TM0,1.5,0 MODE CAVITY FOR LONGITUDINAL BUNCH FEEDBACK KICKER

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TM0,1.5,0 mode cavity has been proposed for a longitudinal kicker of wide band bunch feedback system in B-factory. This is a kind of parallel-plate radial-line power combiner, in its center beams are accelerated or decelerated on axial electric field. In order to improve the power efficiency, the gap width around the beam is made wider than the outer part, as a result the shunt impedance becomes as high as 1.1 kΩ. Because of its simple axial-symmetric structure, we can use well established theory of accelerating cavity and also analyze the HOM problems with minimum ambiguity. There is no floating electrode inside vacuum, it is easy to fabricate and attach cooling water loops.

I. BASIC CONCEPT

The concept of this kicker is shown in Fig. 1. It is basically a kind of power combiner using radial line transformer to connect a number of power amplifiers into one terminal. Beams are accelerated at the center by the longitudinal electric field of combined rf power. There is no actual terminal at the beam center, only the beam absorbs the rf energy, most of the power will be reflected back to the power amplifier and absorbed in the matching resistor (some part of the power heats up solid state in the amplifiers).

In a simple parallel plate radial-line, the wave impedance varies smoothly along the wave propagation, it shows very flat response for wide frequency range[1]. This is very attractive performance for application to fast bunch-by-bunch feedback system. However, the shunt impedance in this radial line is quite low, typically it is less than 100 Ω, thus we need a large amount of rf power to get enough feedback voltage.

In order to improve the power efficiency, we use a step in the radial line as shown in Fig. 1. We choose the position of this step at the fist root of the Bessel's function, and the input terminals at the second peak of the Bessel's function. In order to keep this condition, the bandwidth of input rf is somehow limited, this is discussed later. Now, we have TM0 like mode in this structure. TM010 is used to name the dominant mode in a pillbox cavity, whose voltage takes zero at the cavity wall. In the present mode, the voltage takes peak at the maximum radius, therefore we should name it TM0,1.5,0 mode (TM0,2,0 takes the next zero at the cavity end). The boundary condition at the input terminal is not the "electrical short", but the "magnetic short" which is supported by standing wave in the coaxial cables connected to the power amplifiers.

If we change view point, this structure can be recognized as a pillbox cavity tightly coupled to an external circuit through a parallel plate radial-line. Since the coupling is so tight, the cavity shows quite low Q-factor, and it can response to rather wide frequency spectrum of feedback signal. It is easy to imagine that if we make the coupling looser (narrows the radial line gap), the external Q-factor becomes higher and we can get higher shunt impedance, but the frequency bandwidth becomes narrow. Therefore, we have to compromise these two issues.

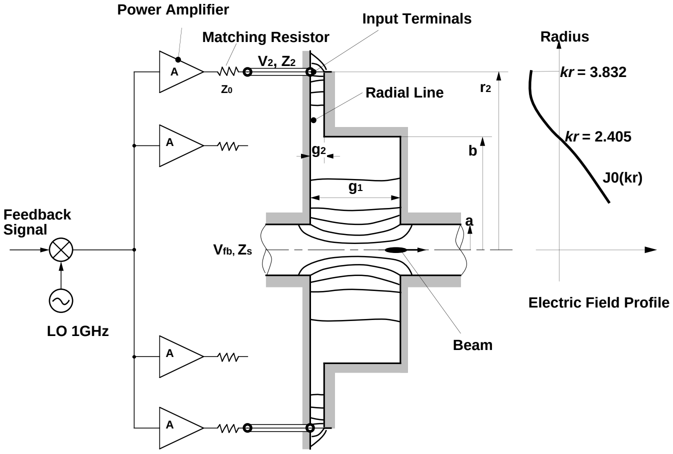

Fig. 1 TM0,1.5,0 Mode Longitudinal Kicker

II. BASIC DESIGN PROCEDURE

The design procedure is as follows.

(1) Choose feedback carrier frequency. It must be high enough to enable the amplitude modulation for wide bandwidth signal, but should be lower than the cut off frequency of beam pipe. Here we choose 1 GHz as a carrier frequency. The radius *b* and *r*2 are determined from its wavelength. Using

$$\begin{aligned} kb &= \rho_{01} = 2.405 \\ kr_2 &= \rho_{11} = 3.832 \end{aligned} \qquad (1)$$

we have *b* = 115 mm, *r*2 = 183 mm. In practical design, we have to determine these parameters on a computer simulation by taking into account beam pipe effect.

(2) Choose number of amplifier. In order to symmetrically drive the input terminals, distance between terminals must be shorter than the half wavelength. Therefore the number of input terminal must be

$$N > \frac{4\pi r_2}{\lambda} = 2\rho_{11} \approx 8 \qquad (2)$$

Here we choose N = 12. In practical design, this will be modified to adjust the impedance for microwave absorbers.

