INVESTIGATIONS IN TURN-BY-TURN OPTICS MEASUREMENTS AT KARA[*]

J. Keintzel[†], R. Tomás, and F. Zimmermann, CERN, Geneva, Switzerland; E. Blomley,
B. Härer, J. Gethmann, E. Huttel, A.-S. Müller, J. L. Steinmann, KIT, Karlsruhe, Germany

Abstract

The Karlsruhe Research Accelerator (KARA) is a synchrotron light source user and test facility, operating at an electron beam energy ranging from 0.5 to 2.5 GeV. Performing optics measurements and comparing with the machine model promises an improved understanding of the lattice and the underlying beam dynamics. Horizontal and vertical turn-by-turn Beam Position Monitor data are acquired and used for performing optics measurements in this storage ring. The results of these studies are presented in this paper.

MOTIVATION

One of the key concepts for the Future electron-positron Circular Collider, FCC-ee [1], is precise centre-of-mass determination at all interaction points. This requires excellent knowledge of the beam energy, which will be measured using Resonant Depolarisation (RDP) scans with previously polarised pilot bunches, as described in [2, 3]. RDP scans are also regularly performed at the Karlsruhe Research Accelerator (KARA) [4], previously known as ANKA [5]. The systematic effects of this technique, which could also be relevant for FCC-ee, are currently being investigated as described in [6]. The results of RDP scans could be spoiled by large orbit and optics errors. To exclude that KARA RDP scans [6] are compromised by such orbit or optics errors, and to establish an optics model for planned future benchmarking simulations of KARA beam polarisation, we are carrying out transverse beam optics measurements at KARA. The initial results are presented in this paper.

At KARA the transverse beam optics is typically measured using K-modulation. For this, the quadrupole gradients are varied and the change of the tune is measured in order to determine the average β-function at each quadrupole. However, since the strength of each quadrupole must be varied, this is a rather time consuming procedure. By contrast, Turn-by-Turn (TbT) optics measurements allow for a fast evaluation of the beam optics at all Beam Position Monitors (BPMs). Therefore, we investigated the feasibility of applying this technique at KARA. First results are compared with model predictions.

RESEARCH ACCELERATOR KARA

Located at Karlsruhe Institute of Technology (KIT), KARA is a synchrotron light source and test facility with a circumference of 110 m and an 500 MHz RF system. KARA is a machine ramping in beam energy from 0.5 to 2.5 GeV. It features a four-fold super-periodicity, where each sector consists of two double bend achromat (DBA) cells, with straight sections in-between, hosting, the RF system, injection magnets or other insertion devices. The double DBA optics for one quarter of the KARA ring is shown in Fig. 1. Each quarter consists of 4 dipoles, 10 quadrupoles, 6 sextupoles and 10 BPMs. They are displayed in the same plot, in blue, red, green and black colour, respectively. It was designed with a flexible lattice [7], which allows for non-dispersive straight sections, low or negative momentum compaction factor optics and theoretical minimum emittance optics [8]. The latter is used during the measurements presented in this paper, with design horizontal and vertical betatron tunes of 6.763 and 2.821, respectively. The model includes the quadrupole and sextupole settings during during the measurement and the measured pole face angles of 9° instead of the nominal 11.25°. No fringe field integrals are considered.

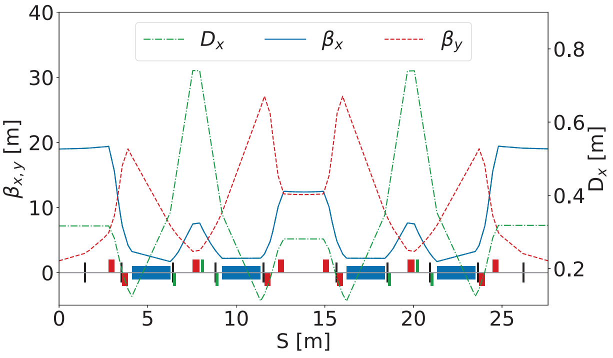

Figure 1: β-functions and lattice of the first quarter of KARA light source. Focusing (defocusing) elements are shown above (below) the horizontal axis.

