimensional plot of an input geometry generated by the mesh generator of MAFIA . The pillbox cavity with grooved beam pipes is symmetric about each of the planes x = 0, y = 0 and z = 0, where we choose the origin of the coordinate system at

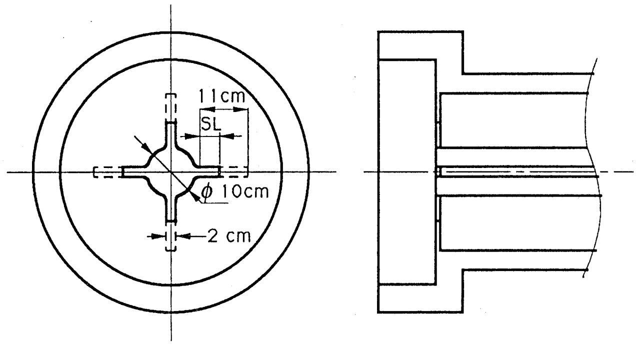

Fig. 4 A schematic drawing of the coupling aperture of the pillbox cavity to the grooved beam pipe.

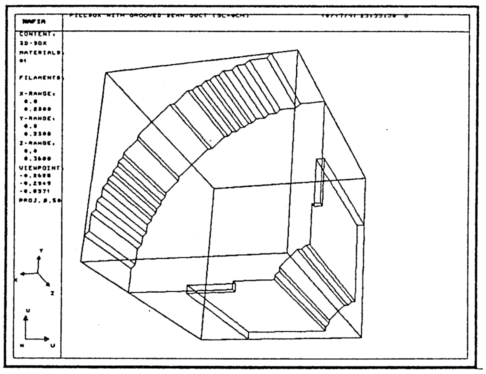

Fig. 5 A three dimensional plot by the mesh generator of MAFIA for the pillbox cavity loaded with the grooved beam pipes.

the center of the cavity and take the beam axis to be the z axis. The symmetric properties make it possible to calculate its electromagnetic field solutions with only one eighth part of the whole structure. The resonant frequency was calculated changing the length of the beam pipe. The boundary at the end of the beam pipe corresponds to the short-circuiting plunger head.

Figure 6 shows the tuning curves obtained for SL = 0, 3, 5 and 9 cm. On the horizontal axis, the frequency is expressed in terms of the guide wavelength λ_g. On the vertical axis, the position of the short-circuiting plane is given by the distance from the plane z = 0. The dashed lines represent the tuning curve behavior when the cavity and the beam pipe are isolated from each other. The vertical dashed line corresponds to the TM110 resonance, whose frequency is independent of the plunger position d. The slant dashed lines $d = n\lambda_g/2$ correspond to the standing-wave modes TE11n in the terminated beam pipe. Near the intersection of the dashed lines, two curves push away each other farther as the slit length SL increases. This behavior suggests that the coupling between the cavity and the beam pipe becomes stronger as SL increases.

Equation (1) assumes that the position of the reference surface is independent of the frequency. This assumption is valid when the coupling between a cavity and a waveguide is loose, in other words, the coupling aperture is small enough compared with the guide wavelength. When the aperture size becomes comparable with the guide wavelength, the reference surface is no more fixed somewhere. Here, we express the position of the reference surface by $s(\lambda_g)$ as a function of the wavelength. Then, Eq. (1) becomes

$$d - s(\lambda_g) = \frac{\lambda_g}{2\pi}\tan^{-1}\frac{1/Q_{ext}}{f/f_a - f_a/f} + \frac{1}{2}n\lambda_g . \qquad (2)$$

When we consider the frequency dependence of the reference position up to the first order in the Taylor expansion of $s(\lambda_g)$, Eq. (2) can be rewritten as follows:

$$d - d_0 = \frac{\lambda_g}{2\pi}\tan^{-1}\frac{1/Q_{ext}}{f/f_a - f_a/f} + \left(\frac{1}{2}n + k\right)\lambda_g , \qquad (3)$$

where d_0 and k are constant.

For each slit length SL, the external Q value of the TM110 mode was determined by fitting the tuning curve with Eq. (3), where there are four free parameters f_a, Q_{ext}, d_0 and k. Figure 7 shows the calculated external Q value as a function of the slit length SL. The external Q value rapidly decreases from more than 2000 to less than 20 as SL increases from 0 cm to 7 cm. On the other hand, it is almost constant in the range SL = 7 cm to 11 cm. That is probably because the group velocity of the TE11 wave sets a lower limit on the external Q value.

