Crab Cavity for the KEK B-Factory

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1. Crab Crossing Scheme

At the KEK B-Factory, in order to attain a luminosity of 10^{34} cm^{-2}s^{-1}, we should probably fill every RF bucket with beams. In this case the bunch spacing is only 0.6 m. To realize this, a finite angle crossing scheme is a powerful solution. However, experince concerning storage rings with a finite crossing angle has shown lower beam-beam limits due to synchrotron-betatron coupling resonances.1),2) In order to overcome the problem, a crab crossing scheme, which was first proposed by R. B. Palmer,3) has to be challenged to realize a large crossing angle.

In the crab crossing scheme, RF deflectors are located at the positions where the betatron phase advance is $\pi/2+n\pi$ (n is an integer) from the interaction region (IR). Bunches are tilted by a transverse kick in a RF deflector before the IR and kicked back to the original orientation in another deflector after the IR. Four RF deflectors are required for two rings.

The RF phase of the deflector should be set such that the deflecting voltage is zero when the bunch center passes the deflector. One of the most promising candidates for the deflector is the use of crab cavities operating in the TM110 mode. In this mode the bunch is kicked transversely by the transverse electro-magnetic field on the axis.

2. Requirements for the Crab Cavity

2.1 Deflecting Voltage

The necessary transverse deflecting voltage is determined by the desired crossing angle at the IR and operating frequency of the crab cavity as

$$V_0 = \frac{cE\tan\varphi}{\omega_{rf}\sqrt{\beta^*\beta_{crab}}}, \qquad (1)$$

where β^*, β_{crab}, E, φ and ω_{rf} are the beta-function at the IR, the beta-function at the crab cavity, beam energy, the half crossing angle and the RF frequency of the crab cavity, respectively. Table 1 summarizes the basic parameters for the crab cavities in cases of the 8- and 3.5-GeV rings of the KEK B-Factory. The necessary deflecting voltages are 0.82 and 1.88 MV for the LER and the HER, respectively.

Table 1. Parameters for the crab cavity of the KEK B-Factory

Ring		LER	HER	
Energy	E	3.5	8.0	GeV
Beam current	I	2.6	1.1	A
β^*		1.0	1.0	m
βcrab		100	100	m
deflecting voltage	Vo	0.82	1.88	MV

(φ=25 mrad and ω_{rf}=2πx508MHz)

2.2 Parasitic Modes

Multibunch instabilities should also be taken care of in the crab cavities, as well as in the accelerating cavities. The Q-values of the higher-order modes (HOMs) should be sufficiently lowered. In addition to the HOMs, two other modes should be adequately damped. One is the TM110 mode, the orientaion of which is rotated axially by $\pi/2$ with respect to the TM110 mode, which is used to tilt the bunch. The other mode to be damped is TM010, whose frequency is lower than that of TM110.

2.3 Tolerances

The phase error of the deflecting RF field causes a relative transverse displacement of both beams at the collision point. The tolerance for this error is estimated[4] as

$$\Delta\theta \ll \frac{\omega_{rf}}{c\tan\varphi}\sigma_x^* . \qquad (2)$$

An amplitude error of the deflecting RF field causes an error regarding the tilt angle and excites synchrotron-betatron resonances. The tolerance is[4]

$$\frac{\Delta V}{V} \ll \frac{\sigma_x^*}{\sigma_z \tan\varphi} . \qquad (3)$$

In (2) and (3), $\sigma_x{}^*$ and σ_z are the horizontal beam size at the IR and the longitudinal bunch length.

Taking φ=25 mrad, ω_{rf}=2πx508 MHz, β^*=1.0 m, βcrab=100 m,

$\varepsilon_x=1.85\times10^{-8}$ m and $\sigma_z=0.005$ m, these tolerances are $\Delta\theta<<3.3$ deg and $|\Delta V/V|<<1.1$. It should be noted that the accuracy requirement for the phase is remarkably strict.

