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VERTICAL BUMP ORBIT STUDY ON EMITTANCE OF INJECTION BEAM IN TRANSPORT LINE FOR THE SUPERKEKB MAIN RING

T. Mori*, N. Iida, M. Kikuchi, T. Nakamura, T. Yoshimoto, D. Zhou
High Energy Accelerator Research Organization (KEK), Tsukuba, Japan

Abstract

The commissioning of the SuperKEKB accelerator, a collider consisting of 7 GeV electron and 4 GeV positron rings, is underway in order to supply a great number of interaction events of electrons and positrons to the Belle II detector, which is used for discovering the new physics beyond the standard model. The important milestone is to obtain integrated luminosity of 4 ab^{-1} in several years. For that purpose, the luminosity should exceed 2×10^{35} $\mathrm{cm}^2\mathrm{s}^{-1}$. To achieve the goal, both rings have to be filled with a high current beam of a few amperes, where the high injection efficiency is vitally important because the lifetime is expected to be very short. Preservation of the emittances of the injection beam passing through the beam transport (BT) line is very important for injection performances. However, unexpected large emittance growths have been observed in both electron and positron BT-lines. Having comprehensive research on this issue through the simulations and measurements, the coherent synchrotron radiation (CSR) wakefields have emerged as a cause of the emittance growths. According to the parallel conducting plates model, CSR wakefields are reduced when the beam passes through the offset position from the median plane of the plates. In this paper, it will be reported that the measured emittance of the injection beam varies with height of the orbit created at the arc section of the BT-line for the electron ring.

INTRODUCTION

The longitudinal impedance for the steady-state CSR with perfectly conducting plates in the horizontal plane $Z_\parallel$ is represented as follows [1]:

$$\frac{Z_\parallel(k)}{L} = \frac{\pi Z_0}{b}\left(\frac{2}{kR}\right)^{\frac{1}{3}} \sum_{n=1}^{\infty} \Lambda_n(y_0, y) F_0(\xi_n)\,, \qquad (1)$$

$$F_0(\xi) = \mathrm{Ai}'\left(\xi^2\right)\left\{\mathrm{Ai}'\left(\xi^2\right) - i\mathrm{Bi}'\left(\xi^2\right)\right\} + \xi^2 \mathrm{Ai}\left(\xi^2\right)\left\{\mathrm{Ai}\left(\xi^2\right) - i\mathrm{Bi}\left(\xi^2\right)\right\}, \qquad (2)$$

$$\xi_n = \frac{n\pi}{2b}\left(\frac{R}{2k^2}\right)^{\frac{1}{3}} \quad \text{for} \quad n = 1, 2, 3, \cdots, \qquad (3)$$

$$\Lambda_n(y_0, y) = \sin\left(\frac{n\pi}{2b}(b + y_0)\right) \sin\left(\frac{n\pi}{2b}(b + y)\right), \qquad (4)$$

where the symbols k, L, b, Z_0, R, y_0, y are defined as,

- k the angular wavenumber,
- L the length of a bending magnet,
- b the half of the distance between the parallel plates,
- Z_0 the impedance in vacuum,
- R the radius of the beam orbit,
- y_0 the vertical offset of the driving beam from the median plane of the conducting plates,
- y the witness-particle position.

Here we assume the driving beam has a transverse distribution of $\rho_\perp(x, y) = q\delta(x)\delta(y - y_0)$. We dropped γ^{-2} term in Eq. (2) since it is negligible in our case. Equation (1) including $\Lambda_n(y_0, y)$ represented as Eq. (4) can be easily derived from the formulations of CSR fields in Ref. [2]. The CSR impedance is a function of y_0 and y. When $y = y_0 = 0$, $\Lambda_n(0, 0) = 1$ for odd $n = 2p + 1$ ($p = 0, 1, 2, \cdots$) and $\Lambda_n(0, 0) = 0$ for even $n = 2p$. Consequently, Eq. (1) reduces to Eq. (A1) of Ref. [1] where it was assumed $\rho_\perp(x, y) = q\delta(x)\delta(y)$ and the CSR impedance was calculated only with $x = y = 0$. In this paper, we consider the case of $y = y_0$, i.e.

