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

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Abstract

Electron cooling is essential for the proposed Medium energy Electron Ion Collider (MEIC) to attain low emittance and high luminosity. To achieve a very high electron beam current for bunched beam cooling in the future high luminosity upgrade, we adopt a circulator ring to reuse the electron bunches. The electron bunches will recirculate for 25 turns, thus the current in the ERL can be reduced by a factor of 25. An ultra-fast kicker is required for this circulator ring, with pulse width less than 2.1 ns (1/476.3 MHz) and high repetition frequency of 19.052 MHz (1/25 of 476.3 MHz). JLab started an LDRD proposal to develop such a kicker. Our approach is to generate a series harmonic mode with RF resonant cavities, electron bunches passing through the cavity will experience an integral effect of all the harmonic fields, thus every 25th bunch will be kicked while all the other bunches un-kicked. Here we present a design of a simplified prototype with every 10th bunch kicked, using 4 cavities to generate 10 harmonic modes. Cavity structure is optimized to get the highest shunt impedance, thus the total power dissipated on 4 cavities for copper material is only 87.72 W, two to three orders of magnitude lower than a strip-line kicker.

INTRODUCTION

Cooling of ion beams is critical in delivering high luminosities for the proposed MEIC [1]. Low ion beam emittance is required to deliver a small beam spot at the interaction point. The present MEIC design utilizes a scheme of multi-stage cooling. In each stage, the velocity of the electron beam needs to be matched with the ion beam. In the booster, the required electron energy is less than or just about 1 MeV, 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, higher energy electron bunches is needed, for example, to cool 100 GeV protons, the required electron energy is 55 MeV. 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.

In the baseline design, a single turn ERL cooler is used, as shown in Fig.1 [2]. After being accelerated to 55 MeV in the SRF linac, the electron bunches will merge with the ion beam and continuously cool the ion bunches in a long cooling channel immersed in a strong solenoid field, then return to the linac for energy recovery, and finally be delivered to the beam dump. The bunch repetition frequency is 476.3 MHz, and the beam current is 0.2 A, which should be achievable with reasonable R&D effort.

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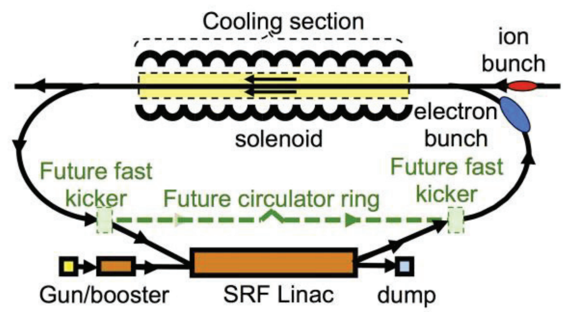

Figure 1: Schematic of bunched beam cooler with option for future recirculation.

In the future high luminosity upgrade, high intensity electron beam is needed. High current (~1.5 A) not only brings the difficulties to build the electron gun and the SRF linac, but also requires high RF power. A great idea to solve this problem is to add a circulator ring to reuse the electron bunches, as shown in Fig. 1 (green). Electron bunches will circulate 25 turns in the circulator ring, and then back to the ERL. In this scheme the beam current and bunch repetition frequency in ERL can be reduced by a factor 25 (0.06 A, 19.052 MHz).

A critical component in this scheme is the ultra-fast kicker that periodically switches electron bunches in and out of the circulator ring from and to the driver ERL. When the electron bunches are kicked into the Circulator Ring (CR) (476.3 MHz), every bunch in the ERL (19.052 MHz) is kicked; when kicked out, every 25th bunch is kicked and other 24 bunches are, ideally, undisturbed. Assuming 55 MeV electron beam energy and a kick angle of 1mrad, the kick voltage would be 55 kV. To avoid the interference to the undisturbed bunches, the pulse width should be very short (less than 2.1 ns for a 476.3 MHz bunch train). In the R&D design, we just prototype a simplified version that kicks every 10th bunch. The ideal kick voltage pulse and the bunch train structure are shown in Fig.2.

