STATUS OF NEGATIVE MOMENTUM COMPACTION OPERATION AT KARA

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This contribution is based on [1].

Abstract

For future synchrotron light sources different operation modes are of interest. Therefore various modes are currently being tested at the Karlsruhe Research Accelerator (KARA) including optics for a negative momentum compaction factor. These optics have been calculated and are under commissioning at KARA. Additionally, studies about expected collective effects in this regime are being performed, including the head-tail and microbunching instabilities. In this contribution we will present the status of operation in the negative momentum compaction regime and discuss expected collective effects that will be studied in this context.

LATTICE AND OPTICS

The KIT synchrotron light source KARA [2] has a four fold symmetry consisting of two double bend achromat like structures per cell. Each such structure contains five quadrupoles, where corresponding quadrupoles in the different structures are connected to the same power supply, as a so called family. Straight sections between magnetic structures are filled with insertion devices, RF cavities and injection magnets.

The momentum compaction factor α_c can be expressed as

$$\alpha_c = \frac{\frac{\Delta L}{L}}{\frac{\Delta p}{p}} = \frac{1}{L} \oint \frac{D(s)}{\rho(s)} \mathrm{d}s \tag{1}$$

where L is the path length for one revolution for a particle with design momentum p, ΔL and Δp are the deviations for particles with different momenta. D describes the dispersion and ρ the local bending radius along the ring. According to this equation, the momentum compaction factor can be influenced by changes to the dispersion in sections where the bending radius is non-zero. For KARA and its lattice, one way to reach smaller values of α_c is to push the dispersion down to negative values by increasing the strength of the center quadrupole in each half-cell, which is acting as a field lens.

At KARA mainly two established operation optics with different momentum compaction factors exist. At maximum energy of 2.5 GeV, the standard operation with a momentum compaction factor of $\alpha_c \approx 9 \cdot 10^{-3}$ is used. The optical functions are displayed in Figure 1. Here, the dispersion is positive over the entire section and therefore in the entire ring.

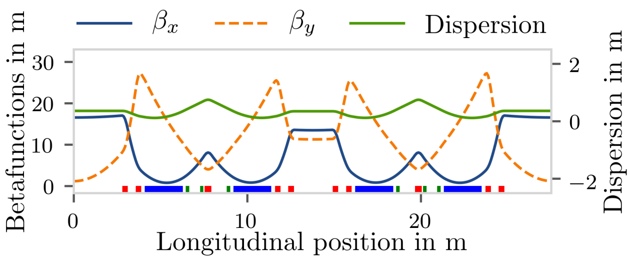

Figure 1: Calculated lattice used for user operation at $\alpha_c = 9 \cdot 10^{-3}$. The bottom depicts the magnets, quadrupoles in red, sextupoles in green and bends in blue.

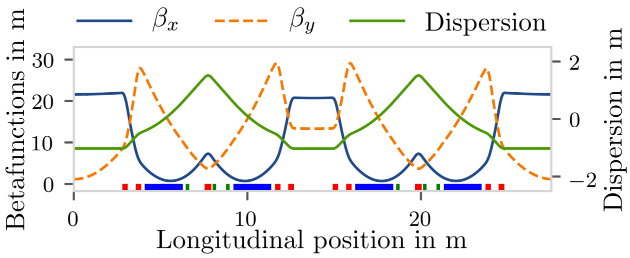

Figure 2: Calculated lattice used for short bunch operation at $\alpha_c = 1 \cdot 10^{-4}$. The dispersion is negative in parts of the bending magnets.

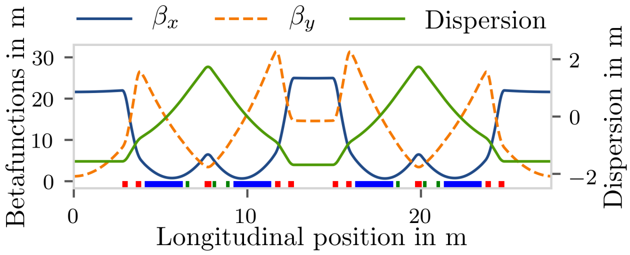

Figure 3: Calculated lattice used for operation with a negative momentum compaction factor of $\alpha_c = -8 \cdot 10^{-3}$. Here the dispersion is largely negative in parts of areas with bending magnets.

At 1.3 GeV a dedicated short bunch mode exists with a momentum compaction factor of $\alpha_c \approx 1 \cdot 10^{-4}$ [3]. Figure 2 shows the optical functions for this operation mode. Note that the dispersion is negative in some areas of the section.

A new mode with various selectable *negative* momentum compaction factors has been implemented recently. Here, as shown exemplary for $\alpha_c = -8 \cdot 10^{-3}$ in Figure 3, the dispersion is largely negative in some parts of the section.

More information about operation optics at KARA can be found in [4].

