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NON-LINEAR BEAM DYNAMICS STUDIES OF THE CLIC DAMPING WIGGLER PROTOTYPE

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Abstract

First beam dynamics studies of a damping wiggler prototype for the CLIC damping rings have been carried out at the KIT storage ring. Effects of the 2.9 T superconducting wiggler on the electron beam in the 2.5 GeV standard operation mode have been measured and compared with theoretical predictions. Higher order multipole components were investigated using local orbit bump measurements. Based on these findings the simulation models for the storage ring optics have been adjusted. The reined optics model has been applied to the 1.3 GeV, low-operation case. This case will be used to experimentally benchmark beam dynamics simulations involving strong wiggler fields and dominant collective effects. We present these measurements, comparisons and the findings of the simulations with the updated low-mode optics model.

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First beam dynamics studies of a damping wiggler prototype for the CLIC damping rings have been carried out at the KIT storage ring. Effects of the 2.9 T superconducting wig-gler on the electron beam in the 2.5 GeV standard operation mode have been measured and compared with theoretical predictions. Higher order multipole components were investigated using local orbit bump measurements. Based on these findings the simulation models for the storage ring optics have been adjusted. The refined optics model has been applied to the 1.3 GeV, low-α operation case. This case will be used to experimentally benchmark beam dynamics simulations involving strong wiggler fields and dominant collective effects. We present these measurements, comparisons and the find-ings of the simulations with the updated low-α mode optics model.

INTRODUCTION

Within a collaboration of CERN, BINP and KIT a superconducting damping wiggler prototype for the CLIC damping rings has been developed and installed at KIT's electron storage ring in 2016 [1]. With the low-α mode one has a test bed for the wiggler's operation with collective effects which might be an issue in the CLIC damping rings. As a prerequisite to the more critical experiments in a low-α optics at a beam energy of 1.3 GeV possible disturbances due to the wiggler operation in the regular user operation optics were carefully studied. Such disturbances could potentially originate from misalignments or multipole fields of the wiggler. For investigating these effects orbit bump measurements and amplitude-dependent-tune-shift measurements were used. In parallel, simulations with elegant [2] and MAD-8 [3] have been carried out to identify the origins of the effects introduced by the wiggler and to improve the predictive power of the simulation models.

MEASUREMENTS

Local octupole components of the wiggler's magnetic field causing dynamic field integrals do not necessarily show up in stretched wire measurements [4] but might nonetheless cause problems, like e. g. a reduced lifetime. Since the lifetime was reduced by the CAT-ACT wiggler (see [5]) it is interesting to investigate this as well for the CLIC damping wiggler prototype. At KIT's storage ring we used two different approaches to examine octupole components of the wiggler which are detailed in the following.

Local Orbit Bump

An orbit bump shifts the beam locally in the wiggler and thereby can be used to map the response of the beam on the wiggler's magnetic field as a function of transverse position. As noted in [4, 6] a quadratic shift of the tune indicates an octupole component. Sextupole components or other even multipoles are not expected since the wiggler is symmetric in the deflection direction x.

To shift the beam inside the wiggler we use a local four corrector bump. These corrector magnets are placed around the wiggler to avoid deflection angles inside the wiggler. Since there are only four times four correctors available in the vertical plane, we must use all correctors of a fourth of the ring to bump the beam. In the horizontal plane there are 28 correctors around the ring. There are no other magnets between the wiggler and the two neighbouring correctors. We observe that the orbit as a whole moves in the opposite direction of the bump when applying the bump. Figure 1 shows one example orbit bump measurement.

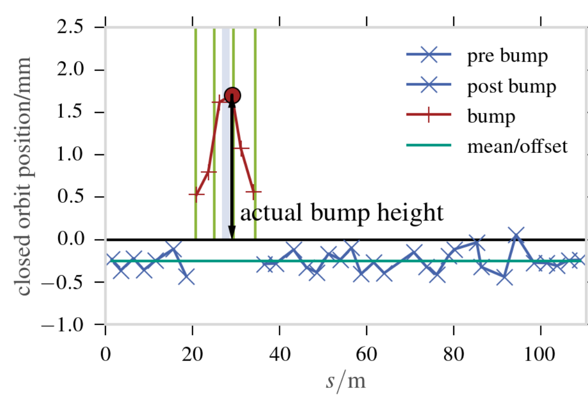

Figure 1: *Example orbit bump* The red colored part (with + as marker) is between the bumping correctors and therefore not taken into account for averaging the orbit (blue, × as marker). For the calculations the bump amplitude (arrow) is the difference between the maximum BPM amplitude (red dot) and the closed orbit. The position of the wiggler is indicated by the vertical blue band and the position of the horizontal corrector by the vertical light green lines.

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In parallel we measured the vertical and horizontal tune with a strip line.

