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AMPLITUDE DEPENDENT TUNE SHIFT MEASUREMENTS AT KARA

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Abstract

KIT operates the storage ring KARA (Karlsruhe Research Accelerator) as an accelerator test facility, which serves as a testbed for different electron beam-based experiments. Thus, it motivates to study the beam conditions extensively. To extend the existing characterisation of non-linear parameters, the amplitude dependent tune shift (ADTS) was measured. ADTS is typically controlled by octupole magnets in a storage ring, which are not available at KARA, but the installed insertion devices exert a certain octupole component on the beam resulting in a change of the ADTS. This contribution presents measurements of the amplitude dependent tune shift for different combinations of active insertion devices.

INTRODUCTION

The storage ring KARA (Karlsruhe Research Accelerator) is a 2.5 GeV electron synchrotron and light source with a circumference of 110.4 m. The ring consists of a fourfold double bend achromat lattice. However, it is usually operated in a mini-beta configuration [1] minimising the vertical beta function in the long straight sections where insertion devices are located. As KARA is a ramping machine with an injection energy of 0.5 GeV the insertion devices can be completely deactivated (physically opening the gap, in case of permanent magnet devices, or turned off, in case of superconducting electromagnetic devices). This provides the possibility to investigate the effects of each insertion device individually. There are five insertion devices installed in KARA at the moment, three of them are electromagnetic while two consist of permanent magnets:

- CLIC - Superconducting wiggler [2] designed as damping wiggler for the CLIC project
- CAT-ACT - Superconducting wiggler used in X-ray spectroscopy for catalysis and actinide research [3]
- SUL - Permanent magnet wiggler used for X-ray imaging [4]
- X-SPEC - Permanend magnet undulator used for X-ray and electron spectroscopy [5]
- SCU20 - Superconducting undulator developed at KIT together with Bilfinger Noell [6]

In its function as accelerator test facility, KARA serves as a test-bed for different electron beam-based experiments. In this regard, a good knowledge of the linear and non-linear parameters is beneficial. One such non-linear parameter is the amplitude dependent tune shift (ADTS) [7]. Which, in short, is the change of tune, or oscillation frequency, of a particle with a certain amplitude in the transverse position

$$\nu_i = \nu_i(A_i) \tag{1}$$

where ν_i, with $i = \{x, y\}$, is the tune and A_i is the transverse amplitude. Knowledge of the ADTS allows to avoid resonances when significant transverse amplitudes are required for an experiment and also allows to make estimates about instabilities (e.g. [8]). In general, the ADTS is also interesting with regard to injection as, depending on the injection scheme, the injection kickers can lead to large amplitudes. In the case of the CLIC wiggler, the ADTS was previously studied as function of magnetic field strength in [9].

MEASUREMENT

In order to measure the amplitude dependent tune shift, an artificial amplitude was introduced to the beam by means of an injection kicker in the horizontal plane. The resulting position oscillation was recorded with a beam position monitor (BPM) read out on a turn-by-turn basis. For the analysis the BPM with the cleanest oscillation pattern was selected as it allows the best frequency and, thus, tune determination.

As the amplitude is damped with time due to synchrotron radiation damping, the tune has to be determined on a small number of turns as to not mix the tune for different amplitudes. A Fourier transformation would result in low accuracy with the limited number of data-points. Therefore, the NAFF (Numerical Analysis of Fundamental Frequencies) algorithm [10] was used in python. Two packages are readily available, PyNAFF [11] and NAFFlib [12]. Results of both of them were compared and are identical up to the precision required for the measurements presented here. Due to its superior calculation speed NAFFlib was chosen in the end.

An example for the beam position after a horizontal kick is shown in Fig. 1. In theory the amplitude dependence of the tune can be determined from a single measurement by selecting a different range of turns after the initial kick as the amplitude naturally changes. However, after a certain time, when the injection kicker field is small, the damping is continuous and the amplitude changes over even a few turns. Therefore, the measurements were performed with different kicker strengths and the analysis was performed on data in the plateau after the initial kick. That way it is ensured, that the amplitude is fairly constant over the range of turns used for the analysis with an amplitude variation below 0.05 mm. The measurement was automated where several measurements were automatically taken per kicker strength for several different kicker strengths.

