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APPLICATION OF THREE FAMILIES OF SEXTUPOLES AT THE KARA RING OF KARLSRUHE INSTITUTE OF TECHNOLOGY

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Abstract

A third family of sextupole magnets was recently incorporated at the KIT storage ring KARA (Karlsruhe Research Accelerator). Computer studies of beam dynamics were performed with an objective to estimate benefits of operation with three sextupole families and possibility of new configuration of ring lattice to control slope and curvature of momentum compaction factor as function of energy offset of particles in a bunch. Adjustment of high order terms of alpha would allow to shorten bunch further down. Simulations of KARA ring model have been benchmarked on existing experiments at Metrology Light Source (MLS) in Berlin (Germany) and SOLEIL (France).

INTRODUCTION

Special techniques are applied to reduce the bunch length in electron storage rings [1,2]. In the so-called "squeezed" operation mode, the high degree of spatial compression of the optics with reduced momentum compaction factor ("low-α optics") entails complex longitudinal dynamics of the electron bunches. Bunch compression theory is based on non-linear longitudinal beam dynamics including high order terms of momentum compaction factor [3].

The path length variation of beam orbit in a ring can be split into two parts: one independent of momentum deviation (χ) and the other dependent on linear and high order terms of momentum offset δ, [4, 5]

$$\Delta L/L_0 = \alpha(\delta)\cdot\delta + \chi. \tag{1}$$

The momentum compaction factor itself depends on energy offset and is, up to the second order of energy deviation δ, defined as

$$\alpha(\delta) = \alpha_1 + \alpha_2\delta + \alpha_3\delta^2. \tag{2}$$

Zero current bunch length σ_l given by expression

$$\sigma_l = L_0\beta_0\delta_p\sqrt{\frac{E_0\cdot\alpha_1}{2\pi\cdot h\cdot eU_{RF}(-cos\varphi_s)}}\ . \tag{3}$$

is proportional to square root of momentum compaction factor α_1 and can be essentially reduced by implying low−α operation mode [6, 7].

Linear and high order components of the momentum compaction factor depend on dispersion function terms [8]

$$\alpha_1 = \frac{1}{L_0}\oint\left(\frac{D_0}{\rho}ds\right). \tag{4}$$

$$\alpha_2 = \frac{1}{L_0}\left[\oint\left(\frac{D_0^2}{2\rho^2}+\frac{D_1}{\rho}+\frac{D'^2_0}{2}\right)ds\right]. \tag{5}$$

$$\alpha_3 = \frac{1}{L_0}\left[\oint\left(\frac{D_0D_1}{\rho^2}+\frac{D_2}{2\rho}+D'_0D'_1\right)ds\right]. \tag{6}$$

The synchrotron tune, F_s , is a function of linear and high order terms of the momentum compaction factor [4], where α can be defined as a derivative of the relative orbit lengthening with momentum offset $\alpha = \partial(\Delta L/L_0)/\partial\delta$ [9, 10]

$$F_s(\delta) = F_0\sqrt{\frac{h\cdot eU_{rf}(-cos\varphi_s)}{2\pi\beta_0^2E_0}}\cdot\sqrt{(\alpha_1+2\alpha_2\delta+3\alpha_3\delta^2)}. \tag{7}$$

Based on Eq. (7), and converting the momentum offset to a variation of RF frequency

$$-\frac{\Delta F_{rf}}{F_{rf}} = \frac{\Delta L}{L_0} = (\alpha_3\delta^2+\alpha_2\delta+\alpha_1)\delta. \tag{8}$$

we benchmarked our simulations and precisely reproduced the synchrotron frequency as a function of RF frequency variation for SOLEIL [4] and MLS [11].

KARA MODEL

The 2.5 GeV KARA storage ring has a four-fold symmetry [12, 13] and operates at an energy range from 0.5 to 2.5 GeV. Our computer model of the KARA ring includes all magnetic and diagnostic elements (Fig. 1) and was described in detail earlier [14, 15].

Two families of horizontal (SH) and vertical (SV) sextupoles are located at the dispersive part of the double bend achromat cell (DBA) of the KARA ring. The original set up of the sextupole magnets was dictated by the necessity to suppress the head tail instability and operate the ring with high positive chromaticity of +2/+6. At present, high current beam is stabilized by a bunch-by-bunch feedback system [16]. The settings of the sextupole magnets were relaxed and stable circulation of electrons at top energy of 2.5 GeV and beam current up to 150 mA (1 mA/bunch) is realized at slightly positive chromaticity +1/+1.

