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SuperKEKB OPTICS MEASUREMENTS USING TURN-BY-TURN BEAM POSITION DATA

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Abstract

SuperKEKB, an asymmetric electron-positron collider, has recently achieved the world record instantaneous luminosity of 2.8×10^{34} cm^{-2s} using crab-waist collision scheme. In order to reach the design value of 6×10^{35} cm^{-2s} a vertical beta function at the interaction point of 0.3 mm is required, demanding unprecedented optics control. Turn-by-turn beam position data could enable fast optics measurements for rapid identification of unexpected error sources. Experiments exploring various data acquisition techniques at different squeezing steps during commissioning are presented and compared to results obtained from closed orbit distortion.

INTRODUCTION

SuperKEKB [1–3], an electron-positron double ring collider with a circumference of about 3.016 km, aims at a luminosity of 6×10^{35} cm^{-2s} [4] and demanding a vertical β-function at the interaction point (IP) β_y^* of 0.3 mm for the so-called nano-beam scheme, which is realised by colliding very low emittance beams under a large crossing angle. Recent studies [5] investigate an optics with β_y^* below this initial design. Accurate optics measurement and control are hence inevitable, motivating these studies.

The high energy electron ring (HER) and low energy positron ring (LER) provide a beam energy of, respectively, 7 GeV and 4 GeV. Analysed measurements are taken from May 2019 to February 2021, with β_y^* from 2 mm to 1 mm for both rings. β_x^* of 80 cm or 60 cm are used for both rings.

MEASUREMENT TECHNIQUES

Closed Orbit Distortion In SuperKEKB optics measurements using the Closed Orbit Distortion (COD) [6–8] method are well established and performed routinely. For the COD method around 466 Beam Position Monitors (BPMs) record the change of beam position after excitation with 6 corrector magnets, leading to a matrix containing large numbers of elements. Optics of both transverse planes are then reconstructed by analytical equations. As corrector strengths need to be varied one after another, COD is a rather time consuming procedure and it depends on BPM calibration.

K-Modulation β^* can be measured by varying quadrupoles close to the IP and measuring the change of tune Q, which is recently demonstrated for SuperKEKB [9]. This technique, known as K-modulation, relies strongly on the measured tune accuracy.

Turn-by-Turn Alternatively to COD Turn-by-Turn (TbT) measurements are performed in SuperKEKB, where 68 or 70 BPMs for TbT data are installed, respectively, in HER or LER. BPMs record orbit data over typically several thousand turns in both transverse planes, x and y, of excited beams, where 2 different excitation methods are used. In SuperKEKB TbT measurements are typically single bunch measurements, with bunch currents from 0.2 mA up to 1.5 mA. An Injection Kicker (IK) performs a single kick to excite the beam, where the particle motion is then damped due to synchrotron radiation in lepton storage rings. Transverse damping times are 46 ms and 53 ms, respectively, for the positron and the electron ring, corresponding to approximately 4600 and 5300 turns. Several IK are installed in both rings, however, only capable of performing horizontal kicks. Optics of the vertical plane can therefore not be measured accurately. A trigger system starts data acquisition automatically when the beam is excited. For IK excitation a bunch current of at least 0.2 mA is required to perform single kicks. Contrarily to single kicks, a continuous beam excitation is achieved by using a Phase Lock Loop (PLL). With a fixed phase the PLL driving frequency follows the natural tune, obtained from Fourier transform, where the PLL excitation amplitude is set manually. PLL is capable of exciting a single bunch in each beam in both transverse planes, where double-plane excitation is tested for the first time and presented here. Simultaneous excitation and measurement of both planes is required to measure transverse coupling and establishing good PLL excitations are inevitable for determining the vertical optics. An automatic trigger system for PLL is not installed, hence data acquisition needs to be started manually, where up to 50000 turns are recorded for measurements. To drive one bunch with PLL a bunch current of at least 0.5 mA is required. It has to be noted that fixing the driving frequency is tested for the first time but it does not so far improve the measurement quality.

