IMPACT OF COHERENT BEAM-BEAM INTERACTION ON THE LANDAU DAMPING OF THE TRANSVERSE COUPLED-BUNCH INSTABILITY*

R. Li, Jefferson Lab, Newport News, Virginia, USA
M. Blaskiewicz, BNL, Upton, New York, USA

Abstract

In the EIC design, at high average-current operation, the transverse coupled-bunch instability (TCBI) induced by the long-range transverse resistive-wall wakefield in the electron storage ring (eSR) has a fast growth rate and requires efficient mitigation. A natural mitigation mechanism is provided by the beam-beam interaction at the interaction point (IP), which gives a strong Landau damping for the TCBI in the eSR. In this study, using a simplified simulation model, we investigate how this Landau damping from the beam-beam interaction behaves when the coherent beam-beam interaction at IP is considered. Our method and results will be presented in this paper.

INTRODUCTION

The Electron-Ion Collider (EIC) design aims at high luminosity for a wide range of beam energies and ion species. The collision between a 10 GeV electron beam and a 275 GeV proton beam gives the highest luminosity of $L = 10^{34}$ cm^{-2} s^{-1} [1]. This luminosity performance is achieved by the choice of the large beam-beam parameters for the electron and proton beams, i.e., $\xi_{ey} = 0.1$ and $\xi_{py} = 0.012$, as well as the high average beam currents, i.e., $I_e = 2.5$ A and $I_p = 1.0$ A. Such high average currents in EIC are attained by using high peak currents (as high as allowed by the single-bunch collective instability) together with a charge distribution pattern of 1160 bunches followed by a gap of 100-bunch spacing. The high average currents with the large number of bunches in the electron storage ring (eSR), combined with the long-range transverse resistive-wall wake field, causes a fast growth of transverse coupled-bunch instability (TCBI) in the eSR. On the other hand, the large beam-beam parameter ($\xi_{ey} = 0.1$) gives rise to large tune shift and tune spread for the electron beam in the eSR which provide a natural mechanism for Landau damping of TCBI. Currently, in the EIC design, this damping of TCBI is demonstrated by simulations [1] using a weak-strong beam-beam interaction at IP. This beam-beam induced damping effect is closely related to the decoherence from the weak-strong beam-beam interaction [2].

On top of the coupling of the dipole motion among bunches within each collider ring via the long-range transverse wakefield (LRTW), there is also the coupling of the dipole motion for each pair of bunches under collision in the two collider rings caused by the coherent beam-beam (CBB) interaction at IP. The CBB dipole coupling has been extensively investigated earlier for symmetric beams, or beams with both symmetric beam-beam parameters and symmetric working points [3-5], and later for asymmetric beams [6-10]. Our question is: how would the coherent beam-beam dipole coupling impact the beam-beam induced Landau damping of TCBI in the eSR of EIC? This question arises in the early phase of EIC design when the use of transverse dampers is considered optional. In this study, we investigate this problem using particle tracking. The weak-strong beam-beam (WSBB) effect on the dipole motion, with or without TCBI, is compared with the strong-strong beam-beam (SSBB) effects, with or without TCBI (for our interest of dipole coupling, SSBB and CBB can be used interchangeably). For the EIC parameters, we find that for small vertical relative beam offset, when the CBB dipole coupling is included, the beam-beam interaction can still provide sufficient Landau damping to mitigate the TCBI instability in the eSR. However, when the relative vertical beam offset at the IP is large enough ($\geq 0.5\,\sigma$), the CBB interaction could excite a transverse instability for both the electron and the proton beams, even when the LRTW is nonzero only for the eSR. In this paper, our numerical method and preliminary results are presented, followed by discussions and possible future improvements.

NUMERICAL METHOD

A complete treatment of our problem for the coupling between CBB and TCBI in EIC requires a simulation of 1160 uneven-filled bunches in each collider ring interacting among themselves via the LRTW, as well as a fully self-consistent simulation of the nonlinear beam-beam interaction for the nearly flat beams (aspect ratio 11.2) at IP as in the EIC design. In order to get some quick and approximate results, we adopt a simplified approach for the TCBI and CBB modeling as described below. In addition, this study focuses only on the coherent vertical dipole dynamics, assuming the horizontal dipole offsets for the electron and proton beams are always zero.

