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SCALING PROPERTIES OF THE SYNCHRO-BETA RESONANCE IN CRAB CROSSING SCHEME OF FUTURE ELECTRON ION COLLIDER*

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Abstract

The synchro - beta resonance due to the beam-beam interaction was predicted by the strong-strong simulation in the future electron-ion collider designs. In this paper, we study the scaling properties of the degradation rate of this unwanted resonance. These studies motivated the possible countermeasures of the luminosity degradation associated with the resonance.

INTRODUCTION

Previous studies have revealed that the crab-crossing scheme may cause luminosity degradation in the future electron-ion collider (EIC), which results from the long bunch length compared with the wavelength of the crab cavity [1]. Later studies suspect that degradation is caused by synchro-beta resonance [2]. However, the detail dynamics and mitigation methods are yet to be studied. As the first step. we will explore the scaling behavior of the luminosity degradation with respect to the crossing angle, beam-beam parameter, as well as the number of macro-particles in simulation.

In all simulation studies below, we use the eRHIC parameters listed in Table 1 as default parameters except for the parameter that to be scaled. The simulation studies use strong-strong beam-beam code BeamBeam3D [3].

Table 1: Related Parameters of eRHIC Ring-Ring Scheme

	Ion	electron
Crossing angle (mrad)	22	
Crab cavity frequency (MHz)	337.8	
Beam size (mm) at IP, horizontal	0.123	0.123
Transverse tune, horizontal	0.31	0.08
β_x^* (m)	0.94	0.62
Longitudinal bunch length (cm)	7	0.43
Synchrotron tune	0.01	0.069
Piwinsky angle (rad)	6.3	0.4
Beam-Beam parameter, horizontal	0.014	0.093

SCALING WITH CROSSING ANGLE

In Ref [2], we learned that luminosity degradation is not observed in the head-on collision, and the degradation rate is largely improved when a lower frequency crab cavity is adopted. In this section, we will explore the relation of luminosity degradation as function of the crossing angle. We use θ_c to denote the half crossing angle. The voltage of the crab cavity is set to linearly cancel the geometric luminosity loss due to the crossing angle.

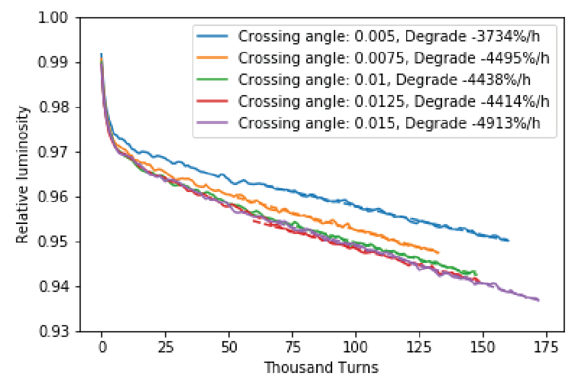

Figure 1: Luminosity degradation with different crossing angle.

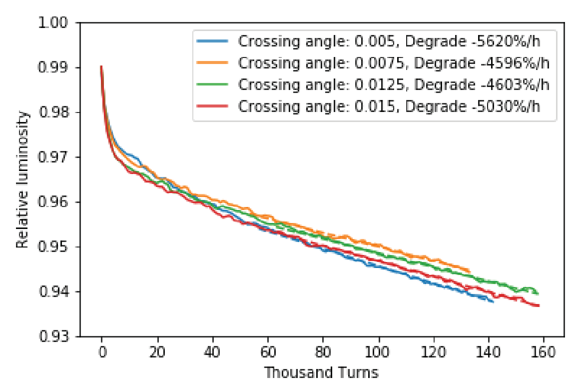

Figure 2: Luminosity degradation with different crossing angle.

Figure 1 shows that the luminosity degradation is more severe with a larger crossing angle. Also, there is a clear saturation trend when the half crossing angle is above 10 mrad. This is an encouraging result for the EIC designs since all current EIC has adopted high crossing angle. However, the reason for this saturation in the degradation rate is still unclear.

We understand that the source of the degradation is the ion beam transverse deviation due to the crab cavity. The deviation should be compared with the beam size at IP. Therefore,