The measured orbit data from BPMs is translated into the ASCII SDDS [10] format. Fourier transformation of the orbit data is performed using HARPY [11], including cleaning with algorithms based on Singular Value Decomposition (SVD) [12], to retrieve the harmonics spectrum, including transverse tunes $Q_{x,y}$ and phase advances μ between BPMs. Together with the SAD [13] model, the output of the harmonics analysis is used for optics calculation, where analysis software [14, 15] developed by the Optics Measurement

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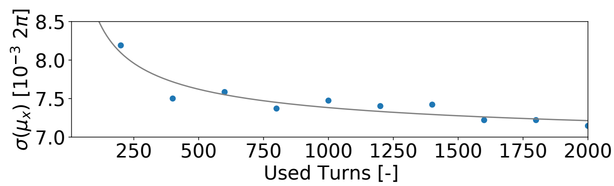

Figure 1: Horizontal rms phase advance error, $\sigma(\mu_x)$, for LER IK measurements for an optics with $\beta^*_{x,y} = 80, 2$ mm. The gray line is a fit of a function $A\, turns^{-1/2} + B$.

and Correction (OMC) team for the Large Hadron Collider (LHC) [16] is used. As the phase advance between BPMs is not close to $\pi/2$ the N-BPM method [17, 18] is suitable to retrieve the β-function. Due to observed possible BPM calibration errors the β-from-amplitude (β^{amp}) method is not used. Off-momentum optics measurements, such as dispersion η or chromaticity Q', demand the computation of the relative momentum offset δ_p by $\delta_p = \langle \eta_x^{\mathrm{mdl}}\, CO_x \rangle / \langle (\eta_x^{\mathrm{mdl}})^2 \rangle$, using the model horizontal dispersion (η_x^{mdl}) and the measured horizontal closed orbit CO_x. To cancel the effect of calibration errors normalised dispersion ($\eta^{\mathrm{n}} = \eta/\sqrt{\beta^{\mathrm{amp}}}$) is used [19]. BPM turn synchronization errors lead to phase advance errors with respect to the model, $\mu_{x,y} - \mu_{x,y}^{\mathrm{mdl}}$, of n times the natural tune $Q_{x,y}$. To correct these synchronization errors the BPM orbit readings need to be shifted by n turns, demanding to repeat harmonics and optics analysis. A maximum synchronization error of $n = 2$ is found.

RESULTS

A measurement campaign aiming to improve the measurement quality and to investigate in proper beam excitation with IK and PLL is performed. Results obtained from TbT are compared to COD measurements. Possible effects of bunch currents on optics measurements are discussed in [20]. BPM resolution in TbT mode, estimated by subtracting the raw orbit data from the cleaned one, is found to be approximately 120 µm and 250 µm at 1 mA bunch current, for HER and LER, and is therefore significantly poorer compared to BPM resolution for COD measurements of 5 µm and 3 µm, respectively.

Injection Kicker In addition to synchrotron radiation damping, decoherence is observed for IK LER measurements for all analyzed optics, leading to a transverse damping time of approximately 30 ms and therefore only the first

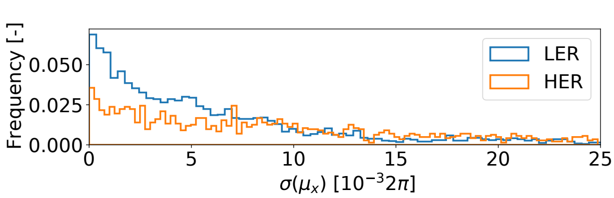

Figure 2: Horizontal rms phase advance error, $\sigma(\mu_x)$, for all BPMs using 2000 turns for IK measurements with $\beta^*_{x,y} = 80, 2$ mm.

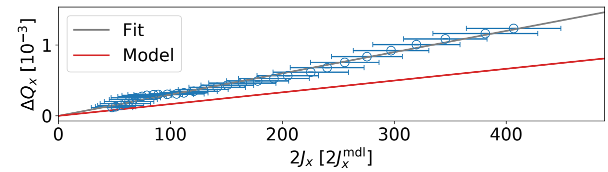

Figure 3: Horizontal amplitude detuning for LER optics $\beta^*_{x,y} = 80, 1$ mm.

3000 turns after the applied kick can be used for optics measurements. For HER measurements decoherence leading to a transverse damping time of 46 ms, corresponding to approximately 4600 turns, is found using an optics with $\beta^*_{x,y} = 60, 0.8$ mm. No decoherence is found for HER single bunch measurements with larger β^*. Using more turns for optics measurements decreases the rms horizontal phase advance difference with respect to the model, $\sigma(\mu_x)$, as seen in Fig. 1 for LER optics with $\beta^*_{x,y} = 80, 2$ mm. Hence, using the first 2000 turns results in the lowest $\sigma(\mu_x)$ of approximately $7 \times 10^{-3}\, 2\pi$ and $1 \times 10^{-2}\, 2\pi$, respectively, for single LER and HER measurements. The distribution of $\sigma(\mu_x)$ for all BPMs for both rings is shown in Fig. 2 for $\beta^*_{x,y} = 80, 2$ mm optics.

