TAPER AND TUNER SCHEME OF A MULTI-FREQUENCY CAVITY FOR THE FAST KICKER RESONATOR IN MEIC ELECTRON CIRCULAR COOLER RING*

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Abstract

An ultra-fast harmonic kicker consisted of normal conducting resonators with high transverse shunt impedance thus less RF power consumption was designed for the proposed Medium energy Electron Ion Collider (MEIC). In the prototype design, four quarter wave resonator (QWR) based deflecting cavities are used to generate ten cosine harmonic waveforms, the electron bunches passing through these cavities will experience an integral effect of all the harmonic fields, thus every 10th bunch in a continues bunch train of 10th harmonic bunch frequency will be kicked while all the other bunches un-kicked. Ten harmonic waves are distributed in the four cavities with the proportion of 5:3:1:1. For the multi-frequency cavities, a great challenge is to tune each harmonic to be exact frequency. In this paper, the taper and tuning scheme for the 5-modes cavity is presented. Five taper points in the inner conductor are chosen to make the five frequencies to be odd harmonics. Five stub tuners on the outer conductor are used to tune every harmonic back to its target frequency from the manufacturing errors.

INTRODUCTION

Electron cooling is essential for the proposed MEIC to attain low emittance and high luminosity [1]. The present MEIC design utilizes a scheme of multi-stage cooling, a DC cooler in the booster and the bunched electron beam cooler in Energy Recovery Linac (ERL) in the ion collider ring. To achieve a high electron beam current in the cooling channel but a relative low current in ERL, a circulator ring is proposed as a backup scheme. The electron bunches will recirculate for 25 turns, thus the current in the ERL can be reduced by a factor of 25. Two ultra-fast kickers are required in this circulator ring, one for kick-in, one for kick-out, all with half pulse width less than 2.1ns (1/476.3MHz) and a high repetition frequency of 19.052MHz (1/25 of 476.3MHz). JLab started an LDRD proposal to develop such a kicker. Our approach is to use RF resonant cavities other than transmission line type devices. Electron bunches passing through these cavities will experience an integral effect of all the harmonic fields, thus every 25th bunch in the bunch train will be kicked while all the other bunches un-kicked. Here we present a simplified design of a prototype with every 10th bunch kicked, using four QWR based cavities to generate 10 harmonic modes. The generation of the flat-top kick voltage with finite harmonic modes, shunt impedance formula, cavity structure optimization, power consumption calculation, and the concept design of stub tuners and loop couplers are already presented in [2]-[3]. In addition, the harmonic voltage combining scheme have been also discussed in [4]. Here we only focused on the taper and tuning scheme design of the 5-harmonics cavity.

CAVITY WITHOUT TAPER

The cavity model used to generate harmonic modes is quarter wave transmission line shorted at one end and a capacitor loaded at the other end, as shown in Figure 1.

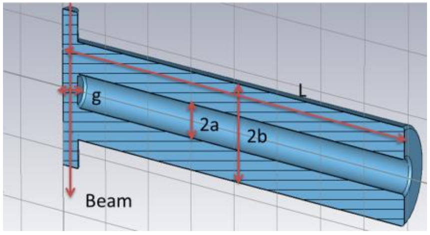

Figure 1: Cavity model without taper

Beam passes through the capacitive gap and is deflected primarily by a transverse electric field. The cavity geometry parameters for the 5-modes cavity are summarized in Tab.1.

Table 1: Cavity Geometry Parameters without Taper

Parameter	Length (mm)
Cavity Length (L)	1578
Inner Radius (a)	55
Outer Radius (b)	157
Gap Distance (g)	70
Beam Pipe Length	500

Here cavity length L is optimized to make maximum required tuning range is minimized. The relationship between the L and the required tuning range of the un-tapered cavity is shown in Fig.2.

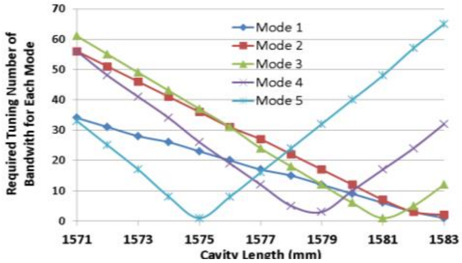

Figure 2: Required tuning range verses cavity lengths.

