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EFFECT OF NEGATIVE MOMENTUM COMPACTION OPERATION ON THE CURRENT-DEPENDENT BUNCH LENGTH

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Abstract

New operation modes are often considered during the development of new synchrotron light sources. An understanding of the effects involved is inevitable for a successful operation of these schemes. At the KIT storage ring KARA (Karlsruhe Research Accelerator), new modes can be implemented and tested at various energies, employing a variety of performant beam diagnostics devices. Negative momentum compaction optics at various energies have been established. Also, the influence of a negative momentum compaction factor on different effects has been investigated.

This contribution comprises a short report on the status of the implementation of a negative momentum compaction optics at KARA. Additionally, first measurements of the changes to the current-dependent bunch length will be presented.

INTRODUCTION

During the effort of reaching lower and lower emittances and higher intensities new concepts for synchrotron light sources are considered. One such concept is the use of multi-bend achromatic structures that come, however, with reduced dispersions and therefore require stronger sextupole magnets in order to keep the chromaticity under control. Increasing the sextupole magnetic fields introduces stronger non-linear effects and therefore can reduce the dynamic aperture of the lattice. To circumvent this problem the use of negative momentum compaction is considered as in that case the chromaticity can be kept negative and thus allows for the reduction of the sextupole magnetic fields.

The KIT storage ring KARA as a test facility is well-suited to perform thorough tests of this new operation regime. As a first step the effect of negative momentum compaction on the current-dependent bunch length is investigated as the bunch length is critical for various instabilities such as the micro-bunching instability [1].

This paper will start with a short overview of the current status of negative momentum compaction at KARA and will continue with a short discussion on why the bunch length could behave differently for negative momentum compaction factors (α_c). Subsequently, the results of simulations and measurements are presented and summed up in a small comparison.

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STATUS

Operation with negative momentum compaction factors has been successfully established at KARA [2]. Injection at 0.5 GeV into multiple optics with negative momentum compaction factors is possible up to a current of about 1 mA in single-bunch and about 22 mA in multi-bunch operation with roughly 120 bunches. The injection requires quite high orbit deviations of up to 8 mm. Reducing these deviations inevitably leads to a reduction in injection rate, maximum stored current and even beam loss. The most prominent difficulty with large orbit deviations, apart from aperture problems, is the fact that the magnets in the storage ring at such large deviations induce higher order magnetic field components on top of their design fields. Additionally, for the injection reduced sextupole strengths leading to negative chromaticities seem beneficial [3].

While the injection energy is fixed by the booster energy at 0.5 GeV, the storage ring in general is capable of ramping the energy up to 2.5 GeV, which is routinely used for normal day-to-day operation. At negative α_c energy ramping has been successfully established to various energies up to 1.3 GeV. At 0.9 GeV an orbit correction scheme can be applied without beam loss obtaining orbit amplitudes below 0.5 mm by correcting the working point in parallel. This is necessary since, due to non-linearities in the magnets, the tunes change while reducing orbit deviations. Afterwards, the energy can be freely ramped without problems to higher energies up to 1.3 GeV. The beam lifetime increases with higher energies as expected.

It is also possible to alter the momentum compaction factor with stored beam at the various available energies with a current minimum of $\alpha_c \approx 3.5 \times 10^{-4}$ at 1.3 GeV. Multiple measurements are being done using this new optics at negative α_c. Measurements shown in the following were conducted in this mode.

CURRENT-DEPENDENT BUNCH LENGTH

The bunch length in an electron storage ring is influenced by phase focusing which in turn is depending on the gradient of the potential seen by the individual particles. The simplest approach would consider only the RF potential. This would then results in no bunch length changes over current as the potential is constant. However, this changes when taking the longitudinal wakefields, generated by the bunch with its environment, into account and thereby considering the effective potential as sum of RF potential and wakefields[1].

[1] A similar concept was used to study the synchrotron motion during the micro-bunching instability in [4].