The relative displacement of the beam orbit and the cavity center should be kept small. When bunches pass off-axis, a longitudinal electric field causes energy gain or energy loss of the bunches. As far as the energy deviation is concerned, a rather large displacement is tolerable. The tolerance for the displacement is related to the power handling ability of the RF system, such as the input coupler and the window, since a large displacement causes an exchange of a large amount of beam power. The beam loading power is estimated to be about 100 kW when bunches pass 5 mm off-axis, assuming the crab cavity is a single-cell cavity.

3. Design of Single Cell Crab Cavity

3-1. Cell Shape

In order to reduce the impedance of HOMs, fewer cells are desirable for the crab cavity. We started to design a single-cell crab cavity in order to examine whether this type cavity can work as a crab cavity for the KEK B-factory supplying the necessary deflecting voltage.

The transverse deflecting voltage is related to the transverse R*/Q calculated with URMEL as

$$V_o=\sqrt{\left(\frac{R^*}{Q}\right)\times\omega_{rf}W}\ , \qquad (4)$$

where W is the stored energy and R*/Q, which is obtained from the URMEL calculation, is

$$\frac{R^*}{Q}=\frac{\left|\int E_z(r=r_o)e^{jkz}dz\right|^2}{(k\,r_o)^2\,\omega_{rf}W}\ . \qquad (5)$$

In (5), k and $E_z(r=r_o)$ are the wave number and the longitudinal electric field calculated off axis by a distance r_o, respectively.

The cell shape is optimized so as to have higher R*/Q of the crab mode (TM110) and lower R*/Q of other modes. Fig. 1 shows the cell shape used for the calculation. Fig. 2 shows the frequency of main longitudinal modes and the cut-off frequency of TM01 mode in the beam pipe as a function of the beam pipe radius. If the beam pipe radius, R_b, is larger than 160 mm, TM020 and TM011 can propagate down the beam pipe. Increasing the beam pipe radius, on the other hand, makes R*/Q for the crab mode (TM110) smaller, as is shown in Fig. 3. However, we will take advantage of the propagating TM011 and TM020, as far as the needed deflecting voltage can be provided. We thus take R_b=165 mm in the following. TM010 and TE111, however, can not propagate down the beam pipe, even if we take Rb=165 mm. Fig. 4 shows the dependence of R*/Q of the crab mode on the radius of iris, Riris, and the cavity length, d. Fig. 5 shows the dependence of R*/Q of the TE111 mode on Riris and d. Changing Riris and d we can optimize R*/Q of the crab mode and can reduce R*/Q of TE111 by some factor. By taking these arguements into account, the cell shape can be optimized. Resonant modes of the best cell shape achieved until now are summarized in Table 2.

Table 2. Resonant modes of the single cell crab cavity

Input data: Rb=165 mm, θ=75 deg, Riris=60 mm and d/2=150 mm.

Crab mode (TM110)

freq.	508 MHz
R/Q	25 Ω/cell
Esp/Vo	13.9 (MV/m)/MV ---> Esp=11.4 MV/m (LER), 26.1 MV/m (HER)
Hsp/Vo	373 Oe/MV ---> Hsp=306 Oe (LER), 701 Oe (HER)

Longitudinal modes

	freq.	R/Q
TM010	389 MHz	72 Ω/cell
TM020	705 MHz	above cut off
TM011	712 MHz	above cut off

Transverse modes

	freq.	R/Q
TE111	501 MHz	2.8 Ω/cell
TM110	508 MHz	25 Ω/cell
TM120	963 MHz	above cut off

The surface peak electric field (Esp) is 11.4 MV/m for the LER and 26.1 MV/m for the HER. The surface peak magnetic field (Hsp) is about 300 Oe for the LER and 700 Oe for the HER. Esp of 20 MV/m and Hsp of 400 Oe have already been achieved with 5-cell 508 MHz superconducting cavities operating in TRISTAN at KEK. As for single cell 1.5 GHz cavities, Esp of 60 MV/m and Hsp of 1500 Oe have been achieved at Cornell. Single cell crab cavities for the LER and the HER can thus provide the necessary deflecting voltages using existing superconducting cavity technology. If we use single cell normal conducting cavities, the power loss at the cavity surface is over 1 MW. Taking into consideration of RF windows and cooling capability, more than 5 cells are needed for each crab cavity.

