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NON-LINEAR OPTICS AND LOW ALPHA OPERATION AT THE STORAGE RING KARA AT KIT

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Abstract

The storage ring Karlsruhe Research Accelerator (KARA) at KIT operate in a wide energy range from 0.5 to 2.5 GeV. Different non-linear effects, in particular, residual octupole components of the magnetic field of the CATACT wiggler at high field level (2.5 T), proximity of the working point to a vertical sextupole resonance Qy=8/3 and weak coupling octupole resonance 2Qx+2Qy=19, high chromaticity, etc. decrease the beam life time. This is because of the reduced dynamic aperture and momentum acceptance for off-momentum particles. A new operation point at high vertical tune Qy=2.81 was tested. For this, injection and ramping tables have been modified. First the values were optimized by simulations, then during beam tests, to minimize betatron tune shaking during beam-energy ramps. It stabilized high-current beams by the fast-feedback system the whole process injection at 0.5 GeV, ramping, and operation at 1.3 GeV cycles. It essentially improved life time and beam current. In addition, new low-alpha tables have been created and tested, resulting in the reduction of the momentum compaction factor to 10-4. Short bunch operation at 0.5GeV injection energy was also tested successfully.

INTRODUCTION

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

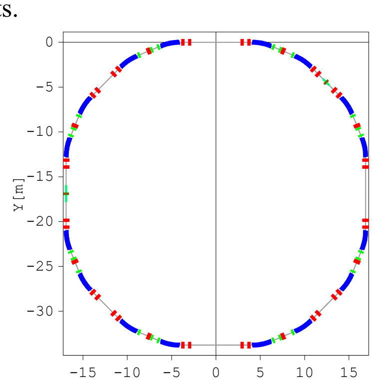

Figure 1: Model of the KARA ring [2]. The 22.5° bending magnets are depicted in blue, quadrupoles in red and the sextupoles are marked in green. The CATACT/CLIC wigglers are shown by long green strips. Octupole components of wigglers are represented by brown strips in the middle of insertion device.

The flexible lattice of KARA ring in Table 1 allows a variety of operation modes, such as the theoretical minimum emittance mode with distributed dispersion (TME ε_x=56 nm) (Fig. 2), the Double Bend Achromat (DBA) regime with D=D'=0 in all straight sections (DBA ε_x=90 nm), as well as low-alpha operation mode, see Fig. 3.

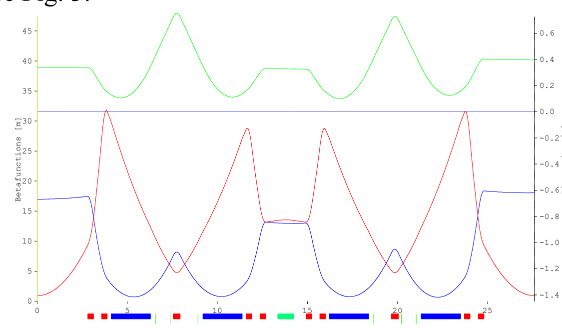

Figure 2: One cell of the KARA lattice is composed of two pairs of 22.5° bends. The middle of long straight section where the CLIC wiggler is located is chosen as an origin (θ_0=0). The horizontal/vertical beta-functions are depicted in blue/red dispersion – green.

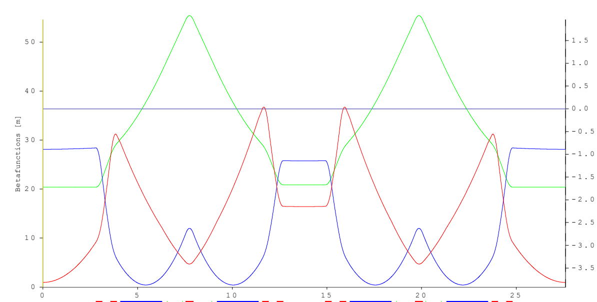

Figure 3: KARA lattice at low-alpha operation mode. Span of dispersion is increased to ±1.8 m in order to compensate positive and negative contribution of dispersion inside bending magnets. Compaction factor at low-α was reduced down to $5{\cdot}10^{-5}{\div}10^{-4}$.

