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Crab Cavity for the B-Factories*

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ABSTRACT

In order to realize the crab crossing scheme desired for B-factories, we have designed single cell superconducting crab cavities operating in TM110 mode. A coaxial beam pipe was attached to damp dangerous monopole and dipole parasitic modes. We designed two kinds of cell shape depending on the method to cure the unwanted polarization of TM110 mode; one is a round cell which will be slightly polarized and the other is an extremely polarized (squashed) cell. Necessary kick voltage can be obtained with the present technology of superconducting cavities. We have measured the coaxial beam pipe and a squashed crab cavity of one-third scale copper/aluminum model. The Q of all the dangerous monopole and dipole modes are damped to less than the order of 100, as was expected by calculations. High Q of the crabbing mode is also assured with a notch filter.

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1. INTRODUCTION

In order to attain the luminosity of 3×10^{33} - 10^{34} $cm^{-2}s^{-1}$ required for the B-factories, a large number of buckets in two rings (HER and LER) should be filled with beams. Consequently it is necessary to separate both beams quickly enough near the interaction point (IP) to avoid parasitic collisions. Also it is necessary to minimize synchrotron radiation generated near the IP, particularly just upstream of the crossing point.

To meet these requirements, a finite angle crossing scheme is the most desirable method. Indeed with a crossing (half) angle of more than 4 mrad we preserve the possibility of filling every bucket in CESR for future luminosity increases. We have selected ±12 mrad, considerably more than the minimum required, in order to limit the number of common quadrupoles on each side of the IP to one. This gives the greatest feasible independence of the two rings [1].

Experiences concerning storage rings with a finite angle crossing have shown, however, lower beam-beam limits due to synchrotron-betatron coupling resonances [2,3]. In order to avoid this, the crab crossing scheme has been invented by Palmer [4] for linear colliders and by Oide and Yokoya [5] for storage rings.

In the crab crossing scheme, as is shown in Figure 1, bunches are tilted by a time dependent transverse kick in RF deflectors located before the IP in each ring and thereby collide essentially head-on. This tilt is kicked back to the original orientation in another deflector after the IP. In total four RF deflectors are needed in the two rings at the positions where the betatron phase advance is $\pi/2 + n\pi$ (n is an integer) from the IP. The RF phase of the deflector should be set such that the deflecting voltage is zero when the bunch center passes the deflector. Several computer simulations have verified this analytical demonstration of the crab crossing scheme, showing no excitation of the synchrotron-betatron coupling resonances [6,7].

We have designed a superconducting crab cavity to realize the crab crossing for B-factories. In this report we describe the design of the crab cavity and some results of measurements of a model cavity.

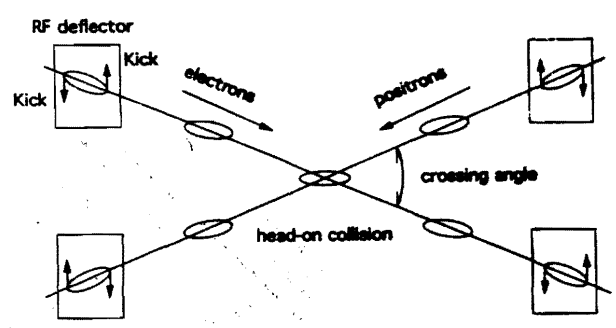

Figure 1. Schematic view of the crab crossing scheme

2. REQUIREMENTS FOR THE CRAB CAVITY

2.1 Deflecting Voltage

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

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

where β^*, β_{crab}, E, φ and ω_{rf} are the beta-function at the IP, 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 basic parameters for the crab cavities in cases of 8 GeV and 3.5 GeV rings of CESR-B. The necessary deflecting voltages are 1.83 MV and 0.80 MV for the HER and the LER, respectively.

Table 1. Parameters for the crab cavity in CESR-B

Ring		HER	LER
Energy	(GeV)	8.0	3.5
Beam current	(A)	0.87	1.98
β^*	(m)	1.0	1.0
β_{crab}	(m)	25.0	25.0
Deflecting voltage	(MV)	1.83	0.80

(φ=12 mrad and ω_{rf}=2πx508MHz)

2.2 Parasitic Modes

Multibunch instabilities should be taken care of also in the crab cavities, as well as in accelerating cavities for B-factories. Q-values of dangerous parasitic modes should be sufficiently lowered to typically the order of 100. In the accelerating cavities, the accelerating mode is the lowest frequency mode and all parasitic modes have higher frequency. In the crab cavity, on the other hand, the deflecting mode used for the crabbing is not necessarily the lowest frequency mode. This requires special attention for damping parasitic modes, as will be described in a later section.