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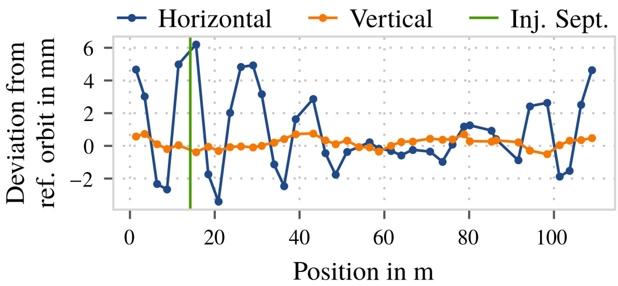

Figure 4: Orbit deviations during injection into an optics with $\alpha_c \approx -8 \cdot 10^{-3}$

STATUS OF OPERATION

At an energy of 500 MeV, injection into multiple optics with negative values of α_c has been successfully established. However, the maximum beam and bunch current is limited to values lower than for other operation modes. The highest achieved current until the end of 2019 is 17 mA for a filling pattern with 30 bunches and 1 mA for single-bunch operation.

Multiple factors affecting this limit were identified. It seems to be beneficial to have high orbit deviations (shown in Figure 4) during injection. This has been tested by changing the energy of the beam via modifications of the RF-frequency. The resulting optics with a dispersive orbit have larger or smaller deviations and a comparable momentum compaction factor.

Furthermore, lower absolute values of α_c seem to result in higher possible beam currents which could be explained by the fact that lower absolute values come from a less stretched dispersion.

Reducing the sextupole strength while keeping the tunes constant and therefore reducing chromaticities also seemed to be beneficial at some values of α_c, which could hint at collective effects.

WORKING POINT AND CHROMATICITY

For multiple negative values of α_c tunes ν and chromaticity ξ have been measured. Changing chromaticity with stored beam and also during injection is relatively easy.

Shifting the horizontal chromaticity had almost no influence, even a change of sign did not result in significant changes to injection rate and current limit. The vertical chromaticity has small effects on the current limit, where lower negative values seem to result in higher current limits. Moving the vertical chromaticity to positive values during injection resulted in a beam loss and a sub mA injection limit. However, moving vertical chromaticity to positive values with stored beam without injection did not result in a beam loss.

The transverse working point was moved from $(\nu_x, \nu_y) = (0.767, 0.793)$ via $(\nu_x, \nu_y) = (0.765, 0.821)$ to $(\nu_x, \nu_y) = (0.801, 0.827)$. It was observed that the starting point has the best conditions for injection rate and current limit. The behaviour at the intermediate point was almost the same while the end point was significantly less beneficial for the injection as the injection rate as well as the maximum achievable beam current was lower than for the other two points.

COLLECTIVE EFFECTS

Various collective effects might change their behaviour for negative momentum compaction which has not been fully studied. One of the most prominent instabilities is the head-tail instability. The growth rate of this instability is given by [5]

$$\tau_{\pm}^{-1} = \mp \frac{N r_0 W_0 c \xi_v \hat{z}}{2\pi\gamma C \eta}, \tag{2}$$

where N is the number of particles, r_0 the classical electron radius, W_0 is the value of the wake field, ξ_v the vertical chromaticity and $\hat{z}$ describes the amplitude of the synchrotron oscillation. $\eta = \alpha_c - 1/\gamma^2$ is the slip factor and C is the circumference of the ring. It clearly depends on the ratio of the chromaticity ξ_v to the slip factor η and therefore on α_c. Here the relative sign between the chromaticity and α_c is especially important.

Another instability to consider is the Transverse Mode Coupling Instability (TMCI). Multiple descriptions exist in literature ([5–7]). This instability manifests itself above a certain threshold which can be expressed as (adapted from [7])

$$N_{\mathrm{b,thr}}^{\mathrm{TMC}} \propto \frac{|\eta|}{|Z_y^{\mathrm{BB}}|}\left(1 + \frac{\xi_v \omega_0}{\eta \omega_r}\right), \tag{3}$$

where Z_y^{BB} is the broadband impedance of the ring, ω_0 is the angular revolution frequency and ω_r is the resonant angular frequency of the impedance. A higher absolute value of the chromaticity increases the threshold as long as the signs of α_c and ξ_v are the same. This is in accordance to the observed lower limit for a positive vertical chromaticity at negative momentum compaction, which could indicate the occurrence of the TMCI at our experiments.

A third instability possibly occurring is the micro-bunching instability. The equation from [8] predicts a threshold at $I_{\mathrm{thr}} = 0.038$ mA for a positive momentum compaction factor of $\alpha_c = +1.8 \cdot 10^{-3}$. THz emission power has been measured above and below this threshold at the negative equivalent momentum compaction factor of $\alpha_c = -1.8 \cdot 10^{-3}$. These measurements suggest a significantly higher threshold for the negative momentum compaction regime. However more systematic tests are planned. Furthermore, the applicability of Inovesa [9] is under investigation to simulate the micro-bunching instability in the negative momentum compaction regime.

ACKNOWLEDGEMENT

This project has received funding from the European Union's Horizon 2020 Research and Inovation programme under Grant Agreement No 730871.

P. Schreiber and T. Boltz acknowledge the support by the DFG-funded Doctoral School "Karlsruhe School of Elementary and Astroparticle Physics: Science and Technology"

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