TOWARDS THE LOW EMITTANCE CANDLE STORAGE RING

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Abstract

Stimulated by the recent approaches and developments in low emittance lattice design and magnet technology a continuous process of CANDLE storage ring lattice improvement has been launched aiming to keep the project competitive in the field. The main goal of the upgrade program is to bring the beam emittances down to sub-nm level, having the condition of cost and performance efficiency. This paper summarizes the results obtained in the above-mentioned direction. The main design characteristics and linear/nonlinear beam dynamics aspects of the obtained new lattices are presented.

INTRODUCTION

The goal of emittance reduction in storage rings is to provide higher emitted light brightness. The particle beam emittance in electron storage ring, being formed as a result of equilibrium between the quantum excitations and damping of betatron oscillations, is defined by the magnetic structure (lattice) and the operation energy of the ring [1]. In the recent decade the most popular types of storage ring lattices for the third-generation synchrotron light sources have been the so-called achromats with multiple bending magnets (MBA), as they provide lower emittance than the well-known simple FODO lattices and supply zero-dispersion straight sections for allocation of insertion devices.

The recent progress in accelerator technology allowed reducing vacuum pipe cross sections and the magnet apertures, thus, making it possible to use short magnets with higher gradients. As a result, more lattice cells can be accommodated within a given ring circumference, leading to the reduction of beam emittance which is inversely proportional to the third power of bending magnets quantity.

The design of the MAX-IV 3 GeV storage ring [2], based on 7BA lattice structure, initiated a generational change in the development and realization of low emittance lattices. Many existing light source centres considered upgrading their storage ring lattices with the aim to reduce the emittance by 1-2 orders of magnitude (to sub-nm range).

The beam emittance can be additionally reduced by the implementation of bending magnets with field longitudinal variation (LGB) [3]. This option is already included in SIRIUS [4] storage ring lattice design.

As another possible way of lowering the emittance, the use of damping wigglers (to increase the radiated power and support the process of radiation dumping) can be considered [5]. It should be noted that all the above-mentioned options of emittance reduction are unavoidably leading to complicated beam dynamics, and one needs to take care of sufficient dynamic and momentum apertures to effectively inject electron beams to the storage ring and store them with sufficiently long lifetime.

The mentioned approaches and developments in low emittance lattice design and magnet technology encouraged us to start a continuous process for CANDLE [6] storage ring lattice improvement. In the current paper the results obtained thus far in this direction are summarized.

THEORETICAL CONSIDERATIONS

The natural horizontal equilibrium emittance ε_{x0}, in a flat storage ring lattice is given by the following well known expression: ε_{x0}[m·rad]$=C_q\gamma^2 I_5/(I_2-I_4)$ where C_q=3.83·10^{-13}m, γ is the Lorentz factor, $I_2=\oint\rho^{-2}\,ds$, $I_4=\oint\eta_x\rho^{-3}\left(1+2k\rho^2\right)ds$ and $I_5=\oint H_x\,|\rho|^{-3}\,ds$ are the corresponding synchrotron radiation integrals with $\rho=P_0/eB_y$ being the orbit radius with P_0 - the reference momentum of the beam and B_y - the vertically oriented bending field, k=e$(B_y)'_x/P_0$ - the focusing gradient in bending magnets, $H_x=\gamma_x\eta_x^2+2\alpha_x\eta_x\eta'_x+\beta_x\eta'^2_x$ - the dispersion betatron amplitude with β_x, $\alpha_x=-\beta'_x/2$, $\gamma_x=(1+\alpha_x^2)/\beta_x$ - the horizontal Courant–Snyder parameters and η_x, η'_x - the dispersion and its derivative. The emittance can be most efficiently reduced by minimization of I_5 integral, since an increase of I_2 is limited because of high synchrotron radiation losses $U_0\sim I_2$ and a manipulation of I_4 is restricted by the requirement to preserve the longitudinal damping and to get a low energy spread [1]. The minimization of I_5 requires small values of dispersion and horizontal beta function in all bending magnets. In addition, by allowing a longitudinal variation of the dipole field out of phase with the dispersion function (i.e. highest field at lowest dispersion and vice versa), one can reduce I_5 further and achieve sub-TME emittances [3].

CANDLE LOW EMITANCE LATTICES

CANDLE is a 3 GeV third generation synchrotron light source facility project in Armenia. The major components of CANDLE light source are the 100 MeV S-Band linac, the full energy booster synchrotron and storage ring with C = 216 m circumference. The latter is composed of N_{period} = 16 DBA cells and provides 8.4 nm horizontal emittance at E = 3 GeV operation energy.