The sextupoles for vertical chromaticity correction were split into two independent families with mirror reflected elements shown as SV1 and SV2 in Fig.1. In addition, a pair of dedicated sextupoles SL were incorporated in a ring model to control the second term of alpha and reduce longitudinal chromaticity at low−α regime. Also, four octu-

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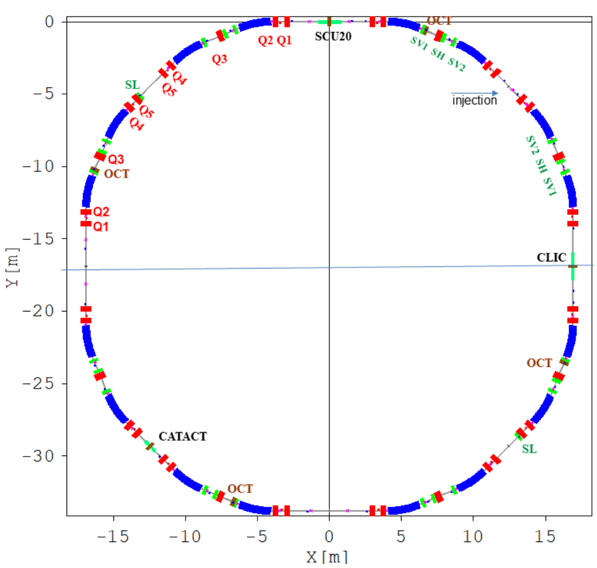

Figure 1: Model of the KARA ring [14]. Bending magnets are depicted in blue, five families of quadrupoles Q1 to Q5 are marked in red and the sextupoles – in green. The superconducting IDs CATACT/CLIC/SCU20 are shown by long green strips. Sextupoles to correct vertical chromaticity were split into two independent families SV1 and SV2. A pair of dedicated sextupoles SL would reduce longitudinal chromaticity while four octupoles OCT marked in brown should reverse curvature of α [11].

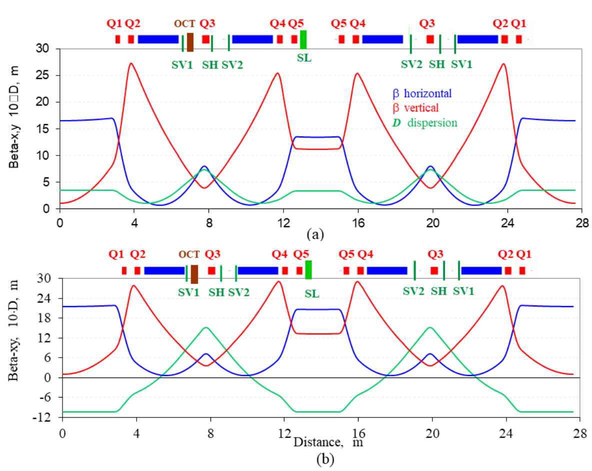

Figure 2: One cell of the KARA lattice with three families of sextupoles SV1, SH, SV2: (a) TME cell, (b) Low–α optics. Dedicated sextupoles SL will correct second term of momentum compaction factor (slope) while octupoles OC – third term of α (curvature). The horizontal/vertical beta-functions are depicted in blue/red, dispersion – green [13].

poles OCT were added in a model to change the sign of the third term of alpha and revers curvature of the momentum compaction factor as function of energy offset. The computer code OPA [17] was used to simulate linear and non-linear beam dynamics at different operation conditions Few operation modes are realized at KARA by applying

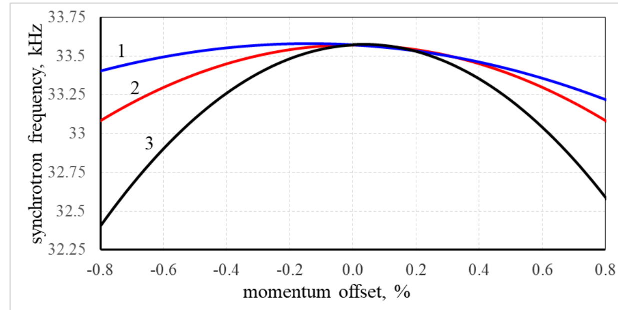

Figure 3: Synchrotron frequency as function of momentum offset for user optics with α_1=9.7×10^{-3}, beam energy of 0.5 GeV and RF voltage of 270 kV. High order terms of momentum compaction factor are varied by three families of sextupoles SV1, SH, SV2. The curve (1) corresponds to α_2=–3.2×10^{-3} and α_3=–0.78, curve (2) – reduced slope with α_2=8×10^{-8} and α_3= –1.46, curve (3) – reversed slope with α_2=+3.2×10^{-3} and α_3=–3.17. Equations (7, 8) and beam tracking by OPA [17] were used for simulations.

flexible optics [12-15]. Ring lattice with marked position of existing SV1, SH, SV2 sextupoles as well as proposed location of longitudinal sextupoles SL and octupoles OCT are shown in Fig. 2.