OPTICS MEASUREMENTS

Transverse optics measurements were performed at the top energy of 2.5 GeV and the injection energy of 0.5 GeV.

Procedure and Set-up

For these optics measurements a total beam current of about 60 mA was stored, spread over roughly 30 bunches. The filling pattern is shown in Fig. 2.

Here, the transverse optics is measured based using a TbT technique, where all bunches of the stored beam are excited using one horizontal injection kicker, while recording the centre-of-charge position for all bunches over a total of 2048 turns. Since the injection kicker excitation is applied for 6 consecutive turns, only data recorded after these 6

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[†] jacqueline.keintzel@cern.ch

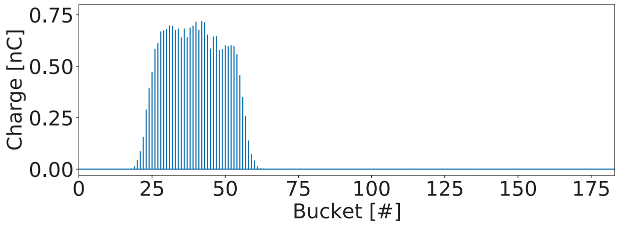

Figure 2: Bunch filling pattern during optics measurements.

turns is processed to ensure that this data corresponds to a free oscillation. The excitation occurs after 312 turns, implying that data from 1724 turns are available for the optics measurements. Synchrotron radiation (SR) naturally damps the oscillation amplitude after a kick. Hence, this technique is not invasive for lepton beams. The SR damping time from the optics model of 3 ms at 2.5 GeV is equivalent to 8150 turns. However, fitting an exponential decay to the measured TbT BPM data reveals a significantly shorter damping time of only 0.7 ms, corresponding to 1900 turns, as is shown in Fig. 3. This could be due to decoherence caused by second-order chromaticity or amplitude detuning, as we discuss later.

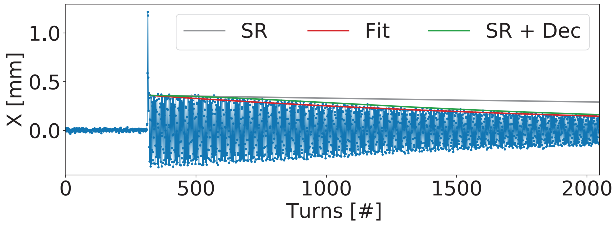

Figure 3: Measured horizontal TbT orbit together with the expected damping from SR, the fitted envelope (Fit) and additional decoherence (Dec).

Although the excitation is purely horizontal, a resulting oscillation in the vertical plane is also observed, as is seen in Fig. 4, albeit with more noise. This indicates the presence of non-negligible betatron coupling.

The measured TbT position data from BPMs is translated into ASCII SDDS [9] format. The optics measurements are processed using OMC3 [10], a code framework developed at CERN, which also accesses the machine model. Cleaning based on Singular Value Decomposition (SVD) is performed, where 4 singular values are retained. For measuring dispersion D or chromaticity, we compute the relative momentum offset δ_p as

$$\delta_p = \langle D_x^{\mathrm{mdl}}\, CO_x \rangle / \langle (D_x^{\mathrm{mdl}})^2 \rangle \tag{1}$$

using the model horizontal dispersion (D_x^{mdl}) and the measured horizontal closed orbit CO_x. The angular brackets, $\langle \cdot \rangle$, signify an average over all BPMs.

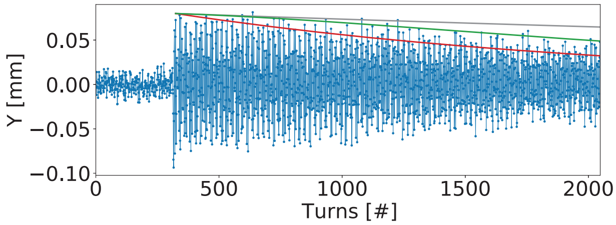

Figure 4: Measured vertical TbT orbit together with the expected SR damping, the fit and additional decoherence.