The measured tune Q depends on the action $2J_x$, which can be estimated using the $peak-to-peak$ of the excitation and the model β-function for all n BPMs by

$$2J_{x,y} = \frac{1}{n} \sum_n \frac{(peak-to-peak/2)^2}{\beta_{x,y,n}^{\mathrm{mdl}}}. \tag{1}$$

Analysing packages of 1000 consecutive turns with different starting turns lead to various actions and respective tunes. Horizontal amplitude detuning, $dQ_x/d2J_x$, resulting from octupolar and sextupolar fields, is measured by fitting obtained actions over tunes, where BPMs suspected to have a calibration error are excluded. It is about $(3.0 \pm 0.1) \times 10^{-3}\,\mathrm{m}^{-1}$ for LER optics measurements obtained in autumn 2019, for a model normalized horizontal emittance of 1.56 nm and a momentum spread of 6.37×10^{-4} and about a factor 2 larger than expected from the model. For HER optics with $\beta^*_{x,y} = 60, 0.8$ mm a 7.5 times larger than expected amplitude detuning of approximately $(29 \pm 1) \times 10^{-3}\,\mathrm{m}^{-1}$ is found, where for other HER optics no amplitude detuning can be measured. Figure 3 shows amplitude detuning for LER optics with $\beta^*_{x,y} = 80, 1$ mm. Off-momentum measurements allow to compute chromatic parameters such as chromaticity. For all LER measurements a purely linear chromaticity, Q'_x, of approximately

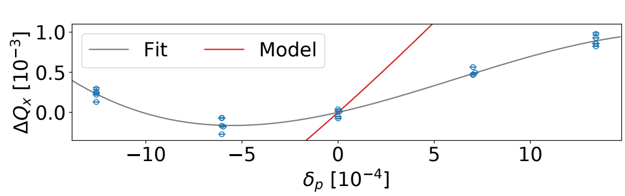

Figure 4: Chromaticity for HER with $\beta^*_{x,y} = 80, 2$ mm.

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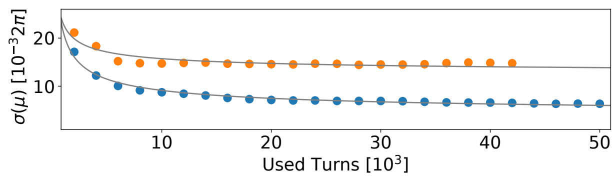

Figure 5: $\sigma(\mu_x)$ (blue), $\sigma(\mu_y)$ (orange) for measurements with PLL excitation in LER for an optics with $\beta^*_{x,y}$ = 80, 1 mm. The gray line is a fit of a function $A\,turns^{-1/2} + B$.

1.7 ± 0.04 is found. Using HER with a $\beta^*_{x,y}$ = 80, 2 mm, however, a $Q'_x = 0.54 \pm 0.04$ and a second-order chromaticity $Q''_x = 680 \pm 35$ is measured, as seen in Fig. 4. Model values are $Q'_x = 2.14$ and $Q''_x = 470$.

Phase Lock Loop The amplitude of the driven motion, estimated by the calculated action using Eq. (1), is approximately 5 to 10 times lower compared to IK excitation measurements for horizontal PLL measurements, and 12 times lower for vertical ones, for both rings, and hence amplitude detuning is negligible. In the frequency spectrum, with a frequency resolution below 1×10^{-5} only the main tune line is found for all measurements and it is therefore assumed that the PLL is capable of driving the beam at the natural tune. Similar to IK measurements, the error with respect to the model, $\sigma(\mu)$, decreases by using more turns for optics measurements, as seen in Fig. 5, for the average of 7 LER double plane PLL excitation measurements, with $\beta^*_{x,y}$ = 80, 1 mm. The vertical amplitude of the beam is stabilized for a maximum of 40000 turns, whereas 50000 turns are recorded horizontally. Compared to IK excitation a larger $\sigma(\mu_x)$ of about $6.5 \times 10^{-3}\,2\pi$ and a $\sigma(\mu_y)$ of about $15 \times 10^{-3}\,2\pi$ is found for PLL excitation.For HER a $\sigma(\mu_x)$ and $\sigma(\mu_y)$ of, respectively, $3.7 \times 10^{-3}\,2\pi$ and $7.5 \times 10^{-3}\,2\pi$ is achieved.

