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IMPACT OF BUNCH CURRENT ON OPTICS MEASUREMENTS IN SuperKEKB

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Abstract

SuperKEKB has recently achieved the world record instantaneous luminosity of 2.8×10^{34} cm^{-2s} and aims at reaching a target luminosity of about 6×10^{35} cm^{-2s}. To accomplish this goal it is planned to increase beam currents up to 3.6 A and 2.6 A for the positron and the electron ring, respectively. Increasing the beam currents and, in particular, the number of leptons per bunch, can impact the optics parameters obtained by turn-by-turn measurements, such as the betatron tune or phase advance. Optics measurements performed at various bunch currents can give first indications of possible intensity dependent effects. In this paper, the effect of varying bunch current on optics measurements at SuperKEKB is explored.

INTRODUCTION

The lepton collider SuperKEKB [1–3] aims at achieving a target luminosity of 6×10^{35} cm^{-2s} [4] with beam currents of 3.6 A and 2.6 A, and beam energies of 4 GeV and 7 GeV, for the low energy positron (LER) and the high electron (HER) rings, respectively. Both rings are designed to collide 2500 bunches, resulting in a nominal bunch current of 1.44 mA and 1.04 mA. With a revolution time of about 10 µs, a beam current of 1 mA corresponds to approximately 6.27×10^{10} leptons. SuperKEKB, currently in commissioning, collides beams using the nano-beam collision scheme [3] with a design vertical β−function at the interaction point, β_y^*, of 0.3 mm.

MEASUREMENT SETTINGS

To study the effect of various bunch currents on optics parameters, single bunch measurements are performed for LER with interaction-point (IP) beta functions of $\beta^*_{x,y} = 80, 2$ mm, at bunch currents ranging from 0.2 mA to 1.25 mA. The optics is measured using Turn-by-Turn (TbT) orbit data, recorded by 70 Beam Position Monitors (BPMs), after single kick excitation with an injection kicker (IK). The orbit data is then SVD-cleaned [5], before harmonics and optics analysis are performed with the same algorithms as used for the LHC [6, 7]. As the IK kicks the beam only horizontally, the vertical optics cannot be measured precisely. The studies presented here, therefore, focus on the effect of the bunch current on horizontal optics measurements. More details on optics measurements in SuperKEKB can be found in [8]. The horizontal rms phase advance difference with respect to the SAD [9] model, $\langle \Delta\mu \rangle = \langle \mu^{\mathrm{meas}} - \mu^{\mathrm{mdl}} \rangle$, is 1.1×10^{-2} (2π), based on data from the first 2000 turns after excitation. Removing BPMs where $\Delta\mu/(2\pi) > 4 \times 10^{-2}$, reduces $\langle \Delta\mu \rangle/(2\pi)$ to about 0.59×10^{-2}. Comparable $\Delta\mu$ values, including localized large $\Delta\mu_x$ outliers, are observed for all measurements. A rms horizontal β−beating with respect to the model of approximately 8.86% is obtained from the measured phase errors using the N-BPM method [10, 11]. The strength of the difference resonance (closest tune approach) $|C_-|$ is estimated to be $(3.3 \pm 0.2) \times 10^{-3}$. The optics model predicts a rms relative momentum spread of 6.37×10^{-4}. The horizontal detuning with amplitude is observed to be about $(8.1 \pm 0.3) \times 10^{-3}$ m^{-1}. Measured horizontal chromaticity Q'_x is approximately 1.54 ± 0.01, which does not match the model expectation of −1. The vertical chromaticity Q'_y is measured to be -2.4 ± 1.6, while the model predicts +3.

The machine impedance can result in an intensity dependent optics, either measured or actual, or both. At SuperKEKB the collimators are an important impedance source. To quantify the impact of collimators, the product $k_\perp \beta_{x,y}$ is used as a figure of merit, where $k_\perp$ denotes the kick factor [12–14], (dipolar and quadrupolar components) which describes the magnitude of the intensity-dependent centroid bunch deflection $\Delta x'$ $(\Delta y')$, in case of a transverse offset x_0 (y_0) at the collimator, as $\Delta x' = k_\perp Q x_0/E$, with Q the bunch charge and E the beam energy. The kick factors are obtained from transverse wake fields computed with GdfidL [15] for a test bunch length of $\sigma_z = 0.5$ mm, about ten times shorter than the actual bunches. The greater $k_\perp \beta_{x,y}$, the larger is the generated impedance contribution from a specific collimator. Too large impedance could induce the Transverse Mode Coupling Instability (TMCI) [16]. Assuming that σ_z is short, the threshold bunch current I_{thr} is given by [17, 18]