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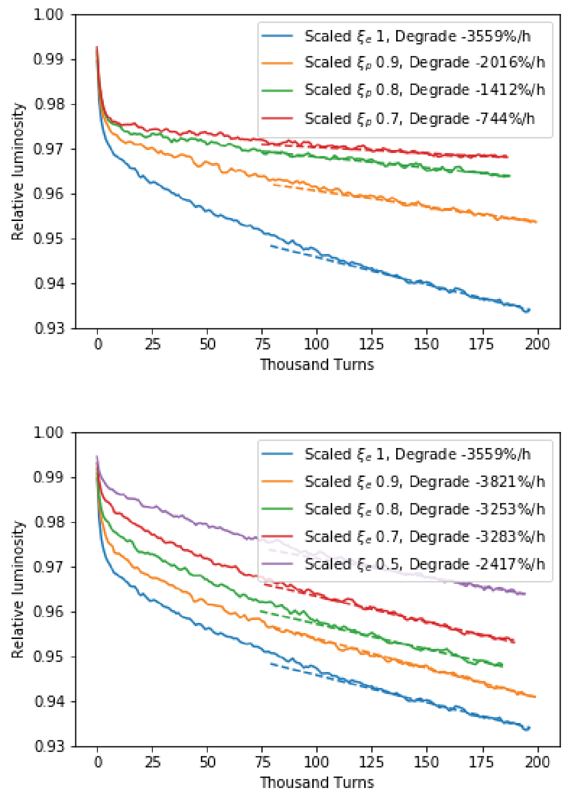

Figure 3: Luminosity degradation with different Beam-Beam parameter of the ion beam (top figure) and of the electron beam (bottom figure).

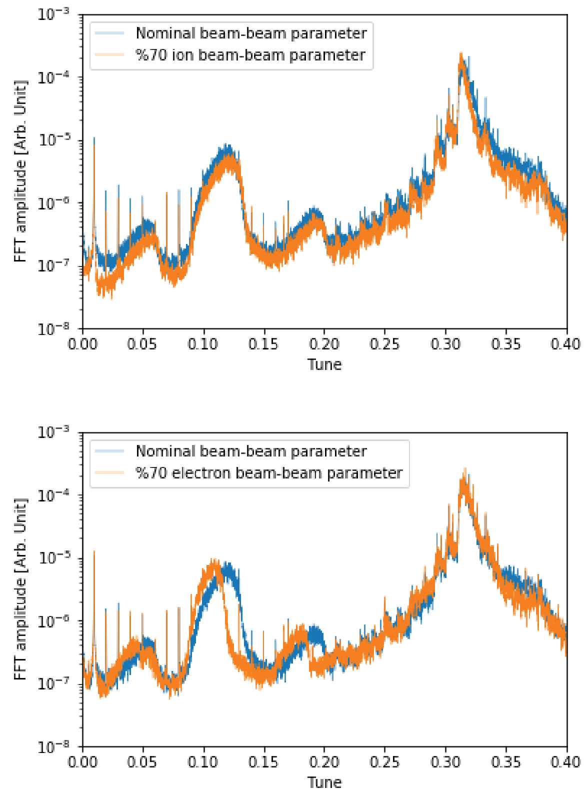

Figure 4: Frequency spectrum of the ion beam centroid with different Beam-Beam parameter of the ion beam (top figure) and of the electron beam (bottom figure).

we define the normalized horizontal deviation at the rms bunch length:

$$\begin{aligned}\frac{\Delta x\,(\sigma_z)}{\sigma_x} &\sim \left(\frac{\theta_c}{k_c}\sin(k_c\sigma_z)-\theta_c\sigma_z\right)/\sigma_x \\ &\sim \theta_c k_c^2\sigma_z^3/\sigma_x \\ &\sim \theta_P\bar{\sigma}_z^2 \qquad (1)\end{aligned}$$

Here θ_P is the Piwinski angle that characterizes the geometric luminosity loss of the crossing angle; $\bar{\sigma}_z$ is the rms bunch length normalized by the crab cavity wave number k_c. When we scale the crossing angle as in Fig. 1, the Piwinski angle changes and the normalized bunch length remains. Alternatively, when scaling the crossing angle, we may also scale the crab cavity frequency and the bunch length, so that both θ_P and $\bar{\sigma}_z$ keep constant, therefore so does the normalized transverse deviation. This scaling relation is shown in Figure 2. It confirms that by keeping θ_P and $\bar{\sigma}_z$, the degradation of different crossing angle are very similar.

SCALING WITH BEAM-BEAM PARAMETER

It is important to understand the luminosity degradation rate and the emittance growth rate as a function of the beam-beam parameter. This may guide the design to achieve the best combination of the beam-beam parameter of two colliding beams to maximize the luminosity. From the nominal design, we scale the beam-beam parameters of the ion beam and electron beam by changing the population of the opposing bunch.

The simulation results of the degradation, shown in Figure 3, show very different scaling behavior with the two beam's beam-beam parameters. When the beam-beam parameter of the ion beam is scaled down to 70% of the design value 0.015, the degradation is improved significantly. However, the degradation rate did not show similar sensitivity to the electron 's beam-beam parameter, even we scale the beam-beam parameter to a half of the design value.

