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NEW OPERATION REGIMES AT THE STORAGE RING KARA AT KIT

A. Papash[†], E. Blomley, T. Boltz, M. Brosi, E. Bründermann, S. Casalbuoni, J. Gethmann,
E. Huttel, B. Kehrer, A. Mochihashi, A.-S. Müller, R. Ruprecht, M. Schuh, J. L. Steinmann,
Karlsruhe Institute of Technology, Karlsruhe, Germany

Abstract

The storage ring Karlsruhe Research Accelerator (KARA) at KIT operates in a wide energy range from 0.5 to 2.5 GeV. Different operation modes have been implemented at KARA ring, so far, the double bend achromat (DBA) lattice with non-dispersive straight sections, the theoretical minimum emittance (TME) lattice with distributed dispersion, different versions of low compaction factor optics with highly stretched dispersion function. Short bunches of a few ps pulse width are available at KARA. Low alpha optics has been simulated, tested and implemented in a wide operational range of ring and now routinely used at 1.3 GeV for studies of beam bursting effects caused by coherent synchrotron radiation in THz frequency range. Different non-linear effects, in particular, residual high order components of magnetic field generated in high field superconducting wigglers have been studied and cured. Based on good agreement between computer simulations and experiments, a new operation mode at high vertical tune was implemented. The beam performance during user operation as well as at low alpha regimes was essentially improved. A specific optics with negative compaction factor was simulated and tested.

INTRODUCTION

The 2.5 GeV KARA storage ring [1] has an four-fold symmetry (Fig. 1). Eight double bend achromat sections (DBA) are formed by sixteen 22.5° bending magnets.

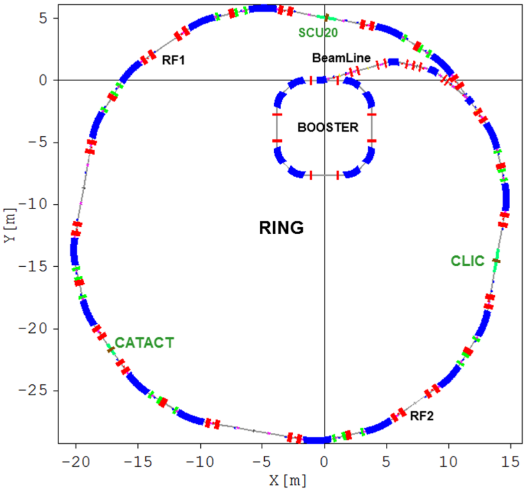


Figure 1: Model of the KARA ring, booster and beam line [2, 3]. Bending magnets are depicted in blue, quadrupoles in red and sextupoles are marked in green.

Four long and four short straight sections are occupied by insertion devices (ID), RF stations and injection (Table 1). The flexible lattice of KARA ring allows a variety of operation regimes, such as the TME mode with distributed dispersion (ε_x=56 nm), the DBA lattice with $D=D'=0$ in all straight sections (ε_x=90 nm). At present a modified TME optics (Table 2) with high vertical tune (Q_y=2.81) is applied for user operation, where the stored beam at current up to 150 mA is ramped from 0.5 to desired energy up to 2.5 GeV [2, 3]. Single- and multi-bunch regimes are available for all operation modes.

COMPUTER MODEL

Computer model of KARA ring, booster and injection line includes all magnetic elements (Fig.1). The computer code OPA [4] was used to simulate linear and high order dynamics at different operation modes. Variation of quads strengths according to the model allows to adjust betatron tunes with high accuracy. Sextupoles are treated in a model as thin lenses with realistic integrated strength. Few iterations of sextupoles current are required to get the desired value of chromaticity. High field superconducting wigglers CAT-ACT and CLIC as well as the superconducting undulator SCU20, are approximated by linear model and shown by long green lines in Fig. 1. Residual octupole components of the high field superconducting wigglers are treated as thin multipole lenses (brown strips in the middle of ID).

