DESIGN STUDY OF DAMPED ACCELERATING CAVITY BASED ON THE TM020-MODE AND HOM COUPLERS FOR THE KEK LIGHT SOURCE PROJECT

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Abstract

We studied a design of a normal conducting, damped accelerating cavity for a 1.5-GHz third-harmonic rf system. To reduce the transient variation of rf voltage due to bunch gaps, we chose the TM020 mode for acceleration by referring to a pioneering work by Ego *et al* [1, 2]. To damp harmful parasitic modes, we placed rod-type higher-order-mode (HOM) couplers at the location where the electric fields of TM020 mode are weak. Electromagnetic simulations showed that most of the principal parasitic modes, except for TM120 and TM021 modes, damped well. If we incorporate some measures to effectively damp these modes, this cavity is promising for the higher harmonic cavity.

INTRODUCTION

In a proposed 3-GeV KEK Light Source (KEK-LS) project [3, 4] which is based on the multi-bend achromat lattice, the third-harmonic cavities having a resonant frequency of 1.5 GHz will be used for mitigating intra-beam scattering and Touschek effect [5]. For these harmonic cavities, we will use the TM020 resonant mode for beam acceleration. Because the TM020 mode has low R_{sh}/Q and high unloaded Q, it is very advantageous to reduce the fluctuations in rf voltage that are induced by bunch gaps. With typical parameters of the KEK-LS, a small fluctuation of ~4.5% p-p is expected with normal conducting (NC) cavities [5]. By applying additional active compensation of rf voltage [5], bunch lengthening which is comparable to that obtained with a superconducting cavity is expected. Then, the NC harmonic cavity can be an attractive solution for the KEK-LS due to their robustness and low construction/operational costs.

A novel damped-cavity scheme using the TM020 mode was first proposed by Ego *et al*. [1, 2]. In their design, the cavity is equipped with two circumferential slots along the magnetic node of the TM020 mode. Parasitic modes, except for the TM020 mode, are damped using absorbing materials which are fit in these slots. In this scheme, excellent parasitic-mode damping is expected while occupying small space in the straight sections of storage rings. Therefore, this cavity is very attractive as rf cavities for the new-generation synchrotron light sources.

We propose in this paper an alternative cavity design which is based on the same TM020 mode but with rod-type HOM couplers for damping parasitic modes. The HOM couplers [6, 7] have been proven reliable in many cavities. We place these HOM couplers where the electric fields of TM020 mode is approximately zero so that they hardly couple to the TM020 mode. In this scheme, openings needed for the HOM couplers can be isolated and smaller, which is advantageous for stiffening the mechanical structure of the cavity.

DESIGN OF THE CAVITY

Configuration

Figure 1 shows a cross section of our designed cavity. An inner radius (R_2) of the cavity was tentatively determined so that the resonant frequency of the TM020 mode fit a frequency of 1.5 GHz before attaching the HOM couplers. The principal parameters of the TM020 mode are shown in Table 1. For damping parasitic modes, four HOM couplers were attached symmetrically at a side wall of the cavity. Each HOM coupler consisted of a rod antenna and a coaxial transmission line. These HOM couplers locate where the electric fields of TM020 mode are very weak, which ensures that they hardly couple to the TM020 mode. The dimensions of the HOM coupler were tentatively chosen as shown in Fig. 1. To minimize the occupation length of each cavity, these HOM couplers should be designed to be longitudinally compact.

Table 1: Parameters of the TM020 Mode

Resonant frequency (f_{res})	1499.75 MHz
Unloaded Q (Q_0)	37,400 (34,400**)
R_{sh}/Q *	77.2 Ω
RF voltage/cavity (V_c)	156 kV
Dissipated power/cavity (P_c)	9.2 kW

* Defined by $R_{sh}=(V_c)^2/P_c$. ** With HOM couplers (L_1=35 mm).

