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OPTIMIZATION OF THE HADRON RING STRIPLINE INJECTION KICKER FOR THE EIC*

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Abstract

The Electron-Ion Collider (EIC) at Brookhaven National Laboratory is a high luminosity, (~ 10^{34} cm^{-2}s^{-1}) accelerator facility colliding polarized electron beam with different ion species ranging from lighter nuclei (proton, deuterium) to heavier nuclei (gold, uranium). Design of a stripline injection kicker for the Hadron Storage Ring (HSR) of EIC for beams with the rigidity of ~ 81 T-m poses some technical challenges due to expected shorter bunch spacing and higher peak current of EIC. This paper focuses on the optimization of the EIC hadron ring injection kicker. Starting from the 2D cross-section design which includes the selection of electrodes shape, we describe the optimization of the kicker's cross-section. Then we discuss converting this 2D geometry to 3D by adding essential components for the stripline kicker and the 3D optimization techniques that we employed. Finally, we show simulation results for the optimized geometry including wakefields and Time Domain Reflection (TDR) from one feedthrough to another.

INTRODUCTION

The EIC is a next generation nuclear science facility aiming to answer fundamental questions of physics about the mass and spin of nucleons by colliding polarized electrons with ions of different species [1]. The current design of the EIC can be found in [2]. Design of a stripline injection kicker for the EIC Hadron Storage Ring (HSR) poses some technical challenges due to expected shorter bunch spacing, heating due to higher peak current and larger number of bunches, and higher pulsed voltage required to operate this kicker. This paper focuses on the optimization of the hadron ring injection kicker for the EIC after providing basic mathematical expressions for its design.

A stripline (also called electromagnetic) kicker consists of two parallel electrodes, each of them forms a transmission line with the grounded beam pipe for the external TEM mode. It employs both the electric and magnetic forces to kick the beam. To utilize both of these forces, the external TEM mode pulse has to be excited to propagate opposite to the direction of beam motion otherwise they cancel to each other. The parallel electrodes are connected with feedthroughs at the ends of each stripline.. Pulsed voltages of equal amplitude but opposite polarities are applied via the downstream feedthroughs to create mostly uniform electromagnetic fields between these electrodes. A charged particle q, having an energy E experiences a kick $\Delta\theta$ with respect to design orbit while passing through a stripline electrodes of length L, given by [3]

$$\Delta\theta = 2g_{\perp}\left(\frac{qV}{E}\right)\frac{L}{d}\,, \tag{1}$$

where V is the pulse voltage applied to the electrodes, d is the gap between them, and $g_{\perp} = tanh\left(\frac{\pi w}{2d}\right)$ is the transverse geometry factor with the width of striplines w.

The length of a stripline kicker is chosen by taking into account of its rise and fall times, the gap between two consecutive bunches, and bunch length of the beam (can be neglected for a short electron bunch). Since the external pulse counter-propagates into the beam direction, the minimum time at which the kicker has to be turned on to deflect the incoming bunch is given by the sum of the kicker's rise and fall times, twice the time it takes to propagate along the stripline electrodes, and the bunch length;

$$t_{min} \geq \tau_r + 2L/c + \tau_f + \tau_b\,, \tag{2}$$

where τ_r and τ_f are respectively the rise and fall times of the pulsar, c is the speed of light in vacuum, and τ_b represents the bunch length. For EIC, bunches from the AGS will be injected into RHIC one at a time on axis. The rise time needs to be short enough to fit in the gap between two adjacent bunches, however, the fall time should just fit in the abort gap which is 1 µs, and hence the fall time becomes irrelevant. Therefore, the length of a stripline kicker becomes

$$L \leq \frac{c}{2}\left(\tau_g - \tau_r - \tau_b\right), \tag{3}$$

where we assume that the minimum time t_{min} is the same as that of the gap between two consecutive bunches τ_g. In case of the EIC hadron ring kicker, τ_g = 40.5 ns, τ_r = 7 ns, and τ_b = 25 ns, therefore the length of required electrode is ~ 3 ns. The design specification for the rise time of the input pulse is chosen to be 7 ns, though its up-limit was 9.5 ns, to leave enough tolerance for variations. All the other design parameters can be found in Table 1 [1].

KICKER GEOMETRY DESIGN

The goals for the design and optimization of a kicker are to produce an excellent field uniformity, obtain a good transmission of input power, minimize the beam coupling impedances, lower peak fields, and to reduce the impedance mismatch between feedthroughs and electrodes. For this our first step was to design a stripline line kicker having the odd (operating) mode characteristic impedance of 50 Ω to match

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Table 1: Injection Kicker Design Parameters

Parameters	Requirements	Unit
Beam rigidity	~81	T-m
Repetition rate	Burst mode	Hz
Full bunch length (τ_b)	25	ns
Rise time (τ_r)	7	ns
Voltage per plate (V)	$\pm$ 16.65	kV
Max. def. angle (θ)/kicker	0.05	m-rad
Electrode length (L)	0.9	m
Number of kicker units	20	NA

those of the feedthroughs and cables, and to maintain the even (storing) mode impedance close to 50 Ω to reduce the beam coupling impedance and heat deposition.