3. DESIGN OF THE CRAB CAVITY

3.1 Design Concept

One possible method to realize the crab crossing scheme is to use RF cavities operating in a transverse deflecting mode. Since the TM110 mode has high transverse shunt impedance, R*/Q, we have designed a superconducting crab cavity operating in this mode. As for the damping of higher order modes, we adopted the beam pipe coupling scheme, which is used in the design of superconducting accelerating cavities for CESR-B. In this scheme, higher order modes propagate in the beam pipe and are absorbed by some absorbing material attached on the beam pipe.

Previous designs of the crab cavity using TM110 mode showed that a single cell superconducting cavity can provide necessary transverse kick required for the B-factories. One-third scale niobium cavity operated in the TM110 mode showed that needed surface field can be achieved without trouble from multipacting [8]. However, since the TM110 mode is not the lowest frequency mode, there are some modes whose frequency is lower than or about the same as this mode. Previous designs showed that four unwanted parasitic modes remain trapped in the cavity region with high Q even if a beam pipe with a large radius is attached. Those are TM010 monopole mode, two polarizations of TE111 dipole mode and one polarization of TM110 mode [8,9].

In order to solve this problem we attached a coaxial beam pipe at one side of the cavity cell (Figure 2). In a coaxial transmission line there is no cut-off frequency for TEM mode waves, but there is a cut-off frequency for dipole modes. By attaching a coaxial beam pipe to the crab cavity, all monopole modes in the cavity can couple to the coaxial beam pipe as a

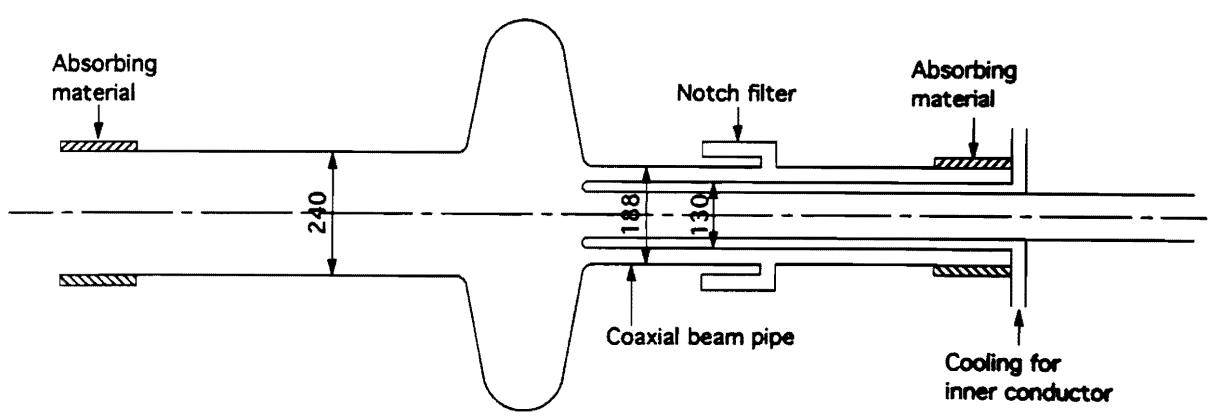

Figure 2. The crab cavity with a coaxial beam pipe

TEM mode wave and propagate. In addition, all dipole modes in the cavity can couple to the coaxial beam pipe as a dipole mode wave and propagate if the frequency is higher than the cut-off. By designing a cell shape such that f(TE111)>f(cut off)>f(TM110), it is possible to make all monopole and dipole modes except the TM110 mode in the cavity to propagate down the coaxial beam pipe.

One dipole parasitic mode still left trapped in the cavity is the unwanted polarization of TM110 mode. Since this mode has high transverse shunt impedance, it has to be cured. We have thought of three possible measures to cure this:

(1) Slightly polarized cell + tuning this mode at a safe frequency.

Based on ZAP[10] calculation, if we keep the frequency of this mode within 80 kHz of revolution harmonics, we can avoid an instability driven by this mode with a rise time faster than the natural damping time.

(2) Slightly polarized cell + making asymmetry on the coaxial beam pipe.

