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RF HARMONIC KICKER R&D DEMONSTRATION AND ITS APPLICATION TO THE RCS INJECTION OF THE EIC

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Abstract

In this paper, we report the progress on a harmonic kicker development as an injection device for the Rapid Cycling Synchrotron (RCS) of the Electron-Ion Collider (EIC) at Brookhaven National Laboratory (BNL).

INTRODUCTION

The RCS of the EIC is an electron energy booster in the injection complex to the Electron Storage Ring (ESR), which provides polarized (~ 80%) electron beam with a high bunch charge (28 nC) in electron-ion collisions in the ESR [1]. In the RCS, the electron beam is accelerated up to 5-18 GeV while forming a 28 nC-bunch out of four "smaller" 7 nC bunches via quasi-adiabatic merging. Injection of these bunches into the ring requires an ultra-fast deflecting kicker on the injected bunches, while not affecting preceding passing bunches spaced by $1/f_b$ = 1.7 ns. A harmonic kicker resonator can generate such a sharp-peaked kick with rise/fall time comparable to $1/f_b$ made of a linear combination of harmonic RF modes. Originally developed for the ultrafast beam exchange scheme in the CCR of the JLEIC [2], a harmonic kicker is applicable to a wide range of beam dynamics in the injection schemes. In this paper, we present a harmonic kicker design compatible with the RCS injection beam parameters of the pulsed beam—unlike the CW beam of the JLEIC—, which is injected at the period of 10 ms and revolves around the ring in T_{rev} =12.8 µs.

A normal conducting quarter wave resonator (QWR) can accommodate a few number of odd harmonic modes in a straightforward way with its co-axial structure and was prototyped as a kicker cavity for the CCR/JLEIC [3, 4]. We derive the expected RF performance of a QWR as a harmonic kicker for the RCS injection via a simple scaling of the figures of merit from a few JLEIC prototype designs. We also report the progress on the latest JLEIC prototype demonstration, whose fabrication is near completion. The prototype will be tested with the low-energy beam at the Upgraded Injector Test Facility (UITF) of the Jefferson Lab.

INJECTION SCHEME OF THE RCS

According to the injection scheme [1], one full-cycle of the beam injection from an injector (linac) to the RCS consists of four pairs of bunches separated by 10 ms—eight pairs with the upgrade. In each pair, two bunches are spaced by 2 µs and each bunch has a bunch charge of 7 nC and beam energy of 400 MeV—for a pulsed beam structure, see Fig. 1 and for the beam parameters, Table 1. In the RCS, each injected pair joins the ring via a harmonic kicker and circulates the ring with the revolution period T_{rev} =12.8 µs. After many passes of the injected pair, the next pair is injected at the moment of one RF cycle ($1/f_b$) after each bunch in the injected pair passes the kick point. At the end of a full injection cycle, there will be two bunch trains with each train consisting of four bunches (eight bunches in upgrade), ready for acceleration and merging, which takes about 0.5~ 1 s.

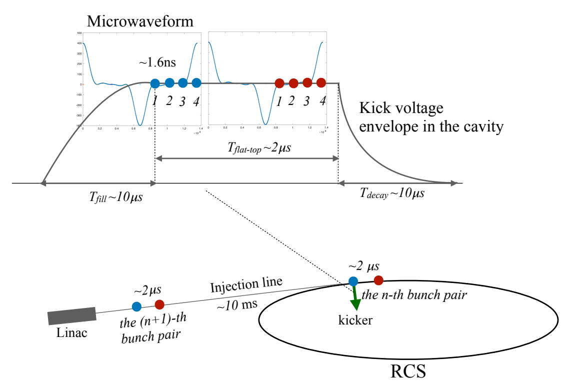

Figure 1: The schematics of the RCS illustrating the injection scheme. The microwaveforms are near zero on passing (1,2,3) pairs while peaked on the injected pair (4).

Table 1: The Beam Parameters of the RCS Injection. The Twiss Parameters are at the Injection Point

Parameters	Unit	Value
Revolution period T_{rev}	µs	12.8
Beam energy E_b	MeV	400
Bunch charge Q_b	nC	7
Bunch length l_b	cm	12
Bunch rep. rate f_b	MHz	591.258
Kick angle θ	mrad	1
Kick voltage V_k	kV	400
Beam aperture g	mm	40

WAVEFORM DESIGN

Baseline Waveforms of a Harmonic Kicker

A fast injection into the RCS without the preceding bunches (by $1/f_b$) affected can be achieved by a harmonic kicker that can provide a sharply peaked kick profile (around the injected bunch) with rise/fall time comparable to the bunch spacing: the kick voltage by a harmonic kicker is given as $V_k(t) = \sum_{n=0}^{N} A_n \cos n\omega_k t$, where N is the number of the modes, A_n amplitude of each mode, and $\omega_k = 2\pi f_k$ with f_k base frequency. The baseline waveforms for the RCS

