

BEAM DYNAMICS ANALYSIS FOR THE ULTRA-FAST KICKER IN CIRCULAR COOLER RING OF JLEIC *

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Abstract

An ultra-fast kicker system consisting of four quarter wavelength resonator based deflecting cavities was developed that simultaneously resonates at 10 subharmonic modes of the 476.3MHz bunch repetition frequency. Thus every 10th bunch in the bunch train will experience a transverse kick while all the other bunches are undisturbed. This fast kicker is being developed for the Energy Recovery Linac (ERL) based electron Circular Cooler Ring (CCR) in the proposed Jefferson Lab Electron Ion Collider (JLEIC, previously MEIC). The electron bunches can be reused 10-30 turns thus the beam current in the ERL can be reduced to 1/10 - 1/30 (150mA - 50mA) of the cooling bunch current (1.5A). In this paper, several methods to synthesize such a kicker waveform will be discussed and the comparison made by beam dynamics tracking in Elegant.

INTRODUCTION

Cooling of ion beams is critical in delivering high luminosities for the proposed JLEIC [1-4]. The present JLEIC design utilizes a scheme of multi-stage cooling, a DC cooler in the booster and bunched beam cooler in the ion collider ring. For energy efficiency and to minimize the power to be dissipated in the beam dump, an ERL based electron cooler configuration is being developed.

The conceptual layout of the single turn ERL based bunched beam cooler ring is shown in Fig.1 (black) [1-2,4]. In the future high luminosity upgrade, high intensity electron beam is needed. A circulator ring was proposed to reuse the electron bunches, as shown in Fig.1 (green). Electron bunches will circulate 10-30 turns in the circulator ring until the beam quality is poor, and then back to the ERL for energy recovery. In this scheme the beam current and bunch repetition frequency in ERL can be reduced by a factor 10-30.

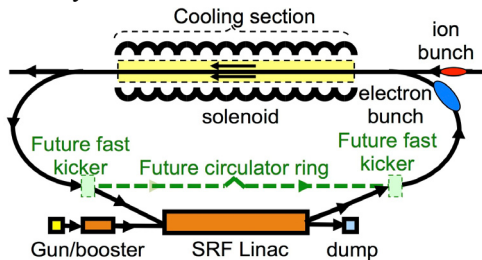


Figure 1: Schematic of ERL based bunched beam cooler (black) with option for future recirculation (green).

A critical component in this scheme is the ultra-fast

kicker that periodically deflect individual electron bunches in and out of the circulator ring from and to the driver ERL, leaving the orbit of adjacent bunches in the circulator ring undisturbed. To avoid the interference to the undisturbed bunches, the half pulse width should be very short (less than the bunch spacing 2.1 ns for a 476.3 MHz bunch train). Pulsed power supplies, especially with these characteristics are beyond state of the art, an alternative driving method is summing simple cosine waves at sub-frequencies of the final beam repetition frequency with appropriate phase and amplitudes to generate a continuous waveform [5-6], as shown in Fig.2, the total kick voltage is 55kV in this paper, which will give a 1mrad deflection angle for 55 MeV electron bunch.

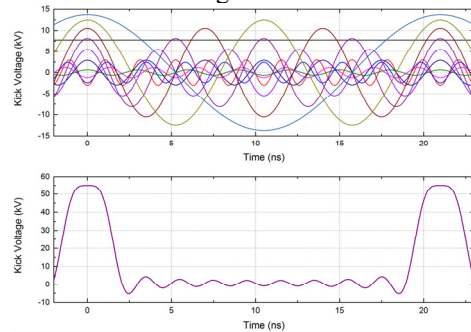


Figure 2: Flat-top kicker waveform (bottom) resulting from summation of a DC offset and 10 subharmonics of the nominal bunch frequency of 476.3MHz (top).

HARMONIC KICKER WAVEFORM

Similar concepts using a combination of a series of harmonic modes have already been explored [7-9]. In this study, several methods are examined to determine the amplitude and phase of the subharmonics, which result in different kicker waveform, as shown in Fig.3.

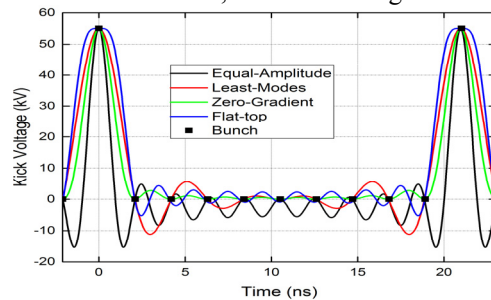


Figure 3: Synthesized Flat-Top (blue), Zero-Gradient (green), Least-Modes (red) and Equal-Amplitude (black) waveforms for circulator ring for 10 turns.

