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DIFFERENT OPERATION REGIMES AT THE KIT STORAGE RING KARA (KARLSRUHE RESEARCH ACCELERATOR)

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Abstract

The KIT storage ring KARA operates in a wide energy range from 0.5 to 2.5 GeV. Different operation modes have been implemented at KARA, so far, the double-bend achromat (DBA) lattice with non-dispersive straight sec-tions, 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 the storage ring and is now routinely used at 1.3 GeV for studies of beam bursting effects caused by coherent synchrotron radiation in the THz frequency range. Different non-linear effects, in particular residual high-order components of the 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 has been improved. A specific optic with negative compaction factor was simulated, tested and is in operation.

INTRODUCTION

The 2.5 GeV KARA storage ring has a four-fold symmetry [1] and operates at an energy range from 0.5 to 2.5 GeV. Computer model of KARA ring, booster and injection line includes all magnetic elements (Fig. 1) and was described in details earlier [2-4].

The computer code OPA [5] was used to simulate linear and high order beam dynamics at different operation regimes. 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).

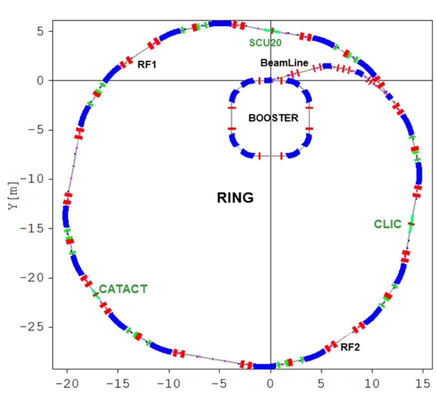

Figure 1: Model of the KARA ring [3]. The 22.5° bending magnets are depicted in blue, quadrupoles in red and the sextupoles are marked in green. The CATACT/CLIC wigglers are shown by long green strips.

Table 1: Parameters of the KARA Ring

Parameter	Split Q Lattice
Energy range	0.5 to 2.5 GeV
Circumference	110.4 m
Chromaticity corrected	+1 / +1
Horizontal/vertical tunes	6.761/2.802
RF frequency/RF harmonic	500 MHz / 184
Current per bunch	0.1 to 1.3 mA
Charge per bunch	0.04 to 0.5 nC
Number of bunches/trains	120/4
Vacuum/gas composition	10^{-9} tor / N_2+CO
Damping time – 0.5 GeV	380/ 370 /180 ms
Damping time – 2.5 GeV	3/3/1.5 ms
Energy loss (SR)	622 keV/turn
Energy spread (0.5/2.5 GeV)	$2{\cdot}10^{-4}$ / 10^{-3}
Natural emitt. (DBA/TME)	90/56 nm

FLEXIBLE LATTICE

The flexible lattice of KARA ring allows a variety of operation regimes, see Fig. 2. In particular, the double bend achromat lattice (DBA) with achromatic straight sections (D=D'=0) and equilibrium rms emittance ε_x=90 nm (Fig. 2(a)), the theoretical minimum emittance lattice (TME) with distributed dispersion and emittance ε_x=56 nm (Fig. 2(b)). At present a modified TME optics with high vertical tune (Q_y=2.802) and momentum compaction factor α=$+9{\cdot}10^{-3}$ is applied for user operation [2, 3]. At this mode the life-time reduction caused by residual octupoles components of 2.5 T super-conducting wiggler was restored to nominal values [2, 3]. The stored beam of 100 to 150 mA is ramped from 0.5 to desired energy up to 2.5 GeV. Single- and multi-bunch regimes are available for all operation modes.

Ring lattice with highly stretched dispersion function (Fig. 2(c)) is routinely used for low–α as well as for negative–α operation regimes [6, 7]. Different options of low momentum compaction factor optics were realized in a

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wide operational range of a ring. Short bunches of a few ps pulse width are available. At low–α mode the momentum compaction factor is reduced in ~100 times, to the level of $\alpha=+10^{-4}$. For that the dispersion function is stretched from positive +1.4 m in the middle of arc sections to −1 m in all straights to compensate positive contribution of dispersion inside bending magnets by negative one [4]. Ring lattice with negative momentum compaction factor is similar to positive low–α optics but dispersion is stretched even more, to ±1.6 m [6, 7]. In order to operate at negative compaction factor, direct injection and storage of 0.5 GeV beam is realized into negative–α lattice with following ramp up of electrons to 0.9 and 1.3 GeV [7].