The first attempt of emittance reduction was the change of the original lattice by considering the implementation of more compact magnets with combined fields, thus, increasing the number of bending magnets without changing the circumference of the machine and the DBA type of cells. This new design of storage ring lattice [7] allowed reducing the beam emittance from original 8.54 nm value down to 5.19 nm, while maintaining

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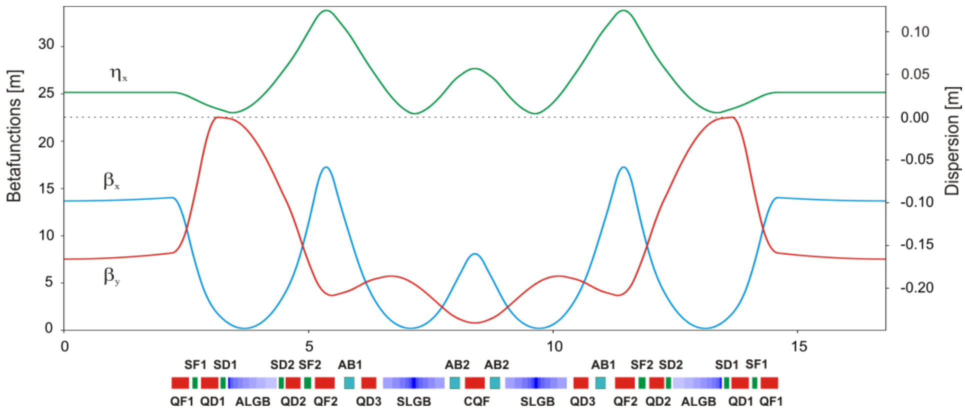

Figure 1: Beta functions and dispersion inside a cell of the new 4BA lattice.

sufficient dynamic and momentum acceptances.

Further, we studied the possibility of using MBA lattices. Several types of MBA lattices with different numbers of bending magnets per cell were considered. It was aimed to preserve the number of straight sections of the original lattice. Finally, a 4BA cell solution [7] was chosen, which provided about 1.1 nm beam emittance. The ring circumference for this solution was, however, 42 m longer as compared to the original CANDLE lattice.

Eventually, an application of LGBs and anti-bends (for dispersion tuning) was discussed, and a new 4BA lattice, providing 0.435 nm beam emittance within 268.8 m circumference, was developed [8]. The new lattice is composed of 16 4BA cells separated by L_{straight} = 4.4 m long straight sections. In Fig. 1 the beta functions and dispersion inside one cell of the new lattice are illustrated.

In order to save space and to decrease the forth radiation integral, in addition to three families of focusing quadrupoles (QF1, QF2, CQF), two families of anti-bends (AB1, AB2) are also supplied by transverse gradients for horizontal focusing. Also gradients for vertical focusing are introduced in four combined-function LGBs (with step-function field profiles) of the cell. During their field shape optimization, which was done by the LGB editor of the OPA program [9], very low values of horizontal beta function in bending magnets, required for the lowest emittance, were excluded to avoid its large values at the focusing quadrupoles neighbouring dipole magnets, which may cause aperture restrictions or difficulties in chromaticity correction.

With the implementation of described LGBs the emittance reduction by about factor of two as compared to the case of homogeneous bending magnets application was achieved. An additional emittance reduction by about 20% was obtained by "detuning" an achromat and allowing some small dispersion (0.03 m) in the straights.

Four families of sextupoles (SF1, SF2, SD1 and SD2) and integrated sextupole components of anti-bends are used to correct large chromaticities (ξ_x, ξ_y), produced by strong quadrupole fields. The chromaticity correction and sextuple optimization was done by OPA. The resulting on and off momentum (δ=±2%) dynamic apertures at the central point of the straight section are shown in Fig. 2.

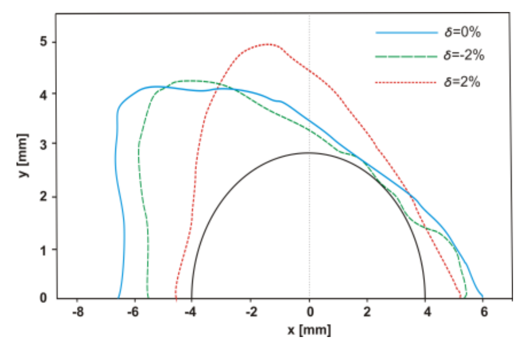

Figure 2: On and off momentum dynamic apertures at the central point of the straight section.

The relatively small values of dynamic apertures are typical for such low emittance lattices and are still acceptable from beam dynamics point of view (taking into account the emittance small value).

Note that anti-bends make the lattice quasi-isochronous which is characterized by the momentum acceptance of 2.6%. According to simulations the overall momentum acceptance (Δ_{accept}) is not limited by the transverse optics and is determined entirely by the longitudinal dynamics. For comparison, the main parameters of original CANDLE storage ring and considered new low emittance lattices are summarized in Table 1, where σ_δ is the beam natural energy spread and ν_x/ν_y are horizontal/vertical betatron tunes.

