INCOHERENT AND COHERENT SYNCHROTRON RADIATION EFFECTS IN THE SUPERKEKB ELECTRON BEAM TRANSPORT

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Abstract

The delivery of 7-GeV low-emittance electron beams into the SuperKEKB lepton collider is essential. However, the beam transport between the linear accelerator (LINAC) and the High-Energy Ring is plagued by significant transverse emittance growths. In general, both incoherent and coherent synchrotron radiations are crucial in beam dynamics. This study reported the measured emittance results of a nominal optics along with the results of particle tracking simulations.

INTRODUCTION

The SuperKEKB is a double-ring collider with 7-GeV electron and 4-GeV positron beams [1]. The electron beam is delivered through the beam transport (BT) following the injector LINAC, as shown in Fig. 1. The BT which was constructed for the previous KEKB project is reused without major changes. A nominal BT optics is illustrated in Fig. 2.

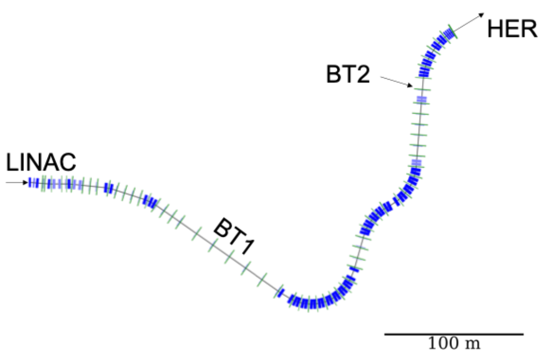

Figure 1: 7-GeV electron beam transport between the SuperKEKB high-energy ring (HER) and the LINAC. It comprises two achromatic sections of BT1 and BT2. The bending and quadrupole magnets are indicated in blue and green, respectively.

The BT has several arc sections with large curvature owing to the geometric constraints from existing photon source facilities. This results in large dispersion functions, as shown in Fig. 2. It is well known that, for multi-GeV low-emittance lepton beams, both the incoherent synchrotron radiation (ISR) and coherent synchrotron radiation (CSR) play crucial roles in beam dynamics.

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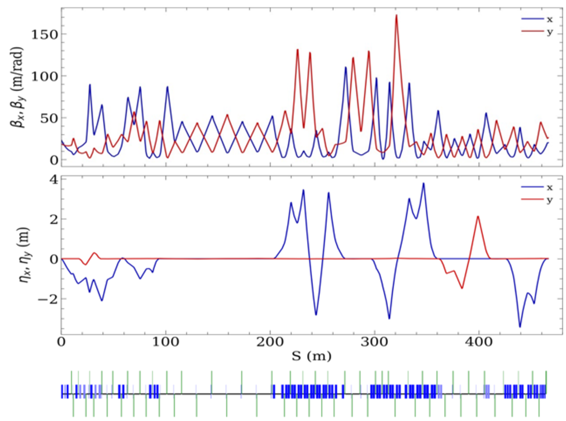

Figure 2: Nominal 7-GeV electron beam transport optics with dispersion functions shown in blue and red for the horizontal and vertical directions, respectively.

RADIATIVE EMITTANCE GROWTHS

Radiative effects on transverse emittances are typically caused by synchro-betatron coupling due to beam energy changes in dispersive sections. However, in contrast to the ISR effect, the CSR effect depends on the height and width of the beam ducts (CSR shielding effect). This study performed particle tracking simulations using ELEGANT [2] to evaluate the ISR effect and CSR shielding effects on transverse emittances in the BT. The steady-state parallel-plate CSR model [3] was employed in the simulations assuming an initial beam distribution, which is shown in Fig. 3. The full heights of the beam ducts inside the bending magnets were 32 mm. The evolution of the beam emittances along the BT for a 2.2-nC beam is shown in Fig. 4.

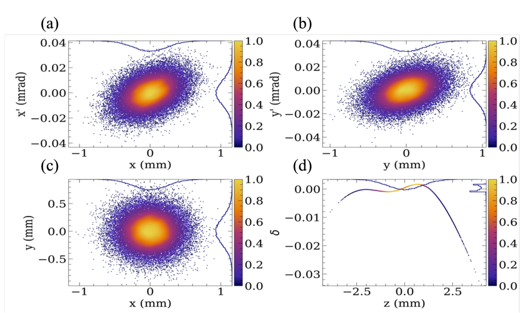

Figure 3: Initial beam distribution on the (a) x–x', (b) y–y', (c) x–y, and (d) z–δ planes, with normalized histograms in dark-blue before the 7-GeV electron beam transport. The color code indicates the density of the beam.

