ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPTS017

STATUS OF OPERATION WITH NEGATIVE MOMENTUM COMPACTION AT KARA

P. Schreiber*, T. Boltz, M. Brosi,
B. Haerer, A. Mochihashi, A. I. Papash, M. Schuh and A.-S. Müller,
Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

For future synchrotron light source development novel operation modes are under investigation. At the Karlsruhe Research Accelerator (KARA) an optics with negative momentum compaction has been proposed, which is currently under commissioning. In this context, the collective effects expected in this regime are studied with an initial focus on the head-tail instability and the micro-bunching instability resulting from CSR self-interaction. In this contribution, we will present the proposed optics and the status of implementation for operation in the negative momentum compaction regime as well as a preliminary discussion of expected collective effects.

INTRODUCTION

Understanding collective effects and instabilities is critical to successful operation of synchrotron light sources and therefore they are subject to ongoing investigations. Most efforts focus on machines and optics with a positive momentum compaction factor, which is defined as

$$\alpha_c = \frac{1}{L} \oint \frac{D_x(s)}{\rho(s)} \, ds, \qquad (1)$$

where L is the circumference of the ring, $D_x(s)$ is the dispersion and $\rho(s)$ the bending radius along the ring. Only a few experiments focus on a negative value of α_c (e.g. [1–3]), however for a thorough understanding of collective effects and instabilities, studies in this regime are also necessary.

As KARA is a synchrotron light source also used as accelerator test facility, it is possible to change the optics and implement a negative momentum compaction factor. This allows to extend the investigations on collective effects and instabilities into the regime of a negative value of α_c.

LATTICE AND OPTICS

The injection energy into the KARA storage ring is 0.5 GeV. The storage ring itself is a ramping machine with a variable operation energy between 0.5 GeV and 2.5 GeV and a circumference of 110.4 m. The accelerating frequency is 500 MHz and the harmonic number is 184.
The KARA lattice consists of a four-fold symmetry with two double bend achromats (DBA) in each sector. The eight resulting straight sections are filled with insertion devices, the RF stations and the injection magnets. The double bend achromats contain five families of quadrupole magnets, three horizontal focusing and two defocusing.

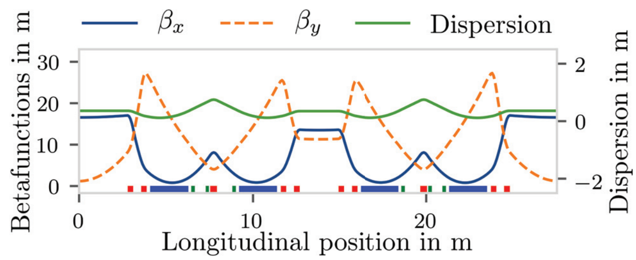

Figure 1: Calculated optics used for user operation at $\alpha_c = 9 \times 10^{-3}$ and 0.5 GeV. The bottom depicts the magnets, quadrupoles in red, sextupoles in green and bends in blue.

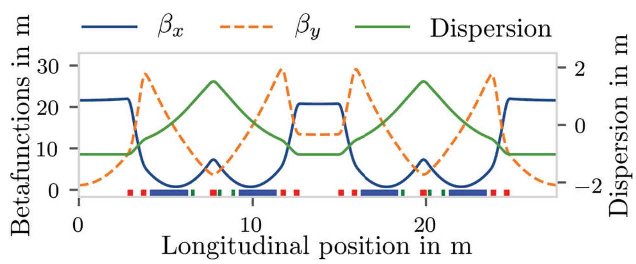

Figure 2: Calculated optics for $\alpha_c = 1 \times 10^{-4}$ at 0.5 GeV. In large parts the dispersion is negative.

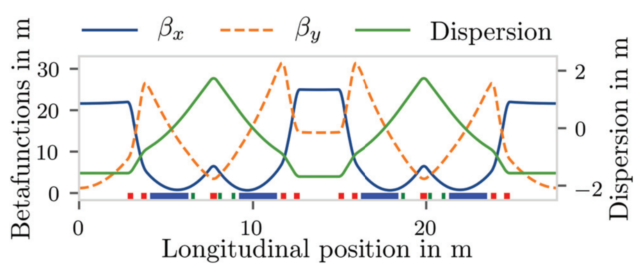

Figure 3: Calculated optics for a negative value of $\alpha_c = -8 \times 10^{-3}$. In large parts the dispersion is negative.

