HIGH ORDER MAGNETIC FIELD COMPONENTS AND NON-LINEAR OPTICS AT THE ANKA STORAGE RING

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Abstract

The Karlsruhe Institute of Technology operates the 2.5 GeV electron storage ring ANKA as an accelerator test facility and synchrotron radiation source. A superconducting wiggler is installed in a short straight section of the ring where the vertical beta-function is large (13 m). The lifetime of the electron beam is reduced from 15 to 12 hours at a high field of the wiggler (2.5 T) even though the coherent shift of vertical tune was compensated locally. Computer simulations show the non-linear nature of the effect. The ANKA storage ring operates with strong sextupoles at a positive chromaticity of +2/+6. Even residual octupole components of the wiggler field, at the tolerance of the specification, can reduce the dynamic aperture for off-momentum particles when the betatron tune is close to a weak octupole resonance and the chromaticity is high. Also the vertical betatron tune is close to the sextupole resonance Qy=8/3. A large resonance stopband and proximity to a sextupole resonance affect the lifetime as well. When the betatron tunes of ANKA are shifted away from suspected high-order resonances the beam lifetime is substantially improved.

INTRODUCTION

The 2.5 GeV ANKA storage ring [1] has a four fold symmetric double bend achromat structure (DBA) formed by sixteen 22.5° bending magnets (Fig.1). The flexible lattice of the ANKA storage ring (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 and ε_x=90 nm, or low-alpha operation.

Two high field superconducting insertion devices are located in straight sections of the ANKA ring (Fig.1). The CATACT wiggler with a magnetic field up to B=2.5 T is installed in a short straight section where the vertical beta-function is large (13 m) (Fig.2). The CLIC wiggler with a field up to B=2.9 T is placed in the long straight section with small vertical beta (0.87 m). Both wigglers might produce residual higher order (octupole) components of magnetic field. A lifetime reduction from $T_{1/2}$=15 hours down to 12 hours was observed during the ramp of the CATACT wiggler at fields above the 2.2 T, even though the coherent shift of the vertical betatron tune due to over-focusing by the wiggler poles was compensated locally, and residual octupole components do not exceed the design values. The CLIC wiggler does not influence the lifetime of the beam, even at high field level (B_{CLIC}=2.9 T) and without any compensation coils.

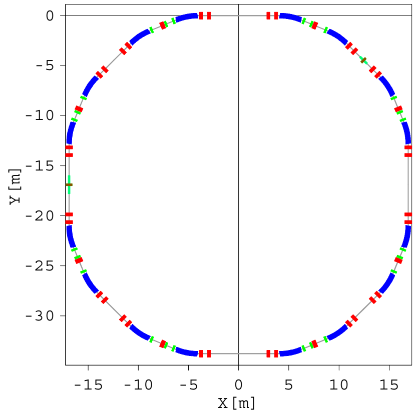

Figure 1: Four fold symmetric model of the ANKA ring [2]. The 22.5° bending magnets are depicted in blue, quadrupoles in red and the thin sextupoles are marked in green. The CATACT/CLIC wigglers are shown by long green strips and are located in long/short straight sections. Higher order field components of the wigglers are modelled as thin octupole lenses in the middle of insertion devices (brown strips).

Table 1: Parameters of the ANKA Ring and the Wigglers

Parameter	**ANKA**
Energy / Magnetic rigidity	2.5 GeV (8.339T·m)
Circumference, m	110.4
Beam current, mA	150–170
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 field, T	2.5
CATACT length / period	0.96 m / 48 mm
Octupole CATACT, $g_3(k_3\cdot L_W)$	≤120 T/m^3 (≤20m^{-3})
CLIC field, T	2.9
CLIC length / period	1.84 m / 51 mm
Vertical β_y (CATACT/CLIC), m	13.3/ 0.87

NON-LINEAR BEAM DYNAMICS

Extensive studies and computer simulations have been done to reproduce the non-linear beam dynamics in the ANKA ring and to better understand the origin of the lifetime reduction and other effects. The computer code OPA [2] was used to simulate high-order effects due to the presence of insertion devices. The model includes the main magnetic elements like bending magnets, quadrupoles and sextupoles with parameters corresponding to those