(3) Adjust the gap size $g2$ to match the TEM-mode impedance in the radial-line to the parallel impedance of the amplifiers. The matching condition becomes,

$$Z_2 = \frac{\varsigma_0}{2\pi}\frac{g_2}{r_2} = \frac{50}{N} \quad , \qquad (3)$$

where ζ is 376.7 Ω. For N = 12, $Z2$ must be 4.3 Ω, and $g2$ = 12.7 mm.

(4) Adjust the gap size $g1$ to get proper coupling to the beam. The shunt impedance is proportional to square of the gap size, so that larger gap size is desirable. But, too large gap size will lose transit-time factor. From the point of view of frequency bandwidth, lower external Q is desirable, this contradicts with the shunt impedance issue. We have to compromise these factors.

Using the analytical equation of mode properties on TM0,1.5,0 mode, the cavity parameters are given by the following equations. The shunt impedance of this cavity is

$$Z_s = \frac{V_{fb}^2}{2P_{in}} = \frac{2\varsigma_0}{\pi}\frac{g_2}{r_2}\left[\frac{g_1}{J_0(\rho_{11})g_2}\right]^2 T^2 \qquad (4)$$

where T is the transit time factor,

$$T = J_0(ka)\frac{\sin(kg_1/2)}{(kg_1/2)} \qquad (5)$$

The input power to get feedback voltage V_{fb} is

$$P_{in} = \frac{V_{fb}{}^2}{2Z_s} \qquad (6)$$

The external Q-factor is,

$$Q_{ext} = \frac{1}{2}\rho_{01}\frac{g_1}{g_2} \qquad (7)$$

We choose the gap size $g1$ = 70 mm, then we have the shunt impedance of 1.33 kΩ. To get 7 kV with this kicker, we need 18 kW input power. In the practical application, we install microwave absorbers in the outer part of vacuums vessel to damp higher order modes. Because they absorb some fraction of the input power, we have to increase the input power to compensate this loading as discussed later.

III. PRACTICAL DESIGN

In the conceptual drawing in Fig. 1, at the input terminal the boundary condition was assumed to be open condition. However, in a practical usage, we need a vacuum vessel and electromagnetic shield outside of this structure. Then the practical design becomes as shown in Fig. 2. Detailed dimensions were determined on computer simulation to tune the resonance at the center frequency of carrier signal of 1 GHz. Figure 3 shows the simulated electric field line plot, where no microwave absorbers were loaded. The calculated electrical performance from this simulation is summarized in Table 1, where the analytically estimated parameters are also listed in parenthesis. The net shunt impedance is lowered due to the loading effect on microwave absorbers, it becomes 1.1 kΩ.

Table-1

Carrier Frequency	*f*c	1.0		GHz
Beam Current	*I*	2.6		A
Feedback Voltage	*V*fb	7.0		kV
Cavity Dimensions	*a*	50		mm
	b	124	(113)	mm
	*r*2	190	(183)	mm
	*g*1	70		mm
	*g*2	13		mm
Transit Time Factor	*T*	0.67	(0.68)	
Without microwave absorber				
Shunt Impedance	*Z*s	1.54	(1.33)	kΩ
With microwave absorber				
Number of Power Amp.	*N*	10		
Shunt Impedance	*Z*s	1.1		kΩ
Required Input Power	*P*in	22.7		kW
Power per Amp.	*P*in/N	2.3		kW
External Q-factor	*Q*ext	5.5	(6.5)	
Response Time	τ	1.75		nsec
-3dB Band Width	*f*BW	182		MHz
Beam Loading Power	*P*b	14.8		kW

Note. (values) are analytically estimated.

Here we consider an example application to KEK B-factory[2]. Since the growth rate of the oupled bunch instability in LER(low energy ring) is faster than HER (high energy ring), here we consider LER case. The required feedback voltage per turn can be estimated by

$$V_{fb} = 2gT_{rev}\Delta E \qquad (8)$$

where g is damping rate, $T_{\rm rev}$ is beam revolution time, ΔE is energy deviation. If we expect the damping rate 100 s^{-1} (10 msec), this is four times faster than the radiation damping, and energy deviation of 10^{-3}, this is the same order as one sigma of natural energy spread, the required kick voltage per turn becomes 7 kV. Input power of 22.7 kW is enough to generate this kick voltage.