At KARA, two operation modes have already been established. Standard operation at 2.5 GeV with a moderate value of $\alpha_c \approx 9 \times 10^{-3}$ and a short bunch mode at 1.3 GeV with a reduced value of $\alpha_c \approx 1 \times 10^{-4}$ [4]. To reduce the value of α_c, the integral in Equation 1 and therefore the integrated dispersion has to be reduced. The dispersion and the beta functions are shown in Figure 1 for the normal operation and in Figure 2 for the short bunch operation. For the lower α_c value the dispersion has negative parts, while for the normal operation it is strictly above zero. More information on different operation modes at KARA can be found in [5].

The method used for establishing a negative α_c injection is described in the next chapter.

* patrick.schreiber@kit.edu

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPTS017

There have now been successful efforts to implement optics with a negative value of α_c at an energy of 0.5 GeV. To reach this the dispersion has to be even lower. Betafunctions and dispersion for the currently used negative alpha optics are shown in Figure 3. The dispersion is now stretched to almost −2 m in some areas, while for the low α_c optics it only reaches around −1 m.

ESTABLISHING NEGATIVE ALPHA

To establish operation with a negative momentum compaction factor the following strategy was applied.

As described in the previous chapter, in order to get a negative value of α_c the dispersion is stretched into negative values. Since this is also the way to reach a low positive value of α_c, optics for a low and a negative value of α_c are similar to each other.

For the experiments, α_c is gradually reduced to a low value. Quadrupole strengths for a reduced value of α_c were simulated. Starting from an optics for standard injection at KARA (500 MeV, $\alpha_c \approx 8 \times 10^{-3}$) the strength of the third quadrupole family (Q3, in the center of the DBA structure), which has the most influence on α_c, was changed stepwise in the direction of the values gained from the simulation.

To avoid resonances and stay at the well known stable transverse working point used for standard operation, at each step in Q3, the “field lens”, the tunes were adjusted using the other quadrupole families. This was done in two to four steps. First, families 2 and 4 were adjusted to keep the vertical tune. Second, the horizontal tune was adjusted using families 1 and 5. If necessary, the third step was to change families 2 and 4 to compensate the residual effect of families 1 and 5 on the vertical tune. In some cases this again made adjustments to families 1 and 5 necessary. That way it was possible to keep the tunes more or less constant during the decrease of α_c and also move the quadrupole strengths only in one direction to avoid hysteresis effects. The sextupole magnet strengths were adjusted according to the changes in Q3 starting from the standard injection settings.

After an optics with a low value of α_c was successfully established, it was chosen to extrapolate the magnet settings to negative values of α_c based on OPA [6] simulations as crossing $\alpha_c = 0$ did not seem feasible.

At this point, on each injection cycle (1 Hz) the beam was lost after a few hundred turns, which was visible on the first turn beam position data. Therefore kicker magnets, injection septum and some corrector magnets were adjusted. After successful injection and storage of the beam, the horizontal tunes were moved to the working point of standard operation at KARA, where injection efficiency and maximum beam current were improved.

STATUS OF OPERATION

Injection into negative values of α_c has been established. At present, the maximum current stored in the ring is limited and the highest achieved beam current was 17 mA while for the normal injection optics a maximum value of 150 mA is typical. Multiple test have been performed and various factors have been identified that affect the limit.

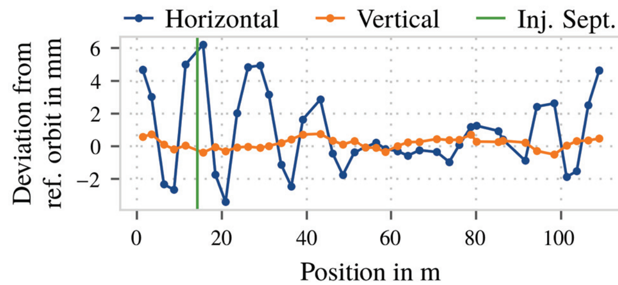

Figure 4: Orbit deviations during injection into optics with a negative value of α_c. Large deviations in the horizontal plane are visible, with the largest value of roughly 6.2 mm, shortly after the injection septum.

One such factor is the horizontal injection orbit. Using the frequency of the accelerating voltage (RF frequency) the orbit was changed and the beam current limit was higher for larger orbit deviations. But above a certain threshold larger deviations resulted in little to no injection rate. The deviations of the currently used settings are shown in Figure 4. The maximum deviation is around 6.2 mm, which is large compared to the 3 mm maximum orbit deviations during normal user optics injection.

