LOM and HOM damping study in a superconducting deflecting cavity for ALS at LBNL *

SHI Jia-Ru(施嘉儒)[1;1)] CHEN Huai-Bi(陈怀璧)[1] TANG Chuan-Xiang(唐传祥)[1]
ZHENG Shu-Xin(郑曙昕)[1] Derun Li[2]

1 (Department of Engineering Physics, Tsinghua University, Beijing 100084, China)
2 (Lawrence Berkeley National Laboratory, CA 94720, USA)

Abstract Superconducting deflecting cavities can be used in synchrotron light source to generate subpicosecond X-ray pulses while the impedance of the lower order modes (LOM) and higher order modes (HOM) in the cavity should be kept below an accepted level to avoid beam instability. These modes can be damped by adding waveguide on beam pipe. Detailed simulation of Q in CST Microwave Studio is introduced and experiment results on an aluminum model cavity with damping waveguide are reported to make a comparison.

Key words deflecting cavity, lower order mode, impedance calculation, HOM damping

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1 Introduction

Zholents et al. proposed a scheme to generate short X-ray pulses[1]. The scheme requires RF deflecting cavity to generate a correlation between longitudinal and transverse phase space within an electron bunch. The subsequent X-rays radiated from bending magnets and undulators are compressed using optics. The deflecting cavity can also be used in colliders such as KEK-B, LHC and ILC to give a head-to-head collision. However, it's usually called the "crab cavity" in this field.

For ALS at LBNL, preliminary studies indicate that up to 2 MV deflecting voltage at 1.5 GHz is required for 1.9 GeV electron beam[2]. Limited by the peak magnetic field, three to four cells superconducuting RF structures may be required to achieve 2 MV deflecting voltage at 1.5 GHz[3].

The deflecting mode (TM_{110}-like) is not the fundamental mode in a cavity. For a single or multi-cell deflecting structure, there are both LOMs and HOMs. The impedance from these modes need to be damped to a level so that they do not cause any beam instability. In addition to these LOMs and HOMs, there is an unwanted degenerate dipole mode in a cylindrical symmetric structure.

KEK-B has already designed and built one-cell superconducting crab cavities for its ring. The TM_{010} mode, which has high longitudinal impedance, is damped using a coaxial pipe inside the beam-pipe. And the frequency of degenerate mode is pushed up by varying cavity geometry[4].

Using a different method while keeping the RF structure cylindrically symmetric, we damp the same order mode as other unwanted modes. This paper introduces the detailed simulations in CST-MicrowaveStudio for damping each mode and discusses some configurations. A cold test experiment is set up to check the most promising configuration using aluminium cavity and the result is presented.

2 Impedance and Q_s in a deflecting cavity

Impedance of the accelerator environment describes the wakefield effect and is used widely in studying beam stability. The impedance spectrum from a cavity-like structure contains numbers of peaks at sharply defined frequency, showing the eigenmodes of the cavity[5].

For longitudinal impedance $Z^{\parallel}$ and transverse impedance $Z^{\perp}$, we have the relationship:

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1) E-mail: shijiaru00@mails.tsinghua.edu.cn

$$Z^{\parallel}(\omega_n)=\frac{1}{2}\cdot\left(\frac{R}{Q}\right)_n\cdot Q\,, \tag{1}$$

$$Z^{\perp}(\omega_n)=\frac{\kappa}{2}\cdot\left(\frac{R}{Q}\right)_n^{\perp}\cdot Q\,, \tag{2}$$

where $\kappa=\omega/c$, ω_n is the angular frequency, and (R/Q) is the shunt impedance[6]. And to avoid beam breakup, we need approximately[7]

$$Z^{\parallel}\times f<125\ \mathrm{k\Omega\cdot GHz}\,, \tag{3}$$

$$Z^{\perp}<2\ \mathrm{M\Omega/m}\,, \tag{4}$$

where f is the frequency.

In CST-MicrowaveStudio, eigen-mode solver can be used to calculate the field distribution of each mode in the cavity and (R/Q)s can be calculated by integral of the electric field.[8, 9] (R/Q)s of each mode are determined by the cavity shape. The impedance actually depends on Q, which can be decreased by damping coupler(s).