Two high field superconducting insertion devices are located in straight sections of the KARA ring (Fig. 1). Both wigglers might produce residual high order (octupole) components of magnetic field. The CATACT wiggler is installed in a short straight section where the vertical beta-function is large (13 m) (Fig. 2). The CLIC wiggler is placed in the long straight section with small vertical beta (0.87 m).

The beam lifetime has been degraded from ~15 hours to ~12 h at high field level of the CATACT wiggler even

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though the coherent shift of vertical tune was compensated locally and residual octupole components of wiggler does not exceed the design values. The CLIC wiggler does not influence the lifetime of the beam, even at high field level and without any compensation coils.

Table 1: Main Parameters of the KARA Beam

Parameter	KARA
Energy / Magnetic rigidity	2.5 GeV (8.339T·m)
Circumference, m	110.4
Compact factor, α_0 (user/low alpha)	$9{\cdot}10^{-3}$ / ($5{\cdot}10^{-5}\div10^{-4}$)
RMS bunch width (user/low α), ps	21.6 / 2.4
Synch. frequency (user/low α), kHz	33.4 / 5 (1.3 GeV)
Long/short straight sections, m	5.604 / 2.236
Natural ε_x (nm·rad) TME/DBA	56 / 90
Natural Chromaticity ξ_X / ξ_Y	−12/−13
High (low) chromaticity ξ_X/ξ_Y	+2/+6 (+1/+1)
Int.Sxt strength,m^{-2} (high) (low)	(+4.9/−4) (+4/−3)
Hor/vertical tunes Q_X / Q_Y	6.779 / 2.691
High tune operation Q_X / Q_Y	6.761 / 2.802
RF frequency (MHz) / h_{RF}	500 / 184
CATACT/CLIC wiggler field, T	2.5 / 2.9
CATACT wiggler length / period	0.96 m / 48 mm
CLIC wiggler length / period	1.84 m / 51 mm
Octupole CATACT, $g_3(k_3{\cdot}L_W)$	≤120 T/m^3 (≤20m^{-3})

NON-LINEAR EFFECTS

Extensive studies and computer simulations have been done to reproduce the non-linear beam dynamics in the KARA ring [2]. The computer code OPA [3] was used to simulate high-order effects due to the presence of insertion devices. The model includes the main magnetic elements. Sextupoles in the model are treated as thin lenses with realistic integrated strength.

Wigglers are approximated by linear model. Coherent tune shift due CATACT wiggler is compensated locally. The vertical tune is restored to the original value by a local reduction of the strengths of the defocusing quadrupoles around the CATACT wiggler, exactly as in tests of the device. Tunes measured during ramp of the wiggler field precisely correspond to simulated values. The CLIC wiggler is located in the middle of long straight section where the vertical betatron function is small. The tune shift of CLIC is small and it is not compensated.

The influence of higher order field components has been modeled by adding thin sextupole and octupole lenses at the wiggler positions. The measured integrated sextupole strength of the CATACT wiggler $k_2{\cdot}L_W$=0.03m^{-2} is small compared to the strong sextupoles of a ring $k_2{\cdot}L_S$=4m^{-2}. Indeed, chromaticity tests at KARA do not indicate drift of chromaticity during ramp of wiggler field.

Nevertheless, the beam life time was reduced at high field level of CATACT wiggler. At specific conditions the residual octupole components of the wiggler field reduce the dynamic aperture even at tolerance limit of the fabrication conditions [2]. Operation point of KARA ring has been located in the vicinity of a weak octupole resonance. At high chromaticity particles with small momentum offset δ=+0.51% cross coupling octupole resonance $2Q_X+2Q_Y$=19 excited by the residual octupole components of wiggler field. Off-momentum particles in a beam halo are pushed towards coupling octupole resonance $2Q_X+2Q_Y$=19 and part of the beam in the tail of the Gaussian distribution should be lost. Dynamic aperture for off-momentum particles was essentially reduced [2] and beam life time has dropt.