The orbit is not centered in the BPM which results in an oscillation around a finite value. To correct this and improve the accuracy of the NAFF calculation, the average beam

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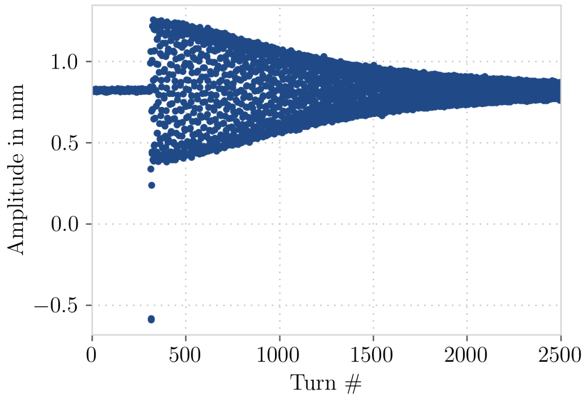

Figure 1: Turn-by-turn measurement of the horizontal beam position after a kick, in the horizontal plane, using an injection kicker. The initial low amplitude before the kick, the kick itself and the subsequent oscillations are clearly visible. Also visible is the damping effect resulting in the reduction of the amplitude with time.

position is subtracted. This centers the oscillations around zero.

As apparent form Fig. 1, there is a significant peak after the kick which is very quickly damped away after a few turns. Since this peak would perturb the analysis, 100 turns after this peak are used. The determination of the amplitude is then performed on these turns by using the 95 percentile of the absolute value (after subtraction of the mean).

RESULT

As reference, the tunes for kicks with no active insertion device were measured and the resulting data for this case is shown in Fig. 2. A clear trend is visible increasing the tune for higher amplitudes corresponding to a positive amplitude dependend tuneshift.

The same measurement was performed after activating the first insertion device (CLIC-Wiggler). The result is shown in Fig. 3. The highest amplitude achieved is slightly reduced compared to the case with no insertion device as the kicker strength was reduced in order not to damage the insertion device (due to the initial large amplitude). A clear change of tune as function of amplitude is visible in this case as well.

The measurements were repeated by activating all five insertion devices one after the other while measuring at each step. The resulting amplitude dependent tune shifts are shown in Fig. 4. The tune shift was calculated as a linear fit to the tune as shown in Figs. 2 and 3 to the equation

$$\nu_{\mathrm{x}}(A_{\mathrm{x}}) = m_{\mathrm{ADTS}} \cdot A_{\mathrm{x}} + b \tag{2}$$

where m_{ADTS} is the ADTS.

The entire measurement for all insertion devices combined took about one hour. The beam current decreased in this time by about 0.35 mA (about 1.5 %), which corresponds to approximately 0.01 mA in decreased bunch currents as the machine was filled with one train of about 33 bunches. Due to this small current decrease it is deemed that the current dependent tune shift is negligible for the presented measurements and the observed tune shift is due to the ADTS.

The individual insertion devices change the ADTS quite differently. While activating the first and last insertion devices (CLIC and SCU20) had almost no effect on the ADTS, the activation of CAT-ACT or X-Spec had a significant one and even changes the ADTS from positive to negative values

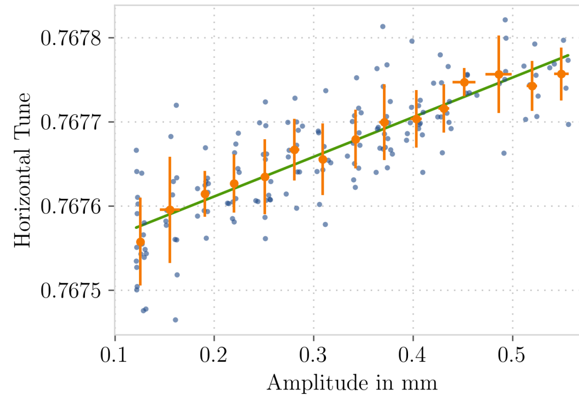

Figure 2: Tune for different amplitudes with no insertion devices active. The tune was determined with NAFFlib based on 100 turns after the initial kick. Blue dots correspond to individual measurements. Measurements with the same kicker strength resulted in different tunes and amplitudes. The orange dots correspond to the mean amplitude and tune for measurements of the same kicker strength. The errorbars show the standard deviation in amplitude and tune. The green line shows a linear fit to the data.