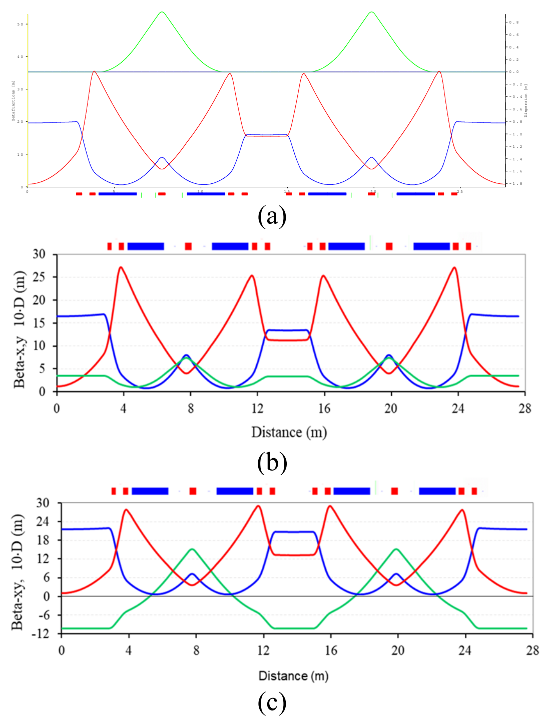

Figure 2: One cell of the KARA lattice is composed of two pairs of 22.5° bends. The horizontal/vertical beta-functions are depicted in blue/red, dispersion – green: a) double bend achromat cell; b) TME cell with positive dispersion ranging from 0.1 to 0.7 m; c) Low–α optics $\alpha=+10^{-4}$ where dispersion is stretched from +1.4 m to −1 m. Ring lattice at negative–α optics is similar to low–α mode while dispersion is stretched even more, to ±1.6 m [6].

OFF-MOMENTUM DYNAMIC APERTURE

In order to describe results of life-time measurements we estimated the momentum acceptance of the ring for different operational conditions. Evolution of momentum acceptance of a ring lattice is shown in Fig. 3. Momentum acceptance of a ring lattice is limited by chamber aperture $2a_x$ and span of dispersion function $MA_L \leq a_x/2 \cdot D_x$. Scrapers installed at KARA to protect beamlines limit momentum acceptance of ring lattice to about ±1.3% at 'user operation' mode, see Fig. 3(a).

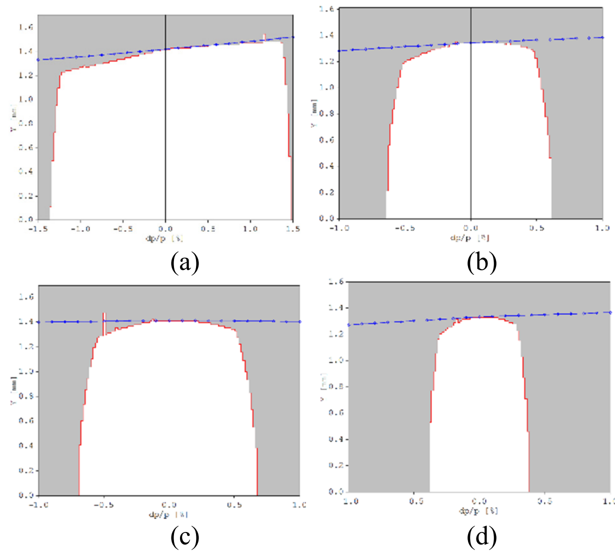

Figure 3: Off-momentum dynamic aperture of KARA ring at different operation regimes: (a) user optics with momentum compaction factor $\alpha=9\cdot10^{-3}$; (b) positive low–α optics with $\alpha=+1\cdot10^{-4}$; (c) negative low–α operation mode with $\alpha=-1.4\cdot10^{-4}$ and (d) negative–α optics with $\alpha=-7\cdot10^{-3}$ and dispersion stretched to ±1.6 m.