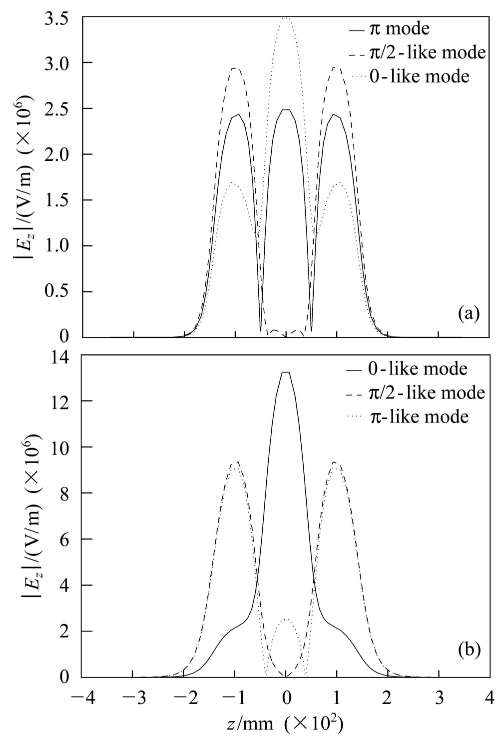

Fig. 1. Electric field distribution of both TM_{110} and TM_{010} mode in a 3-cell cavity, (a) Longitudinal field distribution of TM_{110} mode off axis at r=10 mm; (b) Longitudinal field distribution of TM_{010} mode on axis, showing the trapped mode.

Early studies show that to achieve 2 MV deflecting voltage, a 3-cell cavity design can be chosen where peak surface magnetic field is kept blow 100 mT, which has been approved achievable for Nb cavities. However, a trapped mode was found in the 3-cell cavity.

In the working mode, since the adjacent cells couple mainly through magnetic energy, the frequency of the π mode is the lowest among the TM_{110} series. To make field balance in each cell, the two end cells are a bit enlarged. Fig. 1(a) shows the electric field distribution of the three modes in the 3-cell cavity. The π mode, which is the working mode, has been tuned and balanced in the three cells.

However, the field of monopole mode is different from the dipole and the field balance of cells may break in TM_{010}. The field distribution of TM_{010} is presented in Fig. 1(b), showing that the lowest monopole mode is trapped in the central cell, which will be hard to damp from the beam pipe.

A 2-cell cavity is chosen to avoid these trapped modes. (R/Q)s of the structure is calculated by eigen-mode solver in the code and the result is shown in Table 1. The most harmful longitudinal mode is the LOM, TM_{010}-like mode. By Eqs. (1)—(4), we can estimate the Q threshold (Q_{th}), meaning the required damping, of each mode.

Table 1. (R/Q)s and required damping of the LOMs and HOMs in the 2-cell structure.

mode		f/GHz	$(R/Q)/\Omega$	Q_{th}
TM_{010},	0	1.0439	41.7	5743
	π	1.0473	206.2	1158
mode		f/GHz	$(R/Q)^{\perp}/\Omega$	Q_{th}
TM_{110},	π	1.4983	109.8	1520
	0	1.5081	0.99	1.7×10^5
TE_{111},	0	1.8383	7.31	1.8×10^4
	π	1.9143	7.78	1.7×10^4

Transient solver in CST-MicrowaveStudio can simulate the excitation and damping in a cavity, then the energy decay rate of a cavity coupled through waveguide can be directly computed to get loaded quality factor (Q_{load})[10]. Adding different configurations of waveguide(s) on this cavity to get the required damping is investigated and simulated.

3 Damping waveguide

3.1 Coaxial coupler for damping monopole mode

The field pattern of TEM mode in coaxial line is very similar to TM_{010} in a pillbox cavity, in which the magnetic field is circling around. As the KEK-B crab cavity presents, if a coaxial conductor is put in the beam pipe, it will get high coupling for the monopole mode. Fig. 2 shows the configuration of one cell cavity with a coaxial coupler.