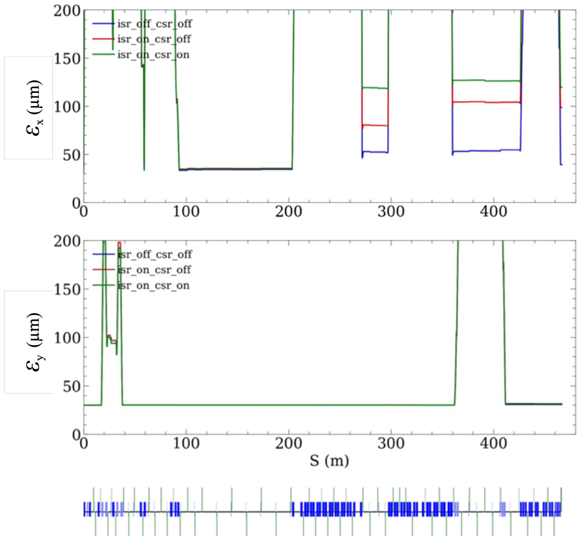

Figure 4: Evolution of the normalized horizontal (top) and vertical (bottom) emittances along the beam transport. The emittances without ISR and CSR, those with ISR, and those with both ISR and CSR are shown in blue, red, and green, respectively. Note that the horizontal and vertical emittances here are calculated by $\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x \cdot x'\rangle^2}$ and $\sqrt{\langle y^2\rangle\langle y'^2\rangle - \langle y \cdot y'\rangle^2}$, respectively.

The simulation results indicated no significant vertical emittance growth, regardless of the effects of ISR and CSR; however, both the effects increased the horizontal emittance between BT1 and BT2. Table 1 summarizes the emittance growths with the nominal measured data. Emittance measurements were performed using four wire monitors at BT1 and with the quadrupole-scan method using a profile monitor at BT2. The measurements and simulations were reasonably consistent only in the horizontal direction, and not in the vertical direction. The source of the vertical emittance growth remains unclear. It may be attributed to the 3D-CSR effect [4]. In addition to the ISR and CSR effects, a slight horizontal emittance growth was observed between BT1 and BT2, which is attributed to high-order dispersions.

Table 1: Normalized rms emittances for a 2.2-nC beam at BT1 and BT2 in the simulations compared with measured values presented in parentheses

Simulation condition			Location	
No.	ISR	CSR	BT1	BT2
			x/y [μm]	x/y [μm]
1	No	No	34/30	54/31
2	Yes	No	35/30	104/32
3	Yes	Yes	36/30 (~30/~30)	132/32 (~120/~80)

The horizontal emittance growth induced by the CSR occurred primarily in the first strong bending sections following BT1 (Arc1). In this region, the bunch exhibited a steep longitudinal profile, as shown in Fig. 5, owing to nonzero R_{56} component of the transfer matrix. Hence, strong CSR wake occurred locally within the beam. The maximum energy modulation of one bending magnet in the bunch was estimated at ~0.6 MeV in the simulation (Fig. 6). Consequently, the energy change that depends on z within the bunch in Arc1, where the horizontal dispersion surpasses 2 m, induces emittance growth in the horizontal direction.

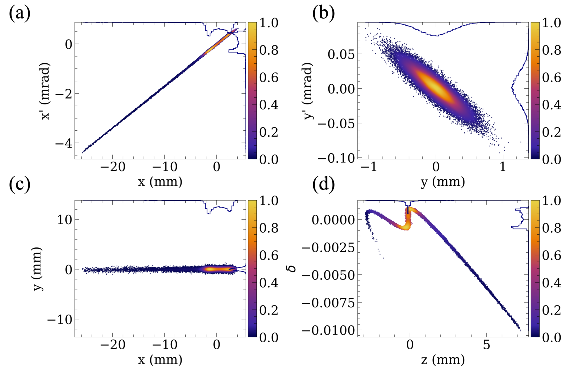

Figure 5: Particle distribution on the (a) x–x', (b) y–y', (c) x–y, and (d) z–δ planes in Arc 1.

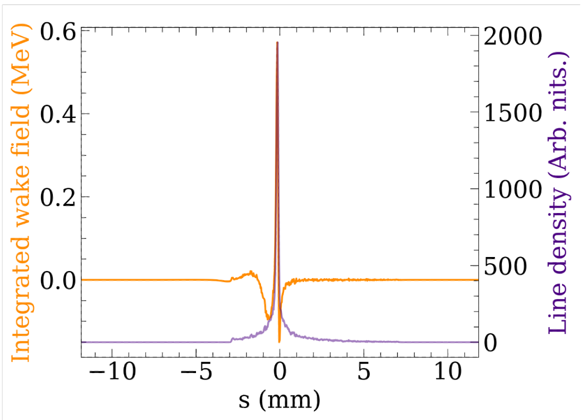

Figure 6: Longitudinal charge profiles (purple) and integrated CSR wake field produced by a bending magnet (orange) in Arc1.

COUNTERMEASURES

Several schemes have been proposed to mitigate the emittance growth due to ISR and CSR effects.