$$I_{\mathrm{thr}} = \frac{C_1 f_s E/e}{\sum_n \beta_n k^{\mathrm{dip}}_{\perp,n}} , \qquad (1)$$

with $C_1 \approx 8$, synchrotron frequency f_s, beam energy E, electron charge e, and a summation over all dipolar (dip) wake-field sources n. For LER the sum of $\beta_n k^{\mathrm{dip}}_{\perp,n}$ over all collimators must, therefore not exceed a value of about 47×10^{15} V/C [19]. More details regarding the SuperKEKB collimation system can be found in [20]. Collimator settings during data acquisition are summarized in Table 1, where H or V in the collimator name refers to a horizontal or a

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vertical collimator, respectively. The β-function is given in the respective plane. $k_\perp$ contains dipolar and quadrupolar contributions.

Table 1: Collimator Settings During Measurements

Name	Width [mm]	$\beta_{x,y}$ [m]	$k_\perp \beta_{x,y}$ [10^{15} V/C]
D06V1	2.74	61.4	15.2
D06V2	3.01	19.2	4.4
D03V1	8.02	17.0	0.9
D02V1	2.36	17.0	5.7
$\sum$V	–	–	26.2
D06H1	10.20	24.2	0.7
D06H3	12.05	24.2	0.5
D03H1	14.51	29.0	0.4
D02H1	8.99	17.7	0.7
D02H2	11.50	27.1	0.6
D02H3	18.00	51.5	0.4
D02H4	10.51	20.1	0.5
$\sum$H	–	–	3.9

RESULTS

Synchrotron radiation will damp the oscillation amplitude of a kicked lepton beam. For LER the expected transverse amplitude damping time due to synchrotron radiation, τ_{SR}, is roughly 46 ms, corresponding to about 4600 turns. Effects such as decoherence, resulting from a tune spread within the bunch, and head-tail damping contribute to the total damping time, τ, limiting the number of turns available for TbT measurements. For example, with $\tau = 22$ ms only the first 2200 turns provide a sufficiently large excitation. To first approximation, the total damping time τ is obtained as the inverse of the sum of the inverse damping times τ_n of all possible contributions n, i.e. $\tau^{-1} = \sum_n \tau_n^{-1}$ [21]. τ is retrieved from TbT measurements by fitting an exponential decay of the measured amplitude A over time by $A(t) = Ae^{-t/\tau}$ at each BPM. It is found that for increasing bunch currents τ decreases, namely from about 30 ms for 0.3 mA to 14 ms for 1.25 mA. The measured detuning with amplitude is fairly low, and in view of the small momentum spread the chromatic decoherence is expected to be small too. Therefore,

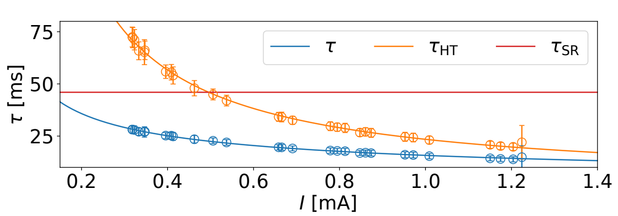

Figure 1: Measured damping time τ, synchrotron radiation damping time τ_{SR} and decoherence damping time τ_{HT} over bunch current. The blue line is a fit of a function $AI^{-1/2} + B$ ($A = 16.2 \pm 0.2$, $B = -0.5 \pm 0.2$) and the orange one of a function $AI^{-1} + B$ ($A = 22.2 \pm 0.2$, $B = 1.3 \pm 0.4$) .

