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BEAM DYNAMICS OBSERVATIONS AT NEGATIVE MOMENTUM COMPACTION FACTORS AT KARA

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Abstract

For the development of future synchrotron light sources new operation modes often have to be considered. One such mode is the operation with a negative momentum compaction factor to provide the possibility of increased dynamic aperture. For successful application in future light sources, the influence of this mode has to be investigated. At the KIT storage ring KARA (Karlsruhe Research Accelerator), operation with negative momentum compaction has been implemented and the dynamics can now be investigated. Using a variety of high-performance beam diagnostics devices it is possible to observe the beam dynamics under negative momentum compaction conditions. This contribution presents different aspects of the results of these investigations in the longitudinal and transversal plane.

INTRODUCTION

At the accelerator test facility KARA (Karlsruhe Research Accelerator) a new optics with negative momentum compaction factors α_c has been implemented in recent years. The aim is to investigate the effects of the negative sign of α_c on beam dynamics as well as to confirm the feasibility of using negative α_c optics in order to allow reduced sextupoles without incurring instabilities such as the head-tail instability. Previous publications showed effects of the switch in sign of α_c such as a shorter bunch length at negative α_c [1]. In this contribution the effect of changes to the sextupole magnet currents, and therefore the chromaticity, on the first and second order of α_c for the currently implemented optics at positive and negative α_c are explored. Furthermore, the transverse stability in regard to head-tail effects at negative α_c is investigated.

SECOND ORDER OF α_c

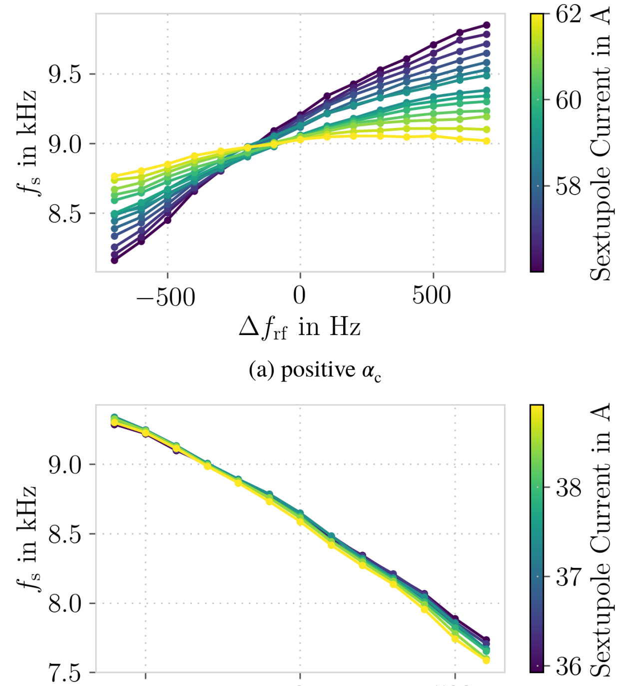
The negative α_c optics are operated with negative chromaticities and therefore reduced sextupoles. This reduction in sextupole magnets strengths affects higher order terms of the momentum compaction factor. When including higher orders α_c is a function of momentum

$$\alpha(\delta) = \alpha_0 + \alpha_1\delta + \alpha_2\delta^2 + \dots . \quad (1)$$

As an analysis of this the second order (first non-linear order) has been investigated by means of measurements of the synchrotron frequency f_s as function of accelerating frequency f_{RF} used as tuning knob for the energy offset. The synchrotron frequency in this case considering the first two orders of α_c is given as [2]

$$f_s = f_{rev}\sqrt{\frac{heV_{RF}\cos\psi_s}{2\pi\beta_0^2 E}} \cdot \sqrt{\frac{\alpha_0}{2} + \sqrt{\frac{\alpha_0^2}{4} - \alpha_1\frac{\Delta f_{RF}}{f_{RF}}}}, \quad (2)$$

where f_{rev} is the revolution frequency, h the harmonic number, V_{RF} the accelerating voltage, ψ_s the synchronous phase, $\beta_0 = \frac{v}{c}$ and E is the particle energy. From this equation the first and second order of α_c (α_0 and α_1) can be identified by fitting the equation to the mentioned measurements.



(a) positive α_c

(b) negative α_c

Figure 1: Synchrotron frequency as function of the frequency of the RF system at positive and negative α_c for various sextupole magnet strengths.

The synchrotron frequency has been measured at positive and negative α_c in order to allow comparison. In both cases the beam energy was set to 1.3 GeV. The measurements were done by using the RF system to vary f_{RF} and by using the BBB feedback system [3, 4] which calculates the beam spectrum from BPM data via a Fourier transformation. In this data the synchrotron frequency is then given as a

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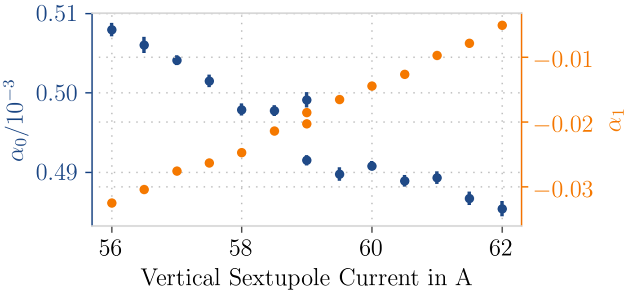

Figure 2: First two orders of α_c extracted as fit of Eq. (2) on the data shown in Fig. 1 for positive α_c as a function of the sextupole current.