For low–α lattice with positive momentum compaction factor $\alpha=+10^{-4}$ the energy acceptance is reduced to ±0.7 % because of the beam deviation from reference orbit is magnified by stretched dispersion (Fig. 3(b)). Span of dispersion at negative low–α optics with $\alpha=-1.4\cdot10^{-4}$ just slightly more than at positive one and momentum acceptance is almost the same (Fig. 3(c)). Off-momentum dynamic aperture is strongly reduced for a ring optics with negative momentum compaction of $\alpha=-7\cdot10^{-3}$ because of the dispersion is highly stretched to ±1.6 m (Fig. 3(d)).

LIFITIME CONSIDERATIONS

Different dissipation processes limit life time of electrons in KARA ring. Single large angle elastic and inelastic scattering of electrons on molecules and atoms of residual gas with scatter angles exceeding dynamic or physical aperture of a ring restrict the lifetime of electrons. Touschek effect adds to vacuum losses and dominates at low beam energies.

RF bucket defines maximum energy offset of particles in a bunch. Contribution of RF to the ring momentum acceptance might be estimated by following Eq. (1)

$$MA_{RF} \equiv \left(\frac{\Delta p}{p_0}\right)_{buck} = \pm\sqrt{\frac{eV_{rf}(-cos\varphi_s)}{\pi h_{rf}\alpha E_0}}, \qquad (1)$$

where V_{rf} and h_{rf} are RF voltage amplitude and RF harmonic, E_0 is beam energy and α is momentum compaction factor. Maximum voltage of RF cavities at KARA is limited to 1.6 MV. At 2.5 GeV energy range the momentum acceptance of KARA ring is restricted by RF to ±1%. The

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Touschek lifetime strongly depends on relativistic factor γ, momentum acceptance, bunch size in all three planes $\sigma_x, \sigma_y, \sigma_s$. In case when $MA_{RF} < MA_L$ the Touschek lifetime should be estimated by Eq. (2)

$$\tau_T = 8\pi\gamma^2 \frac{(\sigma_x\cdot\sigma_y\cdot\sigma_s)}{r_e^2 c\cdot n_e}\left(\frac{\Delta p}{p_0}\right)^3 \frac{1}{D(\zeta)} \sim \gamma^{3.6}\frac{1}{I_b}\left(\frac{V_{RF}}{h_{RF}\cdot\alpha_p}\right). \quad (2)$$

The lifetime as a function of RF voltage has been measured at 2.5 GeV user operation mode of KARA ring and results are presented in Fig. 4, taken from [8]. Limit of the lifetime at high amplitude of RF voltage is clearly visible.

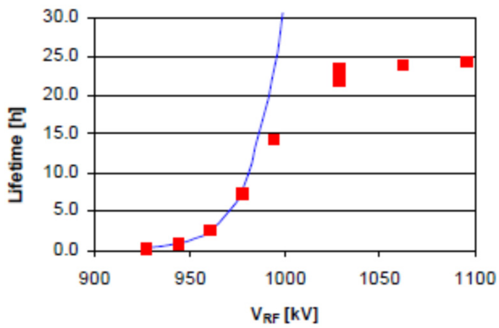

Figure 4: Beam lifetime versus RF voltage at 2.5 GeV user operation mode of KARA ring. Measured data are marked by red squares. Line is the calculated quantum lifetime at low voltage points. Figure is taken from [8].