GENERATION OF KICK VOLTAGE WITH FINITE HARMONIC MODES

The periodical square kick voltage pulse can be described mathematically as a Fourier series expansion in compact trigonometric form [3]:

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

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V_t is the total kick voltage, the constant term V_0 represents a DC offset, ω_0 is bunch repetition frequency 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 DC offset and amplitudes to satisfy the design kick voltage, the reconstructed kick voltage pulse can be seen in Fig. 2 (black). The kicked bunches experience a kick voltage of 55 kV, while the centers of each un-kicked bunch will experience zero kick voltage. The waveform fluctuates between adjacent bunches, generating a head-tail difference in the kick each bunch sees. For the kicked bunches, a flat top kick can be obtained by adjusting the pulse width before FFT; and for the un-kicked bunches, the head and tail difference can be cancelled by an 180^0 betatron phase advance between two kickers.

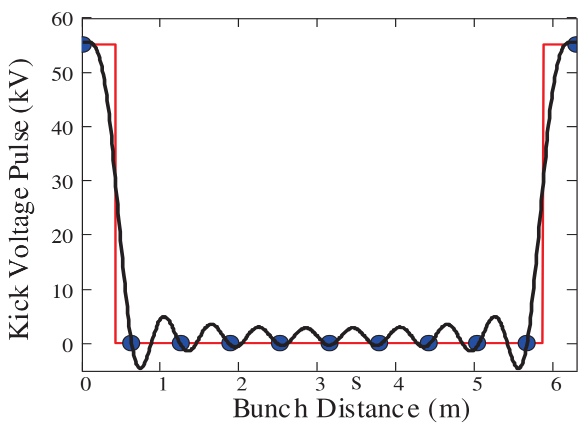

Figure 2: Ideal kicker voltage pulse (red solid line) and bunch train scheme (blue point) to kick every 10th bunch, and the reconstructed kicker pulse with the first 10 harmonic modes (black).

Adjust the Pulse Width to Get a Flat Top

Consider a normalized periodical pulse voltage of width *b*, amplitude *1*, in one period *(-b/2, 2π-b/2),* the square pulse can be expanded as the following form:

$$F(s,b,x) = \frac{b}{2\pi} + \frac{2}{\pi}\cdot\sum_{n=1}^{s}\frac{1}{n}\sin(n\cdot\frac{b}{2})\cos(n\cdot x) \quad (2)$$

s is the harmonic number, *x* is variable. If we consider +/- 3σ of (σ=2cm) electron bunches, for 10 harmonics, we can solve the following equation to optimize the width *b*.

$$F(10,b,0) = F(10,b,0.06) \quad (3)$$

A series *b* is get from this equation, as can be shown in Fig. 3.We define the flatness as:

$$flatF(s,b,x) = \frac{\max F(s,b,x) - \min F(s,b,x)}{F(s,b,0)} \quad (4)$$

Here *maxF(s,b,x)* and *minF(s,b,x)* is the maximum value and minimum value of *F(s,b,x)* in Interval *[0,x]*.

Calculate the flatness for several widths, we can get:

$$flatF(10,0.859324,0.06) = 9.504\times10^{-5} \quad (5)$$

$$flatF(10,1.474168,0.06) = 3.4308\times10^{-5} \quad (6)$$

$$flatF(10,2.079633,0.06) = 1.6348\times10^{-5} \quad (7)$$

Larger *b* gives better flatness, but also requires larger amplitude and power for each mode, and a wider pulse also has effect on the un-kicked bunch. Thus in this case, minimum *b* is enough.

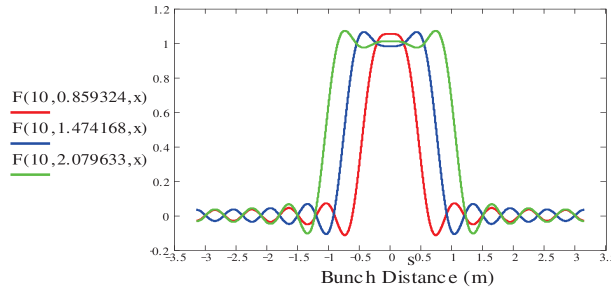

Figure 3: Pulse top flatness with different pulse width.