First, in the simplified model, each ring has 1260 evenly distributed bunches. We then use one bunch per ring to represent the transverse motion of the coupled-bunch mode associated with the fastest growth rate. Meanwhile, the LRTW parameters are adjusted so that the TCBI growth rate and coherent tune shift, obtained for the single-bunch interaction with the adjusted wakefield, are the same as their counterparts obtained for the 1260 bunches interacting with each other via the original LRTW in the EIC design.

Next, a soft Gaussian model [11] and round beams are used for our simulation of the beam-beam interaction at IP. In this model, dynamics of macroparticles in each beam evolves self consistently as governed by the linear optics in the ring, the beam-beam at IP, and the LRTW, yet a round

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Gaussian bunch model (with a timely-updated vertical dipole offset) is used for the calculation of beam-beam force produced by each beam. Here in the simulation the bunch parameters are chosen so that the beam-beam parameters for the two colliding beams at IP are identical to the vertical beam-beam parameters for the electron and proton beams in the EIC design. A thin lens model is adopted with zero bunch length and hence there is no synchro-betatron coupling. Besides, for clarity of presentation, radiation damping is not included here. The characteristic damping or growth time obtained from the simulation can be compared with the transverse radiation damping time in the eSR (4000 turns) when necessary.

SIMULATION RESULTS

In the following, our simulation results for the TCBI and the beam-beam effects are presented, for cases when different effects either stand alone or work together. Linear optics is assumed for each ring, with the working point for the e-beam being (ν_{ex}, ν_{ey})= (51.09, 48.06) and for the proton beam (ν_{px}, ν_{py})= (29.31, 30.05). Each beam is first populated by 10^6 macroparticles with a Gaussian phase space distribution and an initial vertical dipole offset. Then the particle dynamics evolves following the optics and the collective interaction. The dipole offset for each beam at IP as a function of turns is recorded, and the decoherence function and beam coherent dipole spectrum are obtained. The dipole offsets in this paper are given in the unit of designed vertical rms size.

TCBI

The TCBI for the eSR in EIC is described in the EIC CDR [1], where the transverse wake of the form $W_\perp(t) = W_0 e^{-\alpha t}$, with $W_0 = 60$ V/pC and $\alpha = 2.45 \times 10^6$ s^{-1}, is used to represent the long-range transverse resistive-wall effect. This simplification allows the use of phasor update method [12] for the simulation. When the electron beam only experiences the linear optics in the ring and the LRTW, its dipole motion grows rapidly as shown in Fig. 1. The growth rate for the e-beam is $g = 0.021$ turn^{-1}, and the coherent tune is $\nu_{ey} = 0.0635$, slightly shifted from the working point $\nu_{ey0} = 0.06$.

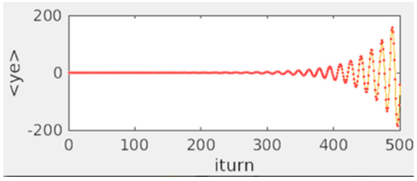

Figure 1: Growth of transverse dipole offset for the electron beam in the eSR due to the LRTW.

Weak-Strong Beam-Beam (WSBB) Effect

Here we consider the case when the electron (or proton) beam experiences only the WSBB force at IP and the optical transport in the ring. The term WSBB implies that for a bunch in each ring, the beam-beam force it encounters at IP is provided by an on-axis opposing bunch with a rigid round Gaussian distribution. This assumption precludes the dipole coupling of the two beams at IP.

The WSBB effect renders both tune shift and tune spread for the beam coherent dipole motion and causes decoherence from the initial dipole offset. An example of such decoherence behaviour is shown in Fig. 2, for the initial offsets $\langle y_e \rangle(0) = 0.1$ and $\langle y_p \rangle(0) = 0.1$. Let τ_e and τ_p denote the decoherence time for the e and p beams respectively, then we have $\tau_e \propto \xi_e^{-1}$ and $\tau_p \propto \xi_p^{-1}$ [2], so the e-beam decoheres around 10 times faster than the p-beam does.