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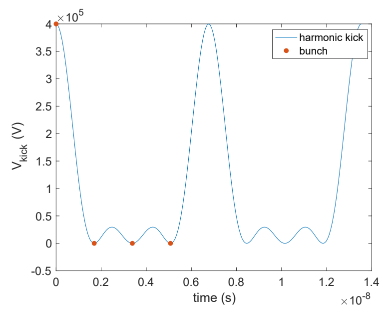
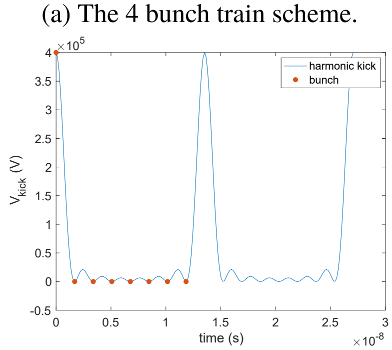
injection are shown in Fig. 2 and the corresponding specification of harmonic kicker is listed in Table 2. As can be seen from Fig. 2, the baseline waveforms deliver zero kicks with zero kick slopes on passing bunches with the least degradation of the beam quality. According to Table 3, the 4-bunch scheme would require two kicker cavities (one at the base frequency of 147.8 MHz with $n = 1, 3$ and the other with $n = 2$), while the 8-bunch scheme needs one more cavity at 73.9 MHz with $n = 1, 3, 5, 7$. Both schemes would need the DC kicks by the magnets as well.



(a) The 4 bunch train scheme.



(b) The 8 bunch train scheme.

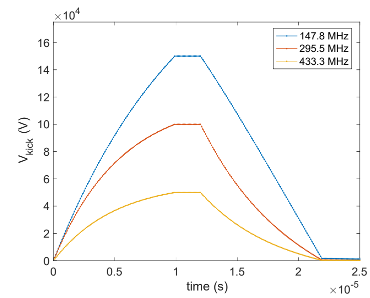
Figure 2: The baseline waveforms for the RCS/EIC.

Table 2: The Specification of a Harmonic Kicker with a Baseline Waveform. Here *f* Refers to Harmonic Frequency and *A* the Amplitude of Kick Voltage. The Phases are All Set to Zero (On-crest Phase)

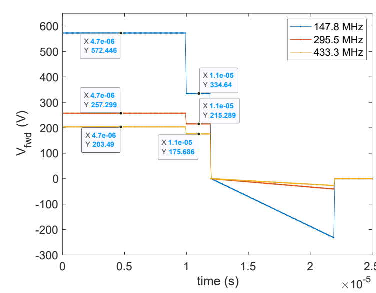
	4-bunch		8-bunch	
Modes	**f (MHz)**	**A (kV)**	**f (MHz)**	**A (kV)**
DC	0	100	0	50
1	147.8	150	73.9	87.5
2	295.5	100	147.8	75
3	433.3	50	221.6	62.5
4			295.5	50
5			369.4	37.5
6			443.3	25
7			517.1	12.5

Pulsed RF Operation

With the injected pairs come in a pulsed beam, the circulating bunches pass through the kicker many times in-between the kicks. The waveforms of a kicker are put into pulsed mode to avoid the "residual kicks" of the waveforms on the circulating bunches. The envelop profile of the waveforms is shown in Fig. 3 with 2 µs long flat-top over the injected bunch pair and charging/discharging within 10 µs, i.e., before the injected bunches comes back after one revolution. This fast charging/discharging is available with the optimized RF coupling β's of the cavity in a special forward power prescription where charging is facilitated with a slightly higher forward power before switching to steady state power at the moment of injection and discharging is with linear power input with phase flipped to π. The prescription is illustrated in Fig. 3.



(a) The kick voltage within the kicker cavity with the optimized β's.



(b) The forward voltage on 50 Ω transmission line.

Figure 3: The pulsed mode operation of a kicker cavity.

QUARTER WAVE RESONATOR (QWR)

A few QWR's have been designed for prototyping in the context of the CCR/JLEIC R&D with its specification compatible with the beam parameters of the CCR/JLEIC. Although the EIC has different beam parameters than the JLEIC, the performance of the kicker for the EIC is projected from the existing JLEIC prototype designs via scaling laws: $R_\perp/Q_0 \propto 1/(f \cdot g)^2$ with $R_\perp, Q_0, f, g$ being transverse shunt resistance, unloaded quality factor, harmonic frequency, and gap size (beam aperture) respectively. Then assuming geometry factor G remains the same against the scaling, the RF peak power for each mode in the RCS/EIC can be estimated as $P_{\rm wall} = V_{\rm k}^2/R_\perp = V_k^2 R_{\rm s}/(G R_\perp/Q_0)$, where $R_{\rm s}$ is surface resistance of copper surface. The projected figures of merit with the baseline waveforms are summarized in Table 3.