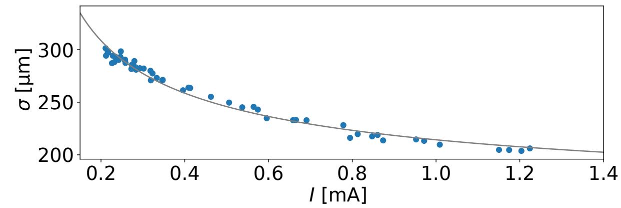

Figure 2: RMS BPM resolution (σ) over bunch current, using the first 1000 turns for analysis. The gray line is a fit of a function $AI^{-1/2} + B$.

the additional damping, τ_{HT}, is tentatively attributed solely to head-tail damping [21, 22]. τ_{HT} can be calculated from τ and the known τ_{SR}. τ_{HT} decreases from 72 ms to 20 ms as the bunch current is increased. The values of τ, τ_{HT} and τ_{SR} as a function of bunch current are shown in Fig. 1. Below 0.5 mA the total damping time is dominated by radiation damping, whereas above 0.5 mA head-tail damping is the main contributor. The head-tail damping would decrease with lower chromaticity [22].

The resolution of installed BPMs depends on the bunch current. BPMs capable of recording TbT orbit data in SuperKEKB are all button BPMs [23]. The BPM resolution at each BPM is estimated by subtracting the svd-cleaned orbit data from the measured one and then computing its rms. The resolution improves with increasing bunch current as seen in Fig. 2, where the first 1000 turns are used for optics measurements. The best BPM resolution of approximately 200 µm is found at the highest bunch current of 1.25 mA.

Due to the impedance the bunch experiences a tune shift with bunch current I,

$$\Delta Q = \frac{I}{4\pi E/ef_0} \sum_n \beta_n k_{\perp,n} \, , \tag{2}$$

with the revolution time f_0 =100 kHz and a summation over all wake-field sources n. For constant kick factors (constant bunch length) the contribution of the collimators listed in Table 1 would lead to a tune shift of approximately -0.78×10^{-3}

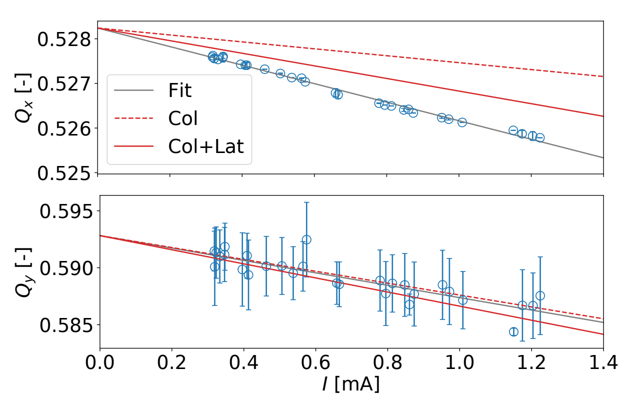

Figure 3: Horizontal (top) and vertical (bottom) tune over bunch current, for the fit, the expected collimator contribution (Col) and additional lattice contributions (Col+Lat).

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and -5.21×10^{-3} per 1 mA bunch current, respectively, for the horizontal and the vertical plane. Studies suggests a contribution from other lattice elements, such as RF, injection and extraction kickers or feedback elements, to lead to a $k_{\perp}\beta_{x,y}$ of 3.19×10^{15} V/C and 4.91×10^{15} V/C, increasing the expected tune shift to -1.41×10^{-3} and -6.19×10^{-3}. Fitting tunes, obtained from TbT data, over bunch currents gives a tune shift of, respectively, $(-2.08 \pm 0.04) \times 10^{-3}$ and $(-5.44 \pm 0.59) \times 10^{-3}$ per 1 mA, as shown in Fig. 3. The extrapolated tunes at zero current, Q_x and Q_y, are 0.5282 and 0.5928. It has to be noted that the larger vertical error bars arise since the beam is kicked only horizontally. Within the measurement error, the vertical tune shift with intensity can be fully explained by known sources, whereas for the horizontal plane they account for approximately 68% of the observed tune shift with intensity. The imaginary part of the effective transverse impedance Z_{eff} can be estimated from the slope of the tune shift with intensity $\mathrm{d}Q/\mathrm{d}I$,

$$\mathrm{Im}(Z_{\mathrm{eff}}) = \frac{8\pi^{3/2}\sigma_z E/e}{\langle\beta\rangle C}\frac{\mathrm{d}Q}{\mathrm{d}I}\,, \tag{3}$$

with the machine circumference C of 3 016.315 m and the average β-function over the ring, $\langle\beta\rangle$, of about 19 m and 24 m, respectively for the horizontal and the vertical plane. For increasing bunch currents σ_z increases too [24]. Neglecting this effect and assuming a constant σ_z of 5 mm [25] $\mathrm{Im}(Z_{\mathrm{eff}})$ results in about 32.7 ± 1.3 kΩ/m and 67 ± 20 kΩ/m.