$$\Lambda_n(y_0, y_0) = \sin^2\left(\frac{n\pi}{2b}(b + y_0)\right), \qquad (5)$$

while the factor $\Lambda_n(y_0, y_0)|_{y_0 \neq 0} \leq 1$ for odd-n suggests the suppression of the CSR field felt by the beam, $\Lambda_n(y_0, y_0)|_{y_0 \neq 0} \geq 0$ for even-n suggests that the even mode can be excited and contribute to the CSR impedance when the beam is offset from the chamber's median plane. Note that Eq. (5) is correct not only in the parallel plate model but also in the rectangular toroid chamber [2].

Each component of Eq. (1) for the vertical Fourier mode n can be written as

$$\frac{Z_\parallel(k, n)}{L} = \frac{\pi Z_0}{b}\left(\frac{2}{kR}\right)^{\frac{1}{3}} \Lambda_n(y_0, y) F_0(\xi_n)\,. \qquad (6)$$

Usually, the low-order modes dominate the CSR impedance, as shown in the next section. The function $\Lambda_n(y_0, y)F_0(\xi)$ multiplied by the beam spectrum determines the radiated power density at specific wavenumbers. The contribution of each mode is calculated by integrating Eq. (6) over k up to the possible maximum value given by the bunch frequency.

IDEA FOR CSR SUPPRESSION

From boundary conditions, the CSR fields E_z and E_x parallel to the conducting plates should vanish at the plate surface ($y = \pm b$). These field components felt by the beam at $y = y_0$ have the scaling law of

$$E_{z,x} \propto E_{z,x}\big|_{y=0} \sin^2\left(\frac{n\pi}{2b}(b + y_0)\right). \qquad (7)$$

This leads to an idea that the CSR field could be suppressed by offsetting the beam in the vertical direction using orbit bumps. Shielding effects from orbit offset are demonstrated in Figs. 1 and 2. One can see that the CSR impedances

* takashi.mori@kek.jp

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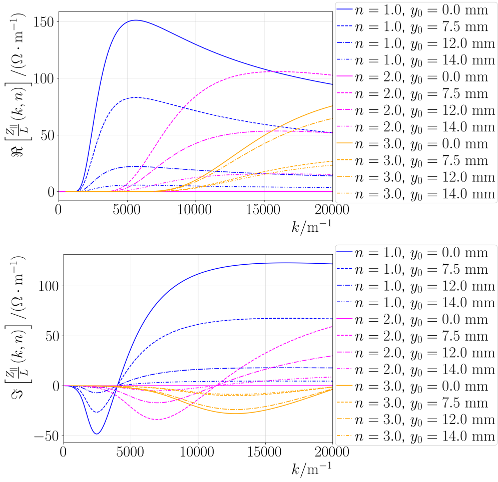

Figure 1: The real (top) and imaginary (bottom) parts of decomposed CSR impedances for the modes $n = 1, 2, 3$ with various y_0 values are plotted, where $b = 16$ mm and $R = 20.8$ m.

from odd-n modes decrease as the offset increases (see blue and yellow lines in Fig. 1) and those from even-n modes increase (see magenta lines in Fig. 1). The net effect is CSR suppression, as shown by the total impedance in Fig. 2. This idea of CSR suppression was tested with beam in the BT-line of SuperKEKB .

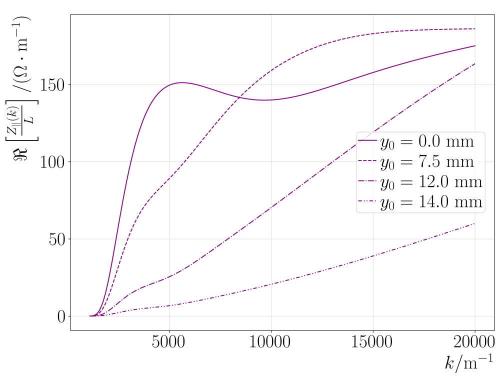

Figure 2: The CSR impedance at the beam position $\left.\frac{Z_\parallel(k)}{L}\right|_{y=y_0}$ for various y_0 are plotted. The shielding effect is clearly seen in the region $y_0 \geq 12$ mm.