First a 2d-map of the tune shift as a function of the horizontal position was measured in order to check the wiggler alignment. The scans showed symmetric behaviour along the horizontal x and vertical y axis, so we concluded that the alignment is sufficient and the wiggler is not skewed. Further scans were only taken along the transverse axes, only bumping in one direction at a time. Each data point is composed of four individual measurements.

- A reference measurement without any bump nor wiggler field,
- a measurement with a bump, but no wiggler field,
- a measurement without a bump, but with a dedicated wiggler field, and
- a measurement with both, a bump and the dedicated wiggler field.

With the first two measurements one spurious influence of the raw bump and possible orbit distortions on the tune shift are determined. Whereas with the second two measurements we get the influence for the wiggler. The difference between the two differences then gives us the effect of the wiggler on the bumped beam.

In the horizontal plane we reached the limits of the kicker magnets at 2.5 GeV and could bump the beam by −3 mm to 2.5 mm. As can be seen in Fig. 2 for the horizontal and in Fig. 3 for the vertical plane there is an effect of the wiggler which is compatible with an parabola and therefore with an octupole component. But since the variation of the measured data is dominant one cannot clearly quantify the effect at this point, but a more detailed measurement is justified. The limits in the vertical plane do not come from the kicker magnet strength, but from beam stability issues and beam pipe limitations. We could not go beyond −2.8 mm to 2.8 mm without wiggler field in that plane. The uncertainty on the measurements at 2.5 GeV caused us to also evaluate other methods, described in the next section.

To separate the effects caused by the wiggler from effects caused by the ring itself one needs to also evaluate measurements done at different beam energies, to distinguish between field errors (proportional to $1/E$) and second-order effects (proportional to $1/E^2$). Tests at the other established operation modes of the KIT storage ring (0.5 GeV, 1.3 GeV, and 1.6 GeV) showed difficulties with high wiggler fields. First tests to ramp the wiggler at injection energy (0.5 GeV) did not succeed to more than 0.2 T, where we lost the beam. At 1.3 GeV within the low-α mode operation, the maximum wiggler field for stable operation was at 1.4 T. The causes for this need to be investigated in detail.

Amplitude Dependent Tune Shift (ADTS)

Another method to investigate octupole components of an insertion device is the amplitude dependent tune shift measurement through beam excitation. Here the beam is excited and the tune is measured depending on the excitation strength. As mentioned in e. g. [7] the ADTS follows the

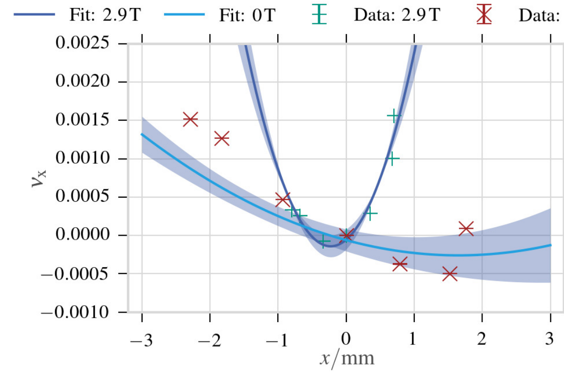

Figure 2: Horizontal tune shift with horizontal bump. Quadratic fit to the data with no wiggler field and with $B_w = 2.9$ T:
$\nu(x) = 0.13(4) \cdot 10^{-3} \frac{x^2}{\mathrm{mm}^2} - 0.32(6) \cdot 10^{-3} \frac{x}{\mathrm{mm}} - 0.06(14) \cdot 10^{-3}$
$\nu(x) = 1.3(2) \cdot 10^{-3} \frac{x^2}{\mathrm{mm}^2} + 0.63(11) \cdot 10^{-3} \frac{x}{\mathrm{mm}} - 0.06(12) \cdot 10^{-3}$

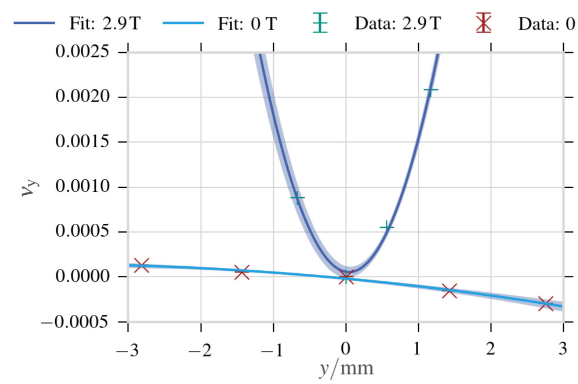

Figure 3: Vertical tune shift with vertical bump. Quadratic fit to the data with no wiggler and $B_w = 2.9$ T:
$\nu(y) = -9(3) \cdot 10^{-6} \frac{y^2}{\mathrm{mm}^2} - 80(5) \cdot 10^{-6} \frac{y}{\mathrm{mm}} - 0.02(6) \cdot 10^{-3}$
$\nu(y) = 0.001\,60(11) \frac{y^2}{\mathrm{mm}^2} - 0.10(8) \cdot 10^{-3} \frac{y}{\mathrm{mm}} + 0.06(2) \cdot 10^{-3}$