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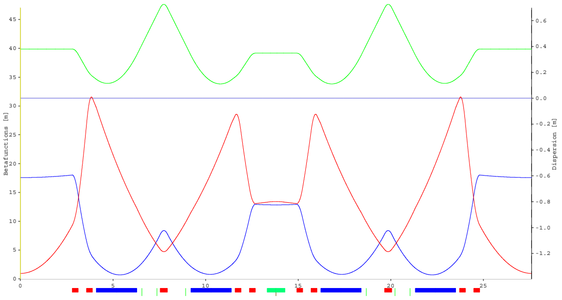


Figure 2: One cell of the ANKA lattice. The origin is at the middle of long straight section (θ_0=0). The horizontal/vertical beta-function is shown by the blue/red line, dispersion – green.

of the actual devices in the ANKA synchrotron (Table 1). Sextupoles in the model are treated as thin lenses at the nominal location of the sextupoles in the ring, with integrated strength corresponding to the actual currents applied during experiments. The CATACT and CLIC wigglers are described in the program by linear models with dimensions and fields corresponding to the actual values. The CATACT wiggler is located in the short straight section of ANKA ring where the vertical betatron function is high (13 m). Thus, the coherent shift of the vertical betatron tune due to over-focusing at high field (B_{CAT}=2.5 T) is large, $\Delta Q_Y \approx +0.045$. The tune shift is compensated and 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. In additions the beta-beat caused by local gradient error introduced by CATACT wiggler was minimized.

The CLIC wiggler is located in the middle of long straight section where the vertical betatron function is low. The vertical tune shift caused by the field of the CLIC is small $\Delta Q_Y \leq -0.008$. It is not compensated in the ANKA ring.

Since the program does not support the modeling of non-linear features of insertion devices we have modelled the influence of higher order field components by adding thin sextupole and octupole lenses at the wiggler positions. The measured integrated sextupole strength of the CATACT wiggler $k_2 \cdot L_W = 0.03 m^{-2}$ is small compared to the strong ANKA ring sextupoles $k_2 \cdot L_S = 4 m^{-2}$, and chromaticity tests at ANKA do not indicate any difference between CATACT OFF and CATACT B=2.5T operation. Nevertheless, the beam life time was reduced during operation at high CATACT field B_{CAT}>2.2 T. Computer simulations as well as further tests have proven the non-linear nature of the effect to be caused by residual octupole components of the wiggler field at tolerance limit of the fabrication conditions, which reduce the dynamic aperture for off-momentum particles if the operation point for the betatron tune is located in the vicinity of a weak octupole resonance (Fig.3). At high chromaticity (+2/+6) particles with momentum offset δ=+0.51% cross-couple via the octupole resonance 2Qx+2Qy=19 (Fig.3) excited by the residual octupole components of wiggler field.

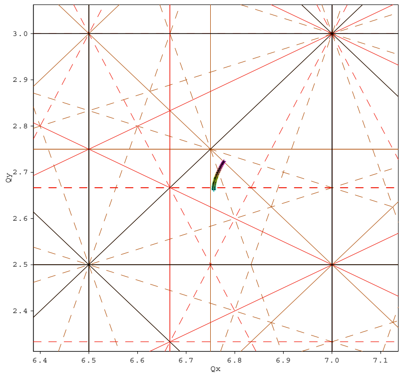
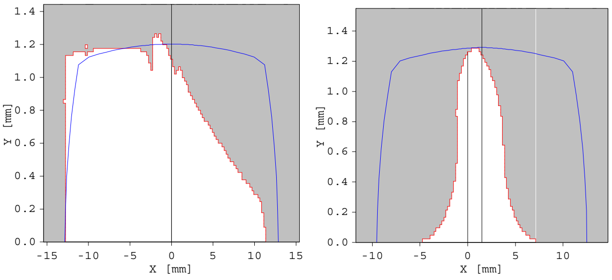
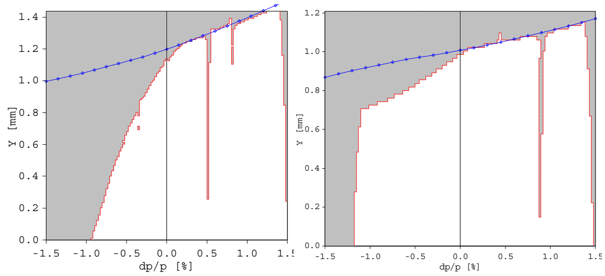