Cancelation of the Head and Tail Difference for the Un-kicked Bunch

For a single particle in a bunch, a transverse kick will change its transverse momentum. As the particle proceeds along the orbit, the transverse momentum and position follows the betatron oscillation. If two kickers are separated of a distance with exactly 180 degree betatron phase advance, particles experience a positive kick will experience another positive kick and then return to its original orbit. The particles experience a negative kick will be the same to return to the original bunch elliptical phase space orbit after the second kicker. The residual kick left due to the voltage difference between two kickers will be cancelled out after 25 turns in the CR due to pulse shape symmetry in time structure as illustrated in Fig. 2. The first cancelation scheme can be illustrated in Fig. 4. Total cancellation hypothesis could be confirmed by the tacking simulation study.

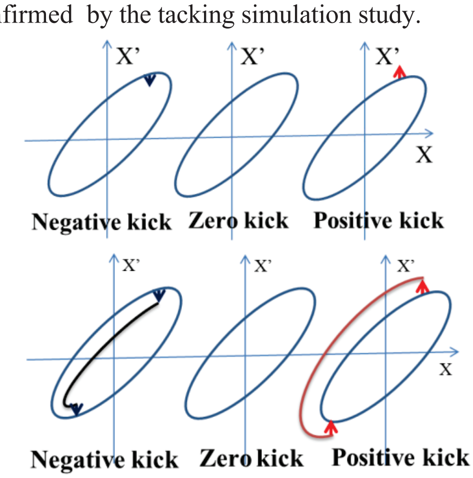

Figure 4: Cancelation of the head and tail difference for the un-kicked bunch.

Build the Kick Voltage with Less Harmonic Modes

In Figure 2, we construct the kick voltage with 10 harmonic modes, and every 10th bunch is kicked. If we want to construct a waveform that kicks every 25th bunch

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using this method, the required harmonic number will be 25, which may impose difficulties for the cavity design. However, with n modes, the number of variables in equation (1) is $2n+1$ (1 DC offset, n amplitudes, n phases). If the waveform has $2n+1$ constraints in a period, i.e. zero at the $2n$ un-kicked bunches and V_t at the kicked bunch, in most cases we should be able to find a set of solution constructed with about n modes, reducing the number of modes by half. We have found such a solution with all the phase set to 0, if

$$V_1 = V_2 = \ldots = V_n = 2V_0 \tag{8}$$

This waveform kicks every $(2n+1)^{th}$ bunch in an odd position at the amplitude of $(2n+1)V_0$.

To construct a waveform that kicks every $2n^{th}$ bunch in the even position, it requires the V_n is half of lower frequency modes:

$$V_1 = V_2 = \ldots = V_{n-1} = 2V_n = 2V_0 \tag{9}$$

Figure 5 compares the waveforms generated by the constraint method with the FFT method. Both waveforms can kick every 25^{th} bunch. The main difference is the flatness for the kicked bunch. To improve the flatness in the constraint method, one or two more harmonic modes can be added.

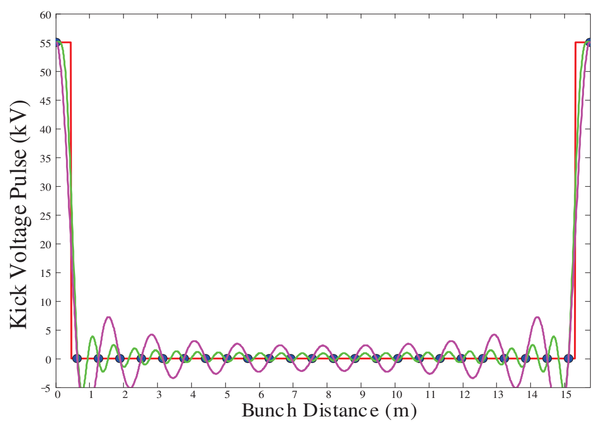

Figure 5: Comparison between the ideal kick voltage (red), reconstructed the kick voltages with 25 harmonics (green) and 12 harmonics (magenta).