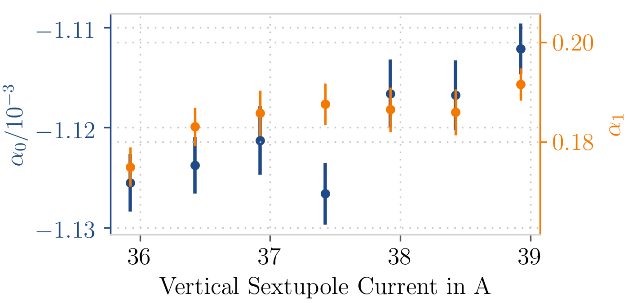

Figure 3: First two orders of α_c extracted as fit of Eq. (2) on the data shown in Fig. 1 for negative α_c as a function of the sextupole current.

peak. These measurements have been repeated for different currents powering the sextupole magnets to explore the dependency. In Fig. 1 the measurements are displayed. By fitting Eq. (2) to this data the mentioned two orders of α_c can be extracted. The results are shown in Fig. 2 and Fig. 3.

The measurements at negative α_c were taken at relatively high absolute values of α_c due to the reduction in lifetime associated with a drastic reduction of $|\alpha_c|$. Furthermore, the necessary reduction in f_{RF} leads to beam loss at lower $|\alpha_c|$ for negative α_c. For both signs of α_c the first order α_0 reduces in absolute value with increasing sextupole magnet strengths (indicated in the plots via the sextupole current). However, as the sign at negative α_c is negative, this means the sextupoles have a different effect on the dispersion. At positive α_c, where the value of α_0 decreases, it can be concluded that the dispersion gets more stretched, while at negative α_c, where the values of α_0 increases, it can be concluded that the dispersion gets relaxed. In both cases the change seems linearly with sextupole current. The change in first order α_c at positive α_c is about 4 % for a change with sextupole magnet current of about 10 %. The equivalent for negative α_c is a change of 1.25 % in α_0 for a sextupole magnet current change of about 8 %. Therefore, it seems the first order of α_c is less sensitive to changes of the vertical sextupole current at negative α_c than at positive α_c for the currently implemented optics at KARA.

The second order α_1 seems linearly dependent on the sextupole magnet current for positive α_c. At negative α_c, a dependency is visible as well, albeit not as clearly linear as for positive α_c. For this order the dependency is the same for both signs of α_c, both increase with increasing sextupole magnet currents. Furthermore, the sign of the second order α_1 flips when flipping the sign of the first order α_0.

These observations show the effect of sextupole magnets on the higher orders of α_c and that these effects have to be considered when implementing optics with different chromaticity values. Influence of different orders of higher orders of α_c on the longitudinal beam dynamics have been studied e.g. in [5]. In general the third order α_2 is of interest as well, for example in regard to alpha-buckets [2], and should be determined in the future.

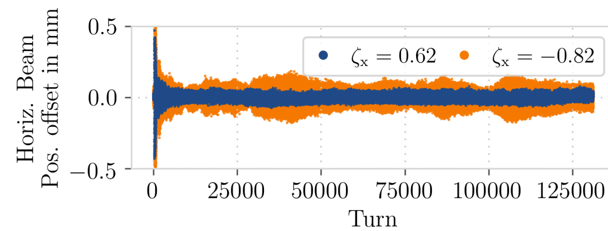

Figure 4: Beam position data after a horizontal kick on a turn-by-turn basis at positive α_c for a positive and a negative horizontal chromaticity.

TRANSVERSE STABILITY

A reduction of sextupole magnet strengths would be ideal for multi-bend achromat lattices as this could increase the dynamic aperture. However, at positive α_c a reduction too far, resulting in negative chromaticities, brings the risk of loosing head-tail damping effects and even incurring the head-tail instability. Therefore, one solution could be the use of negative α_c optics which would in theory allow negative chromaticities without the aforementioned downsides.

In order to investigate this with the negative α_c optics at KARA a combination of kicks and BPM measurements was used. By firing one of the horizontal injection kickers every second and measuring the beam position on a turn-by-turn basis, the stability of the beam was tested at positive as well as negative α_c. In theory the head-tail damping time τ for mode n is given by [6]

$$\beta_n = \frac{1}{\tau} = \frac{NS}{\pi^2 c\gamma m_e}\frac{\zeta}{\alpha_c}\frac{\sigma_z}{4n^2-1}, \tag{3}$$

where τ is the corresponding damping time, N is the number of particles in a bunch, S is the strength of the wakefield and σ_z is the bunch length. The electron mass is denoted with m_e, the chromaticity with ζ and γ is the relativistic Lorentz factor. From this a larger damping time is expected at lower energies which is why the measurements presented here were performed at injection energy (0.5 GeV).