An asymmetry on the tip of the coaxial beam pipe makes the unwanted TM110 mode couple to the coaxial beam pipe as a TEM mode wave, which can then propagate in it.

For both methodes of (1) and (2) we designed a round cell shape cavity using cylindrical symmetric calculations. Slight polarization is necessary to separate the unwanted polarization mode from the crabbing mode.

(3) Extremely polarized cell ("Squashed" crab cavity).

By having a cross section of the cavity cell to be an ellipse or race-track shape with a large eccentricity, we can make the frequency of the unwanted TM110 mode to be above the cut-off of the dipole mode wave in the coaxial beam pipe and propagate. Analytical calculation using a rectanguler cavity showed that by making a ratio of the longer to shorter dimension in the cross section to be 2:1, the unwanted TM110 mode goes up to 700 MHz, while the crabbing mode is kept at 500 MHz. We designed such an extremely polarized cell cavity. In the following we describe both designs of the round cell and the squashed cell.

3.2 Design of the Crab Cavity and Performances

3.2.1 *Coaxial beam pipe*

Since we will operate the crabbing mode, TM110, at 500 MHz, the cut-off frequency of the dipole mode in the coaxial beam pipe should be higher than 500 MHz. In order to have enough attenuation for the crabbing mode, it is desirable to make the cut-off frequency sufficiently high. The cut-off frequency should, on the other hand, be lower than the lowest parasitic dipole mode (TE111 in this case).

The cut-off frequency of TE propagating mode in a coaxial transmission line is calculated from a solution of the relation,

$$J_m'(k_c a)N_m'(k_c b)-J_m'(k_c b)N_m'(k_c a)=0 \qquad (2)$$

here, k_c, a, b, J_m', N_m' are the cut-off wave number, the inner radius, the outer radius, derivative of m-th Bessel funciton and derivative of m-th Neuman function, respectively [11].

We chose the outer and inner radii so that it has (1) a cut-off frequency of 600 MHz, which makes the attenuation for the crabbing mode 60 dB/m, and has (2) a sufficient thickness of the inner conductor to allow a cooling system in it. As a result, we determined the radius of the outer pipe to be 94mm and the outer and the inner radii of the inner conductor to be 65mm and 45mm, respectively (Figure 2).

3.2.2 *Round cell design*

Computational studies to optimize the cell shape with cylindrical symmetry have been carried out. Cell shape parameters varied were the cell length, the iris radius, the equator radius and the slope of the wall.

Several view points taken into account in designing the cell shape are:

-frequency of all dipole parasitic modes should be higher than the cut-off frequency of the dipole mode in the coaxial beam pipe.

-ratio of the kick voltage to the surface peak field should be high.

-R/Q for parasitic modes (especially for the most dangerous TM010 mode) should be low.

-external Q for parasitic modes having high R/Q should be low (typically less than the order of 100).

Some of the requirements listed above contradict each other. Consequently the design is, in a sense, to compromise these requirements. Kick voltage, surface field, frequency and R/Q were calculated using URMEL [12]. External Q for parasitic modes were calculated with URMEL changing the short position of the beam pipe. External Q for monopole modes were also calculated using SEAFISH [13] with Ferrite absorber attached. Loss factor was calculated using TBCI [14]. Figure 3 and Table 2 show the cell shape and RF properties of the finally selected cell shape.

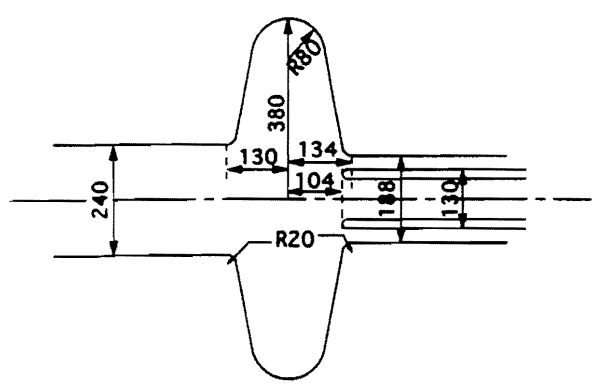

Figure 3. Round cell design of the crab cavity

Table 2. RF properties of the round cell crab cavity

Crabbing Mode (TM110)		
frequency	(MHz)	500
R*/Q	(Ω/cell)	51.2
kick voltage	(MV)	2.0
surface peak field (cell) at 2.0 MV of kick		
Esp=21.7 MV/m, Hsp=750 Oe		
surface peak field (inner conductor)at 2.0 MV of kick		
Esp= 8.7 MV/m, Hsp=450 Oe		
beam power	(kW)	19.5 x D
(D(mm) is a distance of beam off-axis)		
loss factor	(V/pC)	0.58

