HARMONIC STRIPLINE KICKER FOR MEIC BUNCHED BEAM COOLER*

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Abstract

In the current design of JLab's Medium-energy Electron-Ion Collider (MEIC), the ion collider ring needs to be cooled by a bunched electron beam of up to 200 mA 55 MeV, with the possibility to upgrade to 1.5 A. To reduce the technical risk and cost associated with such an ERL, a scheme was proposed to recirculate the electron bunches in a ring for up to 25 turns until the bunch's beam quality is degraded, reducing the beam current in the ERL by a factor of 25. This scheme requires one or a pair of fast kickers that kick one in every 25 bunches. In this paper, we will analyze the efficiency of a harmonic stripline kicker for this circulator ring, and compare to the harmonic resonator kicker.

INTRODUCTION

In the MEIC design, bunched electron beam cooling of the ion beam is essential to achieve and maintain low emittance and small beam size in the colliding ion beam, reaching the luminosity goal [1]. In MEIC's bunched beam cooler, a 200mA 55MeV electron beam with a repetition rate of f_0=476.3MHz will be used to cool the ion beam, with the possibility to be upgraded to 1.5A and/or 952.6MHz. In the baseline design, an ERL will be used to provide such a beam, recovering 80%-90% of the electron beam energy. To reduce the technical risk and cost in such an ERL, especially the beam current and RF power in the booster and gun, a circulator ring scheme [2] has been proposed, as shown in Fig. 1. In this scheme, the electron bunches will be injected from the ERL into the ring with a fast kicker, circulate for N turns in a ring until the beam quality degrades, and then kicked out into ERL for energy recovery. The proposed scheme chose N=25 nominally, but we use the example of N=10 in part of this paper for simpler demonstration. This scheme reduces the bunch repetition rate and the beam current in the ERL by a factor of N, but requires one or two faster kickers with sub-nanosecond rise/fall time and repetition rate of f_0/N, or 19MHz, and a kicking voltage of 55kV to achieve 1mrad deflecting angle for a 55MeV beam. This set of parameters will be prohibitive for switching DC pulse kickers, but could be achieved by harmonic RF kickers, in which the kicking waveform is constructed by a series of CW RF harmonics, plus a DC bias.

There are several different approaches to implement the harmonic kicker. One is the resonant cavity kicker [3], which would be more efficient, but requires a number of bulky cavities to generate the desired waveform. Another option is the stripline kicker, which can be very compact in the system.

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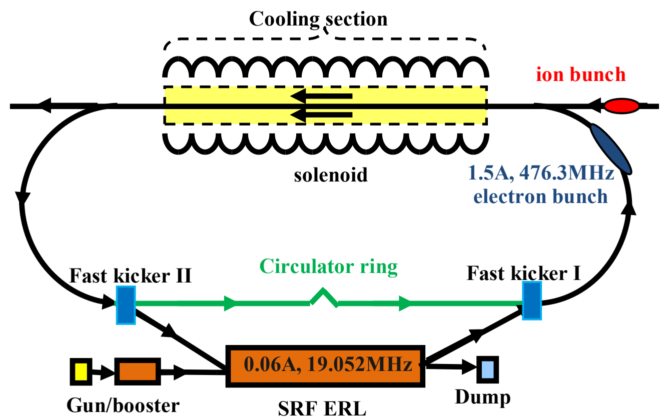

Figure 1: Layout of the MEIC bunched beam cooler, with the option of circulator upgrade.