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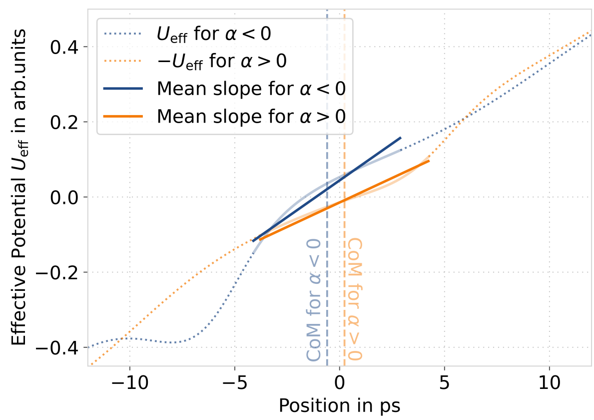

Figure 1: Effective potential of a sample case for positive and negative α_c. The potential for positive α_c was flipped in the display to simplify comparison. Here the dotted lines represent the effective potential while the solid, light lines represent the potential in an area where the bunch is located. The solid, intense lines show the mean gradient over the bunch as an aide. Two dashed, vertical lines indicate the location of the center of mass for both signs of α_c. The wakepotential used here was calculated using Inovesa [5] using the CSR parallel plates impedance.

As the wakefield of a bunch is dependent on the bunch charge so is the effective potential, which means the bunch length is changing with bunch current.

In order to keep phase focusing, operation with negative α_c is done with an RF phase shifted by about π, which means the RF potential is reversed with respect to the one seen by a bunch in a machine with positive α_c. This results in a different gradient of the effective potential and therefore in a different bunch length.

Considering the CSR parallel plates impedance for short bunches, as is the considered case at KARA (due to small absolute values of α_c), the average gradient of the effective potential is larger for negative than for positive α_c at low currents. In fact, it is larger than for the unperturbed pure RF potential for negative and smaller for positive α_c. An example is shown in Fig. 1.

This means that, since with increasing current the wakepotential increases, the mean gradient of the effective potential increases for negative α_c and decreases for positive α_c. Consequently, the bunch length increases with current for positive α_c and decreases for negative α_c.

It is therefore expected to result in a different current dependent behaviour of the bunch length for different signs of α_c.

SIMULATIONS

At KARA the usual negative α_c operation mode is using low absolute values of α_c. Therefore, we only consider the case of short electron bunches. The most prominent longitudinal impedance in this case is the parallel plates CSR impedance.

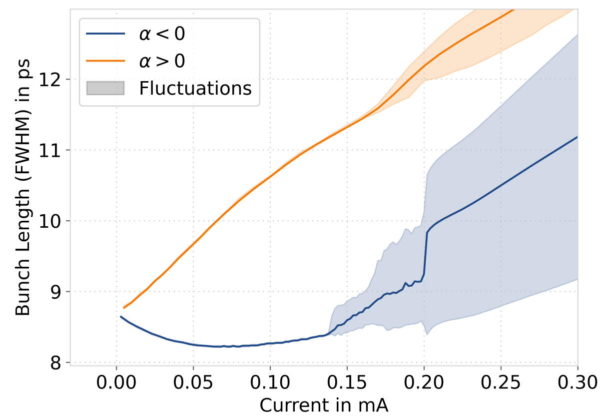

Figure 2: Bunch length simulated with Inovesa for both signs of α_c with the same absolute value. Solid lines denote the mean bunch length over time while the shaded area denote the fluctuation region over time.

Using Inovesa [5] the longitudinal phase space was simulated with the same absolute value $|\alpha_c| \approx 4 \times 10^{-4}$ once for a positive and once for a negative sign of α_c. The resulting bunch length is shown in Fig. 2.

Inovesa simulates a given time range for a fixed bunch current, therefore one simulation run was performed for each bunch current. The bunch length is calculated as full width half maximum from the resulting bunch profiles and averaged over time for each simulated bunch current. The fluctuation range is calculated above and below the mean individually by calculating the standard deviation with respect to the overall mean for just the data points above or below the mean respectively.

For positive α_c it is clearly visible that the bunch length increases with current. This is expected as the wakepotential in this case effectively lowers the gradient of the effective potential. However, for negative α_c at low currents the bunch length shows bunch shortening. For these low currents the bunch profile is almost of Gaussian shape and almost identical, apart from the different bunch length, for positive and negative α_c. Therefore the wakepotential is also similar. While the sum with the RF potential reduced the gradient of the effective potential for positive α_c here it increases it since the RF voltage is reversed. This results in lower bunch lengths. In addition, the wakepotential roughly scales with bunch current (for low bunch currents) and the effect is increased for higher currents. Therefore, the bunch length shrinks with current as seen from the simulation in Fig. 2.