EXPERIMENT

The design of the BT-line is shown in Fig. 3. The BT-line consists of the electron line (BTe) and the positron line (BTp). The injection beam is transported from Linac [3], passing through the BT-line, and finally injected into the SuperKEKB main rings. There are four arcs that have the non-zero dispersion region, depicted by character strings Arc1-4. If the emittance growths observed in the BT-lines are caused by the CSR wake field, the shielding effect could be detected as the suppression of the emittance growth when the beam orbit is vertically offset from the median plane of the beam chamber. According to our studies, a large increase of horizontal emittance on BTe seems to occur in Arc1. Therefore, the study was performed Arc1 in BTe.

Procedure

To measure the CSR shielding effect, the orbit bump was induced with adjusting steering magnets, which is shown in Fig. 4, where the symbols denote the following:

$\beta_{x,y}$ the horizontal (black) and vertical (red) beta-functions,
$\eta_{x,y}$ the horizontal (black) and vertical (red) dispersions,
X, Y the horizontal and vertical position, where the purple dots stand for the measured data, green curves stand for calculation,
Q the charge.

At the end of bump orbit, $\eta_y = \eta'_y = 0$ is required, where the symbols η_y and η'_y denotes the dispersion and the derivative of the dispersion with respect to s, which denotes the location along the orbit. The emittances were measured by the quadrupole scan method [4] with an OTR screen monitor located in front of the entrance to Arc2, where the emittance growth suppression effect could be directly measured.

Results

The measured values are shown in Table 1 and in Fig. 5. The suppression of the emittance growths with the vertical offset of the beam was clearly observed. In contrast, the charge dependency was not seen in the suppression effect.

Table 1: The measurement results are summarized. The symbols $q, \gamma\varepsilon_x, B_{\mathrm{m,x}}$ denotes the charge, normalized emittance and the beta mismatch in horizontal plane.

q/nC	Offset Δy/mm			$\gamma\varepsilon_x/\mu$m	$B_{\mathrm{m,x}}$
	QAD4E	QAD6E	QAD8E		
1.6	18	0	0	202.8 ± 4.5	1.58
	0	0	0	312.7 ± 4.1	1.58
2.2	0	14	0	373.5 ± 7.0	1.56
	0	0	0	369.9 ± 6.1	1.58
	0	-16	0	310.1 ± 8.5	1.75
	18	2	12	246.9 ± 4.1	1.54
	0	0	0	325.7 ± 4.1	1.69
	-12	-7	-11	268.2 ± 8.8	1.82

SUMMARY AND DISCUSSION

Shielding effect of the CSR impedance was investigated based on the parallel plate model assuming steady state for the beam which is offset from the median plane of the plates.

According to our study results, the emittance growth suppression effect of bump orbit was observed clearly. However, bunch charge dependency was not clearly seen in the suppression effect. Generally, the degree of CSR effect depends on the square of the bunch charge. This bunch charge dependency of CSR effect is proper if and only if the longitudinal bunch profile does not changed by the bunch charge, namely, the charge population contributing the CSR effect is proportional to total bunch charge. In our study, even though the RF