New beam transport line

As evident, a smaller number of arc sections directly reduces the radiation effects. We explored the possibility of a new straight BT line as shown in Fig. 7, which replaces the present Arc1 and Arc2. The proposed beam line retains the beam line at downstream of Arc3. The CSR and ISR effects were calculated using a preliminary optics of the new BT line (Fig. 8). Figure 9 shows the evolution of the horizontal emittance along the beam line for the cases 1) without ISR and CSR, 2) with ISR, and 3) with ISR and CSR.

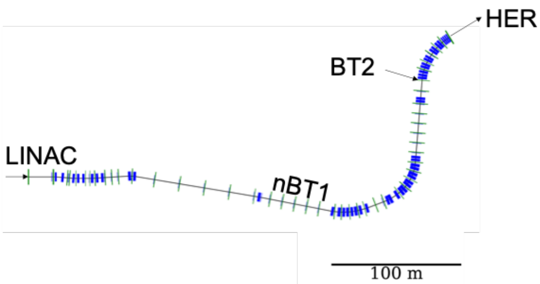

Figure 7: New straight beam transport line with two achromatic segments of nBT1 and BT2.

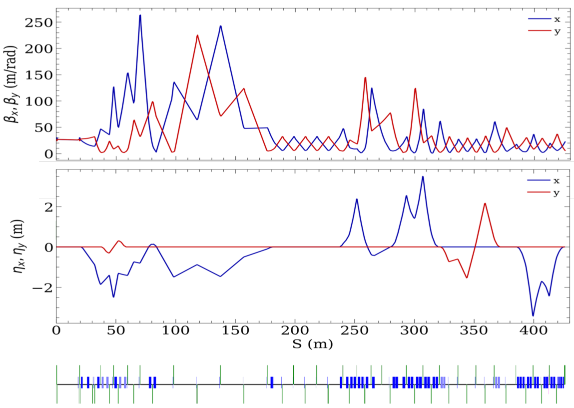

Figure 8: Optics for the new electron beam transport.

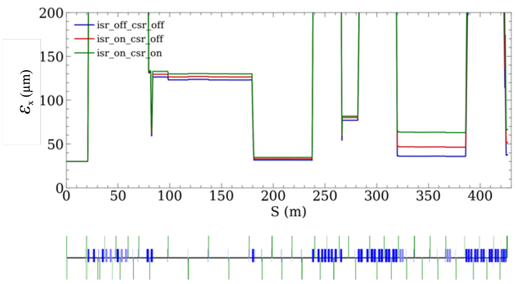

Figure 9: Evolution of the normalized horizontal emittances. The normalized horizontal emittances at the injection point 1) without ISR and CSR, 2) with ISR, and 3) with ISR and CSR are 38, 52, and 66 µm, respectively.

The new BT line shows a significant reduction in the ISR and CSR effects, although their effects are still not negligible. Lower dispersion optics, which may be available by adding more quadrupoles, will contribute to suppress the ISR and CSR effects.

Enhanced CSR shielding

Generally, narrowing the beam ducts is effective to suppress CSR-induced emittance growth. Figure 10 shows an example of the simulation results of the case with a duct height of 10 mm for all bends for a 2.2-nC beam. In this simulation, the CSR effects was underestimated owing to the lack of the transient CSR wake. The simulation results revealed that narrower ducts can effectively suppress the CSR effect. However, the application of this scheme to the BT line necessitates the evaluation of the vacuum conductance, resistive wall effects, as well as the beam tuning feasibility.

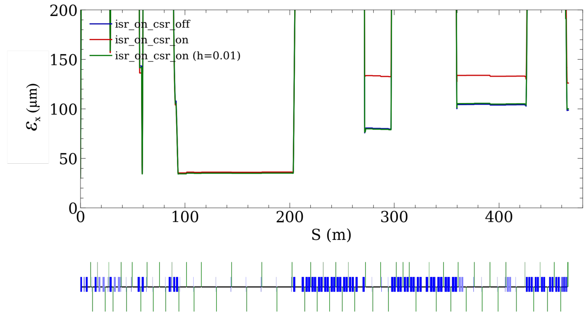

Figure 10: Evolution of the normalized horizontal emittances with narrower beam duct. The normalized horizontal emittances at the injection point 1) with ISR (blue), 2) with ISR and CSR (red), and 3) with ISR and CSR and a duct height of 10 mm (green) are 99, 126, and 100 µm, respectively.

SUMMARY

In the SuperKEKB electron BT line, ISR and CSR play crucial roles in beam dynamics. Their radiative effects on transverse emittances are a result of the synchro-betatron coupling due to beam energy modulation within the bunch in dispersive sections. Based on the numerical simulations in this study, the new BT line which has less dispersive arcs was proposed. Narrower gap height of the beam duct can also effectively suppress the CSR effect.

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