DAMPING WIGGLER CONSIDERATION

The ability of suitably designed and located wiggler magnets to damp the emittance of an electron beam in a storage ring is well known [1]. The effect is given by

$$\frac{\varepsilon_{xw}}{\varepsilon_{x0}} = \frac{1+1.21\times10^{-12}\,\beta_x L_w \lambda_w^2 \rho_0 B_w^5 / J_x \varepsilon_{x0} E^3}{1+7.16\times10^{-3}\,L_w \rho_0 B_w^2 / E^2} \qquad (1)$$

where L_{w}, λ_{w} and B_{w} are the wiggler length, period and peak field, respectively, ρ_0 is the ring curvature radius, β_{x} is the average horizontal beta function in the wiggler and J_{x} is the horizontal dumping partition number.

Table 1: The Main Parameters of CANDLE Original Storage Ring and New Low Emittance Lattices

Param.	Orig.	DBA	4BA	4BA+ LGB
C (m)	216	216	258	268.8
N_{period}	16	24	16	16
$L_{straight}$ (m)	4.8	4.4	4.2	4.4
E (GeV)	3	3	3	3
ε_{x0} (nm rad)	**8.4**	**5.2**	**1.1**	**0.435**
σ_δ (%)	0.1	0.15	0.1	0.11
Δ_{accept} (%)	2.4	2.1	3.9	2.6
ξ_x / ξ_y	-18.91/ -14.86	-13.64/ -24.27	-38.27/ -26.04	-95.16/ -33.92
ν_x/ ν_y	13.2/ 4.26	14.17/ 3.19	24.61/ 14.37	29.2/ 8.36

The complicated term in the numerator (Eq. (1)) is related to the wiggler generated self-dispersion, which can result in additional quantum excitation that may prevent the emittance reduction or even worse – increase it, depending on the wiggler period and peak field. To lower the emittance it is preferable to use wigglers with small period and moderate field, since the longer is the wiggler period, the larger is the self-dispersion and with the increase of wiggler field, at some point the effect of the wiggler is to increase, not decrease, the emittance.

For the 4BA+LGB lattice the possibility of emittance additional reduction, achieved by wiggler usage, was also examined. In this lattice 12 straight sections out of 16 are available for ID allocation. We have studied the case when four wiggler magnets with parameters presented in Table 2 are used.

Table 2: Main Parameters of Used Wigglers

Parameter	Value
λ_w (mm)	40
B_w (T)	2.6
L_w (m)	4
K - Parameter	9.7
Total power (kW), 350 mA beam	54
Photon energy (keV), n=1	0.044

The length and period of used wigglers were chosen based on available straight section length and technical realisation difficulties. The wiggler field of 2.6 T was chosen to provide maximal emittance reduction (see Fig. 3).

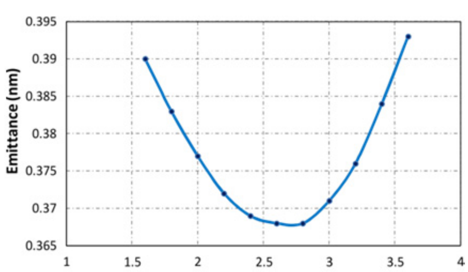

Figure 3: Emittance versus wiggler peak field.

As the study showed, the implementation of such wigglers allows to achieve an additional 15% emittance reduction. However, the impact on the linear optics is considerable, rising concerns about the nonlinear beam dynamics, which are common in any damping wiggler scheme. These issues are currently under investigation.

SUMMARY

This paper summarizes the results obtained during CANDLE storage ring low emittance upgrade program. Based on the implementation of combined function magnets, MBA concept, longitudinal gradient bends and antibends, new low emittance lattices have been developed. The progress of the upgrade program is demonstrated in Fig. 4, where beam emittances, which these lattices would provide if they had 216 m circumference, are charted.

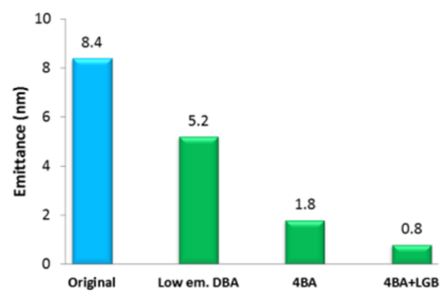

Figure 4: Beam emittances in case of 216 m circumference.

For 4BA+LGB lattice the possibility of emittance additional reduction, achieved by wiggler usage, was also studied. While giving additional 15% emittance reduction, this option, however, seems not optimal from cost and performance points of view.

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