The bunch current dependent phase advance between BPMs can help to localize strong transverse impedance sources and therefore could help explaining missing horizontal contributions. Similar to [17, 26–28] the phase advances at each BPM are fitted over several bunch currents, $\mathrm{d}\mu_x/\mathrm{d}I$, for horizontal TbT measurements. As wake-potentials lead to a negative quadrupolar kick [29] it is aimed to localize these sources from the intensity dependent phase advance and installed quadrupoles using a response matrix approach [30],

$$\mathbf{R}\,\overrightarrow{\Delta K} = \overrightarrow{\Delta\mu}\,, \tag{4}$$

where $\overrightarrow{\Delta K}$ are the resulting quadrupolar strengths to correct for a measured phase advance difference for different bunch currents $\overrightarrow{\Delta\mu}$. $\mathbf{R}$ is a $M \times N$ matrix, with M BPMs and N quadrupolar sources. In order to localize sources of wake-potentials more precisely it is assumed that each installed

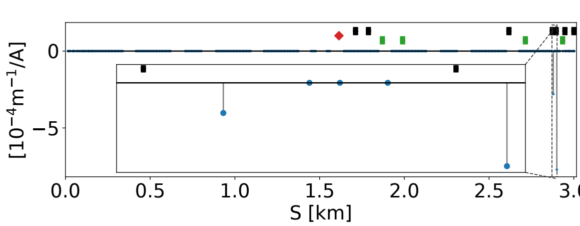

Figure 4: Quadrupole strengths required to reconstructed measured phase advance, including a zoom to the 2 powered correctors. The black and green bars show the location of horizontal and vertical collimators; the red marker the IK.

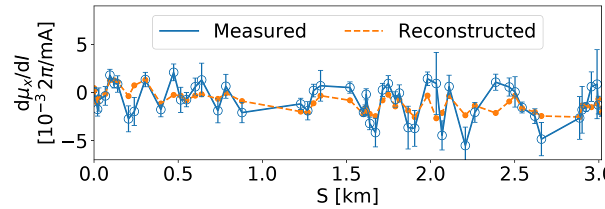

Figure 5: Measured and reconstructed horizontal phase advance over bunch current. BPMs with errors bars greater than $\pm 1 \times 10^{-2}$ 2π/mA are not shown.

quadrupole can be powered individually. Figure 4 shows the required change in negative quadrupole strength to correct for intensity dependent phase advance. Two peaks at $S = 2.88$ km and $S = 2.92$ km are found, tentatively suggesting strong impedance sources close to the 4th and 5th horizontal collimator. The reconstructed phase advance over bunch current using only 2 negative quadrupole gradients as shown in Fig. 4 is shown in Fig. 5 and leads to a rms intensity dependent phase beating of 1.4×10^{-3} 2π/mA. The measured one (rms phase beating of 2.0×10^{-3} 2π/mA) is shown in the same figure. This reconstruction can therefore explain about 72% of the measured value.

CONCLUSION

TbT optics measurements are performed for various bunch currents for LER. Although higher bunch currents improve the estimated BPM resolution, the number turns available for optics analysis decreases. For example at a bunch current of 1.25 mA an estimated BPM resolution of 200 µm is found. However, here, only the first 1500 turns are suitable for optics measurements, due to the short transverse damping time of approximately 14 ms. The observed rapid damping, which is faster than expected from synchrotron radiation, is attributed to head-tail damping and decoherence. Future studies can be performed at different chromaticities to help distinguish contributions from decoherence and head-tail damping, and to increase the total damping time at high bunch currents. Due to the transverse impedance the tune decreases with increasing bunch currents. The vertical tune shift can be explained solely from known wake fields sources, whereas only 68% of the measured horizontal tune shift with current is explained by those. Preliminary results suggest that 2 horizontal collimators significantly contribute to the horizontal tune shift. Using only the 2 found negative quadrupole strengths to reproduce the phase advance over bunch current can explain about 72% of the measured current dependent phase advance. Dedicated future studies aim to reduce this error and to localize, identify, and possibly mitigate other transverse impedance sources.

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