Design of 2D Cross-section and Transition to 3D

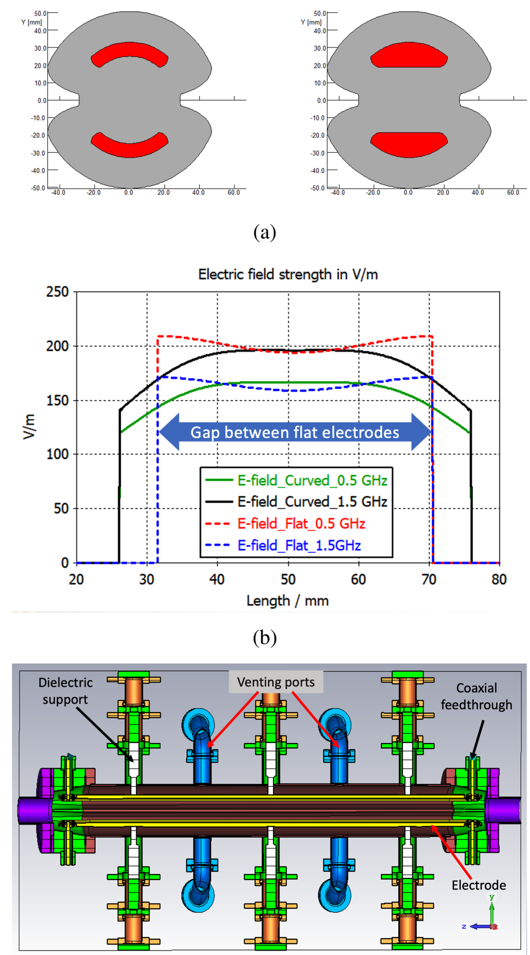
We used the code *Opera 2D* [4] to prepare initial cross-section of the stripline kicker, which can tolerate high voltage feedthroughs and can provide 50 Ω characteristic impedance for the odd mode. Two cross-sections were designed, Fig.1 (a), where the red regions indicate the electrodes. The cross-section with curved (C-shaped) electrodes was selected as it provides better field uniformity in the region of interest, Fig.1 (b) (solid curves). Ref. [5] for the APS-U kicker has reported that half-moon or flat electrodes provided more uniform field than curved electrodes, however in our case, both codes, CST [6] and *Opera 2D*, showed better field uniformity for the cross-section with curved electrodes. The electrode aperture of 5 cm is chosen as the value of β-function is slightly higher in the particular place where the kicker resides. Our kicker is designed to kick beam in the horizontal plane, the electrodes are located to the left and right of the chamber. All pictures used in the report were rotated by 90 degrees for better display of the geometry.

After finalizing the 2D geometry, we converted it into the 3D design, shown in Fig. 1 (b), by adding other essential components such as feedthroughs, four venting ports and six dielectric supports. The dielectric supports help to maintain the straight shape of electrodes if they get deformed due to thermal heating. In addition, these dielectric supports can be adjustable to fine-tune the impedance of the kicker to be compatible with that of the connecting cables and the feedthroughs. To reduce electromagnetic fields propagation via transverse openings for venting ports and supports, we placed stainless steel wire-meshing inside the venting ports, and reduced the dimension of round clearance around the dielectric support from the initial ~ 6 mm to ~ 4 mm.

KICKER GEOMETRY OPTIMIZATION

Optimization of 2D Cross-Section

The cross-sectional geometry that had produced ~ 50 Ω impedance in the code *Opera 2D* resulted only ~ 47 Ω in the 3D electromagnetic code CST. Later, we found that this discrepancy was due to the nature of the codes used for



(c)

Figure 1: (a) Cross-section of the kicker with curved (left) and half-moon (right) electrodes, (b) comparison of electric fields produced by the curved and half-moon (flat) electrodes, where the solid and dashed curves represent curved and flat electrodes respectively, and (c) plain view of the injection kicker geometry with dielectric supports and pumping ports in the middle.

simulation. The initial *Opera 2D* simulation was performed in DC (electrostatic) mode which does not take into account of the skin effect, however the CST is an electromagnetic code and include this effect. Both codes agreed well while comparing CST results with the AC mode of *Opera 2D* above 1.0 MHz.

Our first step for the 2D optimization was to increase the odd mode impedance from 47 Ω to 50 Ω. CST simulations showed that the change in beam pipe diameter changes the value of characteristic impedance for the both odd and even modes significantly more than altering the gap between stripline electrodes and horizontal intrusions (fenders). We have to increase the beam pipe diameter from the initial value of 97.43 mm to 101.53 mm, without changing the electrode aperture of 50 mm, to increase the odd mode impedance

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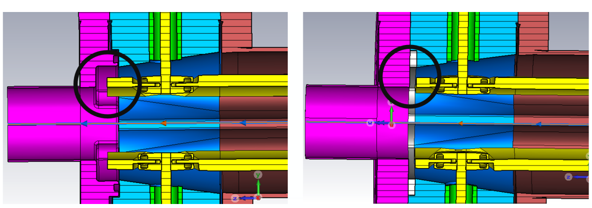
to 50 Ω. The even mode impedance corresponding to this diameter is found to be ~ 60 Ω.