Figure 3: Tune diagram at high chromaticity ξ_X/ξ_Y=+2/+6. Particles with momentum offset $\delta p/p$=+0.51% cross-couple via the octupole resonance 2Qx+2Qy=19 excited by the residual octupole component of wiggler field.



(a) (b)

Figure 4: Dynamic aperture for azimuth θ_0=0 with B_{CAT}=2.5T, residual octupole strength $k_3 \cdot L_W = 16 m^{-3}$, $\xi_{X/Y}$=+2/+6. The blue contour indicated the scraper openings, scaled by the value of betatron functions: a) on-momentum particles b) DA reduced to less than ±3mm at an energy deviation of δ=+0.51%. The rms beam size is σ_x=0.95 mm.



(a) (b)

Figure 5: Projection of the phase space for off-momentum particles at B_{CAT}=2.5 T: a) at high chromaticity $\xi_{X,Y}$=+2+6 the DA shrinks at momentum offset δ=+0.51% b) at low $\xi_{X,Y}$=+1+1 the momentum off-set of reduced DA is shifted away to higher δ=+0.9%.

The ring dynamic aperture at high CATACT field B_{CAT}=2.5 T and residual integrated octupole strength $k_3 \cdot L_W = 16 m^{-3}$ is shown in Fig.4. The stable area for on-momentum particles (δ=0) is similar to that of bare lattice without wiggler, limited by scrapers at ±13 mm (Fig.4a). Central particles stay away from the octupole resonance and are not affected by small octupole field components. At high chromaticity and momentum offset δ=+0.51% the DA is reduced to $\delta x \leq \pm 3$mm (Fig.4b) and $\delta y \leq \pm 0.2$mm (Fig.5a). Off-momentum particles are pushed towards the

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octupole resonance 2Qx+2Qy=19 (Fig.3) and part of the beam in the tail of the Gaussian distribution might be lost. The momentum acceptance of the ANKA ring is limited by the RF buckets to $\delta\leq\pm1\%$, natural energy spread of the ANKA beam is $\sigma_P=10^{-3}$. At high chromaticity and a betatron tune close to the octupole resonance the octupole field components might further reduce the momentum acceptance. Particles with small momentum deviation thus can cross the octupole resonance and might be lost, with the effect that the lifetime is reduced. At low chromaticity $\xi_{X,Y}$=+1+1 the momentum offset where particles can cross the octupole resonance is shifted away to $\delta=+0.9\%$ (Fig.5b). At low chromaticity particles from the tail of the Gaussian distribution will still be affected by the resonance, but only at high momentum deviation. The lifteime is restored even in case small residual octupole components are present.

LIFETIME IMPROVEMENT

Experimental tests were done at ANKA in order to check the theoretical predictions. The lifetime was measured as function of chromaticity at the original tune Qy=2.69 for small, moderate, and high beam currents. When the wigglers are off the lifetime is independent of chromaticity (red line in Fig.6), regardless of beam intensity. At high fields >2.2 T a strong dependence on chromaticity is observed (Fig. 6, blue dots fitted by black line). At small chromaticity the lifetime of the beam can be recovered.

Nevertheless, ANKA operation at high beam current is likely to be affected by instabilities at small chromaticity, even though the Fast Feedback System stabilizes the beam. We therefore decided to shift the operating point to high vertical tune and avoid resonance crossing. Lifetime measurements taken during a tune scan from Qy=2.69 up to Qy=2.83 are presented in Fig.7. When CATACT is off the lifetime pattern is flat except for a drop from 20 to 15 hours when crossing the Qx–Qy=4 structure resonance (Fig.7a). When CATACT 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 second dip is due to the structure resonance (Fig.7b). The normalized lifetime as function of vertical tune is plotted in Fig.8. 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. When the wiggler operates at high field (B_{CAT}=2.5T) two dips in the lifetime are seen. The first drop Qy=2.724 (Qx=6.776) corresponds to the coupling octupole resonance 2Qx+2Qy=19, the second to structure resonance Qx-Qy=4.