Parasitic modes					
Mode	Frequency (MHz)	R/Q (Ω/cell)	Q_{ext} coaxial beam pipe	Q_{ext} hollow beam pipe	Q_{loaded} coax +hollow
(monopole modes)					
TM010	342	135	108 (85-100)	-	108
TM020	731	26	40 (52)	-	40
TM011	914	21	38 (78)	-	38
TM030	1107	1	141	165	76
TM021	~1200	4	<100	<100	<100
()---by SEAFISH					
(dipole modes)					
TE111	720	6	18	-	18
TM120	898	6	160	37	30
TE112	1048	1	~1000	186	~161
TE121	~1100			<100	<100

3.2.3 *Squashed cell design*

Design of the extremely polarized cell has been carried out using MAFIA [15]. Following are taken into account in the design;

-making all dipole modes including the unwanted polarization of TM110 mode higher than the cut-off frequency of the coaxial beam pipe.

-ratio of the kick voltage to the surface peak field should be high.

-external Q for parasitic modes having high R/Q should be low.

-special attention was made so that TM010, the lowest frequency longitudinal mode whose R/Q is the highest, would not hit any of main revolution harmonics in order to prevent a large amount of power from being generated by beams.

Figure 4 and Table 3 show the cell shape and RF properties of the finally selected cell shape.

3.2.4 *Notch filter*

Since the crabbing mode is a dipole mode and its frequency is below the cut-off of the coaxial beam pipe, it attenuates in it. We designed the coaxial beam pipe so that the crabbing mode attenuates sufficiently and the power dissipation due to this mode in the ferrite absorber at the end of the coaxial beam pipe is less than 1 kW. In an actual cavity, however, some asymmetry due to machining inaccuracies or misalignment of the coaxial beam pipe may cause a part of energy of the crabbing mode to couple to the coaxial beam pipe as a TEM mode wave. Once it couples as a TEM mode, it propagates down the coaxial beam pipe without attenuation. This increases the power dissipation at the ferrite absorber. In order to avoid this, we designed a notch filter to reject the TEM-coupled crabbing mode back to the cavity.

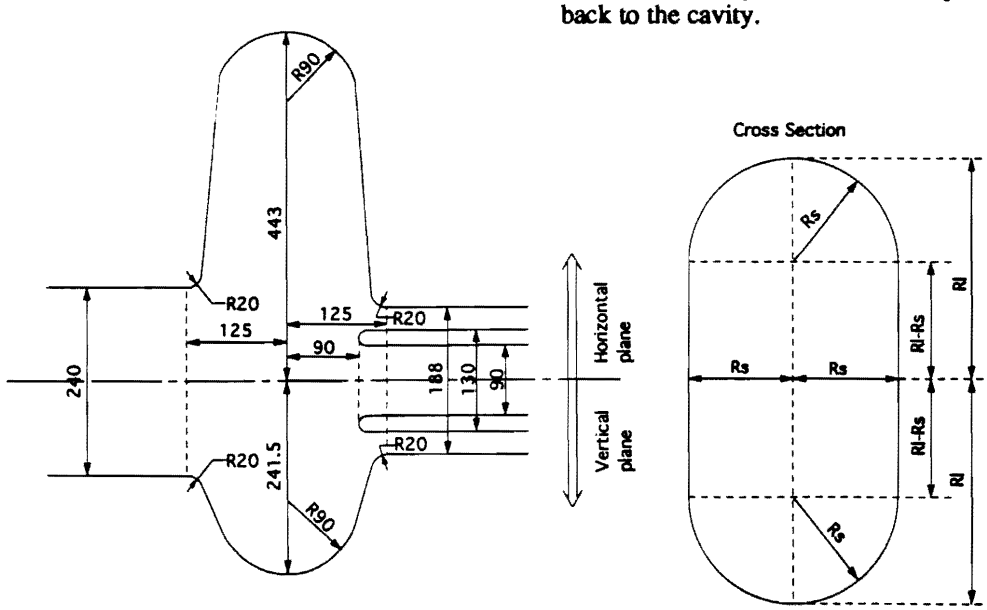

Figure 4. Squashed cell design of the crab cavity

Table 3. RF properties of the squashed cavity (MAFIA calculation and measurement of a model cavity)

crabbing mode (TM2-1-0(rectanguler), TM110(H)(cylindrical))

frequency	(MHz)	501.7	
R*/Q	(Ω/cell)	47.2	
kick voltage	(MV)	2.0	at Esp=24.6 MV/m

monopole-like parasitic modes (mixed with quadrupole component)