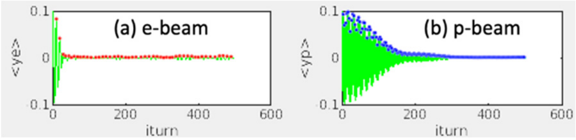

Figure 2: Dipole offsets vs. turn number for $\langle y_e \rangle(0) = 0.1$ and $\langle y_p \rangle(0) = 0.1$.

The decoherence function for the electron beam can be obtained from the envelope of the $\langle y_e \rangle$ oscillation. The comparison of the decoherence function and coherent spectrum for the initial offset $\langle y_e \rangle(0) = 0.1$ and $\langle y_e \rangle(0) = 3.0$ are shown in Fig. 3, indicating a weaker decoherence or damping effect for a larger initial offset. The spectrum in Fig. 3(b) is obtained from $\langle y_e \rangle(n)$ for 4000 turns. It shows that in comparison with the small initial offset case, for $\langle y_e \rangle(0) = 3.0$, the particles only sample the beam-beam force from several rms away from the center of the opposing beam. Hence this yields smaller tune shift and tune spread for the coherent motion, and hence a weaker decoherence (see blue curves in Fig. 3).

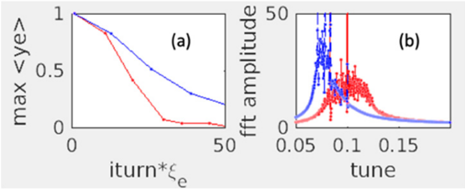

Figure 3: (a) Decoherence function and (b) coherent spectrum for $\langle y_e \rangle(0) = 0.1$ (red) and $\langle y_e \rangle(0) = 3.0$ (blue).

WSBB and LRTW

Next, we include the LRTW in the modeling of the beam dynamics in the eSR and see how the rapidly growing TCBI resulted from the LRTW is suppressed by the WSBB effect. We found that the WSBB interaction can suppress the TCBI growth when the initial beam offset is small. However, for $\langle y_e \rangle(0) = 1.0$, the WSBB interaction is not sufficiently strong to fully damp the TCBI, and the coherent dipole motion has some remaining growth with $g = 0.0013$ turn^{-1}. For $\langle y_e \rangle(0) = 3.0$, the WSBB force loses almost completely its effect in suppressing the TCBI, and the growth rate is back to $g = 0.021$ turn^{-1} as if the WSBB effect is absent.

Strong-Strong Beam-Beam (SSBB) Effect

For the SSBB interaction at IP, the dipole offsets of the two beams in the two collider rings are coupled because the beam-beam force at IP depends on the relative offset of the two beams. So unlike the WSBB case, here a given initial dipole offset for a beam in one collider ring could potentially excite a dipole motion for the beam in the other ring. For the EIC beams with asymmetric beam-beam parameter and working points, when only the linear optics and the SSBB effect are considered, the dipole coupling of the two beams is manifested in Fig. 4 where the two-band feature of the spectral amplitude for the electron (red) and proton (blue) beams is displayed. In this figure, the peak "e1" is around the electron design tune of $\nu_{ey0} = 0.06$ and is called the major band and "e2" being the minor one. Likewise for the proton "p2" is the major band and "p1" is the minor one.

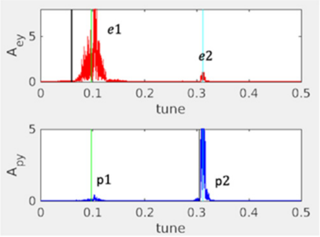

Figure 4: Spectral amplitude for the electron (blue) and proton (red) beams under the SSBB interaction for the EIC design parameters.

The decoherence function for the SSBB case is subsequently studied. When only the initial electron offset is nonzero, the decoherence function for the electron beam resembles the behavior for the WSBB case in Fig. 3(a), with $\tau_e \propto \xi_e^{-1}$, while meanwhile the dipole motion of the proton beam is excited and then decoheres with the decoherence time $\tau_p \propto \xi_p^{-1}$. Similarly, when only the initial p-beam offset is nonzero, the e-beam dipole motion is excited and damped. But interestingly, for this case, its decoherence time the same as the proton one, i.e., $\tau_e \approx \tau_p \propto \xi_p^{-1}$.