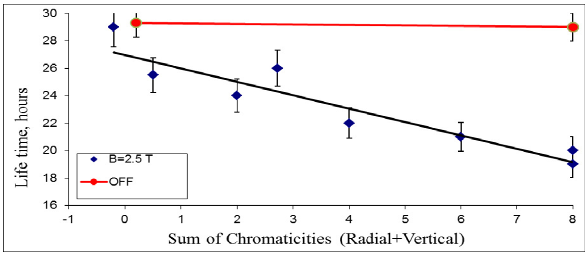
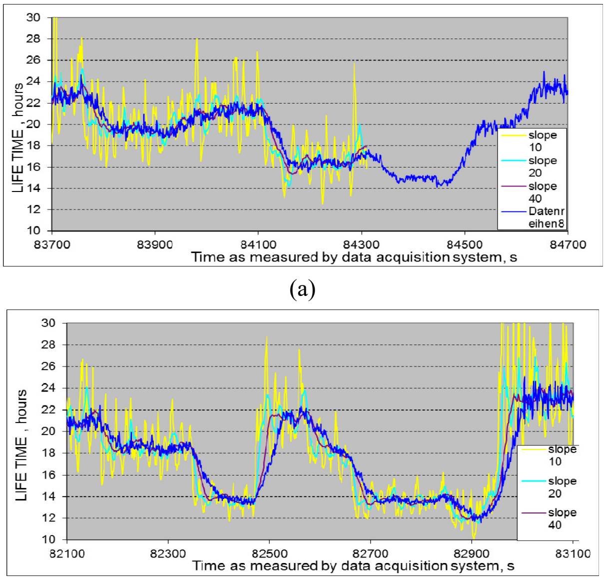


Figure 6: Life time as function of chromaticity, for CATACT off (red points) and CATACT at high field 2.5 T (blue points fit by black line).



(a)

(b)

Figure 7: Lifetime measurements during a tune scan from Qy = 2.69 to Qy=2.83, with a) wiggler is OFF an b) B_{CAT}=2.5 T. The drop in lifetime from 20 to 15 hours in a) is due the crossing of the structure resonance Qx–Qy=4. The first drop in b) is due to the crossing of the octupole resonance 2Qx+2Qy=19, the second dip is due to structure resonance.

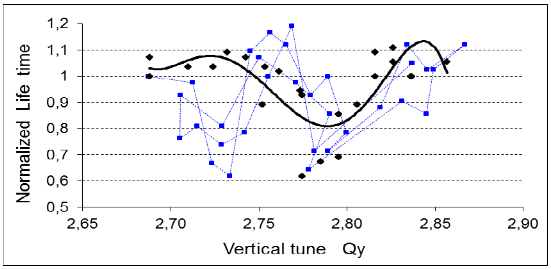


Figure 8: Normalized lifetime as a function of the vertical tune. Black dots and fit by a polynomial (black curve) are for the case that CATACT is OFF. The dip in lifetime at Qy=2.78 is seen during the crossing of the structure resonance Qx–Qy=4. The blue dots for B_{CAT}=2.5 T show an additional drop in the lifetime at Qy=2.724 (Qx=6.776), corresponding to the coupling octupole resonance 2Qx+2Qy=19.

CONCLUSION

Reduced lifetime and non-linear effects have been observed at ANKA during operation at high field level of the CATACT wiggler. Modification of the working point to high vertical tune away of octupole and sextupole resonances as well as reduction of chromaticity helps to restore and even improve the beam lifetime in ANKA.

REFERENCES

[1] E. Huttel *et al.*, PAC2005, p.2467 (2005).
[2] A. Streun, OPA–3.39. User Guide (2012).