		MAFIA calculation						Model measurement	
mode rectanguler	mode cylindrical	frequency (MHz)	R/Q mono.	R/Q quad.	Q_{ext} coax	Q_{ext} hollow	Q_{loaded} total	frequency (MHz)	Q_{loaded} w/ Ferrite
TM1-1-0	TM010	413.3	99.8	3.2	96	-	96	415.0	123
TM3-1-0		670.6	17.3	0.64	76	-	76	672.6	50
TM1-1-1	TM011	946.6	9.9	0.11	118	-	118	938.6	~130
TM5-1-0		967.2	0.08	0.24	358	1273	279	966.2	~130
TM1-3-0		992.3	~2.2	0.06		379	<379	1000.1	~130

dipole parasitic modes

		MAFIA calculation					Model measurement	
mode rectanguler	mode cylindrical	frequency (MHz)	R/Q dipole	Q_{ext} coax	Q_{ext} hollow	Q_{loaded} total	frequency (MHz)	Q_{loaded} w/ Ferrite
TE1-0-1	TE111(V)	650.6	10.0	149	-	149	641.2	66
TE0-1-1	TE111(H)	677.6	5.9	46	-	46	666.4	50
TM1-2-0†	TM110(V)†	686.5	23.0	37	-	37	686.5	22
TM4-1-0	(H)	792.9	8.1	97	99	49	789.4	70
TM3-2-0	(V)	870.0	1.1	161	56	42	891.0	60
TE3-0-1	(V)	964.1	1.2	144	63	44	936.1	<60
TM2-1-1	(H)	1024.9	1.2	29000	1414	1350		<350
TM2-3-0	(H)	1044.1	0.13	74000	578	574		<350
TE1-2-1	(V)	1095.7	0.28	>1000	82	82		

(H)---Horizontal kick, (V)---Vertical kick

†--- the unwanted polarization of the crabbing mode

quadrupole-like parasitic modes

		MAFIA calculation						Model measurement	
mode rectanguler	mode cylindrical	frequency (MHz)	R/Q mono.	R/Q quad.	Q_{ext} coax	Q_{ext} hollow	Q_{loaded} total	frequency (MHz)	Q_{loaded} w/ Ferrite
TM2-2-0	TM210	778.4	0	1.09	-	-	-	780.1	-
TE2-0-1	TE211	874.5	0	0.16	-	-	-	861.8	-
TE1-1-1	TE211	890.0	0.3	0.25	>2000	-	>2000	878.6	1000
TE0-2-1		999.3	0	0.12	-	-	-	986.5	-
TM4-2-0		1027.3	0	0.14	-	-	-	1028.0	-
TE4-0-1		1069.2	0	0.13	-	-	-	1058.6	-

-Frequency and R/Q of MAFIA calculation are without the inner conductor of the coaxial beam pipe.

-Q_{ext} and Q_{loaded} of MAFIA calculation are obtained assuming perfect absorbers.

-Frequency of the model measurement listed is devided by three of the measured frequency of one-third scale model without the inner conductor of the coaxial pipe.

-Q_{loaded} of the model measurement is with Ferrite absorbers attached at the end of the coaxial beam pipe and the hollow beam pipe.

R/Q (dipole) $=\{V(r_o)^2/\omega U\} / (k^*r_o)^2$, R/Q (quad.)$=\{V(r_o)^2/\omega U\} / (k^*r_o)^4$

Figure 5 shows a transmission property of the notch filter calculated using URMEL [12] together with analytical calculation using an equivalent circuit. Having the resonance frequency of the filter to be within ±0.5 MHz the rejection rate of more than 50 dB is expected. Even if the external Q for the crabbing mode might be reduced to 10^5 for some reason, this rejection of 50 dB assures a resulting external Q of 10^{10}, which is sufficiently high.

The resonant frequency of the filter can be tuned by lengthening or shortening the iris of the filter. According to SUPERFISH [16] calculation, the frequency shift by changing the length is expected to be between $\Delta f/\Delta l$=1.8-3.6 MHz/mm depending on which part of the filter is deformed the most.