Position and dimension of diagnostic devices like beam position monitors (BPM), horizontal and vertical correctors (CH, CV) as well as scrapers, kicker magnets were adjusted to real element locations. Kicker magnets are described as thin lens correctors. Extraction septum in the

Table 1: Model Parameters of KARA Ring and Beam

Parameter	**KARA**	
Energy	0.5÷2.5 GeV	
Circumference, m	110.4	
Chromaticity ξ_X / ξ_Y	+1 / +1	
Hor/vertical tunes Q_X / Q_Y	6.761 / 2.802	
RF freq. (MHz)/RF harmonic	500 / 184	
Vacuum, tor / Gas	10^{-10} / H_2	
Number of bunches	100	
Current/charge per bunch, mA/nC	(0.1÷1) / (0.037÷0.37)	
Damping time (hor/vert/long), ms	0.5 GeV	380/370/180
	2.5 GeV	3/3/1.5
SR Energy loss, keV/turn	1 (0.5) / 622 (2.5GeV)	
Natural energy spr. 0.5/2.5 GeV	$1.8{\cdot}10^{-4} / 9{\cdot}10^{-4}$	
Injected beam energy spread	$4{\cdot}10^{-4}$	
Injected beam emittance		150÷180 nm·r

[†] alexander.papash@kit.edu

booster as well as injection septum in the ring are treated as sector magnets with negative (for booster) and positive for ring) curvature. The pulse of ring septum current lasts 250 µs. Thus, stray field of septum affects the orbit of the circulating beam and it is approximated by a horizontal angle kick [5].

In order to estimate kinetic and long term beam dynamics effects such as loss rate, life time etc. the ring model parameters were chosen as measured one (Table 1).

POSITIVE LOW MOMENTUM COMPACTION FACTOR LATTICE

Modified TME and positive low–α lattices (Table 2) were presented earlier [2, 3]. First, the 0.5 GeV beam from the booster (Fig. 1) is injected into a ring with modified TME optics at high vertical tune. Second, stored beam is ramped to desired energy. In case of positive low–α operation a squeezing procedure (stretching of dispersion function) is applied at high energy (usually at 1.3 GeV) to reduce the momentum compaction factor α to low positive values, see Fig. 3 at [2]. Essential growth of chromaticity during low-α squeezing was predicted in simulations and measured during tests. In order to keep chromaticity unchanged while span of dispersion was growing in few times the strength of sextupoles was subsequently reduced in synchronism with stepwise reduction of synchrotron tune. Thus, the chromaticity was kept almost unchanged and small during low-α operation, see Fig. 8 at [2].

The momentum acceptance of KARA lattice drops from ±2 % for modified TME mode down to ±0.5 % at low-α operation due to high span of dispersion function. As a consequence, the life time is reduced. Growth of chromaticity adds to beam losses, see blue curve in Fig. 9 at [2]. After correction of ring optics the life time at low-α has been improved from few minutes to ~3 hours (red curve in Fig. 9 at [2]).

Table 2: Simulated Optics at Different Compaction Factors

Parameter	mod. TME	Low–α	Negative–α
Comp. factor	$\alpha= +9\cdot10^{-3}$	$\alpha= +1\cdot10^{-4}$	$\alpha= -7\cdot10^{-3}$
Nat.emittance 0.5 GeV	2.4 nm·r	11.4 nm·r	18 nm·r
Nat.emittance 2.5GeV	58 nm·r	300 nm·r	460 nm·r
Dispersion	+0.1…0.7 m	–1…+1.4 m	±1.6 m
Natural width 0.5 GeV(rms)	σ_x=0.2 mm β_x=17 m	σ_x=0.5 mm β_x=22 m	σ_x=0.7 mm β_x=26 m
Inj.beam σ_x 0.5 GeV(rms)	σ_x=1.76 mm β_x=17 m	σ_x=2.03 mm β_x=22 m	σ_x=2.3 mm β_x=26 m
Natural width 2.5 GeV(rms)	σ_x=1.05 mm β_x=17 m	σ_x=2.7 mm β_x=22 m	σ_x=3.5 mm β_x=26 m

NEGATIVE MOMENTUM COMPACTION FACTOR LATTICE

In order to transfer from positive low–α to negative–α mode further stretching of dispersion function seems to be a simple solution, but this procedure is not possible at any energy because crossing of zero value of the momentum compaction factor leads to instability and loss of the beam. In order to operate KARA at negative momentum compaction factor, direct injection of 0.5 GeV beam from the booster into negative–α lattice of the ring is mandatory. The ring lattice for negative–α mode is shown in Fig.2. The procedure to build up a negative–α optics is similar to one for positive low–α optics and requires just little bit more stretching of dispersion function (Table 2). We decided first to develop a new positive–α lattice for direct injection of 0.5 GeV beam after the booster. Based on this experience, we simulated a negative–α optics for direct injection and tested it successfully. In the following we describe the procedure of negative–α lattice development.