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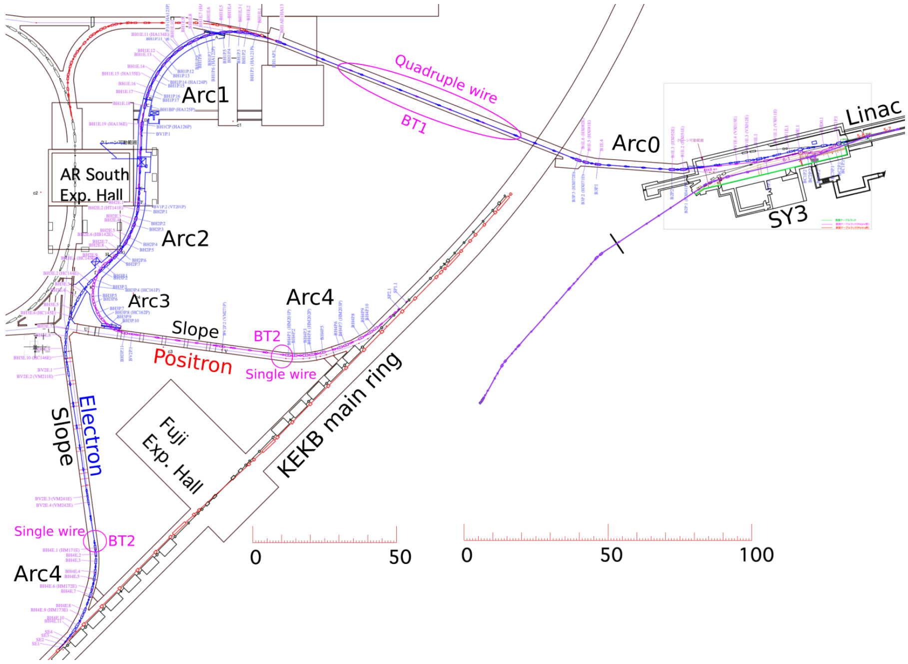

Figure 3: The BT-line and some other lines are shown.

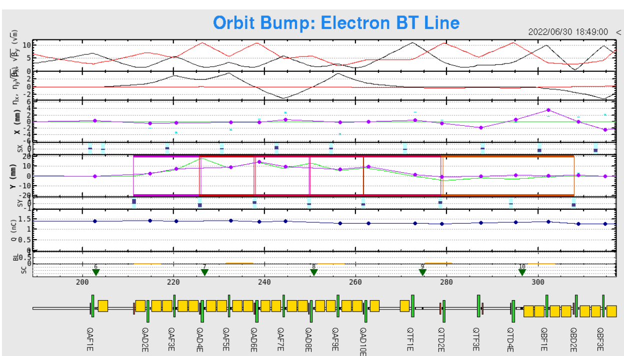

Figure 4: An example of the bump orbit in Arc1 are shown. The horizontal axis indicates s. The schematic view of beam line is shown in the bottom row.

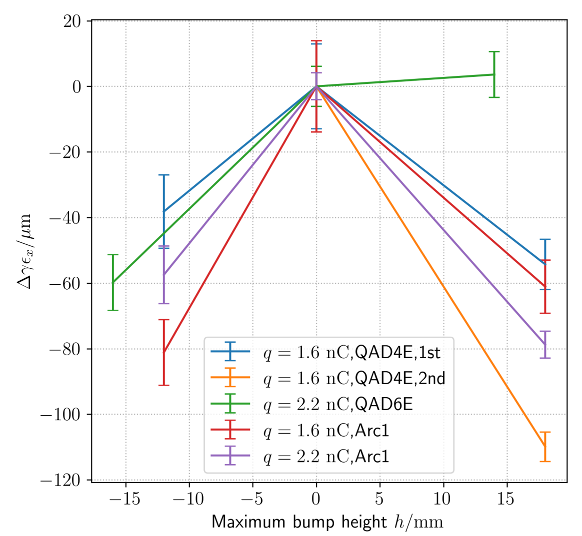

Figure 5: Decrement of the emittances by creating the bump orbit at the Arc1.

phases were adjusted for compensating the wake fields in the acceleration tubes, the longitudinal profile of the bunches might not be kept identically because of the R_{56} component of the transfer matrices in the arcs, when the bunch charge quantity was varied.

Since the study was performed with bump orbit, the beam necessarily passed the vertical position where the $n = 2$ mode induced. The calculation of the CSR impedance integrated along the bump orbit might help more precise understanding of the shielding effect.

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