The spectrum of the ion beam centroid can provide some insight into the different scaling behavior. Figure 4 compares the different spectrum of the nominal beam-beam parameter and 70% reduction of the beam-beam parameter of the ion beam (top figure) and the electron beam (bottom figure). In the top figure, when the ion beam-beam parameter decreases, both amplitudes of the synchrotron lines (multiples of ν_z = 0.01) and the electron transverse imprinted tune (~0.12) drop. This explains that reducing the beam-beam parameter of the ion beam reduces the synchro-betatron resonance and results in a lower degradation rate. On the con-

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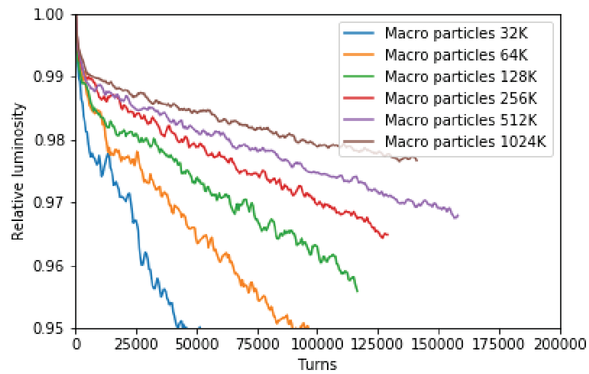

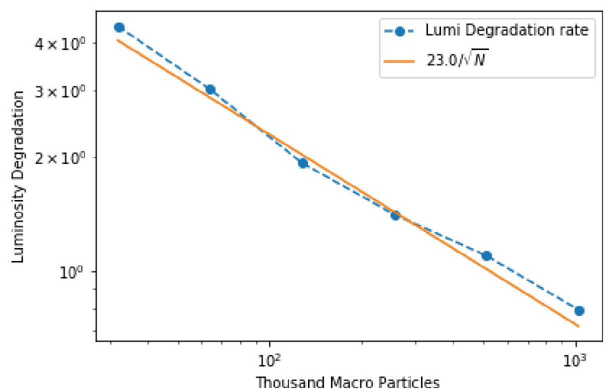

Figure 5: Scaling of luminosity degradation with the number of macro-particle used in simulation with nominal parameter, which leads to synchro-beta resonance.

trary, reducing the electron's beam-beam parameter shifts the imprint tune on the ion beam, without changing its amplitude. The amplitude of the synchrotron lines also won't be affected by the modification of the electron's beam-beam parameter. Therefore, the degradation of the luminosity is not sensitive the reduction of the electron beam-beam parameter.

SCALING WITH MACRO-PARTICLE NUMBER

There is a possibility that the resonance we observed in the simulation fade away since only ~1M macro-particles are used to represent each colliding beams in the strong-strong simulation code. In real beam, about 10^{11} charged particle resides in one bunch. Therefore we are sampling the particle distribution at a rate about one in 10^5 particles. The sub-sampling causes artificial Monte Carlo noise. The noise of beam positions and their linear statistics quantity scales as:

$$\sigma \sim \frac{1}{\sqrt{N}}$$

here, N is the number of the macro-particle. In the degradation study, we are interested in the quantities that have quadrature relation of the beam position, such as the emittance and the luminosity. They should scale as $1/N$.

We studied the scaling behavior with Macro-particles in two cases, the resonance case with the nominal parameter, and the non-resonance one with 10 times smaller synchrotron tune of the ion beam. Both electron and ion 's macro-particles are scaled together. Figure 5 shows that the luminosity degradation scales as $\sim 1/\sqrt{N}$, or power of $-1/2$, which is different from the Monte Carlo estimation -1. In the non-resonance case, shown in Figure 6, the degradation scales with the number of macro-particles with $1/N$, which is expected from the Monte Carlo process. This comparison indicates that with synchro-beta resonance, the luminosity degradation cannot be interpreted as the result of the sub-sampling. The resonance is likely to affect the machine performance even with 10^{11} real number of particles.

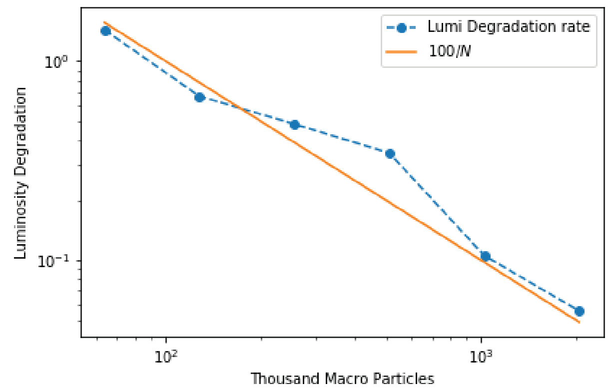

Figure 6: Scaling of luminosity degradation with the number of macro-particle used in simulation with ion synchrotron tune reduced by 10 times which significantly reduce the synchro-beta resonance.

SUMMARY

In this article, we outline the scaling relations of the luminosity degradation in the EIC design. These results further support that there a special synchro-beta resonance the current EIC design, which must be avoided by proper countermeasures. However, there are more unknown yet to be explained, which is important to further optimize the parameter of the EIC design to achieve higher luminosity.

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