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STUDIES OF THE IMPERFECTION IN CRAB CROSSING SCHEME FOR ELECTRON-ION COLLIDER*

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Abstract

The Crab crossing scheme is the essential scheme that accommodates a large crossing angle without loss of luminosity in the design of the Electron-Ion Collider (EIC). The ideal optics and phase advances of the crab cavity pair are set to create a local crabbing bump in the interaction region (IR). However, there are always small errors in the actual lattice of IR. In this article, we will present the simulation and analytical studies on the imperfections in the crab crossing scheme in the EIC design. The tolerance of the imperfection and the possible remedies can be concluded from these studies.

INTRODUCTION

The crab crossing scheme is essential to achieve high luminosity and fast separation of two colliding beams in the Electron-Ion Collider (EIC) project [1]. In the current design, a local crabbing scheme is adopted. In an ideal crab crossing scheme of EIC, the two colliding beams intersect with each other with a crossing angle $2\theta_c$ in the horizontal plane (*x*-*z* plane). For each colliding beam, a pair of crab cavities are placed at $\pm\pi/2$ phase advance upstream and downstream of interaction point (IP) to create a *x*-*z* correlation with amplitude θ_c at IP to cancel the geometric effect of the crossing angle. Later in this article, we refer the $x-z$,$x'-z$,$y-z$ and $y'-z$ correlation as 'crab dispersion functions'. The location of placing crab cavity should be energy dispersion free and the transfer matrix from IP to either crab cavity does not involve any transverse coupling. In short, the ideal crab crossing scheme corresponds to:

$$\text{IP:}\begin{bmatrix}\theta_c\\0\\0\\0\end{bmatrix};\quad\text{outside CC pair:}\begin{bmatrix}0\\0\\0\\0\end{bmatrix}.\qquad(1)$$

In this article, we will explore the realistic factors that deviate from an ideal crab crossing scheme, including in the following sections.

- Phase advance deviation from $\pi/2$ from IP to each side of crab cavity;
- Non-zero energy dispersion at the location of crab cavities;
- Presence of detector solenoid;
- Possibility of tilting the electron storage ring by ~ 200 µrad;
- Noise of RF control of crab cavities, including both the voltage and RF phase control.

TRANSVERSE PHASE DEVIATION

In the realistic lattice, the phase advances between the crab cavities and the IP are not $\pm\pi/2$. We define $\delta\psi_i$ as the phase difference of the i^{th} cavity from the ideal phase. The phases of the two crab cavities will be $\psi_1 = -\pi/2 + \delta\psi_1$ and $\psi_2 = \pi/2 + \delta\psi_2$.

The 'one-turn' map at interaction point including crab cavity is

$$M = \tilde{M}_{CC_1}\tilde{M}_{IP}\tilde{M}_{CC_2},$$

where $\tilde{M}_{IP}$ is the one turn map of IP of with head scheme without crab cavity. $\tilde{M}_{CC}$ is the matrix for linearized crab cavity kick, measured at IP:

$$\tilde{M}_{cc_{1/2}} = M_{CC_{1/2}\to IP}(-\psi_{1/2})M_{cc}M_{IP\to CC_{1/2}}(\psi_{1/2}).$$

From the one turn map, we may get the crab dispersion at IP and outside the crab cavity. Especially, two special cases, $\delta\psi_1 = \pm\delta\psi_2$, yield simple analytical forms.

For the case $\delta\psi_1 = \delta\psi_2 = \delta\psi$, the phase advance of the crab cavity pair remain π. Therefore by scaling the voltages of crab cavities from both sides by a factor of $1/\cos\delta\psi$, the crab dispersions are still confined within the crab pairs, while the horizontal crab dispersion at IP becomes:

$$\begin{bmatrix}\theta_c\\ \theta_c\tan\delta\psi/\beta_x^*\end{bmatrix},\qquad(2)$$

where β_x^* is the horizontal beta function at IP.

In the second case, $-\delta\psi_1 = \delta\psi_2 = \delta\psi$, the crab dispersion outside the crab cavity pair will be inevitably non-zero. Proper voltage can be set so that the crab dispersion at IP remains θ_c, while in this case the crab dispersion at the crab cavity becomes:

$$\frac{\theta_c\sin\delta\psi}{\sqrt{\beta_{cx}\beta_x^*}}\begin{bmatrix}\beta_{cx}\\ 1/\tan(\pi\nu_x-\delta\psi)\end{bmatrix},\qquad(3)$$

where β_{xc} is the horizontal beta function at crab cavity and ν_x is the horizontal tune.

Figure 1 shows the results from the strong-strong simulation code, BeamBeam3D [2], with various phase errors in

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the electron (left figure, ESR) and hadron (right figure, HSR) storage ring. The electron lattice requires a very tight requirement on making the crab dispersion local (between the crab cavity pair). If the phase advance between crab cavity is not π, only 1-degree deviation on each side leads to more than 5% reduction in luminosity, as shown in the left plot. On the contrary, the effect becomes negligible for even 3 degrees deviation on each side if keeping the phase advance between cavities π. Fortunately, ESR has the flexibility to keep the π phase advance between cavities.