Meanwhile the natural energy spread of the electron beam under equilibrium is σ_P=10^{-3}. At high chromaticity the momentum acceptance of a ring might be further reduced. At low chromaticity the momentum offset where particles can cross the octupole resonance is shifted away to δ=+0.9%. Particles from the tail of the Gaussian distribution will still be affected by the resonance, but only at high momentum deviation. The lifetime could be restored even if small residual octupole components are present.

HIGH BETATRON TUNE AND LOW ALPHA

Previous experimental tests have proved our theoretical predictions [2]. The normalized lifetime as function of vertical tune is plotted in Fig.4. The black dots fit by a polynomial (black curve) represent measurements at B_{CAT}=0. The drop of the lifetime at Qy=2.78 is due to a crossing of the structure resonance Qx–Qy=4. When the wiggler at high field 2.5T, two dips in the lifetime were detected. The first drop at Qy=2.72 corresponds to the crossing of a coupling-octupole resonance 2Qx+2Qy=19. The life time has been restored while operating at high betatron tune (Q_Y=2.81).

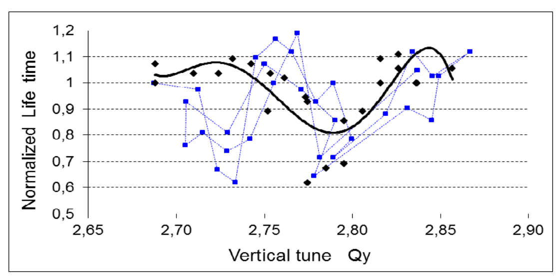

Figure 4: Normalized lifetime as a function of the vertical tune. Black dots and fit by a polynomial (black curve) are for the case that CATACT is OFF. The dip in lifetime at Qy=2.78 is seen during the crossing of the structure resonance Qx–Qy=4. The blue dots for B_{CAT}=2.5 T show an additional drop in the lifetime at Qy=2.724 (Qx=6.776), corresponding to the coupling octupole resonance 2Qx+2Qy=19.

The decision has been made to shift KARA operation towards new working point corresponding to high vertical tune. Based on results of our tests and simulations we have modified operation algorithm and settings of KARA focusing elements.

Firstly, we've varied quads settings at injection energy of 0.5 GeV in order to find out the best injection rate. Highest Injection rate has been achieved at Qy=2.801 and Qx=6.75, see Fig. 5. This operation point corresponds to

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best Life time at 2.5 GeV and minimum of Resonance Driving terms (RDT). Phase dependent RDT are minimized by periodicity of four-fold symmetry of KARA ring.

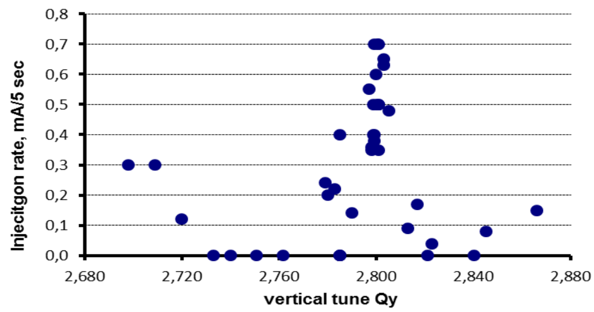

Figure 5: Injection rate of KARA beam at high vertical tune. The best injection conditions correspond to tune Q_Y=2.801.

Next, we've modified ramp tables in order to minimize tune shaking during energy ramp from 0.5 to 2.5 GeV. Corrections of quads settings in ramp tables have been implemented (Fig.6) in order to stabilize high vertical tune during ramp and keep it unchanged (Fig. 7).

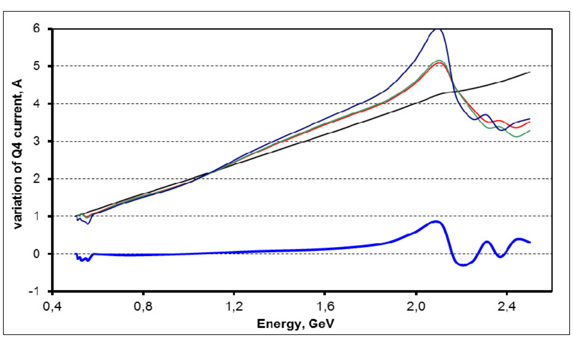

Figure 6: Corrections to ramp table to stabilize vertical tune during energy ramp from 0.5 to 2.5 GeV. Black curve - proportional increase of quads current during ramp. Blue, green and red curves around black curve - deviation of quad current from linear fit in order to minimize tune shaking. Blue line at bottom - difference between simulations and experimental tests.