3-2. Cure for the Parasitic Modes

As described above, there exist four non-propagating parasitic modes (TM010, two polarizations of TE111 and one of two polarizations of TM110). Other HOMs can propagate down the beam pipe. For the propagating HOMs, Qext can be reduced with some absorbers attached at the beam pipe, as was proposed at Cornell for the cavities of CESR-B.5)

As for the non-propagating modes, if we require that the impedance of the crab cavity should be smaller than that of the accelerating cavities, the allowable Qext is estimated as6)

$\mathrm{Qext} < 170$ for TM010,

$\mathrm{Qext} < 1800$ for TM110, and

$\mathrm{Qext} < 10000$ for TE111,

taking R*/Q calculated with URMEL.

One possible method to reduce the Qext of the TM010 mode is to use a coaxial beam pipe, as is shown in Fig. 6. The TM010 mode couples the coaxial beam pipe as TEM mode wave and propagates down the beam pipe. The coaxial pipe has a cut-off for other propagating modes. For the lowest dipole TE mode, the cut-off frequency is

$$fc=\frac{c}{\pi(ro+ri)} \tag{6}$$

where, r_o and r_i are the outer and inner radius of the coaxial pipe, respectively. If we choose the cut-off frequency to be higher than the crabbing mode, the crabbing mode is kept trapped. Then we can use the coaxial beam pipe as a damper for the TM010 mode. Preliminary calculation using URMEL shows that Qext of less than 1000 is achieved.

For the parasitic TM110 mode and one of the TE111 mode, we can follow an idea of fluted beam pipe7), using one set of flutes as is shown in Fig. 7 to make these modes propagate, instead of two sets of flutes in the original idea for two polarizations. Calculation using MAFIA shows that Qext is reduced to 10-40 with the one set of flutes.

Summary

Single cell superconducting crab cavities for the LER and the HER can provide the necessary deflecting voltages. Possible methods to cure the parasitic modes are proposed.

Acknowledgements

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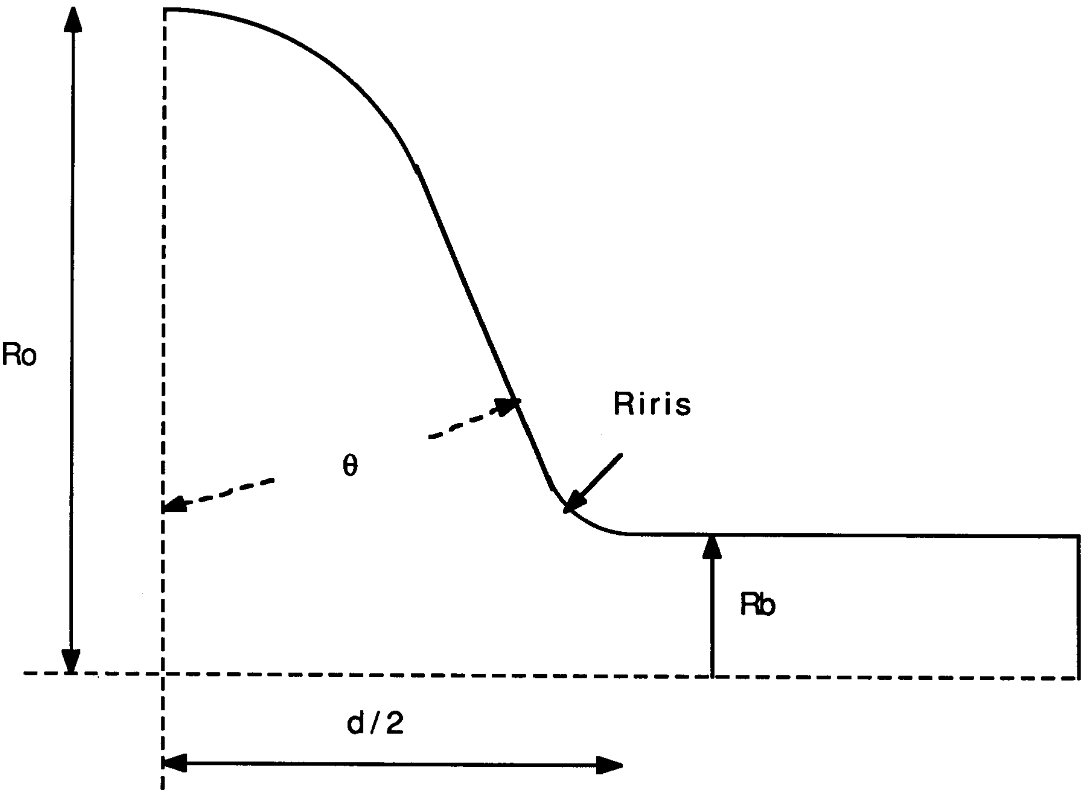