The user optics with a momentum compaction factor of α_1=+9.7·10^{-3} is based on a Theoretical Minimum Emittance (TME) cell where positive dispersion is ranging from 0.1 to 0.7 m (Fig. 2a). At low–α operation with α_1=+10^{-4} the dispersion function is stretched from +1.4 to –1 m (Fig. 2b) to compensate contribution of positive and negative components at azimuth of bending magnets [13].

Variation of synchrotron frequency as function of energy deviation is shown in Fig. 3 for user optics. Beam momentum offset from –0.8 to +0.8% is equivalent to the shift of RF frequency from –40 to +40 kHz, see Eq. 8. Change of slope (α_2) is realized by adjusting of sextupole settings and tuning high order terms of α.

The integrated strength of both SV1 and SV2 sextupole families should be increased in few times to reduce slope of compaction factor from "natural" (curve 1) with α_2=–3.2×10^{-3} (SH·L=+3.9 m^{-2}, SV1·L=–5.9 m^{-2} and SV2·L= 0) to flat (curve 2) with α_2=8×10^{-8} (SH·L=+3.54 m^{-2}, SV1·L=–15.3 m^{-2} and SV2·L=+10 m^{-2}). Extremely high strength should be applied to reverse slope (curve 3) and provide positive α_2=+3.2×10^{-3} (SH·L=+3.2 m^{-2}, SV1·L=–24.5 m^{-2} and SV2·L=+20 m^{-2}).

Location of SV1 and SV2 sextupoles is not favorable for variation of high order terms of alpha. Moreover, the control of high order terms cannot be realized by SV1 and SV2 families at low–α optics. These two families of sextupoles with opposite signs almost compensate each other. Breaking of lattice symmetry and individual powering of quadrupoles would be necessary to manipulate high order terms. At high sextupole strengths the betatron tunes are sharply shifted for off-momentum particles and dynamic aperture shrinks. Technical limits of existing sextupoles would

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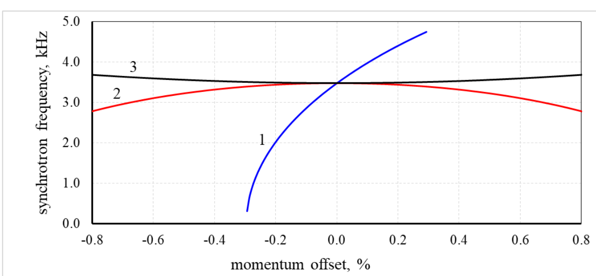
allow to demonstrate the variation of high order terms only at injection energy of 500 MeV.

ULTRA-LOW ALPHA OPTICS

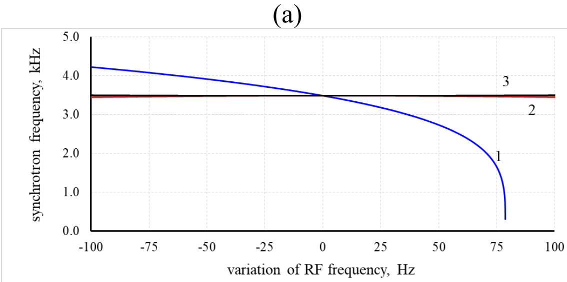
Contribution of sextupoles to vary second term of alpha is magnified by third power of dispersion function [1]. Two dedicated "longitudinal" sextupoles SL were added in the model at position where dispersion function is stretched to high negative value, see Fig. 2b. Also, four octupoles were implemented in the model at location of high magnitude of positive dispersion function (Fig. 2b). Simulations of F_S variation at low–α optics ($\alpha_1=1\times10^{-4}$) are presented in Figure 4. Horizontal SH and vertical SV sextupoles fix chromaticity to +1/+1 while high order terms of alpha are varied by two "longitudinal" sextupoles SL and by family of four octupoles OCT.