EFFICIENCY OF STRIPLINE KICKERS

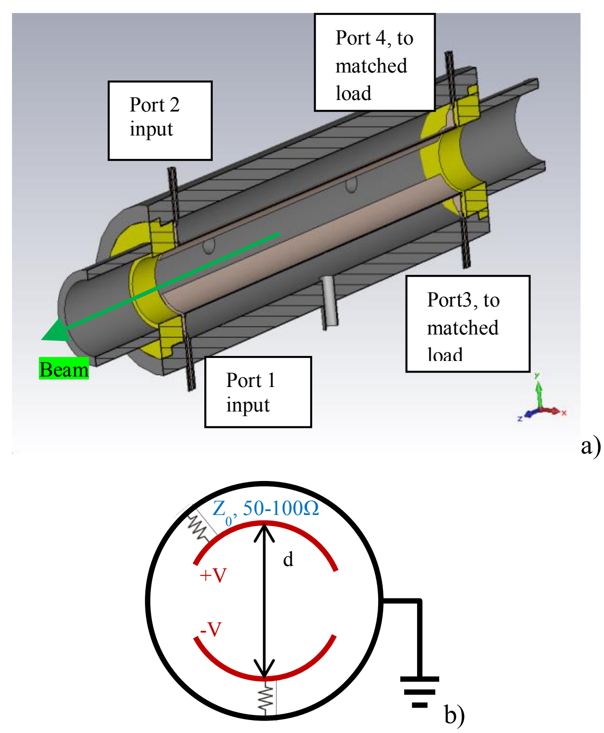

Figure 2. a) 3D model of the stripline kicker; b) cross-section model of the stripline kicker

A typical stripline RF kicker represented by the PEP-II coupled bunch feed-back kicker [5] is shown in Fig. 2. It utilizes the TEM mode travelling wave propagating from the input ports to the terminated ports, between two oppositely biased electrode plates and the grounded outer cylinder. The beam needs to travel in the direction

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opposite to the RF propagation, as the electric kick and magnetic kick will add constructively. This also results in a transit time issue, and the length of the kicker needs to be optimized to maximize the efficiency. This efficiency can be quantified by transverse shunt impedance $R_\perp = V_\perp^2/P$, in which $V_\perp$ is the effective transverse kicking voltage seen by the beam.

In the kicker as shown in Fig. 2b, the transverse electric field at the center of the kicker is

$$E = 2V/(g \cdot d). \tag{1}$$

g is a factor depending on the 2-D cross-section geometry, d is the distance between the two electrodes. Adding the effect of the magnetic kick, the effective kicking filed is $2E$. For the RF mode with angular frequency ω, the kicking field seen by the beam at the speed of light alternates at 2ω. The effective kicking voltage is the longitudinal integral of the transverse effective kicking field. For a kicker with length L and centered at z=0, the kicking voltage of mode ω seen by the particle with initial position z_0 is

$$V_\perp(z_0) = \int_{-L/2}^{L/2} 2E \cdot \cos\left[\frac{2\omega(z-z_0)}{c} + \varphi_0\right] dz$$
$$= \frac{4cV}{\omega g d} \sin(\omega L/c) \cos(\varphi_0 - \omega z_0/c) \tag{2}$$

To maximize the kicking voltage on the bunches to be kicked, we can choose $\varphi_0 - \omega z_0/c = 0$, so

$$V_\perp = \frac{4cV}{\omega g d} \sin(\omega L/c) \tag{3}$$

For the DC mode, $V_\perp = 2VL/(gd)$.

To generate the ±V RF voltage on both plates, the RF power needed from EACH input port will be $V^2/(2Z_0)$, and the total RF power needed is $P = V^2/(2Z_0)$. As a result, the transverse shunt impedance for one mode ω is

$$R_\perp = Z_0 \left[\frac{4\sin(\omega L/c)}{g d \omega / c}\right]^2 \tag{4}$$

Currently, a scaled PEP-II coupled bunch feedback kicker design can be used to evaluate the technology. By solving the 2-D electrostatic problem for this cross-section with Superfish, we can find g=0.843, regardless of scaling. For single mode operation, the transverse shunt impedance of the kicker will be maximized if the kicker is quarter wavelength long, and will be 0 at half or full wavelength. The 0.63m length of the PEP-II kicker is the wavelength of 476MHz and is designed to cover the DC - 119MHz band. For multiple frequency operation, the kicker length needs to be optimized to avoid zero shunt impedance for all the modes and minimize the total power. To compare with the resonant cavity kicker in [3], the cross-section is scaled to d=70mm, while Z_0 is still 50Ω. We simulated such a kicker with L=0.409m in 3_D solver CST MWS for the first 10 harmonics of 47.63MHz. The simulation results agree very well with eq. 4, as shown in Fig. 3.

