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THE DEVELOPMENT OF A NEW FAST HARMONIC KICKER FOR THE JLEIC CIRCULATOR COOLER RING*

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Abstract

After the first harmonic kicker cavity prototyping [1] for the Jefferson Lab Electron-Ion Collider (JLEIC)'s Cooling Circulator Ring (CCR)/Energy Recovery Linac (ERL) and the beam dynamic simulation study of the CCR [2], the CCR injection/extraction scheme has been changed to accommodate the various collision frequencies, requiring a new harmonic RF kicker system. The new kicker design, including the electromagnetic and beam dynamics simulation, is presented here.

INTRODUCTION

As a part of the effort for the JLEIC cooling system R&D, a fast harmonic RF kicker system based on the quarter wave resonators (QWR) was successfully developed for the preliminary beam parameters of the CCR [1], with the first half-scale (95.26 MHz base frequency), 5-mode prototype demonstrated [2]. In the past few years, a new CCR injection scheme has been developed to accommodate different ion ring and CCR bunch repetition rates (including 1, 1/2, 1/4, 1/8 harmonics of 952.6 MHz), and the beam parameters have been further optimized, as shown in Table 1 [3]. The number of revolutions that electrons circulate in the CCR changed from 10 to 11, so the kicker needs to be able to kick every 11th of 952.6 MHz bunches. The base frequency changes to 86.6 MHz. The deflecting angle also increased to 2.5 mrad.

Table 1: The Beam Parameters of the CCR

Parameters	Unit	Value
Beam energy E_e	MeV	55
Kick angle θ	mrad	2.5
Turns $\mathcal{N}$	-	11
Kick frequency f_k	MHz	86.6
Bunch frequency f_b	MHz	476.3
Bunch charge Q_b	nC	1.6
Bunch length l_b	cm	2
Energy spread δE	-	3×10^{-4}
Emitt. ε^n	mm· mrad	1.074
α	-	0
β	m	10

Here Emitt. is the non-magnetized normalized emittance and the Courant-Snyder parameters α, β are at the kicker.

The CCR has a pair of injection and extraction kickers, as shown in Fig. 1. Using a linear combination of harmonic modes with the base frequency 86.6 MHz, we can generate a waveform that kicks every 11th 952.6 MHz bunches and remains zero amplitude at the other 10 bunches, [1].

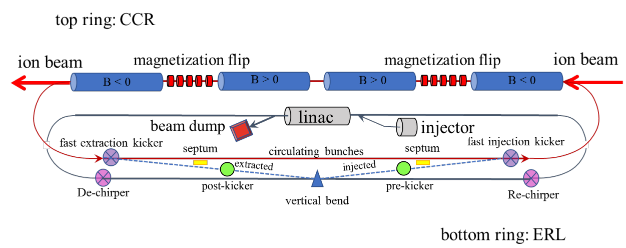

Figure 1: The schematic of the CCR.

We adopted a new waveform synthesization scheme that uses only 5 odd harmonics (1st to 9th) and DC, so the number of cavities in each kicker can be reduced to one, at the cost of slightly higher total RF power and larger voltage slopes at the bunches not to be kicked. The first order effects of the voltage slope is largely cancelled by fit the betatron phase advance from the extraction kicker to the injection kicker to π, and beam dynamics simulation results in the next chapter of this paper will show that these larger slopes are still acceptable.

Table 2: The Harmonic Kick Parameters. n_h is harmonic number, f is frequency, and V is voltage amplitude.

n_h	f [MHz]	V [kV]
1	86.6	25
3	259.8	25
5	433	25
7	606.2	25
9	779.4	25
0	0	12.5
11	952.6	32.4

The waveform is shown in Fig. 2(a), and Table 2 shows the harmonic components of the waveform. To deflect the bunch at E_e = 55 MeV by 2.5 mrad, total kick voltage is 137.5 keV. To suppress the emittance growth, the voltage on the injected/extracted bunches needs to be flat temporally within the bunch length. We chose to use a single frequency 952.6 MHz pre-kicker in the injection transport line to correct the curvature. If we use the 952.6 MHz mode (11th harmonics) in the main kicker cavity instead, we will face the difficulties or more stringent constraints such as minimizing the longitudinal impedance of the 952.6 MHz mode, limiting the first TE11 mode frequency above 952.6 MHz, as well as the larger slopes seen by the unkicked bunches.