Results at Top Energy

First transverse TbT optics measurements were performed at top energy, since a complementary measurement campaign for RDP scans had been carried out at 2.5 GeV, as reported in [6]. Fractional horizontal and vertical betatron tunes are found to be 0.766 and 0.819, respectively, with a measurement error of 10^{-5}. The deviation from the MAD-X model is 0.003 and −0.002, respectively. By contrast, the codes Ocelot [11] and OPA [12], using the actual magnet settings, both predict KARA horizontal and vertical tunes of 6.760 and 2.815, respectively, so that the tune deviations with respect to these models are +0.008 and +0.004. The Ocelot and OPA models take into account, in an approximate way, the saturation of the magnets, which is modelled as causing an effective reduction of the entrance angle to 9°. Investigating other possible sources for the discrepancies between expected and measured tunes, in particular in the vertical plane, the longitudinal, horizontal and vertical mechanical misalignments of all dipoles, quadrupoles and sextupoles were measured. This information is currently being used to construct an improved optics model, which could shed further light on the observed discrepancies.

From the average BPM readings, the horizontal and vertical rms closed orbits (see Fig. 5) are 125 and 100 µm.

The relative error of the β-function with respect to the model, known as β-beating, is inferred using the so-called β from amplitude method [13, 14]. Although this technique would be spoiled by BPM calibration errors, Fig. 6 illustrates a rather low rms β-beating of 1.1 % horizontally and 0.5 % vertically. Instead of using the amplitude information for determining the β-function, the β-functions can also be inferred from the betatron phase advance [13, 15–17]. However, phase advance measurements at KARA were found to be not conclusive due to large fluctuations and errors with respect to the model. This could be due to the delays in the BPM cables. Cable delay measurements indicate a possible ambiguity of up to a few turns depending on the BPM.

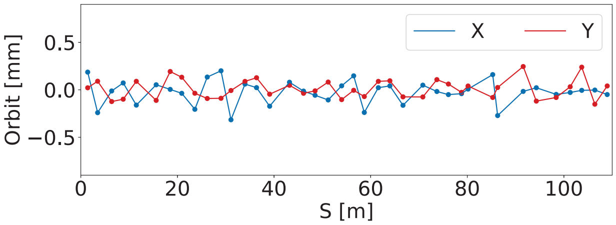

Figure 5: Measured closed orbits at top energy.

Timing-in all BPMs would be an improvement for future measurement campaigns.

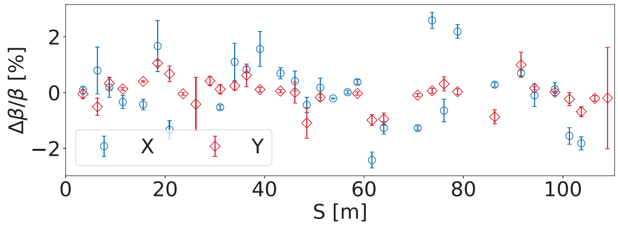

Figure 6: Measured relative error of the β-function with respect to the model at top energy.

To obtain the off-momentum optics the RF-frequency was shifted by roughly ±15 kHz, resulting in a relative momentum offset of $\mp 3 \times 10^{-3}$. An rms dispersion error of 40 mm horizontally and 12 mm vertically was measured. Notably, the majority of BPMs observe a lower horizontal dispersion than predicted by the model, especially in sector 3 (between $S = 55$ and 82.5 m), as is shown in Fig. 7. Since data was acquired at only three distinct energies, possible second-order dispersion [18] could not be reliably determined.

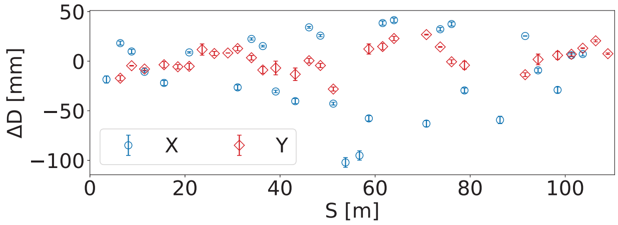

Figure 7: Horizontal and vertical dispersion error with respect to the model at top energy.

