CRAB CROSSING SCHEMES AND STUDIES FOR ELECTRON ION COLLIDER*

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Abstract

This report shows our progress in crab crossing consideration for future electron-ion collider envisioned at JLab. In this design phase, we are evaluating two crabbing schemes viz., the deflecting and dispersive. The mathematical formulations and lattice design for these schemes are discussed in this paper. Numerical simulations involving particle tracking through a realistic deflecting RF cavity and optics illustrate the desired crab tilt of 25 mrad for 1.35 MV. Evolution of beam propagation are shown which provides the physical insight of the crabbing phenomenon.

INTRODUCTION

Electron-ion collider has been the subject to study the hadronic structure in different labs around the world [1]. The Medium Energy Electron-Ion Collider (MEIC) at Jefferson Lab has been envisioned as a first stage high energy particle accelerator beyond the 12 GeV upgrade of the existing continuous electron beam accelerator facility (CEBAF). The basic parameters of MEIC are illustrated in Table 1. High luminosity (~ $6{\times}10^{33}$ cm^{-2} s^{-1}) can be achieved by small beam sizes at the interaction point (IP) in conjunction with a large number of stored bunches having low charge per bunch (4 nC for electron, ~ 0.7 nC for proton) using the finite crossing angle scheme[2]-[4]. This requires the separation of two beams quickly to avoid parasitic collisions and the minimization of synchrotron-betatron resonance near the IP [5]-[8], which can be fulfilled by employing the crab crossing concept [2]-[3] first proposed by Palmer for linear collider [9] and later by Oide et. al. for storage rings [10]. Let us call this original scheme as "transverse crabbing" for the sake of comparison with "dispersive crabbing" which employs the existing accelerating RF cavities [3], [11]. This work is a continuation of our previous work [12], reported the basic calculations such as voltage requirement for both electron and proton and the preliminary study of particle tracking through 499 MHz transverse electromagnetic (TEM) type superconducting deflecting cavity [14]. In this paper, we would like to update the latest developments toward the crab crossing consideration in the MEIC project.

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Table 1: MEIC Design Parameters

Parameters	Proton		Electron
Beam energy E_b (GeV)	60		5.0
Collision frequency f_c (MHz)		750	
Circumference C (m)		1000	
Beam pipe radius r_b (mm)		30	
Harmonic number h		2500	
Number of bunches K_B		2500	
Bunch spacing s_b (cm)		40	
Bunch population N_e (10^{10})	0.416		2.5
Bunch length σ_l (mm)	10		7.5
Bunch profile		Gaussian	
Average beta function $\bar{\beta} = \beta_{crab}$ (m)	1400		350
Total beam current I (A)	0.5		3
Energy spread σ_E (10^{-4})	3		7.1
Normalized horizontal emittance ϵ_x^n (μm-rad)	0.35		54
Normalized vertical emittance ϵ_y^n (μm-rad)	0.07		10.7
Horizontal beta function at IP β_x^* (cm)		10	
Vertical beta function at IP β_y^* (cm)		2	
Luminosity per IP $\mathscr{L}$(10^{33} cm^{-2} s^{-1})		5.6	

The MEIC in its latest design has considered to employ 750 MHz crab cavity. For this purpose, we would like to evaluate the TEM-type RF deflector as shown in Fig. 1. It has advantages over the conventional TM_{110}-type deflecting cavities particularly at low frequency – for details see [15]. The dominant components of EM fields near the axis are shown in Fig. 2. The kick to the beam is mainly contributed by the E-field and directed along the x-direction.

CRAB CROSSING SCHEMES

This section discusses the lattice schematic of crab crossing schemes and its mathematical formulations. The MEIC lattice design includes dedicated chromaticity compensation blocks (CCB's) located near the final focusing blocks and placed symmetrically around the interaction points (IP) [16]. This means that the arrangement shown in Fig. 3 is exactly symmetric about the IP. The orbital dynamics of the CCB's is naturally compatible with both deflecting and dispersive crabbing schemes; the CCB lattice has been designed to provide possibilities for both crabbing options. Fig. 3 shows the lattice for MEIC crabbing schemes – deflecting (CAV-A) and dispersive (CAV-B). The symbols x_b, y_b, Q, S, FFB, CAV-A, and CAV-B represent the positions x and y corresponding to the beta functions, quadrupole and sextupole magnets, final focusing block, deflecting and dispersive RF cavities A and B respectively.