relation coming directly from the field equations of motion for a particle in a wiggler

$$\frac{\Delta \nu_y}{y^2} = \frac{\pi}{4} \frac{L_w}{\lambda_w^2} \frac{\beta_y e^2}{p^2} B \cdot B \qquad (1)$$

where L_w is the total wiggler length, λ_w the wiggler period length, β_y the beta function at the place of the wiggler, B the wiggler's magnetic field amplitude, p the beam momentum and e the elementary charge. y is the amplitude of the excitation and ν the tune.

We used our main injection kicker to kick the beam horizontally and measured the orbit position with all beam position monitors for about 1750 turns. Each measurement consists of 20 individual measurements to compensate fluc-

Table 1: Magnetic Parameters of the Wiggler and Lattice Parameter of the Ring

Period length λ_w	mm	51.4
Total length L_w	m	1.8504
On-axis field amplitude B	T	2.9
β_x at the position of the wiggler	m	18.96
β_y at the position of the wiggler	m	2.17
β_x at 1.3 GeV	m	16.48
β_y at 1.3 GeV	m	10.51

Table 2: Theoretical Horizontal ADTS using Eq. (1)

Wiggler field B/T	Energy E/GeV	Amplitude $\Delta x/\mathrm{mm}$	Tune change $\Delta\nu_x$
1.4	1.3	0.5	0.0002
1.4	2.5	0.75	0.0002
2.3	1.3	0.5	0.0005
2.9	2.5	0.75	0.0007

tuation within the kicks. The kick strength was varied within the limits of the injection kicker.

At 1.3 GeV we did not raise the amplitude Δx above 0.5 mm for beam stability reasons and at 2.5 GeV above 0.75 mm due kicker magnet limitations. For these limits Table 2 shows the theoretical horizontal tune shifts with amplitude. As can be seen one would not expect to see a measurable tune change for the 1.4 T at which one can operate the wiggler stably at 1.3 GeV. Nor does one expect to be able to measure a quadratic behaviour at 2.5 GeV. Therefore it is not surprising that we did not see an effect in the 1.3 GeV measurements we did for establishing this method. With a stable operation at 1.3 GeV at higher magnetic wiggler fields one should be able to measure an amplitude dependent tune shift at KIT's storage ring.

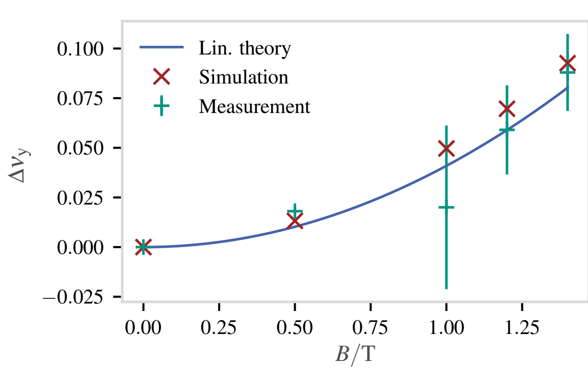

Figure 4: Field dependent vertical tune change at 1.3 GeV

COMPARISON WITH THE SHORT BUNCH MODE MODEL

Measurements at 1.3 GeV show that the vertical tune can be described by the model as can be seen in Fig. 4. The models do not include the small horizontal tune change which was already observed at 2.5 GeV as discussed in [1].

For the 1.3 GeV low-α operation the linear model of the ring was updated with LOCO-fits [8]. This is necessary since the main magnets are not saturated in the 1.3 GeV mode and therefore scaling the 2.5 GeV model is not sufficient.

Although the model predicts the wiggler to be operable up to a field of 2.3 T without changing the optics, which is still less than with the normal user optics, the beam was lost at a field of about 1.7 T in the low-α operation and the life-time shrunk with increasing field from 1.4 T to 1.7 T which also might be caused by tune resonances. As mentioned earlier, the causes for the beam loss still need to be investigated thoroughly.

SUMMARY AND OUTLOOK

The CLIC damping wiggler prototype could be operated in the 1.3 GeV low-α mode stable up to 1.4 T and not beyond 1.7 T. The optics models for this operation case have been upgraded to describe the beam's behaviour under the influence of the wiggler in the low-α operation mode.

Experiments indicated octupole component in the wiggler's magnetic field. Therefore methods to explore these have been evaluated and their experimental boundaries at KIT's storage ring have been studied in experiments and simulations.

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