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Here the curve deflection is due to the tuning range going to other direction from the target frequency. Required tuning range for these 5 modes at the select cavity length listed in Tab.2

Table 2: Required Tuning Range for the Select Cavity Length. Minimum bandwidth is for mode coupling β=1

Design freq. (MHz)	Freq. without taper (MHz)	Q_0 for 300K copper	Min. bandwidth (kHz)	Required tuning in number of bandwidth
47.63	47.790	8613	11	15
142.89	143.304	14921	19	22
238.15	238.611	19276	25	18
333.41	333.541	22826	29	5
428.67	427.874	25896	33	24

Outer radius b is chosen as the half wavelength of highest modes (476.3MHz) of all harmonic modes (not the highest modes of this single cavity). Inner radius a is optimized to get the highest transverse shunt impedance. Gap distance g (also the beam pipe diameter) is chosen as the nominal size of the CEBAF cavity beam pipe. Beam pipe length was chosen to make sure the highest mode frequency would not affect by the beam pipe boundary conditions.

STUB TUNER DESIGN

In order to get all the 5 frequencies tuned, 5 stub tuners insertion to the outer conductor is used. To determine the tuner positions, a stub radius R=40mm, insertion height H=15mm is moved along the cavity outer wall to see the frequency response of each modes, which can be shown in Fig.3. The "cross-talk" by the scheme of all tuner stubs on the same side of outer conductor has been confirmed to be secondary perturbation by the multi-stub simulations.

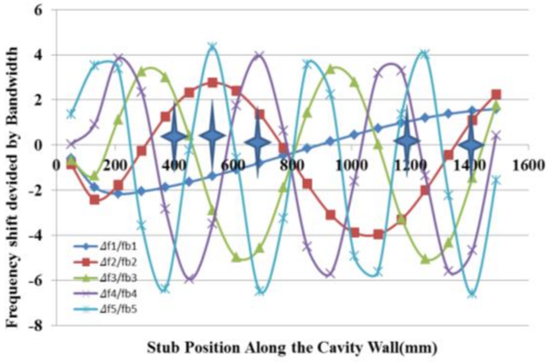

Figure 3: Tuner position simulation for the 5 harmonics modes cavity with a R=40mm H=15mm cylinder perturbation.

Five tuner positions are chosen in order to avoid the zero frequency response point. The position of each tuner is summarized in Tab.3.

Tab.3. Tuner Position along the Cavity Outer Wall

Tuner $^{\#}1$	Tuner $^{\#}2$	Tuner $^{\#}3$	Tuner $^{\#}4$	Tuner $^{\#}5$
400mm	530mm	690 mm	1190mm	1400mm

It is also obvious from Fig.3 that we can't get all 5 modes to be harmonics only with these tuners since the tuning range of the stub tuner is limited. Then tapering of inner conductor is needed. Before the tapering, five stub tuners are inserted 25mm into the cavity vacuum as the baseline, as shown in Fig.4. With such a design, the nonlinearity of the tuner response caused by the curved cavity surface is minimized, and on the other hand, it will achieve a larger tuning range of the stub.

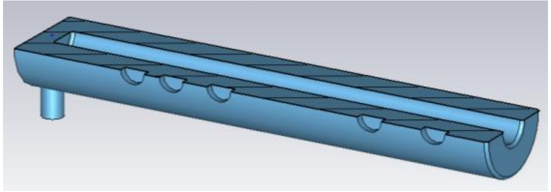

Figure 4: 5 stub tuners inserted H=25mm in the cavity wall as the baseline shape before the taper design.

TAPER DESIGN ITERATION

For the 5-modes cavity, 4 tapering sections are needed. There are many methods to choose these taper points and here we just present one of them. Two end points at $a1$ and $a5$ are chosen to get the least tapering slops along the cylinder; three straight tapering transition points $a2$ to $a4$ corresponding to the 3 middle tuner positions are chosen to make sure the manufactural errors on these points can be easily tuned back by the stub tuners. The positions of each taper section can be shown in Fig.5 and summarized in Tab.4.