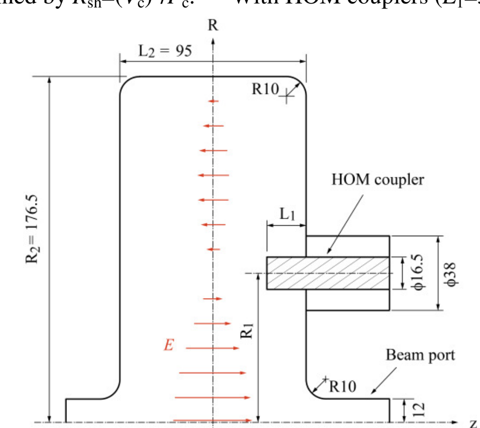

Figure 1: Cross section (upper half) of the harmonic cavity. Electric fields of TM020 mode are schematically shown by red arrows. Unit: mm.

Parasitic Modes

Table 2 shows the resonant frequencies, the longitudinal R_{sh}/Q, and the transverse R_t/Q, of the principal parasit-

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ic modes, which was calculated for an axially symmetric cavity. To avoid coupled-bunch instabilities (CBIs), the loaded Q's (Q_L) of these modes should be damped well. We estimated the target Q_L's from this requirement, and showed them in the fifth column of Table 2. In this estimation, we required that the growth rates of CBIs, which were estimated with simple formulae based on a rigid bunch model, should be less than the radiation damping rates; the parameters of the KEK-LS were used while assuming five harmonic cavities in the ring. Note that these target Q_L's should be modified in future so that an effect of the third-harmonic rf on the beam instabilities is included consistently.

Table 2: Properties of the Principal Parasitic Modes, as well as the Target Loaded Q (Q_L) and Estimated External Q (Q_{ex}) with Four HOM Couplers (at L_1=35 mm)

Mode	f (GHz)	R_{sh}/Q (Ω)	R_t/Q (Ω/m)	Q_L *	Q_{ex} **
TM010	0.6524	168.1	-	45	32
TM110	1.0370	-	1026.4	32	15
TE111	1.6543	-	9.2	3500	n.a.
TM011	1.7149	6.2	-	460	< 55
TM111	1.8913	-	148.3	220	< 20
TM120	1.8969	-	554.2	59	380
TE121	2.1327	-	10.8	3000	n.a.
TM021	2.1865	34.6	-	65	33100
TM030	2.3517	12.8	-	160	< 57
TM121	2.4675	-	632.0	52	< 53
TM130	2.7479	-	20.3	1600	n.a.
TE131	2.7903	-	4.0	8100	n.a.
TM031	2.8464	39.3	-	44	< 39

* Target value. ** Estimated. n.a.: not estimated yet.

Electromagnetic Simulations

We optimized the cavity using an electromagnetic simulation code, ANSYS HFSS. A modeled cavity is shown in Fig. 2. We assigned four exits of HOM couplers the ports 3–5, where these ports were assumed to be terminated by a characteristic impedance of 50 Ω. We also attached tentative probes to the beam ports of the simulation model, and assigned the ports 1 and 2 to the exits of them. The external Q (Q_{ex}) of these tentative probes was ~1.4×10^9 per each for the TM020 mode.

We tentatively fixed the length (L_1 in Fig. 1) of HOM-coupler's rod antennas to be 20 mm. We then optimized the position (R_1 in Fig. 1) of the HOM couplers so as to minimize the coupling of them to the TM020 mode. Figure 3 shows calculated external Q of TM020 mode as a function of R_1. We tentatively chose R_1=76.1 mm which maximized the external Q. Note that the HOM couplers should be positioned accurately, for example, within ±0.2 mm to obtain $Q_{ex} > 10^6$.

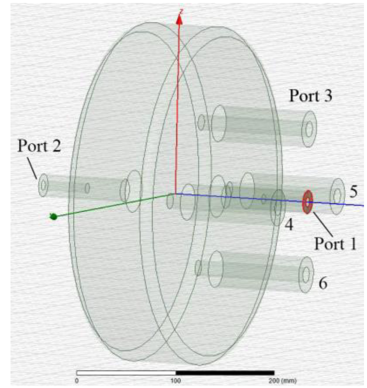

Figure 2: Simulation model of the harmonic cavity.