CAVITY DESIGN

The cavity model used to generate harmonic modes is quarter wave transmission line shorted at one end and capacitive loaded at the other end, as shown in Fig. 6. 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.

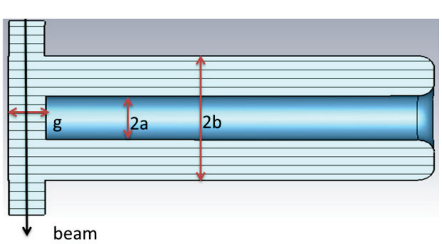

Figure 6: Cavity model.

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, as shown in Fig. 7.

The relationship between cavity number M and maximum harmonic number N can be supported as

$$2^M - 1 \leq N \tag{10}$$

The maximum harmonic modes N distributed in M cavities can be demonstrated in Tab.1 as an example for M=4, N=15, f_0=476.3MHz, calculated by the base frequencies of f_0/N $2f_0/N$, $4f_0/N$, $8f_0/N$.

Table 1: Harmonic Modes in Each Cavity

Cavity #1	Cavity #2	Cavity #3	Cavity #4
$(2n_1+1)\frac{f_0}{N}$	$(2n_2+1)\frac{2f_0}{N}$	$(2n_3+1)\frac{4f_0}{N}$	$(2n_4+1)\frac{8f_0}{N}$
n_1=0~7	n_2=0~3	n_3=0~1	n_4=0

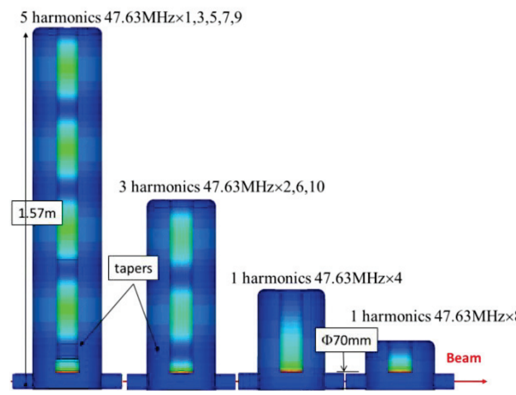

Figure 7: Harmonic modes in four cavity system with the highest harmonic electric field distribution shown in each cavity.

Cavity model is optimized to get the maximum shunt impedance in Microwave Studio CST, with the amplitude and phase from FFT, we can get the dissipated power of each mode on 300 K copper walls, as shown in Tab. 2.

Total power for all modes is 87.72W, two to three orders of magnitude lower than a strip-line kicker [4]. The equivalent transverse shunt impedance for the kicker system can be defined as,

$$R_t = \frac{V_t}{P_{total}} = \frac{V_0 + \sum_{n=1}^{N} V_n \cos(n\omega_0 t + \varphi_n)}{\sum_{n=1}^{N} P_n} \tag{11}$$

Stub Tuner Design

It is crucial to make sure every mode is on its target frequency. From the numerical simulations above, we can calculate the bandwidth of each mode for the room temperature copper wall material. As shown in Table 3, Q_0 for each mode is calculated for 300 K copper. Fundamental mode in each cavity is critically coupled; higher modes in the 5 modes and 3 modes cavities are slightly over coupled. Then the bandwidth for one coupler system:

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$$\Delta f_n = \frac{f_n}{Q_{0n}}(1+\beta_n) \qquad (12)$$

Here f_n, Q_{0n}, β_n and Δf_n is the frequency, quality factor, coupling strength and bandwidth of nth mode.