Figure 8 shows the measured $Q_{x,y}(\delta_p)$ with a fit

$$Q_{x,y}(\delta_p) = \sum_{n=0}^{\infty} (1/n!)\, Q_{x,y}^{(n)}\, \delta_p^n \qquad (2)$$

up to $n = 2$ from which first and second order chromaticity can be inferred. Horizontally a first and second order chromaticity of $Q'_x = -0.477 \pm 0.005$ and $Q''_x = 276 \pm 6$ are obtained, and vertically $Q'_y = -0.813 \pm 0.006$ and $Q''_y = 160 \pm 7$. The predicted second-order chromaticity from the MAD-X model is $Q''_x = 41$ and $Q''_y = 32$. Roughly the same values were obtained two decades earlier (when KARA was still called ANKA) [19], when the discrepancies in $Q''_{x,y}$ were attributed to octupolar fields due to feed-down from a decapole component in the bending magnets with a transverse offset. In the future we would like to cover a larger momentum range to better access the higher-order chromaticities [19, 20]. Decoherence from measured Q''_x and Q''_y [21, 22] explains the observed orbit damping assuming an energy spread of 1×10^{-3} and a synchrotron tune of 0.016, as shown in Figs. 3 and 4. By measuring the tunes and the corresponding oscillation amplitudes at various excitation strengths we can also probe the detuning with amplitude; see e.g. [23]. However, here the amplitude errors were found to be too large compared with the size of the tune change.

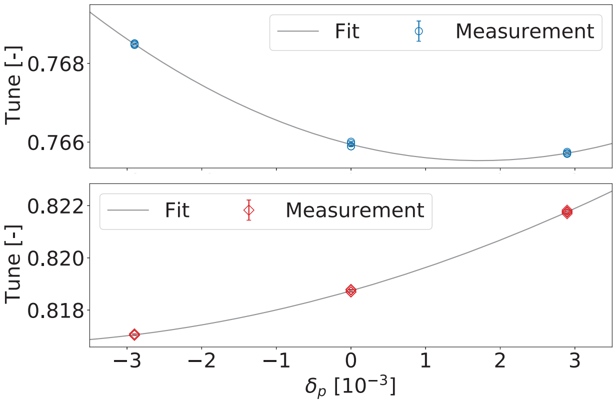

Figure 8: Horizontal (top) and vertical (bottom) chromaticity measurements together with a quadratic fit at top energy.

Results at Injection Energy

TbT position data were acquired at injection after the filling was completed with the same beam current as at top energy. Here, only on-momentum measurements were performed. Measured relative rms β-function errors with respect to the model, shown in Fig. 9, are 5.8 % and 2.6 % respectively, which is a factor 4 or 2 larger than at top energy. Vertically only half of the BPMs remain after cleaning, which remains to be investigated.

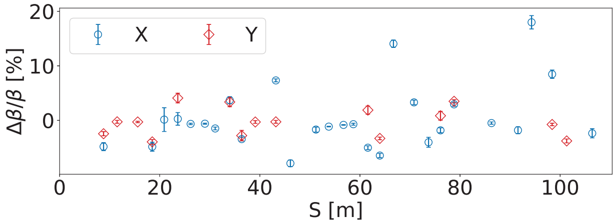

Figure 9: Horizontal and vertical measured relative error of the β-function with respect to the model at injection energy.

SUMMARY AND OUTLOOK

A series of transverse optics measurements were performed in the synchrotron light-source KARA at 0.5 and 2.5 GeV. A reasonable agreement with the available optics models was found. At top energy a low rms β-beating of less than 1.1 % was measured, along with a horizontal and vertical spurious rms dispersion of 40 and 12 mm, respectively, with largest errors in sector 3. Up to second-order chromaticity was determined in both planes. At injection energy a larger rms β-beating of 3–6% is found. Effort is currently underway to construct a more realistic machine model, including the measured element misalignments. This model should allow benchmarking FCC-ee software tools for spin polarisation on KARA.

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