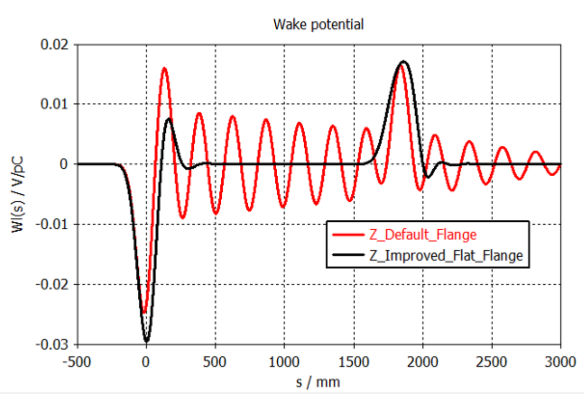
Optimization of 3D Geometry

In addition to the 2D optimization, we have also optimized its 3D geometry using CST simulations. The main goals of this 3D optimization are to reduce the wakefield oscillations (or beam coupling impedance), and to minimize the impedance mismatch at the transition region between the feedthroughs and stripline electrodes. For this, we used a simplified kicker model without venting ports and supports, and with ideal coaxial feedthroughs (50 Ω impedance) as their design is not fully defined yet.

First of all, we ran the wakefield (or coupling impedance) simulations with the EIC proton beam of 60 mm and the bunch charge of 32.9 nC. Surprisingly, we observed oscillations in the wakefield, the red curve in the Fig. 2 (b), for the initially designed geometry. We found that these oscillations are caused by the deep pockets in the end flanges, one of which is shown in Fig. 2 (a) (left) inside the black circle. The deep pockets are removed by using the new flat-flanges shown in Fig. 2 (a) (right). The wakefield comparison for kicker geometries with original and optimized end-flanges is shown in Fig. 2 (b), where the red curve indicates the original design and the black curve indicates the optimized design. Incorporation of flat end-flange washed away the previously observed wakefield oscillations.



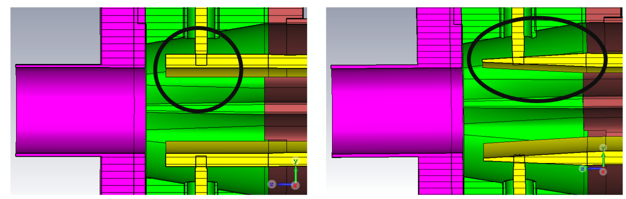
(a)



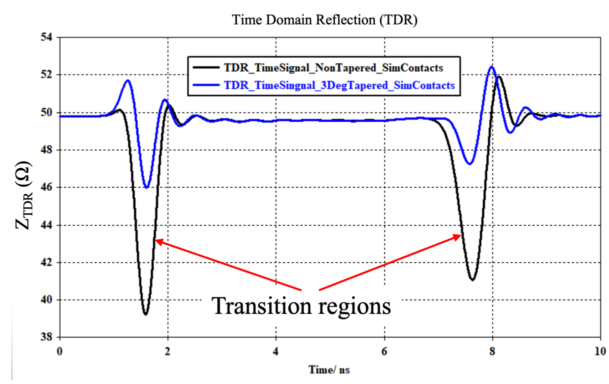
(b)

Figure 2: (a) CAD model of the injection kicker with (left) and without deep pockets (right) in the end-flange. (b) Wakefield comparison between these two geometries.

We also optimized the kicker geometry by reducing the impedance mismatch in the transition region between the feedthroughs and the electrodes. For this, we incorporated tapered electrodes at both ends. Refs. [5,7,8] has also reported the reduction of the impedance mismatch due to the tapered electrodes. Figure 3 (a) shows the CAD designs of the non-tapered (left) and the tapered (right) electrodes that we used for the CST simulations. The tapered length is about 60 mm. The Time Domain Reflection (TDR) comparison between the non-tapered and tapered electrodes, shown in Fig. 3 (b), indicates that the tapered electrodes at the transition regions between the feedthrough and stripline electrode provide smaller impedance mismatch (dark blue curve) in comparison to the non-tapered electrodes (black curve).



(a)



(b)

Figure 3: (a) CAD design showing the non-tapered (left) and tapered electrodes (right). (b) TDR plot comparison between the non-tapered (black curve) and tapered (dark blue curve) electrodes.

SUMMARY AND FUTURE WORK

In this paper, we presented the design and optimization of EIC hadron ring injection kicker. Starting from the basic cross-section design, we reported both 2D and 3D optimization using the code CST. Optimization of 2D cross-section was mainly focused on producing the odd mode characteristic impedance of 50 Ω while the 3D geometry was optimized to reduce the wakefield oscillation and to minimize the impedance mismatch in the transition regions between the feedthrough and stripline electrode. Currently, some discussions are on going to reduce the number of supports and venting ports for this kicker, and we are in the final stage of designing. Future work will focus on the simulation of peak surface electromagnetic fields, thermal simulation due to the power deposited to the kicker, effects of dielectric supports in the beam coupling impedances, and performing simulations with the real feedthroughs.

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