Table 2: Kick Voltage, Shunt Impedance and Dissipate Power for Each Mode

Mode (MHz)	FFT Kick Voltage (kV)	CST Trans. Shunt Impedance (Ω)	Dissipated Power for 300K Copper (W)
47.63	13.711	7.13E6	26.37
95.26	12.462	1.14E7	13.62
142.89	10.532	4.09E6	27.12
190.52	8.1290	1.35E7	4.89
238.15	5.5030	3.14E6	9.64
285.78	2.9170	6.09E6	1.40
333.41	0.6300	2.65E6	0.15
381.04	-1.2090	1.65E7	0.09
428.67	-2.4320	2.40E6	2.46
476.3	-3.0110	4.57E6	1.98
DC	8.2760		
Total	55.508	3.56E7	87.72

It is also shown in Tab.3, when we design the cavity, with an optimized tapering shape design on the cavity inner conductor, harmonic frequencies without tunings can be controlled within the bandwidths of operation modes. However, geometry change due to fabrication error or thermal/mechanical deformation may cause the cavity harmonic frequency deviations more than the natural bandwidths. This fabrication error can be corrected by stub tuners inserted into the cylinder wall. For the cavity with N modes, N stub tuners are needed since they are interacting with each other. Here we use the 3-mode cavity as an example. A small cylinder of 5mm in height, 20mm in diameter is used to find the most sensitive tuning position for each mode along the cavity outer wall. 3 positions are chosen to make sure every mode can be tuned in both positive and negative directions as can be shown in Fig.8.

When the tuner position is confirmed, we can adjust the insertion height of each tuner to get the function of frequency shift and the insertion height. Then we can get a tuning matrix (dependence of each mode on each tuner) and invert it to get the cavity spectrum tuned.

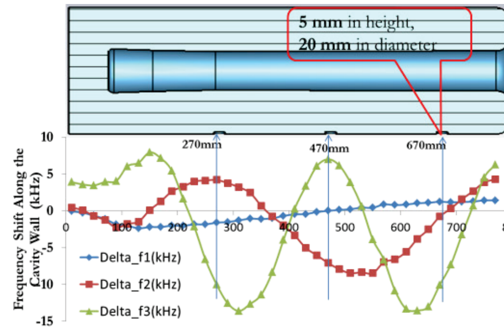

Figure 8: Tuner position simulation for the 3 harmonic modes cavity with a small cylinder perturbation.

Loop Coupler Design

For each cavity, we can use one common power coupler for all the modes. This coupler is inserted into the high magnetic field area near the cavity short end. The coupler optimum position can be simulated by moving a rectangular coupler loop along the cavity. The fundamental mode always has the lowest coupling strength. We can adjust the loop size, rotating angle and the position to make sure the fundamental mode is critically coupled, and the higher modes are over-coupled with minimum coupling [5].

CONCLUSIONS

An ultra-fast (2.1 ns pulse width), high repetition rate kicker was conceptual developed, with great power efficiency (87.72 W for 55kV kick voltage) and cost-effective (just copper or copper plated stainless steel cavities in room temperature). The conceptual design of the RF cavity, stub tuner and input loop coupler has been done for simple cavity case. Further optimization to reduce the number of harmonic modes, strategy to get more efficient tuning scheme is under study. Beam dynamics tracking, mechanical design, HOM damping will be studied further. A prototype cavity will be made; RF bench measurement and the possible vacuum device development for the beam experiment will be done in the future.

Table 3: Bandwidth of Each Mode for 300K Copper

Cavity	Operation Frequency (MHz)	Q_0 for 300K copper	β	Bandwidth for 300K copper (kHz)	Designed Frequency with Taper (MHz)	Error Frequency by Design (kHz)
Five Modes Cavity	47.63	8586	≈1	≈11.09	47.62991	-0.09
	142.89	14689	>1	>19.46	142.8915	0.15
	238.15	18973	>1	>25.10	238.153	3
	333.41	22472	>1	>29.67	333.4117	1.7
	428.67	25536	>1	>33.57	428.6718	1.8
Three Modes Cavity	95.26	12002	≈1	≈16.04	95.26267	2.67
	285.78	20784	>1	>27.50	285.7868	6.8
	476.3	27056	>1	>35.21	476.3087	8.7
One Mode Cavity	190.52	15298	≈1	≈24.91	190.5267	6.7
One Mode Cavity	381.04	19435	≈1	≈39.21	381.0361	3.9

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