Comparison The relative difference between obtained β-functions from TbT and COD measurements, $(\beta^{\text{ph}} - \beta^{\text{cod}})/\beta^{\text{cod}}$, for both rings is found to be about 6% for IK measurements where the distribution for all BPMs is shown in Fig. 6, truncating outliers greater than ±25%. An example of calculated β-beating with respect to the model, $(\beta - \beta^{\text{mdl}})/\beta^{\text{mdl}}$, for HER optics with $\beta^*_{x,y}$ = 80, 2 mm for IK excitation is shown in top Fig. 7. For COD only BPMs also capable of recording TbT data are shown. The rms β−beating is 5.0% and 4.8%, respectively, for IK TbT and COD measurements and are therefore in good agreement. However, the rms error for TbT measurements is

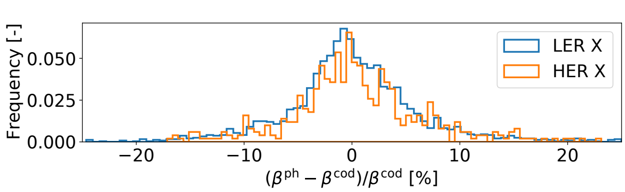

Figure 6: β-beating between COD and IK TbT measurements for LER (blue) and HER (orange).

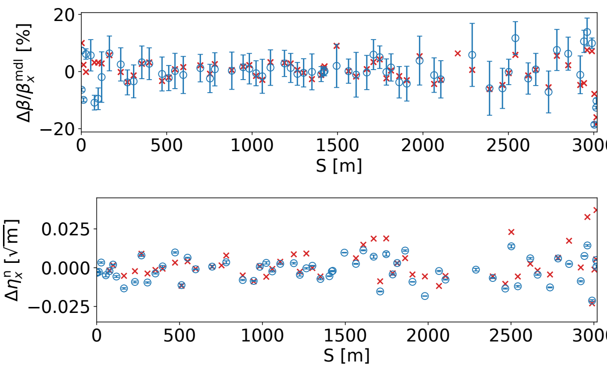

Figure 7: Horizontal β-beating (top) and η^{n} (bottom) with respect to the model for COD (red crosses) and TbT (blue circles) measurements for HER optics with $\beta^*_{x,y}$ = 80, 2 mm.

about 5.5% and therefore comparable with the obtained rms β-beating. Local discrepancies are found close to the IP, where a larger β-beating is measured with TbT measurements than with COD. Normalised dispersion errors with respect to the model, $\Delta\eta^{\text{n}} = \eta^{\text{n}} - \eta^{\text{n,mdl}}$, are shown in bottom Fig. 7 for HER optics with $\beta^*_{x,y}$ = 80, 2 mm and IK excitation. A rms $\Delta\eta^{\text{n}}$ of 0.026 $\sqrt{\text{m}}$ and 0.017 $\sqrt{\text{m}}$ are measured, respectively, using TbT and COD measurements and are therefore in good agreement. Comparing β-functions for PLL excitations a horizontal and vertical β-beating with respect to COD results of, respectively, 14% and 20% are found.

CONCLUSION

Optics measurements using TbT data for IK and PLL excitation are performed for various optics for both rings. Using the IK the beam is only kicked horizontally and hence vertical optics cannot be measured precisely. Larger actions with respect to PLL excitation, and synchrotron radiation damping allow to measure amplitude dependent effects. PLL double-plane excitation allows to measure optics of both transverse planes simultaneously. It is found that at least 20000 turns for TbT measurements are required to reduce the phase advance beating with respect to the model. Measured β_x from IK TbT data and COD measurements agree within a precision of about 6%, where local outliers are found close to the IP. For PLL measurements the error with respect to COD is higher and about 14% and 20%, respectively, for β_x and β_y. Increasing PLL driving amplitude is assumed to improve optics measurements and is therefore aimed to be performed in future runs. Investigations to reproduce observations in simulations are currently ongoing and will help to understand discrepancies and to identify error sources.

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