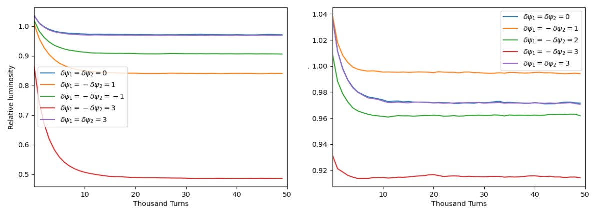

Figure 1: Luminosity comparison of left figure: different phase error $\delta\psi_{1/2}$ at crab cavity in ESR; right figure: different phase error $\delta\psi_{1/2}$ at crab cavity in HSR.

HSR does not have such freedom to keep the π phase advance, since both sides of IP will be slightly less than $\pi/2$. The right plot of Fig. 1 shows that the HSR lattice may tolerate up to 2 degrees phase error on each side of IP. If this requirement can not be met, additional crab cavities may be needed as a countermeasure.

ENERGY DISPERSION

In the interaction region design of the EIC, dispersion is helpful for the energy resolution of detecting the collision products. The location of the crab cavities is designed to have finite dispersion, especially in the forward side of IP in the proton lattice and rear side in the electron lattice. When the dispersion and/or it's derivative at crab cavity do not vanish, the longitudinal position-dependent energy kick will have a residual effect on both the longitudinal and the transverse plane. Follow the matrix manipulation of the previous subsection, the linearized crab cavity matrix at IR can be expressed, using unit-less dispersion functions, $\eta = d_x/\sqrt{\beta_{cx}\beta^*}$ and $\eta' = (\alpha_{cx}d_x + \beta_{cx}d_x')/\sqrt{\beta_{cx}\beta_*}$. The model is implemented in the BeamBeam3D code. Due to the fact that $\beta_{cx} \gg \beta^*$, the effect is mostly contributed by the d' at the crab cavity.

Figure 2 shows that for both ESR and HSR. The derivative of dispersion at crab cavities has to be larger than 0.1 to make a noticeable negative impact on the luminosity. Current EIC design has $d' \sim 0.01$ in both HSR and ESR. Therefore the dispersion at crab cavities will not be a major concern.

DETECTOR SOLENOID

The crab crossing scheme of the electron beam will be affected by the detector solenoid if they cannot be compensated within the crab cavity pair, as shown in the left plot of Fig. 3. The 4-meter detector solenoid is designed to provide up to 3 Tesla longitudinal magnetic field aligned with the electron trajectory.

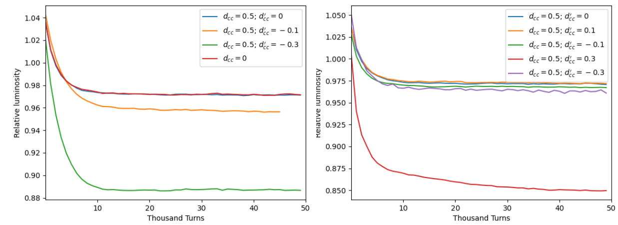

Figure 2: Luminosity comparison of, left figure: different d' at crab cavity in ESR; right figure: different d' at crab cavity in HSR. In all cases, the dispersion is kept 0.5 m.

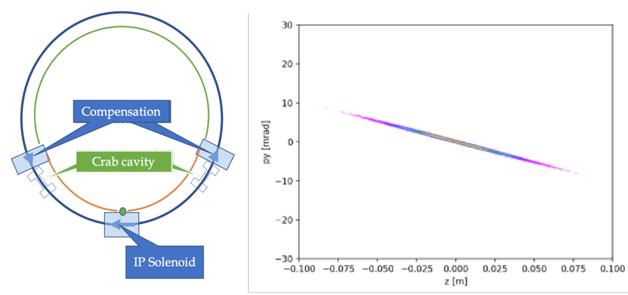

Figure 3: Left: Cartoon of detector solenoid, its compensation and crab cavity; right: The non-zero correlation of $p_y - z$.

The rotation angle θ_s caused by the detector solenoid can be approximated using a hard-edge solenoid model: $\alpha_s = \frac{B_\parallel L_s}{2P_0}$, where $B_\parallel$ is the solenoid field, L_s is the length of the hard-edge model and P_0 is the momentum of the charged particle. If the compensating solenoid is placed outside the crab cavity pair, it creates a non-zero derivative of vertical crab dispersion η'_{cy} in addition to the desired horizontal crab dispersion θ_c:

$$\eta'_{cy} = \frac{\theta_c \sin\alpha_s \sin\mu_y}{\beta_{sy}\cos\mu_y - \beta_{sy}}, \tag{4}$$

where μ_y is the one turn phase advance and β_{sy} is the vertical beta function at IP. This effect is illustrated in the right plot of Fig. 3. As a result, there is significant luminosity reduction due to the large rotation angle of the electron beam if no countermeasure presents, as shown in Table 1.