Here the Flat-Top scheme gives the most uniform kick for the kicked bunch [10], the Zero-Gradient scheme

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gives non-sloping waveform for the unkicked bunches[11-12],the Least-modes scheme will reduce the harmonic modes number by half [10,12], and the Equal-Amplitude scheme has every subharmonic with equal amplitude and no DC offset needed [5].

BEAM DYNAMICS TRACKING

To make a comparison of the four kicker waveforms, the kick effects on transverse beam quality for both kicked and un-kicked bunches were simulated using Elegant [13].Parameter used in the simulation are summarized in Tab. 2[11].

Table 2: Parameters in ELEGANT Simulation

Parameter	Value	Unit
Electron Energy	55	MeV
RMS Bunch Length	3	cm
Bunch Distribution	Gaussian	
Bunch Frequency	476.3	MHz
Transverse Emittance	10	nm
Vertical Emittance	10	nm
Energy Spread	3E-4	
Recirculation Turns	10	#
Kick Angle	1	mrاد
Total Kick Voltage	55	kV

One Kicker Scheme Tracking

In the one kicker scheme tracking, a single bunch with an initial positive transverse momentum angle will receive a negative kick from the kicker and injected to the design orbit. After 10 turns, the bunch receives another negative kick and is extracted to the ERL, as shown in Fig.4.

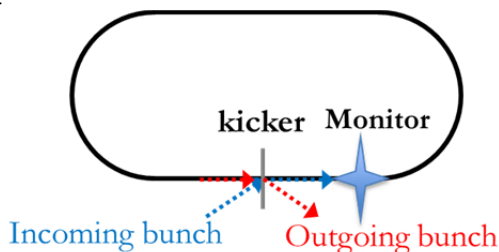


Figure 4: One kicker tracking scheme with only one kicker for injection and extraction.

In the simulation, the circulator ring was approximated by a one turn linear transfer matrix; the kicker waveform was generated using a series of zero-length RF deflectors with appropriate frequencies, phases, and amplitudes. One monitor was put after the kicker. Fig.5 shows the turn-by-turn normalized horizontal emittance for a single bunch in the circulator ring for the different kicker waveforms. For the Flat-Top waveform, less than 1% emittance growth has been seen due to the uniform kick when the bunch is kicked into the ring, but the large gradient of the residual kick voltage caused by the wave fluctuation in the following turns results in a large emittance growth turn by turn, and after 10 turns of recirculation, the emittance is nearly 4.8 times larger than the initial value. For the Zero-

Gradient waveform, 5% emittance growth is seen due to the non-uniformity kick pulse, but negligible emittance growth during the subsequent turns because of the near-zero residual kick voltage as the bunch recirculates. For the Least-Modes waveform, there is 2% emittance growth when kicked in, and about 2.5 times growth during the recirculation. It is a compromise between a flat-top kick and a non-residual gradient kick. For the Equal-Amplitude scheme 25% emittance growth occurs when kicked in, and about 5.5 times growth during the recirculation. Although there is no DC offset required, this is clearly the least favourable option.

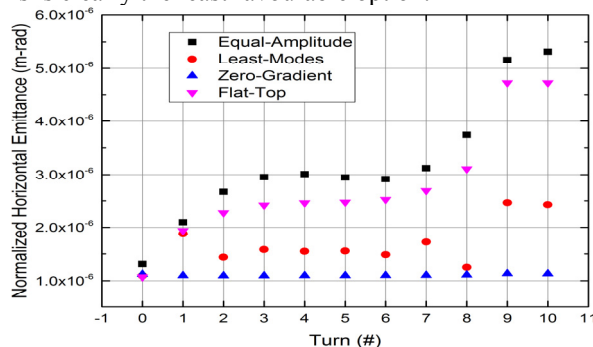


Figure 5: Turn-by-turn normalized horizontal emittance growth for a single electron in one kicker scheme.

Two Kicker Scheme Tracking

One challenge to use only one kicker for both injection and extracting is the possible beam-beam effect during the kicking process. Then a more suitable scheme could use two kickers that one for injection and one for extraction, which is shown in Fig.6. In this scheme, electron bunches will be kicked into the circulator ring by Kicker1, and after 10 turns recirculation, then be kicked out from Kicker 2.

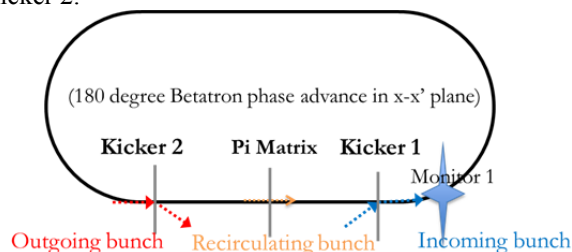


Figure 6: Two kickers tracking scheme with Kicker 1 for injection and Kicker 2 for extraction.