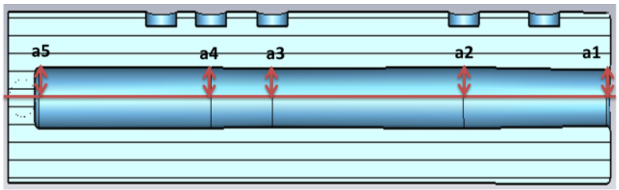

Figure 5: Straight taper sections for the 5-mode cavity

Table 4: Taper Transition Position along the Cavity Inner Conductor Cylinder

Taper $^{\#}1$	Taper $^{\#}2$	Taper $^{\#}3$	Taper $^{\#}4$	Taper $^{\#}5$
1578mm	1190mm	690 mm	530mm	70mm

To calculate the frequency response to each mode at each point, we have got a linear tuning matrix M_{taper}, and solve the equation (1) to get the taper value $a_n = a_0(55\text{mm}) + \Delta a_n$:

$$M_{taper}\Delta a_n = \frac{\Delta f_n}{f_{BWn}} \tag{1}$$

Here Δa_n is for the n^{th} mode in mm, and

$$\Delta a_n = \begin{pmatrix}\Delta a_1 & \Delta a_2 & \Delta a_3 & \Delta a_4 & \Delta a_5\end{pmatrix}^T \tag{2}$$

Δf_n is the frequency shift of n^{th} mode; Δf_{BWn} is the bandwidth of n^{th} mode, and

$$\frac{\Delta f_n}{\Delta f_{BWn}} = \begin{pmatrix}\frac{\Delta f_1}{\Delta f_{BW1}} & \frac{\Delta f_2}{\Delta f_{BW2}} & \frac{\Delta f_3}{\Delta f_{BW3}} & \frac{\Delta f_4}{\Delta f_{BW4}} & \frac{\Delta f_5}{\Delta f_{BW5}}\end{pmatrix}^T \tag{3}$$

M_{taper} is the taper matrix, and the element m_{ij} is the liner frequency response relative to mode bandwidth (BW) of mode i to taper point j per mm. Fig.6 shows an example of linear response of these 5 modes to taper point #4 at position 1190mm with the element unit of BW/mm.

$$M_{taper} = \begin{pmatrix} 8.8634 & 13.266 & 0.2663 & -9.9226 & -13.297 \\ 10.129 & -16.086 & -0.1363 & 15.615 & -10.758 \\ 4.6755 & -4.7684 & -2.8073 & 2.749 & -2.2498 \\ 0.4749 & -1.0485 & 6.4026 & -6.3078 & -2.1708 \\ 0.0679 & 1.2901 & -7.2542 & 6.2967 & -3.6237 \end{pmatrix} \quad (4)$$

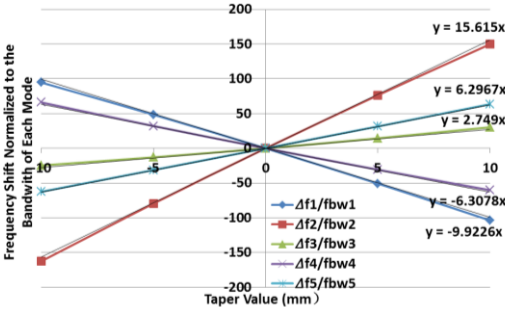

Figure 6: Tuning response of each mode at taper point #4

With this taper matrix, after one or several iterations in CST simulation, we can find the proper taper design values *a*2 to *a*4 getting every design mode within the bandwidth. The frequency and taper design value convergence with simulation iterations are shown in Fig.7 and Fig.8.

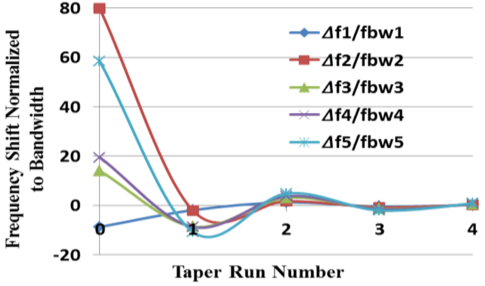

Figure 7: Frequency convergence with taper simulation iteration

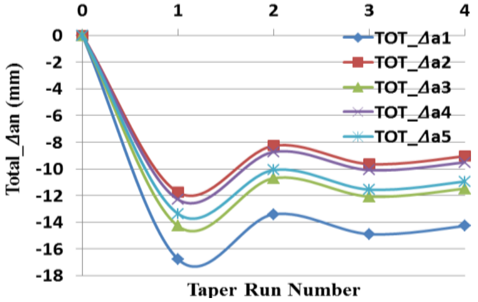

Figure 8: Taper design value convergence with taper simulation iteration

Here the cavity length L is 1578mm, the relative taper result at each point is

$$a_n = (40.728, 45.953, 43.521, 45.495, 44.056)^T \quad (5)$$

From the result, we find the average value of the inner conductor radius is reduced, we then have to change the cavity length *L* to re-taper the inner conductor which uses same matrix in the equation (4). The taper design result at different cavity length L can be shown in Fig. 9. Finally we can adjust the inner radii close to the optimized value of 55 mm to minimize the tapering slopes. When the cavity length L is at 1573 mm, the radius at taper #5 is about 55 mm, which was also optimized gap length for the shunt impedance. The re-tapered design result is