IV. EFFECT OF MICROWAVE ABSORBER

In order to establish TM0,1.5,0 mode, the characteristic wave impedance in external volume outside the input terminals should be much higher than the paralleled impedance of amplifiers, which means large volume vacuums vessel is desired. At the same time, every resonances in this volume have to be damped to ensure flat frequency response and avoid additional beam instability due to higher order modes. For the HOM damping, smaller volume is desired. Compromising these issue, here we choose the radius at 240 mm. The characteristic impedance of this volume as a coaxial line is 24.3 Ω. We install several microwave absorbers made from SiC material, which are cooled by circulating water.

Now, the amplifiers, the radial line and the coaxial line with microwave absorbers are parallely connected, we have to modify the number of amplifiers to meet the impedance matching. In order to keep the frequency response as wide as possible, the impedance looking from the cavity must be equal to the parallel impedance of the microwave absorbers and the power amplifiers. Now, the matching condition of eq. (3) becomes,

$$Z_2 = \frac{50}{N} // Z_{absorber} . \qquad (9)$$

We find $N = 10$ as a best matching solution. The external Q-factor does not change. The shunt impedance becomes 1.1 kΩ, this is 69 % of initial value.

The power dissipation on the microwave absorber is 13 kW, which is came from the input rf power, and 2.5 kW from multi-bunch beam loading. The single bunch beam loading power was estimated to be 121 W, which will be absorbed in microwave absorber.

V. DISCUSSIONS

Since this kicker utilizes a resonance phenomena to raise the kicker voltage, the bandwidth of frequency response is limited. The external Q-factor of 5.5 is relatively low, but it still limits the bandwidth to 182 MHz (full width at -3 dB point). Because the characteristic response time is 1.75 nsec, for the highest order of multi-bunch mode (π-mode on bunch-to-bunch), the effective kick voltage becomes

$$V = V_{fb}\left\{1 - \exp(-t_b / \tau)\right\} = 0.68V_{fb} \qquad (10)$$

This makes the damping time longer, but still 68% of the voltage can effectively kick the beam. This will be quite enough for practical application.

ACKNOWLEDGMENTS

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[1] R. F. Harrington: Time Harmonic Electromagnetic Fields (McGraw-Hill, Inc., New York, 1961) Chap. 5.
[2] KEK Accelerator Design Report for KEK B-factory, to be published as KEK report in 1995.

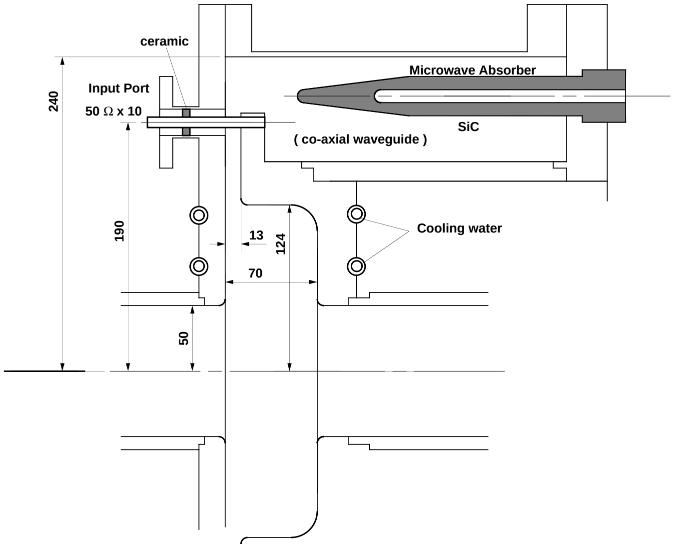

Fig. 2 Longitudinal kicker for B-factory.

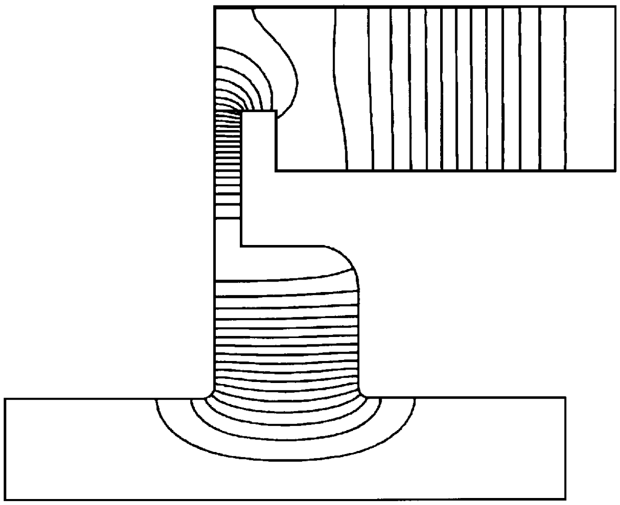

Fig. 3 Electric field line plot of TM0,1.5,0 mode.