Fig. 1: The cell shape of the single-cell crab cavity used for the calculation.

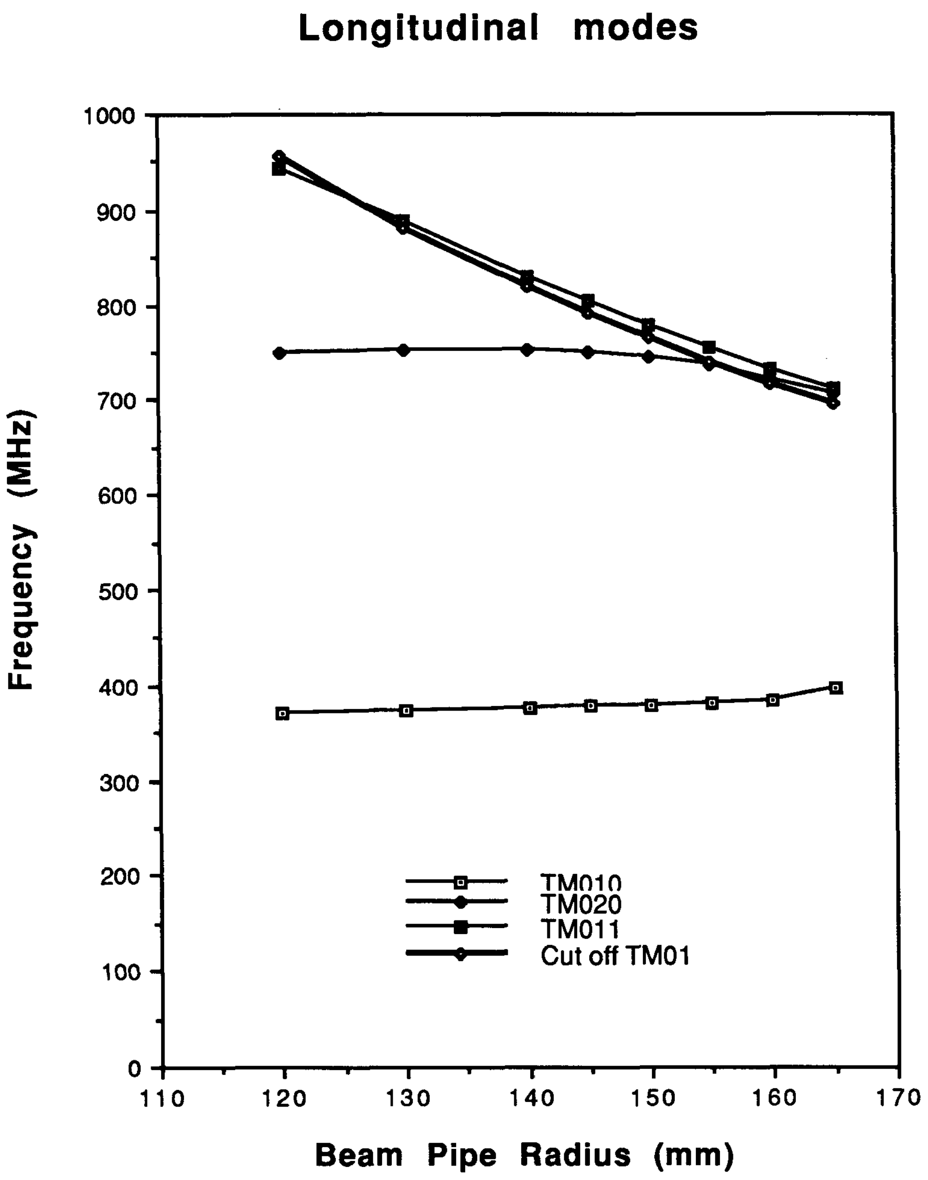

Fig. 2: The frequencies of main longitudinal modes and the cut-off frequency of TM01 mode in the beam pipe as functions of the beam pipe radius.

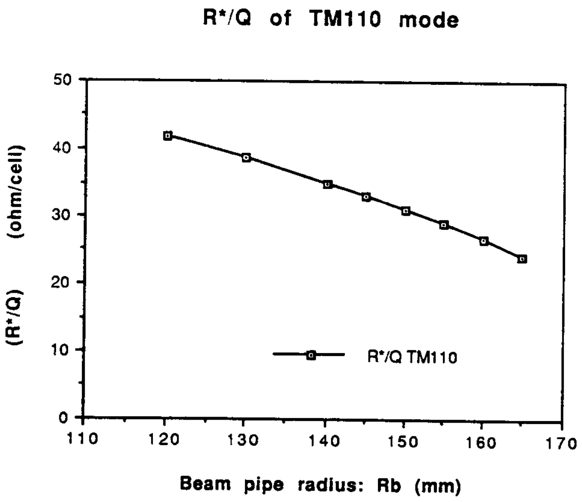