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 a betatron oscillation. If the two kickers are separated of a distance with exactly 180 degree betatron phase advance, particles that experience a positive kick from the Kicker 2 will experience another cancelling kick from Kicker1 and then return to the original phase space orbit. The cancellation scheme was illustrated in [10]. And the cancellation hypothesis is confirmed by the tacking simulation in Elegant, as shown in Fig.7.

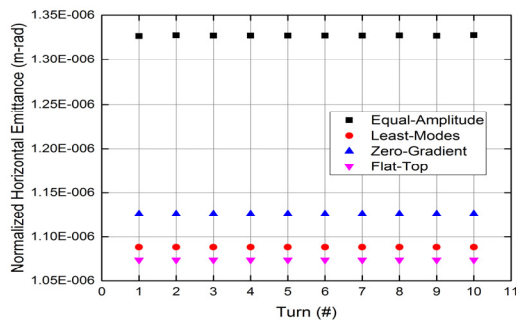


Figure 7: Turn-by-turn normalized horizontal emittance growth for a single electron bunch in two kicker scheme with 180 degree betatron phase advance in between.

With the cancellation of the residual kick voltage with two identical kickers, negligible emittance growth is seen during recirculation for all kicker waveforms. The Flat-Top scheme has the minimum emittance growth due to the uniform kick when the bunch was first kicked into the circulator ring. However the Least-Modes scheme is almost as good with only half the number of harmonic modes.

Multi-cavity Scheme with Kick-drift Tracking

The cavity model used to generate the subharmonic modes is a quarter wavelength resonator, the electromagnetic design and optimization of the cavity have been previously reported [10, 14-15]. Four cavities are needed to generate the 10 subharmonics. In this multi-cavity scheme, the kick is provided by four cavities at discrete locations, as shown in Fig.8.

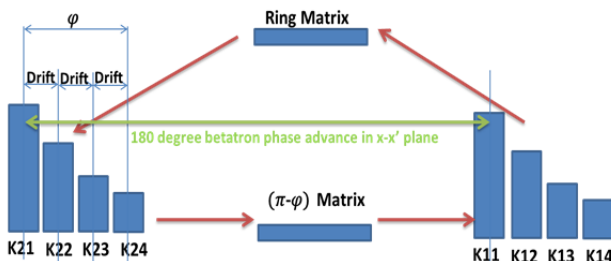


Figure 8: Multi-cavity kick-drift tracking scheme.

In this simulation, we just separate the kick to four parts. In each cavity the kick is generated with a series of zero length deflectors with a drift space between cavities. To ensure cancellation the 180 degree phase advance should be between the two identical cavities; the phase advance between the two kicker systems should be the ideal minus the phase drift within one kicker. For this kick-drift model, the betatron phase advance is given by:

$$\varphi = \int_0^L \frac{ds}{\beta(s)} \quad (1)$$

Here L is the total drift space, and $\beta(s)$ is the betatron amplitude function. With this adjustment, the residual kick was almost totally cancelled, same as shown in Fig.6. Further beam dynamics tracking within the cavity with the 3D field map instead of the idealized kick is planned.

PROTOTYPE CAVITY PROGRESS

A half scale prototype cavity with 5 odd subharmonics of 952.6MHz is under fabrication. The prototype cavity is made of copper, 32 inch long and 6 inch in diameter. 4 separate tapers on the inner conductor are optimized to get the frequencies to be exactly harmonic modes; 5 stub tuners are placed on the outer conductor to tuner 5 harmonics to their target frequencies. One loop coupler port is designed in the high magnet field area for all five modes, and one pickup port in the high electric field area. As shown in Fig.9.

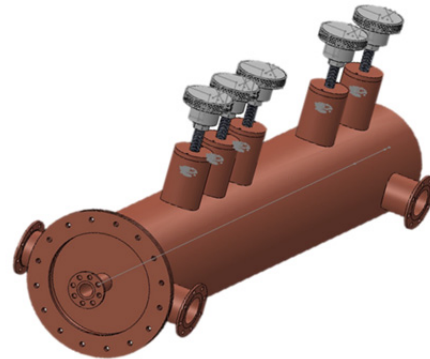


Figure 9: Prototype cavity made of copper.

CONCLUSIONS

The Zero-Gradient waveform has a good performance to maintain the emittance during the recirculation with the one kicker scheme. With the cancellation scheme by using two identical kickers separated by 180 degree betatron phase advance, the residual kick voltage for the recirculating bunches due to the wave slopes for all kicker waveforms can be totally cancelled. The Flat-Top waveform then has the least emittance growth due to its uniform kick pulse. The Least-Modes waveform also has good performance in the two kicker scheme, which can be used to reduce the subharmonic number, and then reduce the difficulties to build the harmonic cavity. For higher power or superconducting use, it also be possible to build 5 single mode cavities to achieve such a kicker pulse. Beam dynamics tracking for the multi-cavity scheme still give an encouraging result. A prototype cavity with 5 harmonic modes is under fabrication and the bench test is estimated to be in summer, 2016.

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