Crossing of zero value by synchrotron tune for off- momentum particles is considered as source of instability and beam loss [5]. Because of the strong second term $\alpha_2=+1.6\times10^{-2}$, see curve 1 in Fig. 4, the momentum acceptance of low–α optics with two families of sextupoles SH and SV is limited to ±0.3%. Energy spread is 5×10^{-4} at 1.3 GeV and beam emittance grows to 80 nm (rms) for low–α optics to compare with 16 nm for user TME optics ($\alpha_1=9.7\times10^{-3}$). Computed lifetime of 1 mA/bunch beam is ~2 hours and in good agreement with measurements [18].

Reduction of slope of synchrotron tune curve by weak "longitudinal" sextupoles SL (SL·L=+0.16 m^{-2}, SH·L= +2.72 m^{-2}, SV·L=–2 m^{-2}) would restore momentum acceptance (curve 2 in Fig.4) and improve lifetime of electrons at low–α operation. By adding a family of weak octupoles with integrated strength of –10 m^{-3} (curve 3 in Fig. 4) the negative curvature of the F_S can be reversed. At present, the reduction of α to the level of 10^{-5} cannot be realized due to high slope of α (curve 1 in Fig. 5). With weak "longitudinal" sextupoles (SL·L=+0.17 m^{-2}) one could flatten the slope (curve 2 in Fig. 5), restore momentum acceptance to ±0.4% and reduce momentum compaction factor further down to 10^{-5}. At low bunch current the pulse length would be reduced further from 2 to 0.7 ps (rms). The 0.5 hours lifetime of ultra-short bunches at 1.3 GeV and 1 mA/b current is satisfactory for measurements of beam parameters. Reversing of curvature by weak octupoles of –8 m^{-3} integrated strength (curve 3 in Fig. 5a,b) will improve lifetime at ultralow–α operation. The natural curvature of alpha is negative (curve 2 of Fig. 5) and one can test ultra-short bunches at negative–α without octupole magnets. Quadrupoles must be stabilized to 10^{-5} to avoid beam losses due to crossing of zero value of synchrotron tune.

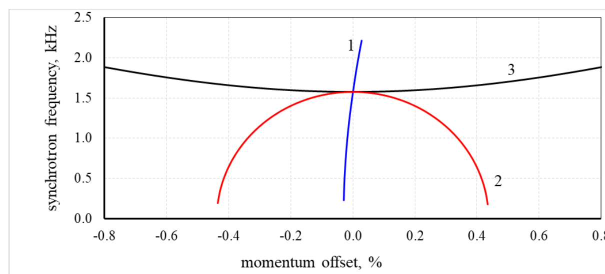


(a)

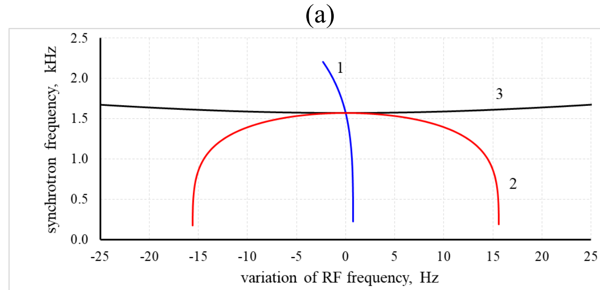


(b)

Figure 4: Synchrotron frequency as function of: (a) momentum offset, (b) RF frequency variation. Low–α optics with $\alpha_1=1\times10^{-4}$, beam energy 1.3 GeV and RF voltage 700 kV. The curve (1) corresponds to $\alpha_2=+1.6\times10^{-2}$ and $\alpha_3=-0.26$, curve (2) – reduced slope with $\alpha_2=-6.7\times10^{-6}$ and $\alpha_3=-0.2$, curve (3) – with $\alpha_2=-6.7\times10^{-6}$ and reversed curvature $\alpha_3=+0.064$.



(a)



(b)

Figure 5: Synchrotron frequency as function of (a) momentum offset, (b) RF frequency variation. Ultralow–α optics with $\alpha_1=1\times10^{-5}$, beam energy 1.3 GeV and RF voltage 1.4 MV. The curve (1) corresponds to $\alpha_2=+1.8\times10^{-2}$ and $\alpha_3=-0.27$, curve (2) – reduced slope with $\alpha_2=-1.1\times10^{-6}$ and $\alpha_3=-0.19$, curve (3) – with $\alpha_2=-1.1\times10^{-6}$ and reversed curvature $\alpha_3=+0.0234$.

CONCLUSION

Strong dependence of the synchrotron tune on energy offset might limit momentum acceptance and lifetime at low and negative–α operation. With two dedicated sextupoles and a family of four octupoles one could realize ultralow–α operation regime at KARA and reduce zero-current bunch length to ~700 fs (rms).

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