$$a_n = (51.24, 56.135, 53.154, 55.355, 54.983)^T \quad (6)$$

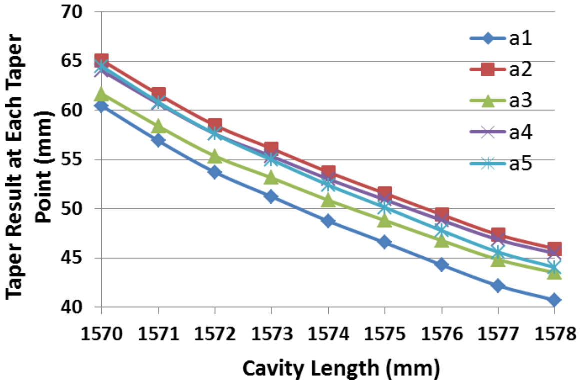

Figure 9: The relationship between inner radius at each taper point and cavity length with 5 stub tuners at each design locations above at R=40mm and H=25mm.

TUNER ITERATION

After the cavity is properly tapered, we can calculate the tuning sensitivity of each mode for each tuner, just as what we have done for the taper design. The tuner equation is

$$M_{tuner} \Delta h_n = \frac{\Delta f_n}{f_{BWn}} \quad (7)$$

Δh_n is the tuning insertion depth value in *mm* of n^{th} tuner,

$$\Delta h_n = (\Delta h_1 \quad \Delta h_2 \quad \Delta h_3 \quad \Delta h_4 \quad \Delta h_5)^T \quad (8)$$

M_{tuner} is the taper sensitivity matrix, and the element n_{ij} is the approximately linear frequency response relative to each bandwidth of i^{th} mode to j^{th} tuner tuning depth per mm. Fig.10 shows an example of linear response of these 5 modes to tuner #3.

$$M_{tuner} = \begin{pmatrix} -0.4203 & -0.3341 & -0.2145 & 0.108 & 0.1949 \\ 0.184 & 0.3762 & 0.1141 & -0.7598 & 0.0506 \\ 0.242 & -0.7703 & -1.0321 & -0.9785 & -0.4635 \\ -1.178 & -0.844 & 0.5083 & 0.1279 & -1.154 \\ -1.179 & 0.6265 & -1.6784 & 0.422 & -1.7042 \end{pmatrix} \quad (9)$$

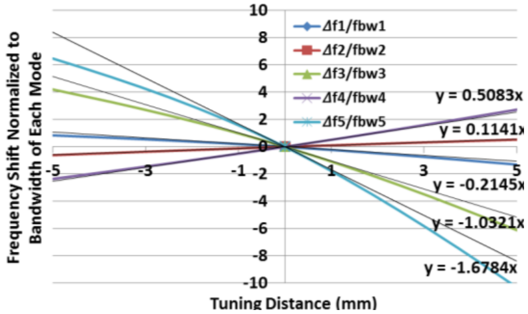

Figure 10: Frequency tuning response of each mode at tuner 3

COUPLER AND PICKUP

When the coupler is inserted, with the coupler loop size in the current design, all mode frequencies are reduced due to the frequency pulling effect. The highest pulling is at the mode 5 in about 500 kHz. A slight change of the cavity length and related taper values within mm range is

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readjusted in order to reduce the required tuning ranges. No adjustment is needed when the pickup port is added since output coupling is very weak.

CONCLUSION

The taper and tuner design scheme of the 5-mode harmonic cavity has been elaborated in this paper. With the present taper design, a very gentle taper slop design is achieved thus the transverse shunt impedance is almost unaffected compared with the non-tapered cavity. With the present tuner design, it has no problem to tune all harmonic modes back within half (12.5mm) tuning range to its target frequencies within the manufactural error of 0.5 mm at two end taper points and even larger at three middle taper points. A half scale prototype cavity is under mechanical design for fabrication, with the input coupler port and output pickup port, low power RF bench measurement will be taken after the prototype cavity is fabricated.

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