The TEM mode in a coaxial line has no cutoff frequency, but the coaxial line still has higher order modes like TE_{11}, which is similar to a dipole mode in cylindrical waveguide and may couple the working mode. When $b<4a$, the cutoff frequency of TE_{11} in a coaxial line can be approximately calculated by

$$\lambda_c \approx \pi(a+b), \tag{5}$$

where λ_c is the cutoff wavelength, a and b are the radii of inner and outer conductor. To make sure the working frequency is below the cutoff frequency of TE_{11}, the radius required as $a+b<60$ mm. When the length of the inserted inner conductor varies, we will obviously get a different coupling and the simulation result is shown in Table 2. To get lower external Q, the coaxial conductor must be inserted in to the cavity, which may cause some problems like multipacting.

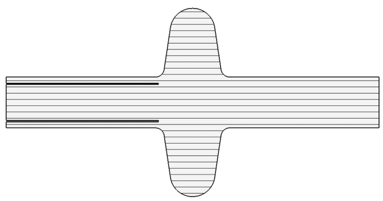

Fig. 2. Coaxial coupler for monopole mode.

Table 2. Q_{ext} of the lower order monopole mode TM_{010} with coaxial damper.

length/mm	Q_{ext}	
	a=27, b=33	a=26, b=34
−6	2620	
−4	2001	
−2	1485	
0	1028	708.7
2	786.2	548.6
4	593.2	421.4

3.2 Waveguide damping of unwanted dipole mode

For cylindrical cavities, the dipole modes are degenerate, and two dipole modes have the same field distribution, but with different orientations. KEK-B crab cavity uses an asymmetry structure in order to obtain the needed polarization, which is hard to build. Cylindrical cavities are easy to fabricate and the problem is to damp the other polarization.

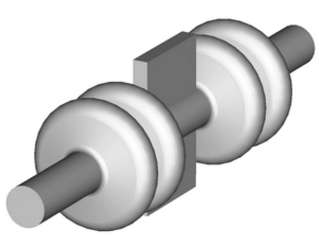

Fig. 3. Waveguide in between to damp unwanted dipole mode.

The dipole mode is not a pure TM_{110} mode but a hybrid mode between TE_{111} and TM_{110}. From cavity to beam pipe, the field mode is gradually transformed from TM_{110} to TE°_{11}. If we add a rectangular waveguide on the beam pipe, the TE°_{11} mode in a beam pipe will be easily coupled into the rectangular waveguide, where the TE_{10} mode has strong transverse electric field.(see Fig. 3)

The cut-off frequency of TE_{10} in a rectangular waveguide depends on the width of the cross section a.

$$f_c = \frac{c}{2a}, \tag{6}$$

where c is the speed of light. For 1.5 GHz wave, $a>100$ mm is required for propagation. To add the waveguide in the middle of two-by-two superstructure, the length of beam pipe in between is chosen as λ (200 mm), and is enough to add a wide waveguide. The results of the 2-cell cavity with 180 mm×30 mm waveguide are given in Table 3.

Table 3. Q_{ext} of the waveguide for unwanted dipole mode.

mode	f/GHz	Q_{ext}
TM_{110},π	1.5022	1774
TM_{110},0	1.5121	1470

3.3 Waveguide damping on beam-pipe for both monopole and unwanted dipole

Figure 4 shows another configuration. The lowest monopole in a cavity, TM_{010}-like mode, which has longitudinal electric field on axis, can be strongly coupled out by the transverse electric field of TE_{010} in a rectangular waveguide. By Eq. (6), since the monopole mode has a frequency of about 1.04 GHz, the waveguide width a should be larger than 150 mm.

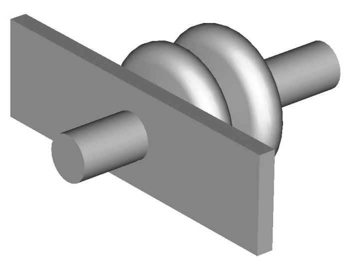

Fig. 4. Waveguide to damp both monopole and unwanted dipole.