Table 1: Residue Luminosity Without Correcting η'_{cy}

	Electron	Proton
Energy (GeV)	10	275
rotation angle (mrad)	90	3
residue luminosity	37%	99.3%

Therefore, the tilting of crabbing plane η'_{cy} created by the detector solenoid and its compensating solenoid must be

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Table 2: Summaries of Imperfections in Crab Crossing Scheme

	HSR	ESR
Non-π phase adv.	2 Degree	π phase adv. in lattice
Dispersion	No degradation using design value	
Detector Solenoid	vertical crabbing	local compensation/vertical crabbing
ESR tilting		Negligible
Crab Cavity noise	Voltage:<0.01% rms; phase:<1e-5 rad	< 1 µm rms offset at IP horizontally

correct in the ESR. Two options are being considered. The first option is to put the compensating solenoids inside the crab cavity pair. There other is to add a new pair of vertical crab cavities at vertical phase advance $\pm\pi/2$ away from IP. The rotation for the highest energy proton beam in HSR is very small to be observed from peak luminosity. However, the long-term stability of the proton beam may be affected. The countermeasure for the HSR can be combined with the next effect.

THE TILTING ESR

There was a recent proposal of rotating the ESR ring to fit the existing RHIC tunnel, using the line connecting IP 6 and IP 8 as the rotating axis. The left plot of Fig. 4 illustrated the ESR ring and its rotating axis. In this section, we will study the impact of this proposal on the crab crossing scheme. The tilting of ESR modifies the crab crossing plane, so that it does not align with the kick provided by crab cavities in both rings. We calculated that the rotation of the crabbing effect is approximately 4 mrad for both the electron and the ion beam. It is worthwhile to note angle for the electron beam is more than one order of magnitude smaller than the effect of the detector solenoid and the angle from proton beam is similar for both cases.

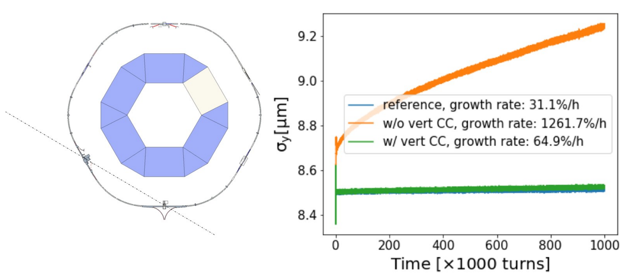

Figure 4: Left: Cartoon of ESR and tilting axis; right: Comparison of vertical beam size evolution of proton beam with and without vertical crabbing compensation.

Since the electron beam is damped by the synchrotron radiation, no countermeasure for this tilting ESR is needed. However, the effect on ion beam is different. Weak-strong simulation, as shown in the right plot of Fig. 4 , illustrated that the vertical beam size will quickly grow if the ~ 4 mrad rotation in crabbing plane is unattended. Therefore, the vertical crabbing effect must be introduced, by either rotating the existing crab cavities or adding new dedicated vertical crab cavities. The same plot also shows that the growth of vertical beam size vanishes when proper vertical is added to the simulation.

RF NOISE

The random noise of RF voltage and phase of crab cavities will cause beam size growth of the proton beam, as summarized in [3]. While the electron beam itself is not much impacted by the RF noise of its crab cavities due to the synchrotron radiation, its orbit jitters may impact the proton beam via beam-beam interaction. We setup a weak-strong simulation to find the tolerance of the above noise sources. All noise sources are assumed to be white noises or pink noises whose power spectrum density scales as an inverse function of frequency.

Figure 5 calculates the horizontal and vertical beam size growth rate of the proton beam as functions of the amplitude of noises. If we set a threshold of allowing 10%/hour growth rate or below. The simulation suggests the relative voltage error should be better than 1×10^{-4}, the rf noise better than 2×10^{-5} rad and the rms horizontal orbit jitter of the electron beam at IP should be smaller than 1 micron.

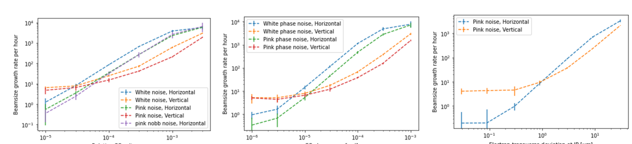

Figure 5: The proton beamsize growth rate as functions of RF voltage noise (left), RF phase (middle) and electron beam position at IP (right).

CONCLUSION

We briefly summarized the simulation findings of 5 imperfections in the crab crossing scheme in EIC design. The requirements and possible countermeasures are listed in Table 2. All of the results are done without detailed the lattice of HSR and ESR. When they are available, all studies should be repeated to update the requirements.

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