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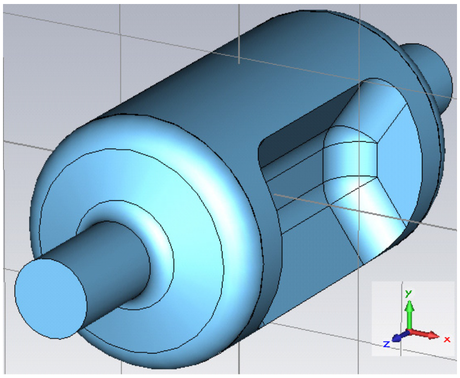

Figure 1: 750 MHz crab cavity for MEIC.

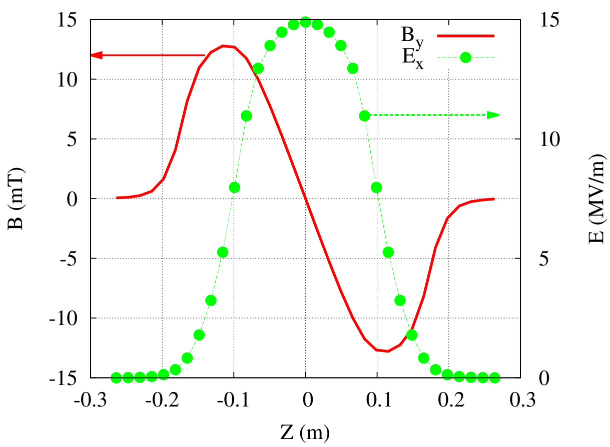

Figure 2: Dominant EM fields near the axis of the cavity corresponding to energy of 1 J.

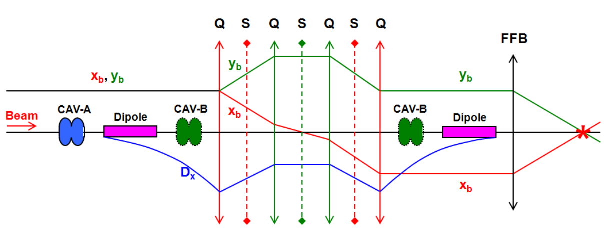

Figure 3: Schematic showing the lattice for deflecting (CAV-A) and dispersive (CAV-B) crabbing schemes of MEIC. Cavity is centered at point with phase advance (n+1/2)π relative to IP [10].

Crabbing by deflecting cavities: Assuming non-coupled optics, the particle trajectory in the horizontal plane for the deflecting crabbing is given by

$$x''_{crab} + g_x x_{crab} = f_d/E_b \qquad g_x \equiv K^2 - n \tag{1}$$

where K is reference orbit curvature by dipole fields, n is quadrupole field index, and f_d is transverse deflecting acceleration in the cavity field. Since $g_x = 0$ in the cavity then after the cavity

$$x'_{crab} = \int \left(\frac{f_d}{E_b}\right) dS = \frac{eV_{da}}{E} \sin\varphi \qquad \varphi \equiv \omega s/c \tag{2}$$

where s is the longitudinal particle position relative to bunch center and V_{da} is the deflecting voltage amplitude. If cavity is centered at the inverse focal point of FFB then the crab angle of a bunch at IP is equal to:

$$\varphi_{crab} = \frac{e\omega V_{da}}{cE_b}\sqrt{\beta_{crab}\beta^*} \quad \Rightarrow V_{da} = \frac{cE_b\varphi_{crab}}{e\omega\sqrt{\beta_{crab}\beta^*}} \tag{3}$$

Crabbing by dispersive cavities: In the dispersive crabbing method (proposed by G. Jackson in 1990 [11]) the crab tilt is created by conventional accelerating/bunching cavities installed in section with dispersion $D(s)$. The revisit derivation recognizes a much stronger effect compared to calculated in [11]. The difference is due to the taking into account coupling effect caused by the dispersion longitudinal gradient D'. Starting with equations for horizontal motion (neglecting all second order terms):

$$x'' + g_x x = Kq \qquad q \equiv \Delta E_b/E_b \tag{4}$$

where ΔE_b is difference in particle energy with reference particle

$$x = Dq + x_{cr} \qquad D'' + g_x D = K \tag{5}$$

We obtain equation for the crab betatron motion $x_{cr}(s)$ as follows

$$x''_{cr} + g_x x_{cr} = -2D'q' - Dq'' \tag{6}$$

where q' and q'' are due to rate of change of energy (longitudinal). Since in the RF section $g_x = 0$, $K = 0$ one can simply integrate the resulting betatron kick angle:

$$-x'_{cr} = \int (2D'q' + Dq'') = D'\delta q = \frac{eV_a}{E_b}D'\sin\varphi \tag{7}$$

where V_a is the integrated RF voltage amplitude in accelerating/bunching mode. In the lattice layout shown in Fig. 3, the resulting crab angle at IP is given by formula

$$\varphi_{crab} = D'\frac{e\omega V_a}{cE_b}\sqrt{\beta_{crab}\beta^*} \quad \Rightarrow V_a = \frac{cE_b\varphi_{crab}}{e\omega\sqrt{\beta_{crab}\beta^*}D'} \tag{8}$$

The required voltages for the deflecting and the dispersive crabbing schemes are tabulated in Table 2.