Fig. 3: The dependence of R*/Q of the crabbing mode (TM110) on the beam pipe radius.

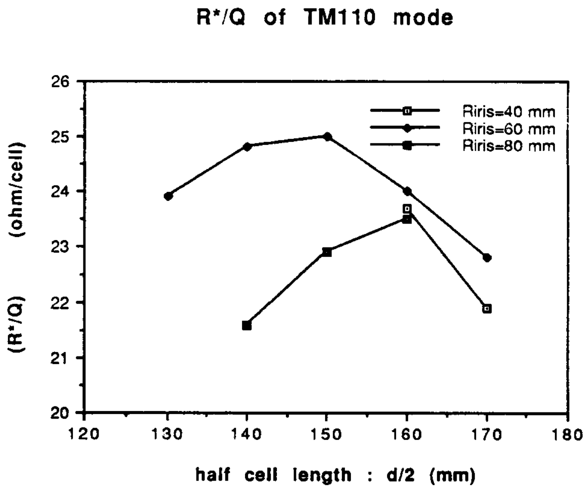

Fig. 4: The dependence of R*/Q of the crabbing mode (TM110) on the radius of the iris and the cavity length.

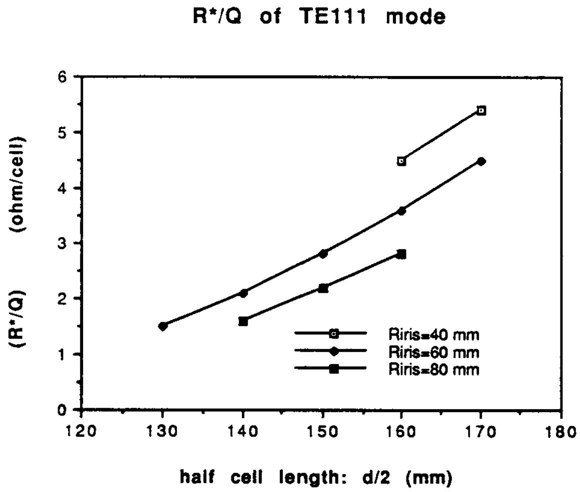

Fig. 5: The dependence of R*/Q of the TE111 mode on the radius of the iris and the cavity length.