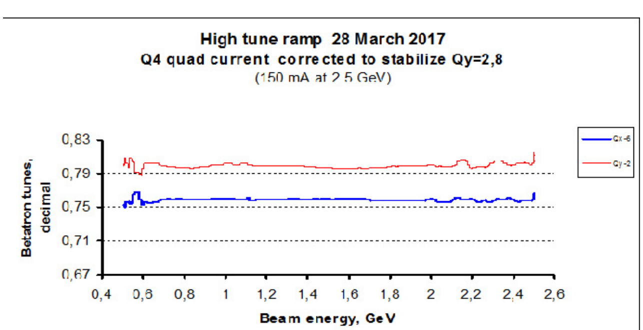

Figure 7: High tune ramp corrected to keep tune unchanged. Red curve is horizontal tune, blue curve is vertical tune.

Also, we've modified ring settings during low compaction factor operation and adjusted it to high tune operation mode. Essential growth of chromaticity has been observed during low-α squeezing. In order to keep chromaticity unchanged while span of dispersion has been growing in few times the strength of sextupoles has been subsequently reduced in synchronism with stepwise reduction of synchrotron tune. The chromaticity has been restored to desired settings, see Fig. 8.

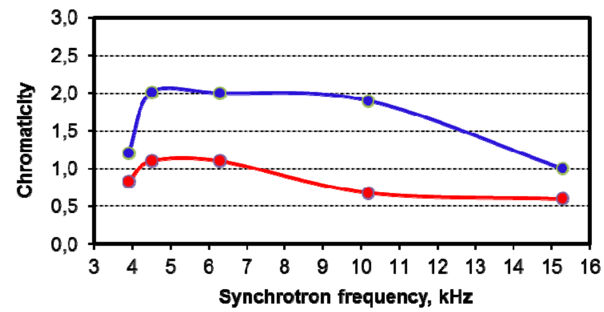

Figure 8: Optimized horizontal (blue) and vertical (red) chromaticity measured during low alpha squeeze.

During low-α operation the momentum acceptance of KARA ring drops from 1% down to 0.2% due to high span of dispersion function (Fig.3). As a consequence, the life time was reduced essentially. Growth of chromaticity during low alpha squeeze adds to beam losses, see blue curve in Fig. 9. Here the black curve depicts results of simulations. After correction of ring optics life time at low-α has been restored to original values. The pattern of life time curve during squeezing (red curve in Fig. 9) is similar to theoretical predictions (black curve). After corrections the beam life time at low-α has been improved to 3-4 hours (red curve in Fig. 9).

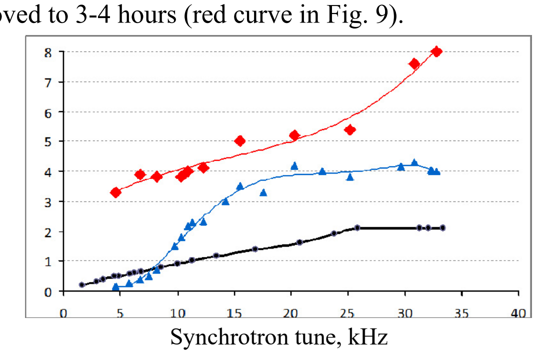

Figure 9: Life time (vertical axes – in hours) as function of syn-chrotron tune. Black curve - simulations, Blue curve – measured data before sextrupole corrections, red curve – after corrections.

CONCLUSION

KARA ring successfully operates at new high vertical tune. Ring performance is essentially improved. The life time at user operation mode as well as at low-α is restored. Beam parameters at low compaction factor mode are improved. More tests are scheduled to further reduce compaction factor, operate short bunches and measure coherent synchrotron radiation in THz range.

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