Table 2: Parameters for MEIC Crabbing Cavity

Parameters	Proton	Electron
Properties of Crab Cavity @ E^*_T = 1 MV/m		
Length (mm)	300.0	
Diameter (mm)	193.0	
Aperture dia. (mm)	60	
E^*_p (MV/m)	4.95	
B^*_p (mT)	8.74	
V^*_{def} (MV)	0.2	
B^*_p/E^*_p (mT/MV/m)	1.83	
Geom. factor (Ω)	138.7	
$[R/Q]_T$ (Ω)	152.9	
Crossing angle φ_{cross} (mrad)	50	
Crabbing angle φ_{crab} (mrad)	25	
Derivative of dispersion (D')	0.16	0.04
V_{da} (MV)	8.0	1.35
V_a (MV)	50.5	33.7

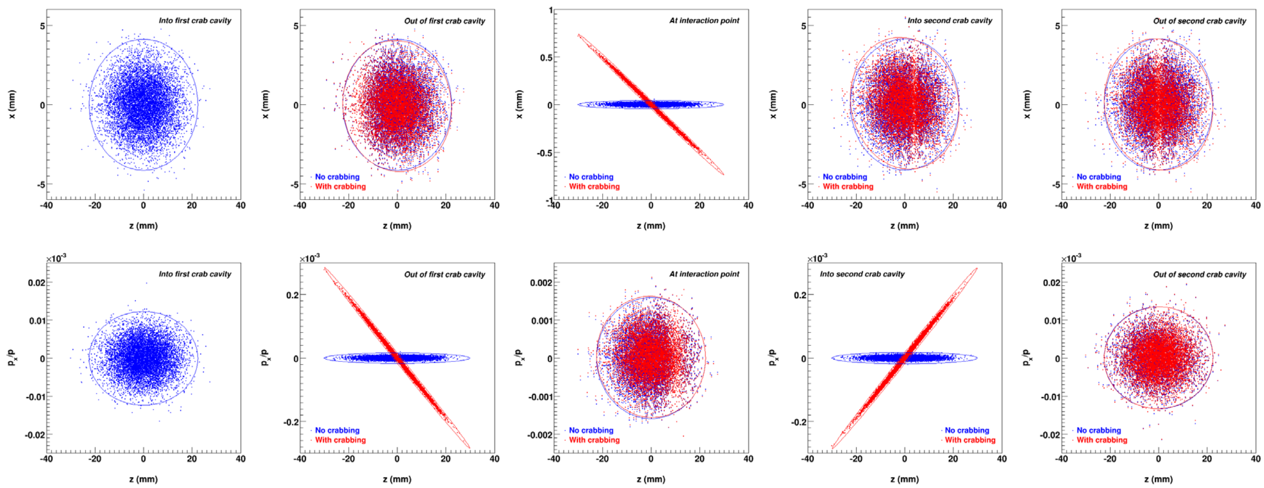

Figure 4: Evolution of e-beam showing the effects of crabbing and its compensation. Top figures show the position and the bottom figures correspond to the angle along the longitudinal z-direction.

NUMERICAL SIMULATIONS

We have performed the tracking study for electrons for the deflecting crabbing arrangement shown in Fig. 3 using the GEANT4 [17] based computer program called 'g4beamline' [18]. Three-dimensional EM fieldmap of the crab cavity simulated via CST microwave studio [19] is translated into the g4beamline. The required voltage to tilt the e-beam by 25 mrad is 1.35 MV as obtained from (3). The evolution of the beam is shown in Fig. 4. Figures on the top row show the position in the horizontal plane and the bottom corresponds to the angle. Clearly, we see the crab and its compensation which confirms that our implementation is correct.

CONCLUSION

In this paper, we report our progress toward the understanding of crab crossing consideration for MEIC. We have discussed the crabbing angle in terms of lattice parameters and cavity voltage. The TEM-type deflecting cavity looks attractive for the current study. The high repetition rate of colliding bunches with the help of crab cavities will restore high luminosity. Deflecting cavities require less voltage than the dispersive one, however, we have to evaluate their own challenges before decision.

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