The Effect of Grooved Beam Pipe on the Accelerating Mode

The RF properties of the fundamental TM010 mode were also calculated with MAFIA to investigate how the grooved beam pipe affects the efficiency of the accelerating cavity itself. Table 1 lists the calculated RF properties of the TM010 mode for the slit length SL = 3, 5 and 7 cm, together with those when the cavity is equipped with circular beam pipes. This table shows that the effect of the grooved beam pipe on the accelerating mode is very small and the reduction in the shunt impedance is negligible. That is due to the following reasons: The wall surface currents of the TM010 mode do not cross the radial slits around the beam bore; The RF structure has four-fold rotational symmetry around the beam axis. This symmetric property inhibits the coupling between the TM010 mode and the TE11 wave.

Table 1
RF properties of the accelerating mode

	SL /cm	f /MHz	Q	R /MΩ	R/Q /Ω
G	3	503.1	4.27e+04	7.93	186
G	5	503.2	4.28e+04	7.95	186
G	7	503.2	4.29e+04	7.98	186
C		502.7	4.26e+04	7.97	187

G = Grooved Beam Pipe, C = Circular Beam Pipe
R = shunt impedance

Conclusions

The computational study with MAFIA on the 500-MHz pillbox cavity equipped with grooved beam pipes has shown that the external Q value of the TM110 mode can be reduced to less than 20. As for the accelerating mode, the reduction in the shunt impedance due to the grooved beam pipe is negligibly small. Thus, the method of grooved beam pipe is simple and effective in damping dipole HOM's without sacrificing the accelerating mode.

Following this idea, a grooved beam pipe is being developed at Cornell University[8]. The beam pipe, named 'fluted beam pipe', will be attached to one end of a super-conducting RF cavity for the CESR B-factory.

References

1. R.B. Palmer, 'Damped Acceleration Cavities', SLAC-PUB-4542, 1988
2. T. Weiland, 'Single Mode Cavities', DESY 83-073, 1983
3. T. Kageyama, 'A design of beam duct cross-section for damping dipole modes in RF cavities', Proc. of the 15th Linear Accelerator Meeting in JAPAN, p. 79, Sept. 1990; KEK B-factory Workshop Oct. 1990
4. R. Klatt et al., Proc. of the 1986 Linear Accelerator Conf., SLAC-Report-303, pp. 276-278, 1986
5. J.C. Slater, Microwave Electronics, Van Nostrand, 1950
6. T. Kageyama, KEK-Report 89-4, 1989
7. N.M. Kroll and D.U.L. Yu, SLAC-PUB-5171, 1990
8. Berkelman et al., CESR-B conceptual design for a B factory based on CESR, CLNS-91-1050, March, 1991

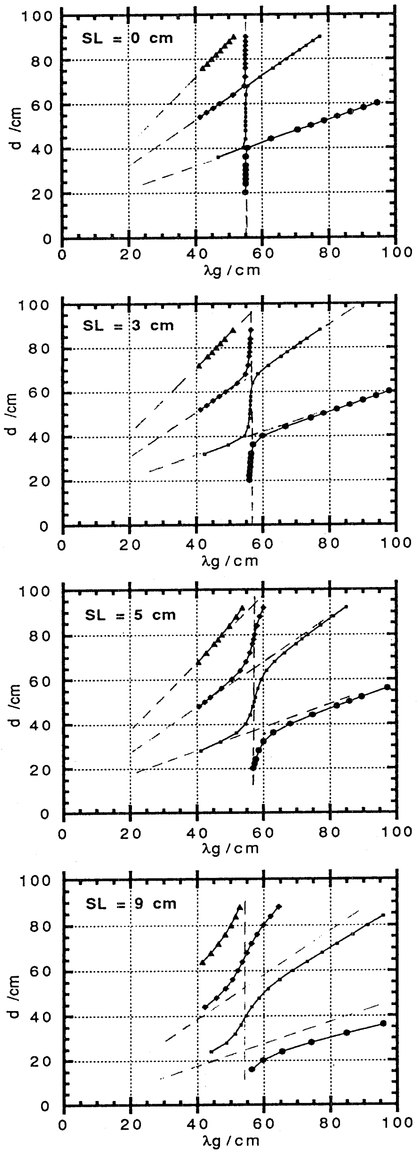

Fig. 6 Tuning curves obtained for the slit length SL = 0, 3, 5 and 9 cm.

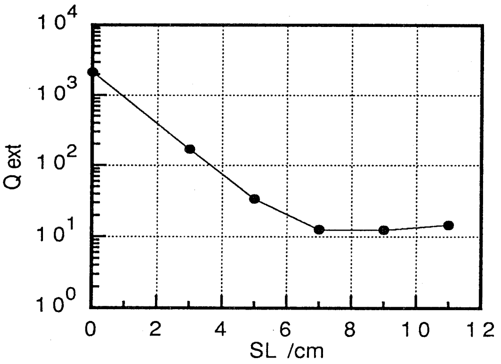

Fig. 7 The dependence of the external Q value of the TM110 mode on the slit length SL.