From hardware point of view, it is always better that the kick can be realized by small number of the cavities with minimum harmonic modes, and with the minimum total dissipated power. This is done by a careful optimization

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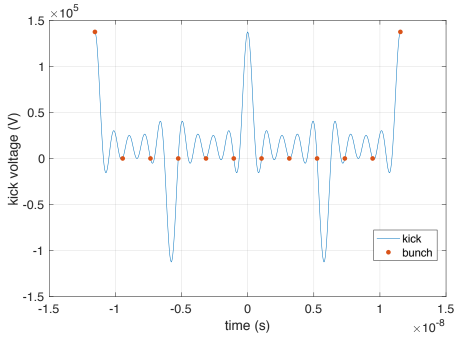
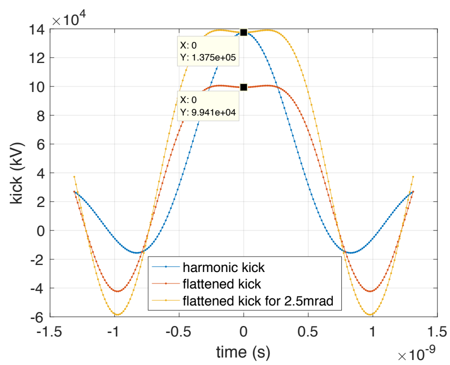
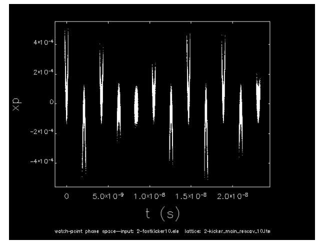


(a) Temporal profile of the harmonic kick.

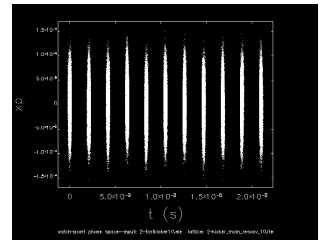


(b) Temporal profile of the in (out)-kick with the pre (post-) kick added.

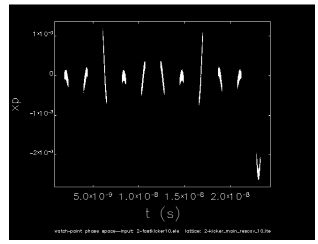
Figure 2: Temporal profiles of the kicks in the CCR.



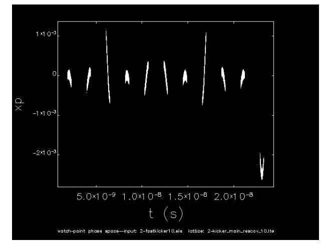
(a) The longitudinal profile of the angular divergence at the cooler (without pre-kicker).



(b) The profile at the cooler with pre-kicker.



(c) The profile at the ERL (without pre-kicker).



(d) The profile at the ERL with pre-kicker.

Figure 3: The longitudinal profiles of the bunch.

of the cavity design. Finally, the delivery of the kick to the bunches must be stable against various degrading conditions.

BEAM DYNAMICS

As a preliminary step, non-magnetized beam dynamics was investigated using the ELEGANT to check the essential features of longitudinal dynamics through the kicker. The simulation set up is shown in Fig. 2. In Fig. 2, the electron bunch is injected by an in-kicker, circulates 11 turns before it exits by an out-kicker. In the simulation, a harmonic kick was modeled by a spatial δ function without the effect from spatial distribution of the field.

The simulation results are shown in Fig. 3 and Fig. 4, where the longitudinal profile of the slope (x') in the bunch is displayed. Each bunch in each turn has an approximate cancellation of the deformation due to the out-kicker (Fi.g 3(c)) by a subsequent in-kick with π phase advance (Fig. 3(a)). Through the kickers, the bunch develops the side-wing whose span is about 0.4 mrad. With the pre-/post kickers, the wing disappears and angular divergence reduces to 0.1 mrad (Fig. 3(b)) and the emittance growth is minimized (Fig. 4(b)).

ELECTROMAGNETIC DESIGN OF THE HARMONIC KICKER

The EM design of the QWR was done with the simplest geometry as shown in Fig. 5.

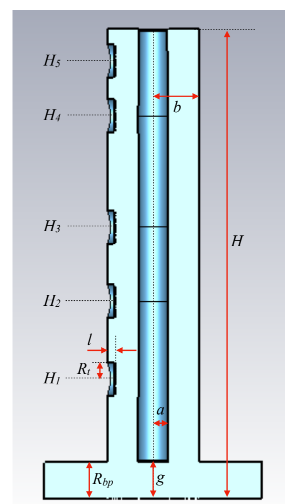


Figure 5: The dimension of the QWR.

The radius of the beam port R_{bp} is set to be $g = \pm 6\sigma = 70\,\mathrm{mm}$, where σ is *rms* value of the transverse beam size. The outer conductor radius b is determined to allow the maximum transit time factor for the 5th mode (oscillating with the highest frequency), i.e., $2b = \lambda_5/2$, where λ_5 is the wavelength of the 5th mode. The remaining geometrical parameter a, is determined to minimize the total dissipated power. To tune all the harmonic modes with target accuracy, the tapering on the center conductor and stub tuner system was implemented.

The power optimization was done with parameter scanning (a and b) in a series of the CST [5] simulations. In scanning, the TE11 mode develops as its frequency lower than 5th harmonic of TEM mode as $a+b$ increasing, limiting the power optimization. The minimum power with engineering margin taken into account, is about $P_{diss} \sim 3.6\,\mathrm{kW}$.

