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HARMONIC RESONANT KICKER DESIGN FOR THE MEIC ELECTRON CIRCULAR COOLER RING*

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Abstract

Bunched-beam electron cooling of the high-energy ion beam emittance may be a crucial technology for the proposed Medium energy Electron Ion Collider (MEIC) to achieve its design luminosity. A critical component is a fast kicker system in the Circular Ring (CR) that periodically switches electron bunches in and out of the ring from and to the driver Energy Recovery Linac (ERL). Compared to a conventional strip-line type kicker, a quarter wave resonator (QWR) based deflecting structure has a much higher shunt impedance and so requires much less RF power. The cavity has been designed to resonate simultaneously at many harmonic modes that are integer multiples of the fundamental mode. In this way the resulting waveform will kick only a subset of the circulating bunches. In this paper, analytical shunt impedance optimization, the electromagnetic simulations of this type of cavity, as well as tuner and coupler concept designs to produce 5 odd and 5 even harmonics of 47.63MHz will be presented, in order to kick every 10th bunch in a 476.3 MHz bunch train.

INTRODUCTION

Cooling of ion beams is critical in delivering high luminosities for the proposed MEIC [1].The present MEIC design utilizes a scheme of multi-stage cooling. In the booster, a DC cooler is used to assist accumulation of injected positive ions and reduce the beam emittance at the low energy. In the ion collider ring, an electron cooler utilizing high energy bunched beam will be responsible for cooling the medium energy ions to suppress intra-beam scattering (IBS) and maintain emittance during collisions. Two critical accelerator technologies in the bunched beam electron cooler are an ERL and a circulator ring (CR) to reduce the current and power of the cooling electron beam from the source and linac. As illustrated by the schematic drawing in Fig. 1, electron bunches are accelerated in an SRF linac, and then kicked into a closed ring that includes part of the ion collider storage ring. In this ring, electron bunches will be merged with the ions, and continuously cool the ion bunches in a long cooling channel, and then return to the linac for energy recovery after 25turns in the CR. In the present MEIC baseline design, the collision frequency is 476.3MHz, thus the repetition frequency of the electron bunches is 476.3MHz in CR and 19.052MHz in the ERL. A critical component in this scheme is a fast kicker system in the CR that periodically switches electron bunches in and out of the ring from and to the driver ERL. When the electron bunches are kicked into the CR (476.3MHz), every bunch in the ERL (19.052MHz) is kicked; when kicked out, every 25th bunch is kicked and other 24 bunches are, ideally, undisturbed. The electron energy is 55MeV, assuming the kick angle is 0.001 rad, thus the kick voltage needed would be 55 kV. In the first R&D design, we just consider kicking every 10th bunch in order to simplify the problem. The kick voltage pulse and bunch distance scheme is shown in Fig. 2 (red).

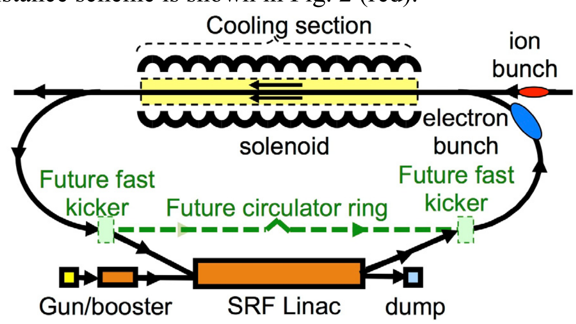

Figure 1: A schematic drawing of a bunched beam cooler based on an ERL, with bypass circulator ring connection in green.

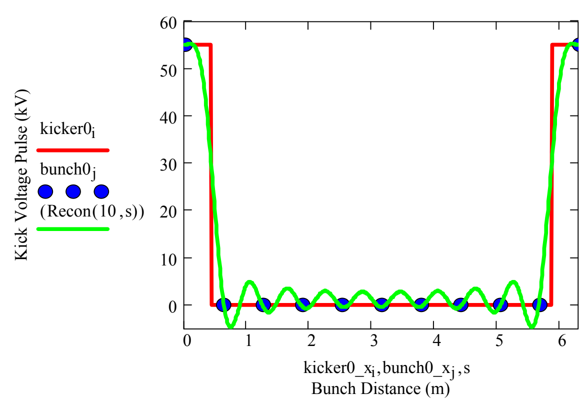

Figure 2: Ideal kicker voltage pulse (red) and bunch train scheme (blue) to kick every 10th bunch, and the reconstructed kicker pulse with the first 10 harmonic modes (green).

