DEVELOPMENT OF AN ULTRA FAST RF KICKER FOR AN ERL-BASED ELECTRON COOLER

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Abstract

The staged approach to electron cooling proposed for Jefferson Lab's Medium Energy Electron-Ion Collider (MEIC) utilizes bunched beam electron cooling with a single-pass energy recovery linac (ERL) for cooling in the ion collider ring. Possible luminosity upgrades make use of an ERL and full circulator ring and will require ultra-fast kickers that are beyond current technology. A novel approach to generating the necessary ultra fast (ns-level) RF kicking pulse involves the summation of specific subharmonics of the cooling electron bunch frequency; the resultant kicking pulse is then naturally constrained to have rise and fall times equal to the electron bunch frequency. The uniformity of such a pulse and its effects on the beam dynamics of the cooling electron bunch are discussed.

INTRODUCTION

JLab's proposed MEIC requires bunched beam cooling of ions at collision energy to maintain design emittances for high luminosity. In the baseline design [1], the bunched electron beam is accelerated and decelerated using an energy recovery linac (ERL) to reduce the active beam power at the beam dump. More intense electron cooling provides a path to a luminosity upgrade, with the required higher average electron current provided by a full circulator cooler ring. Figure 1 shows a schematic of the ERL and circulator cooler ring concept. Use of the circulator ring relaxes the current requirement from the injector by allowing each electron bunch to cool multiple ion bunches. The circulator cooler ring concept requires ultra fast transverse beam kickers to deflect electron bunches into and out of the circulator ring. For a cooler ring frequency of 476 MHz, the bunch spacing is 2.1 ns and the kicker must be able to deflect a single bunch without disturbing the preceding or following bunches in the bunch train. Each pass that a single bunch makes in the circulator ring reduces the required current from the injector by the same amount; for n passes in the circulator ring, the injector current is reduced by a factor 1/n. The transverse beam kicker should then operate at a frequency of 476/n MHz, kicking every n-th bunch in the bunch train into or out of the ring. Thus a suitable kicking pulse will have rise and fall times on the order of the bunch spacing, with MHz repetition rates. A kicking pulse of this type is beyond current driver technology. We describe a novel method for generation of such a suitable kicking pulse and discuss the effects of the kicking pulse on the quality of the cooling electron bunches.

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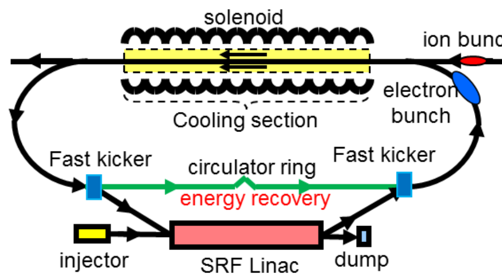

Figure 1: Schematic of an ERL-based electron cooler with full circulator ring.

CONCEPT

The ultra fast RF kicking pulse required for use in the circulator cooling ring concept can be generated by summing subharmonics of the bunch frequency with appropriate phases and amplitudes. A similar concept using the Fourier series representation of a periodic delta function with higher harmonics of the bunch frequency has been explored for the TESLA damping ring [2]. The use of subharmonics of the bunch frequency allows for adjustment of the kicker waveform according to the desired characteristics of the waveform, particularly at intermediate positions between kicking pulses at which circulating bunches should be left undisturbed. The constraints of zero amplitude and zero gradient of the kicking pulse at these undisturbed bunch positions result in the kicking pulse described by

$$f(\theta;\vec{a}) = \sum_{i=0}^{n-1} a_i \cos i\theta \qquad (1)$$

where

n = number of bunches in the bunch train
θ = bunch frequency/n = 476/n MHz
a_i = amplitude coefficients of the subharmonics

$$a_0 = \frac{1}{n} \qquad (2)$$

$$a_j = \frac{2(n-j)}{n^2}, j = 1,2,\ldots,n \qquad (3)$$

The resultant kicker waveform and the subharmonics required for the case of n=25 bunches in the bunch train is plotted in Figure 2. The peaks of the kicking pulse occur with a frequency of 476/25=19.04 MHz, and both the amplitude and gradient of the kicking pulse are zero for non-kicked bunches in the bunch train. The rise and fall time of the pulse is exactly equal to the bunch spacing.