In addition to the stopband at 500 MHz the notch filter has a higher order TEM stopband at 1.45 GHz. Because there are several parasitic modes near this frequency, we opened up the hollow beam tube on the opposite side of the coaxial beam pipe wide enough to allow monopole modes above 1.3 GHz and dipole modes above 1 GHz to propagate.

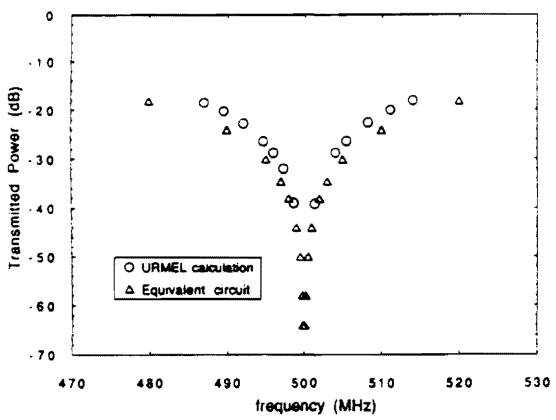

Figure 5. Frequency characteristics of the notch filter

4. MODEL MEASUREMENTS

In order to confirm several concepts of our design, we have made one-third scale (L-band) coaxial beam pipe with a Firrite absorber and one-third scale squashed cavity made of Alminum.

4.1 Coaxial Beam Pipe Measurement

The one-third scale coaxial beam pipe with Ferrite absorber was attached to a round cell L-band cavity made of copper. The reasons for measuring this system are to check the damping property of TM010 monopole mode, to see effects of the coaxial beam pipe on the crabbing mode and to see damping of the unwanted polarization of TM110 mode by making asymmetry of the coaxial beam pipe.

Figure 6 shows the loaded Q of the TM010 mode as a function of penetration length of the inner conductor of the coaxial beam pipe into the cavity cell. Q value is damped below 100 with a moderate penetration. The result is in agreement with SEAFISH calculations within a factor of two.

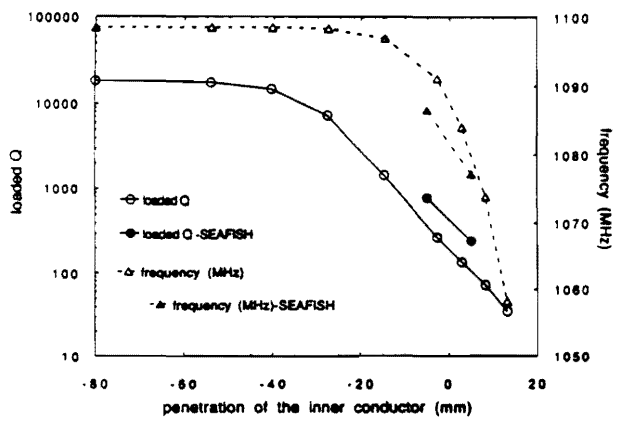

Figure 6. Damping of TM010 mode in the crab cavity with the coaxial beam pipe

Figure 7 shows the effect on the crabbing mode of misalignment of the inner conductor with respect to the outer conductor. The loaded Q is almost the same as without the coaxial beam pipe when the inner conductor is aligned with the accuracy of 1 mm. This means that the external Q to the coaxial beam pipe is at least the order of 10^5 with such an alignment because the intrinsic Q is 23000 for this copper cavity. As we mentioned before, the notch filter assures an additional 50 dB more reduction that makes the external Q more than 10^{10}. The difference of the effect on the Q between the horizontal and vertical displacement is explained as the electric field of this mode at the tip of the coaxial beam pipe is polarized horizontally. Since this is a result of one-third scale model, we can expect the alignment tolerance of about 3 mm for the full scale cavity, which can be achieved easily.

It was also observed that by making an asymmetry at the tip of the inner conductor of the coaxial beam pipe, the Q for the unwanted polarization of TM110 was reduced to 1000 while the crabbing mode kept high Q.