GENERATION OF KICK VOLTAGE WITH FINITE HARMONIC MODES

The periodical kick voltage pulse can be described mathematically as a Fourier series expansion in compact trigonometric form [2]:

$$V_t = V_0 + \sum_{n=1}^{\infty} V_n \cos(n\omega_0 t + \varphi_n) \quad (1)$$

Where V_t is the total kick voltage, the constant term V_0 represents a DC offset, ω_0 is bunch repetition frequency

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in ERL, V_n and φ_n are amplitude and phase terms of these harmonics. Reconstructing the voltage pulse with the first 10 harmonics, and adjusting the offset and amplitude to satisfy the design kick voltage, the reconstructed kick pulse voltage can be seen in Fig. 2 (green). The kick voltage with phase for each mode is summarized in Table 1.

However, this ideal kick is only achieved at the bunch centroid. If we consider +/- 3σ of (σ =2cm) electron bunches, for these kicked bunches, the centroid kick voltage is 55.486 kV, but the head and tail kick voltage is 55.485 kV. The relative difference is 1.741E-5 for the flat-top pulse. For the un-kicked bunches, they experience a larger different voltage between head and tail. The largest ones, next after the kicked bunches, about 6.76 kV of the head, 0.038 kV of the centroid, and -3.789 kV of the tail. These differences might cause problems in the collider ring, but all these head-tail tilts can be cancelled out if two identical kickers (one kick-in, one kick-out) are placed with 180° betatron phase advance in the CR. Their residual tilts can be completely averaged out after 10 turns in the CCR due to the symmetric pulse structure of the harmonics.

CAVITY DESIGN

The cavity model used to generate harmonic modes is shown in Fig. 3. A quarter wave transmission line shorted at one end and capacitively loaded at the other end. Here b and a are the radius of outer and inner conductor, and g is the end gap. Beam passes through the gap and is deflected primarily by a transverse electric field. Because of the boundary conditions of this type cavity, the higher order modes in one cavity can be only odd-harmonics of the fundamental mode of the cavity. Thus to generate the first 10 harmonics of the beam frequency, 4 cavities are needed. The harmonics in each cavity are shown in Fig. 6. To increase the harmonic number to 25, just one more cavity to generate a mode in 47.63MHz×16 is needed. Other modes will be the extension of higher odd harmonics of the original cavities.

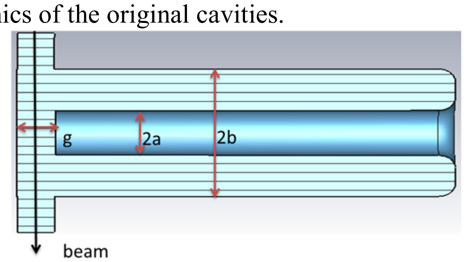

Figure 3: Cavity Model.

Shunt Impedance Formula

The transverse voltage acquired by an on-crest particle is simply the integral of the time-dependent transverse electric field along the beam line [3]. Ignoring the fringe field and just considering the uniform field between the inner end disk and outer disk in the gap, without beam pipes, the total power dissipation Pc on the cylindrical cavity consists of three parts, inner conductor, outer conductor, and the short end disk between outer and inner conductor. Then the transverse shunt impedance can be expressed as

$$R_t(n,b,\xi,g)=\frac{V_t}{P_c}=\frac{128\pi(b\xi)^2 Z_0^2(\xi)T(n,\xi)^2}{g^2R_s(n)\lambda(1)(\frac{1}{b\xi}+\frac{1}{b}+\frac{8}{\lambda(1)}\ln(\frac{1}{\xi}))} \tag{2}$$