ISBN 978-3-95450-174-8

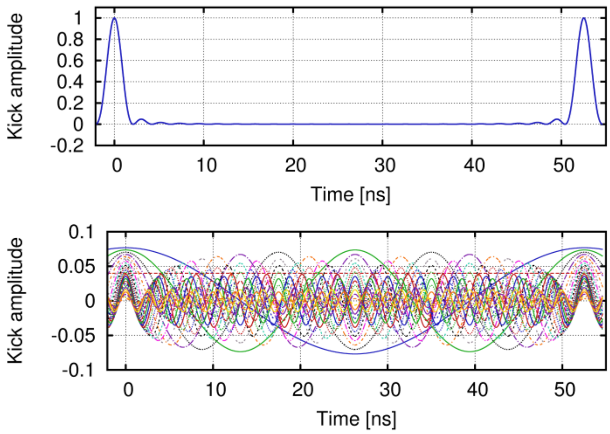

Figure 2: Kicker waveform (top) resulting from summation of 25 subharmonics of the nominal bunch frequency of 476 MHz (bottom).

Kicking Pulse Non-uniformity

The short rise and fall times required of the kicking pulse create a pulse that is not uniform over the length of the cooling electron bunch, and this non-uniformity will have adverse effects on the transverse beam quality of the kicked bunch. The non-uniformity of the kicking pulse is quantified by the percentage of the peak amplitude of the pulse at the center of the bunch seen by the head and tail of the full bunch length. For the waveform described earlier ("zero-gradient pulse") with n=25 bunches, the pulse non-uniformity is 6.4% for an RMS bunch length σ_s=3 cm. Figure 3 shows the non-uniformity of the zero-gradient kicking pulse over the full beam size of +/- 3σ_s.

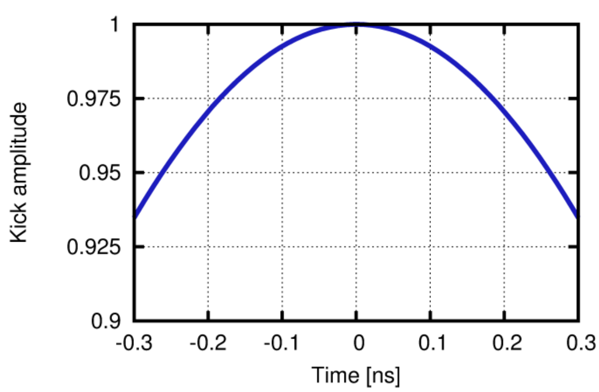

Figure 3: Non-uniformity of zero-gradient kicking pulse over +/- 3σ_s of kicked electron bunch.

The non-uniformity of the kicking pulse can be improved through adjustment of the phases and amplitudes of the subharmonic frequencies comprising the waveform. A waveform with improved non-uniformity of 0.1% ("flat-top pulse") [3] can also be generated and its effects on the transverse beam quality are studied for comparison. The improvement in non-uniformity of the flat-top pulse comes at the expense of nonzero voltage gradients at the nominally undisturbed bunch positions. Figure 4 compares the zero-gradient and flat-top waveforms previously discussed.

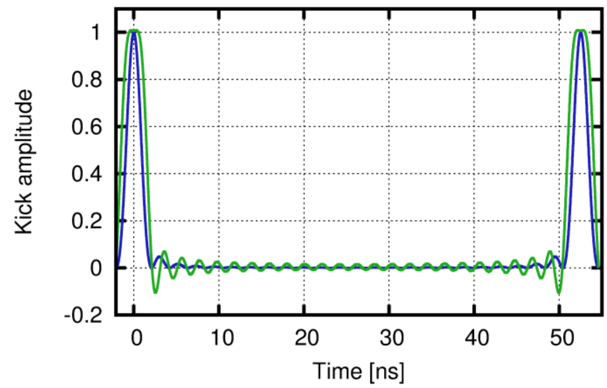

Figure 4: Zero-gradient pulse (blue) and flat-top pulse (green) for nominal bunch frequency of 476 MHz, n=25 bunches.

Residual Voltages

The non-uniformity of the kicking pulse implies a non-uniformity of the waveform in the vicinity of the non-kicked bunches. Though the amplitude and gradient of the voltage waveform are zero at the center of each non-kicked bunch for the zero-gradient pulse, the head and tail of each of these intermediate bunches may also see adverse effects on the transverse beam quality due to these residual voltages. For the flat-top pulse, the voltage gradients are always nonzero for non-kicked bunches and will distort the transverse phase space of the circulating electron bunch. A suitable fast kicker waveform will appropriately balance the phase space distortion from the non-uniformity of the pulse with that from residual voltages seen as the electron bunch circulates in the circulator ring.