Computer simulations of the lifetime as function of RF voltage have been performed for user optics and 2.5 GeV energy (Fig. 5). The lifetime of low intensity beam of 0.2 mA/bunch is marked by black curve, lifetime of 1 mA/bunch beam – by blue curve, lifetime of 2 mA/bunch beam – by green curve. The contribution of vacuum losses due to elastic/inelastic scattering is marked by blue/black dashed lines, and Touschek effect – by red dashed line. Radiation power of 2.5 GeV electrons in KARA ring is 0.622 MeV/turn, to compare black solid curve in Fig. 5 with

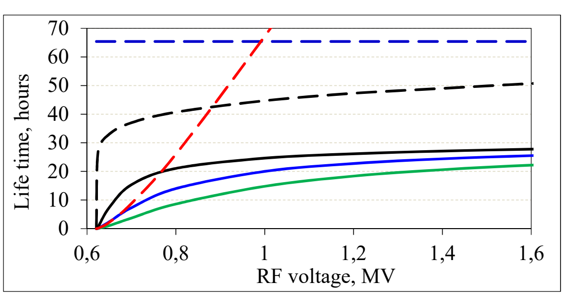

Figure 5: Simulations of the lifetime as function of RF voltage at user optics and 2.5 GeV energy. The lifetime of low intensity beam (0.2 mA/bunch) is marked by black curve, lifetime of 1 mA/bunch beam – by blue curve, lifetime of 2 mA/bunch beam – by green curve. The contribution of elastic/inelastic scattering is marked by blue/black dashed lines, Touschek lifetime – by red dashed line.

experimental data in Fig. 4. The discrepancy is due to calibration of absolute value of RF voltage.

Total loss rate of particles in a ring is a sum of loss rates of different scattering events. The Touschek lifetime at 2.5 GeV exceeds 100 hours at high RF voltage. Elastic scattering limits lifetime to about 65 hours i.e. well above measured lifetime. Contribution of inelastic scattering is a main limiting factor for user optics and high RF voltage. At low RF voltage <1 MV the lifetime of 2.5 GeV electrons is limited by the size of RF bucket. In addition, at high amplitude of RF voltage the momentum acceptance of KARA ring is restricted by the ring lattice. If momentum acceptance is limited by the ring lattice $MA_{RF} \geq MA_L$, the Touschek lifetime should be estimated by Eq. (3)

$$\tau_T \sim \gamma^{3.6}\frac{1}{I_b}(MA_L)^3\sqrt{\frac{\alpha_p}{V_{RF}}} = \frac{1}{I_b}\frac{\gamma^{3.6}}{|D_\pm|^3}\sqrt{\frac{\alpha_p}{h_{RF}\,V_{RF}}}. \quad (3)$$

At low energies, for example, at 1.3 GeV, the Touschek beam losses dominate at all operation regimes. Also momentum acceptance of ring lattice is reduced at low/negative−α, see Fig. 2. At the same, the bunch length is inversely proportional to the square root of RF voltage. By increasing the amplitude of RF voltage the bunch length is reduced and particle density is increased leading to growth of Touschek loss rate.

Beam lifetime as a function of the RF voltage at low compaction factor optics with α=+10^{-4} is shown in Fig. 6. Particle energy is 1.3 GeV. Black, blue and green curves correspond to computer simulations at beam current of 0.2, 0.5 and 1 mA/bunch. Lifetime of electrons at initial intensity of 0.5 mA/bunch has been measured low−α optics. Results of tests are shown by red curve. Simulations are well agreed with measured data.

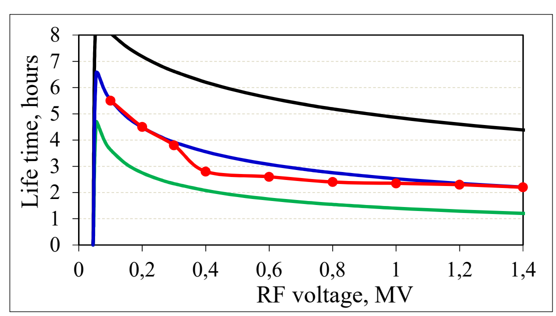

Figure 6: Beam lifetime as a function of the RF voltage at low momentum compaction optics with α=+10^{-4}. Beam energy is 1.3 GeV. Black, blue and green curves correspond to computer simulations at beam current of 0.2, 0.5 and 1 mA/bunch. Measured data are marked by red curve.

CONCLUSION

Ring performance, life time, beam current are essentially improved. Operation at negative compaction factor has been established and physical experiments are in progress.

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