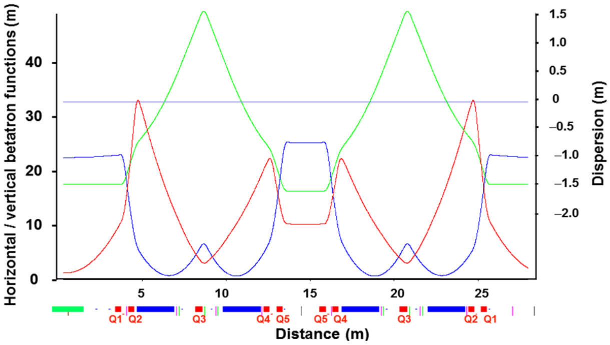


Figure 2: Ring lattice at negative compaction factor α= $-7\cdot10^{-3}$. Span of dispersion function (D) grows to ±1.6 m in order for negative contribution to exceed positive one inside bending magnets. Blue curve is horizontal beta function ***β_X***, red – vertical function ***β_Y***, green – dispersion ***D***.

First, a special algorithm of step-wise change of quads current was computed and used in tests in order to build a new positive low-α lattice at 0.5 GeV from modified TME lattice while keeping the betatron tunes unchanged. According to algorithm, the current of central quadrupole Q3 is slightly increased at each step of squeezing in order to stretch dispersion (Fig. 2). Tiny reduction of strengths of Q1 and Q5 focusing quads located at edges of DBA half-cell is applied in order to decrease horizontal betatron tune Qx and restore it original value. In result, the Qx is restored, but vertical tune Qy grows slightly above original value. By small reduction of current of Q2 and Q4 defocusing quads the vertical tune Qy also restored to its original value. Thus, at each step the compaction factor is reduced while tunes are kept almost unchanged. Variation of quads current in described procedure is monotonic and hysteresis effects are avoided. Keeping betatron tunes unchanged during squeezing procedure helps the fast feedback system to stabilize the beam. The algorithm was simulated using KARA model and has been applied successfully for the new positive low–α tests at 0.5 GeV as well as during negative–α tests.

Injection scheme of KARA ring [5] involves septum, three kicker magnets and few quads located in injection sector of ring (Fig.3). The injected beam passes quads off-axis. Meanwhile, in order to stretch dispersion and create

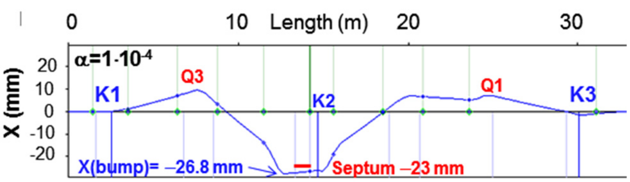


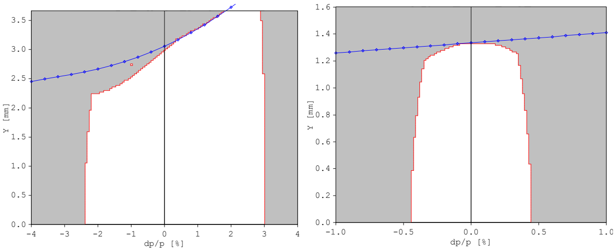
Figure 3: Trajectory of injected beam at low-α settings of ring quads before correction of K1, K2 and K3 kickers.

negative contribution of dispersion function at low–α and even more at negative–α optics, the strength of Q3 quads should be essentially increased. Beam hits septum after first turn, if kickers settings will not be changed from TME optics to new positive low–α lattice and same for negative–α lattice, as shown in Fig. 3. Field strengths of all three kickers were calculated in KARA model and have been subsequently reduced during tests. Beam was successfully stored at the new positive low-α mode. Based on model predictions and experience gained at direct injection of 0.5 GeV beam into the new positive low–α optics, settings of all quads, kickers, sextupoles and some correctors have been tailored for injection into the negative-α lattice [6, 7]. Finally, the beam have been stored at negative-α mode of KARA ring.

Momentum acceptance of ring (MA) and loss rate define life time of a beam. MA of modified TME lattice is ±2 % (Fig. 4a). For negative–α lattice the momentum acceptance is reduced under ±0.4 % (Fig. 4b). High span of dispersion function for negative–α optics (as well as for positive low–α lattice) leads to grows of Dispersion Integral and increase of equilibrium beam emittance, see Table 2.