After power optimization, the harmonic frequencies were tuned by adjusting the height of the cavity (for rough tuning), tapering the center conductor (for finer tuning), and inserting the stub tuners (in case of the fabrication error or frequency shift during the operation). In particular, tapering and stub tuning, guided by Slater's theorem, can be described by 5×5 matrix equation. According to Slater's theorem, frequency response of each mode is linear to any tapering height or

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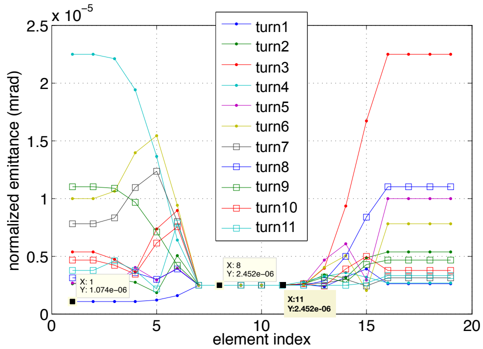
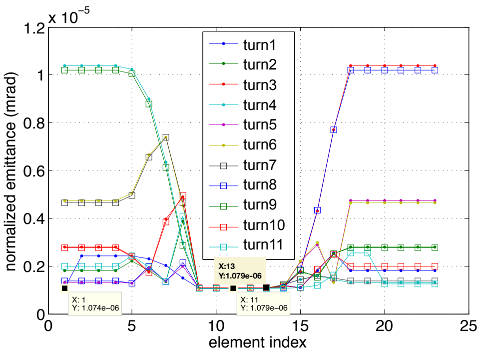


(a) The emittance change without pre-/post-kickers. $x = 1$ is in-kicker (entrance) position, $x = 8$ is the cooler position, and $x = 11$ is out-kicker (entrance) position.



(b) The emittance change with pre-/post-kickers. $x = 1$ is in-kicker (entrance) position and $x = 11$ is the cooler position, and $x = 13$ is out-kicker (entrance) position.

Figure 4: The emittance growth through 11 turns in the CCR.

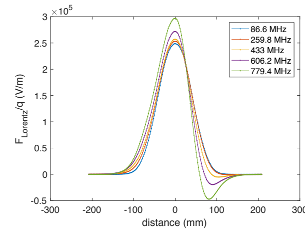
stub insertion, i.e.,

$$\Delta f_i = \mathcal{T}_{ij} \Delta h_{tp,j}, \quad \mathcal{T}_{ij} = \frac{\partial f_i}{\partial h_{tp.j}} \tag{1}$$

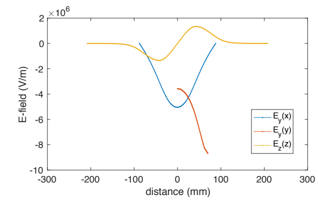
where $\mathcal{T}$ is a 5×5 matrix whose (i, j) element is the frequency response of i-th mode to the tapering on j-th point. Δf_i is a frequency response of the i-th mode and $h_{tp,j}$ is the height of the j-th tapering (or tuning) point. Once $\mathcal{T}$ is known, a frequency deviation can be tuned by solving for Δh_j in (1).

Although the actual frequency response is not linear over long range of tuning, a few iterations of (1) achieves the accurate tuning rapidly. While the tapering leads to $\delta f/f \sim 1\times 10^{-5}$, the tuning range of the stub tuners is about $\delta f/f \sim 1\times 10^{-3}$ in maximum as a result of optimization of the tuner geometry, i.e., the positions and radii of the stubs.

In Fig. 6(a) and 6(b), various field profiles of the cavity are shown. The longitudinal kick profile (See Fig. 6(a)) is approximately Gaussian, with small distortion caused by magnetic field profile of 4, 5-th modes. The unkicked transverse profile $E_y(x)$ in Fig. 6(b) is considered as constant over a few beam sizes. The vertical profile $E_y(y)$ in Fig. 6(b) has some gradient, suggesting a possible non-linear component contribution. The longitudinal field profile $E_z(z)$ is anti-symmetric with respect to the center and its integration is zero.



(a) The profile of the harmonic kick.



(b) The profile of the harmonic kick.

Figure 6: The field profiles of the QWR.

Some thermo-mechanical analysis by ANSYS [6] was done with simplified geometry (3 mm wall thickness, without tapering and tuners) of the cavity. The temperature profile for the 3.6 kW operation is shown in Fig. 7. Preliminary cooling scheme is with total cooling water flow of 25 l/min into the center conductor but without additional cooling on the end-plate. The hottest region, due to the strong magnetic field, is the end-plate with the temperature reaching up to 77°C. For structural stability, the end-plate was reinforced by more thickness and cone-shaped stiffener, reducing the modal vibration (of the pendulum mode) to ~ 39 Hz and holding up the vacuum pressure.

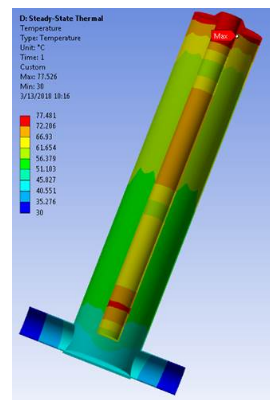


Figure 7: The temperature profile on the QWR.

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