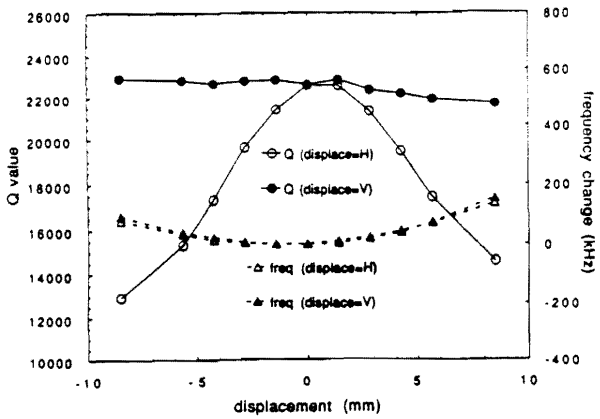

Figure 7. Effect of the misalignment of the coaxial beam pipe on the crabbing mode

4.2 Squashed Cavity Model Measurement

We measured the resonance frequency and the damping properties of the one-third scale squashed crab cavity. The frequency spectrum is shown without the coaxial beam pipe and Ferrite absorbers (Figure 8a) and with them (Figure 8b). Measured resonance frequency of each mode and the Q with the Ferrite absorbers are listed in Table 3 together with the MAFIA calculations. As was expected with the MAFIA calculation, all the dangerous monopole and dipole modes including the unwanted polarization of the crabbing mode are damped to less than the order of 100. The crabbing mode keeps high Q. The external Q of this mode through the coaxial beam pipe is estimated by the measured Q with and without the inner conductor of the coaxial beam pipe and it appeared to be at least the order of 10^5, which is the same result as the coaxial beam pipe attached to the round cell cavity.

5. CONCLUSIONS

We have designed single cell superconducting crab cavities with two different cell shapes; one is a round cell which will be slightly polarized and the other is an extremely polarized (squashed) cell. We attached a coaxial beam pipe to both cell designs in order to damp dangerous monopole and dipole parasitic modes. Necessary kick voltage can be obtained with the present technology of superconducting cavities. We have measured the coaxial beam pipe and a squashed crab cavity of one-third scale copper/aluminum model. All the dangerous monopole and dipole modes are damped to less than the order of 100, as was expected by calculations. High Q of the crabbing mode is also assured with the notch filter installed. We are making a niobium model of the slightly polarized cell with a coaxial beam pipe and a notch filter to be measured in liquid helium.

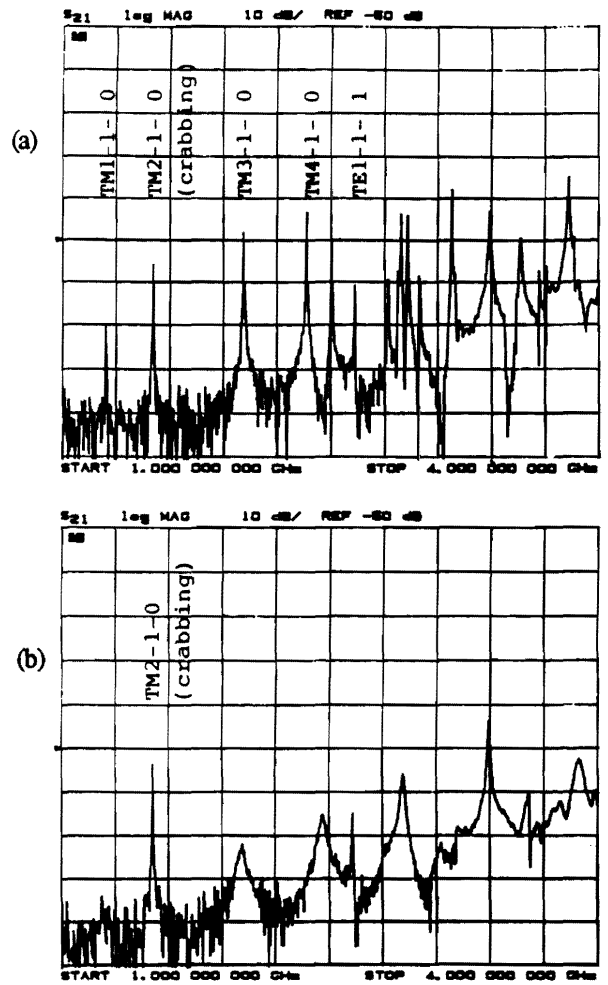

Figure 8. Frequency spectrum from 1 to 4 GHz measured in the squashed crab cavity, (a) without the inner conductor of the coaxial beam pipe and Ferrite absorbers and (b) with the coaxial beam pipe and Ferrite absorbers attached. Some of the peaks are identified as corresponding resonances in a rectanguler cavity.

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