Here $\xi = a/b$ is the diameter ratio between inner and outer conductor, $\lambda(n)$ and $f(n)$ is the wavelength and frequency of nth mode, $R_s(n)=\sqrt{\frac{\pi f(n)\mu}{\sigma}}$ is the surface resistance, $T(n,\xi)=\frac{\sin(2\pi b\xi/\lambda(n))}{2\pi b\xi/\lambda(n)}$ is the transit time factor, and $Z_0(\zeta)=\frac{\eta}{2\pi}\ln(\frac{1}{\xi})$ is the characteristic impedance of the transmission line,η is the vacuum wave impedance . The analytical impedance formula is drawn in Fig. 4.

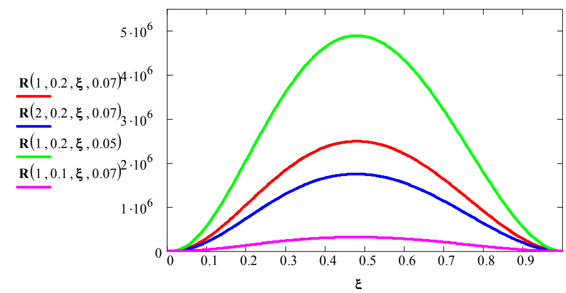

Figure 4:Analytical Shunt Impedance Formula(R is in Ω, b and g is in meter).

To minimize the power dissipation in the cavity, it is necessary to optimize the maximum. We can easily see that R_t is larger when the gap is small, but the gap should be large enough for the beam stay-clear during the transit of the structure. It is also obvious that R_t will get a great increase with a larger b, however, b is also limited by the transit time factor. We can get an optimized ξ about 0.5 from this formula, but this ratio will be smaller when the fringe field effect is added. Further optimization can be obtained using CST Microwave Studio.

Electromagnetic Simulations

Selecting b as 157 mm (quarter wavelength of the highest mode), a was varied at four different gaps g to maximize the shunt impedance, as shown in Fig. 5. With this optimized value, the cavity model is shown in Fig. 6. Here the gap is 70 mm and a is 55 mm (ξ=0.35). The inner conductors are tapered to tune their higher order modes to be true harmonics. The transverse shunt impedance and the power needed for each mode are summarized in Table 1. As can be seen the total dissipated power is only 74.86W, a large reduction compared to a conventional strip-line type kicker, which

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would be about 16.7 kW for the same gap [4].

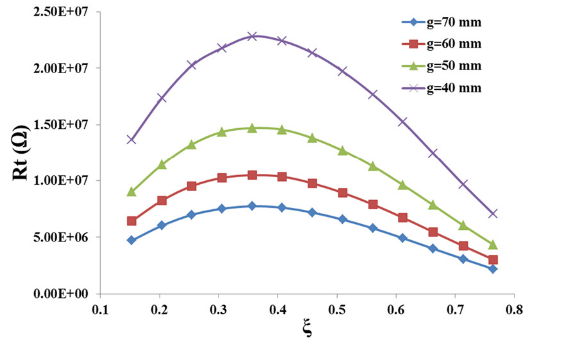

Figure 5: Optimization of the inner conductor for two different gaps when b is 157 mm.

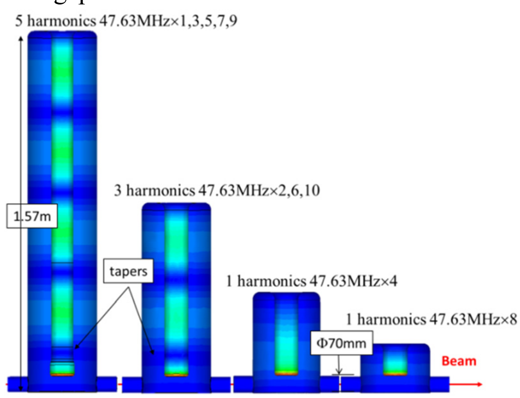

Figure 6: Harmonic modes in four cavity system with the highest harmonic electric field distribution shown in each cavity.