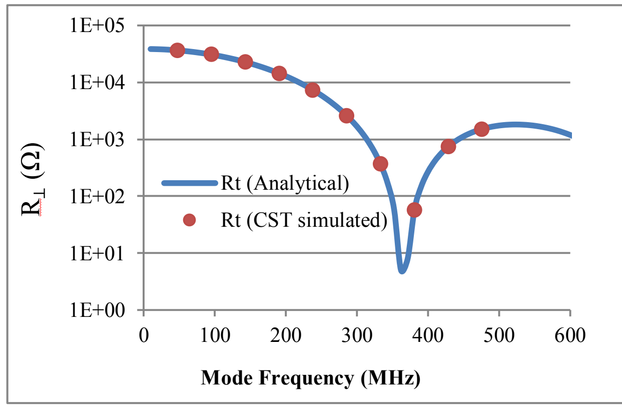

Figure 3: Transverse shunt impedance of a scaled PEP-II kicker, L=0.409m, d=0.07m.

SYNTHESIZING THE KICKER WAVEFORM

In a cooler ring with bunches recirculating for N turns, the required kicker waveform is a square wave with a flat top equals to the length of a bunch bucket and repetition rate of f_0/N, so only one in every N bunches will get a kick, while the others won't be disturbed. The waveform can be synthesized with a set of finite RF harmonics with fundamental frequency at f_0/N, delivered from a broadband amplifier to the input ports. There are several mathematical solutions to approximate the ideal waveform with finite harmonics, such as Fourier series [3] and constraint methods [4, 6]. The result from Fourier series has non-zero voltage and voltage slopes at the center of those bunches not to be kicked, as well as higher required mode voltages (and higher kicker power). The slope will provide unwanted crabbing to the beam, degrading the beam quality, especially when the circulator ring uses only one kicker for both injection and extraction [4]. The alternative is to apply both amplitude and slope constraints at the center of each bunch and solve the equation system and get the "zero gradient" waveform, as shown in the following equation system:

$$V_\perp(z_0) = \begin{cases} 55\text{kV}, & \frac{N\omega_0 z_0}{2\pi c} = 0 \\ 0, & \frac{N\omega_0 z_0}{2\pi c} = 1,2,\ldots,N-1 \end{cases}$$
$$\frac{dV_\perp(z_0)}{dz_0} = 0, \quad \frac{N\omega_0 z_0}{2\pi c} = 0,1,2,\ldots,N-1 \tag{5}$$

A simple solution to eq. 5 is:

$$V_{\perp 0} = 55kV/N$$
$$V_{\perp n} = \frac{55kV \cdot 2(N-n)}{N^2}, n = 1,2,\ldots.N. \tag{6}$$

Fig. 4 illustrates the ideal kicker waveform and synthesized "zero gradient" waveform solution in eq. 6, with N=10. The optimized kicker length for such a set of harmonic kicking voltage is 0.289m. Table 1 lists the transverse shunt impedance and RF power for each RF

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mode in this solution. The total RF power in this kicker is 30.7kW. If we increase the recirculation turns to N=25, the total RF power reduces further to 13kW.

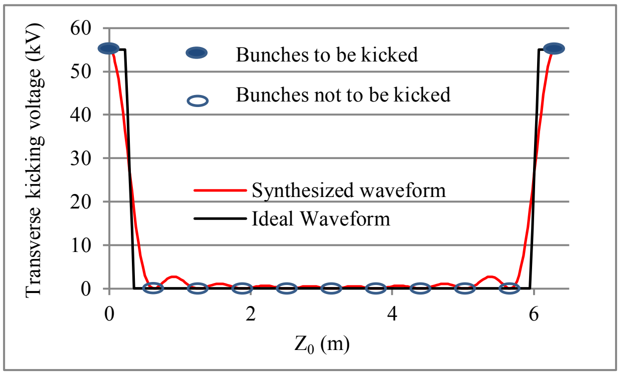

Figure 4: Ideal and synthesized zero gradient kicker waveforms for circulator ring with N=10 turns.