A second observation is that a reduced absolute value of α_c seemed to have a beneficial effect on the maximum injected current. α_c was changed from a value of -1×10^{-2} to -8×10^{-3}. Due to this decrease the dispersion was stretched less and this resulted in smaller orbit deviations. Restoring the previous orbit by shifting the RF frequency improved the possible injected current which could indicate that a bigger momentum offset between injected and stored beam is beneficial. On the other hand modifying the bending magnets to change the energy of the stored relative to the injected beam did not result in the same effect.

Changes to the sextupoles also seemed to affect the total injected current. There were indications that lowering the vertical sextupole strengths and therefore lowering the vertical chromaticity increases the total possible beam current. Since the orbit deviations are quite large, the beam does not traverse the sextupoles in the center and therefore they add additional quadrupole components. Changes of the tune due to variations of the sextupole strengths were roughly compensated by adjusting the quadrupole strengths for these tests. Nonetheless, more systematic tests are necessary to determine the effect of the chromaticity on the maximum injectable beam current.

At $\alpha_c \approx -8 \times 10^{-3}$ the chromaticity ξ has been measured for the vertical and horizontal plane and the results are shown in Figure 5. The horizontal chromaticity is $\xi_h = -0.460(\pm 0.138)$ and the vertical is $\xi_v = -6.624(\pm 0.484)$. Only a positive change in the momentum was carried out, due to the fact, that the orbit deviations were already quite big. Any larger deviations due to decreases in the RF frequency would have resulted in a beam loss.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPTS017

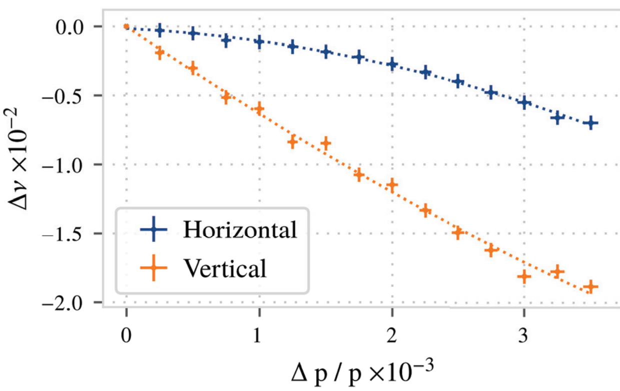

Figure 5: Changes of the tune ν with respect to relative momentum deviations $\Delta p/p$. The points are measurements and the dotted lines depict the following fit results:
$y_{\mathrm{hor}}(x) = -439.230\,(\pm 38.447) \cdot x^2 - 0.460\,(\pm 0.138) \cdot x$
$y_{\mathrm{ver}}(x) = 313.931\,(\pm 133.754) \cdot x^2 - 6.624\,(\pm 0.484) \cdot x$

COLLECTIVE EFFECTS

As described in the previous section the vertical chromaticity might affect the maximum achievable bunch current. This is also suggested when considering the head-tail instability with the growth rate (Equation 4.99 in [7]) for a constant wake field

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

where N is the number of particles per bunch, W_0 is the value of the wake field, $\hat{z}$ is the amplitude of the synchrotron oscillation, C is the circumference of the ring and η is the slip factor $\eta = \alpha_{\mathrm{c}} - 1/\gamma$. For a negative value of α_{c} a lower negative vertical chromaticity ξ_{v} decreases the growth rate of the 0th mode (τ_{+}^{-1}) and the beam is more stable.

Another instability worth considering is the strong head tail or transverse mode coupling instability (TMCI). There are multiple approximations for the threshold of this instability (e.g. [8][9][7]). As the experiments with the negative α_{c} optics proceed the best approach will hopefully become clear. The threshold from [9] (Equation 46 on p. 217) depends on the chromaticity in the same way as we see an increase in the injectable current with changes to the chromaticity, here dependence on the chromaticity and α_{c} is given by (adapted from [9])

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

where the dependence on α_{c} is in the slip factor $\eta = \alpha_{\mathrm{c}} - 1/\gamma^2$, Z_y^{BB} is the broadband impedance, 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.