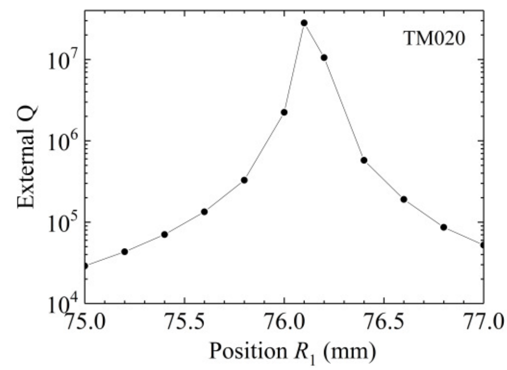

Figure 3: Calculated external Q (with four couplers) of the TM020 mode as a function of the position (R_1) of the HOM coupler. Rod length: L_1= 20 mm.

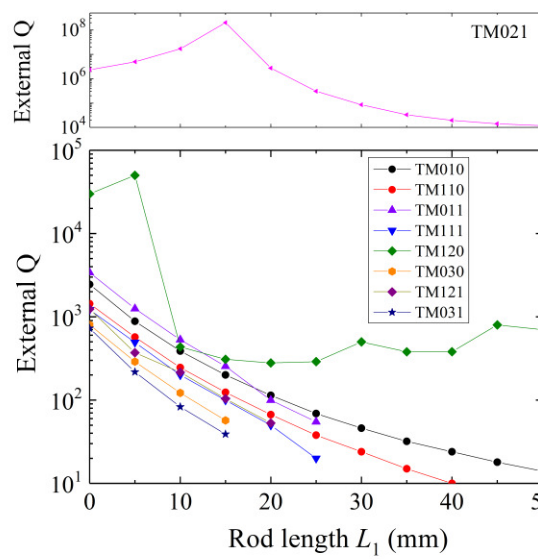

Figure 4: Estimated external Q (with four HOM couplers) of the principal parasitic modes vs. rod length of the HOM couplers.

Next, we estimated the external Q's of the principal parasitic modes. We calculated the S-parameters, S_{21} for monopole modes, and S_{36} for dipole modes, while scanning the excitation frequency around each resonant frequency. We then derived the external Q from a 3dB bandwidth of $|S_{21}|$ or $|S_{36}|$, where no wall loss was included in the simulation. Figure 4 shows thus estimated ex-

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ternal Q's (including four HOM couplers) as a function of the length (L_1) of rod antennas. Since the resonances of TM111 and TM120 modes were overlapped due to their close frequencies, we derived the external Q's of them by fitting a curve of $|S_{36}|$. We should also note that the TM111 and TM120 modes can be mixed together when the HOM couplers are attached, and we need to further investigate their properties, such as R_t/Q, when the HOM couplers are attached.

In Fig. 4, most of the parasitic modes were damped well as the rod length increased. Estimated external Q's at a rod length of 35 mm are shown in the sixth column of Table 2. It shows that most of the parasitic modes, except for the TM120 and TM021 modes, can be damped below the target Q_L's. We found that the TM120 and TM021 modes have weak electric fields at the position of the HOM couplers, and then, they do not couple to the HOM couplers well. In order to make this cavity to practical use, we need to think of an idea to effectively damp these modes. Possible solutions can be a modification of the cavity shape to deform the field patterns of these modes, or some improvements in the HOM couplers.

The resonant frequency of the TM020 mode raised due to perturbation as the rod length increased, as shown in Fig. 5. At the rod length of 35 mm, which is suitable for parasitic-mode damping, the resonant frequency raised by ~7.8 MHz. Then, we need to adjust the inner radius (R_2) of the cavity to compensate for this frequency shift. After this adjustment, we need to optimize the HOM-coupler's position (R_1) for adapting the modification of R_2. Such optimizations should be conducted iteratively when the dimensions of HOM couplers are modified.