Table 1: Transverse Shunt Impedance and RF Power in Each Mode for the "Zero Gradient" Waveform

f (MHz)	$R_\perp$ (Ω)	$V_\perp$ (kV)	Power(kW)
DC	∞	5.5	0
47.63	18662	9.9	5.252
95.26	17151	8.8	4.515
142.89	14851	7.7	3.992
190.52	12047	6.6	3.616
238.15	9071	5.5	3.335
285.78	6241	4.4	3.102
333.41	3820	3.3	2.851
381.04	1975	2.2	2.451
428.67	765	1.1	1.581
Total/avg	98550	55	30.7

If a pair of kickers will be used in the circulator ring, the crabbing due to the voltage slope can be cancelled locally by setting the betatron phase advance between the two kickers to 180°. In this case, the slope constraints in eq. 5 can be removed; the number of modes will be reduced by half, as shown in eq. 7.

$$V_{\perp 0} = 55kV/N$$
$$V_{\perp n} = \begin{cases} \dfrac{2\cdot 55kV}{N}, n = 1,2,\ldots \dfrac{N-2}{2} \text{ or } \dfrac{N-1}{2}. \\ \dfrac{55kV}{N}, n = \dfrac{N}{2} \text{ (even } N \text{ only)} \end{cases} \qquad (7)$$

For N=25 and 55kV total kicking voltage, we only need 12 RF modes with a total of 11.6kW [6].

If we can split the kicking voltage to two kickers, the RF power in each device can be reduced to 1/4, or around 3kW, and the system is still more compact than the resonant kickers. We can also try to redesign the stripline geometry and increase the characteristic impedance to 100Ω, reducing the power by another half. The PEP-II feedback kicker can only handle hundreds of watts of RF power. However, the power capacity of the kicker can also be increased with redesigned ports, making it possible to meet the required kicking voltage and RF power.

SUMMARY

We analyzed the electrodynamics of the stripline RF kicker and re-derived the analytical equation to estimate the shunt impedance; the results well agree with numeric simulation. We are able to optimize the length of such a kicker, so that the RF power needed to construct a waveform using certain set of harmonics can be minimized. To generate a 55kV "zero gradient" kick in every 25th bunches with 24 RF modes in the MEIC recirculating electron cooler, the power needed is 13kW with a kicker scaled from the PEP-II feedback kicker to 70mm electrode plate diameter. The power requirement for the stripline kicker is 2-3 orders of magnitude higher than a set of resonant kickers, but is not prohibitive. With additional measures to reduce the required RF power further, it's possible to design and build a stripline kicker to meet the specification for the MEIC recirculating electron cooler.

REFERENCES

[1] S. Abeyratne et al., "MEIC Design Summary for NSAC EIC Cost Estimate Sub-Committee", edited by G. A. Krafft, (2015).
[2] E. Nissen et al., "A Harmonic Kicker Scheme for the Circulator Cooler Ring in the Medium Energy Electron Ion Collider", MOPWO078, Proc. of IPAC'2013.
[3] Y. Huang et al., "Ultra-fast Harmonic Resonant Kicker Design for the MEIC Electron Circular Cooler Ring", WEICLH2063, Proc. of ERL'2015.
[4] A. Sy et al., "Development of an Ultra Fast RF Kicker for an ERL-based Electron Cooler", TUYAUD04, these proceedings.
[5] Barry, W. et. al. "Design of the PEP-II Transverse Coupled-Bunch Feedback System" Proceedings of the Particle Accelerator Conference 1995.
[6] J. Guo et al., JLAB-TN-15-020.

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