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Table 3: The Expected RF Parameters of Harmonic Kickers for the EIC Scaled from the JLEIC RF Parameters. In the JLEIC, the Beam Aperture was Given as g = 70 mm

EIC	JLEIC	$R_\perp/Q_0$	G	P_{wall}	β_{opt}	P_{fwd}
MHz	MHz			kW	-	kW
147.8	95.3	1146	31	2.4	2.6	3.1
295.5	190.5	959	55	1.0	1.8	1.1
433.3	285.5	262	92	0.7	1.7	0.7

The latest prototype of a QWR for the JLEIC, designed for vacuum tight and high power operation, is under fabrication after a complete design package was delivered [5] (see Fig. 4). The cavity is made of OFC (oxygen free copper) with all the parts CNC machined. The parts are joined by multistage brazing (ports to the outer conductor) and electron beam welding (inner conductor assembly with the final welding to the outer conductor). The frequency deviations due to all of the fabrication errors will be compensated by bench tuning procedure right before the final welding.

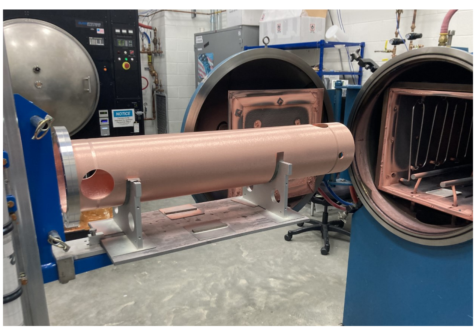

Figure 4: The harmonic kicker prototype in fabrication.

The beam test of the prototype is being planned at the UITF. The test will demonstrate the general feasibility of a harmonic kicker as an ultrafast beam injection device in a preparation for upcoming design for the RCS/EIC, albeit the beam parameters of the JLEIC are different from those of the EIC nor UITF (see Table 4). More specifically, the checking points are: the harmonic RF waveform delivers a selective, periodic deflecting kick along the bunch trains with a sufficiently high temporal precision. The effects of the kicks/residual kicks on the kicked/passing bunches are to be measured in terms of deflection angles and emittances. Moreover, the stability of the operation over extended time (~µs), in coordination with the LLRF system, needs to be confirmed.

The harmonic kick profiles of the prototype compatible with the JLEIC beam dynamics can be tested with the CW beam at the UITF by employing two-beam operation, as illustrated in Fig. 5. The two beams, with the same rep. rate of 12.37 MHz (11th subharmonic of 136.09 MHz) but different relative phase with respect to the RF field (its peak values), will be run alternatively. The first beam is at zero phase (on-crest) and the every bunch is kicked.

Table 4: The Beam Parameters for the Baseline Test at the UITF. The Operation Mode Refers Both to the Beam and Cavity

Specifications	Unit	Values
Beam energy E_b	MeV	5~10
Bunch charge Q_b	pC	0.5
Bunch length l_b	cm	12
Bunch rep. rate f_b	MHz	12.37
Kick frequency f_k	MHz	86.6
Deflection angle θ	mrad	1~2
Total RF power P_{fwd}	W	230
Operation mode (beam/cavity)	-	CW/Pulsed

The second beam is shift by 7.35 ns (1/136.09 MHz) and the every bunch is subject to zero kick. Subsequently, other beams can be added with the same rep.rate but the phase of multiples of $1/f$ ~ 2.1 ns (with f bunch rep. rate of the JLEIC) to check on other zero kick locations. This defines our baseline test—However, the kicker could also be operated in the pulsed mode while driven by a harmonic generator/combiner developed by Electrodynamic, Inc [6].

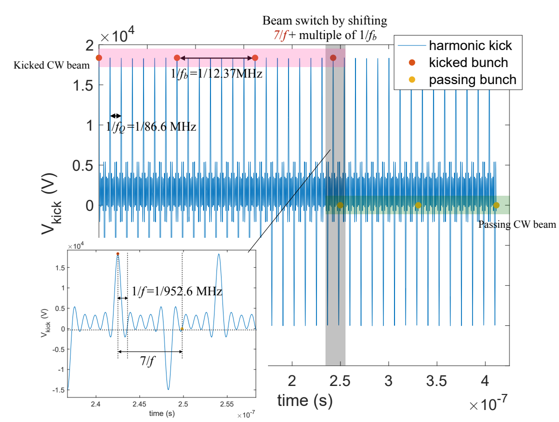

Figure 5: The alternating operation of two CW beams. The harmonic kick profile is with base frequency of 86.6 MHz using five odd harmonics. The profile has 10 zero kick locations spaced by $1/f$.

CONCLUSION AND ACKNOWLEDGMENT

A harmonic kicker waveform for the injection scheme of the RCS/EIC is designed and the JLEIC prototyping is well under way. We would like to thank Jim Follkie, James Henry, Matt Marchlik, Adam O'Brien and Scott Williams for their support. The work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177.

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