SSBB and LRTW

Finally, we examine how the WSBB-induced Landau damping of the TCBI is modified when the WSBB interaction is replaced by the SSBB interaction. We find that for a small initial dipole offset in either the electron or the proton beams, the SSBB interaction can fully suppress the TCBI in the eSR as the WSBB case does. Yet when the initial dipole offset gets larger, the instability cannot be suppressed completely. Moreover, the combination of the SSBB and the LRTW (only in the eSR) can cause coupling of the transverse instability for the two colliding beams.

An example of our finding is shown in Fig. 5. Here for the initial dipole offset at IP being $\langle y_e \rangle(0) = 1.0$ ($\langle y_p \rangle(0) = 0$), the growth of the transverse instability for the two beams is exhibited. Besides the initial decoherence, the dipole motion of the e-beam has a slow growth with the growth rate $g_e = 4.3 \times 10^{-4}$ turn^{-1}, much weaker than its counterpart in the WSBB case meaning that the SSBB interaction provides a stronger Landau damping for the TCBI than the WSBB interaction does. Notice the coupling of the transverse instability from the e-beam to the p-beam, with $g_p = 1.6 \times 10^{-4}$ turn^{-1}, despite of the zero-valued transverse wake in the HSR. The spectral amplitude of the two beams in the tune range around the e-beam working point is shown in Fig. 6. It indicates clearly that the growth takes place when the spectral peak is near the TCBI coherent tune $\nu_{ey} = 0.0635$ in the Esr.

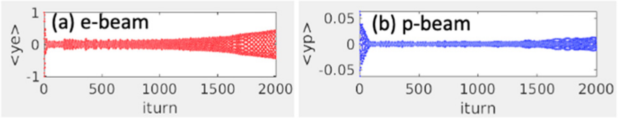

Figure 5: Dipole offset vs. turn number for the (a) e-beam and (b) p-beam, with $\langle y_e \rangle(0) = 1.0$ and $\langle y_p \rangle(0) = 0.0$.

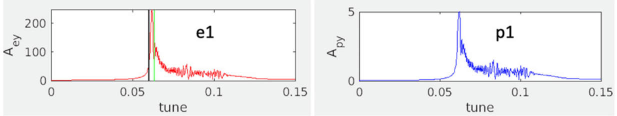

Figure 6: Spectral amplitude for the dipole motion in Fig. 5 around the electron beam working point (black line).

Another interesting example of the dipole instability for the e-beam is shown in Fig. 7, when the initial dipole offset at IP for the e-beam is zero, $\langle y_e \rangle(0) = 0.0$, and only the p-beam has a nonzero offset $\langle y_p \rangle(0) = 0.5$. Although the HSR has a zero long-range transverse wake, the SSBB interaction can couple the dipole motion of the two beams and causes excitation of TCBI for the e-beam. Here the growth rate is $g_e = 2.0 \times 10^{-4}$ turn^{-1}.

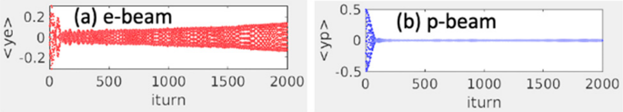

Figure 7: Dipole offset vs. turn number for the (a) e-beam and (b) p-beam, with $\langle y_e \rangle(0) = 0.0$ and $\langle y_p \rangle(0) = 0.5$.

CONCLUSION

In this work, the effect of SSBB interaction on the Landau damping of TCBI in the eSR is explored for the EIC design. With a simplified model, our simulation shows that SSBB interaction provides sufficient Landau damping when the initial relative offset of the two beams at IP is small. But if the initial relative offset is of the order of the transverse rms size, the beam-beam tune spread and the tune shift are not enough to damp the TCBI in the eSR. A remaining slow growth of the dipole instability may take place in both colliding beams due to the dipole coupling by SSBB. With the use of transverse dampers, this coupled dipole instability can be mitigated. Otherwise, it could cause problem during the preparation of beam collision in the commissioning phase. Future improvement of our study includes scan of working points, modeling of the SSBB interaction for flat beams [13], fixing the tune dependence of the TCBI growth rate in the single-bunch model, and extending the study to include the coupling of the CBB synchro-betatron effect with the beam head-tail instability in the EIC design [14].

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