SIMULATIONS

The adverse effects on transverse beam quality for both kicked and non-kicked bunches were simulated using elegant [4]. Gaussian electron bunches with P=55 MeV/c, ε_x= ε_y=10 nm, σ_s=3 cm were generated with the proper offset such that the horizontal kick aligned the kicked bunch with the design orbit. The circulator cooler ring was approximated with a one-turn linear transfer matrix. The kicker waveforms were generated with a series of zero-length RF deflectors with the appropriate phases, amplitudes, and frequencies. The peak amplitude of the kicking pulse was chosen to give a 1 mrad deflection. Table 1 lists notable simulation parameters. Each simulated bunch is kicked onto the design orbit, circulates for n turns, and sees the kicking pulse again after the n-th pass in the circulator ring. The transverse emittances are observed immediately after the bunch interacts with the kicker waveform.

Figure 5 shows the turn-by-turn normalized horizontal emittance for a single bunch in the circulator ring for deflection with both the zero-gradient pulse and the flat-top pulse. For this horizontal deflection, the vertical emittance is left undisturbed.

ISBN 978-3-95450-174-8

Table 1: ELEGANT Simulation Parameters

Parameter	Unit	Value
P	MeV/c	55
$\varepsilon_{x,y}$	nm	10
σ_s	cm	3
$\sigma_{\Delta P/P}$		3e-4
n	#	25
f	MHz	476
Deflection angle	mrad	1

For the zero-gradient pulse, the simulations show a 4% growth in the normalized horizontal emittance due to the non-uniformity of the kick, and negligible emittance growth due to the residual voltages as the bunch circulates in the circulator ring. Additional growth is seen after the bunch is kicked out of the ring, but this growth occurs immediately after the final kick, and is therefore insignificant with regards to the cooling properties of the electron bunch. The effect of the flat-top pulse is more detrimental: the non-uniformity of the kick only contributes a 0.4% increase in the emittance, but the large gradients in the residual voltages on subsequent turns cause emittance growth by as much as a factor of 4 by the time the bunch has completed its circulations.

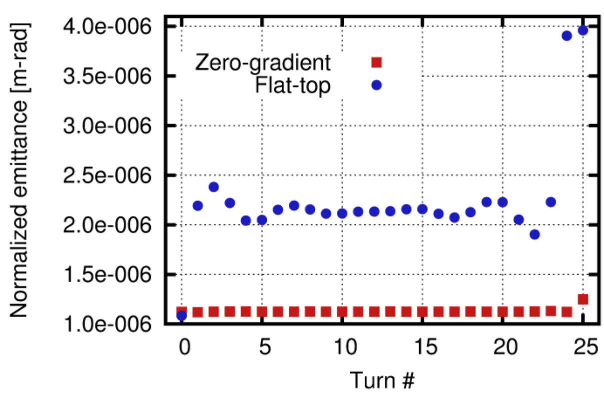

Figure 5: Turn-by-turn normalized horizontal emittance for an electron bunch kicked by the zero-gradient pulse (red squares) and flat-top pulse (blue circles).

Compensation of Phase Space Distortion

The non-uniformity of the kicking pulse is mirrored in the transverse phase space of the kicked bunch as seen in Figure 6. In the case of the flat-top pulse, this phase space distortion is amplified by the large voltage gradients felt by the bunch on subsequent turns. From a beam quality standpoint, any advantage gained from the more uniform kick is negated by the large emittance growth in the ring. The emittance growth due to the amplification of the phase space distortion suggests that a circulating bunch with little to no distortion will exhibit reduced emittance growth due to the residual voltages.

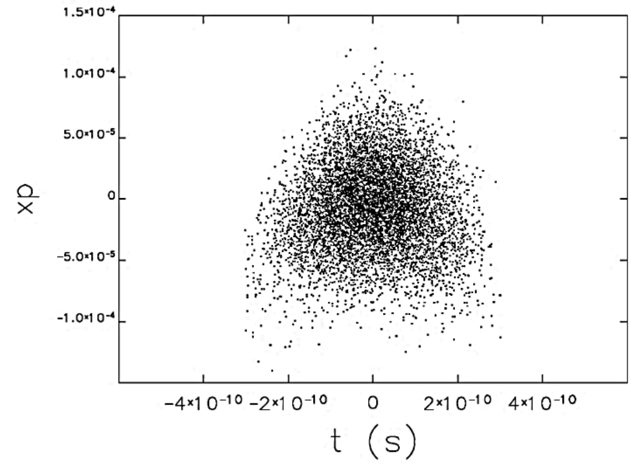

Figure 6: Distorted bunch after kick into circulator ring.