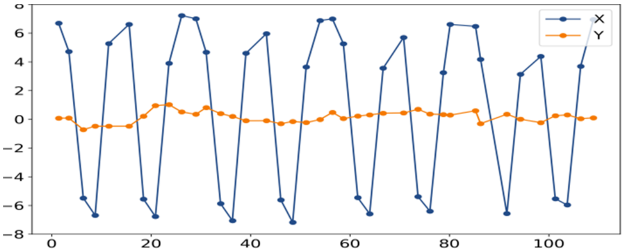
At 0.5 GeV the Touschek effect gives main contribution to beam losses for all described lattices. According to simulations for modified TME lattice at 0.5 GeV, the calculated life time is ~1.5 h at low beam current (0.1 mA/bunch) and 0.26 MV RF voltage amplitude. Results of simulations agree with experimental data. For same conditions, but at negative–α optics simulations predict reduction of life time to $T_{1/2} < 0.1$ hour.

Applying of high RF voltage is excessive during injection into negative–α optics as well as into new positive low–α lattice. At 0.5 GeV the energy losses due to synchrotron radiation are < 1 keV/turn. The high RF voltage leads to bunch compression causing growth of intra-beam scattering rate. Simulations predicted increase of life time in 3 to 4 times by reduction of RF voltage from 0.26 MV down to 0.02 MV for negative–α mode. During direct injection into negative–α lattice as well as into positive low–α lattice the amplitude of RF voltage was decreased from 260 kV down to 30–50 kV and life time was restored to $T_{1/2} \approx 1.5$ hour. Current of bending magnets and RF frequency have been optimized to get a good injection rate at negative–α (as well as positive low–α) injection tests. We found, that good injection rate is realized, when beam trajectory is captured by high dispersion pattern (Fig. 5a). Beam trajectory was reproduced in simulations (Fig. 5b). Energy offset between injected beam and reference orbit (magnetic rigidity of ring) could cause effect of orbit mismatching. Further experiments and simulations are planned to improve injection rate, minimize span of orbit oscillations and increase beam current.

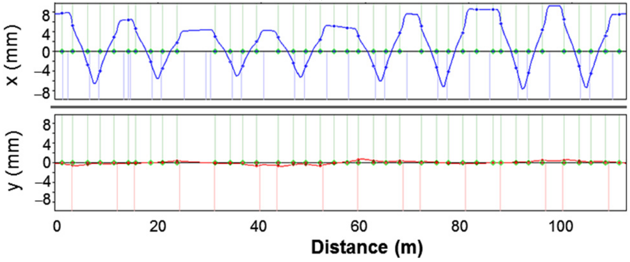


(a) (b)

Figure 4: Momentum acceptance of 0.5 GeV beam in vertical plane: (a) MA of TME lattice is ±2 %; (b) MA of negative–α lattice is reduced to ±0.4 % and even less.



(a)



(b)

Figure 5: Negative–α operation: Oscillations of beam orbit in the ring. Similar results were obtained for positive low–α optics at injection: (a) measured data, blue/red curves – horizontal/vertical position; (b) simulations for beam trajectory with energy offset and random misalignment errors σ_x=30 μ, σ_y=10 μ, energy of injected beam is less than reference orbit energy at δ= –0.35 %.

CONCLUSION AND OUTLOOK

Different operation modes were successfully tested and are in operation at KARA ring. Ring performance, life time, and beam current are essentially improved. Operation at negative momentum compaction factor has been simulated and first experiments were performed. Further tests on negative alpha are foreseen to deliver a contribution for R&D of future light sources.

REFERENCES

[1] E. Huttel *et al.*, "Operation with a low emittance optics at ANKA", in *Proc. Particle Accelerator Conf. (PAC'05)*, Knoxville, USA, May 2005, pp. 2467-2469.

[2] A. Papash *et al.*, "Non-linear optics and low alpha operation at the storage ring KARA at KIT", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, May 2018, pp. 4235-4238.

[3] A. Papash *et al.*, "High Order Magnetic Field Components and Non-Linear Optics at the ANKA Storage Ring", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 2586-2588.

[4] A. Streun. OPA Lattice Design Code, `https://ados.web.psi.ch/opa/`.

[5] D. Einfeld *et al.*, "The Injection scheme for the ANKA storage ring", in *Proc. 6th European Particle Accelerator Conf. (EPAC'98)*, Stockholm, Sweden, June 1998, pp.2135-2137.

[6] P. Schreiber *et al.*, "Status of operation with negative compaction factor at KARA", presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper MOPTS017, this conference.

[7] M. Brosi *et al.*, "Synchronous Measurements of Electron Bunches Under the Influence of the Micro-bunching Instability", presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, this conference.