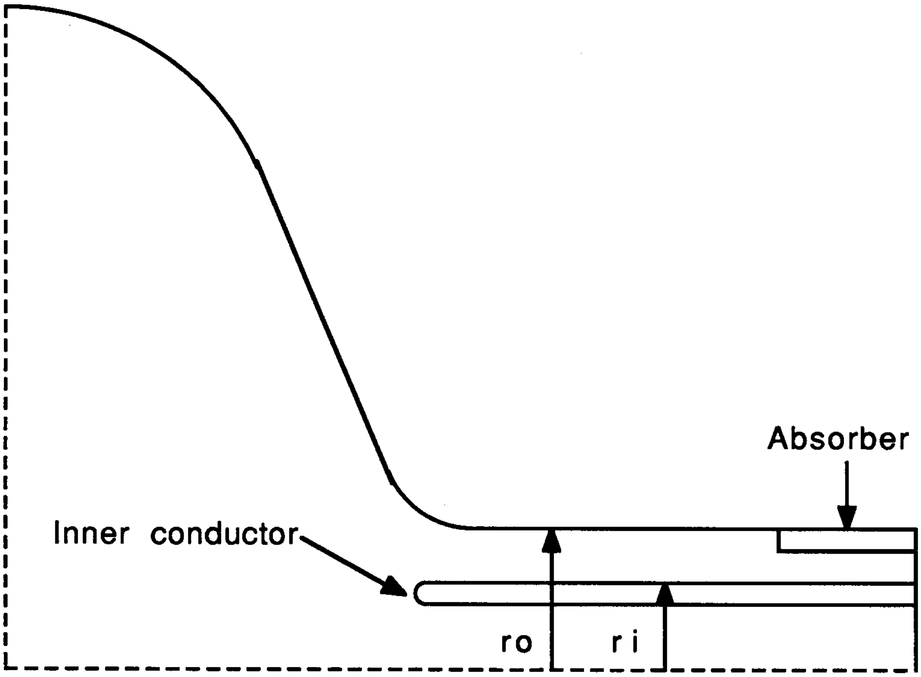

Fig. 6: A coaxial beam pipe attached to the crab cavity to reduce the Qext of the TM010 mode.

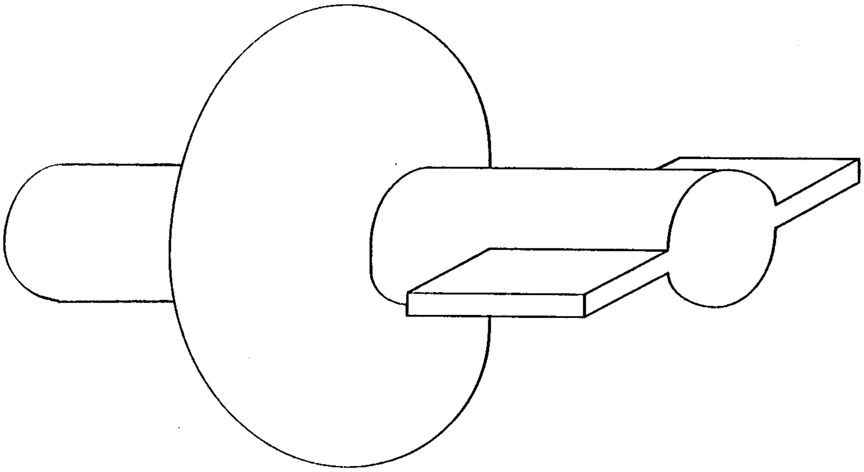

Fig. 7: One set of flutes attached to the beam pipe to reduce the Qext of the parasitic TM110 mode and one polarization of TE111 mode.