At the rod length of 35 mm, a calculated unloaded Q of TM020 mode was 34,400, which was about 92% of that without the HOM couplers. To produce a typical rf voltage of 156 kV, a dissipated power of 9.2 kW/cavity is needed. About 9% of this power, ~820 W, will be dissipated on the surfaces of four rods of the HOM couplers. This power loss is acceptable when the rods are cooled by water.

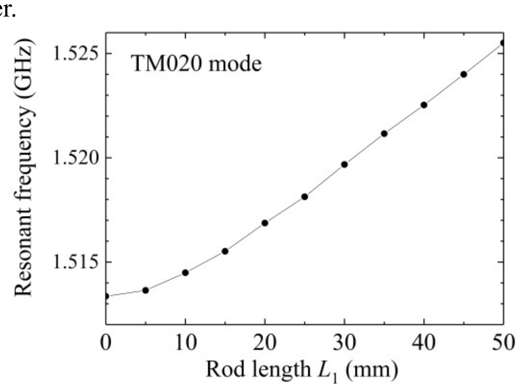

Figure 5: Calculated resonant frequency of TM020 mode as a function of the rod length of the HOM couplers.

Consideration on the Symmetry of the Cavity

The cavity shown in Figs. 1 and 2 is symmetric under operations, $\{E, C_4, C_4^2, C_4^3, \sigma_x, \sigma_y, \sigma_d, \sigma_d'\}$, where E is an identity operation, C_4, C_4^2, C_4^3 are the rotations about the cavity (z-) axis by $\pi/2$, π, and $3\pi/2$, respectively, σ_x is a mirror reflection about the vertical (y-z) plane, and σ_y, σ_d, σ_d' are the mirror reflections about the other three symmetric planes. These operations form a group which is denoted by the point group C_{4v} according to Schönflies symbols. The symmetric patterns of any functions, including the field patterns of eigenmodes, can be classified using the irreducible representations of the group [8]. The point group C_{4v} has the irreducible representations of A_1, A_2, B_1, B_2 (1-dimensional), and E (2-dimensional). Then, each eigenmode in our designed cavity can be classified into one of these irreducible representations.

We can correspond the eigenmodes of an axially symmetric cavity (before attaching HOM couplers) which is characterized by the point group $D_{\infty h}$ [9] with those of a HOM-coupler-equipped cavity. Table 3 shows this correspondence, which was obtained by calculating the compatibility relations between the irreducible representations of $D_{\infty h}$ and C_{4v}. Note that the eigenmodes having the same irreducible representation of C_{4v} can be mixed together when these modes have close eigen frequencies. Such discussions are useful in understanding the properties of parasitic modes in the HOM-coupler-equipped cavity.

Table 3: Correspondence of Eigenmodes of an Axially Symmetric Cavity to Those of a HOM-Coupler-Equipped Cavity

Axially symmetric cavity modes	**Irr. Rep. of C_{4v}**
TM_{0mp}-like	A_1
TE_{0mp}-like	A_2
TM_{nmp}-, TE_{nmp}-like (n=4k, $k > 0$)	A_1+A_2
TM_{nmp}-, TE_{nmp}-like (n=4k+1, $k \geq 0$)	E
TM_{nmp}-, TE_{nmp}-like (n=4k+2, $k \geq 0$)	B_1+B_2
TM_{nmp}-, TE_{nmp}-like (n=4k+3, $k \geq 0$)	E

m: positive integer, *p* and *k*: zero or positive integers

CONCLUSIONS

We studied a design of a normal conducting, 1.5-GHz-frequency cavity for the higher harmonic rf system. To reduce the transient variation of rf voltage due to bunch gaps, we chose the TM020 mode for acceleration by referring to a pioneering work by Ego *et al*. We attached rod-type HOM couplers at the location where the electric fields of TM020 mode are weak. Electromagnetic simulations showed that most of the parasitic modes, except for two, damped well with the HOM couplers at a proper length of rod antennas. We found that two modes, TM120 and TM021, could no be damped well because the electric fields of them are weak at the position of the HOM couplers. If we incorporate some measures to effectively damp these modes, this cavity is promising for the higher harmonic cavity. Investigation of the other parasitic modes than those given in Table 2 is also important.

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