At higher currents the bunch is deformed due to the self-interaction with its own wakefield. This perturbs the behaviour and leads to an increase in bunch length. While at low currents no fluctuations are visible this is not the case at higher currents. Such fluctuations were already seen in [6] and in conjunction with coherent synchrotron radiation emission bursts in [7]. For positive α_c these fluctuations start at roughly 0.160 mA and for negative α_c they start at about 0.137 mA. They arise when the micro-bunching instability

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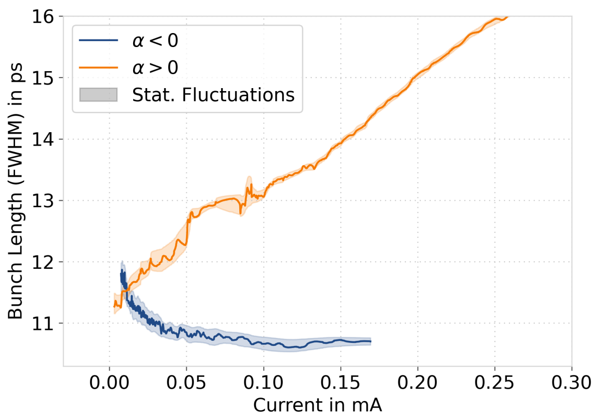

Figure 3: Bunch length measured using a streak camera for positive α_c and negative α_c with the same absolute value of α_c. Solid lines represent a moving average and the shaded areas represent the statistical fluctuations calculated from multiple measurements for similar currents.

occurs, which leads to non-static deformations of the bunch profile [7]. For negative α_c at about 0.20 mA a sharp increase in bunch length is visible. This is due to a change in the regime of the micro-bunching instability and results in even larger deformations in bunch profile and corresponding bunch length.

MEASUREMENTS

The bunch length at KARA can be measured with a dual sweeping streak camera[2]. The fast time axis is used to resolve the bunch length and the streak time is set to the smallest value of 190 ps. The slow time axis is used to resolve the evolution of the bunch length over time. Its value is set in such a way that multiple synchrotron oscillations can be resolved while an adequate intensity is still kept and varies depending on the machine settings used.

Bunch length measurements were conducted for the same absolute value of α_c as used in the simulations for both signs. All measurements were performed during single-bunch operation to exclude effects of bunch interaction or overlapping images on the streak camera. The results are shown in Fig. 3.

During the natural decrease of bunch current a measurement sequence consisting of 100 pictures with a duration of around 8 s per sequence was taken every 10 s. After correcting for center-of-mass movements, due to e.g. synchrotron motion, the longitudinal profiles resulting from the images are averaged and a full width half maximum bunch length is calculated.

Solid lines in Fig. 3 refer to a moving average of the data while shaded areas display the statistical fluctuations calculated as standard deviation from a few points for very similar bunch currents assuming the bunch length changes slowly compared to the acquisition speed. The accuracy of measurements is better than $\Delta l < 0.3$ ps [8].

[2] Model: Hamamatsu C5680.

Since the slow time axis is chosen to resolve the synchrotron oscillation it cannot resolve single turns. Therefore, the bunch length fluctuations seen in simulations are not visible in these measurements. However, parallel measurements using a Shottky barrier diode sensitive in the THz range[3] showe that the micro-bunching instability occurred above about 0.150 mA for positive α_c. For negative α_c a threshold at about 0.08 mA was observed. Further studies on this threshold and the micro-bunching instability at negative α_c are ongoing. Due to operational limitations it was not possible to measure up to higher bunch currents for the negative α_c measurements up to now.

COMPARISON

Similar to the simulations the positive α_c bunch length increases with current. In the area round 0.05 mA and 0.1 mA an increased bunch length was measured. The reason for this is not yet clear and is under investigation. Apart from that and a general offset of about 2 ps the measurement fit quite well to the simulations.

The measured bunch length for negative α_c displays a bunch shortening for low bunch currents similar to the shortening seen in simulations. For almost zero current the bunch length for negative α_c seems to be higher than for positive α_c which is not expected from both simulations and theoretical considerations. This effect hints at an offset between the bunch length measurements for the two signs of α_c.

The otherwise good agreement for the evolution of bunch length over current also indicates a good fit of the used impedance for the simulations.

CONCLUSION

The bunch length was simulated and measured for positive as well as negative α_c. Measurements and simulations fit well qualitatively and for low currents they also fit well to the theoretical considerations. In general the measurements and simulations suggest significantly shorter bunches for negative compared to positive α_c. This has to be taken into account for the design of new low emittance machines and the associated effects need to be investigated.

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[3] For more information on the measurement method see [1].

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