For positive alpha with the usual (positive) chromaticity, an initial damping of the large position offset is visible in Fig. 4 in blue. Afterwards over the remaining turns oscillations of a fairly constant amplitude are present. These oscillations conform to the synchrotron and betatron frequencies

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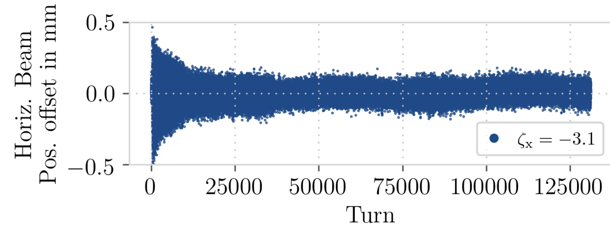

Figure 5: Beam position data after a horizontal kick on a turn-by-turn basis at negative α_c for a negative horizontal chromaticity.

and are expected. For the kick at a negative chromaticity for positive α_c the situation is different. This is shown in Fig. 4 in orange. After a short initial damping, large non-constant in amplitude oscillations are present. These oscillations are not linked to synchrotron or betatron oscillation frequencies and are not expected for a stable beam. From this it can already be guessed that head-tail damping effects are present at the measurement with a positive chromaticity and absent in the measurement for a negative chromaticity.

To test whether this effect can be reversed at negative chromaticities when using negative α_c such measurements were also performed in these settings. Figure 5 shows such a measurement. Again an initial damping is visible followed by fairly large but constant in amplitude oscillations. These residual oscillations are in accordance to synchrotron and betatron frequencies. The larger amplitude can be explained by the largely increased dispersion necessary for the negative momentum compaction factor. For comparison, at positive α_c the dispersion at the used BPM is about 0.17 m while at negative α_c it is about 1.25 m. Through this increased dispersion the usual energy oscillations from the synchrotron oscillation manifest in enlarged horizontal position offsets. Therefore, combined with the rather constant amplitude of the oscillations, these measurements hint at the presence of the head-tail damping effect at negative α_c with negative chromaticity.

From the BPM data a damping time can be extracted, at least in the damped cases of positive α_c with positive chromaticity and negative α_c with negative chromaticity. While the absolute damping time is a composition of at least radiation damping and the head-tail effect, the presence of the head-tail effect can be assessed by analyzing the bunch current dependency of the extracted damping time. In order to do this, the previously shown measurements were repeated at multiple bunch currents and the damping time extracted. The current dependency for positive α_c with positive chromaticities can be seen from the results in Fig. 6. A clear increase of $\frac{1}{\tau}$ with current is visible. The same measurements were conducted at negative α_c with negative chromaticities which are shown in Fig. 7. Again a clear increase of $\frac{1}{\tau}$ with current is visible. In both cases the relative sign between α_c and ζ_x is positive. Therefore, the observed current dependency of the damping time is in accordance to the theory in Eq. (3). Thus, it can be concluded that indeed head-tail damping is present

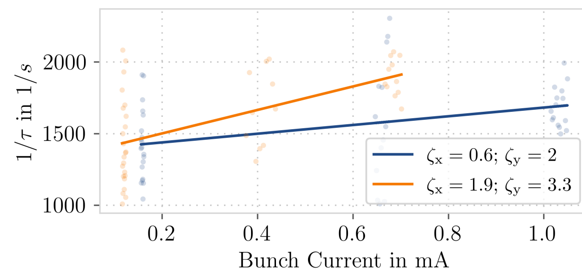

Figure 6: Inverse damping time $\frac{1}{\tau}$ after an initial kick as function of bunch current for positive $\alpha_c \approx 8.1 \cdot 10^{-3}$ at two different positive chromaticities.

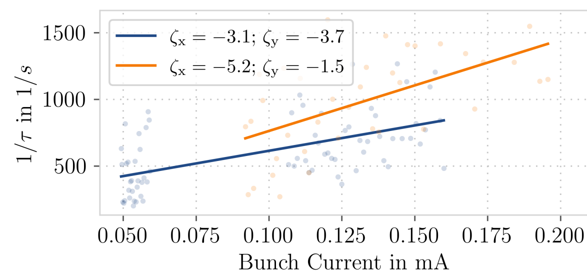

Figure 7: Inverse damping time $\frac{1}{\tau}$ after an initial kick as function of bunch current for negative $\alpha_c \approx -1.5 \cdot 10^{-3}$ at two different negative chromaticities.

in both cases. This means the negative α_c operation mode at KARA successfully circumvented the head-tail instability when using negative chromaticities.

SUMMARY

The negative momentum compaction regime is a possible solution to circumvent the need for high sextupole currents in multi-bend achromat structures. This contribution described the effects of possible changes in sextupole current on the first and second order of α_c seen at KARA in both, positive and negative α_c operation.

Furthermore, the validity of this mode has been investigated by studying the transverse beam stability. Kick measurements show a loss of head-tail damping at positive α_c with negative chromaticity and a regaining of head-tail damping at negative α_c with negative chromaticity.

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