Table 1: Kick Voltage, Shunt Impedance and Dissipate Power for each Mode

Mode (MHz)	Kick Voltage (kV)	Trans. Shunt Impedance (Ω)	Power (W)
47.63	13.71	9.13E6	20.6
95.26	12.46	1.09E7	14.2
142.89	10.53	5.18E6	21.4
190.52	8.129	1.23E7	5.39
238.15	5.503	3.88E6	7.81
285.78	2.917	6.75E6	1.26
333.41	0.630	3.14E6	0.13
381.04	-1.209	1.77E7	0.08
428.67	-2.432	2.66E6	2.22
476.3	-3.011	5.12E6	1.77
DC	8.276		
Total	**55.503**	4.1E7	**74.86**

Stub Tuner Design

From the numerical simulations above, we can also calculate that the bandwidth of the fundamental mode is only 10 kHz for the copper wall material. It is crucial to make sure every mode is on its target frequency. Any mistuning due to manufacturing tolerance can be returned by stub tuners inserted into the cylinder wall. For the cavity with 5 odd modes, 5 stub tuners are needed since they are interacting with each other. A small cylinder of 20mm in height, 20mm in diameter is used to find the most sensitive tuning position for each mode along the cavity outer wall. 5 positions are chosen with optimum tuning sensitivity for the 5 modes as shown in Fig. 7. When the tuner position is confirmed, we can adjust the insertion height of each tuner to make sure the 5 modes are linear response.

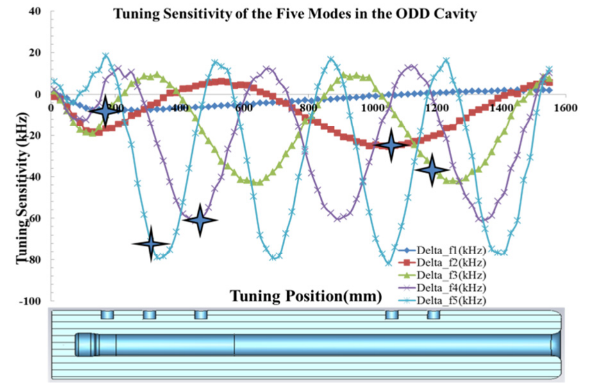

Figure 7: Tuner position simulation for the 5 harmonic modes cavity with a small cylinder perturbation.

Loop Coupler Design

One common loop coupler inserted into the high magnetic field area near the cavity short end can be used on each cavity to couple the power. The coupler position of the 5 mode cavity is optimized by moving a rectangular coupler loop of 30mm in length, 46mm in width along the cavity, which can be seen in Fig. 8. The fundamental mode has the lowest coupling strength but requires the highest power, so the 1360mm position is selected to place the loop coupler, where the fundamental mode is critically coupled, and the higher modes are least over-coupled.

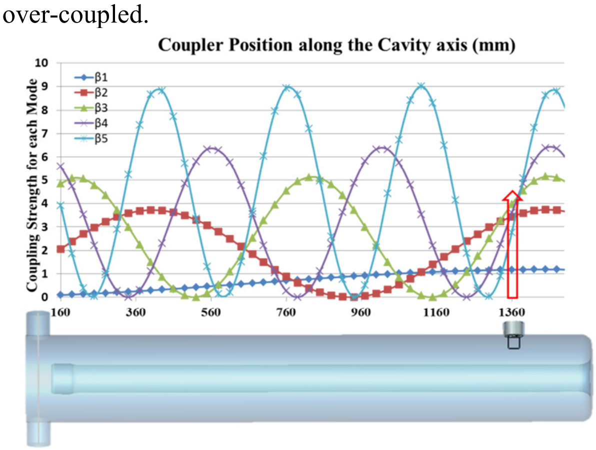

Figure 8: Loop coupler position optimization.

CONCLUSION

A conceptual design of a harmonic quarter wave resonator (QWR) based deflecting structure with high shunt impedance thus lower dissipated power for a given kick angle is presented in this paper, with the analytical and numerical optimization, the cavity tapers, tuners and coupler. Further optimization about the cavity structure and the kicker scheme to cancel the head tail difference of the un-kicked bunch is still under investigation.

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