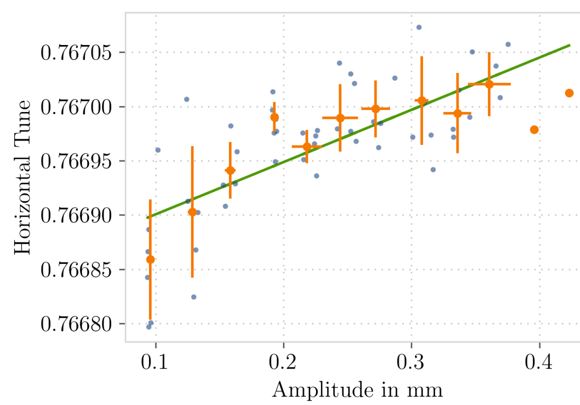

Figure 3: Tune for different amplitudes with one insertion device active (CLIC-Wiggler). The tune was determined with NAFFlib based on 100 turns after the initial kick. Blue dots correspond to individual measurements, orange dots correspond to mean amplitude and tune for measurements with the same kicker strength and the green line show a linear fit (c.f. Fig. 2).

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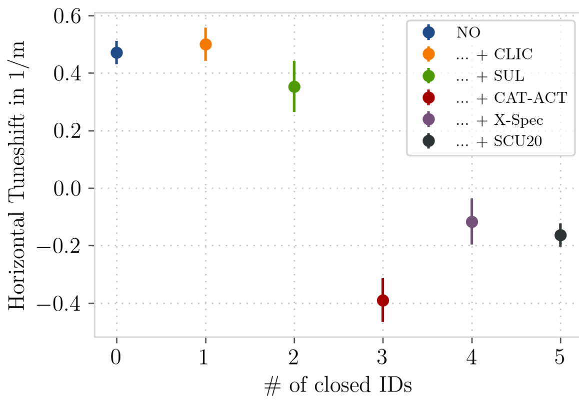

Figure 4: Linear tune shift for different insertion devices active. The data was determined by means of a linear fit ($\nu_x(A_x) = m \cdot A_x + b$, see Figs. 2 and 3) to the change in tune. The vertical error-bars signify the fit uncertainty of the fitted slope.

Table 1: Change of the ADTS produced by each insertion device. The data was calculated as the difference of ADTS shown in Fig. 4 before and after activating the respective insertion device.

ID	Change of ADTS in m^{-1}
CLIC	0.029
SUL	-0.147
CAT-ACT	-0.743
X-Spec	0.273
SCU20	-0.047

in the case of CAT-ACT. The effect of each insertion device is shown in Table 1.

Some insertion devices seem to exhibit significant octupole components resulting in the presented change of the ADTS. For the CAT-ACT wiggler this was also previously discussed in [13]. As there are no dedicated octupoles present in KARA it is not possible to correct for these additional components excerted by the insertion devices.

SUMMARY

At KARA the amplitude dependent tune shift can not be directly influenced as no dedicated octupole magnets exist. However, the insertion devices excert octupole magnetic field components which can affect the beam dynamics. Therefore, the horizontal ADTS has been measured for no activated insertion device as well as for activated insertion devices where one was activated after the other and the ADTS was measured at each step. The measurements were performed by introducing an artificial horizontal amplitude via an injection kicker and the tune was calculated using the NAFF algorithm from measured turn-by-turn beam position data. While three of the insertion devices had only small effects, the remaining two, CAT-ACT and X-Spec, had a significant effect. The superconducting wiggler CAT-ACT (at 2.1 T) had the largest effect, resulting in a change of the ADTS by almost $-0.75\,m^{-1}$. In the future the presented measurements and results will enable further studies into the octupole components of these insertion devices and the associated change in non-linear optics.

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