A third notable instability is the micro-bunching instability. In [10] a threshold for a positive value of α_{c} was presented. Using this threshold and the absolute value of α_{c} the expected micro-bunching instability threshold is at $I_{\mathrm{thr}} = 0.516$ mA for a single bunch. This current has been crossed during experiments, with a maximum single bunch current of roughly 1 mA. Due to a lack of further investigations, it is not clear if the instability occurred. However studies in this direction are planned in the future and the applicability of the Vlasov-Fokker-Planck solver Inovesa [11] for simulations in the negative α_{c} regime is under investigation.

SUMMARY

At KARA an optics with a negative momentum compaction factor has been successfully realised and first experiments were conducted. So far the maximum bunch current is limited but multiple factors with influence on this limit have been identified. Large orbit deviations seem to be beneficial and a lower absolute value of α_{c} resulted in a higher maximum bunch current. This could be due to the fact, that for a lower value of α_{c} the dispersion needs to be stretched less. There are also signs that the sextupole strengths and therefore the chromaticity might have an influence on the limit, where a lower negative vertical chromaticity yields a higher bunch current limit. This might be in accordance with the head-tail instability.

Outlook

There will be efforts to increase the current limit. Also better characterisations of the negative α_{c} optics are necessary. In particular more investigations for the head-tail instabilities as well as measurements on the micro-bunching threshold and behaviour are foreseen in the future. Simulations for the micro-bunching instability are planned and the applicability of Inovesa in the negative α_{c} regime is under investigation.

ACKNOWLEDGEMENT

We would like to thank R. Nagaoka, A. Gamelin (SOLEIL, F) and M. Aiba (PSI, CH) for inspiring discussions and ideas. This project has received funding from the European Union's Horizon 2020 Research and Innovation 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“

REFERENCES

[1] M. Ries, "Nonlinear momentum compaction and coherent synchrotron radiation at the Metrology Light Source," Ph.D. Thesis, Humboldt-Universität zu Berlin, Mathematisch-Naturwissenschaftliche Fakultät I, 2014, doi: 10.18452/16979.
[2] P. Kuske, "CSR-Driven Longitudinal Single Bunch Instability with Negative Momentum Compaction Factor," in *Proceedings of the 7th Int. Particle Accelerator Conf. (IPAC'16)*, paper TUPOR003, Busan, Korea, May 2016, pp. 1651–1654, doi: 10.18429/jacow-ipac2016-tupor003.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-MOPTS017

[3] I. Martin, R. Bartolini, J. Rowland, B. Singh, and C. Thomas, "A Low Momentum Compaction Lattice for the Diamond Storage Ring," in *Proceedings of the 23rd Particle Accelerator Conf. (PAC'09)*, paper TH6PFP032, Vancouver, Canada, May 2009.

[4] M. Klein *et al.*, "Modeling the Low-Alpha-Mode at ANKA with the Accelerator Toolbox," in *Proceedings of the 24th Particle Accelerator Conf. (PAC'11)*, paper WEP005, Mar.-Apr. 2011, New York, USA.

[5] A. Papash *et al.*, "New Operation Regimes at the Storage Ring KARA at KIT," Presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), paper TUPGW016, Melbourne, Australia, May 2019.

[6] S. Andreas, *OPA*, version 3.39, Mar. 14, 2012, https://ados.web.psi.ch/opa/opa.pdf

[7] A. W. Chao, *Physics of Collective Beam Instabilities in High Energy Accelerators*, ser. Wiley Series in Beam Physics and Accelerator Technology. New York: Wiley, 1993, ISBN: 978-0-471-55184-3.

[8] V. Balbekov, "Single bunch transverse instability in a circular accelerator with chromaticity and space charge," *Journal of Instrumentation*, vol. 10, no. 10, P10032–P10032, Oct. 2015, DOI: 10.1088/1748-0221/10/10/P10032.

[9] W. Herr. (2014). CAS - CERN Accelerator School: Advanced Accelerator Physics Course, https://cds.cern.ch/record/1507631

[10] K. L. F. Bane, Y. Cai, and G. Stupakov, "Threshold studies of the microwave instability in electron storage rings," *Physical Review Special Topics - Accelerators and Beams*, vol. 13, no. 10, Oct. 7, 2010, DOI: 10.1103/PhysRevSTAB.13.104402.

[11] P. Schönfeldt *et al.*, *Inovesa/Inovesa: Gamma Three*, Zenodo, Apr. 29, 2019, DOI: 10.5281/zenodo.2653504.