The dipole mode still has two polarizations. Both of them have longitudinal electric field off axis. Assuming we need y-direction deflecting, the unwanted dipole mode gives x-direction momentum and its longitudinal electric field is still on the mid-plane of the x-direction rectangular waveguide, so it may strongly couple the TE_{10} in it. The electric field of working mode is zero at the mid-plane of the waveguide and the working mode couples the TE_{20} mode. The cutoff frequency of TE_{20} also depends on the width of cross section of the waveguide:

$$f_c = \frac{c}{4a}, \tag{7}$$

which is simply twice that of TE_{10}. Choosing a= 170 mm for propagation of TE_{10}, we got the cut-off frequency about 2 GHz of TE_{20}, whose excitation frequency is 1.5 GHz. Although the frequency of TE_{20} is below the cut-off, we still need to lengthen the waveguide to make the mode decay at a low level under −60 dB or even lower, in order to increase the Q limitation.

Simulation result of the model shown in Fig. 4 with 170 mm×30 mm waveguide is shown in Table 4.

Table 4. Preliminary experimental result of waveguide damper compared with simulation.

mode		cold test		CST MWS T	
		f/GHz	Q_{ext}	f/GHz	Q_{ext}
TM_{010}		1.0401	1895	1.0400	2286
		1.0435	1565	1.0438	1686
TM_{110},	x	1.4951	376	1.4917	686
		1.5045	536	1.5025	930
	y	1.4928	1.3×10^5	1.4894	–
		1.5037	–	1.5013	–
TE_{111},	x	1.8529	121	1.8465	196
		1.9260	206	1.9243	338
	y	1.8587	187	1.8539	174
		1.9293	117	1.9278	260

4 Cold model experiment

A cold model of 2-cell cavity with damping waveguide is built (Fig. 5). The cavity is made of aluminum and the waveguide is made of stainless steel and copper coated on inner surface. Pieces of ferrite are sticken at the waveguide end using as absorbing load. Exciting and probing the cavity by small antennas and loops, Qs can be directly read from S_{21} on the network analyzer. First measured on the cavity are the Q_0s, followed by the Q_{load} on the cavity with waveguide. We can calculate Q_{ext} and compare it with the simulation in Table 4. The frequencies and Qs of LOM agree very well while the unwanted dipole mode has a frequency difference of about 3 MHz and Qs with an error $< 40\%$.

For the working mode, TM_{110} at y-direction, there is very little power coming from the damper in simulation while choosing the material as perfect conductor. But in experiment, we got a Q_{ext} at about 10^5. This may come from the power dissipated on waveguide wall and the measurement error of Q_0,

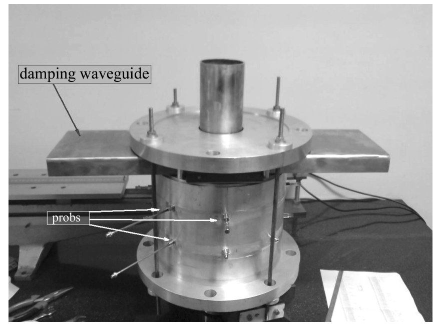

Fig. 5. Cold test model of LOM damper.

Also concerned is the frequency shift of the same order mode with the other polarization of the working mode (TM_{110}), which is damped by the waveguide. The frequency shift by the damper is about 2.2 MHz, showing that the simulation and the cold test model give the same result.

5 Conclusion

Some configurations are discussed for damping the LOM, HOM and the unwanted degenerate mode. The obtained Q after adding waveguide(s) is around the level of required damping for beam instability consideration. Detailed design will be carried out, including optimization of some geometry, combination of two kinds of dampers to reach the impedance.

A preliminary design of a waveguide damper in 2-cell superconducting deflecting structure is presented and the experiment on an aluminium model shows that the simulation agrees well for frequencies and damping result. However, the measurement and simulation of Q_{ext} give an error which is a bit large. New waveguide load will be prepared and more accurate results are expected.

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