The distortion in the kicked electron bunch can be removed with an identical kicker separated from the main kicker by a phase advance of $\Delta\psi_x=\pi$. The transverse phase space behavior due to such a scheme is illustrated in Figure 7. The electron bunch is pre-distorted by the first kicking pulse. The pre-distorted electron bunch undergoes half of a betatron oscillation by the time it arrives at the main kicker, and the kick from the main kicker then cancels the pre-distortion. The cancellation of the distortion results in a matched bunch for the bunched beam electron cooling. With this phase space distortion compensation, an electron bunch kicked by the flat-top pulse experiences 5% emittance growth for the bulk of the time spent in the circulator ring, comparable to the zero-gradient case with no compensation. Figure 8 plots the turn-by-turn normalized horizontal emittance for the compensated flat-top pulse and non-compensated zero-gradient and flat-top pulses. It is noted that even with this compensation scheme, large emittance growth is still seen near the end of the bunch lifetime in the ring.

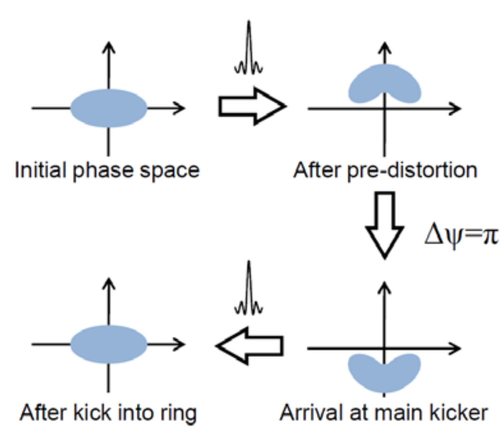

Figure 7: (Clockwise, from top left) Transverse phase space behavior for compensation scheme utilizing multiple identical kickers. Pre-distortion is induced in the electron bunch such that the main kick removes this distortion.

ISBN 978-3-95450-174-8

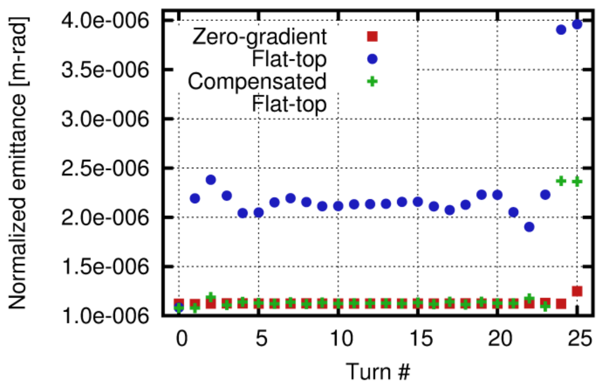

Figure 8: Turn-by-turn normalized horizontal emittance for an electron bunch kicked by the zero-gradient pulse (red squares), flat-top pulse (blue circles), and compensated flat-top pulse (green crosses).

DISCUSSION

The few percent transverse emittance growth imparted by the zero-gradient kicker waveform is a promising result for the use of such an ultra fast RF kicker based on the summation of subharmonic frequencies. Both the non-uniformity of the kicking pulse over the length of the electron bunch, as well as the residual voltages in the kicking waveform on intermediate turns in the circulator ring, contribute to the emittance growth in the plane of the deflection. Large voltage gradients on the intermediate turns in the circulator ring can amplify even very small distortions in the transverse phase space, as seen in the case of the flat-top pulse. Multiple kickers can be used to cancel this phase space distortion and prevent large emittance growth due to large voltage gradients; this compensation scheme allows for further optimization of the kicker waveform but requires further study, as the compensation is imperfect and large emittance growth can occur in the final few turns in the circulator ring. Further study of this concept for an ultra fast RF kicker is ongoing.

ACKNOWLEDGMENTS

The authors acknowledge early work regarding this concept by Edward Nissen, Balša Terzić, and Andrew Hutton. This manuscript has been authored by Jefferson Science Associates, LLC under Contract No. DE-AC05-06OR23177 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non- exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

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